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Istituto Nazionale di Fisica Nucleare

International MUON Collider Collaboration

MuCol

Co-funded by the European Union

Overview of Muon Collider detectors

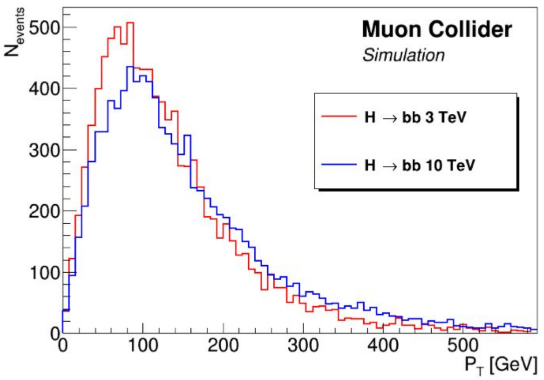
Davide Zuliani, University and INFN Padova
On behalf of the **International Muon Collider Collaboration**

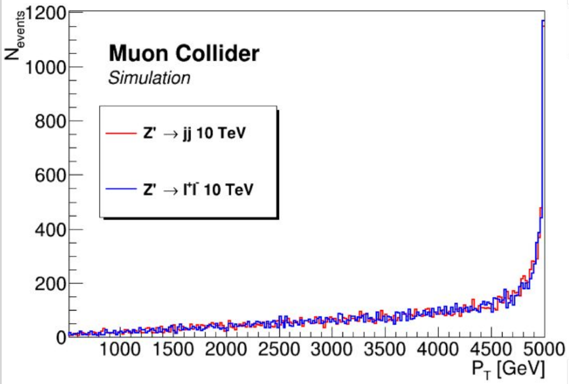
Workshop on FCC-ee and Lepton Colliders,
LNF Frascati, 22-24 January 2025

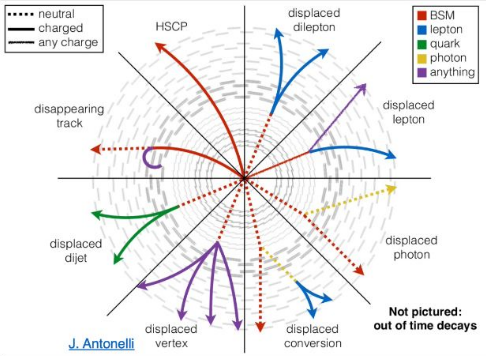
Driving factors for a Muon Collider detector

- Requirements from physics are similar to those of other multi-TeV machines:
  - **boosted low-p_T physics** objects from SM processes (e.g. Higgs physics)
  - **central energetic physics objects** from decays of NP massive states
  - **less conventional experimental signatures**: disappearing tracks, displaced leptons, displaced photons or jets, …

see talk by D. Lucchesi







- Constraints from the **machine design**:
  - final focusing quadrupoles at ±6 m from the interaction point
  - machine background conditions

The challenge: Beam-Induced Background (BIB)

- The Muon Collider environment poses important challenges
  - presence of the Beam-Induced Background (BIB) from muons decay
    - **high hit multiplicity in tracker**
    - **diffuse background in calorimeters**

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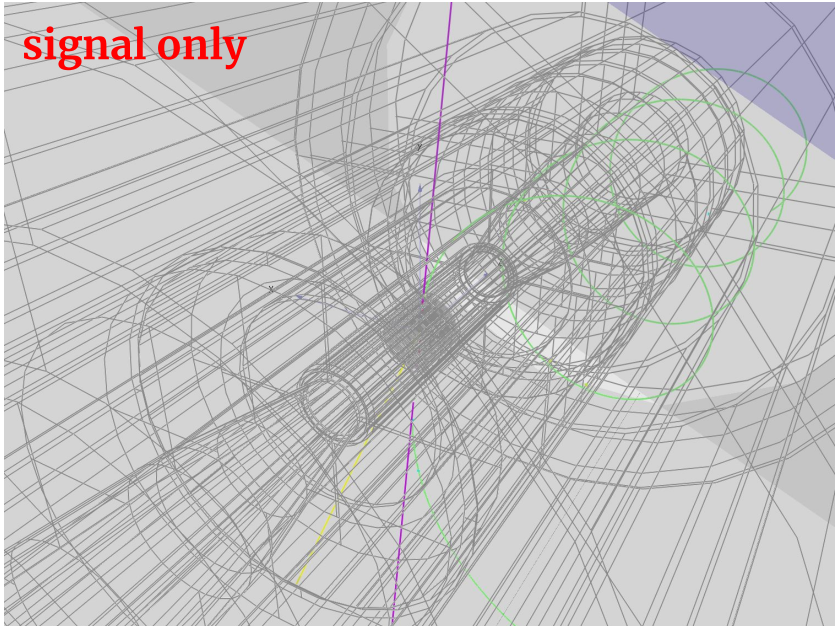
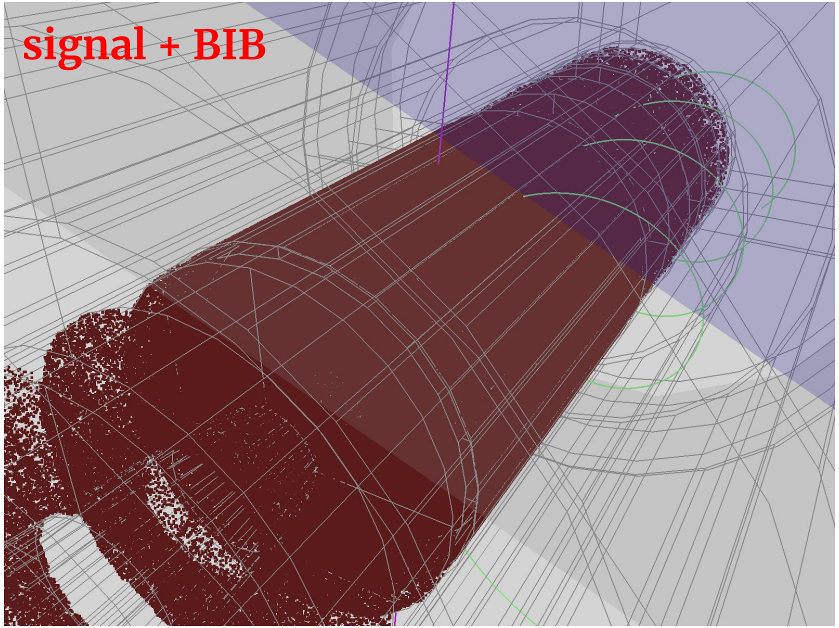
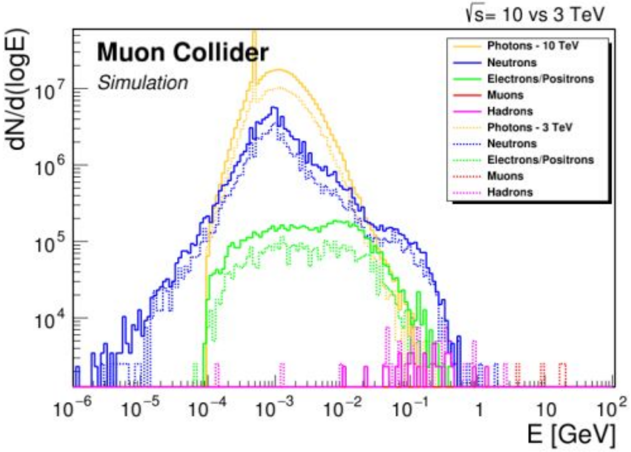


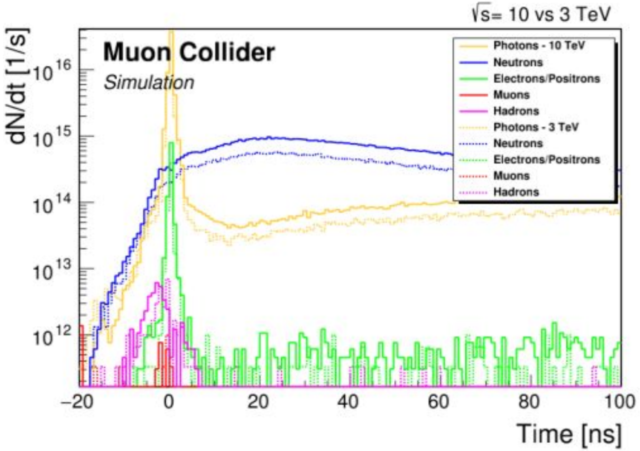


The challenge: Beam-Induced Background (BIB)

- The Muon Collider environment poses important challenges
  - presence of the Beam-Induced Background (BIB) from muons decay
    - high hit multiplicity in tracker
    - diffuse background in calorimeters

- Luckily, we can exploit **BIB features** to keep it under control
- This is where **detector design** plays an important role!





see talk by D. Calzolari

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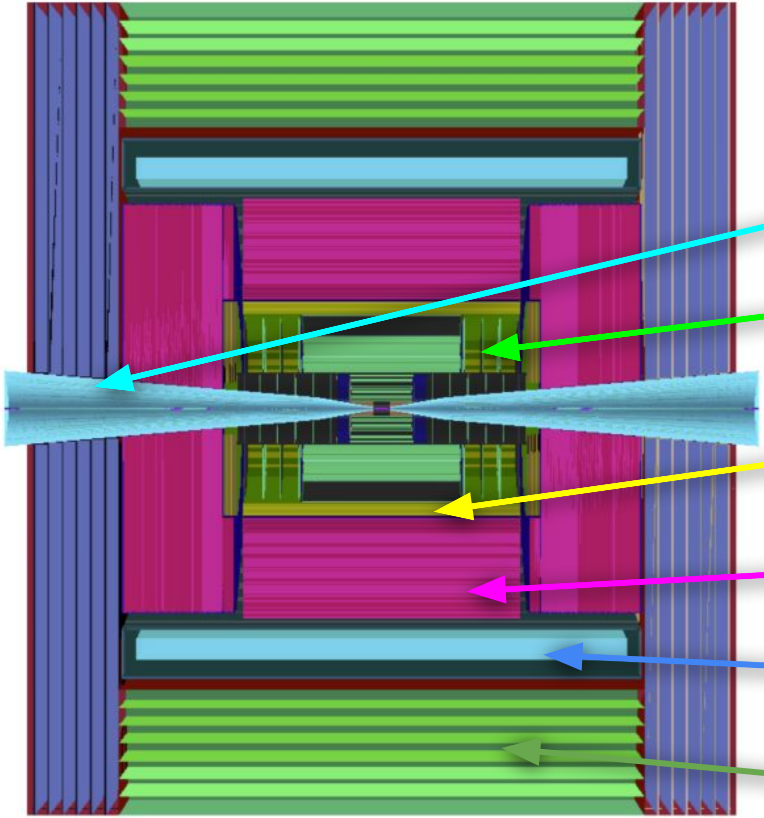
Designing the 3 TeV detector



The detector model is based on the **CLIC concept**

- Nozzles
- Silicon tracker (with Double Layers in VXD)
- ECAL (Tungsten+Silicon)
- HCAL (Steel+Scintillators)
- 3.57 T Solenoid
- Muon chambers (RPC) in magnet yoke

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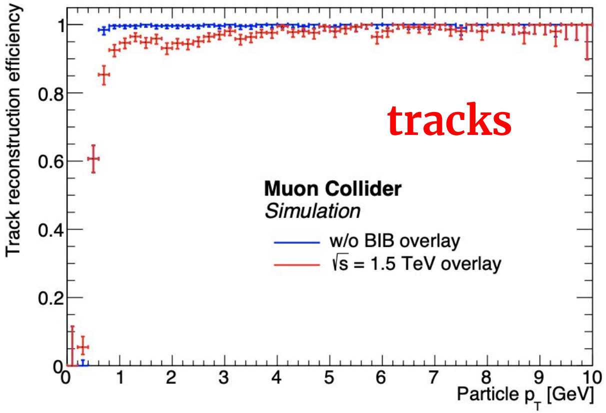
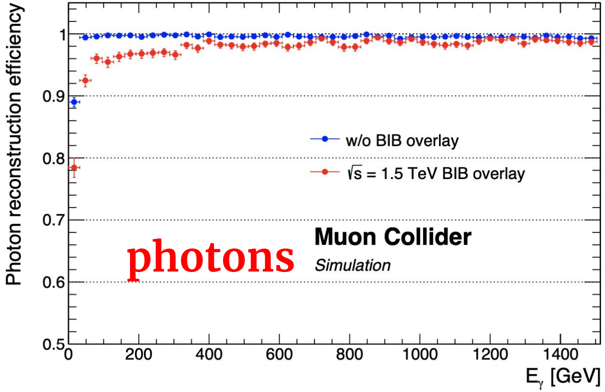
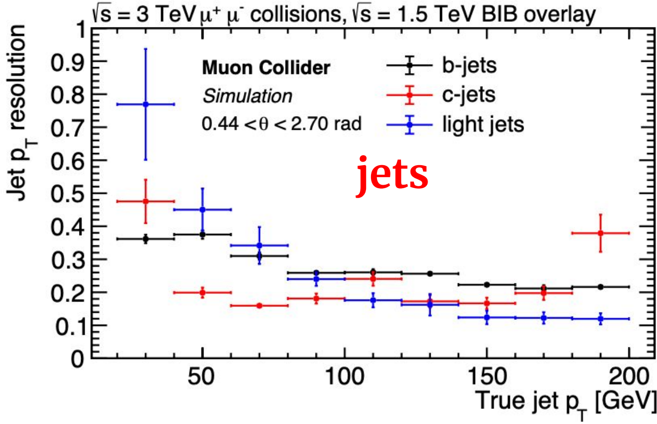
Designing the 3 TeV detector: performance

- Obtain **“LHC-level” performance** without using optimised techniques
- 3 TeV detector as starting point to design 10 TeV Muon Collider detectors





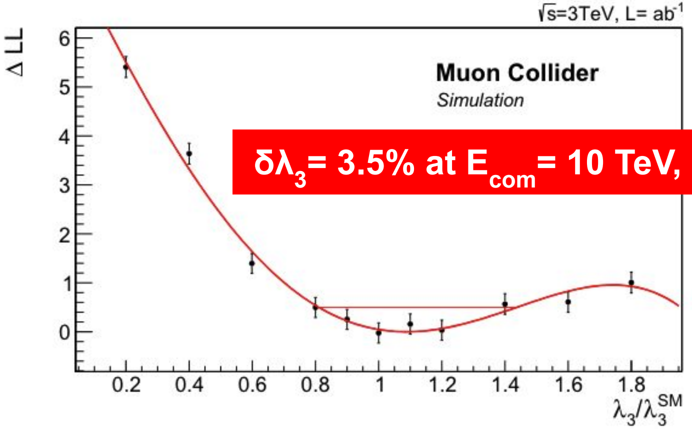


Designing the 3 TeV detector: physics studies

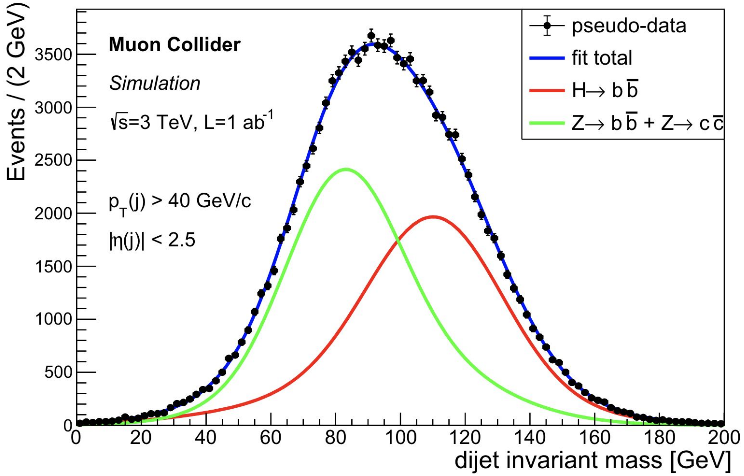
- Higgs physics as main focus
  - prove that **BIB is under control**
  - validate parametric studies (Delphes card) with detailed simulations
- **We can do Higgs physics at Muon Collider**
- BIB is under control, good agreement between parametric and detailed simulations

2405.19314

Channel	Detailed simulation with BIB $\Delta\sigma/\sigma$ [%]	Target performance $\Delta\sigma/\sigma$ [%]
$H \to b\bar{b}$	0.78	0.55
$H \to WW^*$	2.9	2.0
$H \to ZZ^*$	17	12
$H \to \mu^+\mu^-$	39	38
$H \to \gamma\gamma$	7.5	7.0

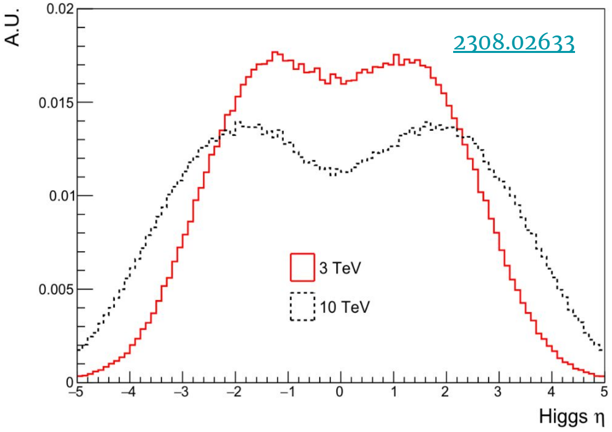


$\delta\lambda_3$= 3.5% at E_{com} = 10 TeV, 10 ab^{-1}



Designing the 10 TeV detectors

- Start from physics to define detector requirements
- Higgs Physics at 10 TeV is **similar** to 3 TeV
  - Objects **more boosted in the forward region**
  - Transverse momentum distributions are similar



- Important to define the **target performance** to achieve for different physics objects

Requirement	Baseline $\sqrt{s} = 3$ TeV	Baseline $\sqrt{s} = 10$ TeV	Aspirational
Angular acceptance	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$	$\|\eta\| < 4$
Minimum tracking distance [cm]	~ 3	~ 3	< 3
Forward muons ($\eta > 5$)	–	tag	$\sigma_p/p \sim 10\%$
Track σ_{p_T}/p_T^2 [GeV^{-1}]	4×10^{-5}	4×10^{-5}	1×10^{-5}
Photon energy resolution	$0.2/\sqrt{E}$	$0.2/\sqrt{E}$	$0.1/\sqrt{E}$
Neutral hadron energy resolution	$0.5/\sqrt{E}$	$0.4/\sqrt{E}$	$0.2/\sqrt{E}$
Timing resolution (tracker) [ps]	$\sim 30-60$	$\sim 30-60$	$\sim 10-30$
Timing resolution (calorimeters) [ps]	100	100	10
Timing resolution (muon system) [ps]	~ 50 for $\|\eta\| > 2.5$	~ 50 for $\|\eta\| > 2.5$	< 50 for $\|\eta\| > 2.5$
Flavour tagging	b vs c	b vs c	b vs c, s-tagging
Boosted hadronic resonance ID	h vs W/Z	h vs W/Z	W vs Z

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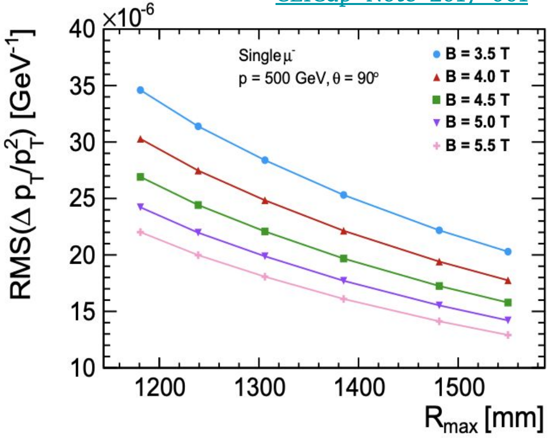
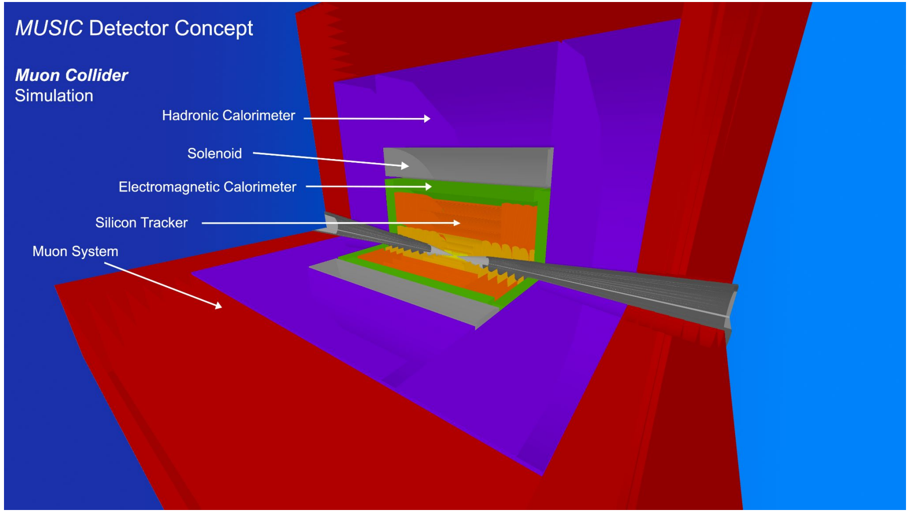
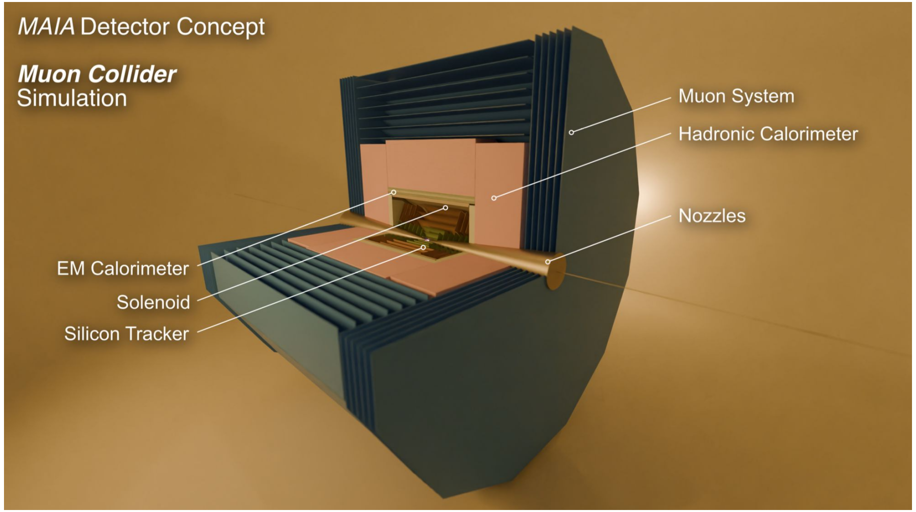


Designing the 10 TeV detectors: two proposals

- **Two main concepts** making different detector-design choices, e.g.
  - **Position of solenoid**
  - **Tracker layouts**
  - **ECAL technology**



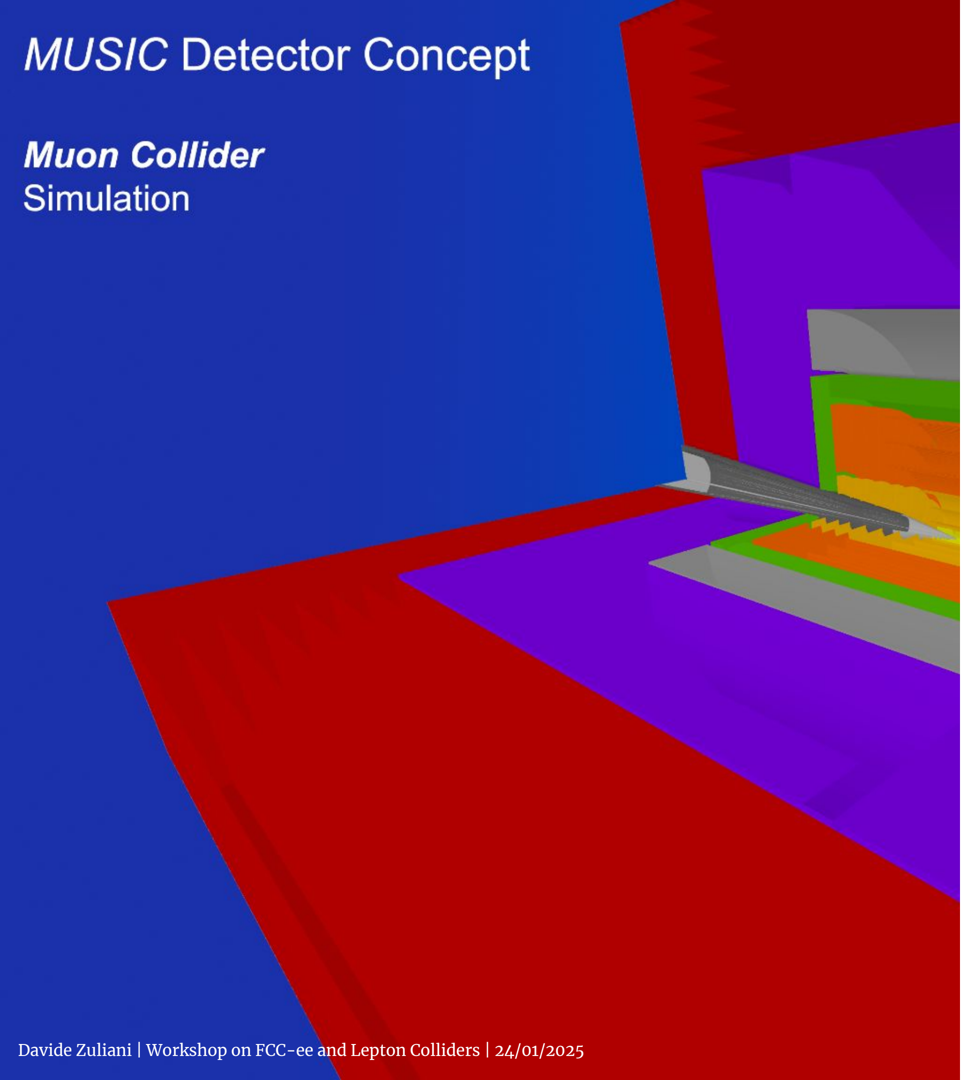
MUSIC - MUon System for Interesting Collisions



MAIA - Muon Accelerator Instrumented Apparatus

MUSIC Detector Concept

Muon Collider
Simulation



- Silicon Tracker with **longer VXD barrel**
  - higher occupancy but better reconstruction at lower angles
  - removal of double layers
  - assuming **MAPS** (currently developed in Padova)

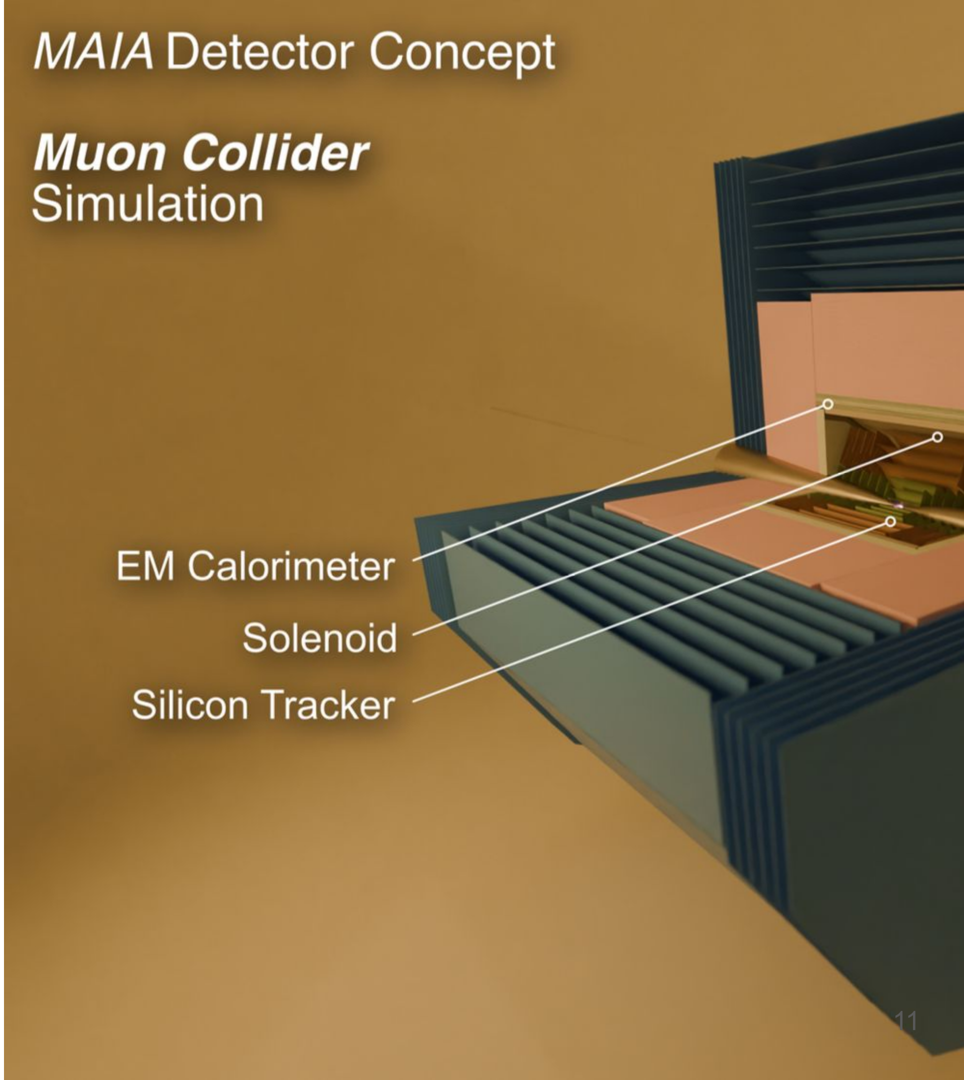
	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	macro-pixels
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	$25\,\mu m \times 25\,\mu m$	$50\,\mu m \times 1\,mm$	$50\,\mu m \times 10\,mm$
Sensor Thickness	$50\,\mu m$	$100\,\mu m$	$100\,\mu m$
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	$5\,\mu m \times 5\,\mu m$	$7\,\mu m \times 90\,\mu m$	$7\,\mu m \times 90\,\mu m$

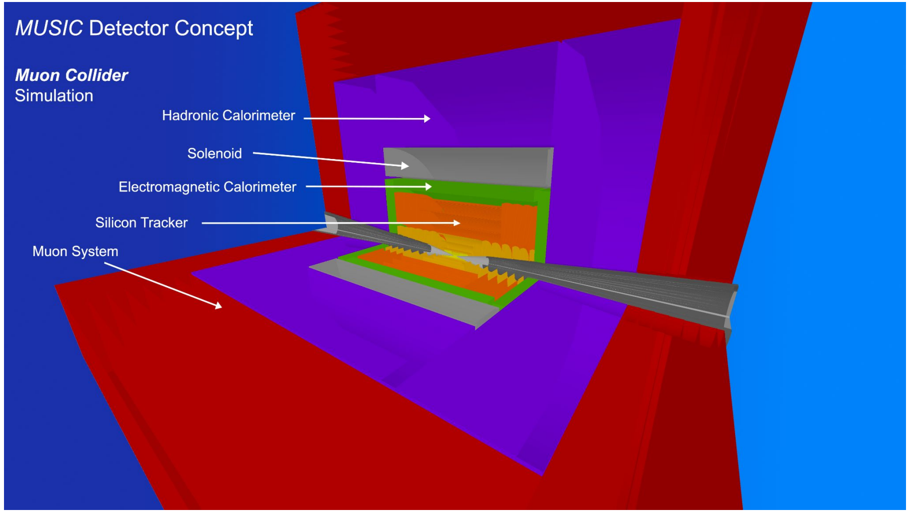
- 6 layers **Crilin** technology ECAL (26 X_0)
- **5T** solenoid **between calorimeters**
- HCAL with scintillator+iron layers
- Muon system not yet optimised
  - possibility to **remove RPC** and use scintillating tiles

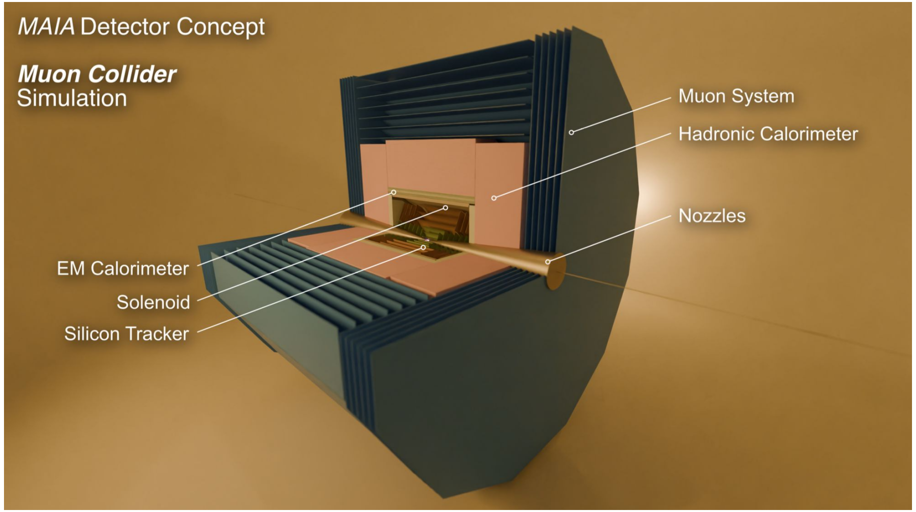
- Silicon Tracker similar to 3 TeV concept
  - removal of double layers

	Vertex Detector	Inner Tracker	Outer Tracker
Sensor type	pixels	macro-pixels	macro-pixels
Barrel Layers	4	3	3
Endcap Layers (per side)	4	7	4
Cell Size	25 µm × 25 µm	50 µm × 1 mm	50 µm × 10 mm
Sensor Thickness	50 µm	100 µm	100 µm
Time Resolution	30 ps	60 ps	60 ps
Spatial Resolution	5 µm × 5 µm	7 µm × 90 µm	7 µm × 90 µm

- 50 layers of Tungsten+silicon ECAL technology (26 X_0)
- **5T** solenoid **in front of ECAL**
  - **thinner solenoid**
  - reduce BIB radiation in calorimeters
- HCAL with scintillator+iron layers
- Muon system not yet optimised
  - possibility to remove RPC and use scintillating tiles



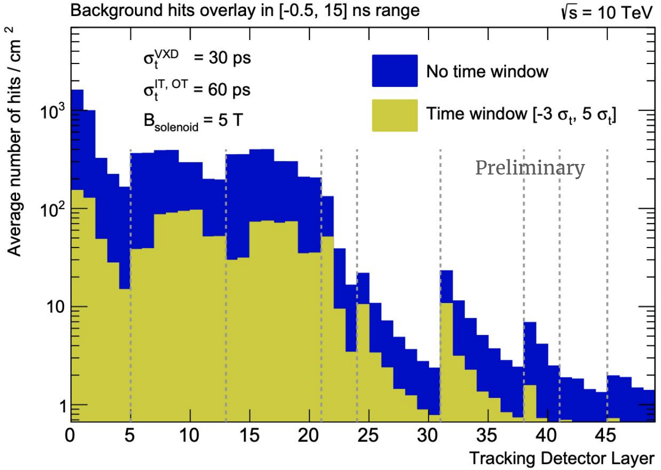


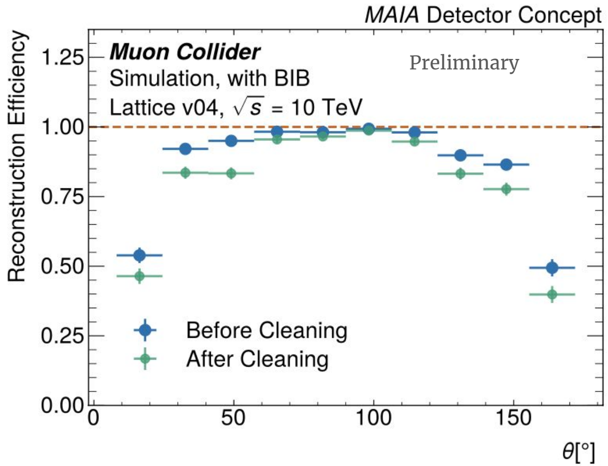


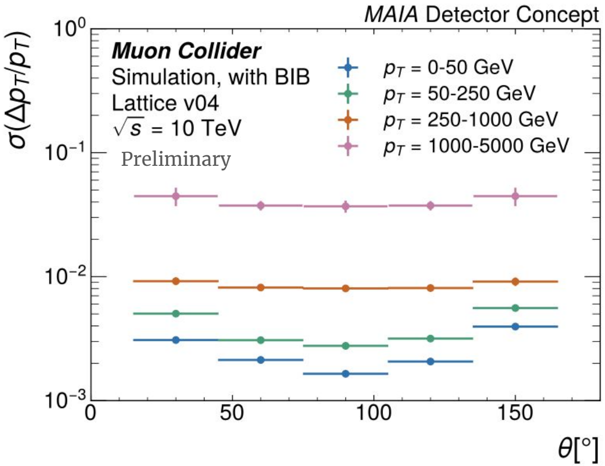
In the following, performance is evaluated using a detailed simulation of the detector, with the inclusion of BIB and incoherent pair production

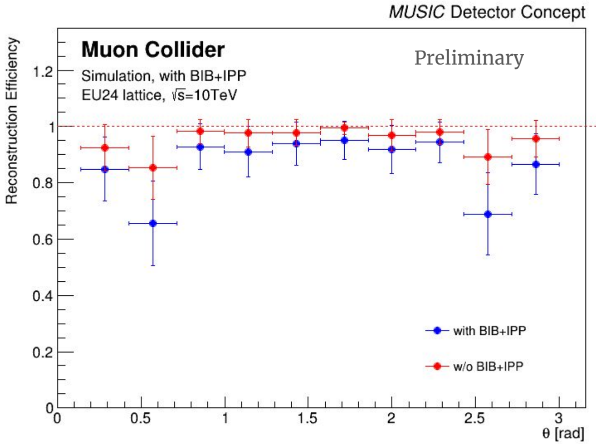
Tracker performance

- Tracker performance are evaluated using muon guns
- Tracks are reconstructed using the ACTS algorithm
  - Seeding procedure tailored to Muon Collider environment
- Cleaning procedure to remove most of BIB tracks
- Despite high occupancy, good performance is obtained

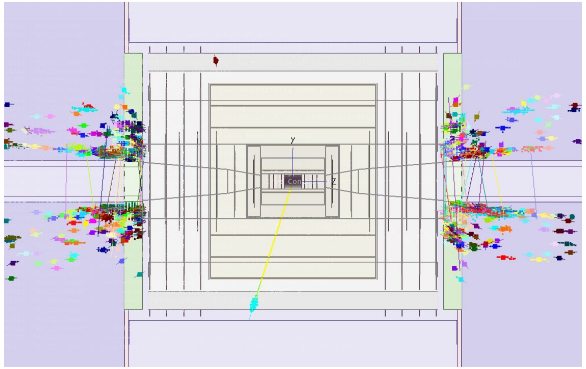




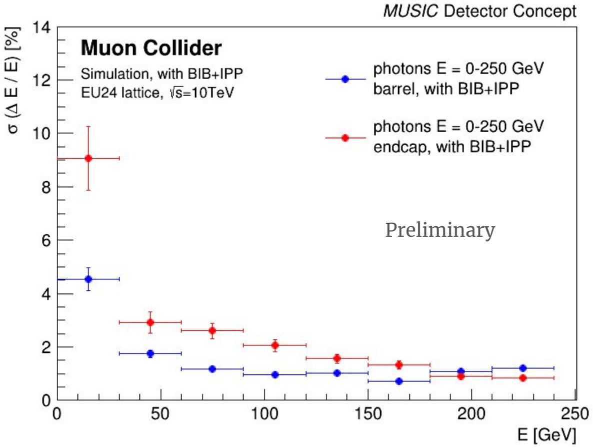


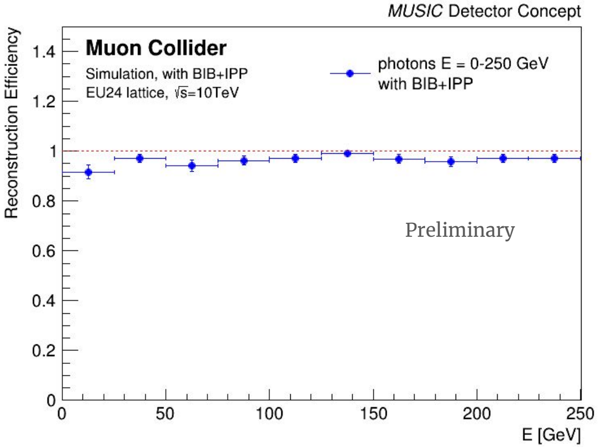


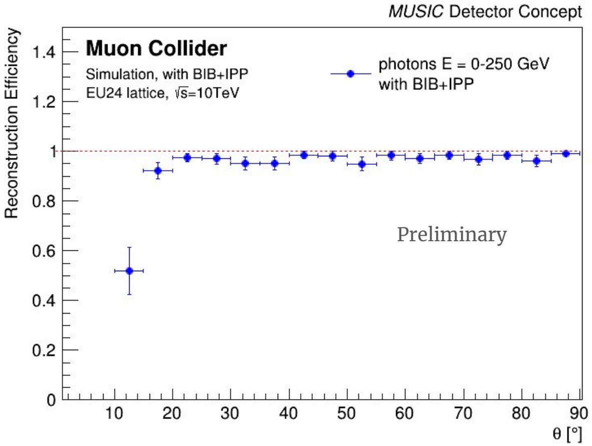
ECAL performance: photons



- ECAL performance is evaluated using photon gun
  - Diffuse BIB in ECAL requires ad hoc subtraction procedure
  - Optimised digitisation and calibration procedure
- Excellent reconstruction efficiency and energy resolution (~ 10%/√E)

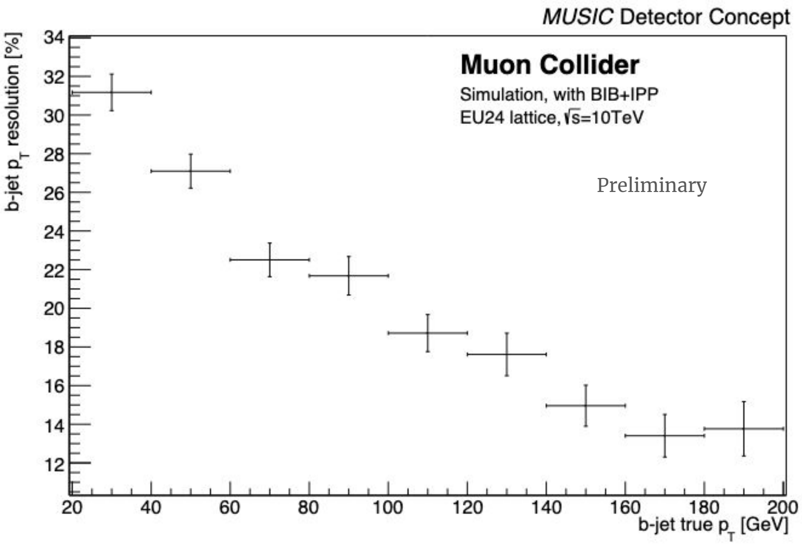


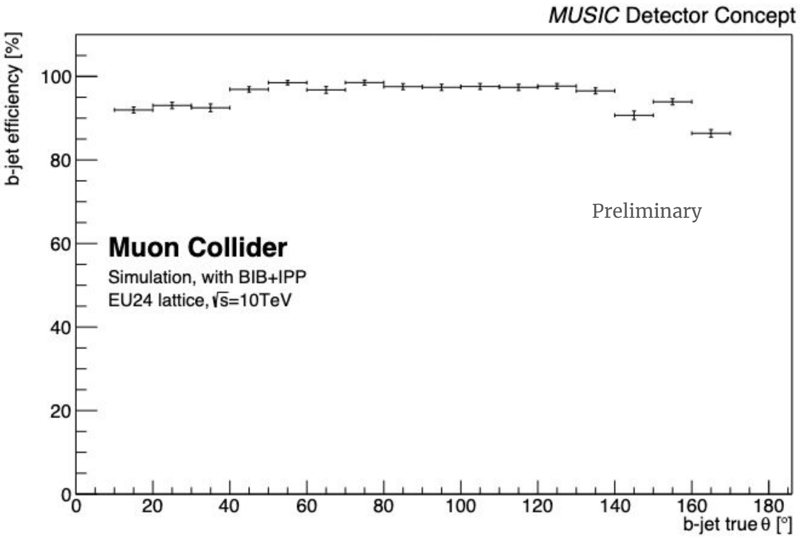




Jet reconstruction

- Jets are reconstructed using tracks and clusters as inputs to **Pandora PFA**
- Samples of b, c and light quarks are used
  - **Quality cuts** are applied to remove fake jets generated by BIB
- Good reconstruction efficiency and resolution similar to 3 TeV case
  - **Room for optimisation** to achieve better energy resolution

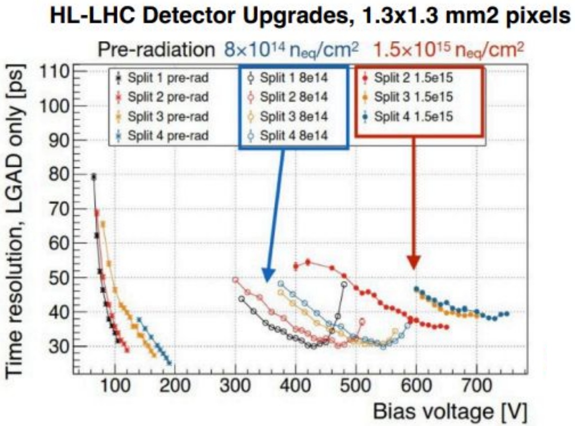




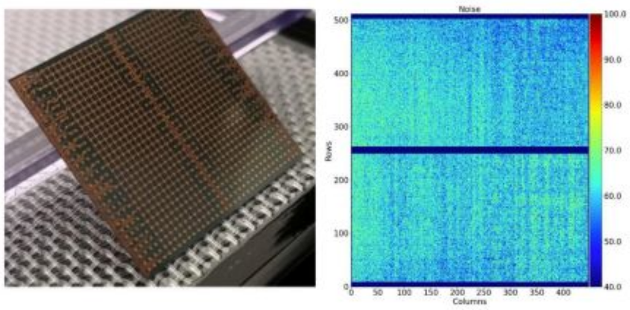
R&D and new technologies: tracker

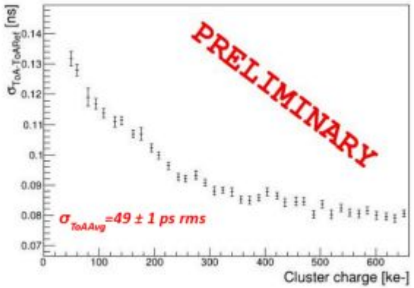
- Same pathway as many other experiments
  - radiation hardness
  - excellent time resolution (~<50 ps)
- R&D on sensors is quite advanced
  - LGAD might soon meet our requirements
  - Monolithic devices is a good option for the future

- ASIC development is a large challenge
  - Demonstrator chips already exist



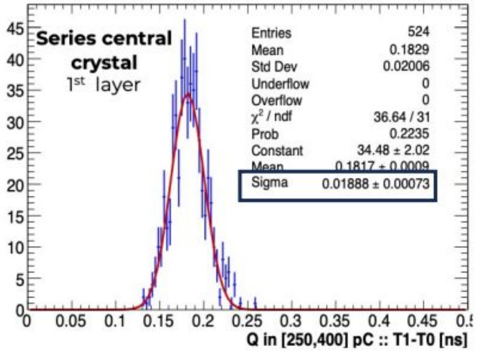
First tests of TSV

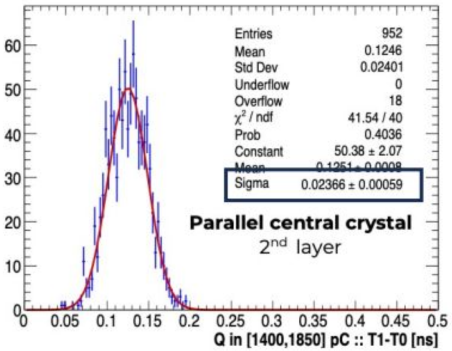




R&D and new technologies: calorimeters

- **CRILIN**: semi-homogeneous PbF_2 calorimeter
  - implemented in DD4HEP
  - meets ECAL requirements

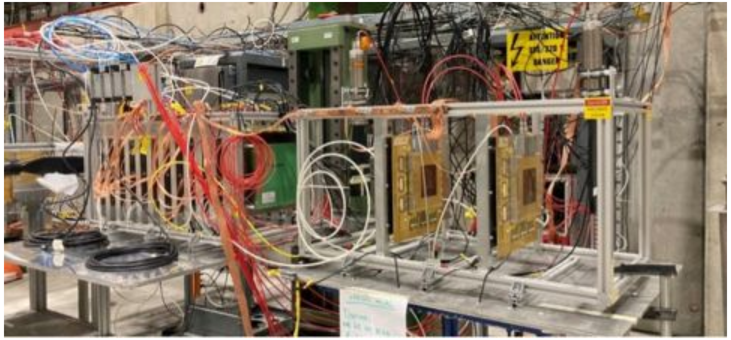




- At 120 GeV, time resolution O(20 ps)
- Testbeams performed at BTF and SPS
- Complete 9x9 cells module under development

see talk by I. Sarra

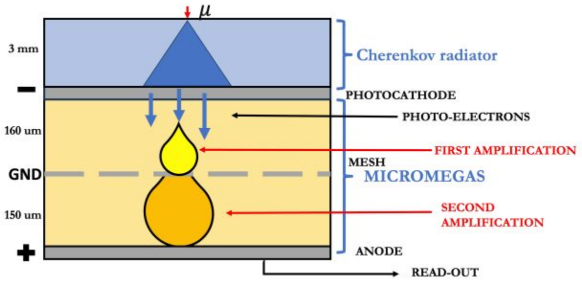
- **Micro-pattern Gas Detectors** read-out layers for HCAL
  - implemented in DD4HEP
  - On-going simulation studies



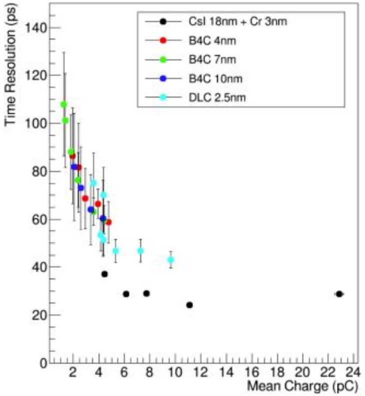
- Testbeam at SPS with high energy muons and at PS with low energy pions
- Future large detectors (50x50 cm^2) and common testbeams with CRILIN

R&D and new technologies: muon system and solenoid

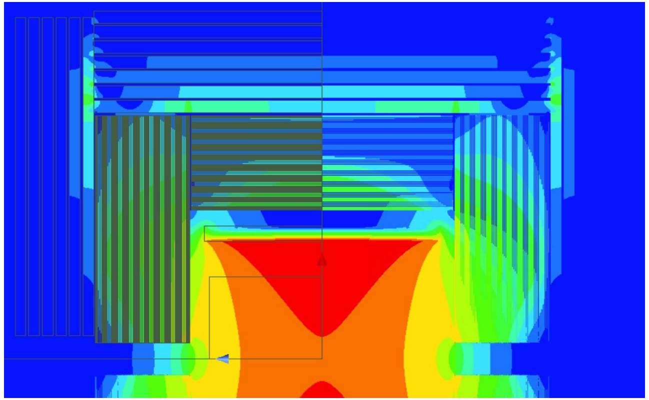
- **Picosec**: MPGD capable of reaching high performance in terms of time resolution (~ O(10) ps)



- Ongoing study aimed at proving the feasibility of bigger Picosec detector and scalability of technology



- Effort to **properly design** the solenoid for the two detector proposals
- **Deep integration** between magnet and detector design is fundamental



- **No technical showstopper** is evident yet, but the cable, which is being investigated

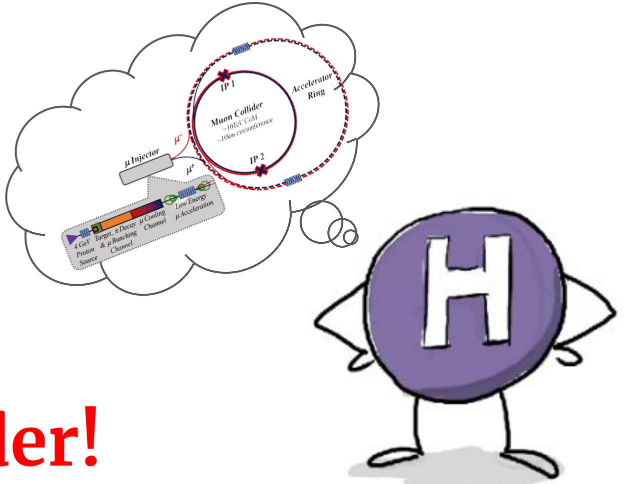
Conclusions

- It’s been a long way since the first detector studies for a Muon Collider

- What have we achieved so far?
  - We managed to tackle the BIB challenge with the 3 TeV detector design
  - We demonstrated the feasibility of physics studies, particularly Higgs physics

- What are we achieving right now?
  - Design of 10 TeV detectors!
  - Several levels of studies:
    - sub-detectors design and new technologies
    - software and algorithm optimisation

- What would we like to achieve?



...build the Muon Collider!


Thank you for
your attention