e/mu-LHC proposal:initial discussion

mu-LHC detector concept

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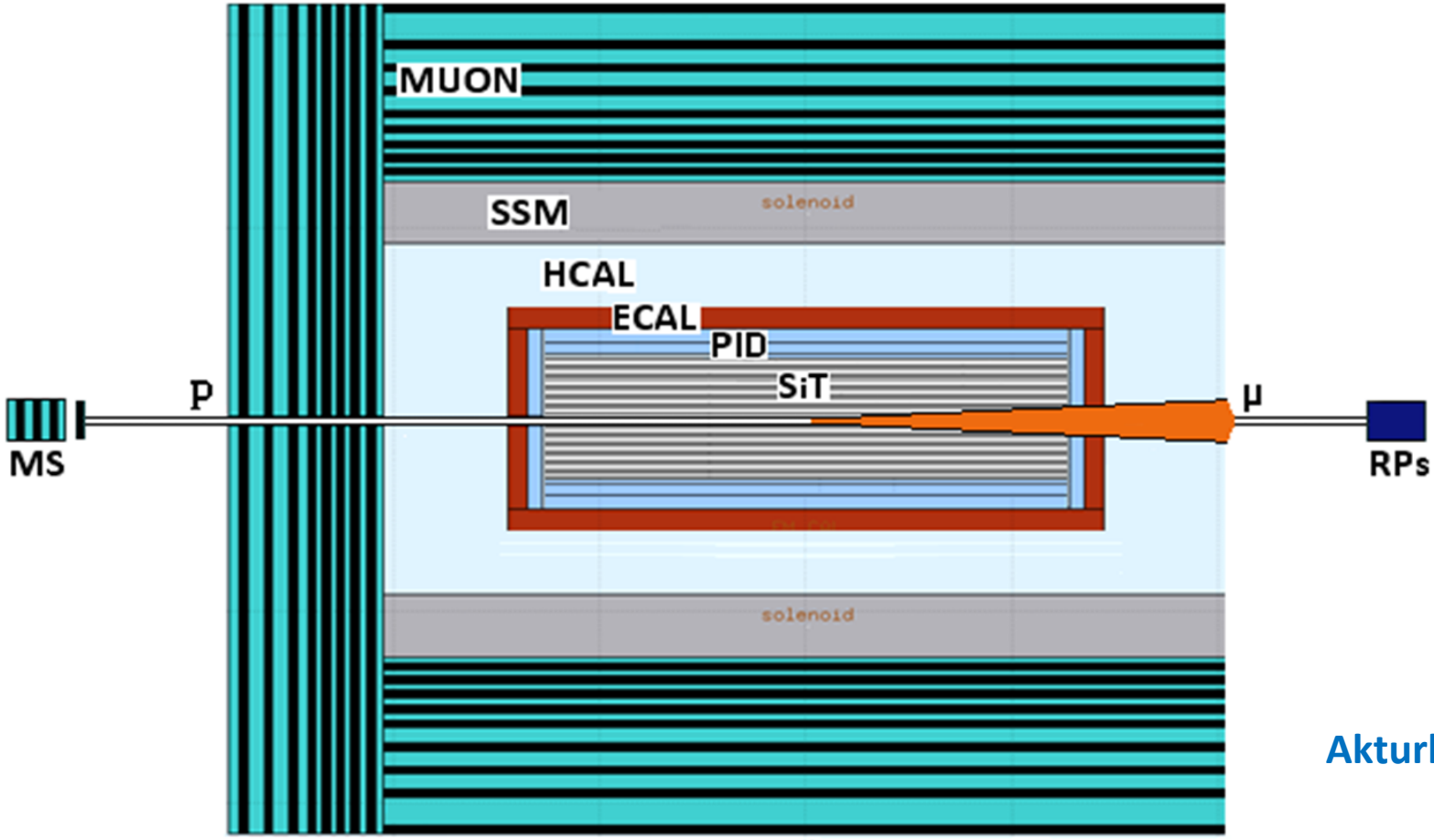
Detector is needed to detect particles at $\sqrt{s}$ = 5.3 TeV produced from a 7 TeV proton beam against a 1 TeV muon beam collision.

The scattered parton (e.g., jets) and muon are mostly going toward the backward direction.

The detector;

- an asymmetric cylindrical layout
- configured superconducting solenoid magnet (SSM) for precise momentum measurements for charged tracks
- a tracker (SiT) to provide precision timing and position information
- a particle identification (PID) system located outside of the silicon tracker
- calorimeters (ECAL and HCAL) to precisely measure the energies of the particles
- muon spectrometer (MUON) to measure muons with proper resolution

The conceptual design of a general purpose μh detector structure



Akturk, D. et al., 2025

On the beam pipe outside the detector, Roman Pots (RPs) in the far forward direction and a muon system (MS) in the far backward direction are mounted to detect the scattered protons and muons respectively.

Acosta, D. et al., 2023

Beam-induced backgrounds (BIB)

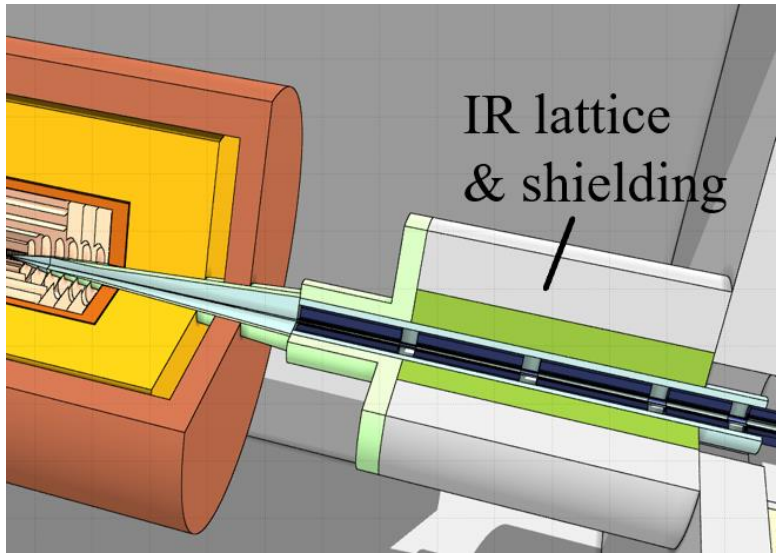
One of the main challenge in the design of the μh detector.

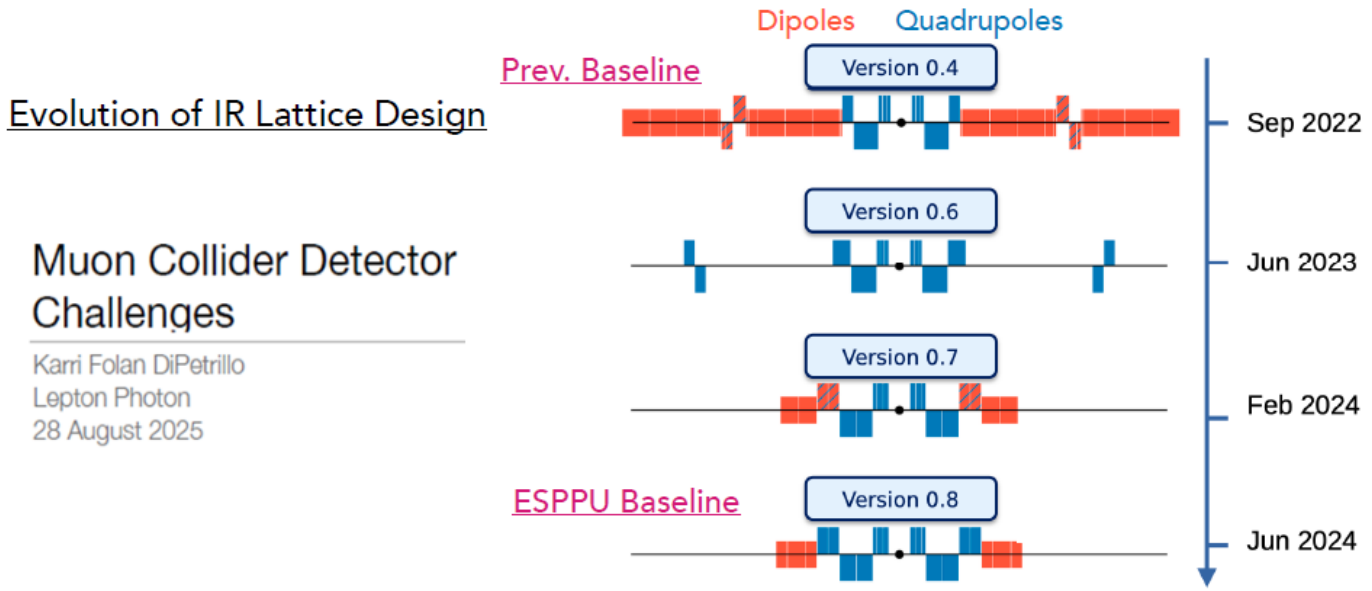
Decays products of the muon beams cause the presence of a large amount of the background particles (such as photons, electrons and neutrons) in the detectors.

Three ways in BIB Mitigation

Timing selection- Can reduce BIB, especially low-energy contributions

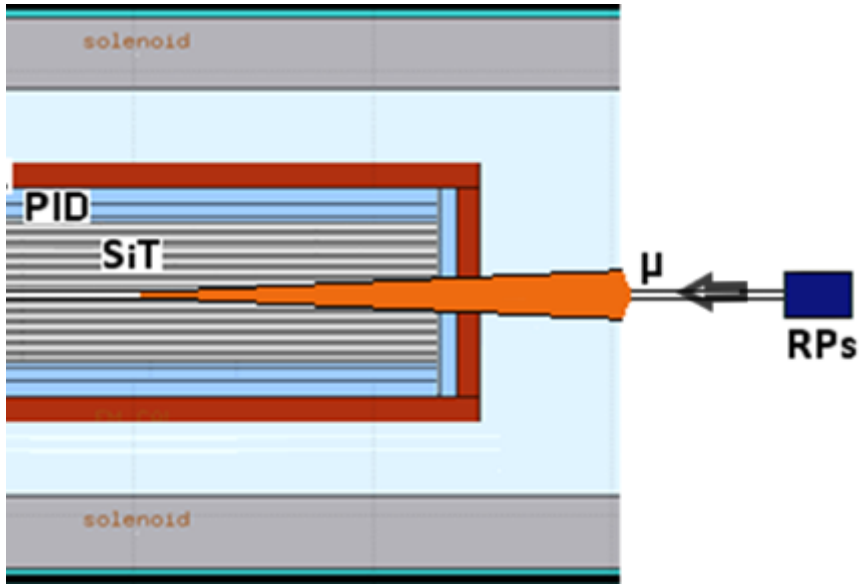
Designing of the Collider Lattice- Configuring lattice near the IR reduces the BIB





Shielding Nozzles- Change the BIB composition and reduce the BIB by several orders of magnitude

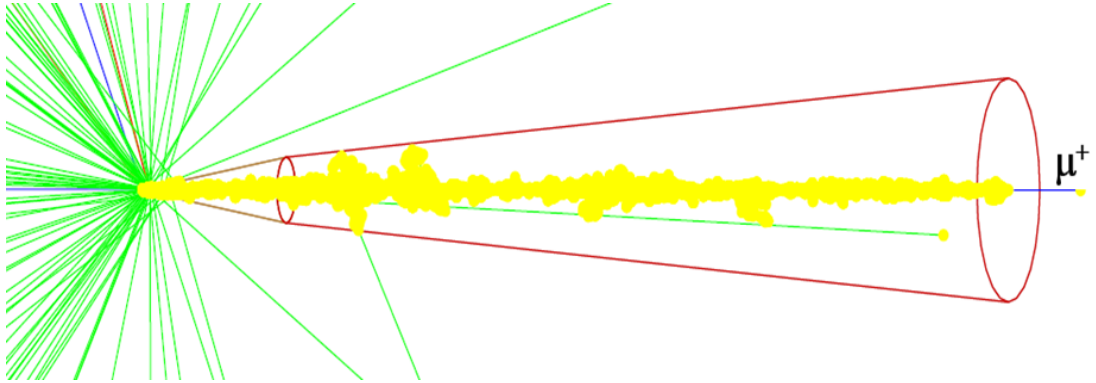
A shielding nozzle is used to protect the innermost detector elements. The shielding tungsten nozzle cladded with borated polyethylene is placed to the muon coming side, as seen as brown conical shape in Figure.



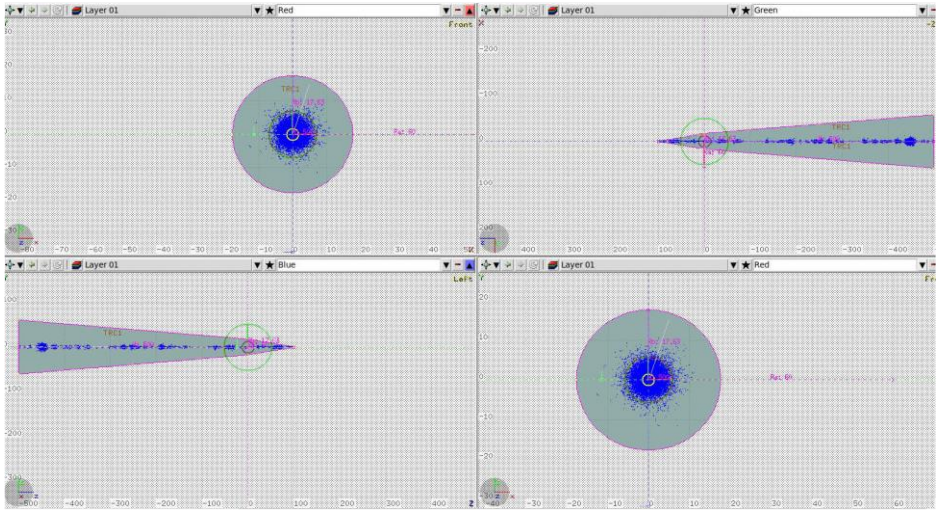
The location of the nozzle in the detector

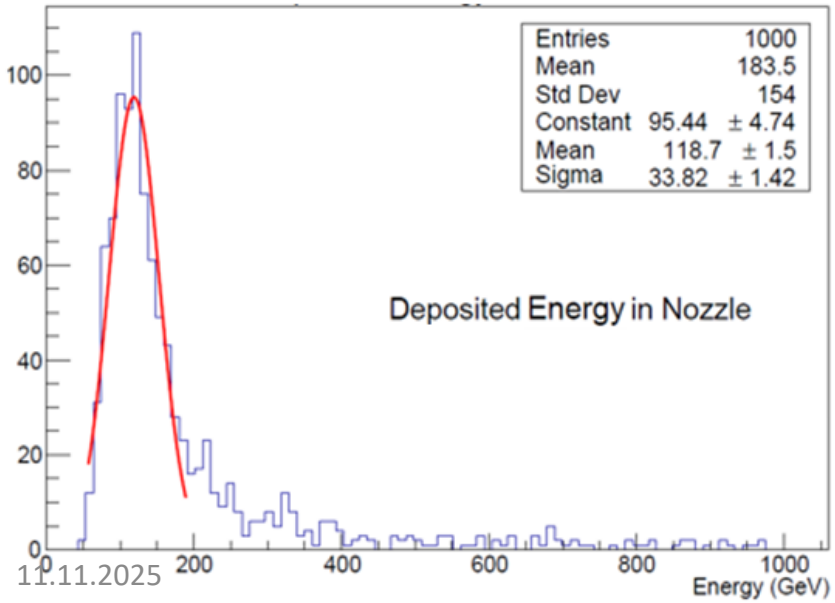
The nozzle affects the physics performance by limiting the angular acceptance of the detector.

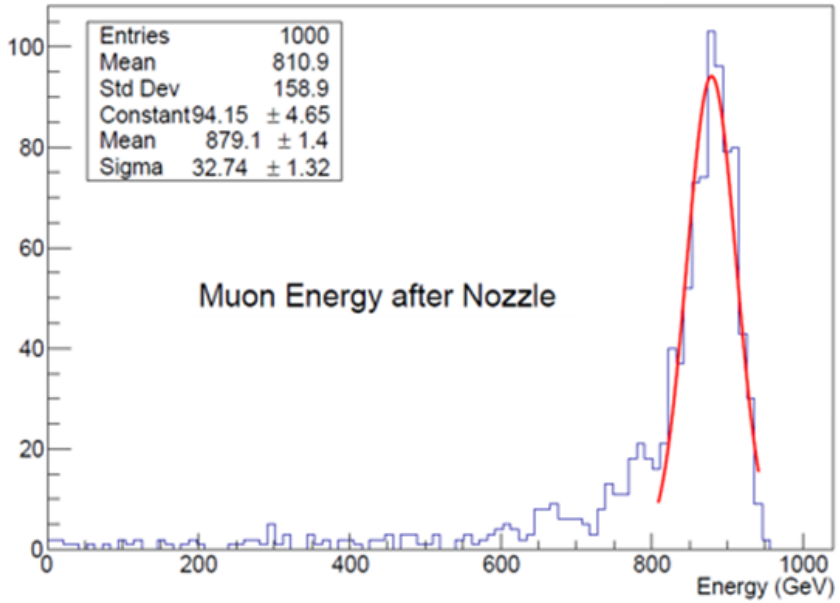
The GEANT4 and FLUKA simulation codes have been used to simulate the energy loss of high energy muons passing through the 6 meter long tungsten shielding.



Simulated energy loss of 1 TeV muons traversing such a tungsten cone.



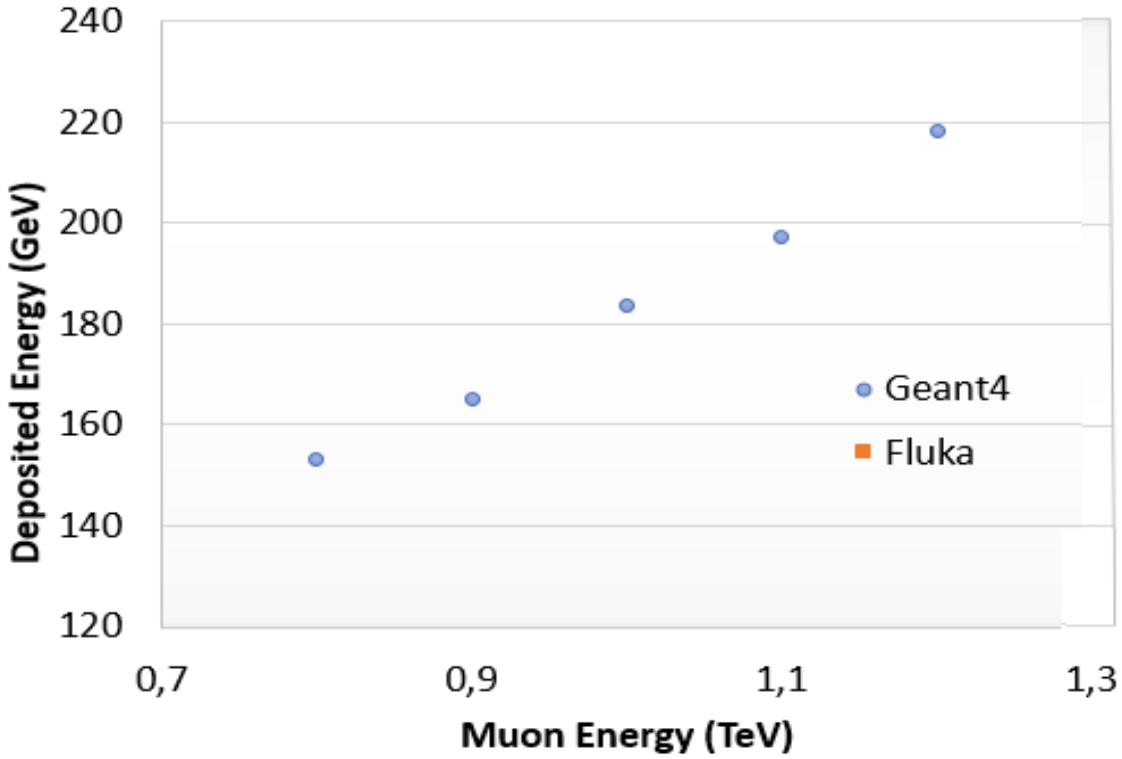


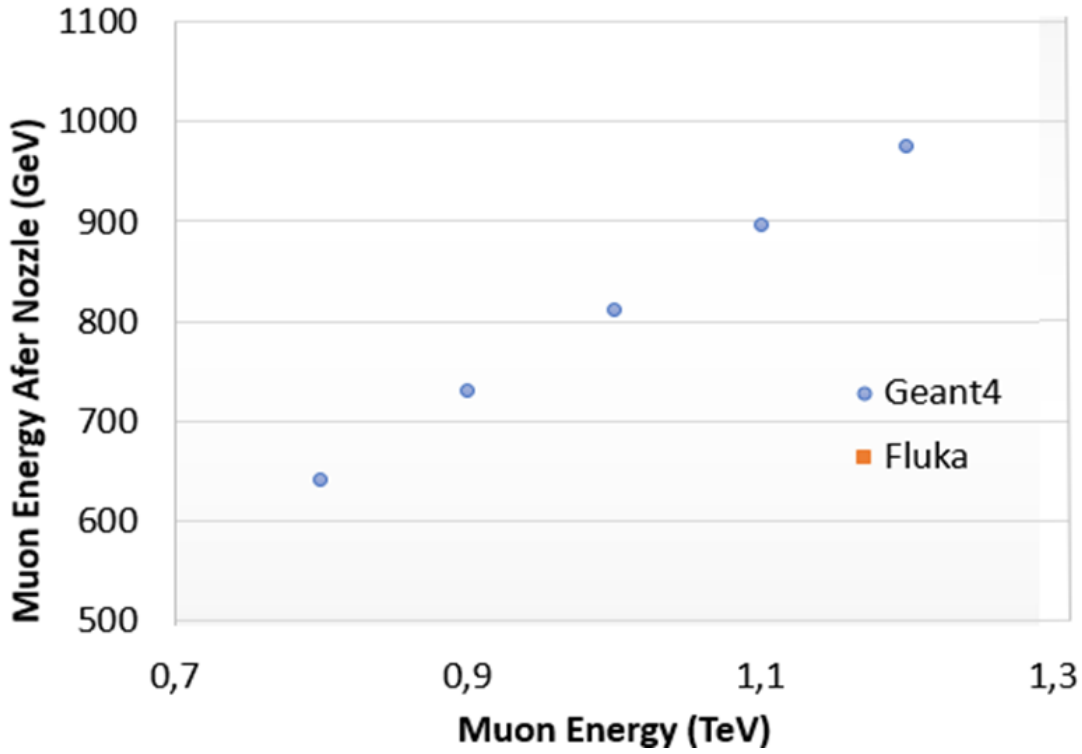


The average deposited and passing muons energies around as 19 % and 81 % respectively.

Akturk, D. et al., 2025

The energy depositions in the cone volume and the remaining energies after passing the cone were calculated for the muons between 0.8 TeV and 1.2 TeV energies.





BIB mitigation using shielding nozzles studies for different cone material combinations are ongoing.

Geant4 and FLUKA Simulations for Nozzle Optimization

Through Geant4 and FLUKA simulations, nozzle design for the muon-proton detector should focus on material and geometry optimization (including determining the optimal nozzle size while keeping the structure as light-weight as possible):

- Add nozzles with different materials, small-angles (10°, 15°, 20°, etc.), and lengths to the mu-LHC detector geometry, and generate BIB and signal particle fluxes for each configuration.
- Perform acceptance optimization for detector angular coverage.
- Conduct detailed dose and activation analysis: detector sensors, electronics, cables, and magnet coils experience long-term radiation damage. Dose maps along the nozzle region, beam pipe, and inner tracker volume should be produced to identify areas requiring more radiation-resistant materials.
- Carry out material optimization and cooling/protection design: Which materials provide both radiation hardness and low mass? How can the accumulated heat (deposited energy) be removed? How can other detector components and electronics be shielded from radiation?
- Study the correlation between nozzle angle, BIB suppression, and physics acceptance:
  A larger nozzle angle → stronger BIB suppression but smaller physics acceptance;
  a smaller angle → wider acceptance but more background leakage.

Thus, the optimal angle will be determined through Geant4/FLUKA simulations balancing background suppression and physics reach.

Castelli, L. 2025

Other detector design option

The baseline LHeC detector

Covering from 1 to 179 degrees

All-silicon tracker extended forward wheels

EM calorimeter — Covering wide η with small X_0

Solenoid and dipole

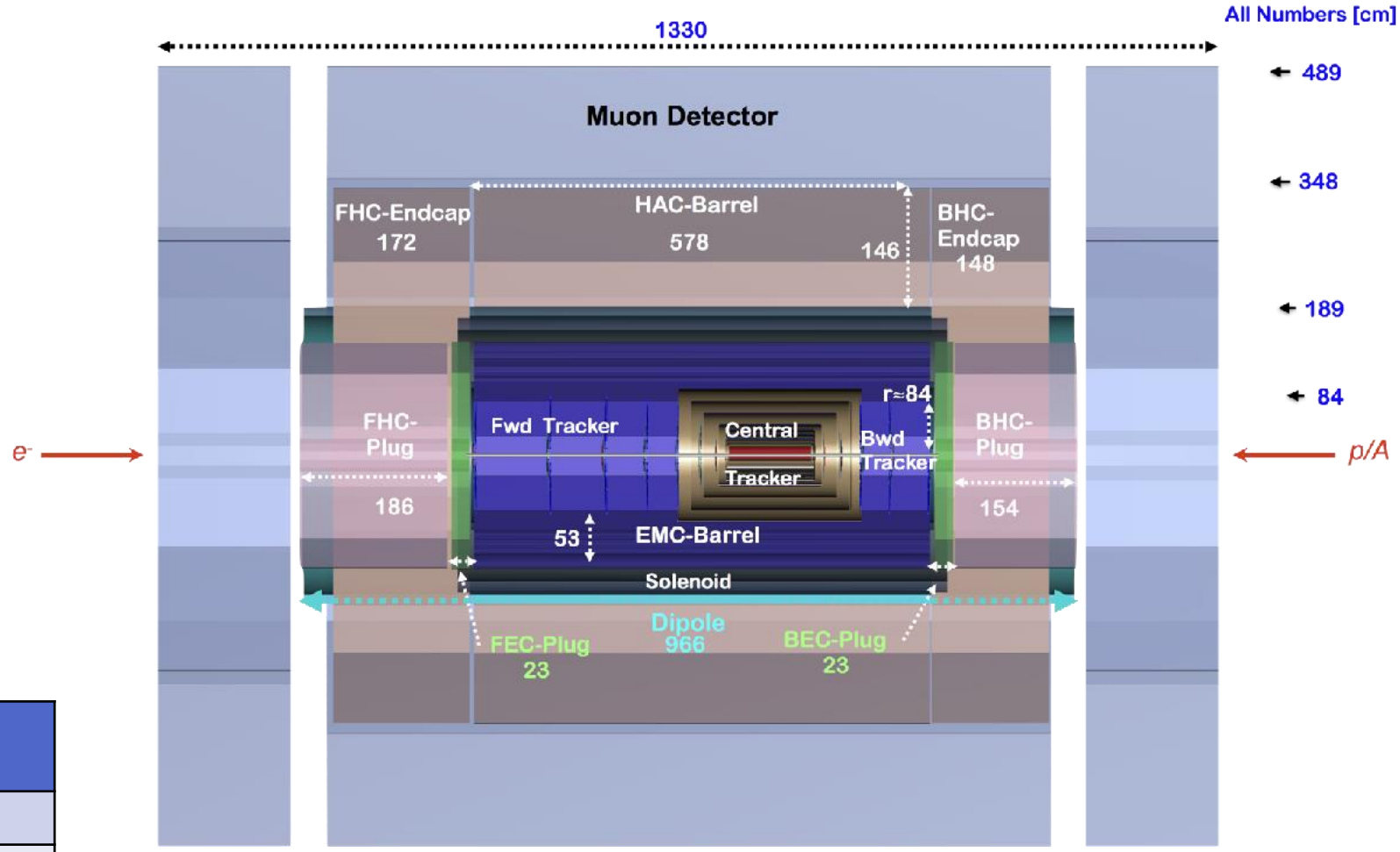
HCAL — Good resolution for HCAL

Muon system embedded in return yoke

+ Forward/backward detectors along beamline (p/n/e/γ-tagger)

LHeC CDR, 2012

Calorimeter Baseline configurations	
EM barrel	LAr
Had barrel + Endcap	Sci-Fe
EM+Had forward Plug	Si-W
EM+Had backward Plug	Si-Pb/-Cu



Aiming for compact, modular and very hermetic detector

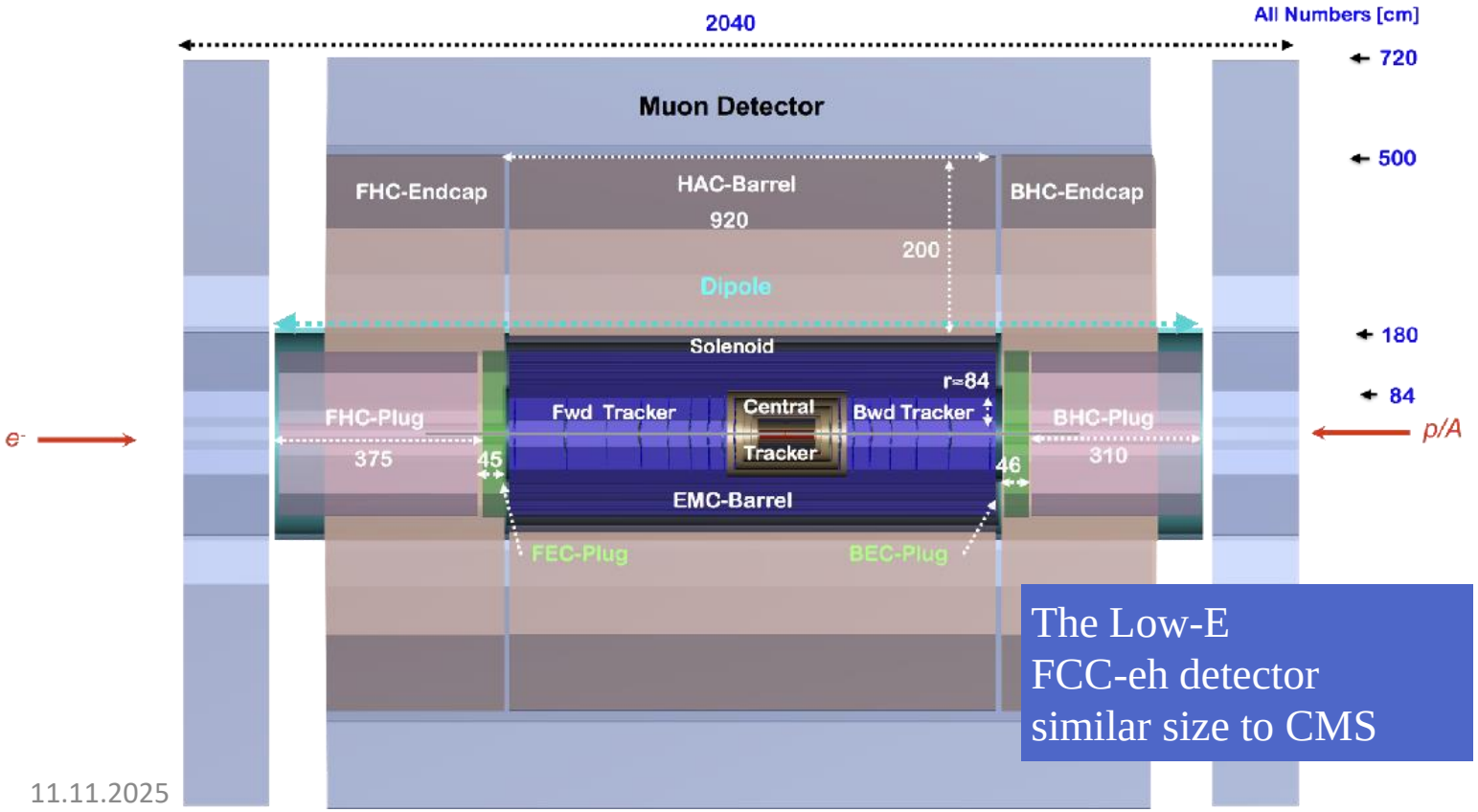
Detector design studies for FCC-eh

The fcc detector was considered as extended volume of the LHeC detector

- Proton 20 and 50 TeV, electron 60 GeV
  - As for LHeC 50 or 60 GeV electrons to be measured in backward direction
- Design for LHeC with extended volume / layers will serve also for FCC-eh
  - **Forward/Central: scales in $\sim \log E_{had}$ for calo**

Agostini, P. et al., 2021

— Experiment Magnets: Solenoid + Dipole
— Even longer track region
to retain 1° performance



The Low-E
FCC-eh detector
similar size to CMS

Total length 13.3 → 20.4m
Radius 4.9 → 7.2m

Central tracker also with (possibly tilted) wheels

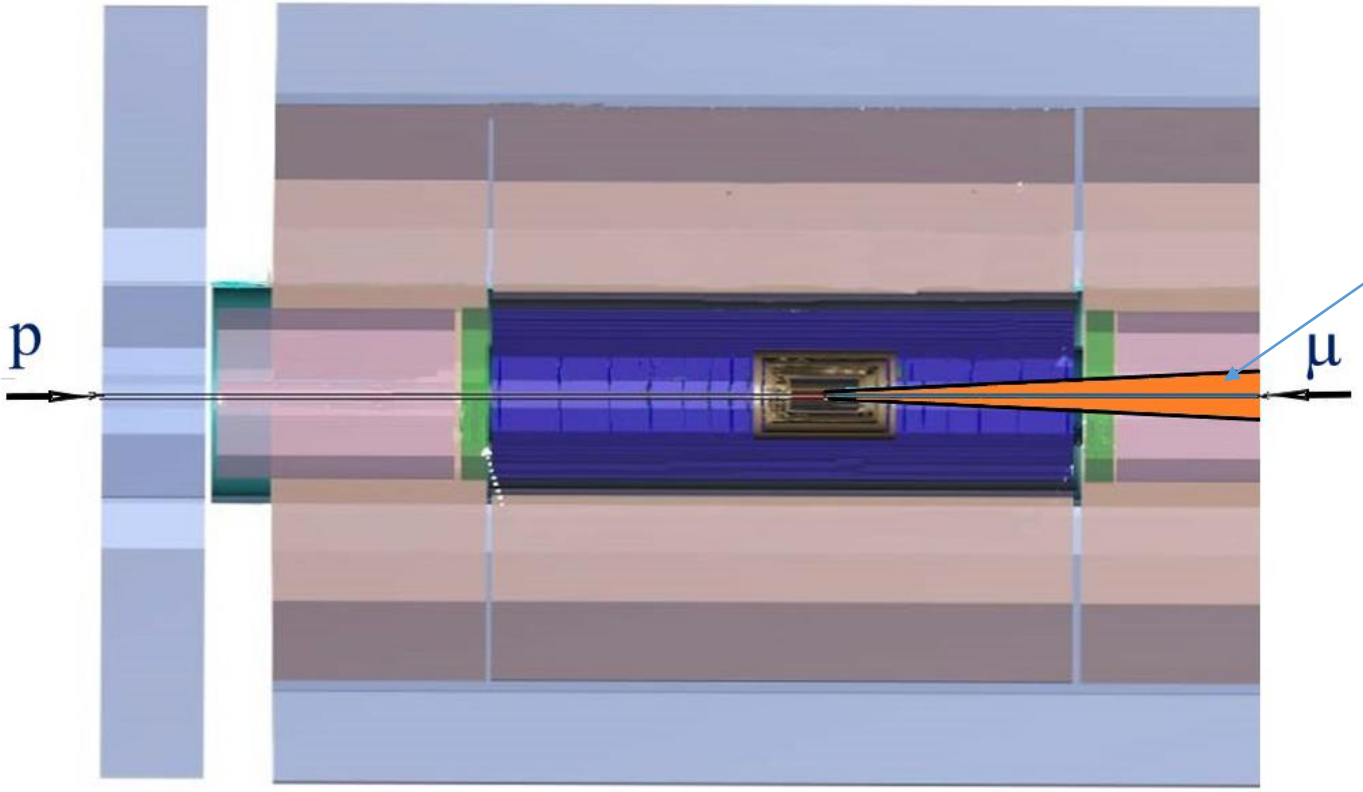
Fwd tracker 4 → 8 disks
Bwd tracker 2 → 6 disks

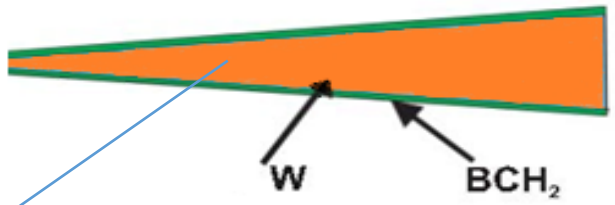
HadCal:
12-15 interaction lengths

Most demanding: forward detectors

From LHeC to mu-LHC: Possible detector changes and technical challenges

Major challenges such as reduced small-angle acceptance, background control and mechanical redesign. Successful integration requires joint optimization of the Machine-Detector Interface and timing systems.





Geometry: The nozzle cone blocks small-angle regions → the tracker's inner radius must be increased, and the first pixel layer and endcap disks should be placed outside the nozzle shadow.

Acceptance: Small-angle physics in the forward (muon) direction would be partially lost due to the presence of the nozzle, while the backward (proton) acceptance would remain largely preserved.

IR integration: The nozzle's opening angle, typically between 10° and 20°, should be selected carefully so that it fits well with the beam pipe, final-focus magnets, and service lines

Timing: To reduce background signals, fast timing detectors with precise timing resolution such as LGAD or PICOSEC-MM should be added to precisely measure the arrival time of particles, allowing the system to distinguish true physics events from delayed background hits.

Magnetic structure: The solenoid + dipole configuration should be re-optimized; nozzle shielding replaces synchrotron-radiation (SR) masks.

Radiation and cooling: The flux around the nozzle increases → radiation-hard sensors and efficient cooling are required.

Calorimeters and muon systems: Fast-timing and shielding layers should be integrated to reduce the effects of background particles on these outer detector components

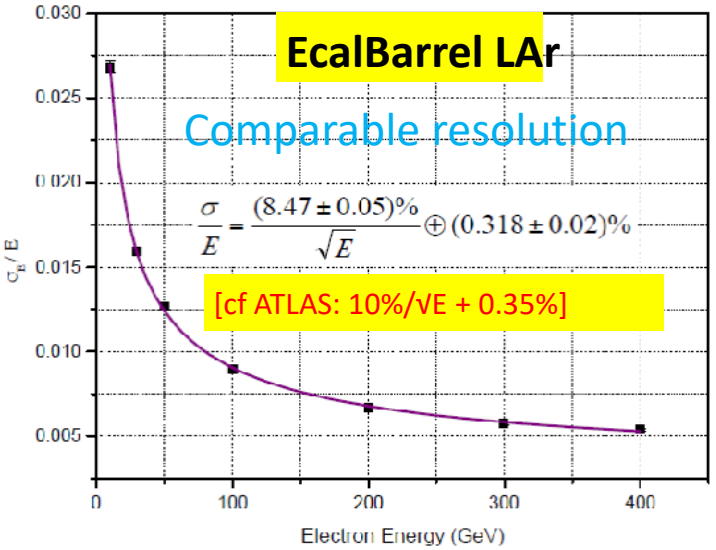
Calorimetric energy resolutions

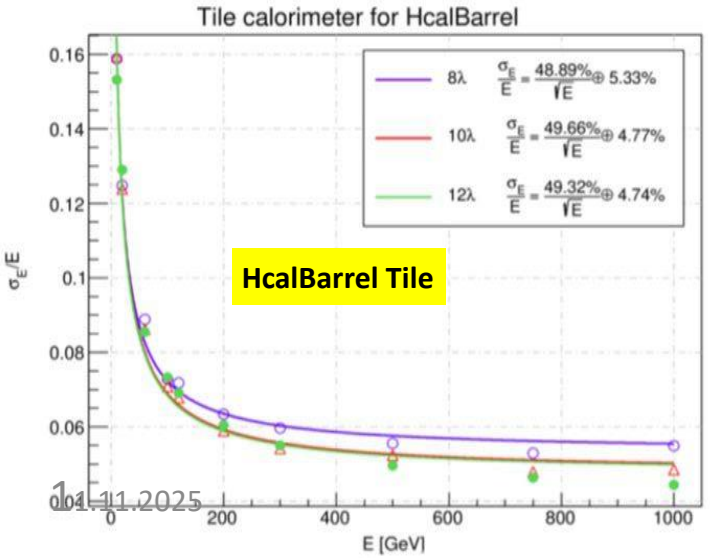
Cold Option

2.2mm lead + 3.8mm LAr layers

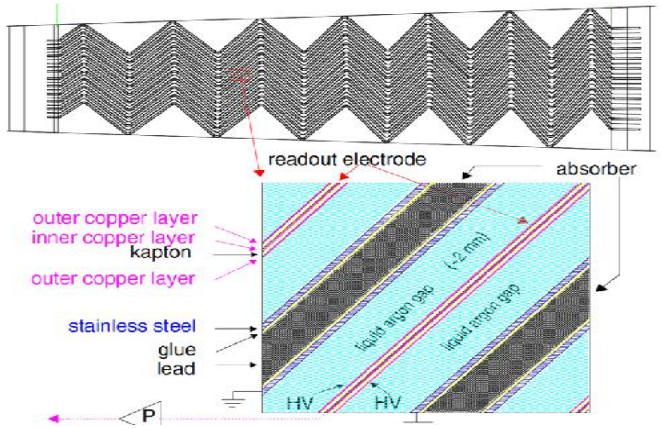
LAr (~25X_0) 8.47 /$\sqrt{E}$ ⊕ 0.32%

LHeC CDR, 2012

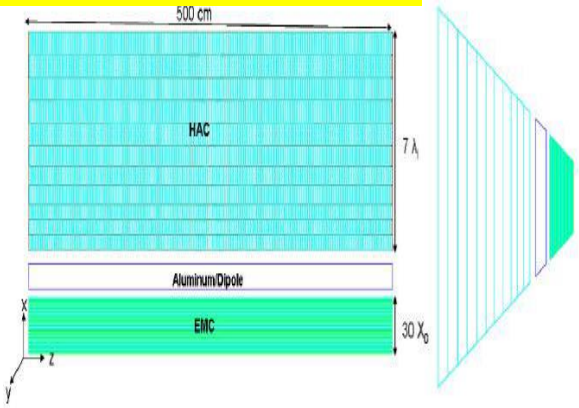




GEANT4 simulation of response to electrons at normal incidence



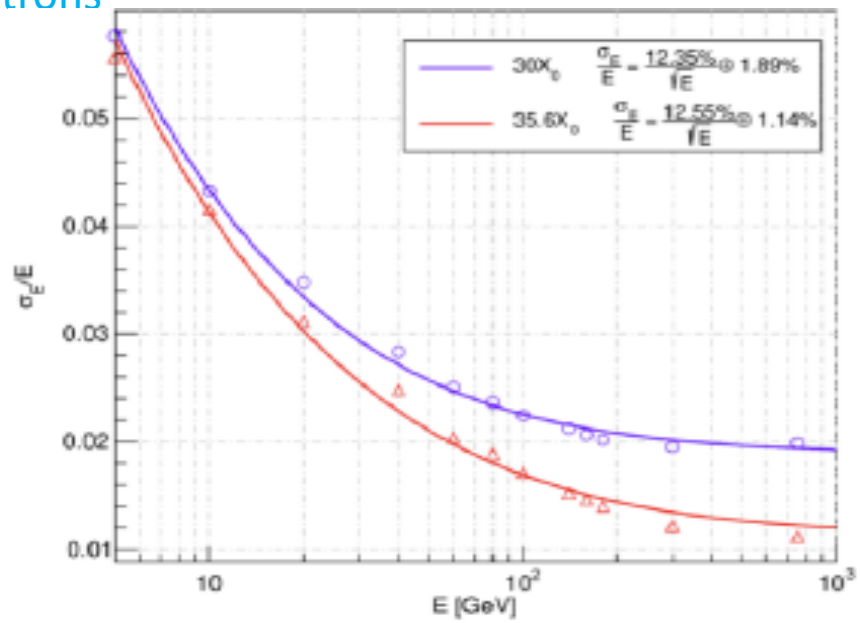
Ecal Barrel LAr + HcalBarrel Tile



Warm Option

20 x 0.85 cm Pb layers interspaced by 4 mm Scint.

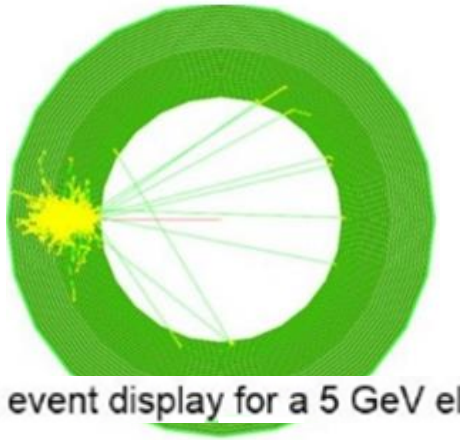
Sci-Pb (30X_0) 12.55/ $\sqrt{E}$ ⊕ 1.89%



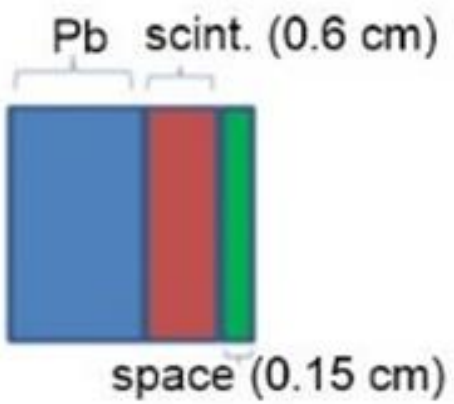
The ongoing evaluations aim to determine if the entire calorimeter's resolution meets the specifications required for specific physical events, such as the decay of the Higgs boson into two W bosons (H->WW), bottom quark pairs (bb), and the top quark

Calorimetric energy resolutions

Geant4 Simulation for the Higher Energies



an event display for a 5 GeV electron



$30X_0$

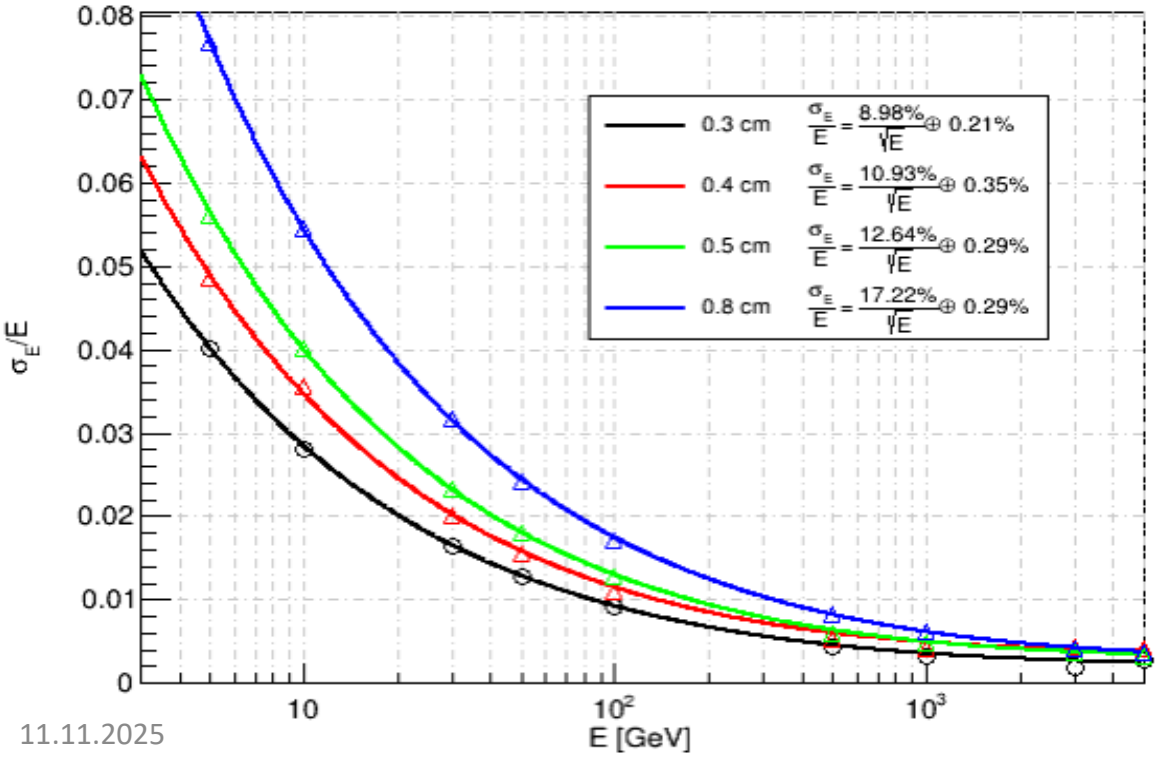
v1

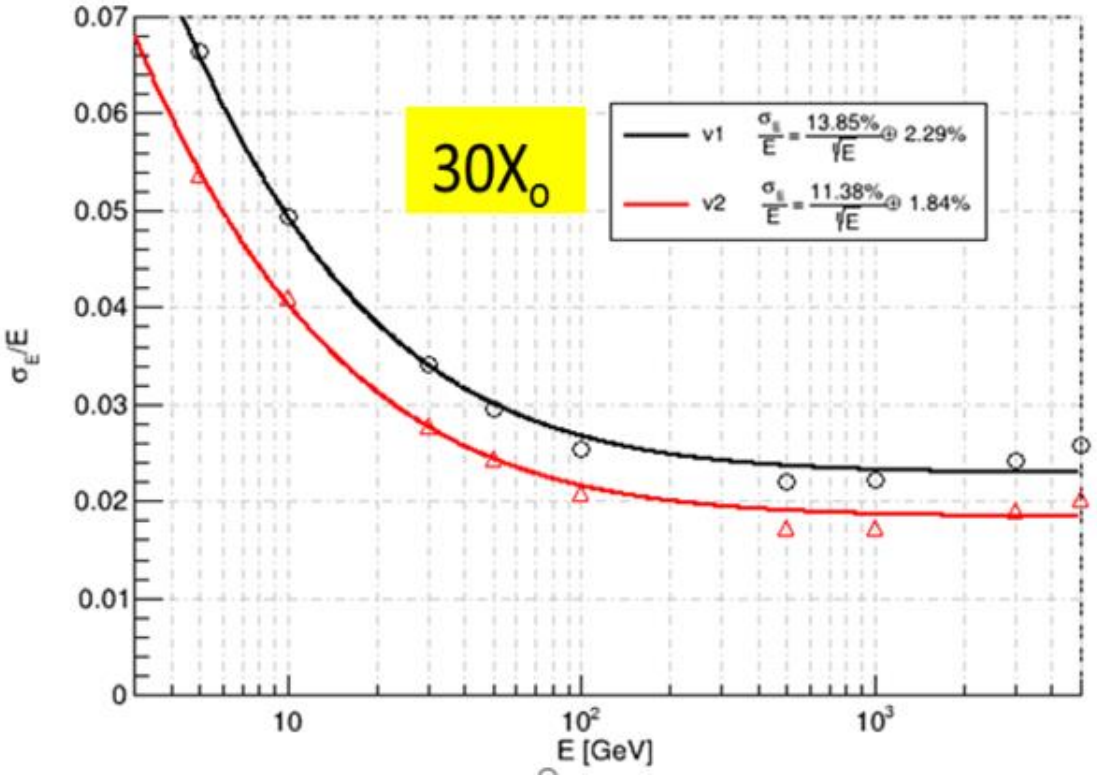
Number of Layers	6	8	11
Thickness of Pb (cm)	0.5	0.6	0.8

$30X_0$

v2

Number of Layers	8	13	18
Thickness of Pb (cm)	0.3	0.4	0.5





Design considerations for mu-LHC calorimeters

The technology and the design of the calorimeters should be chosen to reduce the effect of the BIB, while keeping good physics performance. This can be achieved with:

- High granularity to reduce the overlap of BIB particles in the same calorimeter cell.
- Good timing resolution can be use to reduce the out-of-time component of the BIB
- Longitudinal segmentation since the signal energy profile in the longitudinal direction is different from the BIB one, hence a segmentation of the calorimeter can help distinguish the signal showers from the fake showers produced by the BIB
- 10%/√E energy resolution in the ECAL system is expected to be enough to obtain good physics performance.

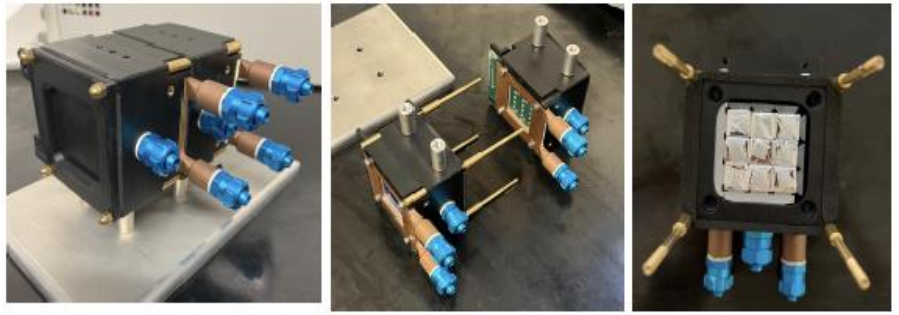
ECAL: W absorbers + silicon pad sensors / Pb absorbers + plastic scintilator

HCAL: steel absorbers + plastic scintillating tiles

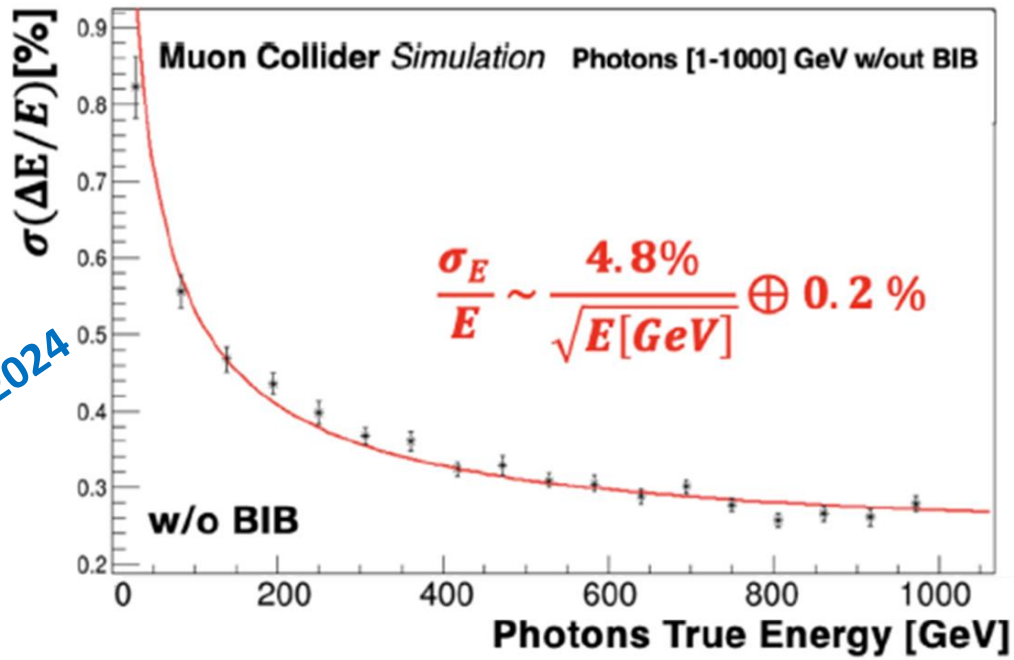
Crilin : CRystal calorImeter (PbF_2 – Lead Fluoride) with Longitudinal INformation

Crilin is a semi-homogeneous electromagnetic calorimeter made of crystal matrices interspaced and readout by SiPMs.Each crystal is independently read by 2 channels,each consisting of 2 SiPMs in series.

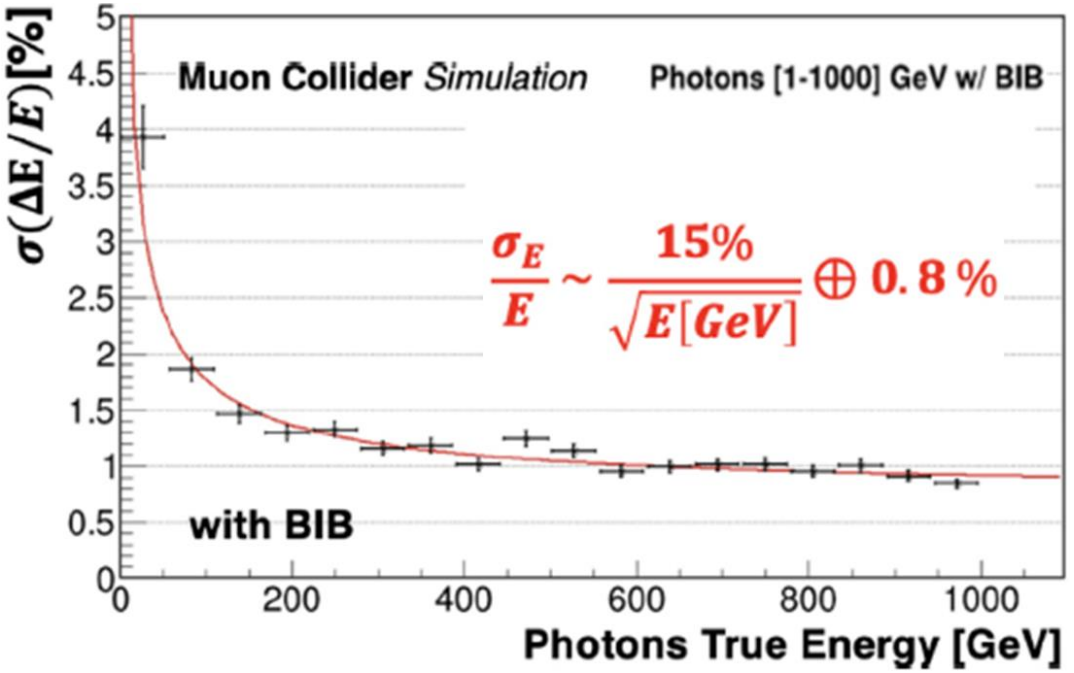
Crystal	PbF_2	PWO-UF
Density [g/cm^3]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur



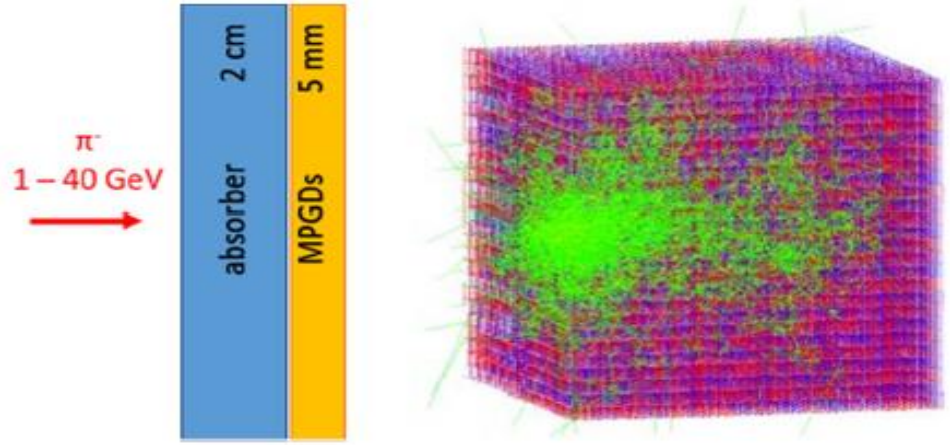
Key properties:
- Fine granularity:5 layers of 10x10x40 mm^3
- Timing resolution ~100 ps @ 1 GeV
- Good energy resolution ~ 10% / sqrt(E)



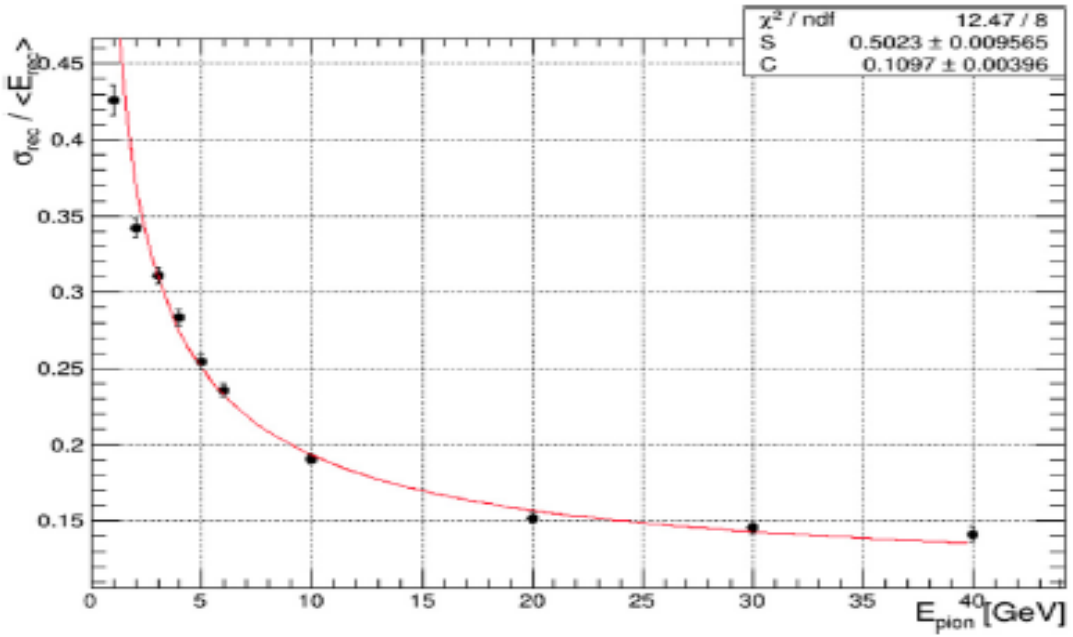
Ceravolo. et al., 2024



MPGD based hadronic calorimeter



On the left: Sketch showing one layer of the calorimeter made of 2 cm of iron for the absorber (in blue) and 5 mm of argon for the active layer (in yellow). On the right: Event display of a 20 GeV $\pi-$ developing a shower inside the calorimeter.



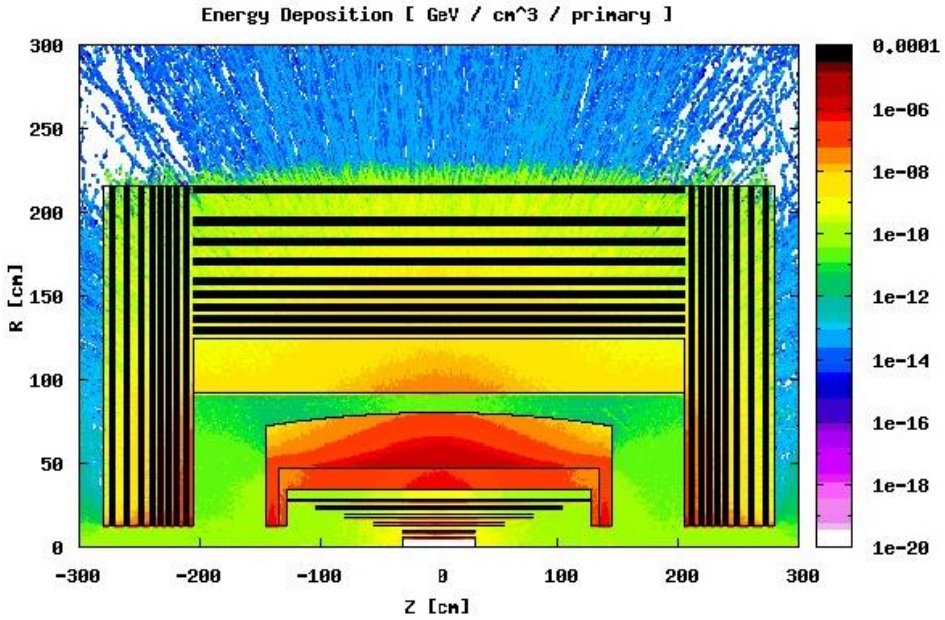
Aruta, C. et al., 2023

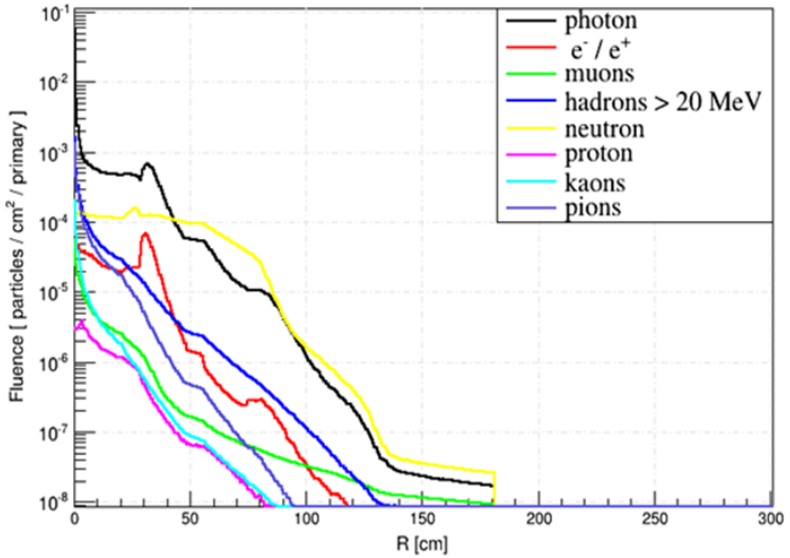
For the hadron calorimeter (HCAL), a new development is under investigation consisting of a sampling of absorber and Micro Pattern Gas Detectors (MPGD) as active layer.

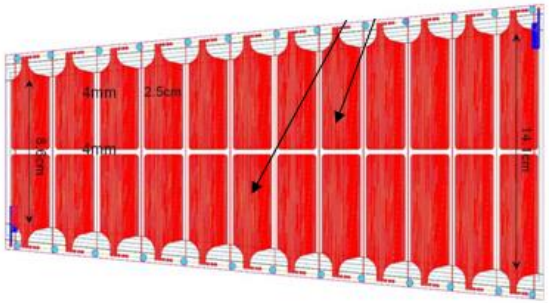
Gas detectors can indeed satisfy the requirements that are needed to cope with the BIB: they are robust against radiation, they can offer high granularity and modest cost for large area instrumentation.

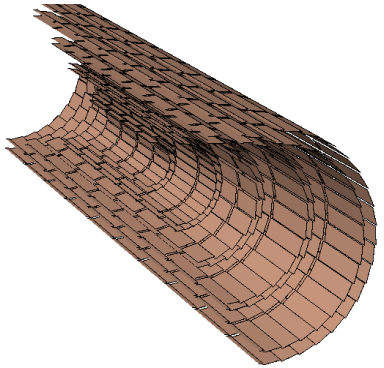
Conclusion

A systematic studies of the detector performance for the HL-LHC based muon-proton colliders are necessary for long-term planning of High Energy Physics. The realistic dimensions of the detector and its sub-components could be determined using detailed GEANT4 and FLUKA simulations to get the detector's response to particles generated from the muon-proton collisions.









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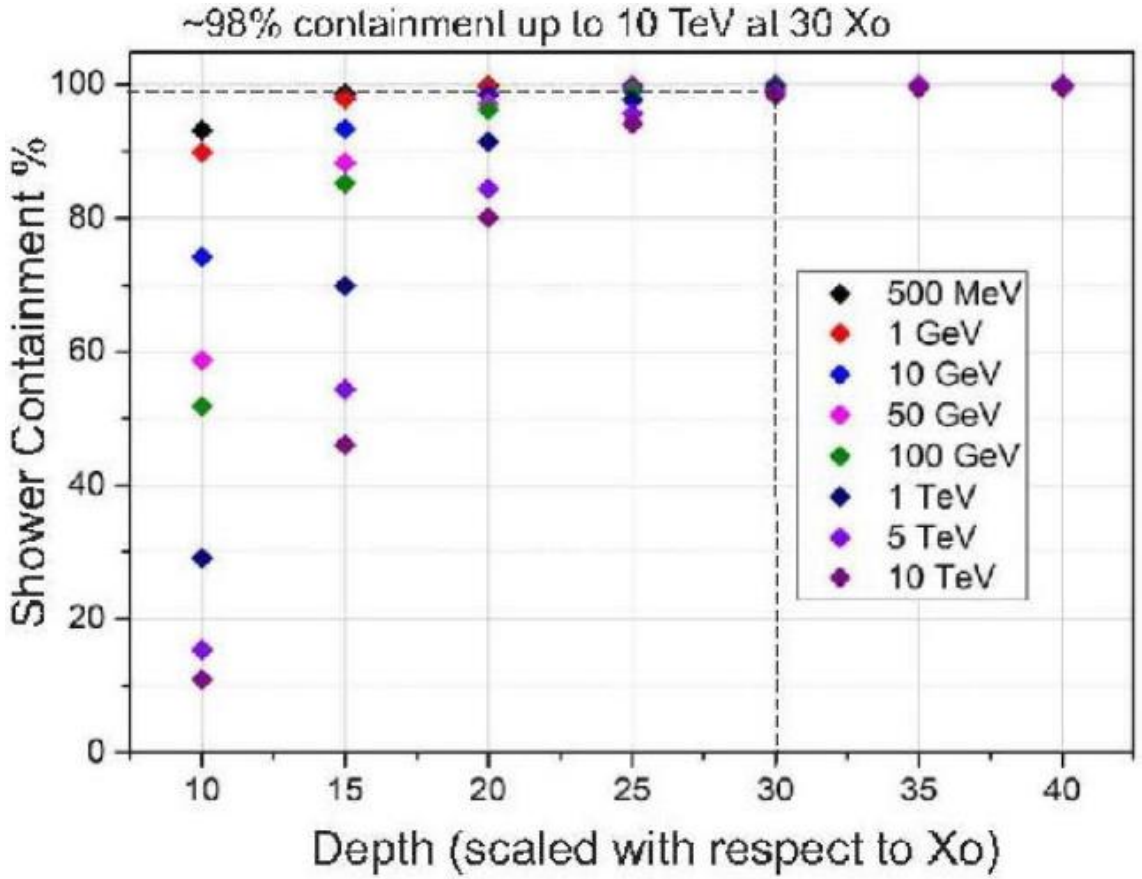
Backup slides



In the simulations for electromagnetic particles between 500 GeV and 10 TeV, it was seen that shower containment was almost completed for a radiation length of 30 X_0.