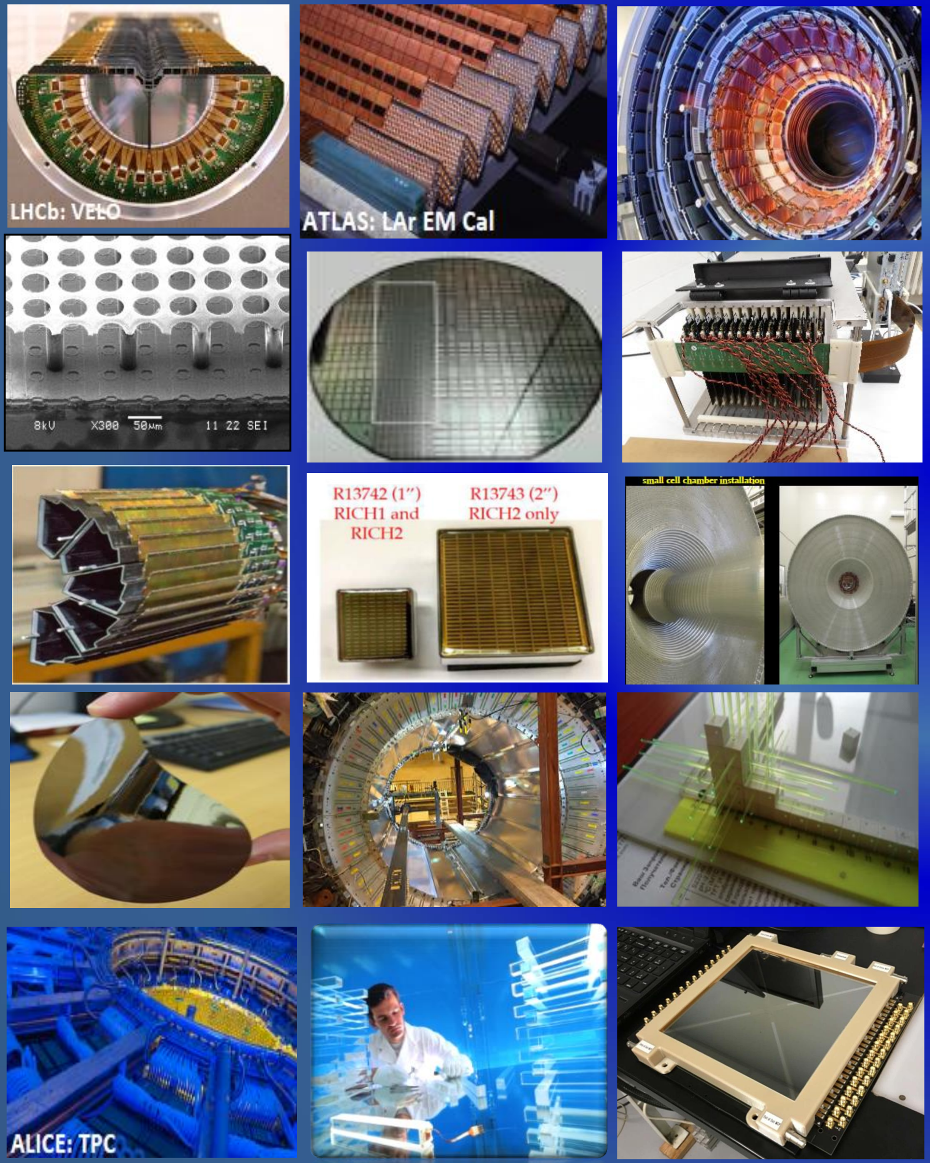
Next Frontiers in Particle Physics Detectors

Maxim Titov, CEA Saclay, Irfu, France



TALK OUTLINE:

- Introduction and Overview
- Advancing Concepts in Vertex/Tracking
    - Solid State (Silicon) Detectors
    - Micro-Pattern Gaseous Detectors
- Advancing Concepts in Picosecond-Timing Detectors
- Advanced Concepts in Particle Identification and Photon Detectors
- Advanced Concepts in Calorimetry
- Advanced Concepts in TDAQ, Computing
- Summary and outlook

RAL Particle Physics Department
Seminar, December 2, 2020

Future Collider Facilities: A Wealth of Detector R&D Activities

- ➢ Plethora of excellent instrumentation conferences each year
- ➢ Too many different experiments and R&D techniques to cover even partially

THIS TALK: attempt to list the key technology challenges in the context of the future Energy Frontier collider facilities: using synergies in detector R&Ds between hadron & lepton colliders (not much about Intensity and Cosmic Instrumentation Frontier needs → apologies)

→ It is (mostly) based on the summary talk & proceedings of the INSTR2020 conference:
https://indico.inp.nsk.su/event/20/timetable/#20200224.detailed

→ Linear Collider Collaboration Detector R&D Liaison Report (new update early 2021):
http://ww2.linearcollider.org/P-D/Working-groups/Detector-R-D-liaison

International Conference on Instrumentation for Colliding Beam Physics

INSTR - 2020

24 - 28 February, 2020, BINP, Novosibirsk, Russia

The International Conference «Instrumentation for Colliding Beam Physics» (INSTR 20) will be cohosted by the Budker Institute of Nuclear Physics (BINP) and Novosibirsk State University (NSU), Novosibirsk, Russia, from 24 to 28 February,2020.

This conference is in close relationship with those held in Vienna (VCI or Vienna Conference on Instrumentation) and on Elba (PM or Pisa Meeting on Advanced Detectors). The conference covers novel methods of particle detection used in various experiments at particle colliders and other accelerators as well as in astrophysics.

SCIENTIFIC PROGRAM

The aim of the Conference is to review the status and progress in instrumentation for experiments at colliding beams and related fields. The main topics include:

- Colliders and detector integration
- Tracking and vertex detectors
- Timing detectors
- Micropattern gas detectors
- Particle Identification
- Calorimetry
- Instrumentation for Astroparticle and Neutrino physics
- Electronics, Trigger and Data Acquisition
- Computing and software in HEP

The program will consist of plenary and poster sessions.

Organized by Budker Institute of Nuclear Physics SB RAS and Novosibirsk State University

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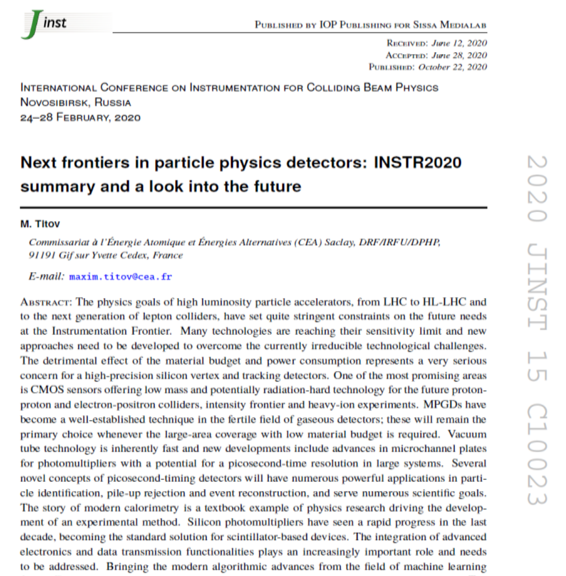

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *June 12, 2020*
ACCEPTED: *June 28, 2020*
PUBLISHED: *October 22, 2020*

INTERNATIONAL CONFERENCE ON INSTRUMENTATION FOR COLLIDING BEAM PHYSICS
NOVOSIBIRSK, RUSSIA
24–28 FEBRUARY, 2020

Next frontiers in particle physics detectors: INSTR2020 summary and a look into the future

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ABSTRACT: The physics goals of high luminosity particle accelerators, from LHC to HL-LHC and to the next generation of lepton colliders, have set quite stringent constraints on the future needs at the Instrumentation Frontier. Many technologies are reaching their sensitivity limit and new approaches need to be developed to overcome the currently irreducible technological challenges. The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision silicon vertex and tracking detectors. One of the most promising areas is CMOS sensors offering low mass and potentially radiation-hard technology for the future proton-proton and electron-positron colliders, intensity frontier and heavy-ion experiments. MPGDs have become a well-established technique in the fertile field of gaseous detectors; these will remain the primary choice whenever the large-area coverage with low material budget is required. Vacuum tube technology is inherently fast and new developments include advances in microchannel plates for photomultipliers with a potential for a picosecond-time resolution in large systems. Several novel concepts of picosecond-timing detectors will have numerous powerful applications in particle identification, pile-up rejection and event reconstruction, and serve numerous scientific goals. The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method. Silicon photomultipliers have seen a rapid progress in the last decade, becoming the standard solution for scintillator-based devices. The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed. Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge. The timescales spanned by future projects in particle physics, ranging from few years to many decades, constitute a challenge in itself, in addition to the complexity and diversity of the required accelerator and detector R&D. This paper summarizes advances and recent trends in the instrumentation techniques for particle physics experiments, largely based on the presentations given at the International

2020 JINST 15 C10023

LINEAR COLLIDER COLLABORATION

Detector R&D Report

Deadline for submissions: May 15th, 2020
DRAFT
VERSION 2020.1

Editors

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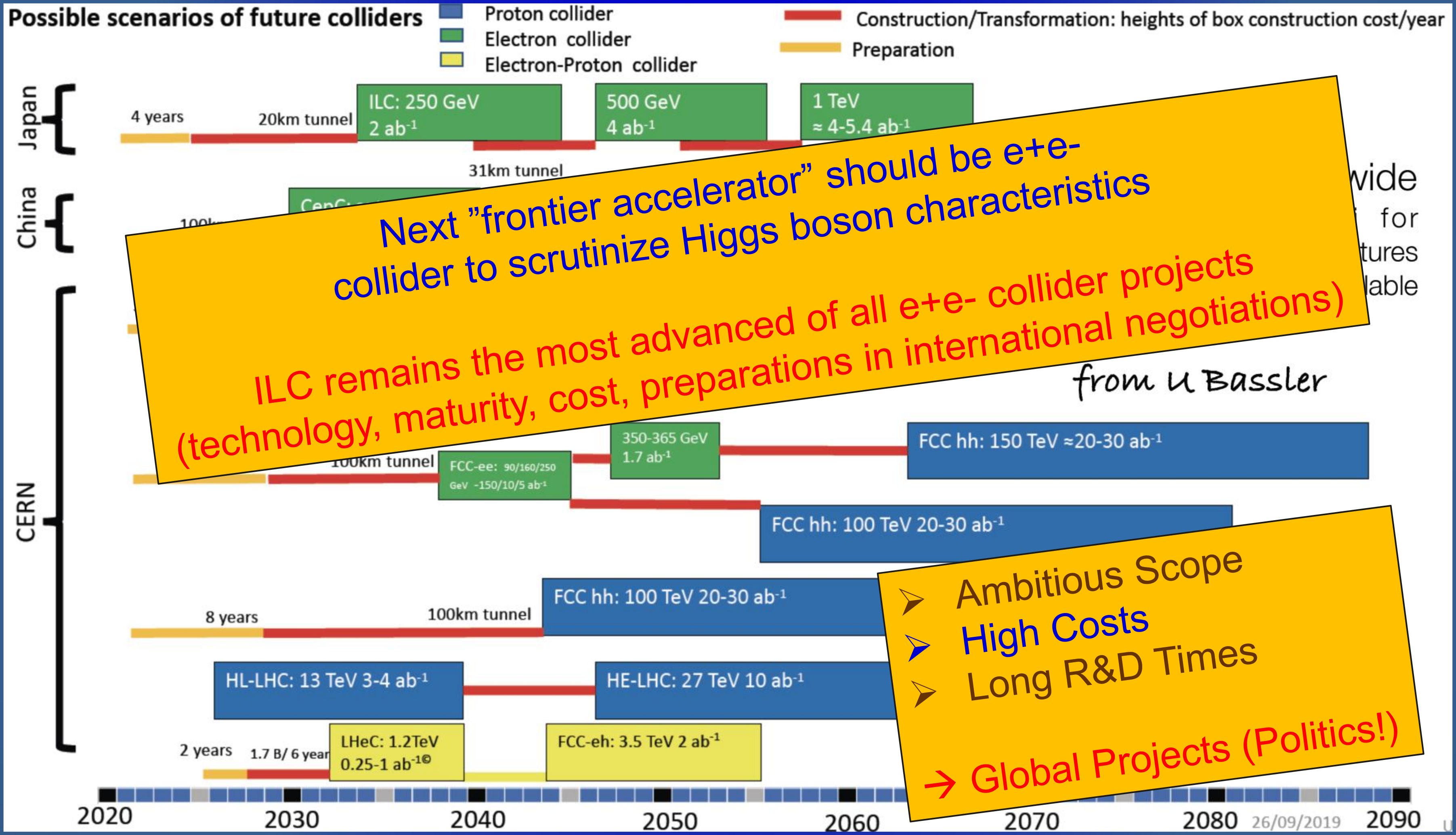
Update to be released early 2021

April 25, 2020

European Strategy Update: Shaping the Future of Particle Physics

- Global vision for our domain going beyond regional boundaries
- In the case of global facility outside of Europe, CERN should act as the European regional hub providing strategic coordination and technical support



Next "frontier accelerator" should be e+e- collider to scrutinize Higgs boson characteristics

ILC remains the most advanced of all e+e- collider projects (technology, maturity, cost, preparations in international negotiations)

- Ambitious Scope
- High Costs
- Long R&D Times

→ Global Projects (Politics!)

European Strategy Update also calls for **Accelerator & Detector R&D** Technology **Roadmaps**

Storage Rings or Linear Collides for Future e+e- Accelerator

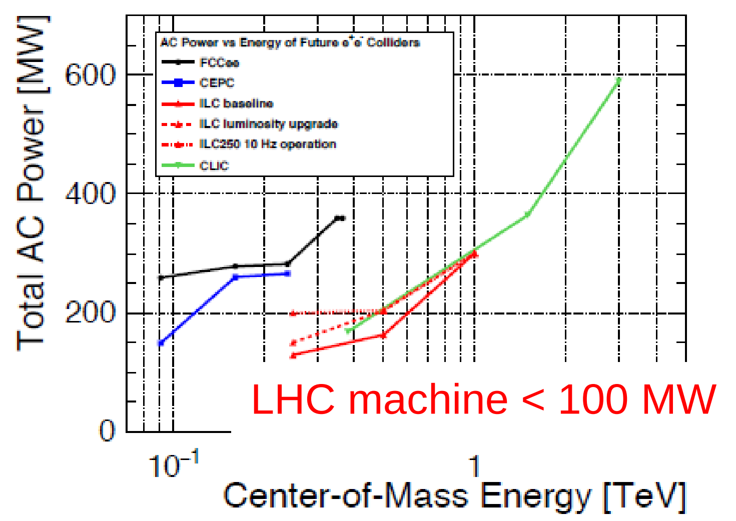
Accelerator R&D Roadmap (intensify accelerator R&D and sustain it with adequate resources):
https://indico.cern.ch/event/966397/contributions/4067075/attachments/2147034/3619166/AccRoadMap_LRivkin_PECFA.pdf

Power consumption is an important consideration!

- Energy tends to be the cost driver:
  → hadrons - high-field magnets;
  → e+e- - high-gradient RF

Circular collider:
→ high-luminosity from Z peak to top threshold

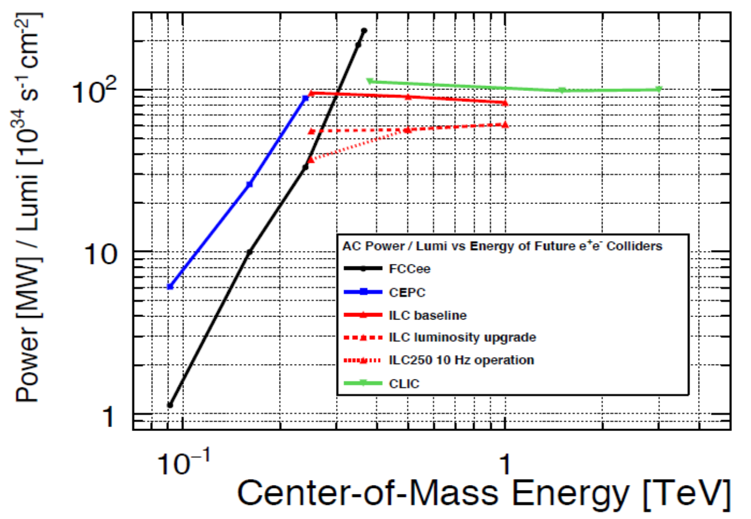
Linear colliders:
→ extendability to high energies / beam polarization



LHC machine < 100 MW

- $\mathcal{L} \times E_{CM}$ drives the MWatts (at least for leptons):
  → it's all about COST per GeV | inv fb

https://indico.fnal.gov/event/20759/contributions/58924/attachr
nts/36900/44905/Lum-Energy-doc-preliminary.pdf

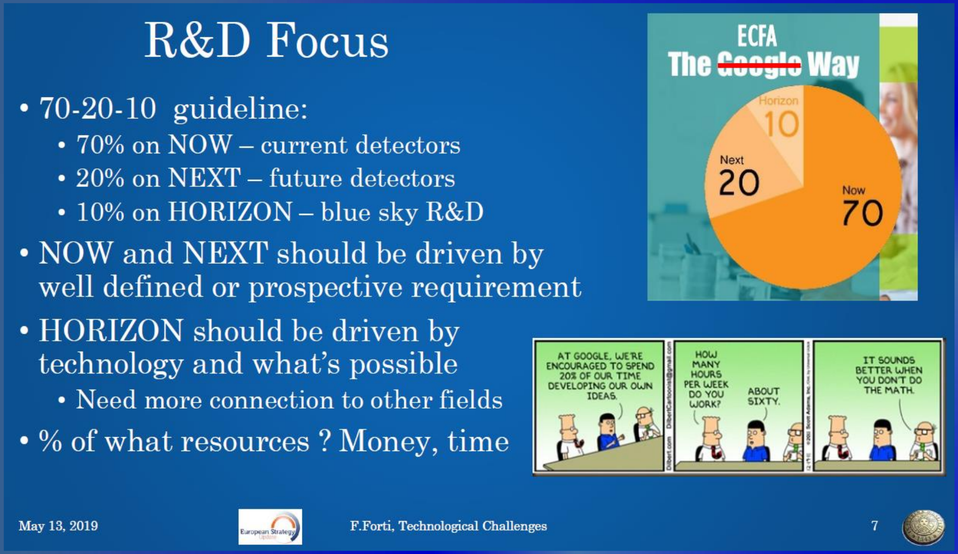


- Where are the acceptable limits? (not the technical limits)
- High running costs may need to be shared (global project)
- R&D needed in increasing efficiencies and/or recovering the energy

Linear Collider provides power
efficient luminosity for > 250 GeV

European Strategy Discussion on (Future) Instrumentation R&D

ESPP Symposium (Granada, May 2019): https://indico.cern.ch/event/808335/timetable/#all.detailed



R&D Focus

- 70-20-10 guideline:
  - 70% on NOW – current detectors
  - 20% on NEXT – future detectors
  - 10% on HORIZON – blue sky R&D
- NOW and NEXT should be driven by well defined or prospective requirement
- HORIZON should be driven by technology and what's possible
  - Need more connection to other fields
- % of what resources ? Money, time

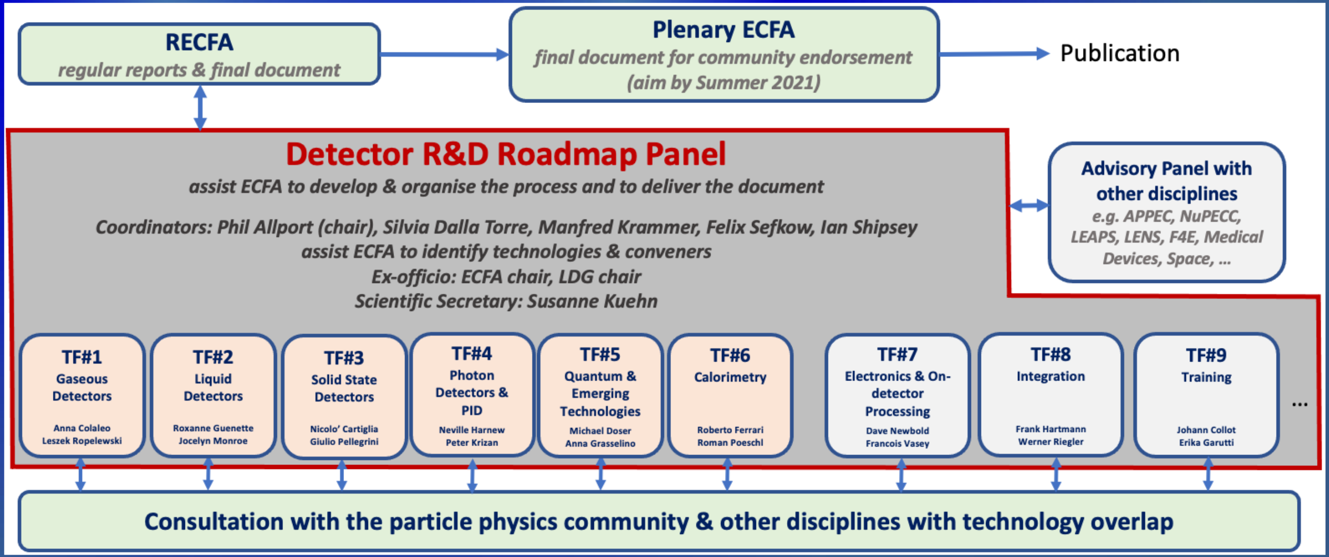
May 13, 2019 F.Forti, Technological Challenges 7

- **Importance (at an appropriate level) of Generic / "blue sky" R&D**
- **Recognition of excellence in instrumentation → Career opportunities for detector physicists in universities/ research institutes must be greatly strengthened to foster participation of young people in this branch of science**

Detector R&D Roadmap (to guide Detector R&D process in Europe and define inclusive roadmap):
https://indico.cern.ch/event/966397/contributions/4067074/attachments/2146995/3619108/EFCA_DetRDRoadmap_ECFA201120_SK.p

Chair: P. Allport (RAL, UK)

ambitious timeline to
present European
Detector Roadmap
at the EPS-HEPP
Conference in July 2021



RECFA
regular reports & final document

Plenary ECFA
final document for community endorsement
(aim by Summer 2021)

Publication

Detector R&D Roadmap Panel
assist ECFA to develop & organise the process and to deliver the document

Coordinators: Phil Allport (chair), Silvia Dalla Torre, Manfred Krammer, Felix Sefkow, Ian Shipsey
assist ECFA to identify technologies & conveners
Ex-officio: ECFA chair, LDG chair
Scientific Secretary: Susanne Kuehn

Advisory Panel with other disciplines
e.g. APPEC, NuPECC, LEAPS, LENS, F4E, Medical Devices, Space, …

- **TF#1** Gaseous Detectors — Anna Colaleo, Leszek Ropelewski
- **TF#2** Liquid Detectors — Roxanne Guenette, Jocelyn Monroe
- **TF#3** Solid State Detectors — Nicolo' Cartiglia, Giulio Pellegrini
- **TF#4** Photon Detectors & PID — Neville Harnew, Peter Krizan
- **TF#5** Quantum & Emerging Technologies — Michael Doser, Anna Grasselino
- **TF#6** Calorimetry — Roberto Ferrari, Roman Poeschl
- **TF#7** Electronics & On-detector Processing — Dave Newbold, Francois Vasey
- **TF#8** Integration — Frank Hartmann, Werner Riegler
- **TF#9** Training — Johann Collot, Erika Garutti
- …

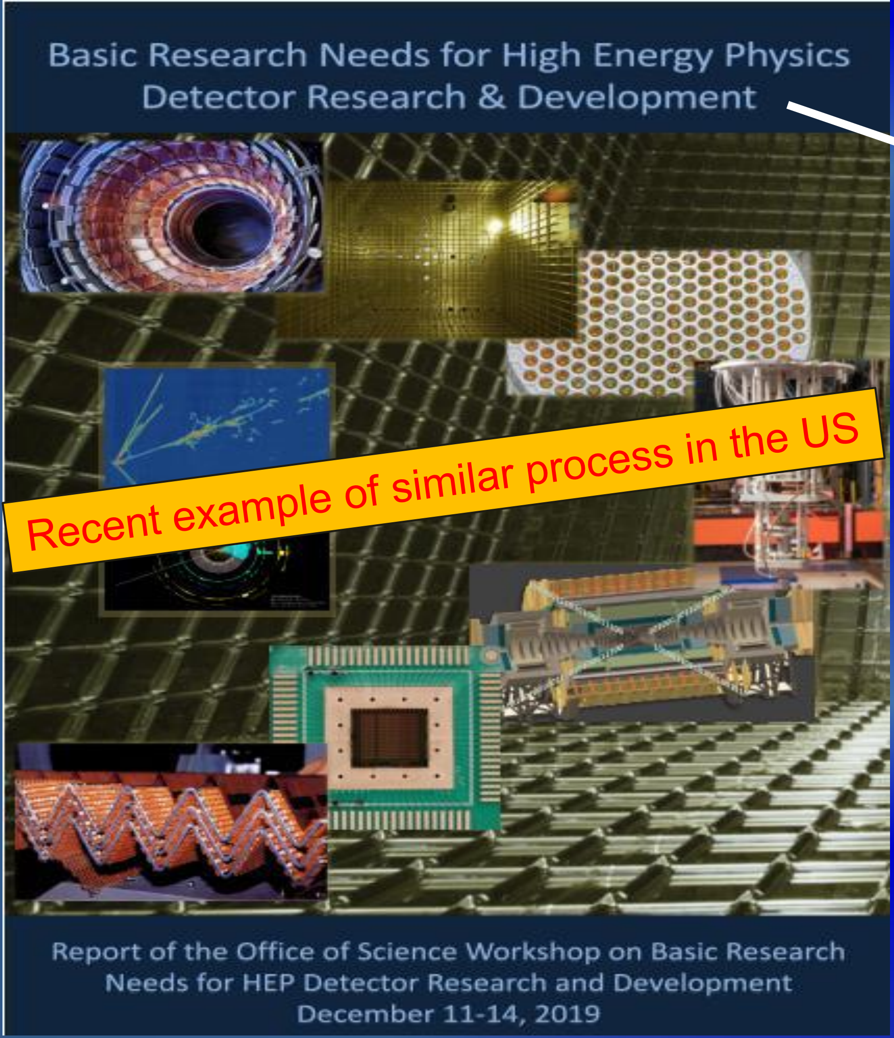
Consultation with the particle physics community & other disciplines with technology overlap

US: Basic Research Needs Report & Snowmass Process

The Snowmass Process is organized by the DPF of the American Physical Society: **https://snowmass21.org**

→ Identify and document a vision for the future of particle physics (PP) in the US in a global context

→ Communicate opportunities for discovery in PP to broader community and to the (US) government.



Basic Research Needs for High Energy Physics
Detector Research & Development

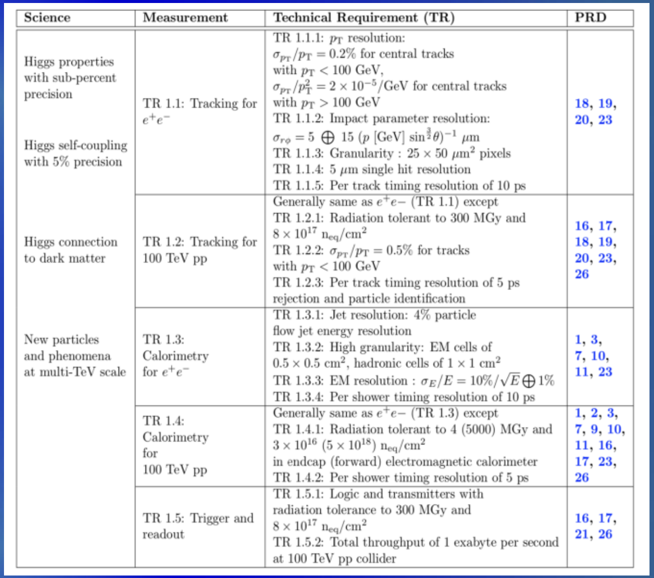
Recent example of similar process in the US

Report of the Office of Science Workshop on Basic Research
Needs for HEP Detector Research and Development
December 11-14, 2019

BRN Report published in Sep. 2020:

https://science.osti.gov/hep/Community-Resources/Reports

EF physics/instrumentation drivers in BRN are Higgs-centered:



Science	Measurement	Technical Requirement (TR)	PRD
Higgs properties with sub-percent precision Higgs self-coupling with 5% precision	TR 1.1: Tracking for e^+e^-	TR 1.1.1: p_T resolution: $\sigma_{p_T}/p_T = 0.2\%$ for central tracks with $p_T < 100$ GeV, $\sigma_{p_T}/p_T^2 = 2 \times 10^{-5}$/GeV for central tracks with $p_T > 100$ GeV TR 1.1.2: Impact parameter resolution: $\sigma_{r\phi} = 5 \bigoplus 15\ (p\ [\mathrm{GeV}] \sin^{\frac{3}{2}}\theta)^{-1}\ \mu\mathrm{m}$ TR 1.1.3: Granularity : $25 \times 50\ \mu\mathrm{m}^2$ pixels TR 1.1.4: 5 μm single hit resolution TR 1.1.5: Per track timing resolution of 10 ps	18, 19, 20, 23
Higgs connection to dark matter	TR 1.2: Tracking for 100 TeV pp	Generally same as e^+e- (TR 1.1) except TR 1.2.1: Radiation tolerant to 300 MGy and $8 \times 10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.2.2: $\sigma_{p_T}/p_T = 0.5\%$ for tracks with $p_T < 100$ GeV TR 1.2.3: Per track timing resolution of 5 ps rejection and particle identification	16, 17, 18, 19, 20, 23, 26
New particles and phenomena at multi-TeV scale	TR 1.3: Calorimetry for e^+e^-	TR 1.3.1: Jet resolution: 4% particle flow jet energy resolution TR 1.3.2: High granularity: EM cells of $0.5 \times 0.5\ \mathrm{cm}^2$, hadronic cells of $1 \times 1\ \mathrm{cm}^2$ TR 1.3.3: EM resolution : $\sigma_E/E = 10\%/\sqrt{E} \bigoplus 1\%$ TR 1.3.4: Per shower timing resolution of 10 ps	1, 3, 7, 10, 11, 23
	TR 1.4: Calorimetry for 100 TeV pp	Generally same as e^+e- (TR 1.3) except TR 1.4.1: Radiation tolerant to 4 (5000) MGy and 3×10^{16} (5×10^{18}) $\mathrm{n_{eq}/cm^2}$ in endcap (forward) electromagnetic calorimeter TR 1.4.2: Per shower timing resolution of 5 ps	1, 2, 3, 7, 9, 10, 11, 16, 17, 23, 26
	TR 1.5: Trigger and readout	TR 1.5.1: Logic and transmitters with radiation tolerance to 300 MGy and $8 \times 10^{17}\ \mathrm{n_{eq}/cm^2}$ TR 1.5.2: Total throughput of 1 exabyte per second at 100 TeV pp collider	16, 17, 21, 26

Within Snowmass process, compile extended list of physics drivers and base technology requirements on them, e.g.:

- ✓ LLP searches – requirements on granularity (low mass tracking) and and PID(ps-timing) – benchmark for timing/trigger;
- ✓ Boosted / Substructure object reconstruction
- ✓ Higgs Couplings to light quarks (charm, strange) and tau-tagging;

Technology Synergies in Detector R&D with non-HEP/Industry

European Commission funded programs, such as EUDET, AIDA, ATTRACT play important role in enabling and supporting generic R&Ds

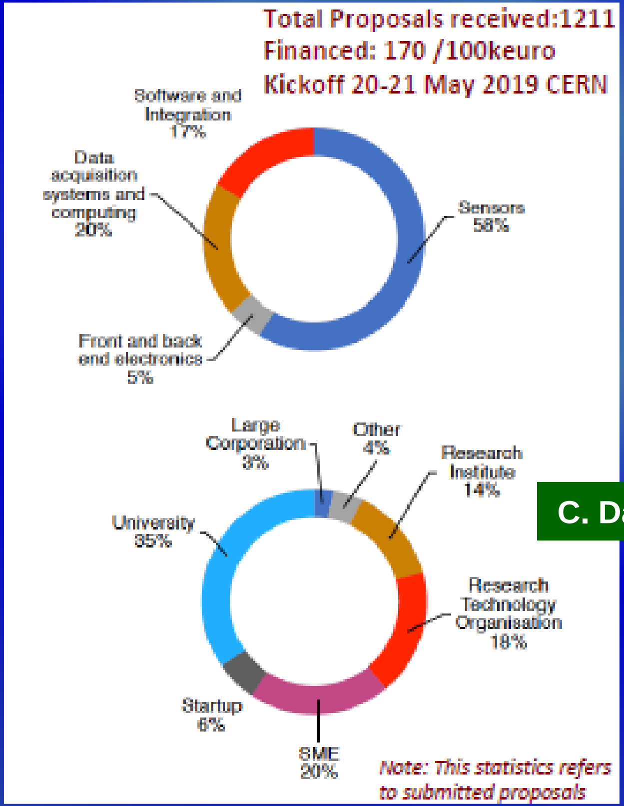
2018 ATTRACT CALL: Funds for multi-disciplinary detectors and imaging R&D

→ Initiative bringing together Europe's fundamental research and industrial communities to lead the next generation of detection and imaging technologies (**https://attract-eu.com**)

ATTRACT Phase I Statistics:

- Phase 1 is officially closed since October 31st, 2020
  → Presentation of 170 papers happened in September and is available online

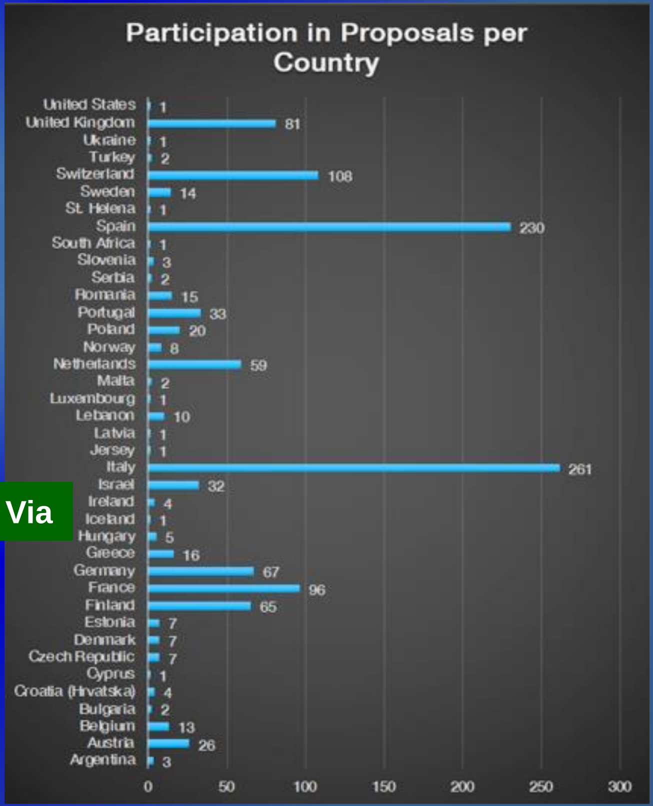
- Phase 2 has been approved and should kickoff in January 2021



Total Proposals received:1211
Financed: 170 /100keuro
Kickoff 20-21 May 2019 CERN

Note: This statistics refers to submitted proposals

C. Da Via

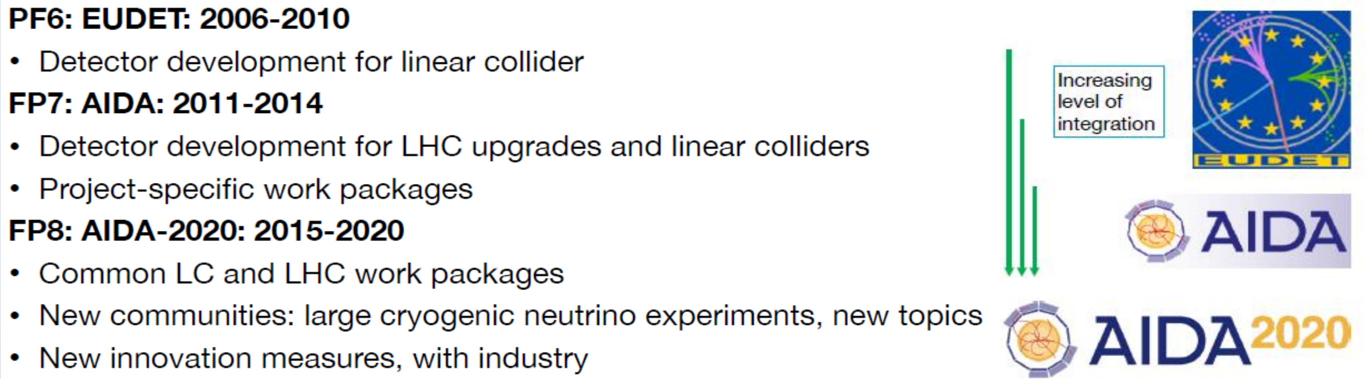


Complementary funding for new concepts or original extensions of existing ideas with emphasis of important industrial impact:

The New AIDAinnova Project and Detector R&D for Higgs Factories

https://indico.cern.ch/event/932973/contributions/4066737/attachments/2140131/3606033/Ainnova-HiggsF-FSefkow20201110.pdf

History: EC-funded Detector R&D Projects



PF6: EUDET: 2006-2010
- Detector development for linear collider

FP7: AIDA: 2011-2014
- Detector development for LHC upgrades and linear colliders
- Project-specific work packages

FP8: AIDA-2020: 2015-2020
- Common LC and LHC work packages
- New communities: large cryogenic neutrino experiments, new topics
- New innovation measures, with industry

Increasing level of integration

F. Sefkow

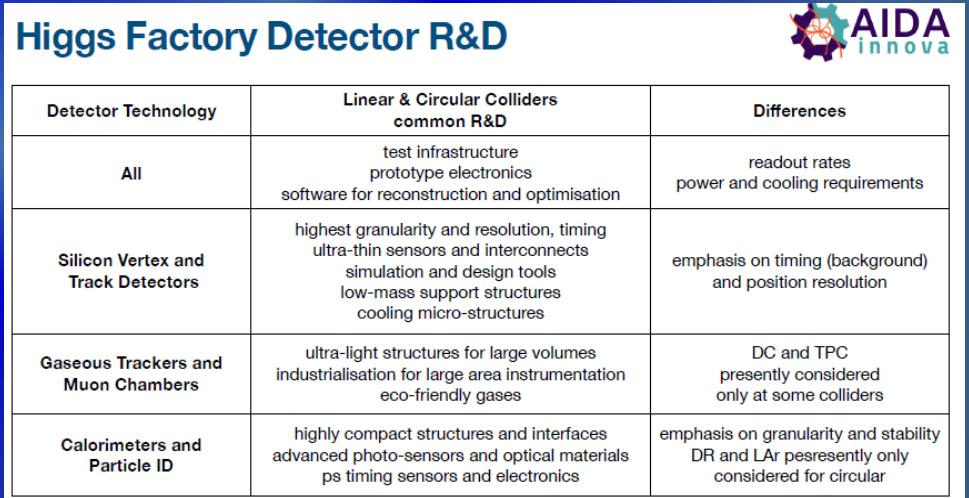
New AIDAinnova Call / Objectives:

- ✓ Support research **infrastructure** networks developing and implementing a **common strategy/ roadmap** including technological development required for improving their services through **partnership with industry**
- ✓ Support **incremental innovation** and cooperation with industry

- Complementarity to ATTRACT
- Increased focus on industrial partners
- No Transnational Access Proposed
- Funding 10 M€ for 4 years

Some targeted applications:

- ✓ **Higgs Factories**
- ✓ **ATLAS, CMS LS4, ALICE, LHCb LS3 pre-TDR**
- ✓ **Accelerator-based neutrino experiments**



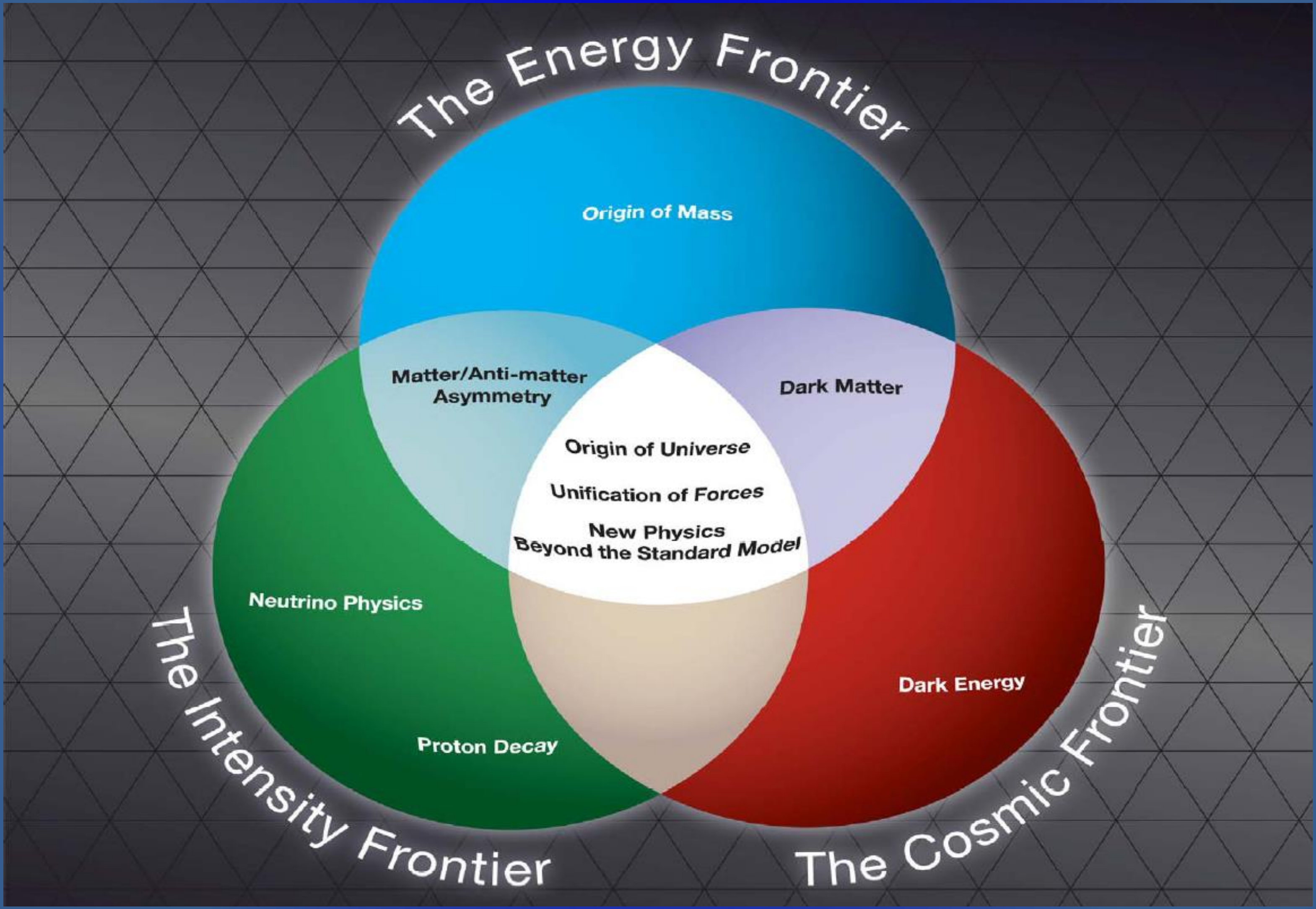
Higgs Factory Detector R&D

Detector Technology	Linear & Circular Colliders common R&D	Differences
All	test infrastructure prototype electronics software for reconstruction and optimisation	readout rates power and cooling requirements
Silicon Vertex and Track Detectors	highest granularity and resolution, timing ultra-thin sensors and interconnects simulation and design tools low-mass support structures cooling micro-structures	emphasis on timing (background) and position resolution
Gaseous Trackers and Muon Chambers	ultra-light structures for large volumes industrialisation for large area instrumentation eco-friendly gases	DC and TPC presently considered only at some colliders
Calorimeters and Particle ID	highly compact structures and interfaces advanced photo-sensors and optical materials ps timing sensors and electronics	emphasis on granularity and stability DR and LAr pesresently only considered for circular

Nov. 2020: AIDAinnova project has been invited to the grant preparation phase

Cutting Edge Science Relies on Cutting Edge Instrumentation

Technologies developed under generic R&D and/or experiment-oriented programs at the Energy Frontier provide a boost in novel designs that often suit the needs of Intensity / Cosmic Frontiers



What will be the role of quantum sensors in Particle Physics in the future ?

Technology-Oriented R&D Collaborations

- Originally: ”Cell” approach, oriented to select the different LHC experiment detector technologies
  CERN DRDC program (90’s): http://committees.web.cern.ch/Committees/obsolete/DRDC/Projects.html

→ Today: Successful approach to streamline efforts/resources, handle new techniques and common components to on-going detector engineering challenges/production:

✓ RD42 – Diamond detectors
✓ RD50 – Silicon radiation hard devices
✓ RD51 – Micropattern gas detectors
✓ RD53 – Pixel readout chip for ATLAS and CMS (65 nm)

} Mostly EU-based, with world-wide participation

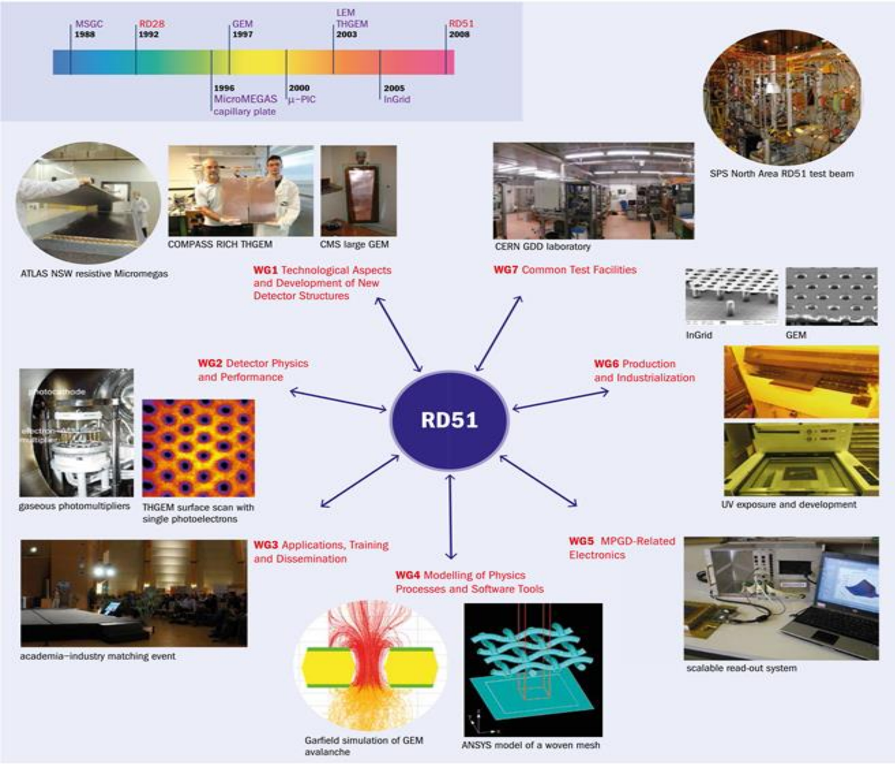
→ In general, large collaborations of interacting institutes
→ Good model, allows to consolidate resources – especially people
→ CERN is central, but support needed from other labs and agencies

- **Detector R&D Programs – originally focused on ILC and CLIC Linear Colliders**
  (exploit complementary / commonalities of technological developments for different facilities)

  - CALICE high granularity electromagnetic and hadronic calorimeters (since 2001 for ILC)
  → CALICE enabled high granularity calorimetry for CMS HL-LHC upgrade

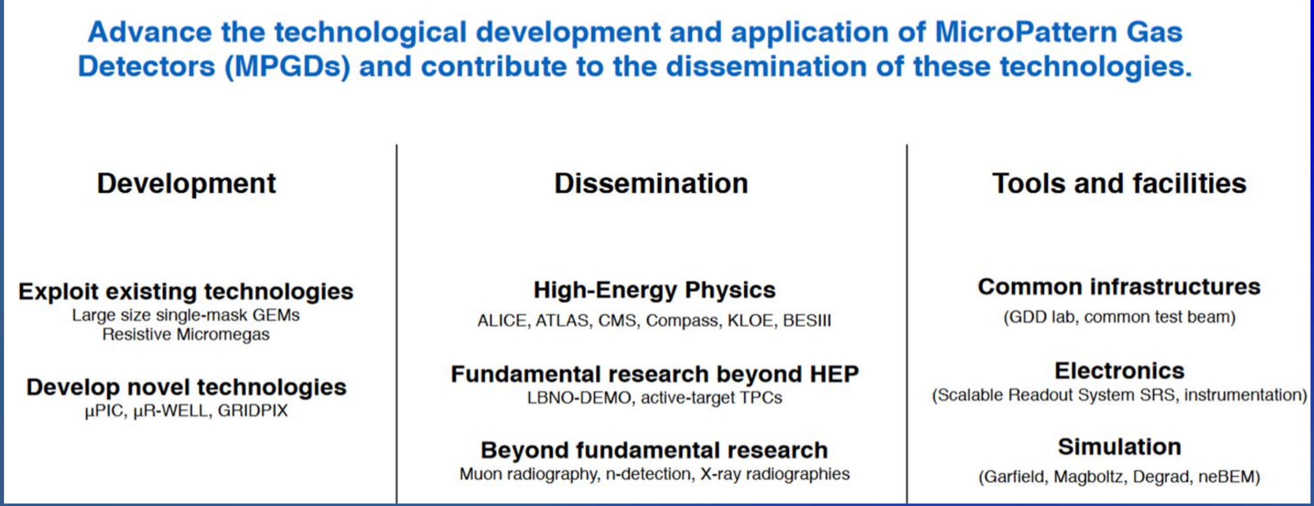
  - Developments of Monolithic Active Pixels (MAPs) (since 1998 for ILC)
  → MAPs enabled application in EUDET telescope, STAR (RICH), ALICE ITS, CBM, …

Micro-Pattern Gaseous Detectors: RD51 Collaboration



- **CERN – RD51 website (recently updated):** https://rd51-public.web.cern.ch/welcome
- Today: ~ 90 RD51 institutes in 25 countries
- RD51 proposal for extension beyond 2018: arXiv: 1806.09955
- Started in 2008, **RD51** technological collaboration approved by the CERN Research Board for the third five-years term (2018-2023)

Coordination through RD51 (« RD51 Model »):



Advance the technological development and application of MicroPattern Gas Detectors (MPGDs) and contribute to the dissemination of these technologies.

Development	Dissemination	Tools and facilities
Exploit existing technologies Large size single-mask GEMs Resistive Micromegas	**High-Energy Physics** ALICE, ATLAS, CMS, Compass, KLOE, BESIII	**Common infrastructures** (GDD lab, common test beam)
Develop novel technologies μPIC, μR-WELL, GRIDPIX	**Fundamental research beyond HEP** LBNO-DEMO, active-target TPCs	**Electronics** (Scalable Readout System SRS, instrumentation)
	Beyond fundamental research Muon radiography, n-detection, X-ray radiographies	**Simulation** (Garfield, Magboltz, Degrad, neBEM)

combination of generic and focused R&D with bottom-top decision processes, full sharing of "know-how", information, common infrastructures → **This model can be exported to other detector domains**

Linear Colliders Detector R&D's

LC Detector Liaison Report: http://ww2.linearcollider.org/P-D/Working-groups/Detector-R-D-liaison

- ➢ No specific choices are made / keep various options for technologies to realise the individual sub-detectors
  → advantage that technologies can be further advanced until the project is approved.

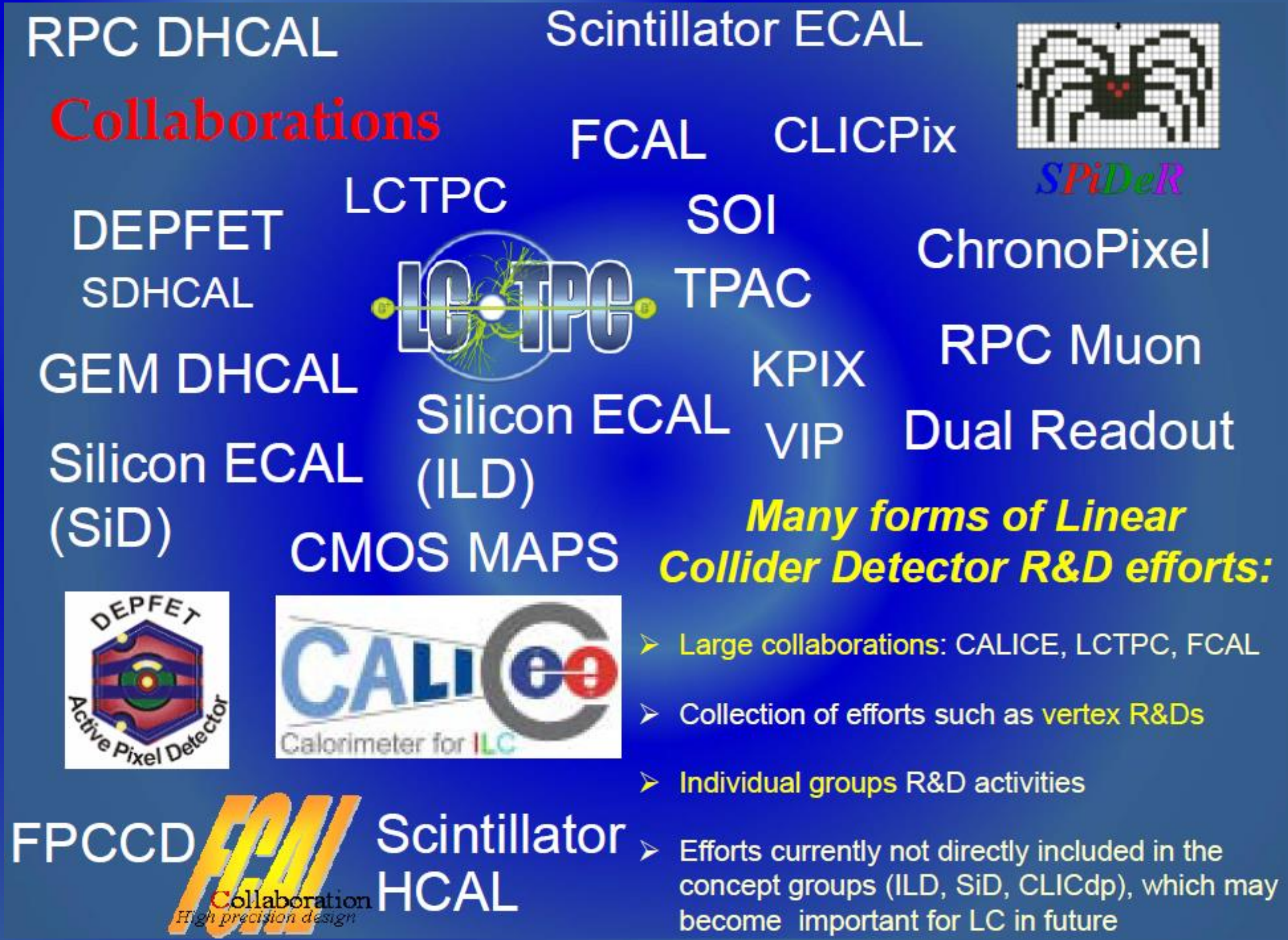
- ➢ Furthermore — and as important — this keeps a broad community of R&D groups at universities and labs involved and increases the chance to arrive at the best technically possible solution when it has to be built.

ILC Project Timeline:

→ International Development Team IDT (2020-2022);
→ ILC Pre-Lab (2022-2025);
→ ILC Laboratory >=2025;

Preliminary timeline for ILC Detector technology choices:

- 2022 – Call for EOIs
- 2023 - Call for LOIs
- 2024/25 - Selection and merger process;
- 2025 - Technical Proposal submission
- 2026/27 – TDRs submission

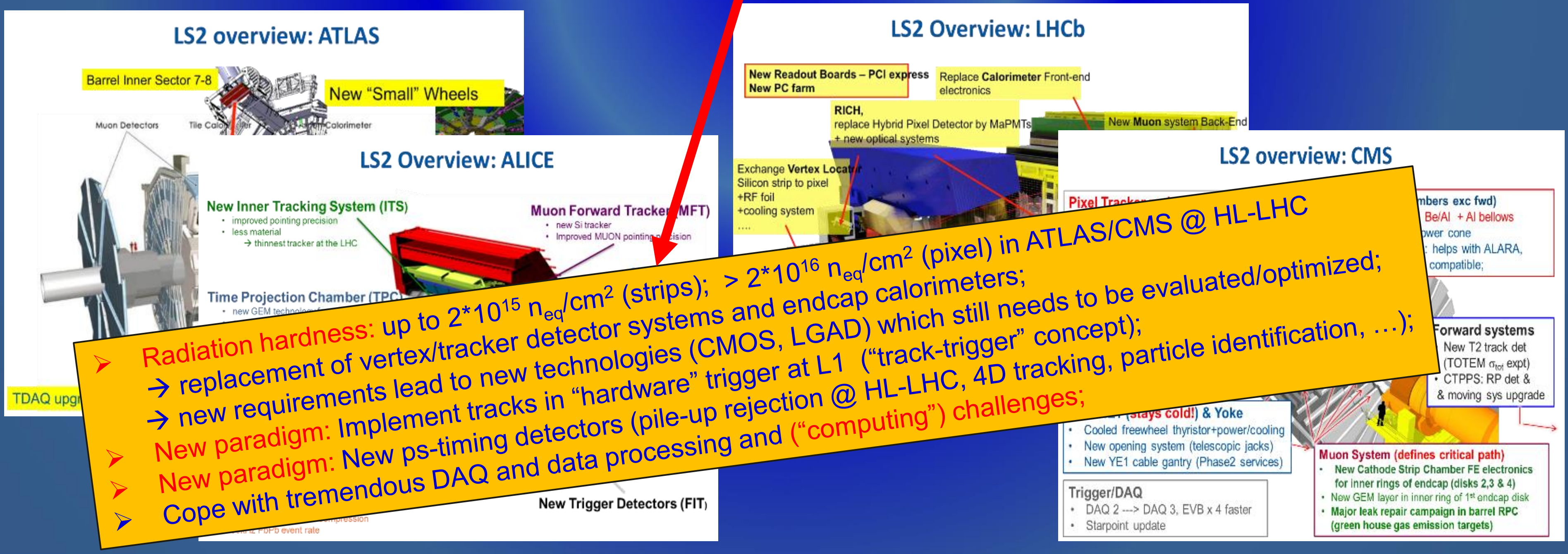


Many forms of Linear Collider Detector R&D efforts:

- ➢ Large collaborations: CALICE, LCTPC, FCAL
- ➢ Collection of efforts such as vertex R&Ds
- ➢ Individual groups R&D activities
- ➢ Efforts currently not directly included in the concept groups (ILD, SiD, CLICdp), which may become important for LC in future

LHC Run 2 is Over … The HL-LHC Era is Upon Us …

Major Considerations for Detector Upgrades During LS2:



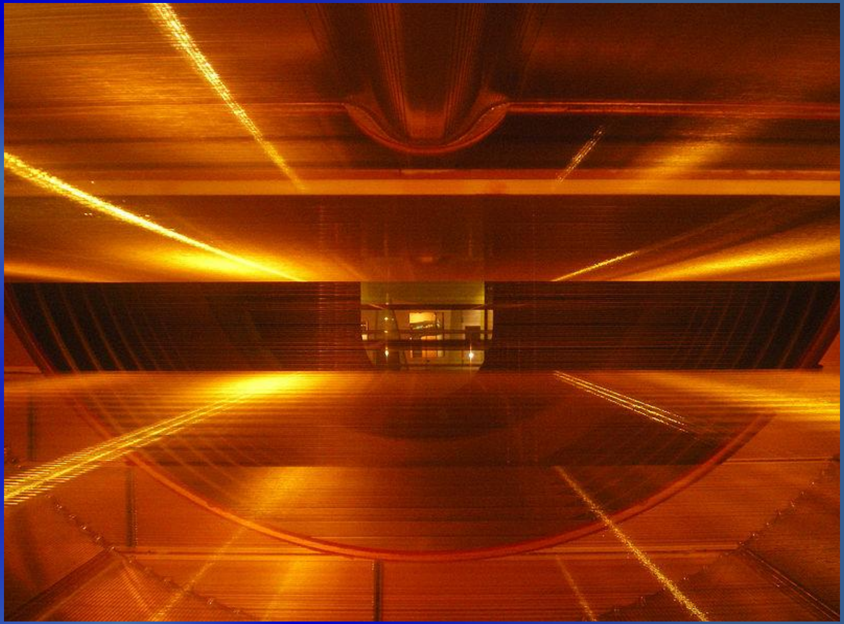
- ➢ Radiation hardness: up to $2*10^{15}$ n_{eq}/cm^2 (strips); > $2*10^{16}$ n_{eq}/cm^2 (pixel) in ATLAS/CMS @ HL-LHC
  - → replacement of vertex/tracker detector systems and endcap calorimeters;
  - → new requirements lead to new technologies (CMOS, LGAD) which still needs to be evaluated/optimized;
- ➢ New paradigm: Implement tracks in "hardware" trigger at L1 ("track-trigger" concept);
- ➢ New paradigm: New ps-timing detectors (pile-up rejection @ HL-LHC, 4D tracking, particle identification, …);
- ➢ Cope with tremendous DAQ and data processing and ("computing") challenges;

State-of-the-Art in Tracking and Vertex Detectors

3 major technologies of Tracking Detectors:

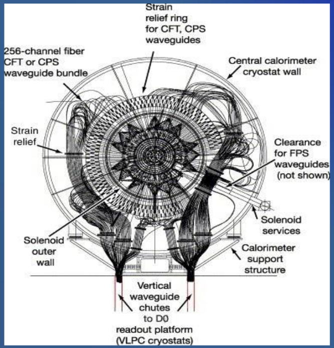
Silicon strips, hybrid, monolithic detectors:

Gaseous (MWPC, TPC, RPC, MPGDs):

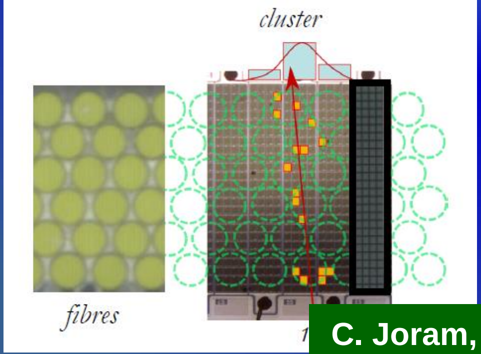


Fiber Trackers: UA2 upgrade, CHORUS, CFT @D0 Experiment, LHCb Upgrade

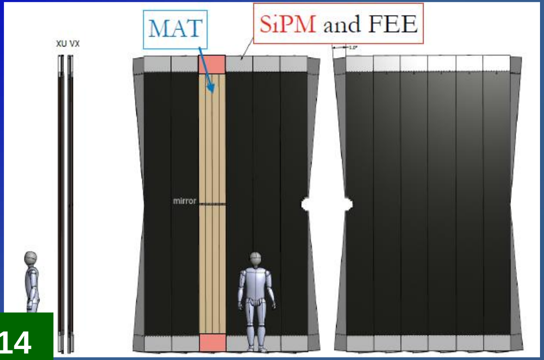
CFT @ D0:



LHCb Tracker Upgrade (Sci-fibers with SiPM readout):

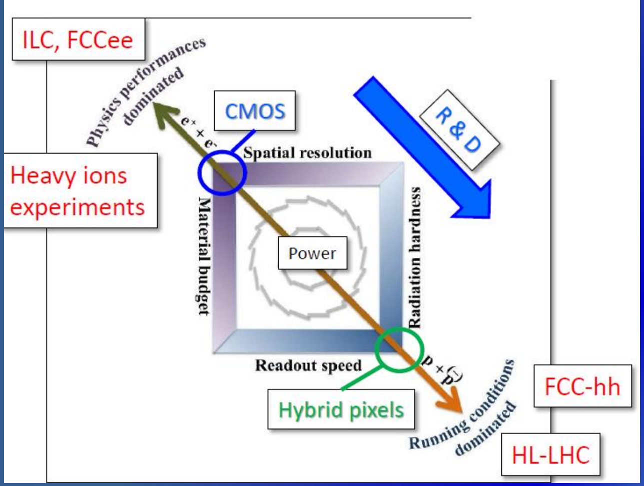


12 layers covering a sensitive area of 6 x 4.8 m2 result in the largest high-precision scintillating fiber tracker (sci-fibers 250µm readout by SiPM array)



C. Joram, PH Detector Seminar, 23/05/2014

Vertex and Tracking Systems: State-of-the-Art



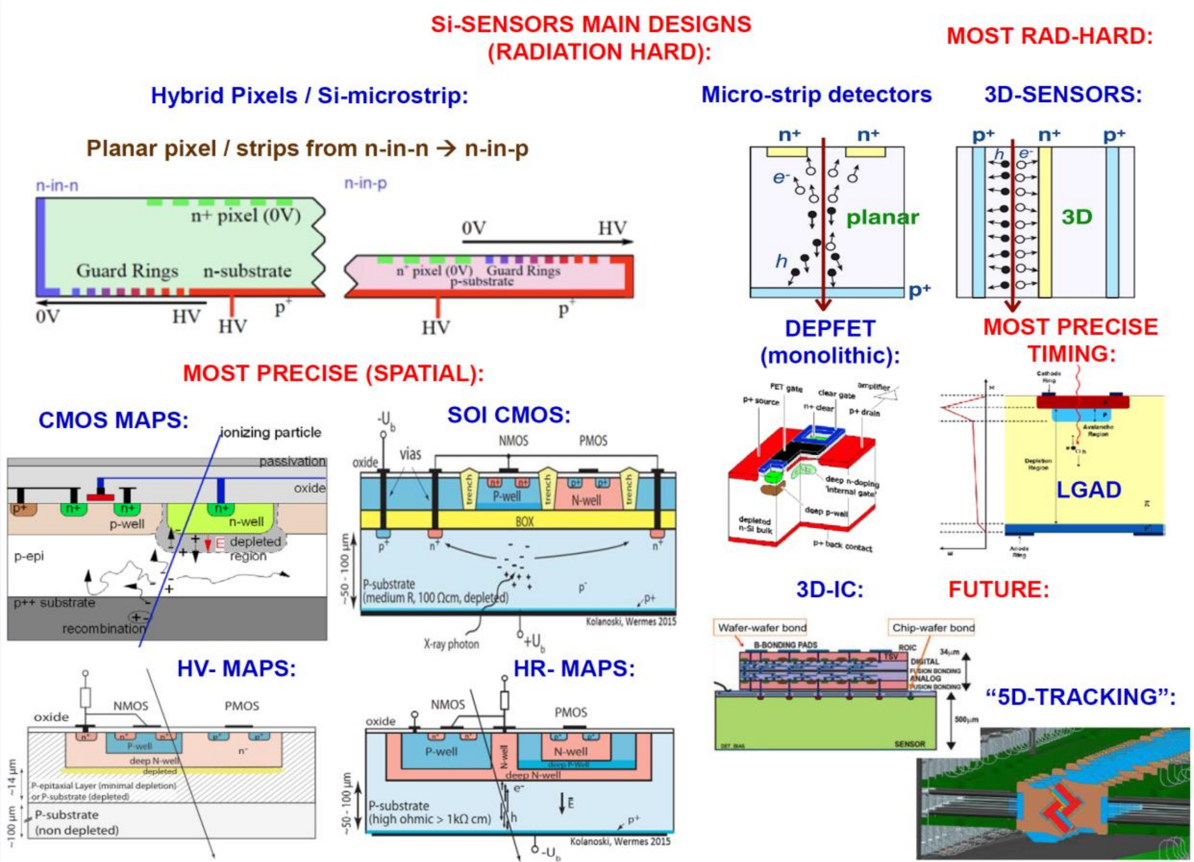
- ✓ Basic applications are optimized for two different realms of interest : electron and hadron colliders → different optimizations/requirements (pp: radiation hardness, speed; e+e-: granularity, material budget)
- ✓ Design problems include: granularity vs the power (particularly for precision timing) and the inactive material to service power and data readout etc. for both accelerator types. Radiation hardness and a strong emphasis on data reduction / feature extraction for the on-detector electronics are particular issues for hadron colliders.

Hadron Colliders:

- ✓ Hybrid pixel detectors (planar & 3D)
- ✓ HV/HR-CMOS for outer pixel layers for HL-LHC upgrades;
- ✓ LGADs for ps-timing

Lepton Colliders:

- ✓ CMOS (STAR HFT, ALICE ITS)
- ✓ DEPFET (Belle II)
- ✓ Chronopix
- ✓ SoI
- ✓ FPCCD
- ✓ 3D-IC (Global Foundries, LAPIX, TJas,…industries)

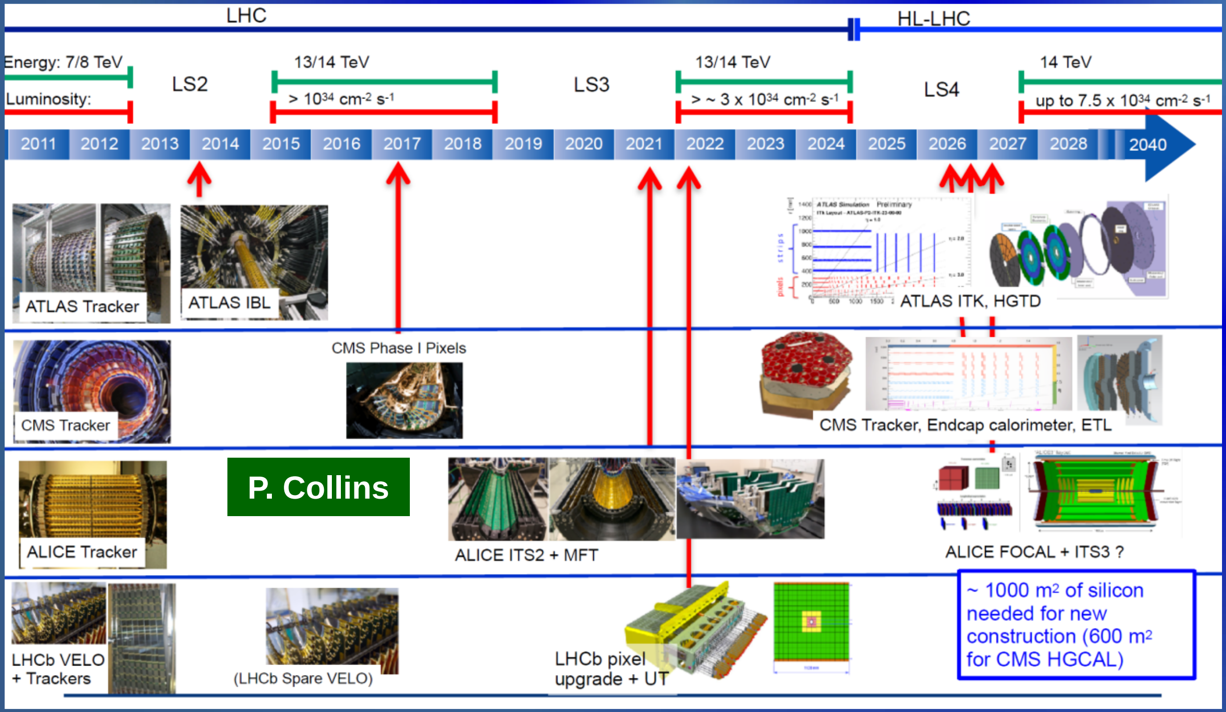


Silicon @ LHC: State-of-the-Art & Upgrades

Lots of common developments for ATLAS, CMS Pixel Upgrades @ HL-LHC (2026):

- ✓ Pixel chips based on common 65 nm CMOS RD53 development
- ✓ Planar n-in-p sensors → cost-effective single sided processing
- ✓ 3D sensors for innermost layers;
- ✓ Option of MAPS for outer pixel layer (ATLAS)
- ✓ CO2 cooling, Serial powering , LpGBT

Exp. / Timescale	Application Domain	Tech.	Detector size / Module size / Channel count	Radiation Environment	Special Req. / Remarks
ATLAS ITK Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel – 12.7 m^2 ; strips - 165 m^2 **Single unit:** pixel- 50x50 (25x100) μm^2 strip len./pitch: ~24 – 80 mm / ~70 μm **Channels count :** pixels – 5 G ; strips – 60 M	**Fluences up to 2 x 10^{16} n$_{eq}$/cm^2**	Option for outermost pixel layer: MAPS RD53 ASIC 65 nm CMOS
CMS Tracker Upgrade CERN LS3	Hadron Collider (Vertex / Tracking)	Si hybrid pixels (n-in-p), 3D innermost, Si-Strips	**Total area:** pixel - 4.9 m^2 ; strips - 200 m^2 **Single unit:** pixel- 25x100 (50x50) μm^2 strip len./pitch: 50-24-1.5 mm /~100 μm **Channels count :** pixels – 3 G ; strips – 175 M	**Fluences up to 2.3 x 10^{16} n$_{eq}$/cm^2**	Special p$_T$-modules in outer strip layers RD53 ASIC 65 nm CMOS
ALICE ITS Upgrade CERN LS2	Heavy Ion Physics (Tracking)	CMOS MAPS, 7 barrel layers	**Total area:** 10 m^2 ; **Single unit:** pixel size 30x30 μm^2 **Channels count :** 12.5 G	**Fluences up to 1.7 x 10^{13} n$_{eq}$/cm^2**	0.3% X$_0$ per layer (inner barrel) ASIC: 180 nm TowerJazz
LHCb VELO Upgrade CERN LS2	Hadron Collider (B Physics)	Si hybrid pixels (n-in-p)	**Total area:** 0.12 m^2 ; **Single unit:** pixel size 55x55 μm^2 **Channels count :** 41 M	**Fluences up to 8 x 10^{15} n$_{eq}$/cm^2**	130 nm CMOS, 40 MHz VELOPIX readout, rates up to 20 Gb/s
LHCb Upstream Tracker Upg. CERN LS2	Hadron Collider (B Physics)	Si strips (n-in-p & p-in-n)	**Total area:** 9 m^2 ; **Single unit:** strip length/pitch: 50 -100 mm / 100 – 200 μm^2 **Channels count :** ~ 500k	**Fluences up to 5 x 10^{14} n$_{eq}$/cm^2**	
BELLE II PXD / SVD	e+e- Collider (B Physics)	DEPFET / Si-strips (p-in-n)	**Total area:** 0;03 m^2 / 1.2 m^2 ; **PXD unit:** pixel size ~50x50 μm^2 **SVD unit: strip-** 120 mm / 50–240 μm^2 **Channels count :** 7.7 M / 245 k	**Fluences up to 10^{13} n$_{eq}$/cm^2**	0.15 X$_0$ per layer



~ 1000 m^2 of silicon needed for new construction (600 m^2 for CMS HGCAL)

Pixel Systems will enlarge dramatically:

- Surface: ATLAS by factor of ~15
- Channel count : ALICE will reach 12.5 billion pixels with CMOS MAPS
- Cell size: LHCb by ~1000 (strips → pixels)

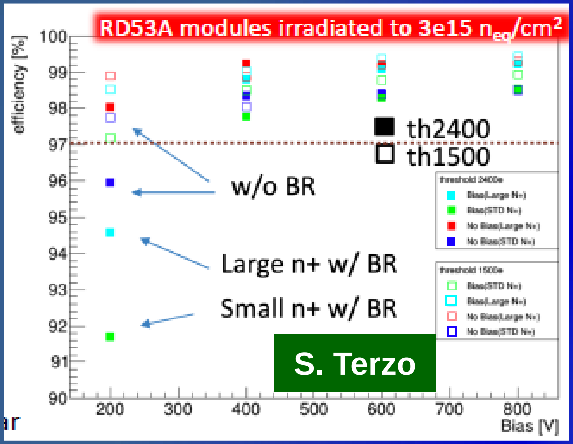
✓ The Si-strip sensors will consist of (n-in-p) and replace (p-in-n) → radiation hardness consideration,

✓ 3D sensors develop. (FBK, CNM) has been focused on ATLAS-IBL pixels plus several joint MPW production runs with CMS / LHCb.

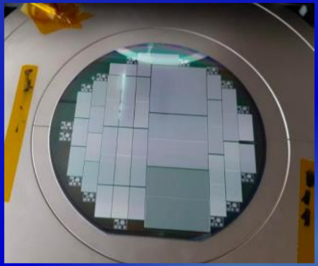
ATLAS, CMS, LHCb Trackers for HL-LHC

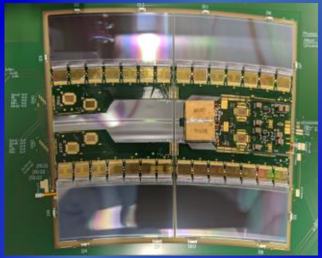
ATLAS ITK: 165 / 12.7 m² strips / pixels

Thin n-in-p planar
pixel sensors:



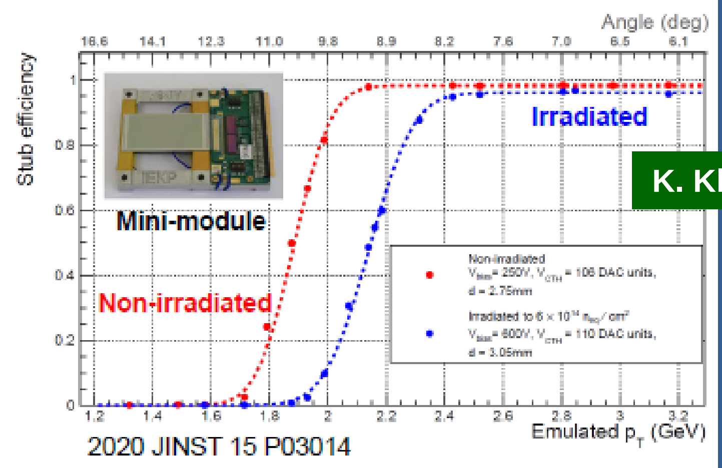
S. Terzo





CMS Phase II Tracker: 200 /4.7 m2 strips / pixels

Outer Tracker (2S Module):



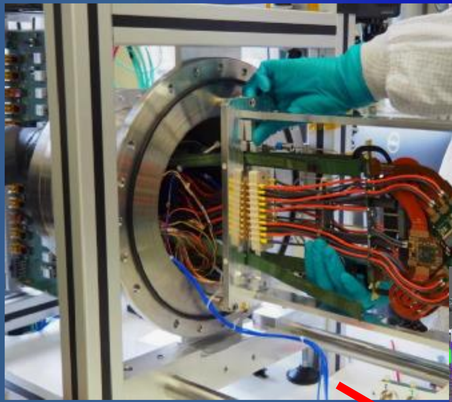
2020 JINST 15 P03014

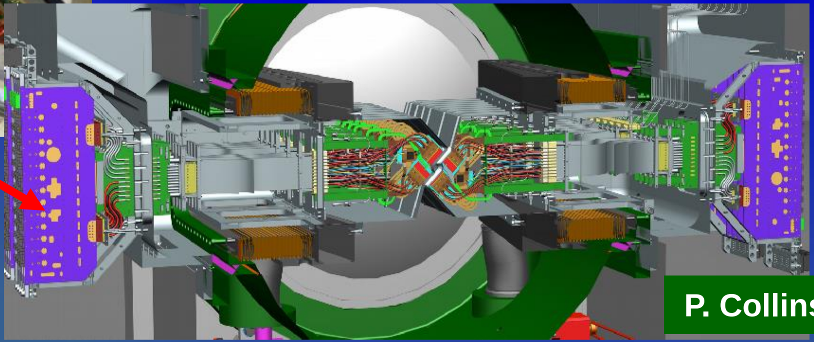
K. Klein

LHCb hybrid silicon pixel modules for Phase I upgrade (Run3/4) :

- ✓ Sensors: 200 μm thick, 55 x 55 μm², ≃ 10 μm hit resolution
- ✓ 120 x 120 μm² micro cooling-channel etched in sensor substrate

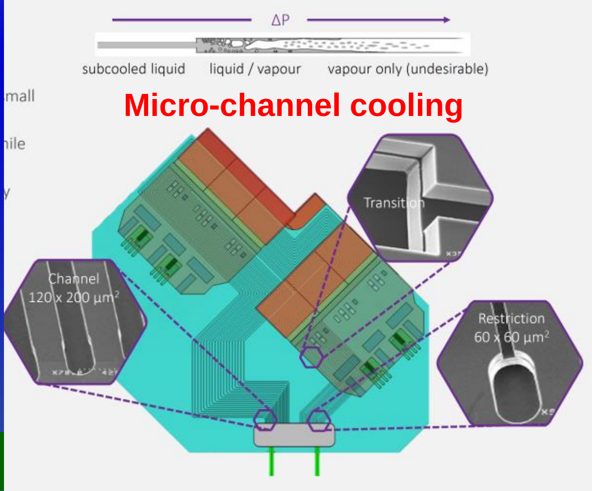
- ✓ VeloPix ASIC in 130 nm CMOS
- ✓ Triggerless binary readout @ 40 MHz
- ✓ >20 Gb/s/ASIC 40M pixels





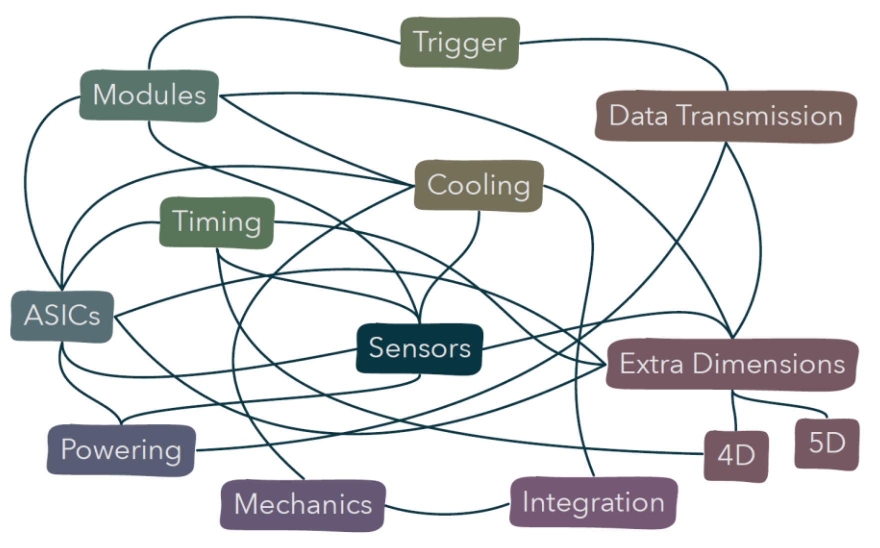
VELO mounted within
a secondary vacuum in
the primary LHC vacuum

P. Collins



Micro-channel cooling

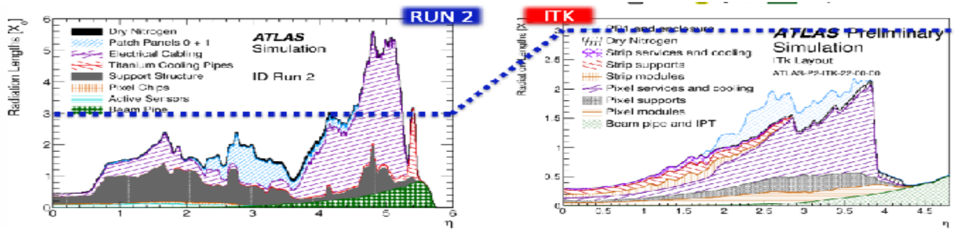
More than ASICs and Sensors, we have to take care of all aspects – Mechanics and Cooling, Powering Schemes, Optical Links, Integration …



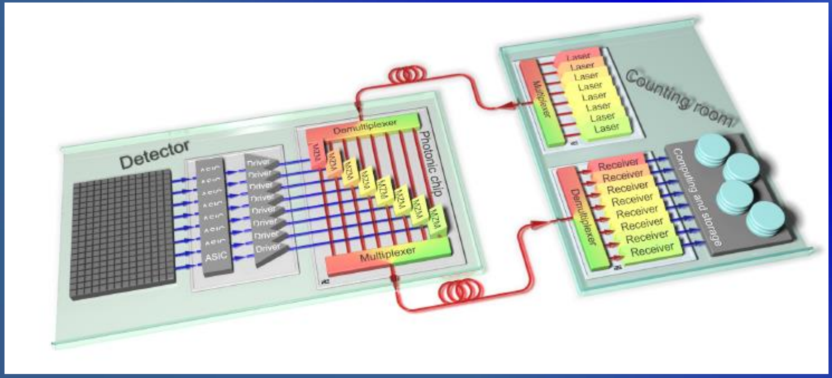
Keeping the radiation budget under control needs efforts in all areas:

- Advanced serial powering schemes
- Ultra-light structural materials and integration
- Heat management (CO_2 cooling) integrated in the detector design

Significant budget reduction for ATLAS ITK:



- ✓ Current link implementation based on vertical cavity surface emitting lasers (VCSEL)
- ✓ Higher bandwidth requirements could be addressed by silicon photonics and Wavelength Division Multiplexing (WDM)



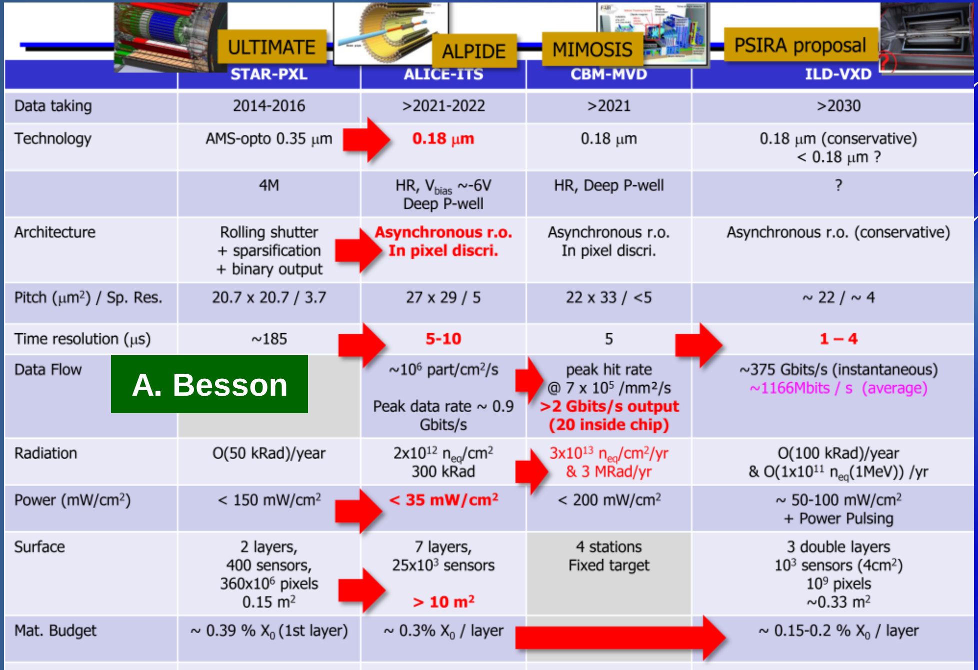
DC-DC powering widely accepted in HEP

Experiment	Sub-detector	What	How	Where
CMS	Outer Tracker	Strip modules, LpGBT, VTRx+	DC-DC	Front-end
	Phase-1 pixel	Pixel modules	DC-DC	Patch panel
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Endcap calorimeter	Silicon modules, LpGBT, VTRx+	DC-DC	Patch panel or front-end
	Barrel calorimeter	Crystal ADC	DC-DC	Front-end
	Muon system (GEM)	Chambers	DC-DC	Front-end
	Timing detector	Readout, LpGBt, VTRx+	DC-DC	Front-end
ATLAS	Strips	Strip modules, LpGBT, VTRx	DC-DC	Front-end
	Phase-2 pixel	LpGBT, VTRx+	DC-DC	Patch panel
		Pixel modules	Serial	
	Tile calorimeter	Electronics	DC-DC	Patch panel
	Liquid argon calorimeter	Electronics	DC-DC	Front-end
	Muon micromegas	GBTx, VTRx	DC-DC	Front-end
LHCb	Velo	Pixel modules, GBTx	DC-DC	Patch panel
	Fiber tracker	Fiber modules, GBTx, FPGA	DC-DC	Front-end
ALICE	Pixels	Pixel modules	DC-DC	Front-end
Belle 2	SVD	Silicon modules	DC-DC	

A. Mussgiller

Monolithic Sensors (MAPS): State-of-the-Art

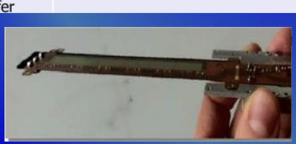
CMOS MAPS for charged particle tracking was initiated for ILC in 1998



	ULTIMATE STAR-PXL	ALPIDE ALICE-ITS	MIMOSIS CBM-MVD	PSIRA proposal ILD-VXD
Data taking	2014-2016	>2021-2022	>2021	>2030
Technology	AMS-opto 0.35 μm	**0.18 μm**	0.18 μm	0.18 μm (conservative) < 0.18 μm ?
	4M	HR, V_{bias} ~-6V Deep P-well	HR, Deep P-well	?
Architecture	Rolling shutter + sparsification + binary output	**Asynchronous r.o.** **In pixel discri.**	Asynchronous r.o. In pixel discri.	Asynchronous r.o. (conservative)
Pitch (μm²) / Sp. Res.	20.7 x 20.7 / 3.7	27 x 29 / 5	22 x 33 / <5	~ 22 / ~ 4
Time resolution (μs)	~185	**5-10**	5	**1 – 4**
Data Flow		~10^6 part/cm²/s Peak data rate ~ 0.9 Gbits/s	peak hit rate @ 7 x 10^5 /mm²/s **>2 Gbits/s output (20 inside chip)**	~375 Gbits/s (instantaneous) ~1166Mbits / s (average)
Radiation	O(50 kRad)/year	2x10^{12} n_{eq}/cm² 300 kRad	3x10^{13} n_{eq}/cm²/yr & 3 MRad/yr	O(100 kRad)/year & O(1x10^{11} n_{eq}(1MeV)) /yr
Power (mW/cm²)	< 150 mW/cm²	**< 35 mW/cm²**	< 200 mW/cm²	~ 50-100 mW/cm² + Power Pulsing
Surface	2 layers, 400 sensors, 360x10^6 pixels 0.15 m²	7 layers, 25x10^3 sensors **> 10 m²**	4 stations Fixed target	3 double layers 10^3 sensors (4cm²) 10^9 pixels ~0.33 m²
Mat. Budget	~ 0.39 % X_0 (1st layer)	~ 0.3% X_0 / layer		~ 0.15-0.2 % X_0 / layer
Remarks	1st CPS in colliding exp.	(with CERN)	Vacuum operation Elastic buffer	Evolving requirements

A. Besson

MIMOSA @ EUDET BT Telescope
→ 3 um track resolution achieved

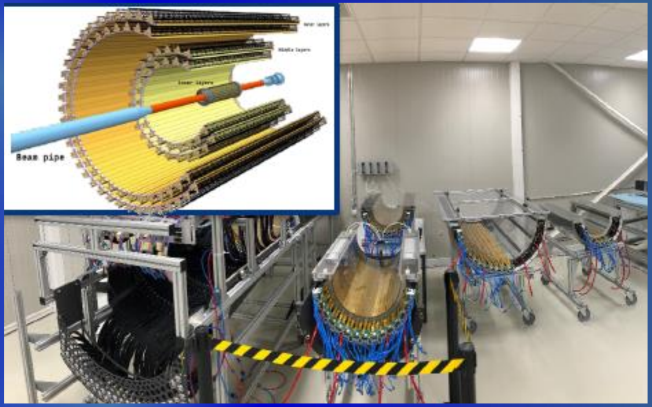


STAR Heavy Flavour Tracker (2014):

Ladder with 10 MAPS sensors (~2x2 cm each) mounted on carbon fiber sectors: 356M pixels on ~0.16 m²(Si); 50 um thin sensors; 20 to 90 kRad/year

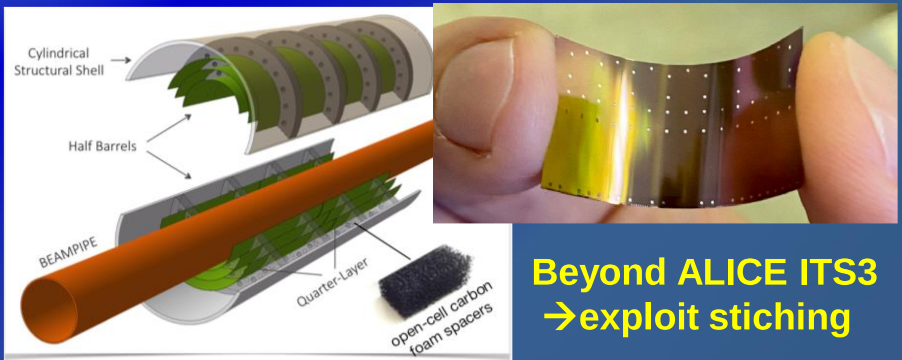
CMOS MAPS for ALICE ITS2 (Run 3):

- TowerJazz 180 nm technology; on-chip digital readout architecture → rad-hard to >TID 2.7 Mrad
- 7 layers of MAPS ≃ 10 m² with 12.5 Gpix
- High resistivity eps layer → rad hard to TID 2.7 Mrad;



CMOS MAPS for ALICE ITS3 (Run 4):
(LOI: CERN-LHCC-2019-018)

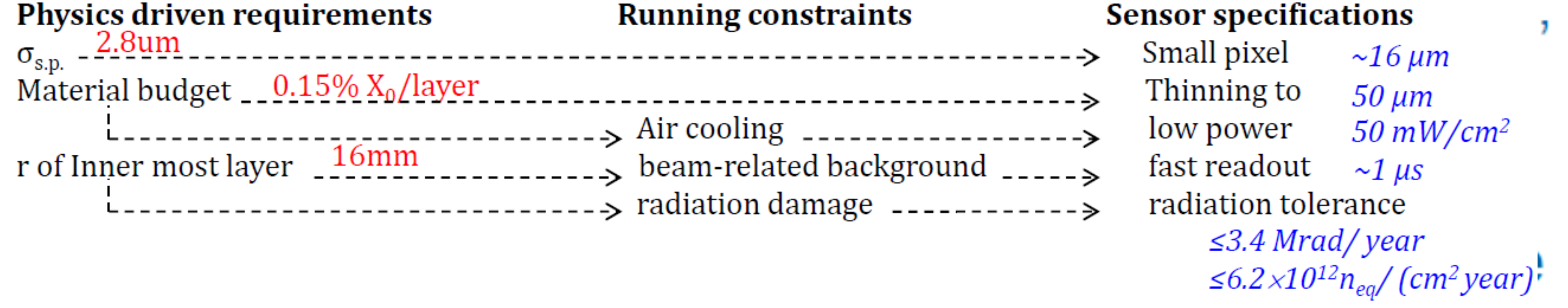
- ✓ Three fully cylindrical, wafer-sized layers based on curved ultra-thin sensors (20-40 μm), air flow cooling
- ✓ Almost massless (IB), < 0.02-0.04% per layer



Beyond ALICE ITS3
→exploit stiching

Vertex Technologies for ILC : State-of-the-Art

- **Exploiting the ILC low duty cycle 0(10^{-3}): triggerless readout, power-pulsing**
- **Readout strategies:**
  - → continuous during the train with power cycling → mechanic. stress from Lorentz forces in B-field
  - → delayed after the train → either ~5μm pitch for occupancy or in-pixel time-stamping



Physics driven requirements **Running constraints** **Sensor specifications**

$\sigma_{s.p.}$ 2.8um → Small pixel ~16 μm

Material budget 0.15% X_0/layer → Thinning to 50 μm

→ Air cooling → low power 50 mW/cm²

r of Inner most layer 16mm → beam-related background → fast readout ~1 μs

→ radiation damage → radiation tolerance

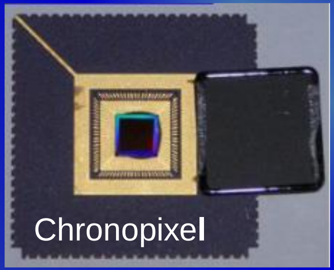
≤3.4 Mrad/year

≤$6.2\times10^{12} n_{eq}/(cm^2 year)$

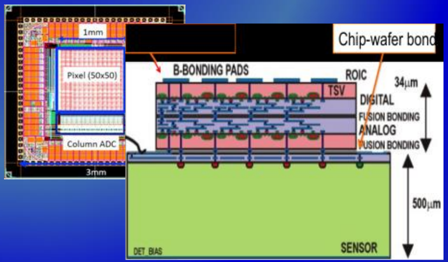
Sensor's contribution to the total material budget is 15-30% (majority from cables + cooling +support)

CMOS (CPS): continuous readout, stiching

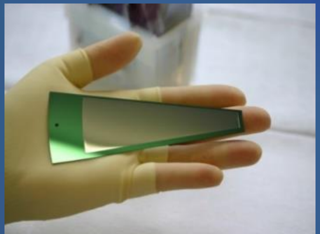
Chronopixel: delayed readout, monolithic CMOS, 50 um thick



SOI: delayed / continuous readout; suited for 3D integration

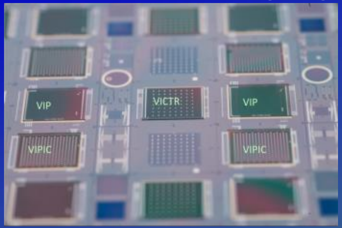


DEPFET: continuous readout, 75 / 50 um thick (Belle II)



Fine pixel CCD: delayed readout, 5 um pitch, 50 um thickness

3D Integration (in-pixel data processing, on-hold): MWR in 2010, VIP(ILC)



✓ Ultra-light self-supported layers with stitching CMOS sensors (available in Tjas 180 nm process: ALPIDE, MIMOSIS)

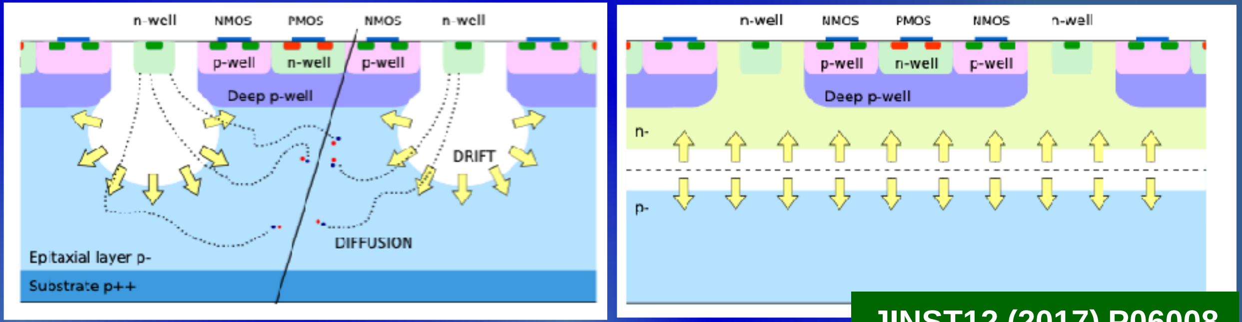
✓ SoI based 3D integration is coming (SoI for ILC rely on high-density in-pixel circuitry, with double-tier option recently addressed)

Towards Radiation-Hard MAPS

- ➢ Advances in commercial CMOS technologies combined with dedicated designs allowed significant progress from STAR to ALICE to ATLAS in areas like radiation hardness, response time, and hit rates
- ➢ Strong interest for R&D to fully exploit potential of MAPS in future trackers
- ➢ High granularity, low material budget and power, large area at reduced cost (compared to hybrid pixels)

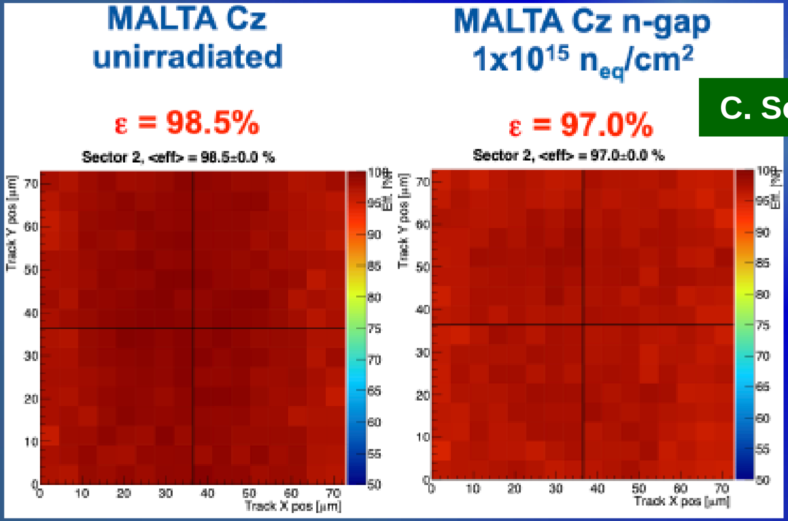
From ALPIDE to MALTA/Monopix: modified Tower Jazz 180 nm process

- ✓ Malta designed as a radiation hard high speed monolithic CMOS sensor for ATLAS
- ✓ Uniform n-implant blanket in epitaxial layer gives lateral depletion right through to small input capacitance electrode



JINST12 (2017) P06008

Efficiency of MALTA on Cz substrate:


MALTA Cz unirradiated

ε = 98.5%

MALTA Cz n-gap $1x10^{15}$ n_{eq}/cm^2

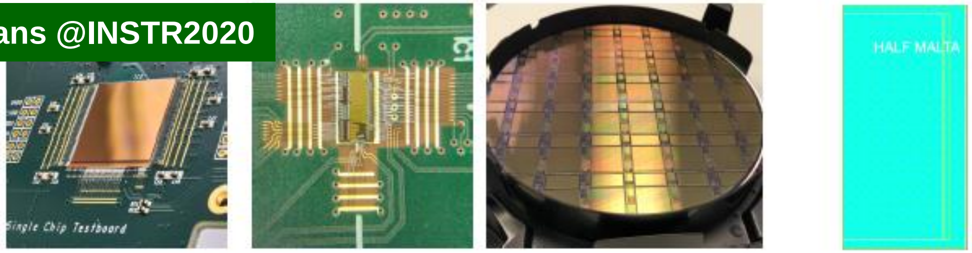
ε = 97.0%

C. Solans @INSTR2020

Almost full efficiency with additional process modification (gap in the n- layer)

MALTA reprocessed on high resistivity Czochralski substrate:

- ✓ Resistivity of ~800 Ω·cm; increased charge collection
- ✓ Aim for better time resolution and higher radiation hardness



MALTA1 & MLVL	Mini-MALTA	MALTA C	MALTA 2
Jan 2018	Jan 2019	Aug 2019	~~Aug 2020~~ Oct 2020
Large demonstrator Asynchronous readout Electrode size and reset mechanism evaluation	Small demonstrator Process and mask modification	Substrate engineering (MALTA C on Czochralski) Slow control improvements	Smaller matrix Process and substrate engineering
Poor lateral field after irradiation	Full efficiency after 1e15 n/cm²	Enlarged cluster size Improved time resolution	Baseline for CERN EP R&D WP 1.2

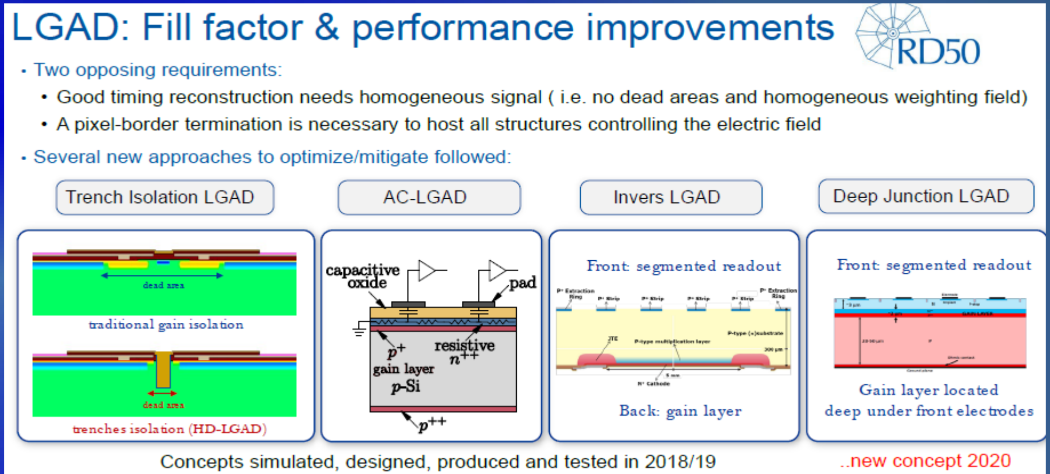
RD50 Collaboration: Radiation Hard Semiconductor Devices

Sensors for 4D Tracking: Development of Radiation Hard Timing Detectors (LGAD)

Incredible success story → pioneered by RD50 and CNM since 2010 (> 50 production runs)

Areas of LGAD developments within RD50:

- Timing performance
  (~ 25 ps for 50 um sensors)
- Fill factor and signal homogeneity
- Radiation Hardness (~2x10^{15} n_{eq}/cm^2)
- Performance Parameterisation Model



LGAD: Fill factor & performance improvements

- Two opposing requirements:
  - Good timing reconstruction needs homogeneous signal (i.e. no dead areas and homogeneous weighting field)
  - A pixel-border termination is necessary to host all structures controlling the electric field
- Several new approaches to optimize/mitigate followed:

Trench Isolation LGAD | AC-LGAD | Invers LGAD | Deep Junction LGAD

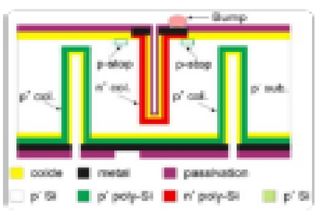
Concepts simulated, designed, produced and tested in 2018/19 ..new concept 2020

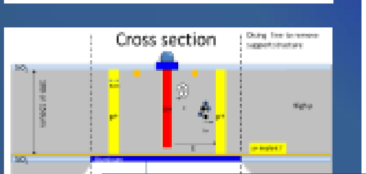
One of the biggest riddles remains the understanding of the radiation damage microscopic mechanisms that lead to the degradation of the gain layer in the LGAD devices.

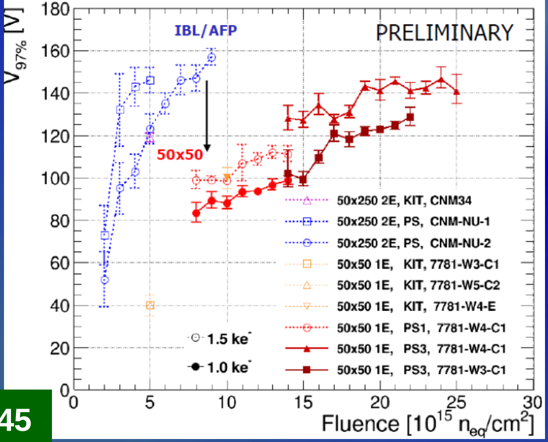
M. Moll

Optimization of 3D sensors for HL-LHC Upgrades:

Good efficiency even up to ~ 3x10^{16} n_{eq}/cm^2 & time resolution: 30 ps at V_{bias} > 100V and T = -20C

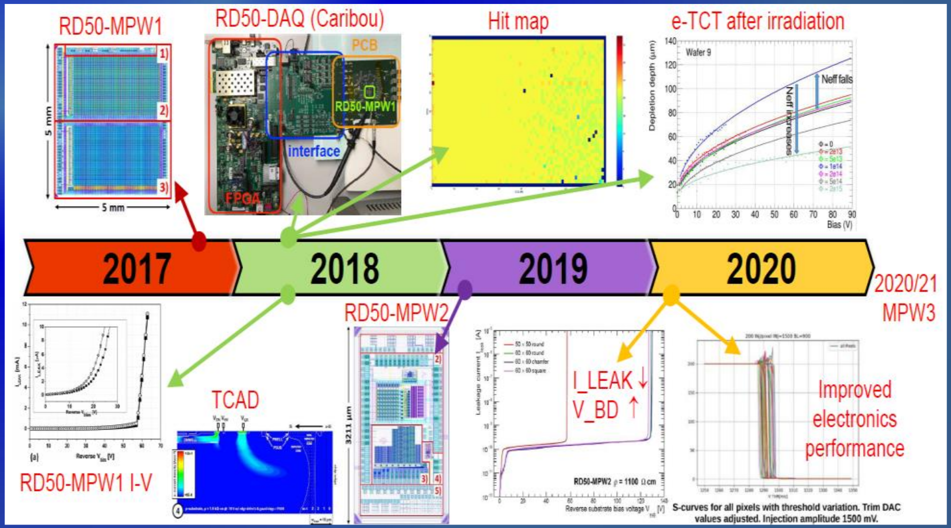






arXiv: 1910.06045

Development of Radiation-Hard (HV-CMOS) sensors:



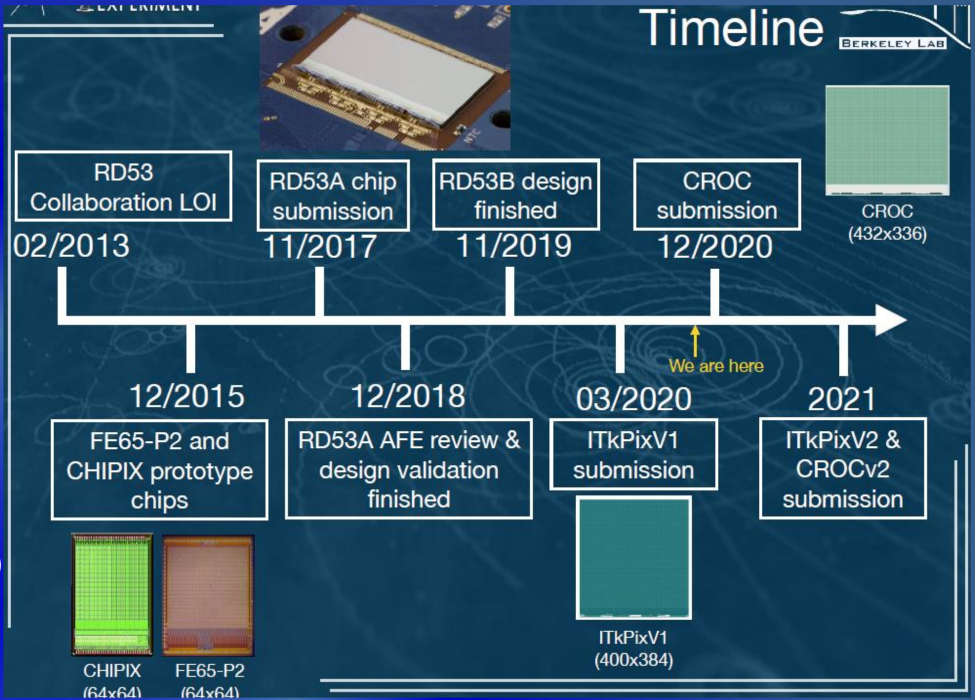
S-curves for all pixels with threshold variation. Trim DAC values adjusted. Injection amplitude 1500 mV.

RD53 Collaboration: 65 nm ASICs for HL-LHC

Established in 2013 recognizing that HL-LHC requirements are extremely challenging, yet very similar for both experiment → joint effort to go

RD53 Collaboration in charge of:

- ✓ Detailed understanding of radiation effects in 65nm technology
- ✓ Design of readout chip for the use in the ATLAS/CMS HL-LHC Pixel detectors:
  - → Analog front-end
  - → Analog IPs (Bias DACs, monitoring ADC, CDR /PLL, high-speed serialiser, SLDO, References)
  - → Digital logic (hit buffering, data compression, …)
- ✓ Initial end-goal was half-size RD53 demonstrator
- ✓ RD53 extended in 2018 to design pre-production and production version of readout chips



Timeline

RD53 Collaboration LOI 02/2013

12/2015 FE65-P2 and CHIPIX prototype chips

RD53A chip submission 11/2017

12/2018 RD53A AFE review & design validation finished

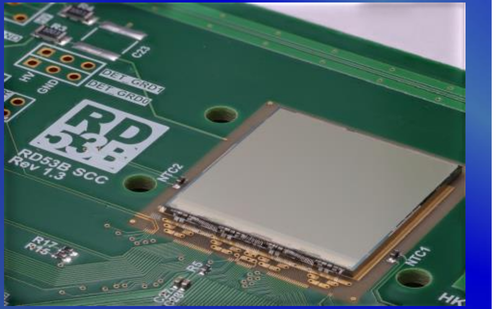
RD53B design finished 11/2019

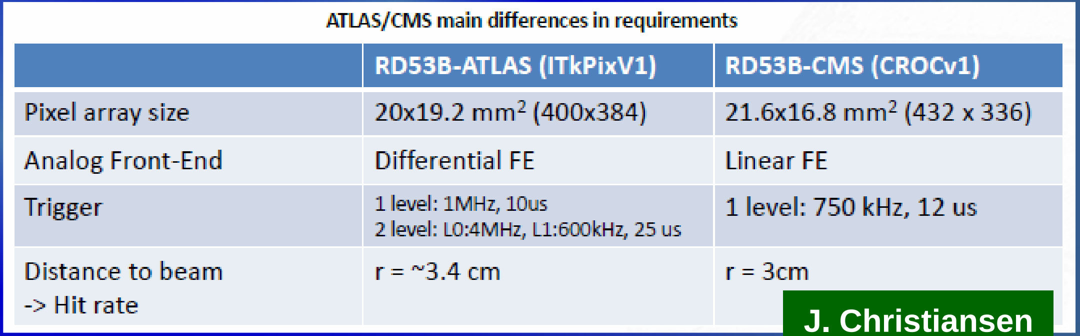
03/2020 ITkPixV1 submission

CROC submission 12/2020

2021 ITkPixV2 & CROCv2 submission

ITkPixV1 : June 2020





ATLAS/CMS main differences in requirements

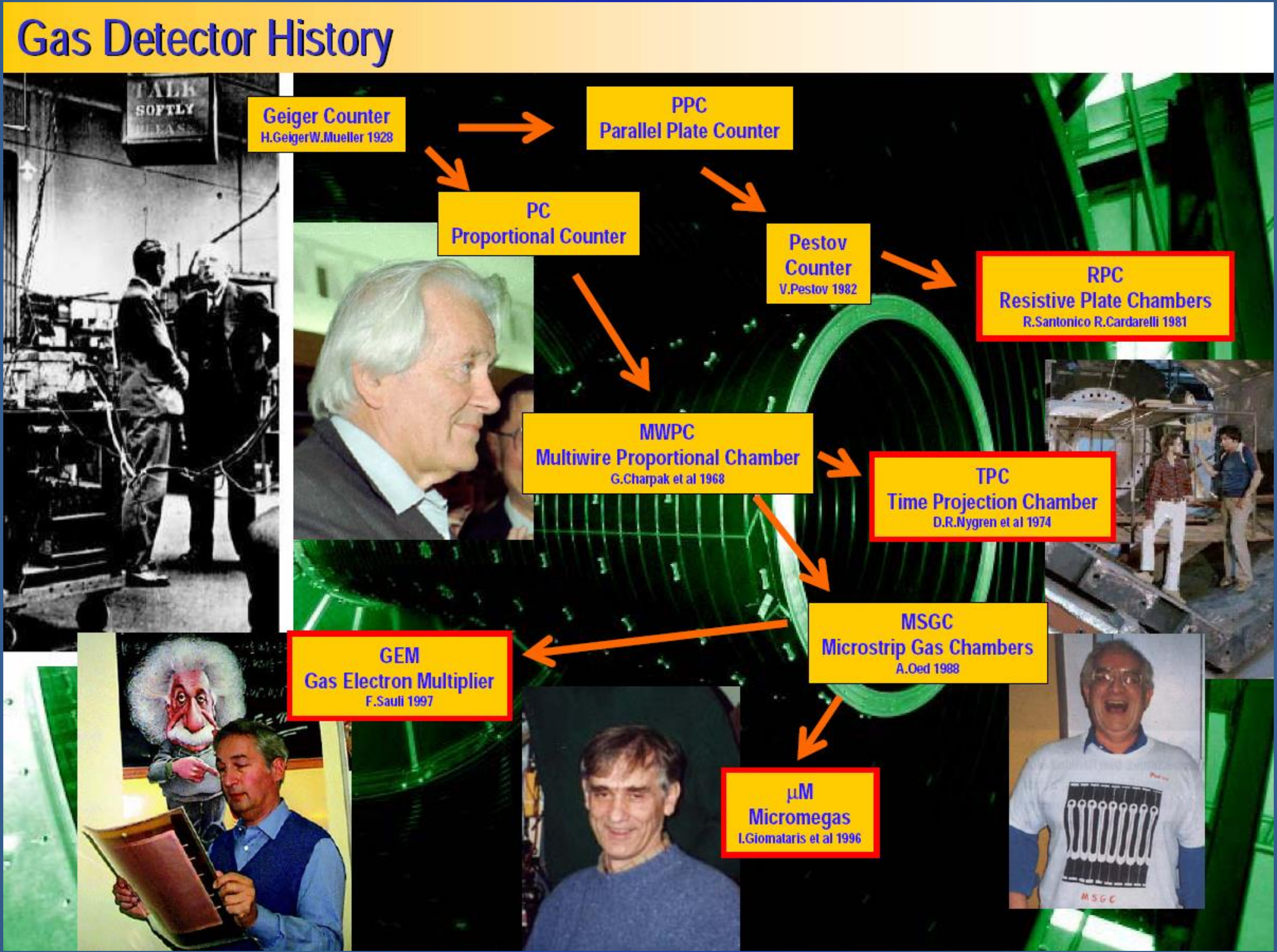
	RD53B-ATLAS (ITkPixV1)	RD53B-CMS (CROCv1)
Pixel array size	20x19.2 mm^2 (400x384)	21.6x16.8 mm^2 (432 x 336)
Analog Front-End	Differential FE	Linear FE
Trigger	1 level: 1MHz, 10us 2 level: L0:4MHz, L1:600kHz, 25 us	1 level: 750 kHz, 12 us
Distance to beam -> Hit rate	r = ~3.4 cm	r = 3cm

J. Christiansen

All main digital functionalities working as expected, but very large digital current on a rail → patch in ITkPixV1.1

- ➢ **Long time to develop radiation tolerance in 65 nm O(Grad) and large cost → technology is not straightforward;**
- ➢ **HEP Community now looks into 28nm for the future and dedicated 130/65nm technologies for monolithic pixels;**

Advanced Concepts in Gaseous Detectors



Gas Detector History

Geiger Counter
H.GeigerW.Mueller 1928

PPC
Parallel Plate Counter

PC
Proportional Counter

Pestov Counter
V.Pestov 1982

RPC
Resistive Plate Chambers
R.Santonico R.Cardarelli 1981

MWPC
Multiwire Proportional Chamber
G.Charpak et al 1968

TPC
Time Projection Chamber
D.R.Nygren et al 1974

MSGC
Microstrip Gas Chambers
A.Oed 1988

GEM
Gas Electron Multiplier
F.Sauli 1997

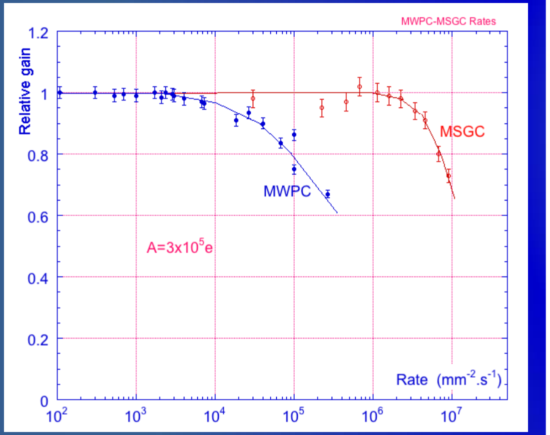
µM
Micromegas
I.Giomataris et al 1996

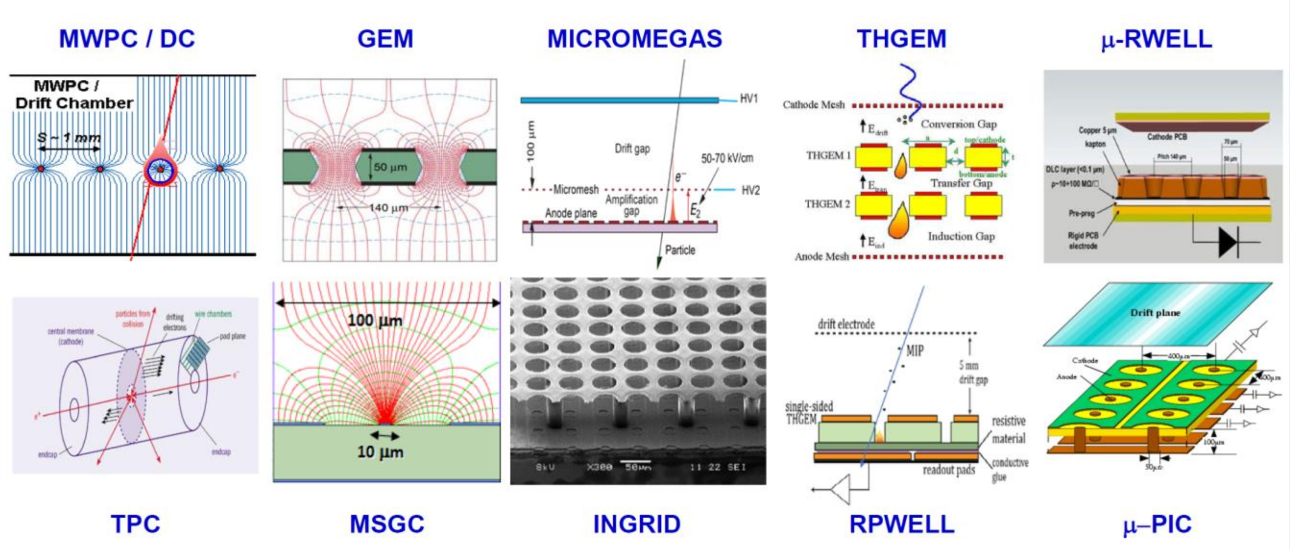
Gaseous Detectors: From Wire/Drift Chamber → Time Projection Chamber (TPC) → Micro-Pattern Gas Detectors

Primary choice for large-area coverage with low material-budget (+ dE/dx measurement)

1990's: Industrial advances in photolithography has favoured the invention of novel micro-structured gas amplification devices (MSGC, GEM, Micromegas, …)

Rate Capability:
MWPC vs MSGC





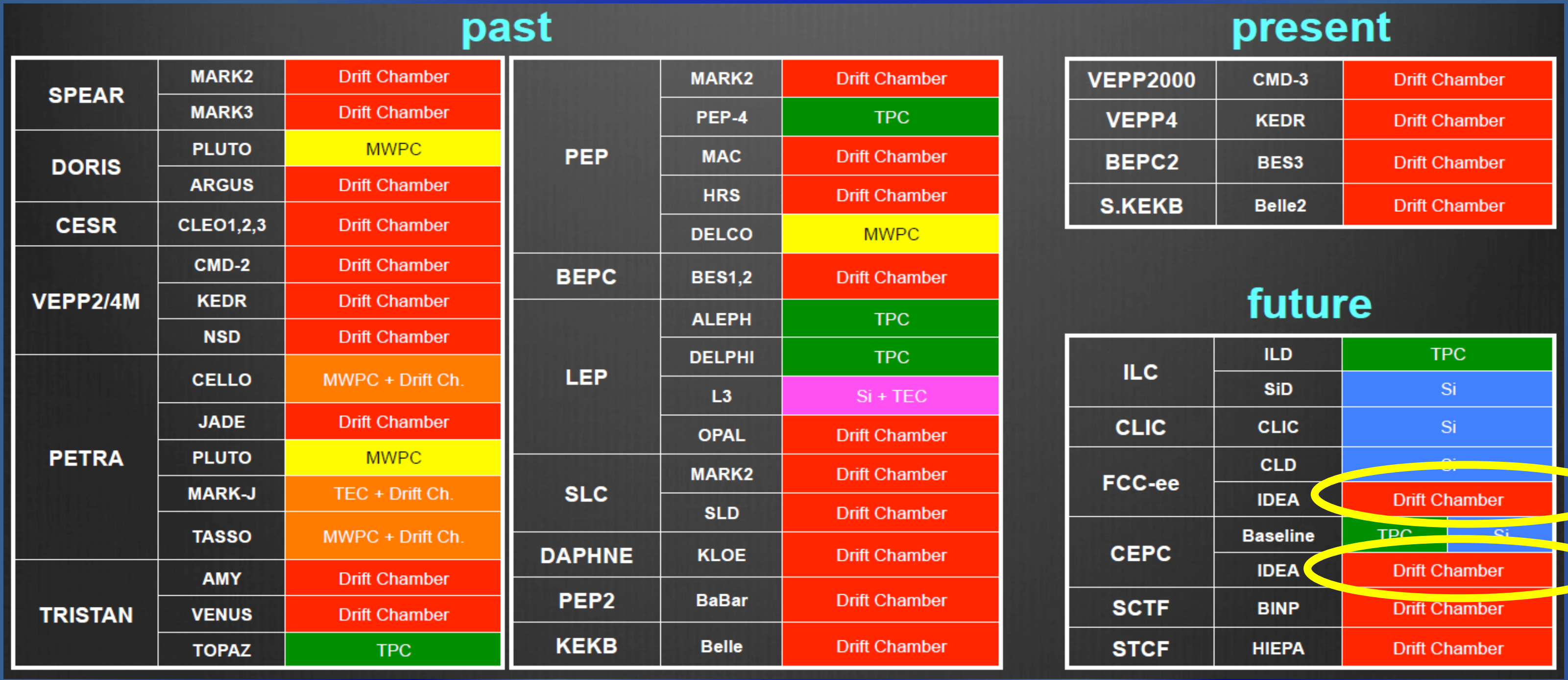
HL-LHC Upgrades: Tracking (ALICE TPC/MPGD); Muon Systems: RPC, CSC, MDT, TGC, GEM, Micromegas;

Future Hadron Colliders: FCC-hh Muon System (MPGD - OK, rates are comparable with HL-LHC)

Future Lepton Colliders: Tracking (FCC-ee / CepC - Drift Chambers; ILC / CePC - TPC with MPGD readout)
Calorimetry (ILC, CepC – RPC or MPGD), Muon Systems (OK)

Future Election-Ion Collider: Tracking (GEM, µWELL; TPC/MPGD), RICH (THGEM), TRD (GEM)

The Evolution of Drift Chambers at e+e- Colliders



past

SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC

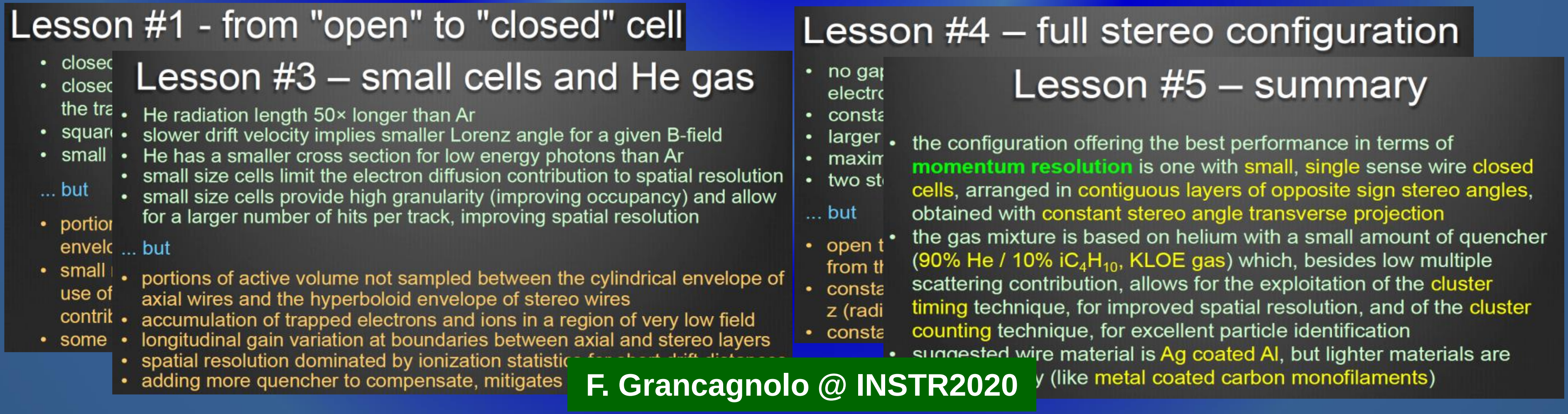
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

present

VEPP2000	CMD-3	Drift Chamber
VEPP4	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber

future

ILC	ILD	TPC
	SiD	Si
CLIC	CLIC	Si
FCC-ee	CLD	Si
	IDEA	Drift Chamber
CEPC	Baseline	TPC Si
	IDEA	Drift Chamber
SCTF	BINP	Drift Chamber
STCF	HIEPA	Drift Chamber



Lesson #1 - from "open" to "closed" cell

- closed
- closed
  the tra
- square
- small

... but

- portion
  envelo
- small
  use of
  contrib
- some

Lesson #3 – small cells and He gas

- He radiation length 50× longer than Ar
- slower drift velocity implies smaller Lorenz angle for a given B-field
- He has a smaller cross section for low energy photons than Ar
- small size cells limit the electron diffusion contribution to spatial resolution
- small size cells provide high granularity (improving occupancy) and allow for a larger number of hits per track, improving spatial resolution

... but

- portions of active volume not sampled between the cylindrical envelope of axial wires and the hyperboloid envelope of stereo wires
- accumulation of trapped electrons and ions in a region of very low field
- longitudinal gain variation at boundaries between axial and stereo layers
- spatial resolution dominated by ionization statistic
- adding more quencher to compensate, mitigates

Lesson #4 – full stereo configuration

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... but

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- consta
  z (radi
- consta

Lesson #5 – summary

- the configuration offering the best performance in terms of momentum resolution is one with small, single sense wire closed cells, arranged in contiguous layers of opposite sign stereo angles, obtained with constant stereo angle transverse projection
- the gas mixture is based on helium with a small amount of quencher (90% He / 10% iC_4H_{10}, KLOE gas) which, besides low multiple scattering contribution, allows for the exploitation of the cluster timing technique, for improved spatial resolution, and of the cluster counting technique, for excellent particle identification
- suggested wire material is Ag coated Al, but lighter materials are
  y (like metal coated carbon monofilaments)

F. Grancagnolo @ INSTR2020

An ultra-light drift chamber (IDEA concept) targetted for FCC-ee and CePC was inspired by DAFNE KLOE Wire Chamber and by more recent version of it for MEG2 experiment

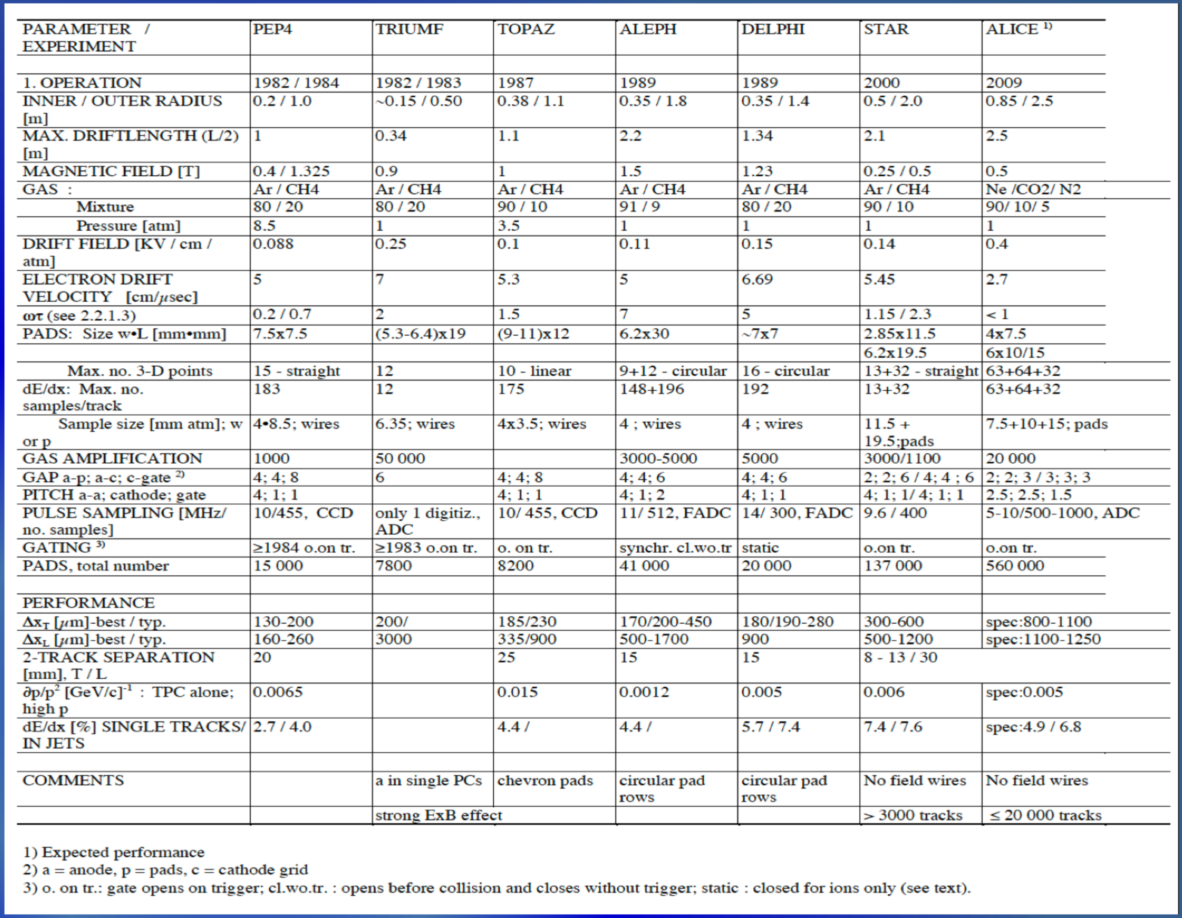
Some TPC Examples in Particle / Ion Physics

✓ Invented by David Nygren (Berkeley) in 1974

✓ Proposed as a central tracking device for the PEP-4 detector @ SLAC 1976

➢ More (and even larger) were built, based on MPWC readout

➢ New generation of TPCs use MPGD-based readout: e.g. ALICE Upgrade, T2K, ILC, CepC

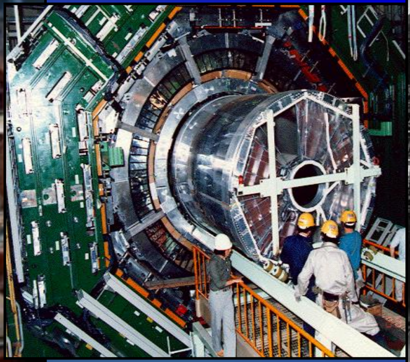


PARAMETER / EXPERIMENT	PEP4	TRIUMF	TOPAZ	ALEPH	DELPHI	STAR	ALICE [1]
1. OPERATION	1982 / 1984	1982 / 1983	1987	1989	1989	2000	2009
INNER / OUTER RADIUS [m]	0.2 / 1.0	~0.15 / 0.50	0.38 / 1.1	0.35 / 1.8	0.35 / 1.4	0.5 / 2.0	0.85 / 2.5
MAX. DRIFTLENGTH (L/2) [m]	1	0.34	1.1	2.2	1.34	2.1	2.5
MAGNETIC FIELD [T]	0.4 / 1.325	0.9	1	1.5	1.23	0.25 / 0.5	0.5
GAS :	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ar / CH4	Ne /CO2/ N2
Mixture	80 / 20	80 / 20	90 / 10	91 / 9	80 / 20	90 / 10	90/ 10/ 5
Pressure [atm]	8.5	1	3.5	1	1	1	1
DRIFT FIELD [KV / cm / atm]	0.088	0.25	0.1	0.11	0.15	0.14	0.4
ELECTRON DRIFT VELOCITY [cm/μsec]	5	7	5.3	5	6.69	5.45	2.7
$\omega\tau$ (see 2.2.1.3)	0.2 / 0.7	2	1.5	7	5	1.15 / 2.3	< 1
PADS: Size w•L [mm•mm]	7.5x7.5	(5.3-6.4)x19	(9-11)x12	6.2x30	~7x7	2.85x11.5	4x7.5
						6.2x19.5	6x10/15
Max. no. 3-D points	15 - straight	12	10 - linear	9+12 - circular	16 - circular	13+32 - straight	63+64+32
dE/dx: Max. no. samples/track	183	12	175	148+196	192	13+32	63+64+32
Sample size [mm atm]; w or p	4•8.5; wires	6.35; wires	4x3.5; wires	4 ; wires	4 ; wires	11.5 + 19.5;pads	7.5+10+15; pads
GAS AMPLIFICATION	1000	50 000		3000-5000	5000	3000/1100	20 000
GAP a-p; a-c; c-gate [2]	4; 4; 8	6	4; 4; 8	4; 4; 6	4; 4; 6	2; 2; 6 / 4; 4 ; 6	2; 2; 3 / 3; 3; 3
PITCH a-a; cathode; gate	4; 1; 1		4; 1; 1	4; 1; 2	4; 1; 1	4; 1; 1/ 4; 1; 1	2.5; 2.5; 1.5
PULSE SAMPLING [MHz/ no. samples]	10/455, CCD	only 1 digitiz., ADC	10/ 455, CCD	11/ 512, FADC	14/ 300, FADC	9.6 / 400	5-10/500-1000, ADC
GATING [3]	≥1984 o.on tr.	≥1983 o.on tr.	o. on tr.	synchr. cl.wo.tr	static	o.on tr.	o.on tr.
PADS, total number	15 000	7800	8200	41 000	20 000	137 000	560 000
PERFORMANCE							
Δx_T [μm]-best / typ.	130-200	200/	185/230	170/200-450	180/190-280	300-600	spec:800-1100
Δx_L [μm]-best / typ.	160-260	3000	335/900	500-1700	900	500-1200	spec:1100-1250
2-TRACK SEPARATION [mm], T / L	20		25	15	15	8 - 13 / 30	
$\partial p/p^2$ $[GeV/c]^{-1}$: TPC alone; high p	0.0065		0.015	0.0012	0.005	0.006	spec:0.005
dE/dx [%] SINGLE TRACKS/ IN JETS	2.7 / 4.0		4.4 /	4.4 /	5.7 / 7.4	7.4 / 7.6	spec:4.9 / 6.8
COMMENTS		a in single PCs	chevron pads	circular pad rows	circular pad rows	No field wires	No field wires
		strong ExB effect				> 3000 tracks	≤ 20 000 tracks

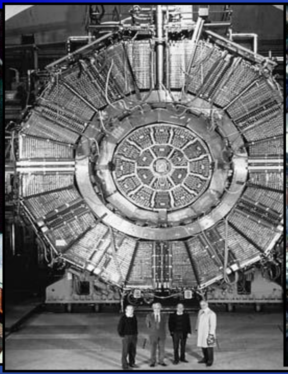
1) Expected performance
2) a = anode, p = pads, c = cathode grid
3) o. on tr.: gate opens on trigger; cl.wo.tr. : opens before collision and closes without trigger; static : closed for ions only (see text).

PEP4 (SLAC)

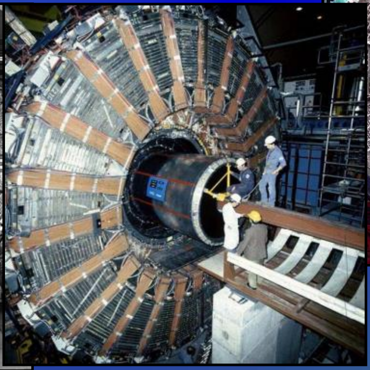
TOPAZ (KEK)



ALEPH (CERN)



DELPHI (CERN)



STAR (BNL)

ALICE (CERN)

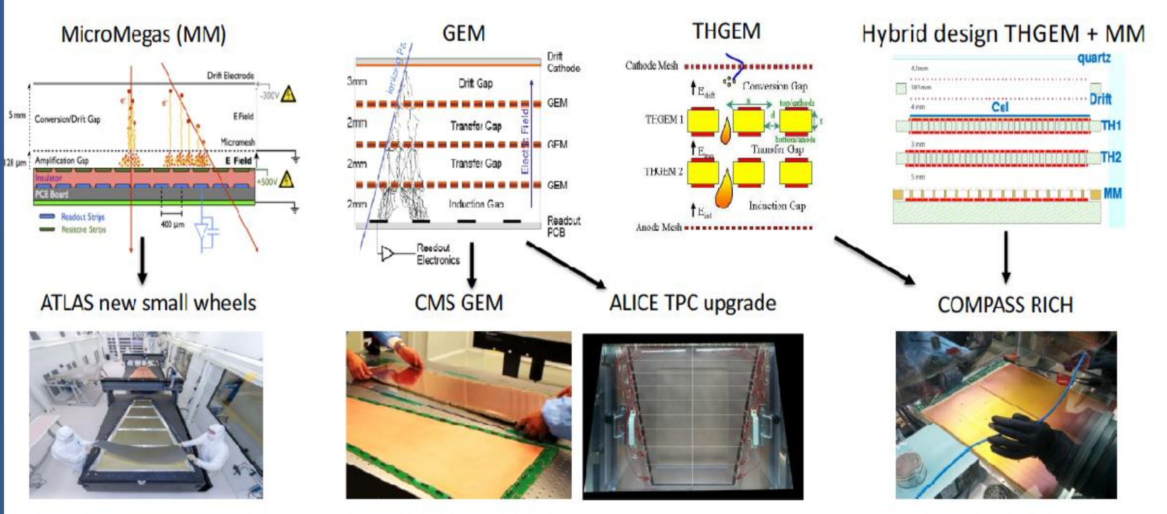
MPGD Technologies @ CERN Experiments

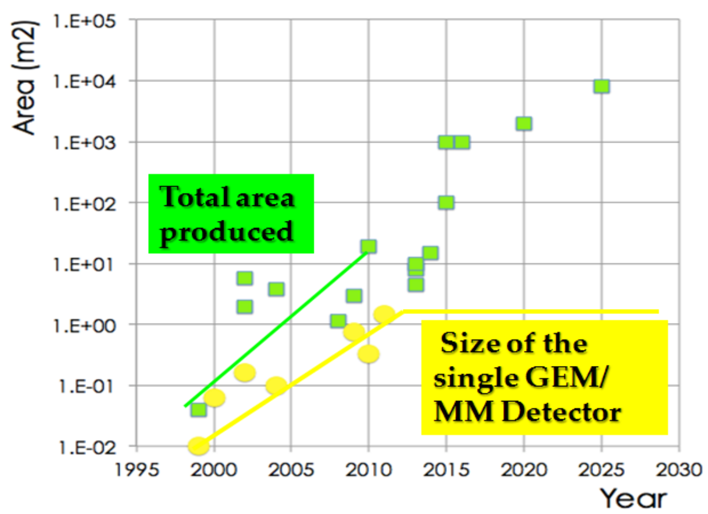
- The integration of MPGDs in large experiments was not rapid, despite of the first large-scale application in COMPASS at SPS in the 2000's

- Scaling up MPGD detectors, while preserving the typical properties of small prototypes, allowed their use in the LHC upgrades
  → Many emerged from the R&D studies within the CERN-RD51 Collaboration

- Successful accomplishment of LHC upgrades will help to disseminate MPGD technologies even wider

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS TRACKING > 2002	Fixed Target Experiment (Tracking)	3-GEM Micromegas w/ GEM preampl.	Total area: 2.6 m^2 Single unit detect: 0.31x0.31 m^2 Total area: ~ 2 m^2 Single unit detect: 0.4x0.4 m^2	**Max.rate**: ~100kHz/mm² **Spatial res.**: ~70-100µm (strip), ~120µm (pixel) **Time res.**: ~ 8 ns **Rad. Hard.**: 2500 mC/cm²	Required beam tracking (pixelized central / beam area)
TOTEM TRACKING: > 2009	Hadron Collider / Forward Physics ($5.3 \leq \lvert\eta\rvert \leq 6.5$)	3-GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	**Max.rate**:20 kHz/cm² **Spatial res.**: ~120µm **Time res.**: ~ 12 ns **Rad. Hard.**: ~ mC/cm²	Operation in pp, pA and AA collisions.
LHCb MUON DETECTOR > 2010	Hadron Collider / B-physics (triggering)	3-GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	**Max.rate**:500 kHz/cm² **Spatial res.**: ~ cm **Time res.**: ~ 3 ns **Rad. Hard.**: ~ C/cm²	Redundant triggering
COMPASS RICH UPGRADE > 2016	Fixed Target Experiment (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m^2 Single unit detect: ~ 0.6 x 0.6 m^2	**Max.rate**:100 Hz/cm² **Spatial res.**: <~ 2.5 mm **Time res.**: ~ 10 ns	Production of large area THGEM of sufficient quality
ATLAS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	Resistive Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	**Max. rate**:15 kHz/cm² **Spatial res.**: <100µm **Time res.**: ~ 10 ns **Rad. Hard.**: ~ 0.5C/cm²	Redundant tracking and triggering; Challenging constr. in mechanical precision
CMS MUON UPGRADE CERN LS2	Hadron Collider (Tracking/Triggering)	3-GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	**Max. rate**:10 kHz/cm² **Spatial res.**: ~100µm **Time res.**: ~ 5-7 ns **Rad. Hard.**: ~ 0.5 C/cm²	Redundant tracking and triggering
ALICE TPC UPGRADE CERN LS2	Heavy-Ion Physics (Tracking + dE/dx)	4-GEM / TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	**Max.rate**:100 kHz/cm² **Spatial res.**: ~300µm **Time res.**: ~ 100 ns **dE/dx**: 11 % **Rad. Hard.**: 50 mC/cm²	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution





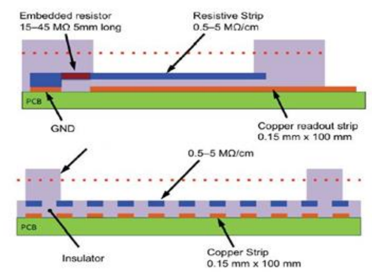
Large-Area MM / GEM Detectors for ATLAS / CMS Upgrade

Resistive MM for ATLAS NSW Muon Upgrade:

Standard Bulk MM suffers from limited efficiency at high rates due to discharges induced dead time
Solution: Resistive Micromegas technology:

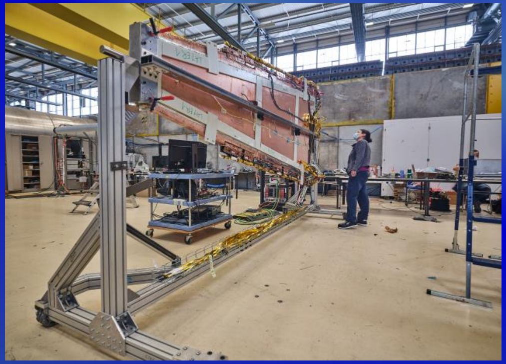
- Add a layer of resistive strips above the readout strips

- Spark neutralization/suppression (sparks still occur, but become inoffensive)



Still, main issue encountered: HV unstability
==> found to be correlated to low resistance of resistive strip anode
==> applied solutions + passivation in order to deactivate the region where R<0.8 MΩ

Production, sector integration ongoing (~1200m^2 resistive MM):



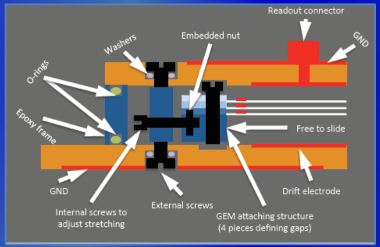
Challenging Timeline:

- **NSW-A completion: Apr/May 2021**
- **NSW-C completion: Mid Sep 2021 w/ very little contingency**

GEMs for CMS Muon System Upgrade:

- Single-mask GEM technology (instead of double-mask)
  → Reduces cost /allows production of large-area GEM

- Assembly optimization: self-stretching technique:
  → assembly time reduction to 1 day

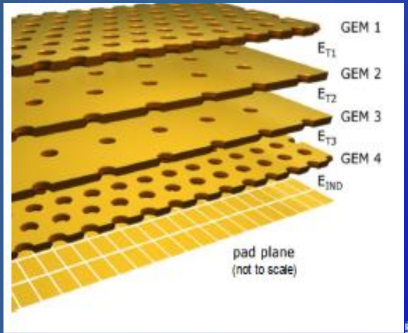


September 2020: 144 GEM chambers installed

Important milestone for CMS collaboration as the first complete Phase II Upgrade detector, with a brand new detector technology, the GEMs, complementing the Muon system

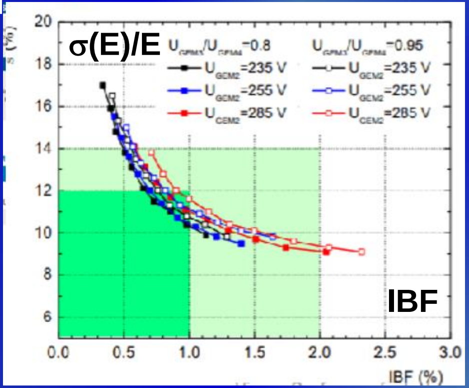
TPC with MPGD Readout for ALICE Upgrade and ILC

ALICE TPC → replace MWPC with 4-GEM staggered holes (to limit space-charge effects)

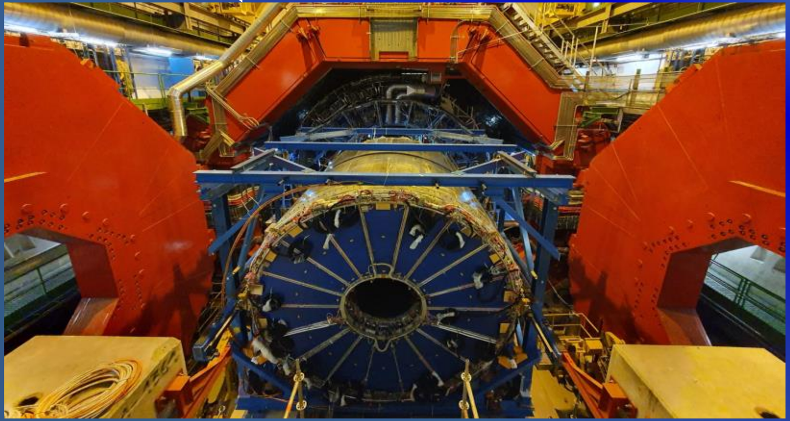


- Upgrade for continuous TPC readout @ 50 kHz Pb-Pb collisions

- Phys. requirements:
  IBF < 1%,
  Energy res. σ(E)E < 12%



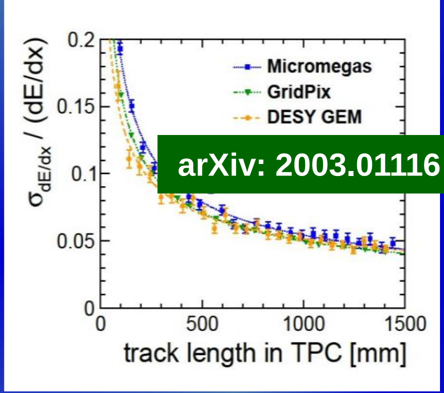
TPC reinstallation in the ALICE cavern (August 2020)



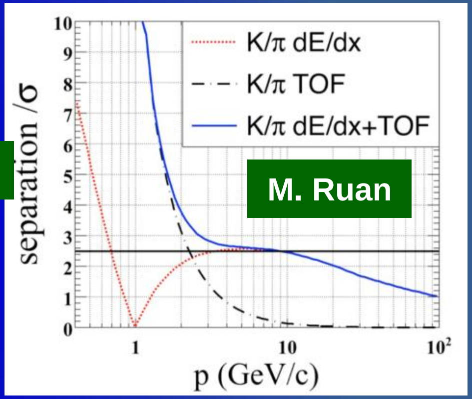
ILC –TPC with MPGD-based Readout

Target requirement of a spatial resolution of 100 um in transverse plane and dE/dx resolution < 5% have been reached with all technologies (GEM, MM and GridPix)

If dE/dx combined with ToF using SiECAL,
P < 10GeV region for pion-K separation covered



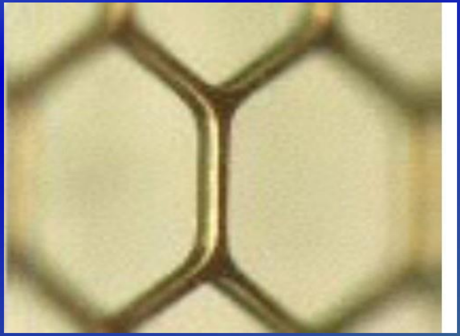
arXiv: 2003.01116

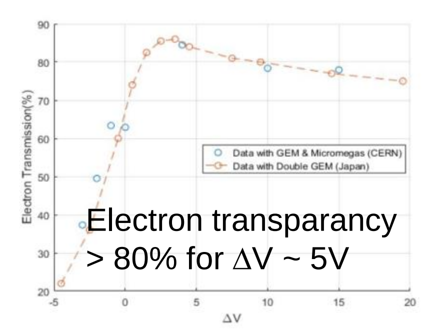


M. Ruan

ILC: gating scheme, based on large-aperture GEM

→ Machine-induced background and ions from gas amplific.
→ Exploit ILC bunch structure (gate opens 50 us before the first bunch and closes 50 us after the last bunch)





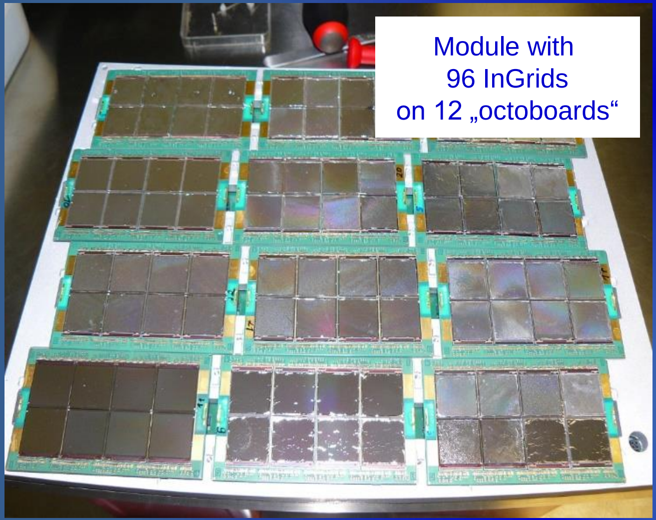
Electron transparancy
> 80% for ΔV ~ 5V

Pixel TPC / GridPix Readout for ILC and CePC

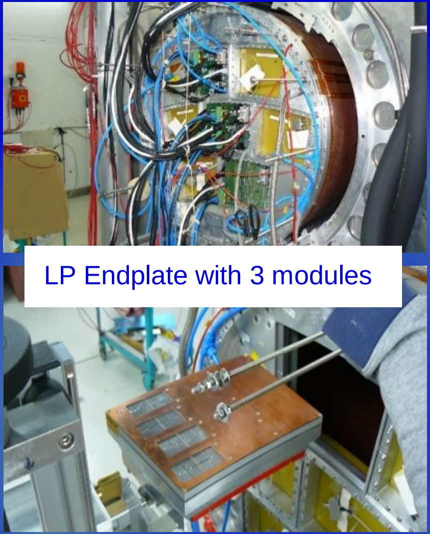
Feasibility is shown @ DESY test-beam with 160 GridPix

3 modules for Large TPC Prototype : 1 x 96 and 2 x 24 GridPixs

320 cm² active area, 10,5 mio. channels, new SRS Readout system

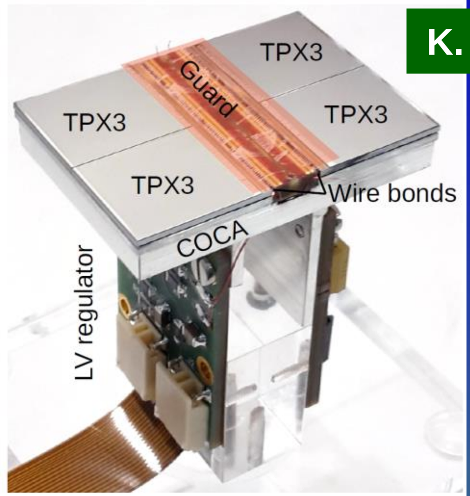


Module with
96 InGrids
on 12 „octoboards“

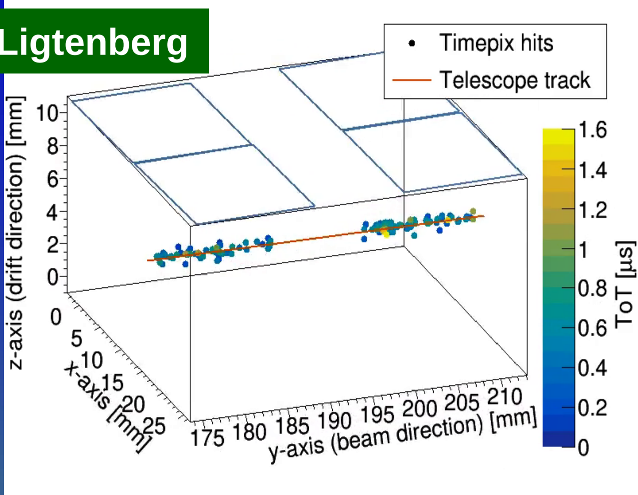


LP Endplate with 3 modules

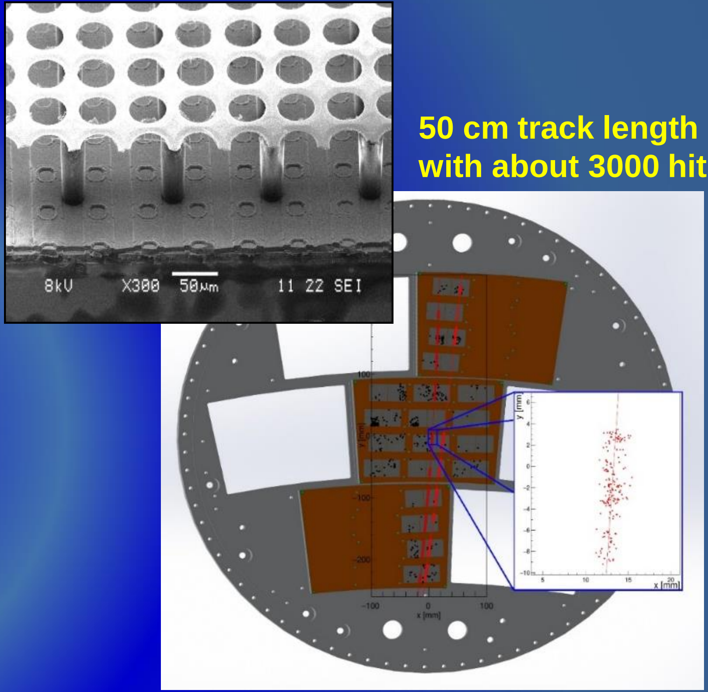
Quad board (Timepix3) → development of 8 quad detector (2020)



K. Ligtenberg



- GridPix: INTEGRATE MICROMEGAS amplification grid directly on top of CMOS (“Timepix”) ASIC
- 3D Gaseous Pixel Detector → 2D (pixel dimensions) x 1D (drift time)



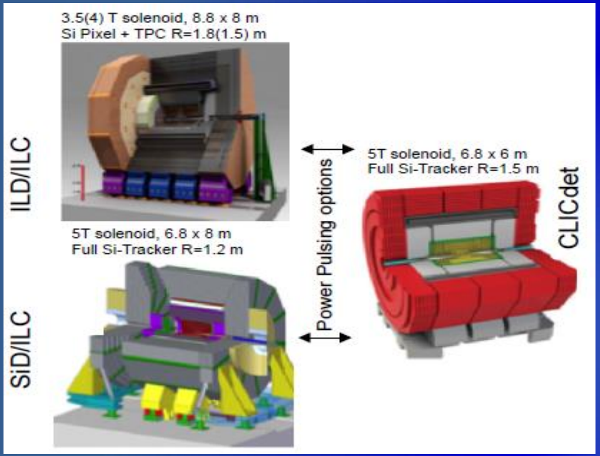
50 cm track length with about 3000 hits

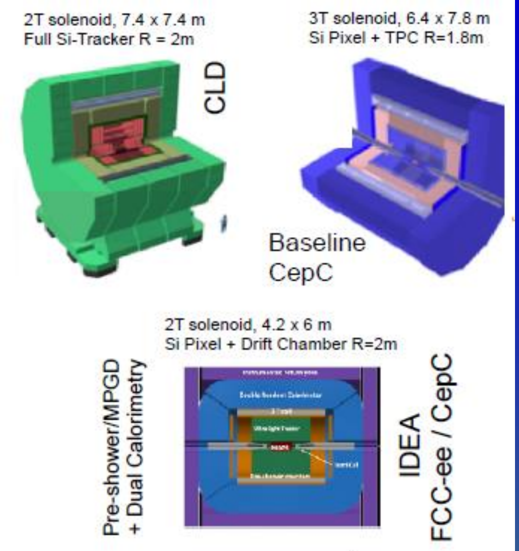
Physics properties of pixel TPC:

- Improved dE/dx by cluster counting
- Improved meas.of low angle tracks
- Excellent double track seperation
- Much reduced hodoscope effect
- Lower occupancy @ high rates
- Fully digital read out (TOT)

Vertex & Tracking Challenges @ Future Lepton Colliders

Beam parameters	ILC		CLIC			FCC-ee			CepC	
Energy(TeV)	0.25	0.5	0.38	1.5	3	0.091	0.24	0.36	0.091	0.24
Luminosity (x 10^{34} cm^{-2} s^{-1}) per IP	1.35	1.8	1.5	3.7	5.9	230	8.5	1.7	32	1.5
Bunch train frequency (Hz)	5		50							
Bunch separation (ns)	554		0.5			20	994	3000	25	680
Number of bunches / train - beam	1312		312	312		16640	393	48	12000	242





All-Silicon vs Silicon + Gaseous Tracking:

some open technology questions remains to be addressed:

All-Silicon tracker (ILC / SiD, CLICdp, FCC / CLD, CEPC / FST concepts)

- ✓ ILC: number of layers; thin detectors, time-stamping capability, minimize material budget (2D/ stitching); power savings / engineering;
- ✓ Circular colliders: continuous operation → power-pulsing is not possible (aim less power consumption & active (increased) cooling) → increased material budget;

Silicon + TPC (ILC /ILD, CEPC baseline concepts)

- ✓ ILC: use of GEM-grid gating; dE/dx performance looks OK;
  CC: can TPC stand for (extremely) high readout rate; ion feedback – can it cope @ Z-pole;
- ✓ Calibration and detector alignment;
- ✓ Low power consumption FEE ASIC;
- ✓ Mechanical (field cage rigidity) and distortion (field cage quality, module flatness) challenges;

Silicon + Wire/Drift Chamber (FCC / IDEA, CEPC / IDEA)

- ✓ Can it cope with high rates @ Z-pole;
- ✓ Half as many hits as in TPC → more Si-layers → momentum resolution sufficient ?;
- ✓ Aging effects: hydrocarbon-based mixtures are not trustable for long-term operation in DC → search for different gas mixtures;
- ✓ Very long wires (~4m), study/optimize wires material;
- ✓ dE/dx by cluster counting (depends on N_{hits} in DC);

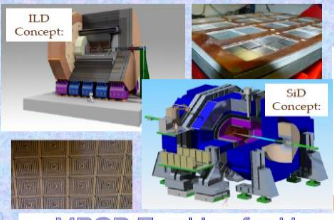
MPGD Concepts for Energy / Intensity / Cosmic Frontiers

2017 MPGD Conference Summary: https://indico.cern.ch/event/581417/timetable/#20170525.detailed

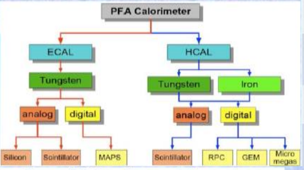
Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
ATLAS Muon System Upgrade: Start: 2019 (for 15 y.)	High Energy Physics (Tracking/Triggering)	Micromegas	Total area: 1200 m^2 Single unit detect: (2.2x1.4m^2) ~ 2-3 m^2	Max. rate:15 kHz/cm^2 Spatial res.: <100μm Time res.: ~ 10 ns Rad. Hard.: ~ 0.5C/cm^2	- Redundant tracking and triggering; Challenging constr. in mechanical precision:
ATLAS Muon Tagger Upgrade: Start: > 2023	High Energy Physics (Tracking/triggering)	μ-PIC	Total area: ~ 2m^2	Max.rate:100kHz/cm^2 Spatial res.: < 100μm	
CMS Muon System Upgrade: Start: > 2020	High Energy Physics (Tracking/Triggering)	GEM	Total area: ~ 143 m^2 Single unit detect: 0.3-0.4m^2	Max. rate:10 kHz/cm^2 Spatial res.: ~100μm Time res.: ~ 5-7 ns Rad. Hard.: ~ 0.5 C/cm^2	- Redundant tracking and triggering
CMS Calorimetry (BE) Upgrade Start > 2023	High energy Physics (Calorimetry)	Micromegas, GEM	Total area: ~ 100 m^2 Single unit detect: 0.5m^2	Max. rate: 100 MHz/cm^2 Spatial res.: ~ mm	Not main option; could be used with HGCAL (BE part)
ALICE Time Projection Chamber: Start: > 2020	Heavy-Ion Physics (Tracking + dE/dx)	GEM w/ TPC	Total area: ~ 32 m^2 Single unit detect: up to 0.3m^2	Max.rate:100 kHz/cm^2 Spatial res.: ~300μm Time res.: ~ 100 ns dE/dx: 12 % (Fe55) Rad. Hard.: 50 mC/cm^2	- 50 kHz Pb-Pb rate; - Continues TPC readout - Low IBF and good energy resolution
TOTEM: Run: 2009-now	High Energy/ Forward Physics ($5.3 \le \lvert eta \rvert \le 6.5$)	GEM (semicircular shape)	Total area: ~ 4 m^2 Single unit detect: up to 0.03m^2	Max.rate:20 kHz/cm^2 Spatial res.: ~120μm Time res.: ~ 12 ns Rad. Hard.: ~ mC/cm^2	Operation in pp, pA and AA collisions.
LHCb Muon System Run: 2010 - now	High Energy / B-flavor physics (muon triggering)	GEM	Total area: ~ 0.6 m^2 Single unit detect: 20-24 cm^2	Max.rate:500 kHz/cm^2 Spatial res.: ~ cm Time res.: ~ 3 ns Rad. Hard.: ~ C/cm^2	- Redundant triggering
FCC Collider Start: > 2035	High Energy Physics (Tracking/Triggering/ Calorimetry/Muon)	GEM, THGEM Micromegas, μ-PIC, InGrid	Total area: 10.000 m^2 (for MPGDs around 1.000 m^2)	Max.rate:100 kHz/cm^2 Spatial res.: <100μm Time res.: ~ 1 ns	Maintenance free for decades

MPGD Technologies for the International Linear Collider

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
ILC Time Projection Chamber for ILD: Start: > 2030	High Energy Physics (tracking)	Micromegas GEM (pads) InGrid (pixels)	Total area: ~ 20 m^2 Single unit detect: ~ 400 cm^2 (pads) ~ 130 cm^2 (pixels)	Max. rate: < 1 kHz Spatial res.: <150μm Time res.: ~ 15 ns dE/dx: 5 % (Fe55) Rad. Hard.: no	Si + TPC Momentum resolution : dp/p < 9*10^{-5} 1/GeV Power-pulsing
ILC Hadronic (DHCAL) Calorimetry for ILD/SiD Start > 2030	High Energy Physics (calorimetry)	GEM, THGEM RPWELL, Micromegas	Total area: ~ 4000 m^2 Single unit detect: 0.5 - 1 m^2	Max.rate:1 kHz/cm^2 Spatial res.: ~ 1cm Time res.: ~ 300 ns Rad. Hard.: no	Jet Energy resolution: 3-4 % Power-pulsing, self-triggering readout



Particle Flow Calorimetry (ILD/SiD):



MPGD Tracking Concepts for Hadron / Nuclear Physics

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
COMPASS @ CERN Run: 2002 - now	Hadron Physics (Tracking)	GEM Micromegas w/ GEM preampl.	Total area: 2.6 m^2 Single unit detect: 0.31x0.31 m^2 Total area: ~ 2 m^2 Single unit detect: 0.4x0.4 m^2	Max.rate:10^7 Hz (~100kHz/mm^2) Spatial res.: ~70-100 μm (strip), ~120μm (pixel) Time res.: ~ 8 ns Rad. Hard.: 2500 mC/cm^2	Required beam tracking (pixelized central / beam area)
KEDR @ BINP Run: 2010-now	Particle Physics (Tracking)	GEM	Toral area: ~0.1 m^2	Max. rate:1 MHz/mm^2 Spatial res.: ~70μm	
SBS in Hall A @ JLAB Start: > 2017	Nuclear Physics (Tracking) nucleon form factors / struct.	GEM	Total area: 14 m^2 Single unit detect. 0.6x0.5m^2	Max. rate:400 kHz/cm^2 Spatial res.: ~70μm Time res.: ~ 15 ns Rad. Hard.: 0.1-1 kGy/y.	
pRad in Hall B @ JLAB Start: 2017	Nuclear Physics (Tracking) precision meas. of proton radius	GEM	Total area: 1.5m^2 Single unit detect. 1.2x0.6 m2	Max. rate:5 kHz/cm^2 Spatial res.: ~70μm Time res.: ~ 15 ns Rad. Hard.: 10 kGy/y.	
SoLID in Hall A@ JLAB Start: ~ > 2020	Nuclear Physics (Tracking)	GEM	Total area: 40m^2 Single unit detect. 1.2x0.6 m2	Max. rate:600 kHz/cm^2 Spatial res.: ~100μm Time res.: ~ 15 ns Rad. Hard.: 0.8-1 kGy/y.	
E42 and E45 @JPARC Start: ~2020	Hadron Physics (Tracking)	TPC w/ GEM, gating grid	Total area: 0.26m^2 0.52m(diameter) x0.5m(drift length)	Max. rate:10^6 kHz/cm^2 Spatial res.: 0.2-0.4 mm	Gating grid operation ~ 1kHz
ACTAR TPC Start: ~2020 for 10 y.	Nuclear physics Nuclear structure Reaction processes	TPC w/ Micromegas (amp. gap -220 μm)	2 detectors: 25*25 cm2 and 12.5*50cm2	Counting rate < 10^4 nuclei but higher if some beam masks are used.	Work with various gas (He mixture, iC4H10, D2…)

Cylindrical MPGDs as Inner Trackers for Particle / Nuclear Physics

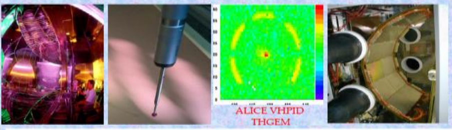
Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics/ Performance	Special Requirements/ Remarks
KLOE-2 @ DAFNE Run: 2014-2017	Particle Physics/ K-flavor physics (Tracking)	Cylindrical GEM	Total area: 3.5m^2 4 cylindrical layers L(length) = 700mm R (radius) = 130, 155, 180, 205 mm	Spatial res:(r phi) = 250um Spat. res.(z) = 350um	- Mat. budget 2% X0 - Operation in 0.5 T
BESIII Upgrade @ Beijing Run: 2018-2022	Partcile Physics/ e+e- collider (Tracking)	Cylindrical GEM	3 cylindrical layers R ~ 20 cm	Max. rate: 10 kHz/cm^2 Spatial res:(xy) = 130um Spat. res.(z) = 1 mm	- Material ≤ 1.5% of X_0 for all layers - Operation in 1T
CLAS12 @ JLAB Start: > 2017	Nuclear Physics/ Nucleon structure (tracking)	Planar (forward) & Cylindrical (barrel) Micromegas	Total area: Forward ~ 0.6 m^2 Barrel ~ 3.7 m^2 2 cylindrical layers R ~ 20 cm	Max. rate: ~ 30 MHz Spatial res.: < 200μm Time res.: ~ 20 ns	- Low material budget : 0.4 % X0 - Remote electronics
ASACUSA @ CERN Run: 2014 - now	Nuclear Physics (Tracking and vertexing of pions resulting from the p-antip annihilation	Cylindrical Micromegas 2D	2 cylindrical layers L = 60 cm R = 85, 95 mm	Max. trigger rate: kHz Spatial res.: ~200μm Time res.: ~ 10 ns Rad. Hard.: 1 C/cm^2	- Large magnetic field that varies from -3 to 4T in the active area
MINOS Run: 2014-2016	Nuclear structure	TPC w/ cylindrical Micromegas	1 cylindrical layer L=30 cm, R = 10cm	Spatial res.: <5 mm FWHM Trigger rate up to ≈1 KHz	- Low material budget
CMD-3 Upgrade @ BINP Start: > ~2019 ?	Particle physics (z-chamber, tracking)	Cylindrical GEM	Total arear: ~ 3m^2 2 cylindrical layers	Spatial res.: ~100μm	

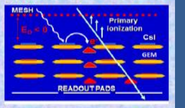
MPGD Tracking for Heavy Ion / Nuclear Physics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements/ Remarks
STAR Forward GEM Tracker @ RHIC Run: 2012-present	Heavy Ion Physics (tracking)	GEM	Total area: ~ 3 m^2 Single unit detect: ~ 0.4 x 0.4 m^2	Spatial res.: 60-100 μm	Low material budget:: < 1% X0 per tracking layer
Nuclotron BM@N @ NICA/JINR Start: > 2017	Heavy Ions Physics (tracking)	GEM	Total area: ~ 12 m^2 Single unit detect: ~ 0.9 m^2	Max. rate: ~ 300 MHz Spatial res.: ~ 200μm	Magnetic field 0.5T orthogonal to electric field
SuperFRS @ FAIR Run: 2018-2022	Heavy Ion Physics (tracking/diagnostics at the In-Fly Super Fragment Separator)	TPC w/ GEMs	Total area:~ few m^2 Single unit detect: Type I : 50 x 9 cm^2 Type II: 50 x 16 cm^2	Max. rate:~ 10^7 Hz/spill Spatial res.: < 1 mm	High dynamic range Particle detection from p to Uranium
PANDA @FAIR Start > 2020	Nuclear physics p - anti-p (tracking)	Micromegas/ GEMs	Total area: ~ 50 m^2 Single unit detect: ~ 1.5 m^2	Max. rate: < 140kHz/cm^2 Spatial res.: ~ 150μm	Continuous-wave operation: 10^{11} interaction/s
CBM @ FAIR: Start: > 2020	Nuclear Physics (Muon System)	GEM	Total area: 9m^2 Single unit detect: 0.8x0.5m^2~0.4m^2	Spatial res.: < 1 mm Max. rate: 0.4 MHz/cm^2 Time res.: ~ 15ns Rad hard.: 10^{13} n.eq./cm^2/year	Self-triggered electronics
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout Large area GEM planar tracking detectors	Total area: ~ 3 m^2 Total area: ~ 25 m^2	Spatial res.: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} Spatial res.: ~ 50- 100 um Max. rate: ~ MHz/cm^2	Low material budget Low material budget

MPGD Technologies for Photon Detection

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
COMPASS RICH UPGRADE Start > 2016	Hadron Physics (RICH - detection of single VUV photons)	Hybrid (THGEM + CsI and MM)	Total area: ~ 1.4 m^2 Single unit detect: ~ 0.6 x 0.6 m^2	Max.rate:100 Hz/cm^2 Spatial res.: <~ 2.5 mm Time res.: ~ 10 ns	Production of large area THGEM of sufficient quality
PHENIX HBD Run: 2009-2010	Nuclear Physics (RICH – e/h separation)	GEM+CsI detectors	Total area: ~ 1.2 m^2 Single unit detect: ~ 0.3 x 0.3 m^2	Max. rate: low Spatial res.: ~ 5 mm (rϕ) Single el. eff.: ~ 90 %	Single el. eff. depends from hadron rejection factor
SPHENIX Run: 2021-2023	Heavy Ions Physics (tracking)	TPC w/GEM readout	Total area: ~ 3 m^2	Multiplicity: dNch/dy ~ 600 Spatial res.: ~ 100 um (rϕ)	Runs with Heavy Ions and comparison to pp operation
Electron-Ion Collider (EIC) Start: > 2025	Hadron Physics (tracking, RICH)	TPC w/GEM readout + Cherenkov RICH with GEM readout	Total area: ~ 3 m^2 Total area: ~ 10 m^2	Spatial res.: ~ 100 um (rϕ) Luminosity (e-p): 10^{33} Spatial res.: ~ few mm	Low material budget High single electron efficiency


ALICE VHPID THGEM



HBD Concept:

MPGD-based Neutron Detectors

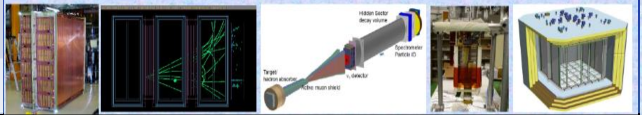
MPGD coupled to n-converters:

- ITER / Spallation Sources
- Neutron-beam diagnostics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size)	Operation Characteristics / Performance	Special Requirements / Remarks
ESS NMX: Neutron Macromolecular Crystallography Start: > 2020(for 10 y.)	Neutron scattering Macromolecular Crystallography	GEM w/ Gd converter	Total area: ~ 1 m^2 Single unit detect: 60x60 cm^2	Max.rate: 100 kHz/mm^2 Spatial res.: ~500μm Time res.: ~ 10 us n.-eff: ~ 20% efficient - γ rejection of 100	Localise the secondary particle from neutron conversion in Gd with < 500um precision
ESS LOKI- SANS: Small Angle Neutron Scattering (Low Q) Start: > 2020(for 10 y.)	Neutron scattering: Small Angle	GEM w/ borated cathode	Total area: ~ 1 m^2 Single unit detect: 33x40 cm^2 trapezoid	Max.rate: 40 kHz/mm^2 Spatial res.: ~4 mm Time res.: ~ 100 us n. –eff. >60% (at λ= 4 Å) - γ rejection of 10^-7	Measure TOF of neutron interaction in a 3D borated cathode
SPIDER: ITER NBI PROTOTYPE Start: ~ 2017(for 10 y.)	CNESM diagnostic: Characterization of neutral deuterium beam for ITER plasma heating using neutron emission	GEMs w/ Al-converter (Directionality - angular) capability)	Single unit detect: 20x35 cm^2	Max.rate: 100 kHz/mm^2 Spatial res.: ~ 10 mm Time res.: ~ 10 ms n.-eff: >10^-5 γ rejection of 10^-7	Measurement of the n-emission intensity and composition to correct deuterium beam parameters
n_TOF beam monitoring/ beam profiler Run: 2008-now	Neutron Beam Monitors	MicroMegas μbulk and GEM w/ converters	Total area: ~ 100cm^2	Max.rate:10 kHz Spatial res.: .: ~300μm Time res.: ~ 5 ns Rad. Hard.: no	

MPGD Technologies for Neutrino Physics

Experiment / Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation Characteristics / Performance	Special Requirements / Remarks
T2K @ Japan Start: 2009 - now	Neutrino physics (Tracking)	TPC w/ Micromegas	Total area: ~ 9 m^2 Single unit detect: 0.36x0.34m^2~0.1m^2	Spatial res.: 0.6 mm dE/dx: 7.8% (MIP) Rad. Hard.: no Moment. res.:9% at 1 GeV	The first large TPC using MPGD
SHiP @ CERN Start: 2025-2035	Tau Neutrino Physics (Tracking)	Micromegas, GEM, mRWELL	Total area: ~ 26 m^2 Single unit detect: 2 x 1 m^2 ~ 2m^2	Max. rate: < low Spatial res.: < 150 μm Rad. Hard.: no	Provide time stamp of the neutrino interaction in brick"
LBNO-DEMO (WA105 @ CERN): Start: > 2016 DUNE Dual Phase Far Detector Start: > 2023?	Neutrino physics (Tracking+ Calorimetry)	LAr TPC w/ THGEM double phase readout LAr TPC w/ THGEM double phase readout	Total area: 3 m^2 (WA105-3x1x1) 36 m^2 (WA105-6x6x6) Single unit detect. (0.5x0.5 m2) ~0.25 m^2 Total area: 720 m^2 Single unit detect. (0.5x0.5 m2) ~ 0.25 m^2	WA105 3x1x1 and 6x6x6: Max. rate: 150 Hz/m^2 Spatial res.: 1 mm Time res.: ~ 10 ns Rad. Hard.: no Max. rate: 4*10^{-7} Hz/m^2 Spatial res.: 1 mm Rad. Hard.: no	Detector is above ground (max. rate is determined by muon flux for calibration) Detector is underground (rate is neutrino flux)

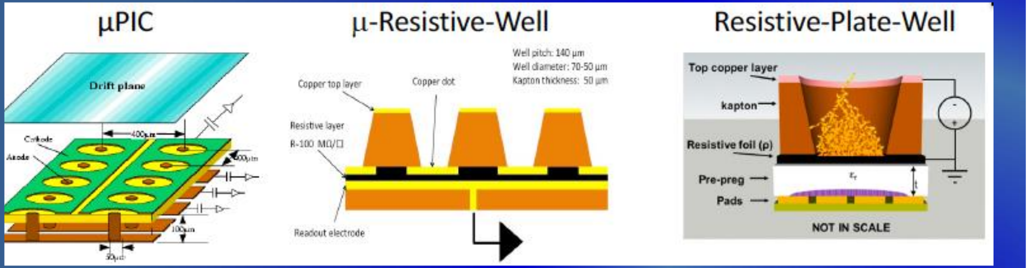


MPGD Technologies for X-Ray Detection and γ-Ray Polarimetry

Experiment/ Timescale	Application Domain	MPGD Technology	Total detector size / Single module size	Operation characteristics / Performance	Special Requirements/ Remarks
KSTAR @ Korea Start: 2013	Xray Plasma Monitor for Tokamak	GEM GEMPIX	Total area: 100 cm^2 Total area: 10-20 cm^2	Spat. res.: ~ 8x8 mm^2 2 ms frames; 500 frames/sec Spat. res.: ~50x50 μm^2 1 ms frames;5 frames/sec	
PRAXyS Future Satellite Mission (US-Japan): Start 2020 - for 2years	Astrophysics (X-ray polarimeter for relativistic astrophysical X-rays	TPC w/ GEM	Total area: 400 cm^3 Single unit detect. (8 x 50cm^3) ~400cm^3	Max.rate: ~ 1 lcps Spatial res.: ~ 100 um Time res.: ~ few ns Rad. Hard.: 1000 krad	Reliability for space mission under severe thermal and vibration conditions
HARPO Balloon start >2017?	Astroparticle physics Gamma-ray polarimetry (Tracking/Triggering)	Micromegas + GEM	Total area: 30x30cm2 (1 cubic TPC module) Future: 4x4x4 = 64 HARPO size mod.	Max.rate: ~ 20 kHz Spatial res.: < 500 um Time res.: ~ 30 ns samp.	AGET development for balloon & self triggered
SMILE-II: Run: 2013-now	Astro Physics (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 30 x 30 x 30 cm^3	Point Spread Function for gamma-ray: 1°	
ETCC camera Run: 2012-2014	Environmental gamma-ray monitoring (Gamma-ray imaging)	GEM+μPIC (TPC+ Scintillators)	Total area: 10x10x10 cm^3	Point Spread Function for gamma-ray: 1°	

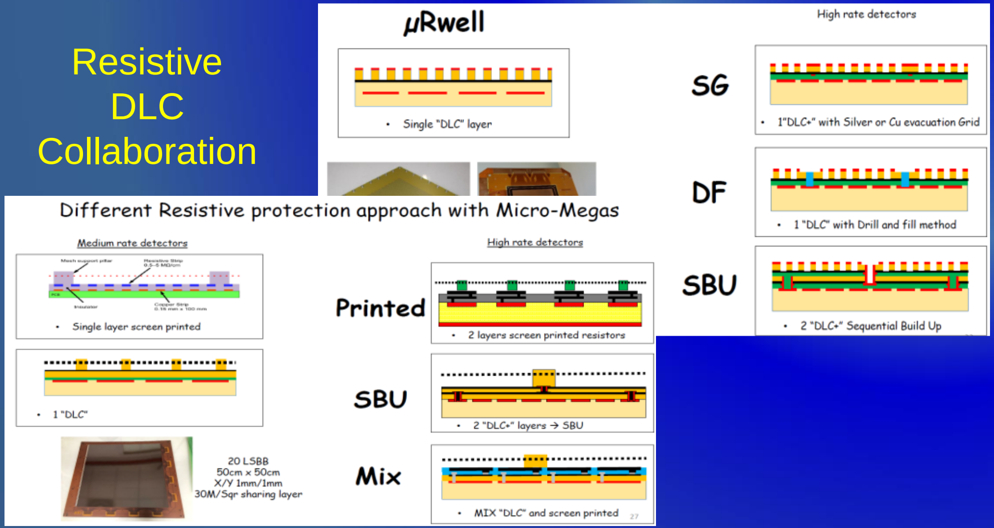
MPGD Technologies @ Future R&D Trends

- **Resistive materials and related detector architectures for single-stage designs (µPIC, µ-RWELL, RPWELL, resistive MM)**
  → improves detector stability; single-stage is advantage for assembly, mass production & cost.



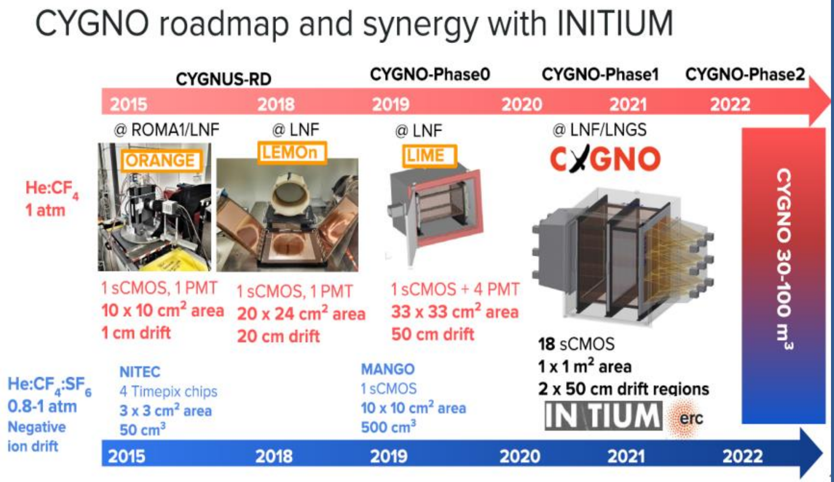
- **Diamond-like carbon (DLC) resistive layers**
  → Solutions to improve high-rate capability (≥ MHz)

Resistive DLC Collaboration



✓ Picosecond Timing Detector (RD51 PICOSEC Collaboration) – MM device with radiator and radiation-hard PC (see next slides)

- **Optical readout of MPGDs:** hybrid approaches combining gaseous with non-gaseous in a single device (e.g. CYGNUS- TPC project):


CYGNO roadmap and synergy with INITIUM

- **New manufacturing techniques & structures:**

  - Solid-state photon and neutron converters, innovative nanotechnology components;

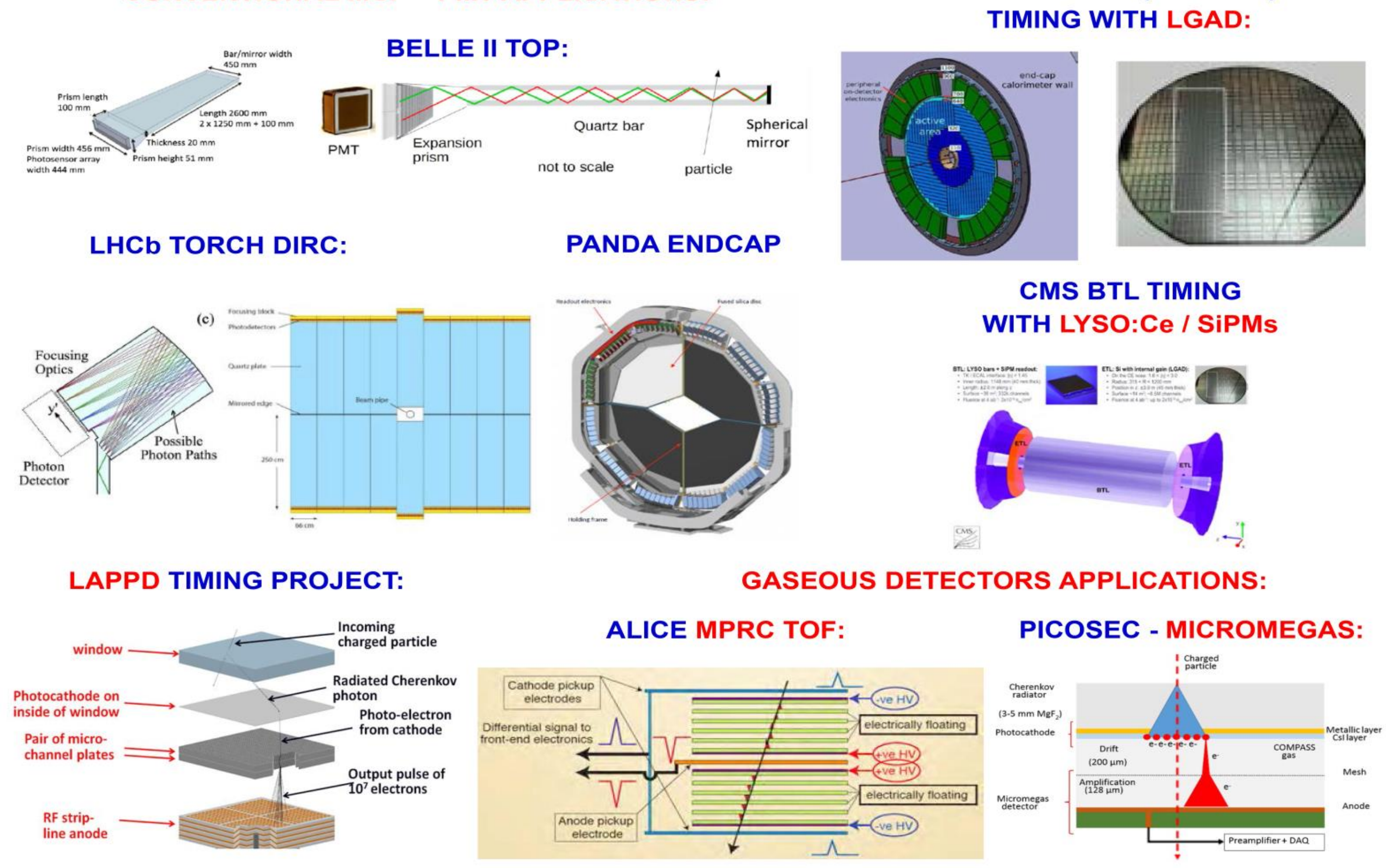
  - Material studies (low out-gassing, radiation hardness, radio-purity, converter robustness and eco-friendly gases.

  - Emerging technologies related to novel PCs, MicroElectroMechanical Systems (MEMS), sputtering, 3-D printing of amplifying structures and cooling circuits

Advanced Concepts Picosecond (a few 10’s) Timing Detectors

Several types of technologies are considered for “Picosecond-Timing Frontier”:

- Ionization detectors (silicon detectors or gas-based devices)
- Light-based devices (scintillating crystals coupled to SiPMs, Cherenkov absorbers coupled to photodetectors with amplification, or vacuum devices)



Examples of timing detectors at a level of~ 30 ps for MIPs and ~ 100 ps for single photons

TIMING Detectors with a few 10's of picosecond resolution

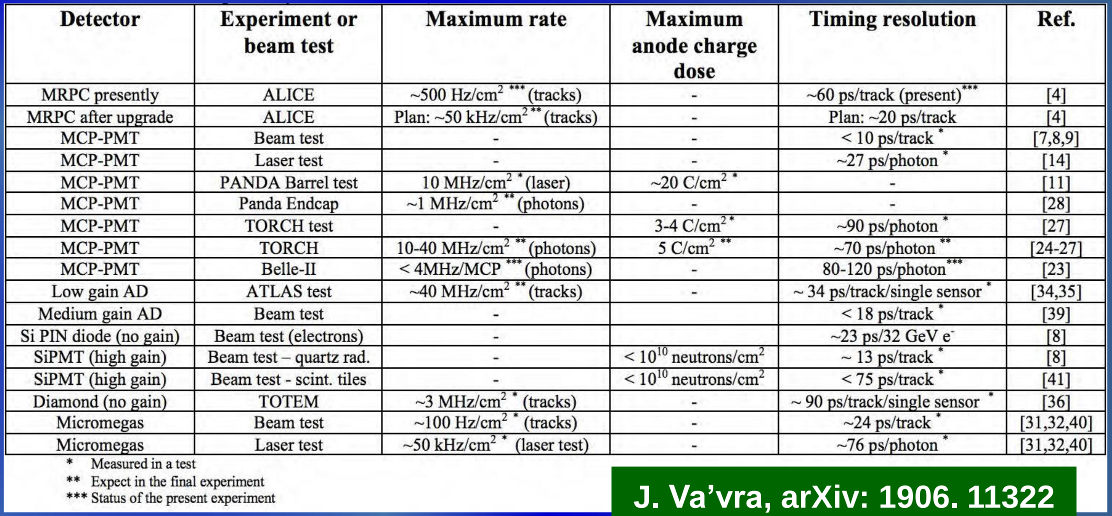
Picosecond-level timing was not the part of initial HL-LHC detector requirements:

Became available through pioneering R&D on LGAD / crystals / precise timing with Si:

Fast development of precise timing sensors:

- ✓ 4D pattern recognition for HL-LHC pile-up rejection: tracking ~O(10's) µm & timing detectors ~O(10's) ps
  → ATLAS HGTD, CMS ETL (LGAD)
  → CMS BTL (LYSO +SiPM)
- ✓ ps-timing reconstruction in calorimetry (resolve develop. of hadron showers, triangulate H → $\gamma\gamma$ prim. vertices)
  → CMS HGCAL (Si & Sci.+ SiPMs)
- ✓ TOF and TOP (RICH DIRC) PID → new DIRC applications (~ 10's of ps & 10's of µm per MIP/pixel)
  → both at hadron / lepton colliders
- ✓ General push for higher luminosity at LHC, Belle-II, Panda, Electron-Ion Collid.
  → Fast timing is needed at colliders, fixed target, and neutrino experiments

- ➢ Regular PMTs → large area, … but slow
- ➢ MCP-PMT → fast, but small, and not available in quantities to over large areas:
  → ultimate time resolution ~ 3.8 ps (single-pixel devices)
  → radiation hardness up to ~ 20 C/cm (HPK, ALD-coated MCP-PMT°



Detector	Experiment or beam test	Maximum rate	Maximum anode charge dose	Timing resolution	Ref.
MRPC presently	ALICE	~500 Hz/cm^2 *** (tracks)	-	~60 ps/track (present)***	[4]
MRPC after upgrade	ALICE	Plan: ~50 kHz/cm^2 ** (tracks)	-	Plan: ~20 ps/track	[4]
MCP-PMT	Beam test	-	-	< 10 ps/track *	[7,8,9]
MCP-PMT	Laser test	-	-	~27 ps/photon *	[14]
MCP-PMT	PANDA Barrel test	10 MHz/cm^2 * (laser)	~20 C/cm^2 *	-	[11]
MCP-PMT	Panda Endcap	~1 MHz/cm^2 ** (photons)	-	-	[28]
MCP-PMT	TORCH test	-	3-4 C/cm^2 *	~90 ps/photon *	[27]
MCP-PMT	TORCH	10-40 MHz/cm^2 ** (photons)	5 C/cm^2 **	~70 ps/photon **	[24-27]
MCP-PMT	Belle-II	< 4MHz/MCP *** (photons)	-	80-120 ps/photon***	[23]
Low gain AD	ATLAS test	~40 MHz/cm^2 ** (tracks)	-	~ 34 ps/track/single sensor *	[34,35]
Medium gain AD	Beam test	-		< 18 ps/track *	[39]
Si PIN diode (no gain)	Beam test (electrons)	-		~23 ps/32 GeV e$^-$	[8]
SiPMT (high gain)	Beam test – quartz rad.	-	< 10^{10} neutrons/cm^2	~ 13 ps/track *	[8]
SiPMT (high gain)	Beam test - scint. tiles	-	< 10^{10} neutrons/cm^2	< 75 ps/track *	[41]
Diamond (no gain)	TOTEM	~3 MHz/cm^2 * (tracks)	-	~ 90 ps/track/single sensor *	[36]
Micromegas	Beam test	~100 Hz/cm^2 * (tracks)	-	~24 ps/track *	[31,32,40]
Micromegas	Laser test	~50 kHz/cm^2 * (laser test)	-	~76 ps/photon *	[31,32,40]

* Measured in a test
** Expect in the final experiment
*** Status of the present experiment

J. Va'vra, arXiv: 1906. 11322

Challenges:

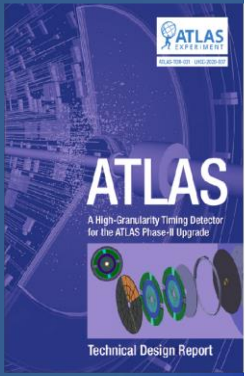
- ✓ Radiation hardness: LGAD-sensors, 3D-trench Si sensors, …
- ✓ Large scale applications : system aspects of timing detectors
- ✓ "5D reconstruction": space-points / ps-timing are available at each point along the track → LHCb EoI for LS4 is of general interest across experiments;
- ✓ LAPPD → large-area ps- PID/TOF for hadron/lepton colliders
  Incom Inc. company started to produce LAPPDs → cost still has to be controlled

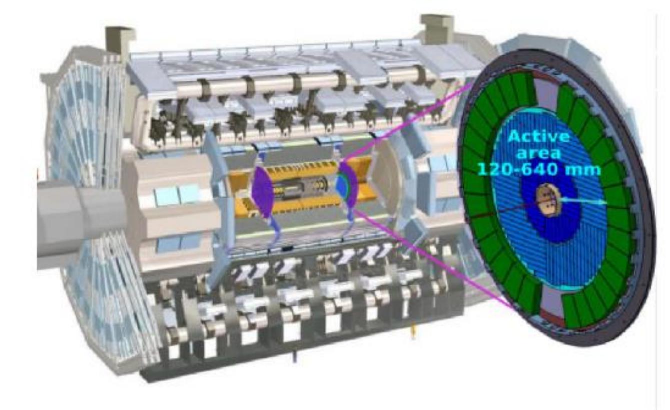
TIMING DETECTORS for ATLAS / CMS Phase-II Upgrade

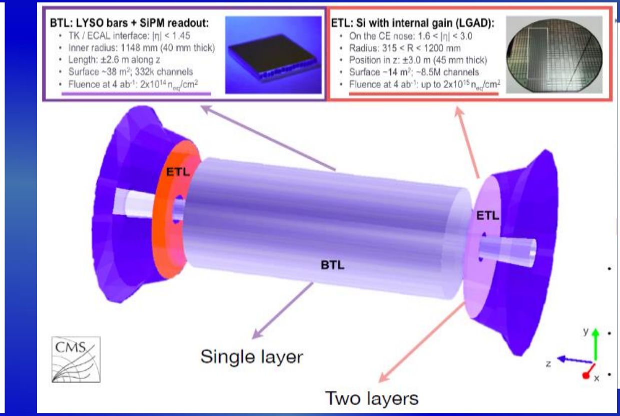
ATLAS High Granularity Timing Detector:

CMS Endcap Timing Detectors:

Equipped with LGADs (1.3 x 1.3 mm^2 pads) targetting > 50 ps resolution (rad-hard only viable solution)


ATLAS EXPERIMENT
ATLAS-TDR-031 LHCC-2020-007
ATLAS
A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade
Technical Design Report

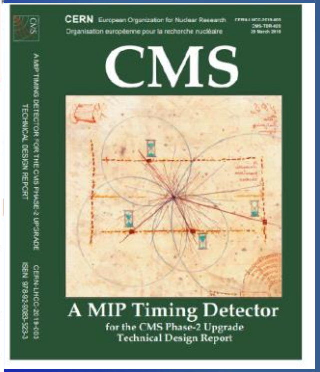



BTL: LYSO bars + SiPM readout:

- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n$_{eq}$/cm^2

ETL: Si with internal gain (LGAD):

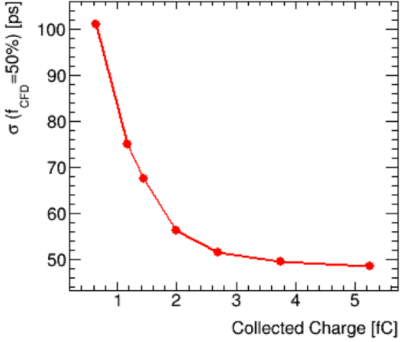
- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2x10^{15} n$_{eq}$/cm^2

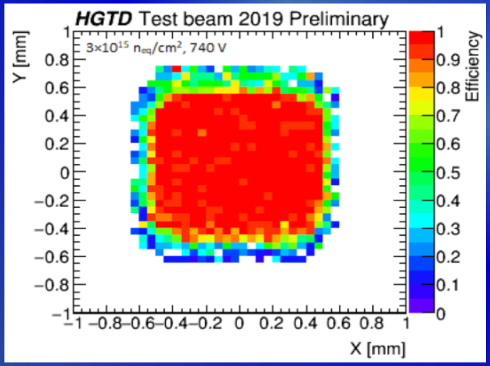

CERN European Organization for Nuclear Research
Organisation européenne pour la recherche nucléaire
CMS
A MIP Timing Detector for the CMS Phase-2 Upgrade
Technical Design Report

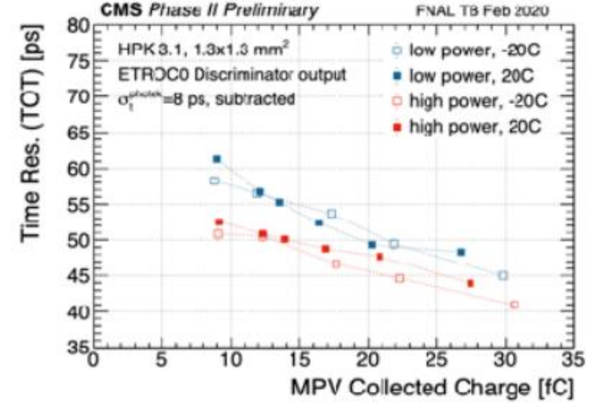
Two double sided layers in front of Calorimeter endcaps:
Fluence < 2.5 x 1015 neq/cm2
Coverage: 2.4 < η < 4.0 with 12 cm < R < 64 cm @ z = 3.5 m

Two double sided layers in front of Calorimeter endcaps:
fluence < 1.7 x 1015 neq/cm2
Coverage: 1.6 < η < 3.0 with 0.31 < R < 1.2 @ z = 3 m

Post irradiation: 4 fC and 50 ps achieved (high/uniform efficiency)







P. Collins @ ICHEP2020

Pre irradiation 40-50 ps after discriminator with full efficiency

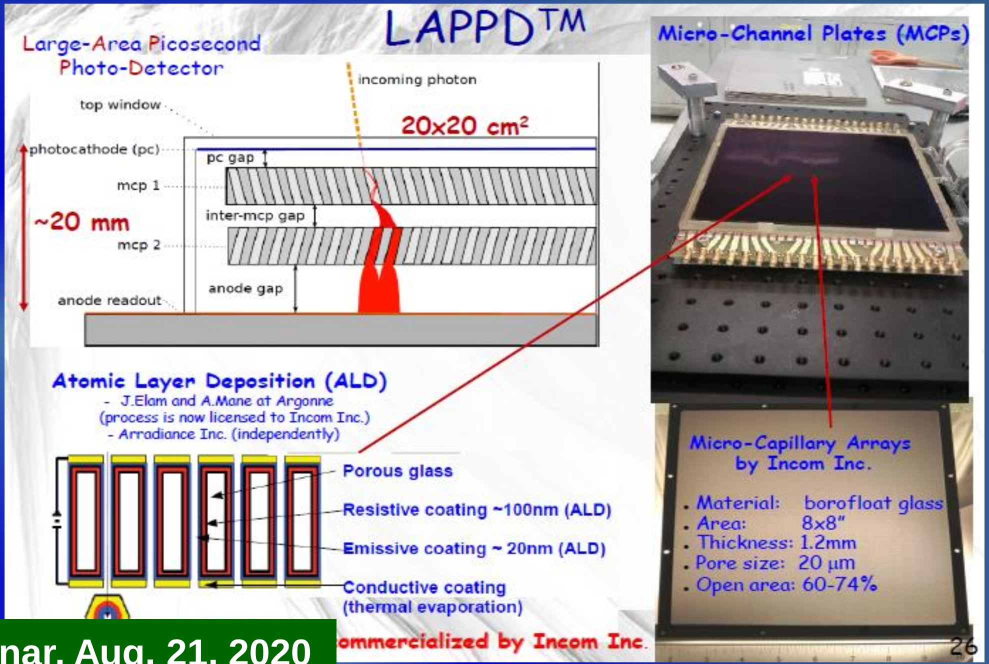
- LGAD are currently produced by 3 foundries (CNM, FBK, HPK)
- LHCb is developing a time-tracking device O(100 ps) device, based on 3D trench Si-sensors with a more uniform field/charge collection, and a goal to withstand fluence of 10^{16} - 10^{17} n_{eq}/cm2

Towards Large Area Picosecond Photodetectors (LAPPD)

Targets large-area systems to measure the time-of-arrival with O(1ps) resolution

→ Move away from lead-glass MCP's (soft glass impregnated with H_2 during (the 80-step!) processing, to a hard glass with the secondary-emitting layer being a hard pure substance, in this case MgO.

→ ALD-process used to simplify the manufacturing of MCPs, to allow tuning of its amplification properties independent of the substrate, and to eliminate the ion feedback destroying the PC and limiting the lifetime.

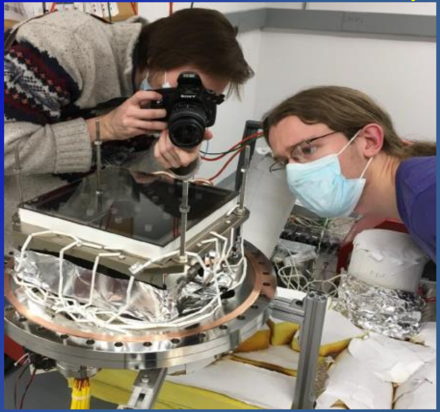


A. Elagin, Fermilab Wine Cheese Seminar, Aug. 21, 2020

System performance demonstrated:

- ✓ Radiation tolerant up to ~ 7 C / cm ^{2},
- ✓ Gains of 2×107
- ✓ Time resolution (single-PE) below 60 ps
- ✓ Differential time resolution of below 5 ps for large signals, with an extrapolated number below 2 ps as N/S approaches zero
- ✓ Spatial resolution of ~ 300 um using charge sharing

How LAPPD can become affordable for large-scale experiments (now commercially available from Incom Inc.)



US provisional Patent (62928598) submitted for a batch production using 'vacuum-transfer', capable of 100's of modules /week

https://psec.uchicago.edu/

Towards Large Area in Fast Timing GASEOUS DETECTORS

Multi-Gap Resistive Plate Chambers (MRPC):

- ✓ ALICE TOF detector (160m^2) achieved time res. ~ 60 ps
- ✓ New studies with MRPC with 20 gas gaps using a low-resistivity 400 µm-thick glass → down to 20 ps time resolution

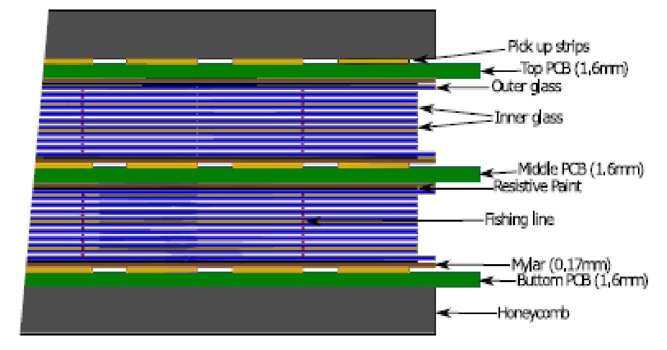
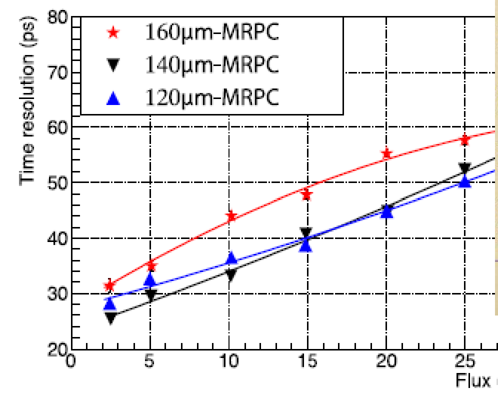
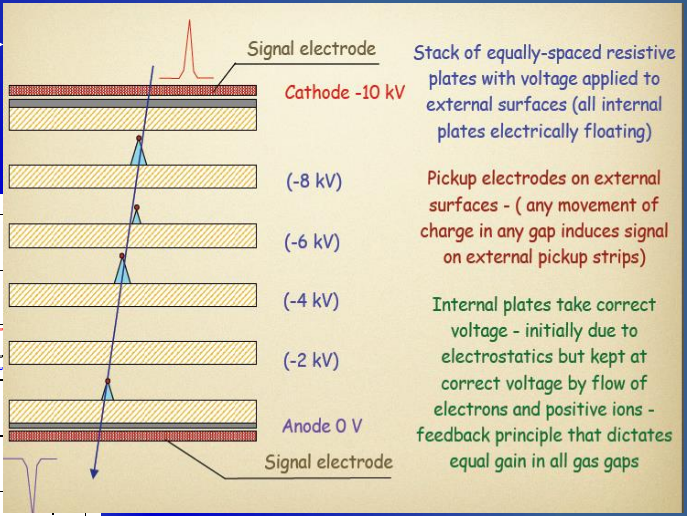


Fig. 1. Cross section of the double stack 20-gap MRPC.





Stack of equally-spaced resistive plates with voltage applied to external surfaces (all internal plates electrically floating)

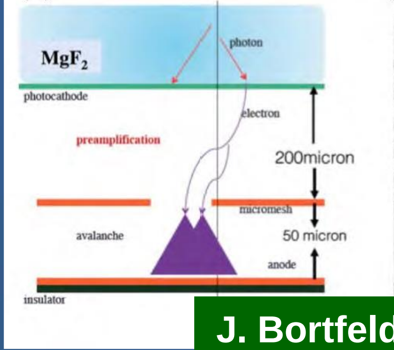
Pickup electrodes on external surfaces - (any movement of charge in any gap induces signal on external pickup strips)

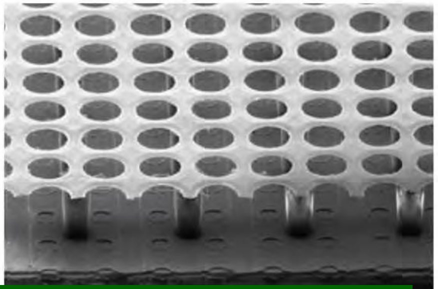
Internal plates take correct voltage - initially due to electrostatics but kept at correct voltage by flow of electrons and positive ions - feedback principle that dictates equal gain in all gas gaps

Z.Liu, NIMA927 (2019) 396

Gaseous Detectors: Micromegas with Timing (RD51 Picosec Collaboration)

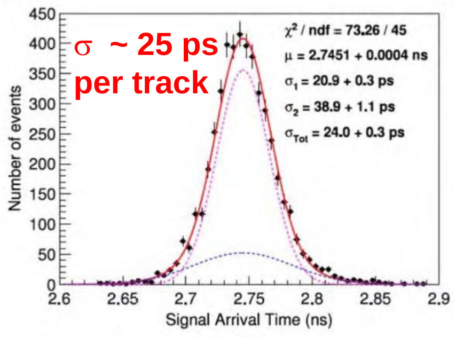
Cherenkov radiator + Photocathode + MM



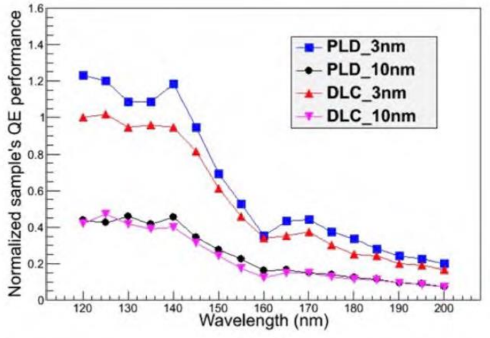


J. Bortfeldt, NIMA903 (2018) 317

Timing (MIP test-beam):



CsI / DLC PC:



Towards large-area: stability (res. MM), PC robustness, large-area (from single to multi-pad)

Advanced Concepts in PARTICLE IDENTIFICATION (PID)

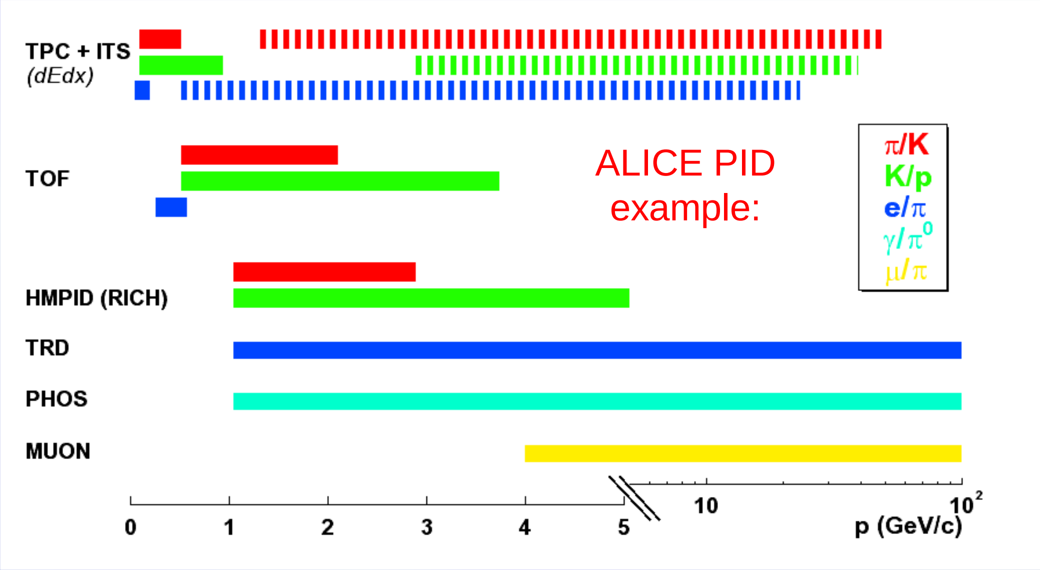
Essential to identify decays when heavy flavour are present: everywhere

Three legs: dE/dx, Time-of-Flight, Cherenkov radiation

Admirable workmanship in radiators and light transport:

- ✓ **Vacuum Photon Detectors**
  - – PMT, MaPMT, MCP - PMT
  - – Hybrid Tubes (APD, HAPD)
  - - LAPPD
- ✓ **Solid State Photon Detectors**
  - – Silicon-based (VLPC, CCD, SiPM)
- ✓ **Gas-based Photon Detectors**
  - - Photosensitive (TMAE/TEA in gas)
  - - MWPC / MPGD + CsI
- ✓ **Superconducting Photon Detectors**
  - – Transition Edge Detectors
  - – Kinetic Inductance detectors
  - - Quantum dots, carbon nanotubes

Excellent PID capabilities by combining different techniques over a large momentum range



- ➢ Threshold Cherenkov Counters – photon counting (Aerogel + PMT)
- ➢ RICH Detectors (particle momentum and velocity → Cherenkov angle and/or yield):
  - - TOP principle: 1-time of propagation + Cherenkov angle (instead of 2D imaging)
  - - RICH + TOF: Measure timing of Cherenkov light
  - - ALICE MRPC: Gaseous timing
  - - TRD: Cluster Counting method (dN/dx)

Photon Detection for PID: State-of-the-Art

- RICHes with focalisation
  (SELEX, OMEGA, DELPHI, SLD-CRID, HeraB, HERMES, COMPASS, LHCB, NA62, EIC dRICH)

✓ Extended radiator (gas)
✓ Mandatory for high momenta

- RICHes with Proximity focusing
  (STAR, ALICE HMPID, HERMES, CLEO III, CLAS12, EIC mRICH, Belle ARICH, FARICH (Panda, ALICE, Super Charm-Tau)

✓ Thin radiator (liquid, solid, aerogel)
✓ Low momenta

- DIRC and its derivatives (Detector of Internally Reflected Cherenkov light)
  Babar DIRC,BELLE II TOP, Panda Barrel/Endcap & EIC (focusing DIRCs), LHCb TORCH, FDIRC GLUEX

✓ Quartz as radiator and light guide
✓ Low momenta

- Time-Of-Flight (TOF) detectors
  (ALICE, BES III)

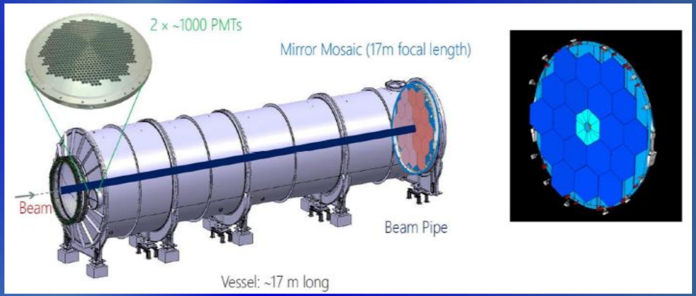
✓ Use prompt Cherenkov light
✓ Fast gas detector

LHCb RICH I and II Upgrade for Run-III:

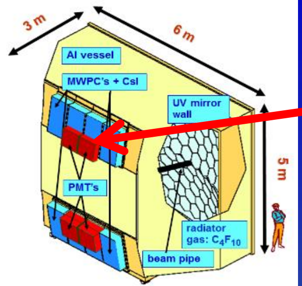
✓ New electronics @ 40 MHz
✓ New optics layout for RICH 1
✓ MaPMTs sill replace HPDs for RICH 1 and RICH2

NA62 RICH with 2000 PMTs :

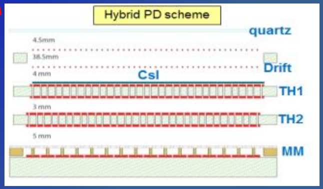
✓ Good test for GPU-based online selection (RICH participates in the low level trigger)



COMPASS RICH Upgrade:



Replace 8 MWPC's/CsI with hybrid (THGEM /Micromgas) with CsI



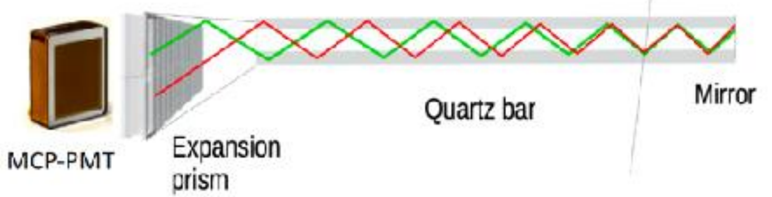
✓ Exploring a possibility to use more robust PC: hydrogenated nano-diamond crystals
✓ R&D towards compact RICH for the future EIC

Many Clever Techniques for Ultra-Fast TOF and TOP

Fast progress in the new DIRC-derived concepts, including time-of-propagation counters - exceptional time-resolution of O(10ps), based on MCP-PMTs

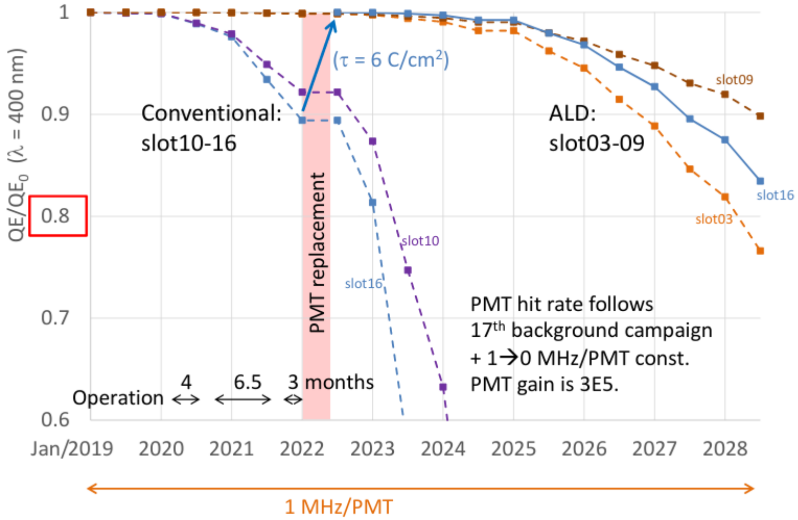
Belle II Time of Propagation RICH (TOP)

Based on a DIRC concept: instead of 2D-imaging
→ 1D + Time Of Propagation (TOP, path length)



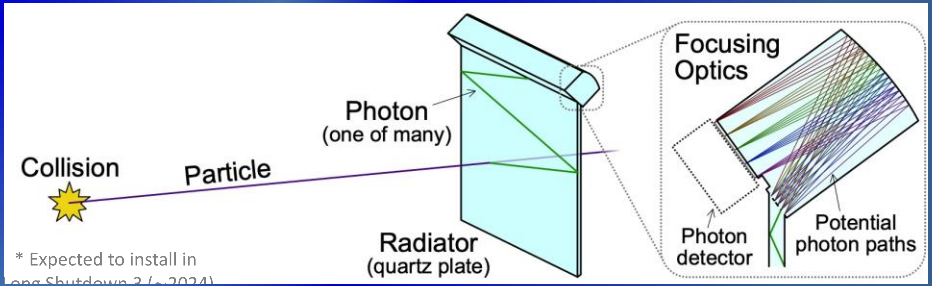
Installed between drift chamber and calorimeter
- ✓ Single photon efficiency; < 100 ps SPTR
- ✓ few mm spatial res.; operation in 1.5T B field

2022: Replacement conven. PMT with ALD-PMT



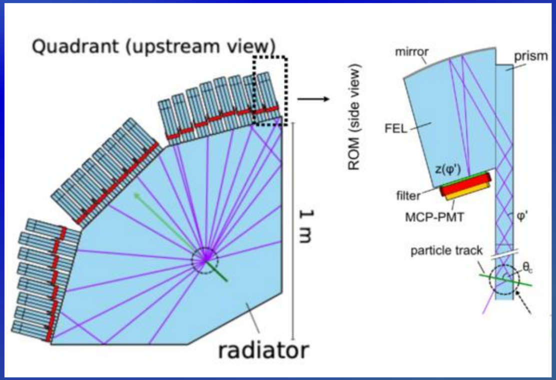
LHCb TORCH (Time Of internally Reflected CHerenkov light) for Run 4/5:

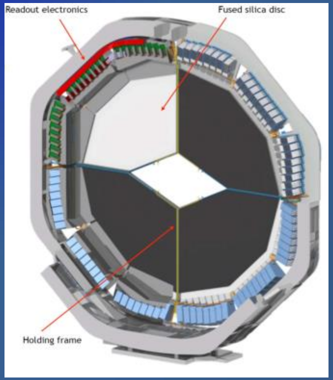
- ✓ Prompt production of cherenkov light in quartz bars
- ✓ Cherenkov photons travel to detector plane via total internal reflection and cylindrical focusing block
- ✓ 70 ps per photon →15 ps per track
- ✓ Photons detected by square micro channel plate PMTs; resolution improved by charge sharing



* Expected to install in Long Shutdown 3 (~2024)

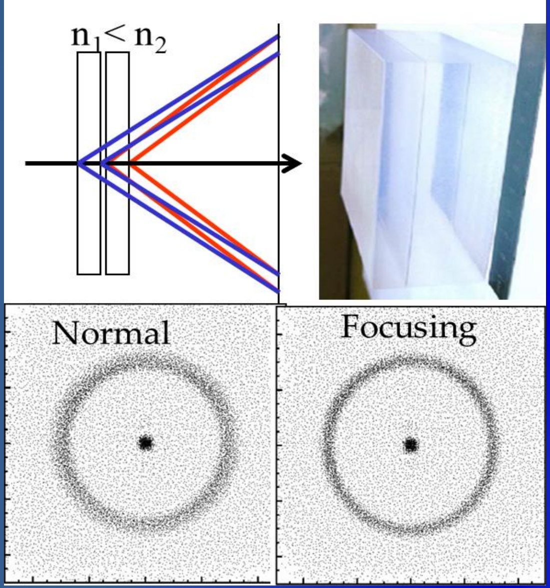
Panda DIRC has many similar features to LHCb TORCH:

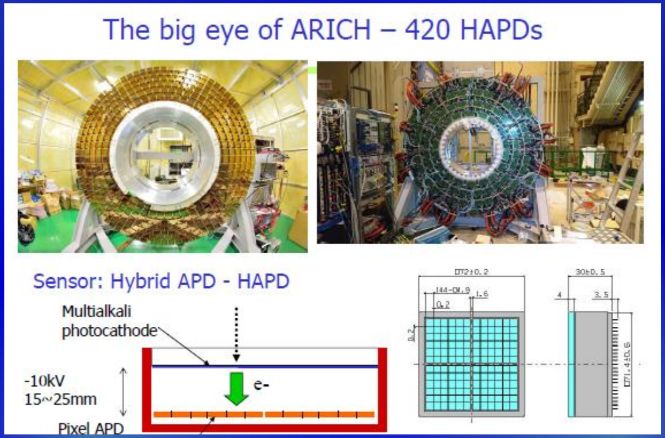




Trends in Proximity Focusing Aerogel Radiator RICH

Use of focusing configuration: ARICH (Belle), FARICH (PANDA, ALICE, Super c-τ)



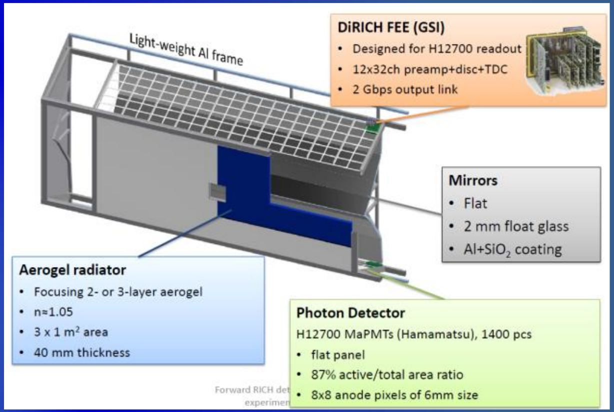


← **BELLE-II ARICH:**

Two 2 cm thick layers of aerogel radiator:

Forward RICH for PANDA: →

Focusing 2-layer aerogel configuration



DiRICH FEE (GSI)
- Designed for H12700 readout
- 12x32ch preamp+disc+TDC
- 2 Gbps output link

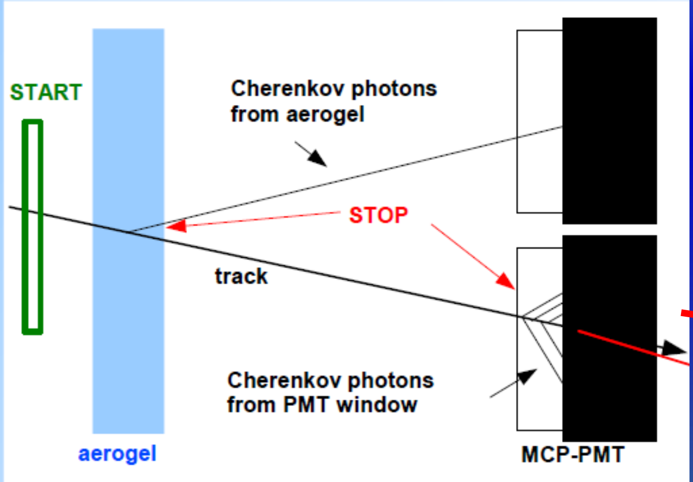
Mirrors
- Flat
- 2 mm float glass
- Al+SiO_2 coating

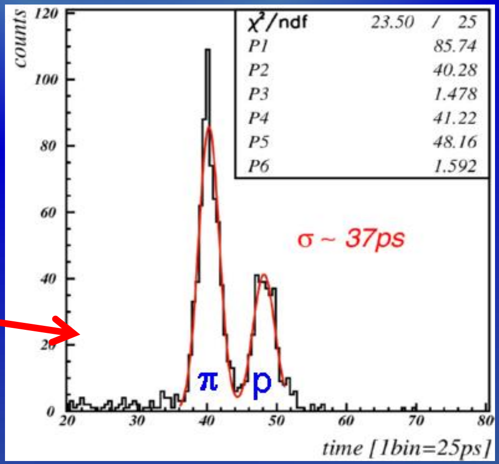
Aerogel radiator
- Focusing 2- or 3-layer aerogel
- n≈1.05
- 3 x 1 m^2 area
- 40 mm thickness

Photon Detector

H12700 MaPMTs (Hamamatsu), 1400 pcs
- flat panel
- 87% active/total area ratio
- 8x8 anode pixels of 6mm size

R&D: combination of proximity focusing RICH + TOF with fast new photo-sensors
→ MCP-PMT or SiPM using Cherenkov photons from PMT window

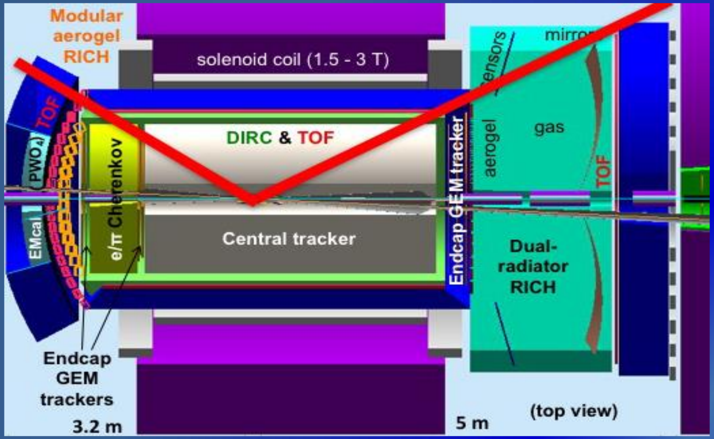




Cherenkov photons from PMT window can be used to positively identify particles below threshold in aerogel

P. Krizan @INSTR2020
T. Credo, 2004 IEEE NSS/MIC Conference Record

Major Challenge for EIC Detectors: Particle Identification

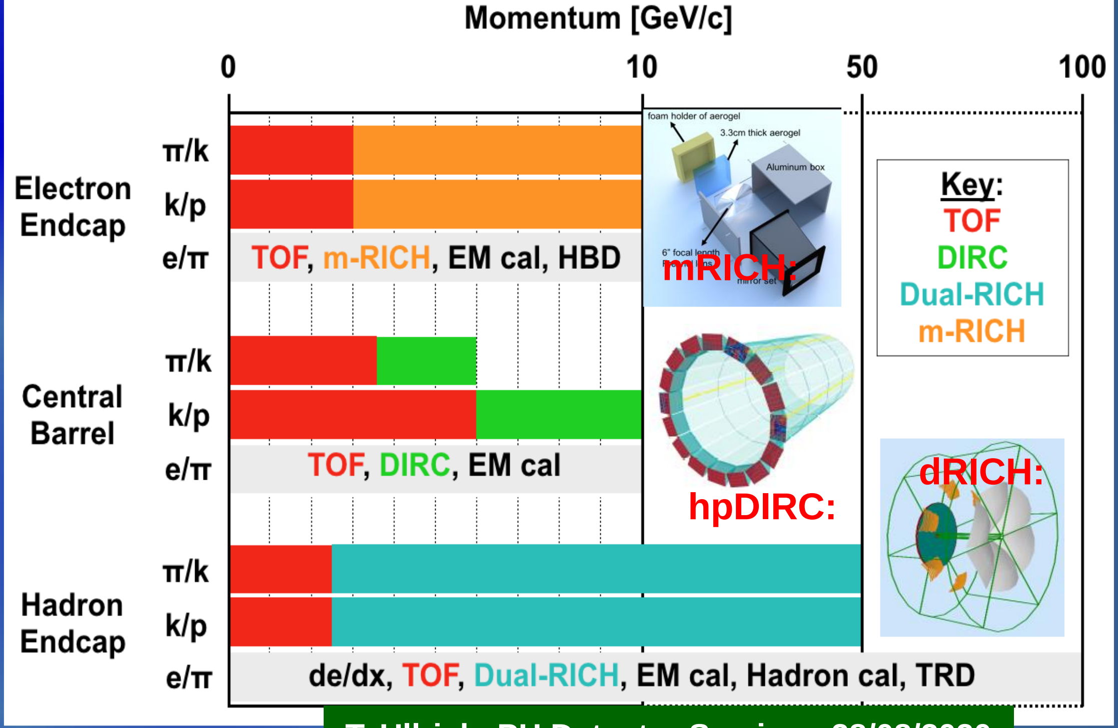


h-endcap: A RICH with two radiators (gas + aerogel) is needed for
π/K separation up to ~50 GeV/c dRICH

e-endcap: A compact aerogel RICH which can be projective
π/K separation up to ~10 GeV/c mRICH

barrel: A high-performance DIRC provides a compact and cost-effective way to cover the area.
π/K separation up to ~6-7 GeV/c DIRC

TOF (and/or dE/dx in TPC): can cover lower momenta

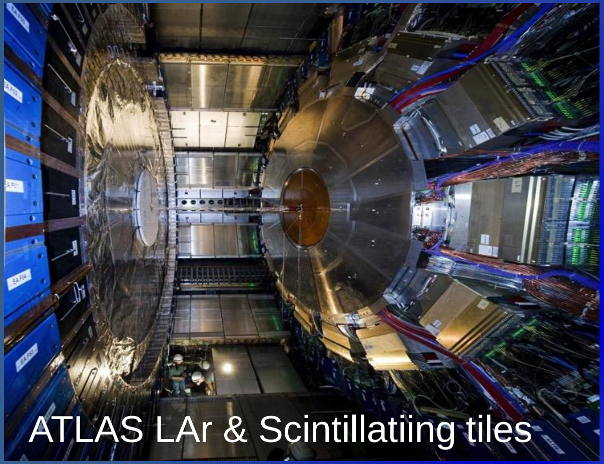


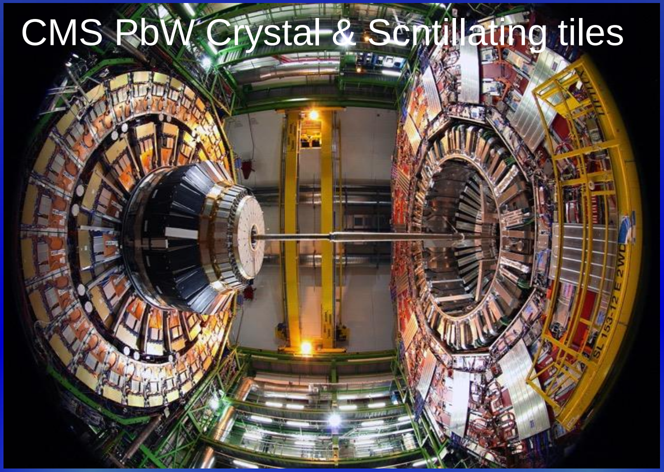
T. Ullrich, PH Detector Seminar, 28/08/2020

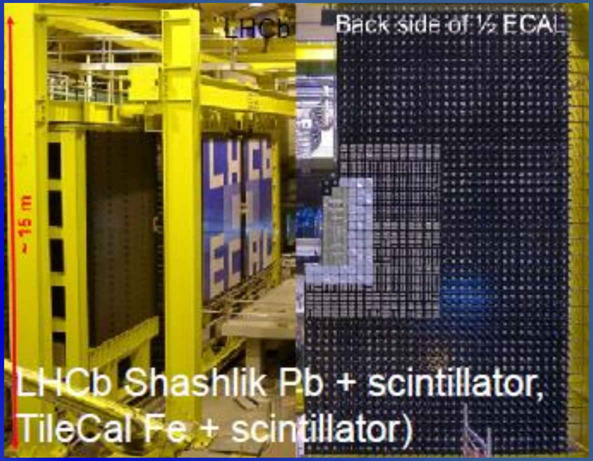
General Challenges for Photodetectors:

- Photodetectors: Big challenge is to provide a reaiable highly-pixelated photodetector working at 1.5 – 3 T field
- SiPMs: high dark count rate and moderate radiation hardness prevented their use in RICH detector, where single photon detector required qt low noise
- ✓ MCP-PMTs: very expensive, not tolerantto magnetic fields;
- ✓ Large-Area Picosecond Timing Detector (LAPPD): promising, still not fully applicable for EIR yet → need pixellation, efforts underway, control of cost;

Advanced Concepts in CALORIMETRY

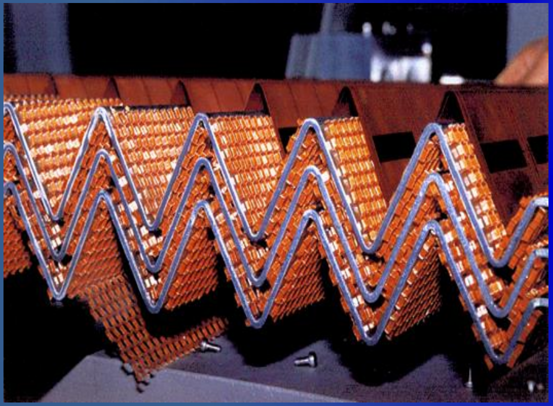

ATLAS LAr & Scintillatiing tiles


CMS PbW Crystal & Scntillating tiles



LHCb Shashlik Pb + scintillator, TileCal Fe + scintillator)

4 main technologies: LAr, Scintillators, Crystals (tiles or fibers), Silicon sensors



Two main concepts:

Homogeneous crystals (CsI, LYSO):
- Best possible resolution
- Application to PET

Sampling:
- Imaging: Particle Flow Algorithm
- Dream: Dual readout
- Sampling with Crystals, shashlik-type

Two main approaches for improving jet energy resolution:

Dual (or triple) readout, e.g. DREAM (FCC-ee, CePC) improvement of the energy resolution of hadronic calorimeters for single hadrons:

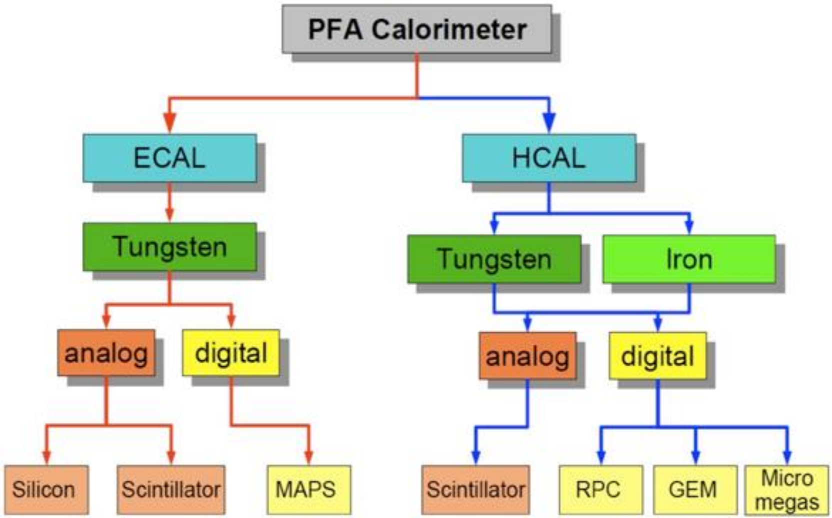
Cherenkov light for relativistic (EM) component
Scintillation light for non-relativistic (hadronic)

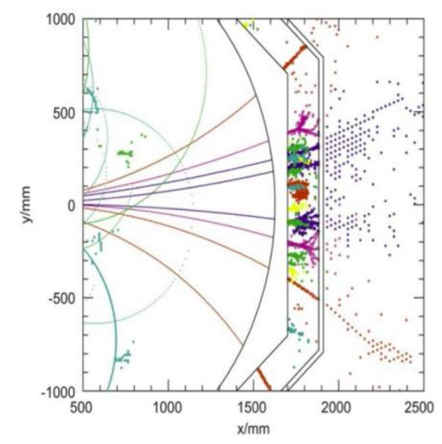
Particle flow algorithm and imaging calorimeters (CALICE detectors for ILC, CLIC, CMS HGCAL):

→ Precise reconstruction of each particle within the jet (reduction of HCAL resolution impact)

Particle Flow Calorimeters: CALICE Collaboration

Development and study of finely segmented / imaging calorimeters: initially focused on the ILC, now widening to include developments of all imaging calorimeters):





Imaging Calorimetry → high granularity (in 4D), efficient software (PFA)

Energy share in a typical jet:
- 60 % charged hadrons;
- 30 % photons (from p0)
- 10 % neutral hadrons (mainly n, K_L)

ParticleFlow Concept
- Tracking for charged particles
- ECAL for photons (π0)
- Neutral hadrons from HCAL

Issues: overlap between showers, complicated topology, separate "physics event" particles from beam-induced background

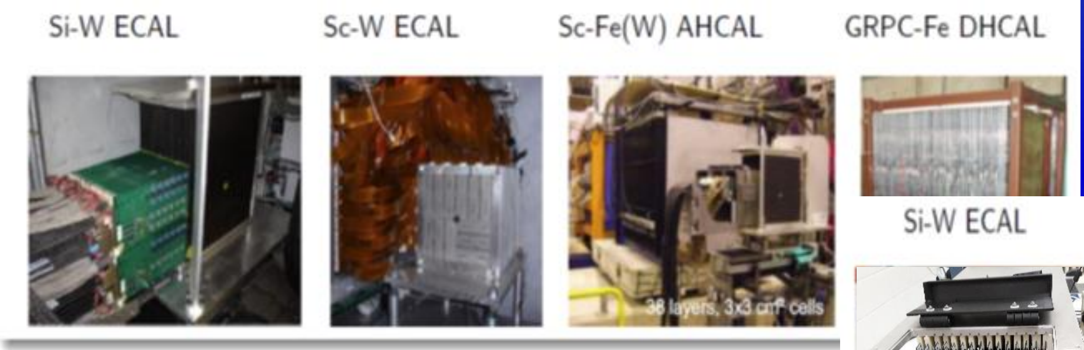
Example: **ILD detector for ILC**, proposing **CALICE** collaboration technologies

	ECAL option	ECAL option	HCAL option	HCAL option
Active layer	silicon	scint+SiPM	scint+SiPM	glass RPC
Absorber	tungsten	tungsten	steel	steel
Cell size (cm×cm)	0.5×0.5	0.5×4.5	3×3	1×1
# layers	30	30	48	48
Readout	analog	analog	analog	Semi-dig (2 bits)
Depth # (X_0/Λ_{int})	24 X_0	24 X_0	5.5 Λ_{int}	5.5 Λ_{int}
# channels [10^6]	100	10	8	70
Total surface	2500	2500	7000	7000

PFA calorimetry also adopted by:

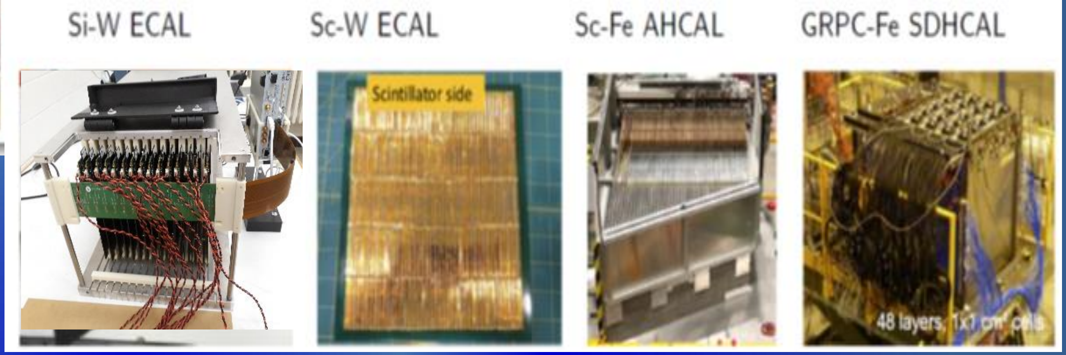
CLIC
FCC-ee
CePC
FCC-hh
CMS HGCAL
ALICE FoCAL
DUNE ND

Particle Flow Calorimeters: CALICE Collaboration



← Proof-of-principle with first generation physics prototypes (2003-2012)

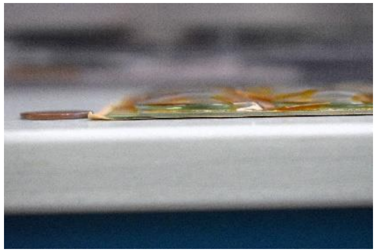
Scalability tests with 2nd generation (>2010) technological prototypes (power pulsing, compact mechanical design, embedded electronics, assembly, calibration approaches) →



Rationalization / minutiarization of components:

Current detector interface card and thin detection unit for SiW Ecal

R. Poeschl

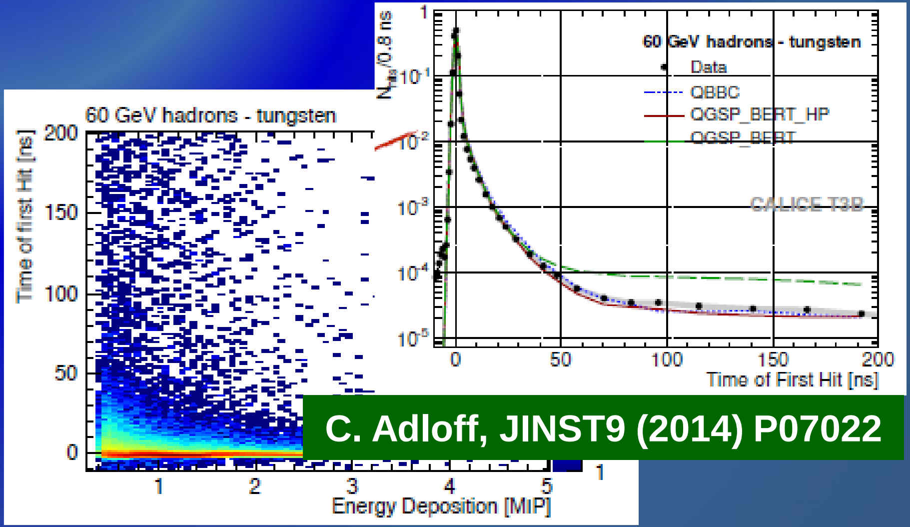


CALICE & CMS: common test-beams since 2017

Common tests beals benefit from common approach in CALICE and networking acivities: EUDQA2, AIDA2020

Time structure of hadronic showers (from 4D to 5D):

New technological prototypes (SiW ECAL, AHCAL) will provide cell-by-cell nanosecond-level timing
→ studies of hadronic showers in space, amplitude & time



C. Adloff, JINST9 (2014) P07022

CMS High Granularity Calorimeter for Phase II Endcap Upgrade

CMS endcap region:

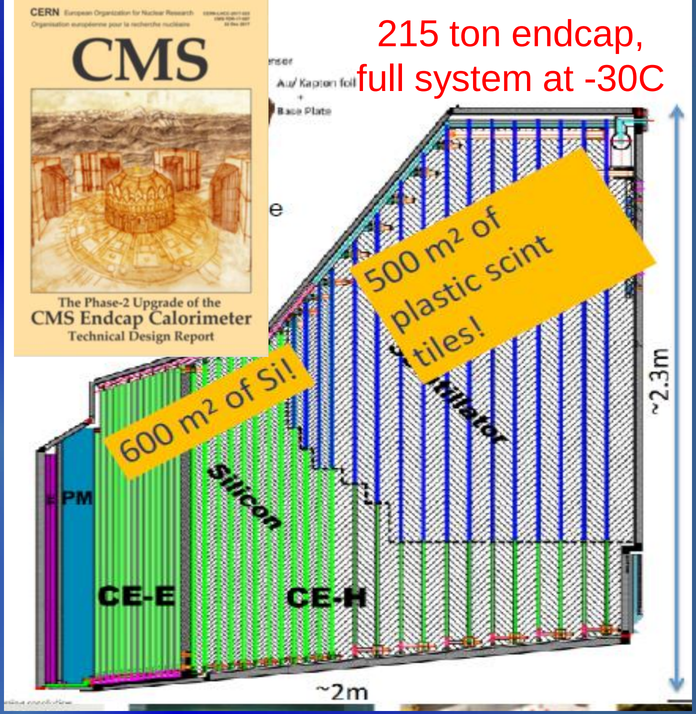
- PbWO4 crystal transmission loss due to radiation damage
- Worsening energy resolution due to increased pileup

✓ Build a fine segmented ‘particle flow’ calorimeter, ECAL + HCAL combined.

✓ Use Si sensors as long as radiation and particle flow requires, then switch to cheaper scintillator tiles + SiPM (à la CALICE). (27000 Si-modules, 6M Si-channels, 400000 SiPMs)

- CE-E: Si, Cu, CuW,Pb absorbers, 28 layers, 25 X0 & ~1.3λ
- CE-H: steel absorbers, 24 layers, ~8.5λ

✓ Si pad sensors from 8’’ wafers. Different sensor geometries and thicknesses (300,200,120 µm); fluences 2x10^{14} - 10^{16} n_{eq}/cm^2



CERN European Organization for Nuclear Research

CMS

The Phase-2 Upgrade of the CMS Endcap Calorimeter Technical Design Report

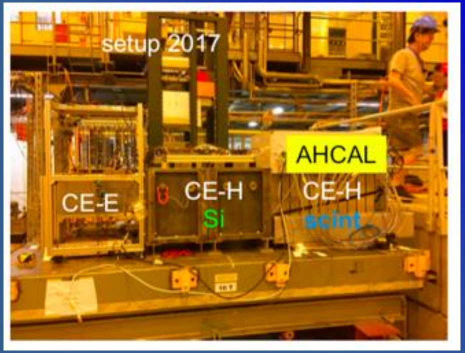
215 ton endcap, full system at -30C

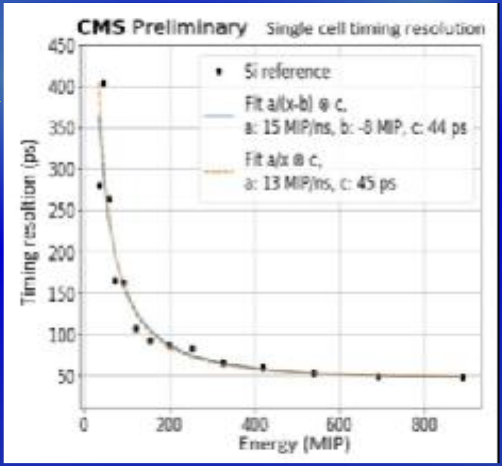
500 m² of plastic scint tiles!

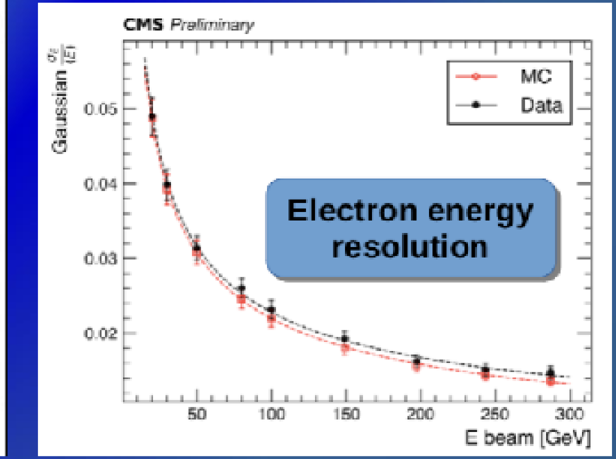
600 m² of Si!

New (combined) HGCAL + AHCAL test-beam results:

- 28 EM layers, 12 Si-HAD layers,
- 39 Sci-layers from CALICE AHCAL



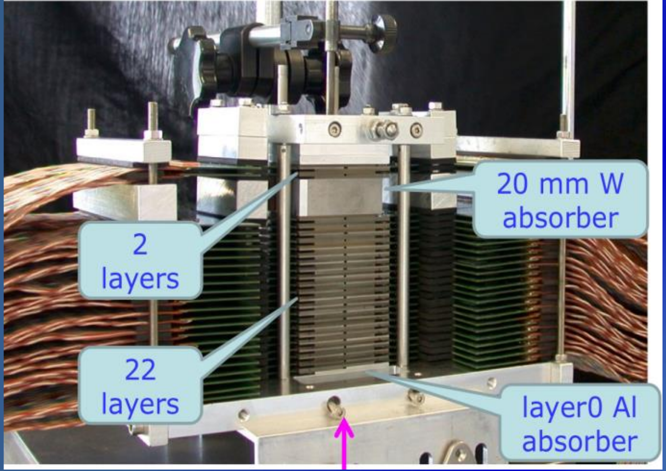


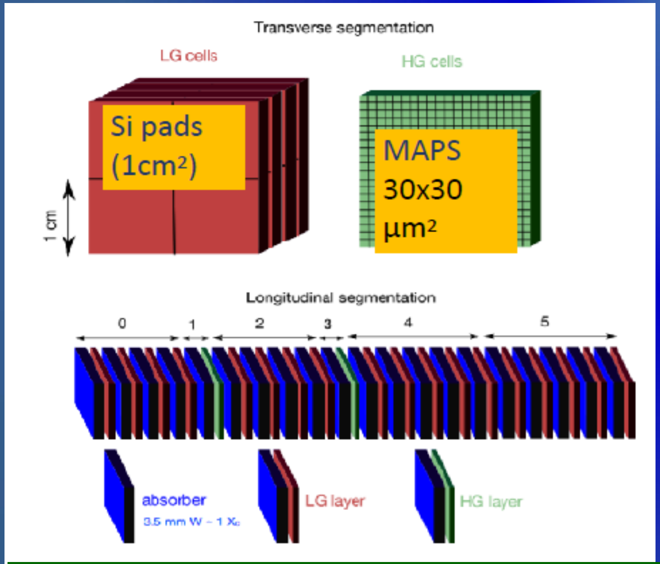


Multi-layer measurements of shower signal allows precise ToF estimate of e/γ/h0 : ~ 30 ps has been achived for S/N >20

R&D for ALICE FoCAL – MAPS based SiW ECAL

24 layer MIMOSA CMOS sensor calorimeter Si-W stack (test-beam with MIMOSA HG)





Forward electromagnetic and **hadronic calorimeters;**

- ✓ FoCal-E: high-granularity Si-W sampling calorimeter → direct γ, $\pi 0$
- ✓ FoCal-H: Pb-Sc sampling calorimeter for photon isolation and jets

Digital ECAL prototype:

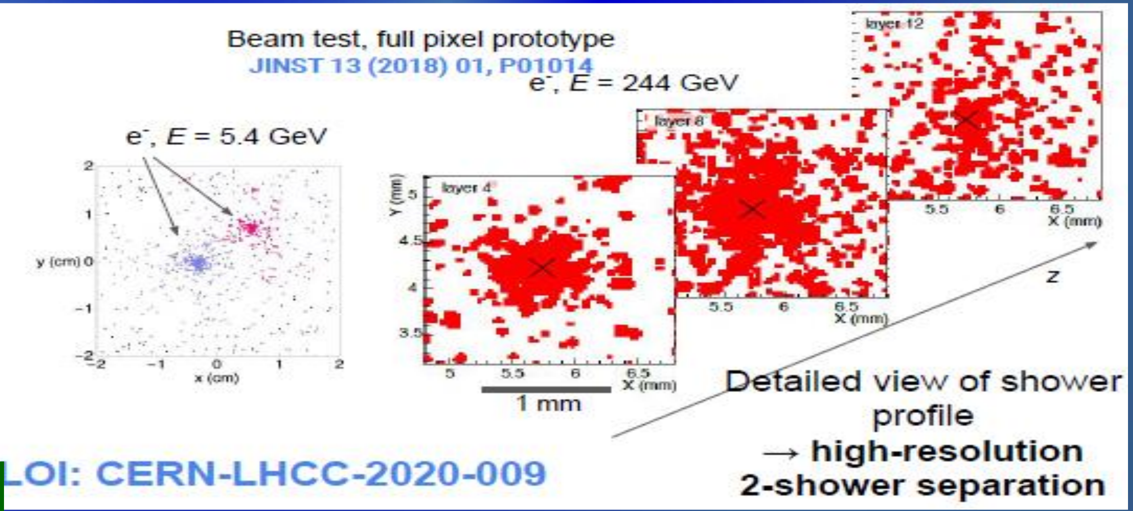
- number of pixels above threshol ~ deposited energy
- Monolithic Active Pixel Sensors (MAPS) PHASE2/MIMOSA23 wit a pixel size: 30x30 μm2
- 24 layers of 4 sensors each: activ area 4x4 cm2 , 39 M pixels
- 3 mm W absorber for 0.97 X0 pe layer R_M ~ 11 mm

FoCAL: assuming ≈ 1m^2 detector surface

	LG	HG
pixel/pad size	≈ 1 cm^2	**≈ 30x30 μm^2**
total # pixels/pads	≈ 2.5 x 10^5	**≈ 2.5 x 10^9**
readout channels	≈ 5 x 10^4	**≈ 2 x 10^6**

A. Rossi @ ICHEP2020

Could be a unique tool to improve shower simulation …



LOI: CERN-LHCC-2020-009

Detailed view of shower profile
→ high-resolution 2-shower separation

T. Peitzmann, PH Detector Seminar, 25/10/2019
P. Allport, PH Detector Seminar, 10/09/2020
A. De Haas, JINST13 (2018) P01014

DESY Test-Beam with ALPIDE sensors in Nov. 2019 → results soon

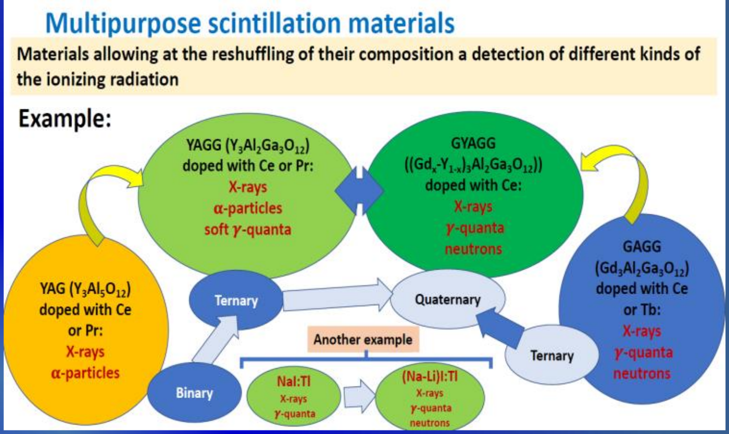
Other Calorimetry R&D: Crystals, Scintillating/Cherenkov Fibers

Main Calorimetry concepts & techniques:

- ✓ **Noble Liquid** (intrinsic radiation hard, 3D imaging, good timing resolution, finely segmented readout)
  → reference design for FCC-hh, also for FCC-ee
- ✓ **Homogeneous crystals** (ultimate resolution)
  → CMS CALO based on $PbWO_4$
- ✓ **Particle Flow Calorimetry** (5D imaging)
  → ILC/CLIC concepts, CMS HGCAL
- ✓ **Scintillator-based** (cost-effective, mod. rad.-hard)
  → rad-hard crystals (LYSO, BaF_2 crystal scintillators, YAG, GAGG);
  → LHCb ECAL upgrade (shashlyk, spagetti-type);
  → FCC-hh hadronic barrel similar to ATLAS Tile Calo;
- ✓ **Dual-readout calorimetry**
  → Dual-fibre readout calorimeter for FCC-ee, CePC

SiPMs are mostly used in HEP Calorimetry:

→ SiPMs readout of plastic scintillators, crystals, dual-readout calorimeters;
→ Challenge: cold operation at -30C to keep radiation damage under control



Multipurpose scintillation materials

Materials allowing at the reshuffling of their composition a detection of different kinds of the ionizing radiation

Example:

LHCb Phase-2 upgrade sampling electromagnetic crystal calorimeter

- ≃ 300 Mrad, ≃ 50 ps

Dual-readout R&D:

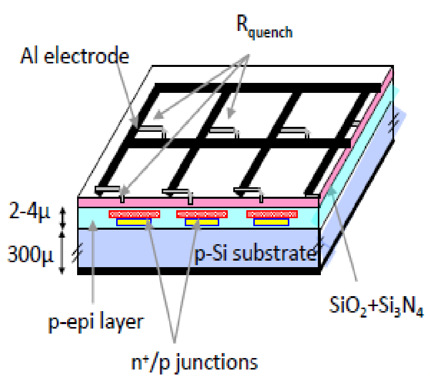
32 + 32 scint./cerenkov fibers protoype

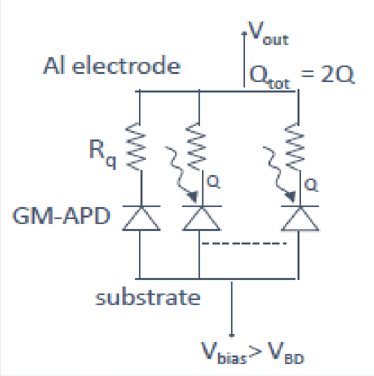
σ(E)/E≃ 10(30)%/√E + 1% for e/γ(π)

State-of-the-Art in Silicon Photomultipliers (SiPM)

Calorimetry is the dominant area of the SiPM use in particle physics

A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov (1989)





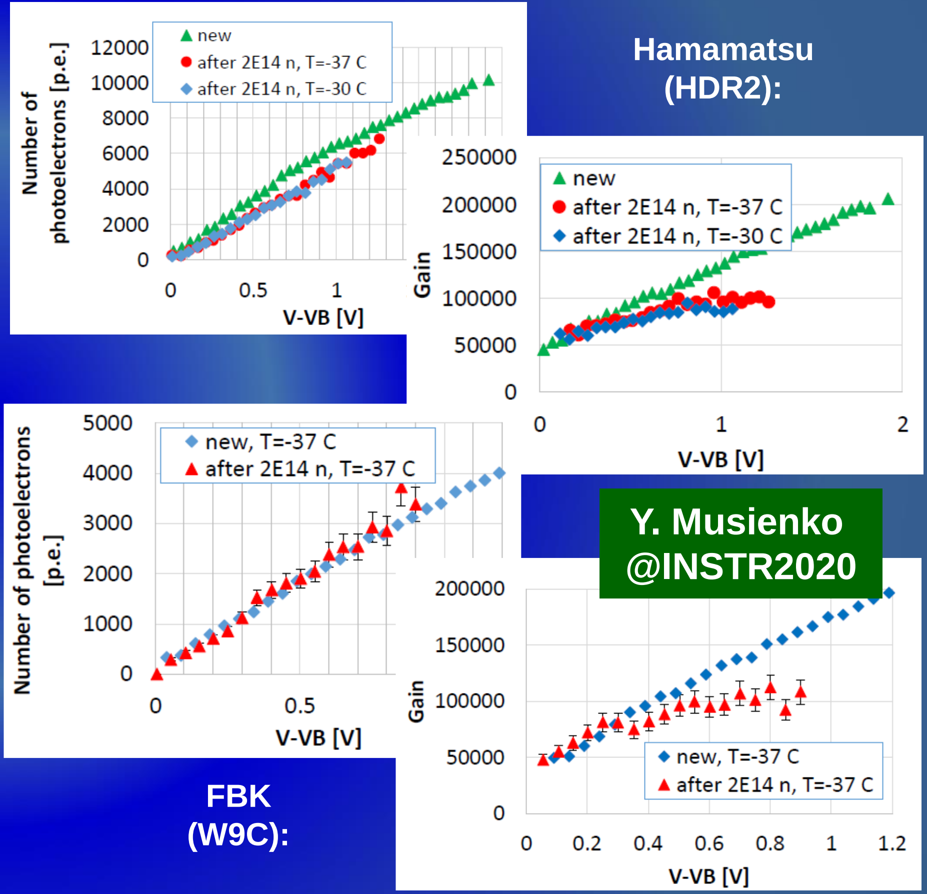
Significant progress in understanding of SiPM physics was achieved during last 5 years:

Breakthrough in SiPM production:

- ✓ **Reduced correlated noise**
  - **→ cross-talk, afterpulsing**
- ✓ **Improved PDE (50-65 %, blue-green light)**
- ✓ **Reduced dark noise**

Y. Musienko, PH Detector Seminar, 30/06/2017
G. Kollazuol, PH Detector Seminar, 13/11/2020
F. Simon, NIM926 (2019) 85

Encouraging results with 15 µm cells (FBK, HPK) and operation at -30C indicate ability to operate up to very high neutron flux o ≃ 2x1014 neq/cm2



Hamamatsu (HDR2):

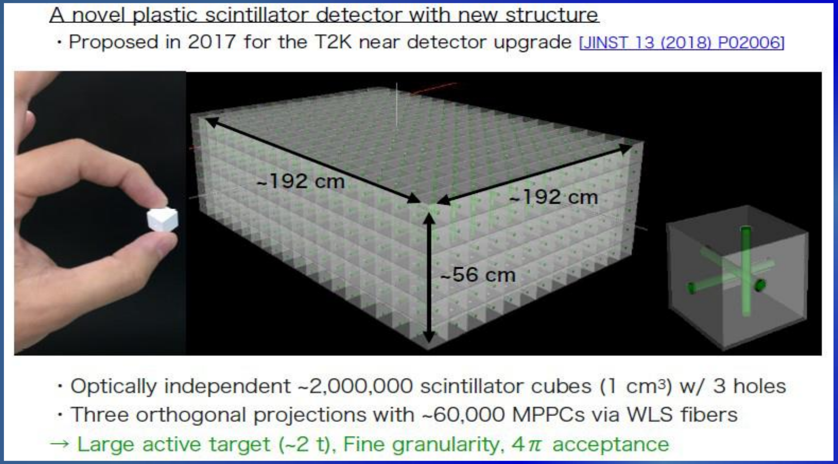
FBK (W9C):

Y. Musienko @INSTR2020

The HPK and FBK SiPM are still operational after ≃ $2x10^{14}$ neq/cm^2 → main limitation is due to high power dissipation, caused by dark current increase, limiting to operation at ΔV ~< 1V

Some Examples of SiPM Applications in Experiments

T2K Near Detector: **Large scale (~60 000) use of SiPMs: 3D Sci-Tracker with WLS fibers**



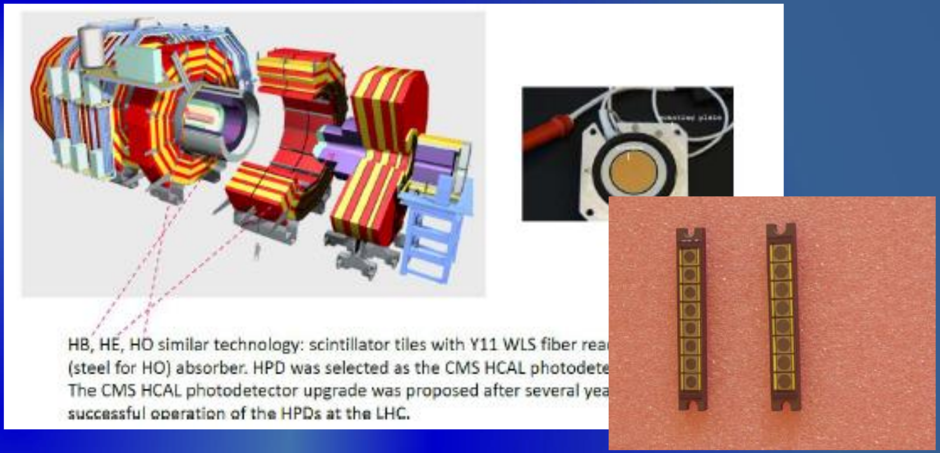
A novel plastic scintillator detector with new structure

- Proposed in 2017 for the T2K near detector upgrade [JINST 13 (2018) P02006]

- Optically independent ~2,000,000 scintillator cubes (1 cm³) w/ 3 holes
- Three orthogonal projections with ~60,000 MPPCs via WLS fibers

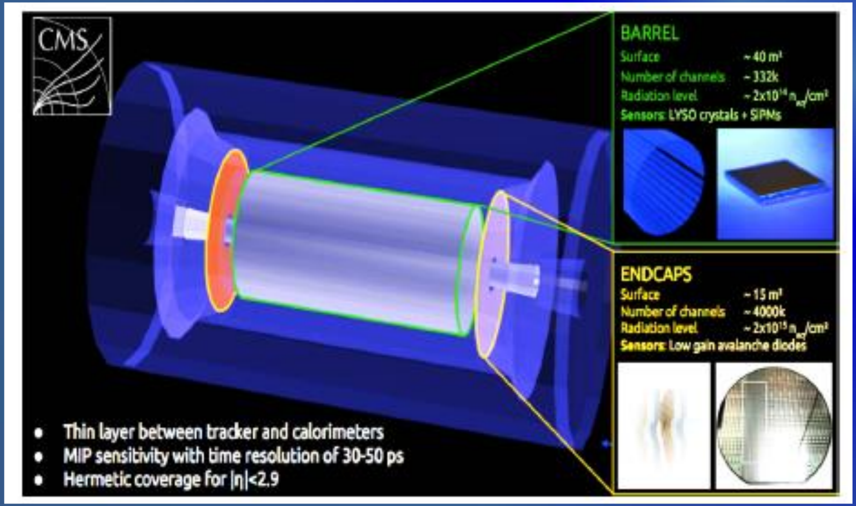
→ Large active target (~2 t), Fine granularity, 4π acceptance

CMS HCAL Phase I Upgrade: **replacement of HPDs with 20 000 SiPMs – higher QE, better immunity to magnetic fields, depth segmentation, timing (kill bkg)**



HB, HE, HO similar technology: scintillator tiles with Y11 WLS fiber rea
(steel for HO) absorber. HPD was selected as the CMS HCAL photodete
The CMS HCAL photodetector upgrade was proposed after several yea
successful operation of the HPDs at the LHC.

CMS Barrel Timing layer (BTL): **36 m^2 area, 250000 LYSO tiles readout by 330000 SiPM; operation @ -30C between tracker and calorimeter**

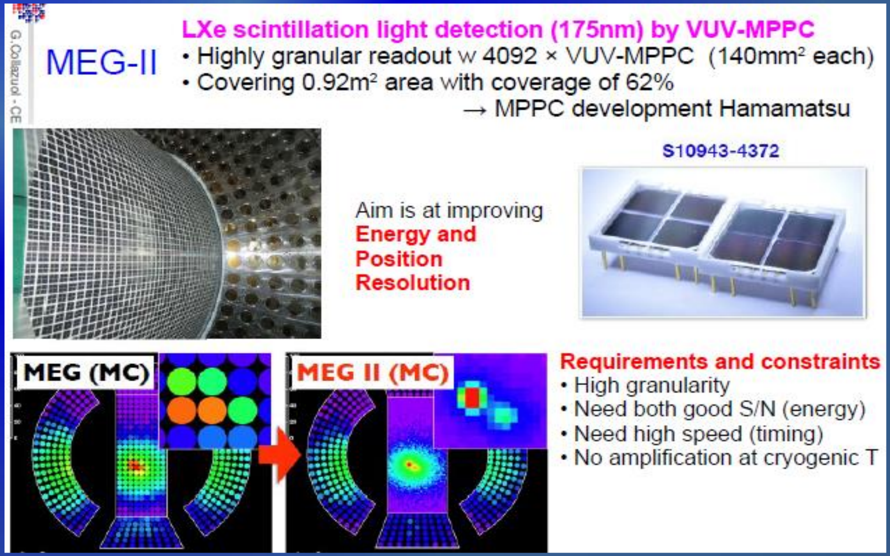


BARREL
Surface ~40 m²
Number of channels ~332k
Radiation level ~2x10¹⁴ n_eq/cm²
Sensors: LYSO crystals + SiPMs

ENDCAPS
Surface ~15 m²
Number of channels ~4000k
Radiation level ~2x10¹⁵ n_eq/cm²
Sensors: Low gain avalanche diodes

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage for |η|<2.9

MEGII Experiment: **SiPM will replace PMT (large surface Cryogenic SiPM readout – VUV)**



LXe scintillation light detection (175nm) by VUV-MPPC

- Highly granular readout w 4092 × VUV-MPPC (140mm² each)
- Covering 0.92m² area with coverage of 62%

→ MPPC development Hamamatsu

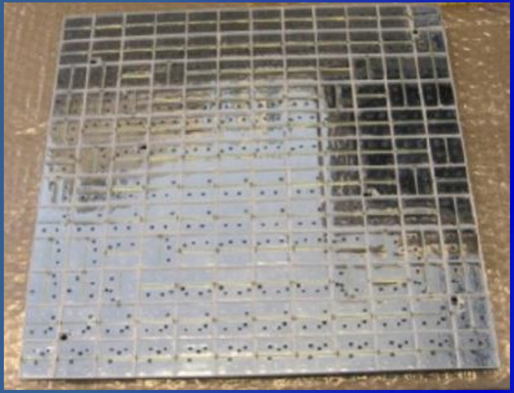
Aim is at improving **Energy and Position Resolution**

Requirements and constraints

- High granularity
- Need both good S/N (energy)
- Need high speed (timing)
- No amplification at cryogenic T

From SiPM-based ILC Imaging Calorimeter to Advanced PET Systems

2006: ILC Developemnt
CALICE-AHCAL (8k ch.):
First large experience
with SiPM operation (2006):



C. Monet, Nymphéas et Pont Japonais

NuclearInstrumentsandMethodsinPhysicsResearchA809(2016)67–75

Today's PET imaging platforms
using SiPMs:

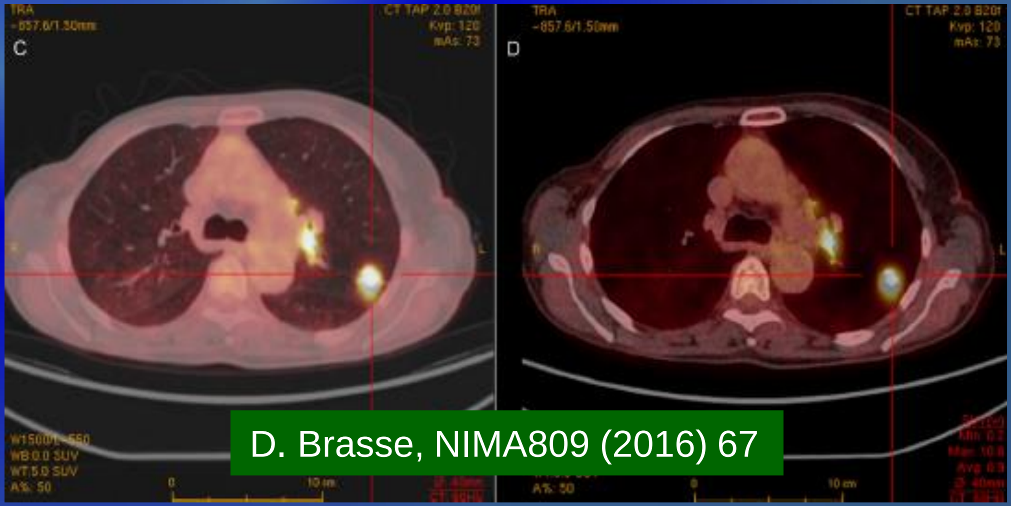
- GE clinical PET/MR uses analog SiPM
- VEREOS Philips PET/CT uses digital SiPM

Multi-channels arrays of crystals + SIPM:

- minimum dead material between crystals
- SiPM packaging is crucial →up to 50% sensitivity improvement
- Monolithic arrays/high density of channels;

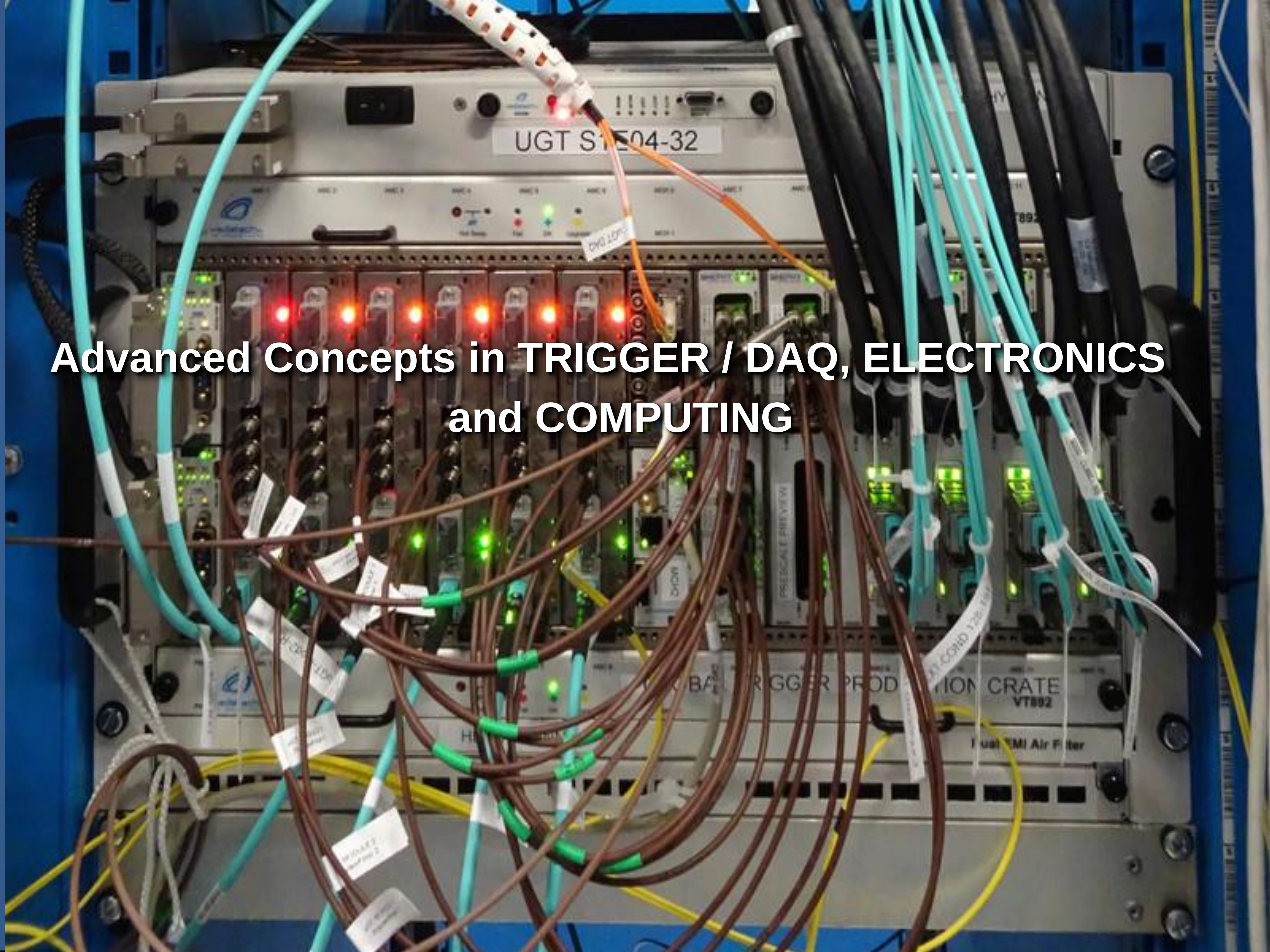
SiPMs represent today the future of Nuclear Medical Imaging → the slowing down factor at the moment being the high associated cost.

Multi-modality approach (PET/CT,PET/MR) will be more and more requested in the clinical practice.



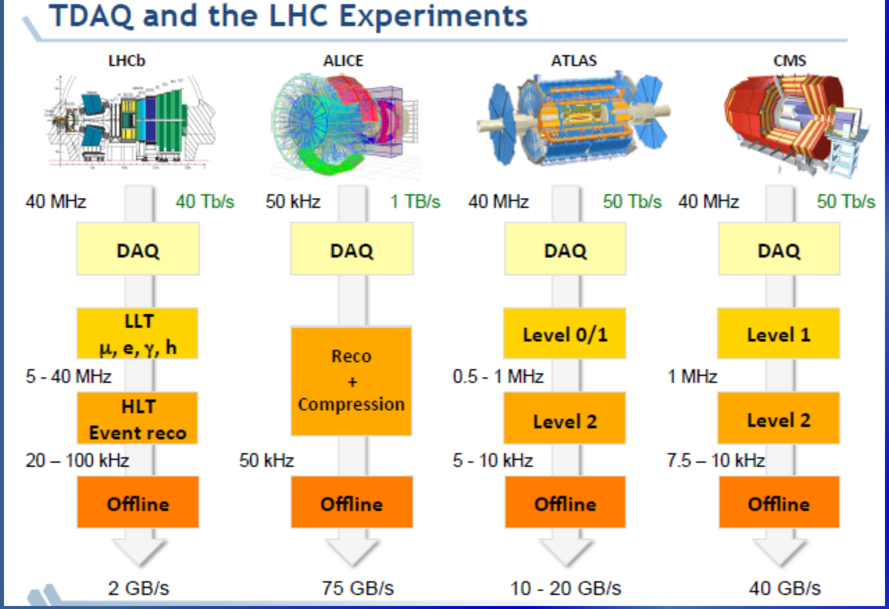
D. Brasse, NIMA809 (2016) 67

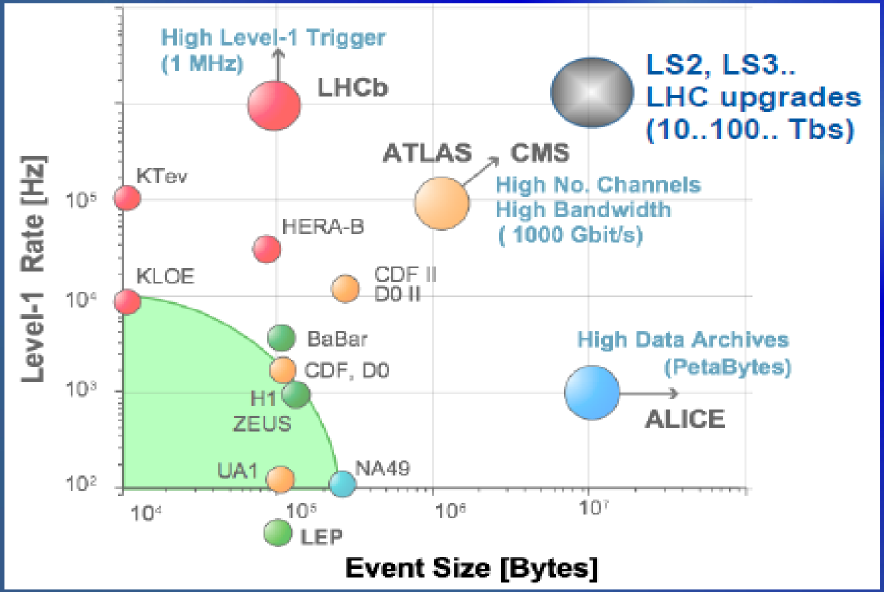
Advanced Concepts in TRIGGER / DAQ, ELECTRONICS and COMPUTING



Advanced Concepts in TRIGGER and DAQ (TDAQ)

Massive amounts of data coming of upgraded and next generation experiments





- Optical data transmission is key in readout modern HEP detectors:

✓ Current links at 10 Gb/s, and limited to 5×10^{15} n_{eq}/cm^2, 100 Mrad in radiation tolerance;
→ current state-of-the art – VCSEL;

✓ Silicon photonics for optical conversion and multiple amplitude modulation can provide high bandwidth;

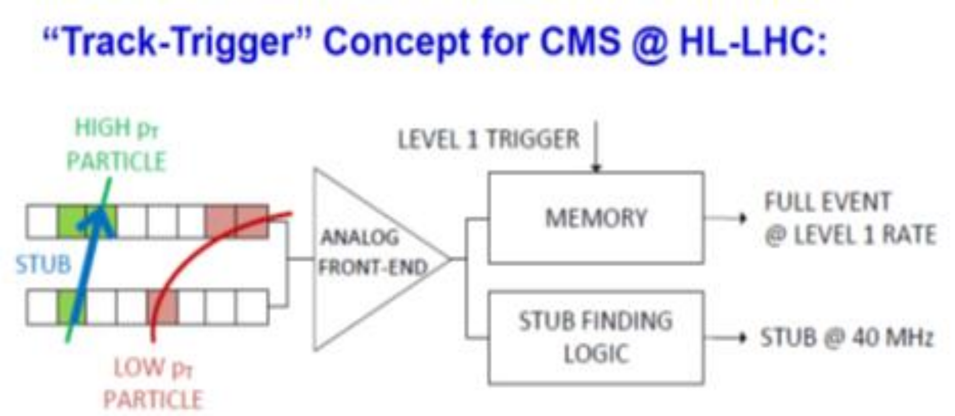
- Wireless transmission (60 GHz), could allow on-detector data reduction (e. g. for trigger readout of trackers) → promising upcoming alternative

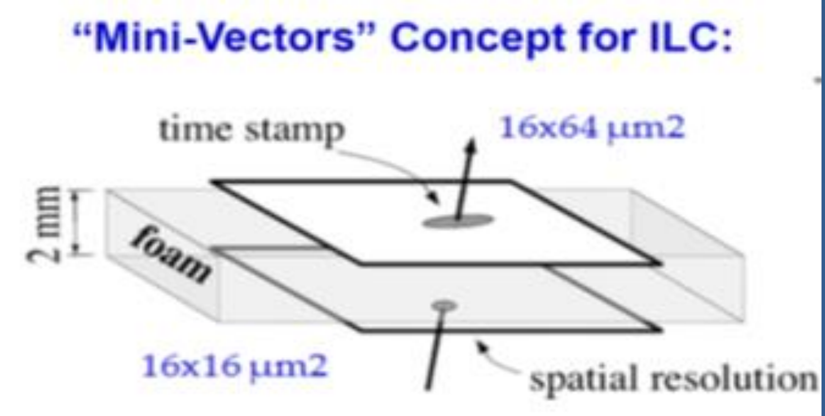
Trigger Architecture:
→ multi-layered (event building, event processing); triggerless, multi-level trigger;
Trigger Tools:
→ ASICs, ATCA, FPGA, CPU, GPU

- General trend: progressive replacement of the complex multi-stage trigger system with a single level trigger system and a large farm of Linux computers for the final online selection:

➢ ATLAS TDAQ → single-level hardware trigger (max. rate 1 MHz and 1 um latency);
➢ ALICE and LHCb will be triggerless (no hardware trigger) after LHC Phase I upgrade

“Intelligent Trackers”: Frontier Application for HEP ?


“Track-Trigger” Concept for CMS @ HL-LHC:


“Mini-Vectors” Concept for ILC:

- ✓ Cannot send all hits to trigger at 40 MHz → local “intelligence” is based on recognition of high-p_T tracks using hit correlation in 2 closely-spaced layers:

  - Store billion(s) of patterns in dedicated associated memory for L1 Track-Trigger;
  - Region of Interest Builders;
  - Advanced FPGS for data processing/transmission;

- ✓ 65 nm CMOS ASIC allows to satisfy power requirem. Despite of large amount of necessary logic @ 40 Mhz

- ✓ Particle Flow” approach now possible at L1 trigger – use information from all detectors:
  - trigger on secondary vertices using NN
  - ”anomaly detection” by machine learning)

- ✓ Issues: L1 latency, backhround

- ✓ ILC will run without trigger

- ✓ Develop concept of 2-sided ladders using 50 µm thin CPS → “mini-vectors” providing high spatial resolution & time stamping

- ✓ Realization of double-sided ultra-light ladders (PLUME) equipped with two complementary types of CPS

- ✓ Introduce NN in CPS to mitigate data flow from beam-related background

- ✓ Issues: high precision alignment & power cycling in high magnetic field (ILC)

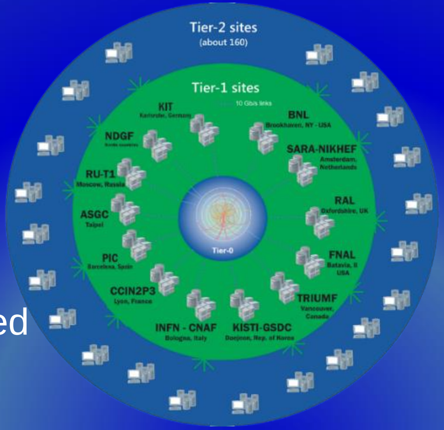
M. Winter,
R. Zhao, Dev. of CMOS sensors with on-chip artificial NN, PhD, Univ. Strasbourg, 2019

Worldwide LHC Computing Grid (WLCG) Collaboration

Initiated in 2001, an International collaboration was launched to distribute/analyse LHC data (Belle II, LBNF/DUNE and Linear colliders)

Challenges on HL-LHC computing:

- ✓ HEP computing much more capacity is needed
- ✓ New computing models and more efficient software have to be developed



WLCG Grid & Computing power:

- ✓ ~170 sites, 42 countries
- ✓ 2 million jobs / day
- ✓ CPUs: 6.500.000 of today's fastest cores

- ➢ **Additional resources are needed – Cloud computing, High-Performance Computing (HPC)**

- Cloud resources are much more competitive in terms of cost than in the past
- Increasing usage of HPC resources in the mid-term to long term future

- ➢ **HPC often employ GPU architectures to achieve record breaking results (towards exa-scale) - this will requite a fundamental re-write/optimization of the LHC software**

- ➢ **Modern tools and methods are used – Big-data, Machine Learning - Deep learning** (monitoring, analysis optimization, particle classification)

2018 HEP Software Fondation White paper: https://cerncourier.com/a/time-to-adapt-for-big-data/

LHC Computing - Towards a Change of Paradigm …

Machine Learning algorithms (NN, BDT, …) in particle physics has a long history:

1992:

Courtesy of J.-L. Faure

M^r FAURE

C.R. 92/13

DSM

Département d'Astrophysique, physique des Particules, physique Nucléaire et d'Instrumentation Associée

SÉMINAIRES TECHNIQUES DU DAPNIA

Le Mardi 19 Mai 1992 à 11 heures

RÉSEAUX DE NEURONES
EN PHYSIQUE
DES HAUTES ÉNERGIES

par Jean-Louis FAURE
du
Service de Physique des Particules
DSM - DAPNIA - Saclay

Ce séminaire,
fait par un non-spécialiste pour des non-spécialistes,
a pour but :

1) - D'introduire la terminologie et les méthodes utilisées par les Réseaux Neuronaux Artificiels (RNA), pour résoudre des problèmes de classification, clustering, identification, contrôle, analyse du signal ou des images, en essayant de montrer l'originalité des RNA par rapport aux méthodes plus classiques.

2) - De présenter les applications actuelles et les espoirs pour le traitement de certains problèmes de physique, en particulier en Hautes Énergies.

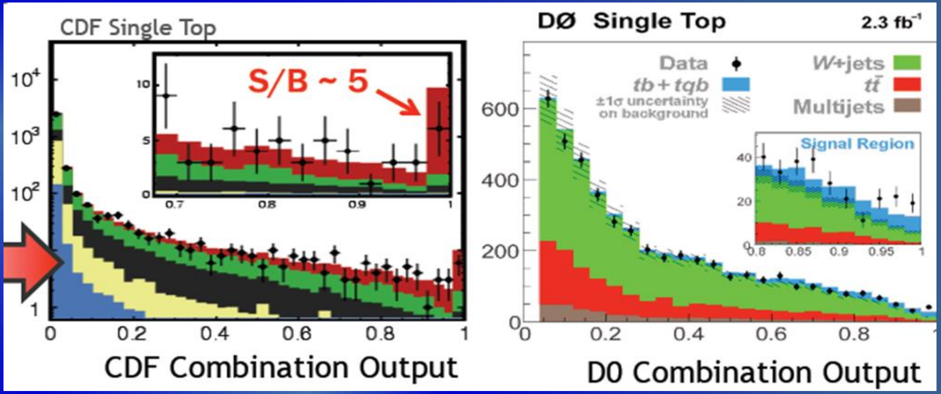
Salle «André BERTHELOT» - Bâtiment 141, pièce 143

Les séminaires techniques s'adressent
à tout le personnel du DAPNIA.

D.A.P.N.I.A. communication

Discovery of single top quark at FNAL (before the LHC)

2009:



Bringing modern advances in machine learning from offline to online/trigger is a major challenge:
Machine Learning in High Energy Physics Community Paper: arXiv: 1807.02876

Computing infrastructure so far has been largely based exclusively on X86 architecture using CPUs. GPUs are gaining a lot of popularity as co-processors due to the success of Machine Learning and „Artificial Intelligence“:

- ✓ ALICE will employ a GPU based Online/Offline system (O2)
- ✓ CMS is porting part of their trigger software to run on GPU processors
- ✓ LHCb is exploring GPUs for their online data reduction
- ✓ ATLAS is developing algorithms to run on GPUs

SUMMARY and OUTLOOK

The progress in experimental particle physics was driven by the advances and breakthrough in instrumentation, leading to the development of new, cutting-edge technologies:

- ✓ The detrimental effect of the material budget and power consumption represents a very serious concern for a high-precision silicon vertex and tracking detectors;
- ✓ CMOS sensors offers low mass and (potentially) radiation-hard technology for future proton-proton and electron-positron colliders;
- ✓ MPGDs have become a well-established technique in the fertile field of gaseous detectors;
- ✓ Several novel concepts of picosecond-timing detectors (LGAD, LAPPD) will have numerous powerful applications in particle identification, pile-up rejection and event reconstruction;
- ✓ The story of modern calorimetry is a textbook example of physics research driving the development of an experimental method;
- ✓ The integration of advanced electronics and data transmission functionalities plays an increasingly important role and needs to be addressed;
- ✓ Bringing the modern algorithmic advances from the field of machine learning from offline applications to online operations and trigger systems is another major challenge;
- ✓ The timescales spanned by future projects in HEP, ranging from few years to many decades, constitute a challenge in itself, in addition to the complexity and diversity of the required R&D.