SOCIETÀ ITALIANA DI FISICA
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UNIVERSITÀ DEGLI STUDI DI BARI ALDO MORO

INFN

Full simulation study of a hadronic calorimeter for a future muon collider

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Lisa Generoso
University and INFN Bari
On behalf of the IMCC Collaboration

International MUON Collider Collaboration

WHY A MULTI-TEV MUON COLLIDER ?

Point-like particle
- Clean collisions
- Full CoM energy available for hard collisions

(as in e^+e^- colliders)

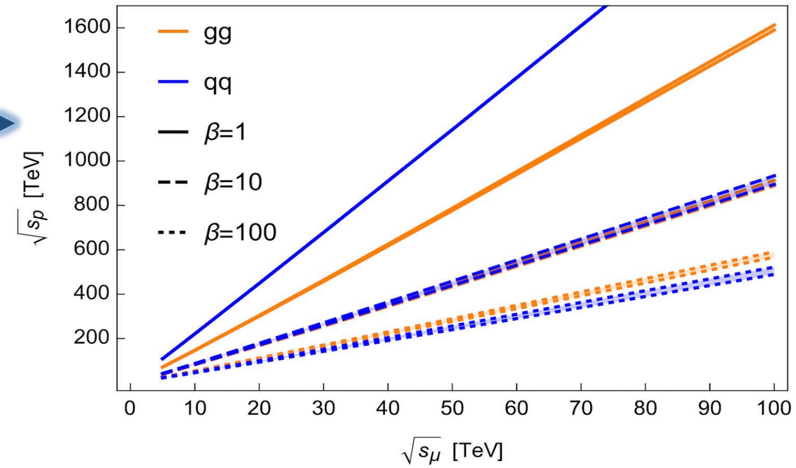
$m_\mu \approx 200 m_e$
- negligible loss of the beam energy due to bremstrahlung

→ High energy frontier
(as in hadron colliders)

≈ Proton collider of a much higher CoM energy

Vector Boson Fusion
→ **Higgs Factory**

https://arxiv.org/abs/2303.08533



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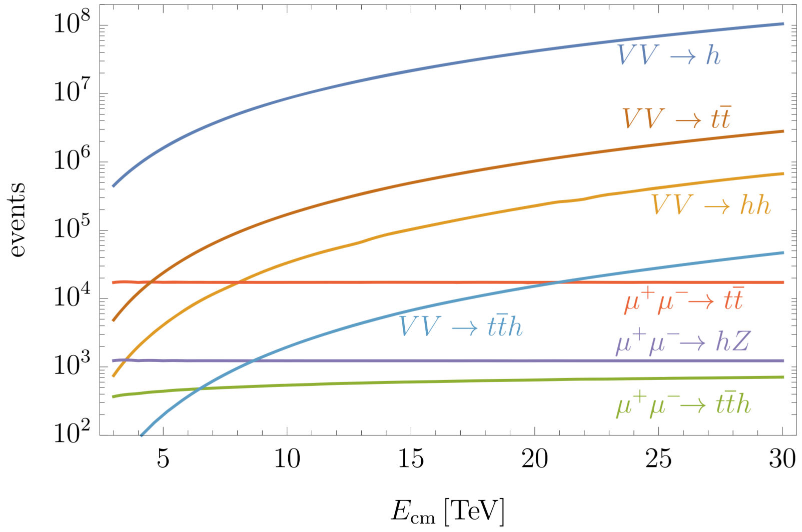
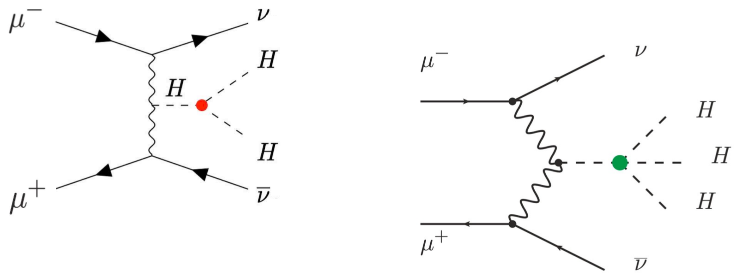


- 5 years of operation
- Ideal probe for Higgs physics

$\sqrt{s}$	$\mathcal{L}_{int}$	#Higgs
3 TeV	1 ab^{-1}	5 x 10^5
10 TeV	10 ab^{-1}	1 x 10^7

- Improve the precision of Higgs **couplings** to the **per-mille level**
- Measure Higgs **self-coupling constant**
- Observe **trilinear** and **quartic** coupling



MUON COLLIDER CHALLENGE

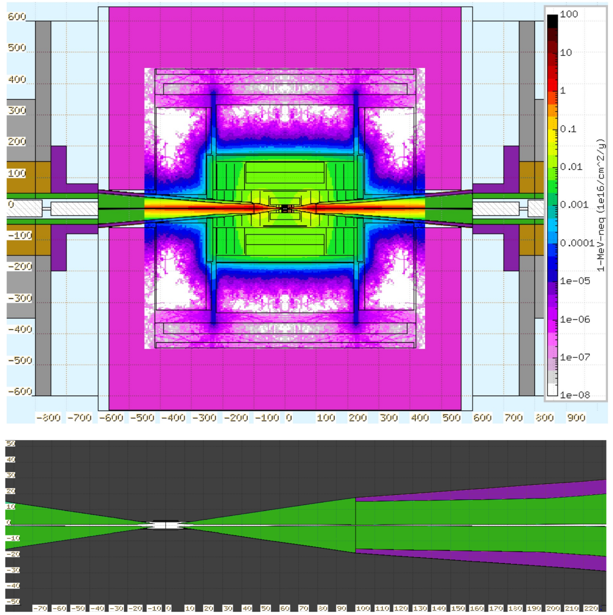
UNSTABLE NATURE OF MUONS

$$\mu^+ \rightarrow e^+ \overline{\nu_\mu} \nu_e$$

Beam Induced Background (BIB)

- Muon decay products + interaction with the detector material (mostly photons and neutrons)
- Asynchronous arrival time

MDI : shielding tungsten nozzles



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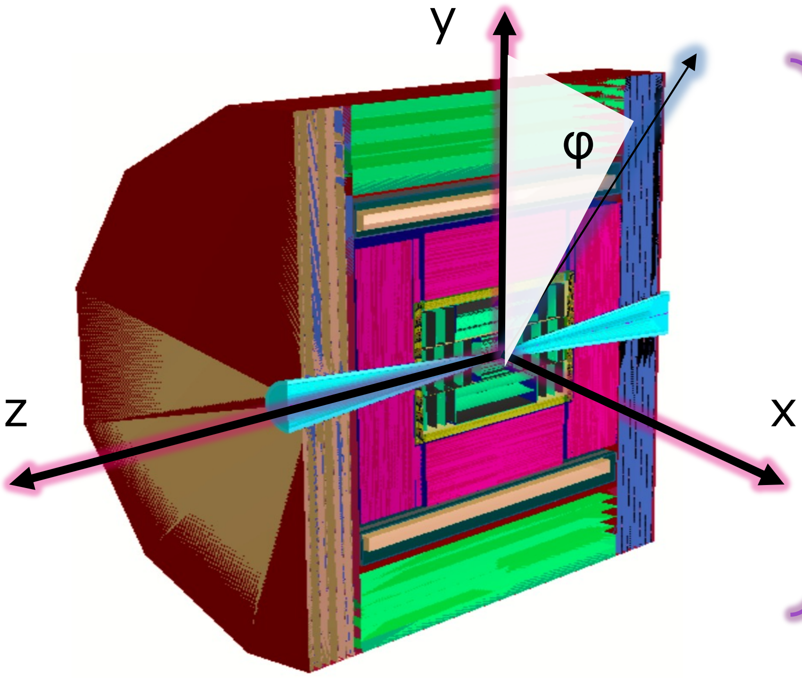


DETECTOR :
- Radiation hard technology
- Good time resolution

DESIGN FOR A

3 TeV MUON COLLIDER DETECTOR

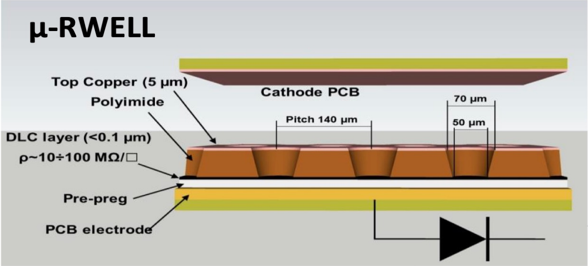
- Tracking system
- Calorimeter system
  - **PbF_2 ECAL (CRILIN):** new proposal from LNF-PD INFN
  - **MPGD HCAL:** **new proposal and protptype developement from INFN Bari**
- 3.6 T magnet yoke + muon system

WHY AN MPGD-BASED HCAL?

HCAL requirements:

- Radiation hard to withstand ~10^{-5} **GRad/year**
- Time resolution of **O(ns)**
- Energy resolution ≥ **60% /√E**
- Fine granularity **(1 - 3 cm²)**
- Longitudinal segmentation

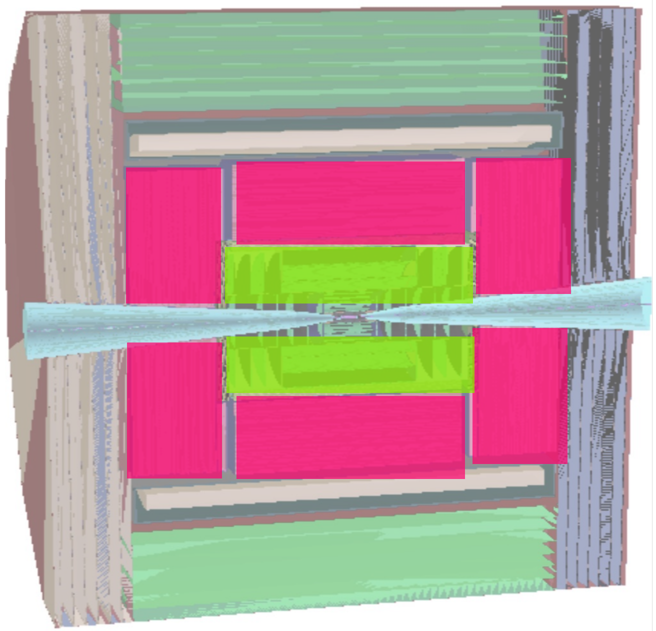
→ **Resistive Micro Pattern Gaseous Detectors**



- Satisfy all the previous requirements ✓

+

- High rate-capability O(MHz/cm²)
- Cost-effective for large-area instrumentation



GEOMETRY OF THE CALORIMETER SYSTEM IMPLEMENTED IN THE FULL DETECTOR SIMULATION SOFTWARE (iLCSoft)

CRILIN ECAL

5-layer SEMI-HOMOGENEOUS CALORIMETER of PbF_2

Layer thickness: **4 cm** - depth: 0.9 λ_I

MPGD-based HCAL

60-layer SAMPLING CALORIMETER

Layer thickness: **2.65 cm** - cell: **1 cm²**

→

HCAL LAYER COMPOSITION:

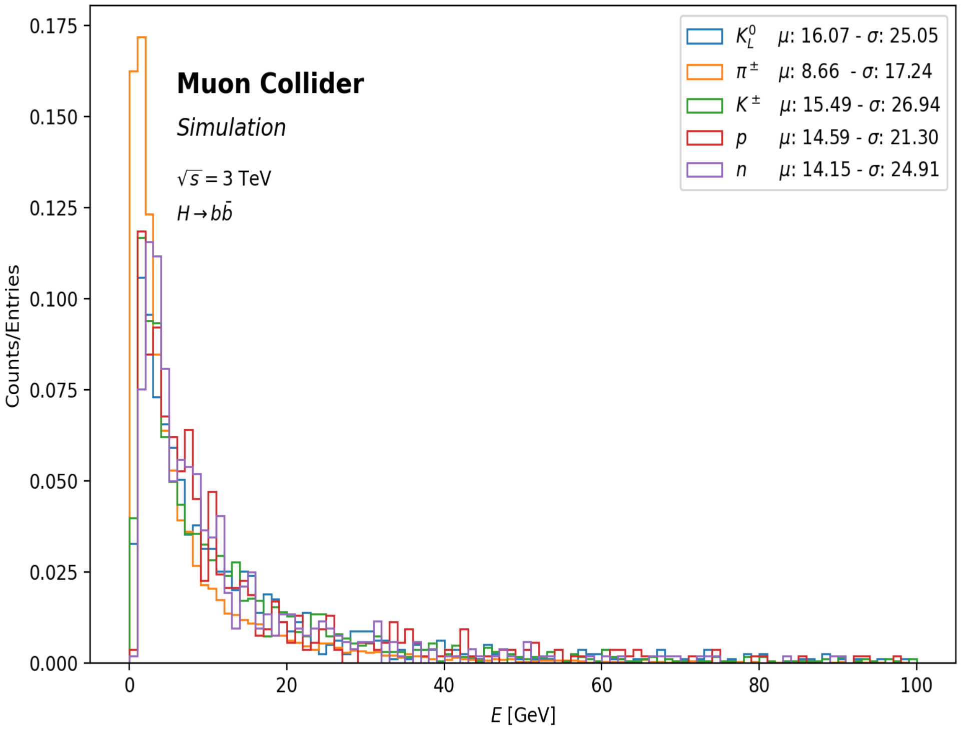
Iron (absorber)	20 mm
Argon (active material)	3 mm
Copper (RO electronics)	0.1 mm
PCB (RO electronics)	0.7 mm
Air (environment)	2.7 mm

STUDY OF $\mu\mu \rightarrow H \rightarrow b\bar{b}$
DI-JETS EVENT ANALYSIS

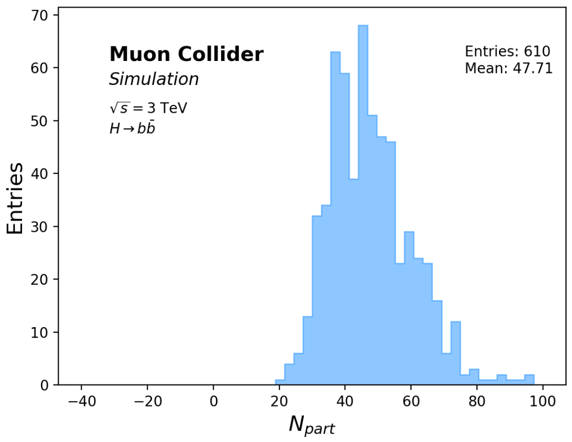
1000 events generated with [*Whizard*] at 3 TeV

On average :

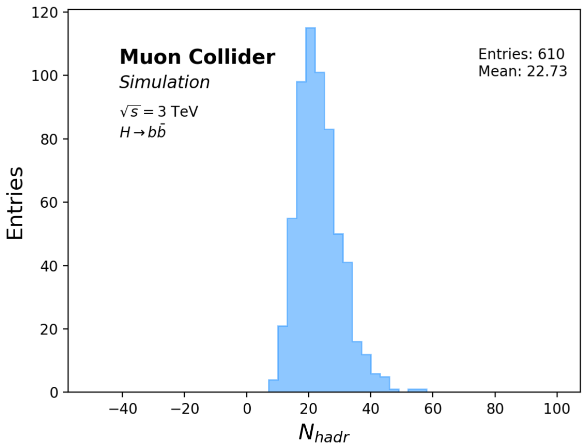
- **~50 particles** in each di-jet event
- **~10 hadrons** per jet



#PARTICLES PER EVENT



#HADRONS PER EVENT



- mean energy : **~9 GeV** for $\pi^\pm$ **(~80% of the hadrons)**

  ~15 GeV for p, n, $K^\pm$, K^0

- **~95%** of particles below **20 GeV**

Most of the particles produced at the interaction point convert their energy into **hadronization** processes

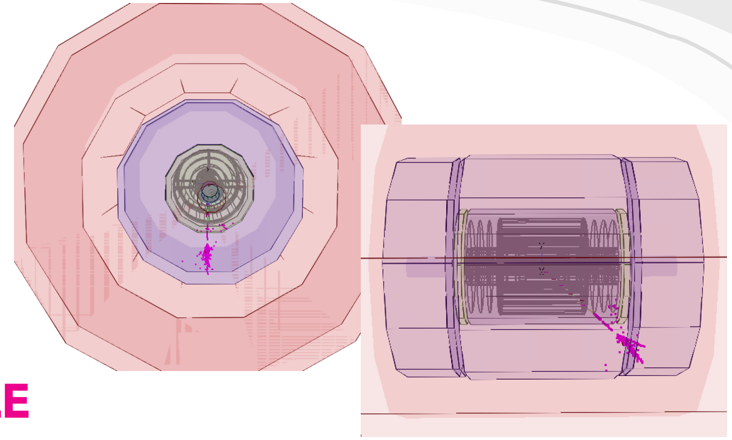
→ **high particle multiplicity / low particle energy**

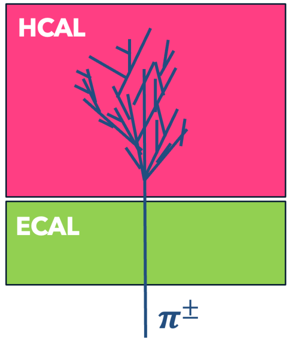
- Detector characterization **with monochromatic $\pi^\pm$ guns** with energy in the observed range **1.5-100 GeV**

CALORIMETER SHOWERS

Simulation of **monochromatic $\pi^{\pm}$ guns** performed through the [DD4HEP](DD4HEP) package

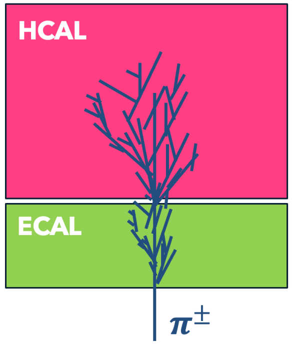
- Particles release energy deposits (**HITS**) in the calorimeter volume





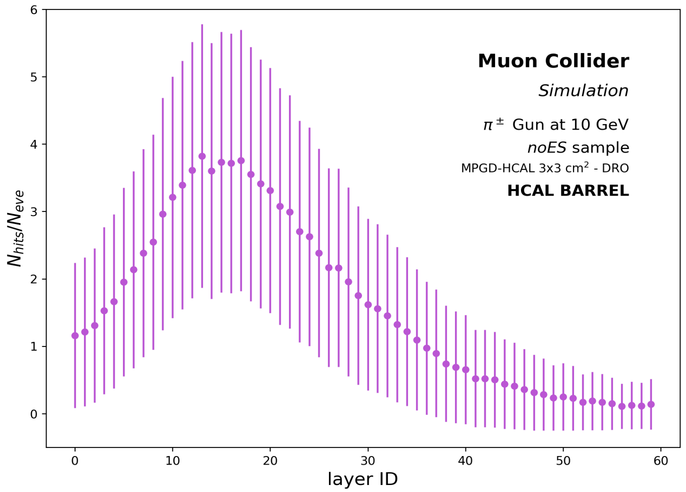
noES SAMPLE

- MIP-like behaviour in ECAL
- Shower starts in HCAL
- **Shower profile** in HCAL



EH SAMPLE

- ECAL absorber ~ $\mathbf{1\lambda_I}$
- Shower starts in ECAL



CLUSTER FORMATION

- **PANDORA PFA**

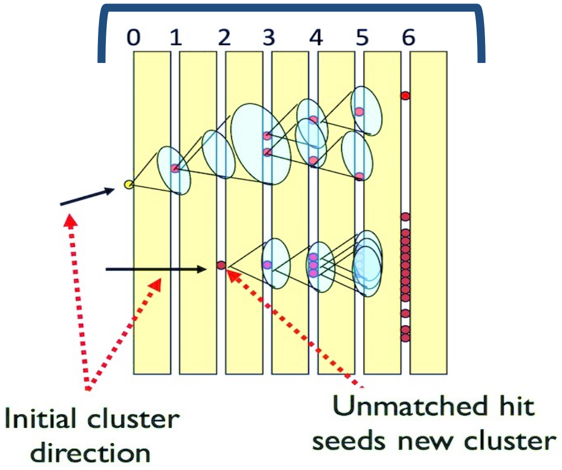
  A cone-based forward projective clustering algorithm grouping ECAL and HCAL hits into clusters

ENERGY RECONSTRUCTION OF CLUSTERS

- **ECAL HITS** → ANALOG READOUT: $E_{ECAL} = \sum_{i=0}^{N_{EHit}} E_i$
- **HCAL HITS** → DIGITAL READOUT: $E_{HCAL} = f(N_{HHit})$

$$E_{raw} = E_{ECAL} + E_{HCAL}$$

ECAL+HCAL

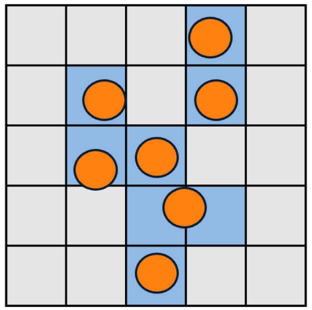


CLUSTER ENERGY - HCAL

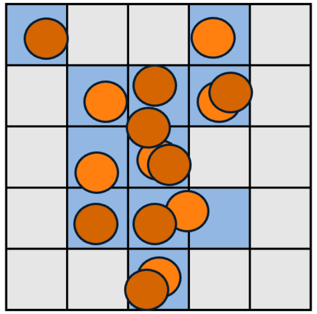
Event digitization and reconstruction with ***Marlin*** through the [*DDMarlinPandora*] package

DIGITAL READOUT

LOW ENERGY



HIGH ENERGY

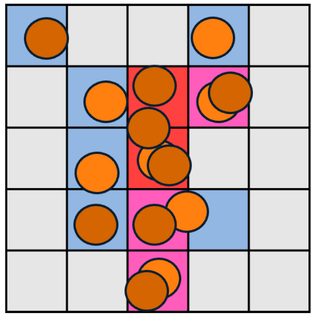


IMPROVEMENT

3 LEVEL DIGITIZATION

SEMI-DIGITAL READOUT

HIGH ENERGY



- Set **3 energy thresholds:** T_1 - T_2 - T_3
- Count separately HCAL hits within the different energy ranges (N_1, N_2, N_3)

- **HCAL energy**: increasing function of the **total number of HCAL hits** associated with the cluster

$$E_{HCAL} = f(N_{TOT})$$

- At high E_{MC}, more shower particles might impinge on the same cell
- **Larger energy deposit** in the cell, but **one single hit is counted**

→ **Saturation of energy resolution at high energies**

- The **cluster energy** is a weighted sum

$$E_{HCAL} = \alpha N_1 + \beta N_2 + \gamma N_3$$

with α , β and γ depending on N_{TOT}

- To assess the best combination of T_1 - T_2 - T_3 : **threshold scan** based on the energy distributions of hits at different E_{MC} of the incoming $\pi^{\pm}$

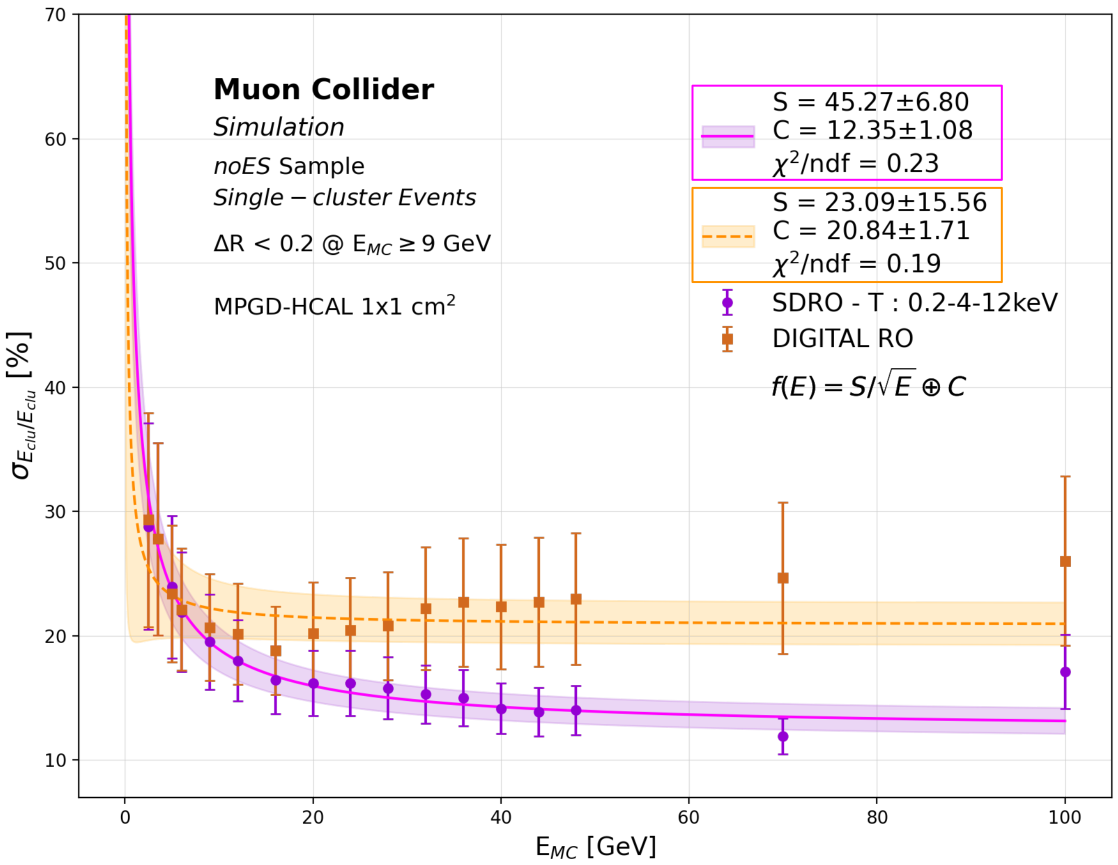
→ Energy resolution as final the figure of merit :

0.2 - 4 - 12 keV

HCAL ENERGY RESOLUTION

DIGITAL vs SEMI-DIGITAL READOUT (RO)

- Reconstruction of the **noES samples** with Digital RO (DRO) and Semi-Digital RO (SDRO) Thr: 0.2-4-12 keV
- Linear calibration of the energy spectra of clusters, accounting for energy underestimation due to **invisible energy**



- Gaussian fit of the calibrated energy distributions
- Extract the mean $\mathbf{E_{clu}}$ and the sigma σ

  → **resolution points** $\sigma/\mathbf{E_{clu}}$
- Fit function $f(E) = S/\sqrt{E} \oplus C$

- Comparable performances below 6 GeV
- **DRO: Saturation** at high energies of the fit function with an evident increase in the experimental points
- **Better performances of the SDRO :**

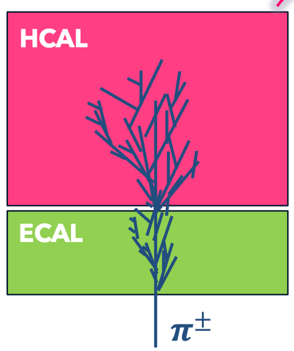
$$\sigma/E_{clu} = 45.27\%/\sqrt{E} \oplus 12.35\%$$

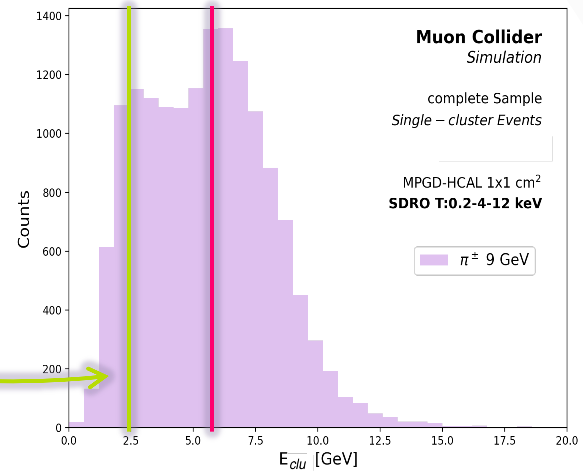
ENERGY RESOLUTION OF THE FULL CALORIMETRIC SYSTEM

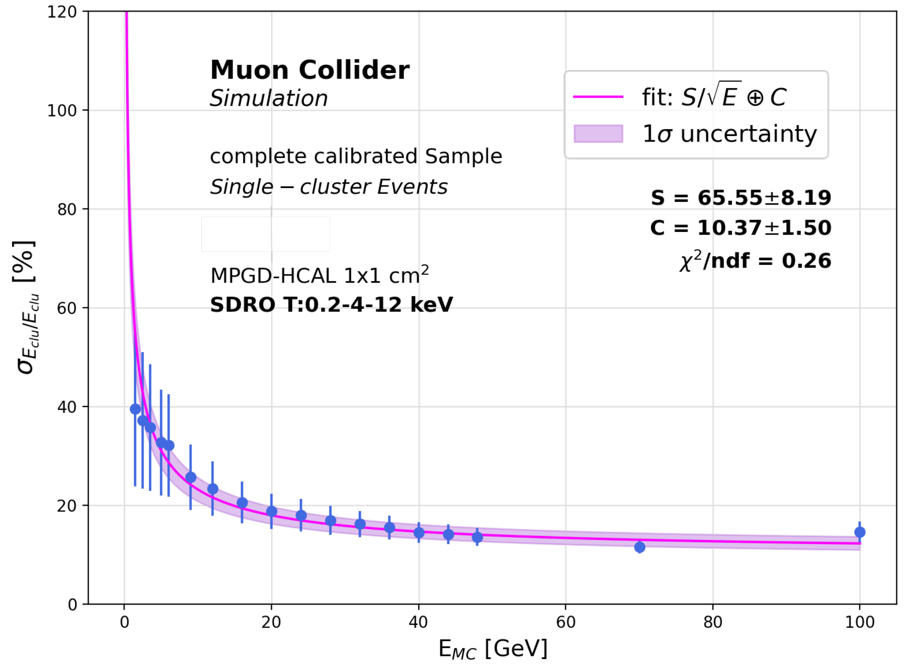
CRILIN ECAL + MPGD HCAL (SDRO)

$\pi^{\pm}$ guns with E_{MC} of 1.5-100 GeV noES + EH sample

Ad hoc **calibration** of the energy spectra accounting for **different responses of ECAL and HCAL**







- Average resolution from the fit:

$$\sigma/E_{clu} = 65.55\%/\sqrt{E} \oplus 10.37\%$$

- With respect to the intrinsic HCAL resolution :

  The constant term **C slightly decreases** → better reconstruction at high energies

  The stochastic term **S increases** → fluctuations due to analog read out of the **ECAL**

BIB IN HCAL

- 1500 events of BIB generated at the $\sqrt{s} = \mathbf{1.5\ TeV}$ Muon Collider in 1 BX : $\mu^+ \rightarrow e^+ \overline{\nu_\mu} \nu_e$

BIB containment within the first 20 layers of HCAL

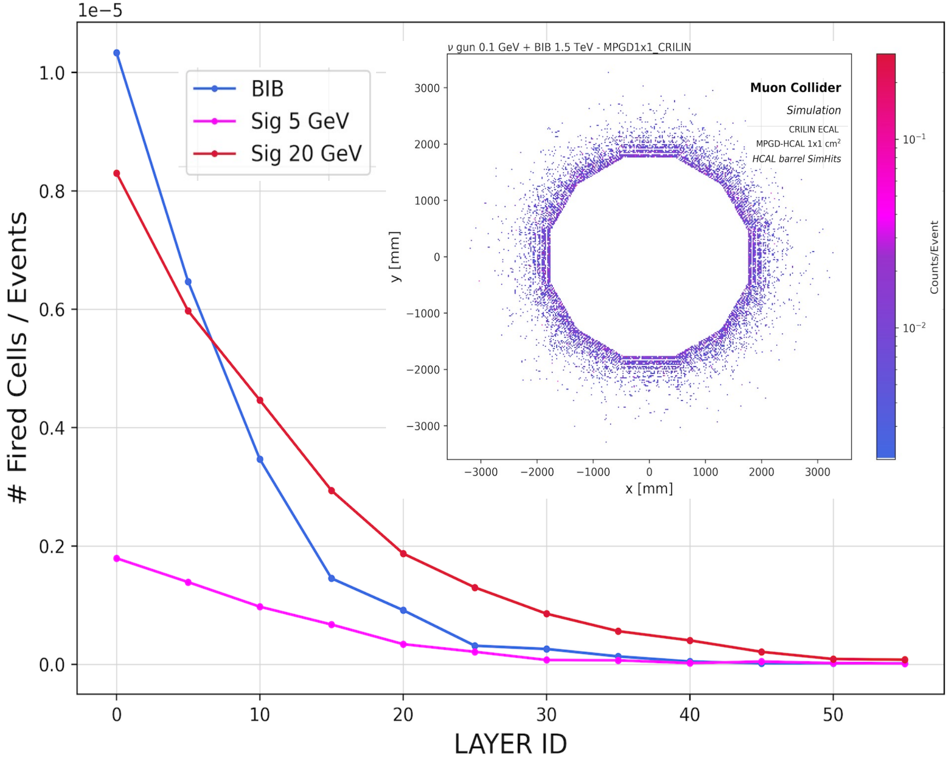
- Probability of a cell to be fired in the first layer :

BIB : ~ 1 x 10^{-5}

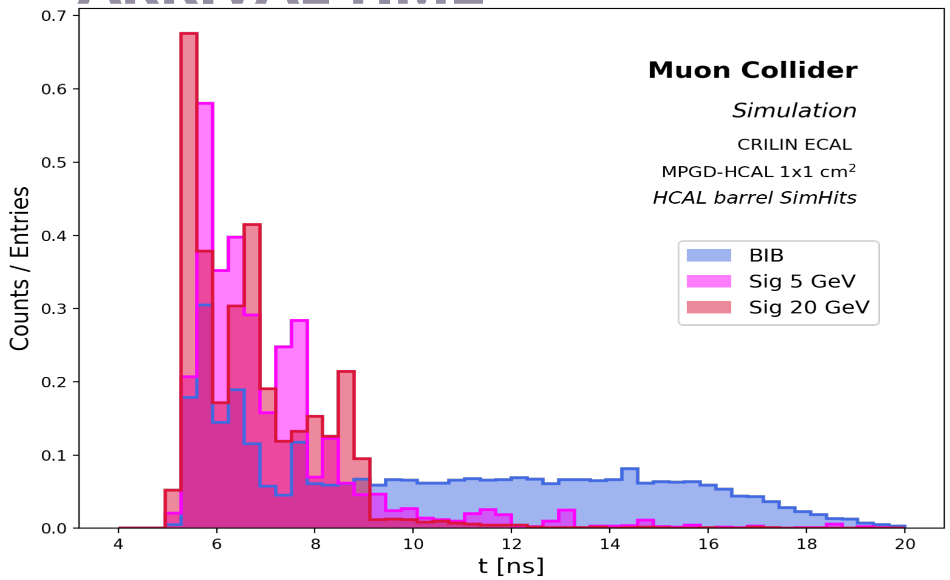
$\pi^{\pm}$ 5 GeV : ~ 0.2 x 10^{-5}

$\pi^{\pm}$ 20 GeV : ~ 0.8 x 10^{-5}

} potential problems for low energy pion reconstruction



ARRIVAL TIME



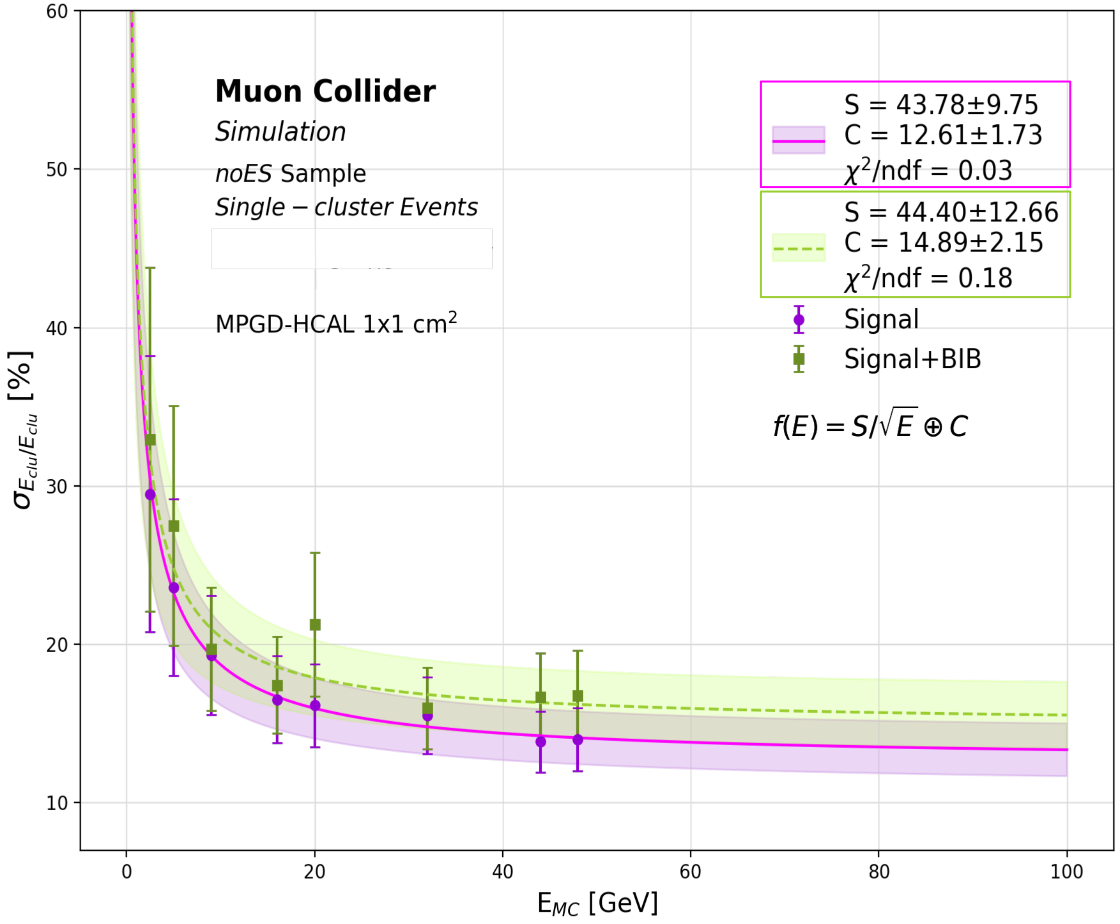
- Arrival time distribution is uniform in the range 7-20 ns, while signal peaks at 6 ns

→ **Cut at t > 10 ns ~50% BIB rejection**

CLUSTER ENERGY RECONSTRUCTION WITH BIB

BIB IMPACT ON ENERGY RESOLUTION

- Reconstruction of the w/wo BIB noES samples with **SDRO Thr: 0.2-4-12 keV**



- Compatible in resolution with BIB overlaid

	Signal	Signal+BIB
S [%]	43.78 ± 9.75	44.40 ± 12.66
C [%]	12.61 ± 1.73	14.89 ± 2.15

- However, the **parameter S**, accounting for uncertainties, remains **below 60%**

→ Satisfied the energy resolution requirements for an imaging HCAL in a multi-TeV Muon Collider

CONCLUSIONS

Characterization and optimization of the innovative MPGD-based HCAL for the Muon Collider in a full simulation of the detector environment

CLUSTER RECONSTRUCTION

Implementation of **SDRO** with the optimal threshold choice:

0.2-4-12 keV

- HCAL intrinsic energy resolution :

$$\sigma/E_{clu} = 45.27\%/\sqrt{E} \oplus 12.35\%$$

→ **Significant improvement wrt DRO**

→ Stochastic term **below 60%,** as required for imaging HCALs at Muon Colliders

- In the innermost layers of HCAL, occupancy of the BIB hits comparable to that of the Signal
- However, the **energy resolution is negligibly affected by the BIB overlay**

  → further improvement is expected for a **cut on BIB** hits at **arrival times > 10 ns** provided the necessary electronics

FUTURE STEPS

- Optimize Particle Flow event reconstruction to analyze **energy of jets**

THANK YOU

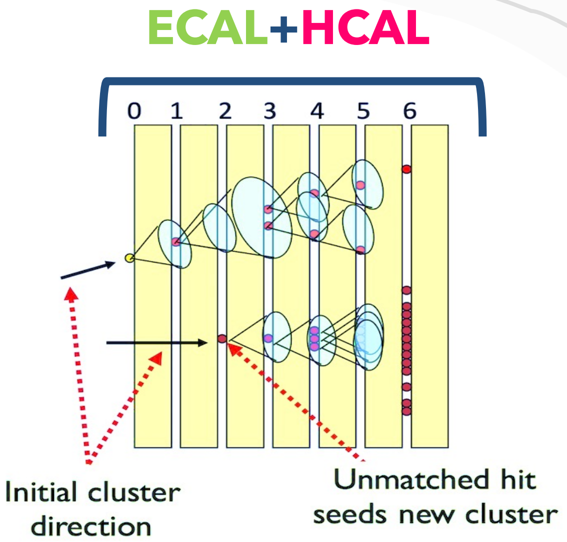
FOR THE ATTENTION

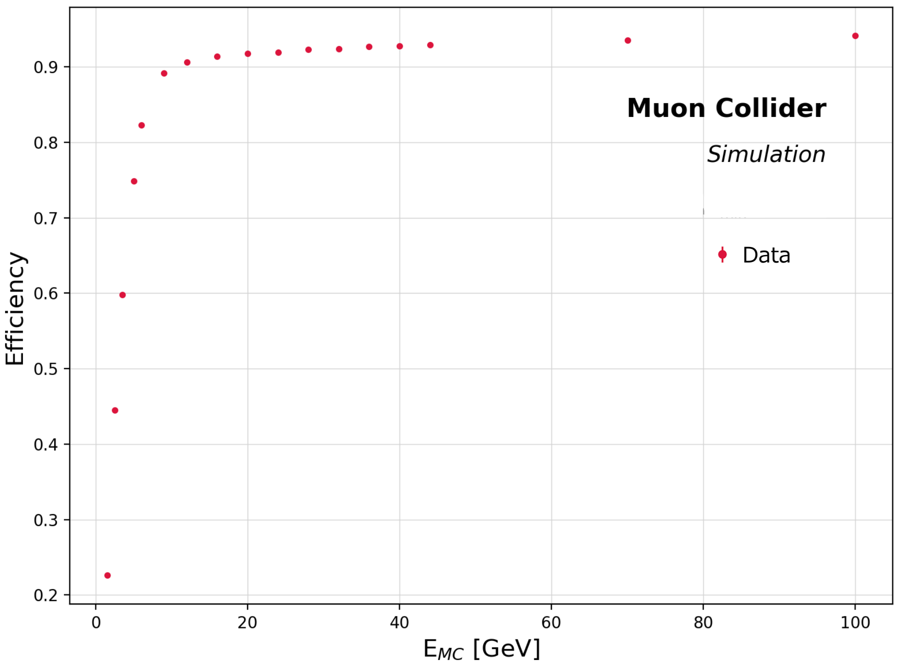
BACKUP SLIDES

CLUSTERING

PANDORA PARTICLE FLOW ALGORITHM

- **Cluster** = **ECAL** hits + **HCAL** hits
- **Cone-based** forward projective **clustering algorithm** from the innermost to the outermost layer
- Efficiency tested with 1 $\pi^{\pm}$ per event → expected **1 cluster per event**



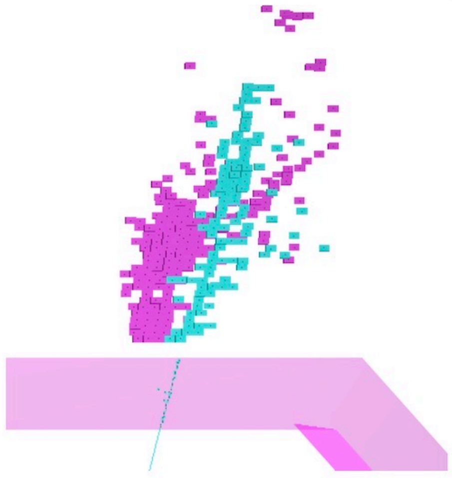


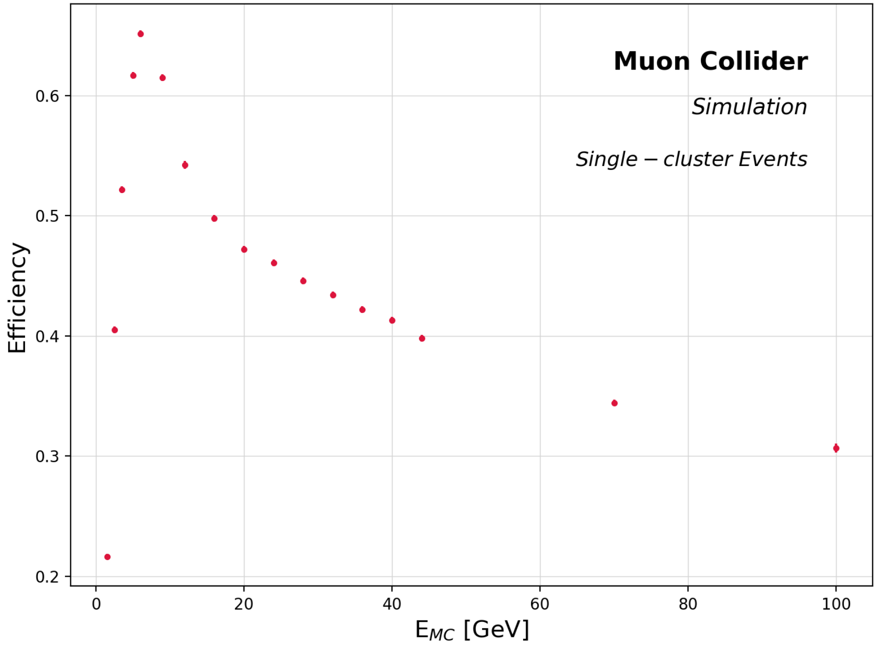
- **Detector efficiency** = **(nr. events with ≥1 cluster) / (sample size)**
- **Low** energies $\mathbf{E_{MC}}$ → big fraction of **zero-cluster events** due to impossibility of finding and merging neighboring hits
  - low multiplicity of produced and reconstructed hits
- For $\mathbf{E_{MC}}$ > 9 GeV, saturation at ~95%
- BUT many **MULTIPLE CLUSTERS →** Discard all the multiple-cluster events and perform the cluster energy analysis with **SINGLE CLUSTER** events

CLUSTERING

PANDORA PARTICLE FLOW ALGORITHM

- Algorithm Efficiency tested with 1 $\pi^{\pm}$ per event → expected **1 cluster per event**
- Algorithm Effective efficiency is given by **(nr. single-cluster events) / (sample si**
  - **At low** energies $\mathbf{E_{MC}}$ → dominates the fraction of **zero-cluster events**
  - For $\mathbf{E_{MC}}$ > 9 GeV, increasing number of **MULTIPLE CLUSTERS**





- **Algorithm logic:**

  → designed to **rather separate true clusters** than merge energy deposits from multiple particles into a single cluster

  → multiple clusters result from unmerged groups of hits, each carrying a fraction of the true cluster energy

- Discard all the multiple cluster events, and associate **single clusters** within a $\Delta R < 0.2$ from the MC $\pi^{\pm}$

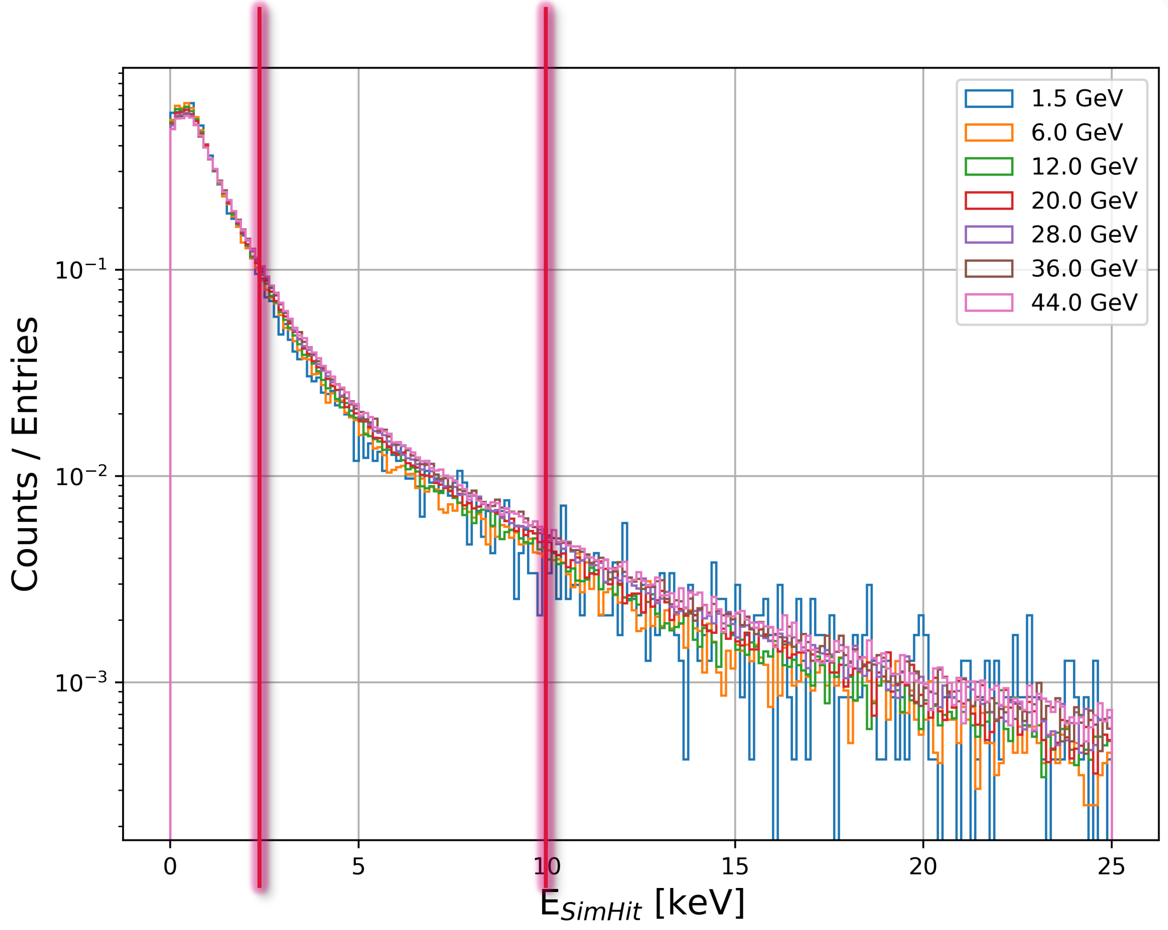
SEMIDIGITAL READOUT

THRESHOLD CHOICE

ENERGY DISTRIBUTIONS OF SIMHITS NORMALIZED BY THE NUMBER OF ENTRIES

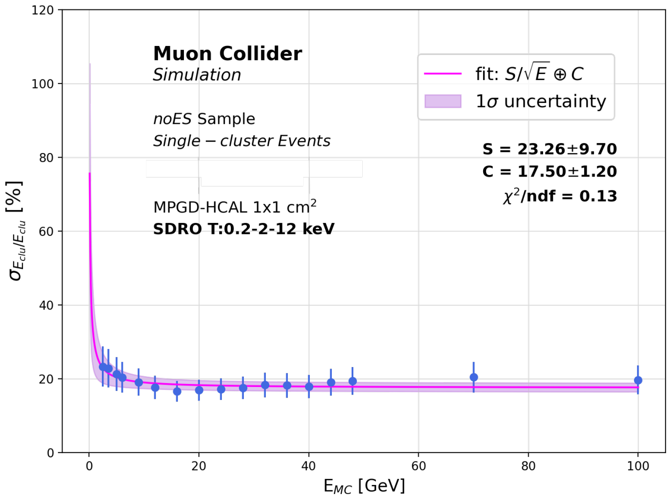
The choice of T_2 and T_3 should be based on the E_{SimHit} values at which the difference between the curves is more evident :

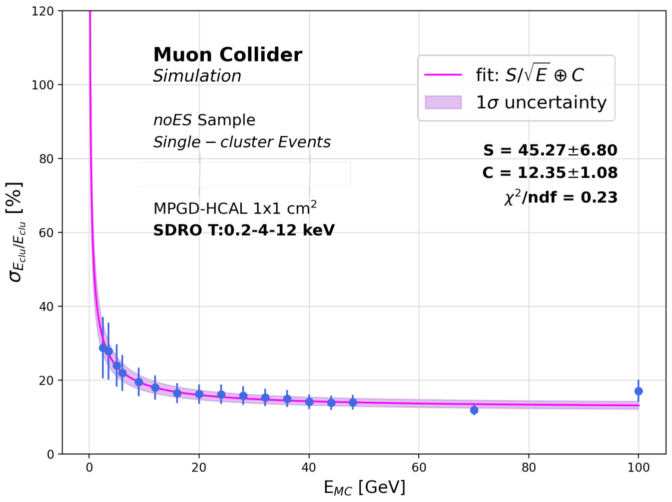
- **From 0 to ~2.5** keV the curves are almost indistinguishable
- **After 2.5 keV**, the tails tend to increase with E_{MC} → the probability of having larger energy deposits for high E_{MC} is higher
- **For $E_{SimHit} \geq$ 10 keV**, the curves feature significant fluctuations (especially at low E_{MC}) → the number of entries above a high threshold decreases significantly

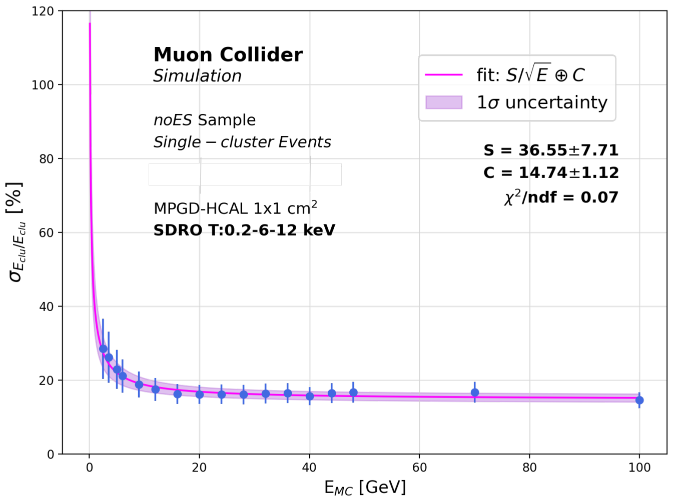


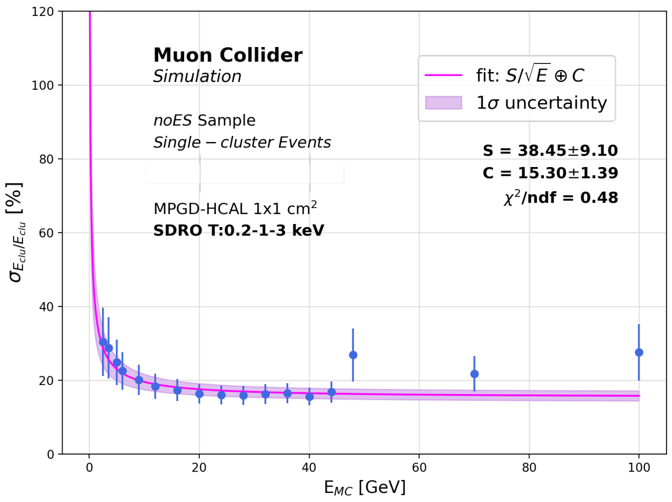
HCAL ENERGY RESOLUTION

SEMIDIGITAL RO - THRESHOLD CHOICE







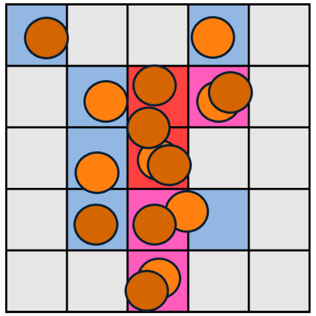


- Energy resolution as the figure of merit to assess the best threshold combination
- A too-small **T_3 (~3 keV)** makes the resolution above 48 GeV worse
- Comparable results obtained for fixed **T_3 = 12 keV** and varying **T_2**

→ The best combination is the one providing the minimum C parameter: **0.2-4-12 keV**

CLUSTER ENERGY - HCAL

SEMI-DIGITAL READOUT



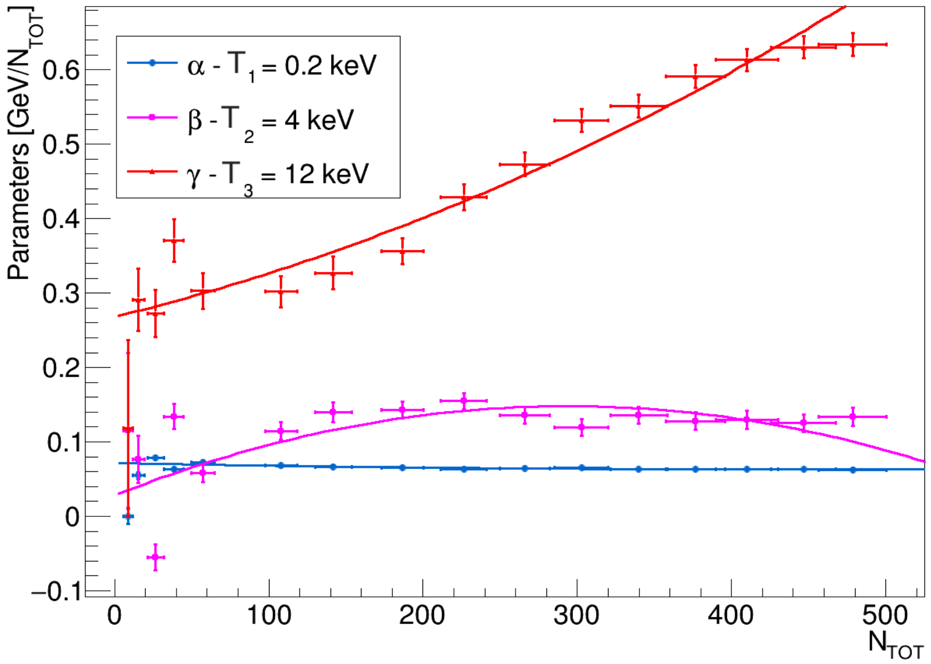
ENERGY THRESHOLDS

- T_1 **= 0.2 keV :** set by the sensitivity [10 fC] of the readout electronics
- T_2 **-** T_3 **: threshold scan based on the energy distributions of hits at different** E_{MC}
  → Energy resolution as the figure of merit to assess the best combination :
  0.2-4-12 keV

- At each energy point E_{MC}, α, β, and γ are obtained by a χ^2 **minimization**

$$\sum_{i}^{N_{eve}} \frac{(E^i_{MC} - E^i_{REC})^2}{\sigma_i}$$

- The dependence of α, β and γ on on $\boldsymbol{N_{TOT}}$ is obtained by a 2^{nd} order polynomial fit



CLUSTER ENERGY

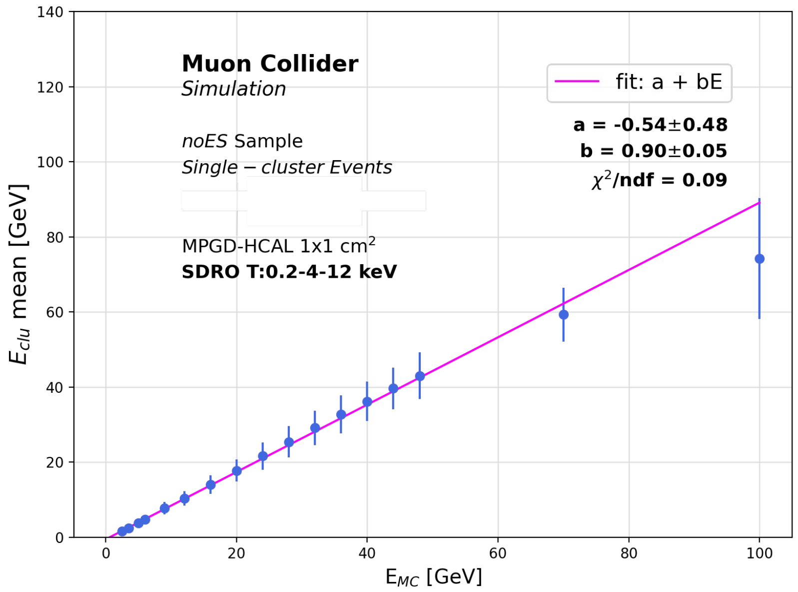
LINEAR CALIBRATION – noES selection

- HCAL → **invisible energy** → energy underestimation

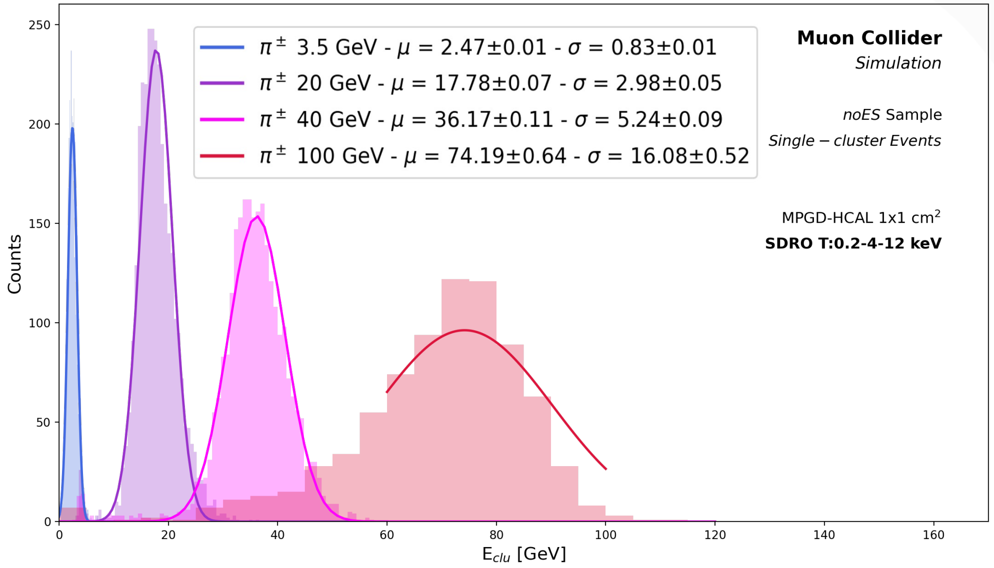
CALIBRATION

- Gaussian fit of the cluster energy distributions
- Represent $\mathbf{E_{clu}}$ **mean =** $\boldsymbol{\mu}$ as a function of E_{MC}
- Linear fit → apply the corrective parameters :

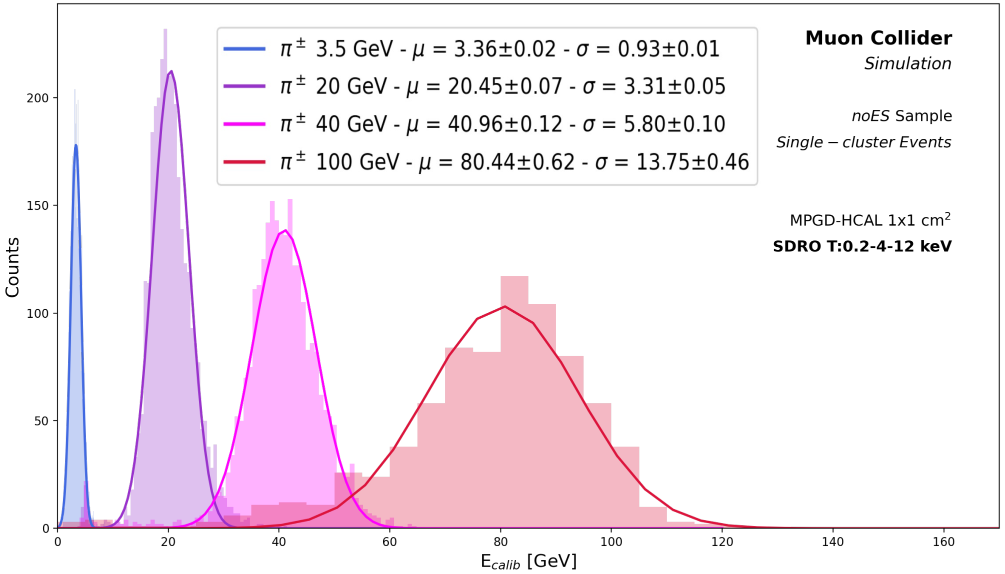
$$E_{calib} = (E_{clu} - b)/a$$



BEFORE CALIBRATION



AFTER CALIBRATION



CLUSTER ENERGY

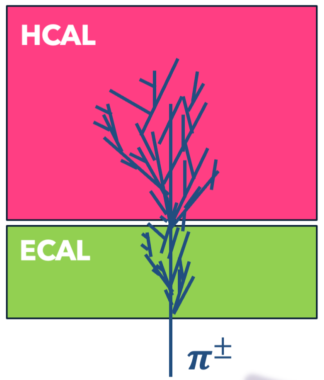
CALIBRATION – noES + EH SAMPLE

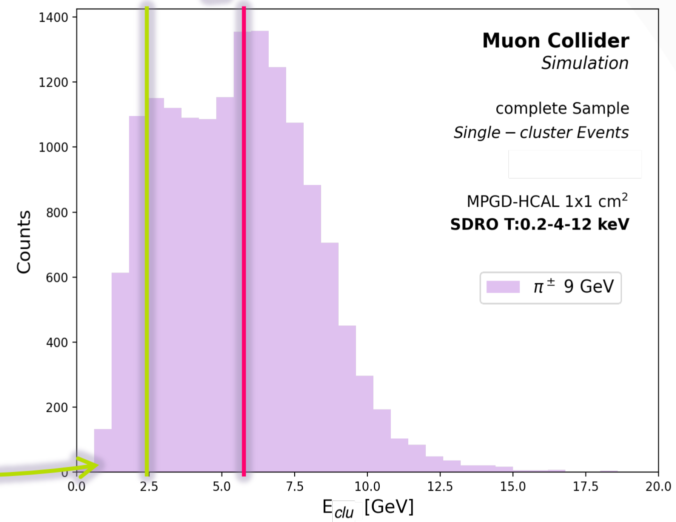
- ECAL and HCAL have **different responses**
- Double peaks in monochromatic **$\pi^{\pm}$ guns**

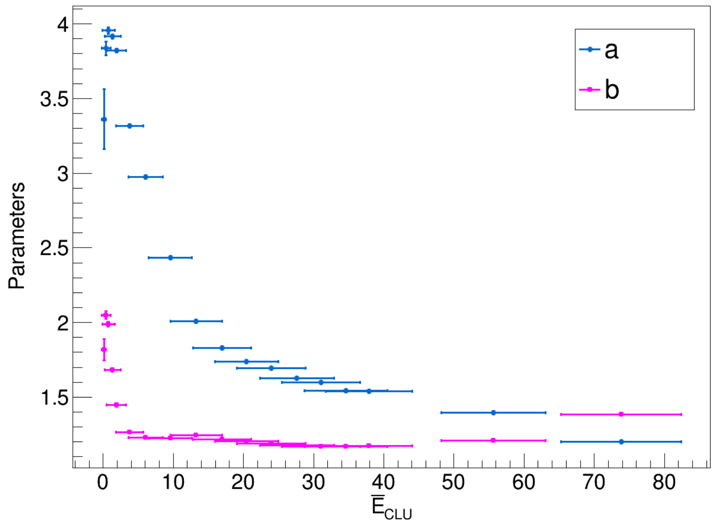
→ separate calibrations

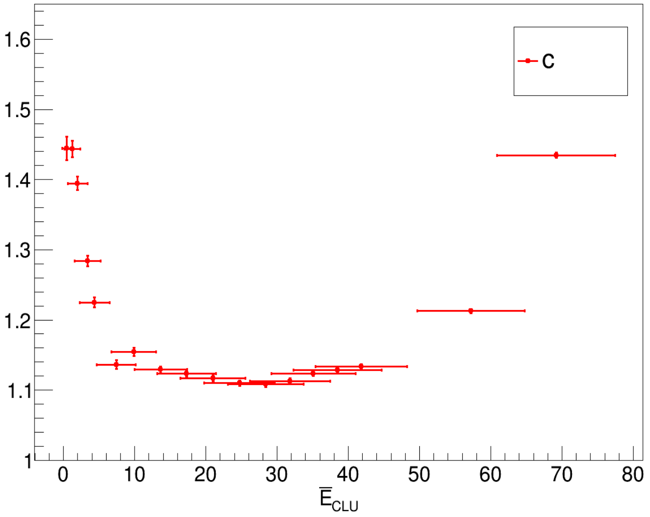
  - **EH :** $E_{calib} = \mathbf{a}\, E_{rawECAL} + \mathbf{b}\, E_{rawHCAL}$
  - **noES:** $E_{calib} = \mathbf{c}\, E_{rawHCAL}$

- **a**, **b** and **c** are obtained by χ^2 minimizations

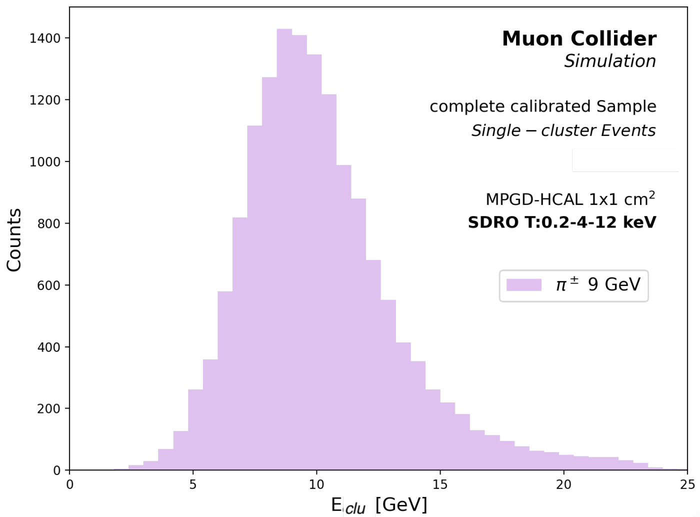








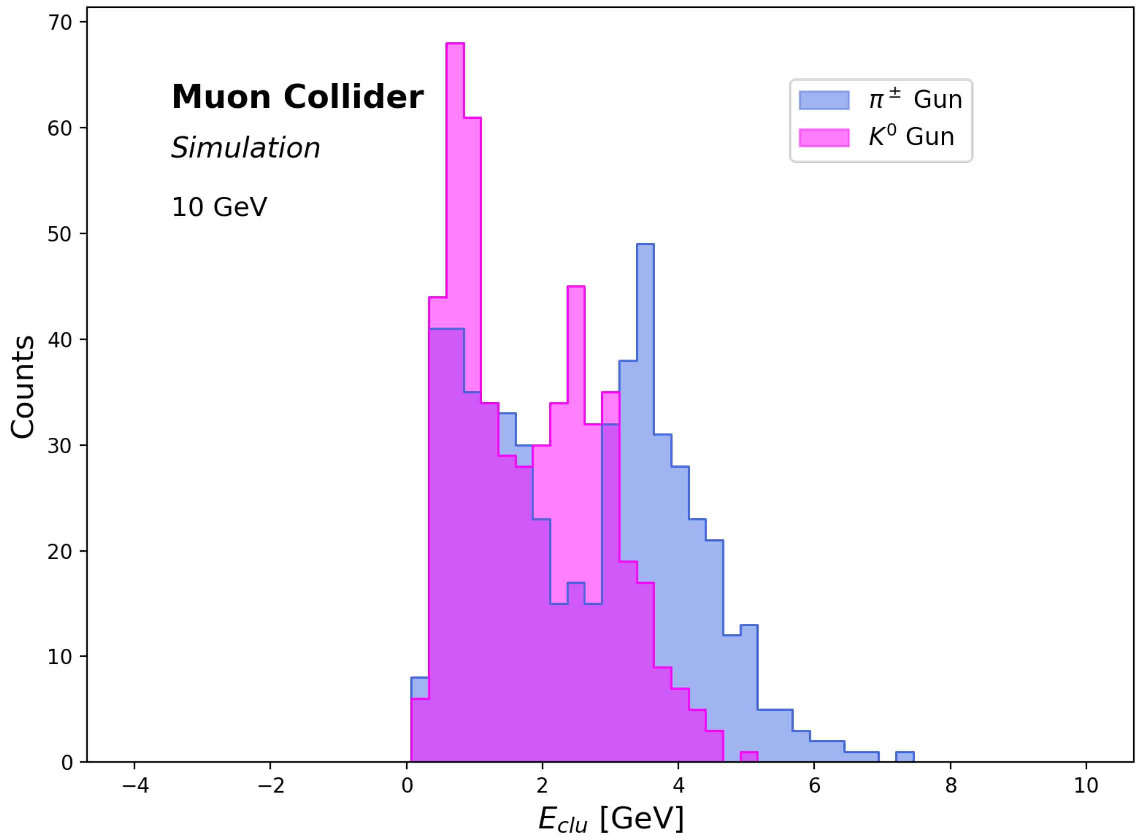
AFTER CALIBRATION



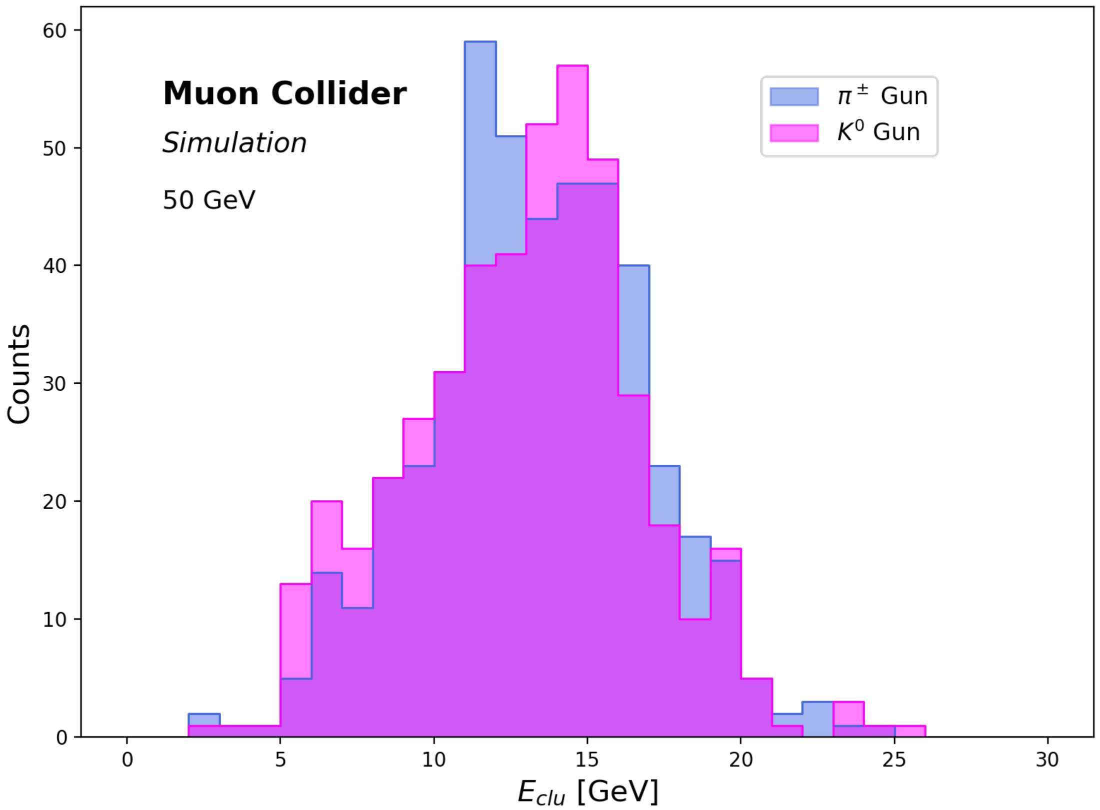
CHARGED VS NEUTRAL HADRONS

- Similar cluster energy reconstructed for $\pi^{\pm}$ and K^0 at corresponding energy points

10 GEV



50 GEV

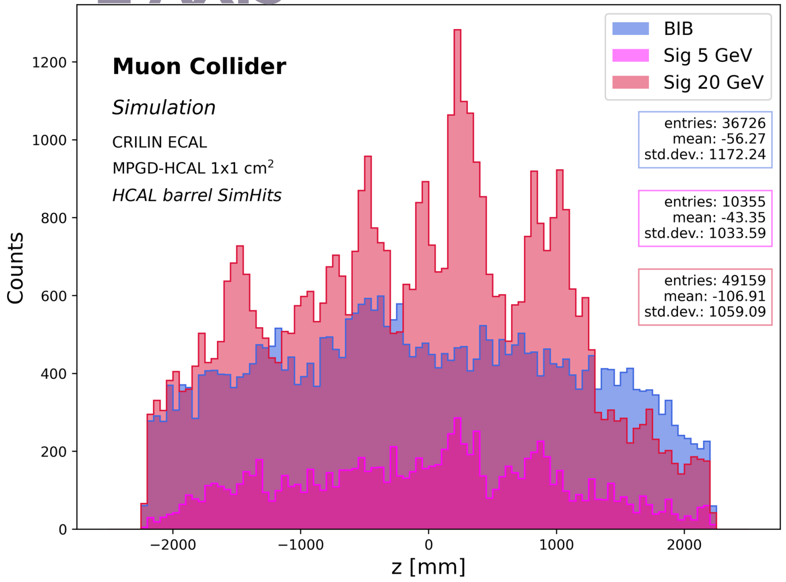


BIB CHARACTERIZATION

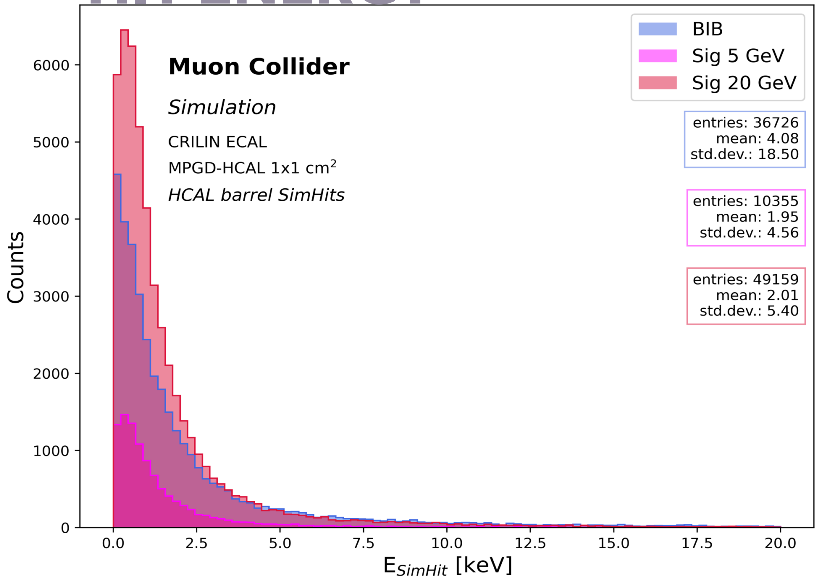
HCAL HITS

- Uniform longitudinal distribution without prominent differences from the pion guns
  → **No** possible **cut on the z**
- SimHit average energies of ~ 4 keV → twice the value of the signal hits
  → **No** possible **cut** changing the RO **energy** thresholds
- Arrival time distribution is uniform in the range 7-20 ns, while signal peaks at 6 ns
  → **Possible cut at t > 10 ns**

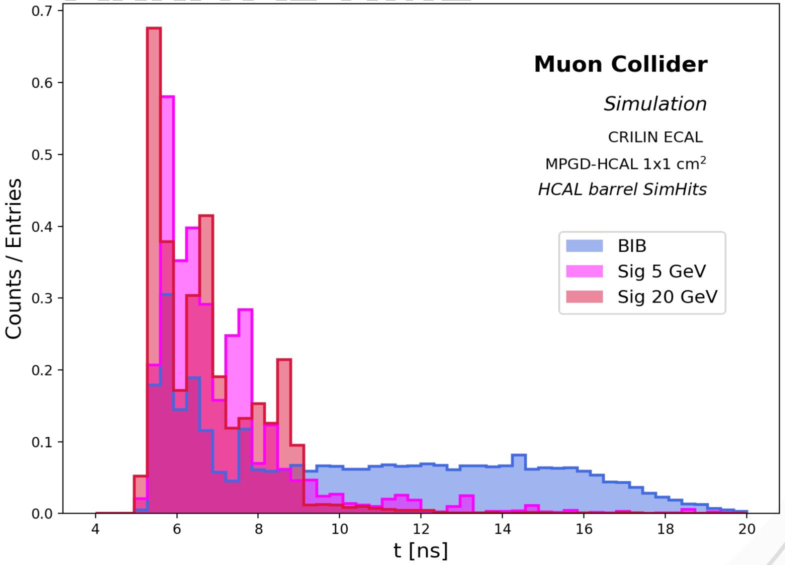
Z-AXIS



HIT ENERGY



ARRIVAL TIME

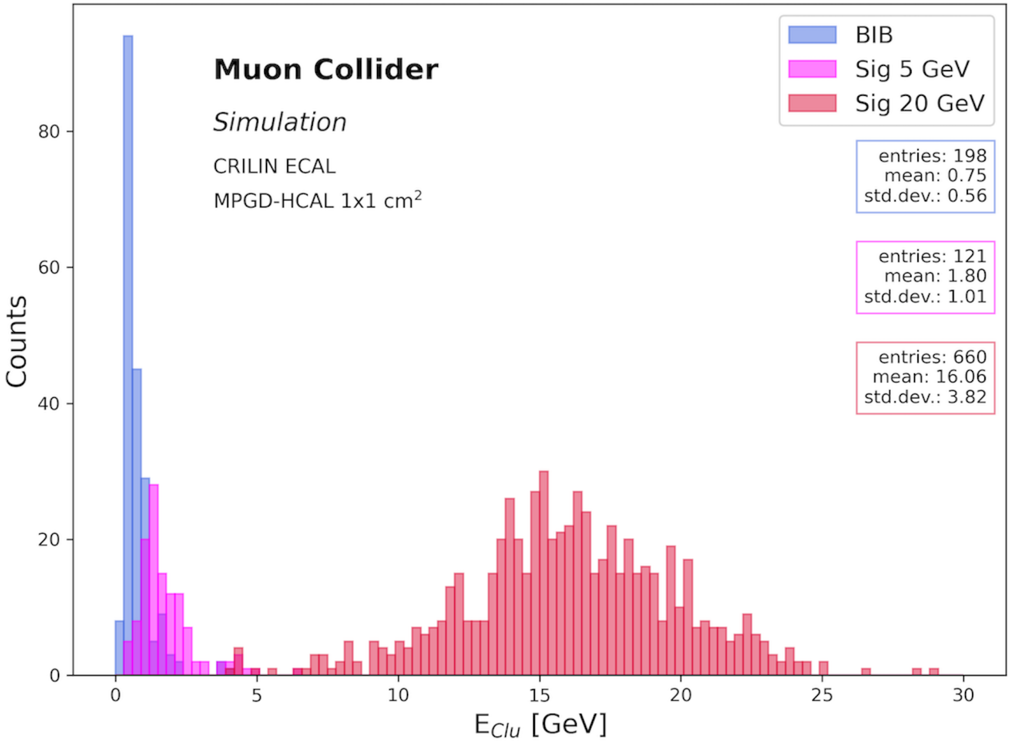


CLUSTER RECONSTRUCTION WITH BIB

SIGNAL AND BIB SEPARATELY

BIB-only clusters have average energies of ~ **0.75 GeV**

- small high-energy tail partially overlapping with cluster energies of 5 GeV pions
- well distinguishable from cluster energies of 20 GeV pions

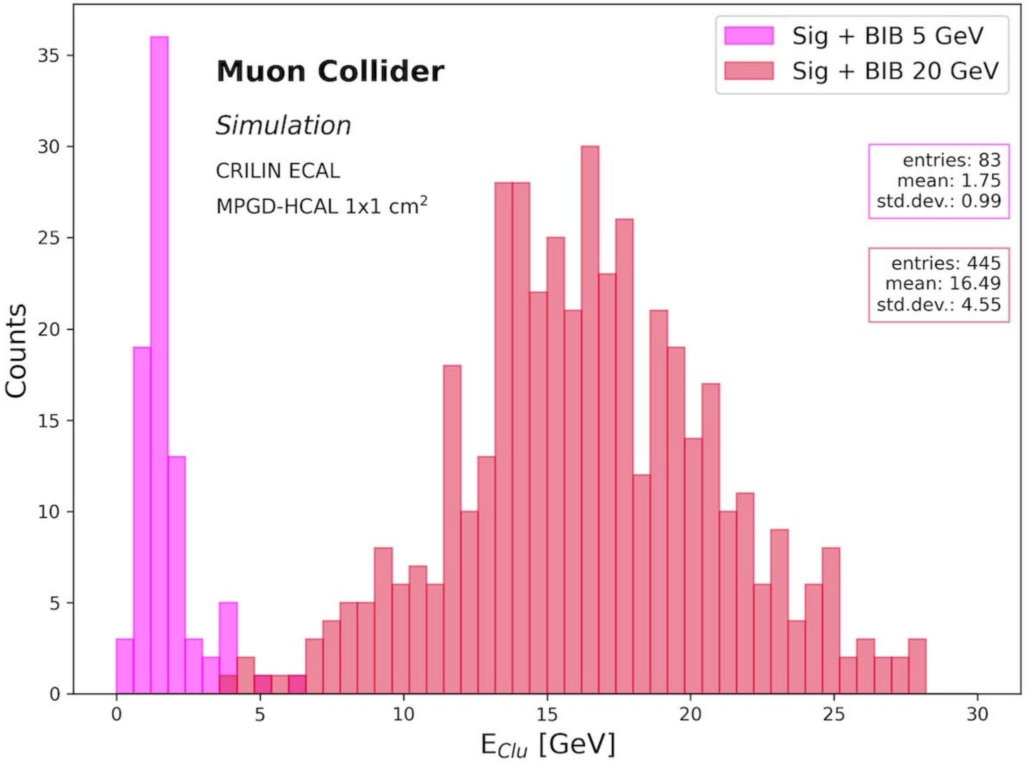


BIB OVERLAY ON SIGNAL

Almost negligible **decrease in energy** :

- Due to **BIB ONLY CLUSTERS** produced by low-energy particles

→ Overall BIB does not affect Custer energy reconstruction at E_{MC} > 5 GeV



CLUSTER MULTIPLICITY

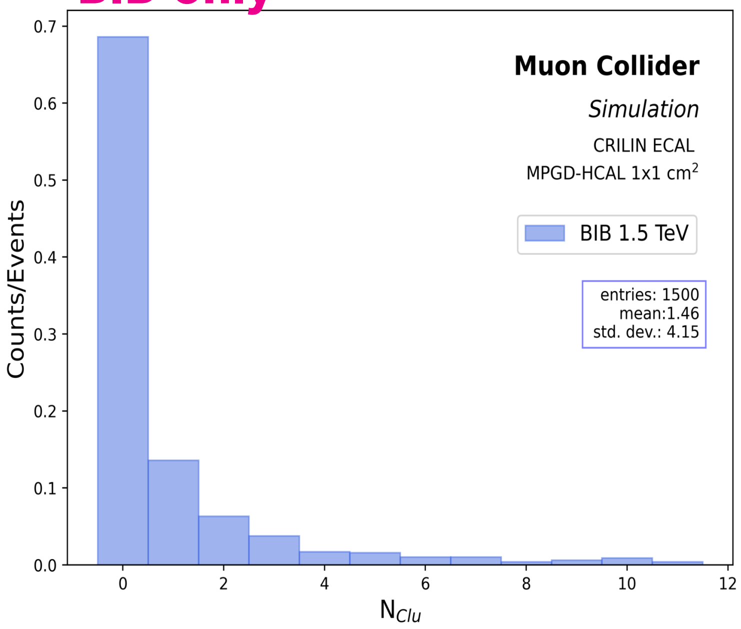
COMPARISON AT 20 GEV

BIB-only: Low clustering efficiency: ~70% of 0-cluster events

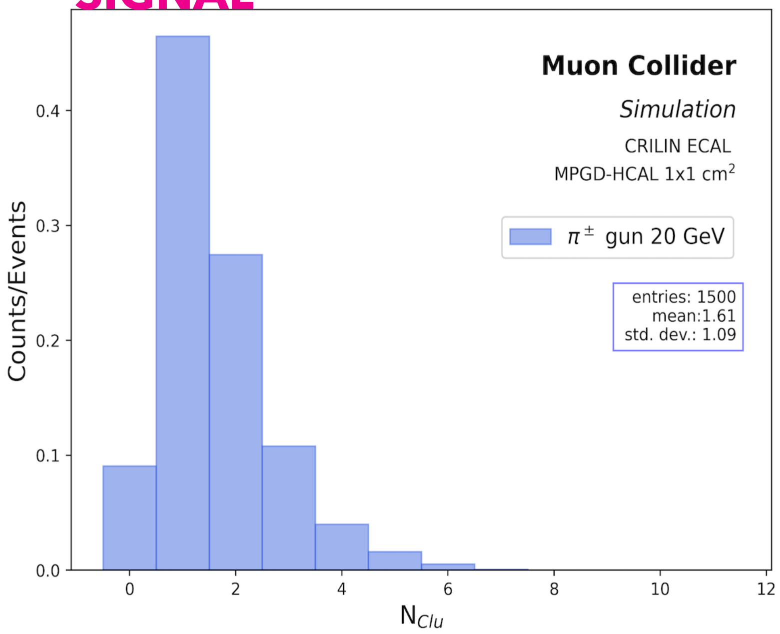
SIGNAL vs SIGNAL+BIB:

- Increase of multicluster events: on average from 1.61 (SIGNAL-only) to 3.09 (SIG+BIB) clusters per event
- Decrease in clustering efficiency: from ~50% (SIGNAL-only) to ~35% (SIG+BIB) 1-cluster events

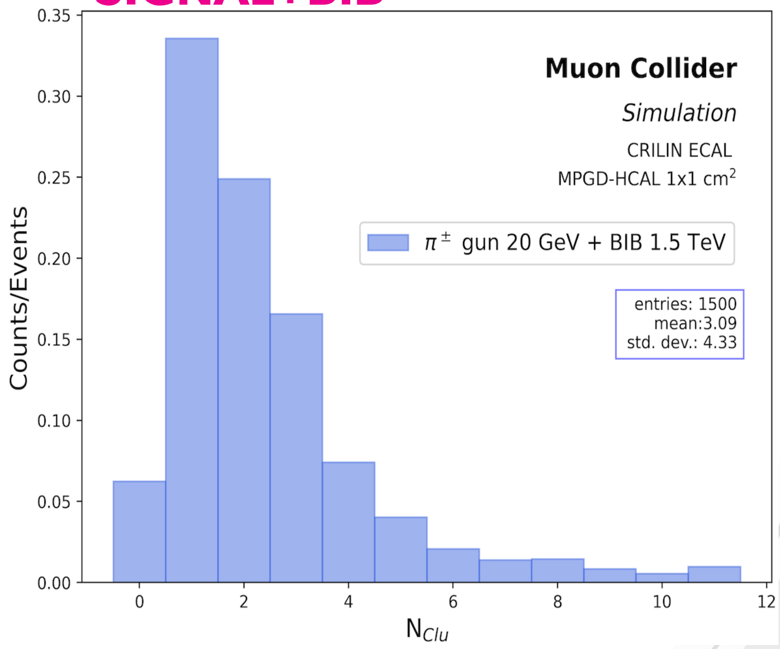
BIB-only



SIGNAL



SIGNAL+BIB



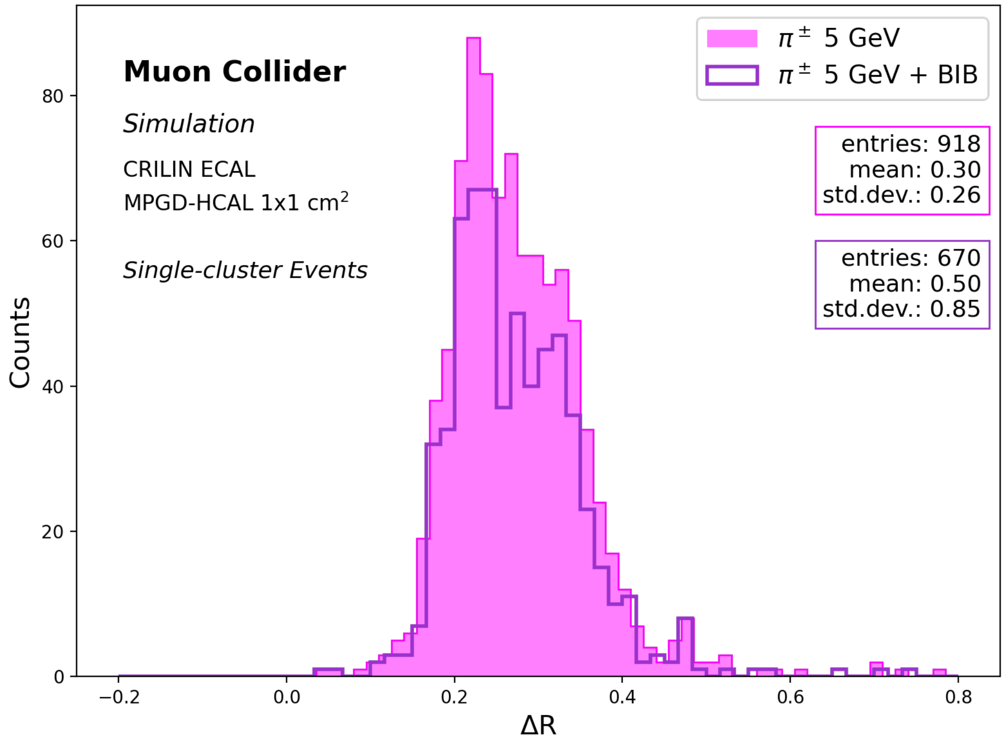
CLUSTER-PION ΔR

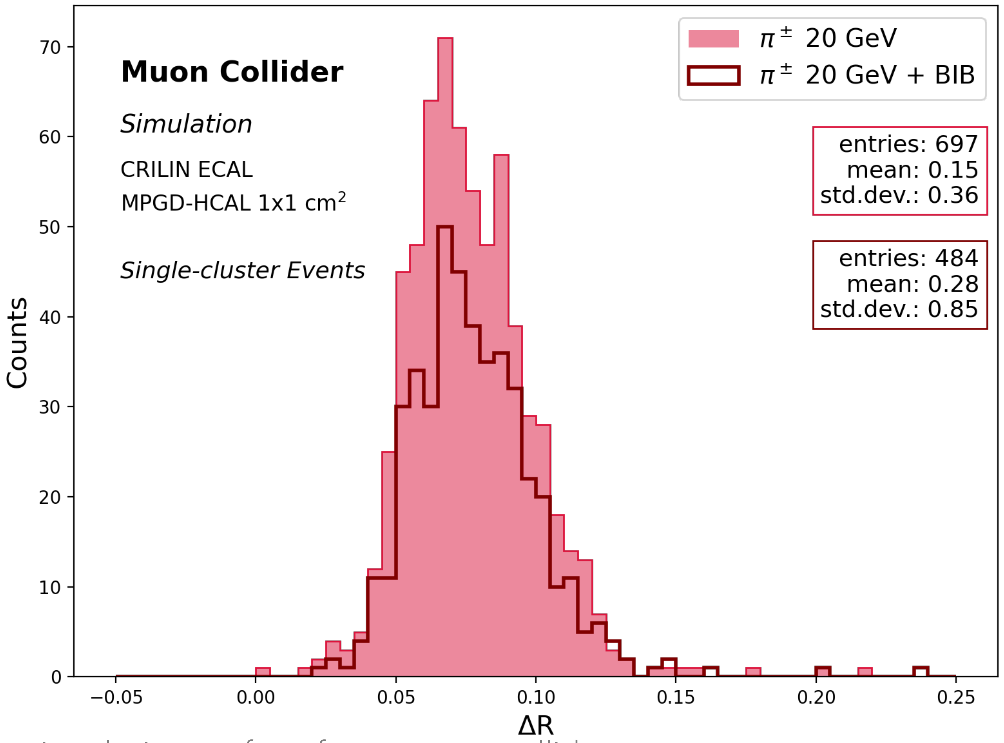
COMPARISON : SIGNAL - SIGNAL+BIB

- Selection on single-cluster events (fewer entries in SIGNAL+BIB)
- The SIGNAL+BIB has **SIGNAL clusters**, **BIB clusters**, or **MIXED clusters** (RecHits from the pion or the BIB)
- Hits from the BIB are uniformly distributed in space and arbitrarily far from the pion path

  → BIB and MIXED clusters result in having **larger ΔR** wrt the MC pion

  → Distribution means : 66% increase at 5 GeV - 87% increase at 20 GeV





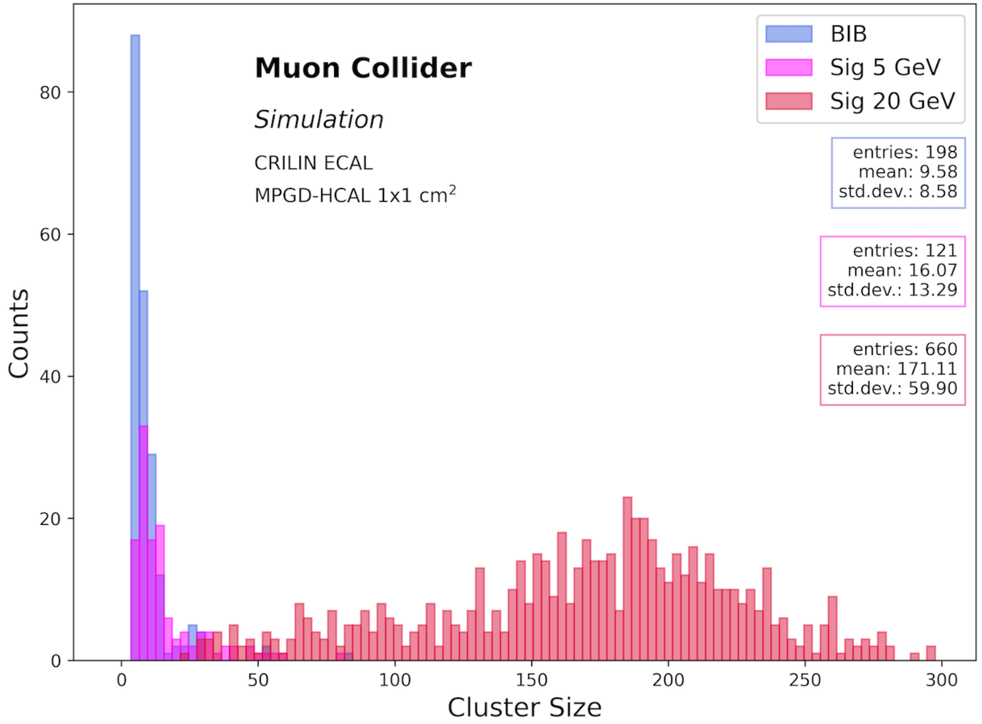
CLUSTER SIZE

COMPARISON: SIGNAL - SIG+BIB

Overlaying BIB on the signal → slight **decrease** in **clustering efficiency** and **cluster size**

- BIB and MIXED clusters have on average a larger **ΔR < 0.2** not passing the matching selection criterion
- BIB-only clusters have a small number of hits → decrease the mean of the distributions

SIGNAL AND BIB SEPARATELY



SIGNAL AND BIB MERGED