Detector requirements at a 10 TeV muon collider

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on behalf of the Muon Collider Physics and Detector Group

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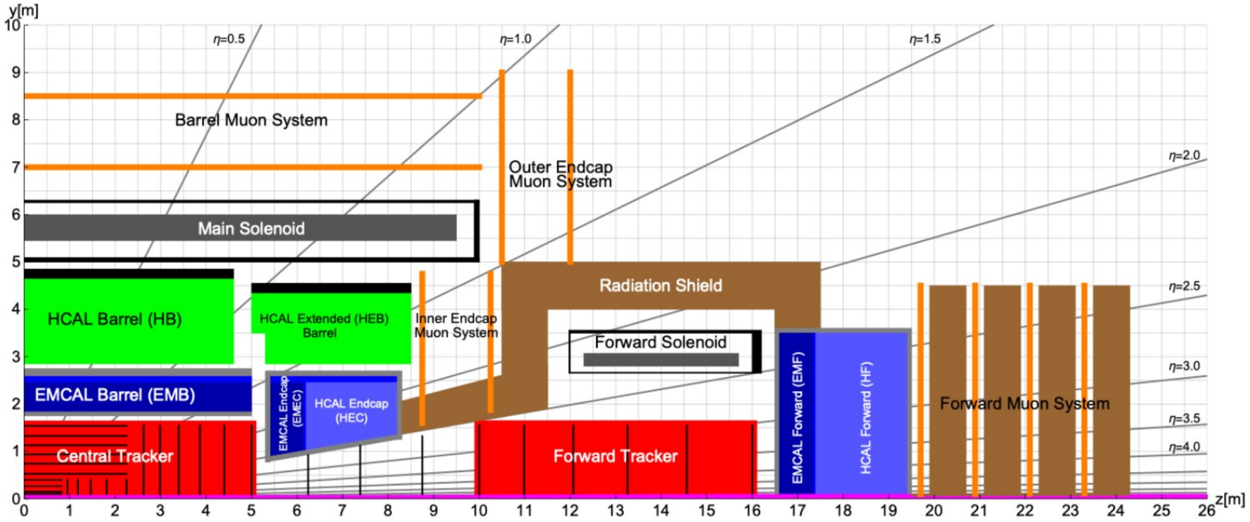
Workshop on the Detector Magnet for a 10 TeV Muon Collider, CERN, October 5, 2023

Outline

- Quick overview of magnet systems in other collider detectors.
- Driving factors for the design of a detector at a 10 TeV muon collider.
- Short description of the 3-TeV detector concept.
- First preliminary studies towards a 10-TeV detector concept.
- Summary.

Magnet systems of other HEP detectors (I)

FCC-hh detector



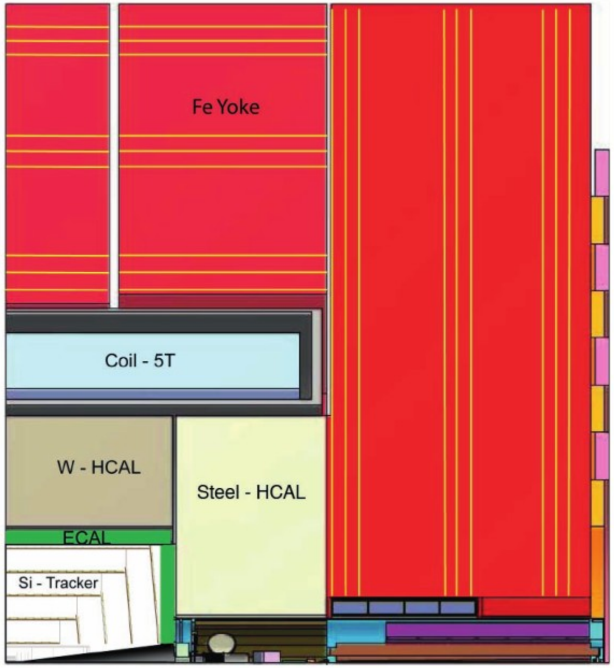
Open central solenoid:

- inner diameter: 10 m;
- length: 20 m;
- field: 4 T.

Two forward solenoids:

- inner diameter: 5.5 m;
- length: 4 m;
- field: 3.2 T.

CLIC_SiD detector

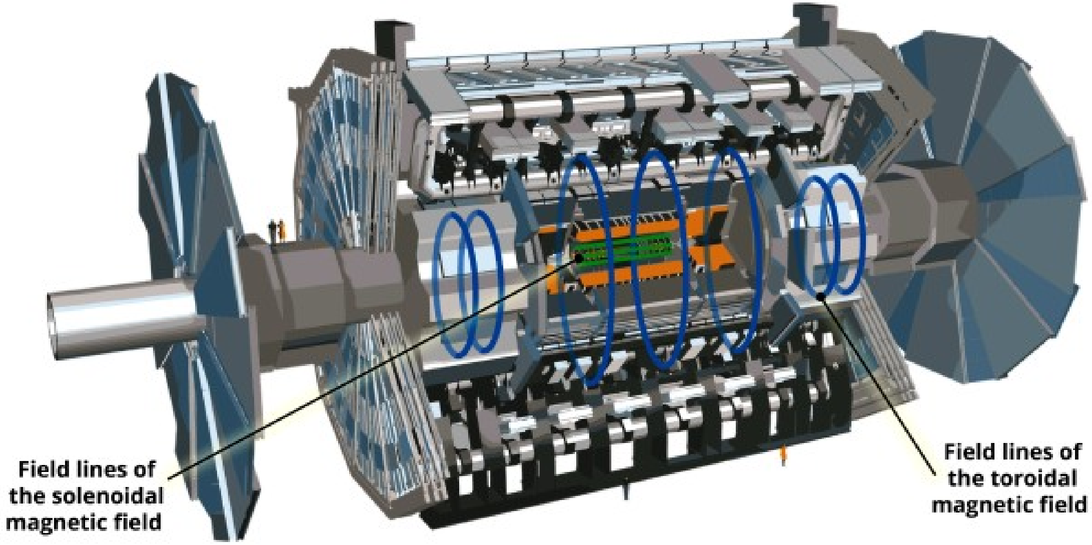


Solenoid:

- inner diameter: 5.8 m;
- length: 6.8 m;
- field: 5 T.

Magnet systems of other HEP detectors (II)

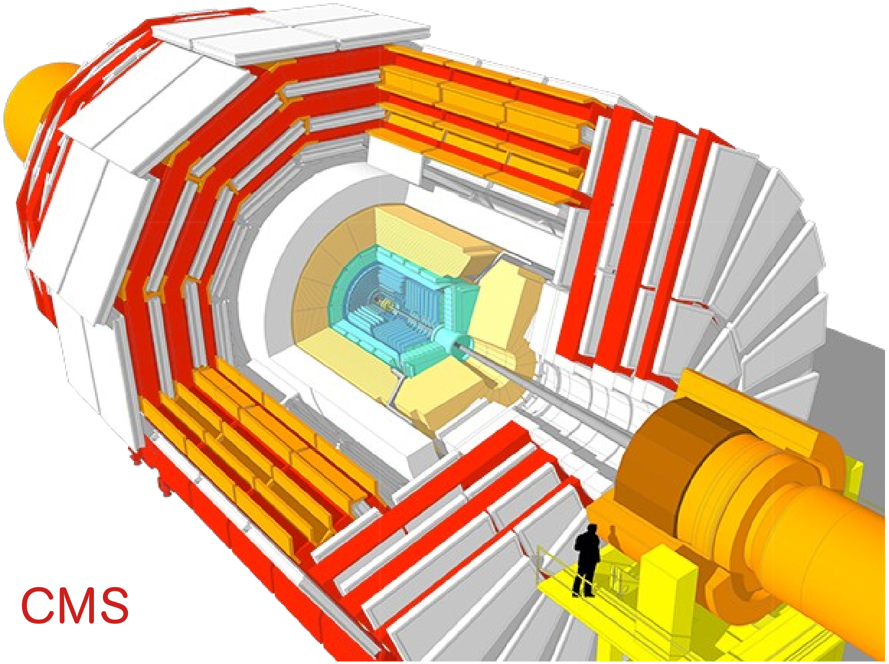
ATLAS



Solenoid:
- inner diameter: 2.6 m;
- length: 5.8 m;
- field: 2 T.

Central and forward toroids:
- field: 0.8 T.

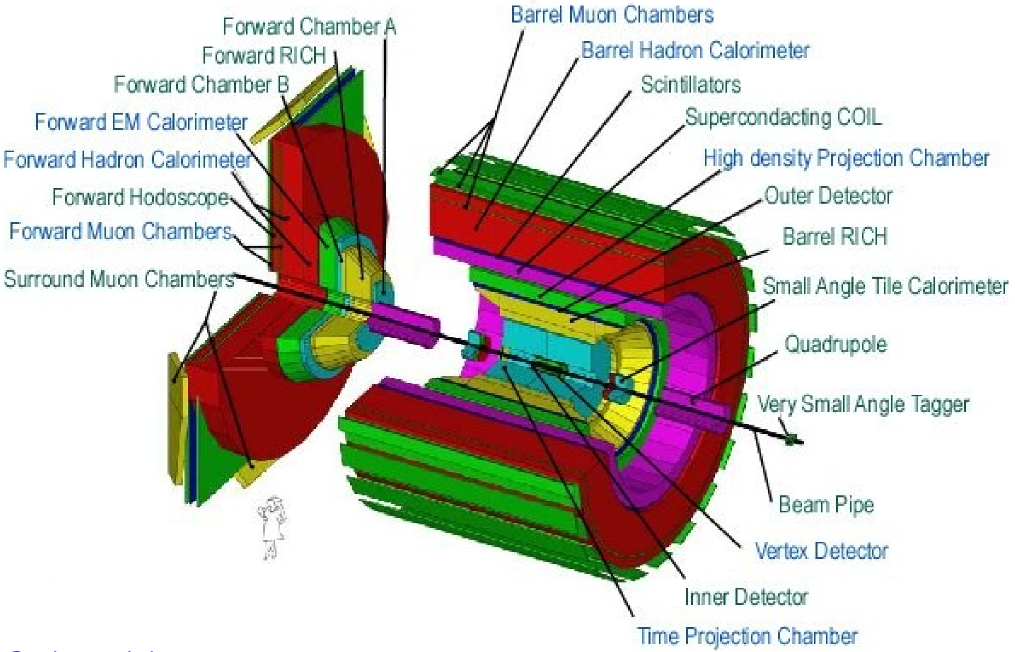
Solenoid:
- inner diameter: 6 m;
- length: 12.5 m;
- field: 4 T.



CMS

Magnet systems of other HEP detectors (III)

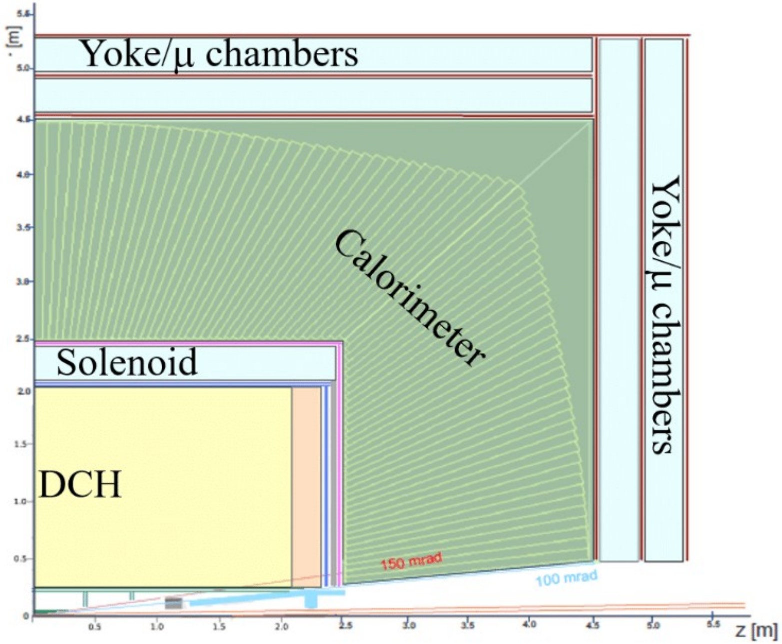
DELPHI (LEP)



Solenoid:

- inner diameter: 5.2 m;
- length: 7.4 m;
- field: 1.2 T.

IDEA detector (FCC-ee)



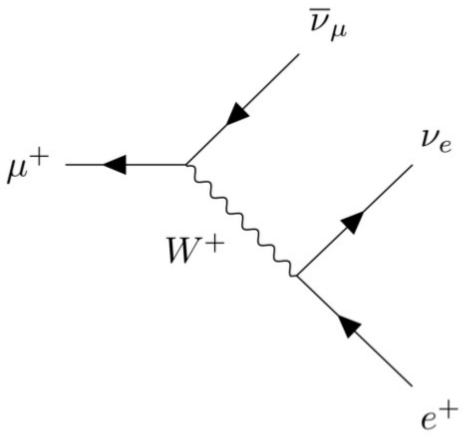
Solenoid:

- inner diameter: 4.2 m;
- length: 5 m;
- field: 2 T.

Detector design for a 10 TeV muon collider

- An experiment at a 10 TeV muon collider has many features in common with the experiments at the other multi-TeV machines (synergic R&D), but also has unique characteristics due to the unstable nature of muons.

- The design of the detector at a muon collider is mainly driven by:
  - the physics program requirements;
  - the background conditions;
  - constraints from the machine layout.



In the laboratory reference frame:

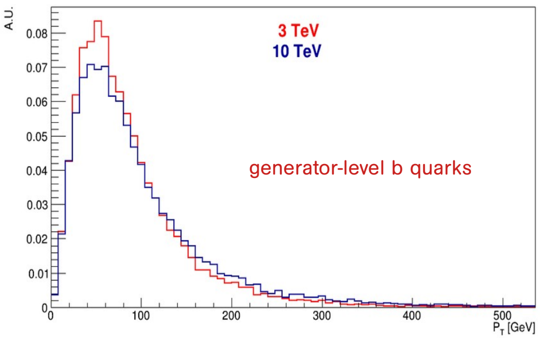
- at 10 TeV, t_μ = 104 ms
  ➔ expected 6.4×10^4 decays/m per bunch in the machine;
- at 3 TeV, t_μ = 31 ms
  ➔ expected 2.1×10^5 decays/m per bunch in the machine.

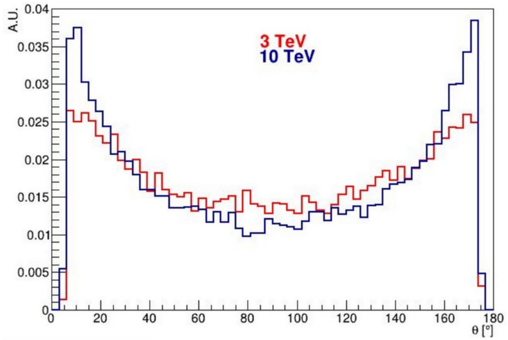
Requirements form the physics program (I)

- Detector requirements determined by considering three classes of physical phenomena, characterized by:
  - low-mass particles: e.g. the SM Higgs boson;

low-p_T and forward-boosted physical objects

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ = 3 and 10 TeV

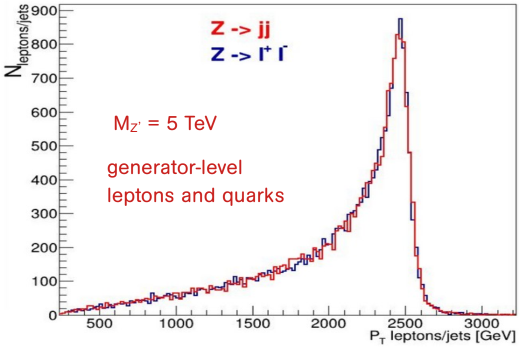


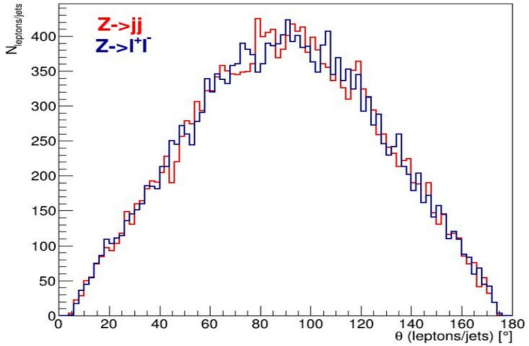


  - high-mass particles, typically produced via s-channel: e.g. Z';

very high-p_T and central physical objects

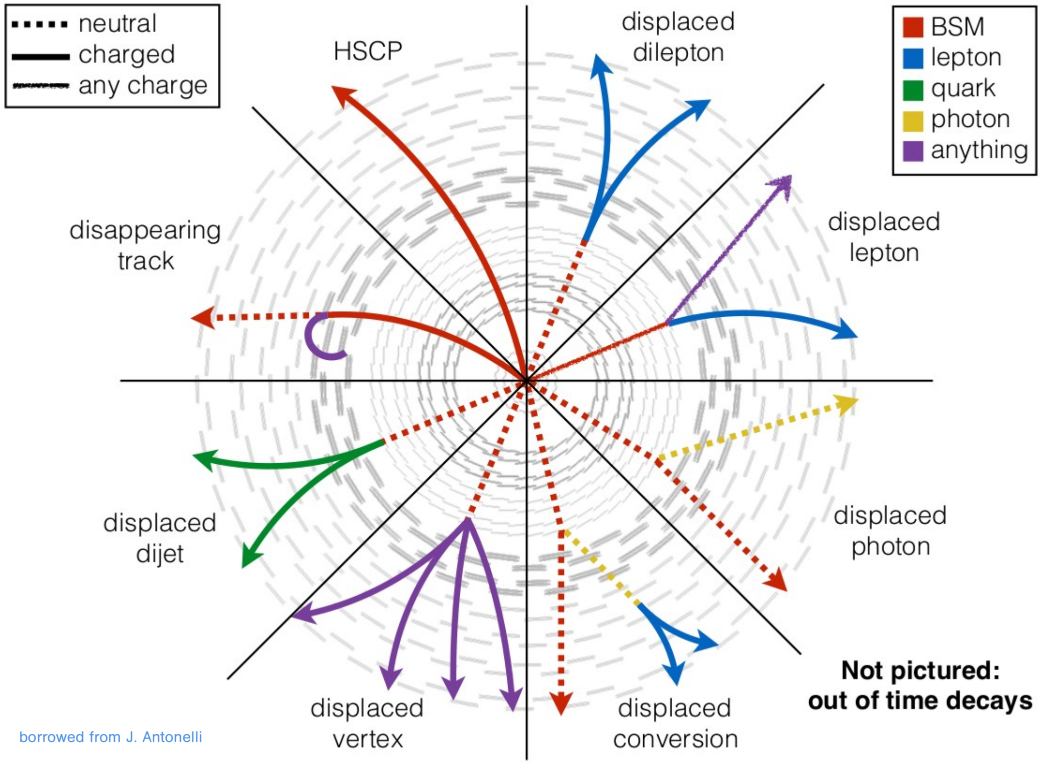
$\mu\mu \rightarrow Z'X \rightarrow q\bar{q}/\ell\ell$ X at $\sqrt{s}$ = 10 TeV





Requirements form the physics program (II)

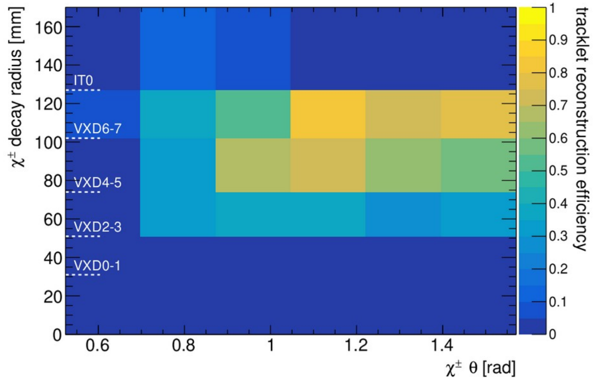
- less conventional signatures from BSM models:



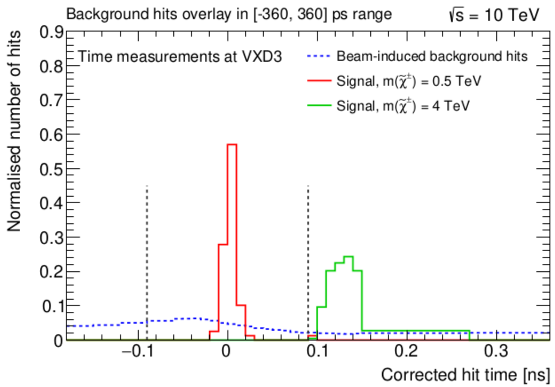
Not pictured: out of time decays

borrowed from J. Antonelli

reconstruction efficiency for disappearing tracks vs decay radius and θ



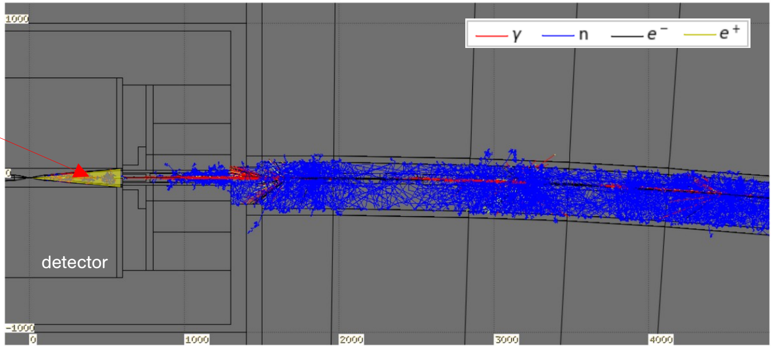
tracker hits time



Background conditions

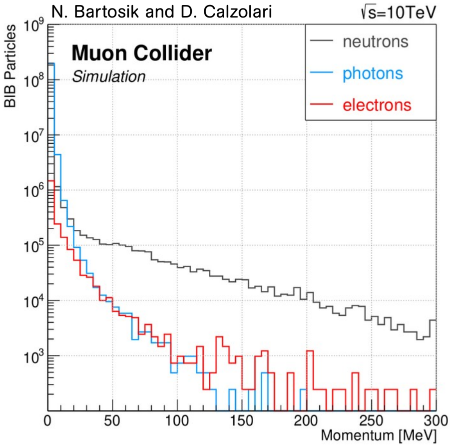
N. Bartosik et al., arXiv:2203.07964

nozzle

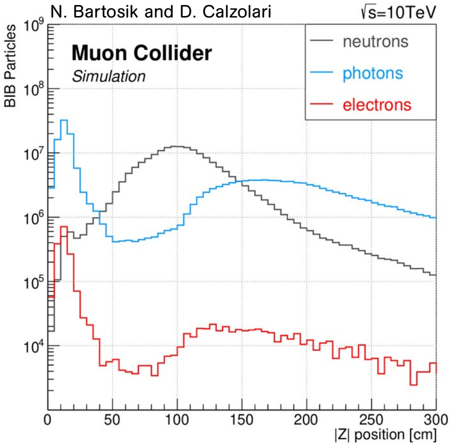


- High levels of background are expected in the detector due to the interactions between decay products of the muons in the beams and machine components (beam-induced background, BIB).
- Appropriate shielding ("nozzles") must be placed inside the detector volume to mitigate the BIB effects.

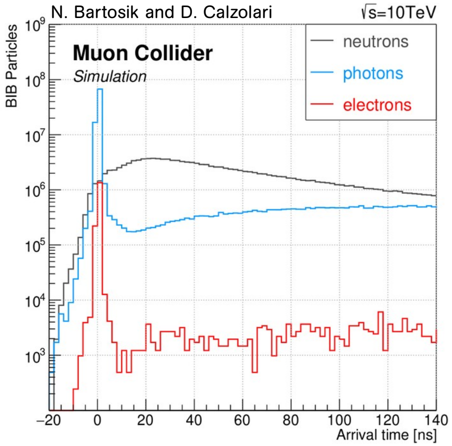
BIB particles momenta



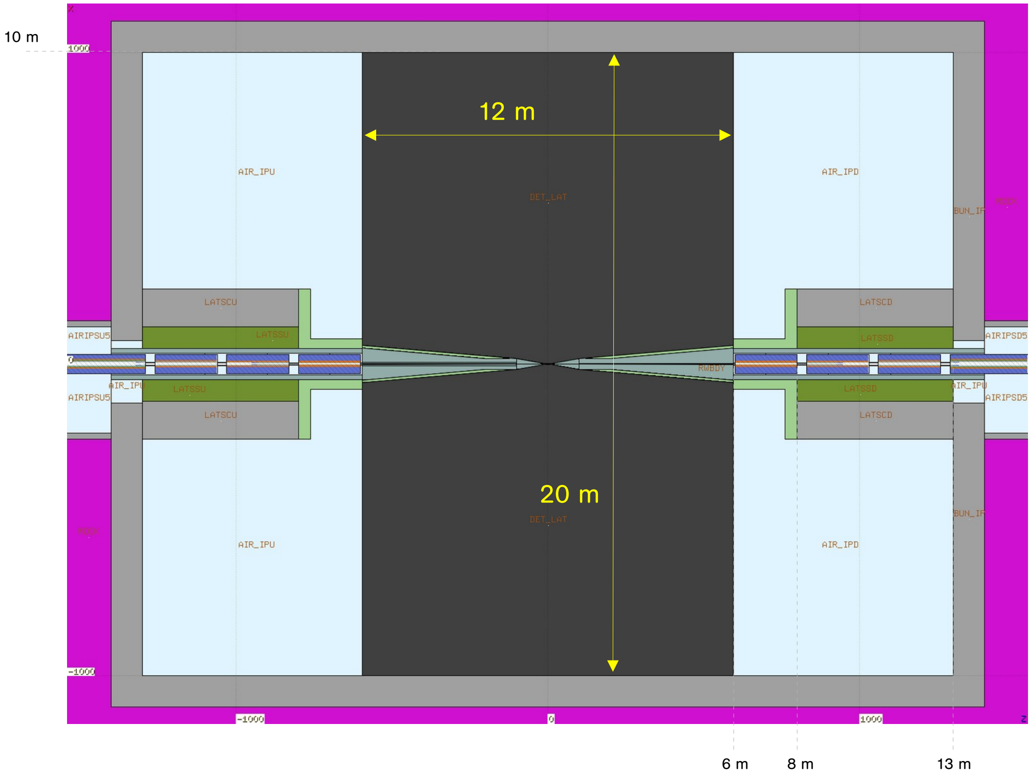
BIB particles origin w.r.t. the interaction region



BIB particles time of arrival w.r.t. the bunch crossing

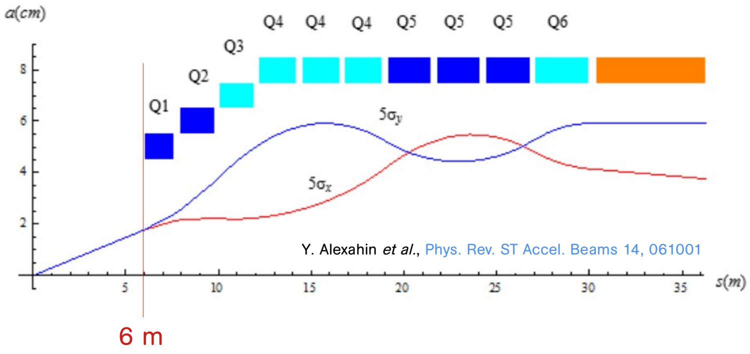


Spatial constraints from the machine layout



- The longitudinal size of the detector will most likely be determined by the position of the machine's final focusing magnets, which are currently located at ±6 m from the interaction point.

preliminary interaction-region configuration for a 3 TeV collider



Y. Alexahin *et al.*, Phys. Rev. ST Accel. Beams 14, 061001

Detector concept for a 3-TeV muon collider

hadronic calorimeter

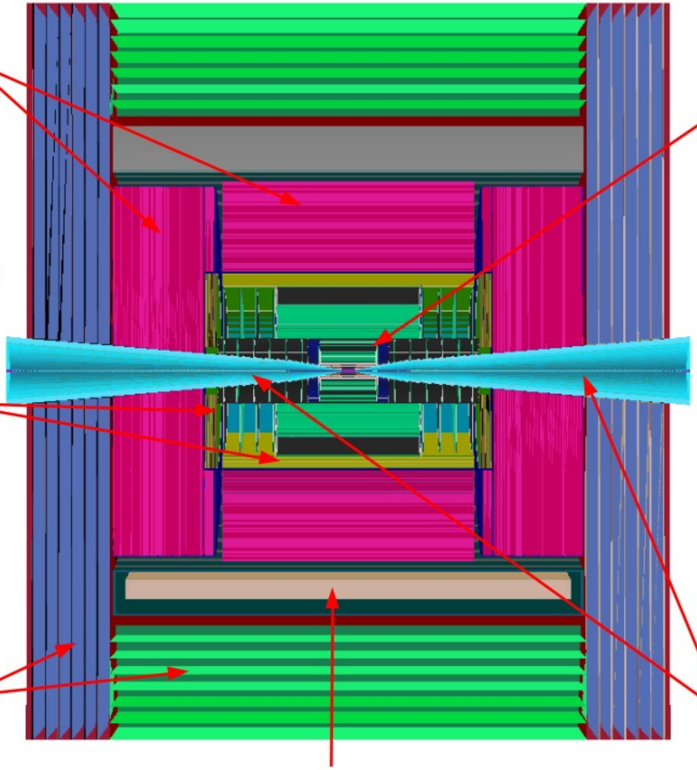
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

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

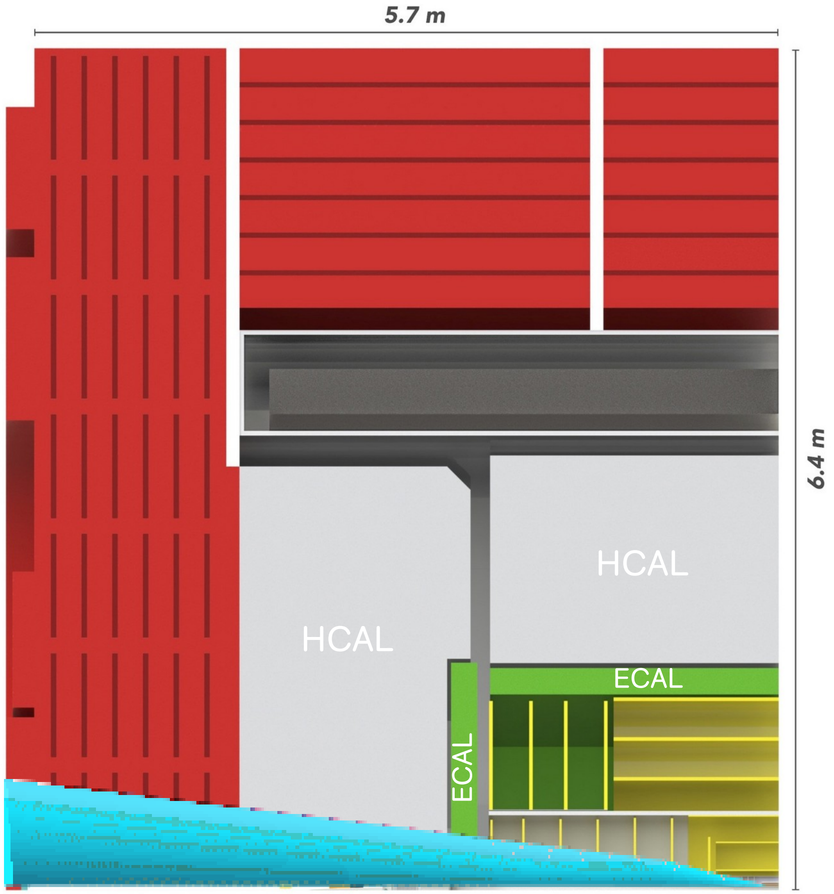
- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 µm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 µm x 10 mm micro-strip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

shielding nozzles

- Tungsten cones + borated polyethylene cladding.

The detector model for 3-TeV studies is based on CLIC's CLICdet detector concept (CLICdp-Note-2017-001) with MAP's MDI and vertex detector.

Magnet system of the 3-TeV detector



borrowed from CLIC

Magnet specs:

Aluminum coil:

- inner diameter = 7.3 m;
- length = 7.8 m;
- thickness = 34.4 cm;
- field = 3.57 T.

4-cm thick steel vacuum tank:

- inner diameter = 7.0 m;
- outer diameter = 8.6 cm;
- length = 8.3 m.

- Same magnet geometry as that of CLIC.
- B field value chosen for consistency with the field used by MAP to generate the beam-induced background sample in use.

3-TeV detector performance

- Tracking detectors:
  - transverse momentum resolution:

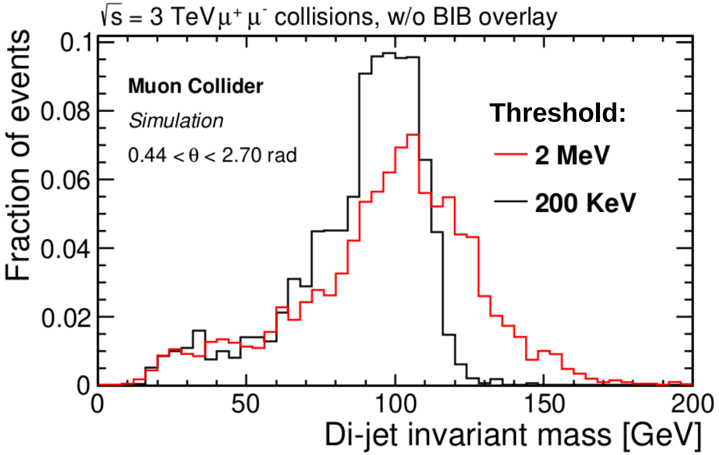
$$\frac{\sigma_{p_T}}{p_T} \approx 0.0018\ p_T\ ;$$

  - transverse impact parameter resolution:

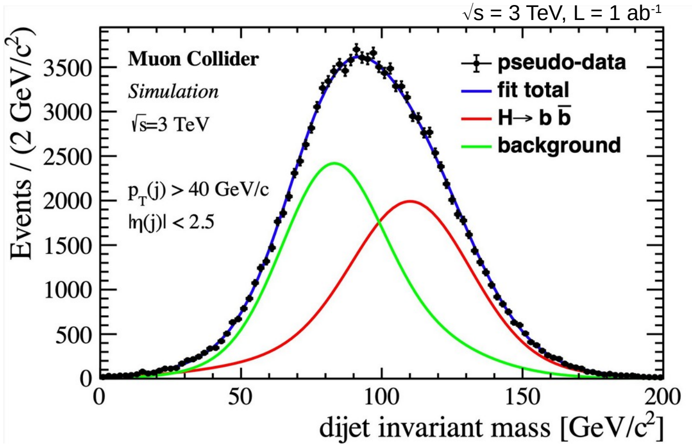
$$\sigma_{d_0} \approx 3 \oplus \frac{18}{p_T}\ \mu\text{m at } \theta = 90°.$$

- Calorimeters:
  - energy resolution slightly degraded by the high threshold (2 MeV) set on the calorimeter hit energies, necessary to mitigate the effect of BIB.
  - Nevertheless, achieved a good diphoton mass resolution and satisfactory Z→bb/H→bb separation.

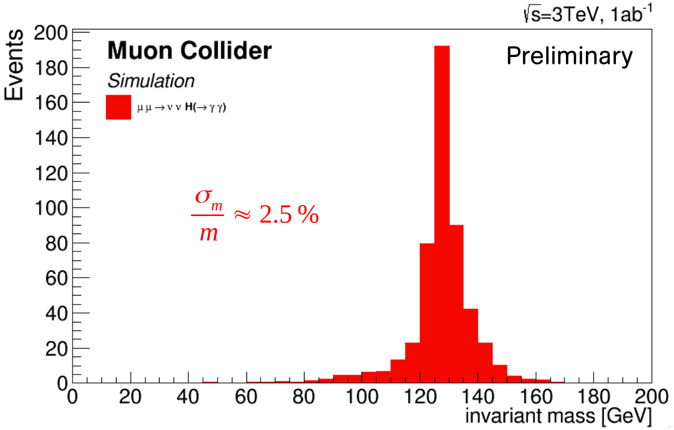
effect of the calorimeter hit energy threshold



$\mu\mu \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$

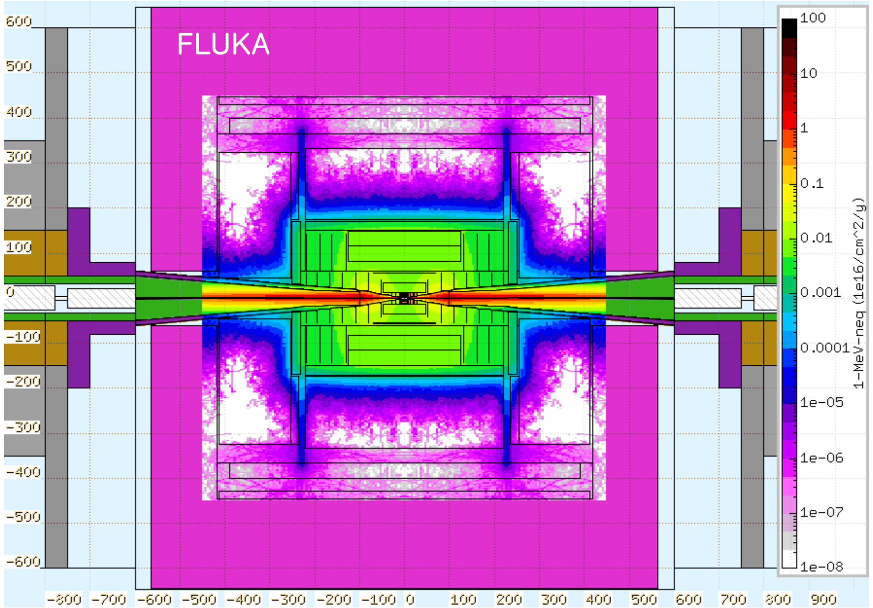


$\mu\mu \to H\nu\bar{\nu} \to \gamma\gamma\nu\bar{\nu}$



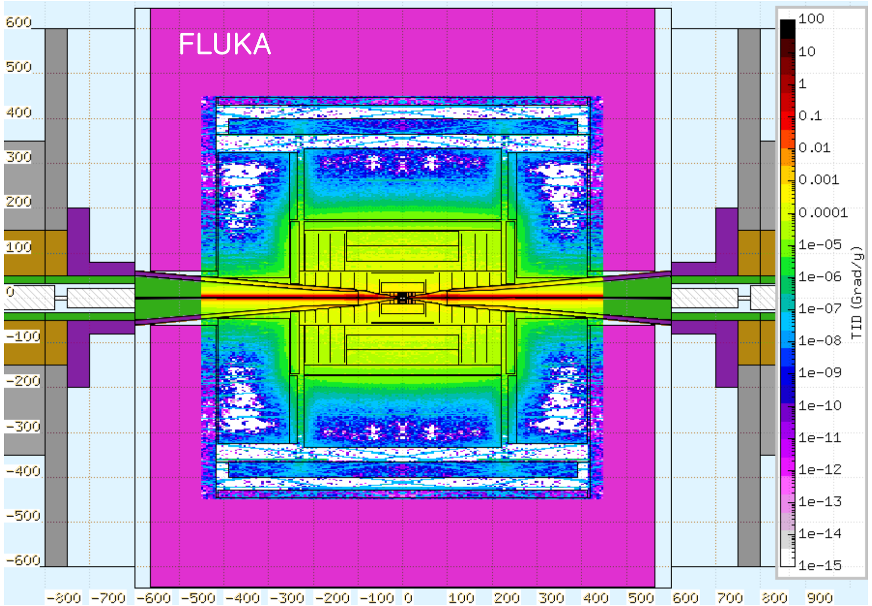
Radiation environment

1-MeV neutron equivalent fluence per year



total ionizing dose per year

C. Accettura et al., arXiv:2303.08533



Assumptions:

- collision energy: 1.5 TeV;
- collider circumference: 2.5 km;
- beam injection frequency: 5 Hz;
- days of operation per year: 200.

	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 similar to what expected at HL-LHC.

The path towards a 10-TeV detector

- Initial preliminary generator-level studies at 10 TeV were focused on some representative physical precesses and provided a general idea of the range of energies and momenta involved, typical decay lengths of long-lived particles, angular distributions ...

- Next step was to process these events with the 3-TeV detector full simulation and reconstruction algorithms (without BIB overlay for the time being) and to study the detector response, its performance and limitations.

- The results of such studies provide a first guideline for the design of a detector for muon collisions at 10 TeV:
  - global detector layout;
  - tracker size and magnetic field intensity;
  - calorimeter size and depth;
  - first look at reconstruction of very high-momentum muons.

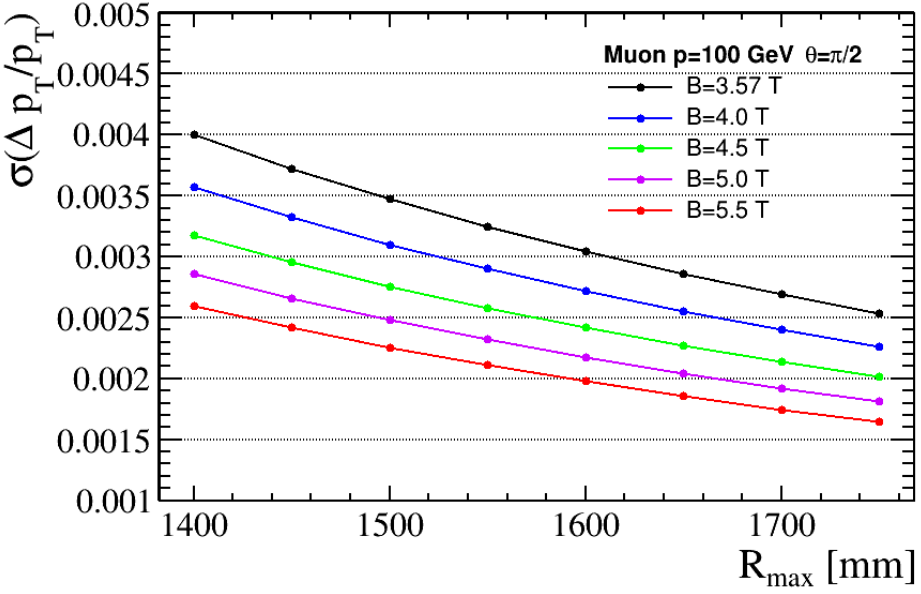
Track momentum resolution

- Effect of the tracker size and the magnetic field intensity on the track momentum resolution (the multiple scattering contribution is not taken into account):

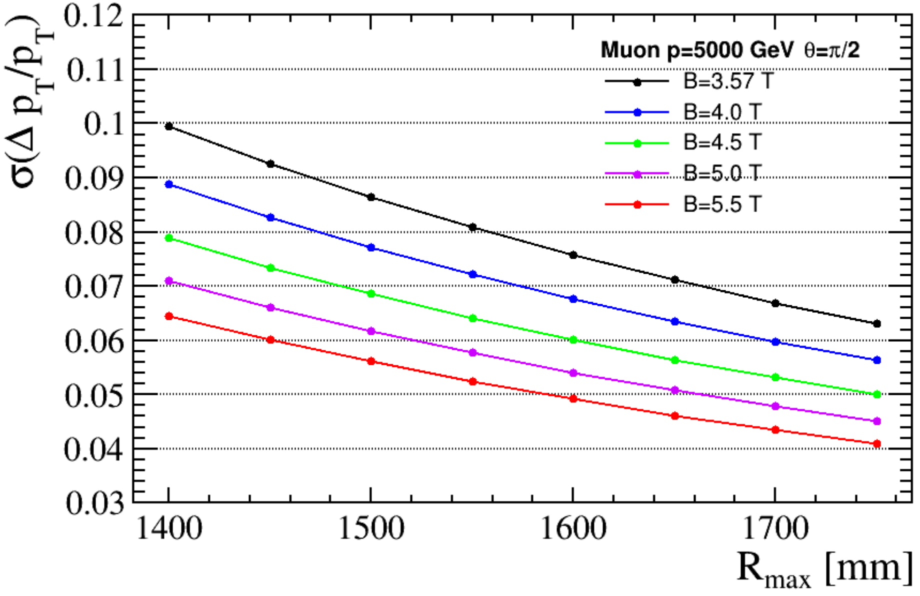
$$\left.\frac{\sigma_{p_T}}{p_T}\right|_{res} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B\,L^2}\sqrt{\frac{5}{N+5}}$$

Z. Drasal and W. Riegler, NIM A 910 (2018) 127

p_μ = 100 GeV at θ_μ = 90°



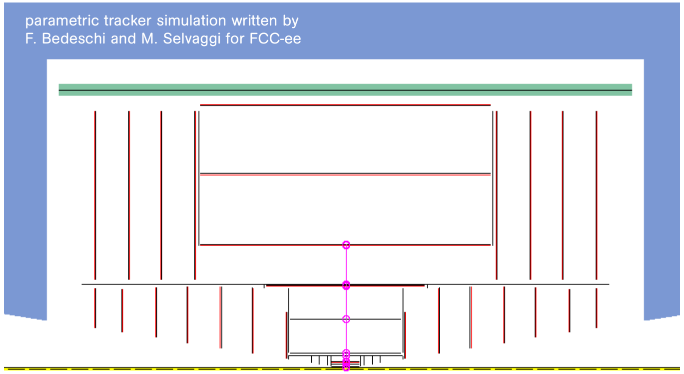
p_μ = 5000 GeV at θ_μ = 90°



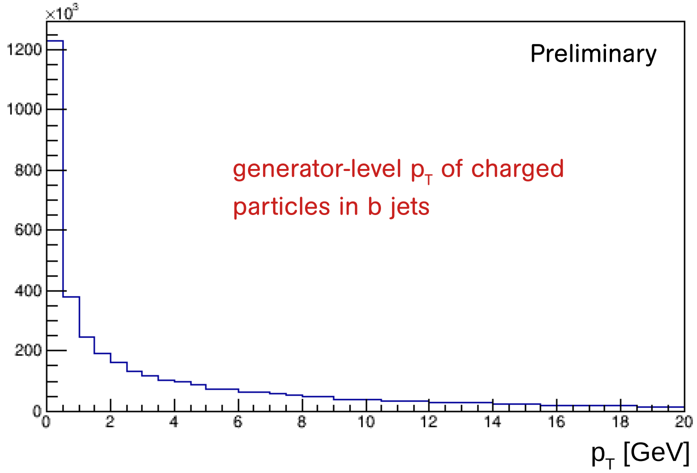
Reconstruction of low-p_T tracks (I)

- Need to reconstruct efficiently the low-momentum charged particles produced in quarks and gluons hadronization.

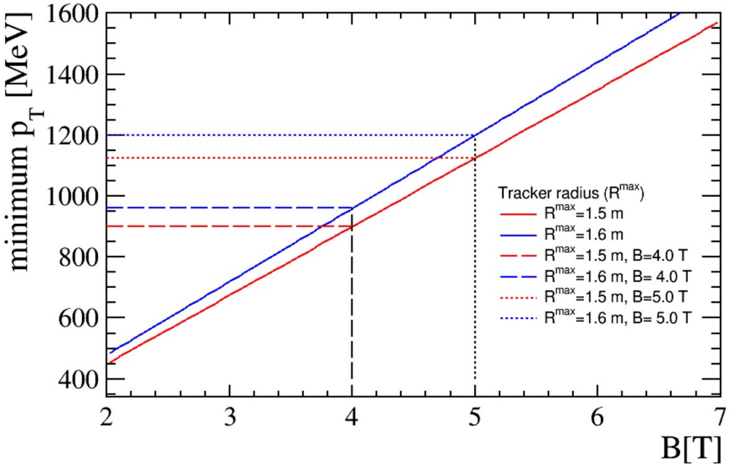
p_T = 0.8 GeV at θ = 90° with B = 5 T



$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$



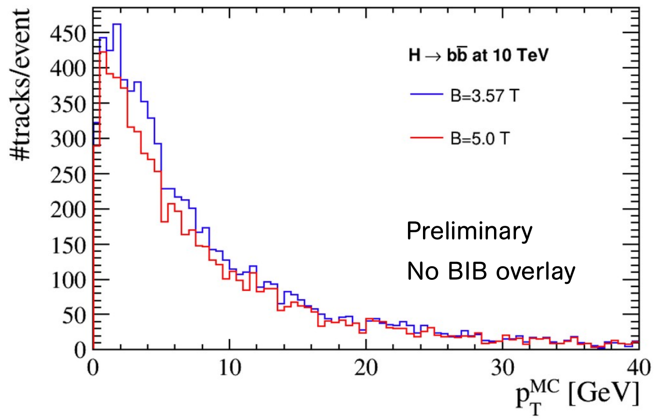
minimum p_T needed to reach the outer tracker layer



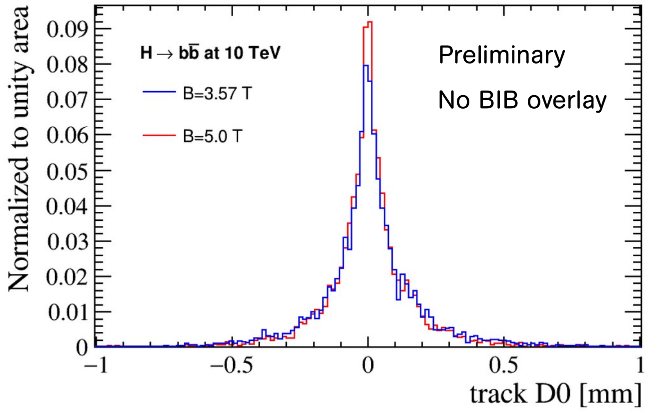
Reconstruction of low-p_T tracks (II)

- With B = 5 T, found a tracking inefficiency of about 15% w.r.t. B = 3.57 T for H→bb at $\sqrt{s}$ =10 TeV.
- The tracking inefficiency seems to be more significant for displaced tracks, potentially affecting the b-tagging performance and all the searches relying on displaced tracks.

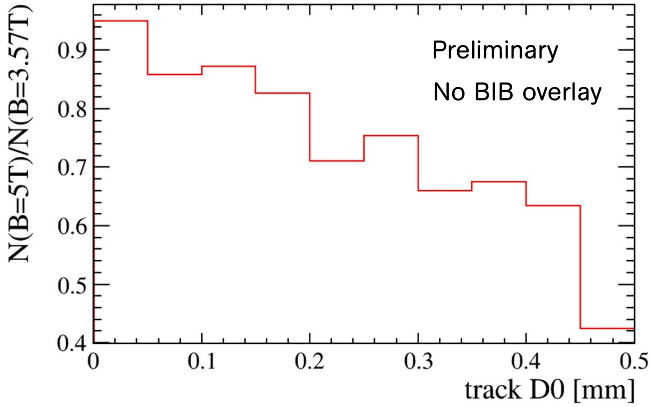
generator-level p_T of the reconstructed tracks



transverse impact parameter



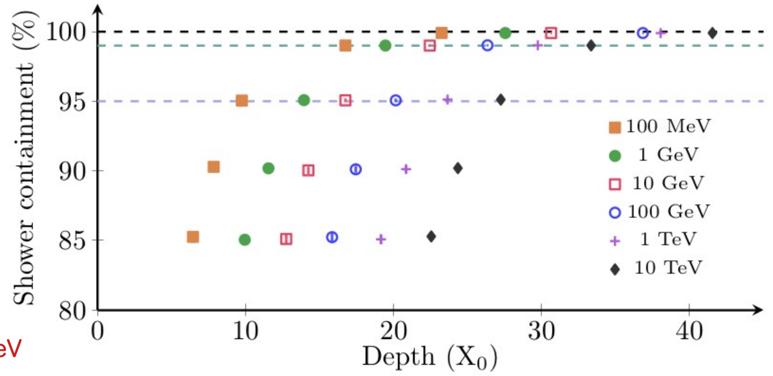
N_{tracks}(b=5 T)/N_{tracks}(b=3.57 T) vs track impact parameter



Photons and jets reconstruction

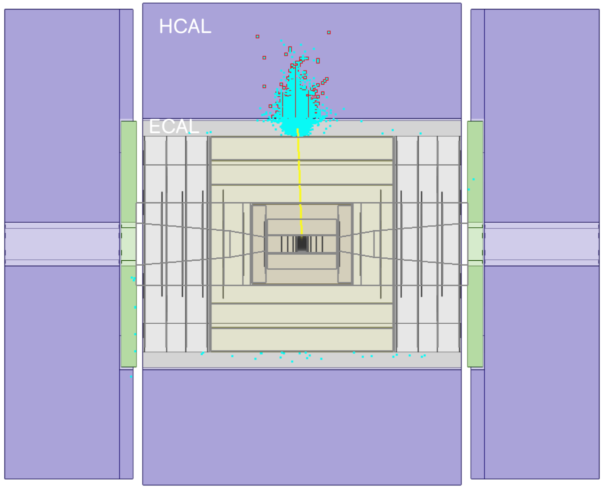
- Needed deep calorimeters to contain the showers produced by very energetic particles, but also capable of reconstructing softer objects with energies below 100 GeV and identify or resolve boosted overlapping objects.

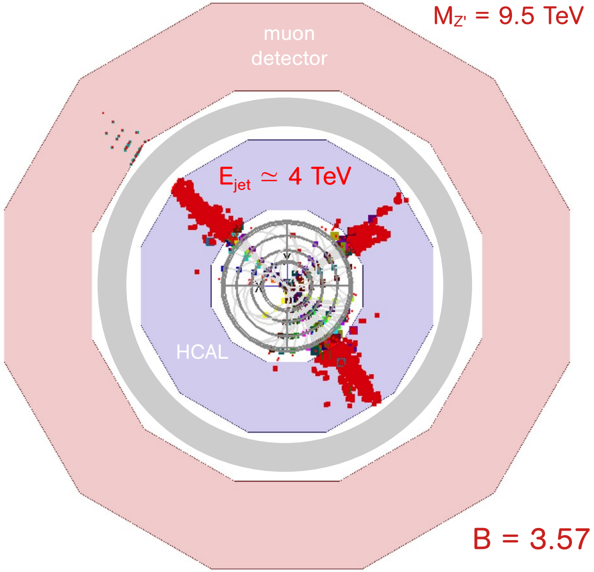
M. Aleksa et al., arXiv:1912.02.09962v1



$\mu\mu \rightarrow Z' \rightarrow q\bar{q}$ at $\sqrt{s}$ = 10 TeV

central 5 TeV photon

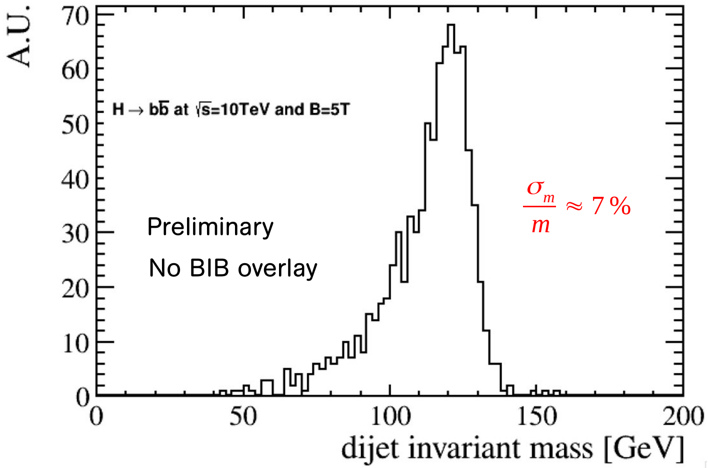




$M_{Z'}$ = 9.5 TeV

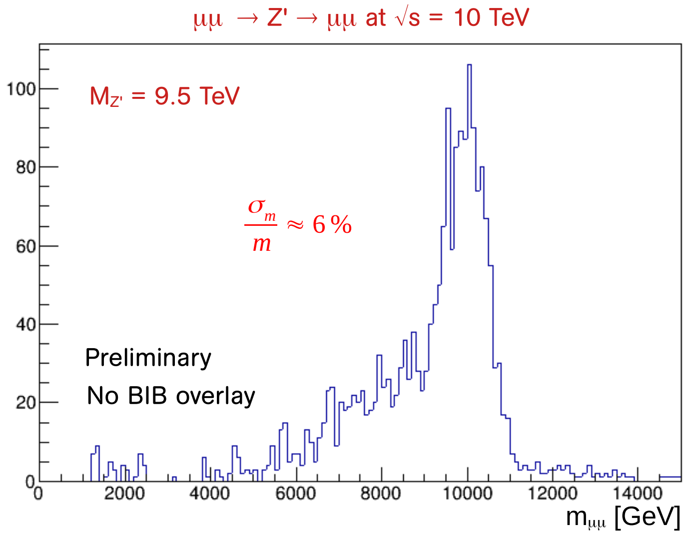
B = 3.57 T

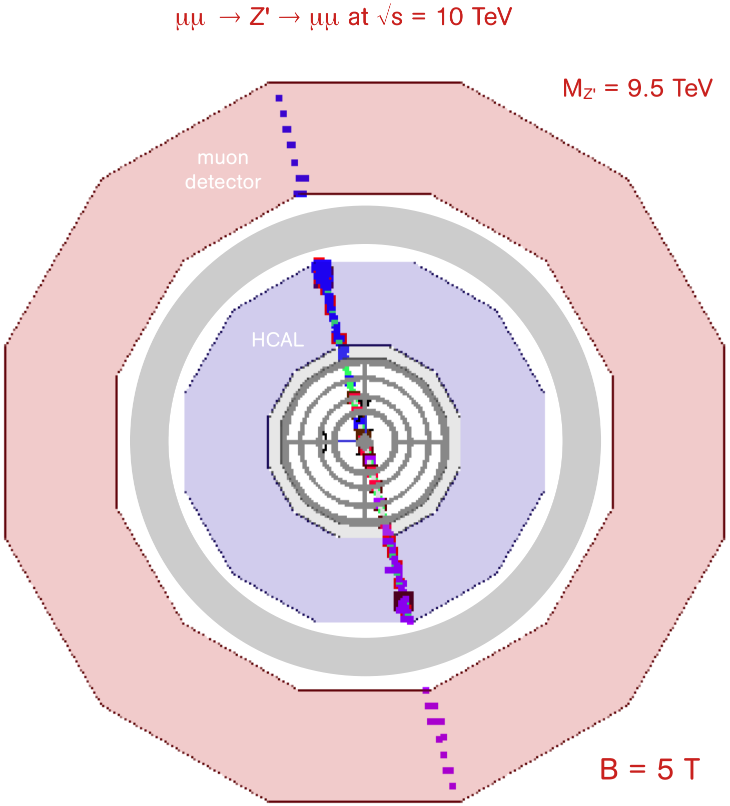
$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$ at $\sqrt{s}$ =10 TeV



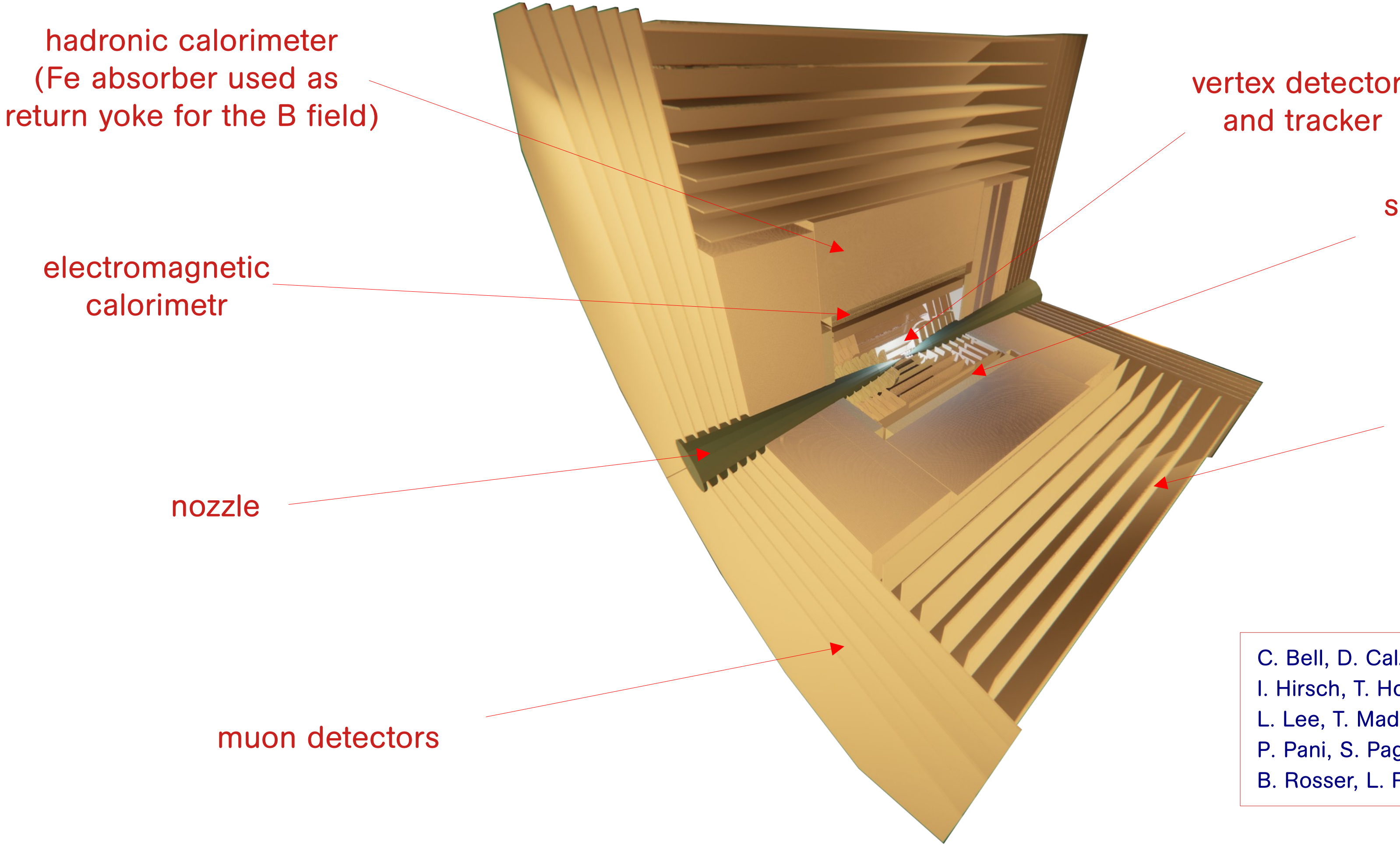
Muons reconstruction

- Required reconstruction of muons from a few GeV up to a few TeV.
- A precise measurement of the momentum (and the charge) of very high-p_T muons will be challenging.
- A novel global approach will be needed which possibly combines information from the tracker, the calorimeters, and the muon detectors.





Ongoing studies for an ATLAS-style detector



solenoid:
- inner diameter: 3 m
- length: 4.5 m
- field: 5 T

C. Bell, D. Calzolari, K. DiPetrillo, M. Hillman, I. Hirsch, T. Holmes, S. Jindariani, B. Johnson, L. Lee, T. Madlener, F. Meloni, I. Ojalvo, P. Pani, S. Pagan Griso, K. Pedro, R. Powers, B. Rosser, L. Rozanov, A. Vendrasco, J. Zhang

Summary

- An overview has been given of the current studies on the design of a detector for a 10 TeV muon collider.

- The magnet system is a fundamental component of the detector, whose overall layout is ultimately determined by its configuration.

- As a result of today's discussion, we expect to gain a clearer understanding of the options available for the magnetic system of a detector at a 10 TeV muon collider.