EPS HEP2023 HAMBURG

INFN
Istituto Nazionale di Fisica Nucleare

# R&D towards the detector for the Muon Collider


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aMUSE

MuCol

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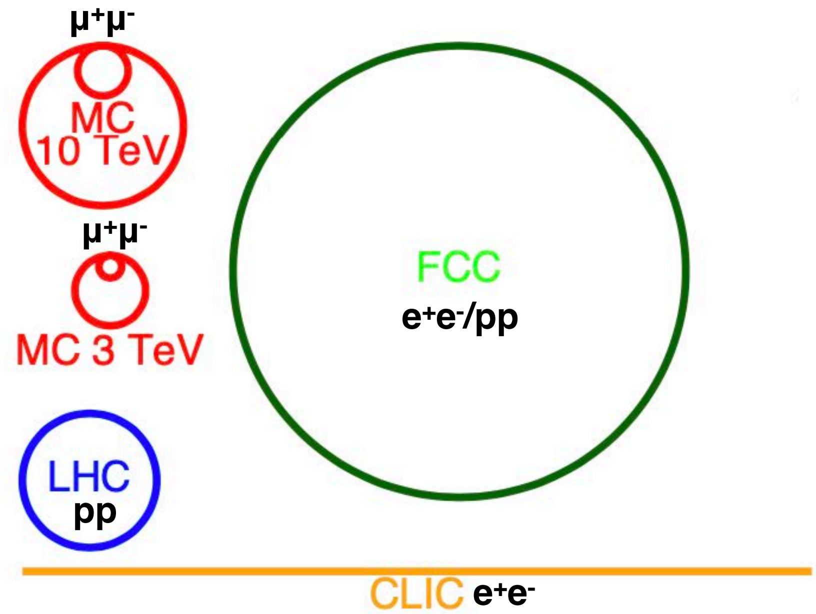
International MUON Collider Collaboration

# Introduction: Muon Collider

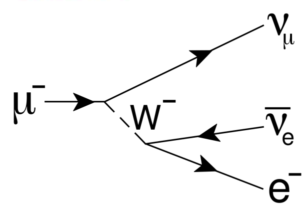
- The **Muon Collider is the dream facility for particle physics: it is both a precision and a discovery machine**

- **In fact it puts together the advantages of electron-positron and hadron colliders:**
    - muons are elementary particles, all beam energy available, clean events
    - muon mass is 200 times the mass of the electron, small radiation losses




- **The International Muon Collider Collaboration** has proposed a first stage at $\sqrt{s}$ = 3 TeV to be built by the 2045

- Second stage at $\sqrt{s}$ =10 TeV **check talk by K. Skoufaris**



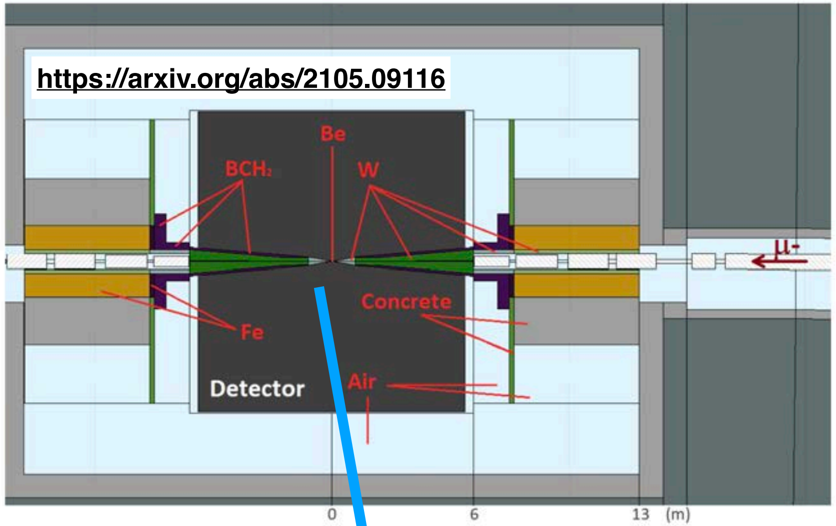

$\tau$ **= 2.2 μs**

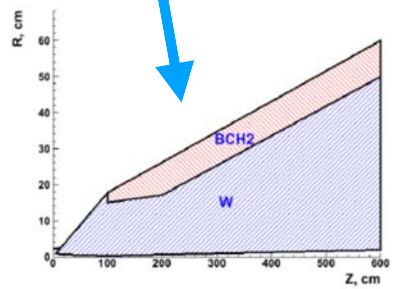
**Muons are unstable and decay!!** → **technological challenge**

# Beam-induced background (BIB)

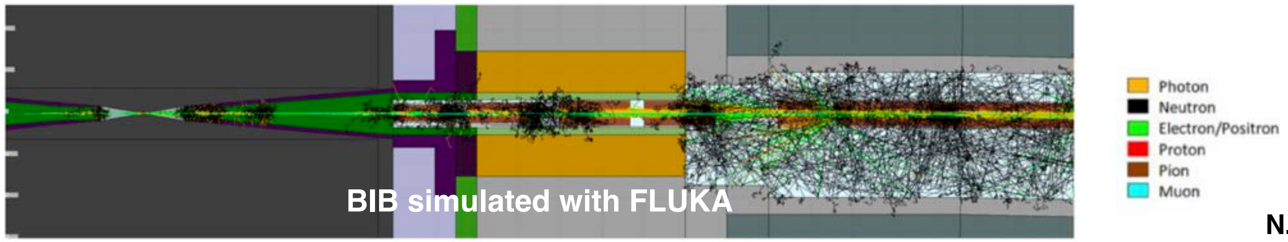
- The major challenge for the detector development is posed by the **Beam-Induced Background (BIB)**
- It is produced by the decay in flight of muons in the beams, and subsequent interactions (around $3 \cdot 10^{13}$ decays/s/beam at $\sqrt{s}$ = 1.5 TeV)
- All kind of particles are produced: photons, electrons, neutrons etc.
- **The BIB is mitigated by the Machine Detector Interface** (*e.g.* two tungsten nozzles are inserted)
- **Even in this way O(100M) particles per bunch crossing arrive at the detector**

**Interaction region optimized for $\sqrt{s}$ = 1.5 TeV**



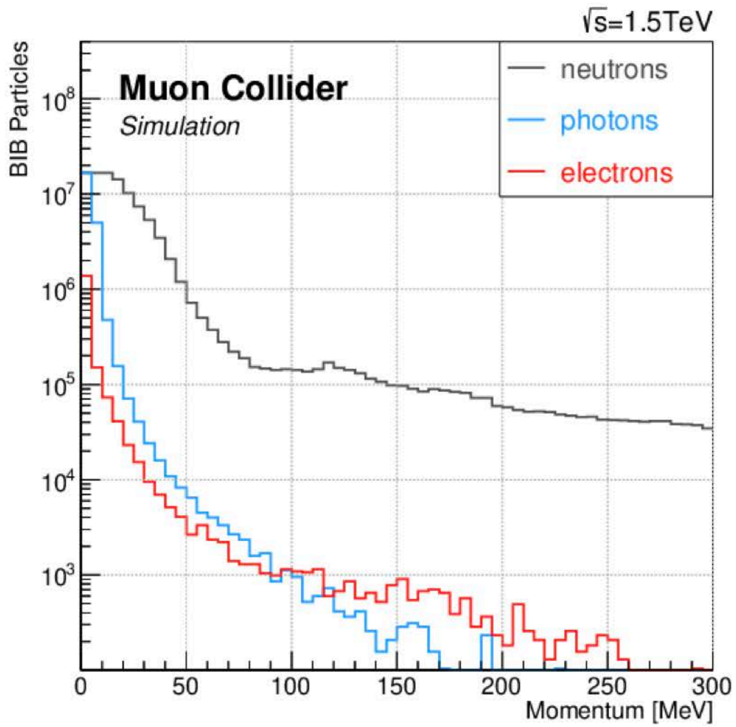

**But we know how to simulate BIB (with MARS15 or FLUKA)**



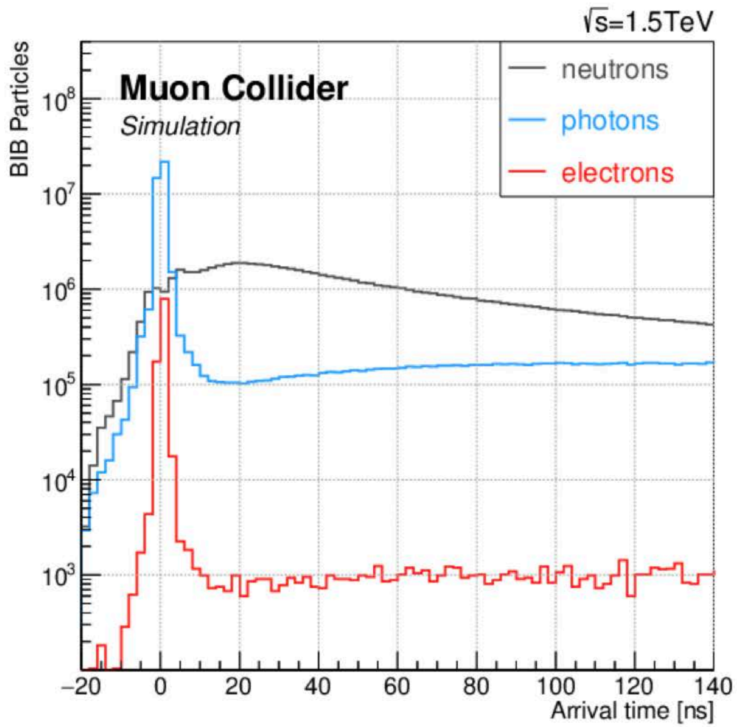

**N.V. Mokhov and S.I. Striganov, Phys. Procedia 37 (2012) 2015**

# BIB characterization

BIB particles have low energies: **we can reject them by applying thresholds**




Many BIB particles are out of time with respect to the bunch crossing: **timing measurements are crucial**

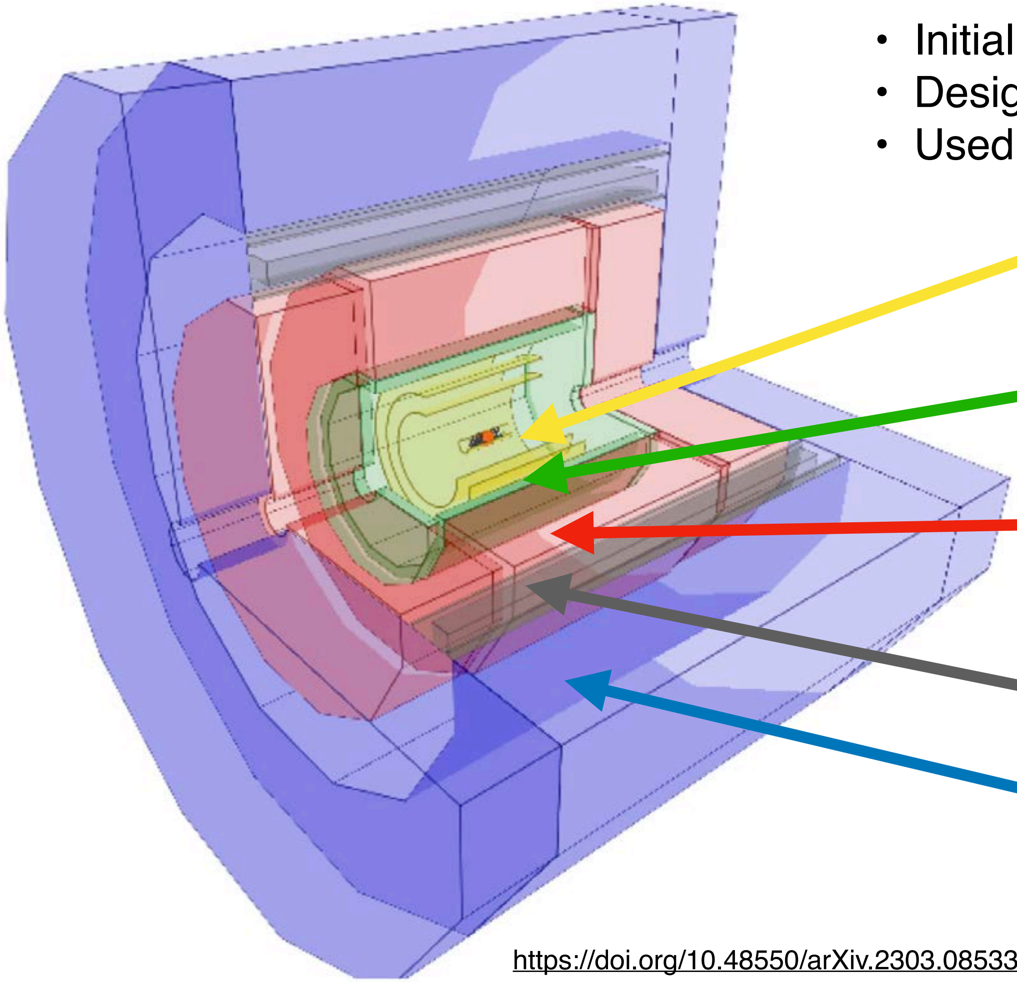



**We have studied the √s = 1.5 TeV BIB because it was the first optimized MDI design available**

**New studies on 3 TeV BIB on-going**

**More info in the talk "Machine-Detector interface for multi-TeV Muon Collider" by D. Lucchesi**

# First detector concept



- Initially based on CLIC detector
- Designed for suppressing the 1.5 TeV BIB
- Used also for 3 TeV studies with full simulation

**Tracking system** with silicon sensors

**Electromagnetic calorimeter**
40 layers of tungsten+silicon pads

**Hadronic calorimeter**
60 layers of
steel absorber + plastic scintillating tiles

**Superconducting solenoid** (3.57 T)

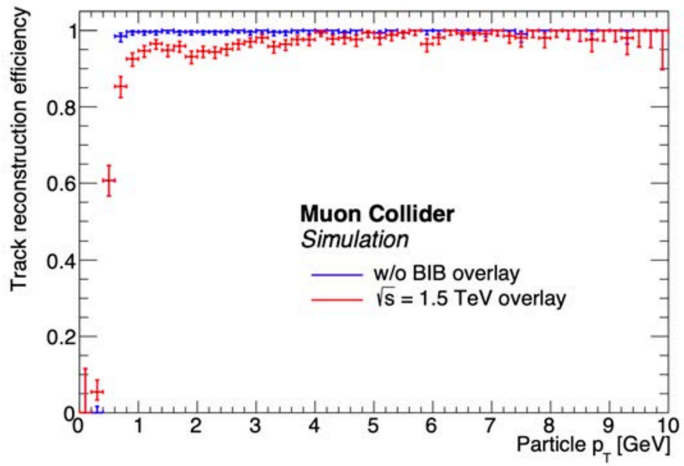
**Muon system**
Resistive Plate Chambers (RPC) interleaved in the magnets's iron yoke

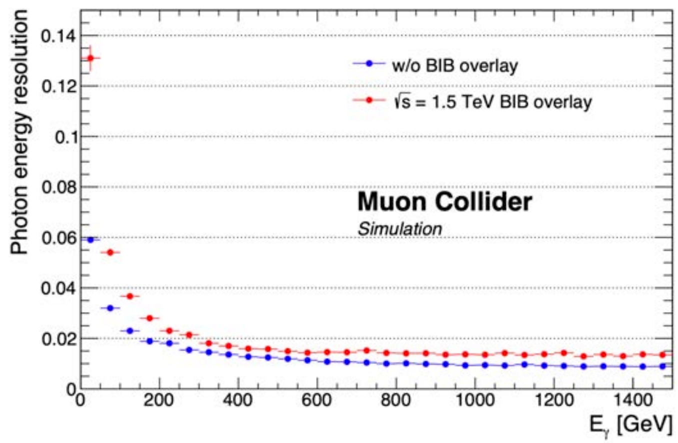
https://doi.org/10.48550/arXiv.2303.08533

# Detector performance

- Reconstruction algorithm are tuned to suppress the BIB
- The presence of the BIB degrades the performance
- **Detectors and reconstruction algorithms are not yet fully optimized**
- However physics is already possible with this configuration, check other EPS-HEP 2023 talks:
  - **"Higgs physics prospects at Muon Collider with a detailed detector simulation" by M. Casarsa**
  - **"Detecting disappearing tracks and other exotica at a Muon Collider" by F. Meloni**
  - **"New physics and hidden sectors at Muon Collider" by C. Aimé**

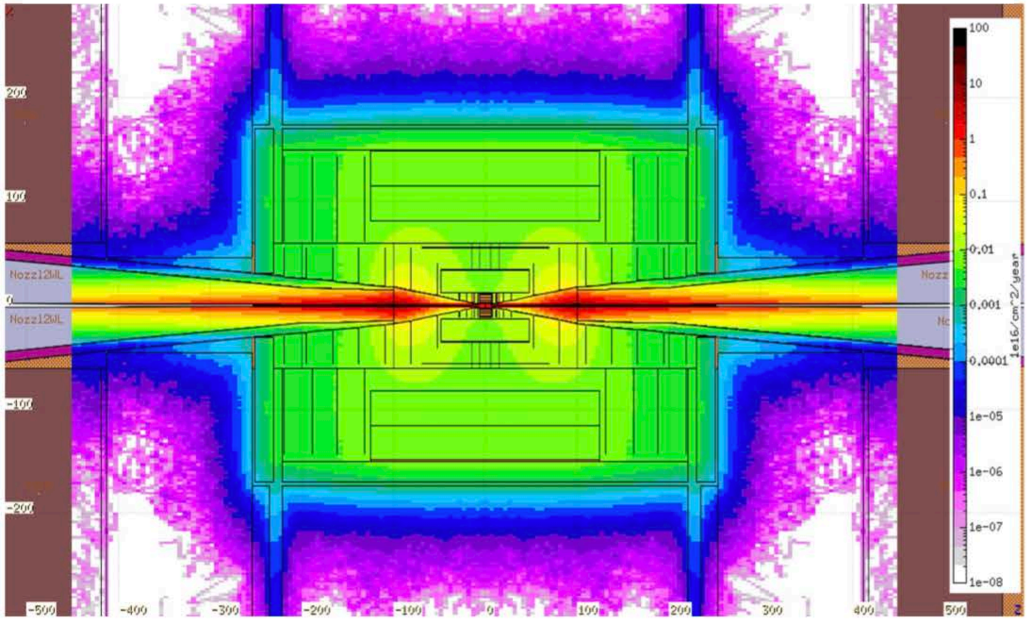
**Tracks and photons performance with and w/o BIB**



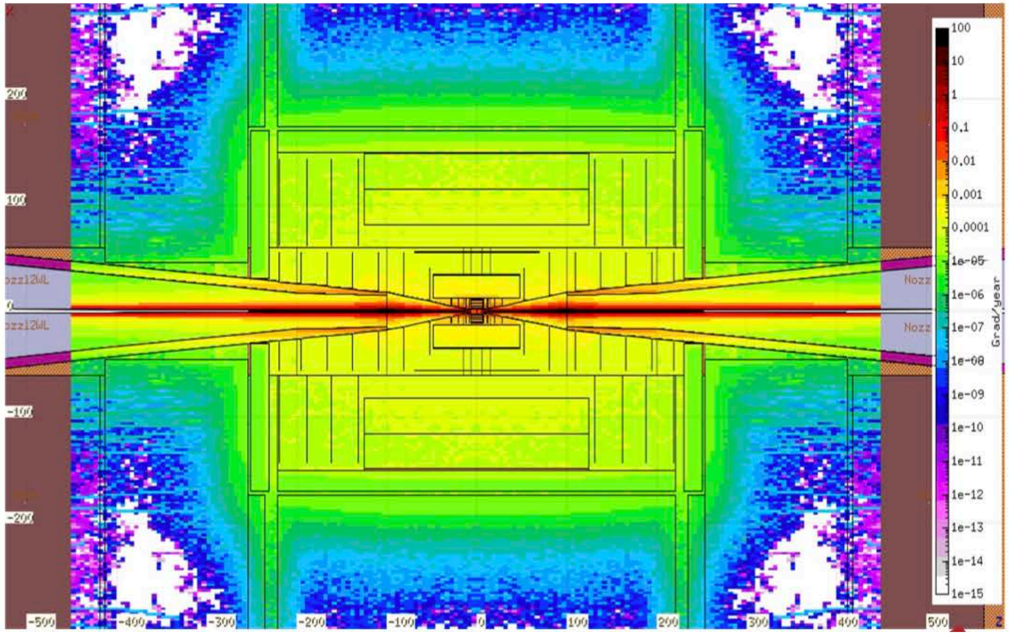



# Radiation environment

**1-MeV-neq fluence for one year of operation (200 days) at 1.5 TeV**



**Total Ionizing Dose for one year of operation (200 days) at 1.5 TeV**

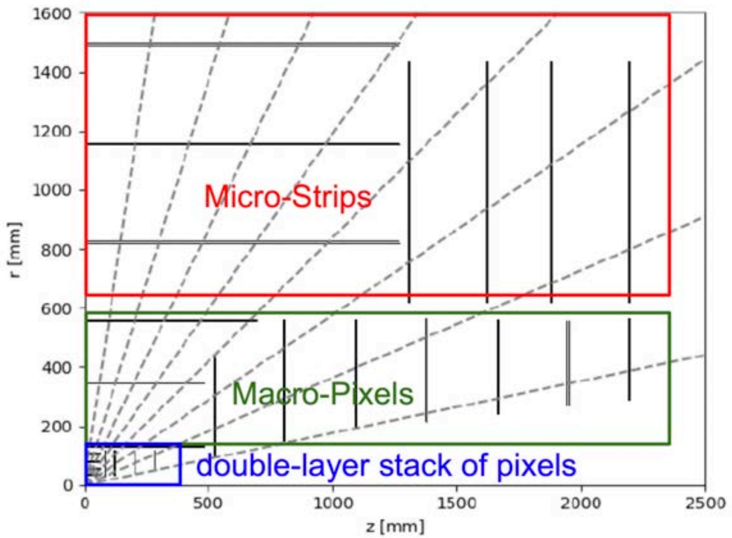


| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |

**Radiation hardness requirements are pretty similar to what expected at HL-LHC**

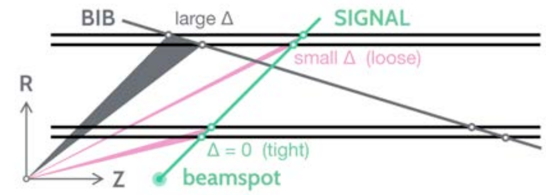
# Tracking R&D

### Baseline tracking geometry

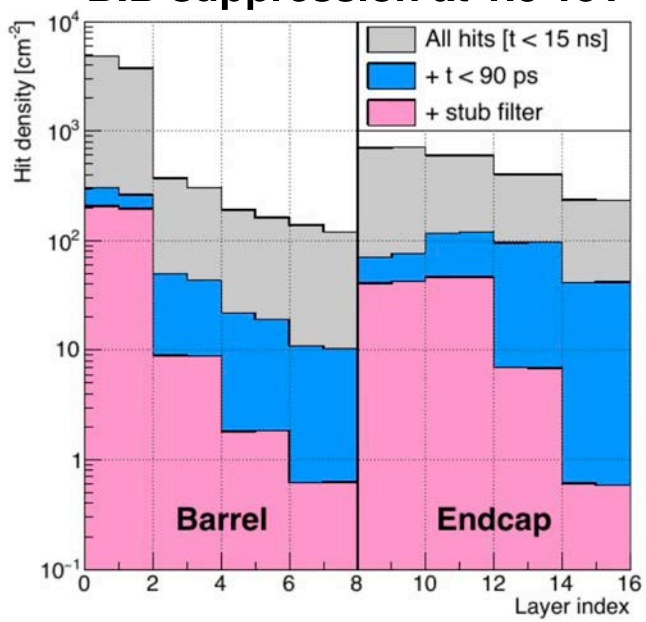



### Key features

- **Timing**: to suppress out-of-time BIB hits
- **Directional information**: BIB does not come from the interaction point
- **Energy depositions**: pulse shape analysis for rejecting soft component




### BIB suppression at 1.5 TeV




**Higher occupancies than LHC detectors are expected but 100 kHz crossing rate (MuC with single bunch) vs 40 MHz (LHC)**

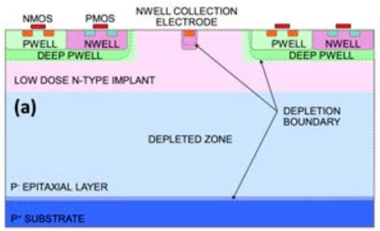
| Detector Reference | Hit Density [$mm^{-2}$] MCD | ATLAS ITk | ALICE ITS3 |
|---|---|---|---|
| Pixel Layer 0 | 3.68 | 0.643 | 0.85 |
| Pixel Layer 1 | 0.51 | 0.022 | 0.51 |

# Tracking R&D

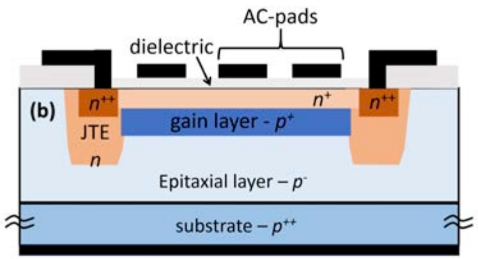
| | Vertex Detector | Inner Tracker | Outer Tracker |
|---|---|---|---|
| Cell type | pixels | macropixels | microstrips |
| Cell Size | $25\,\mu m \times 25\,\mu m$ | $50\,\mu m \times 1\,mm$ | $50\,\mu m \times 10\,mm$ |
| Sensor Thickness | $50\,\mu m$ | $100\,\mu m$ | $100\,\mu m$ |
| Time Resolution | 30 ps | 60 ps | 60 ps |
| Spatial Resolution | $5\,\mu m \times 5\,\mu m$ | $7\,\mu m \times 90\,\mu m$ | $7\,\mu m \times 90\,\mu m$ |

**Sinergy with timing sensors development for HL-LHC**

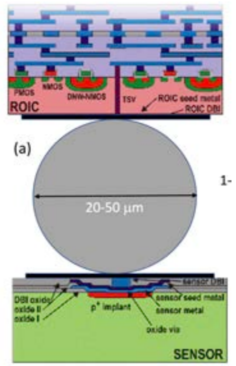
## Promising technologies




**Monolithic devices (CMOS):**
Good timing and spacial resolution, but radiation hardness to be improved



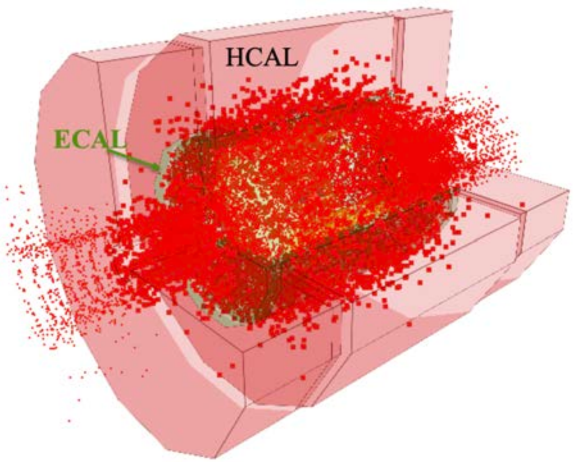

**Low Gain Avalanche Detectors (LGAD):**
Large and fast signal (20-30 ps resolution), moderate radiation hardness



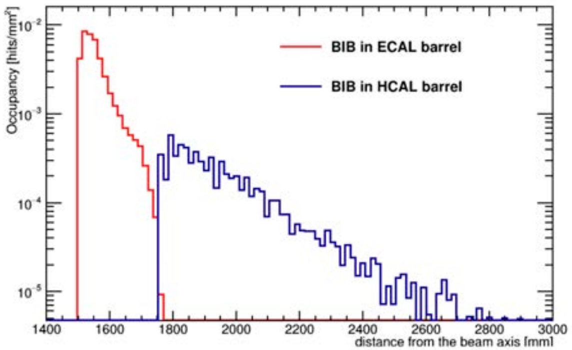

**Hybrid small pixel devices:**
No gain but fast timing (20-30 ps resolution) and good position resolution. Intrinsically radiation hard

# Calorimeter R&D

## BIB hits in the calorimeters



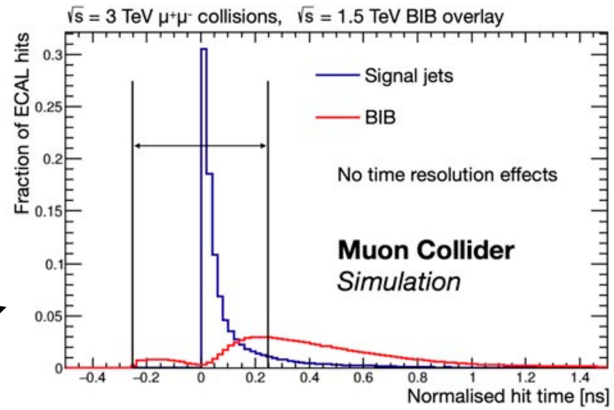

Occupancy in ECAL > 10 times occupancy in HCAL



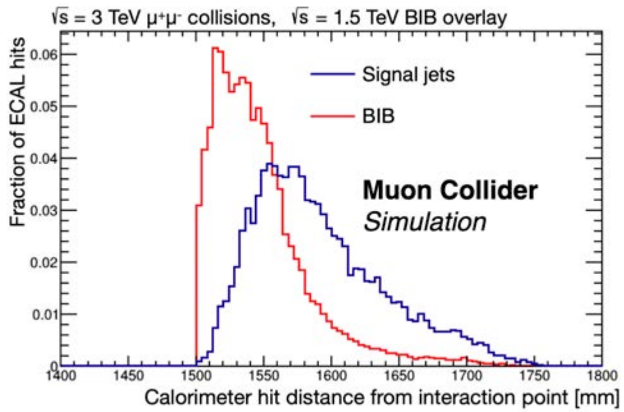

- Flux of 300 particles per cm$^2$ through the ECAL surface
- 96% photons and 4% neutrons
- Average photon energy 1.7 MeV

### Key features

- **Timing**: BIB hits are out-of-time a resolution in the order of 100 ps is desiderable




- **Longitudinal segmentation**: different profile for signal and BIB

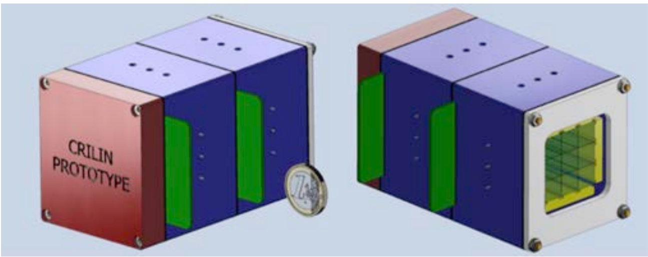



- **Granularity**: helps in separating BIB particles from signal, avoiding overlaps in the same cell
- **Energy resolution:** target $\frac{\Delta E}{E} \simeq \frac{10\,\%}{\sqrt{E[\mathrm{GeV}]}}$

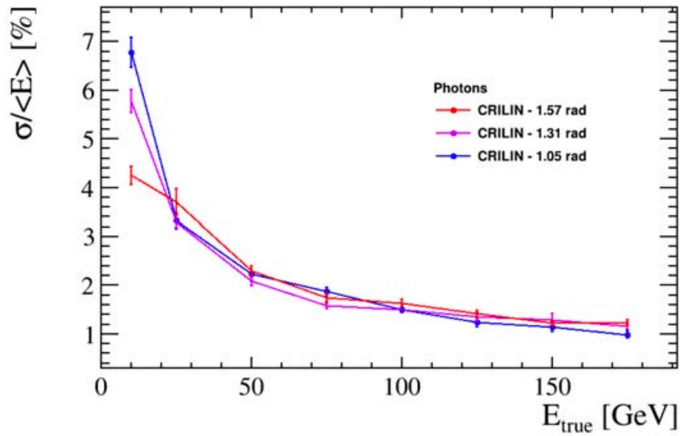
# Calorimeter R&D - ECAL

- **Crilin**: **A CRystal calorImeter with Longitudinal InformatioN** for a future Muon Collider
- Module formed by 5 layers of $PbF_2$ crystals (10 x 10 x 40 mm$^3$), Cerenkov light detected with SiPMs
- Prototype module built and tested at Laboratori Nazionali di Frascati
- Time measurement resolution better than 100 ps
- **It costs 10 time less than the baseline tungsten-silicon calorimeter**

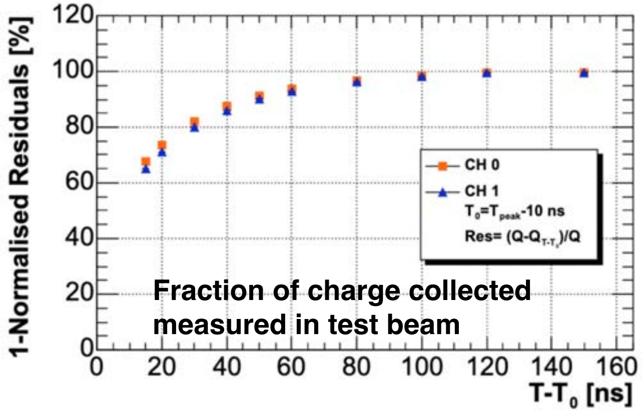
Journal of Instrumentation, Volume 17, September 2022



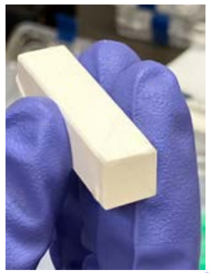

**ECAL performance in Muon Collider environment (1.5 TeV) determined from full simulation**




$$\frac{\Delta E}{E} \simeq \frac{14\,\%}{\sqrt{E[\mathrm{GeV}]}}$$

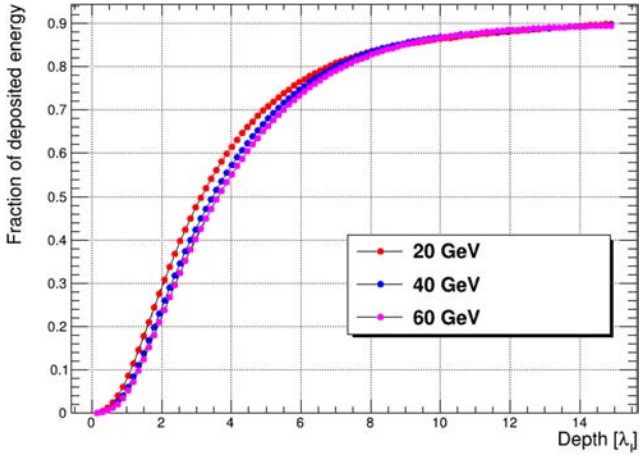



**Characterization of modules in dedicated test beams**



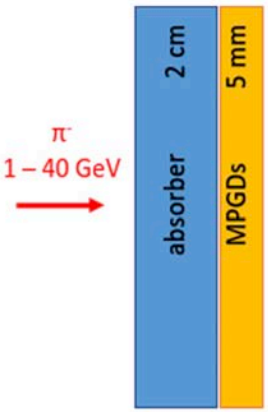
# Calorimeter R&D - HCAL

- 7.5 kHz/cm$^2$ photon flux is expected at the HCAL surface
- Total ionizing dose $10^{-5}$ GRad per year in HCAL
- HCAL based on **Micro Pattern Gas Detectors** (MPGDs) under investigation: high rate capability (MHz/cm2), modest time resolution (few ns) and robust against radiation
- Design studied with stand-alone Geant4 simulation

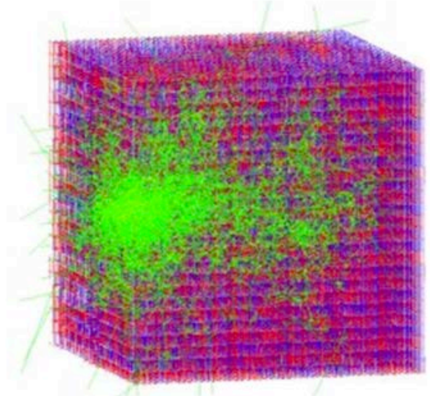



90% of pion energy contained in 14 $\lambda_I$ (100 layer)

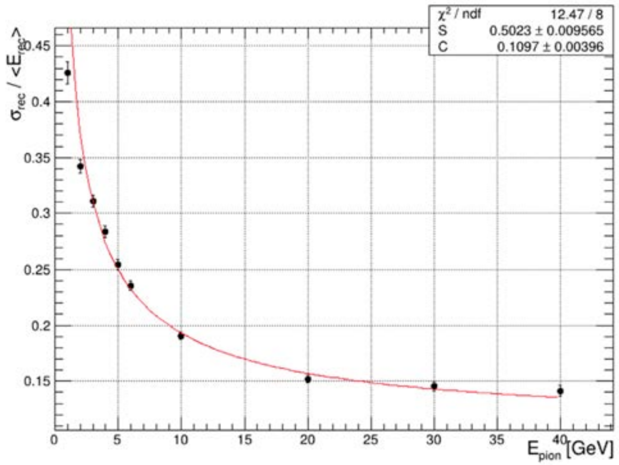
https://doi.org/10.1016/j.nima.2022.167731




Iron



1 x 1 cm$^2$ cells
Filled with argon (30 eV average ionization potential)




For pions:

$$\frac{\Delta E}{E} \simeq \frac{50\,\%}{\sqrt{E[\mathrm{GeV}]}}$$

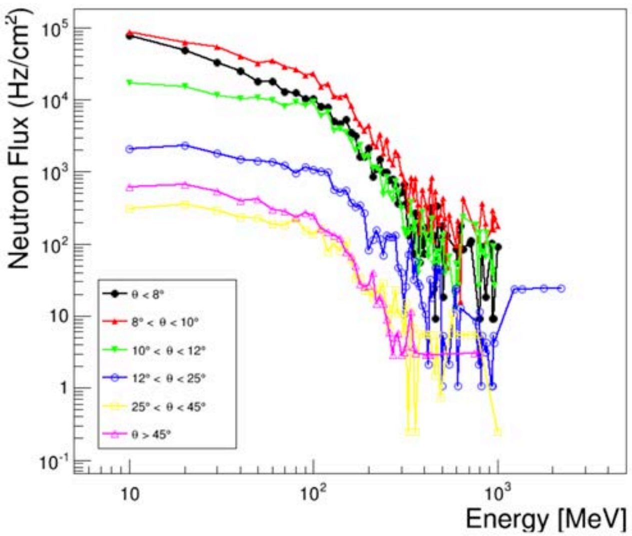
**Results to be validated at dedicated (on-going) test beams with prototypes**

# Muon System R&D

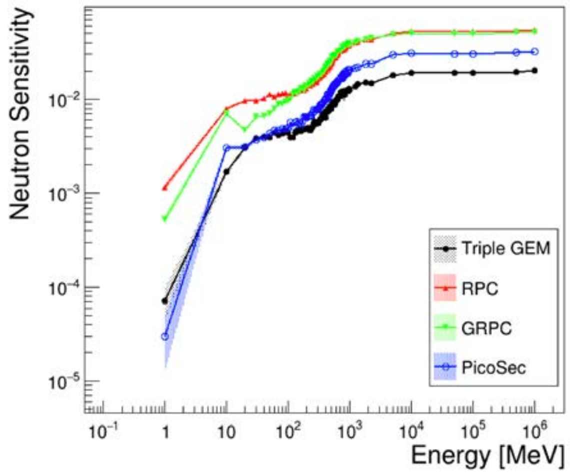
- In the Muon System BIB hits are concentrated in the endcaps
- Some technologies like RPCs are already at the rate limit
- Requirements: good spacial resolution (100 μm) possibly sub-ns time resolution

NIM A Volume 1046, 11 January 2023, 167800

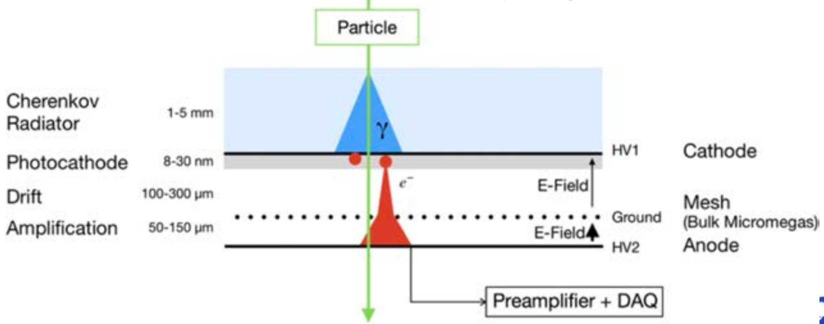
**Neutron flux in the muon system with 1.5 TeV BIB**




**Technology comparison: probability for a BIB particle to generate a visible signal in the detector (simulation)**




**PicoSec MICROMEGAS detector is a valid option: time resolution better than 25 ps, very high rate capability**

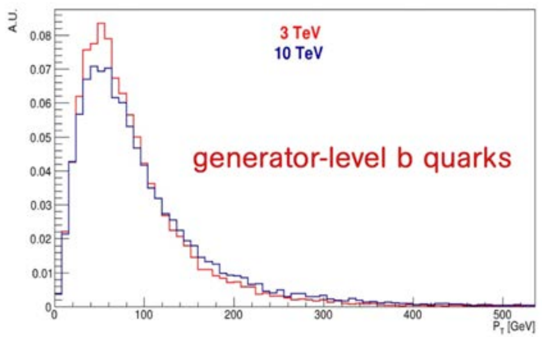



**Test beams for the characterization are on-going**

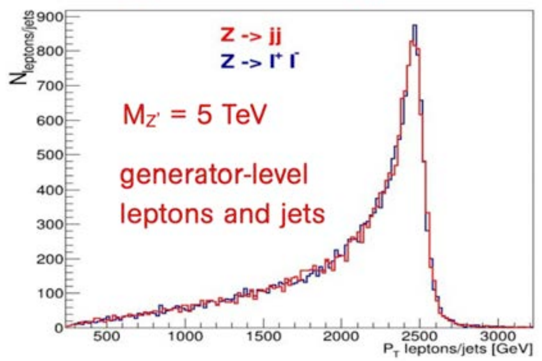
# Towards a 10 TeV detector

At 10 TeV we have to measure signals from Higgs decays (~100 GeV $p_T$) but also search for high-mass new particle decays (up to 5 TeV $p_T$)

$\mu\mu \rightarrow H\nu\nu \rightarrow bb\nu\nu$

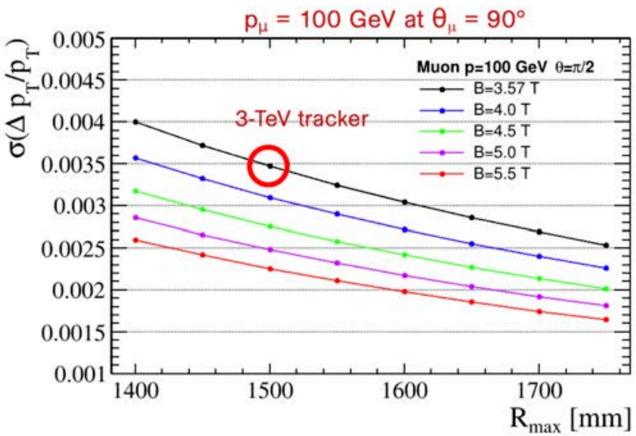


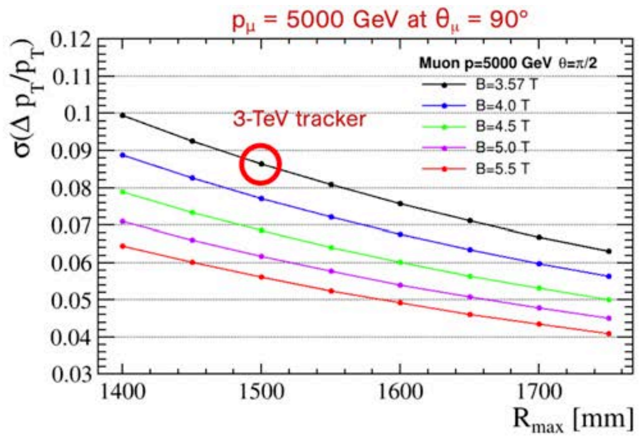

$\mu\mu \rightarrow Z'X \rightarrow qq/\ell\ell\ X$




**Tracker optimization, several handles:**

- Maximum distance from beam axis ($R_{max}$)
- Magnetic field (B)
- Minimum distance from beam axis (for impact parameter resolution)



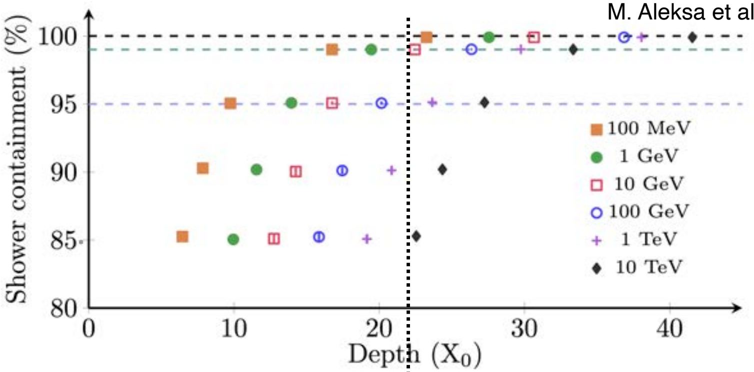




- The working point should be decided with physics requirements
- **The magnetic field is limited by technological issues: a discussion with experts is necessary!**

# Towards a 10 TeV detector

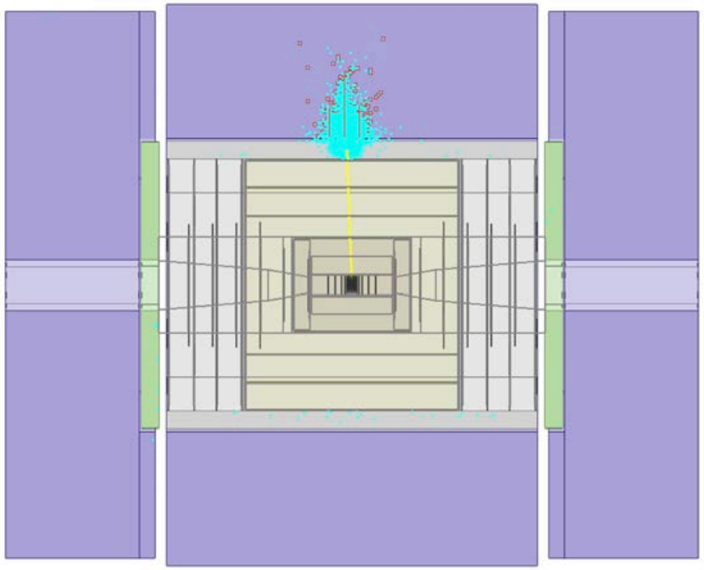
- **TeV photons are not fully contained in ECAL**
- Detector dimensions limited by machine magnets
- Need to explore other solutions

M. Aleksa et al., arXiv:1912.02.09962v1



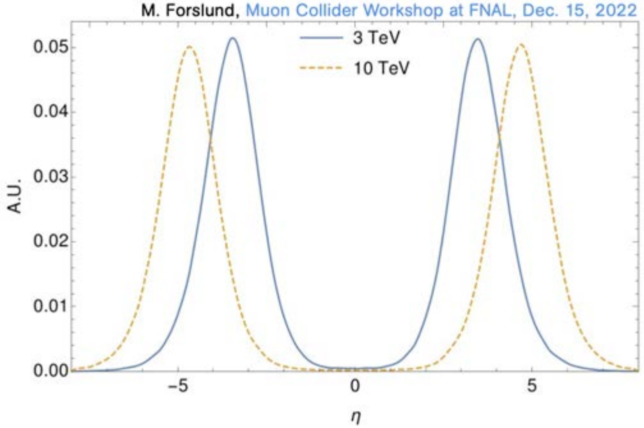

**3 TeV ECAL depth**

**5 TeV photon**



Another desideratum is the possibility to detect forward muons from ZZ-fusion processes

M. Forslund, Muon Collider Workshop at FNAL, Dec. 15, 2022




It is necessary to instrument the beam line, studies on-going

# Conclusions

- The **Muon Collider** environment is **different from other known machines**: the decay in flight of muons produces the **beam-induced background**
- Detectors should meet specific requirements, from radiation hardness to excellent timing resolution
- Starting from a detector concept designed for suppressing BIB at 1.5 TeV collisions, several R&D activities are on-going to improve the general performance
- The design of the 10 TeV detector is challenging, original and ground-breaking solutions should be explored
- Participation to the European Strategy and Snowmass process, integration in the ECFA Detector R&D roadmap. MuCol project funded by the EU. Small group of people, more personpower needed!