International
MUON Collider
Collaboration

# IMCC and MuCol MDI workshop 2024
## 11-12 March CERN

MuCol

# Detector design: status, achievements and plans

Donatella Lucchesi University and INFN of Padova,

for the

**Physics and Detector group**

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Università degli Studi di Padova

INFN Istituto Nazionale di Fisica Nucleare

# Detector design and performance highly influenced by MDI

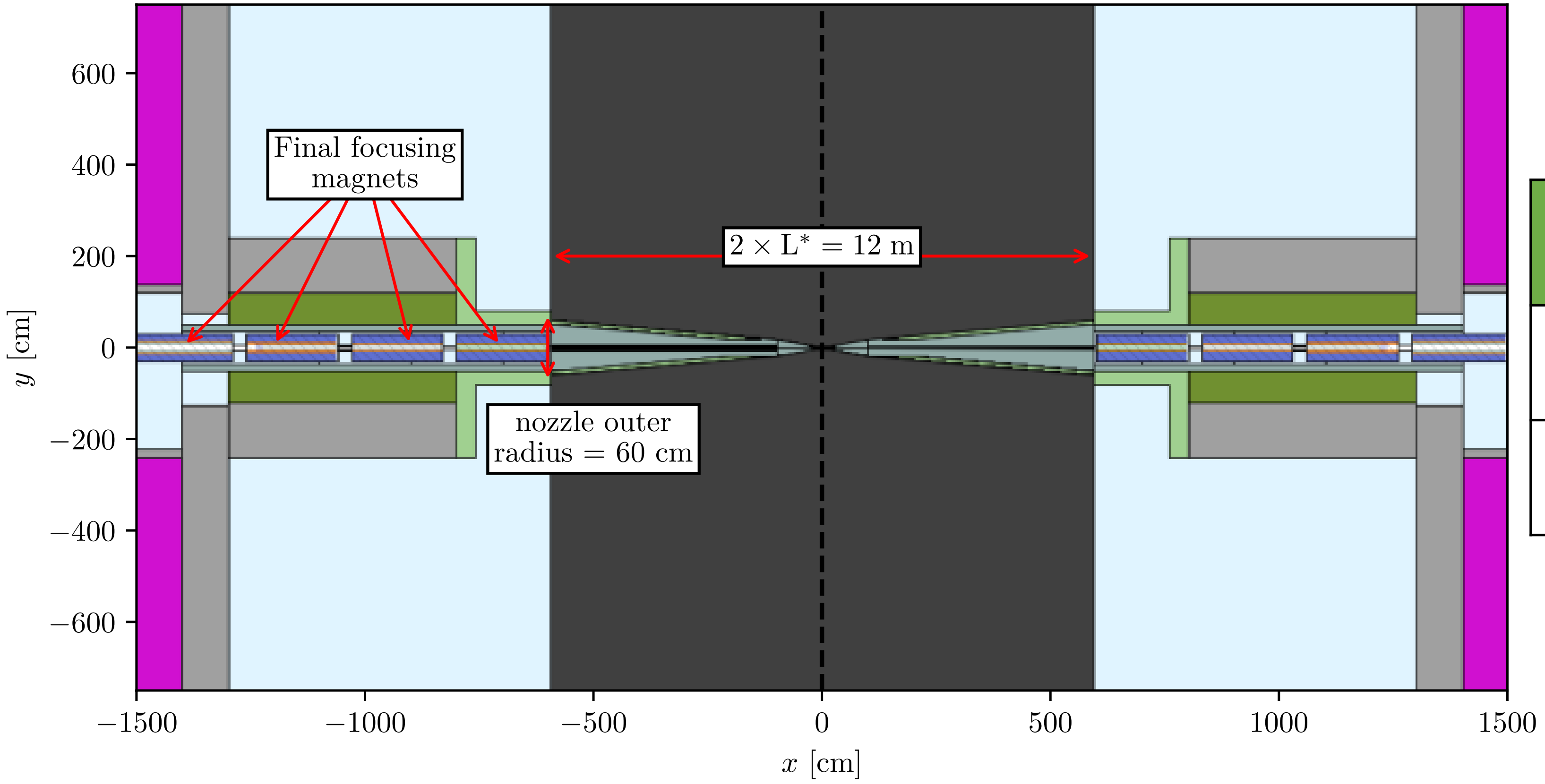
- ✗ Interaction region configuration
  - ❈ Dimensions
  - ❈ Nozzles
- ✗ Beam-induced background
  - ❈ Kinematical and time distributions

When MDI is defined and optimized, detector technologies enter the game to optimize the performance.

# Collider interaction region

Longitudinal size of the detector determined by position of final focusing magnets.
it would be very difficult from the the lattice point of view to have more than $\pm 6$ m

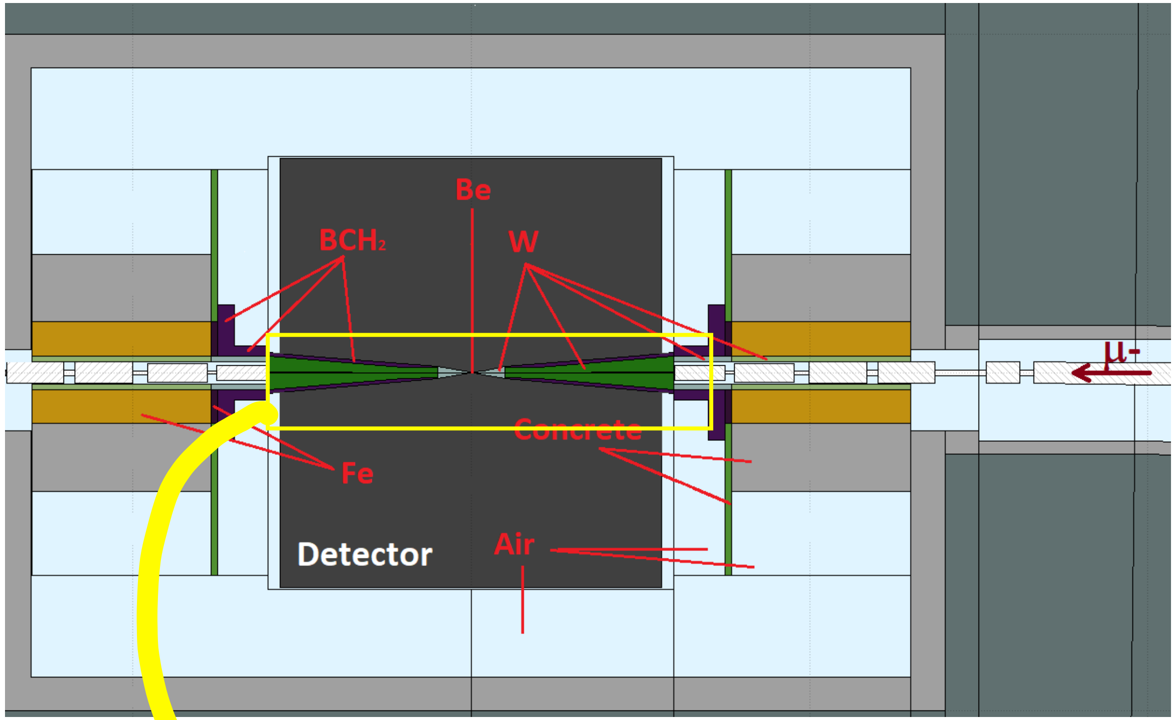
C. Carli, A. Lechner, **D. Calzolari**, K. Skoufaris




| | LHC | MC $\sqrt{S} = 10$ TeV |
|---|---|---|
| bunch length $\sigma_z$ | 7.7 cm | 1.5 mm |
| bunch size $\sigma_\perp$ | 16.7 $\mu m$ | 0.9 $\mu m$ |

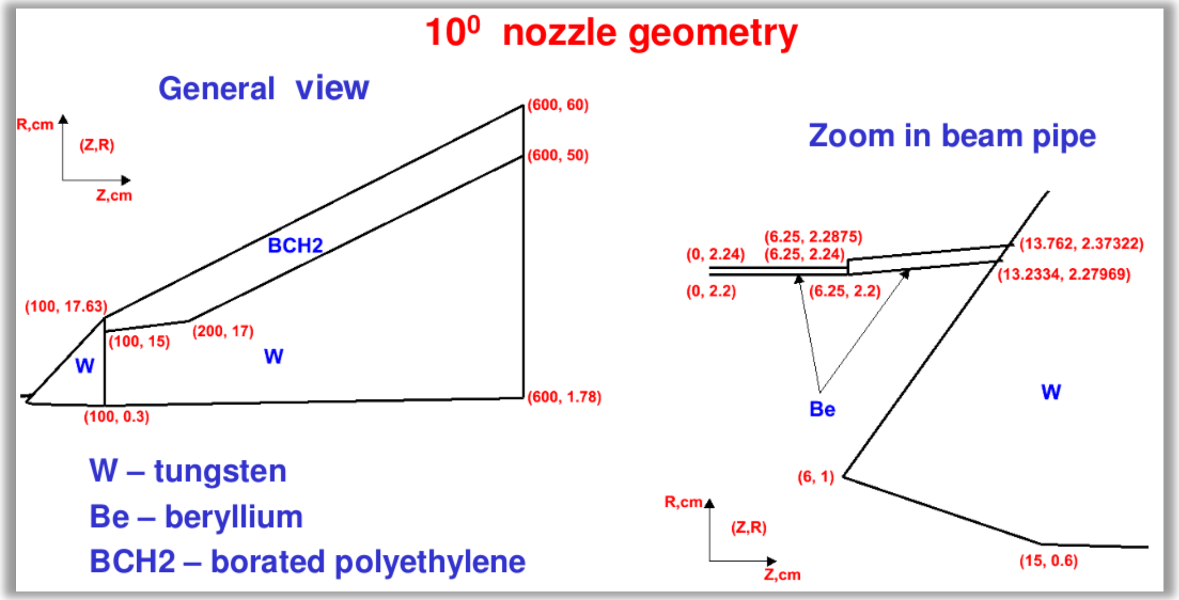
Single bunch mode

# Shielding structure: the nozzles



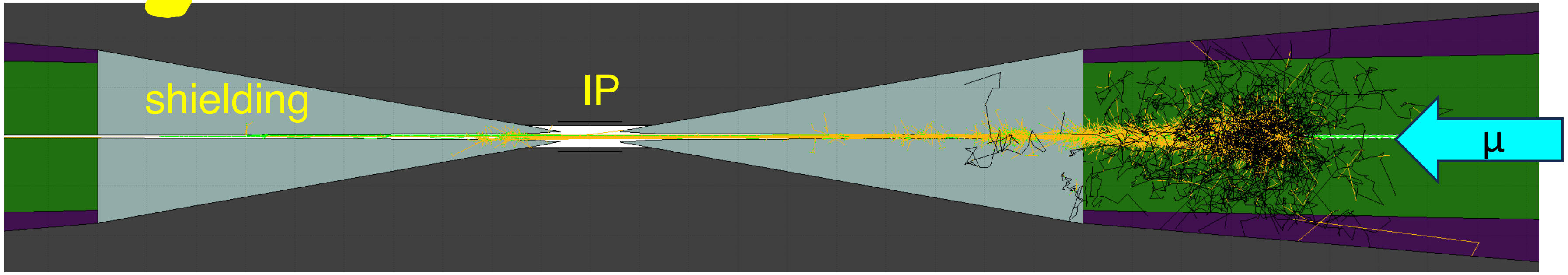

Designed by MAP (Muon Accelerator Program)

N.V. Mokhov et al. *Muon collider interaction region and machine-detector interface design* Fermilab-Conf-11-094-APC-TD




Optimized for $\sqrt{s} = 1.5$ TeV

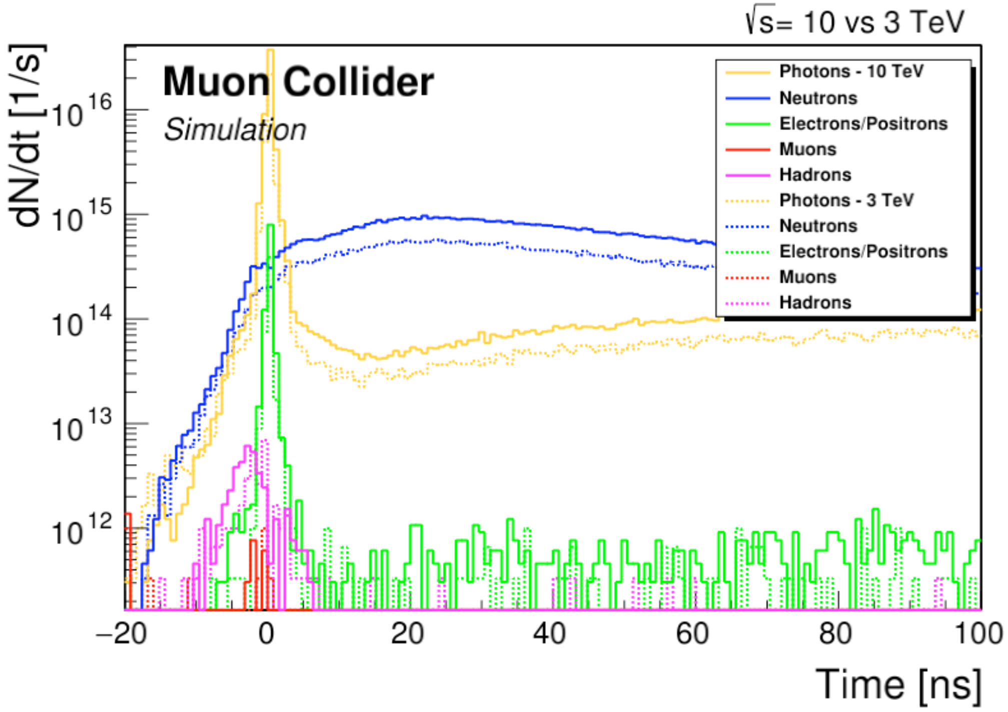
F. Collamati et al. 2021 JINST 16 P11009



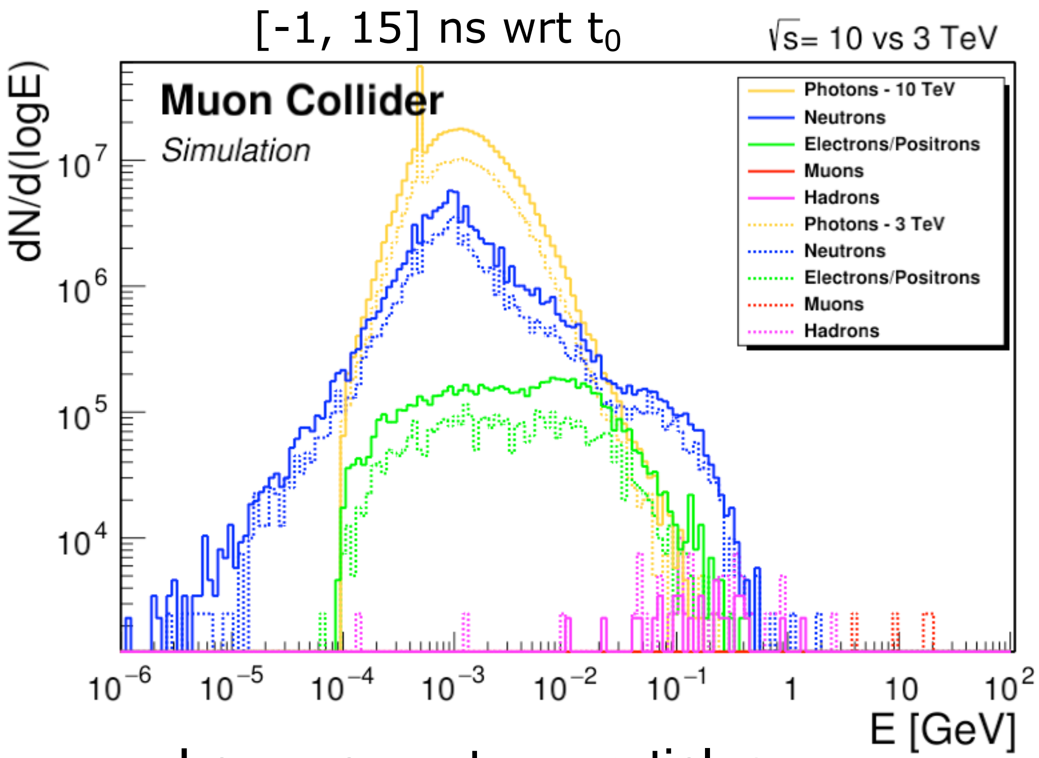

Single muon decay tracks

$N_\mu^\pm \sim 2x10^{12}$/bunch

# Beam-Induced background properties




Partially out of time vs beam crossing




Low momentum particles

- Use the same nozzle structure of $\sqrt{s} = 1.5$ TeV ⟹ optimization for $\sqrt{s} = 3$ TeV (L. Castelli) and $\sqrt{s} = 10$ TeV (D. Calzolari) in progress.
- Fluxes at $\sqrt{s} = 3$ and $\sqrt{s} = 10$ TeV quite similar ⟹ beam-induced background characteristics determined by the nozzles.

# First detector concept at $\sqrt{s} = 3$ TeV

Modified CLIC"s detector concept:

- Removed forward luminosity detectors
- Inserted nozzles
- Adapted tracker detector
- Magnetic field modified to cope with available beam-induced background

**hadronic calorimeter**

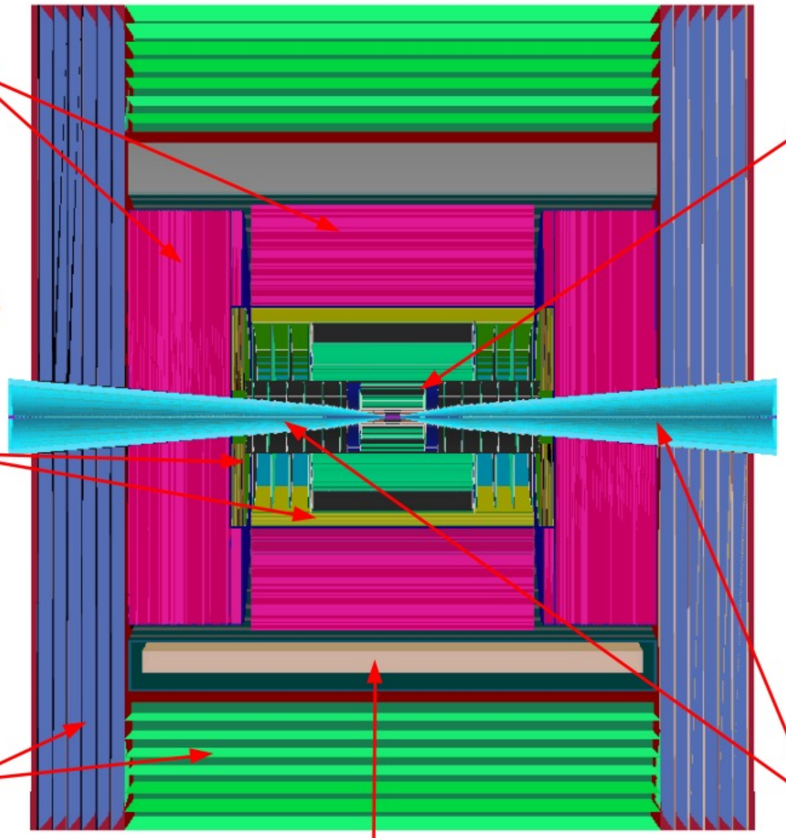
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 $mm^2$ cell size;
- 7.5 $\lambda_I$.

**electromagnetic calorimeter**

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 $mm^2$ cell granularity;
- 22 $X_0$ + 1 $\lambda_I$.

**muon detectors**

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 $mm^2$ cell size.



superconducting solenoid (3.57T)

**tracking system**

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 $\mu m^2$ pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

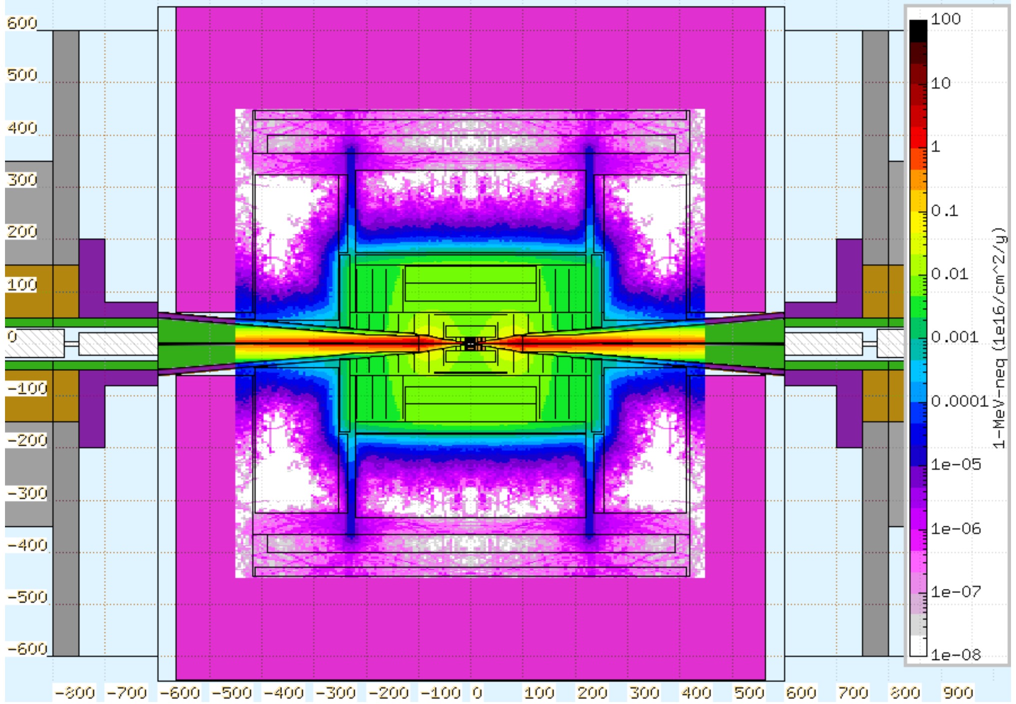
**shielding nozzles**

- Tungsten cones + borated polyethylene cladding.

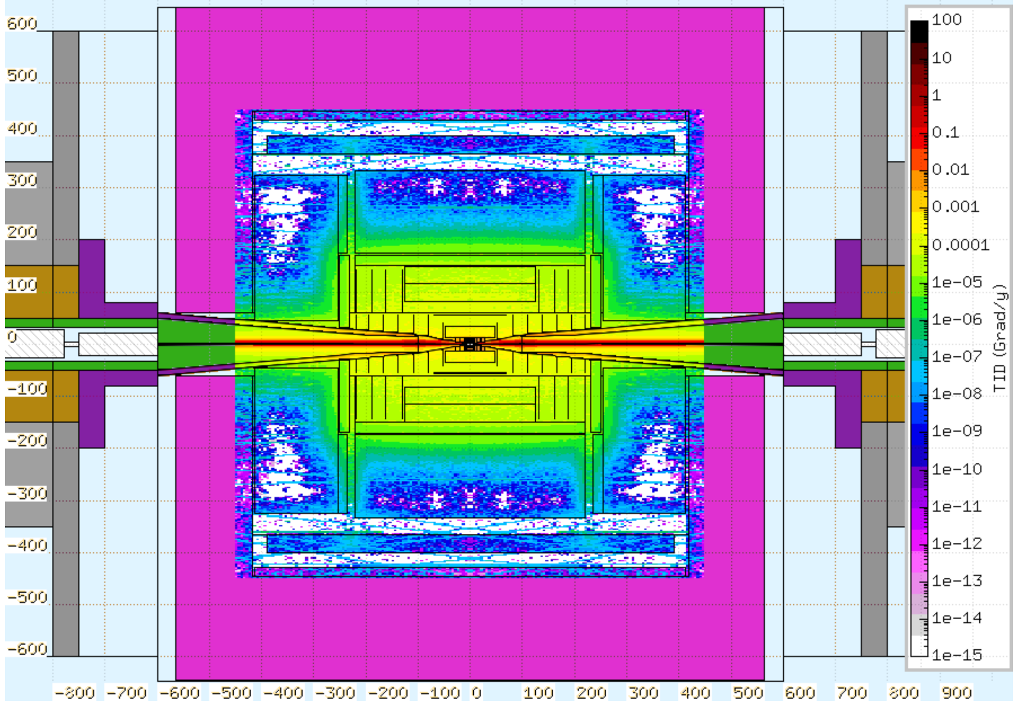
C. Accettura et al. "Towards a muon collider"
CLIC: H. Abramowicz et al., Eur. Phys. J. C 77, 475 (2017)

# Radiation environment

## 1-MeV neutron equivalent fluence per year




## Total ionizing dose per year




Assumptions:

- Collision energy 1.5 TeV
- Collider circumference 2.5 km
- Beam injection frequency 5Hz
- Days of operation/year 200

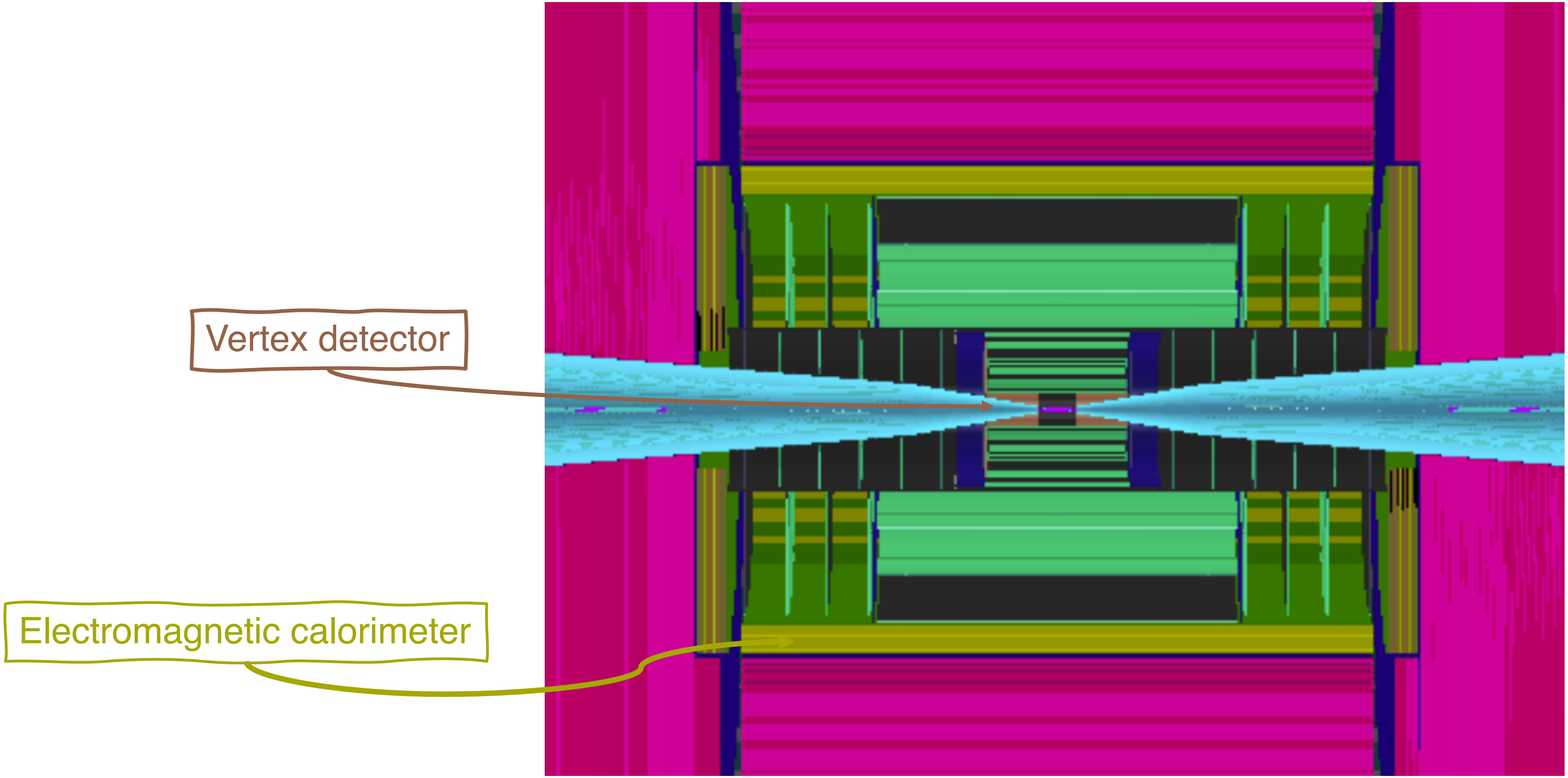
Expected Radiation hardness requirements like HL-LHC

| | 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 | $10^{15}$ | $10^{13}$ |

K. Black, Muon Collider Forum Report

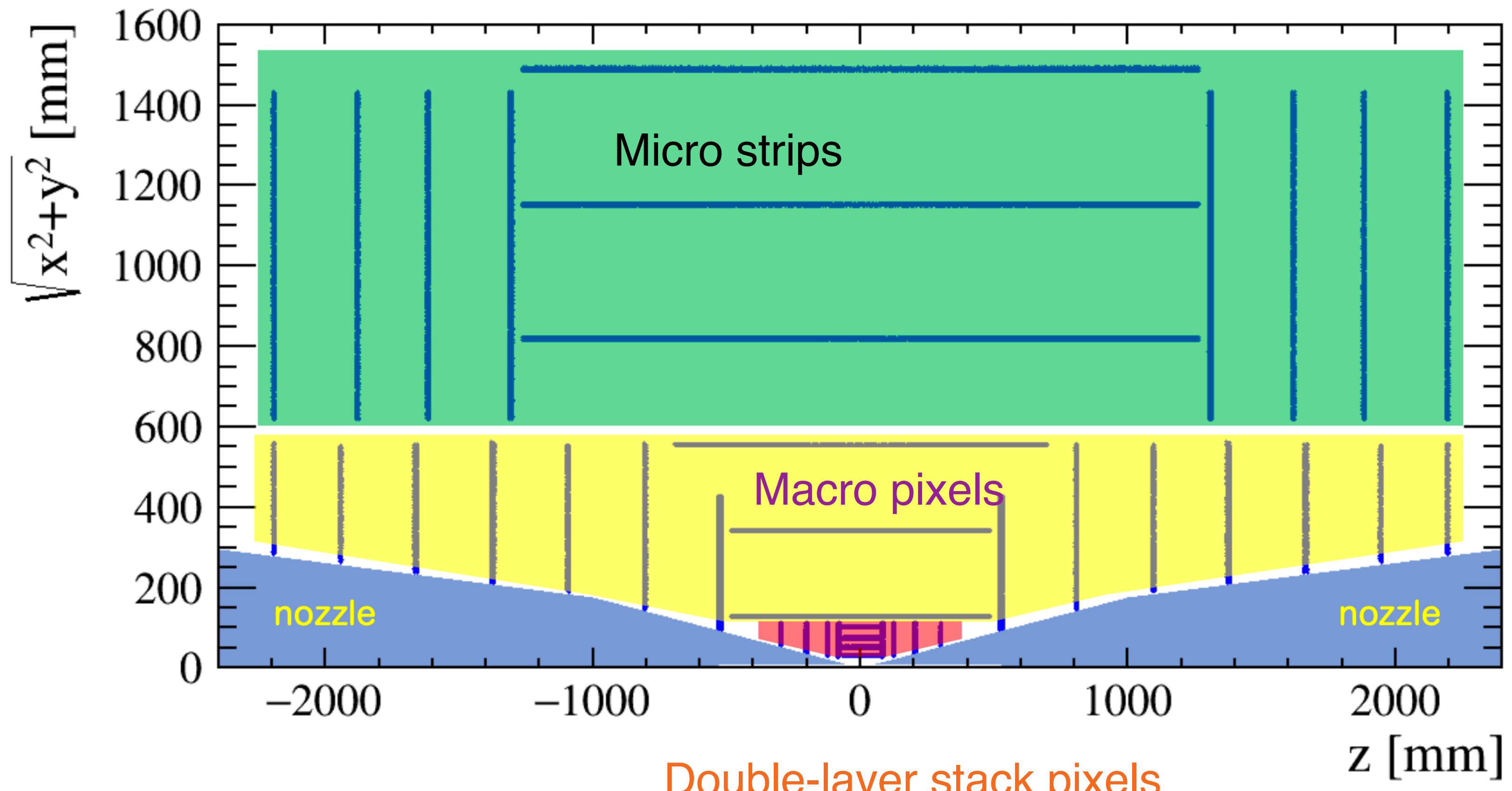
$\sqrt{S} = 3$ TeV and $\sqrt{S} = 10$ TeV similar values expected ⇒ dominated by BIB

# Beam-induced background impacts mainly few sub-detectors

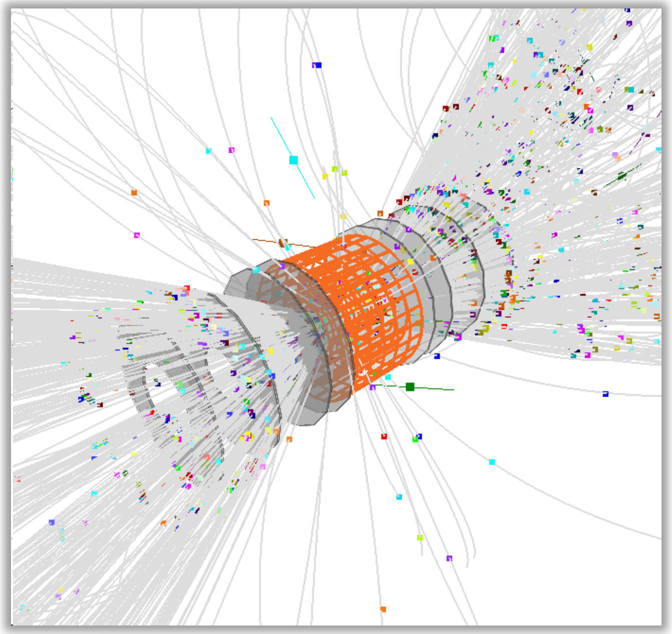


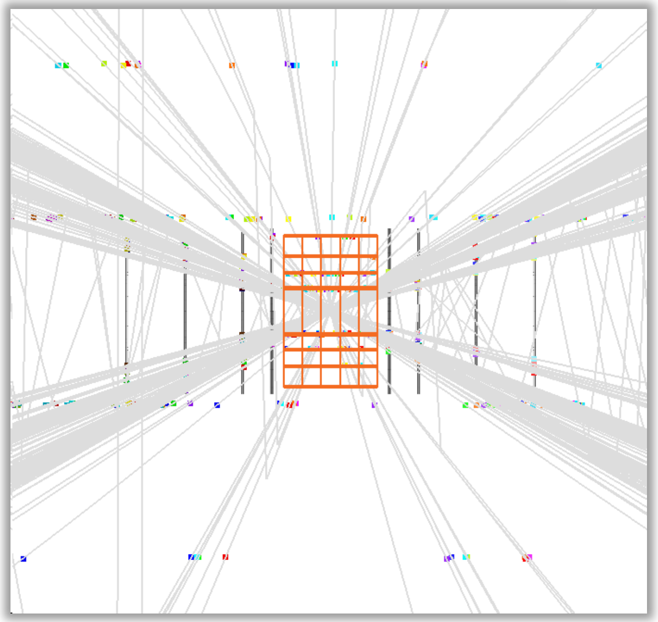
# Tracking system

First layers of barrel vertex detector & forward disks highly impacted BIB




Double-layer stack pixels



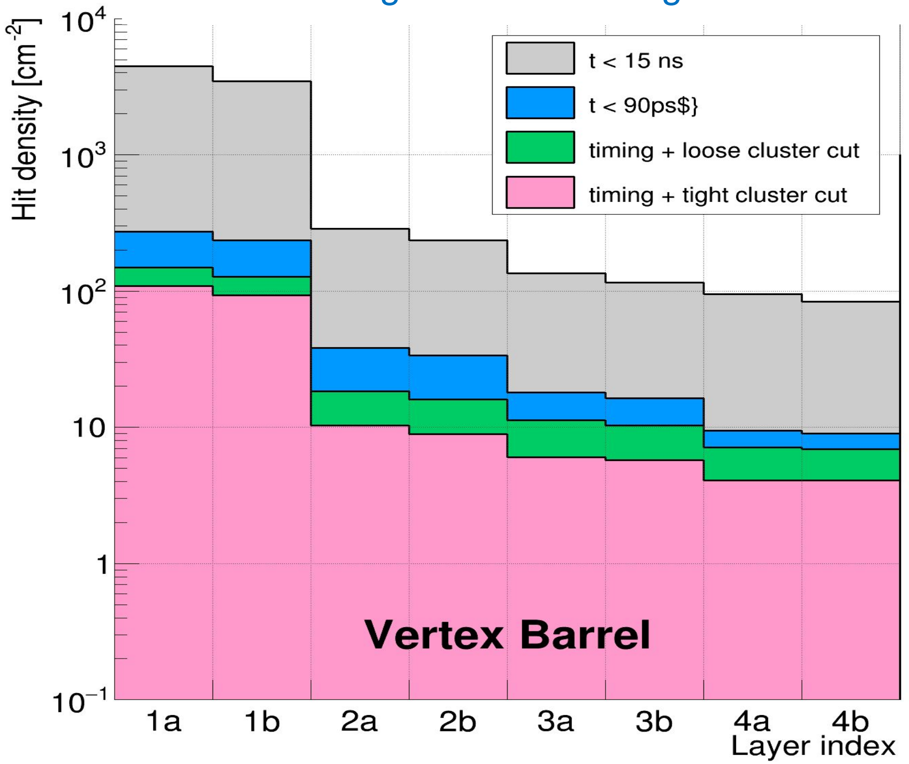


# Tracker requirements

Vertex requirements

- High time determination resolution, ~ 20-30 ps to suppress out of time BIB.
- High granularity with energy deposition measurement to exploit different cluster shapes.
- Double layers to apply when possible directional filtering.

S. Pagan Griso C. Sellgren

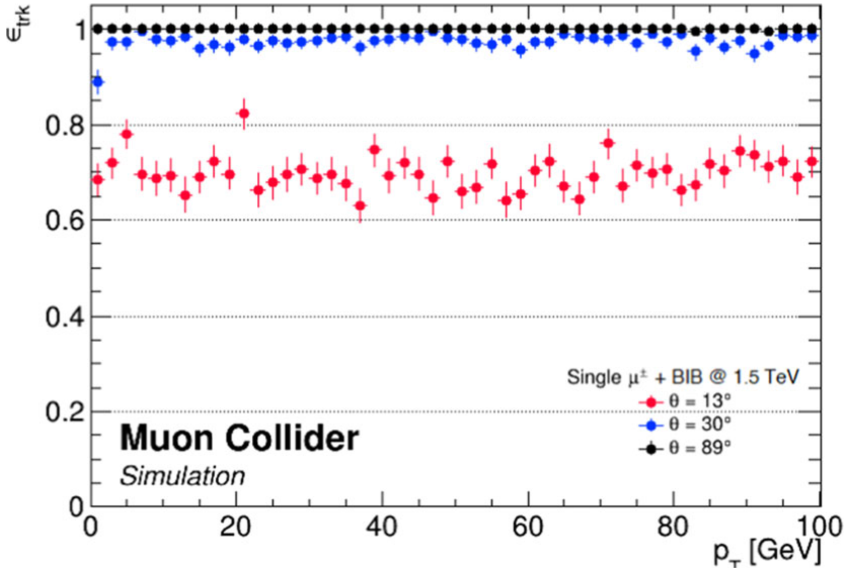


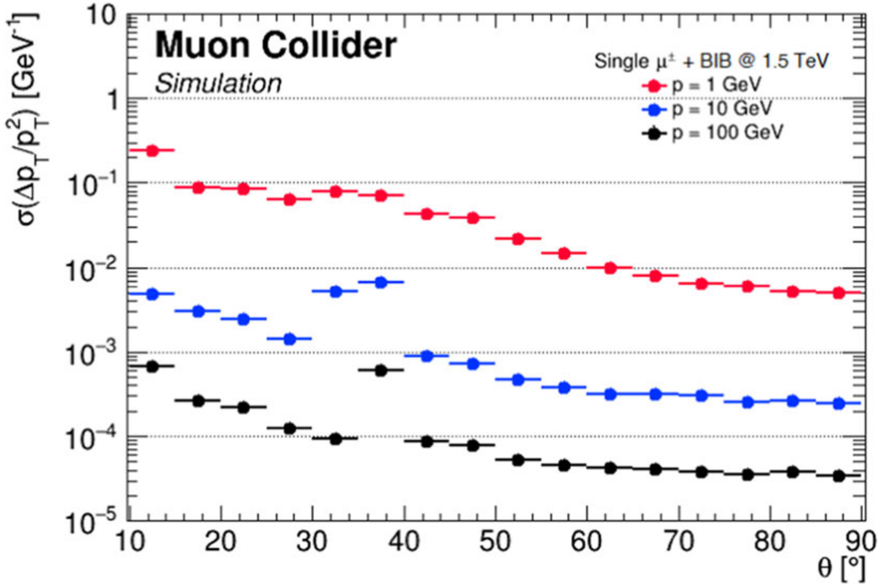

Higher occupancies with respect to LHC detectors crossing rate 100 kHz vs 40 MHz

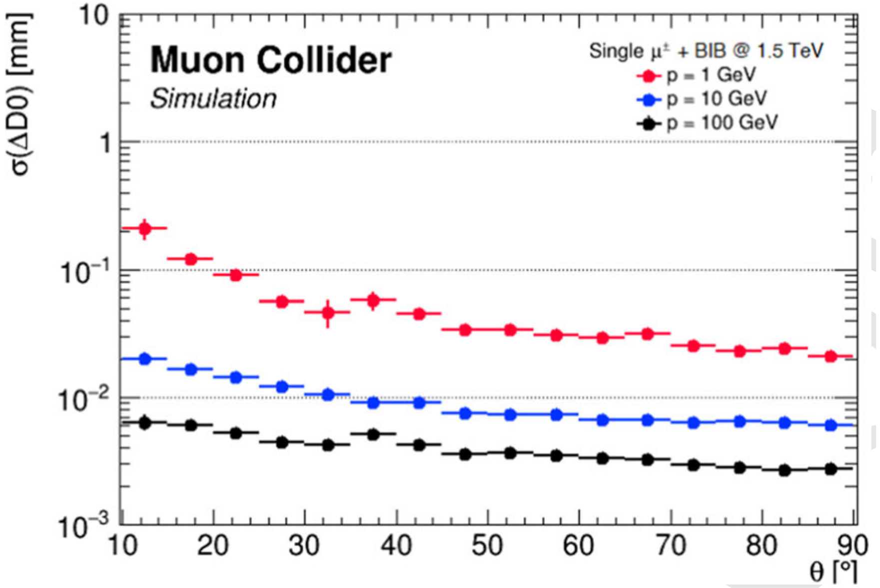
Fully engaged in ECFA DRD and US CPAD silicon tracker

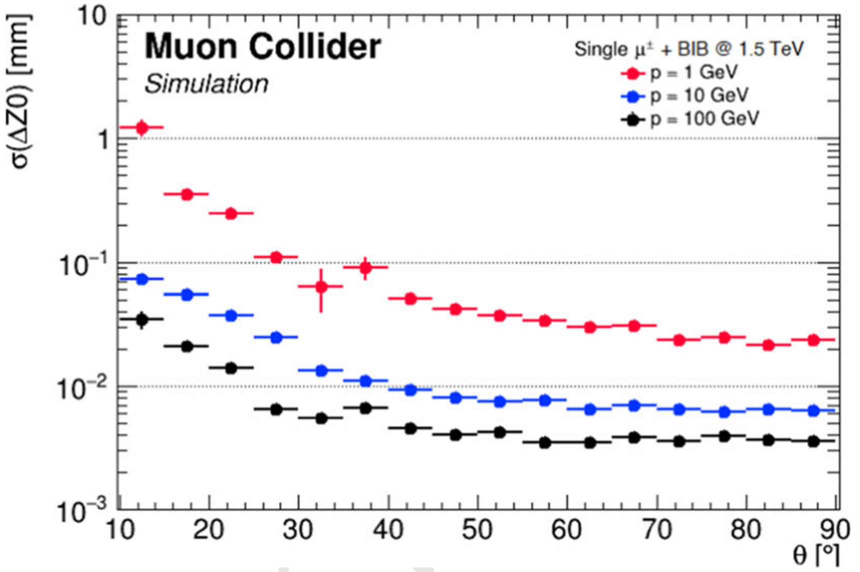
| Detector reference | Hit density [mm$^{-2}$] | | |
|---|---|---|---|
| | MCD | ATLAS ITk | ALICE ITS3 |
| Pixel Layer 0 | 3.68 | 0.643 | 0.85 |
| Pixel Layer 1 | 0.51 | 0.022 | 0.51 |

# Track reconstruction performance

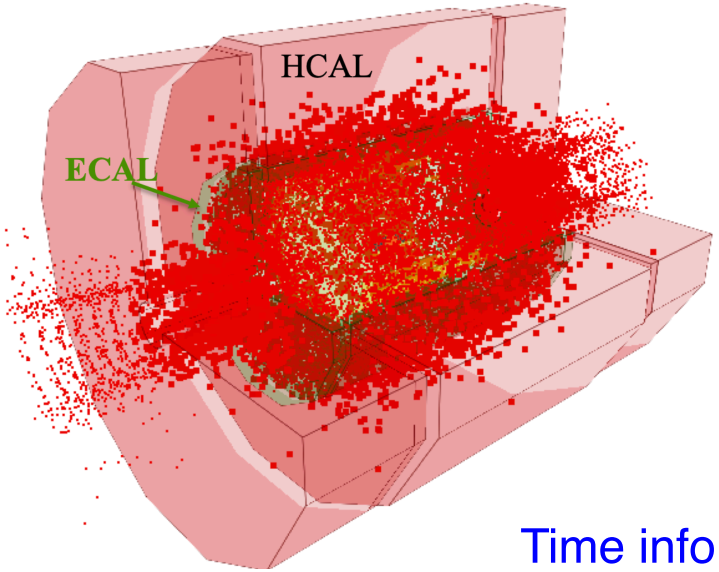


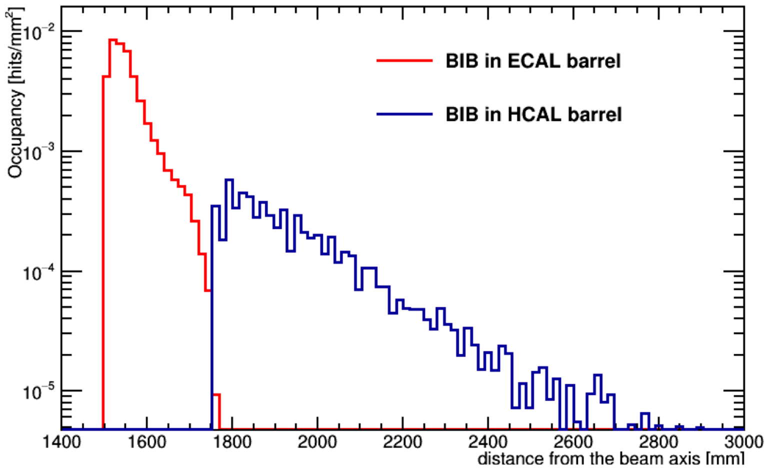
# Calorimeter system



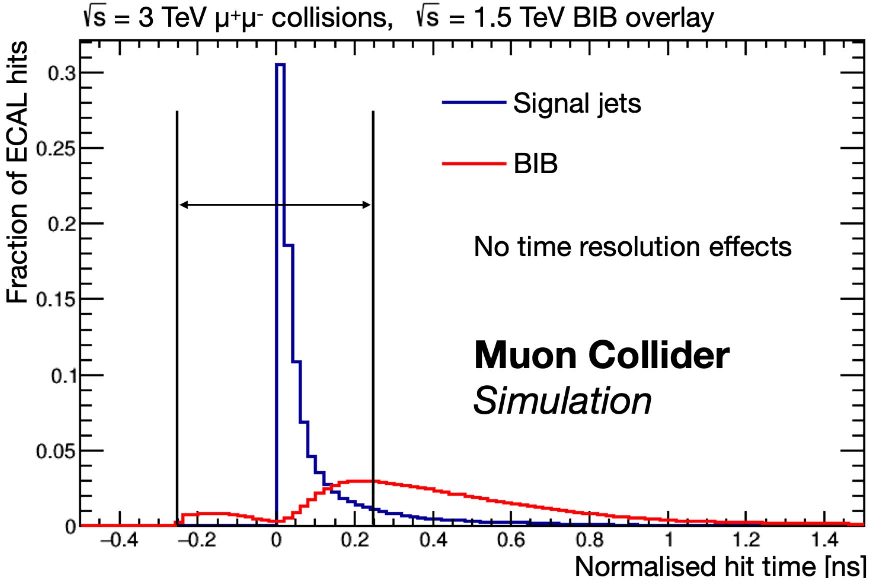

ECAL surface flux: 300 particle/cm$^2$

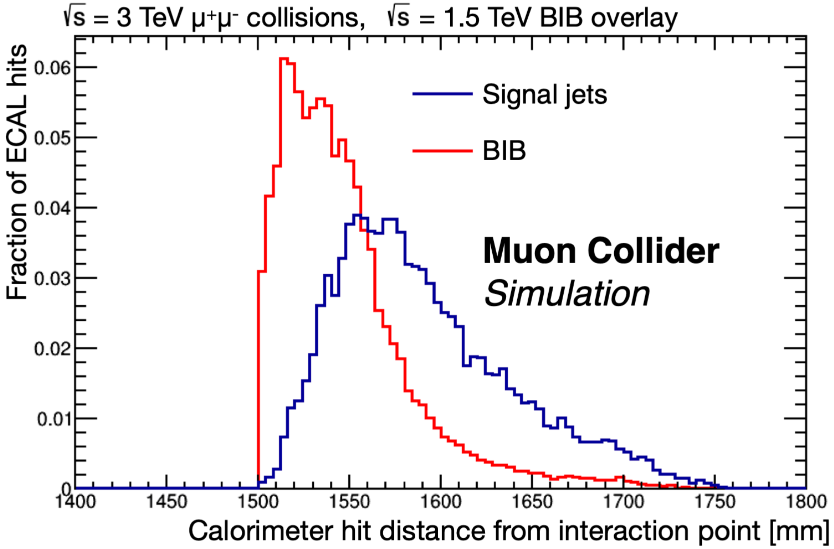
- 96% photons, 4% neutrons
- $E_{\gamma}^{Ave.} \sim 1.7$ MeV

Occupancy: ECAL > 10 times HCAL




Time information




Cluster shape

# Electromagnetic calorimeter requirements

## Calorimeter requirements

- Time-of-arrival of hit resolution ~100 ps to reject out-of-time particles.
- Adequate longitudinal segmentation to exploit different shower profiles between signal and beam-induced background.
- High granularity to avoid as much as possible overlap of signal and beam-induced background particles in the same cell.

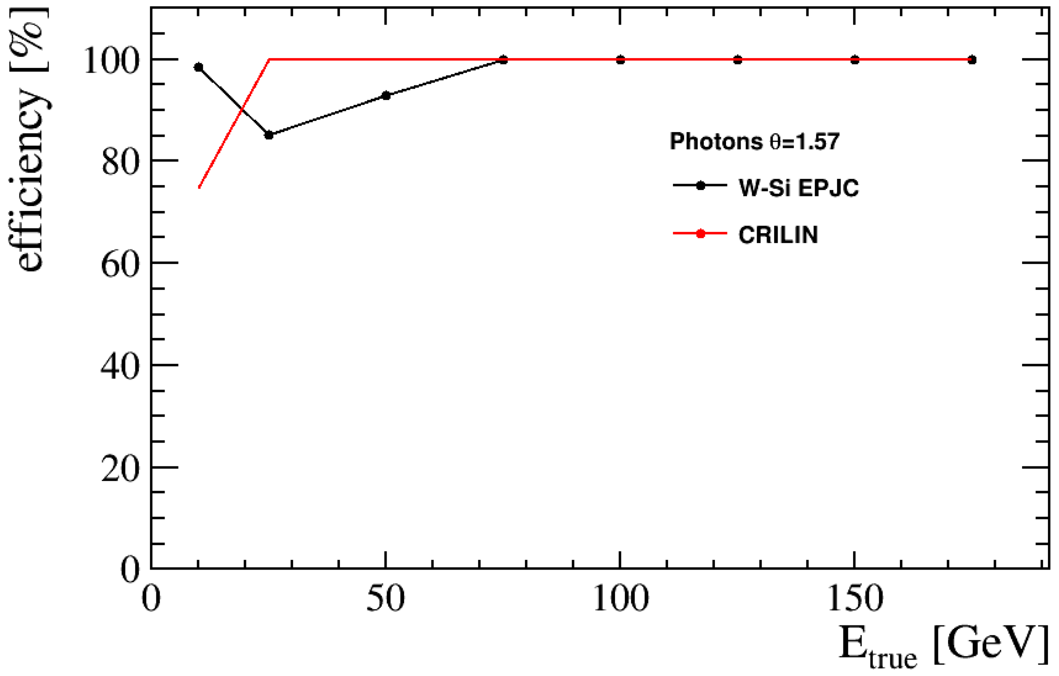
Dedicated ECAL R&D: **Crilin** semi-homogeneous calorimeter. It could reduce energy fluctuations helping in beam-induced background mitigation.
Each module: 5 layers of $PbF_2$ crystals ($10x10x40$ $mm^3$) Cerenkov light detected with SiPMs

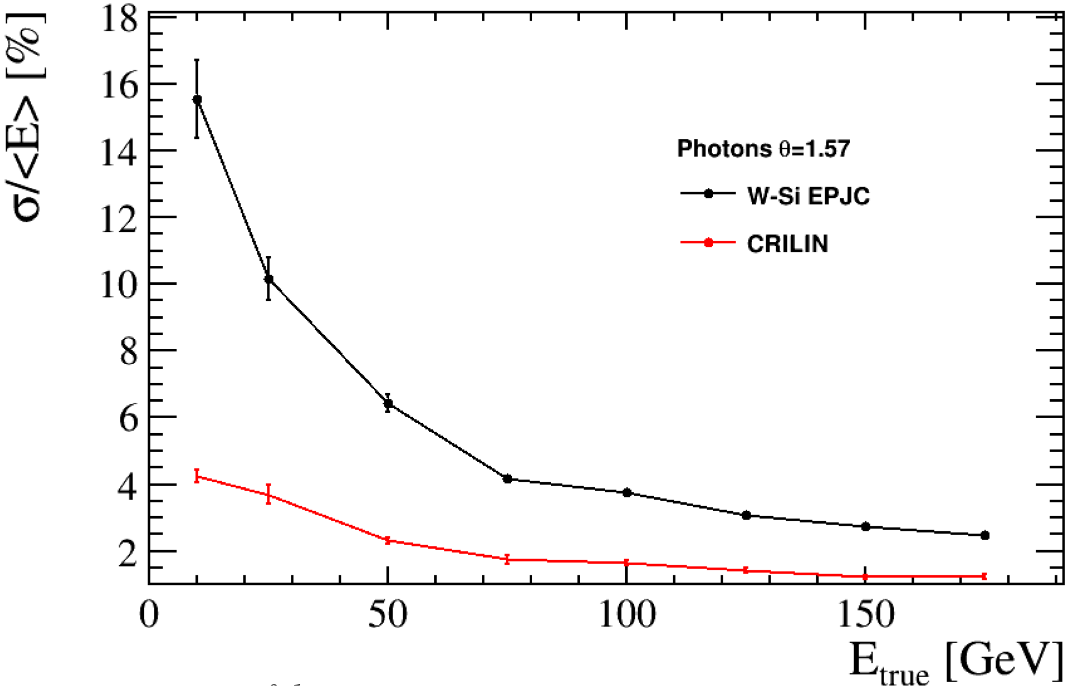
Dedicated HCAL proposal in progress.

# Photons reconstruction   See Lorenzo's presentation

CRILIN reconstruction optimized for MuC, no optimization for W-Si, not performance comparison!

- Dedicated BIB treatment in CRILIN
- Threshold 2 MeV applied to W-Si




$N^{fake}_{CRILIN} \simeq 0$   $N^{fake}_{W-Si} \simeq 60$

Jet & electrons reconstruction with CRILIN in progress

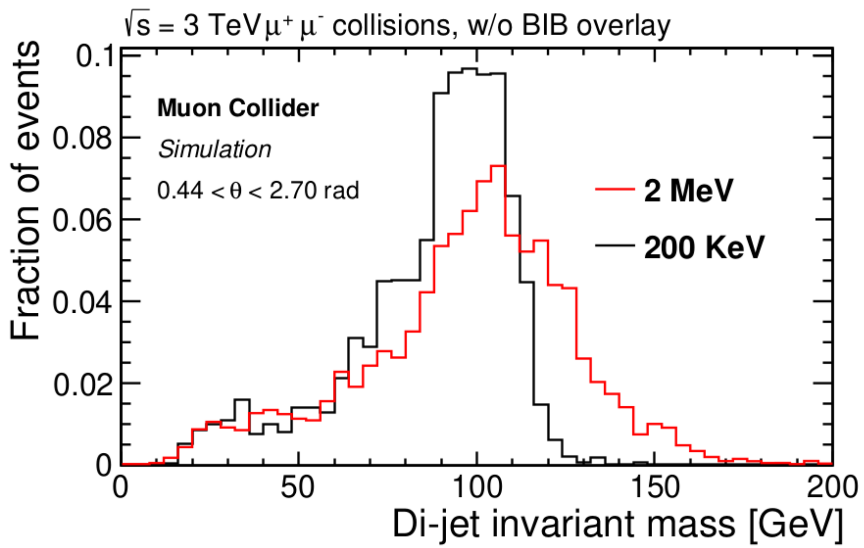
# Jets reconstruction performance

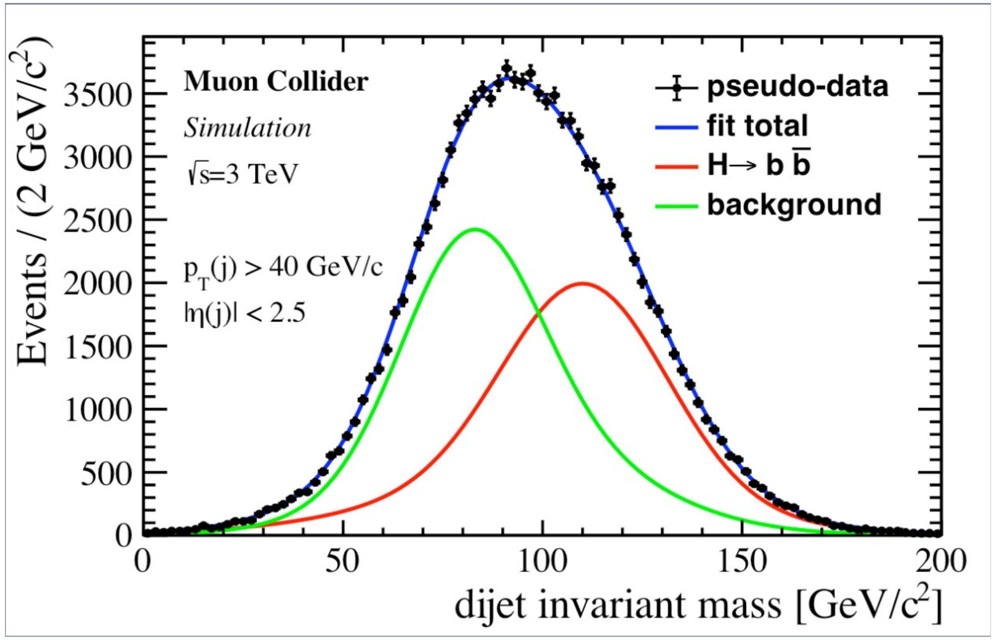
## Jet reconstruction:

- $E_{th} \geq 2$ MeV EM calorimeter cells to mitigate BIB effect
- efficiency: $80 \div 90\%$
- Negligible fake rate

## b-jet identification:

- Simple algorithm, secondary vertex
- Efficiency:45% (20 GeV) 70% (120 GeV)
- c-jet mis-identification ~20%
- light jets mis-identification few %

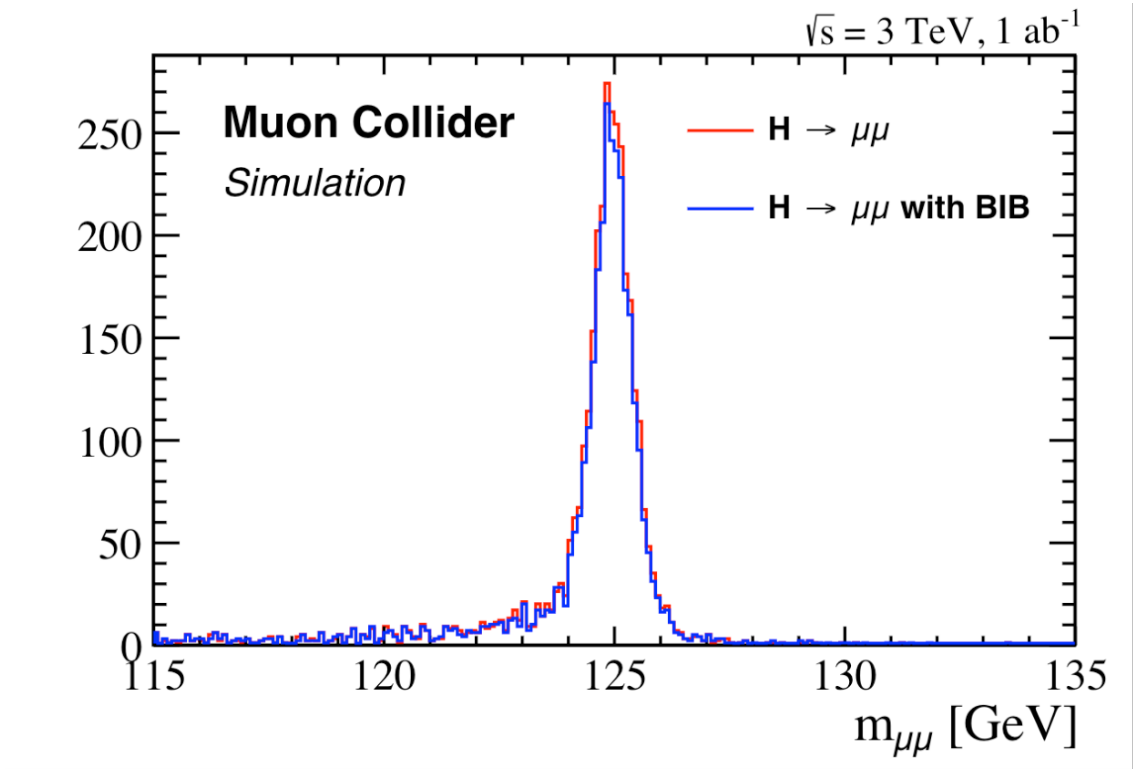


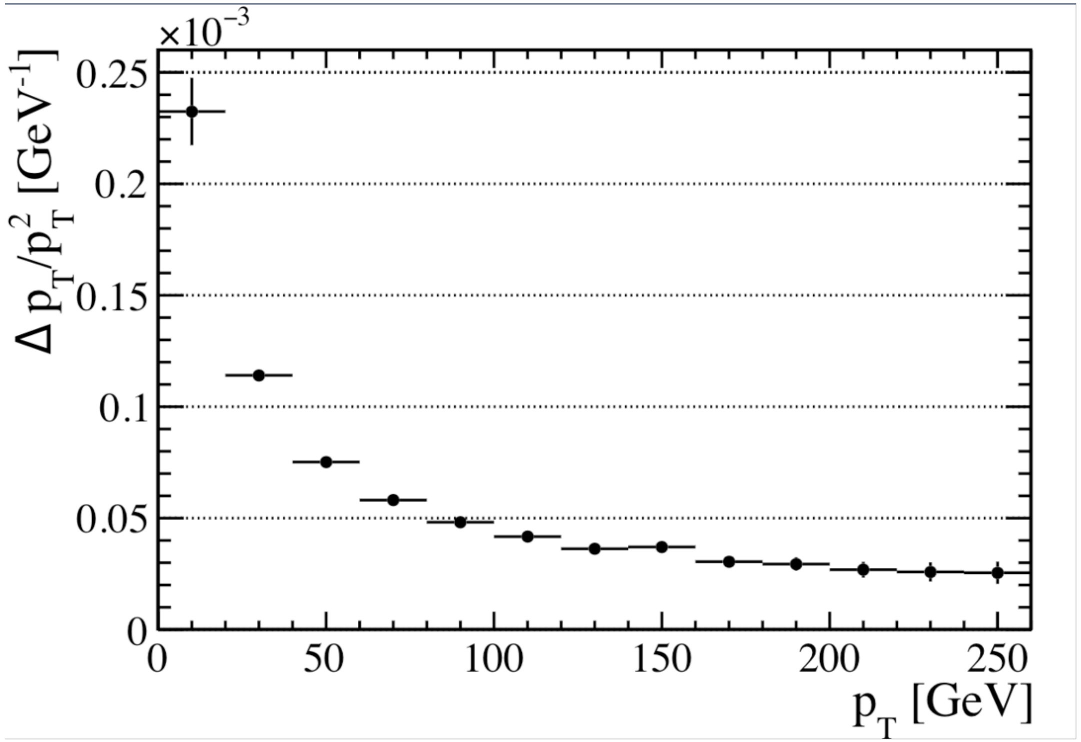




Invariant mass resolution: 18%

# Muon reconstruction

Muons in the barrel (central) are not affected by beam-induced background



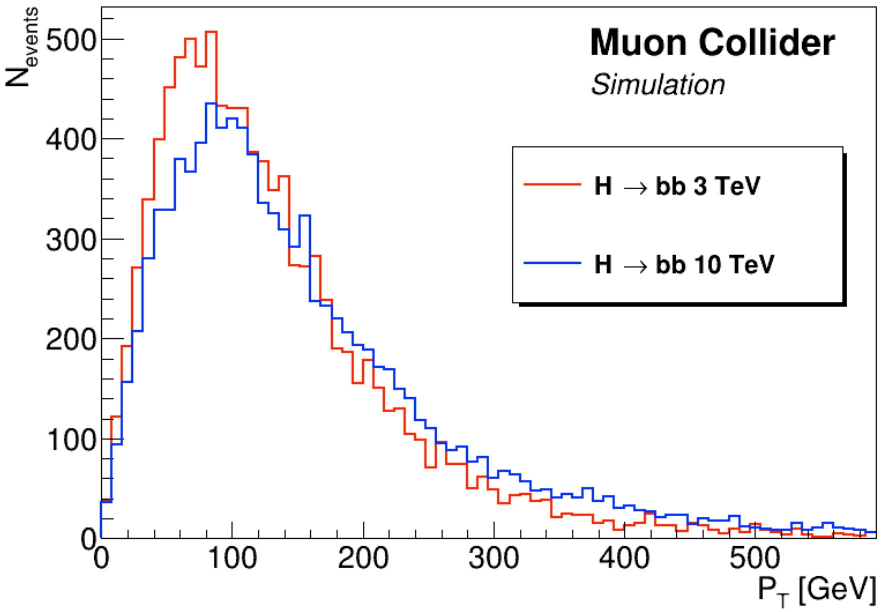



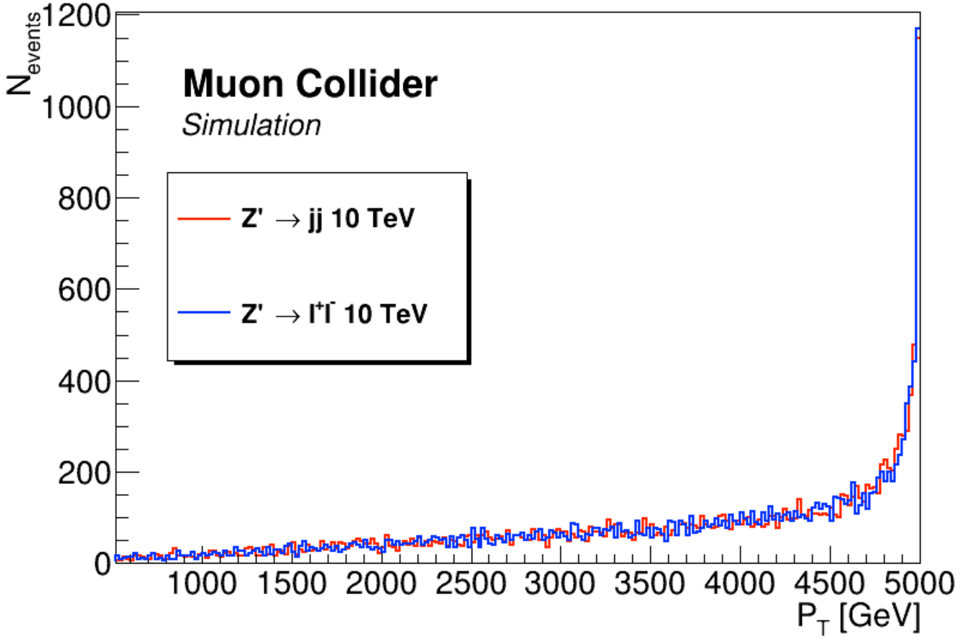

Summary of detector performance at 3 TeV center-of-mass energy in Massimo's talk tomorrow

# Detector concept at $\sqrt{S} = 10$ TeV

Detector must be designed to have high performance for :

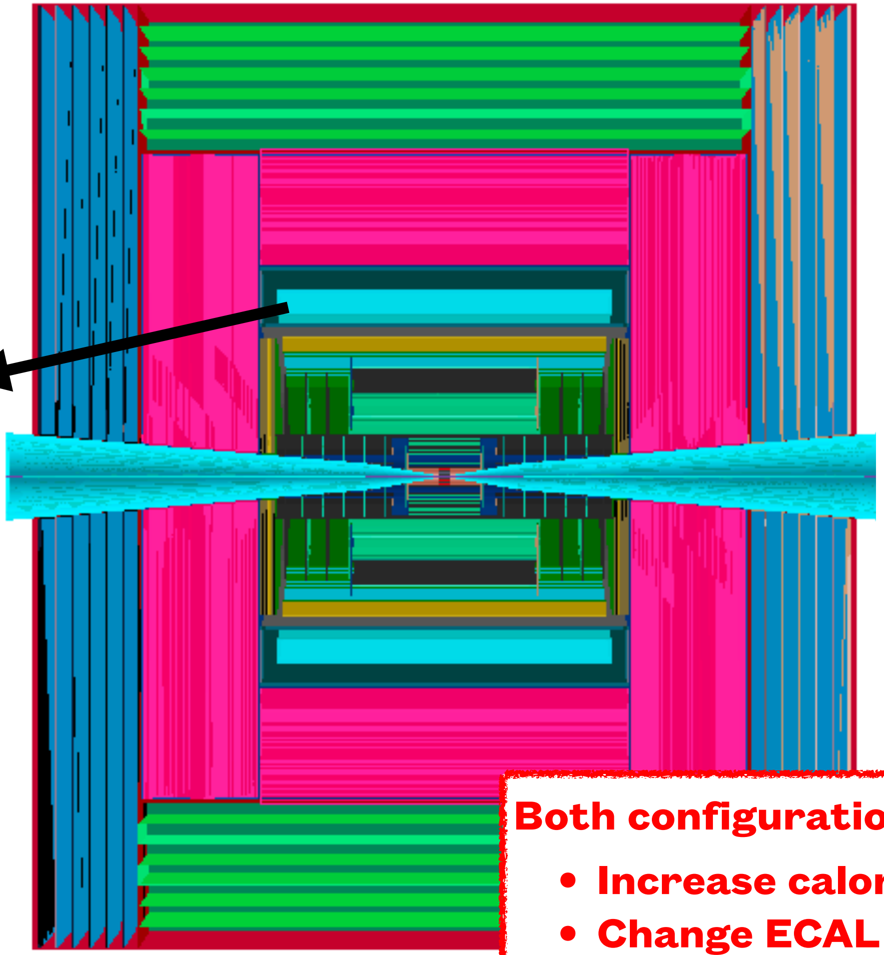
- Low energy physics: electroweak processes, Higgs
- High energy phenomena: $Z'$ with high masses
- Unconventional signatures: disappearing track, emerging jets,…

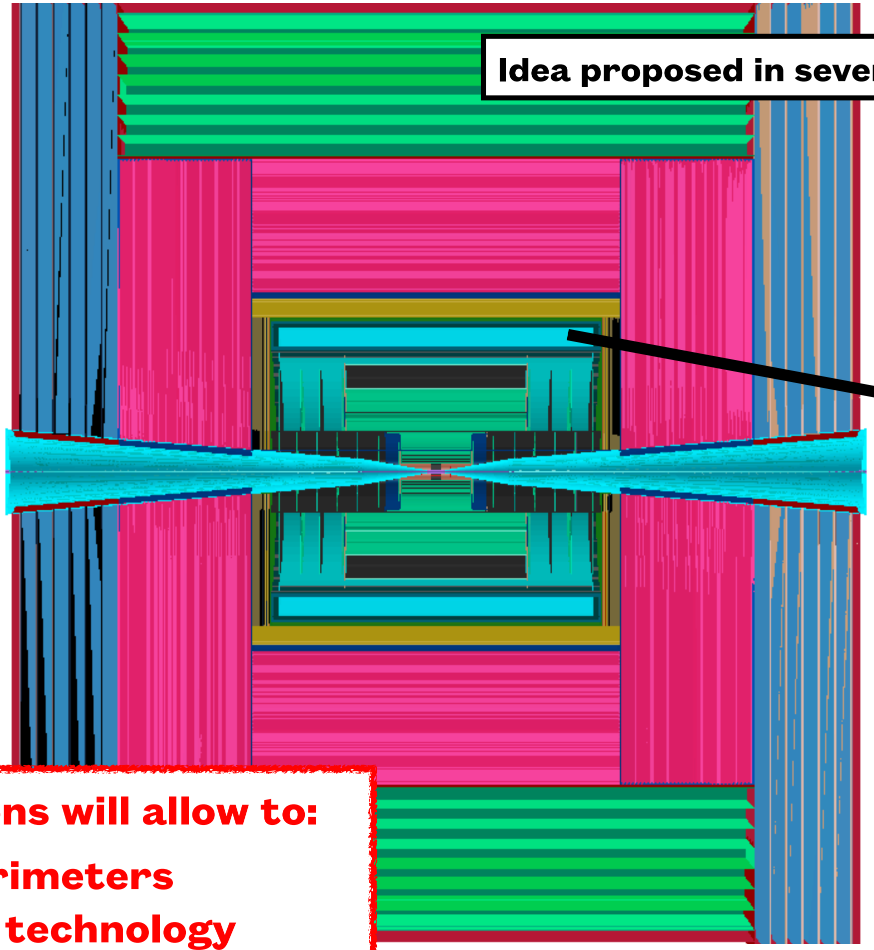


# Detector concept at $\sqrt{S} = 10$ TeV

See P&D presentation by Davide



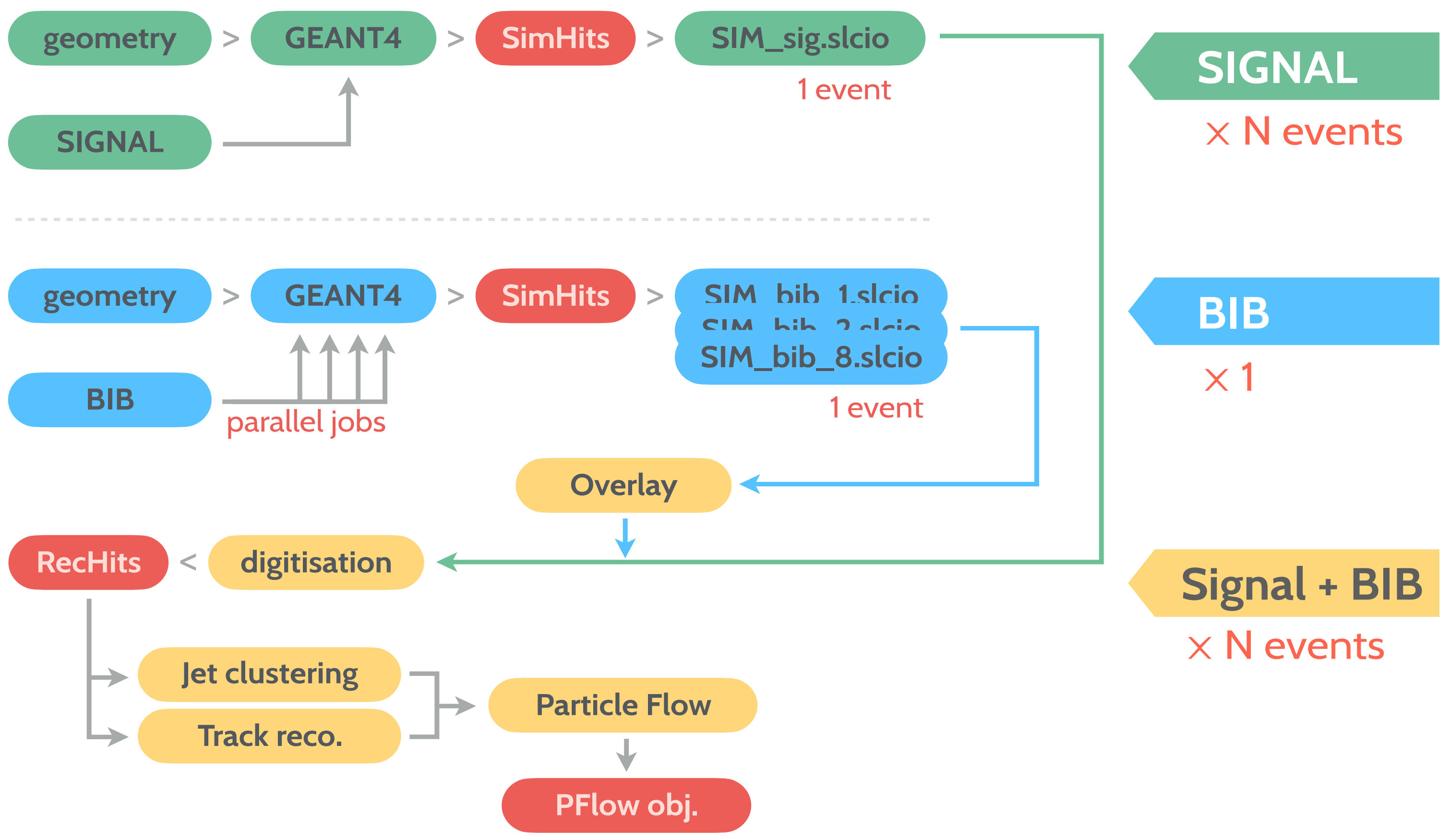

**Both configurations will allow to:**

- **Increase calorimeters**
- **Change ECAL technology**
- **Increase tracker**

Description of detector design at 10 TeV center-of-mass energy at Annual Meeting tomorrow

# Software and Computing

MuC software workflow




Software infrastructure currently supported and maintained by 2 INFN computing experts

Computing resources
- CPU: provided by INFN and CERN
- storage: 600 TB at INFN sites and 100 TB at CERN

# Next steps in detectors design

First step in detectors design has been made with the “old”, MAP, version of the nozzle.

a) Next steps would require an optimized, or at least appropriated, configuration of the nozzles for each center-of mass energy. This means:
   - Nozzles definition
   - Beam-induced background validation in the current version of the detectors
   - Sizeable beam-induced background statistics

b) Path of detector study with frozen nozzles configuration:
   1. Simulation of beam-induced background in the detector
   2. Tuning of sub-detector configuration by looking at occupancies
   3. Reconstruction of major physics objects tuning algorithms to minimize beam-induce background impact

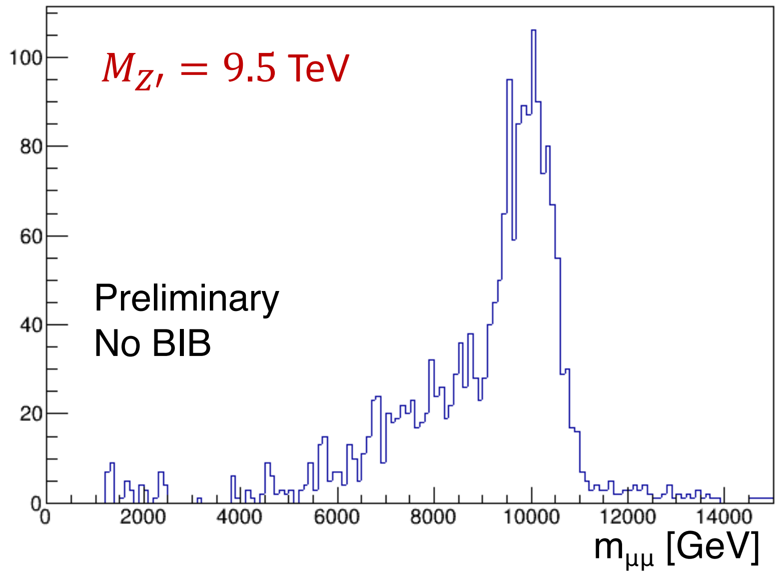
The activities in **a)** and **b)** are **CPU intensive** and **human time-consuming**, the complete process require about one year.

# Additional material

# Muon reconstruction

- Need to cover a momentum range from few GeV up to TeV
- New approach needed:
  - usual methods for low momentum;
  - combine information from muons detector, tracker and calorimeter information, jet-like structure.

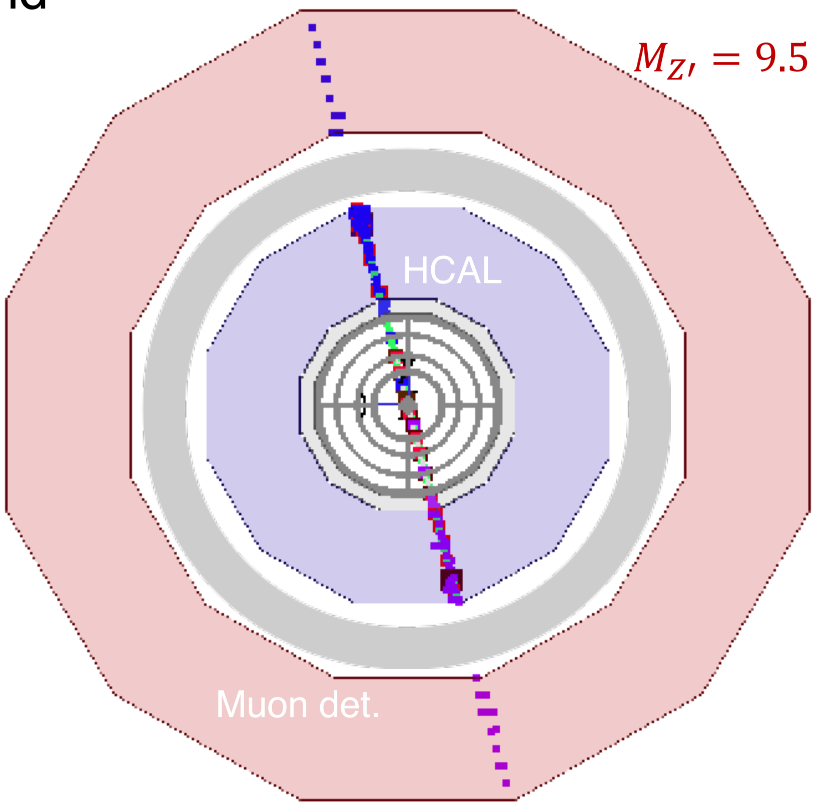
$\mu^+\mu^- \to Z'X \to \mu\mu X$ $\sqrt{s} = 10$ TeV




B = 5 T

$\mu^+\mu^- \to Z'X \to \mu\mu X$ $\sqrt{s} = 10$ TeV

$M_{Z'} = 9.5$ TeV

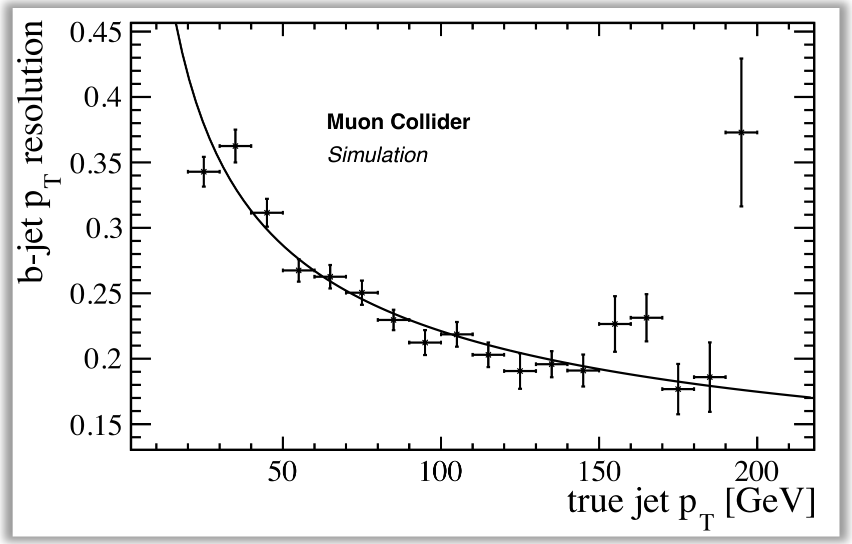


# Jets reconstruction performance

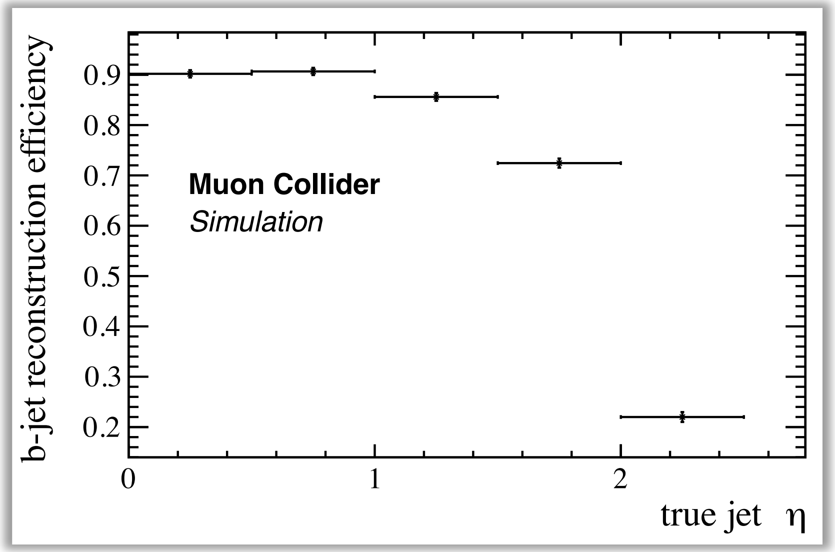
Jets reconstruction proceeds:

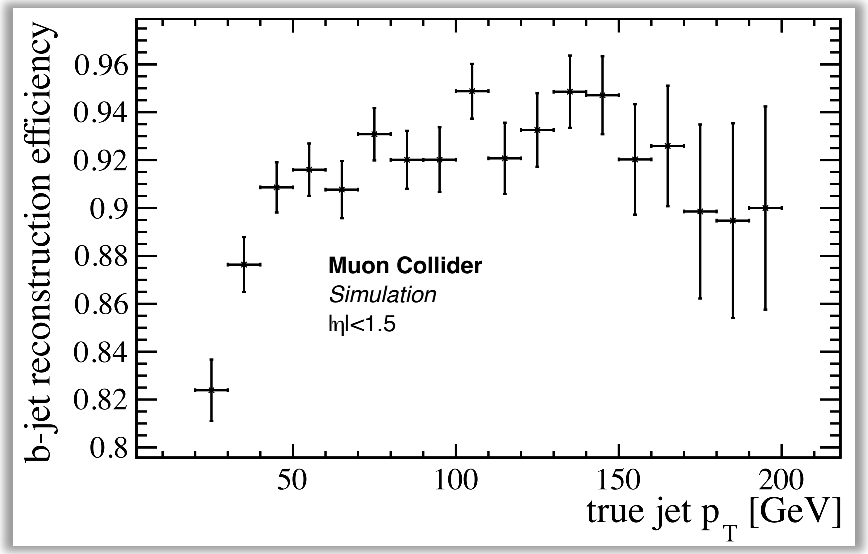
- Filter ”on time” calorimeter hits
- Combine track and calorimeter information to reconstruct particles
- Use $k_T$ algorithm to cluster particles in jets
- Apply requirements to remove fake jets (max 0.7%)
- Correct energy

Resolution




Efficiency



# Heavy Flavor Jets Identification Performance

b-quark

c-quark

light-quark/fake jets