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

15th Pisa Meeting on Advanced Detectors
May 22 – 28, 2022

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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

\[ \sqrt{s_U} \text{ [TeV]} \]

\[ \text{Without QCD corrections} \]
\[ \text{With QCD corrections} \]

Ref. [1]

SM processes at a muon collider

Ref. [1]

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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"
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
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
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
  - \( \mu R\text{Well} \) and resistive Micromegas as best candidates to mitigate effects due to discharge in the gas
MPGDs technologies

- High spatial ( < 60 µm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability tested up to 10 MHz/cm²

- High spatial ( 80 µm) and time (7 - 10 ns) resolution
- High rate capability
  - Gain stability > 1 MHz/cm²
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

Implemented geometry

- Layers made of
  - 2 cm of Fe (absorber)
  - 5 mm of Ar (active gap)
- Granularity given by cell of 1x1 cm²
- Pion gun of variable energies to study the shower response
- Physics list: QGSP_BERT

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 ($\lambda_\pi$)

Containment at 90% with 1x1 m² transversal area

1 pion at 40 GeV
Shower lateral containment

Containment evaluated from deposited energy in a cylinder as a function of the cylinder radius in units of nuclear interaction length ($\lambda_i$)

Containment at 90% with $\sim 3 \lambda_i$ with 100 layers

1 pion at 20 GeV

PRELIMINARY

Fraction of energy deposited

- 20 GeV
- 40 GeV
- 60 GeV

R [$\lambda_i$]
• Pion gun of variable energies ($E_{\text{pion}}$ 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
**GEANT4 Simulation – Energy resolution workflow**

**1st step**: Get the $N_{\text{hit}}$ distribution for each energy value $E_{\text{pion}}$ and extract the mean value $<N_{\text{hit}}>$

**2nd step**: Plot $<N_{\text{hit}}>$ as a function of $E_{\text{pion}}$ 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 $<E_{\text{rec}}>$ and $\sigma_{\text{rec}}$

**4th step**: Get the energy resolution parameters fitting $E[GeV] = \frac{S}{\sqrt{E[GeV]}} \oplus C$ 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]
Energy reconstruction and resolution

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

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

![Energy reconstruction and resolution graph](image_url)
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 cm² with 1 cm² pad size – to be extended to 50x50 cm²

- For Read Out 32 channels FATICasic [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
    • $3 \lambda_i$ for 90% lateral containment
    • $14 \lambda_i$ for 90% longitudinal containment
  • Energy resolution
    \[
    \frac{\sigma}{E_{\text{rec}}} = \frac{50\%}{\sqrt{E_{\text{rec}}}} \oplus 11\%
    \]
• 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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• [9] J. Repond "First Results from the CALICE Digital Hadron Calorimeter (DHCAL)" https://inspirehep.net/files/91249d1db962b9a01e2a675cf7d4d3e4
• [10] C. Adloff et al. "Micromegas for Particle Flow Calorimetry" https://inspirehep.net/files/f55704efaea8daf8a1b763351ae953dd