# Overview on my contributions in Muon Collider collaboration

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# why work at the muon collider?

- I started collaborating on the Muon Collider project during my **bachelor’s thesis**.
- I continued to work at the Muon Collider also for my **master's thesis**.

- From a point of view of a student, why choose to collaborate in the Muon Collider project?

✓ Opportunity to work on a completely **new and cutting-edge project**.

✓ Chance to **contribute to many different fields**, from he purely theoretical to the experimental side.

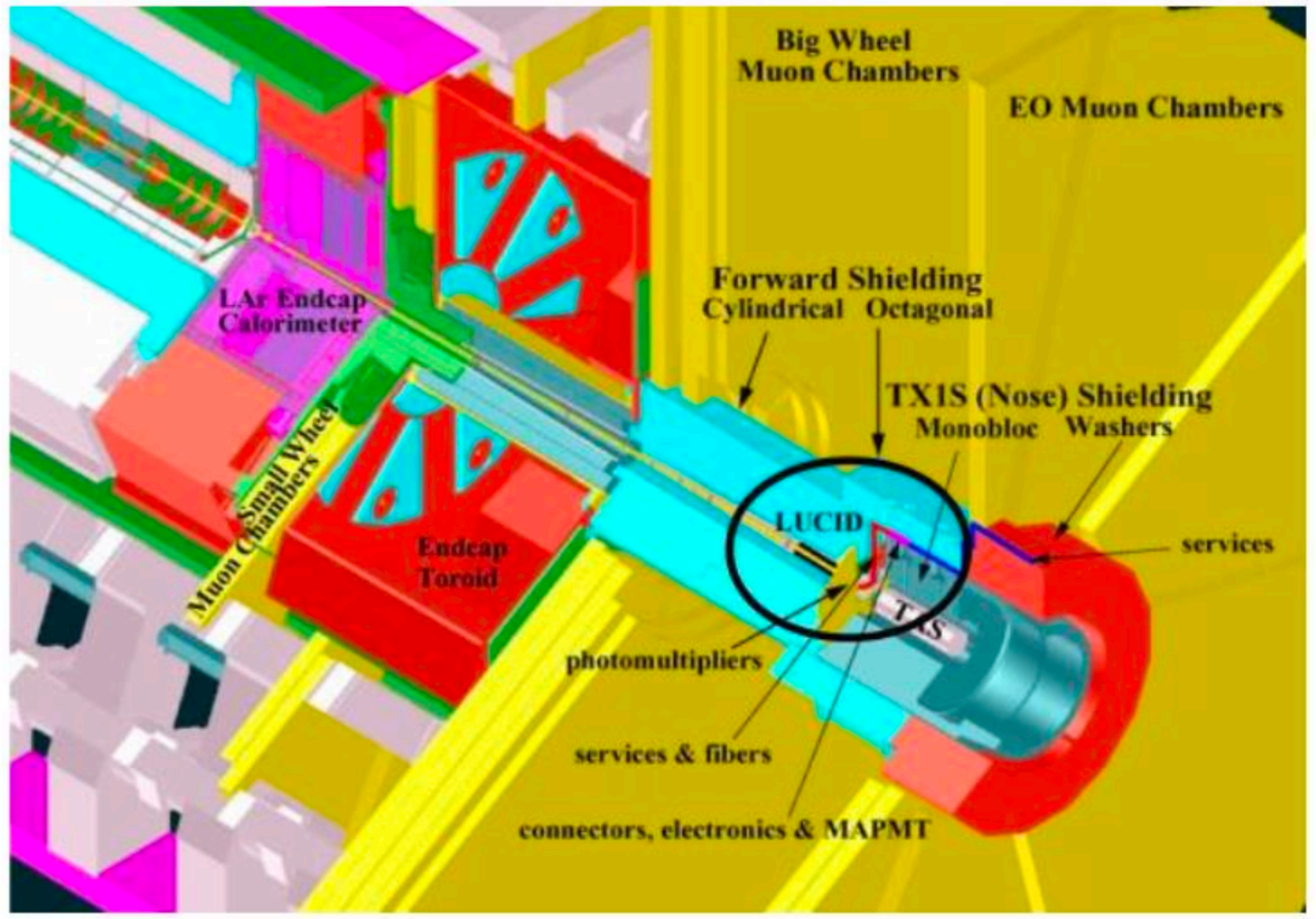
✓ Being part of an **international collaboration** that, at same time, offer **space and responsibility to students** providing them a good starting point for the research carrier.

# Luminosity studies

- Bachelor's thesis: study the uncertainty in the measurement of the luminosity at Muon Collider.
- **Luminosity** provides a measure of the **number of interactions** that occur between the particles of the colliding beams **per unit time and area** [cm$^{-2}$s$^{-1}$].

$$\mathcal{L} = \frac{R}{\sigma}$$

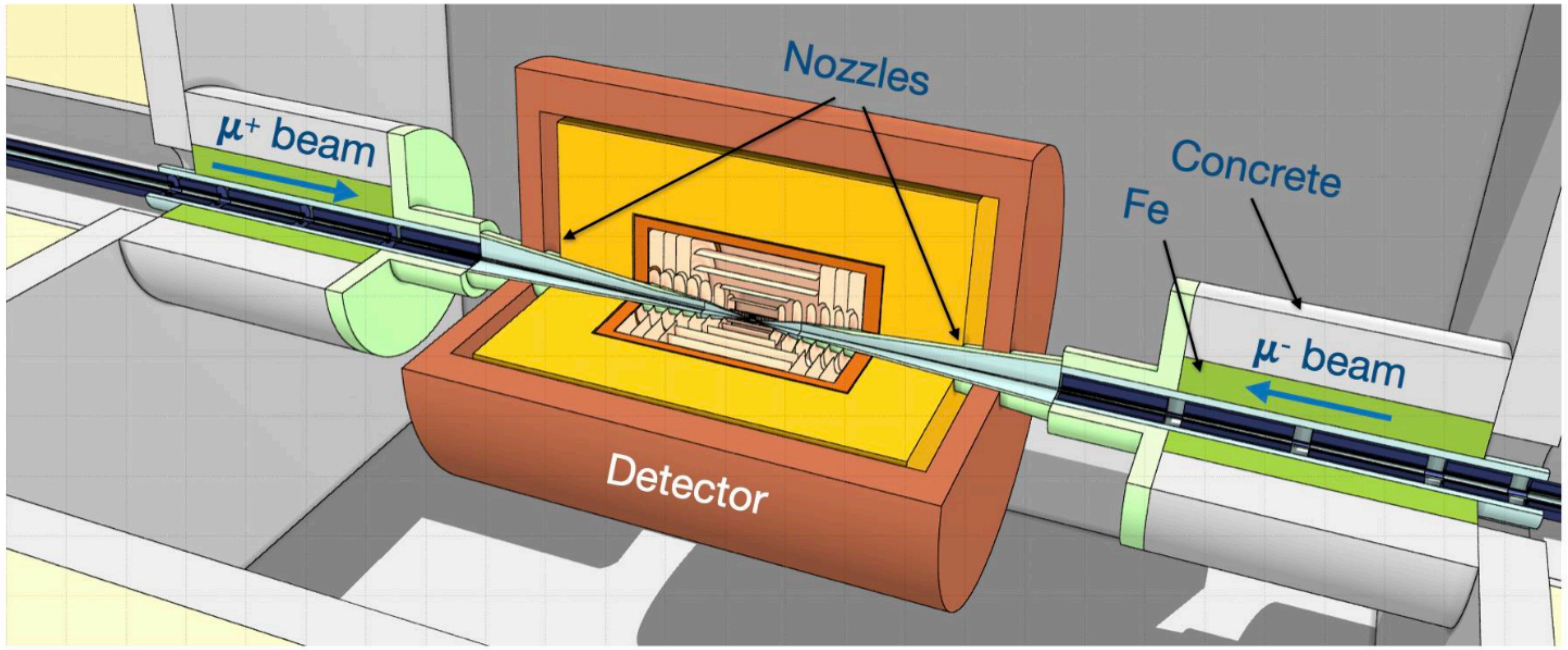
→ High precision to obtain **accurate cross section estimates**




- The **measurement of the luminosity** can be obtained **directly** by determining the parameters of the colliding beams.
  - Van del Meer scan
  - Luminometers

# Luminosity studies

- In the case of the muon collider:
  - presence of absorber cones (nozzles). Regions not instrumented for direct measurement of luminosity.
  - unstable particle beams are not compatible with the scan times for the Van del Meer method.



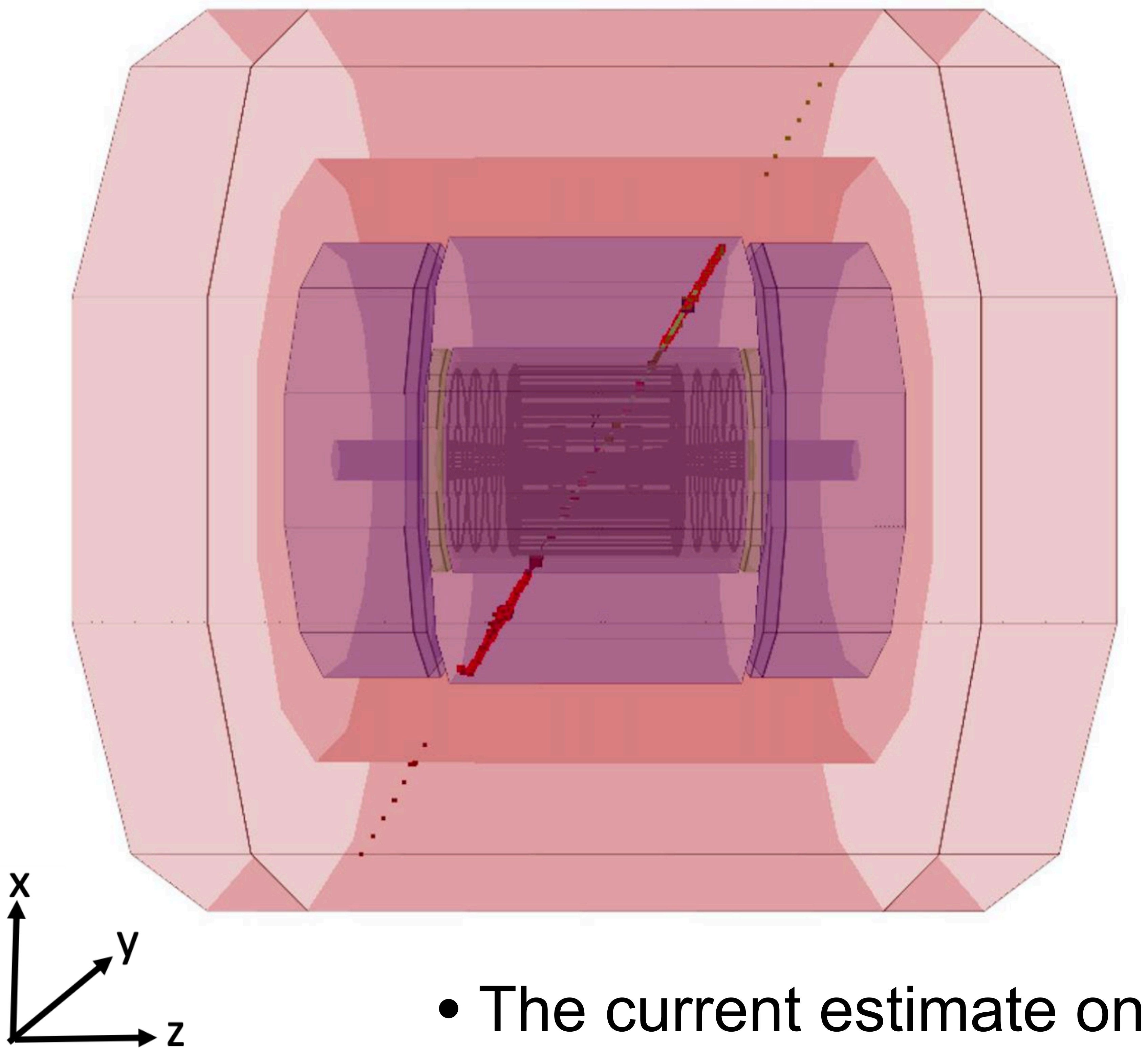

- **Indirect method:**
  - By determining the number $\mathbf{N_{ev}}$ of observed events of a **particular process** whose cross section is known with high precision, it is possible to determine the **integrated luminosity**:

$$L_{int} = \frac{N_{ev}}{\epsilon \cdot \sigma}$$

$\epsilon$: reconstruction efficiency

# Luminosity studies

- Some $e^+e^-$ leptonic colliders use this method by exploiting the **Bhabha scattering process**.
- In the case of the muon collider I used the muon Bhabha process at large emission angles with respect to the beam direction: $\theta \in$ **[30°,150°]**.




$$\mu^-\mu^+ \to \mu^-\mu^+$$

- In one year of data taking ($10^7$s): $N_{Bhabha}$~200000 with a $\mathcal{L}=1.25 \times 10^{34}$ cm$^{-2}$s$^{-1}$ at $\sqrt{s}$=1.5 TeV.

$$\frac{\Delta N^*_{Bhabha}}{N^*_{Bhabha}} = \frac{1}{\sqrt{N^*_{Bhabha}}} = 0.002$$

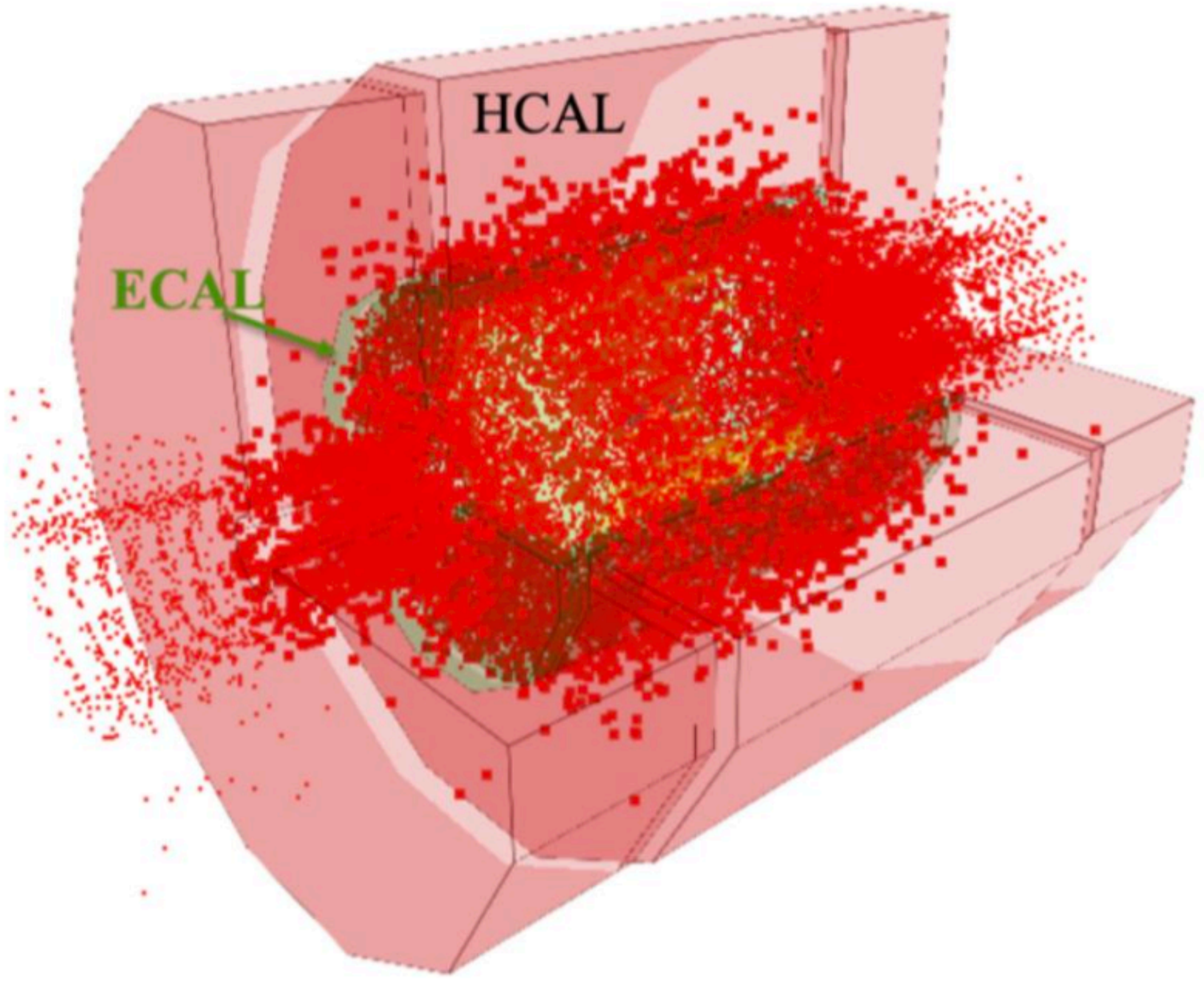
$$\frac{\Delta L_{int}}{L_{int}} = \sqrt{\frac{\Delta N_{ev}{}^2}{N_{ev}{}^2} + \frac{\Delta \sigma_B{}^2}{\sigma_B{}^2}} = \left(\frac{\Delta N_{ev}}{N_{ev}}\right) \oplus \left(\frac{\Delta \sigma_B}{\sigma_B}\right)$$

- The current estimate on the uncertainty on the Bhabha cross section is ~0.1%, but not at Muon Collider center of mass energy level.

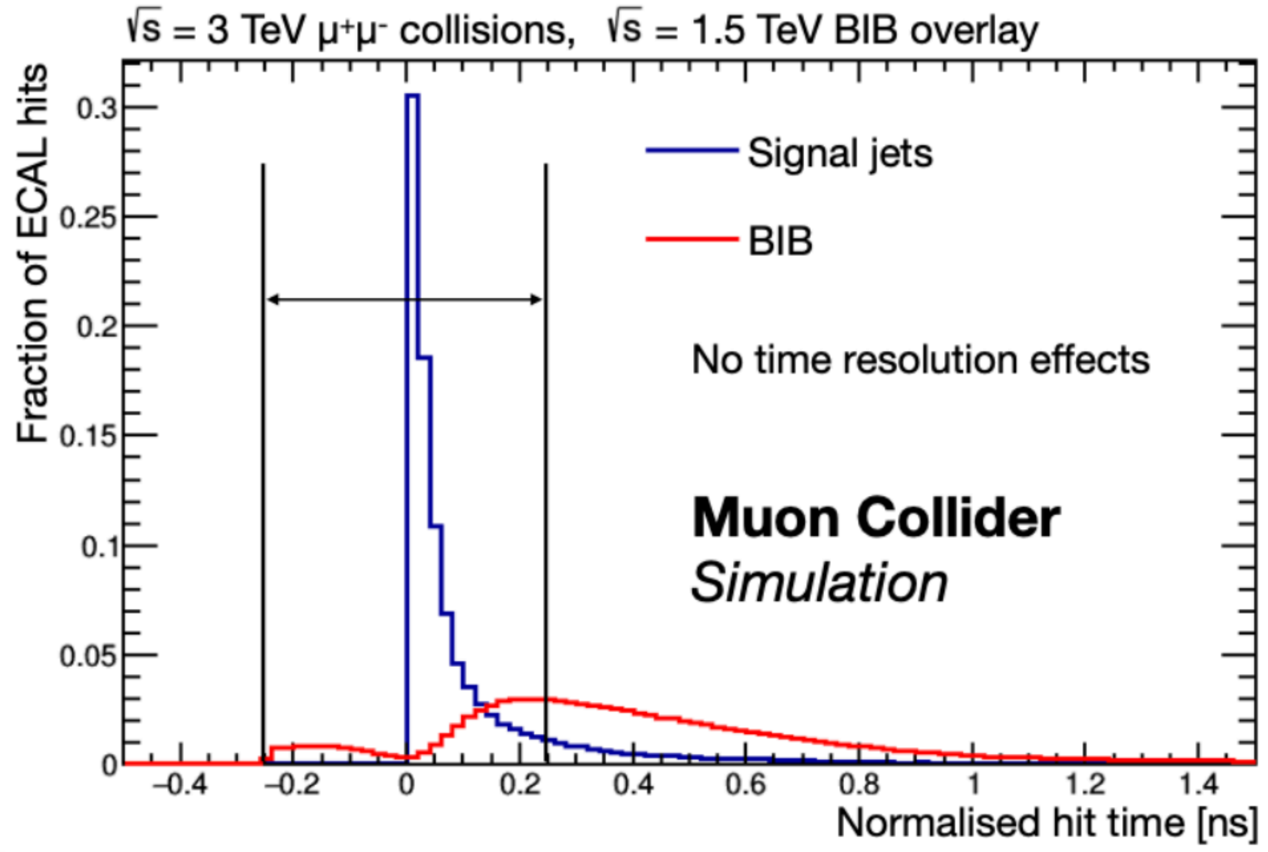
# Calorimeter simulation studies

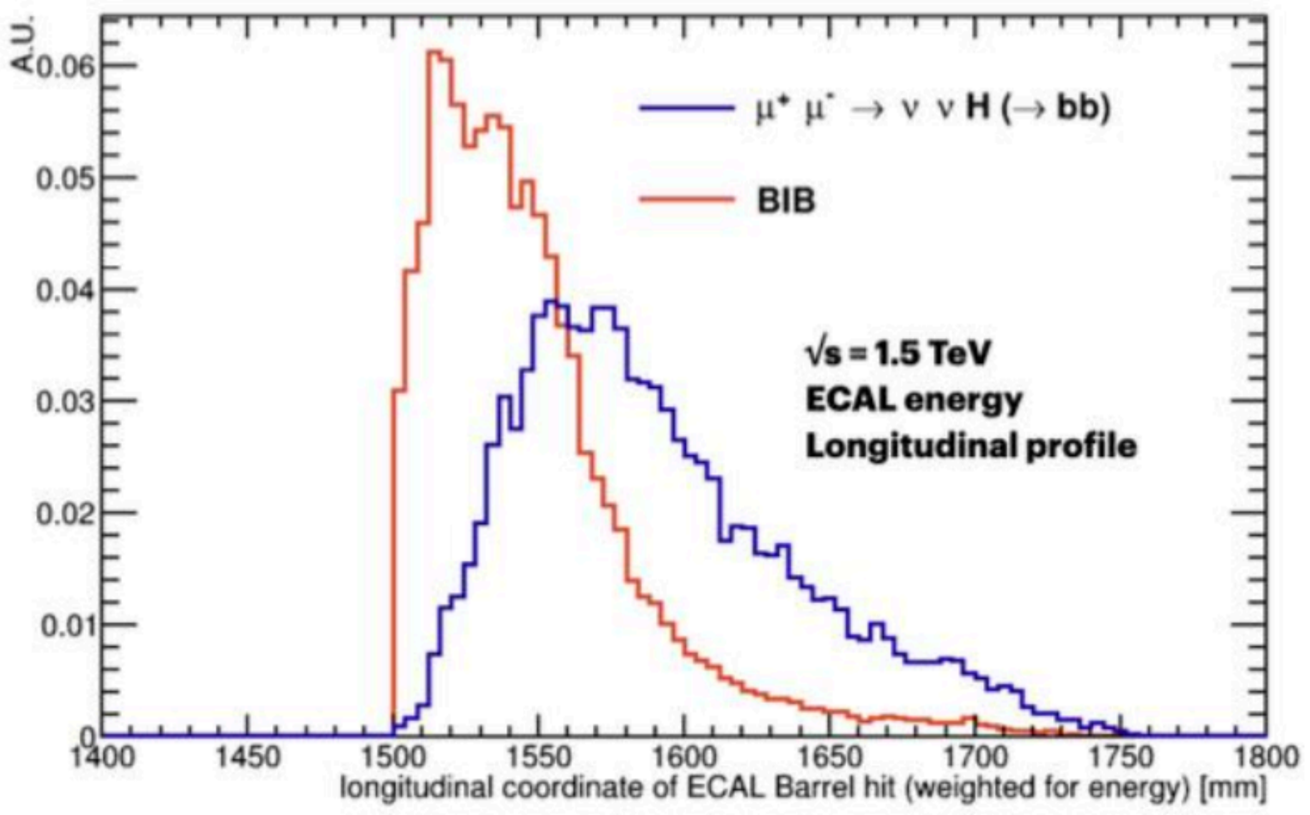
- The BIB flux at the inner surface is estimate to be of **~300 particles/cm$^2$** in a single bunch crossing.

- **Photons** (96%) with average energy of **1.7 MeV** and **neutrons** (4%).




- **High granularity:** to reduce the **overlap of BIB hits** in the same calorimeter cell and distinguish them form the **hits from signal**.
- **Excellent arrival time resolution (<100 ps):** reduction of the **out-of-time** component of the BIB, preserving most of the signal.
- **Longitudinal segmentation:** distinction of **electromagnetic showers** due to BIB particles.
- **Good energy resolution: ~ 10%/√E** precise energy measurements.
- **Radiation resistance: stable performance**.



# Calorimeter simulation studies

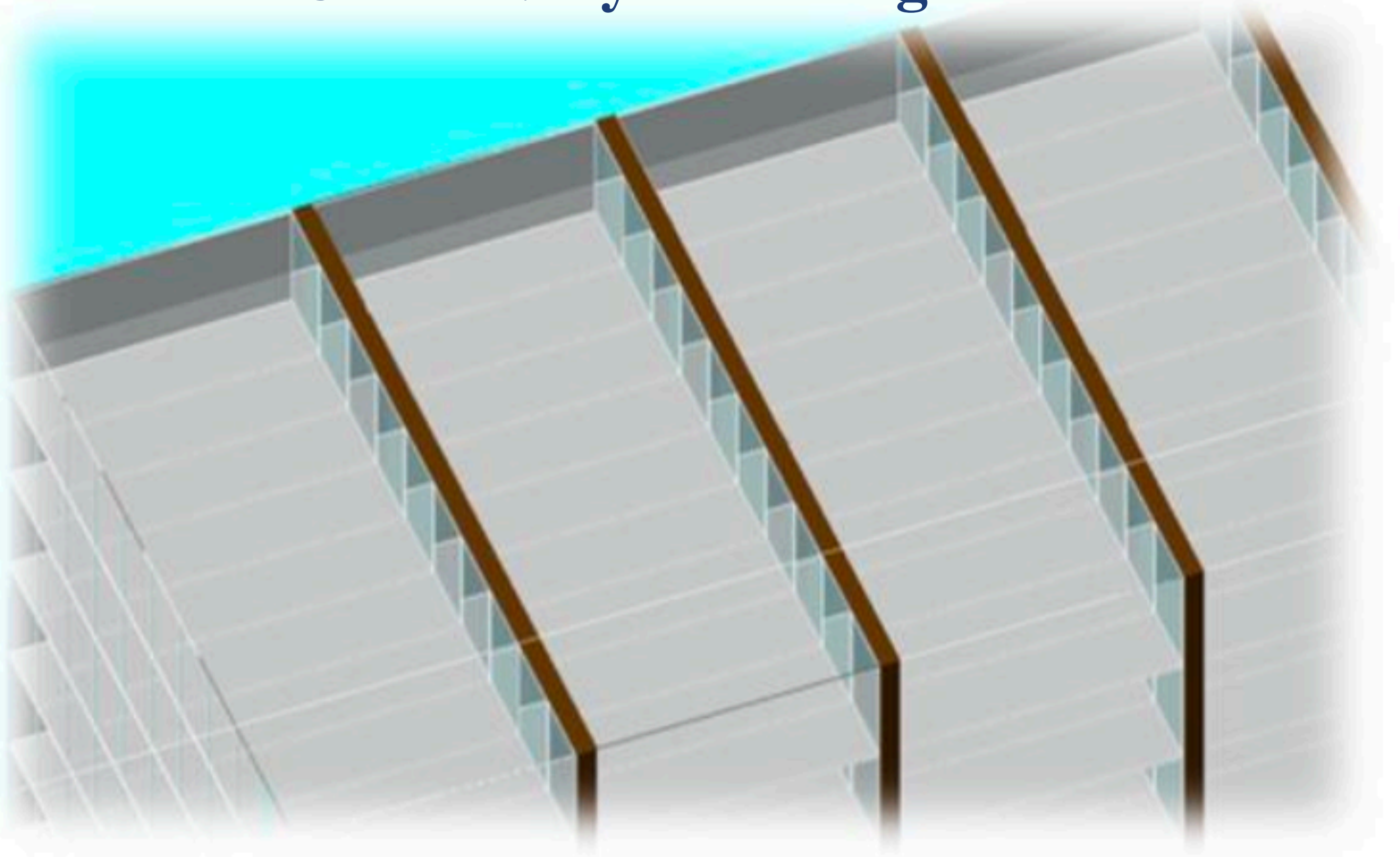
- **CRILIN** (Crystal calorimeter with longitudinal information): it consists of a **semi-homogeneous calorimeter** based on layers of **Lead-Fluorite ($PbF_2$) crystals**, read out by **Silicon Photomultipliers (SiPM)**.

- **Cherenkov calorimeter**.

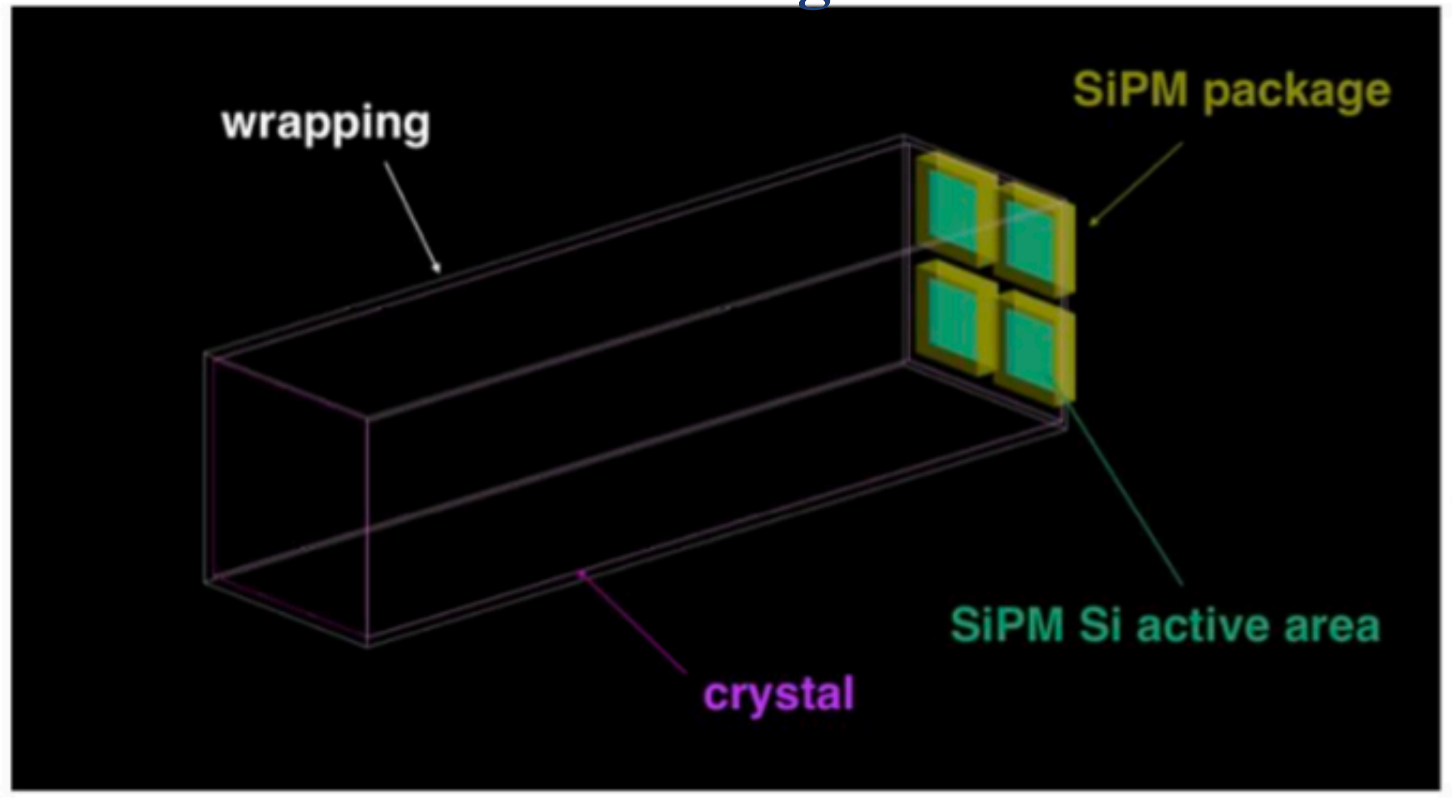
- **Good candidate** to match the calorimeter requirements for the Muon Collider.

| | |
|---|---|
| ✓ **Longitudinal segmentation**<br>**6 crystal layers (26 $X_0$)** | ✓ **High granularity**<br>**Cell size 1x1x4 $cm^3$** |
| ✓ **Excellent time resolution**<br>**Fast signals** | ✓ **Radiation hardness**<br>**Both $PbF_2$ crystal and SiPMs** |

CRILIN layers arrangement



CRILIN single cell



# Calorimeter simulation studies

- Characterization of the CRILIN calorimeter with **5 crystal layers**:

  ◉ **Energy resolution**

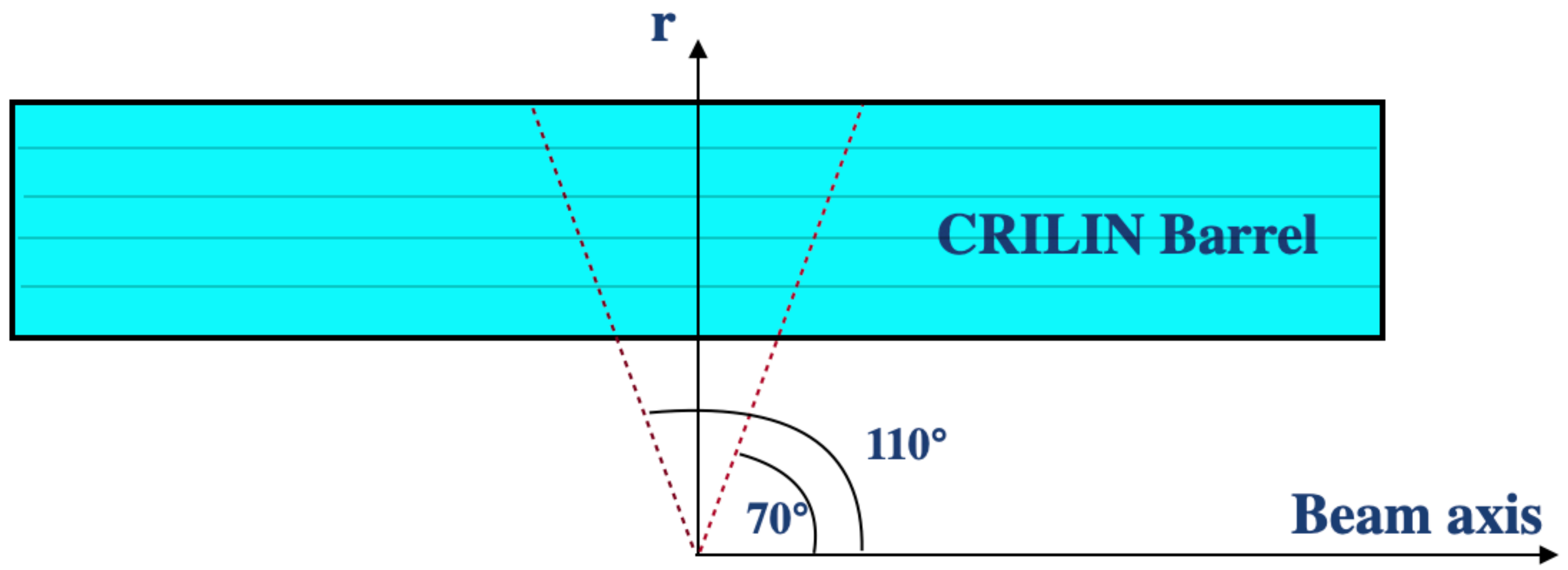
  ◉ **Reconstruction efficiency**

  ◉ **Energy containment**

- Simulation studies based on a sample of single **photons generated with a Monte Carlo program:** .

  ▸ **Uniform energy $E_{Gen} \in$ [1, 1000] GeV**

  ▸ **Uniform polar angle $\theta_{Gen} \in$ [70°, 110°]**

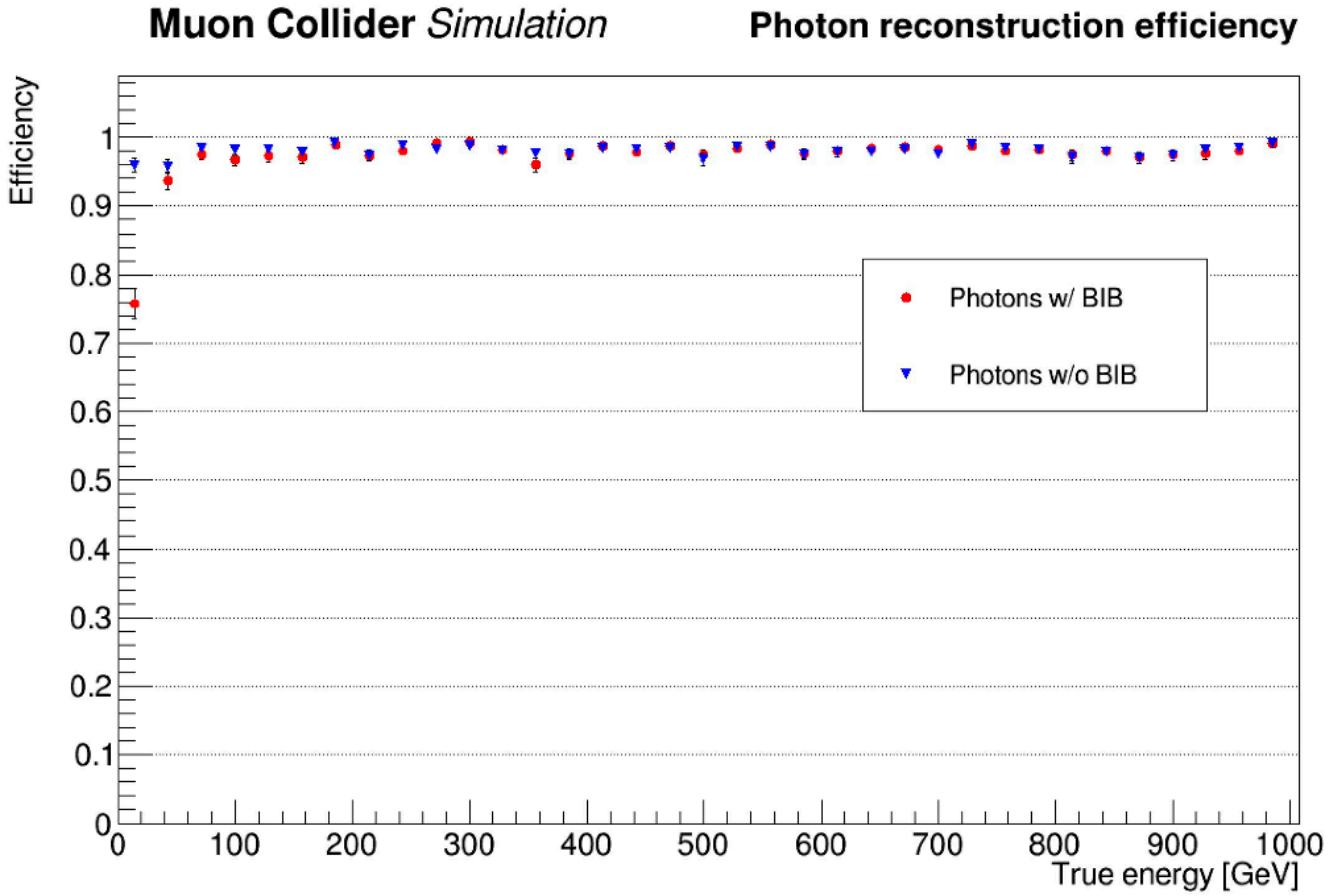


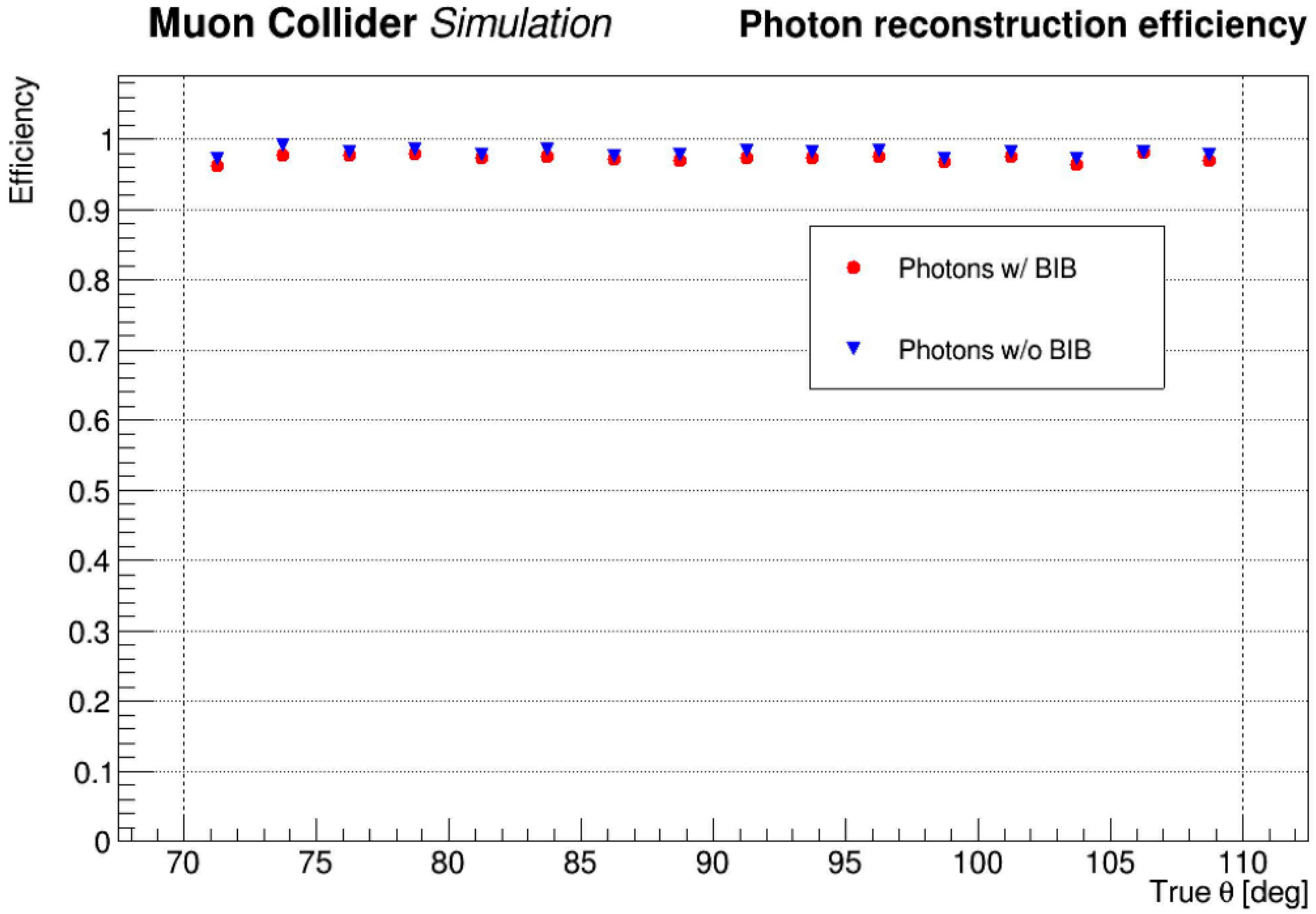

- Performance evaluated both **without** and **with** the **BIB contribution** at **√s=1.5 TeV**.

- Reconstruction process based on **Particle Flow method** → PandoraPFA algorithm

# Calorimeter simulation studies

- **Photon reconstruction:** based on **hits** collected in the calorimeter.
- **Clustering:** hits are **filtered** and **grouped** using a dedicated clustering algorithm.
- **Photon identification:** analysis of cluster structure, using **topological models** of electromagnetic showers, within the electromagnetic calorimeter.



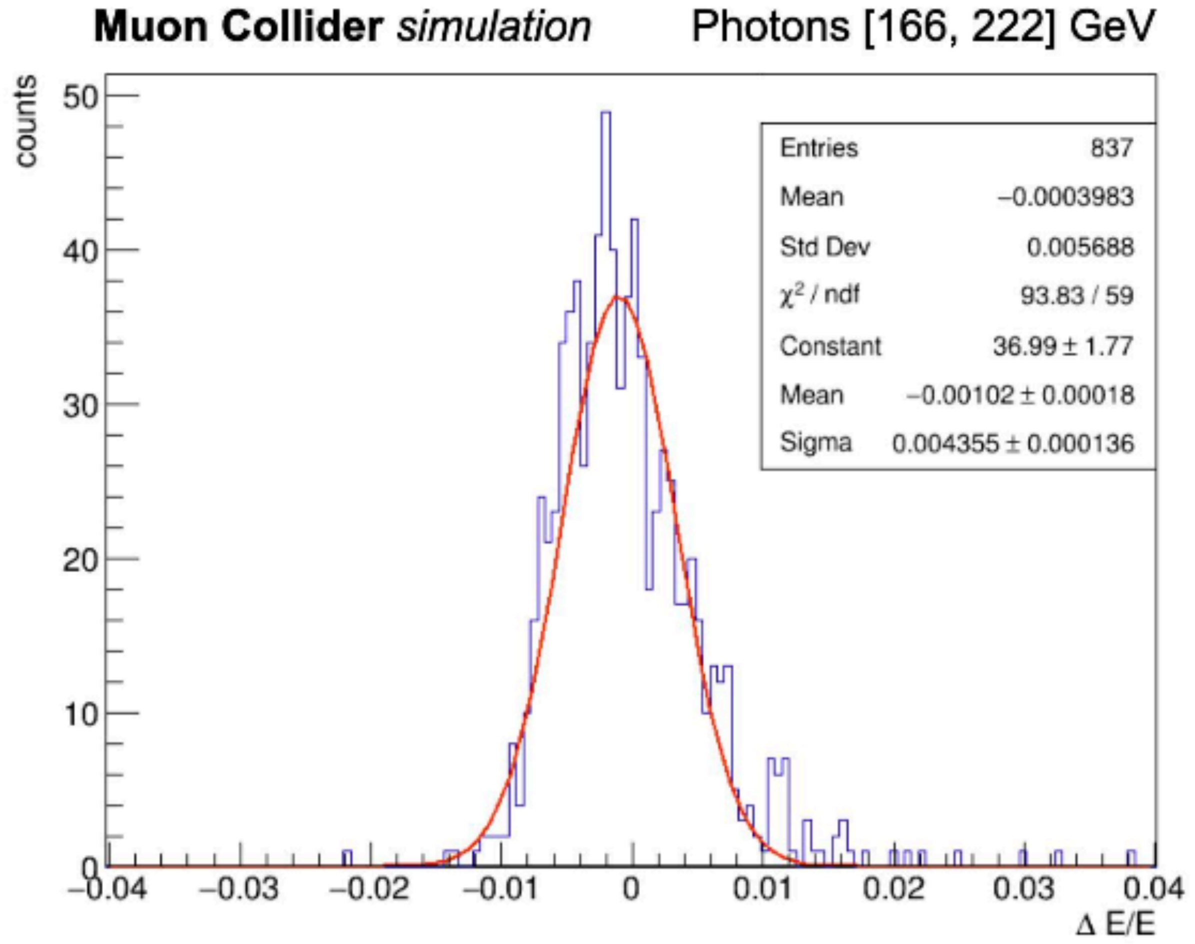

**Efficiency > 95% w/ and w/o BIB**

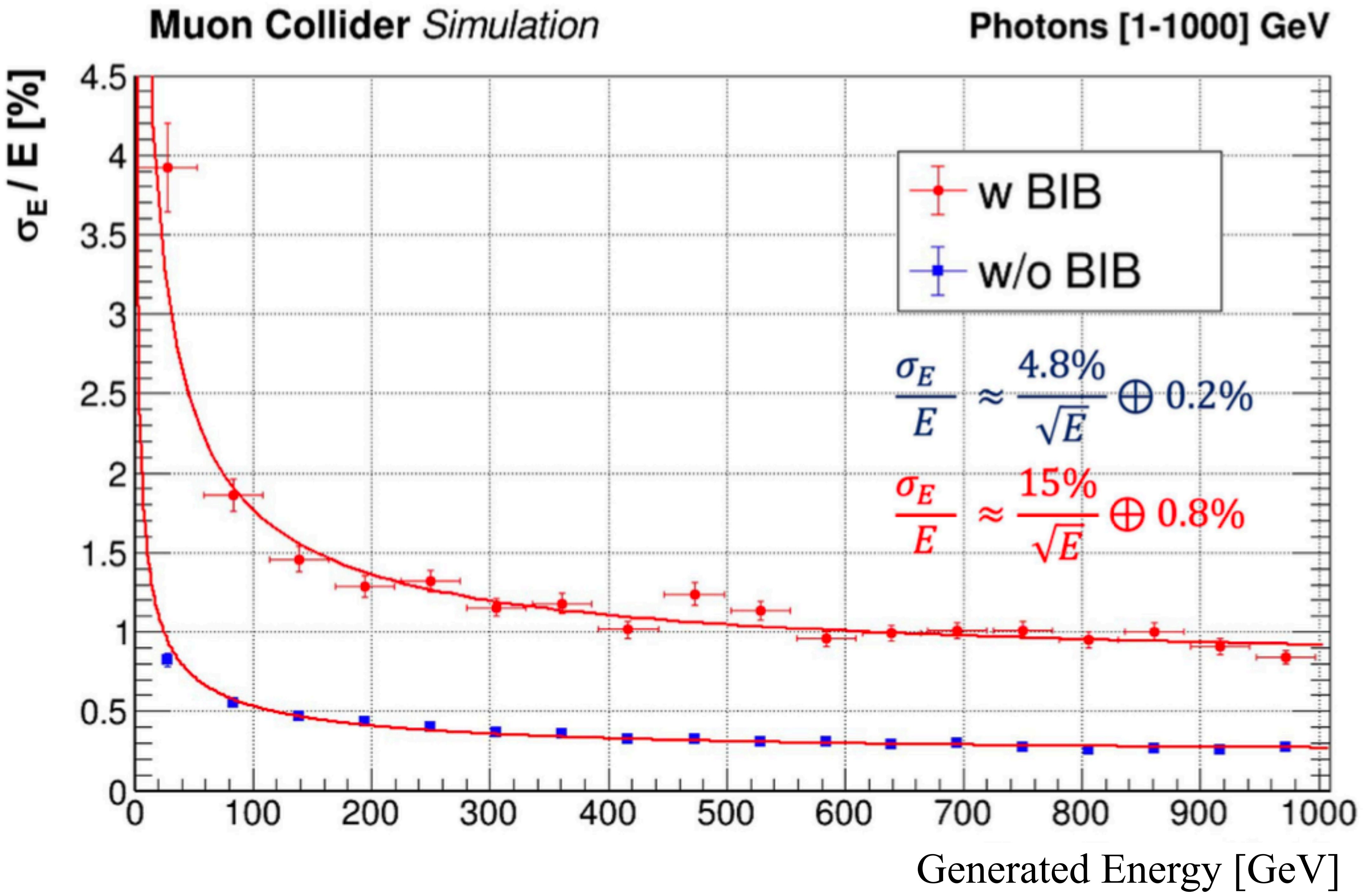
# Calorimeter simulation studies

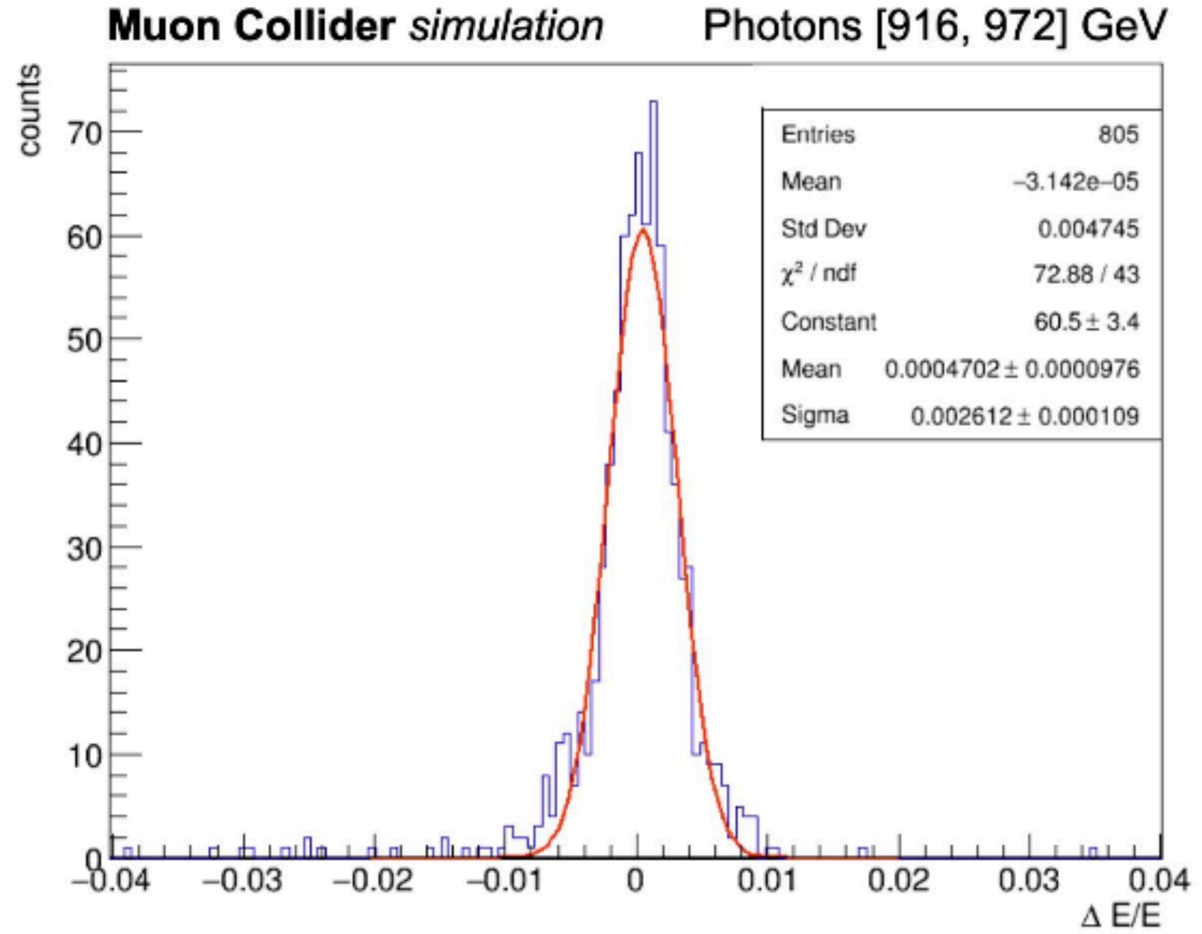
- The true energy range was divided in sub-intervals, and the relative energy difference, **$\Delta E/E_{Gen}$**, was calculated for each, applying a **correction factor**.

$$\frac{\Delta E}{E_{Gen}} = \frac{(E_{Gen} - E_{Reco} \cdot K_{corr})}{E_{Gen}}$$

- A **Gaussian fit** was applied to each distribution, and the **sigma value** was extracted.



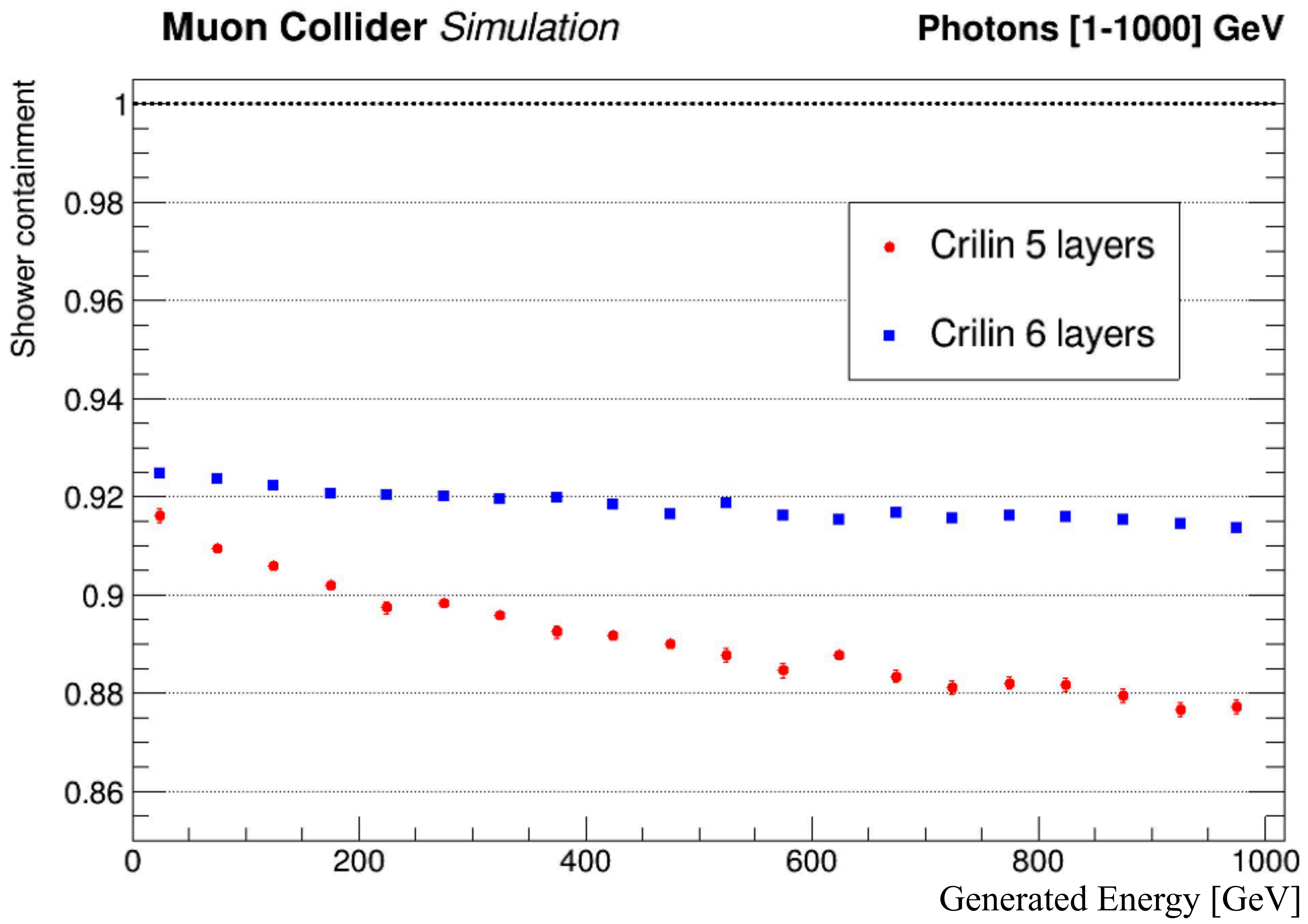



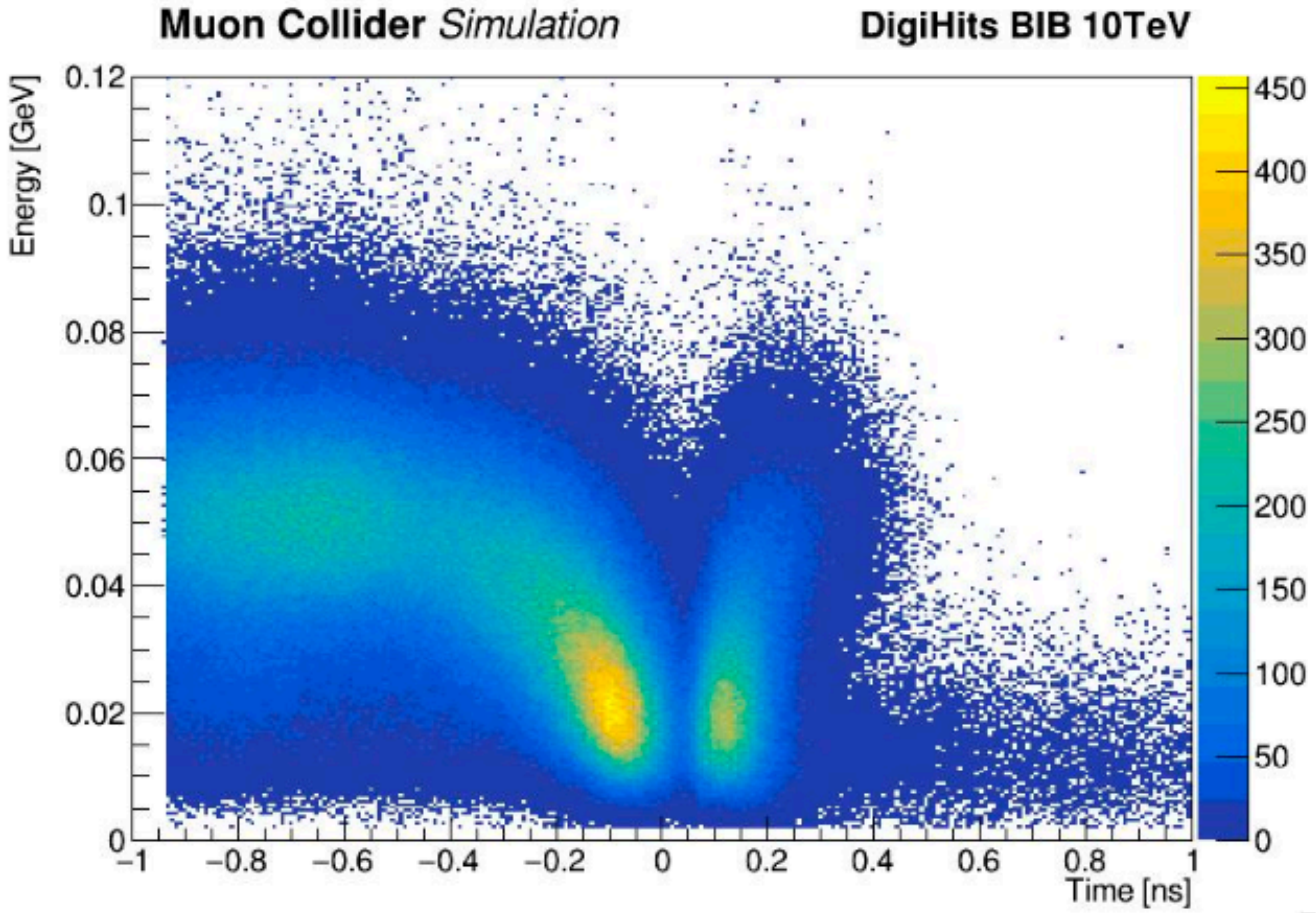




➡ Results compatible with the requirements!

# Calorimeter studies for √s=10 TeV Muon Collider

- CRILIN characterization with BIB at **√s = 10 TeV**.
- Configuration with **6 layers of crystals**.
- Improvement of ~3% in energy containment of electromagnetic showers by going from 5 (**22*X*$_0$**) to 6 layers (**26*X*$_0$**).

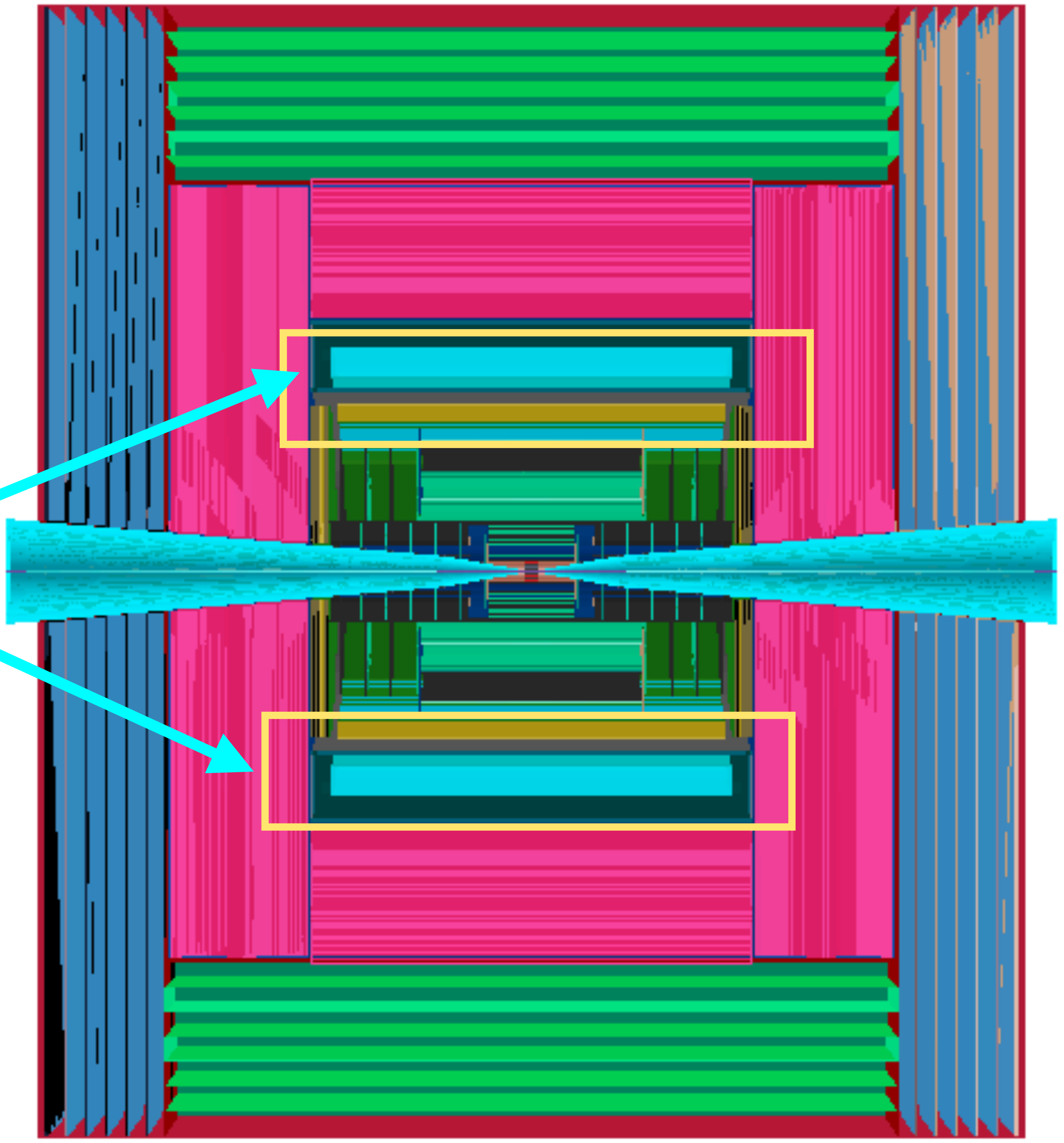



- BIB hits distribution on the first layer as a function of **arrival time** and **energy**: the most affected layer by the background.
- **Current clustering algorithm** requires optimization.
- **Improvements** ongoing, including a **new nozzle designs** optimized for the √s=10 TeV.

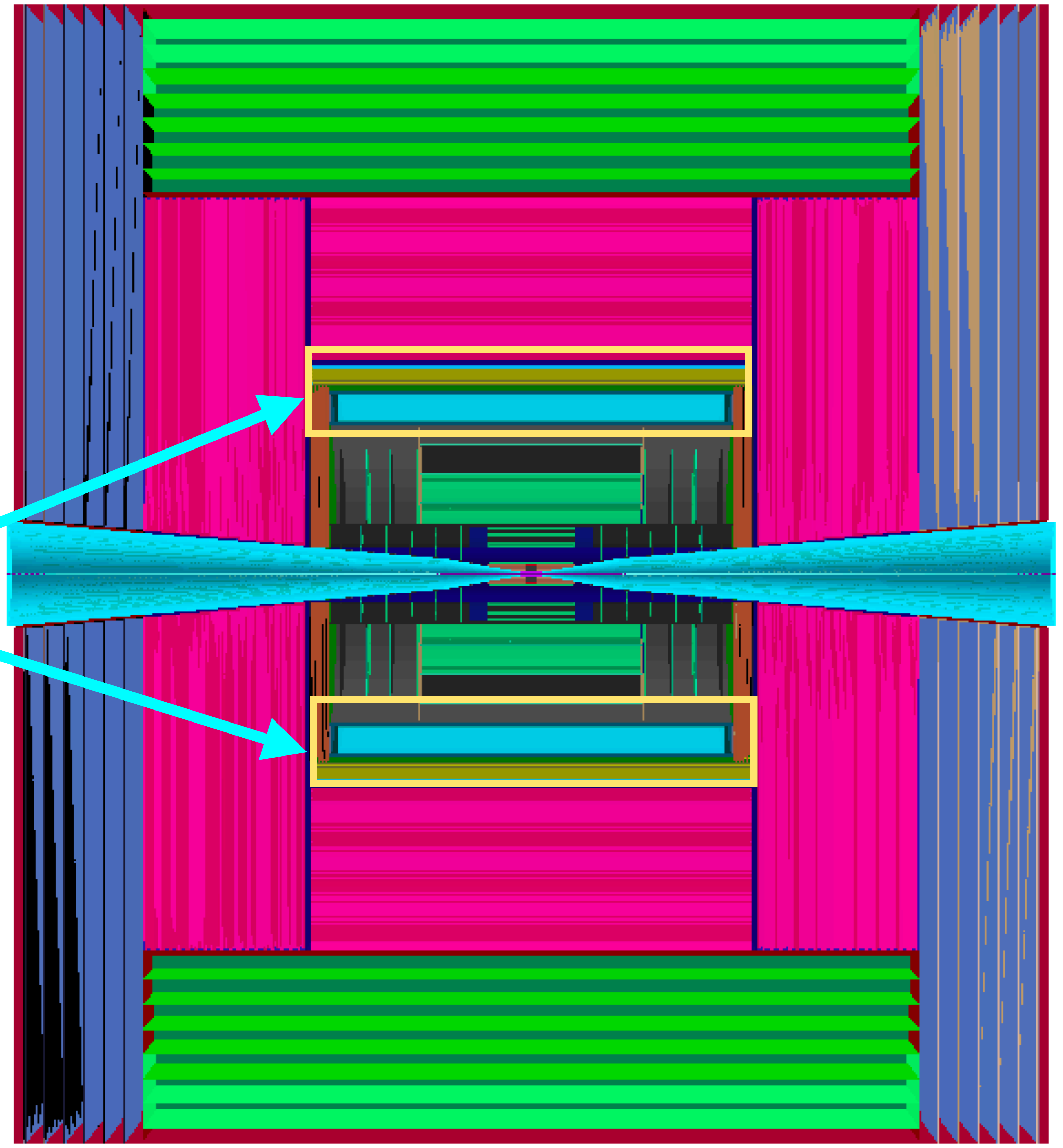
# Calorimeter studies for √s=10 TeV Muon Collider

Solenoid between ECAL and HCAL



- MUSIC detector concept

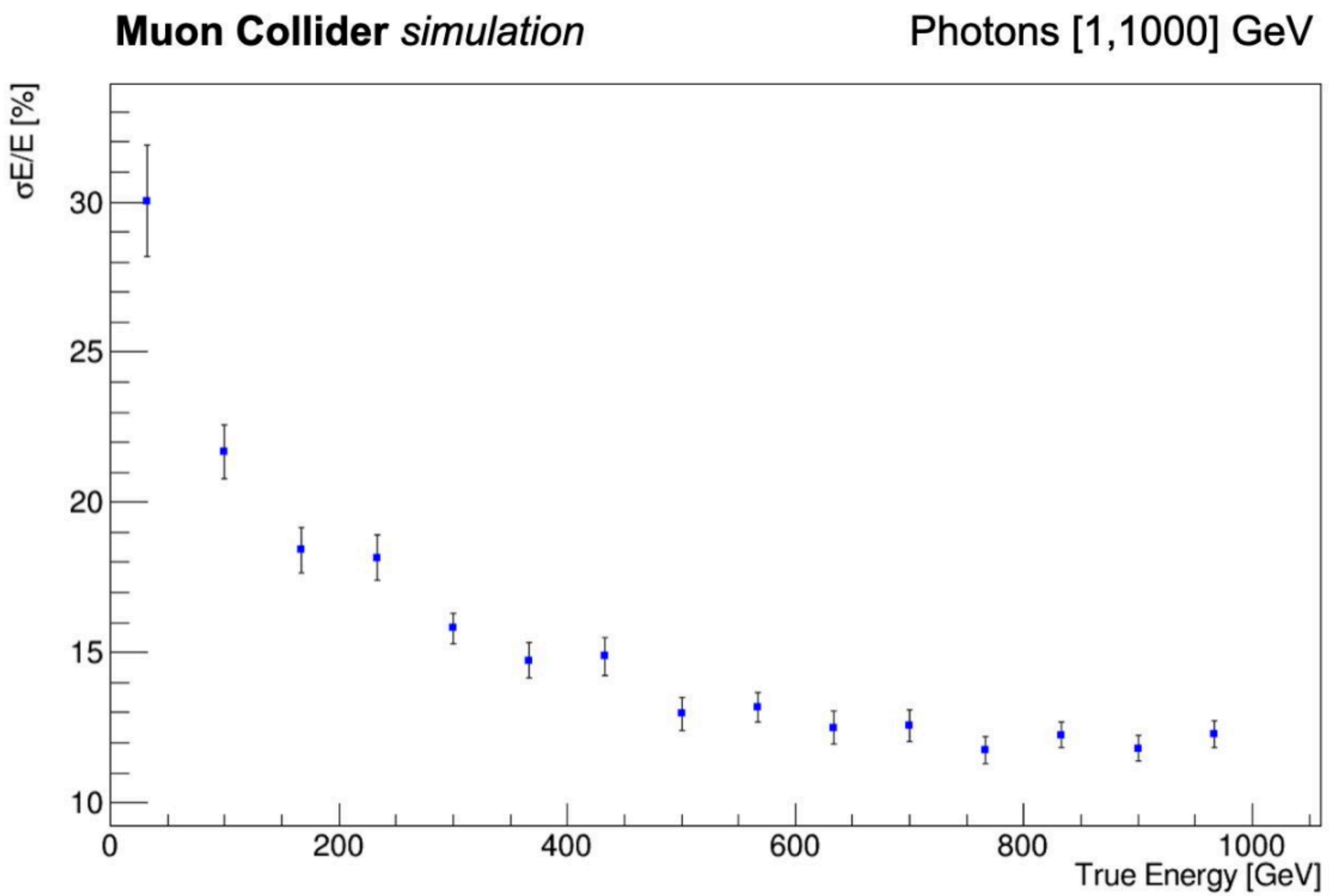
Solenoid placed before the ECAL



- MAIA detector concept

# Calorimeter studies for √s=10 TeV Muon Collider

- This solution allows for:
  - a **more uniform magnetic** field within the tracking system.
  - makes it **easier to achieve a higher magnetic field strength**, around 5T, from a construction perspective.
  - it can help to **shield the calorimeter system form the BIB particles**.




- However, this solution involves a **degradation of the energy resolution** due to the presence of the solenoid in front of ECAL.
- Specific calibration methods must be applied.

# Calorimeter studies for $\sqrt{s}$=10 TeV Muon Collider

- Together to the simulation studies, I participated in two test beams on the CRILIN prototype:

  - **Laboratori Nazionali di Frascati** (Beam Test Facility-BTF): **test the radiation resistance** of the PbF2 from photon irradiation ($^{60}$Co source).

  - **CERN (SPS-H2):** characterization of the **time resolution** using electron beam with energies between 40 GeV and 150 GeV.


- The results on the experimental test will be presented by Elisa Di Meco in the next talk