Design and simulation of a MPGD-based hadronic calorimeter for Muon Collider

15th Pisa Meeting on Advanced Detectors

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Overview

- Muon Collider: a discovery and precision machine
- Beam Induced Background
- R&D for Hadron Calorimeter
- Results
- Conclusions and perspectives

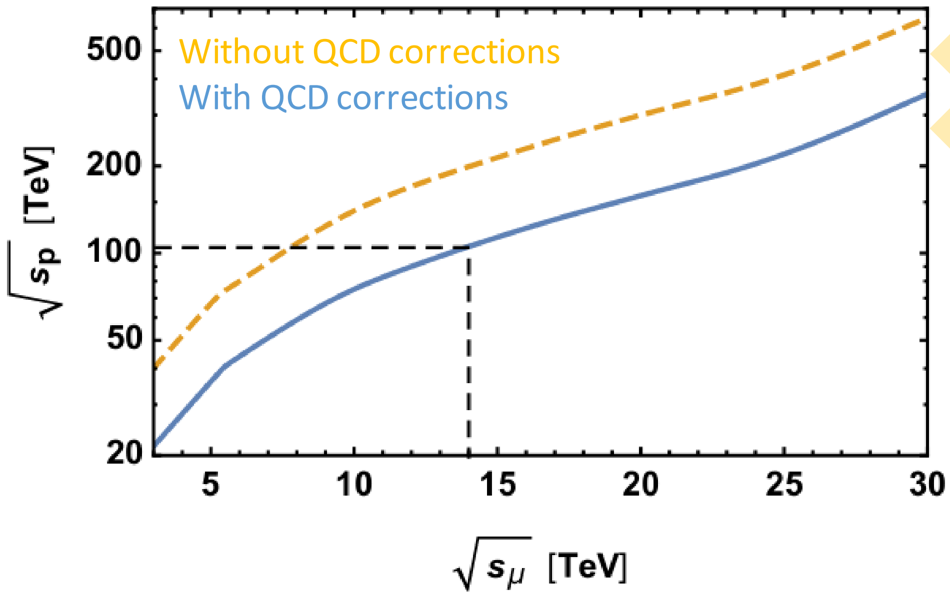
Muon Collider: a discovery and precision machine

The Muon Collider option was indicated as one of the crucial tool for future HEP by **European Strategy for Particle Physics**

- All the beam energy is available to the collision
- Strong suppression of synchrotron radiation
- Probe multi-TeV energy range for new physics
- Allow to complete the SM picture by precise measurements in Higgs sector (mass, width, coupling, self-coupling...)

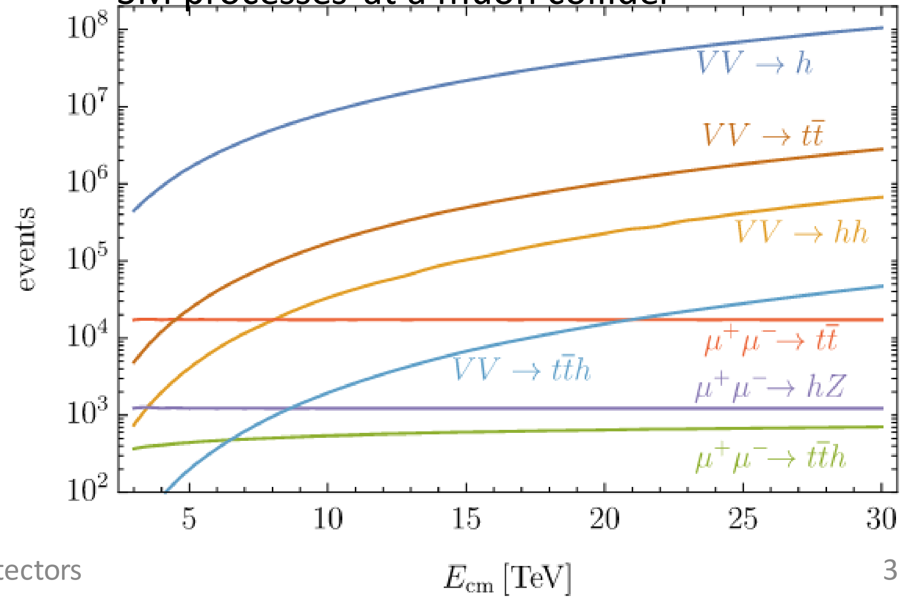
Equivalent proton collider energy

Ref. [1]



SM processes at a muon collider

Ref. [1]



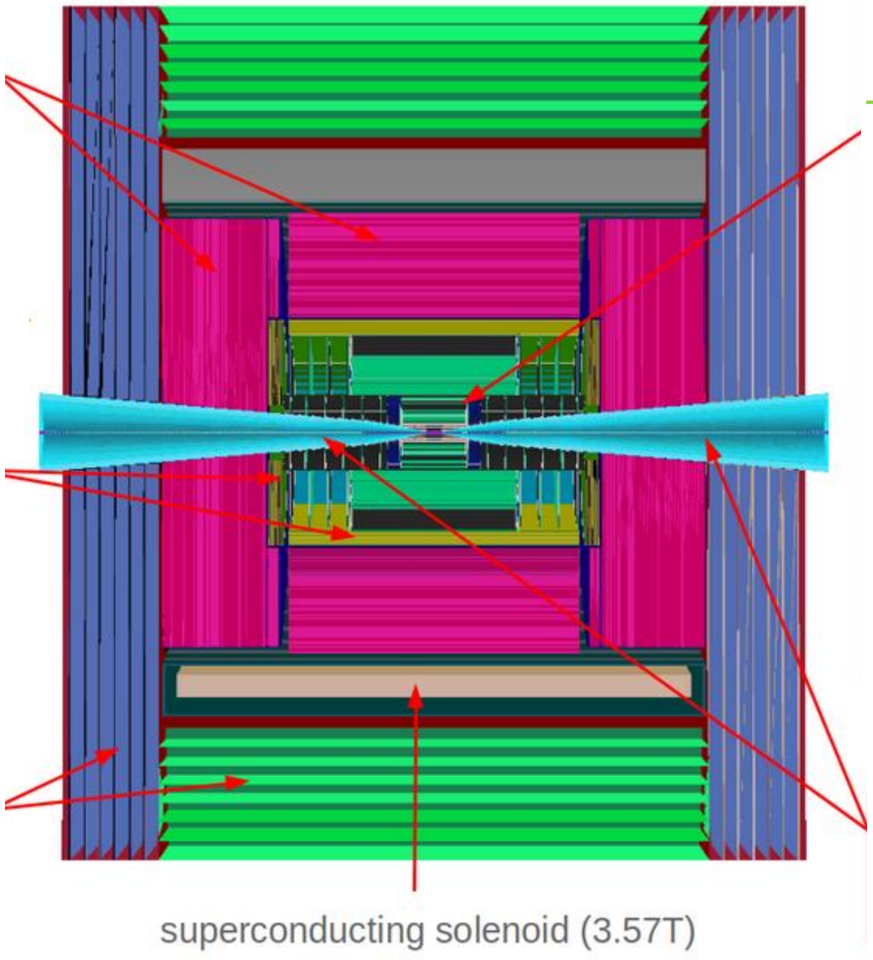
Muon Collider Experiment

Current HCAL proposal

- 60 layers 19 mm of steel + plastic scintillating tiles
- Cells of 30x30 cm²

Our Proposal: Micro Pattern Gas Detector (MPGD) based HCAL

Ref [2]



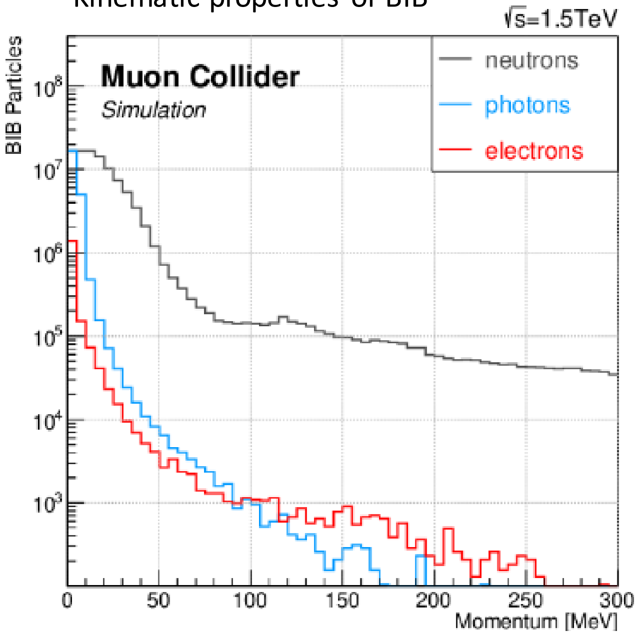
From simulations [2] a photon flux of 4.5 MHz/cm² at the surface of ECAL and 7.5 kHz/cm² at the surface of HCAL are expected

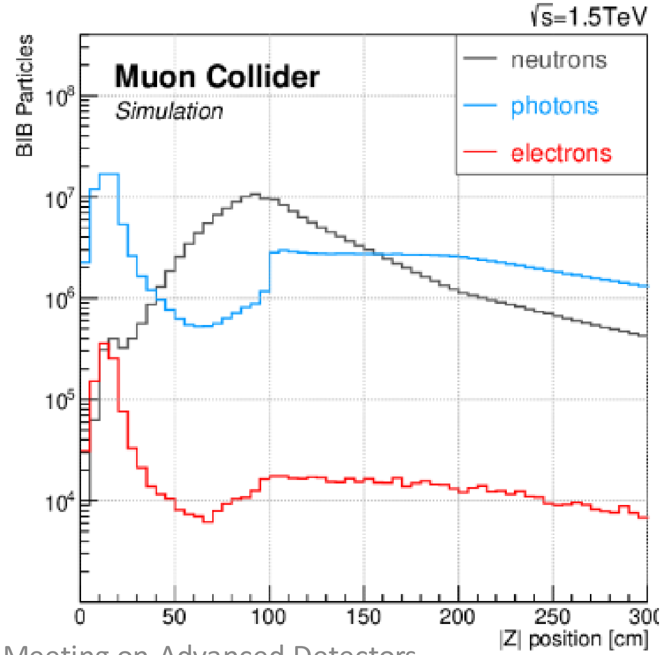
Short muon lifetime: beam induced background (BIB)

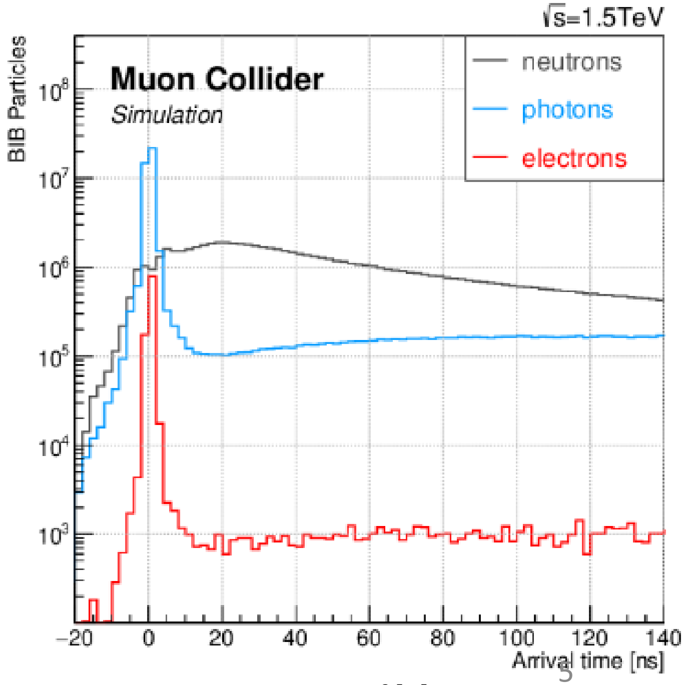
- $\mu \rightarrow e\, \nu_\mu\, \nu_e$ decay + following interaction with machine and detector material: main source of background

- BIB particles have:
  - High occupancy
  - Low momentum
  - Displaced origin
  - Asynchronous time of arrival

Kinematic properties of BIB







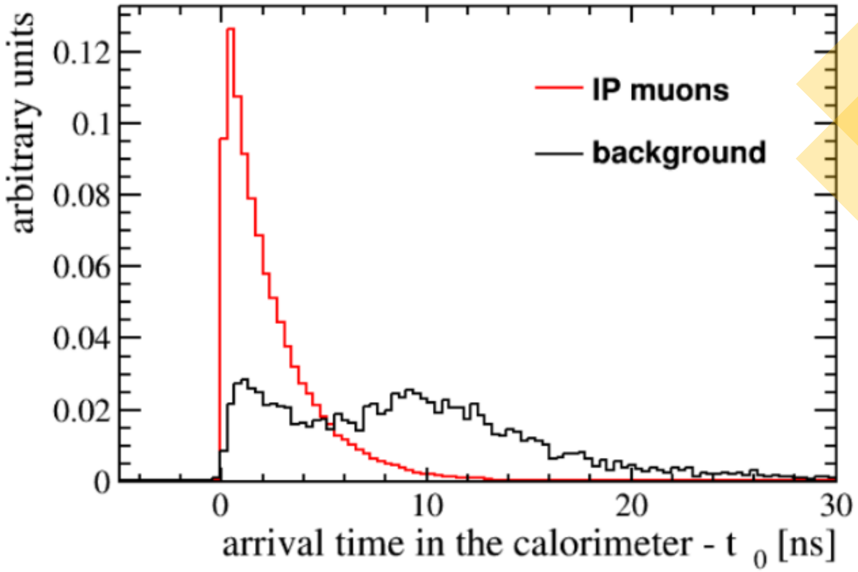
Ref [3]

Requirements for HCAL

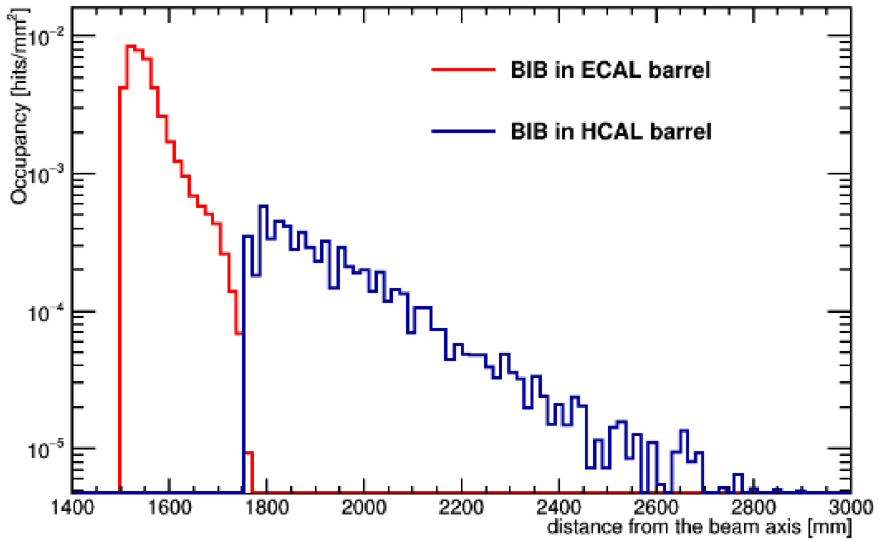
- High level of radiation due to BIB
  - Needed **radiation hard** technology
  - High **granularity** and **energy resolution** for particle reconstruction
  - **Fast response** to discriminate signal to background particles

- The calorimeter should provide 5D information for reconstruction with particle flow algorithm
  - Spatial and time coordinate
  - Energy

Particles arrival time at calorimeter Ref [4]



Background Occupancy Ref [6]



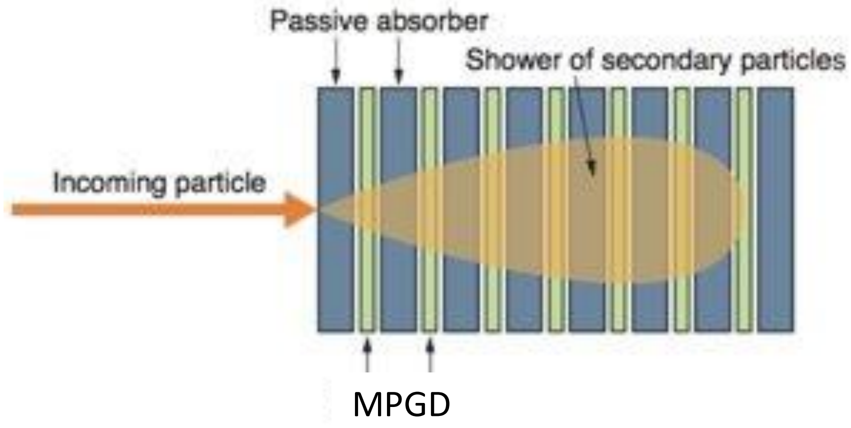
Hadron Calorimeter Proposal

- Gaseous detectors
  - Robust against radiation
  - Allow high granularity
  - Low cost to instrument large area

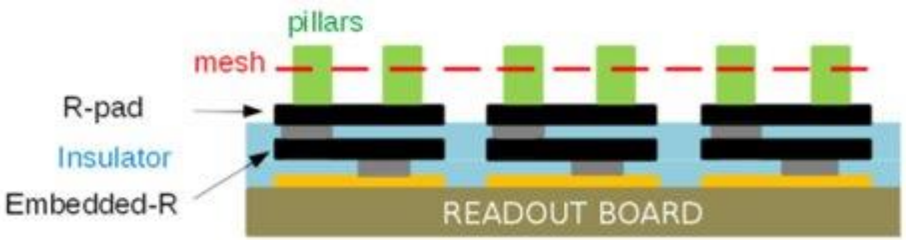
- Micro Pattern Gas Detectors (MPGD)
  - High rate capability
  - Good energy and time resolution
  - Good response uniformity
  - Use of environmental-friendly gas mixtures

- MPGD-based HCAL: use MPGD as active layer
  - **µRWell** and resistive **Micromegas** as best candidates to mitigate effects due to discharge in the gas

MPGD-based HCAL layout

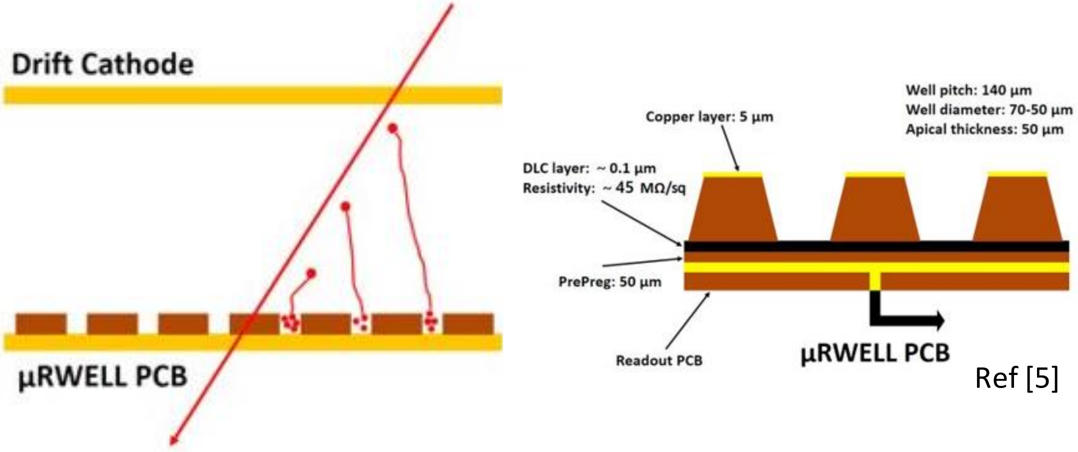


Micromegas detector layout



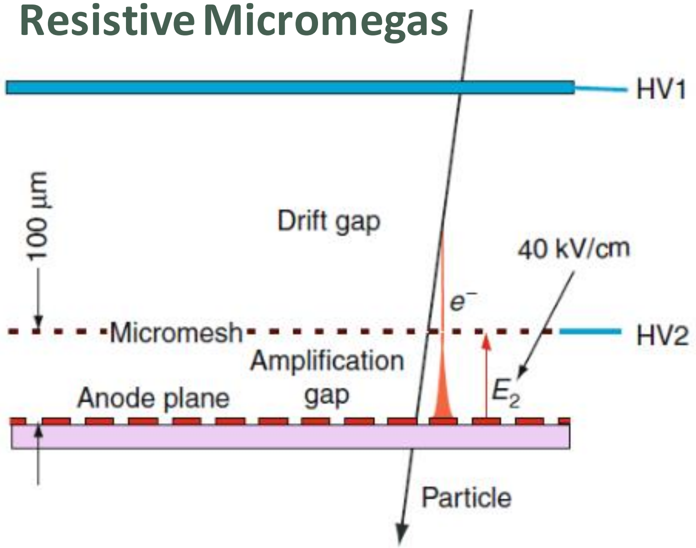
MPGDs technologies

μ-RWell



Ref [5]

Resistive Micromegas



- Good spatial (< 60 μm) and time (7 - 10 ns) resolution (Ref [6])
- High rate capability
  - Gain stability tested up to 10 MHz/cm^2
- Relatively simple construction and assembly

- High spatial (80 μm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability tested up to 100 kHz/cm^2
- Relatively low cost

Strategy for the MPGD-based HCAL design

From simulation to prototype

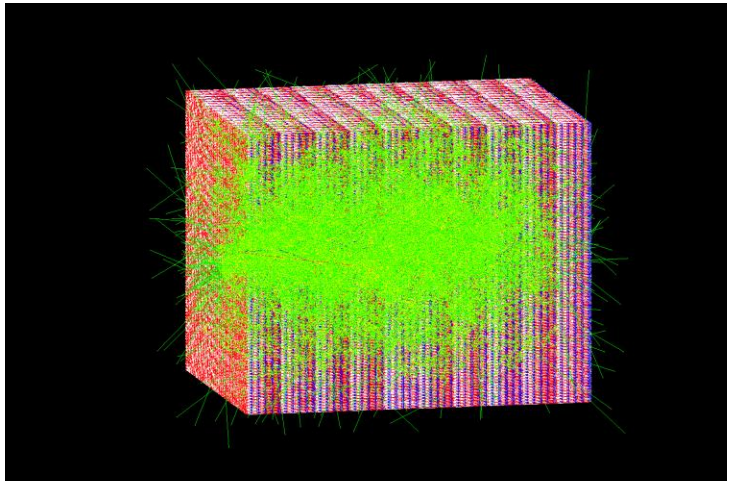
- Simulation in GEANT4 to study the response to the hadronic showers
- Implement the design in the context of full apparatus to study the impact on the particle reconstruction
- Build a HCAL cell prototype and measure its performance in test beam campaign

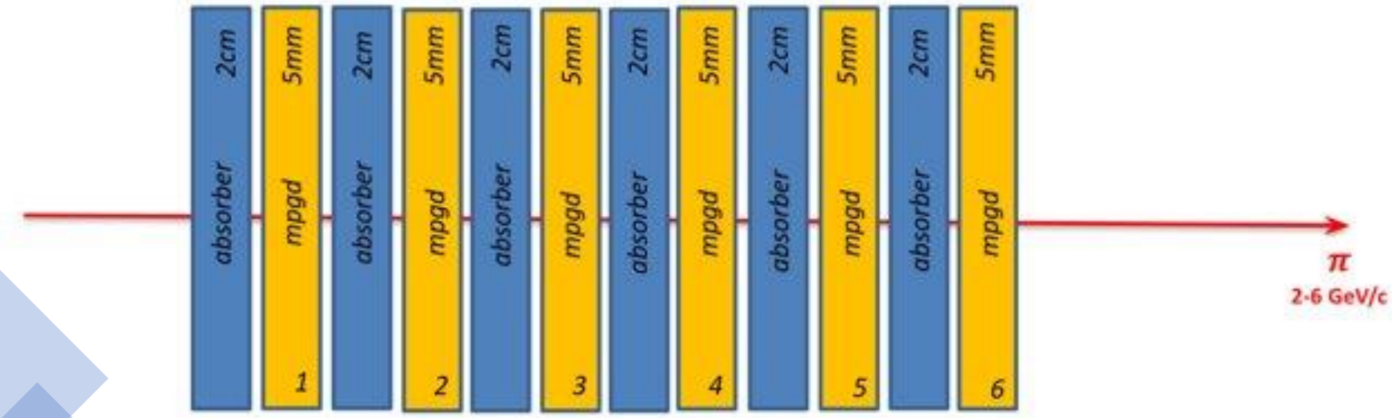
GEANT4 Simulation studies - HCAL Geometry

Optimization of geometry

- number of layers
- transversal dimensions

taking the **full shower containment** as figure of merit





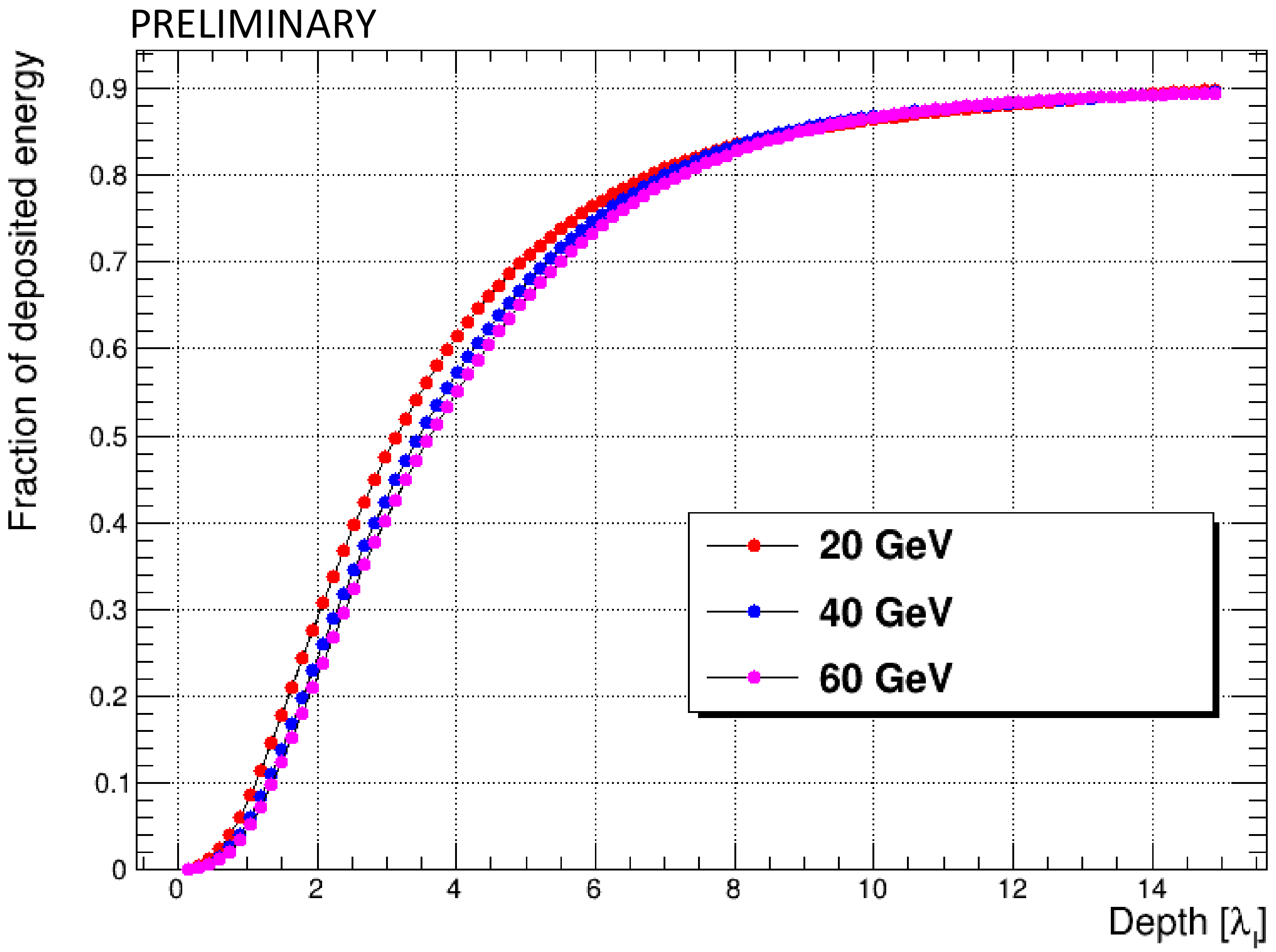
Implemented geometry

- Layers made of
  - 2 cm of Fe (absorber)
  - 5 mm of Ar (active gap)
- Granularity given by cell of 1x1 cm^2
- Pion gun of variable energies to study the shower response

Shower longitudinal containment

Containment at 90% with

- 100 layers
- 1x1 m² transversal area

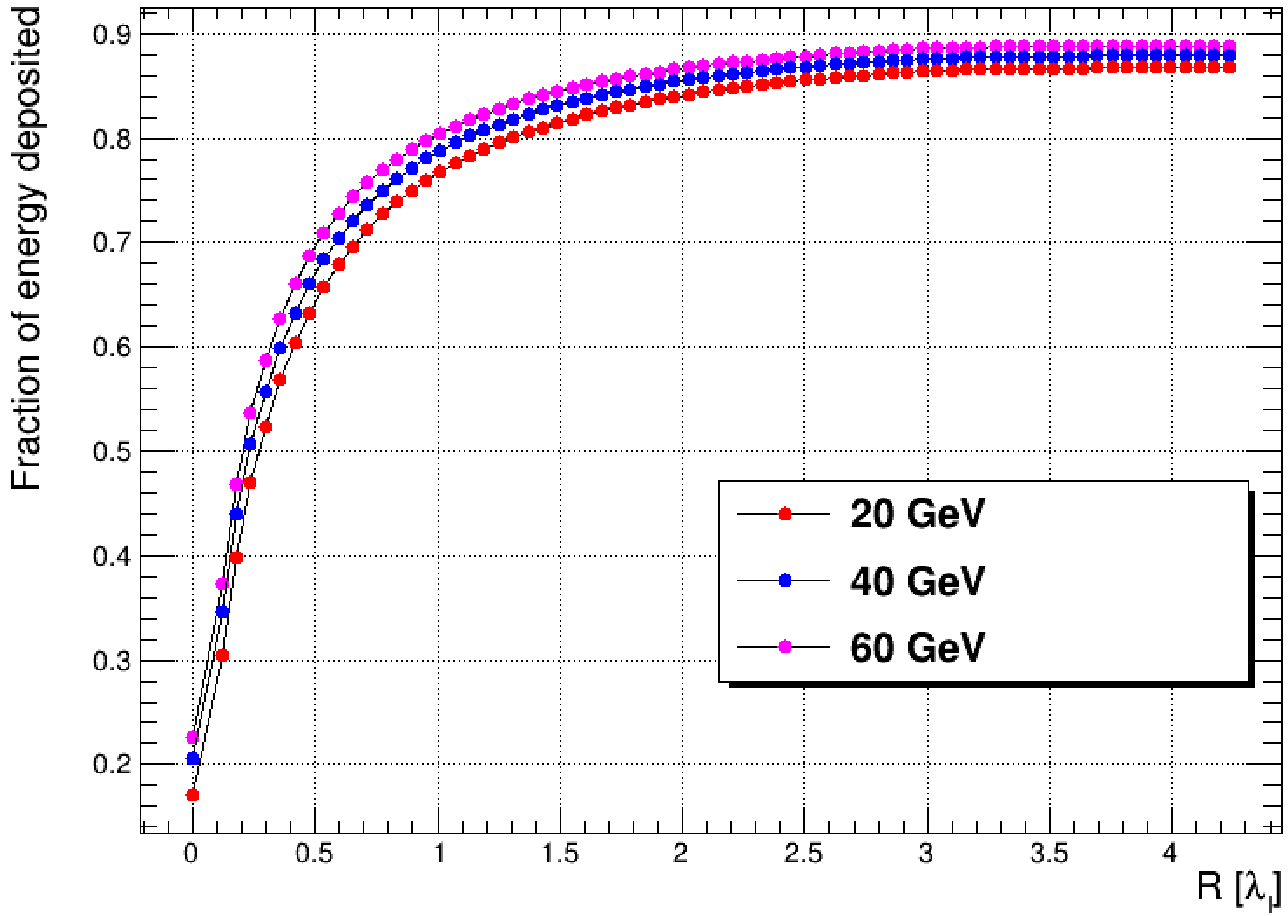


Shower transveral development

Containment at 90% with

- 100 layers
- 1x1 m² transversal area

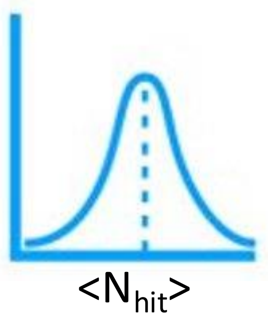
PRELIMINARY



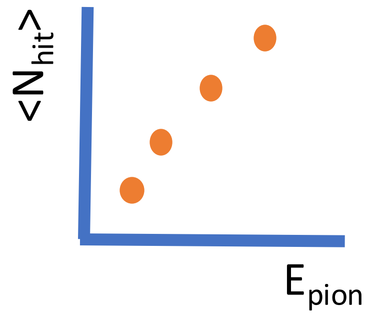
GEANT4 Simulation – Energy resolution workflow

- Pion gun of variable energies (E_{pion} from 1 to 60 GeV)
- Digital Read Out: 1 hit = 1 cell with deposited energy higher than 30 eV
- Detector Geometry: 50 layers, 1x1 cm^2 cell

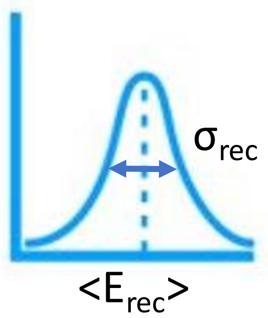
1st step: Get the N_{hit} distribution for each energy value E_{pion} and extract the mean value $\langle N_{hit} \rangle$



2nd step: Plot $\langle N_{hit} \rangle$ as a function of E_{pion} to find the calorimeter response function N = f(E)



3rd step: Reconstruct the energy distribution through the inverse response function $E = f^{-1}(N)$ and extract $\langle E_{rec} \rangle$ and σ_{rec}

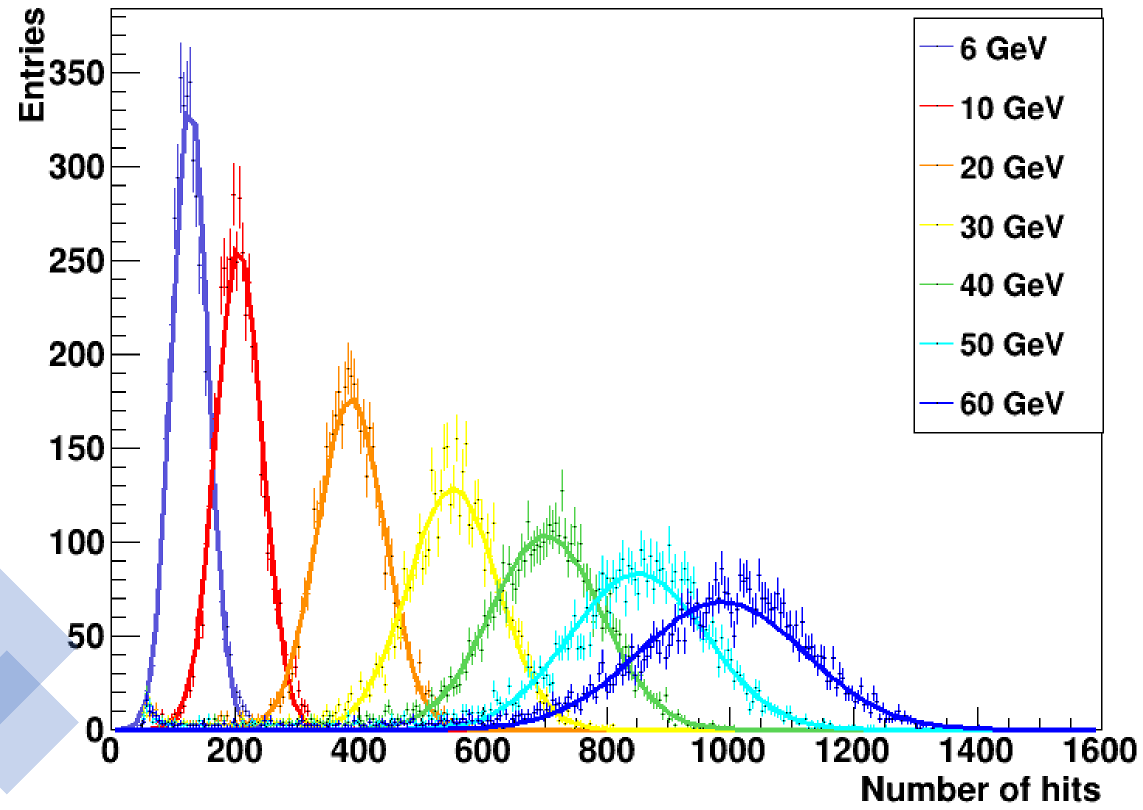


4th step: Get the energy resolution parameters fitting $\frac{\sigma}{E[GeV]} = \frac{S}{\sqrt{E[GeV]}} \oplus C$ to the data

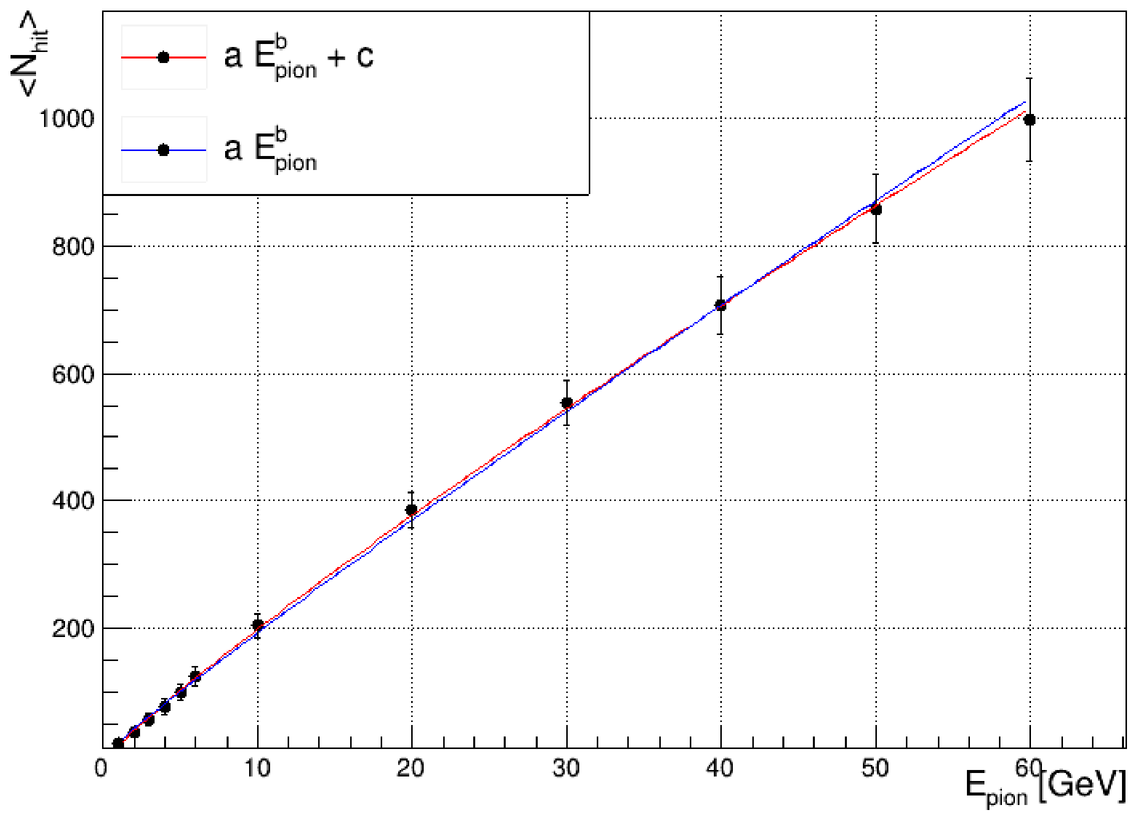
Response function of the calorimeter

PRELIMINARY

- From simulation get the distribution of the number of hits for each pion energy



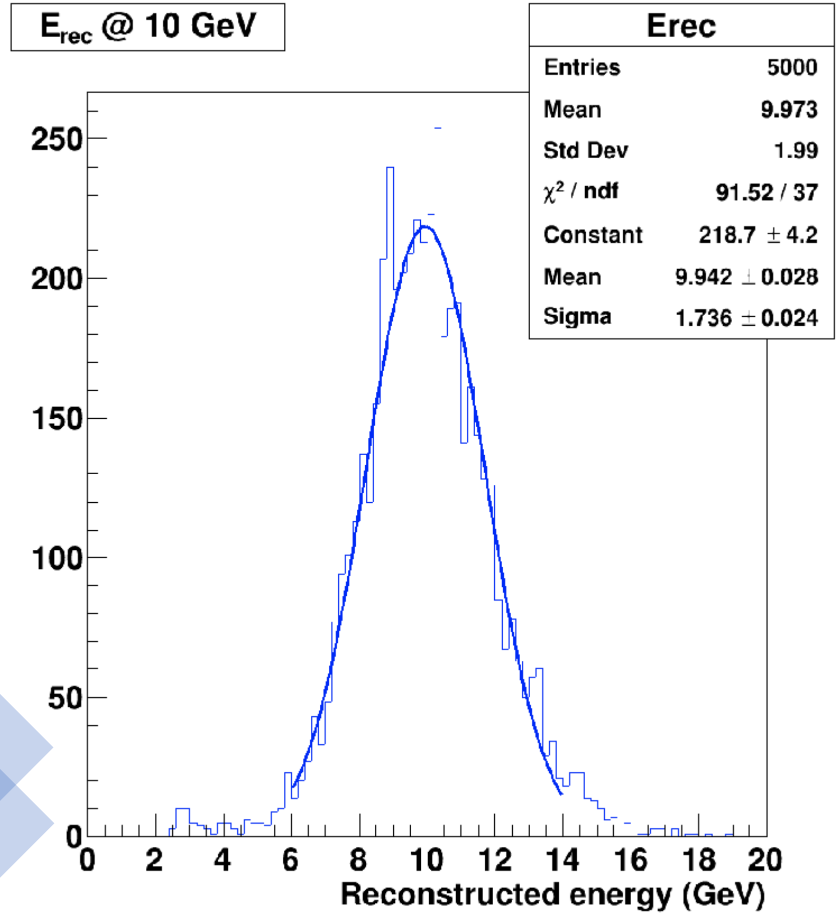
- Response function fitted with power law function



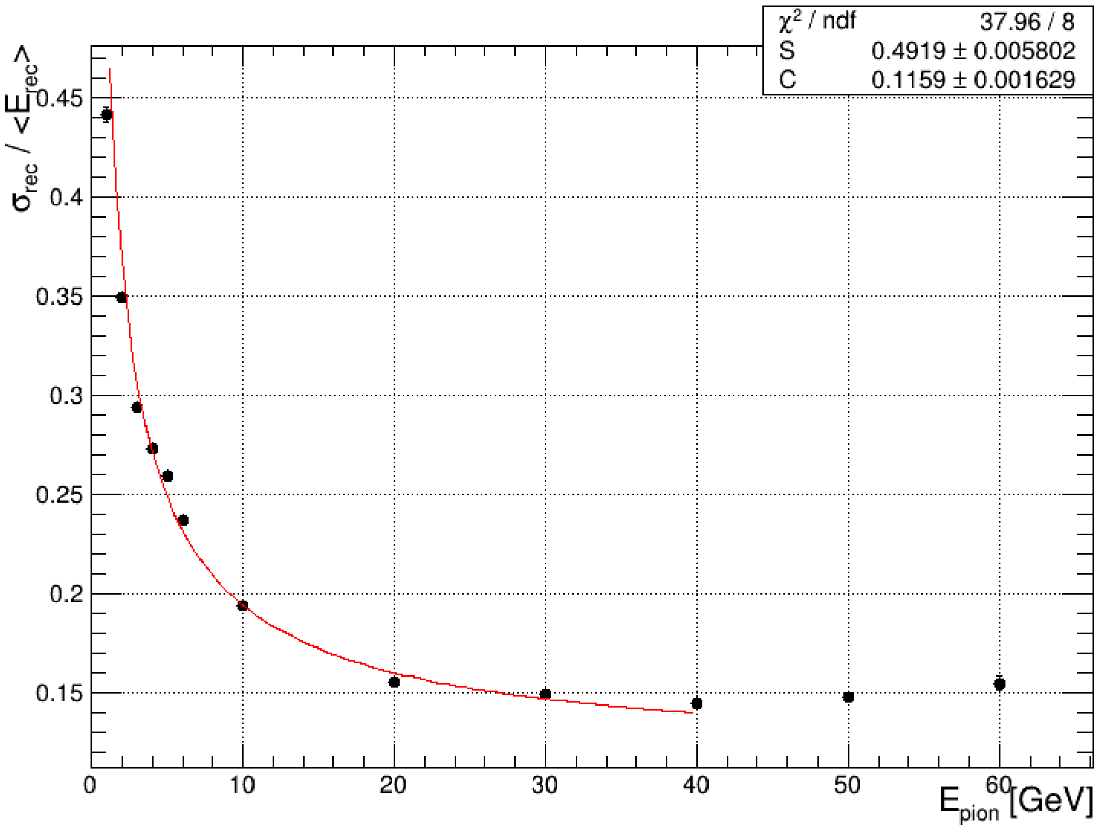
Energy reconstruction and resolution

PRELIMINARY

- Reconstruct the energy from the inverse response function



- Fit the energy resolution to the function $\frac{\sigma}{E[GeV]} = \frac{S}{\sqrt{E[GeV]}} \oplus C$



HCAL Prototype Project

A cell prototype will be constructed and its performances will be tested in test beams

- Adapted to low energy pions (1 – 6 GeV)
  - Dimensions to be extracted from simulation
- **Active layer** made of state of the art resistive MPGDs
  - Resistive **μ-RWell** or **MicroMegas**
  - 50x50 cm^2 with 1 cm^2 pad size
- For Read Out 32 channels FATIC asic [7]
  - for timing and charge measurements of the hits
  - Emulate semi-digital readout
- Production and testing in Bari INFN laboratories to study the performance
- Test at CERN SPS with pion and muon beam to measure
  - Efficiency and pad multiplicity of the hits
  - Time resolution for MIPs

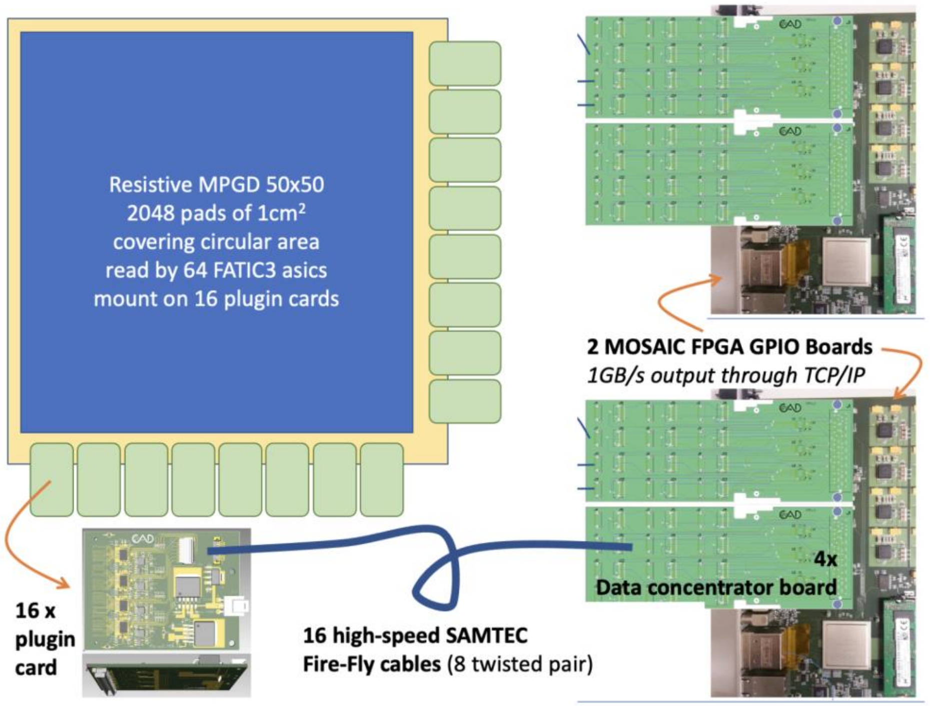


Fig. 2.5: Layout of the readout of a single 50x50cm^2 resistive MPGD chamber. The 2048 1cm^2 pads are read by 64 32-channel FATIC3 asics, mounted on 16 plugin-cards. The MOSAIC General Purpose I/O FPGA board reads up through 8 plugin-cards (32 FATIC3 asics). 2 MOSAICs in Master-Slave configuration read an entire chamber. 11 MOSAIC boards will be daisy-chained for the full readout of the HCAL prototype.

Conclusions and future plans

- Optimization studies in GEANT4 presented here
  - Geometry optimization for full shower containment
  - Energy resolution
- Future development of simulation
  - Implement a detailed geometry
  - Implement detector efficiency and read-out time window
  - Implement semi-digital readout
- Implement the optimized geometry in the Muon Collider software to test the performance in the full geometry
- Construct and test a cell prototype
- Project approved by the CERN-based MPGD R&D collaboration RD-51

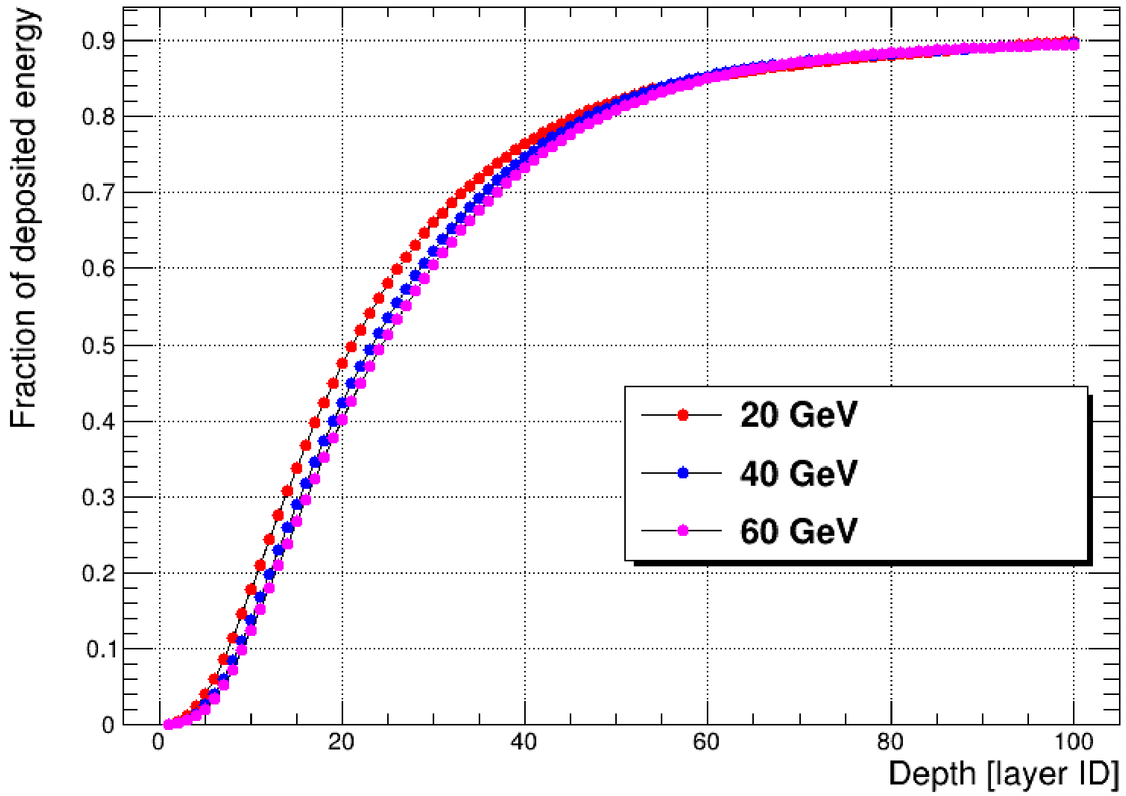
References

- [1] J. P. Delahaye, M. Diemoz, K. Long, B. Mansoulié, N. Pastrone, L. Rivkin, D. Schulte, A. Skrinsky, and A. Wulzer, Muon Colliders, arXiv:1901.06150 [physics.acc-ph]
- [2] F. Collamati et al., Advanced assessment of beam-induced background at a muon collider, JINST16 (2021) P11009
- [2] https://muoncollider.web.cern.ch/design/muon-collider-detector
- [3] C. Aimé et al. "Simulated Detector Performance at the Muon Collider" https://arxiv.org/pdf/2203.07964.pdf
- [4] N. Bartosik et al. “Detector and Physics Performance at a Muon Collider”. Journal of Instrumentation 15.05 (2020)
- [5] Y. Zhou et al. "Fabrication and performance of a μ-RWELL detector with Diamond-Like resistive electrode and two-dimensional readout"
- [6] C. Aimé et al. "Promising Technologies and R&D Directions for the Future Muon Collider Detectors"
- [7] https://ieeexplore.ieee.org/document/8791274

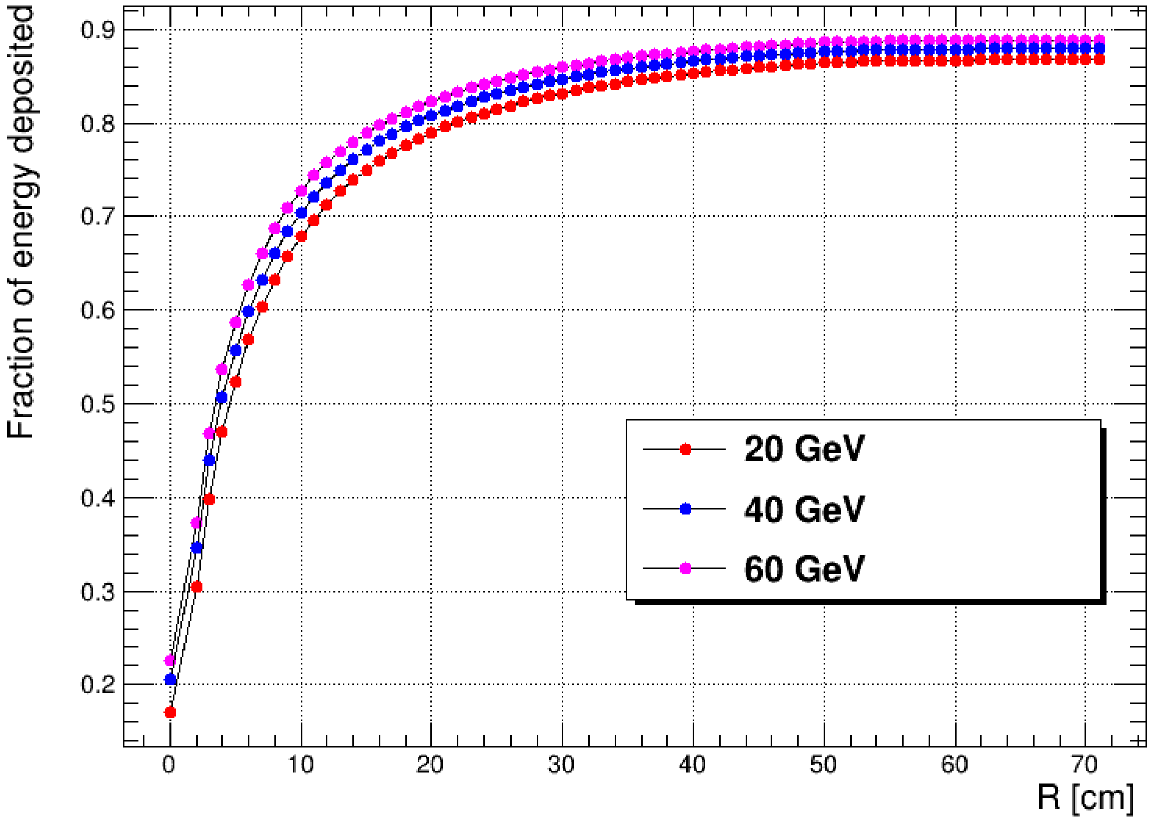
Backup

Shower containment

Longitudinal containment

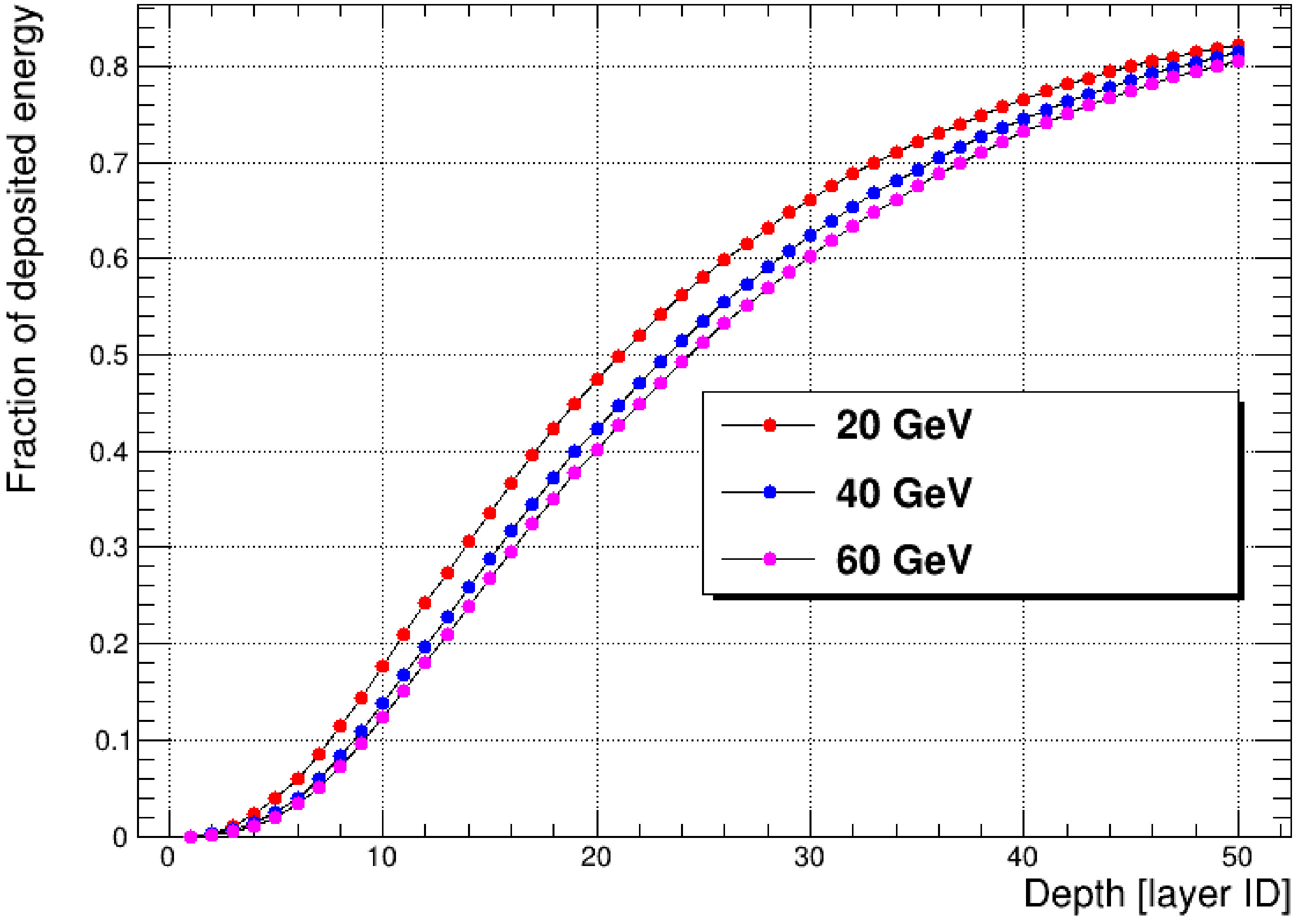


Transversal containment



Shower containment

80 % with 50 layers



Resistive Micromegas

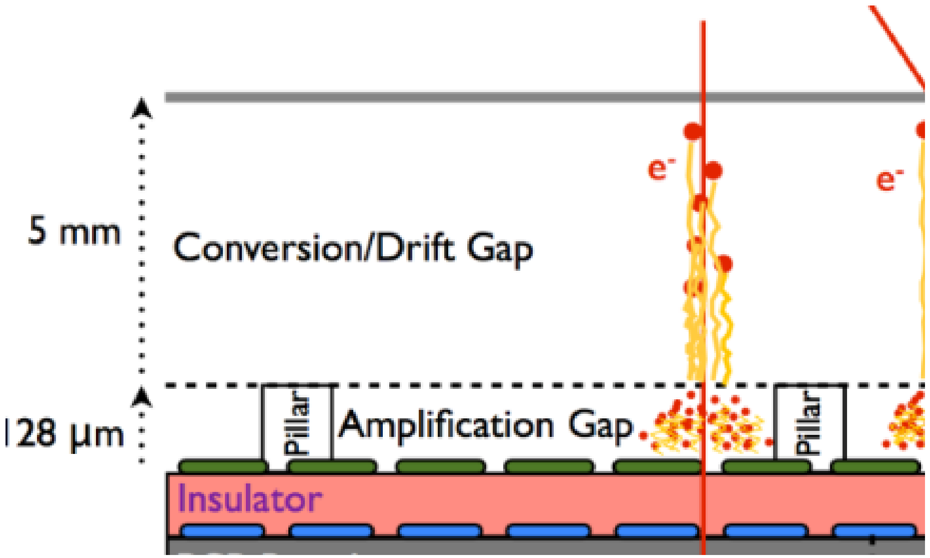
Micromegas are parallel-plate chambers

- The amplification occurs in a thin gap
- The conversion and amplification region are separated by a metallic mesh

Detector performance:

- High spatial (80 µm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability tested up to 100 kHz/cm²
- Good resistance to ageing effetcs
- High safety towards spark phenomena

- Relatively low cost



μ-RWell

The detector is realized by
- a single patterned kapton foil for the amplification stage
- a resistive stage for discharge suppression
- a standard PCB for the readout

Detector performance:
- High spatial (< 200 μm) and time (< 6 ns) resolution
- High rate capability
  - Gain stability tested up to 1 MHz/cm^2
- Good resistance to ageing effetcs
- High safety towards spark phenomena
- Relatively simple construction and assembly
- Relatively low cost