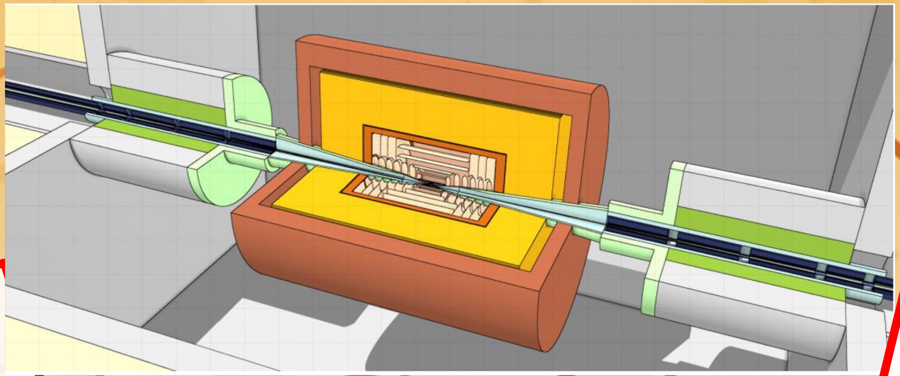
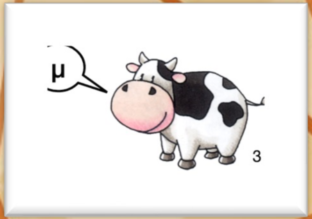
Detector Challenges at a Muon Collider

Alessandro Cerri, University of Sussex, Universita di Siena

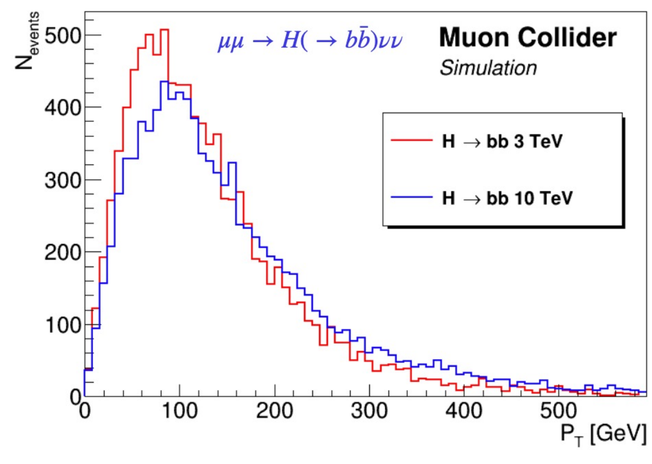


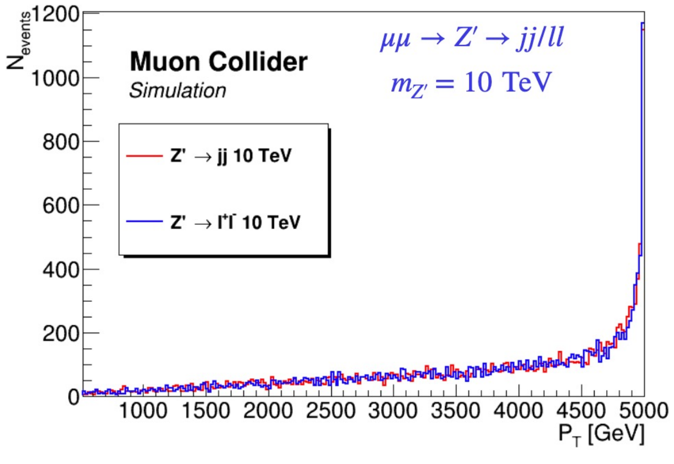


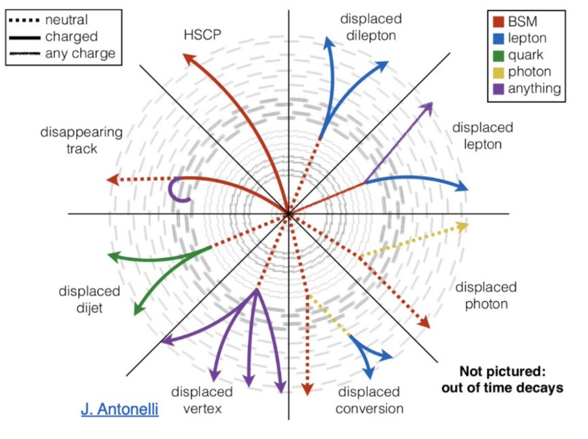
It’s all about the physics case!

Three broad areas:

- 100s of GeV → EW scale (VB, H production etc.)
- TeV-scale → Direct production of New Physics
- Unconventional signatures (llp, etc.)







- Initially: ILC detector adapted to a 3 TeV muon collider
- Evolution: 10 TeV experiment design

Physics Case Influences Machine Design

Aim at ~% level precision on EW-mediated 2-2 processes [$\sigma \sim 1\, fb \times \left(\frac{10\, TeV}{E_{CM}}\right)^2$] in 5 years:

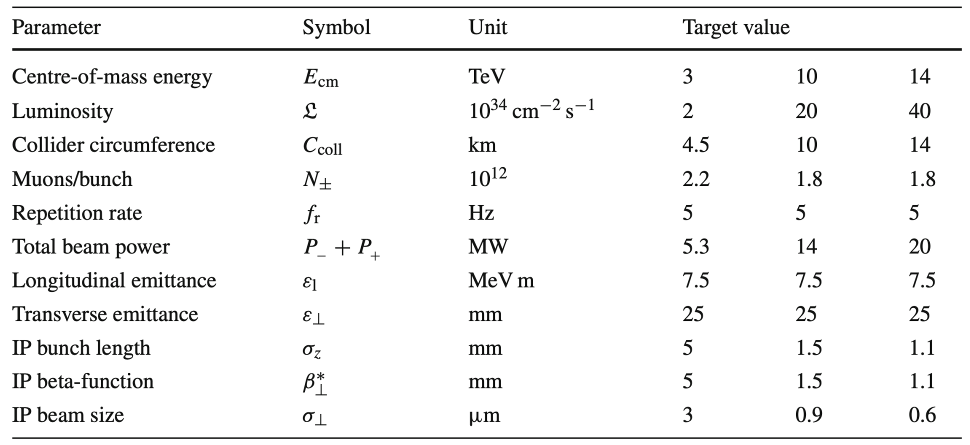
$$L_{int} \sim 10\, ab^{-1} \times \left(\frac{E_{CM}}{10\, TeV}\right)^2$$

$$L_{inst} \sim \frac{5 \text{ years}}{\text{time}} \left(\frac{E_{\text{cm}}}{10 \text{ TeV}}\right)^2 2 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$$

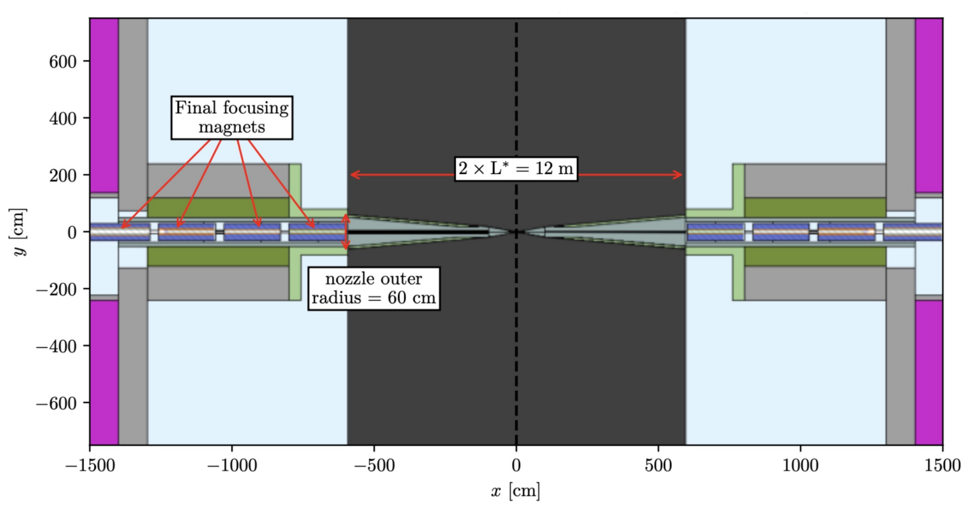
Collision environment: Machine→ Detector

Three “environmental” drivers on detector design:

- Collision rate
- Radiation levels
- Beam background



Parameter	Symbol	Unit	Target value		
Centre-of-mass energy	E_{cm}	TeV	3	10	14
Luminosity	$\mathfrak{L}$	10^{34} cm^{-2} s^{-1}	2	20	40
Collider circumference	C_{coll}	km	4.5	10	14
Muons/bunch	$N_{\pm}$	10^{12}	2.2	1.8	1.8
Repetition rate	f_{r}	Hz	5	5	5
Total beam power	$P_{-} + P_{+}$	MW	5.3	14	20
Longitudinal emittance	ε_{l}	MeV m	7.5	7.5	7.5
Transverse emittance	$\varepsilon_{\perp}$	mm	25	25	25
IP bunch length	σ_{z}	mm	5	1.5	1.1
IP beta-function	$\beta^{*}_{\perp}$	mm	5	1.5	1.1
IP beam size	$\sigma_{\perp}$	µm	3	0.9	0.6

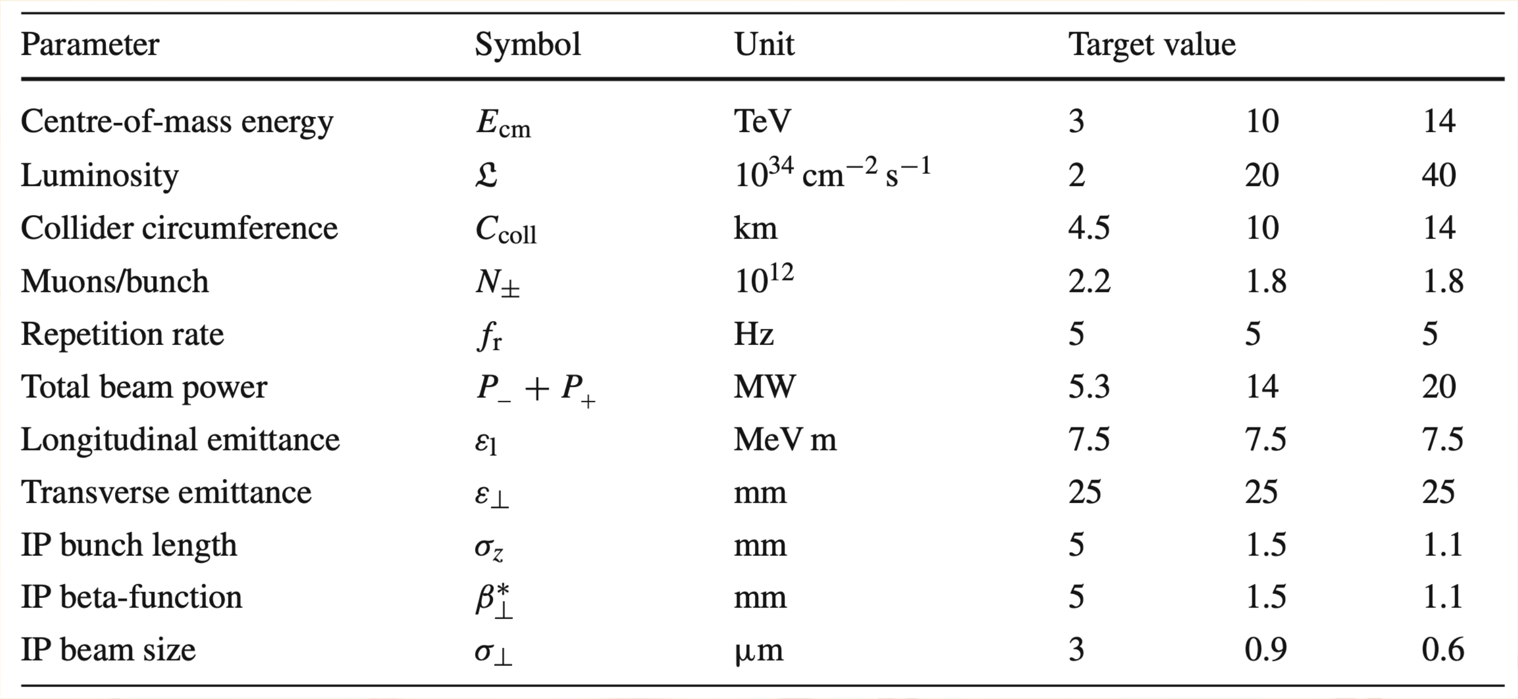


Bottomline(s):

- Moderate collision rate
- Detector irradiation comparable to HL-LHC
- Beam Induced Background (BIB) is the most specific (AND STRINGENT) driver to the detector design

Detail in the next slides!

Event Rate



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1 bunch, 100 kHz rate, >10 us crossing

not a severe constraint on DAQ: could opt for a triggerless design.

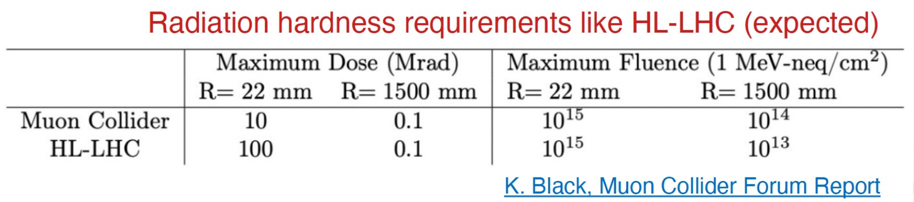
Detector Irradiation

n-eq fluence and total ionising doses simulated:

- $10^{14\text{-}15}$ 1 MeV neq/yr/cm^2 fluence
  - Decreasing by x10 from tracker to calorimeter
- 1 Mrad/y [tracker]
  10^{-1} Mrad/y [calo]

Simulation @ 1.5 TeV for a 2.5 Km collider

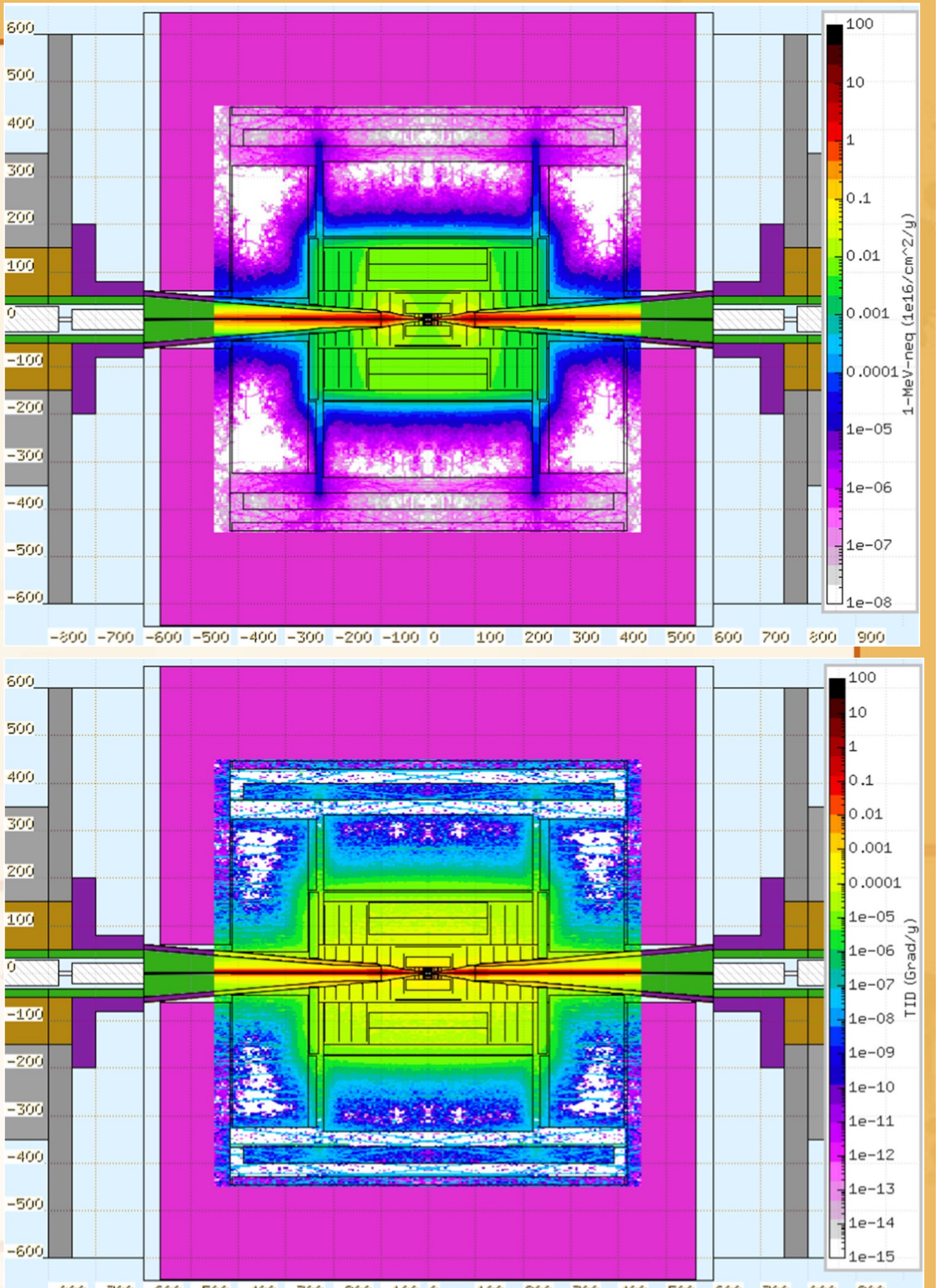
Environment is HL-LHC-like:



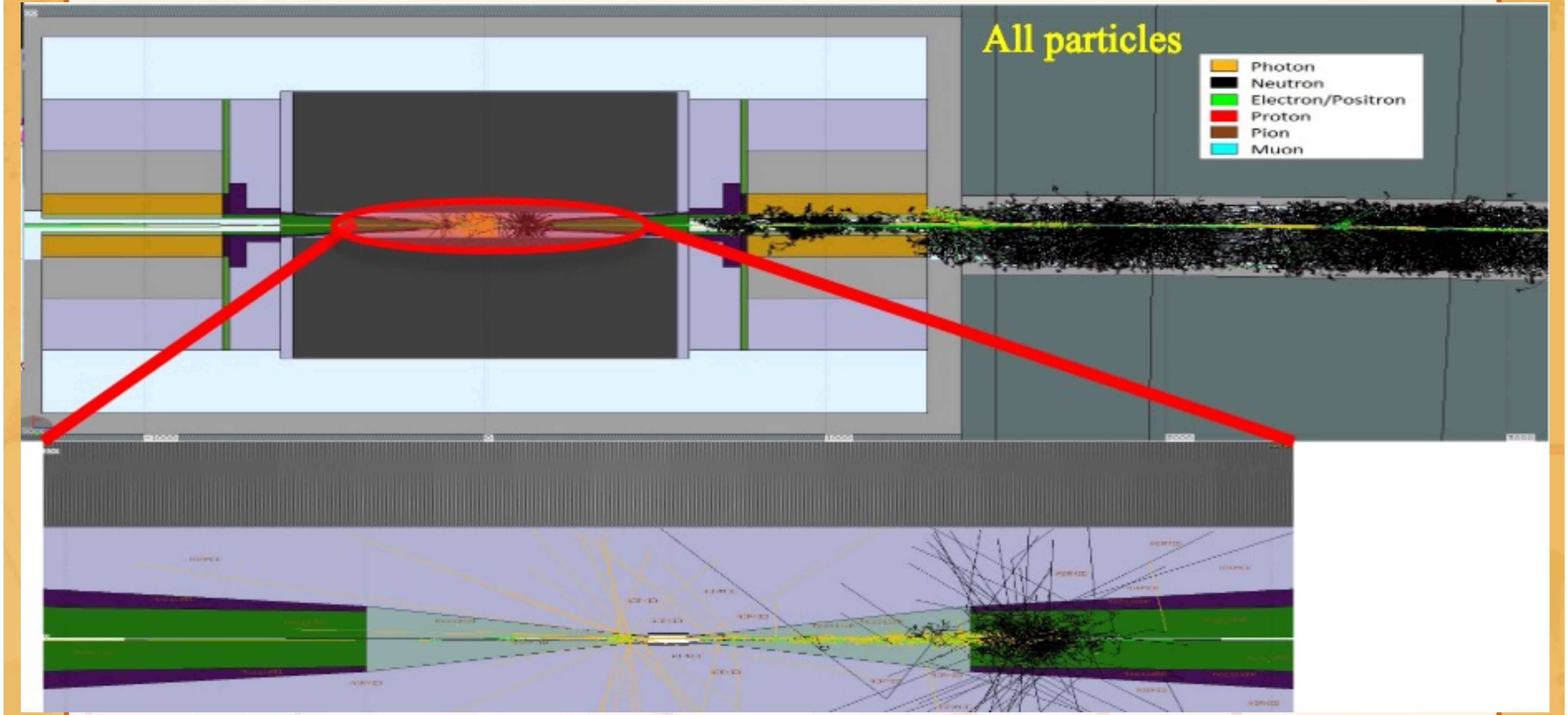
Radiation hardness requirements like HL-LHC (expected)

	Maximum Dose (Mrad)		Maximum Fluence (1 MeV-neq/cm^2)	
	R= 22 mm	R= 1500 mm	R= 22 mm	R= 1500 mm
Muon Collider	10	0.1	10^{15}	10^{14}
HL-LHC	100	0.1	10^{15}	10^{13}

K. Black, Muon Collider Forum Report



Beam Background



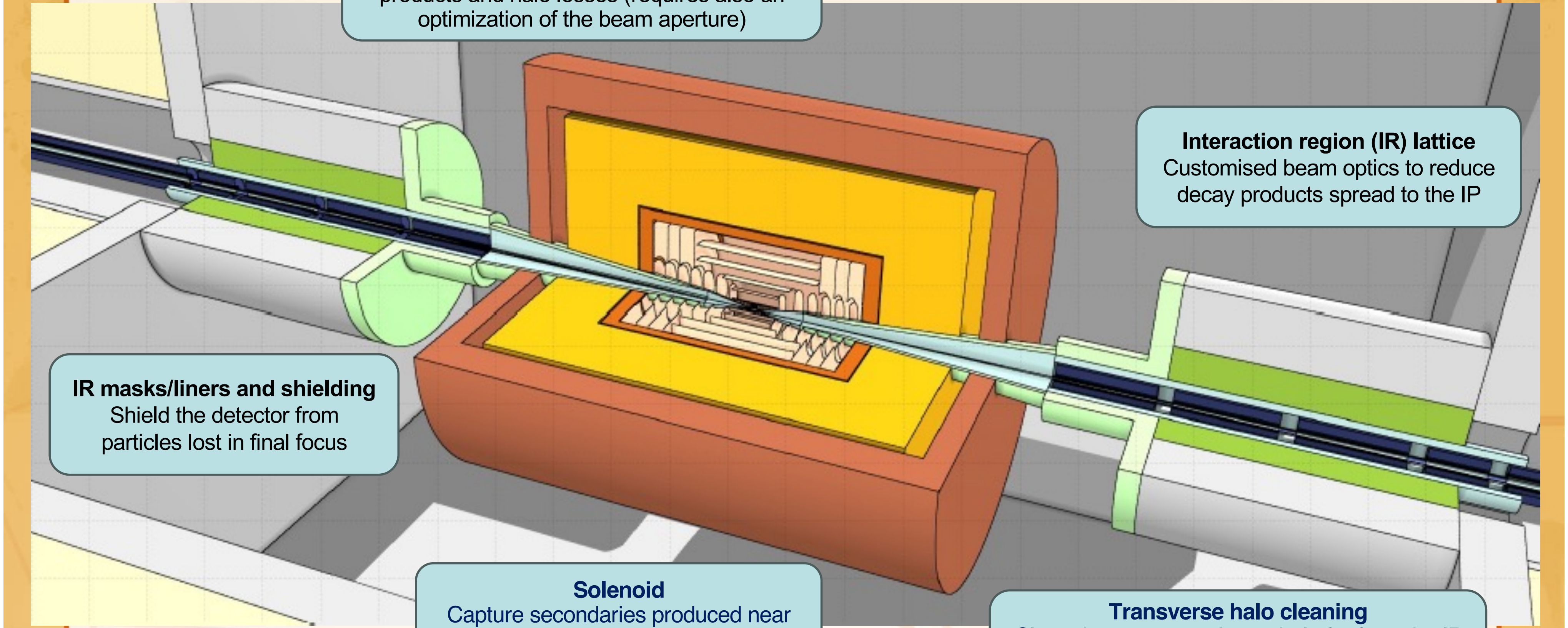
Beam Background

From D. Calzolari

	Description	Relevance as background
Muon decay	**Decay of stored muons around the collider ring**	**Dominant source**
Synchrotron radiation by stored muons	Synchrotron radiation emission by the beams in magnets near the IP (including IR quads → large transverse beam tails)	**Small**
Muon beam losses on the aperture	Halo losses on the machine aperture, can have multiple sources, e.g.: •Beam instabilities •Machine imperfections (e.g. magnet misalignment) •Elastic (Bhabha) μμ scattering •Beam-gas scattering (Coulomb scattering or Bremsstrahlung emission) •Beamstrahlung (deflection of muon in field of opposite bunch)	**Can be significant** (although some of the listed source terms are expected to yield a small contribution like elastic μμ scattering, beam-gas, Beamstrahlung)
Coherent e^-e^+ pair production	Pair creation by real* or virtual photons of the field of the counter-rotating bunch	**Expected to be small** (but should nevertheless be quantified)
Incoherent e^-e^+ pair production	Pair creation through the collision of two real* or virtual photons emitted by muons of counter-rotating bunches	**Significant**

Design must prove the ability to mitigate and cope with the residual background: this is one of the main drivers at a muon collider detector.

Machine-Detector Interface



Conical absorber inside detector (nozzle)
Shield the detector from high-energy decay products and halo losses (requires also an optimization of the beam aperture)

Interaction region (IR) lattice
Customised beam optics to reduce decay products spread to the IP

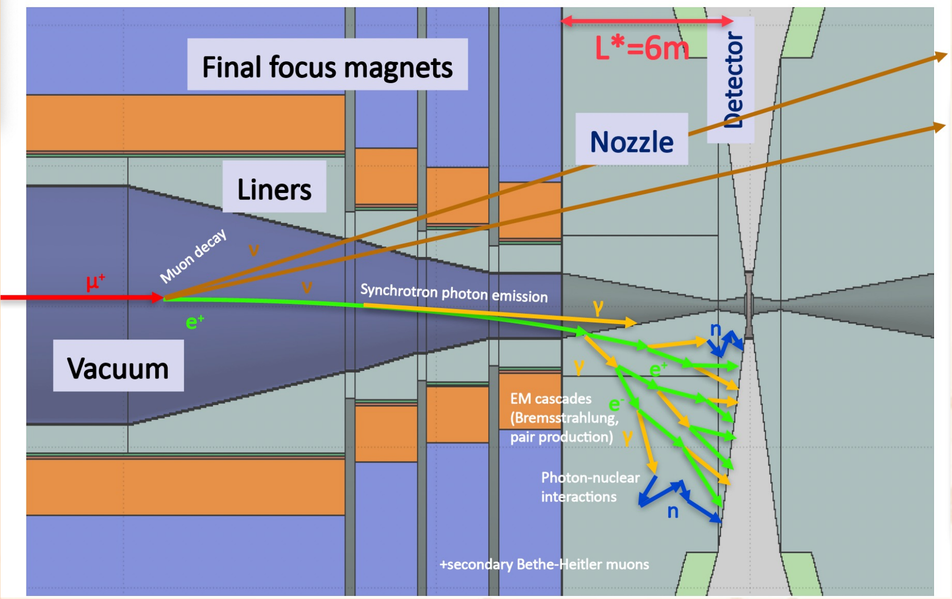
IR masks/liners and shielding
Shield the detector from particles lost in final focus

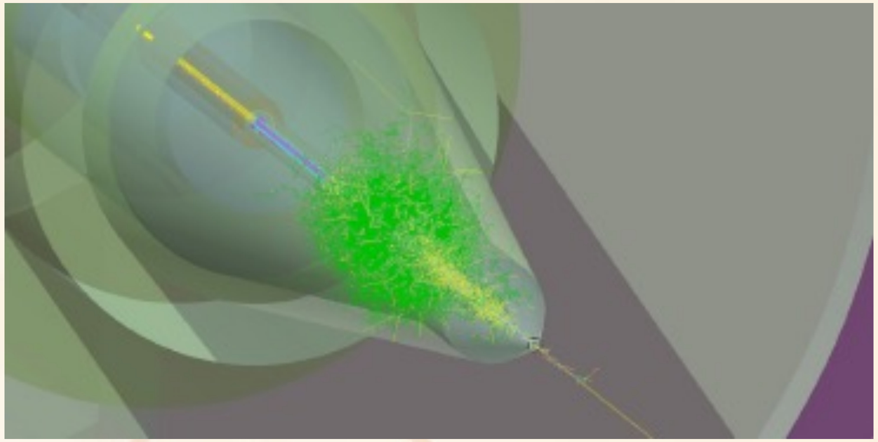
Solenoid
Capture secondaries produced near the IP (e.g. incoherent e-e+ pairs)

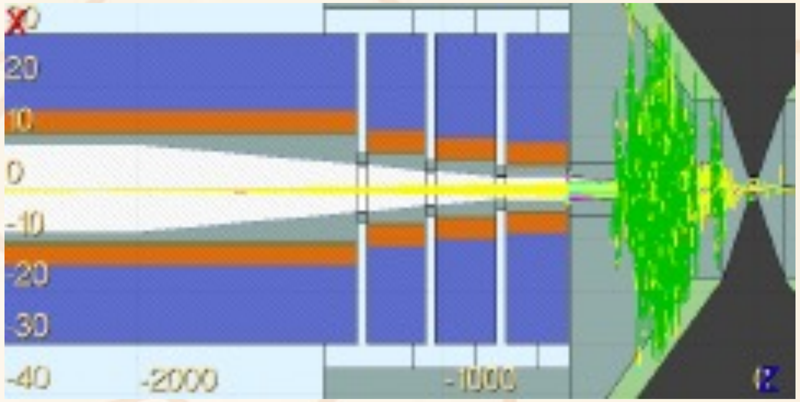
Transverse halo cleaning
Clean the transverse beam halo far from the IP to avoid halo losses on the aperture near the detector (IR is an aperture bottleneck)

Muon Decay: the dominant source

Here’s what a single muon decay can do:

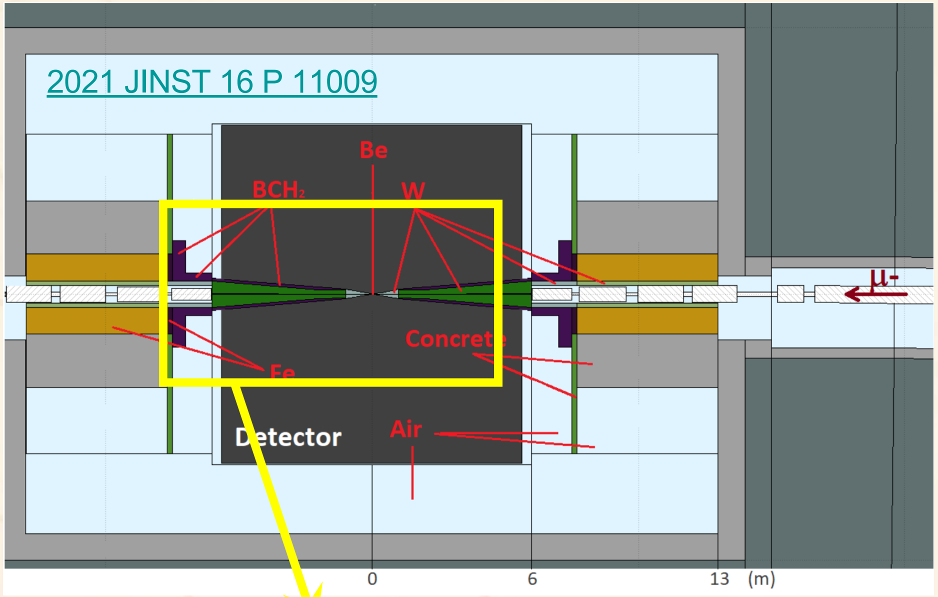






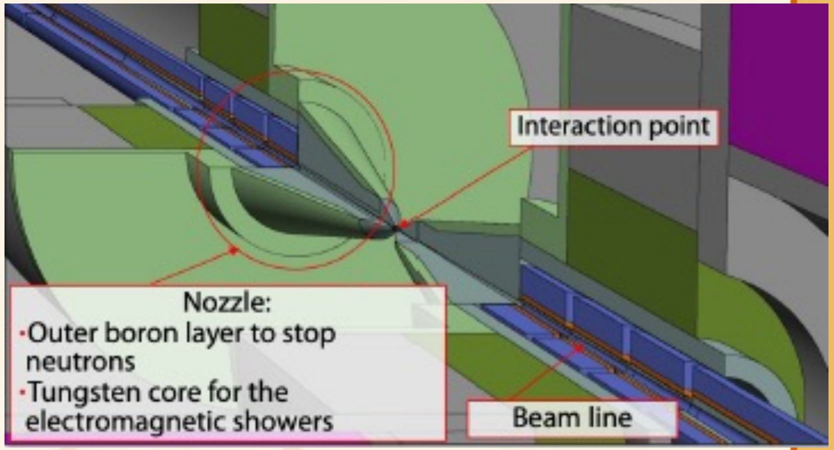
D. Calzolari

Detector Shielding: nozzles!


2021 JINST 16 P 11009

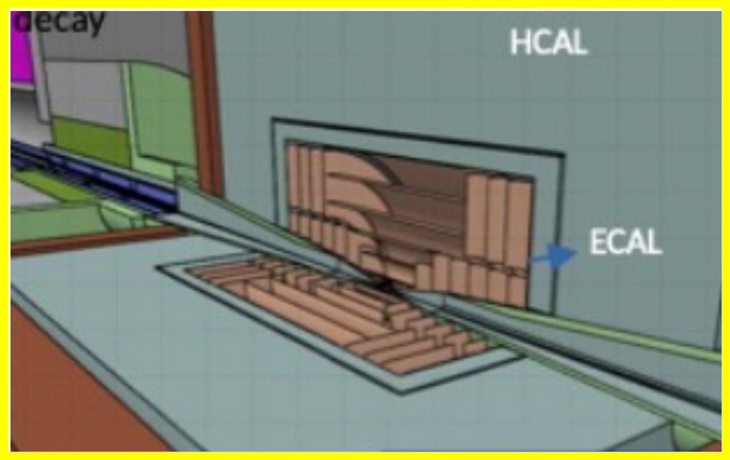
MAP Design (Fermilab-Conf-11-094-APC-TD)

D. Calzolari: 2023 IMCC Annual meeting



Nozzle:
- Outer boron layer to stop neutrons
- Tungsten core for the electromagnetic showers

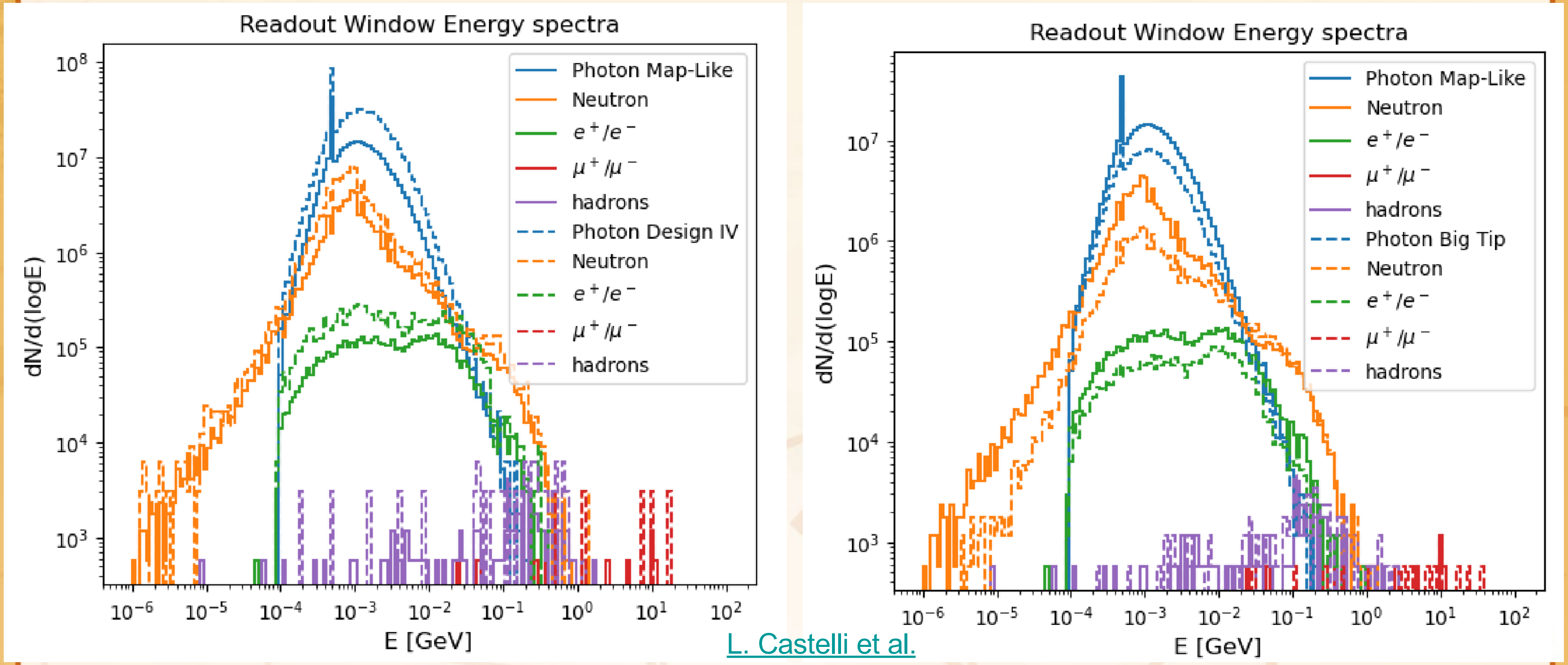
Nozzles extend well into the detector volume



Beam background features depend critically on the details of the nozzle design!

Nozzle Optimisation

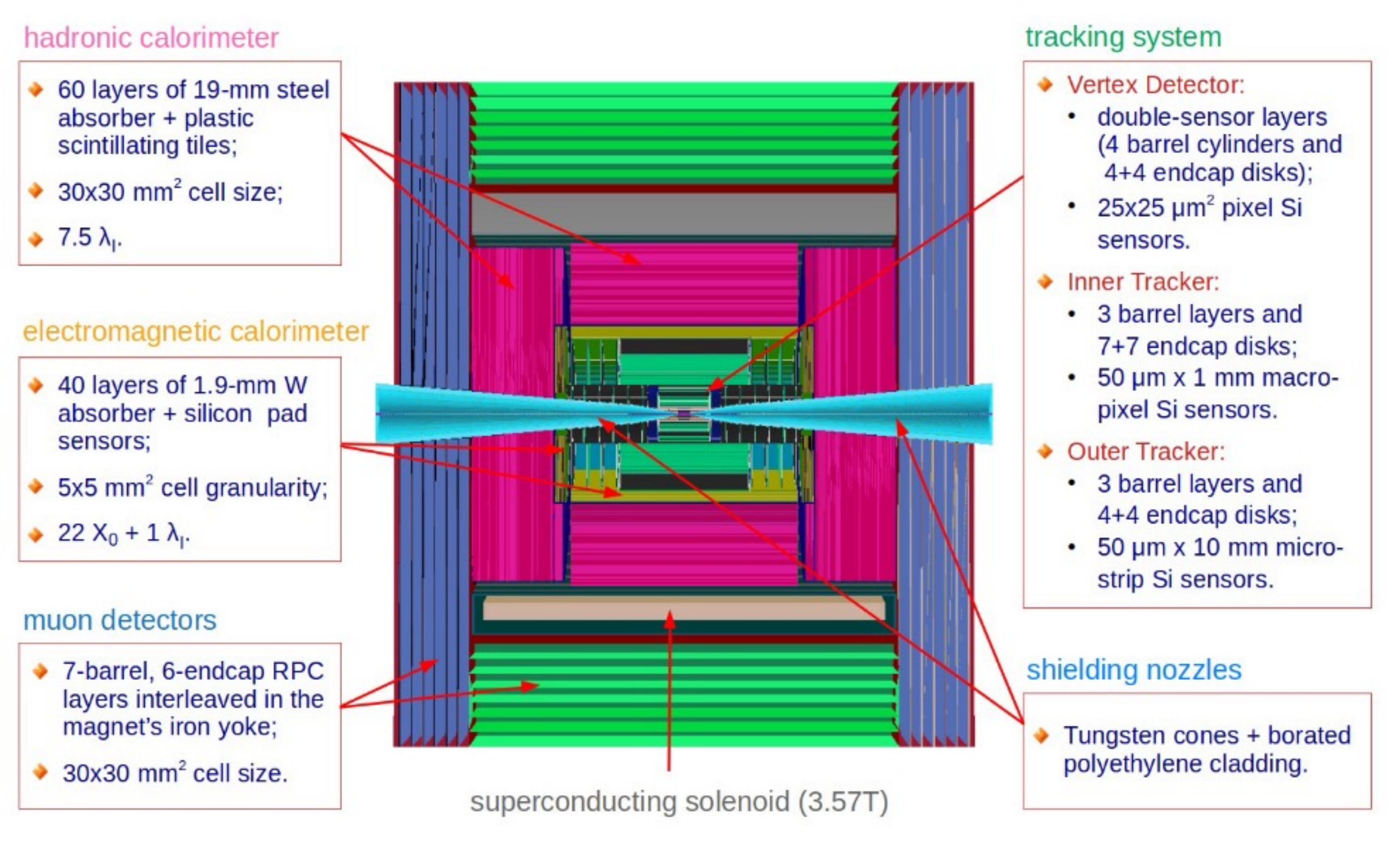
- Lengthy delicate process
- Small design changes → significant effects on flux, occupancy



L. Castelli et al.

Aim: choose a baseline design that can be later improved

Baseline Detector Model: 1.5-3 TeV



hadronic calorimeter

- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

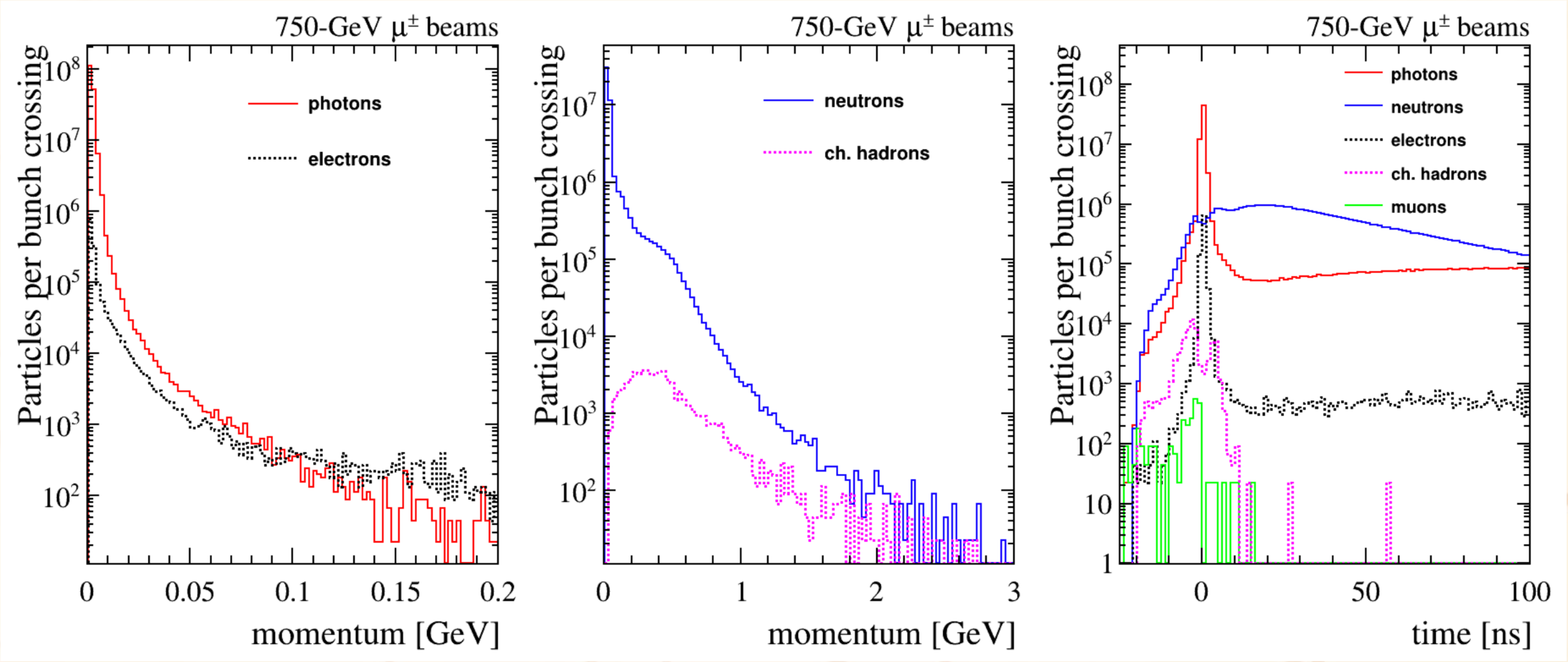
superconducting solenoid (3.57T)

Starting point: CLIC design, including nozzles and modified ID from MAP studies

BIB Reaching the Detector

Spectra and composition of BIB particles reaching the 1.5-3 TeV detector

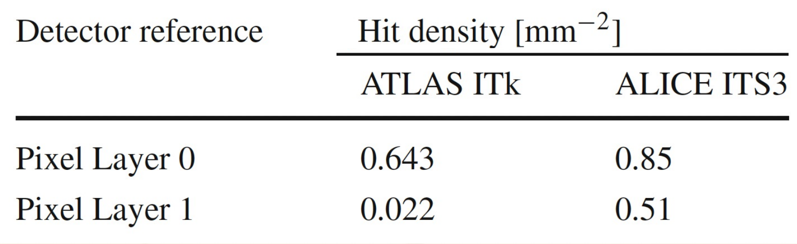
Time of arrival of BIB hits relative to BC



Good timing resolution essential to reduce BIB impact on detector readout and reconstruction complexity!
Solenoidal field intensity: contrasting needs between BIB mitigation and low-momentum tracking

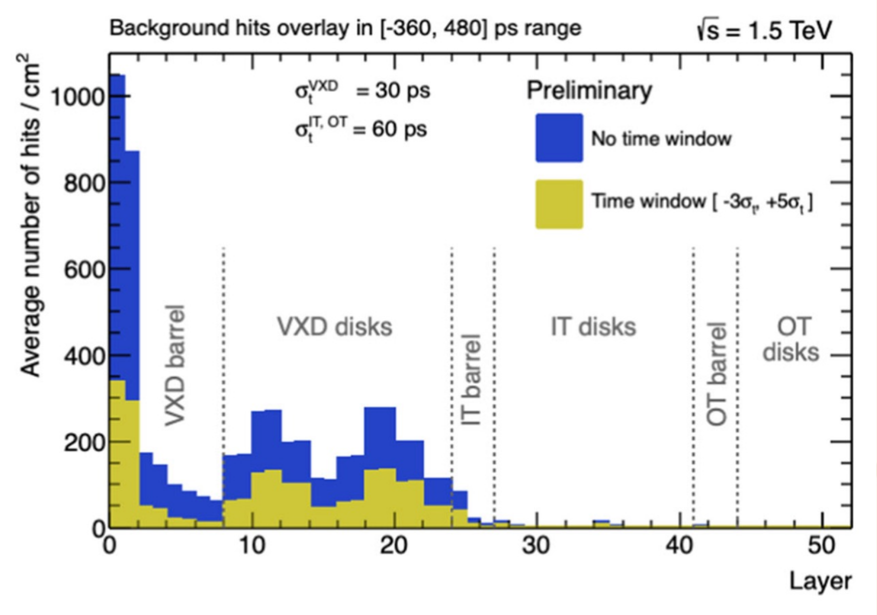
Detector Occupancy: Tracker

- Full detector and BIB simulation performed
- Innermost tracker layer occupancy vs HL-LHC:



Detector reference	Hit density [mm^{-2}]	
	ATLAS ITk	ALICE ITS3
Pixel Layer 0	0.643	0.85
Pixel Layer 1	0.022	0.51

Subdetector	Granularity [μm^2]	Timing resol. [ps]
VXD	25x25	30
IT	50x100	60
OT	50x10000	60



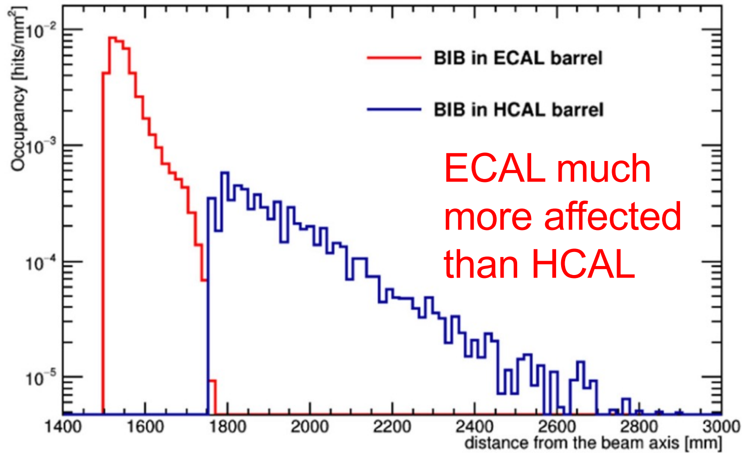
Additional handles that could help BIB mitigation:

- Cluster shape
- Directionality on layer doublets

The Muon Collider detector has a peculiar (BIB-induced) high-occupancy of the innermost part of the detector, dominated by EM components

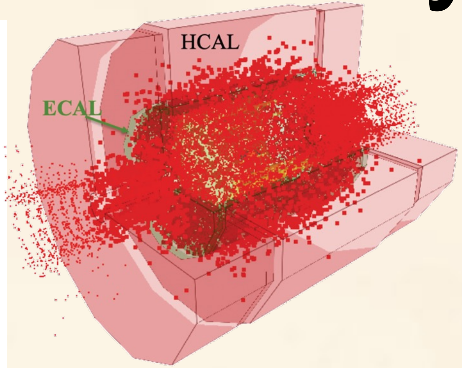
Composition and spectra depend on shielding (eg nozzle) and detector (e.g. B field) design choices

Calorimetry



ECAL much more affected than HCAL

Fig. 25 BIB hit occupancy in the calorimeter barrel region in a single bunch-crossing



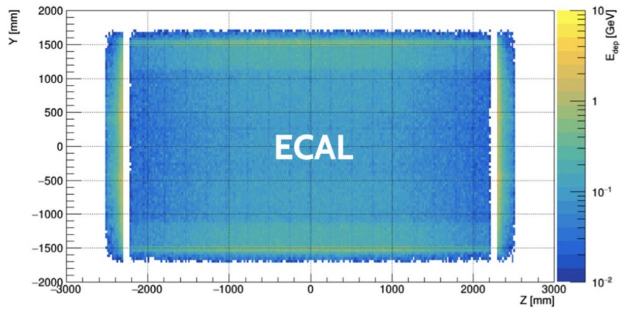
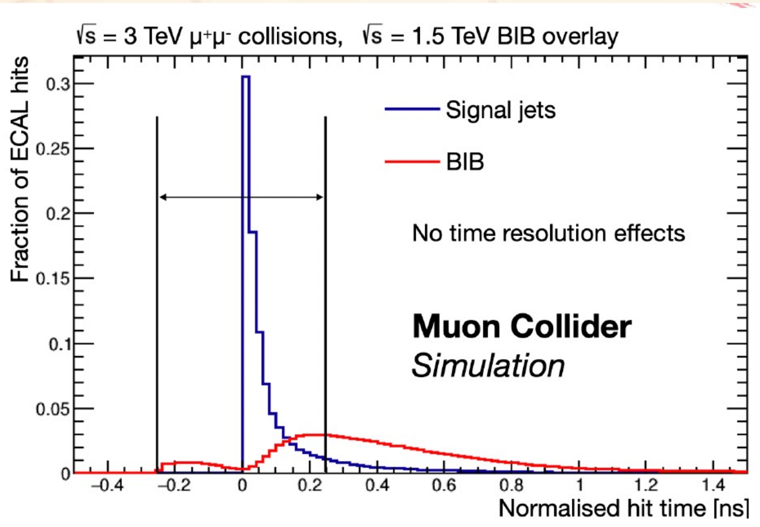
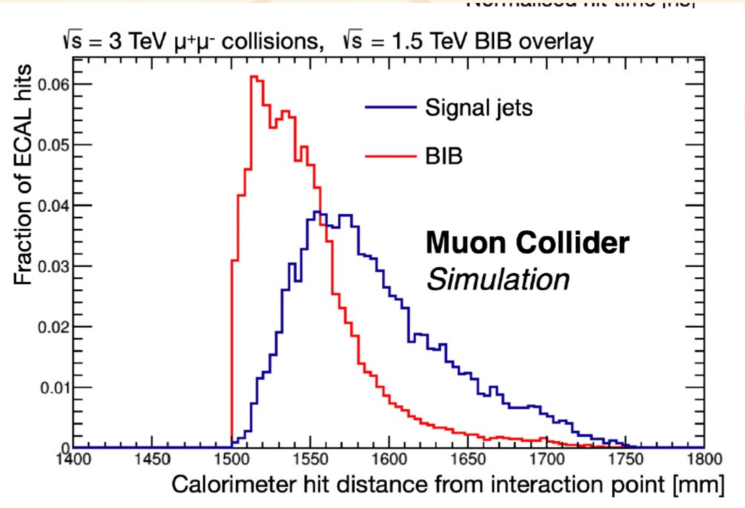


Fig. 27 Energy deposited by the BIB in a single bunch-crossing in the ECAL

- ~300 particles/cm^2 @ ECAL surface 96% γ @ <E>~1.7 MeV / 4% n
- 100 krad/y, 10^{13}-10^{14} 1 MeV neq/cm^2

~100 ps resolution to reject BIB tails





Longitudinal shower profile helps with BIB rejection

Calorimetry: HCAL

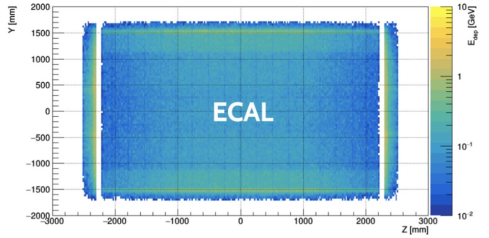
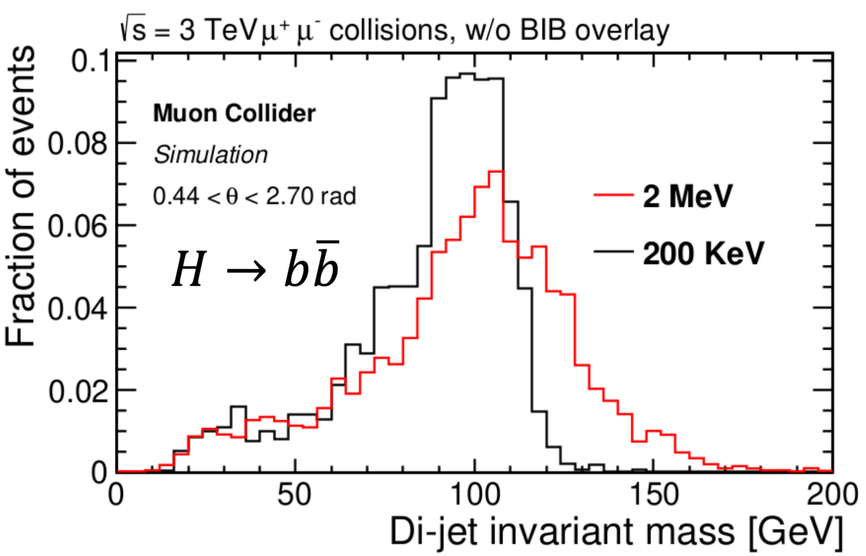


Fig. 27 Energy deposited by the BIB in a single bunch-crossing in the ECAL

Aim is 3-5% σ_E/E for >100 GeV jets to e.g. separate W/Z →jj

BIB rejection: 100ps resolution+2 MeV/cell threshold (dominant effect on energy resolution)



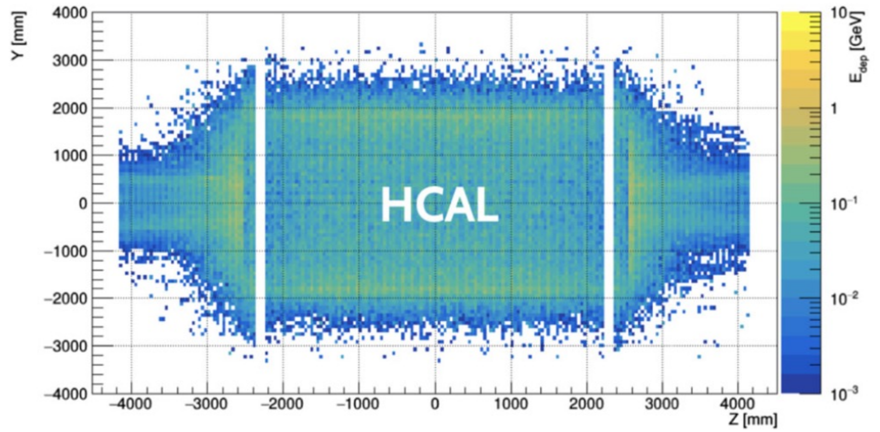
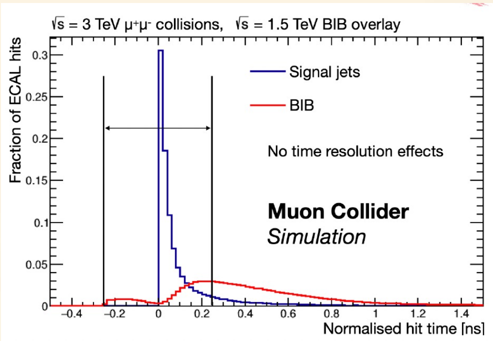


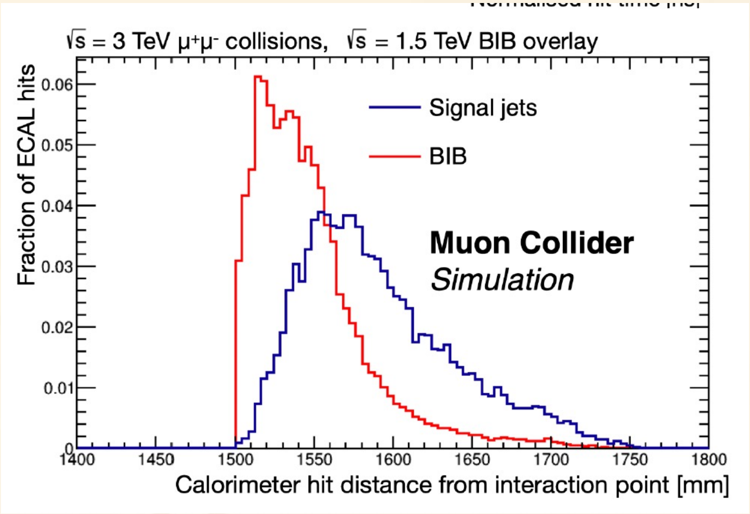
Fig. 28 Energy deposited by the BIB in a single bunch-crossing in the HCAL

HCAL occupancy much less severe (0.1x ECAL)

Back to the realm of less “BIB driven” detector designs

Calorimetry Requirements





- Good timing
- Longitudinal and transversal (~cmxcm) segmentation
- Good energy resolution [10%/$\sqrt{E}$ ECAL, 30%/$\sqrt{E}$ HCAL]

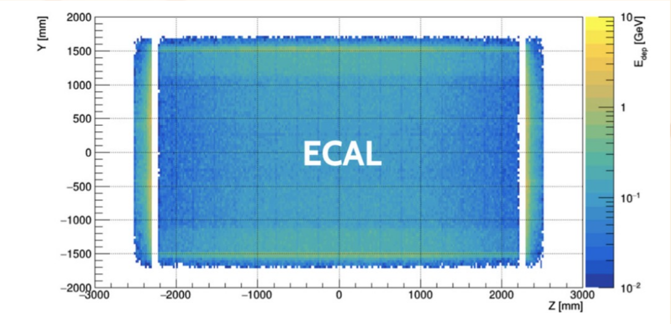


Fig. 27 Energy deposited by the BIB in a single bunch-crossing in the ECAL

Several R&D opportunities from DRD efforts are being evaluated

Muon Detectors

- BIB affects mostly the detector's endcaps, close to the beamline
- Dominated by ~<100 MeV n and ~M10 MeV γ
- ~100μm x <1ns resolution

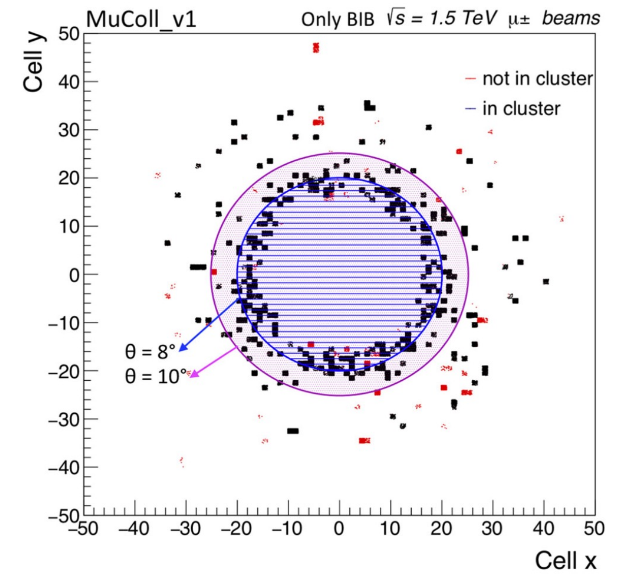


Fig. 30 BIB muon hit spatial distribution in the first layer of the muon endcap. The detector hits not associated to a cluster are shown by the red markers. The blue circle corresponds to region $\theta < 8°$, while the purple to $\theta < 10°$

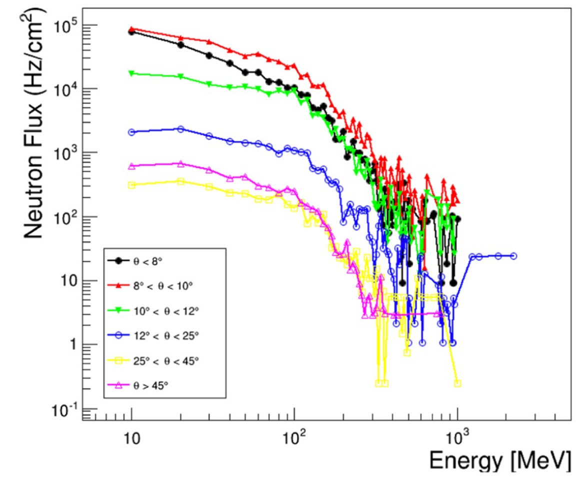


Fig. 31 Energy distribution of neutrons from BIB. Colours represent different geometrical regions of the muon system

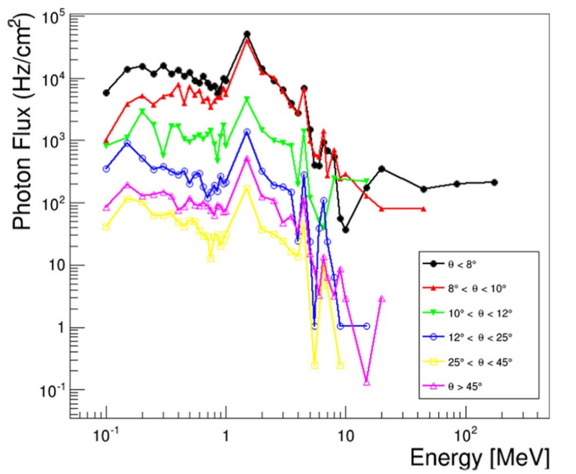


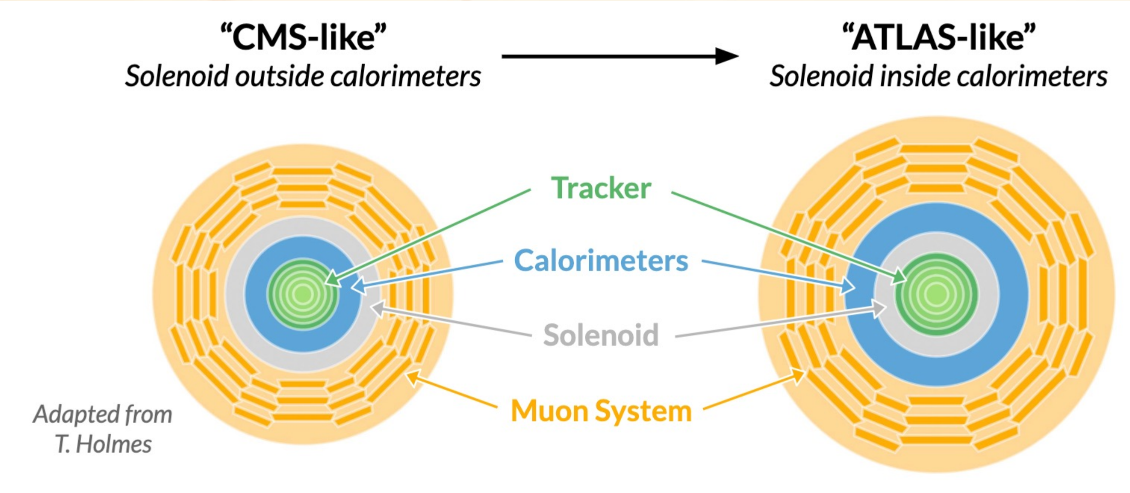
Fig. 32 Energy distribution of photons from BIB. Colours represent different geometrical regions of the muon system

Requirements are at the limit of existing (e.g. RPC technology): boost MPGD [Micromegas and GEM] R&D with excellent timing capabilities

10 TeV Detector Design Effort

Executive Summary

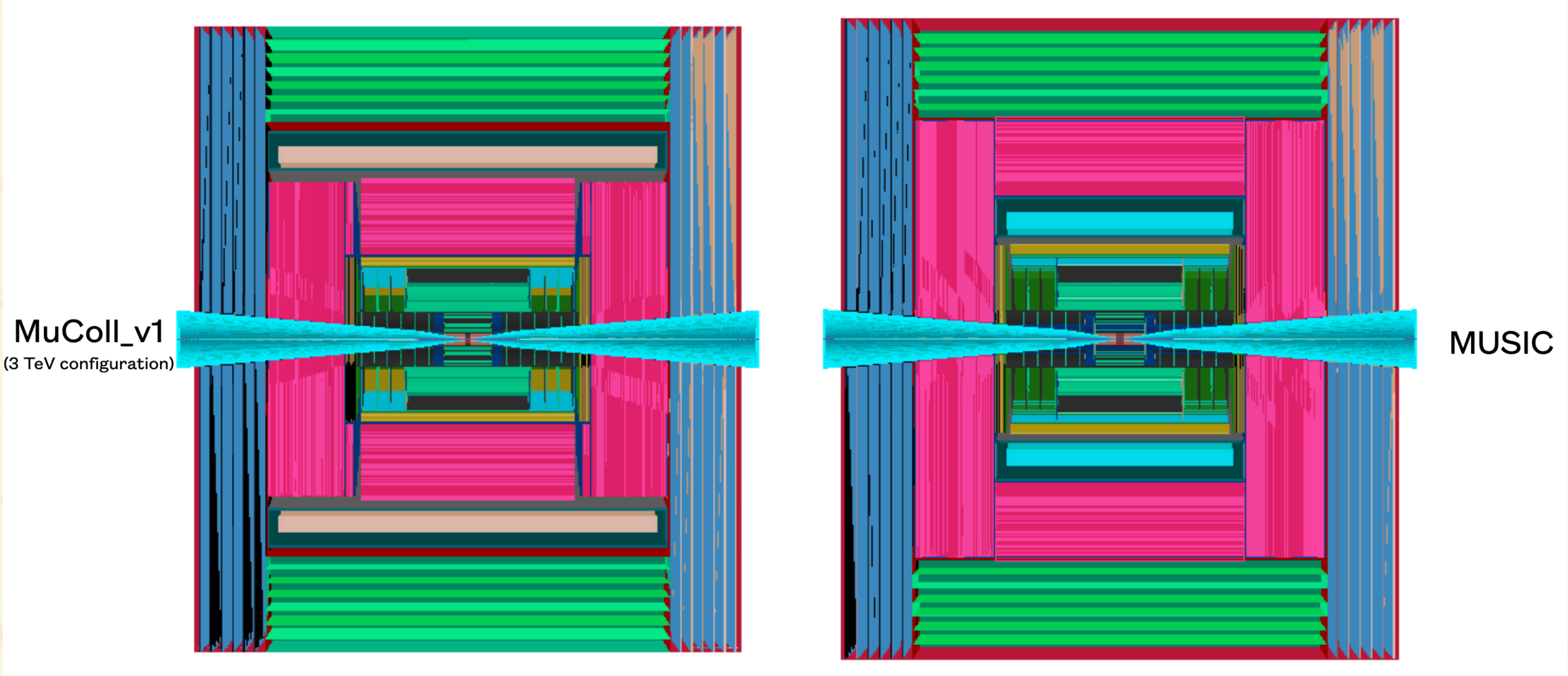
- Design is BIB-driven
  - Studies so far based on 1.5 TeV BIB: 3 TeV and 10 TeV under production
- Timeline driven by European Strategy milestones
- Two detector “flavours” under study



Critical aspects:

- Solenoid strength and location
- MDI optimisation: nozzles shape and materials
- Different detection technologies for complementarity and 2x IP readiness

MUSIC



- 4-5 T solenoid to contain BIB
  - Compromise between BIB exposure, high-pT tracking resolution and low-pT tracking reach
- HCAL iron used to close magnetic flux
- ECAL within magnet volume to achieve $10\%/\sqrt{E}$ energy resolution

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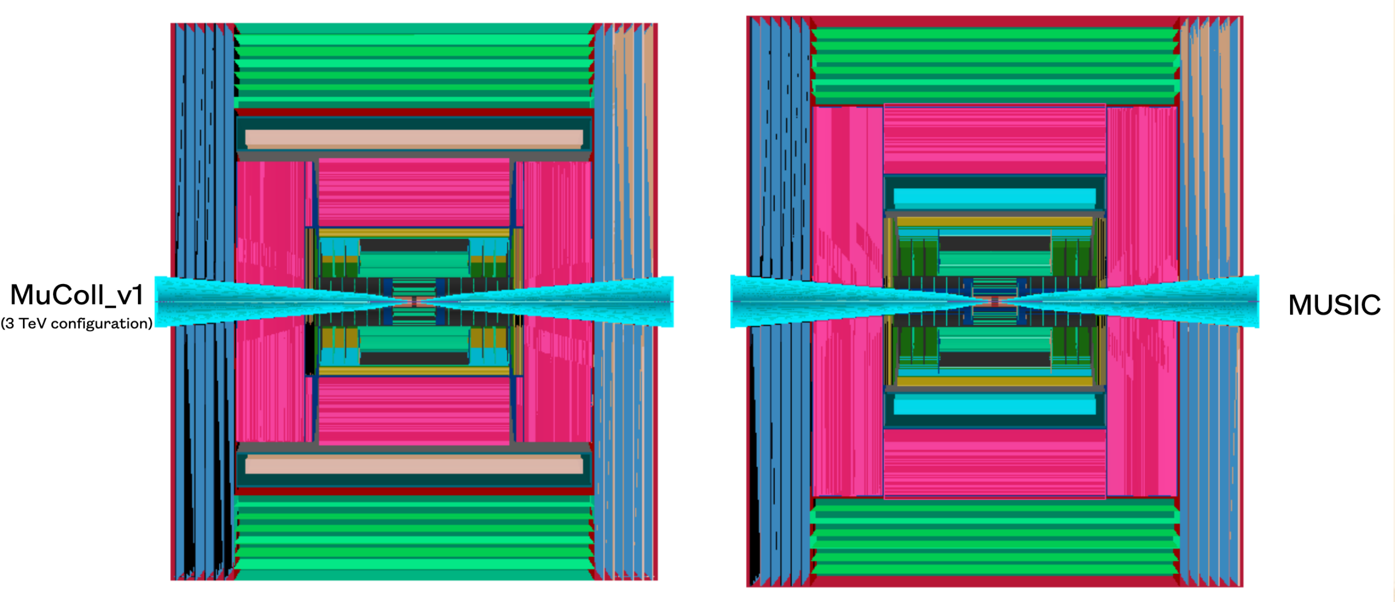

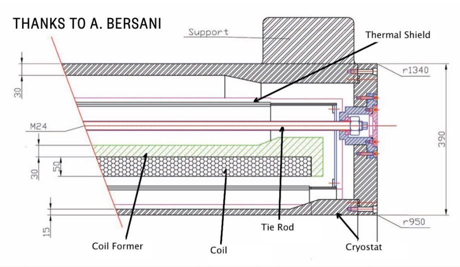

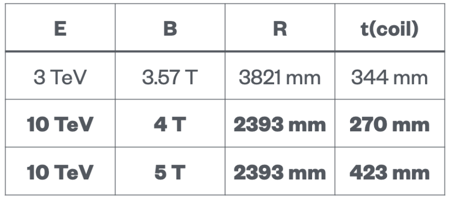

E	B	R	t(coil)
3 TeV	3.57 T	3821 mm	344 mm
10 TeV	**4 T**	**2393 mm**	**270 mm**
10 TeV	**5 T**	**2393 mm**	**423 mm**

+About 40 mm steel vacuum tank

- 4-5 T solenoid to contain BIB
    - Compromise between BIB exposure, high-pT tracking resolution and low-pT tracking reach
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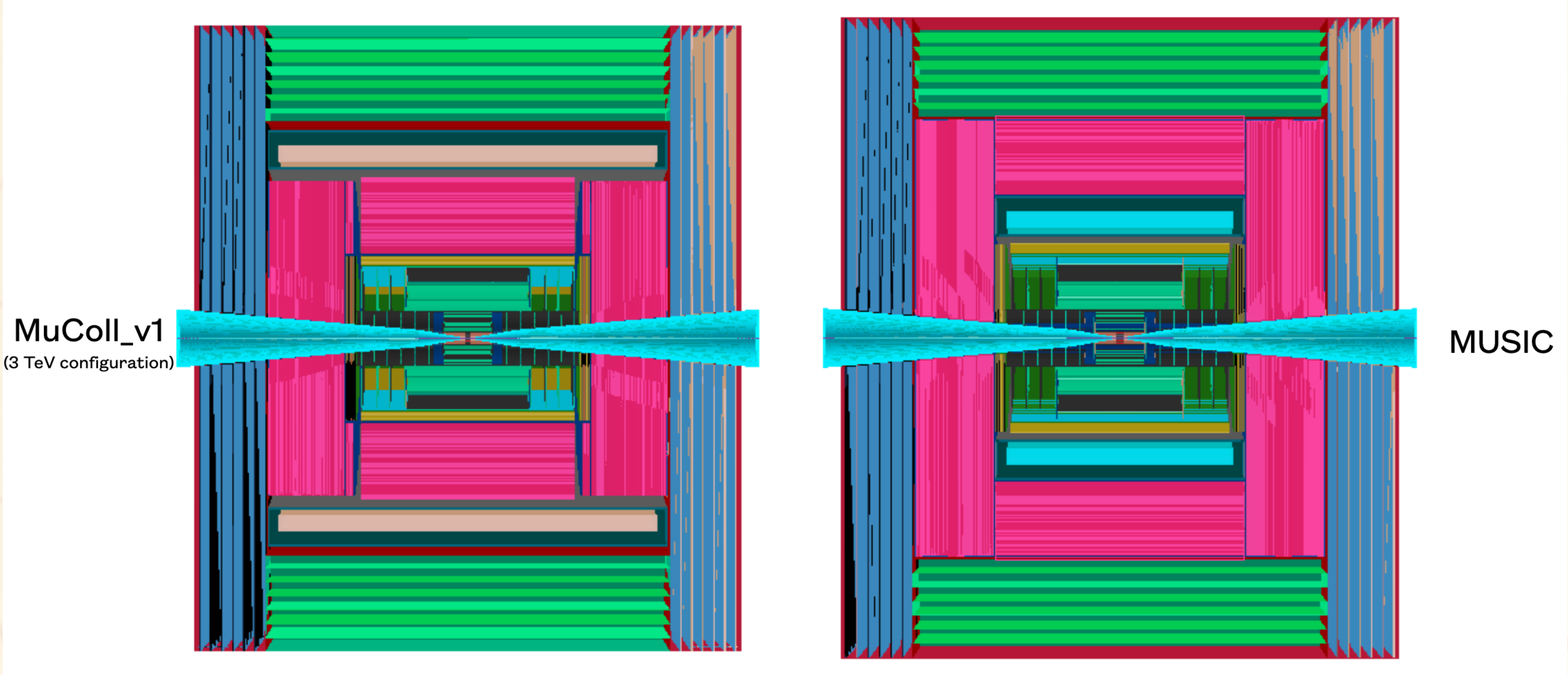

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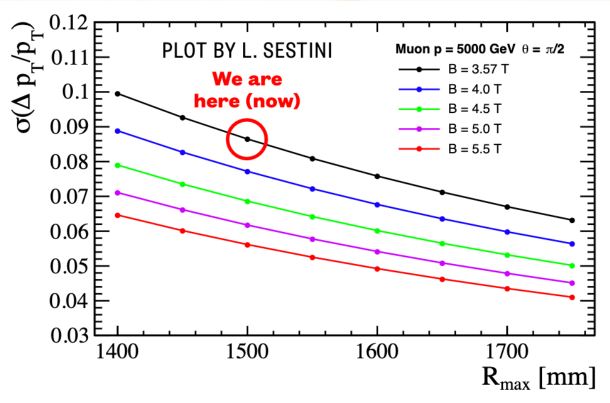
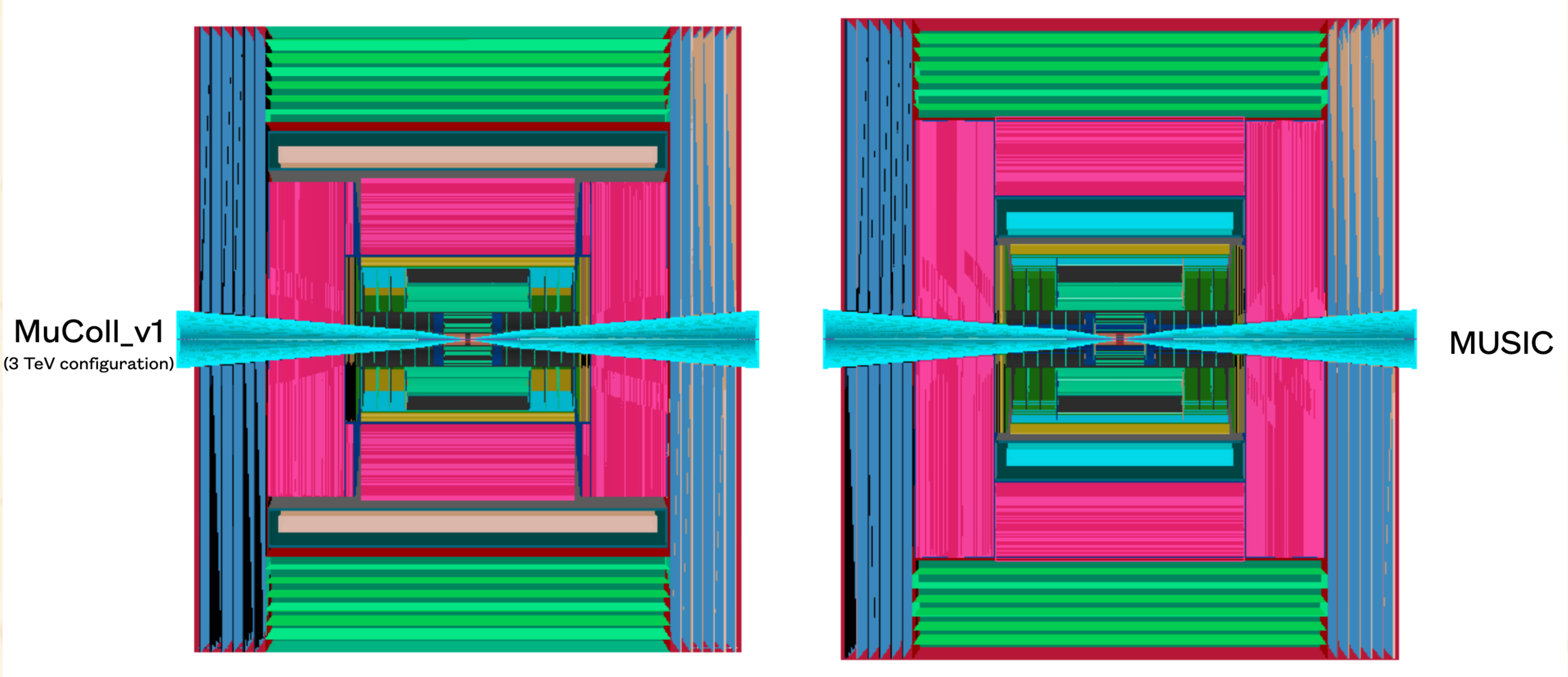
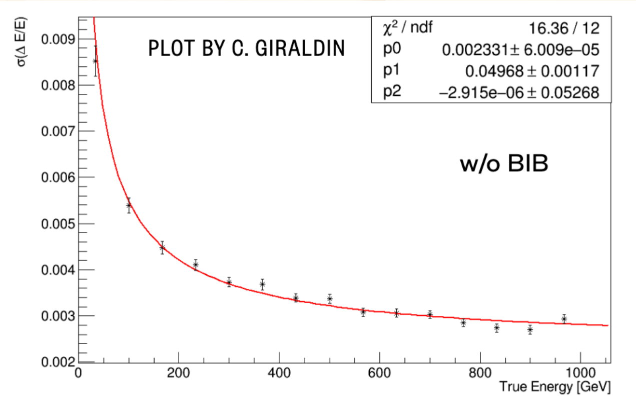


MUSIC



- 4-5 T solenoid to contain BIB
  - Compromise between BIB exposure, high-pT tracking resolution and low-pT tracking reach
- HCAL iron used to close magnetic flux
- ECAL within magnet volume to achieve $10\%/\sqrt{E}$ energy resolution



Detector Technologies

Tracker

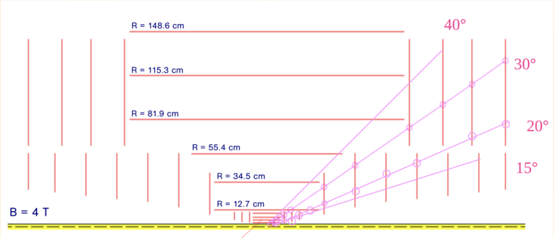
- Mix of Micro and Macro pixels
- Geometry and field optimisation on-going, jointly with nozzle layout

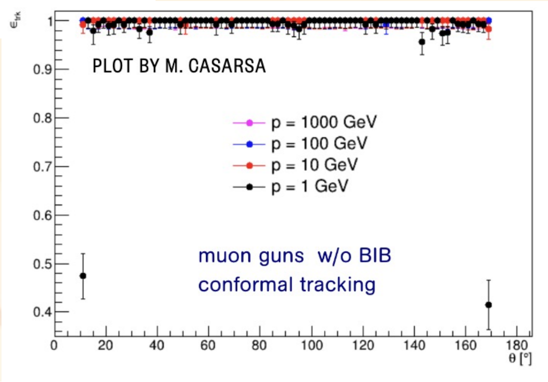
Calorimetry

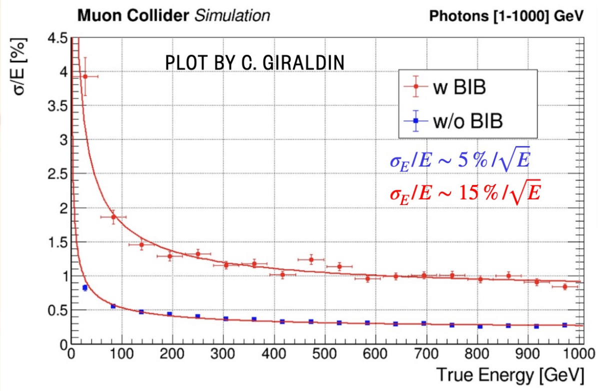
- ECAL: 5 layers (22 X_0) 10x10x40 mm^3 PbF_2 crystals with SiPM readout
- HCAL: evaluating 3 TeV design (Polystyrene-steel)

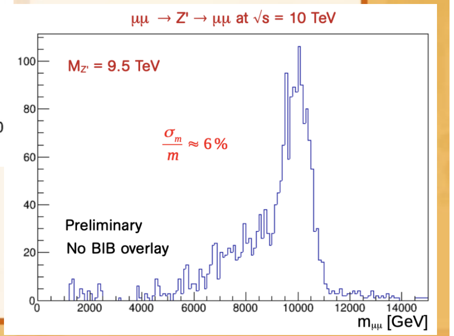
Muon detectors

- Keep 3 TeV design





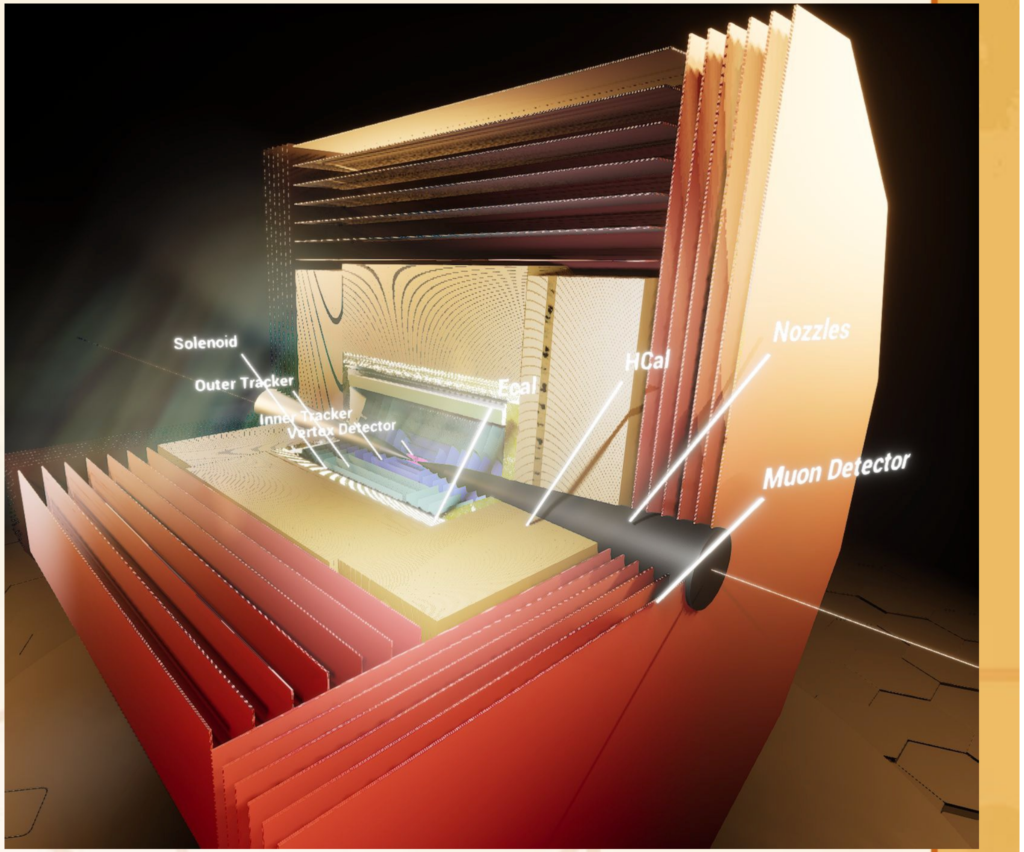




Reference

Design 2 & studies

- 1.5 TeV Nozzle
  - W+B/PE
- Tracker VXD+IT+OT
- 5T Solenoid
- High Granularity calorimeters
  - ECAL: SiW
  - HCAL: Fe+Scintillator
- Muon spectrometer
  - RPC+Air

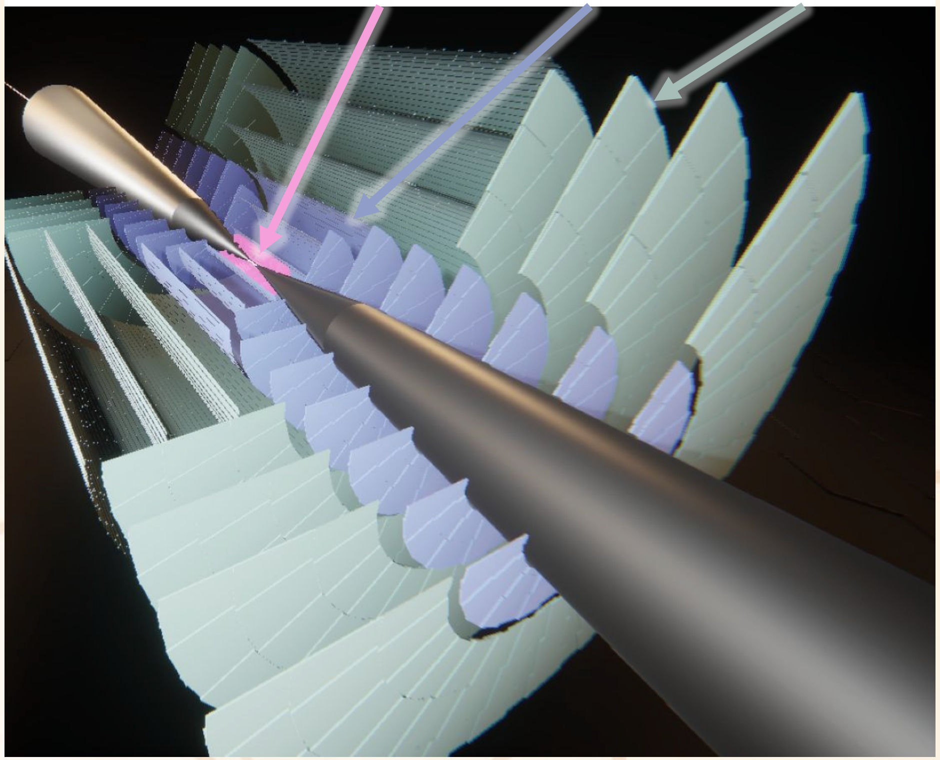


Reference

Design 2 & studies

- 1.5 TeV Nozzle
  - W+B/PE
- Tracker VXD+IT+OT
  - VXD doublets @ 3 TeV, removed (all but 1) @ 10 TeV

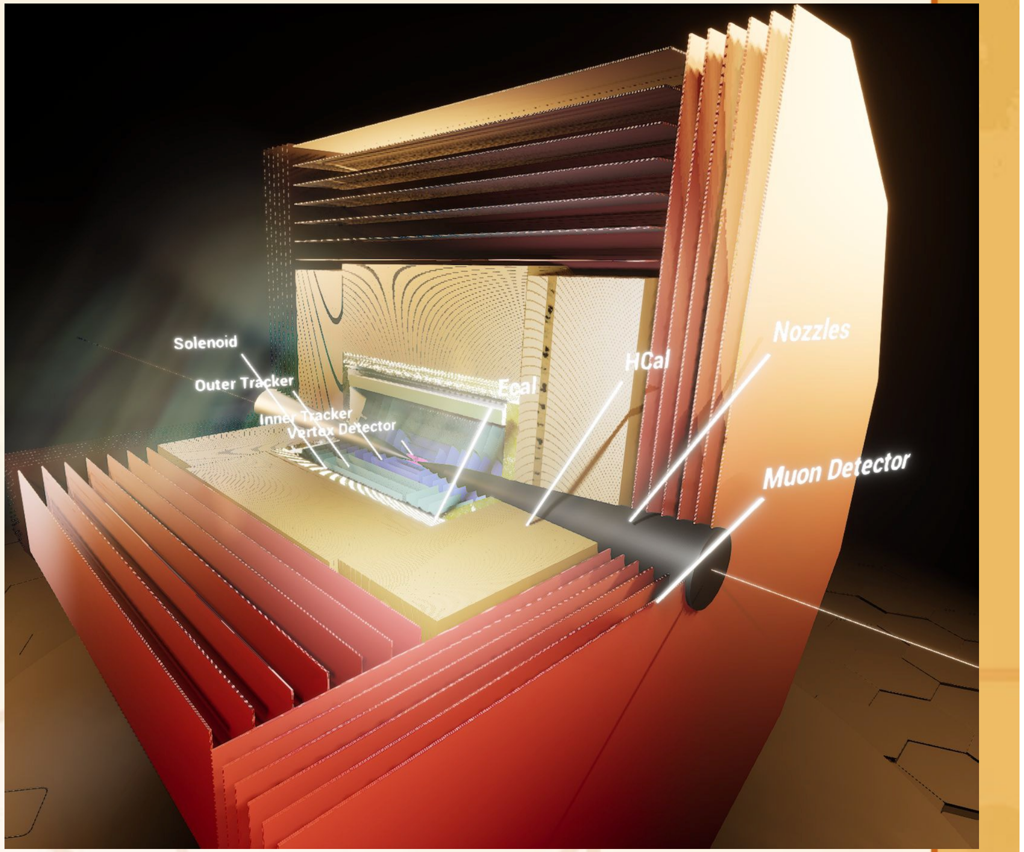
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	25μm × 25μm	50μm × 1mm	50μm × 10mm
Sensor Thickness	50μm	100μmm	100μmm
Time Resolution	30ps	60ps	60ps
Spatial Resolution	5μm × 5μm	7μm × 90μm	7μm × 90μm



Reference

Design 2 & studies

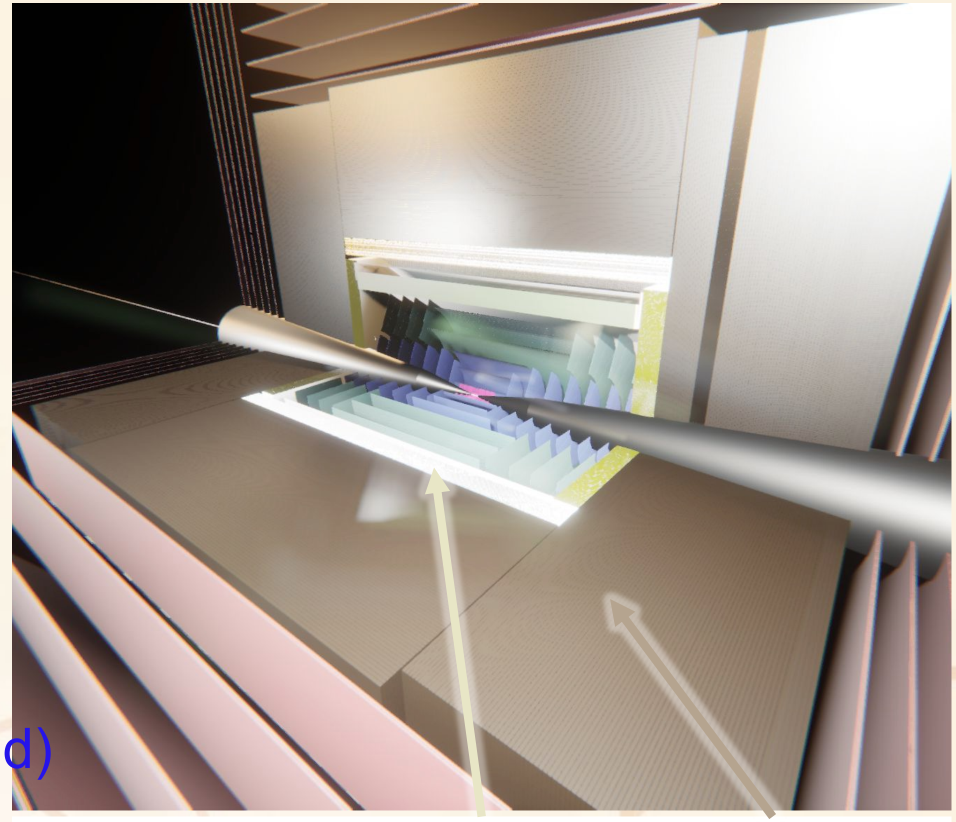
- 1.5 TeV Nozzle
  - W+B/PE
- Tracker VXD+IT+OT
- 5T Solenoid
  - Moved inside calorimetry
  - ~4X_0 of material
  - Further feasibility studies needed



Reference

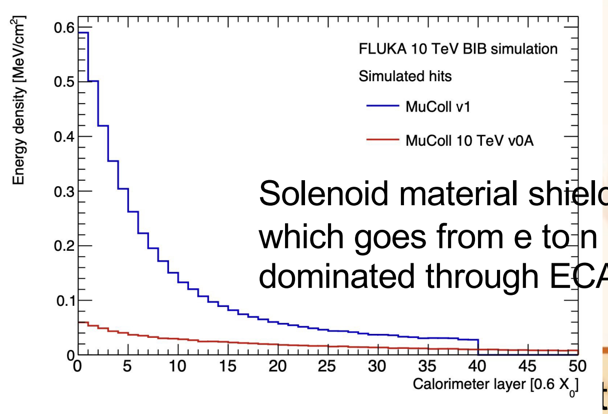
Design 2 & studies

- 1.5 TeV Nozzle
  - W+B/PE
- Tracker VXD+IT+OT
- 5T Solenoid
- High Granularity calorimeters
  - ECAL: SiW (outside solenoid)



	ECAL	HCAL
Cell type	Silicon - Tungsten	Iron - Scintillator
Cell Size	5.1mm × 5.1mm	30.0mm × 30.0mm
Sensor Thickness	0.5mm	3.0mm
Absorber Thickness	2.2mm	20.0mm
Number of layers	50	100

$10\%/\sqrt{E}$ $35\%/\sqrt{E}$



Solenoid material shields BIB which goes from e to n dominated through ECAL

Conclusions and Outlook

- MuCol detector design is Physics and BIB-driven
  - BIB particles reaching the detector are dominated by secondary production: EM and n
    - Strong radial dependence of density
    - Solenoidal field helps mitigate the EM component
  - Detector irradiation comparable to HL-LHC
  - …but with much higher background occupancy
  - Excellent/good timing resolution
  - High granularity
- Technologies are not sufficiently mature at this stage: R&D is needed (and will keep the community engaged)
- An LHC or HL-LHC class detector would not be the solution: at most can be seen as a “demonstrator” of the most critical technologies
- 3 TeV detector design CLIC inspired with variations to mitigate BIB
- 10 TeV detector design on-going, in two different flavours

DAQ and DataFlow

Simplified model:

- Tracker: 100 kHz event rate, 1ns/event window, x2 safety margin, 32bits/hit
  → 40 Mb/event, 30 Tb/s [BIB dominated]
- ECAL: 90 MCH, 10-3 hits/mm2, 0.2 MeV threshold, 20 bits/hit
- HCAL: 10% of ECAL
  → 40 Mb/event, 30 Tb/s
- Total: ~60 Tb/s

What kind of trigger farm would this require?

HLT Processing time (tracking dominated):

- >10 tracks with pT>2.5 GeV found with 240E6 3D-HT cells
- X4 BIB reduction (e.g. loose timing) would bring this into a more feasible range (40E6 3D-HT cells) → 1 track @ pT>2.5 GeV

Dataflow

Detector readout: ~10^4 20 Gb/s links, 60 Tb/s event building bandwidth (could mitigate with filtering)

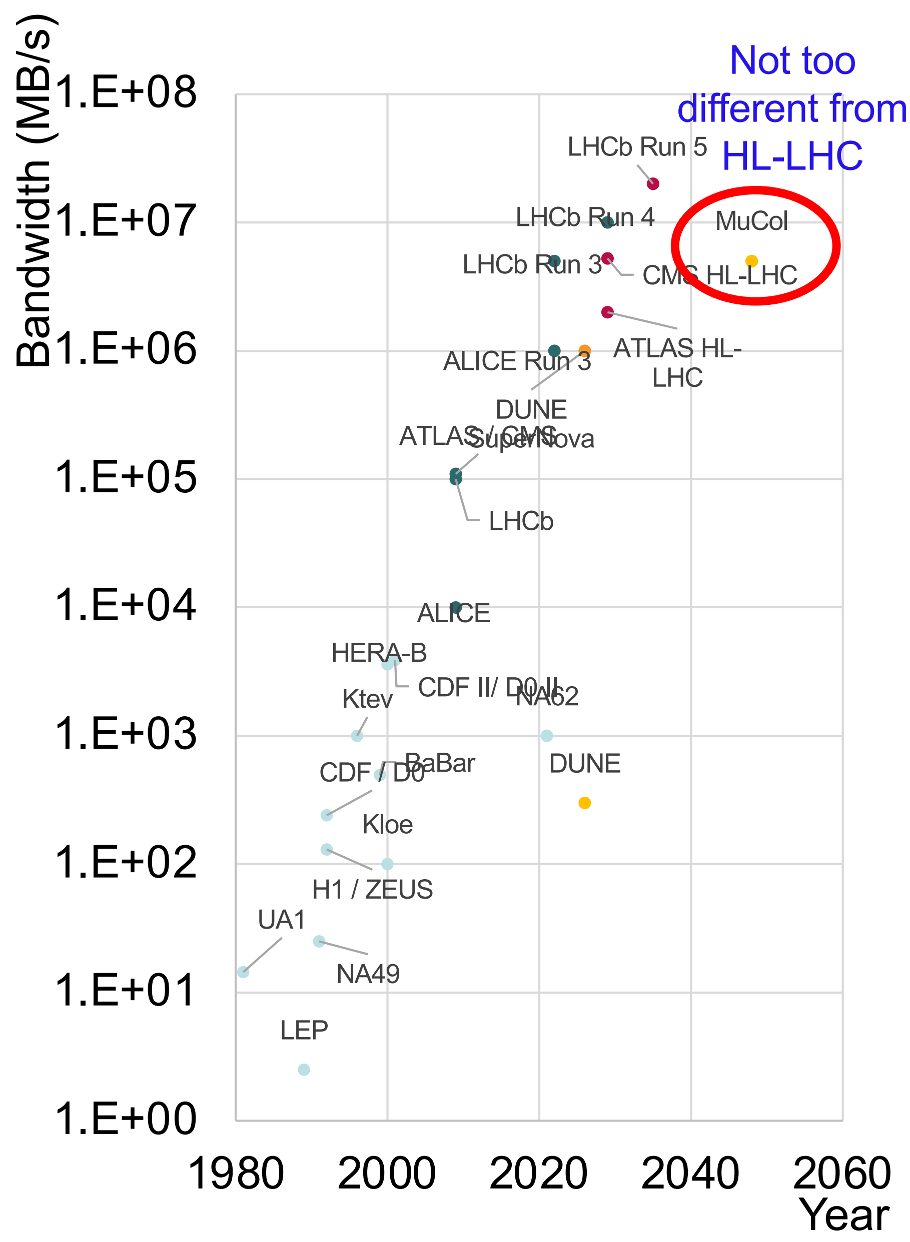
Storage:
No selection: 4 PB/day of storage

Assuming to target HL-LHC storage capacity (~60 GB/s):

- Full event storage ~750 Hz
  - H is ~0.1 Hz, WW is ~1 Hz
- Event cleaning (BIB rejection): 99% BIB hits rejection → 100 kHz

Triggering:
HLT Processing time (tracking dominated):

- >10 tracks with pT>2.5 GeV
- X4 BIB reduction (e.g. loose timing) would bring this into a more feasible range



Not too different from HL-LHC

Backup Material