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

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Physiscs and Detector Muon Collider Group

Overview

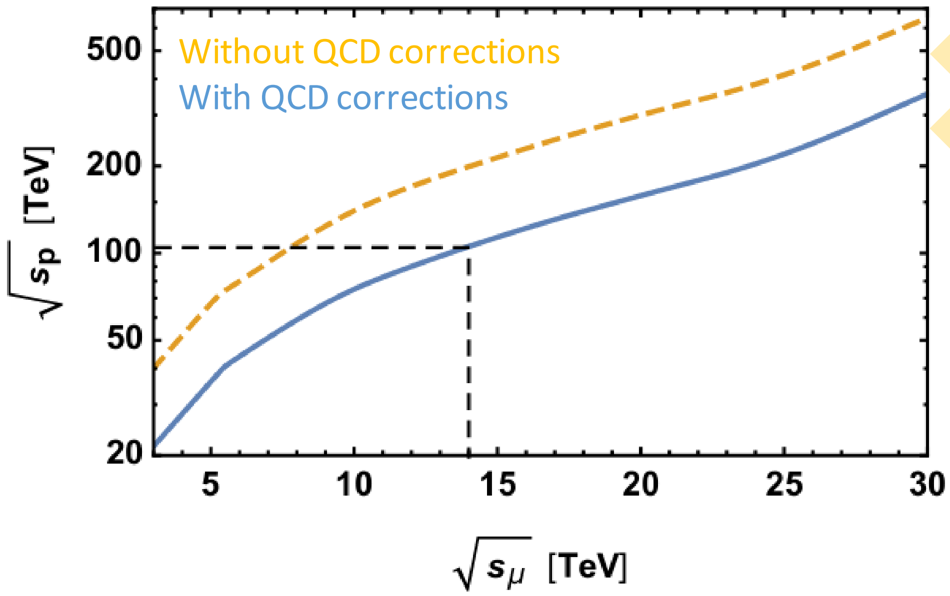
- Muon Collider: a discovery and precision machine
- Beam Induced Background
- R&D for Hadron Calorimeter
- Results
- Conclusions and perspectives

Muon Collider: a discovery and precision machine

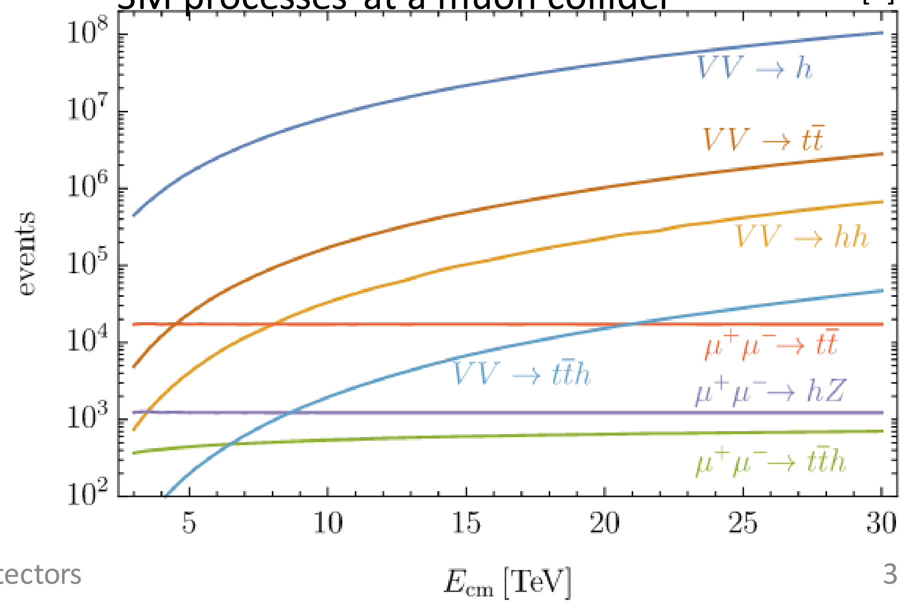
The Muon Collider option was indicated as one of the crucial tool for future HEP by **European Strategy for Particle Physics**

- 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

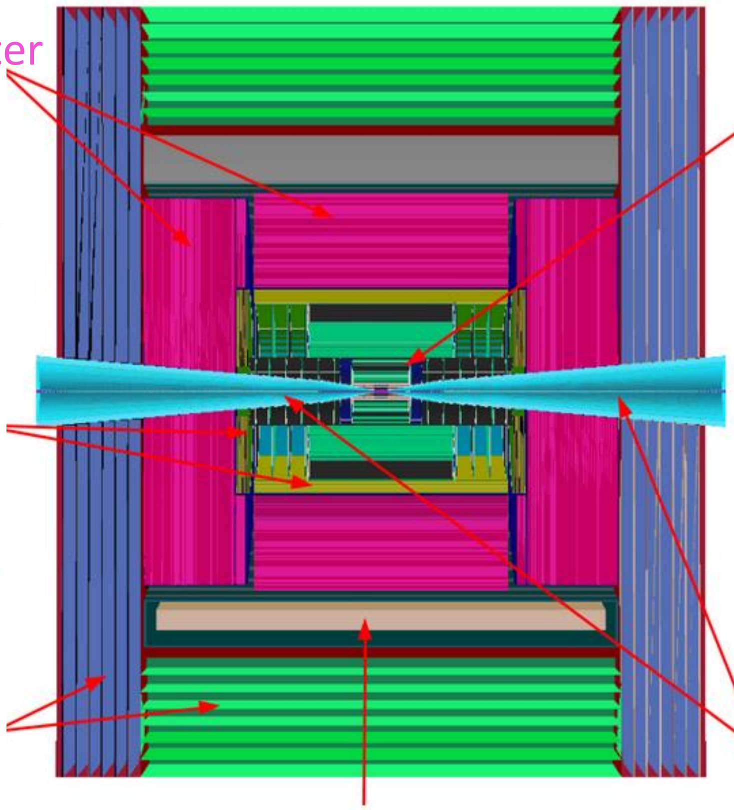
Our Proposal: Micro Pattern Gas Detector (MPGD) based HCAL

From simulations [2] a photon flux of

- 4.5 MHz/cm² at the surface of ECAL
- 7.5 kHz/cm² at the surface of HCAL

For more details see Massimo Casarsa's talk "Detector design for a multi-TeV muon collider"

Ref [2]



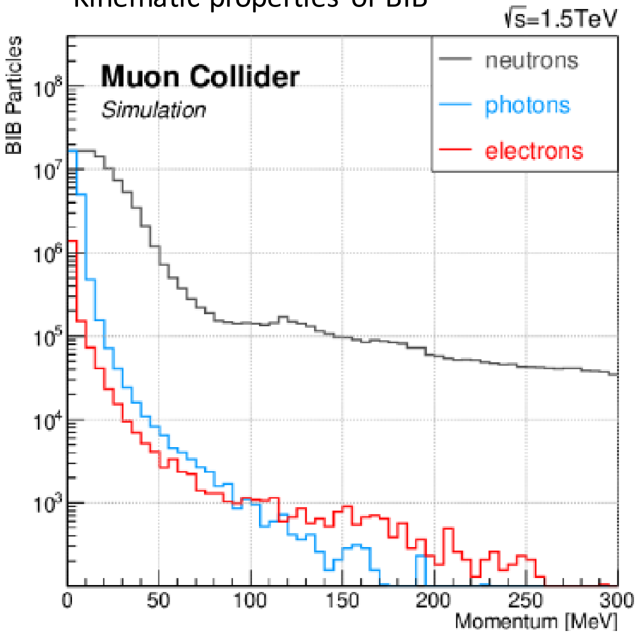
Short muon lifetime: beam induced background (BIB)

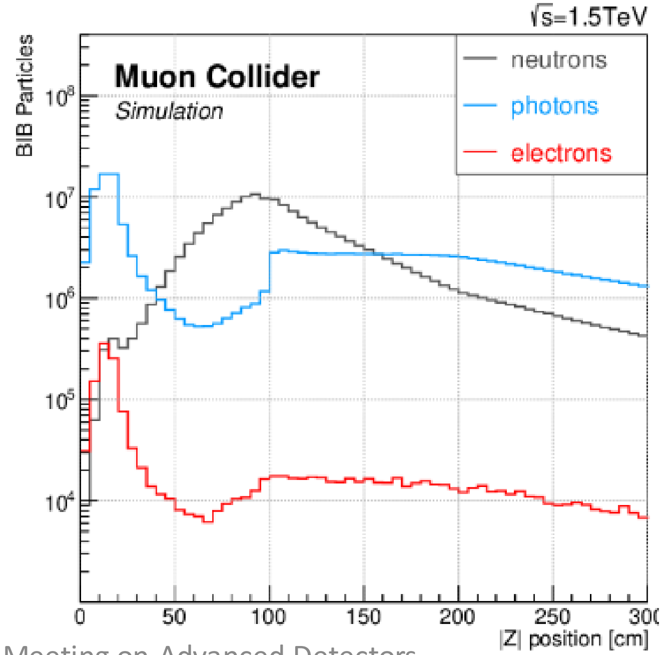
- $\mu \rightarrow e\ \nu_{\mu}\ \nu_{e}$ decay + following interaction with machine and detector material: main source of background

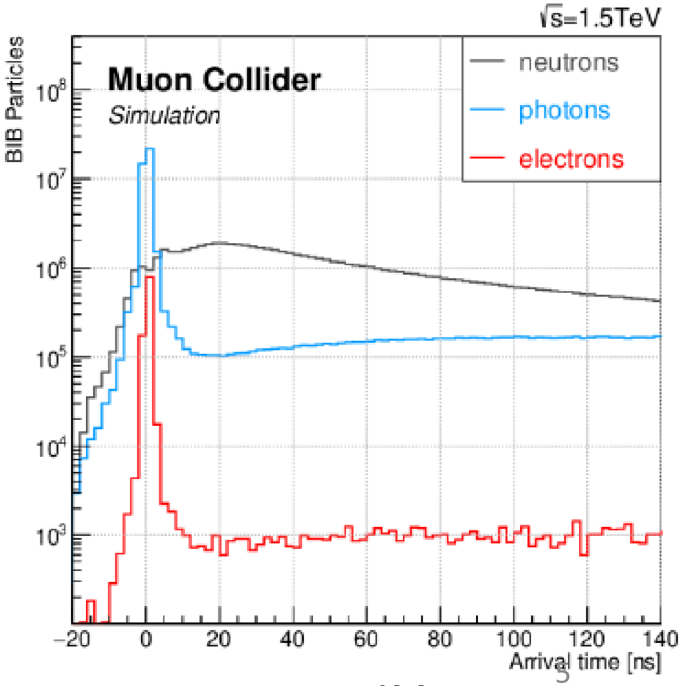
- BIB particles have:
  - High occupancy
  - Low momentum
  - Displaced origin
  - Asynchronous time of arrival

- It is important to have a detector with high granularity and high time resolution

Kinematic properties of BIB







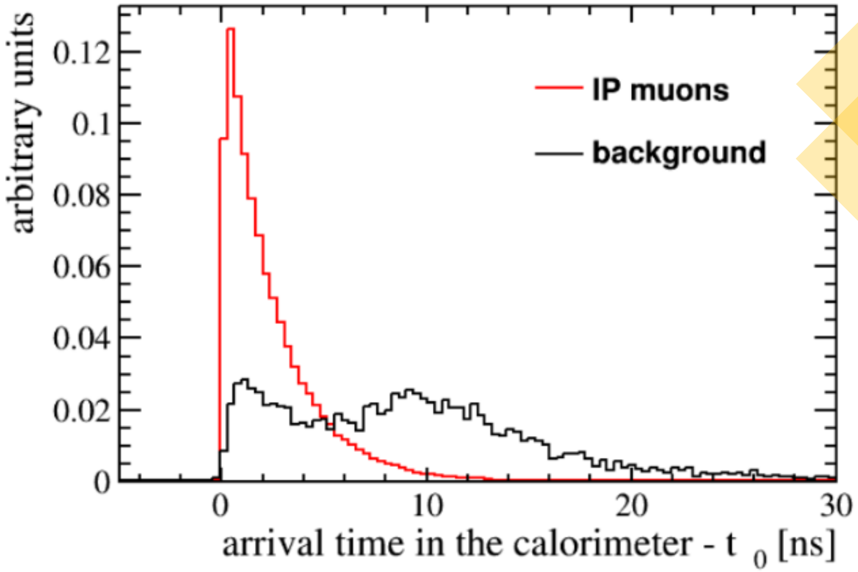
Ref [3]

Requirements for HCAL

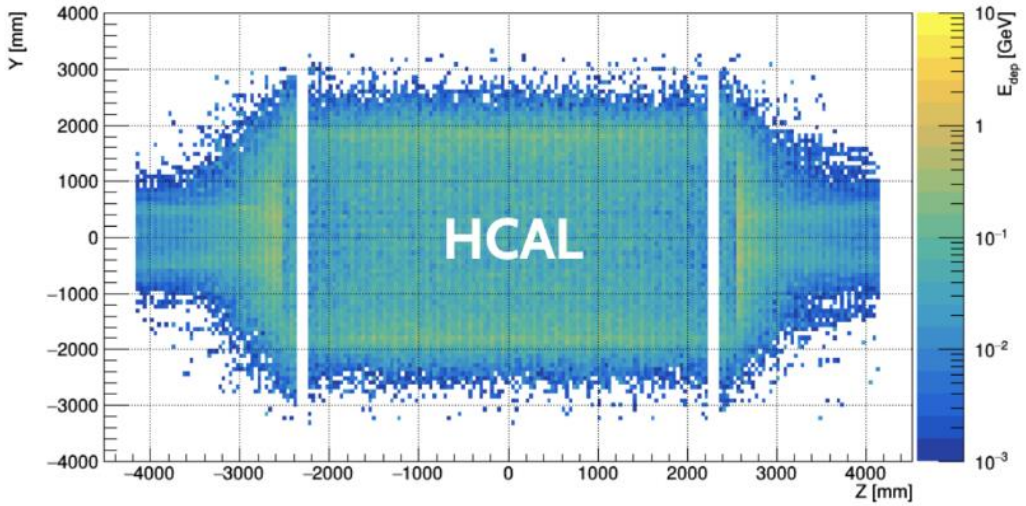
- High level of radiation due to BIB
  - Needed **radiation hard** technology
  - High **granularity** and **energy resolution** for particle reconstruction
  - **Fast response** to discriminate signal to background particles

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

Particles arrival time at calorimeter Ref [4]



Energy deposited by the BIB Ref [5]



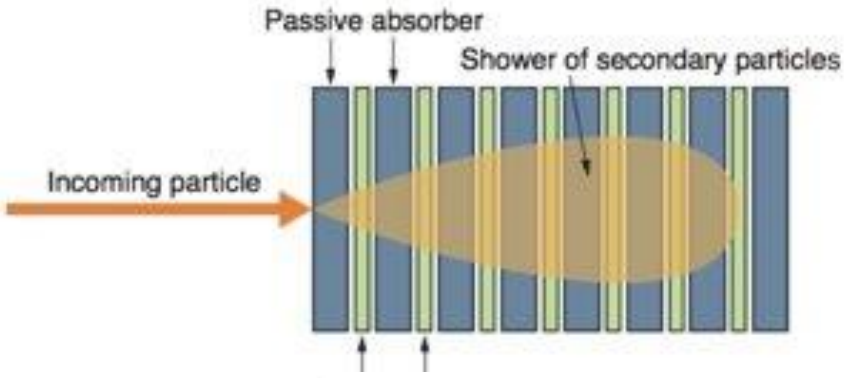
Hadron Calorimeter Proposal

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

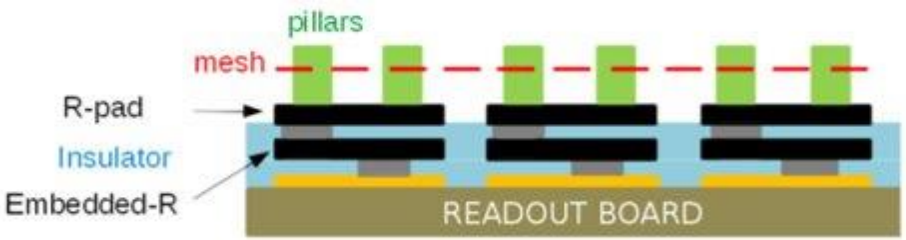
- Micro Pattern Gas Detectors (MPGD)
  - High rate capability
  - Good energy and time resolution
  - Good response uniformity
  - Use of environmental-friendly gas mixtures

- 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

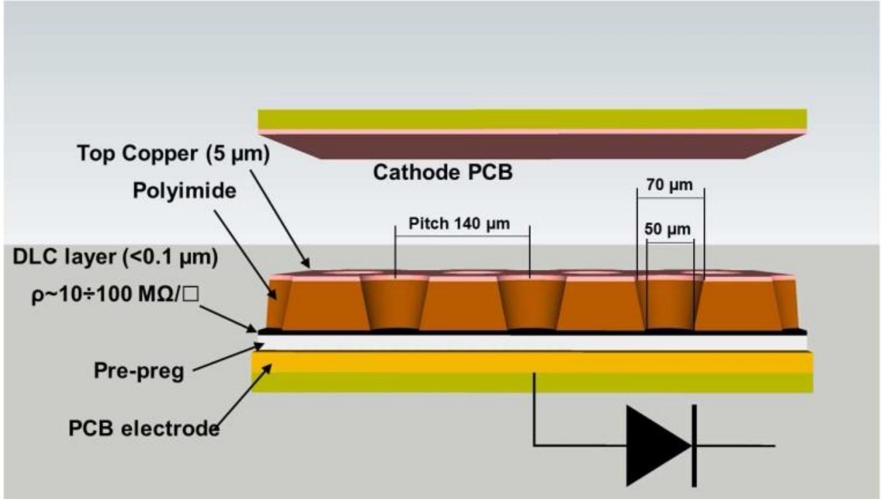


Micromegas detector layout



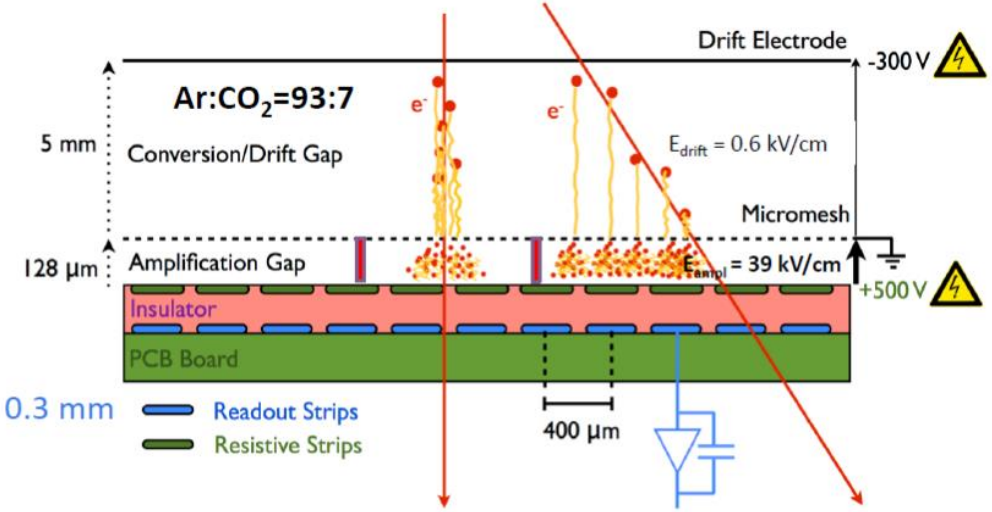
MPGDs technologies

µ-RWell



Ref [6]

Resistive Micromegas



Ref [7]

- High spatial (< 60 µm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability tested up to 10 MHz/cm^2

- High spatial (80 µm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability > 1 MHz/cm^2

Strategy for the MPGD-based HCAL design

From simulation to prototype

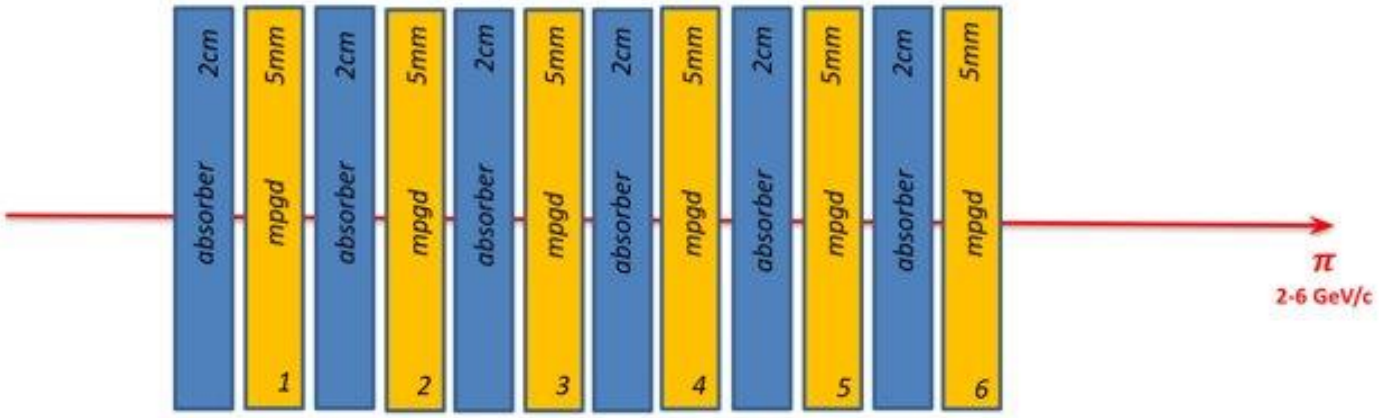
Simulation in GEANT4 to study the response to the hadronic showers:
- shower containment, read-out granularity, energy resolution, background discrimination.

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

Sketch of the implemented calorimeter

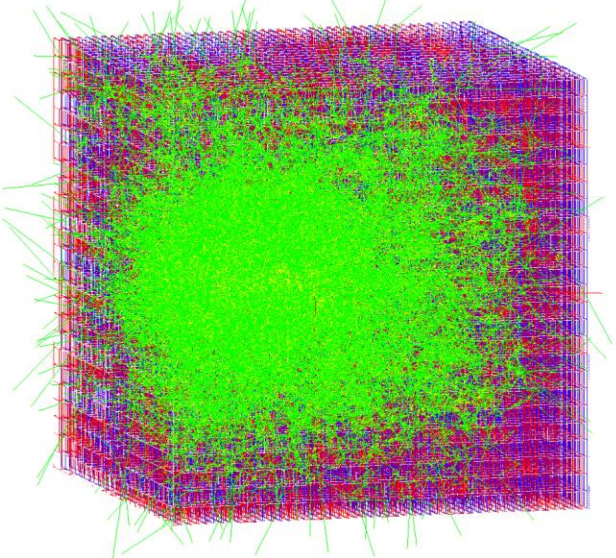


Implemented geometry

- 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
- Physics list: QGSP_BERT

1 pion at 60 GeV



Optimization of geometry

- number of layers
- transversal dimensions

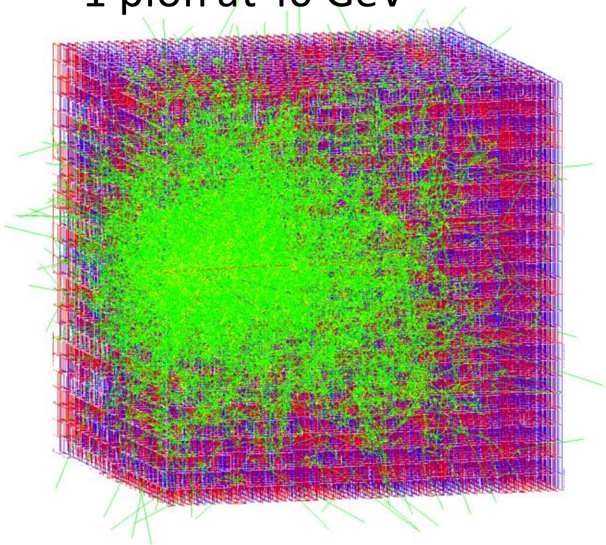
taking the **full shower containment** as figure of merit

Shower longitudinal containment

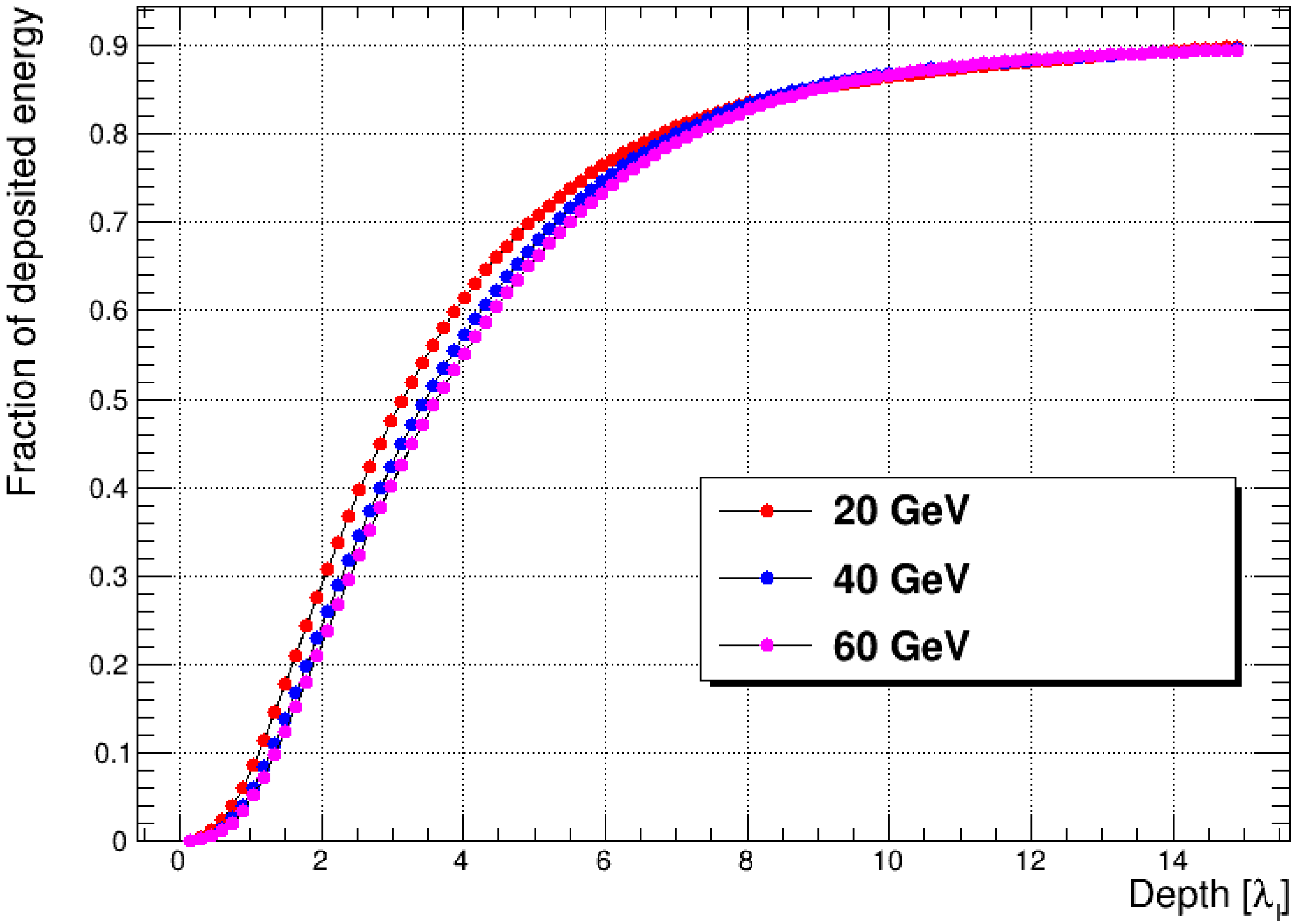
Containment evaluated from deposited energy as a function of depth in the pion direction in units of nuclear interaction length (λ_I)

Containment at 90% with 1x1 m² transversal area

1 pion at 40 GeV



PRELIMINARY

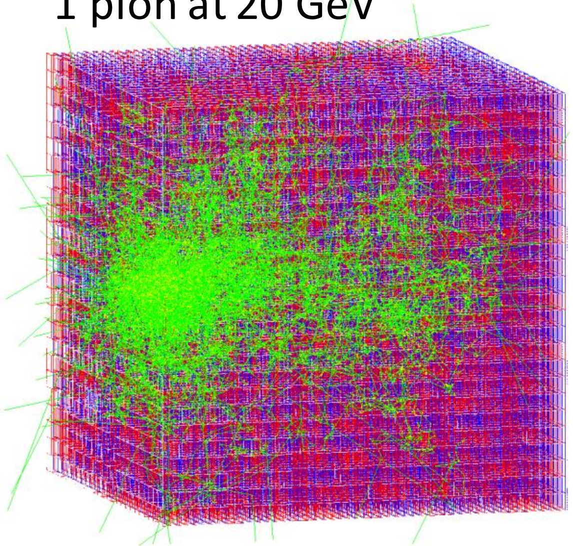


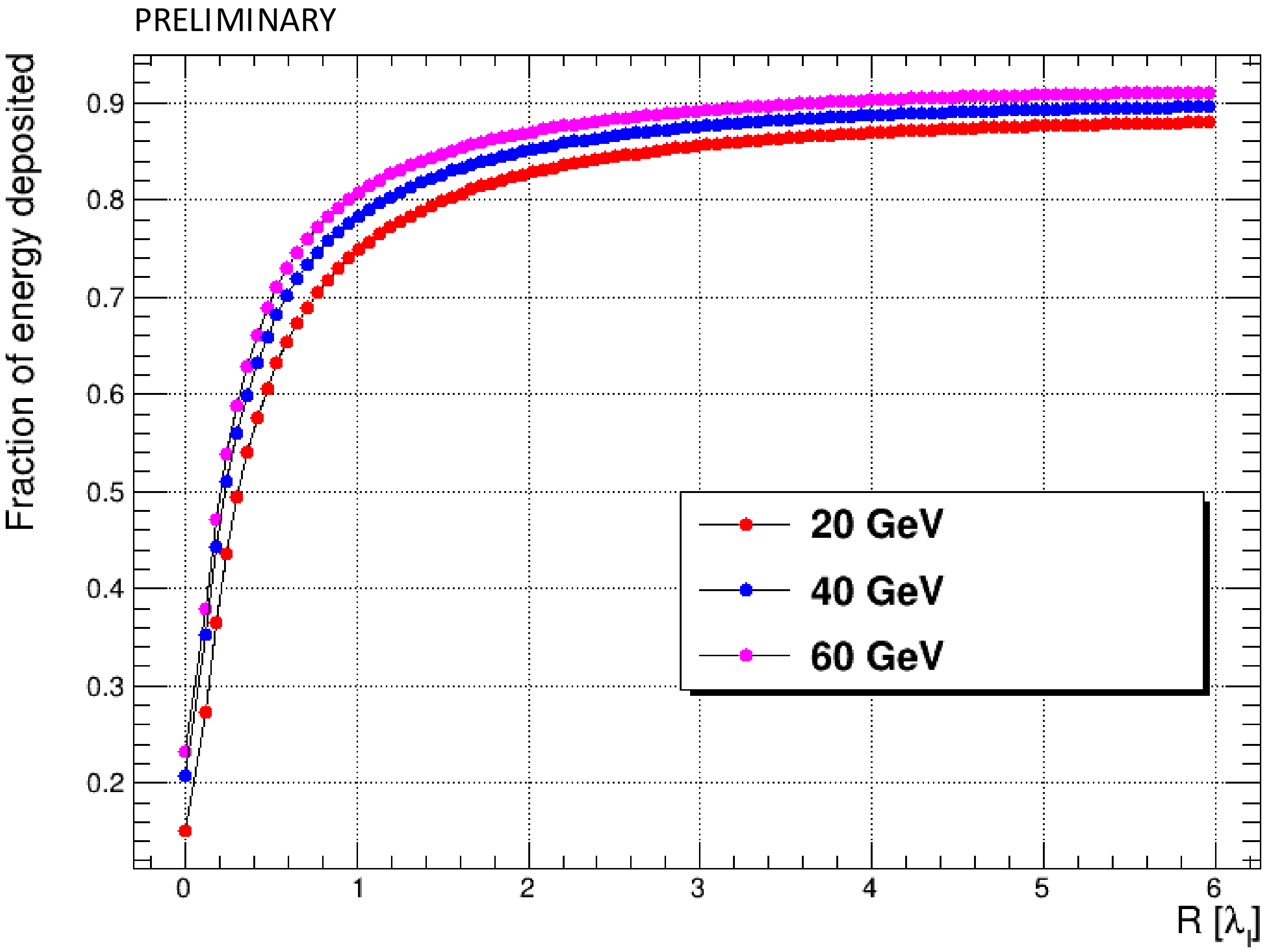
Shower lateral containment

Containment evaluated from deposited energy in a cylinder as a function of the cylinder radius in units of nuclear interaction length ($\boldsymbol{\lambda}_I$)

Containment at 90% with ~ 3 $\boldsymbol{\lambda}_I$ with 100 layers

1 pion at 20 GeV





GEANT4 Simulation - Digitization

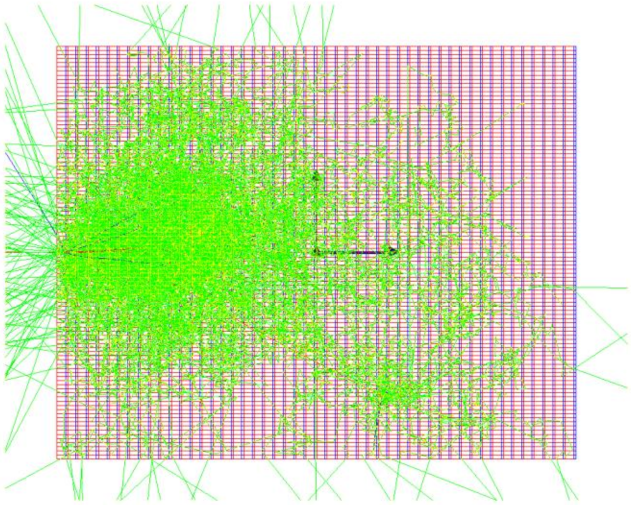
- Pion gun of variable energies (E_{pion} from 1 to 40 GeV)
- Detector Geometry:
  50 layers, 1x1 m² total transverse size, 1x1 cm² cell (80 % shower containment)

- **Digital** Read Out:
  1 hit = 1 cell with deposited energy higher than 30 eV

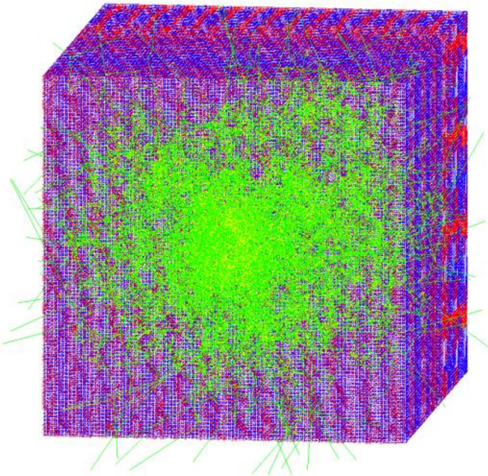
- Future plans: simulate semi-digital and analogic readout

Shower of a 20 GeV pion

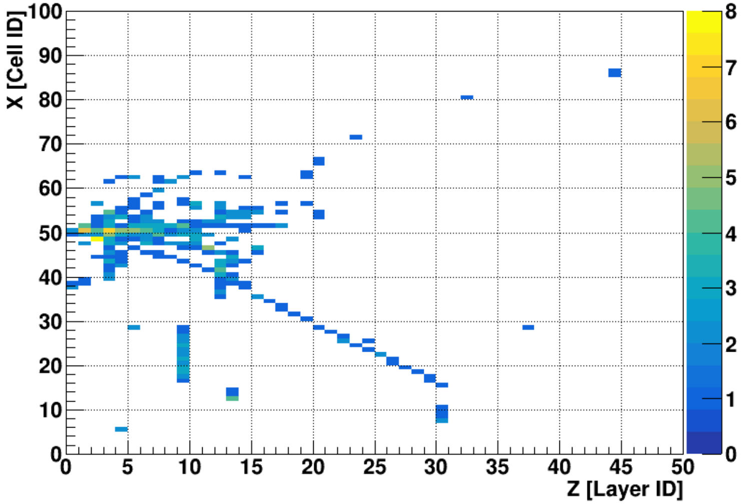
X-Z view

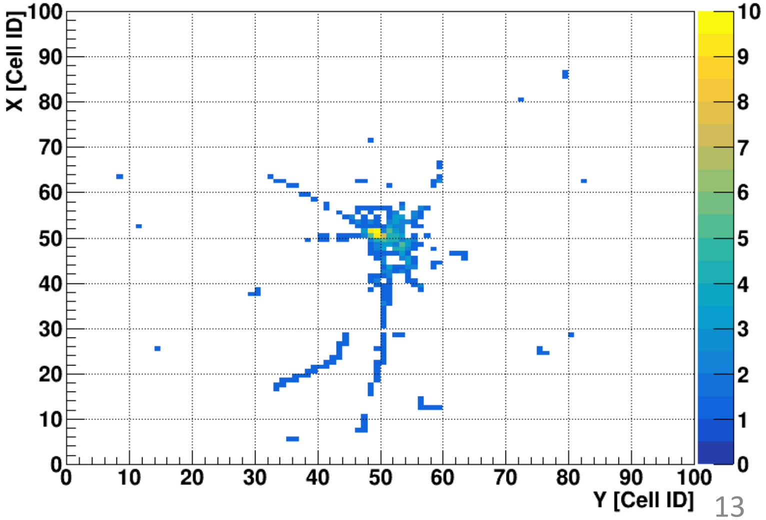


X-Y view



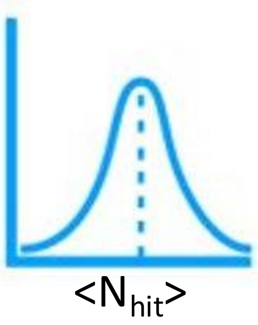
Digitised shower of a 20 GeV pion



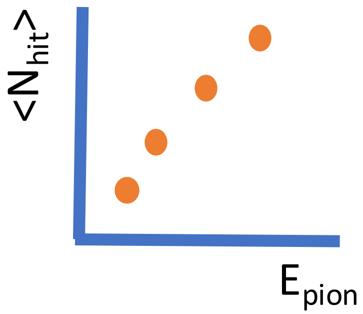


GEANT4 Simulation – Energy resolution workflow

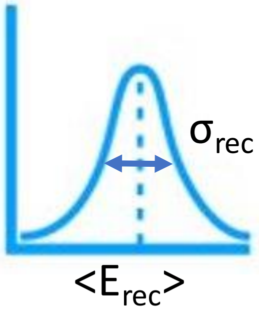
1st step: Get the N_{hit} distribution for each energy value E_{pion} and extract the mean value $\langle N_{hit} \rangle$



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



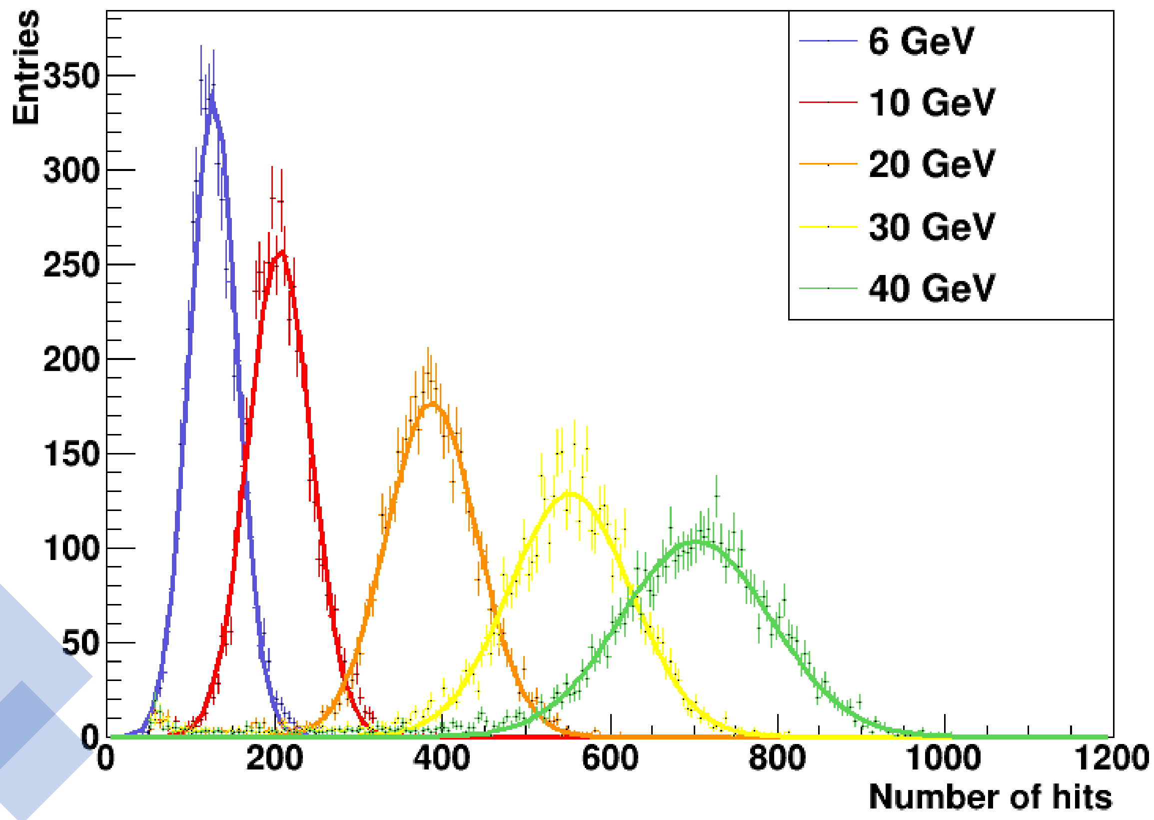
3rd step: Reconstruct the energy distribution through the inverse response function $E = f^{-1}(N)$ and extract $\langle E_{rec} \rangle$ and σ_{rec}



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

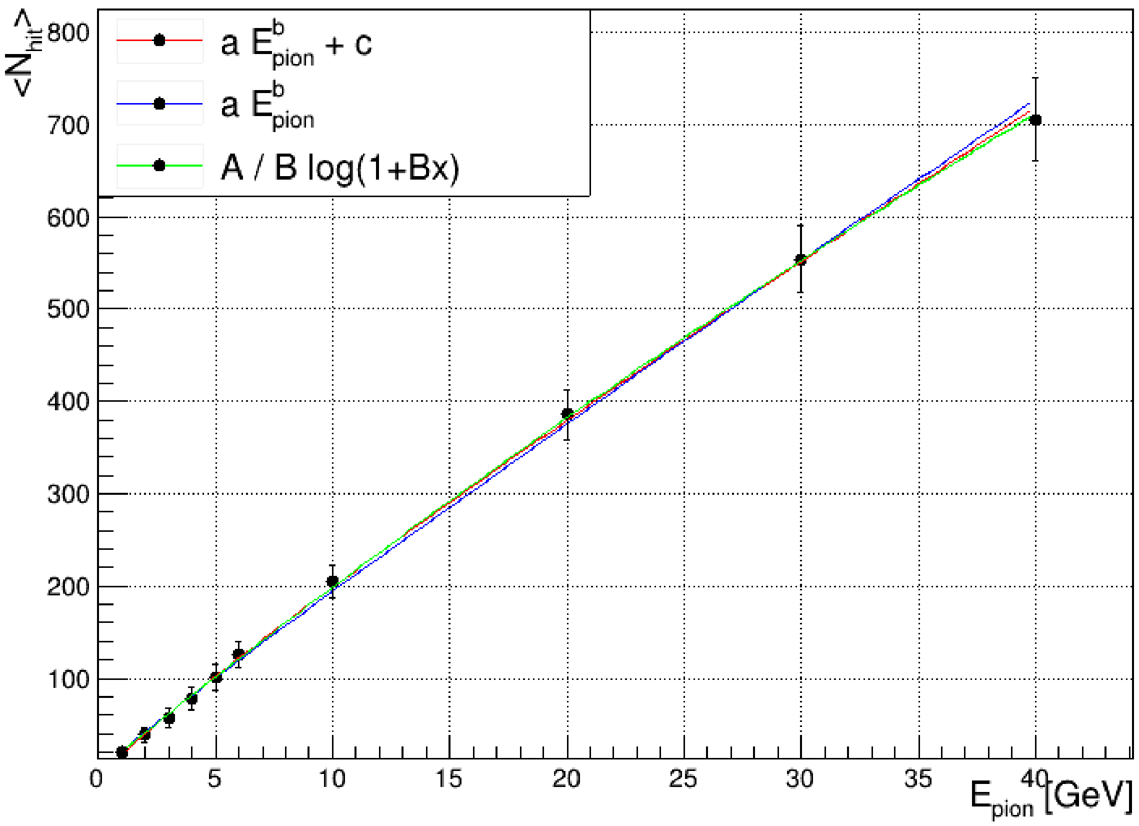
Response function of the calorimeter

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



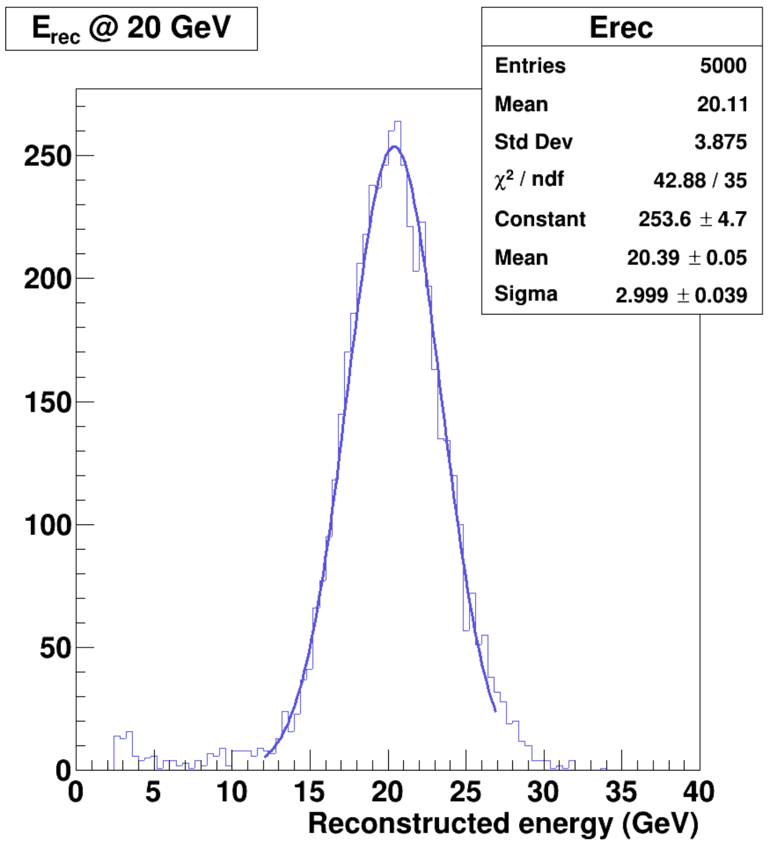
- Response function fitted with different functions
  - Power law [8 -9]
  - Logarithmic law [10]

PRELIMINARY

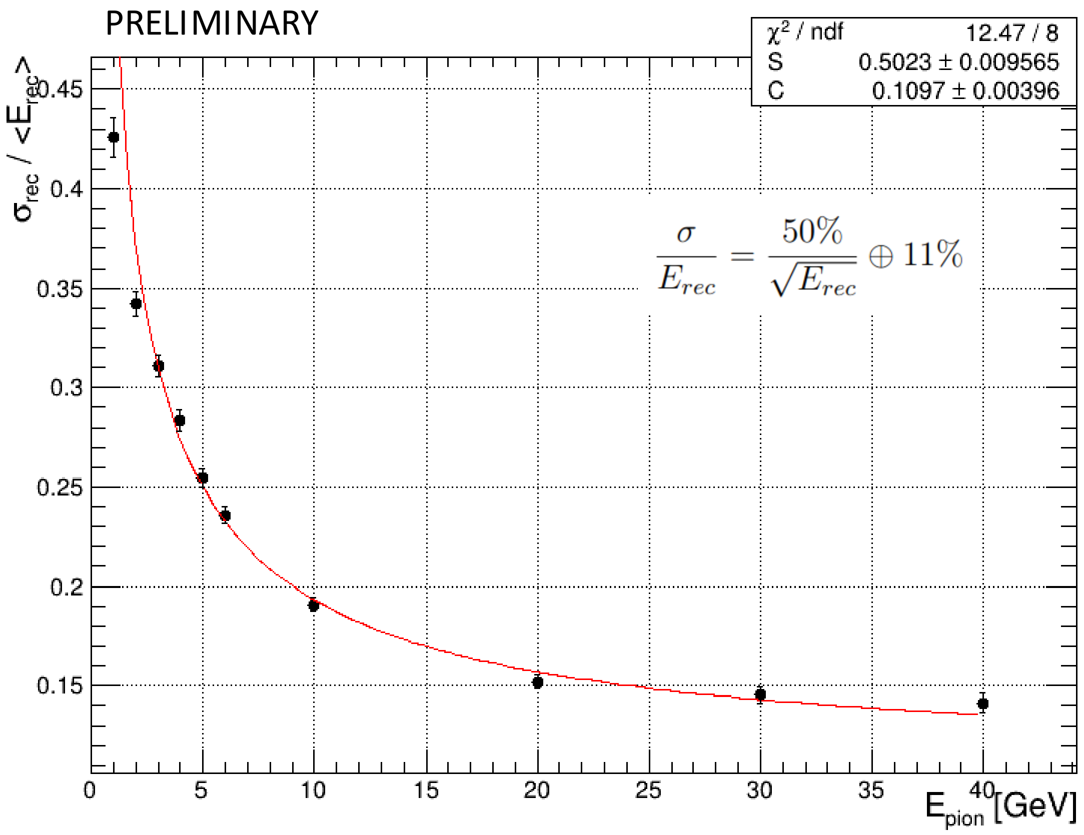


Energy reconstruction and resolution

- Reconstruct the energy from the inverse of the response function $<N_{hit}> = a\ E^{b}_{pion} + c$



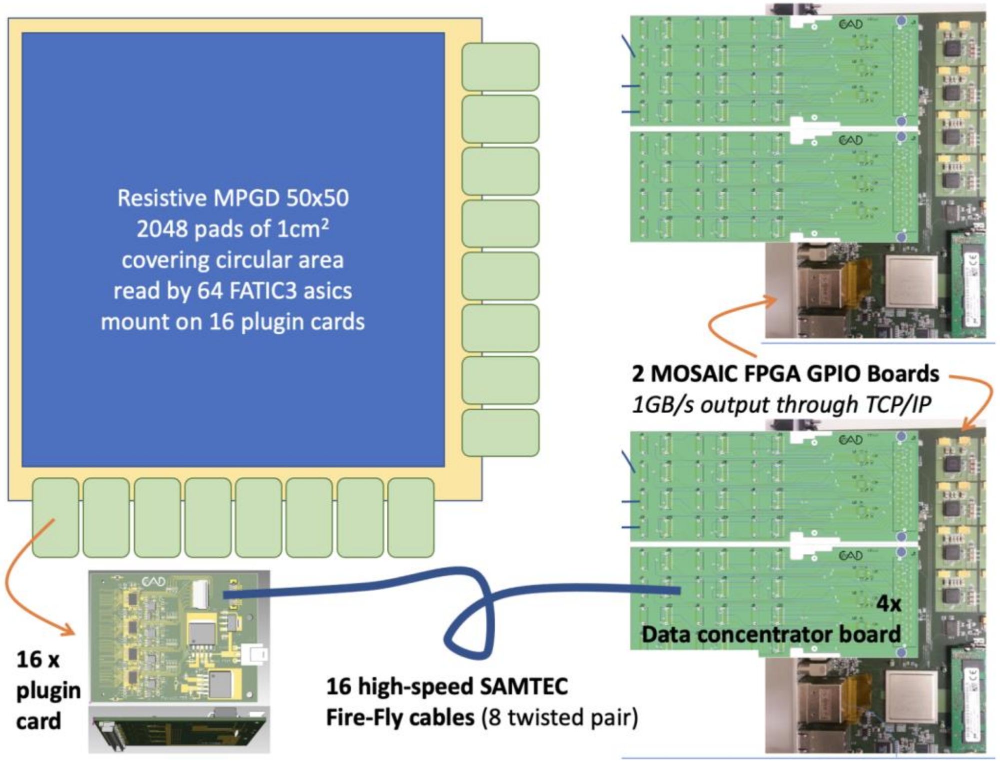
- Fit the energy resolution to the function $\frac{\sigma}{E[GeV]} = \frac{S}{\sqrt{E[GeV]}} \oplus C$



HCAL Prototype Project – Design under development

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

- Design 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**
  - 20x20 cm^2 with 1 cm^2 pad size – to be extended to 50x50 cm^2
- For Read Out 32 channels FATIC asic [11]
  - for timing and charge measurements of the hits
  - It is possible to emulate semi-digital readout
- Design, Construction & Test by INFN Bari, Frascati, Roma3 & Napoli
- Test at CERN SPS with pion and muon beam to measure
  - Efficiency and pad multiplicity of the hits
  - Time resolution for MIPs



Conclusions and future plans

- Studies in GEANT4 presented here
  - Geometry optimization for shower containment
    - 3 λ_I for 90% lateral containment
    - 14 λ_I for 90% longitudinal containment
  - Energy resolution $\frac{\sigma}{E_{rec}} = \frac{50\%}{\sqrt{E_{rec}}} \oplus 11\%$
- Future development of simulation
  - Implement a detailed geometry
  - Implement detector efficiency and read-out time window
  - Implement semi-digital readout
  - Add neutron and photon background flux to simulate the BIB
  - Test the response to multiple MIPs
- 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 and founded by the INFN - CSN1 and CERN-based MPGD R&D collaboration RD-51

References

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- [11] F. Licciulli et al. "FATIC: an ASIC for Fast Timing Micro-Pattern Gas Detectors"