RAL Particle Physics seminar, 12 May 2021
Claude Vallée, CPPM Marseille

PHYSICS BEYOND COLLIDERS RELOADED: post-EPPSU mandate and prospects

- **EPPSU recommendations and PBC updated mandate**
- **PBC science:**
  - ***Facilities***
  - ***QCD-oriented experiments***
  - ***BSM-oriented experiments***
  - ***New experimental and theoretical directions***
- **PBC updated organization**

NB: credit to PBC working groups and projects for most plots shown here

INITIAL PBC MANDATE AND DELIVERABLES FOR EPPSU

Excerpt from the 2016 PBC mandate by CERN Management:

"Explore the opportunities offered by the CERN accelerator complex and infrastructure to address some of today's outstanding questions in particle physics through experiments complementary to high-energy colliders and other initiatives in the world."

Information on organization, workshops, meetings, etc… visible on pbc.web.cern.ch

Deliverables to EPPSU:

PBC Summary Report: arXiv:1902.00260

PBC BSM Report: arXiv:1901.09966

PBC QCD Report: arXiv:1901.04482

PBC Accelerator Reports:

http://cds.cern.ch/collection/PBC%20Reports?ln=en

EPPSU DELIBERATION DOCUMENT

General statements of interest for PBC

...

A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy. ***Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***

...

The particle physics community must further strengthen the unique ecosystem of research centres in Europe. In particular, cooperative programmes between CERN and these research centres should be expanded and sustained with adequate resources in order to address the objectives set out in the Strategy update.

...

Synergies between particle and astroparticle physics should be strengthened through scientific exchanges and technological cooperation in areas of common interest and mutual benefit.

...

EPPSU DELIBERATION DOCUMENT

A few specific projects mentioned…

• • •

These include measurements of electric or magnetic dipole moments of charged and neutral particles, atoms and molecules, rare muon decays with high intensity muon beams at PSI, FNAL and KEK, rare kaon decays at CERN and KEK, and a variety of charm and/or beauty particle decays at the LHC,

• • •

Accelerator-based beam-dump and fixed-target experiments can perform sensitive and comprehensive searches of sub-GeV dark matter and its associated dark sector mediators, complementary to high-energy colliders and other approaches.

• • •

Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

• • •

. In addition to the examples already mentioned above, a broad programme of axion searches is proposed at DESY, a search for low-mass dark matter particles with a positron beam is under way at Frascati, and the COSY facility could be used as a demonstrator for measuring the electric dipole moment of the proton at Jülich. These initiatives should be strongly encouraged and supported.

• • •

The possible implementation and impact of a facility to measure neutrino cross-sections at the percent level should continue to be studied.

• • •

The design studies for next-generation long-baseline neutrino facilities should continue.

UPDATED PBC MANDATE: SCIENTIFIC GOALS

Scientific goal

The main goal of the Study Group remains to explore the opportunities offered by CERN's unique accelerator complex, its scientific and technical infrastructure, and its know-how in accelerator and detector science and technology, to address today's outstanding questions in particle physics through initiatives that complement the goals of the main experiments of the Laboratory's collider programme. Examples of physics objectives include dedicated experiments for studies of rare processes and searches for feebly interacting particles. The physics objectives also include projects aimed at addressing fundamental particle physics questions using the experimental techniques of nuclear, atomic, and astroparticle physics, as well as emerging technologies such as quantum sensors, that would benefit from the contribution of CERN competences and expertise. The study group will primarily investigate, and, where appropriate, provide support to, projects expected to be sited at CERN. The study group may also examine ideas and provide initial support for contributions to projects external to CERN. The study group is also expected to act as a central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape.

UPDATED PBC MANDATE: ORGANIZATION

Organization

The group will continue to be led by three coordinators representing the scientific communities of accelerator, experimental, and theoretical particle physics. The coordination team reports to the CERN Directorate. The coordinators will update the PBC working group structure to reflect the updated PBC mandate and input from the community.

The PBC study group will act as CERN's initial portal for new ideas which may come in spontaneously or through specific calls launched by the PBC coordination team. The group will facilitate and support an initial evaluation of the relevance and technical feasibility of the ideas in a global context, and will regularly inform the CERN scientific committees (INTC, SPSC or LHCC) about their findings. Where appropriate, oversight of PBC studies will be passed to the relevant CERN scientific committee once they are adequately mature for scrutiny and review of possible implementation.

PBC SCIENCE

1) NEW FACILITIES

2) QCD-ORIENTED EXPERIMENTS

3) BSM-ORIENTED EXPERIMENTS

4) NEW EXPERIMENTAL AND THEORETICAL DIRECTIONS

For details see PBC workshop of 1-4 March 2021
https://indico.cern.ch/event/1002356/

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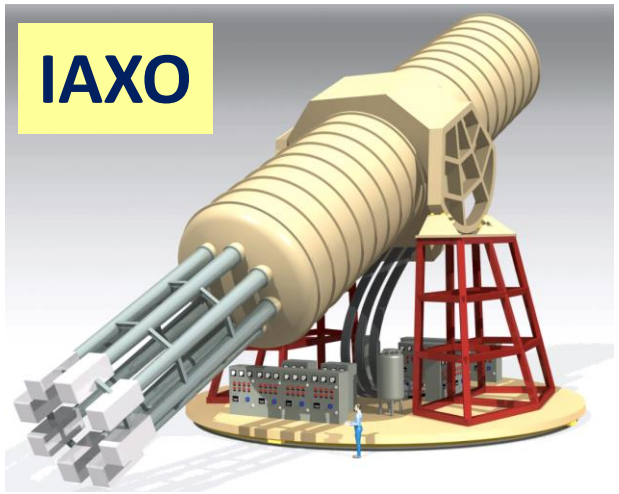
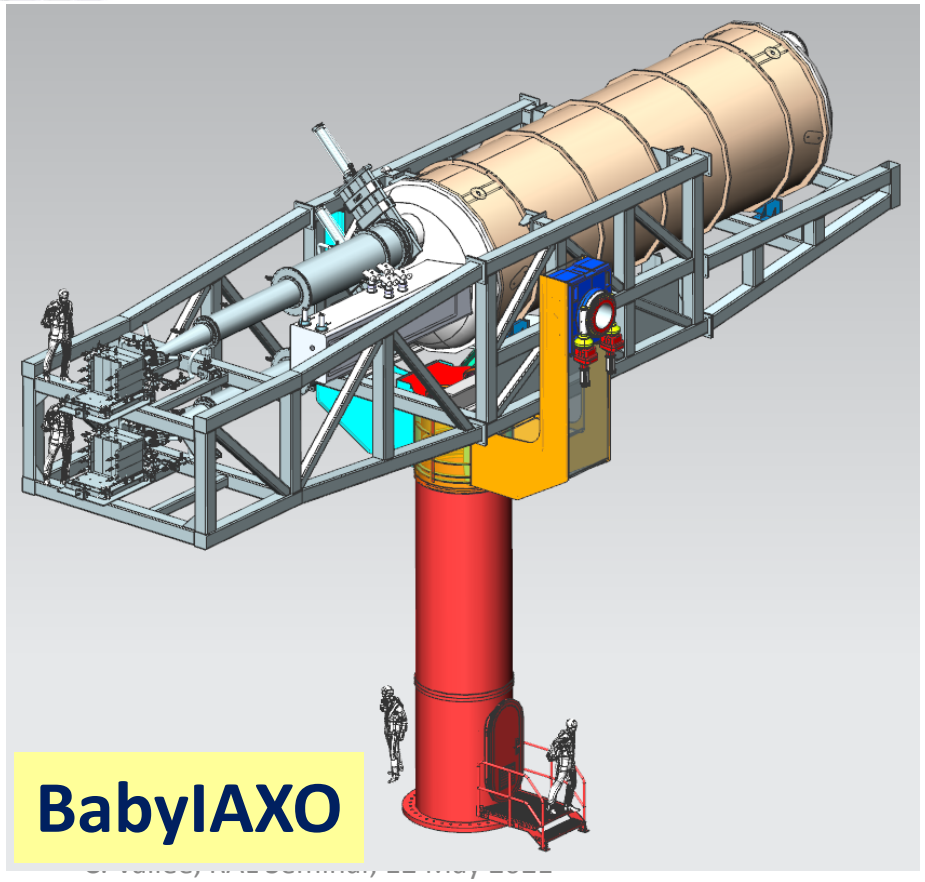


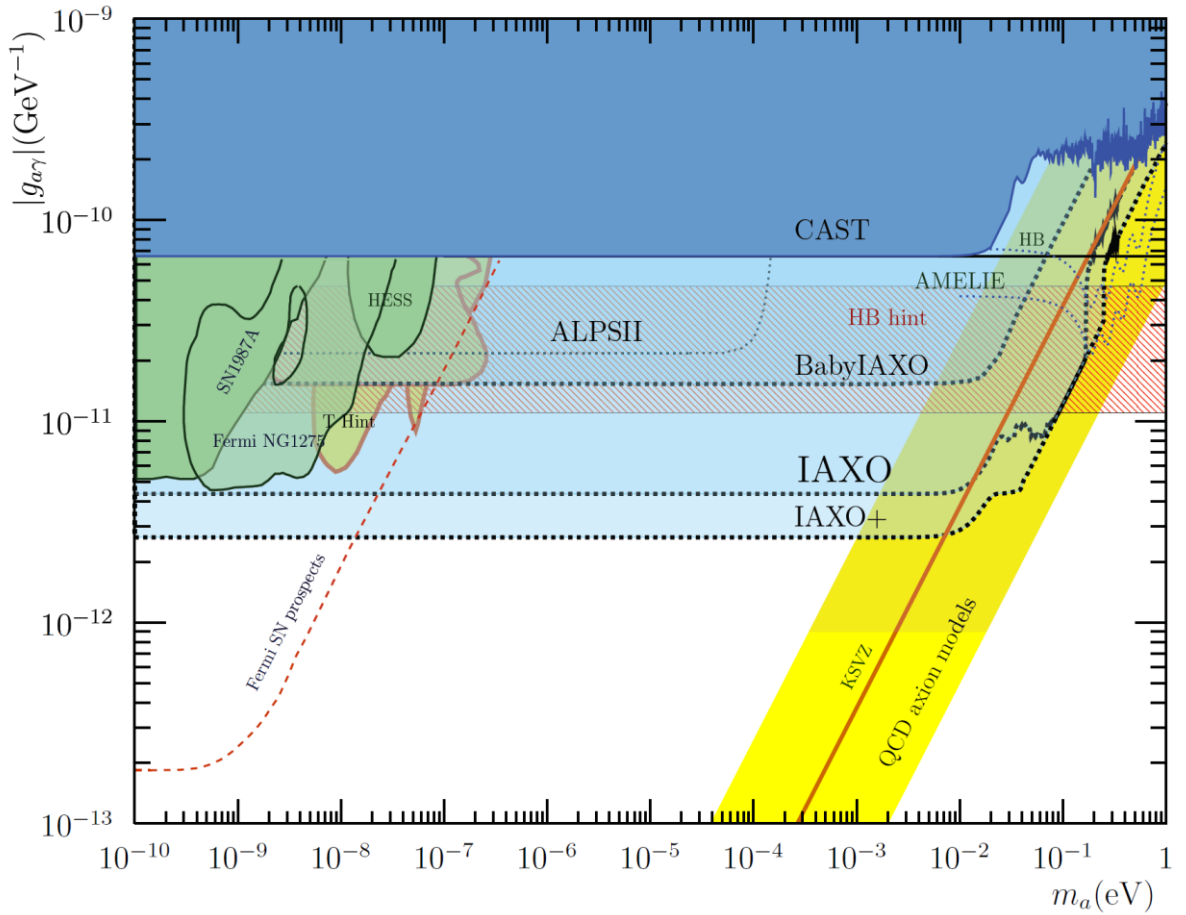
INTERNATIONAL AXION OBSERVATORY

BabyIAXO precursor approved and in construction at DESY

CERN PBC support to magnet design was instrumental for convergence, and is expected to go on in construction stage

Unique physics reach for ALPs searches



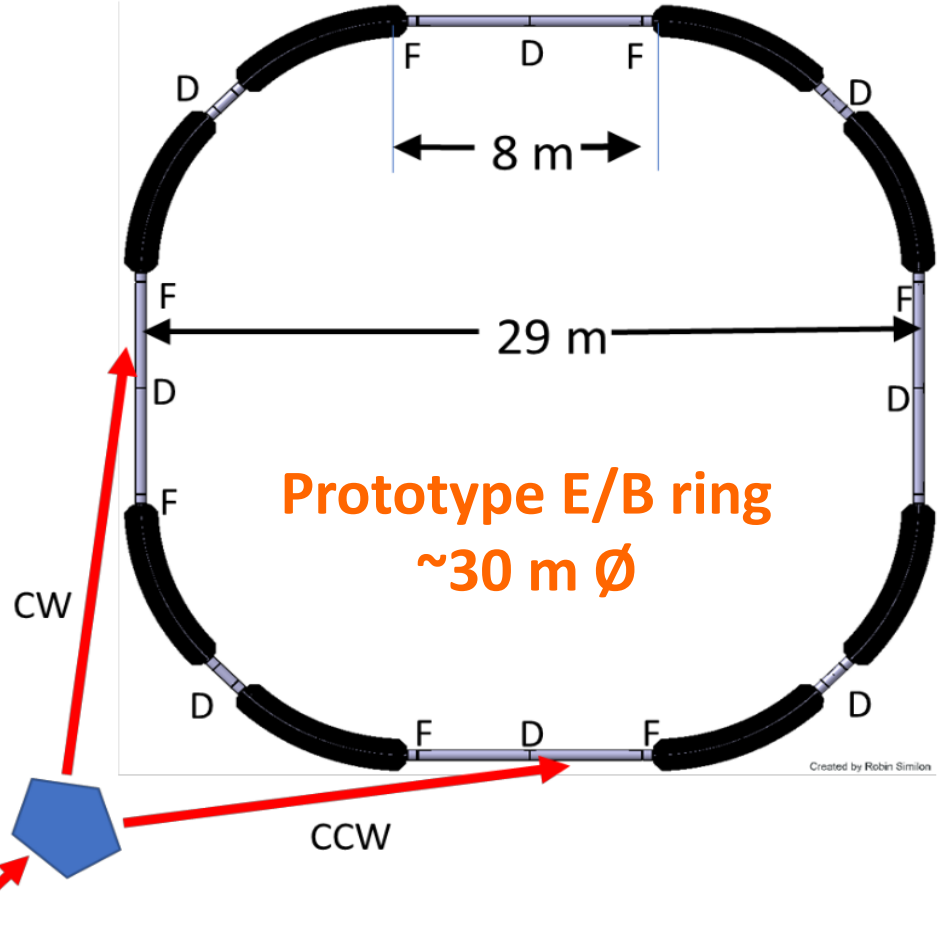


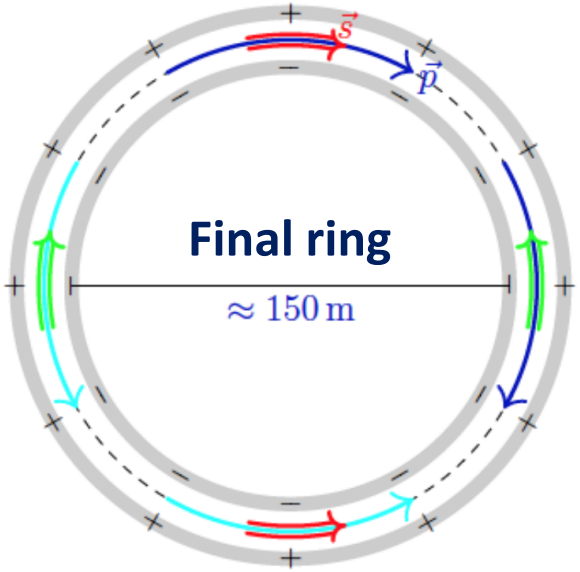
Physics B

PROTON EDM RING

COSY at Jülich supported by EPPSU as possible site for developing the project

Ongoing precursor experiment at Jülich (magnetic ring)





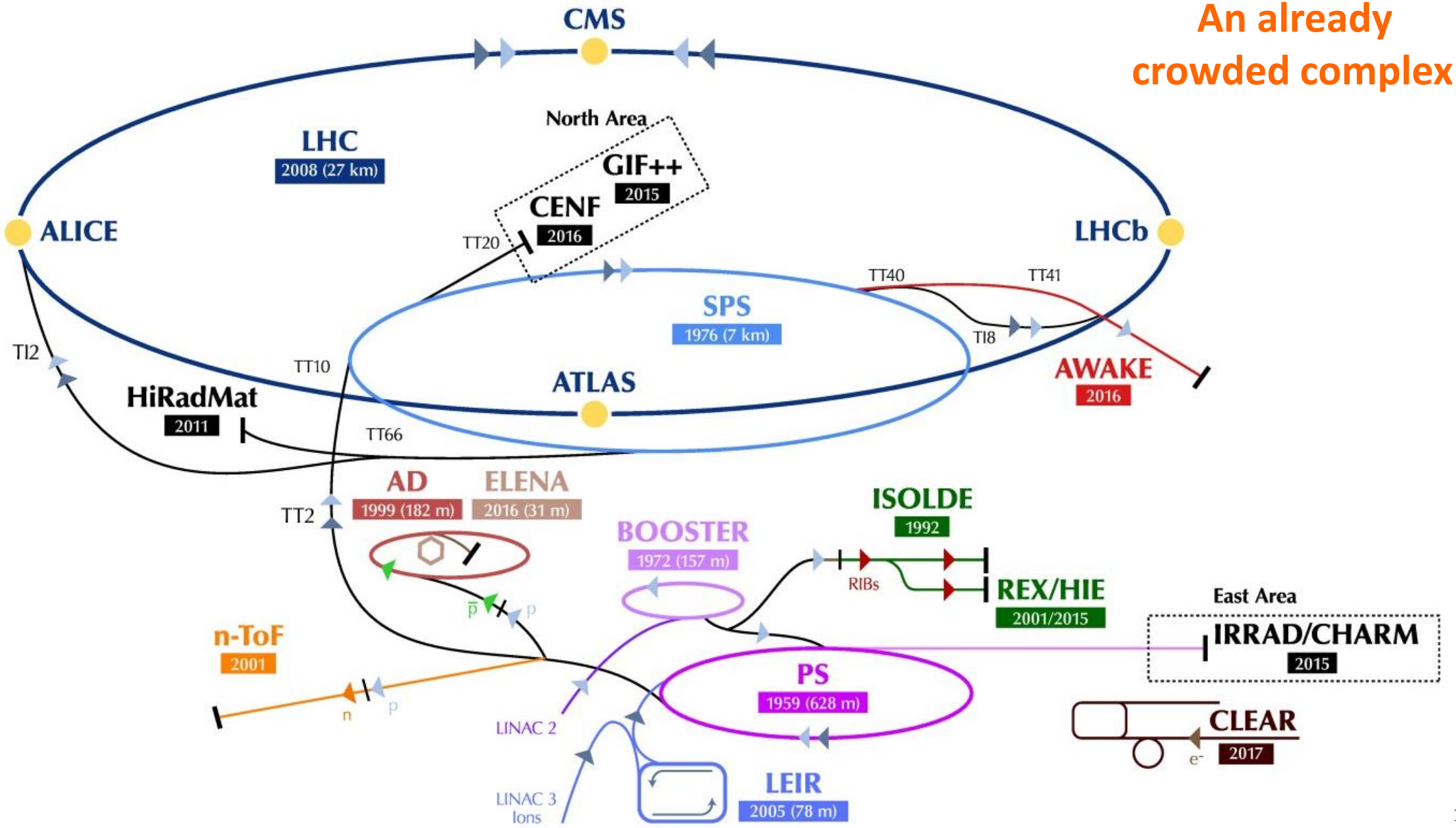
Design sensitivity: 4. 10^{-29} e.cm

TDR for prototype ring in preparation by CPEDM Collaboration (incl. CERN)

Many systematics issues to be solved: lattice, deflectors, RF cavities, B-shield, BPMs…

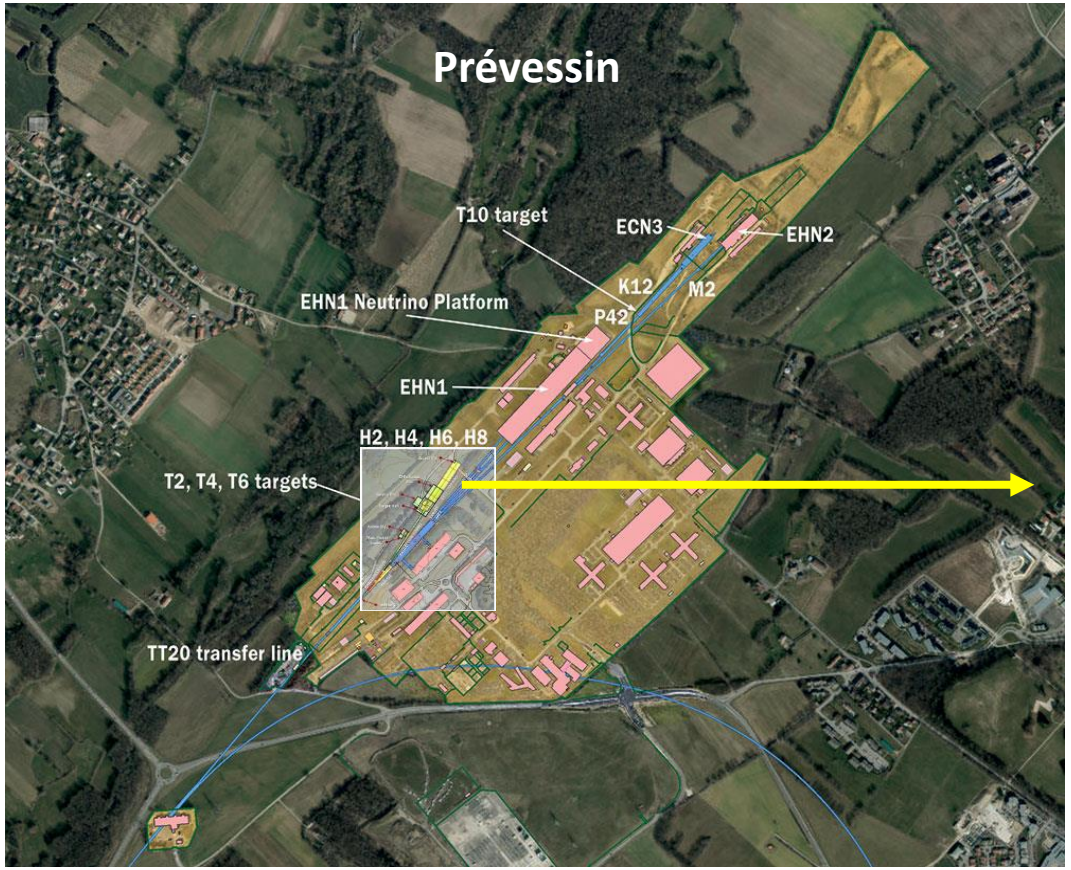
NEW CERN ACCELERATOR FACILITIES

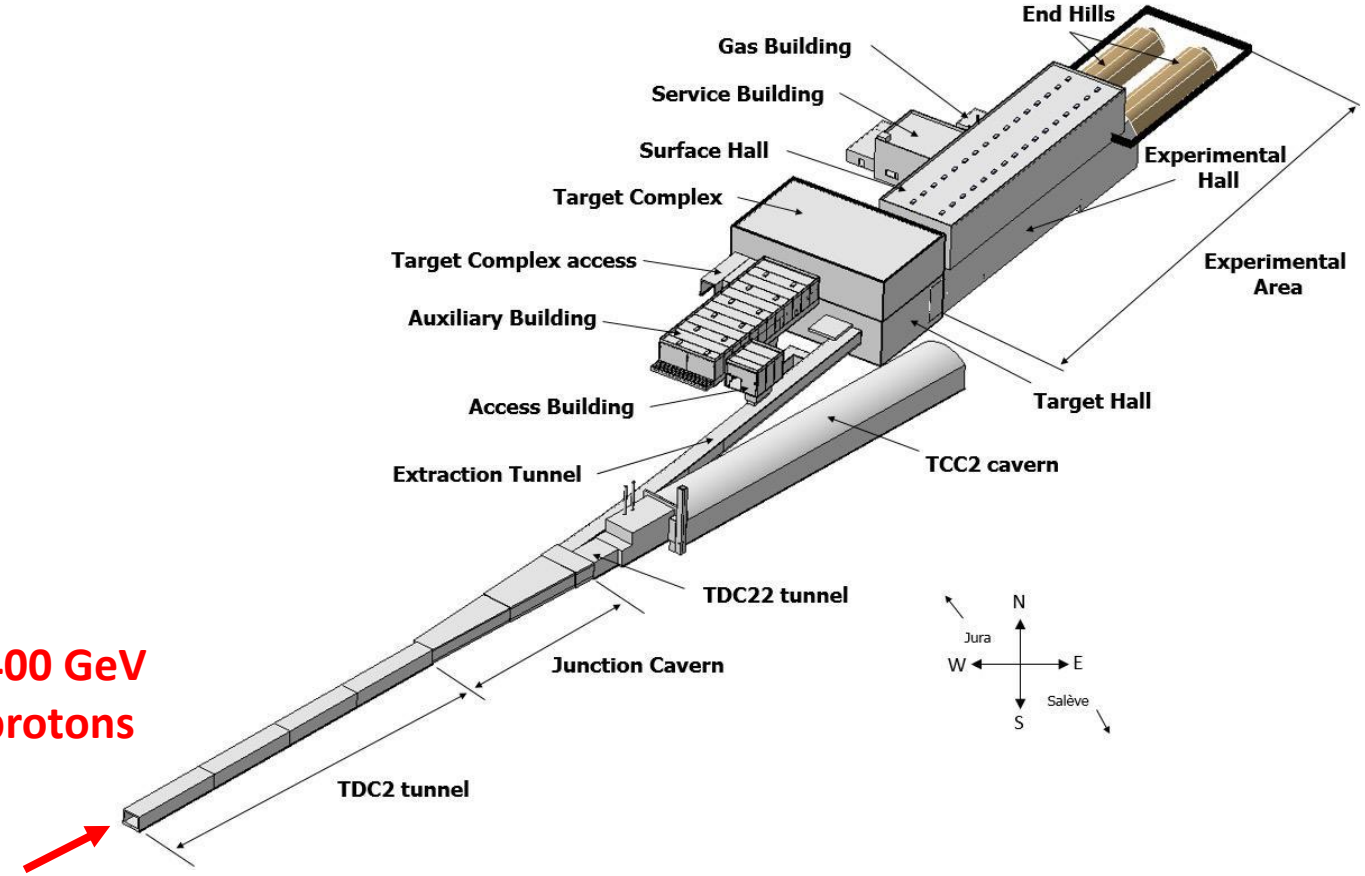
An already crowded complex!



PROTON BEAM DUMP FACILITY

Comprehensive Design Study done within PBC





Continued R&D towards TDR for next EPPSU:

Slow extraction, target design, cost optimization incl. alternative siting (CNGS, West Area)

→ of general interest for intensity upgrades of other CERN extracted beams

NEW e-BEAM: AWAKE++

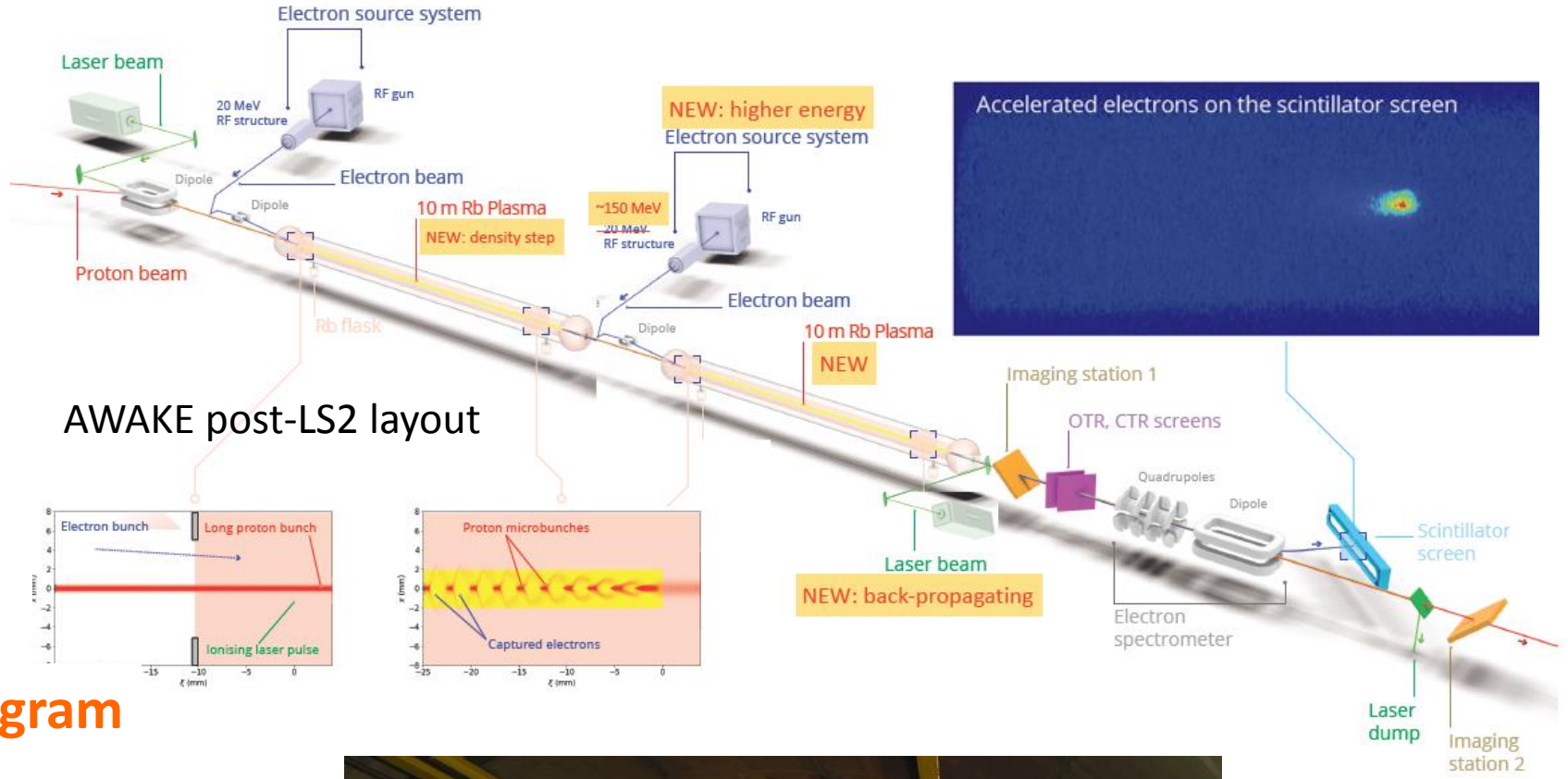
Electron acceleration on wake fields from proton micro-bunches in a plasma cell

Proof of principle validated in 2018 with electrons accelerated up to 2 GeV

Well-defined consolidation program to be conducted after LS2, under SPSC supervision

Could serve the purpose of an electron beam dump experiment located in the CNGS decay tunnel in the post-LS3 era

→ to be followed by PBC



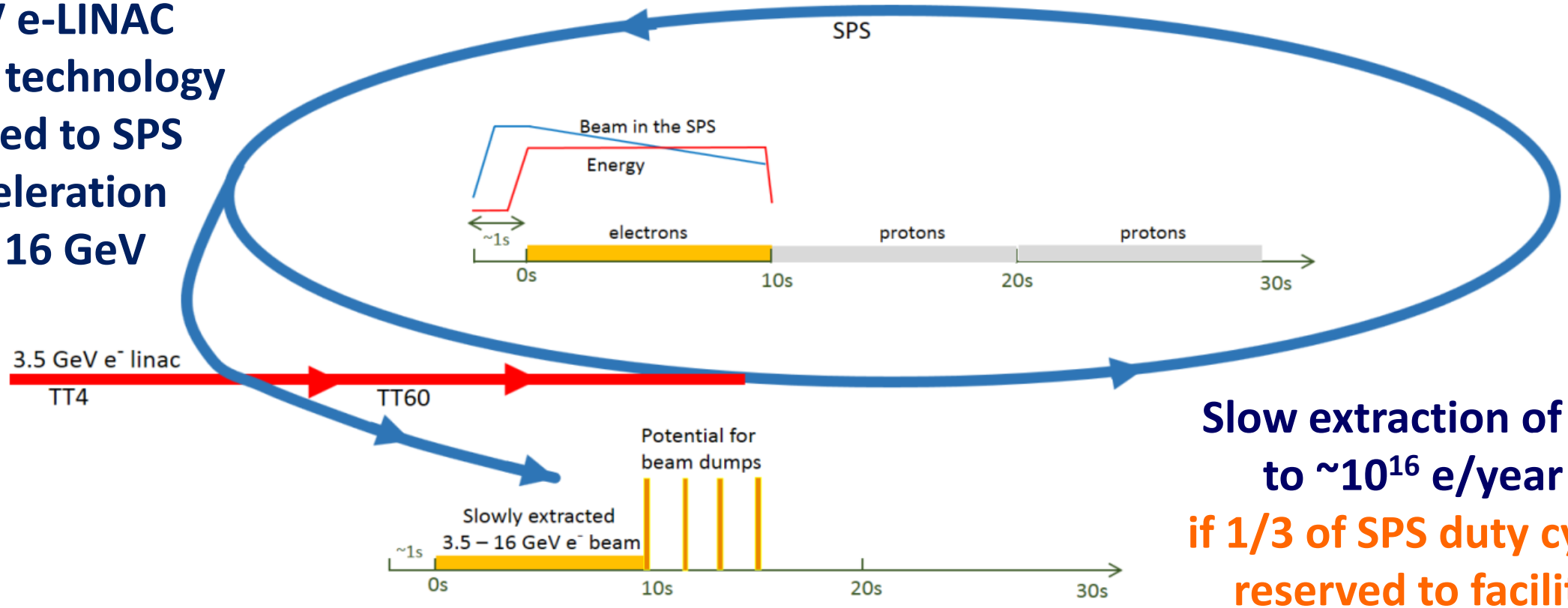
AWAKE post-LS2 layout

CNGS decay tunnel

NEW e-BEAM: eSPS

… building on CLIC R&D

3.5 GeV e-LINAC with CLIC technology connected to SPS for acceleration up to 16 GeV



Slow extraction of up to ~10^{16} e/year

if 1/3 of SPS duty cycle reserved to facility

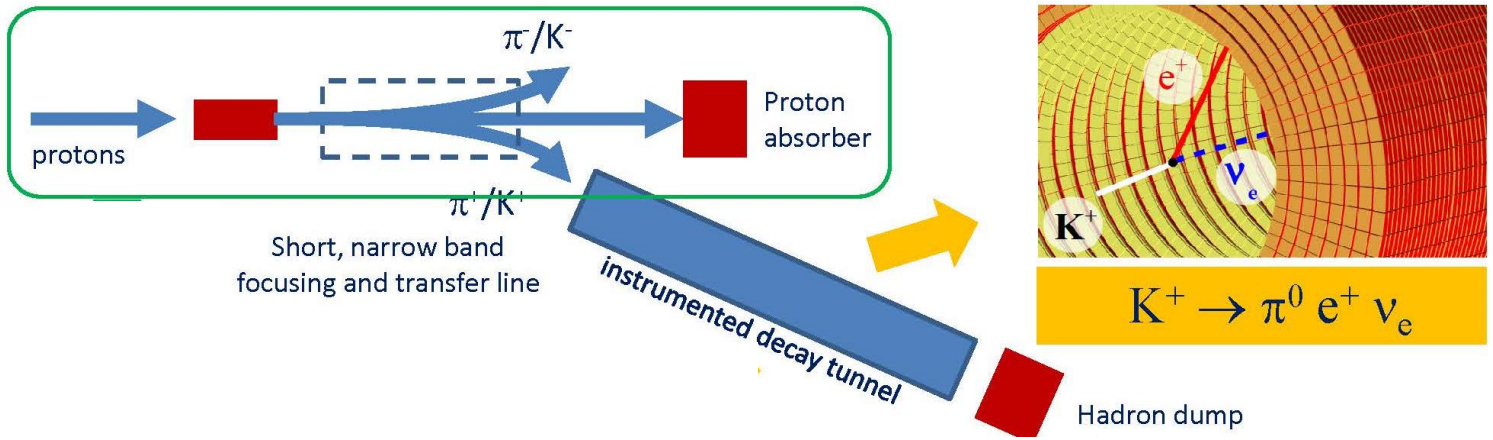
Conceptual Design Report released in 2020 under PBC

Project now on hold following positive momentum of LCLS-II/LDMX competitor at SLAC

LONG TERM R&D FOR NEUTRINO BEAMS

NuSTORM:

- ν beam from a μ storage ring
- Possible siting@CERN studied within PBC
- *Technology to be followed in context of the CERN muon collider study*

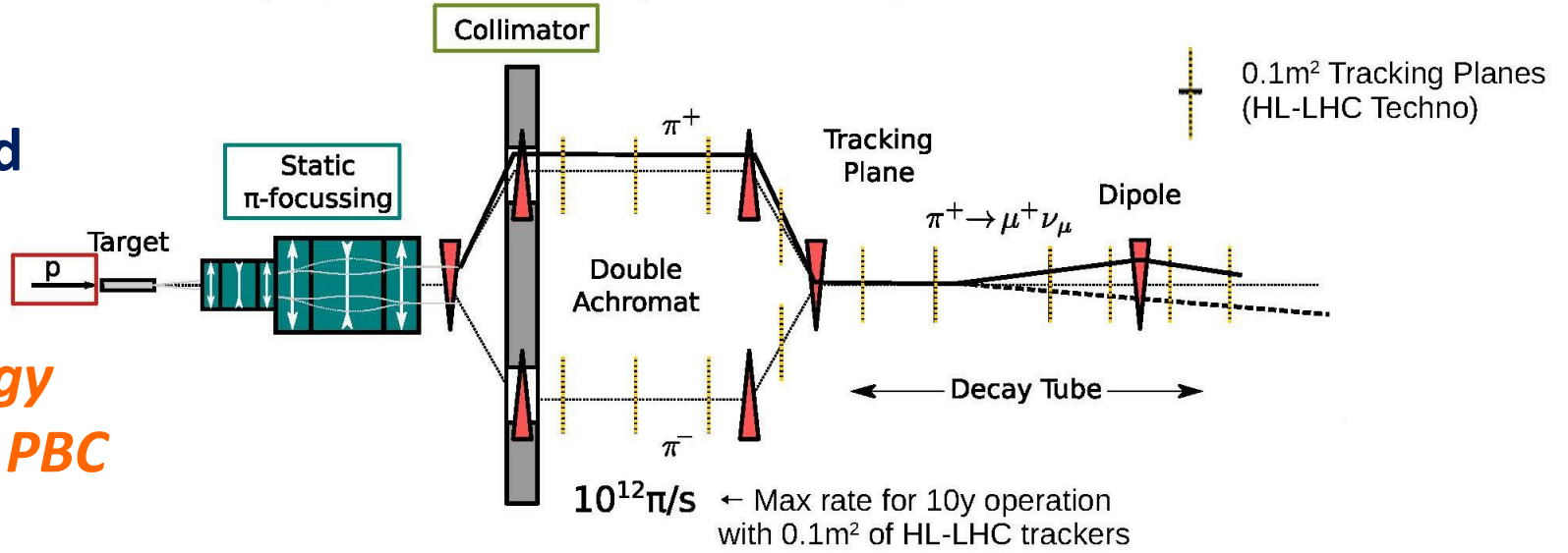


ENUBET:

- ν_e beam monitored from K decays
- Prototyping ongoing in Neutrino Platform within ERC grant
- *Possible implementation at CERN to be studied in PBC*

NuTAG:

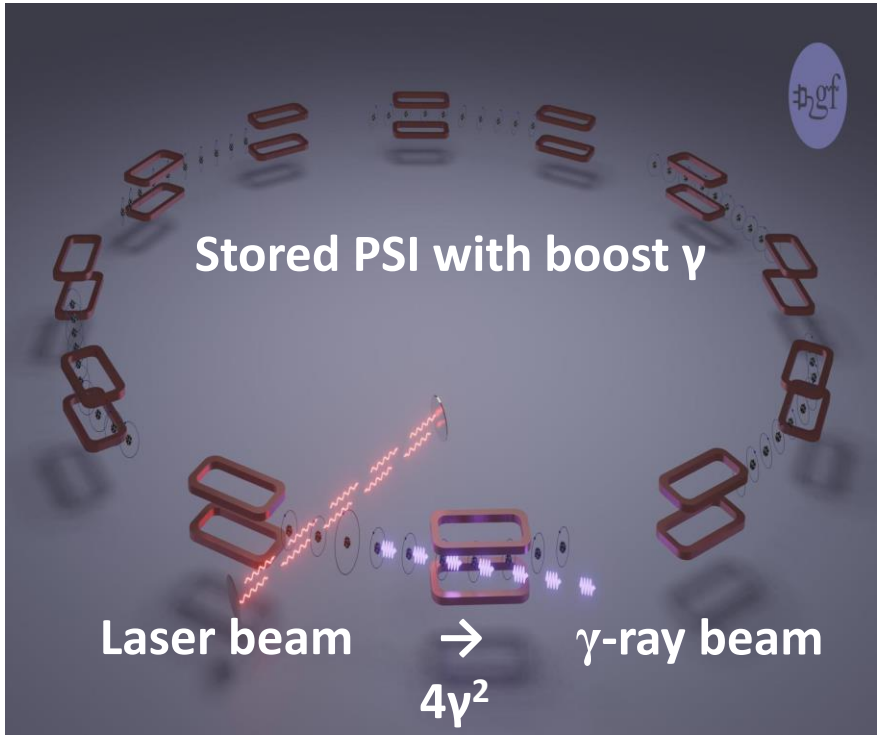
- ν_μ beam with $(E_\nu,\theta_\nu,\phi_\nu)$ tagged from individual π decays with HL-LHC silicon trackers
- *Feasibility and possible synergy with ENUBET to be studied in PBC*

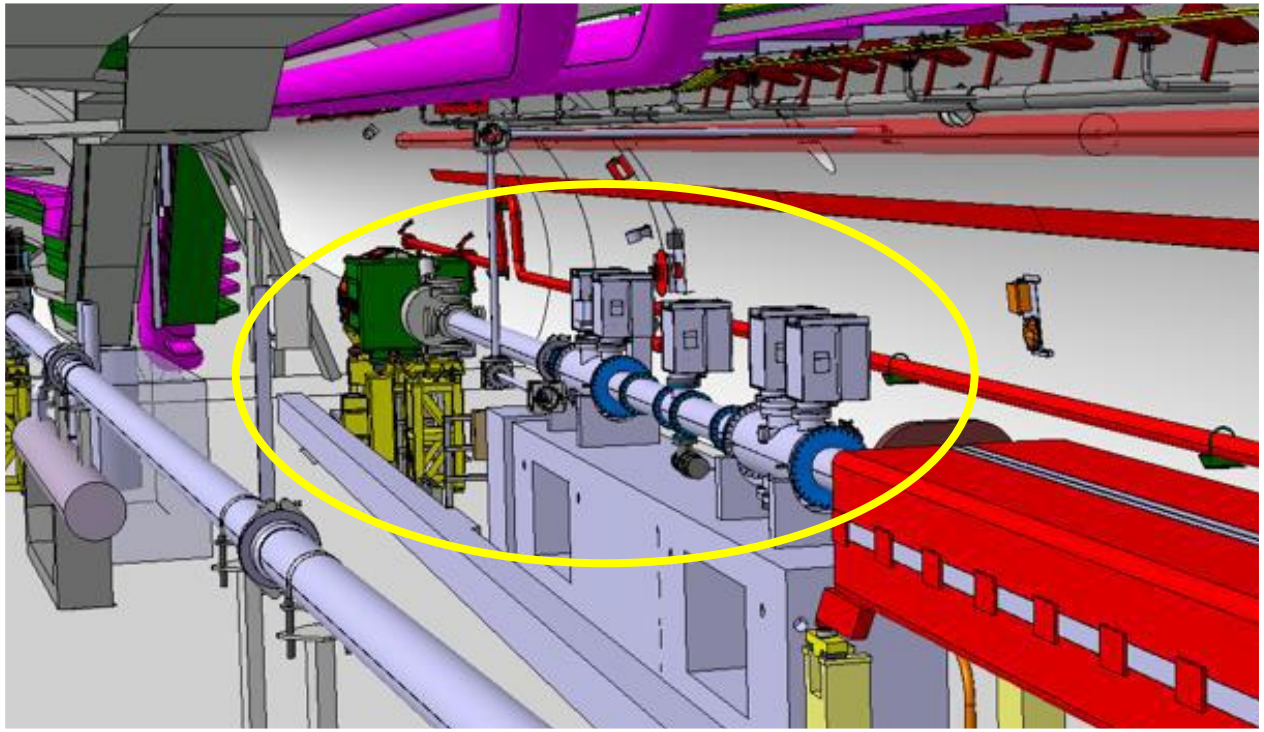


Goal of 10^7 intensity gain versus existing facilities

GAMMA FACTORY

New idea introduced within PBC





Important milestone reached within PBC with successful acceleration and storage of Partially Stripped Ions in LHC

Proof of Principle experiment with full configuration in preparation at SPS

First general workshop on applications in atomic, nuclear, particle and applied physics held end of 2020, see https://indico.mitp.uni-mainz.de/event/214/overview

→ to be followed by PBC BSM group

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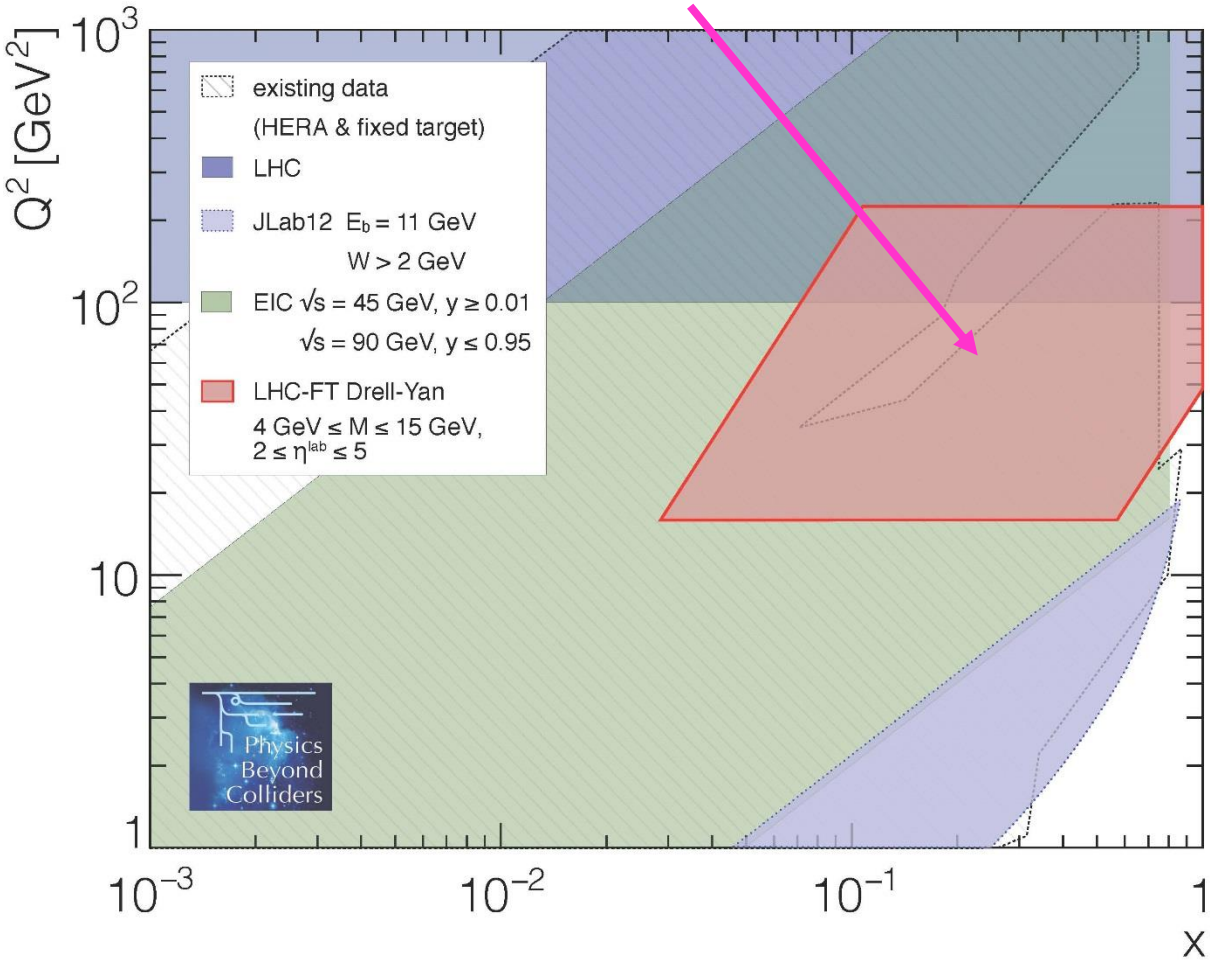
PBC QCD PROJECTS IN WORLDWIDE LANDSCAPE

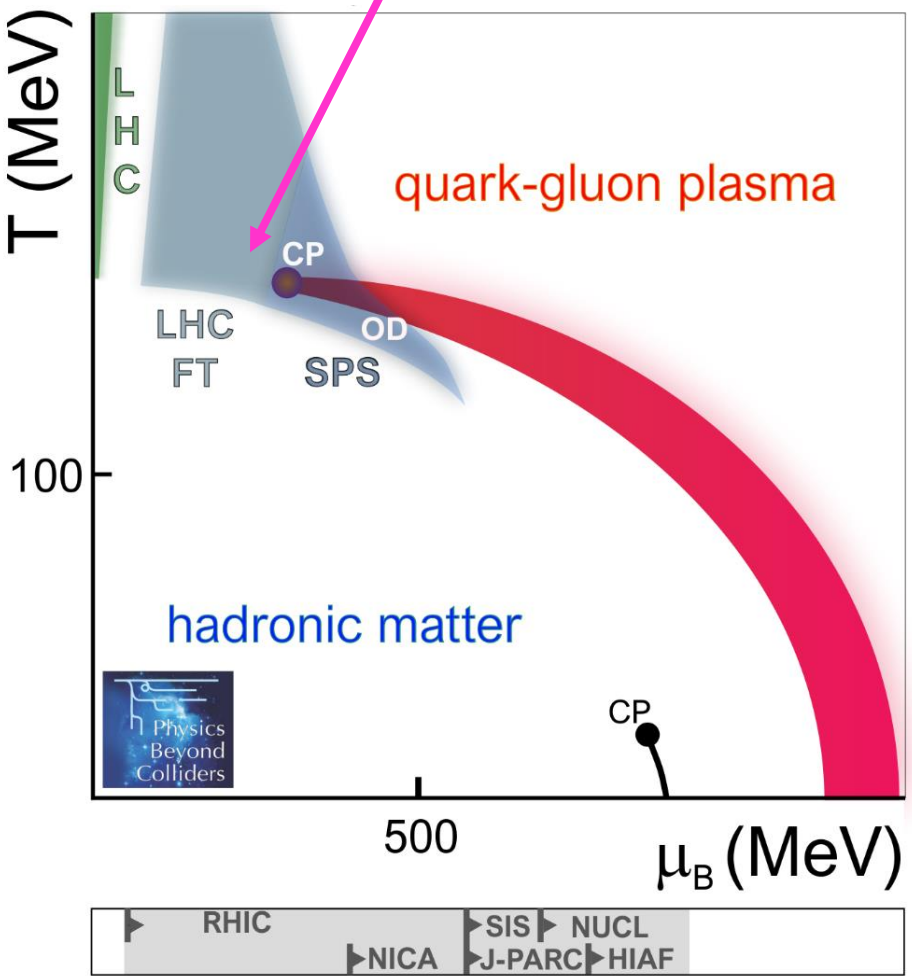
Structure Functions

Unique reach of LHC-FT with high statistics at high-x / high Q^2



QCD Phase Transition

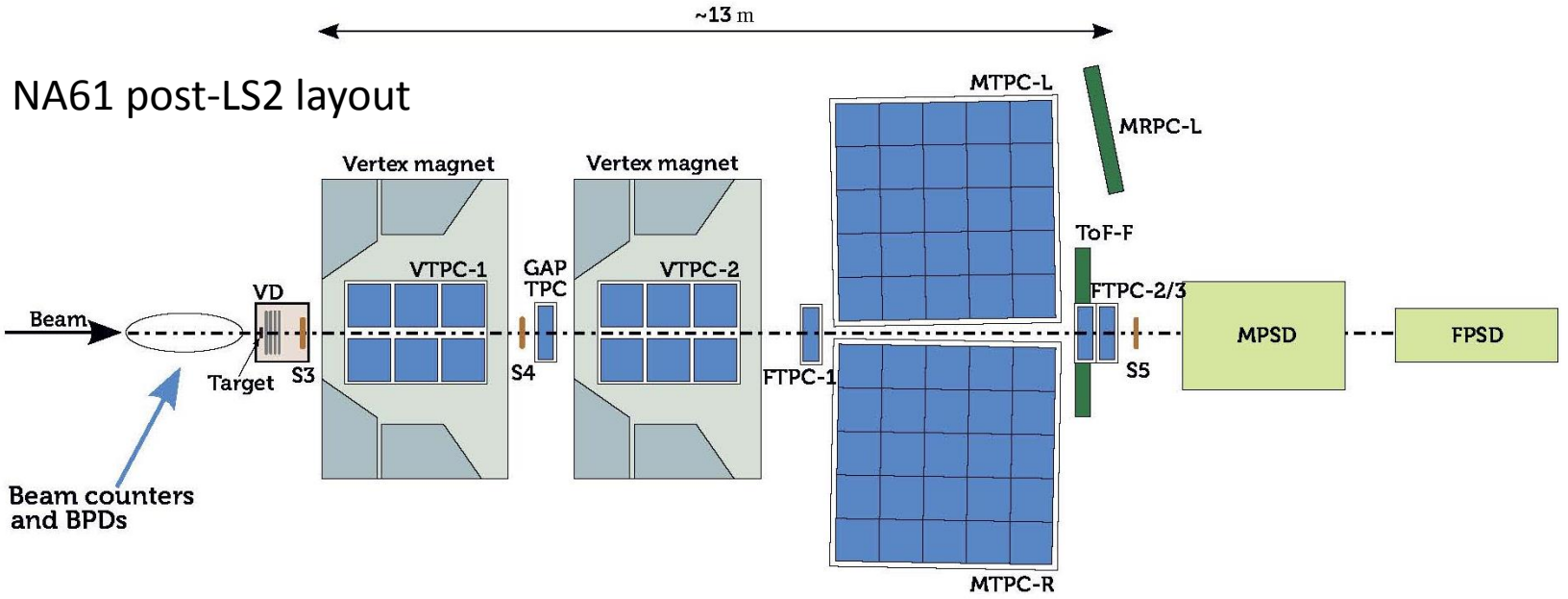
Unique reach of LHC-FT & SPS in transition region to high-μ_B



NA61++

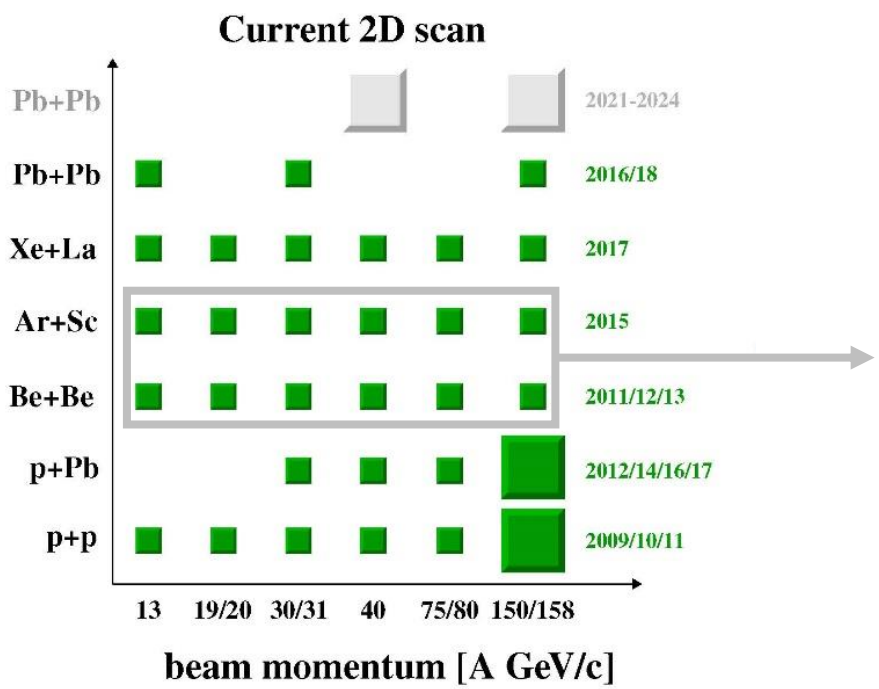
Post-LS2:

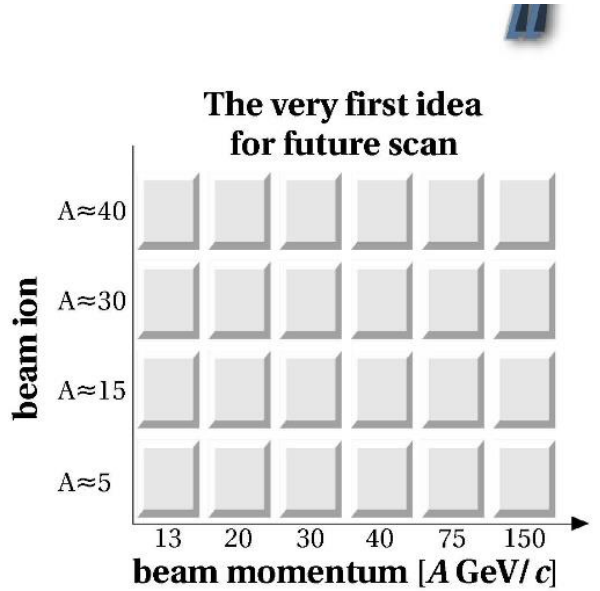
- ***Successful upgrades to study open charm close to expected CP-region.***
- Also unique measurements for ν-beams and cosmic rays
- ***To be followed by SPSC***



Post-LS3: *(preliminary ideas)*

- ***Finer grain 2-D scan to study onset of fireball***
- Antiproton and low-E beams for baryon stopping studies
- Continued measurements for ν-beams and cosmic rays
- ***To be followed by PBC***

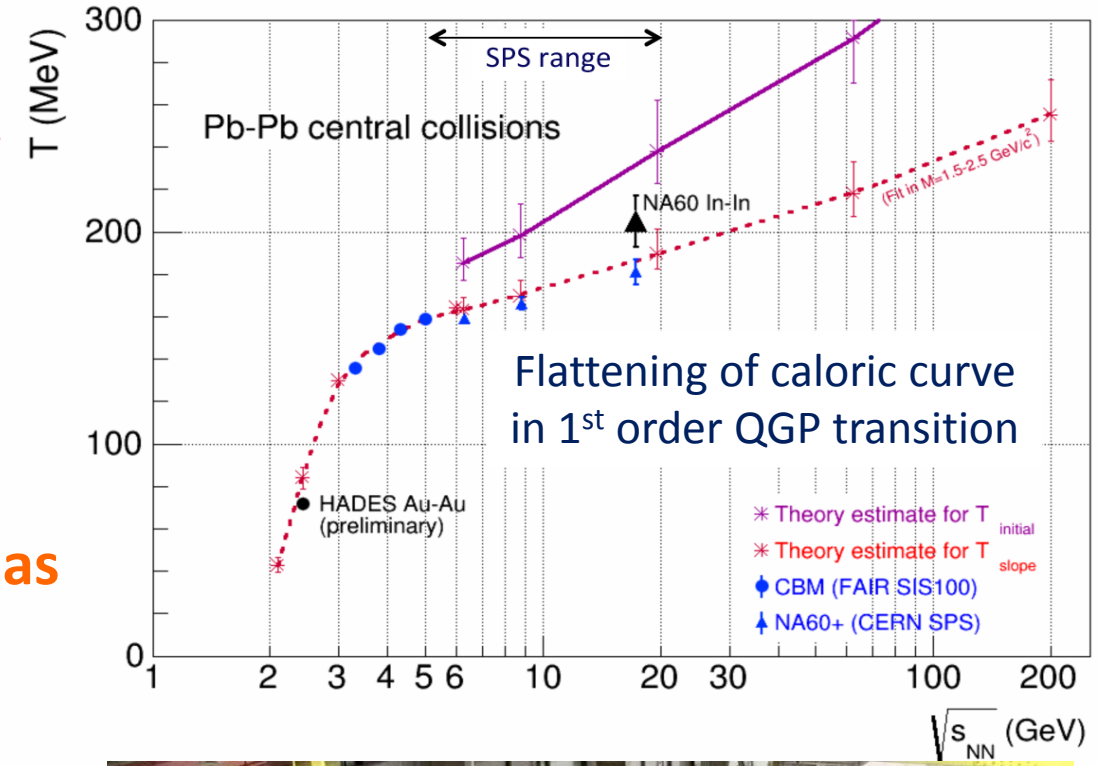


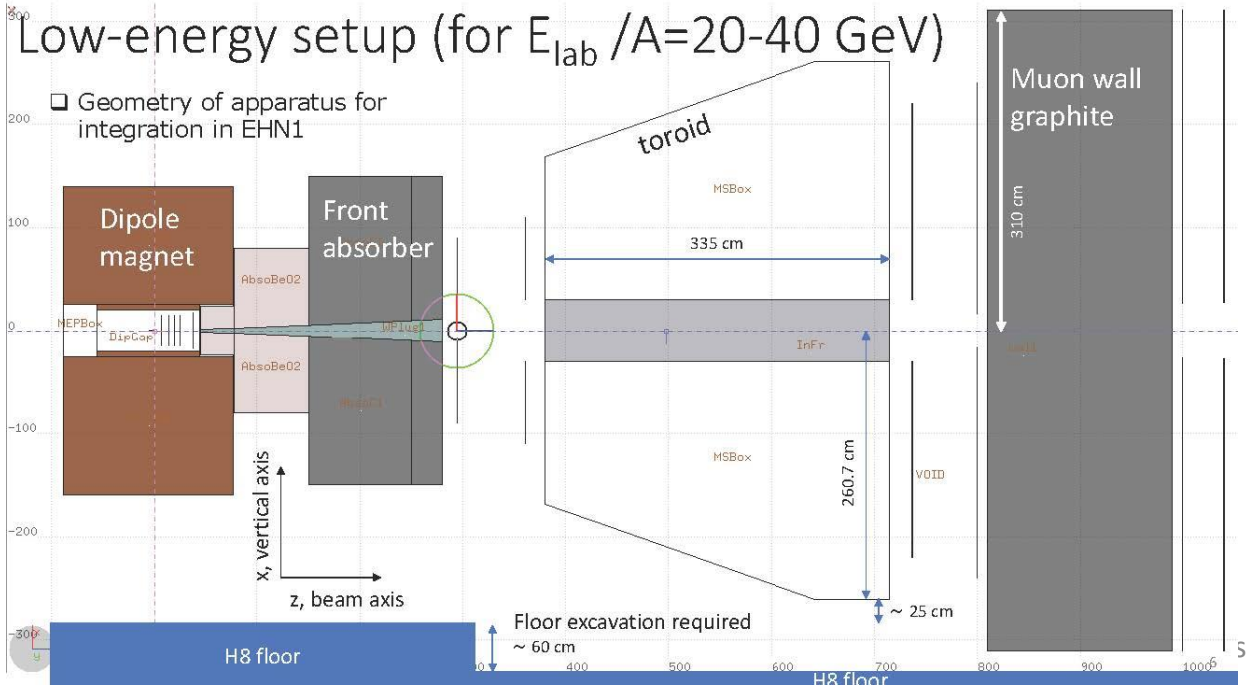


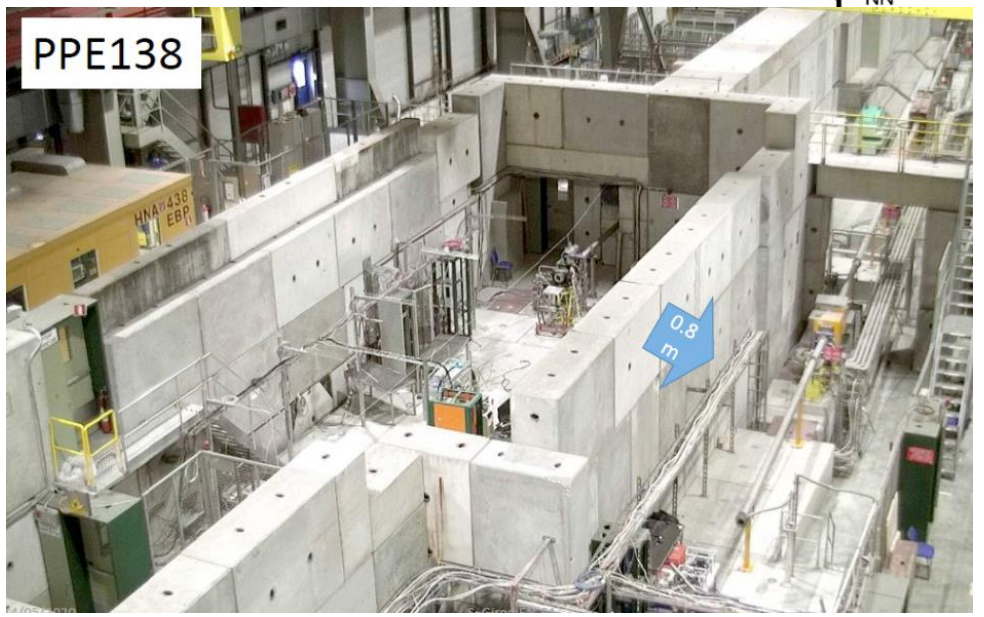
NA60++

Revival of NA60 concept to measure caloric curve of 1st order QCD transition with low-E dimuons

- **New location found on EHN1 H8 beam to avoid conflict with NA62 in ECN3 → *impact of reduced intensity by factor 4 to be quantified***
- **Toroid design ongoing with PBC support, as well as detector developments in synergy with HL-LHC**







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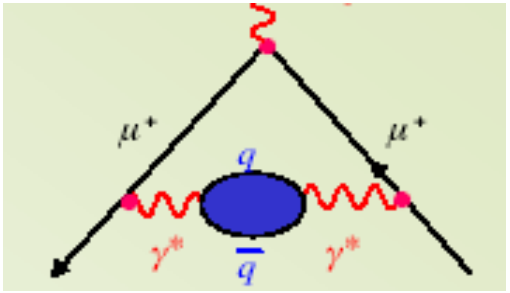
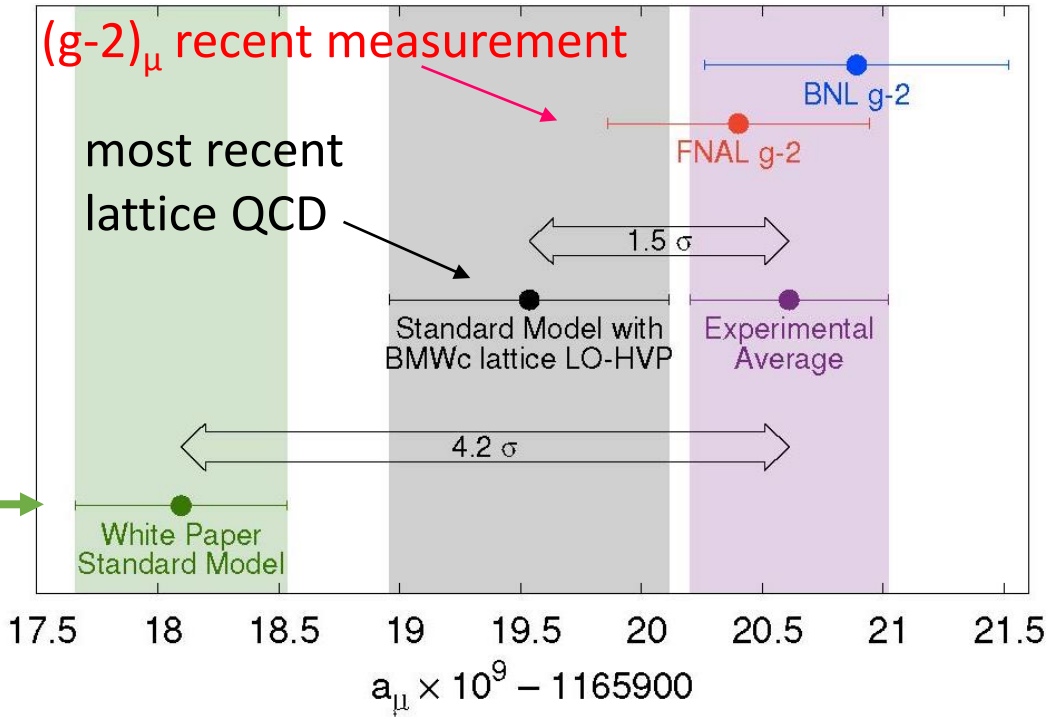
New idea introduced within PBC:

MUonE

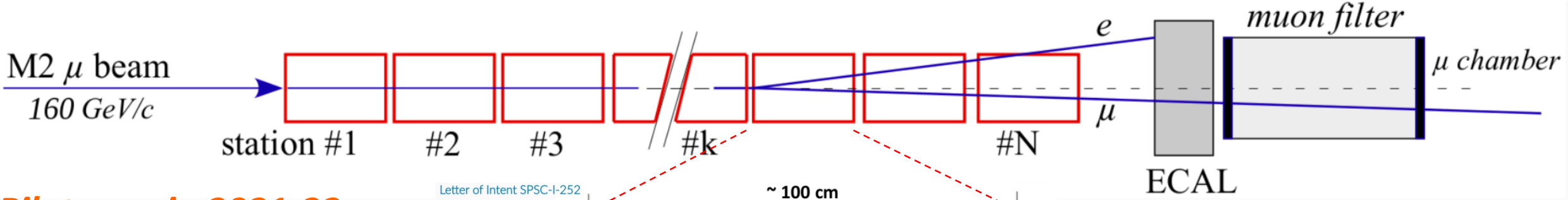
Direct measurement of HVP contribution to $(g-2)_\mu$ with μ-e elastic scattering



Complementary to prediction based on dispersion relation with e^+e^- data

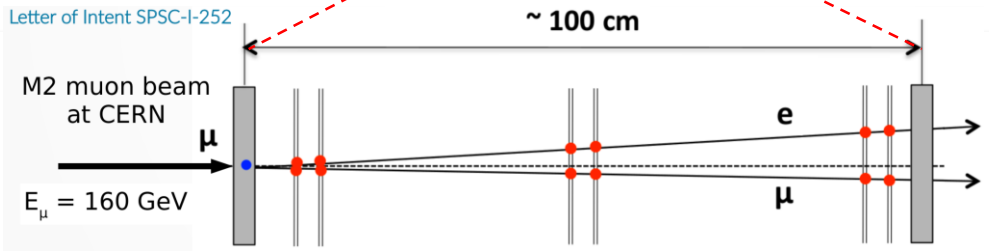


Very challenging experimentally:
10^{-5} precision required on cross-section



Pilot runs in 2021-22

Full data taking aimed for during run 3



Now in the hands of the SPSC

COMPASS(R_p)

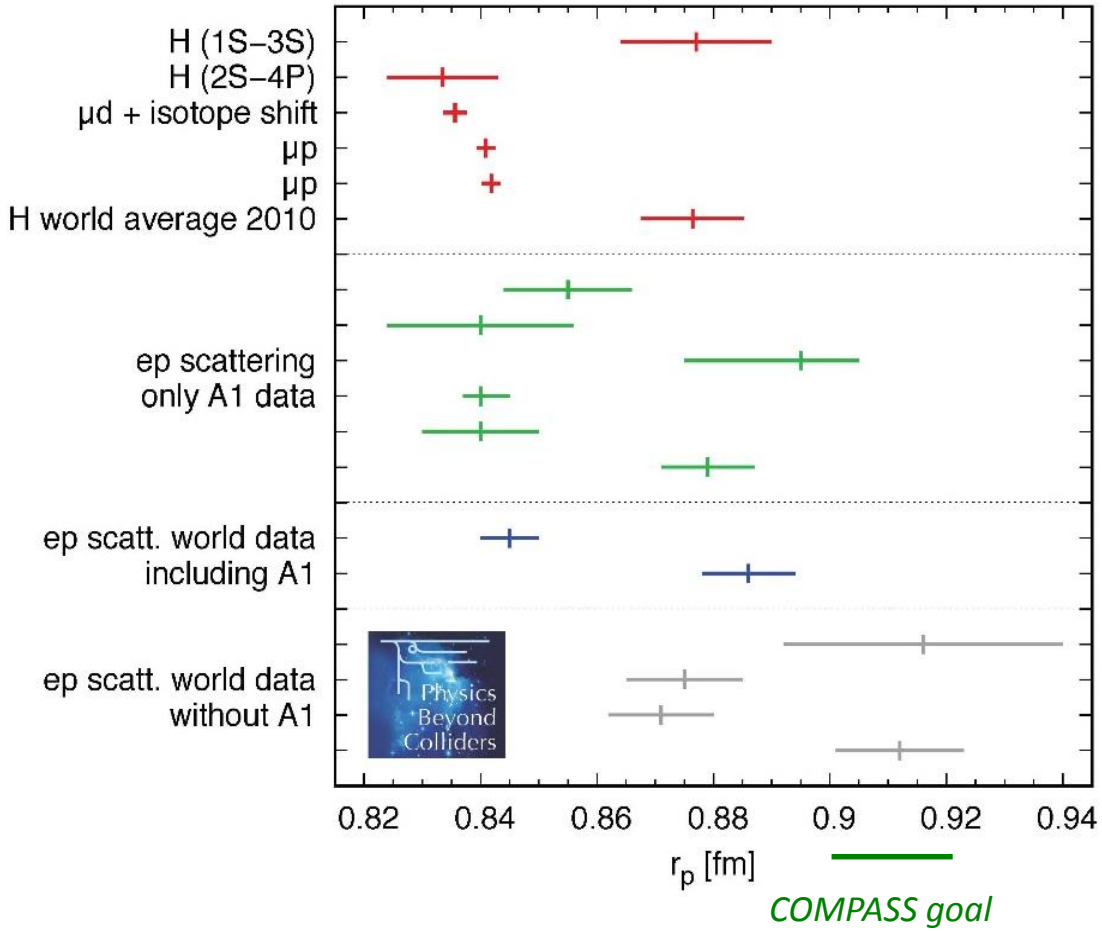
μ-p elastic scattering

In competition with MUonE on same μ-beam in EHN2

→ COMPASS spectrometer

new COMPASS TPC

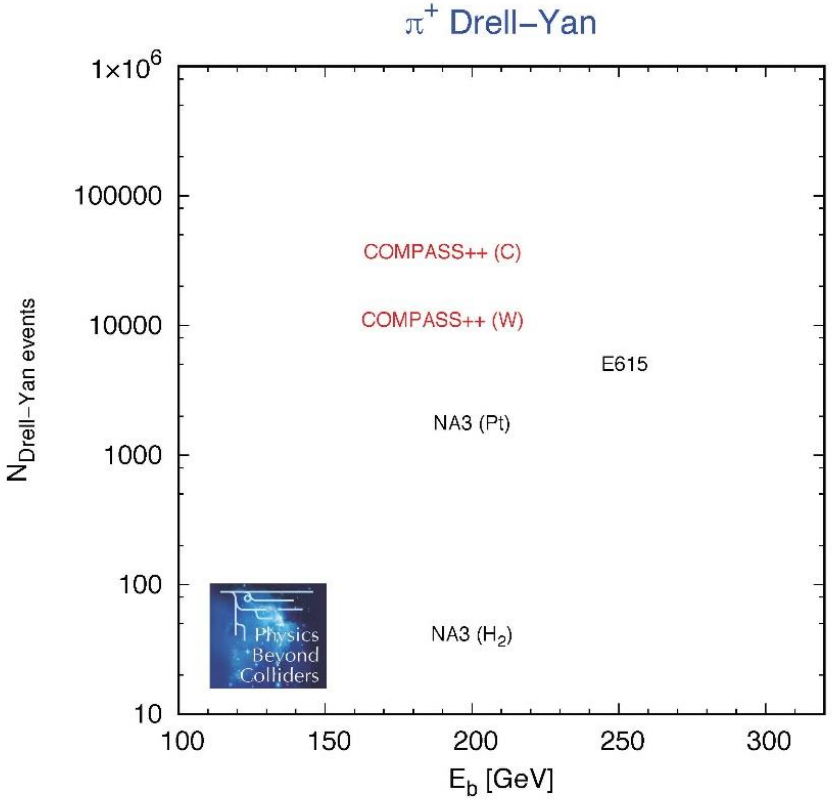
Proton radius puzzle



Data taking planned during run 3 provided successful pilot run

Project now in the hands of the SPSC

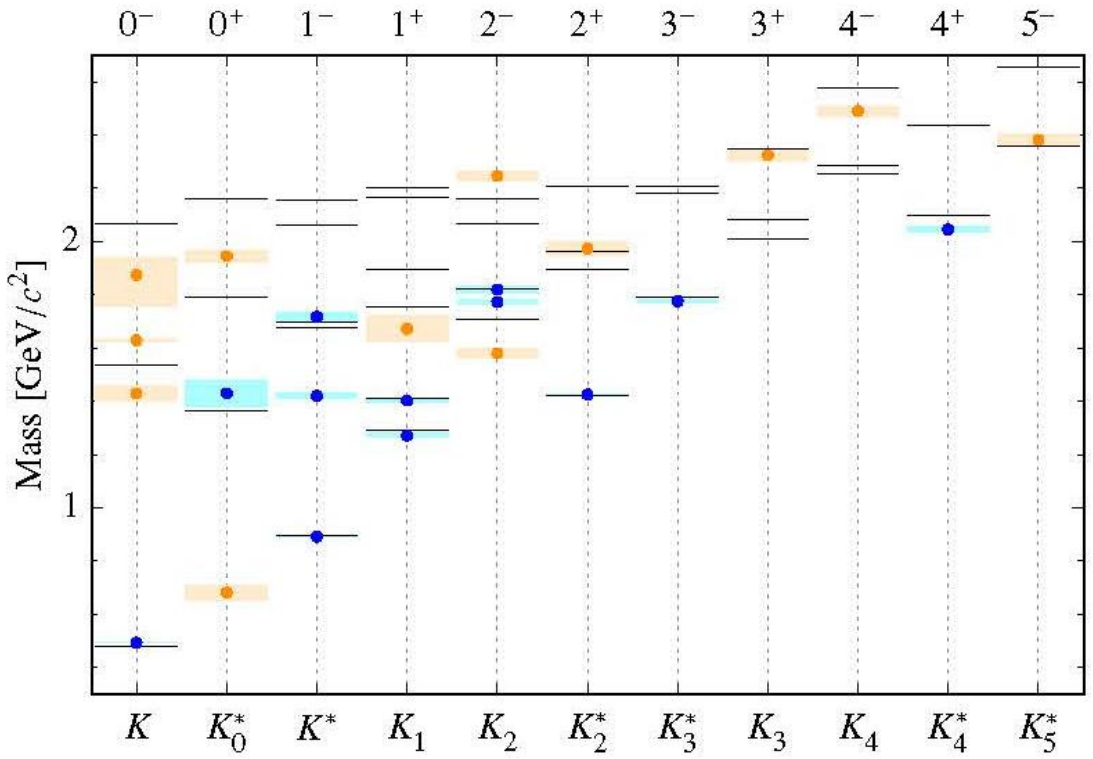
LONGER TERM PROGRAM OF AMBER "QCD FACILITY" (excerpts)



With existing beams:

Unique opportunity for higher precision pion structure measurements

In the hands of SPSC

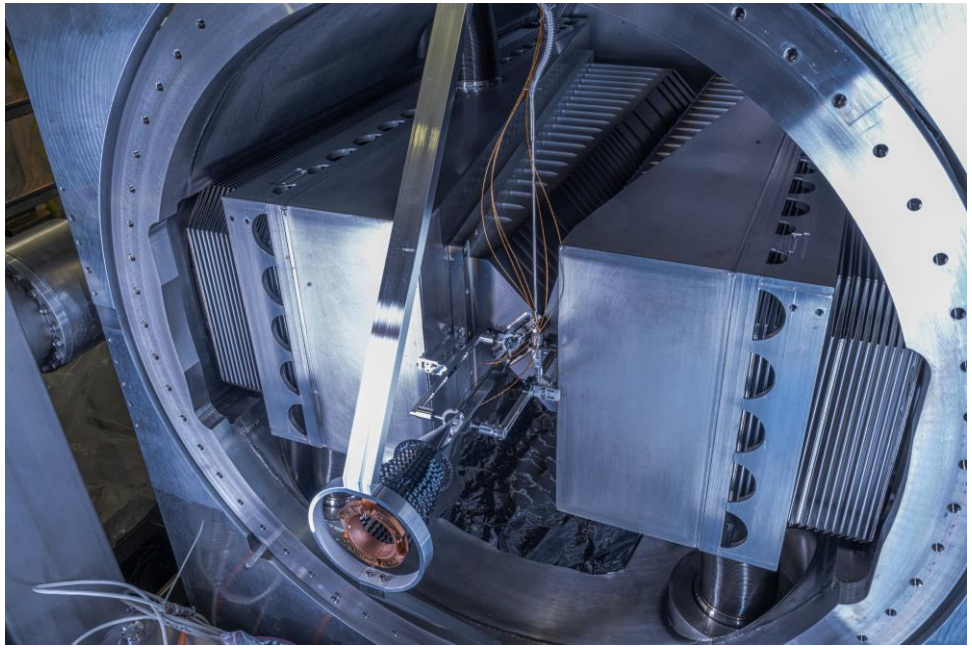


With new RF-separated K-beam:

(significant investment possible for post-LS3):

Comprehensive measurement of strange spectroscopy

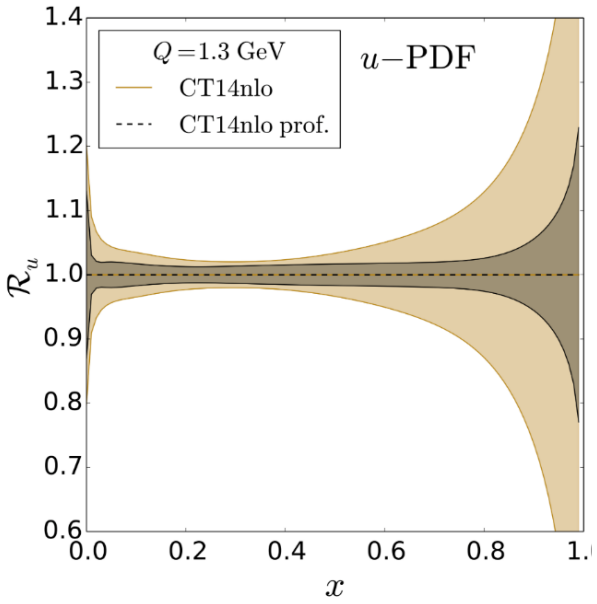
To be followed by PBC

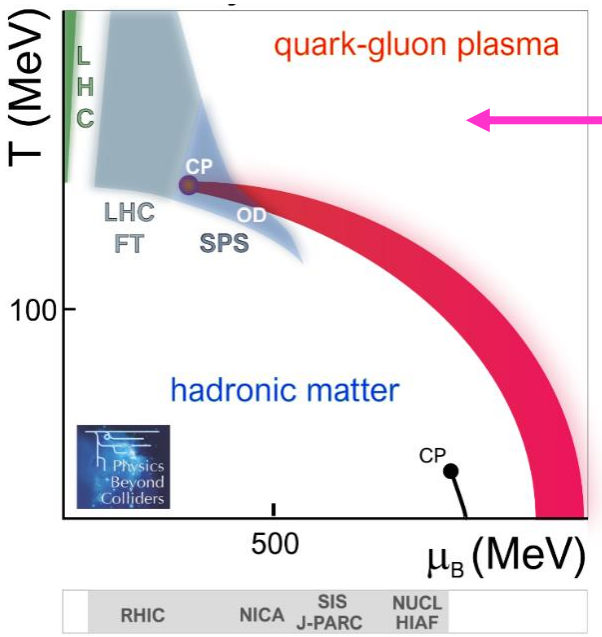


LHC FIXED TARGET

Already started by LHCb in run 2 with SMOG

SMOG2 storage cell installed for run3,
promises FT lumi x ~100 vs SMOG





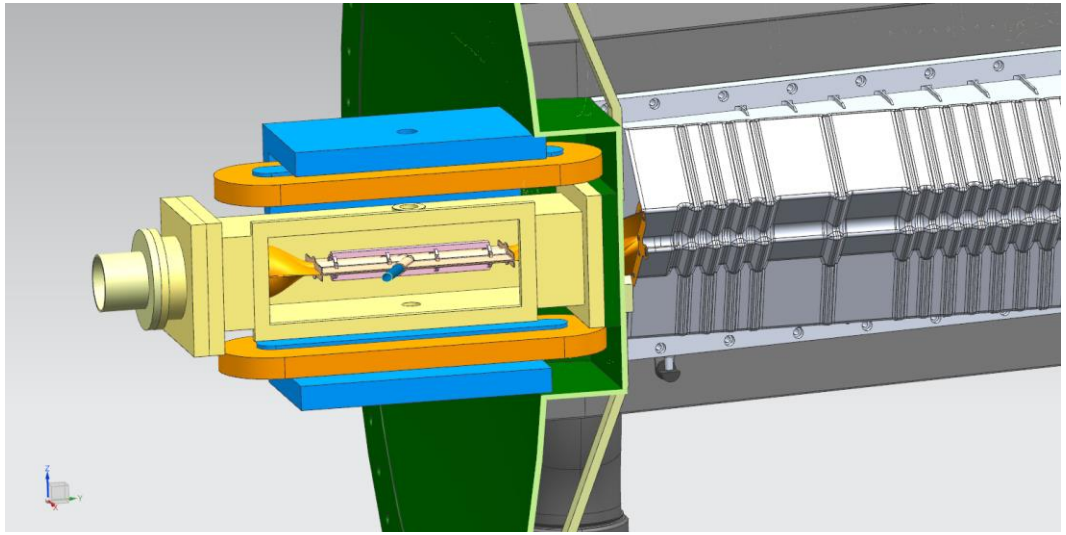
"Simple" storage cells already open unique opportunities in both hadron and QGP physics

Optimization of FT- and collider-operation required to maximize LHC-FT physics reach

SMOG2 project now in the hands of the LHCC

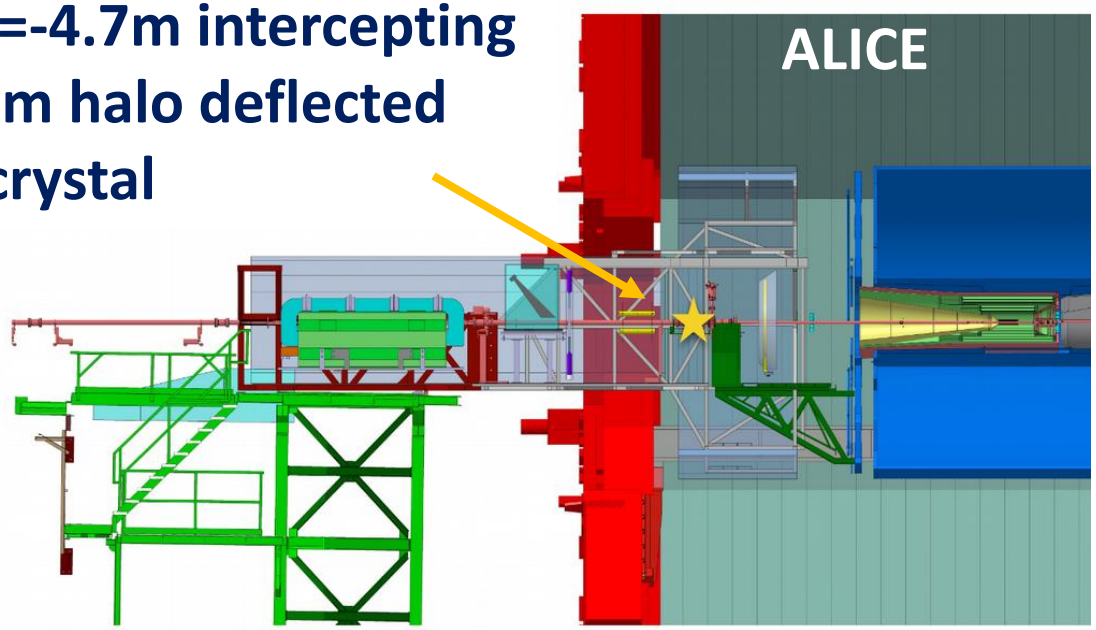
LHC FIXED TARGET cont'd

Longer term developments under PBC

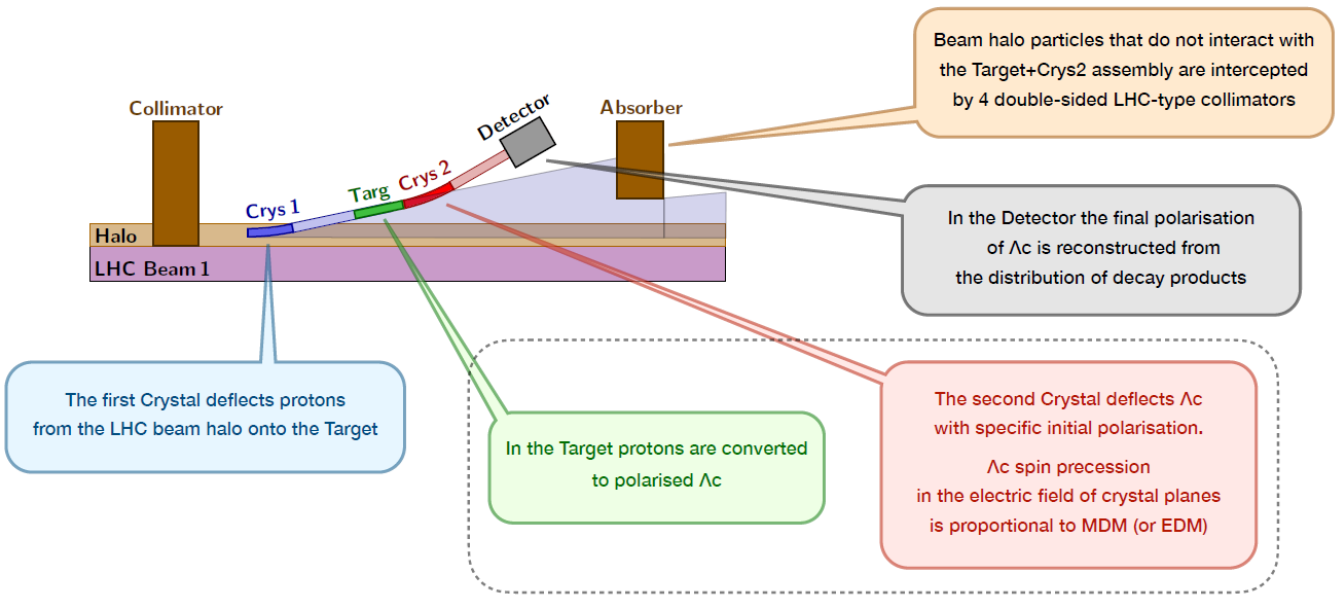


LHCSpin study of polarized storage cell for LHCb

ALICE wire target at z=-4.7m intercepting beam halo deflected by crystal



D. Mirarchi et al., Eur. Phys. J. C 80, 929 (2020)



Double crystal set-ups for measurement of short-lived baryons electric and magnetic moments, either by LHCb or at a dedicated location

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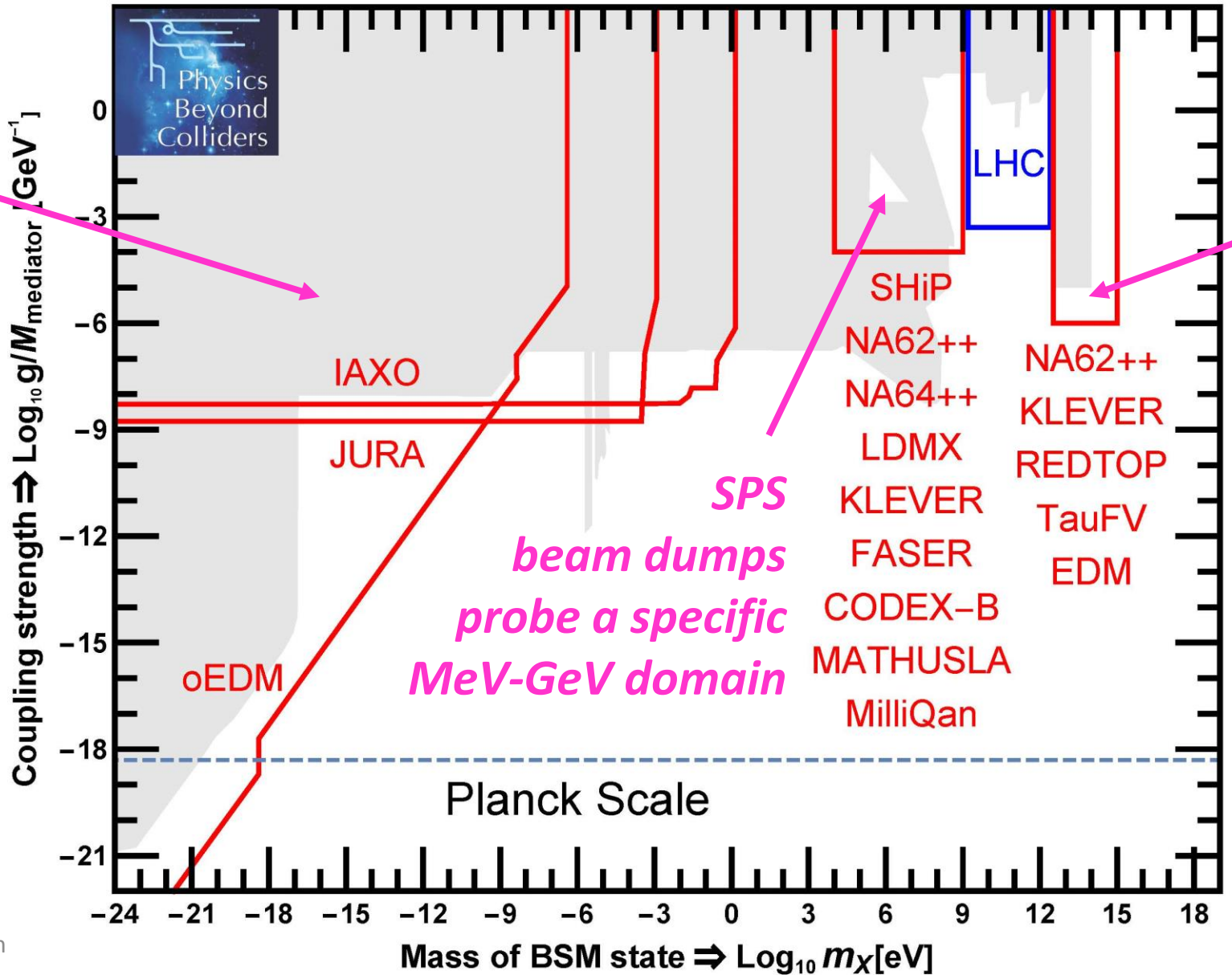
PBC BSM PROJECTS IN WORLDWIDE LANDSCAPE

EDM & non-accelerator projects cover the very low-mass domain



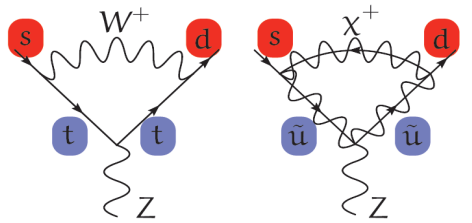
SPS beam dumps probe a specific MeV-GeV domain

Precision & rare processes experiments extend reach of high-E colliders

$K \to \pi \nu \bar{\nu}$ (BR ~ 10^{-10})

NA62

Ultra-rare K^+ decays

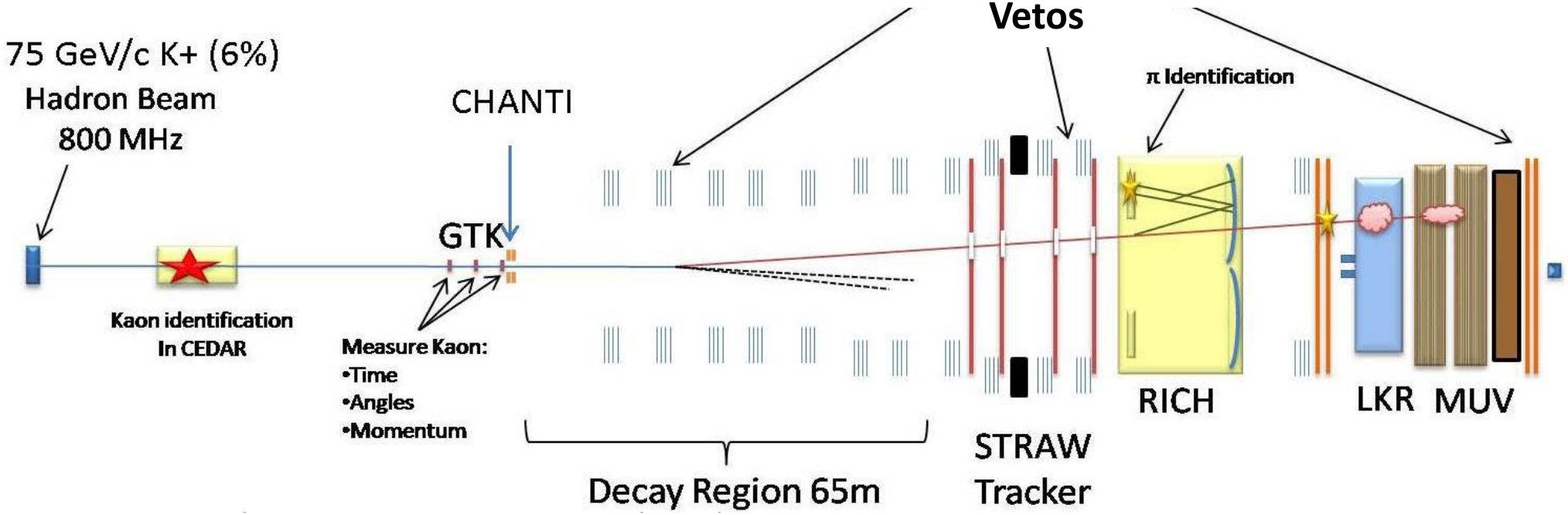


Regular data taking since 2016

Run 2: 20 events seen for 17 expected (10 SM + 7 BG)

Run 3: detector upgraded to reach ~100 signal events

Now considering a factor 4 intensity increase after LS3

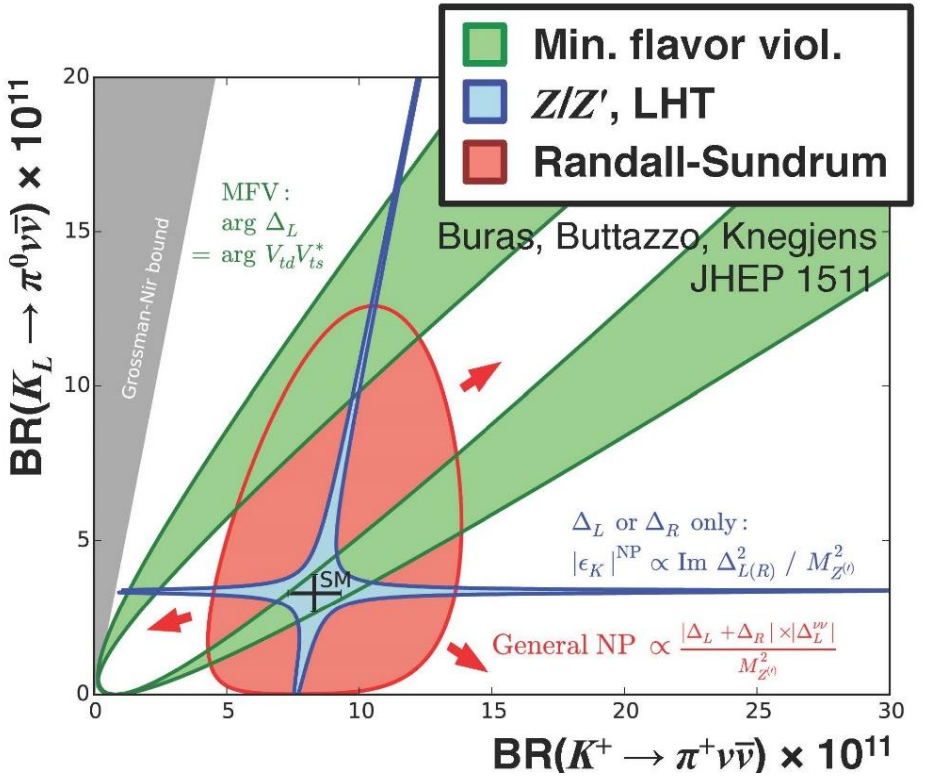


ULTRA-RARE KAON DECAYS:
NA62 ($K^+ \to \pi^+\nu\nu$) ↔ KLEVER ($K^0 \to \pi^0\nu\nu$)

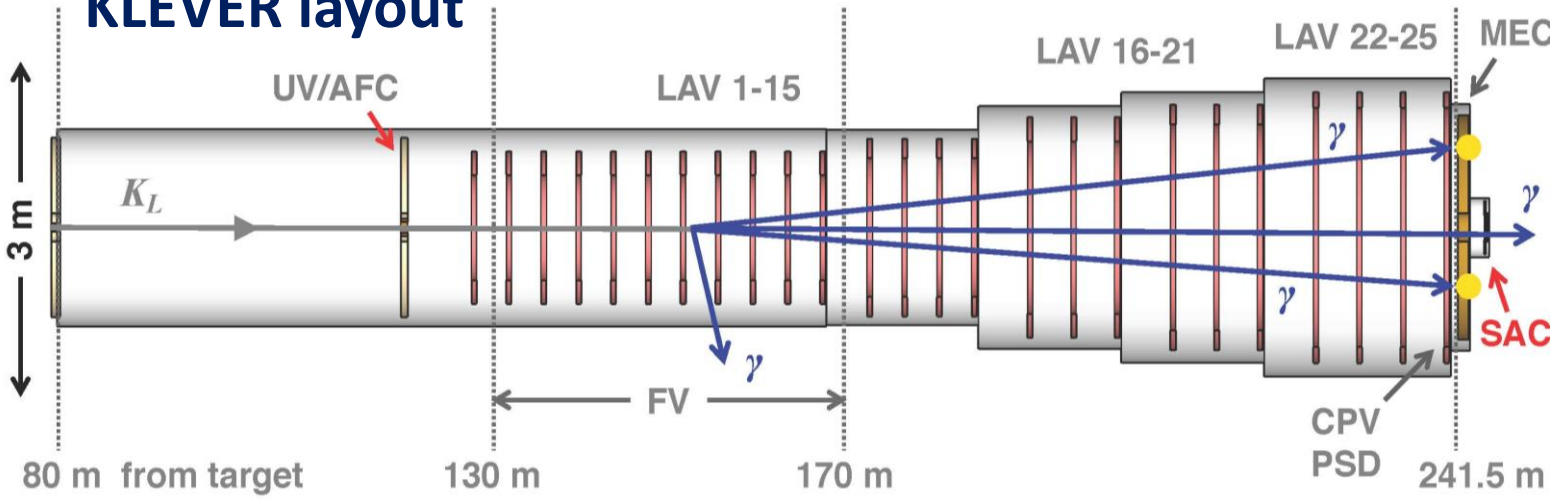
K^0 decays complementary to K^+ decays for the CKM matrix and BSM searches.

Would require a new high intensity K^0 beam.

~50 signal events could be collected in a few years by optimizing the detector to neutral decays



KLEVER layout



NA62 & KLEVER now considered as an integrated project with a multi-parameter internal phasing:

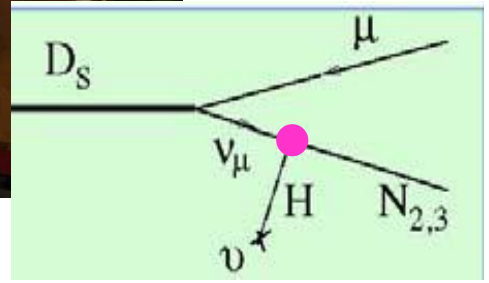
K^+ results ↔ K^+/K^0 sensitivity ↔ B-anomalies ↔ KOTO competition in Japan

NA62 PROTON BEAM DUMP MODE

Some NA62 data taking in beam dump mode foreseen for run 3

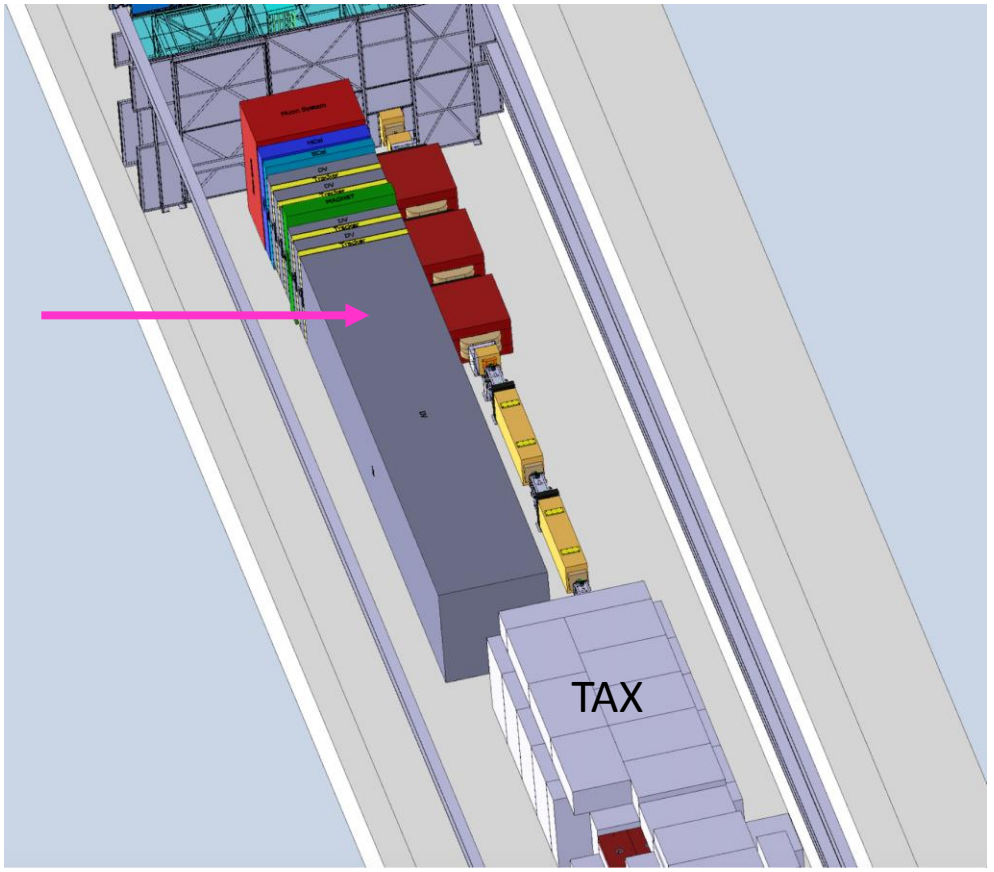
Achieved by closing the TAX collimator, 1 year would correspond to ~10^{18} PoT

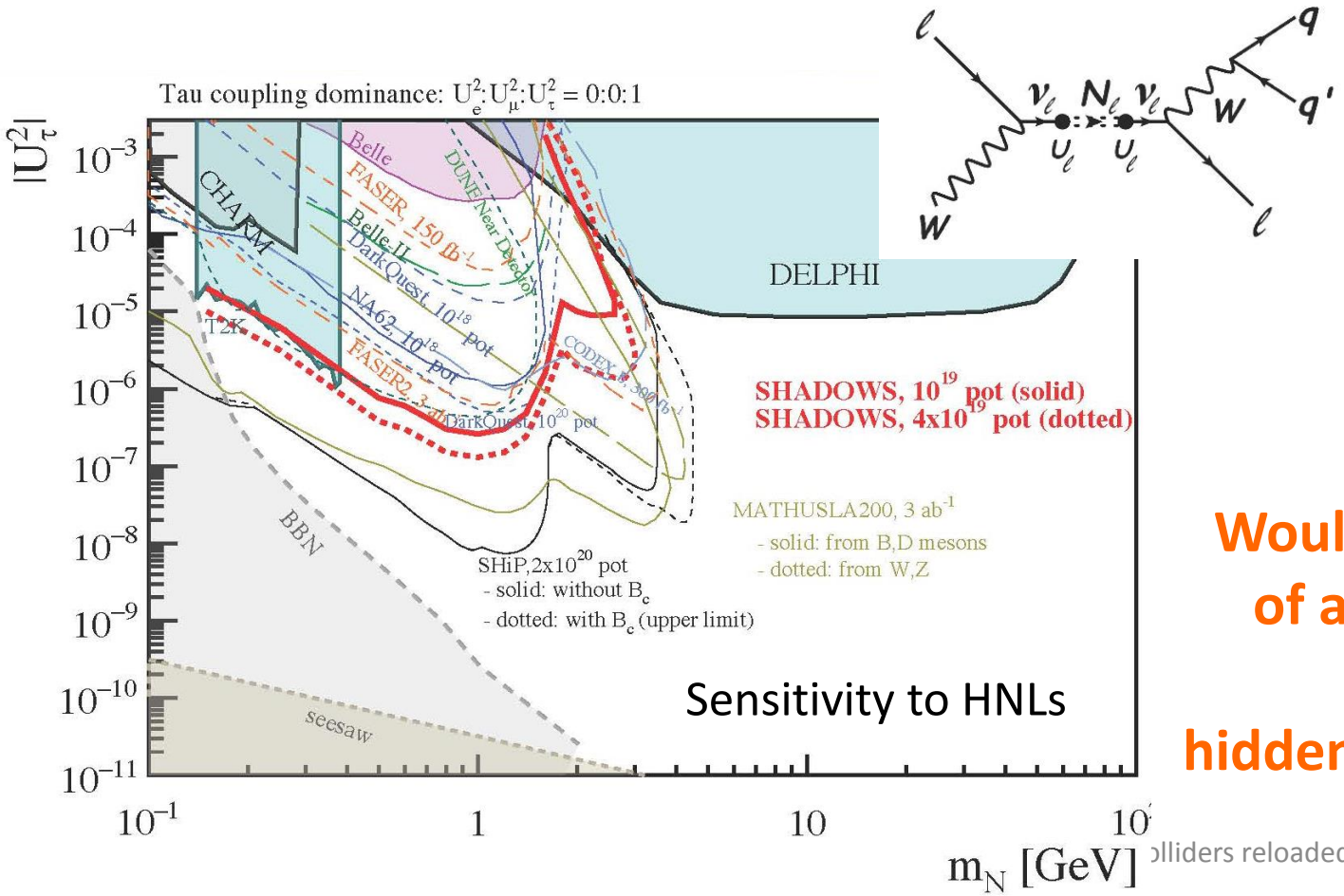
Instrumentation of NA62 decay vessel well adapted to searches in visible decay mode



SHADOWS

Recent new idea to complement the NA62 beam dump with a new "low cost" detector slightly off axis of TAX (decay vessel + spectrometer)

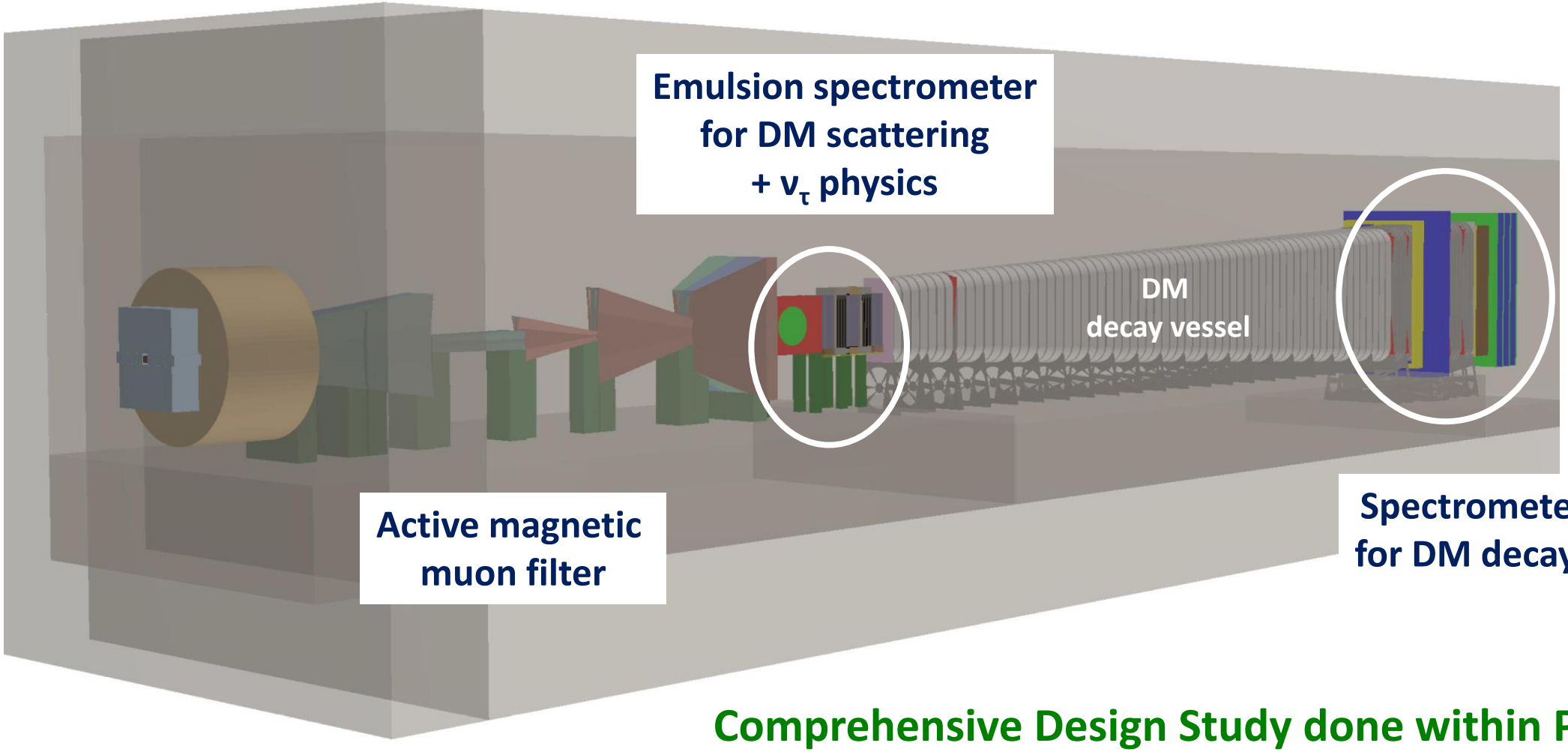




Would significantly enhance the potential of an NA62 high-intensity beam dump by extending sensitivity to hidden particles produced in D and B decays

SHiP ON THE BEAM DUMP FACILITY

State-of-the-Art Dual Spectrometer for hidden particle searches



Comprehensive Design Study done within PBC

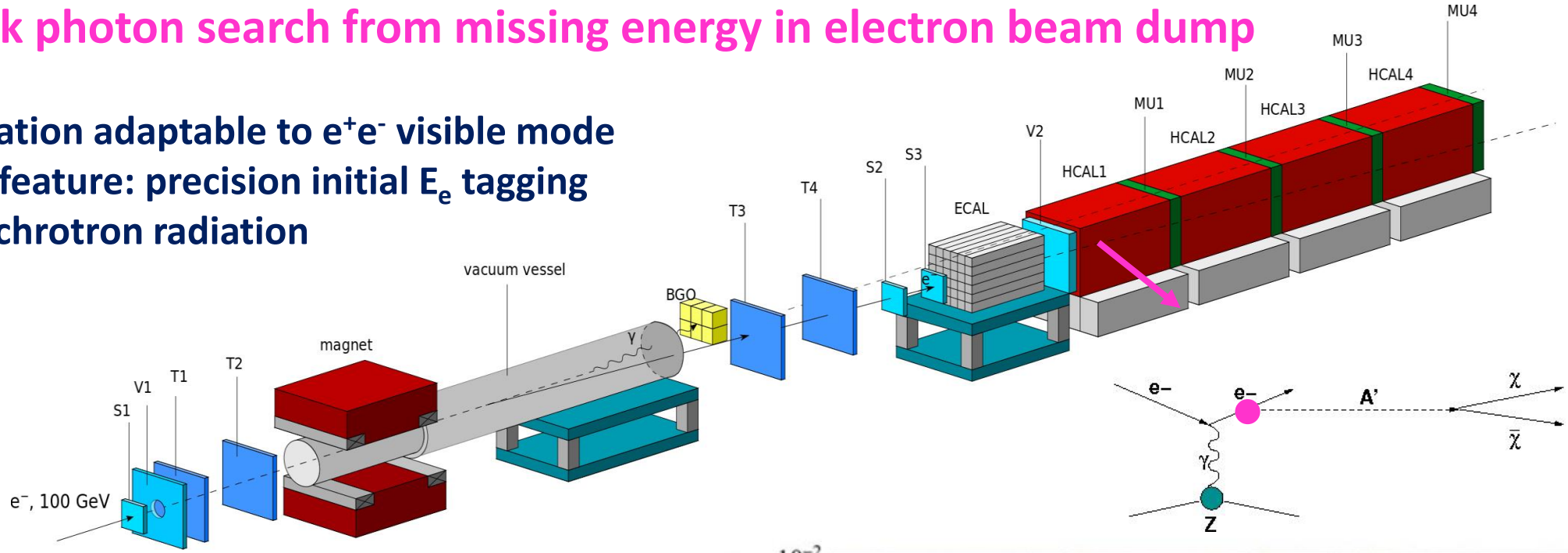
Next step: prepare TDR for next EPPSU

with emphasis on muon shield and decay vessel prototyping as well as cost reduction

NA64

Dark photon search from missing energy in electron beam dump

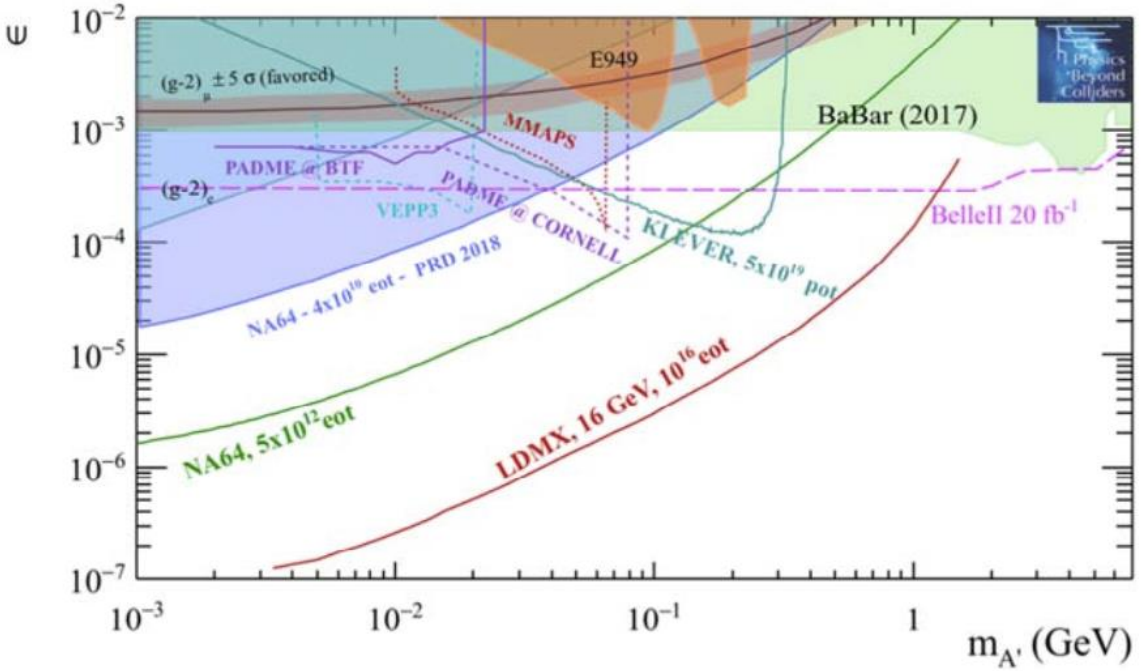
Configuration adaptable to e^+e^- visible mode
One key feature: precision initial E_e tagging with synchrotron radiation



"Cheap" setup implemented in 2015 on H4 e test beam

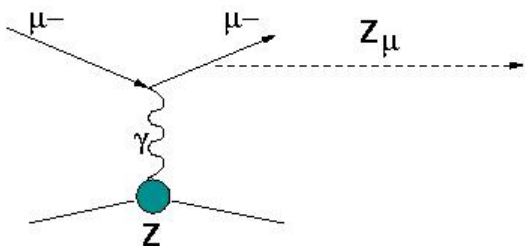
Currently leading the field!

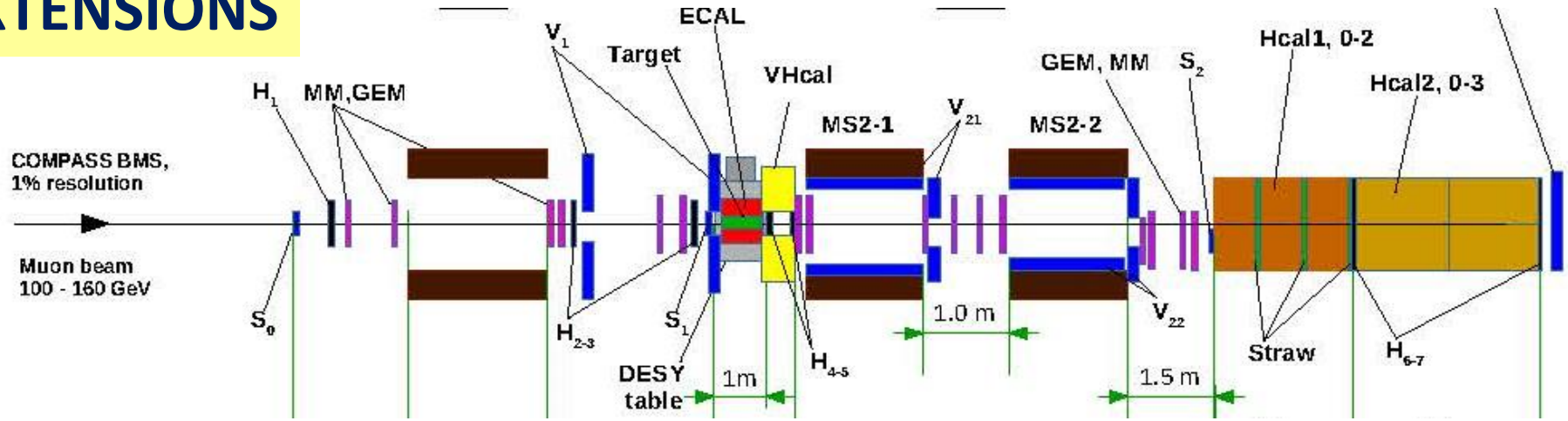
Upgrades and permanent setup being implemented for higher intensities after LS2



NA64 PROPOSED EXTENSIONS

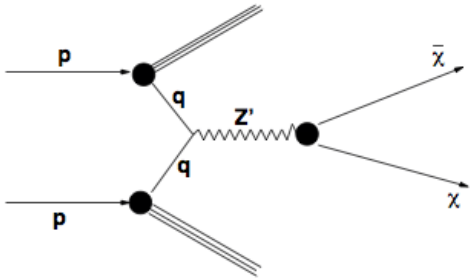
μ beams





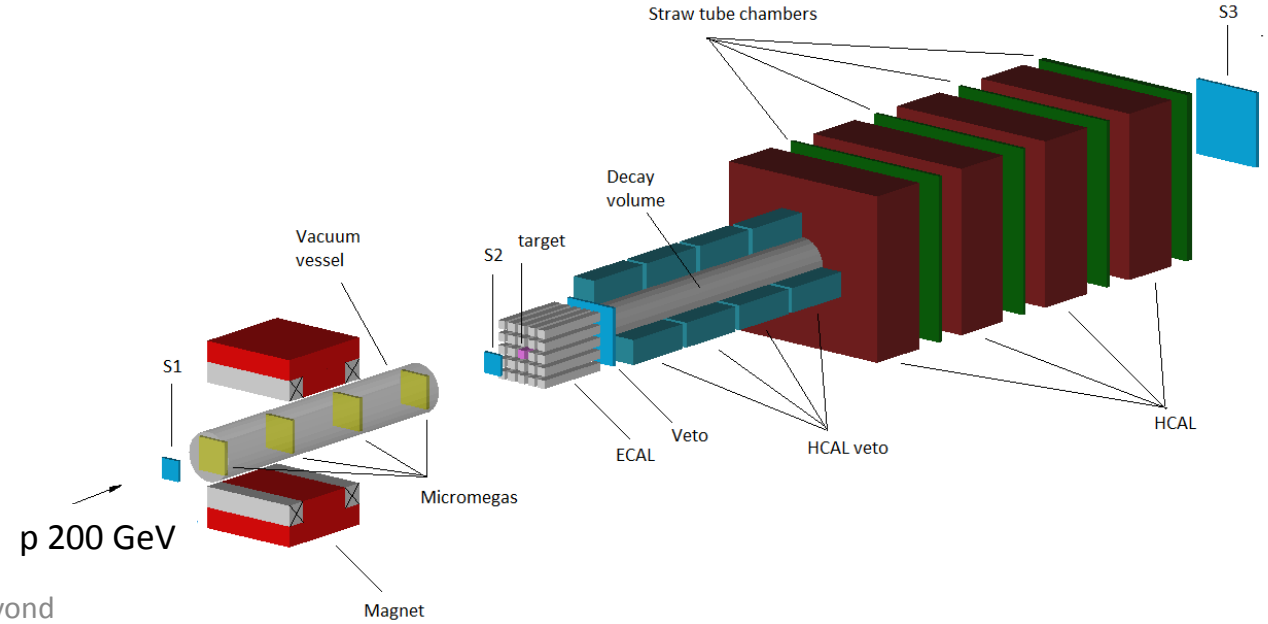
- After LS2: few months of μ beam would test a $(g-2)_\mu$ interpretation
- Longer term: few years of μ beam would improve limits on μ-coupled dark sector

Hadron beams



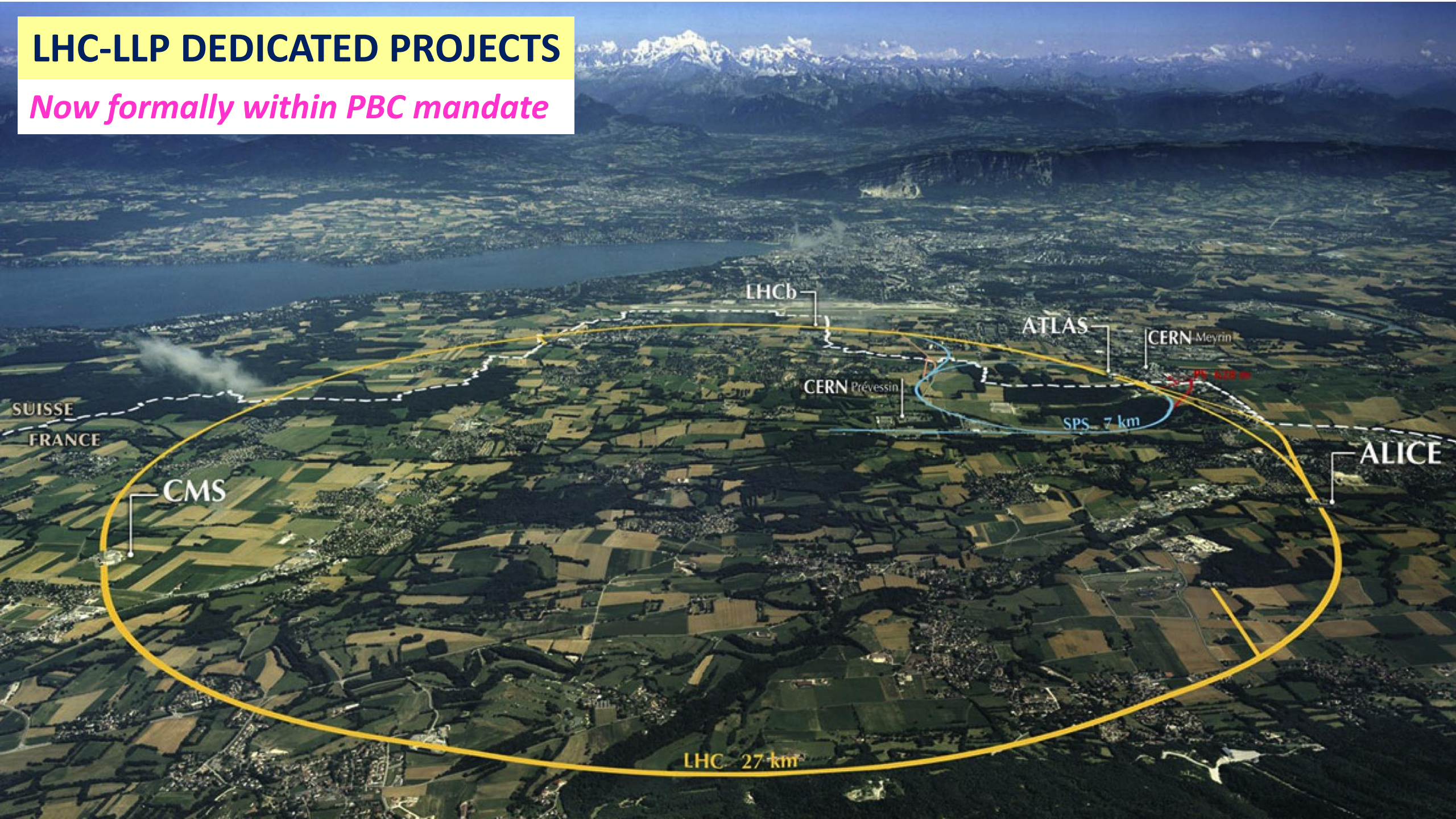
Would improve limits on

- meson decays to invisible particles
- leptophobic dark vectors



LHC-LLP DEDICATED PROJECTS

Now formally within PBC mandate



LHC-LLP DEDICATED PROJECTS

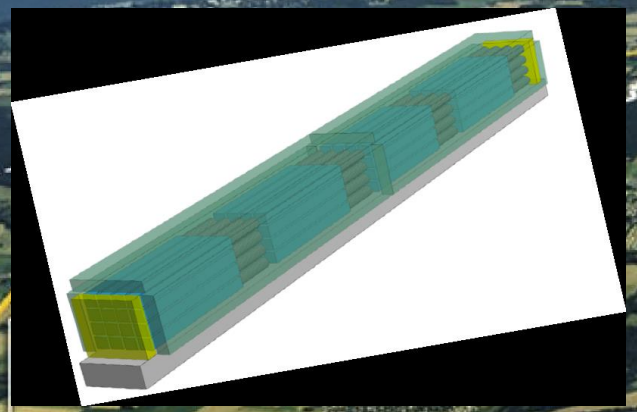
Pioneered by FASER, SND@LHC and milliQan, now under LHCC review

FASER:

Dark photons & TeV neutrinos

480m from ATLAS IP

Detector installed for run 3

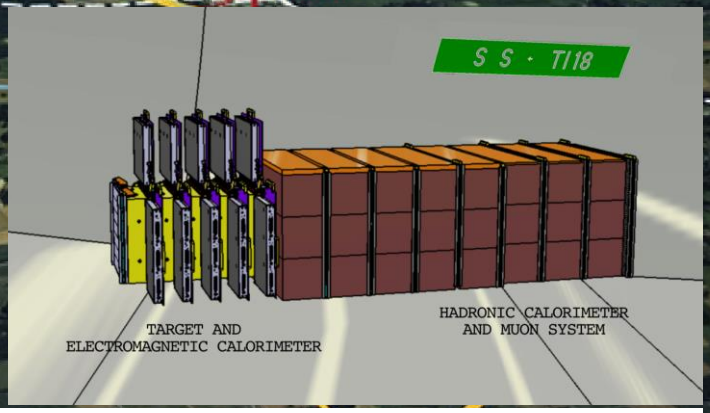


milliQan: milli-charged particles

33m from CMS IP

Successful demonstrator in run 2

Detector in construction for run 3



SND@LHC: *TeV neutrinos*

Slightly off axis opposite to FASER

Detector in construction for run 3

LHC-LLP DEDICATED PROJECTS

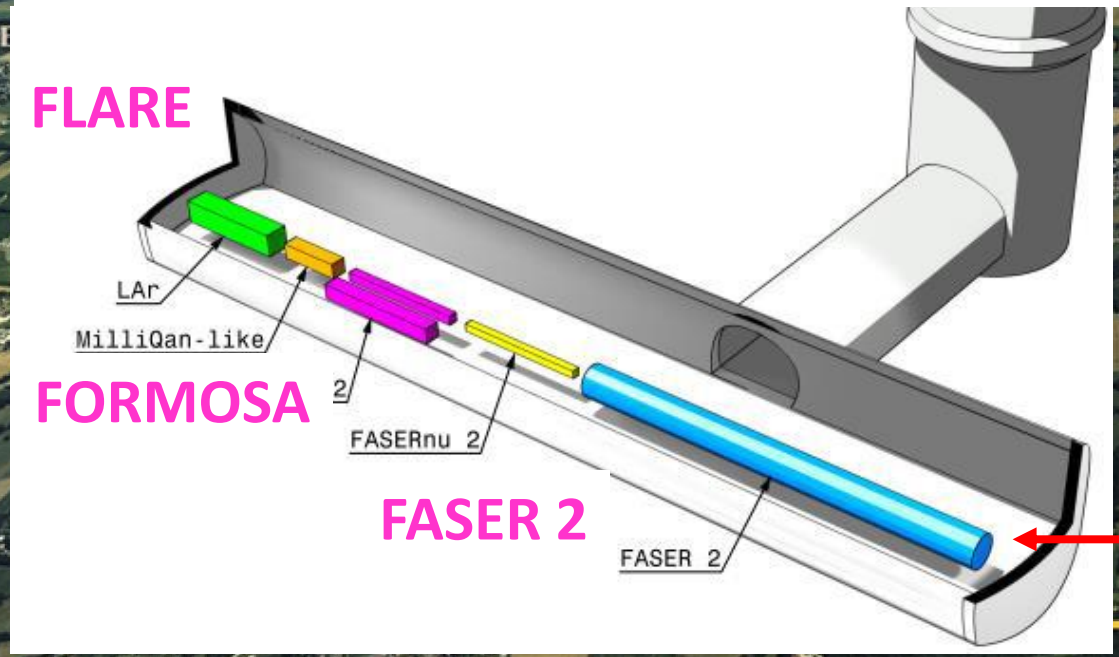
Options for a Forward Physics Facility under study within PBC

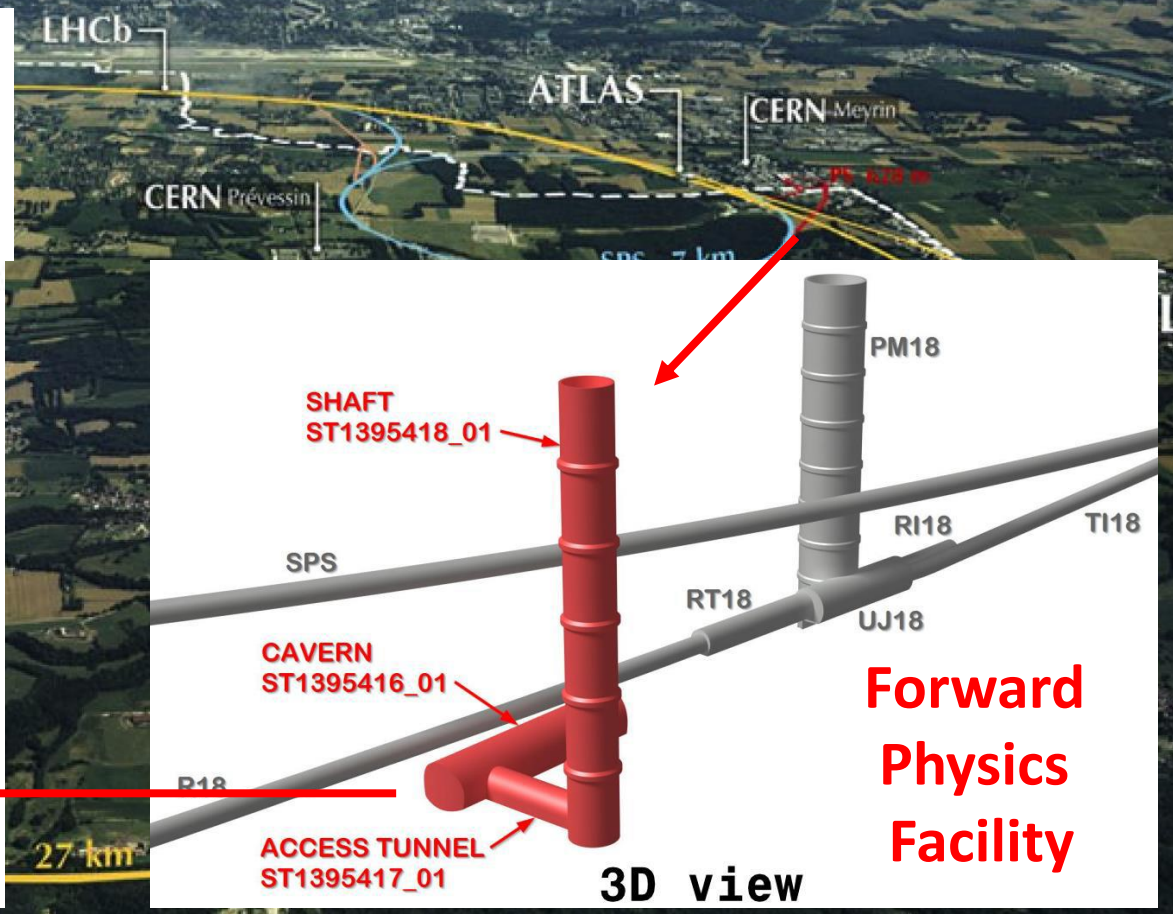
Goal is to provide enough space for larger scale forward detectors in the HL-LHC era

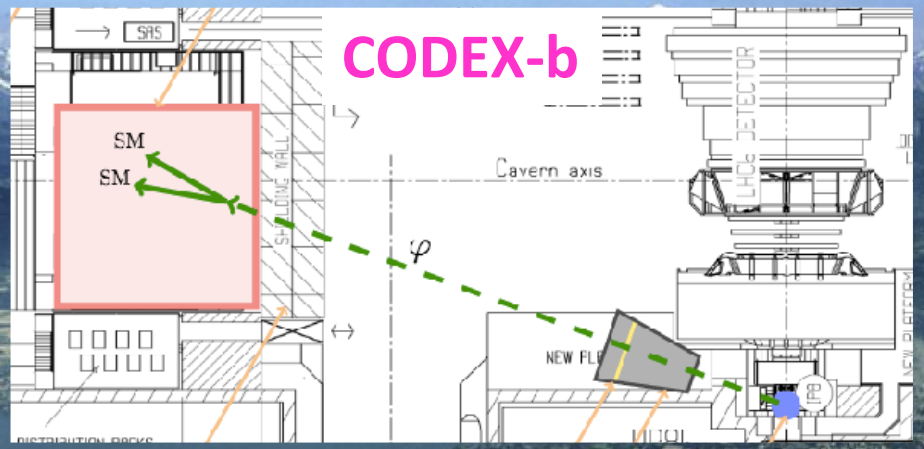
FLARE

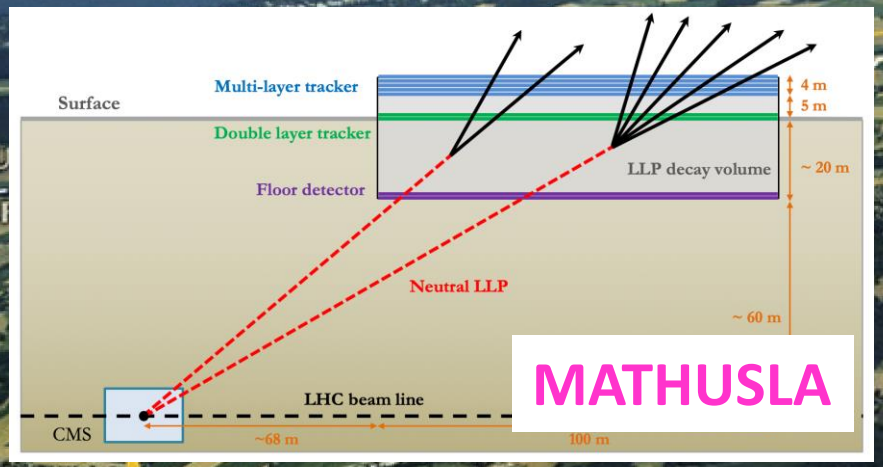
FORMOSA

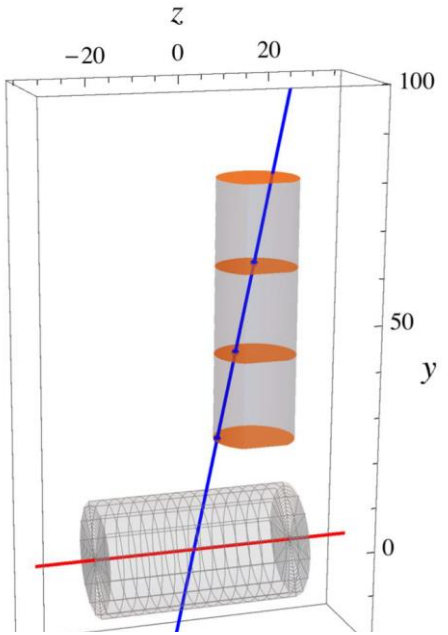
FASER 2











ANUBIS:
similar concept
as MATHUSLA
but in ATLAS
access shaft

Further demonstrators and
detailed simulations planned
during run 3

LHC-LLP DEDICATED PROJECTS

Larger scale projects at large angle

PBC SCIENCE

1) NEW FACILITIES

2) QCD-ORIENTED EXPERIMENTS

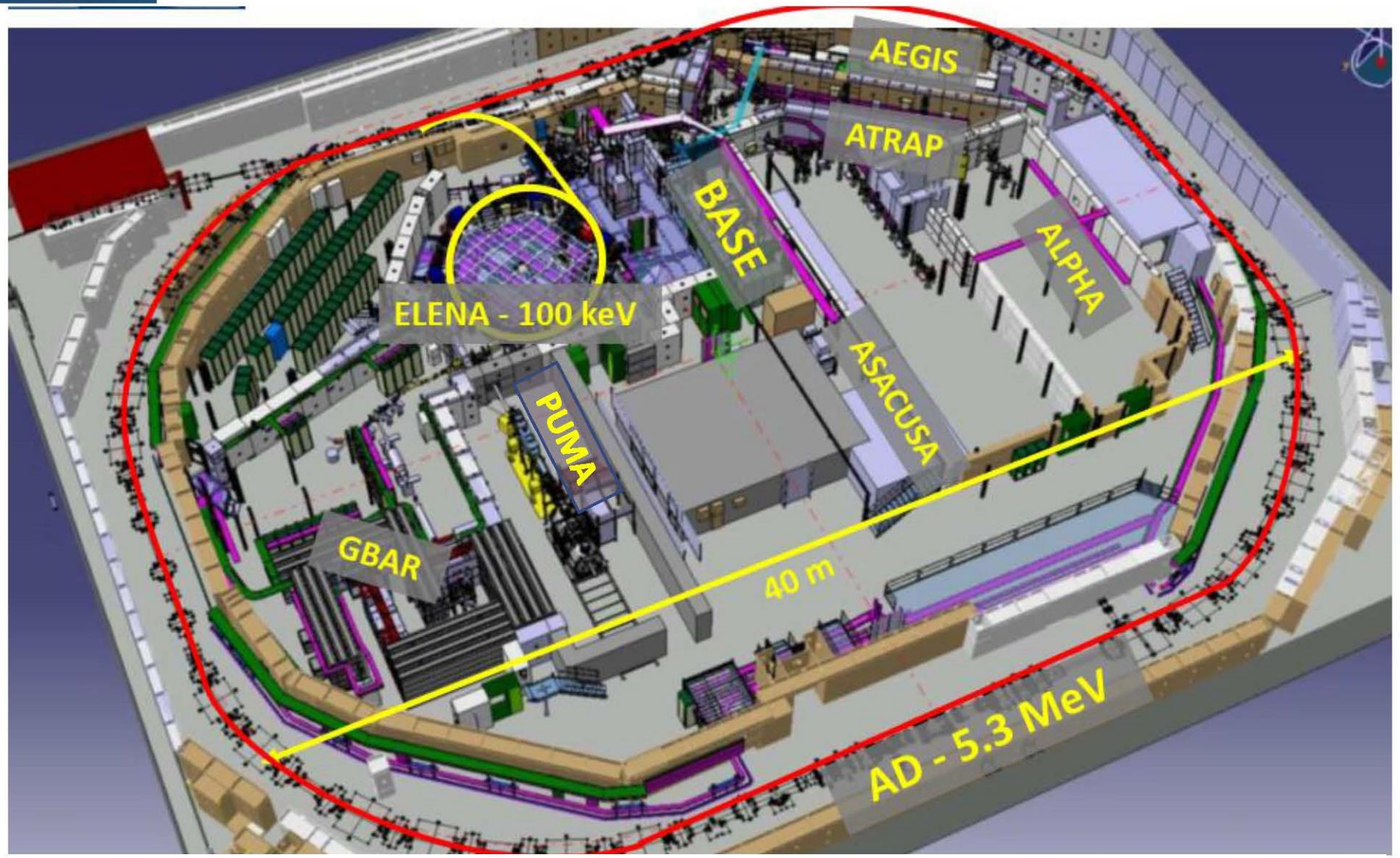
3) BSM-ORIENTED EXPERIMENTS

4) NEW EXPERIMENTAL AND THEORETICAL DIRECTIONS

For details see PBC workshop of 1-4 March 2021
https://indico.cern.ch/event/1002356/

ANTIMATTER FACTORY

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.



BASE,
Fundamental properties of the antiproton

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen

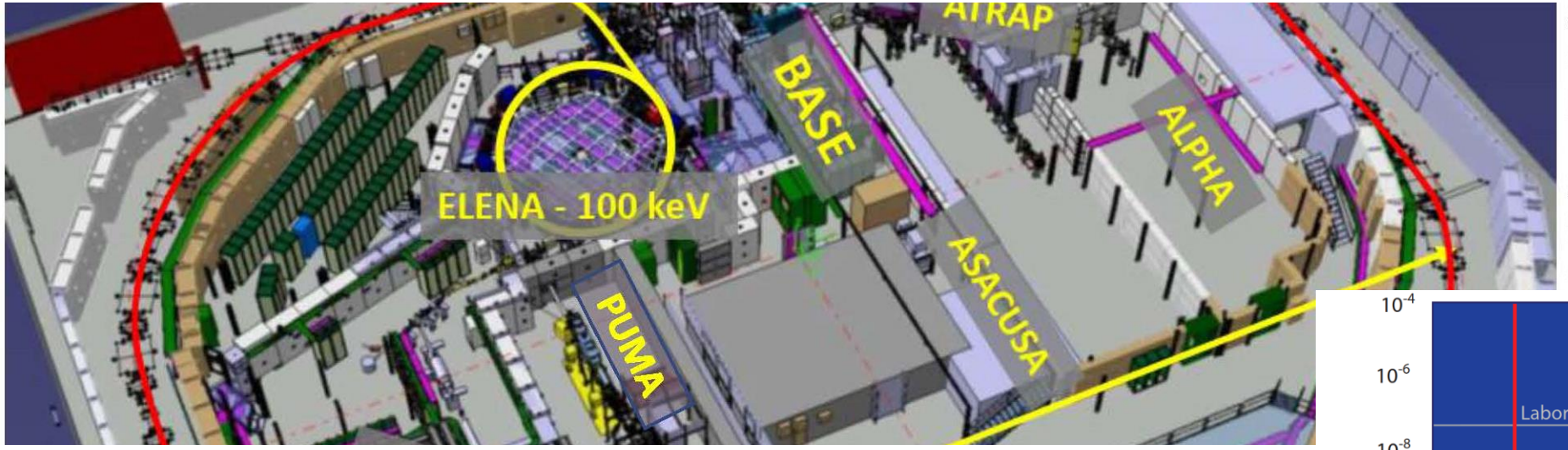
PUMA
Antiproton/nuclei scattering to study neutron skins

ELENA upgrade during EPPSU → **not considered by PBC up to now**

ANTIMATTER FACTORY

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

Many quantum technologies at work for precision measurements: CPT, fundamental constants, axion searches…

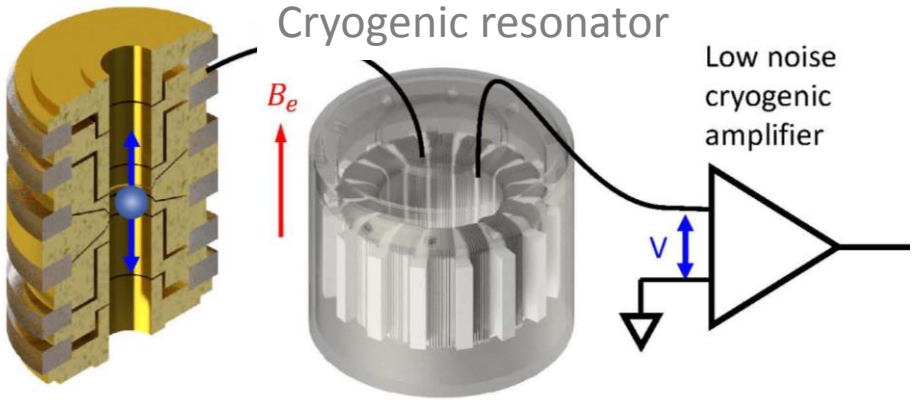


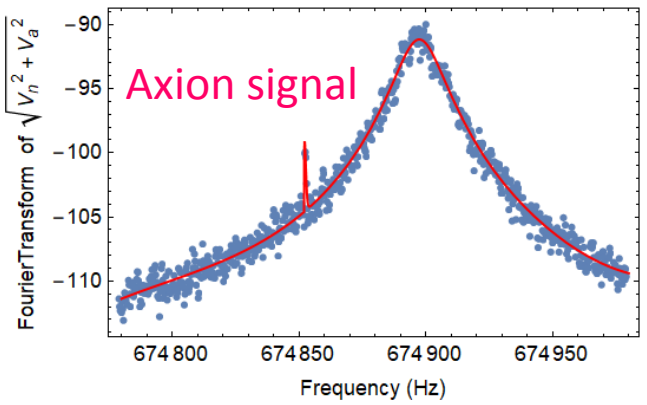
BASE,
Fundamental properties of the antiproton

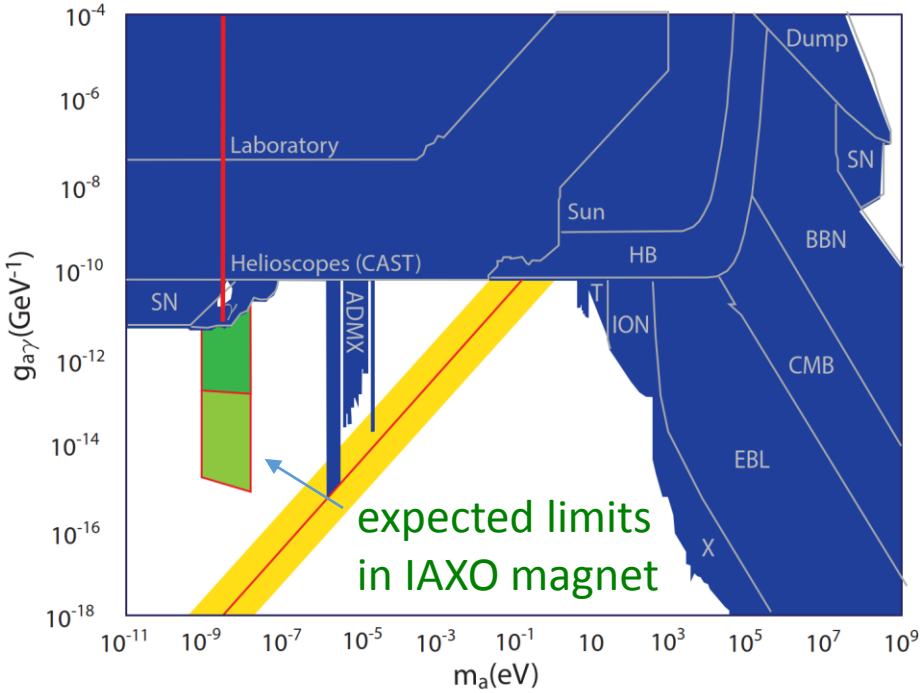
ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

e.g. BASE DM axion searches





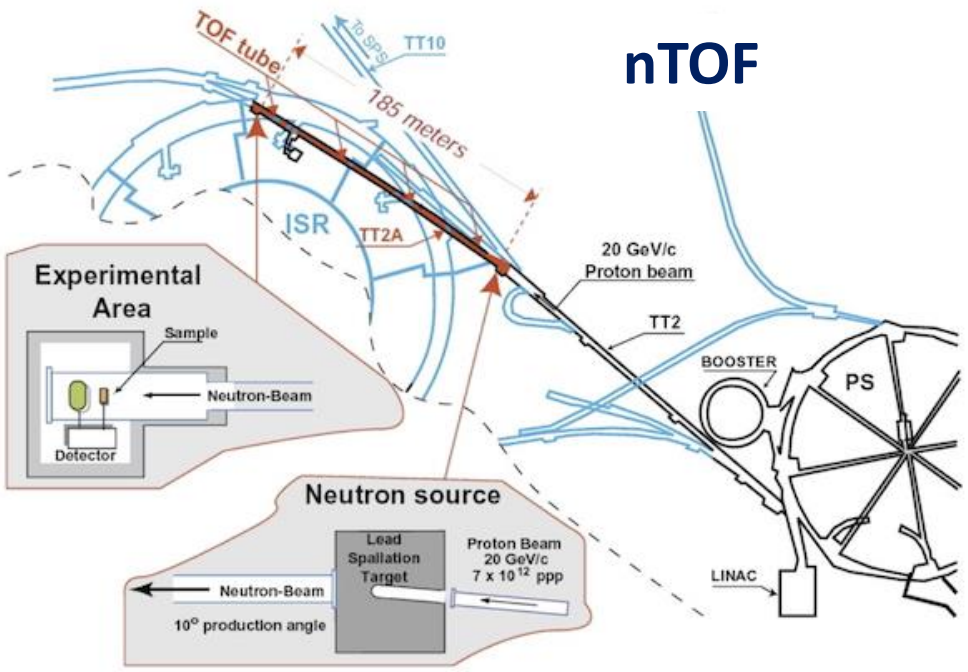


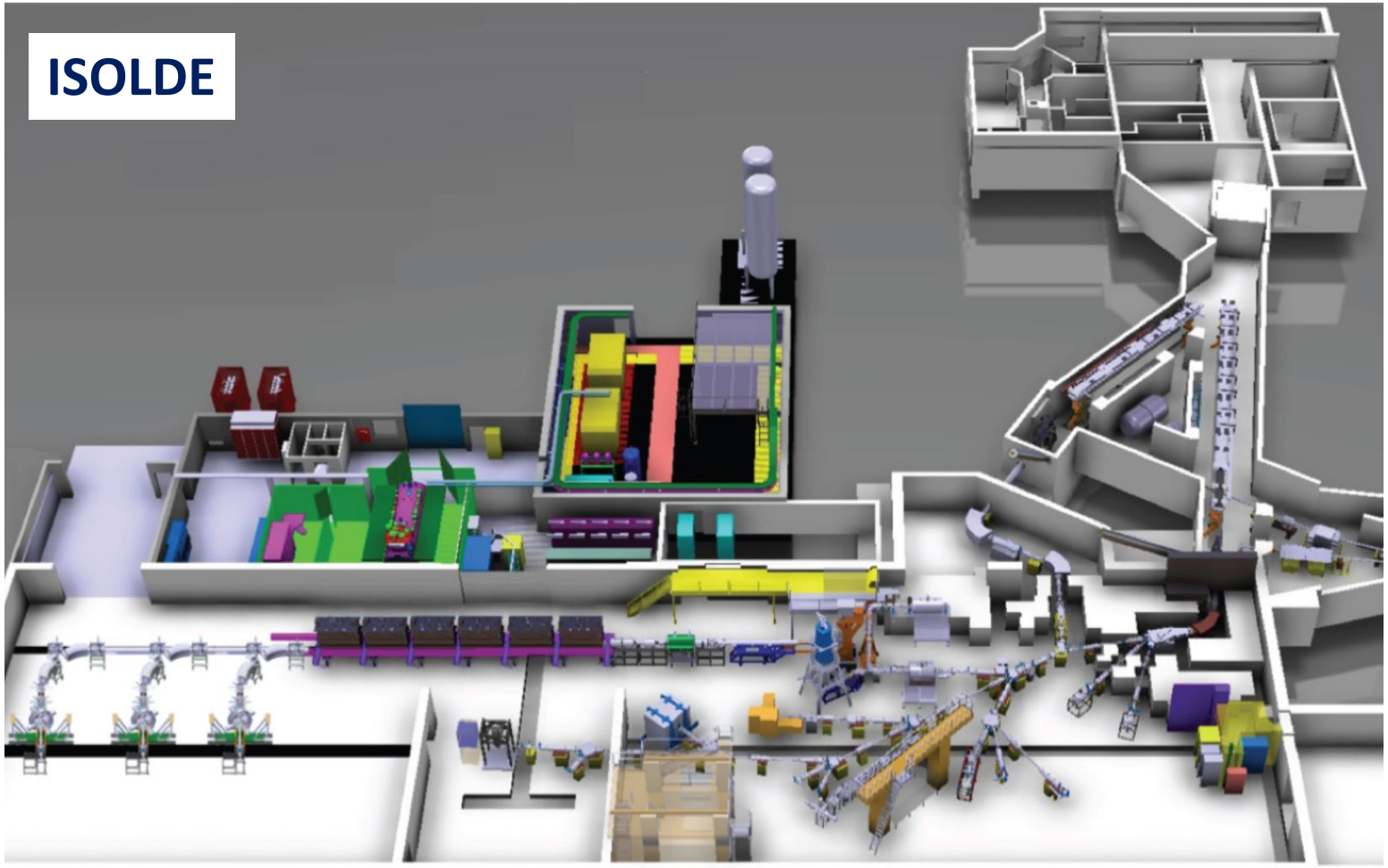
ISOLDE & nTOF

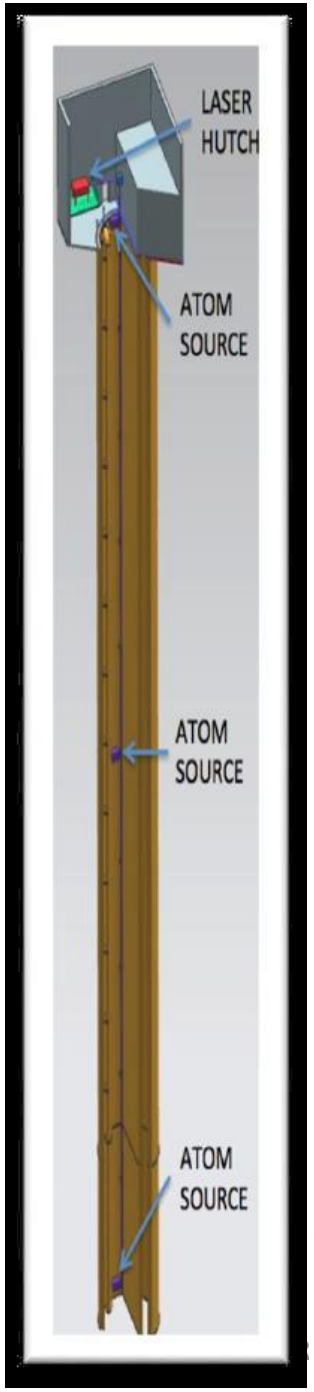
Similar technologies as at antimatter factory, with a fundamental physics potential for e.g.

- EW tests
- EDMs
- Spectroscopy of new states
- Nuclear clocks
- …

EPIC proposal to upgrade ISOLDE to higher energy (2 GeV) and intensity with a new experimental hall







QUANTUM SENSORS
a few recent developments

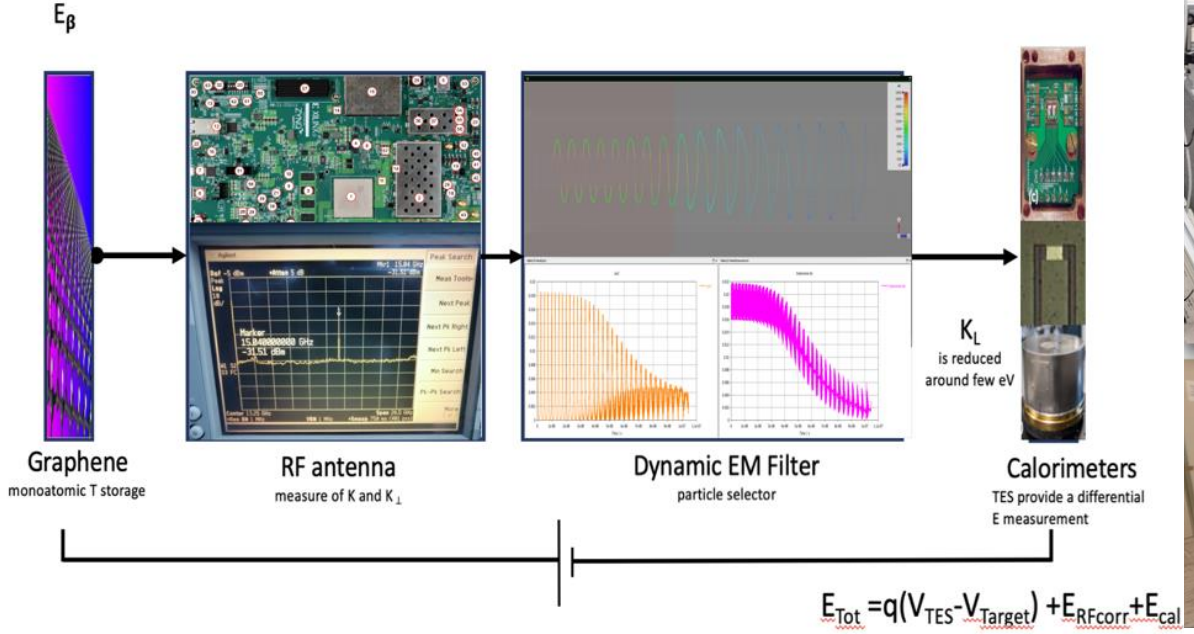
AION
Atom interferometry for ultra-light DM
and mid-frequency gravitational waves

Proof-of-Principle 10m setup being built in UK

Possible siting of a 100m setup in a CERN LHC shaft under investigation in PBC

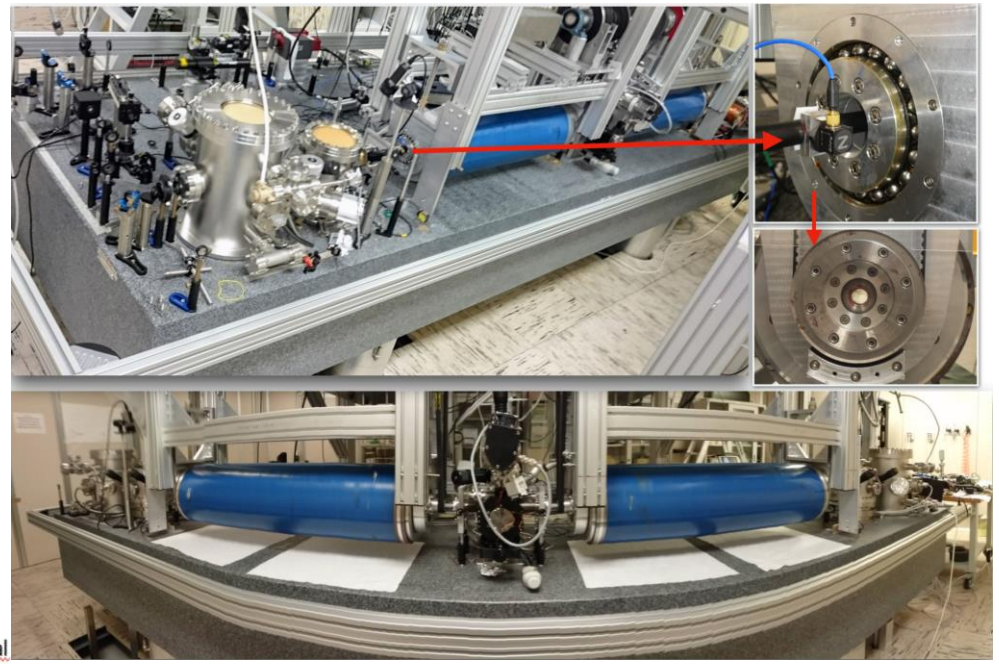
PTOLEMY
Measurement of cosmic neutrino background

New idea submitted to Snowmass and PBC



VMB@CERN
Vacuum Magnetic Bi-refringence

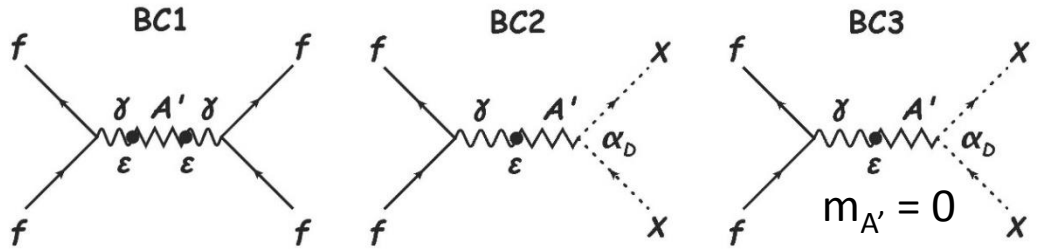
Optical set up being developed in Ferrara for a CERN implementation with (HL-)LHC magnets



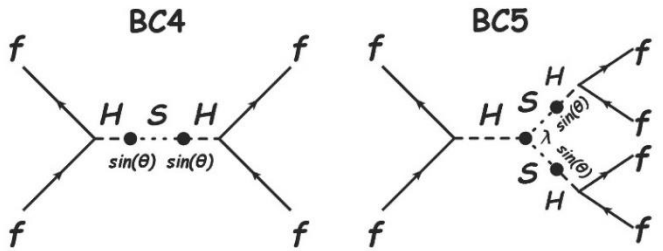
NEW THEORETICAL DIRECTIONS

A highlight of PBC for EPPSU: definition and wide acceptation of hidden sector benchmark models to compare reach of projects under same assumptions

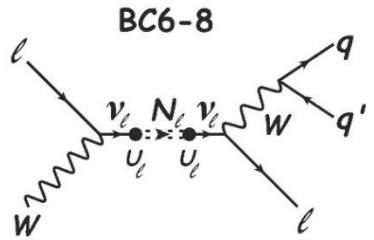
Dark Photons, Dark Matter & millicharged particles



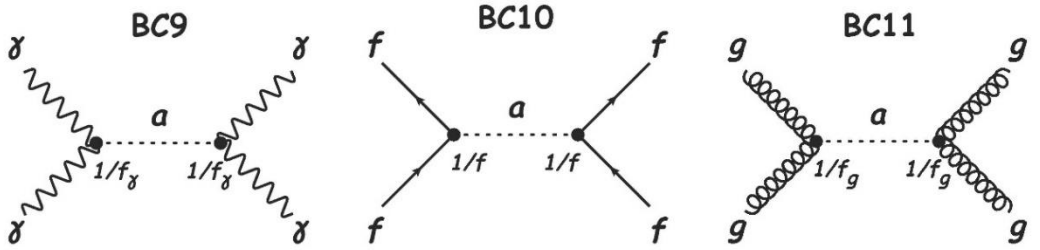
Dark Scalars



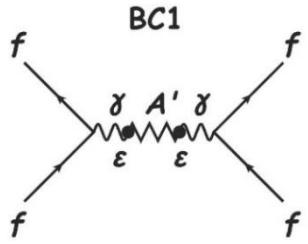
Heavy Neutral Leptons



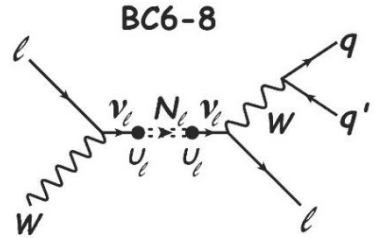
Axion-Like Particles



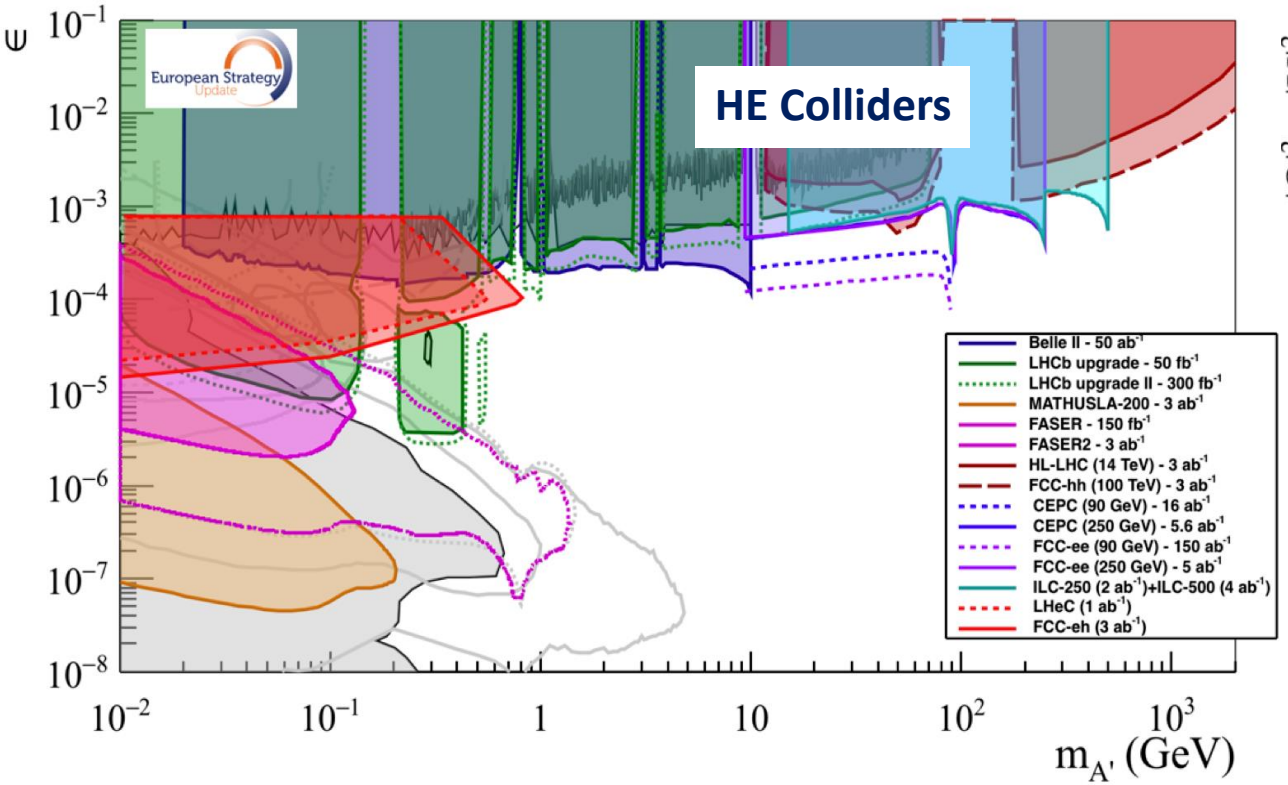
NEW THEORETICAL DIRECTIONS



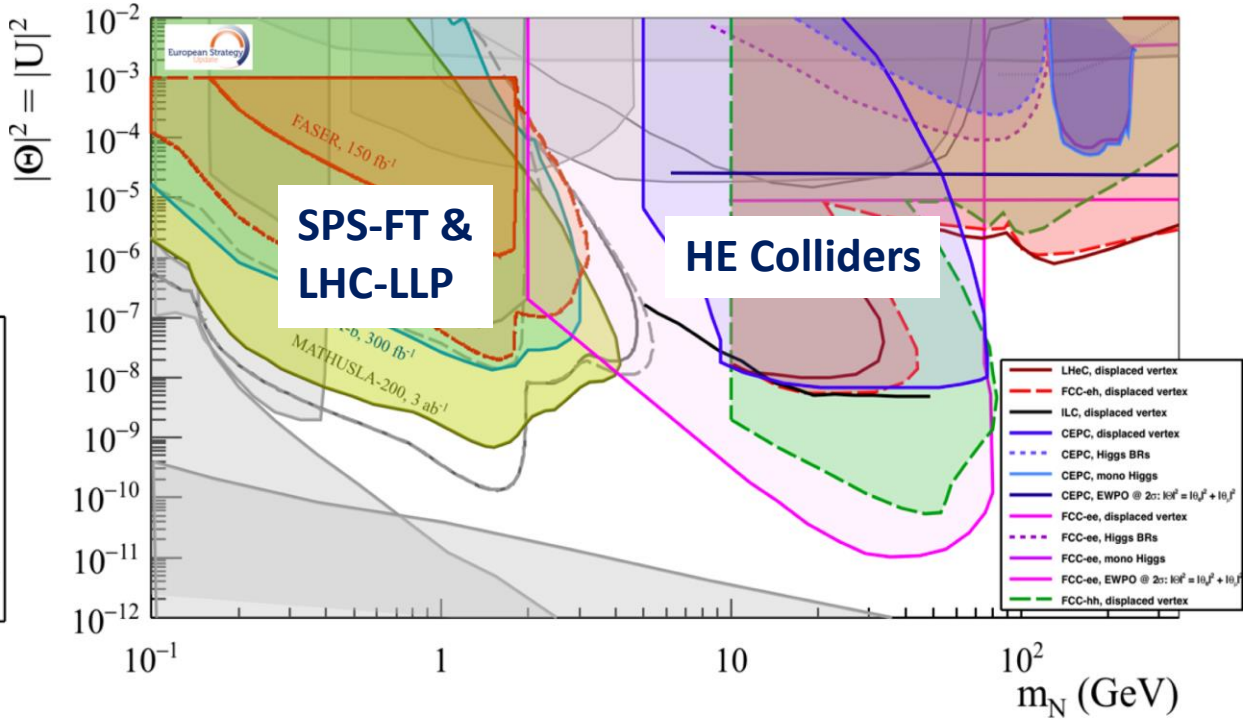
Method was extended to colliders for EPPSU Briefing Book



Dark Photons



HNLs

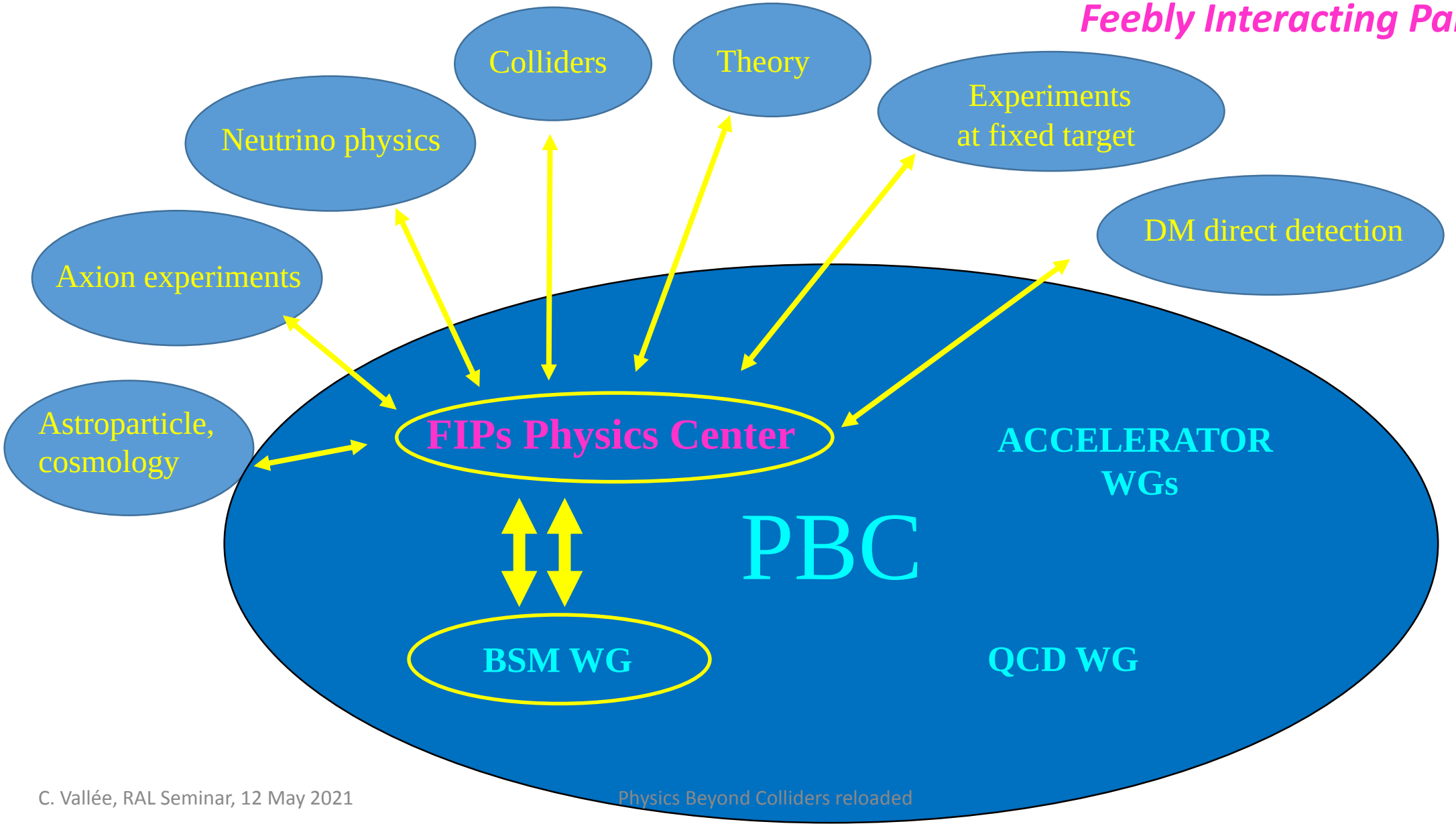


Further extension to all domains dealing with Feebly Interacting Particles has started

see FIPs kick-off workshop https://indico.cern.ch/event/864648/ and report arXiv:2102.12143

NEW THEORETICAL DIRECTIONS

"FIPs Physics Center" now embedded within PBC as a "portal" towards the external world for Feebly Interacting Particles



PBC UPDATED ORGANISATION

Beam Dump Facility

Conventional Beams

LHC – Fixed Target

Technology

PBC-A&T
Committee

Civil Engineering, Integration,
Radiation Protection

Accelerator Complex
Capabilities

Forward Physics Facility

Gamma Factory

Proto-EDM

PBC OUTLOOK

WG content, project representatives, conveners being finalized in close relation with Scientific Committees and the community

3 MCHF/year secured in the CERN Medium Term Plan for PBC support

New ideas may be submitted any time to the PBC Coordinators along instructions given on the PBC web site http://pbc.web.cern.ch/

ADDITIONAL SLIDES

HISTORY OF PRE-EPPSU PBC EVENTS

PBC KICK-OFF WORKSHOP, CERN, September 2016

Call for abstracts → 20 selected for presentation

1st GENERAL WORKING GROUP MEETING, CERN, March 2017

Identification of main issues to be studied

2nd PBC WORKSHOP, CERN, November 2017

Working groups project reports

New call for abstracts → 7 selected for presentation

2nd GENERAL WORKING GROUP MEETING, CERN, June 2018

3rd PBC WORKSHOP: CERN, January 16-17, 2019

Summary of inputs to EPPSU and survey of future studies

3rd GENERAL WORKING GROUP MEETING, CERN, 5-6 November 2019

Updated status of projects before EPPSU drafting session

PBC DELIVERABLES: ACCELERATOR WGs

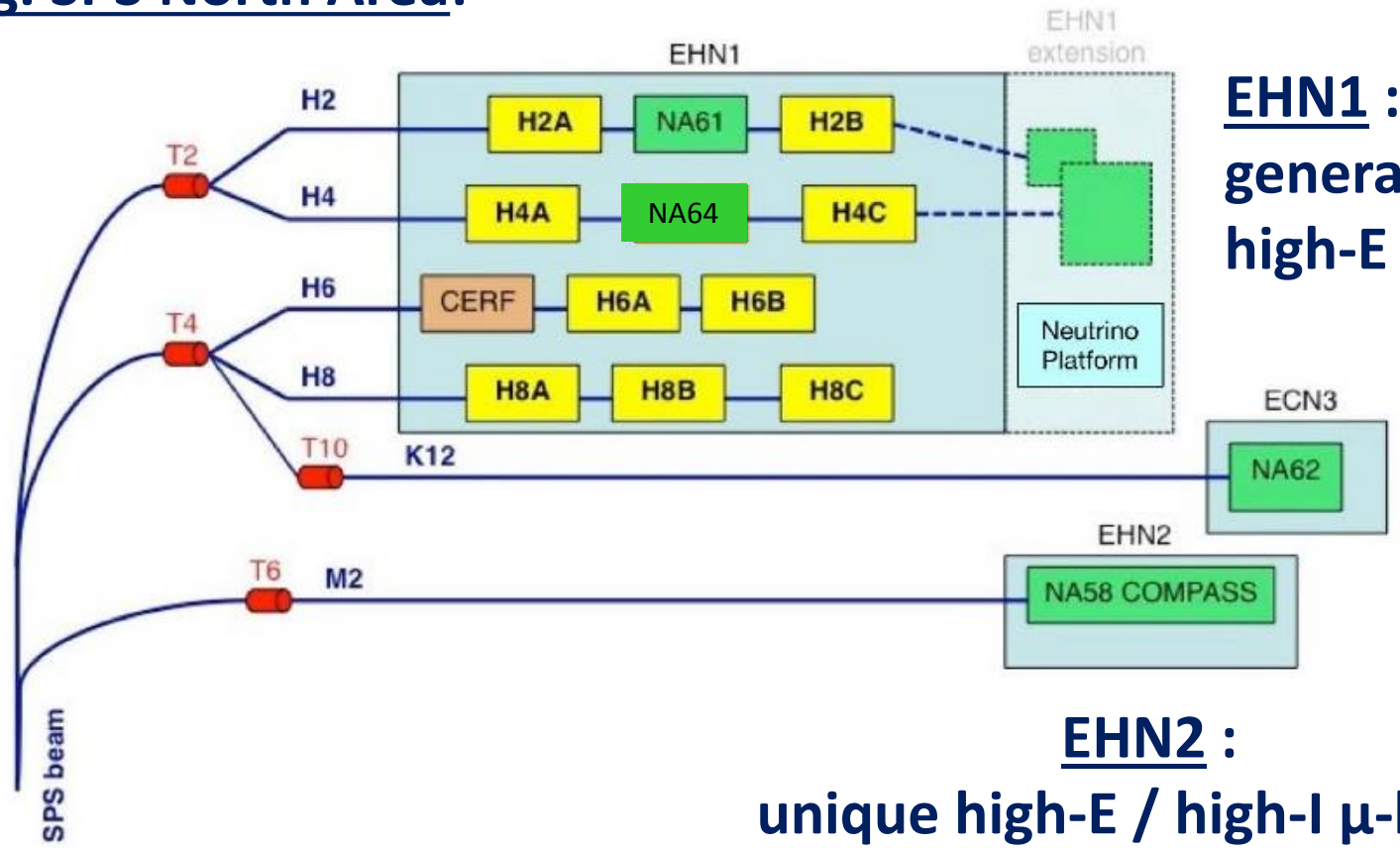
Working group	10 pager for ESPP for 18th December - WG dependent	Possible proponents/clients submitting 10 pager to ESPP	PBC deliverable for 18th December * (referenced by 10 pager)
AWAKE++	Y	Proposed client experiment	Exploratory study
BDF	Y	SHiP, tauFV	Comprehensive Design Study - tauFV as appendix
Conventional beams	Y	NA61, NA62++, KLEVER etc.	Description of the conventional beam upgrades associated to the proposed projects
EDM	Y		3 appendices: COSY; prototype; full ring (feasibility study).
eSPS	Y	LDMX,BD	Technical report on possible implementation at CERN
FASER acc.	N	FASER	Technical report on possible implementation in LHC
Gamma factory	Y		Exploratory study
LHC FT	N	AFTER@LHC, LHCspin, MDM/EDM	Technical study of feasibility
nuSTORM	Y		Broad outline of a possible nuSTORM implementation at CERN
Perf post-LIU	N		Injector complex performance after LIU
Technology	Y	IAXO et al	Exploration and evaluation of possible technological contributions of CERN to non-accelerator projects possibly hosted elsewhere

Reports publicly available on CERN CDS: http://cds.cern.ch/collection/PBC%20Reports?ln=en

IMPLEMENTATION CONSTRAINTS OF NEW PROJECTS

Governed to a great extent by existing beamlines/halls/experiments

e.g. SPS North Area:



EHN1 :
general purpose hall with unique high-E / medium-I beams for all particles

ECN3 :
unique underground hall for high-I hadron beams

EHN2 :
unique high-E / high-I μ-beam

EXPERIMENTS READINESS

Summarized in a semi-quantitative table

Quote:	A B C	ready need upgrade to be built	ready under design need R&D	adequate to strengthen to be built	< 10 M€ 10-50 M€ > 50 M€	Run 3 Run 4 Run 5
Project	**Physics highlight**	**Beam requirement**	**Detector maturity**	**Collaboration**	**Cost beam+det**	**Earliest operation**
NA61++	QGP Charm	B	B	A	A	A
COMPASS+	R_p & QCD	A	B	A	A	A
COMPASS++	QCD	B	B	B	B	B
MUonE	HVP(g-2)$_\mu$	A	B	B	A	A
LHC-FT	QCD	A	B	B	A	A
LHC-FT++	spin/MM/EDM	A	C	B	A	B
NA60++	QGP phase	C	B	C	B	B
DIRAC++	chiral QCD	C	B	C	B	B
NA62++	dark sector	B	A	A	A	A
KLEVER	$K^0 \to \pi^0 \nu\bar{\nu}$	B	C	B	B	B
NA64++	dark photon	A	B	A	A	A
SHiP	dark sector & ν_τ	C	B	A	C	B
TauFV	$\tau \to 3\mu$	C	C	B	C	C
REDTOP	η decays	B	C	B	B	B
EDM ring	p EDM	C	C	B	C	C
eSPS	dark photon	C	B	B	C	B
AWAKE++	dark photon	C	B	A	B	B
nuSTORM	$\sigma(\nu)$	C	C	B	C	B
γ-Factory	high rate γ	C	C	C	-	C

New projects also constrained by existing beamlines/halls/experiments

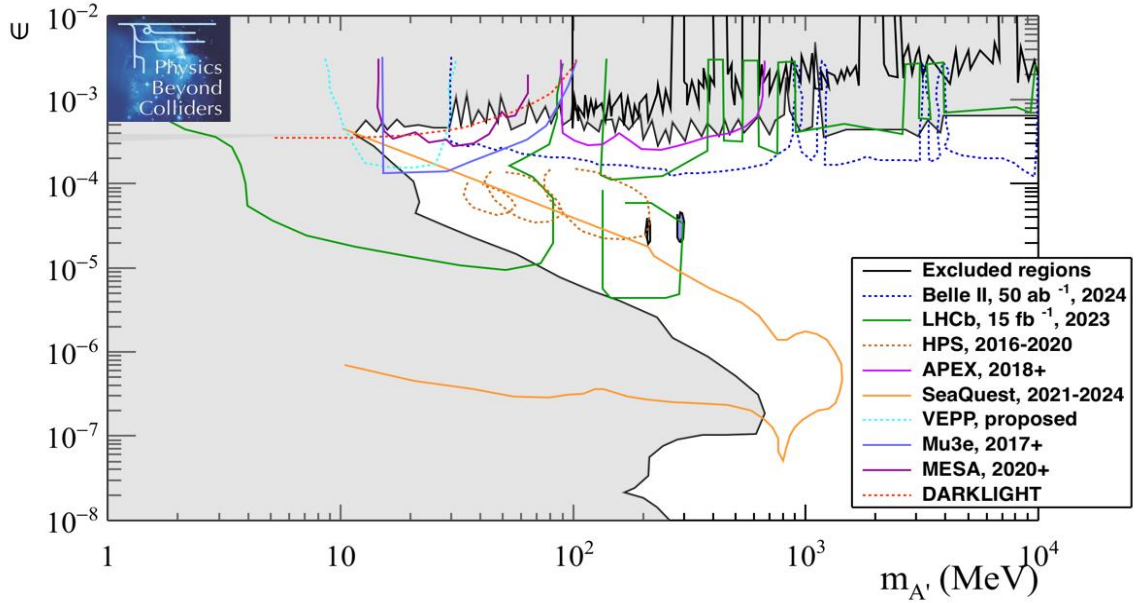
Physics Beyond Colliders

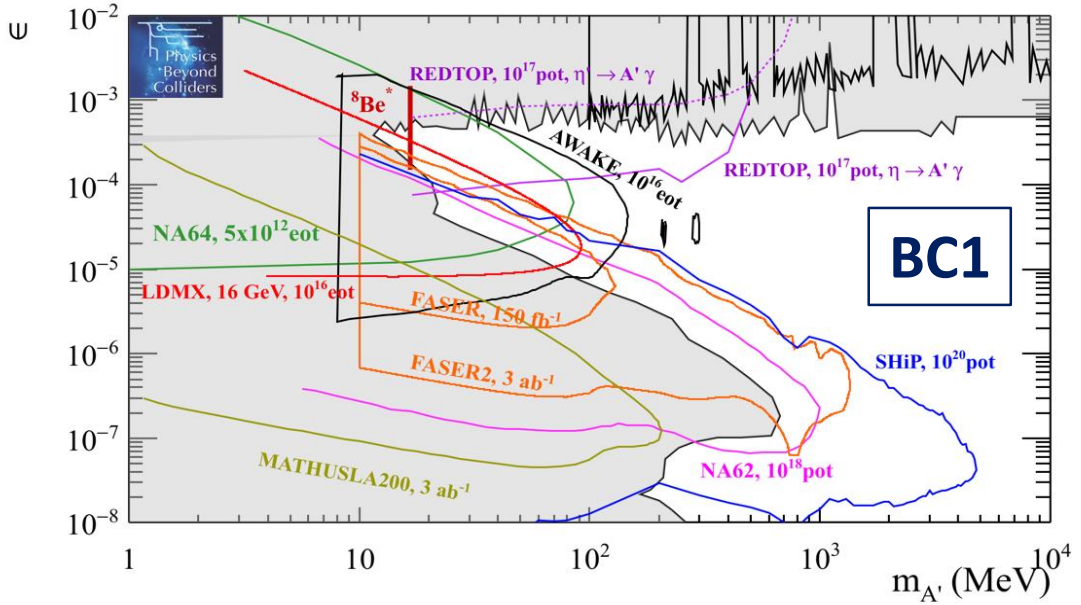
LEVEL OF MATURITY OF SENSITIVITY ESTIMATIONS

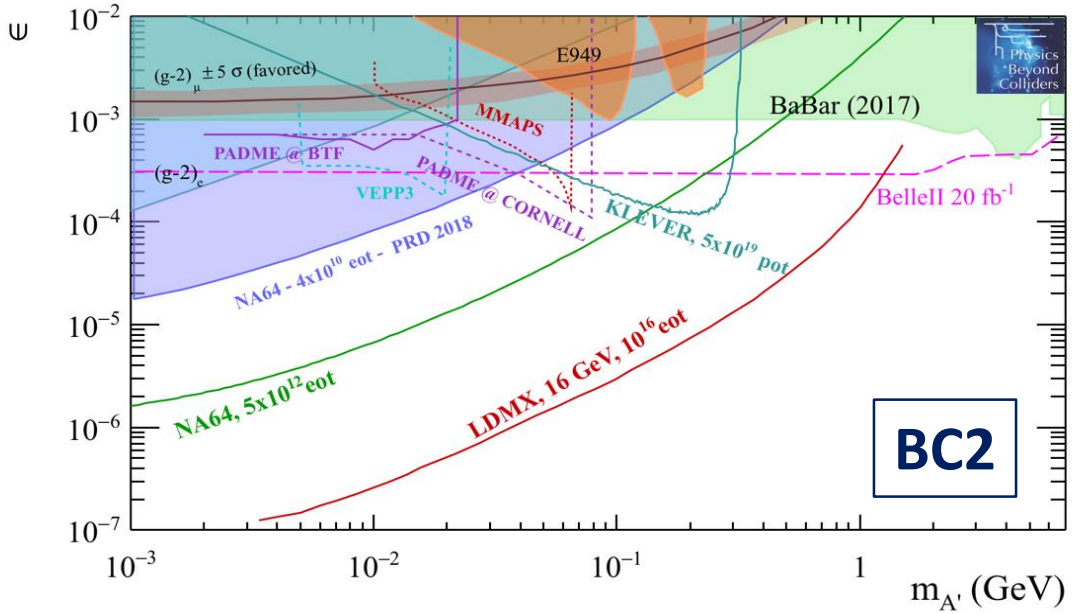
Project	Background	Efficiency	Inputs
NA62++	0-BG assumed	partly included	10^{16} PoT run in BD mode
KLEVER	partly included	included	fast simulation
REDTOP	included	included	full simulation
NA64++(e)	included	included	real data
NA64++(μ)	0-BG assumed	100 % assumed	M2 μ beamtest
eSPS/LDMX	included	included	full simulation at 4 GeV
AWAKE++	0-BG assumed	100 % assumed	toy model
SHiP	0-BG assumed	included	full simulation
CODEX-b	0-BG assumed	included	full simulation
FASER	0-BG assumed	100 % assumed	BG simulations & in situ measurements
MATHUSLA200	0-BG assumed	100 % assumed	cosmic & LHC BG fluxes
milliQan	included	included	full simulation

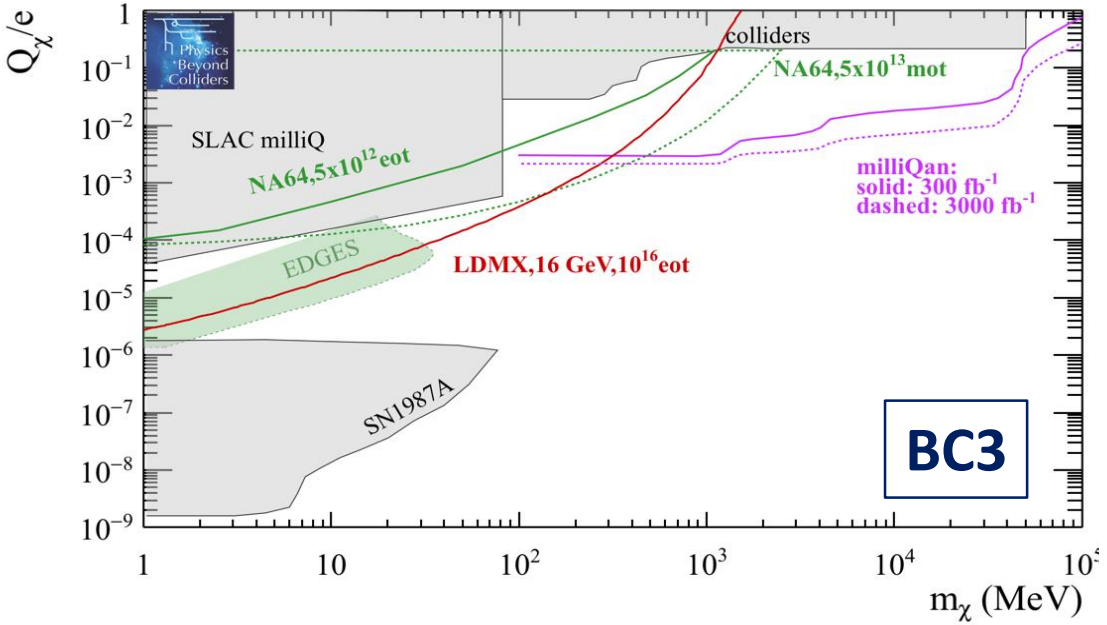
DARK VECTORS

BC1 worldwide context



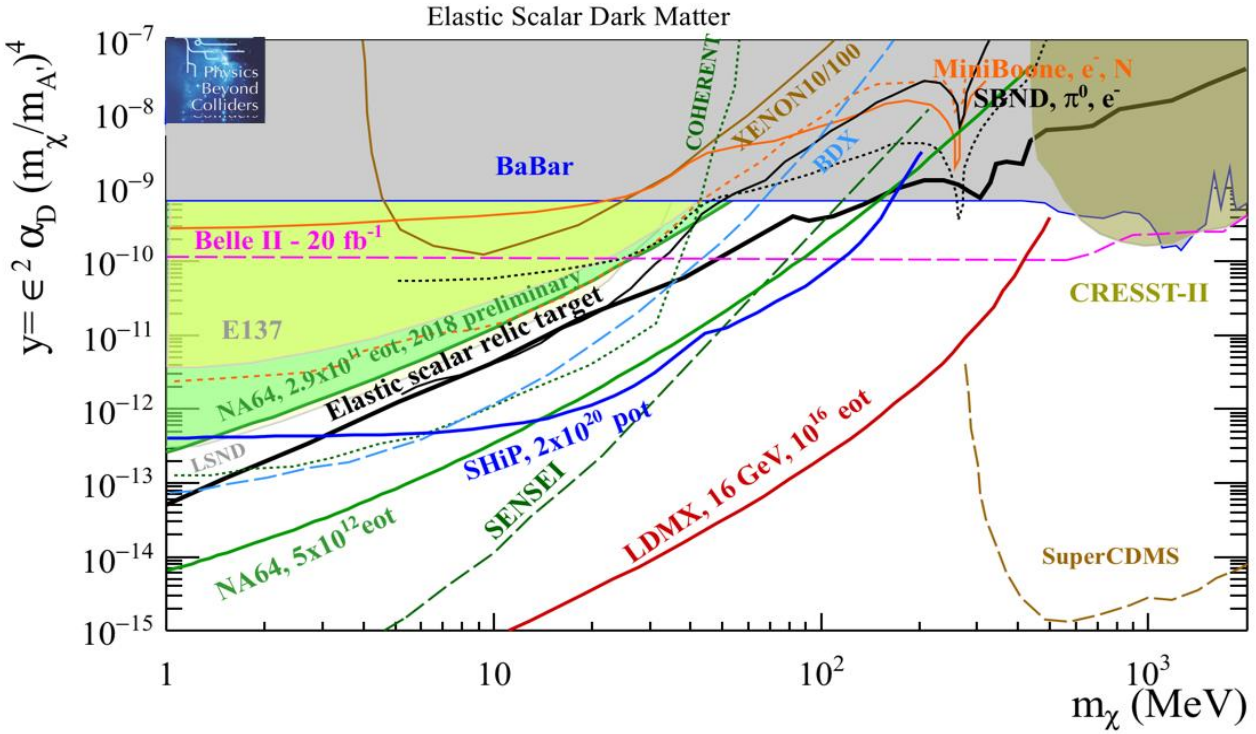


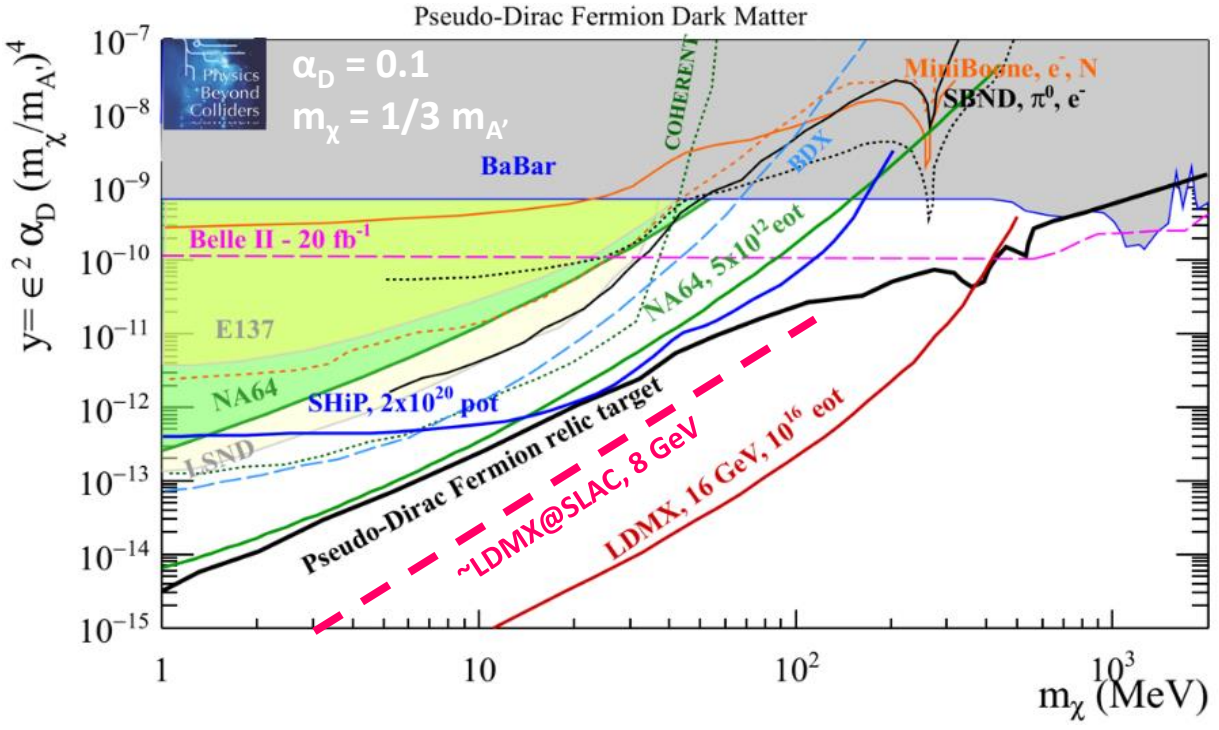




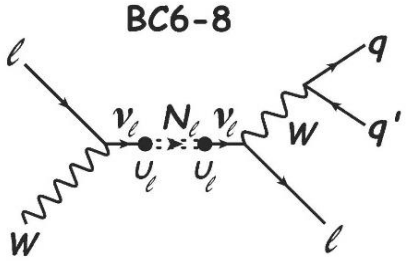
DARK VECTORS IN DM PARAMETER SPACE (BC2)

$\alpha_D = 0.1$ $m_\chi = 1/3\ m_{A'}$

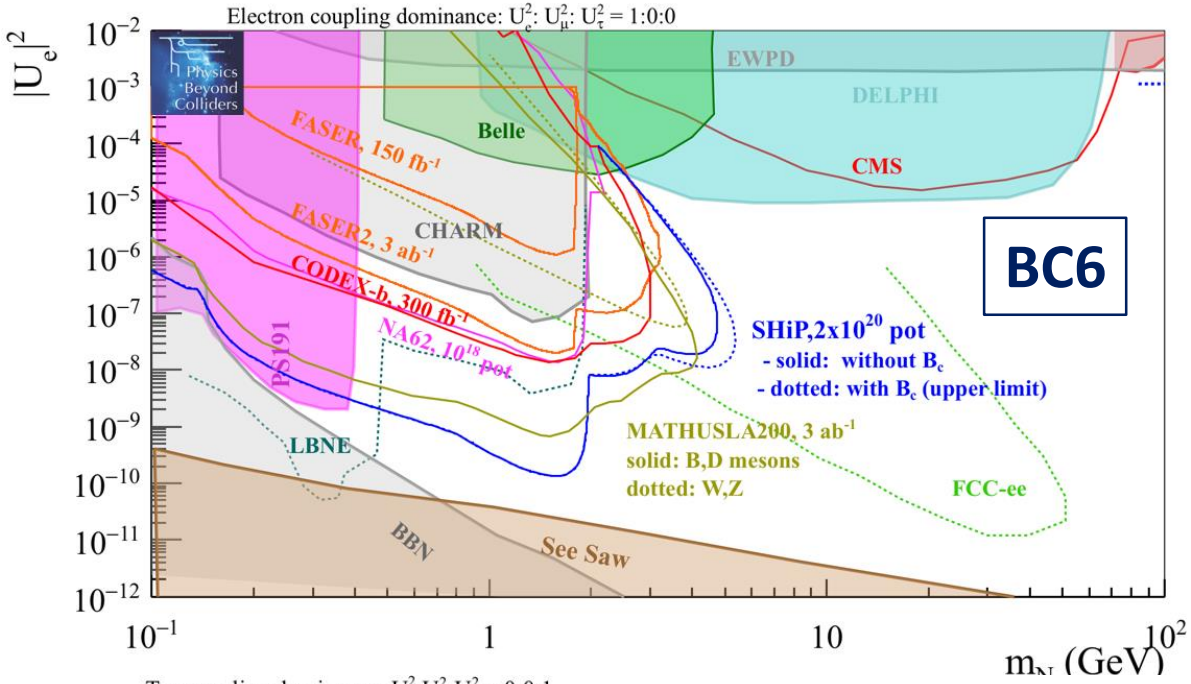


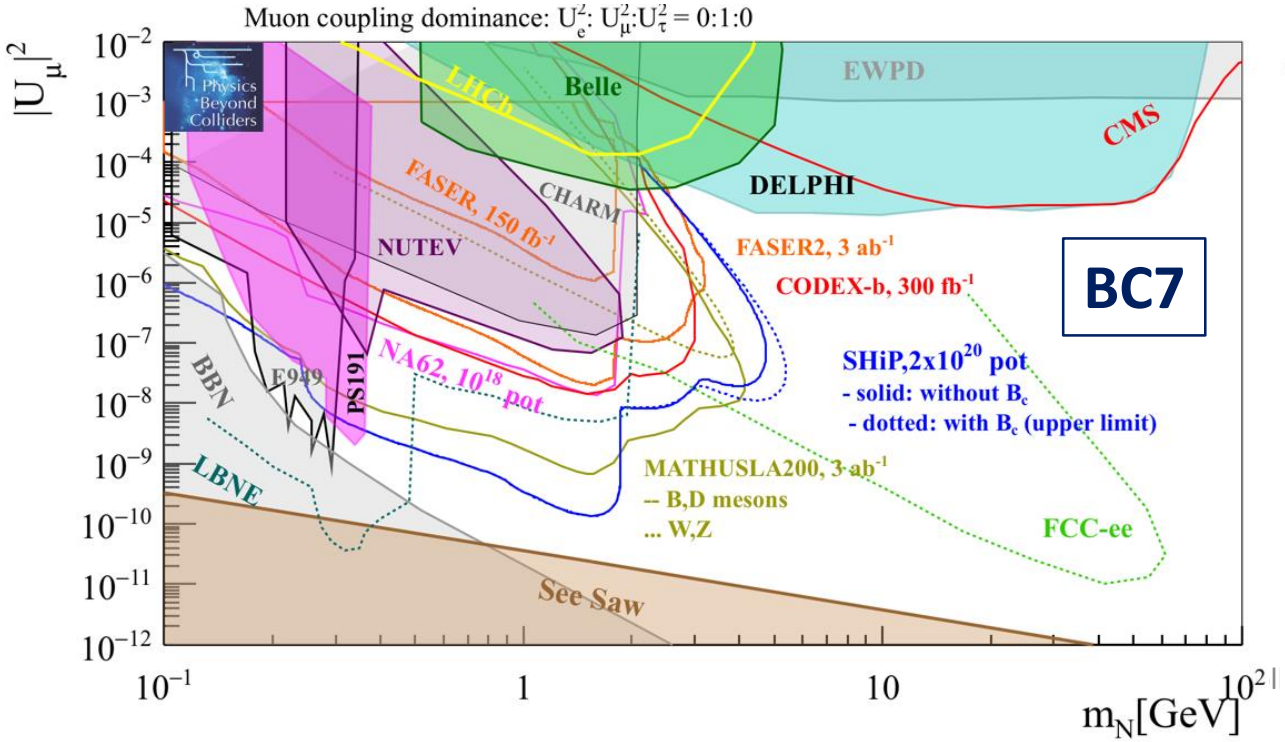


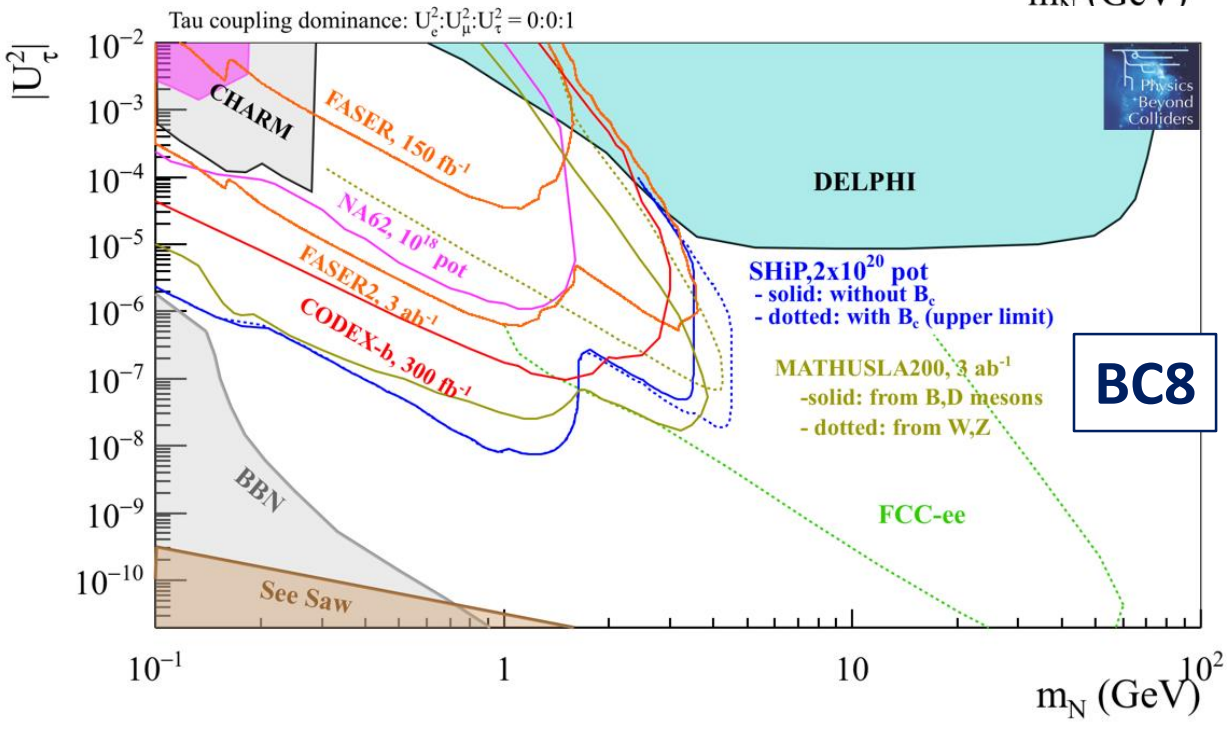
SENSITIVITIES TO DARK FERMIONS (HNL's)



- **Unique short term opportunities with NA62 Beam Dump and FASER**
- **SHiP has the highest reach on the long term**

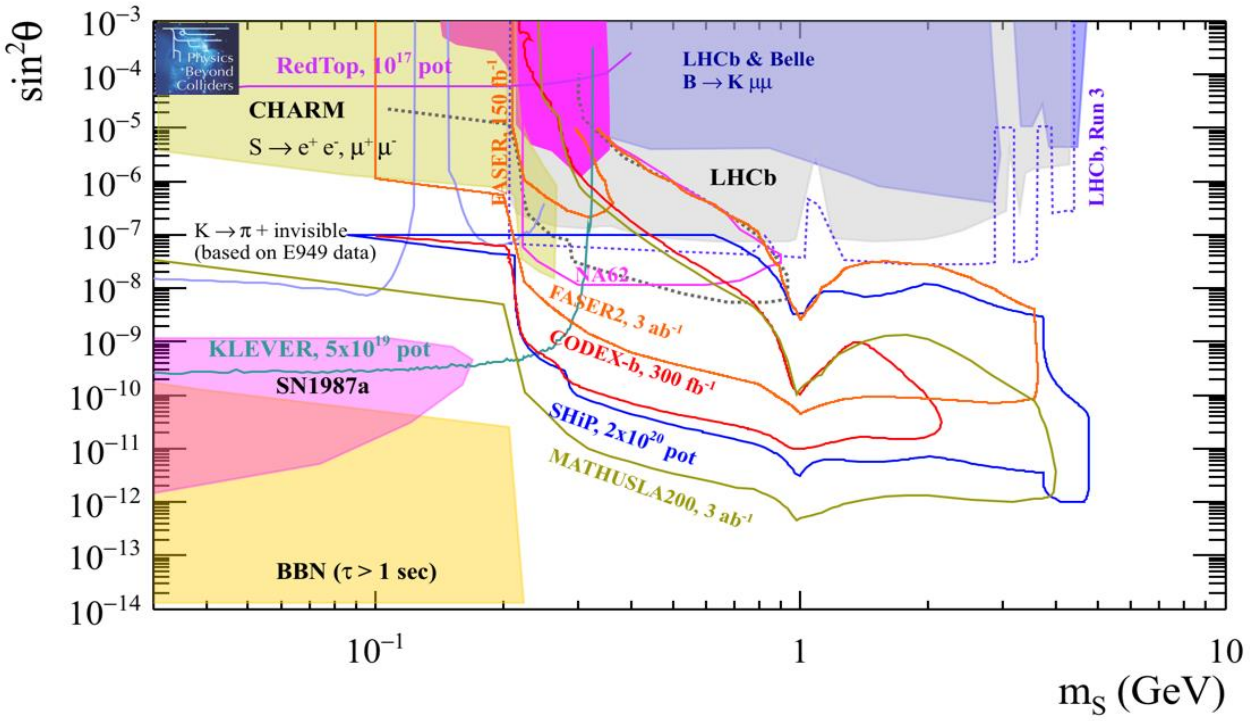




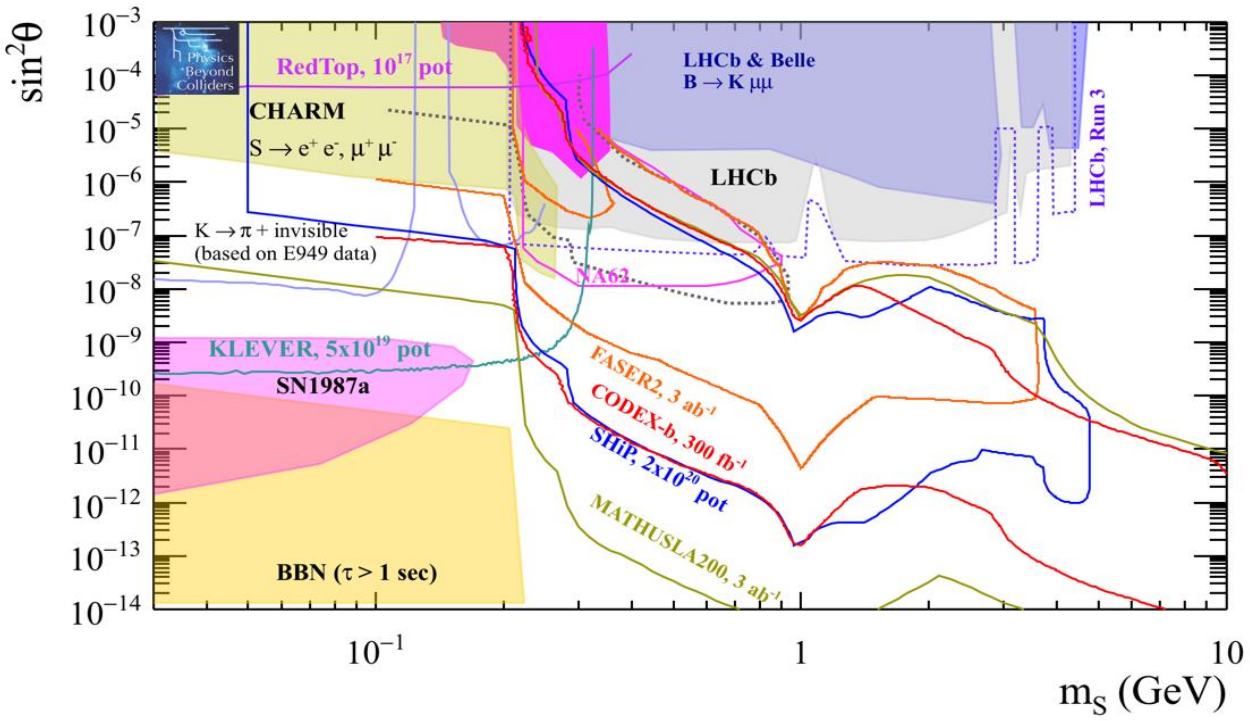


DARK SCALARS

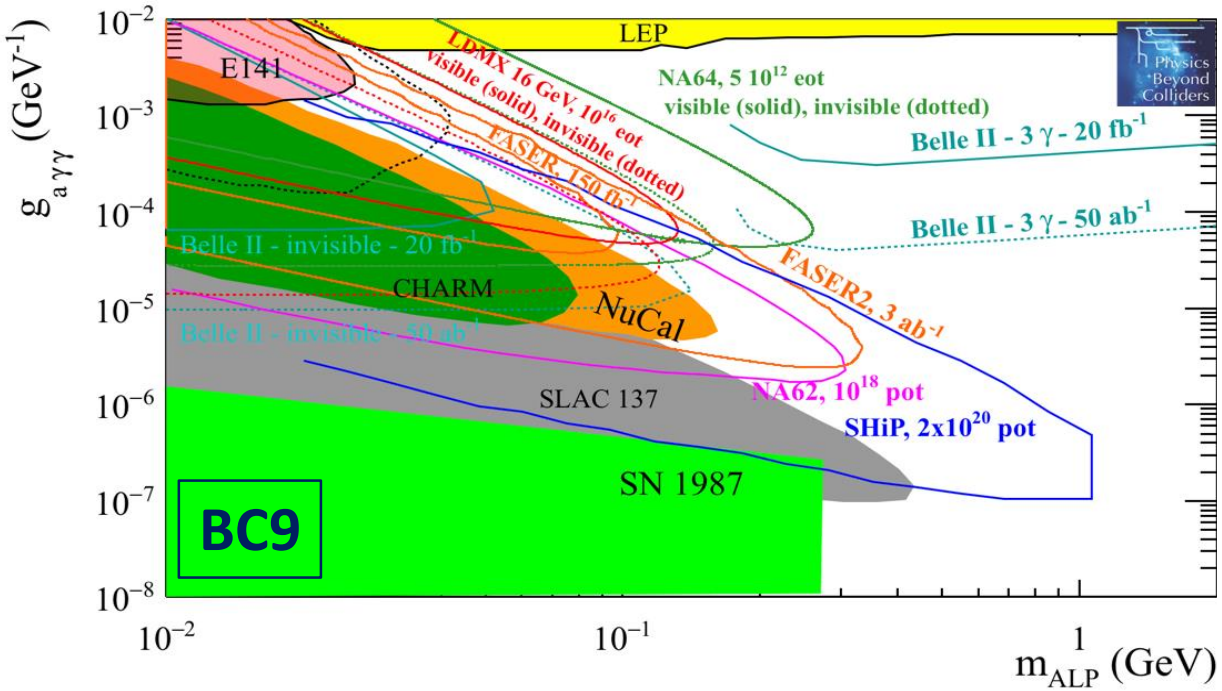
BC4

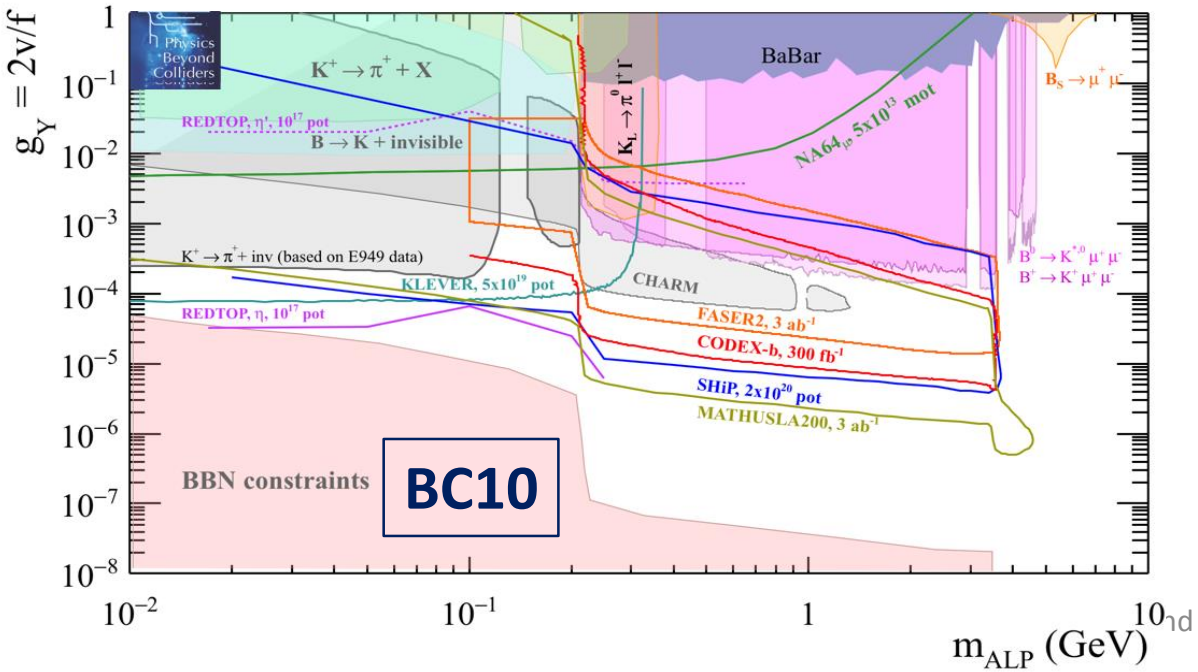


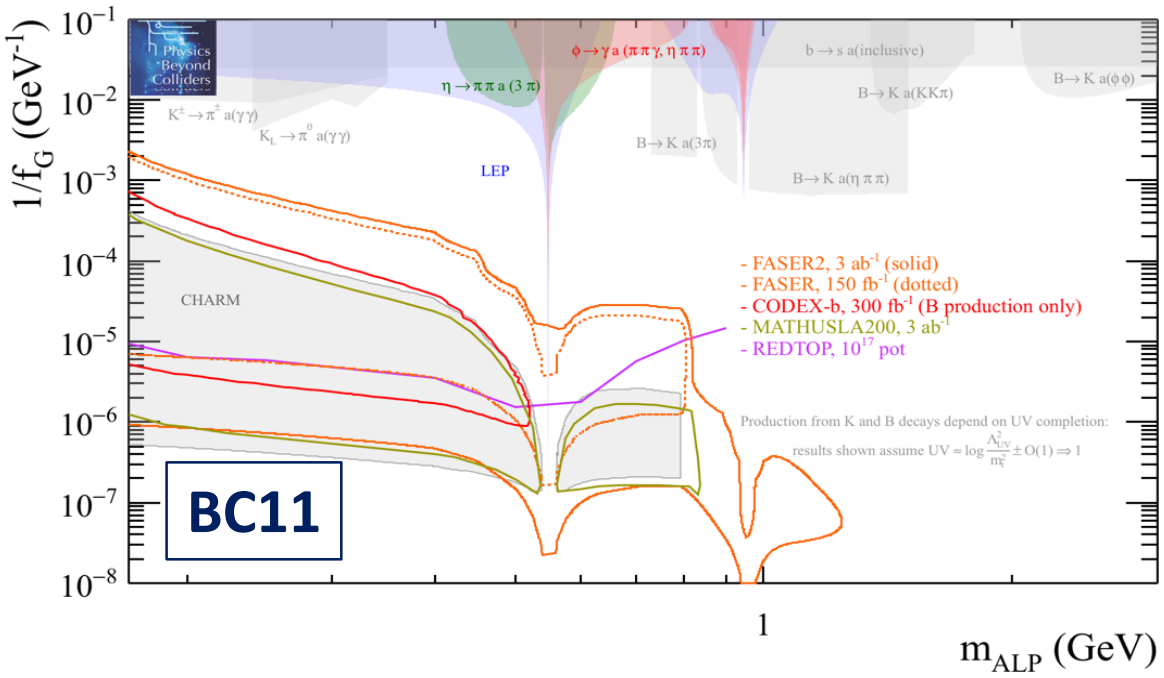
BC5



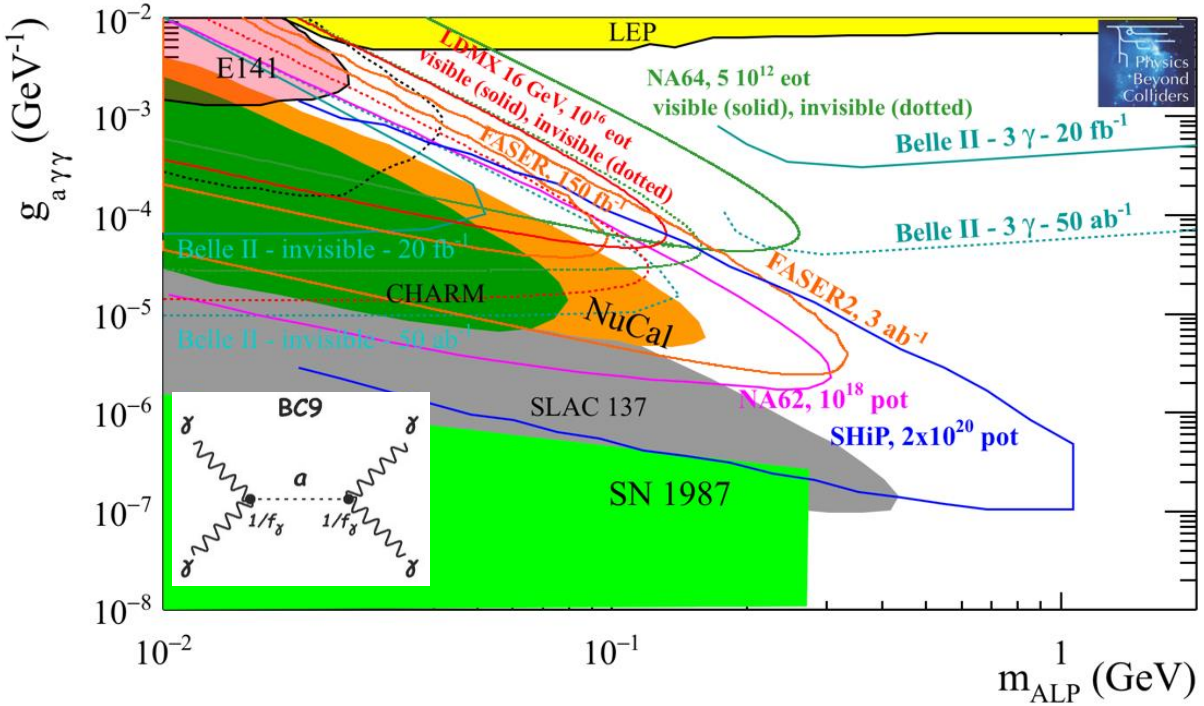
ALPS IN BEAMDUMPS

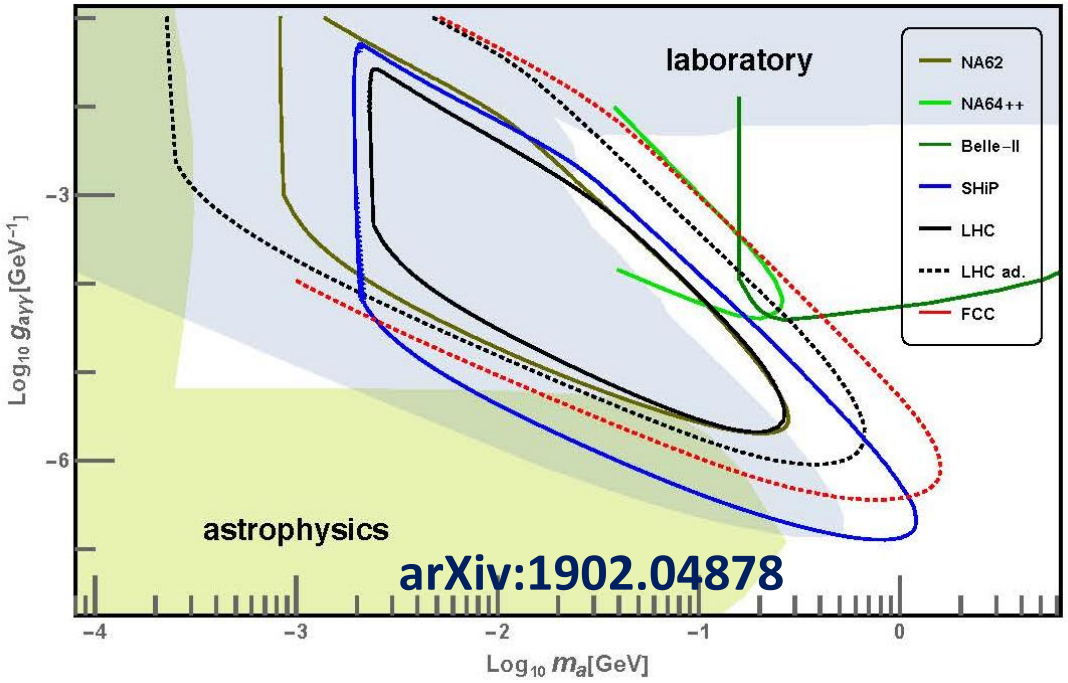






EXPLORATORY STUDY OF HIGHER-ENERGY BEAM DUMPS POTENTIAL
the example of ALPs

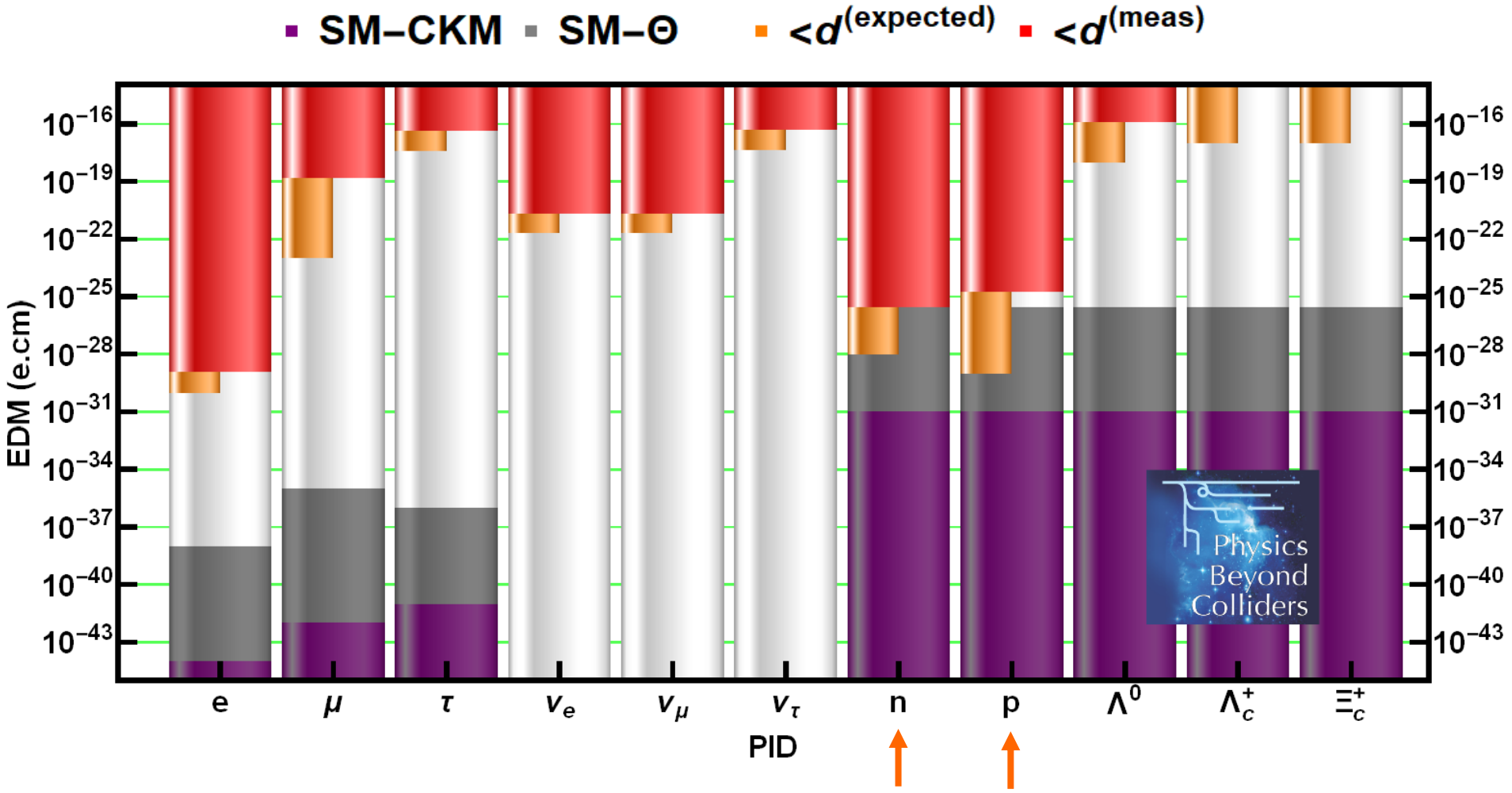




PBC projects have a similar reach as for visible A'
(similar signatures γγ and e^+e^-)

No real breakthrough of
LHC/FCC beam dumps:
SPS seems to offer a quite optimal
energy-intensity mix in the present context

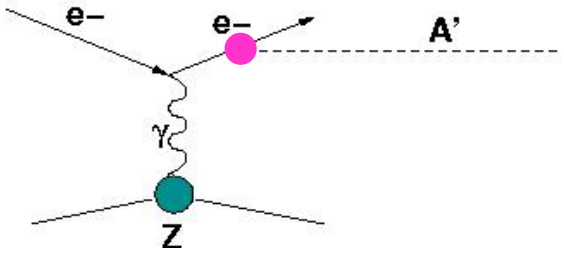
EDM LANDSCAPE

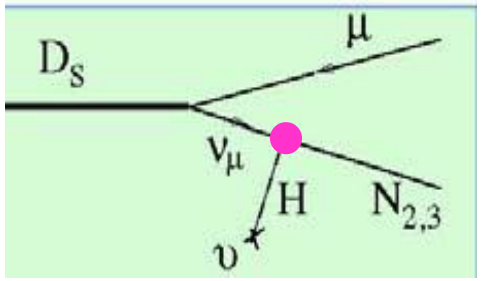


Neutron EDM is leading the field for hadrons

Catching up in precision is a challenge for the proton

HIDDEN SECTOR MAIN PRODUCTION MODES





Primakov/Bremstrahlung:
Mass reach mainly in sub-GeV domain, weakly dependent on beam energy

Meson decays:
Mass reach in multi-GeV domain dependent on accessible meson mass thresholds (K,D,B)

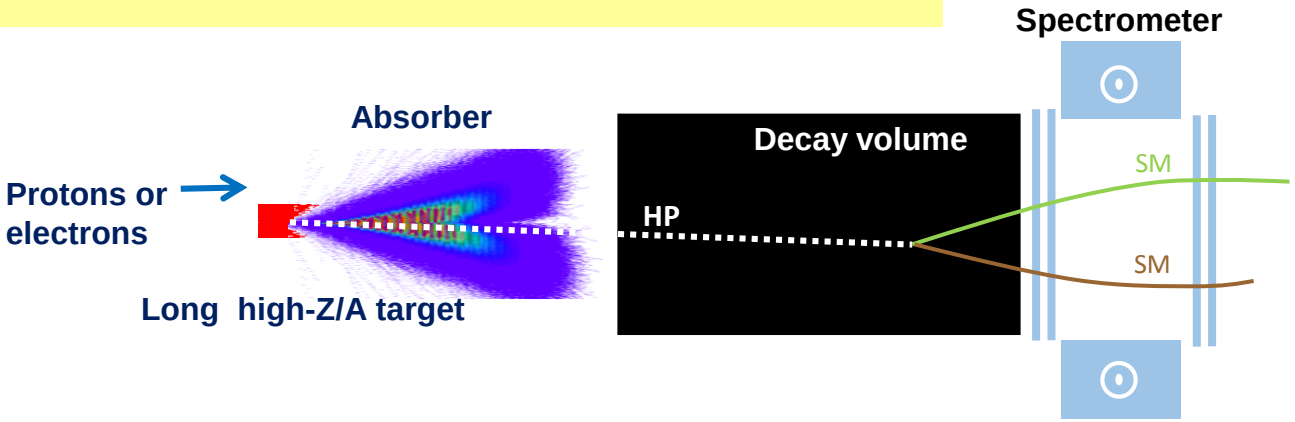
EXPERIMENTAL SIGNATURES

Models	*Final states*
HNL, SUSY neutralino	$l^+\pi^-$, l^+K^-, $l^+\rho^-$ $\rho^+ \rightarrow \pi^+\pi^0$
Vector, scalar, axion portals, SUSY sgoldstino	l^+l^-
HNL, SUSY neutralino, axino	$l^+l^-\nu$
Axion portal, SUSY sgoldstino	$\gamma\gamma$

+ recoil particles or missing energy for rescattering / missing energy methods

PBC PROPOSED BEAM DUMPS

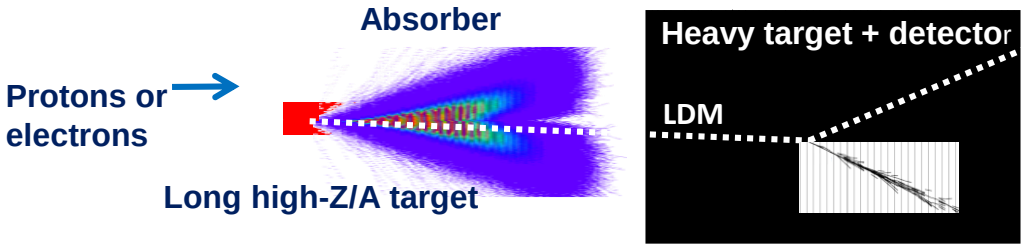
All experimental methods represented



Visible decay to SM particles

$signal \propto \epsilon^4$

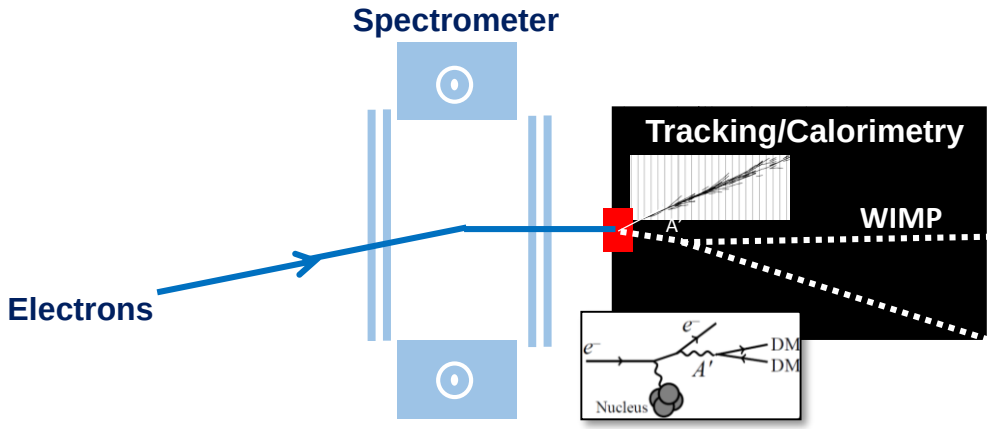
Critical: BG control



Recoil e/N from rescattering

$signal \propto \epsilon^4$

Critical: BG control



Missing energy from invisible decays

$signal \propto \epsilon^2$

Critical: initial particle and pileup control

Graphics Courtesy Richard Jacobsson

NB: reach in (m,ε) depends on many parameters:
beam energy & intensity, decay length, signatures, background …

MAIN PAST BEAM DUMP PROJECTS

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
E137 @SLAC	80's	e 20 GeV	$2\ 10^{20}$	recoil e	DP, ALPs
E141 @SLAC	80's	e 9 GeV	$2\ 10^{15}$	visible e^+e^-	DP, ALPs
E774 @FNAL	80's	e 275 GeV	$5.2\ 10^{9}$	visible e^+e^-	DP
NuTeV @FNAL	90's	p 800 GeV	$2\ 10^{18}$	visible μ	HNL
NUCAL @Serpukhov	80's	p 70 GeV	$1.7\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, ALPs
PS191 @CERN	80's	p 19 GeV	$0.8\ 10^{19}$	visible	HNL
CHARM @CERN	80's	p 400 GeV	$2.4\ 10^{18}$	visible $\gamma\gamma$, e^+e^-, $\mu^+\mu^-$	DP, DS, HNL

NB: most past beam dumps were "cheap" by-products of other experiments

MAIN CURRENT BEAM DUMP PROJECTS OUTSIDE CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
HPS @JLAB	2016-20	e 2-6 GeV	~10^{20}	visible e^+e^-	DP, ALPs
APEX @JLAB	2018-19	e 1-4.5 GeV	~10^{20}	visible e^+e^-	DP, ALPs
BDX @JLAB	~2022	e 12 GeV	~10^{22}	recoil e	DP, ALPs
LDMX @SLAC	> 2022	e 4-8 GeV	2 10^{16}	invisible	DP, ALPs
MiniBooNe @FNAL	2013-14	p 8 GeV	1.8 10^{20}	recoil e, N	DP
SBND @FNAL	>2020	p 8 GeV	6 10^{20}	recoil Ar	DP
SEAQUEST @FNAL	2021-30	p 120 GeV	$10^{18} \rightarrow 10^{20}$	visible e^+e^-	DP, DS, HNL
LBND @FNAL	>2025	p 120 GeV	~10^{21}	recoil e, N	DP, DS, HNL

Recent dedicated experiments demonstrate a regain of interest for beam dumps

Flavour factories (BELLE II, …) have also some sensitivity from exotic decays

BEAM DUMP PROJECTS AT CERN

DP = Dark Photon
DS = Dark Scalar
HNL = Heavy Neutral Lepton
ALP = Axion-Like Particle

EXPERIMENT	PERIOD	BEAM	PARTICLES ON TARGET	SIGNATURE	MODELS
NA64++(e)	2015-24	e 100 GeV	~5 10^{12}	invisible & visible e^+e^-	DP, ALPs
eSPS/LDMX	> 2026	e 16 GeV	10^{16}	invisible	DP, ALPs
AWAKE++	> 2026	e ~50 GeV	~10^{15}	visible e^+e^-	DP, ALPs
NA62++	> 2022	p 400 GeV	10^{18}	visible	DP, DS, HNL, ALPs
SHiP	> 2026	p 400 GeV	2 10^{20}	recoil & visible	DP, DS, HNL, ALPs
NA64++(μ)	> 2022	μ 160 GeV	5 10^{13}	invisible	DZ_μ, ALPs

NB: CERN offers unique opportunities with both lepton and hadron beams

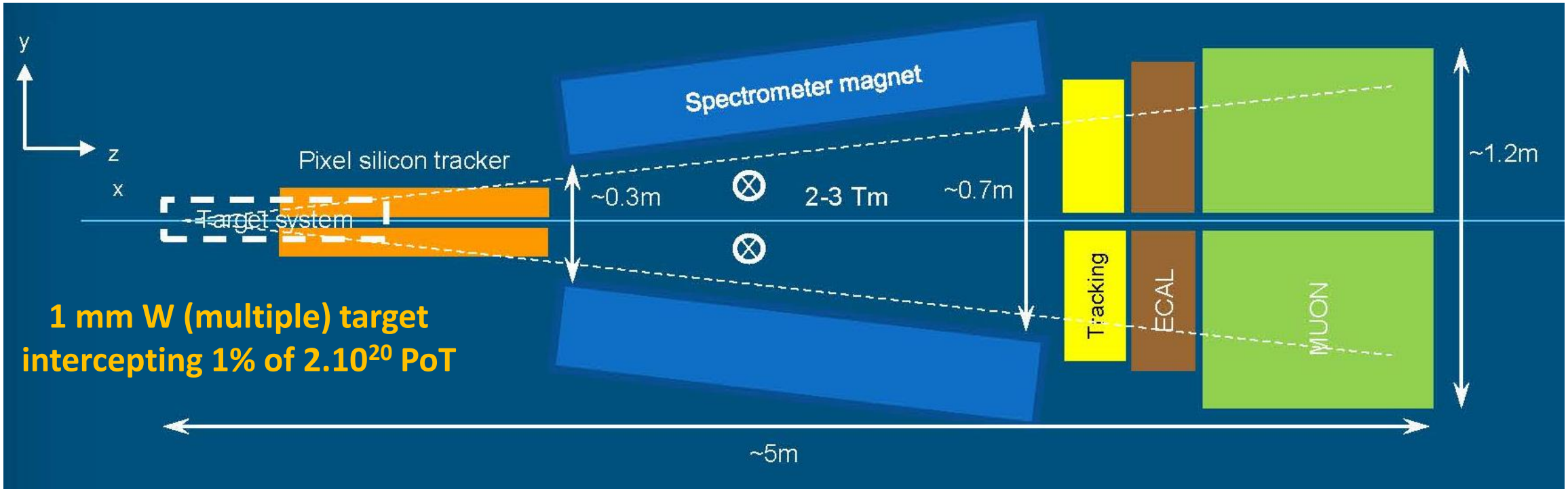
LHCb and LHC-LLP dedicated projects (FASER, milliQan, CODEX-b, MATHUSLA) have also sensitivity in similar mass range

TauFV

New idea introduced within PBC

Interception of small BDF beam fraction to look for τ → 3μ decays

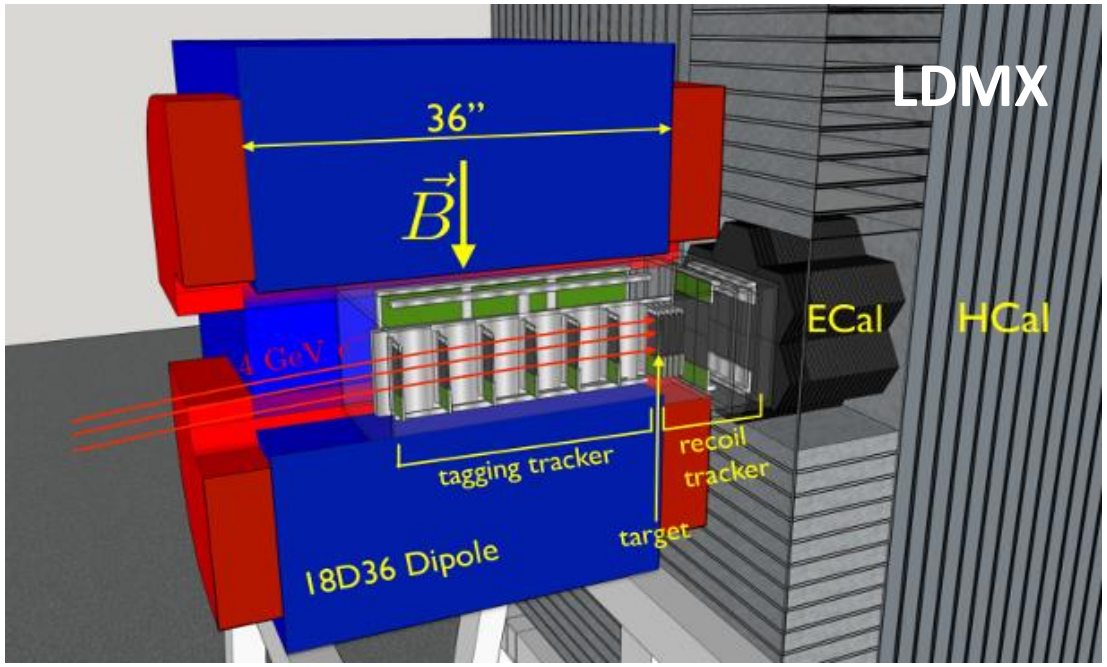
Could set limits on branching ratio better than 10^{-10} level targeted by BELLE-II



Implementation layout under study

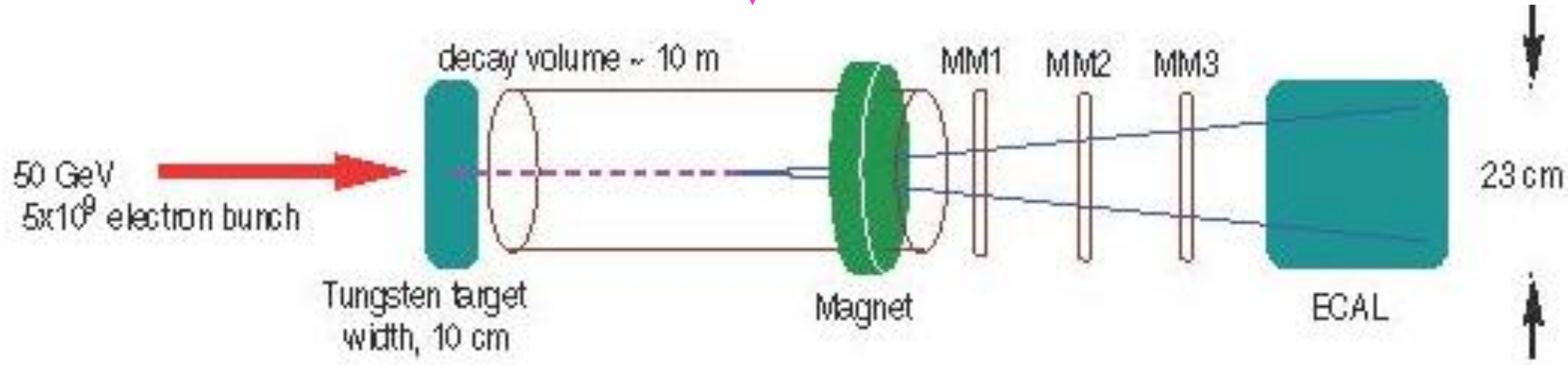
A small experimental hall upstream of BDF target could trigger a unique rare decay facility

EXPERIMENTS ON NEW e-BEAMs



Dark Photon and Axion-Like Particle searches with:

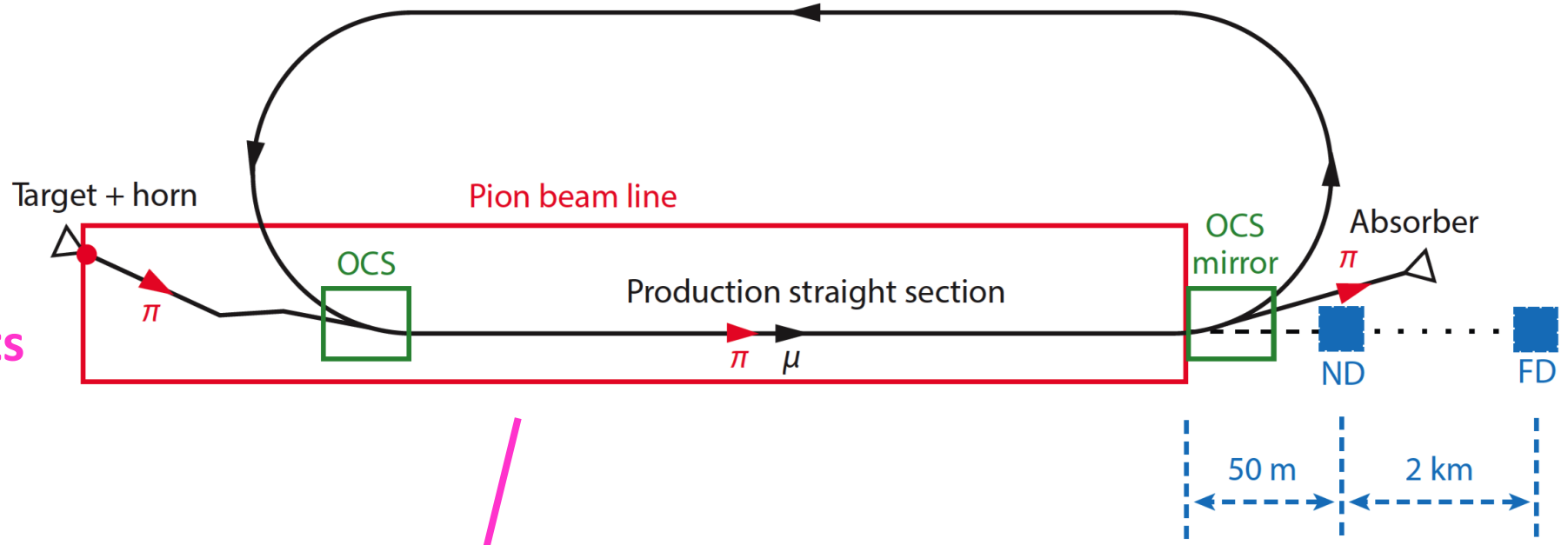
- **a LDMX-like detector on eSPS (invisible mode)**
- **An experiment on AWAKE++ in the CNGS decay tunnel (e^+e^- visible decay mode)**

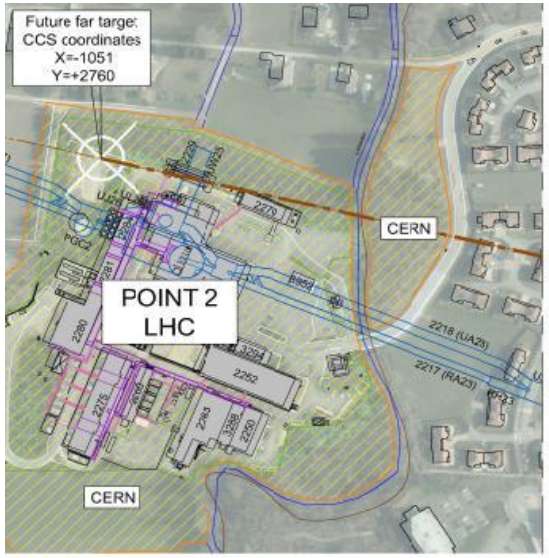


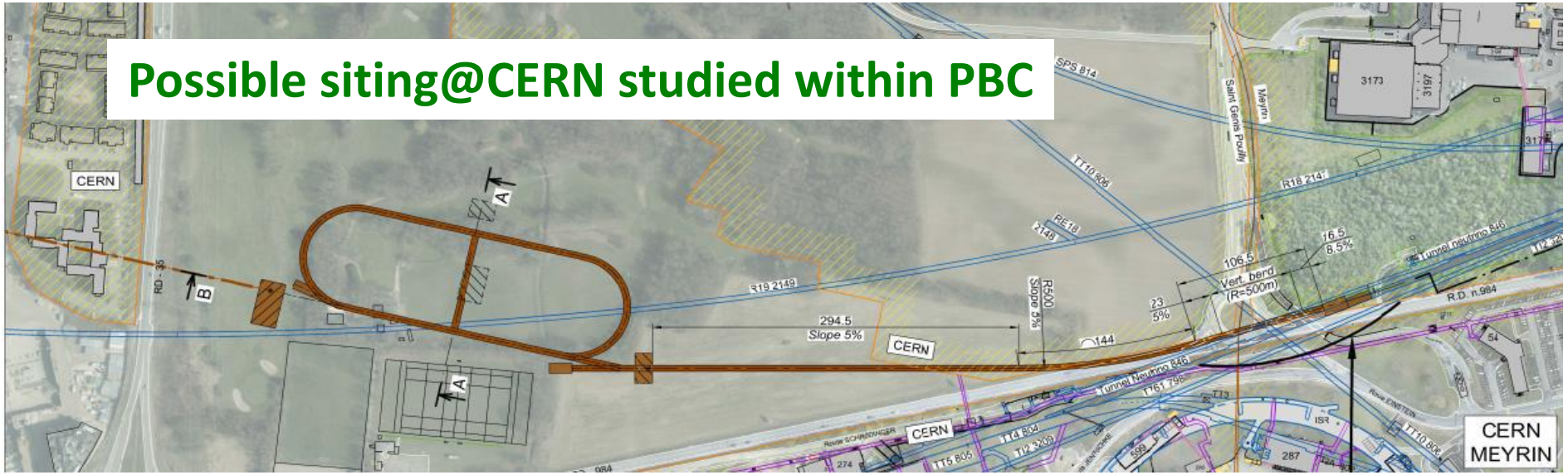
NuSTORM

Well controlled ν beam from a μ storage ring

Precise σ(ν) measurements and a path towards a ν factory or a μ collider.







NA60++ and DIRAC++

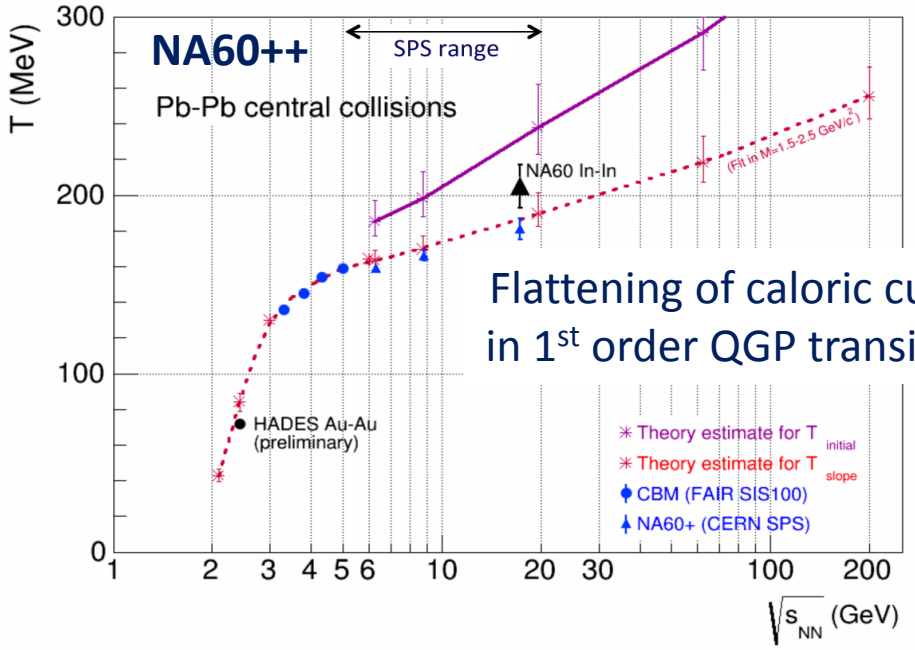
Unique physics reach for both

High hadron beam intensities

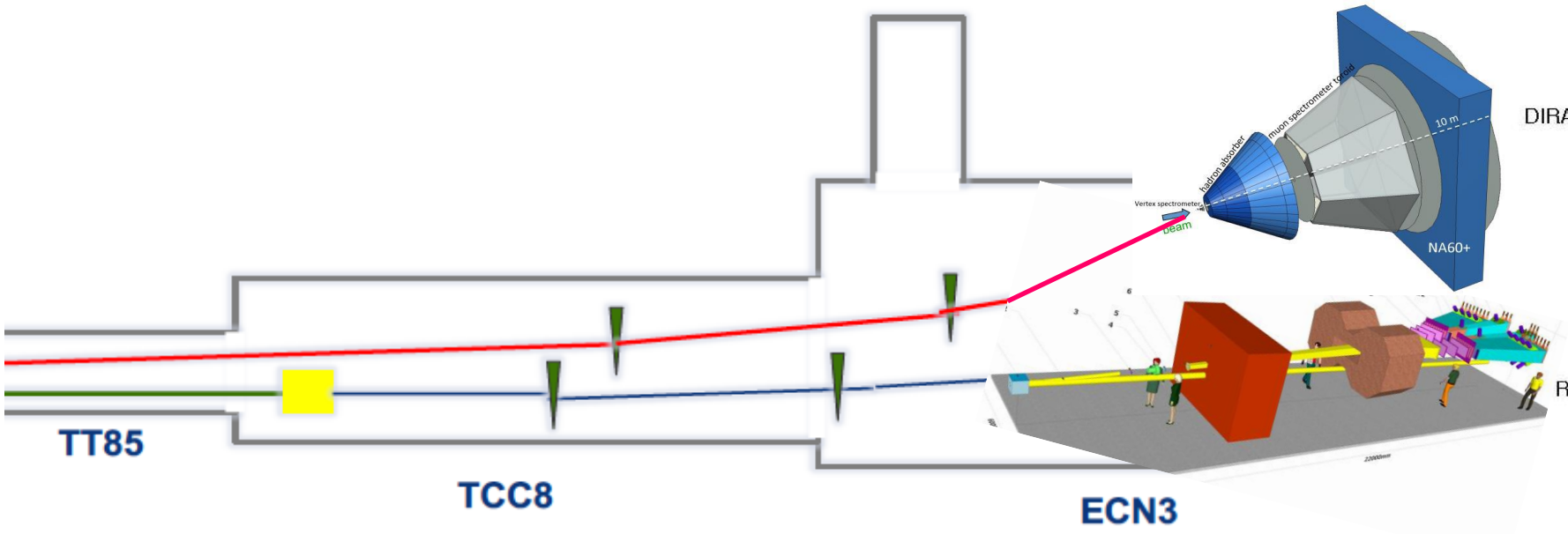
→ only reasonable implementation is in ECN3

Both beams could fit together in ECN3

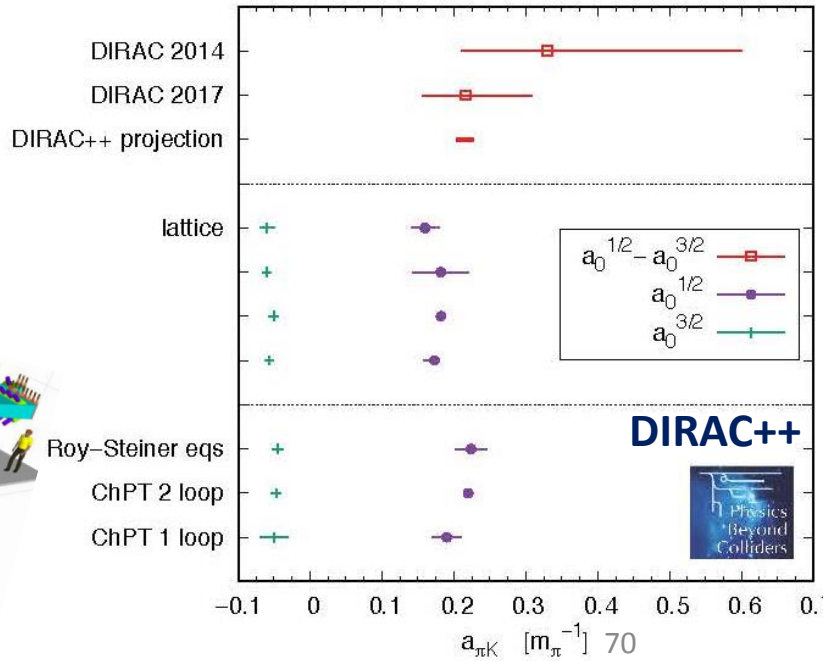
But implementation can be done only once NA62 has freed the hall



Flattening of caloric curve in 1st order QGP transition



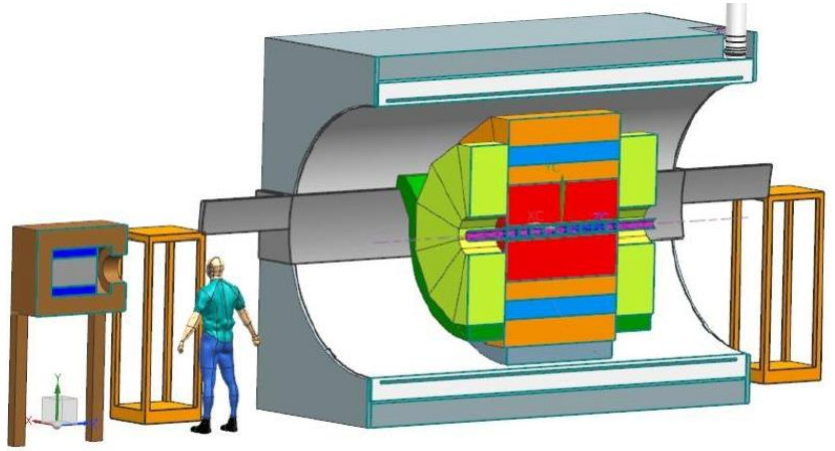
πK scattering lengths



REDTOP

η – η' factory

Also in discussion at FNAL



- It is a Goldstone boson → Symmetry constrains its QCD dynamics
- It is an eigenstate of the C, P, CP and G operators (very rare in nature): $I^G J^{PC} = 0^+ 0^{-+}$ → It can be used to test C and CP invariance.
- All its additive quantum numbers are zero (very clean state) $Q = I = j = S = B = L = 0$ → Its decays are not influenced by a change of flavor (as in K decays) and violations are "pure"
- All its possible strong decays are forbidden in the lowest order by P and CP invariance, G-parity conservation and isospin and charge symmetry invariance.
  EM decays are forbidden in lowest order by C invariance and angular momentum conservation → It is a very narrow state (Γ_η=1.3 KeV vs Γ_ρ=149 MeV)
  Contributions from higher orders are enhanced by a factor of ~100,000
  Excellent for testing invariances

Main issues:

- 2 GeV continuous proton beam (PS best option but non-nominal for REDTOP)
- Demanding detector technology (Optical TPC and dual readout calorimetry)