Detector design for the 10 TeV center-of-mass energy

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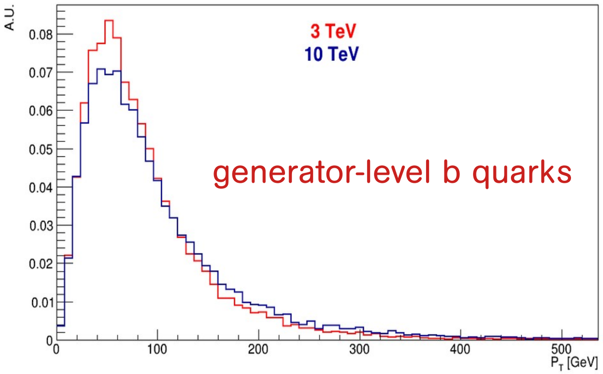
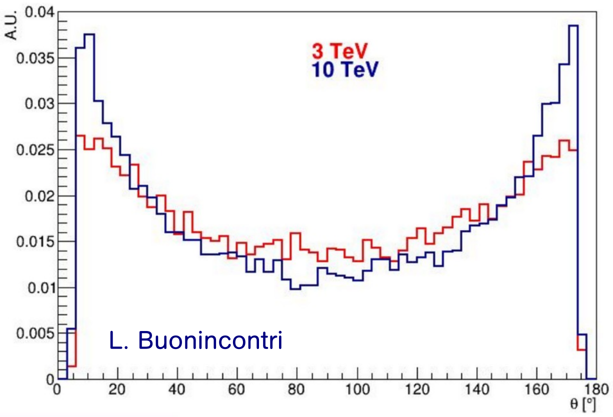
Towords a detector for 10 TeV collisions

- The natural starting point is the experience gained with the detector full-simulation studies at 1.5 TeV and 3 TeV, in particular for the beam-induced background mitigation.
- Identify the goals and crucial challenges for a detector at a 10 TeV muon collider.
- Try to outline a strategy to coordinate and align the efforts towards a detector for collisions at 10 TeV.
- The focus will be on the detector global structure for the time being.

Requirements form the physics program

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



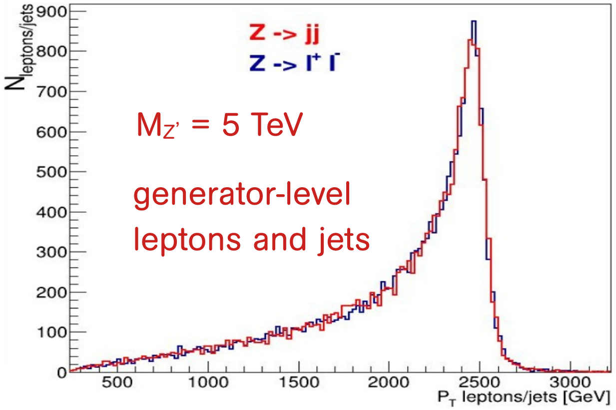


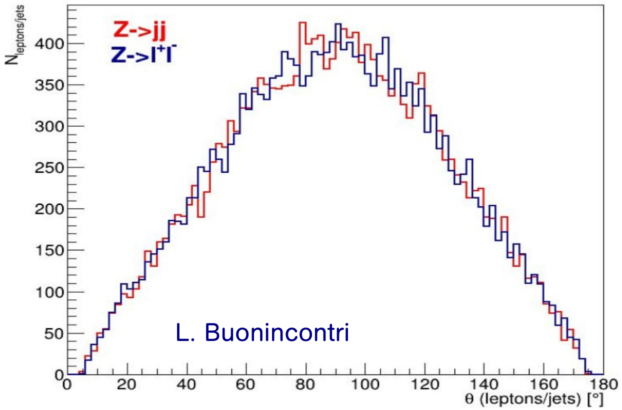
- The muon collider will pursue a vast physics program:
  - high-precision measurements of Standard Model processes with:
    - relatively light SM particles;
    - forward-boosted physical objects.
  - search for new physics with:
    - new, possibly heavy, states;
    - very energetic and mostly central physical objects.

Use two types of representative physics cases to study the physics objects characteristics at 10 TeV:

- SM Higgs boson channels;
- new heavy particle production.

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



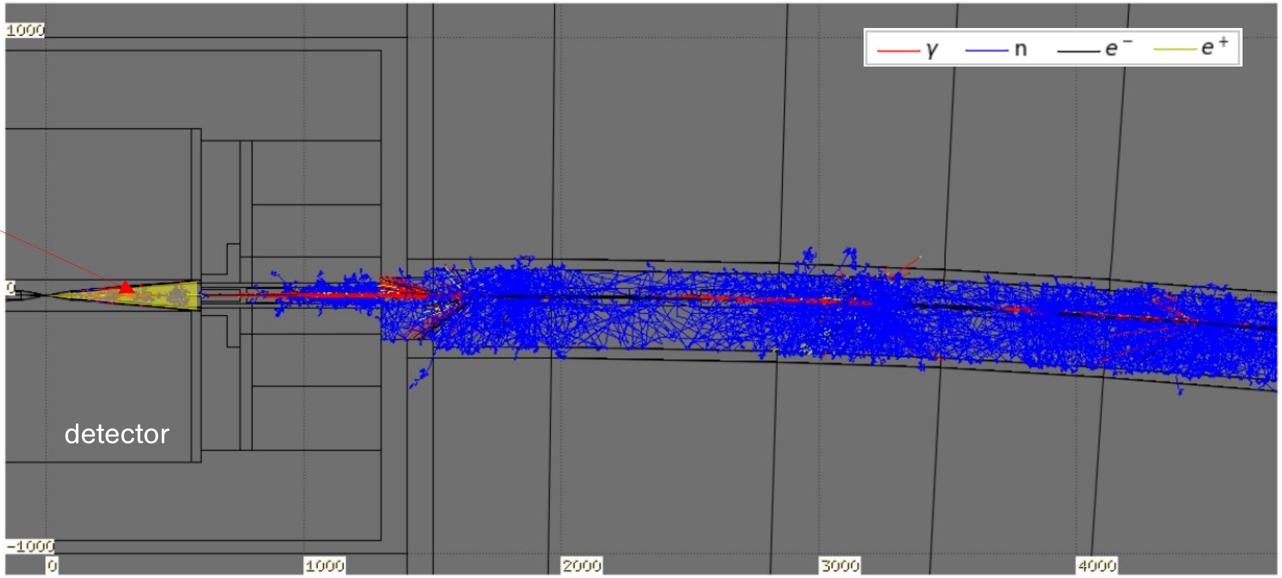


Requirements from experimental conditions

- Using suitable shieldings ("nozzles") inside the detector volume to mitigate the beam-induced background (BIB) will most likely be unavoidable.

N. Bartosik et al., arXiv:2203.07964

nozzle

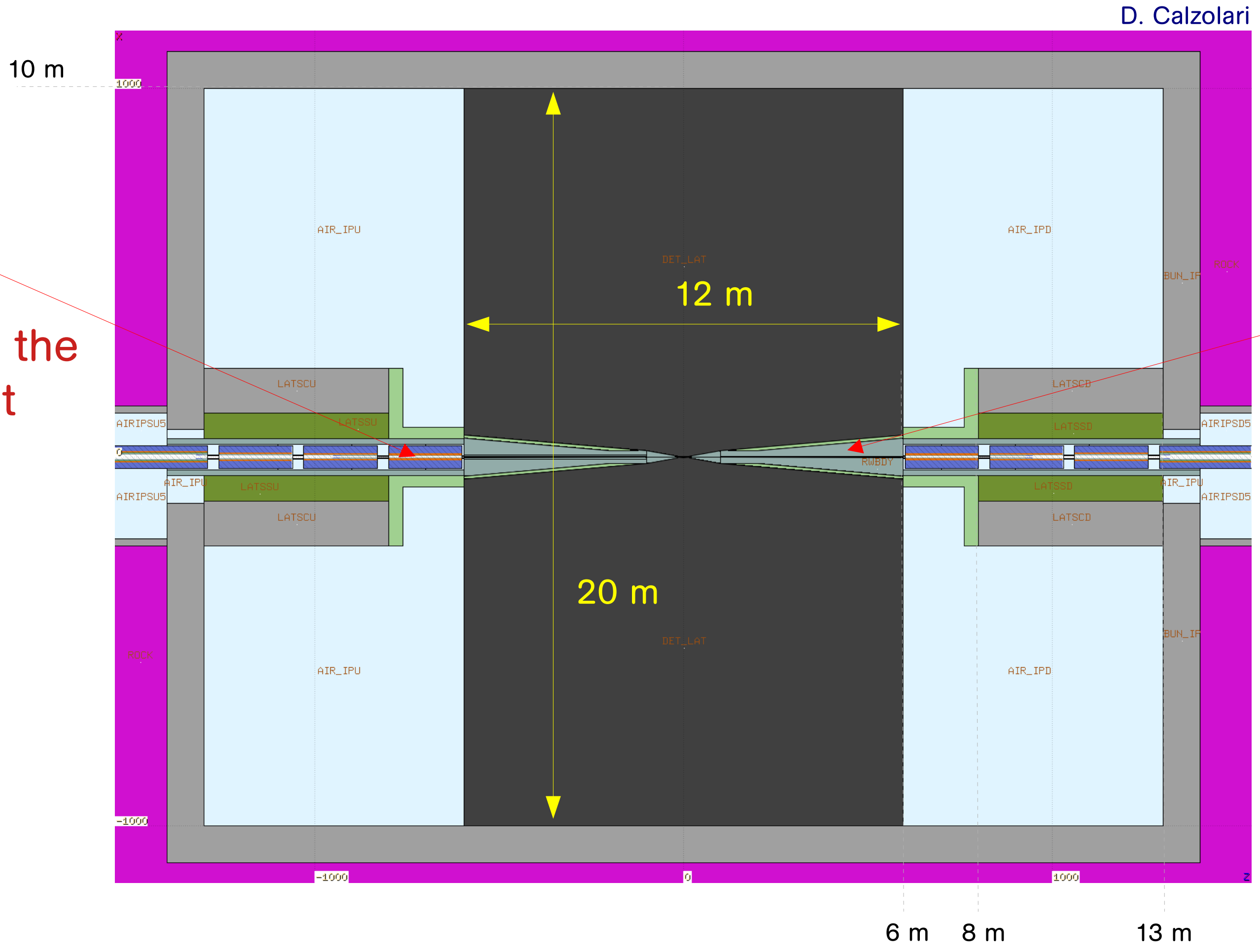


FLUKA studies show that BIB levels inside the detector are mainly determined by the nozzle configuration (similar results at 1.5, 3, and 10 TeV with same nozzles)

⇒ to first order, use conservatively 1.5-TeV nozzles in the 10 TeV detector

Additional boundary conditions

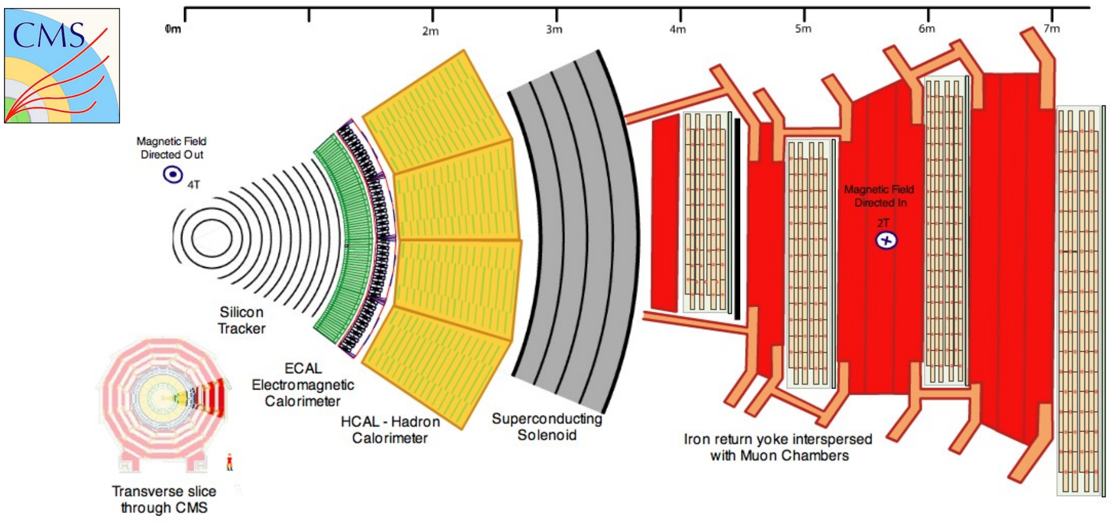
final focusing magnets at ±6 m (L*) from the interaction point

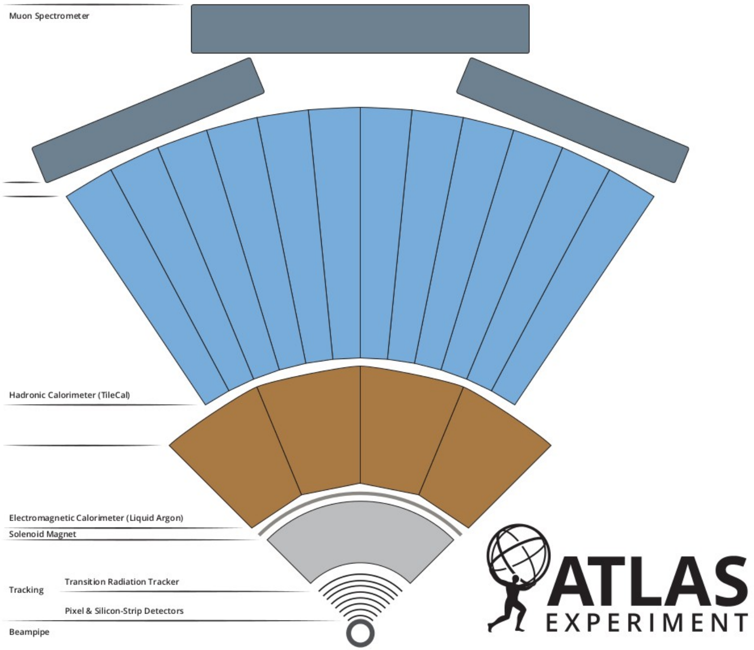


shielding nozzles inside the detector volume

Detector magnet system

- The choice of the magnet system is going to shape the detector layout (and might affect the IR configuration).
- Two different approaches at LHC:
  - large central solenoid (CMS);
  - smaller central solenoid + external toroid (ATLAS).



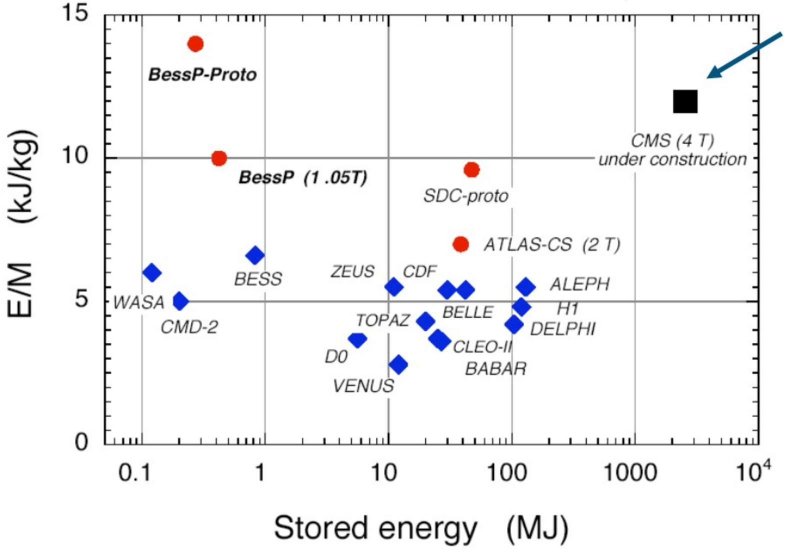


- Alternative and novel approaches, like an iron-free solenoid (J. Hauptman, Physics and Detector Simulation Meeting on June 7, 2022).

Superconducting solenoid à la CMS

- Had an interesting chat with R. Musenich and S. Farinon (INFN-Genova), who were part of the team who built the CMS magnet:
  - the CMS solenoid still represents a technological milestone and is considered a reference for future detector magnets (CLIC's detector is based on CMS model);
  - a magnet, based on the same technology, with a different conductor, can reach fields of ∼5 T;
  - but the expertise is fading as time goes by and the magnet production chain and its custom machinery do not exist anymore.

P. Fabbricatore, EUCAS'07



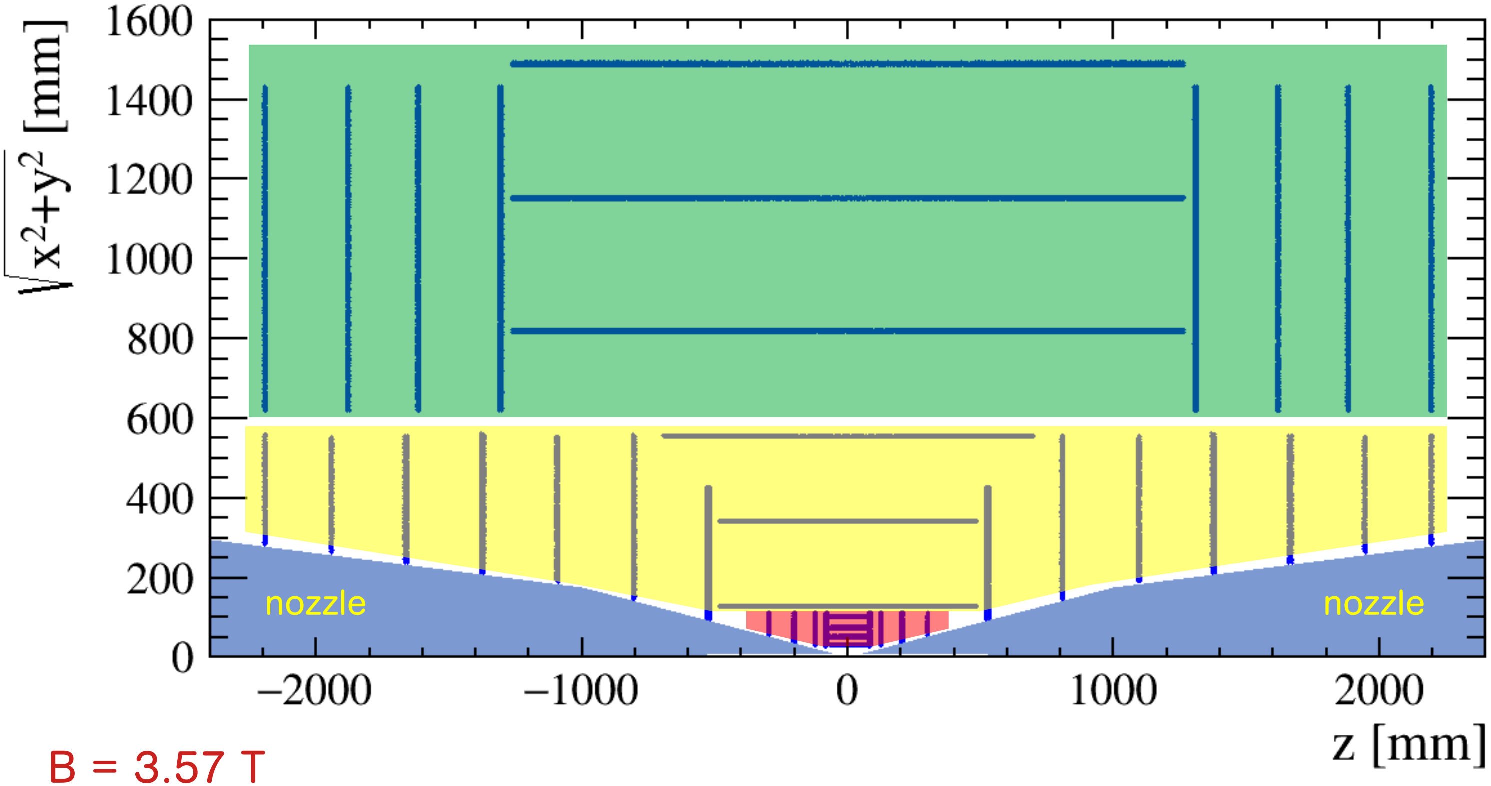
This 'anomalous' positioning meant that innovative solutions were needed to face this challenge

We will organize a dedicated meeting with detector-magnet experts in the fall to review all the available options.

Magnet specs:

- Al-reinforced NbTi conductor
- bore diameter = 6 m
- solenoid length = 12.5 m
- design field = 4 T
- stored energy = 2520 MJ

The tracker of the 3-TeV detector



B = 3.57 T

With IT and OT from CLIC's detector, VXD from MAP's.

Outer Tracker (OT)

- barrel: 3 cylindrical layers
  endcaps: 4 + 4 disks
- Si sensors:
  50 µm x 10 mm micro-strips
  $\sigma_{r\text{-}\phi}$ = 7 µm, σ_z = 90 µm
  σ_T = 60 ps

Inner Tracker (IT)

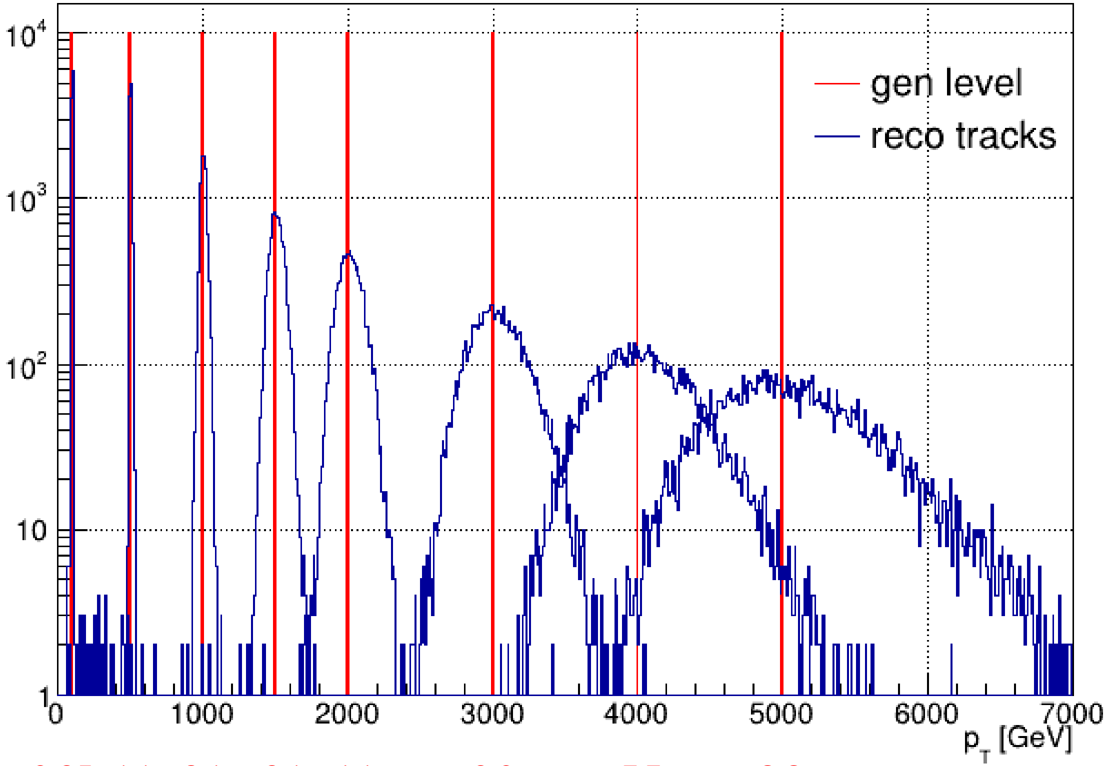
- barrel: 3 cylindrical layers
  endcaps: 7 + 7 disks
- Si sensors:
  50 µm x 1 mm macro-pixels
  $\sigma_{r\text{-}\phi}$ = 7 µm, σ_z = 90 µm
  σ_T = 60 ps

Vertex detector (VXD)

- barrel: 4 cylindrical layers
  endcaps: 4 + 4 disks
- double-layer Si sensors:
  25x25 µm^2 pixels
  $\sigma_{r\text{-}\phi}$ = 5 µm, σ_z = 5 µm
  σ_T = 30 ps

Challenge: momentum resolution at high p_T

- Muon gun samples at θ = 90° with p = 100, 500, 1000, 1500, 2000, 3000, 4000, 5000 GeV.



$\frac{\Delta p_T}{p_T}$ [%] → 0.35 1.1 2.1 3.1 4.1 6.0 7.7 8.8

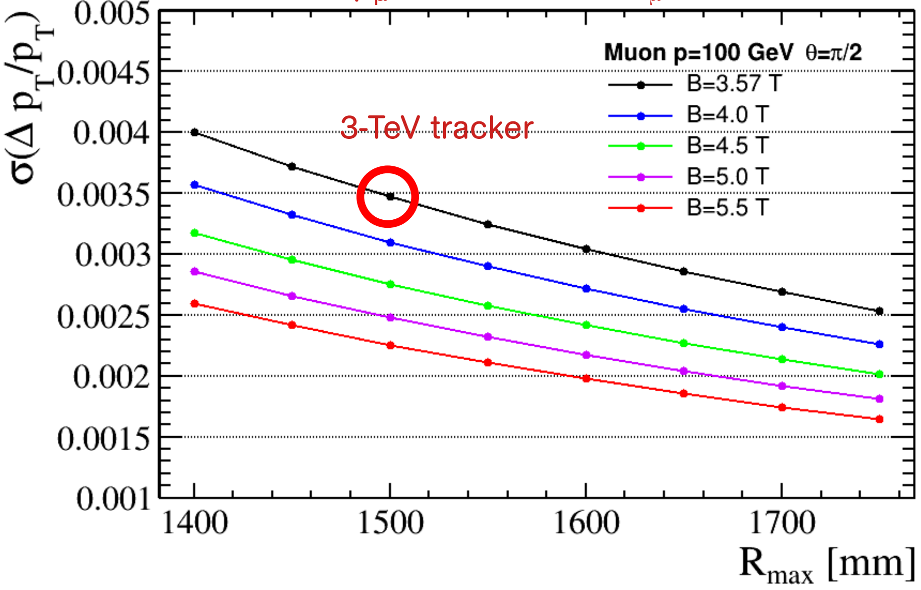
Two handles to improve

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

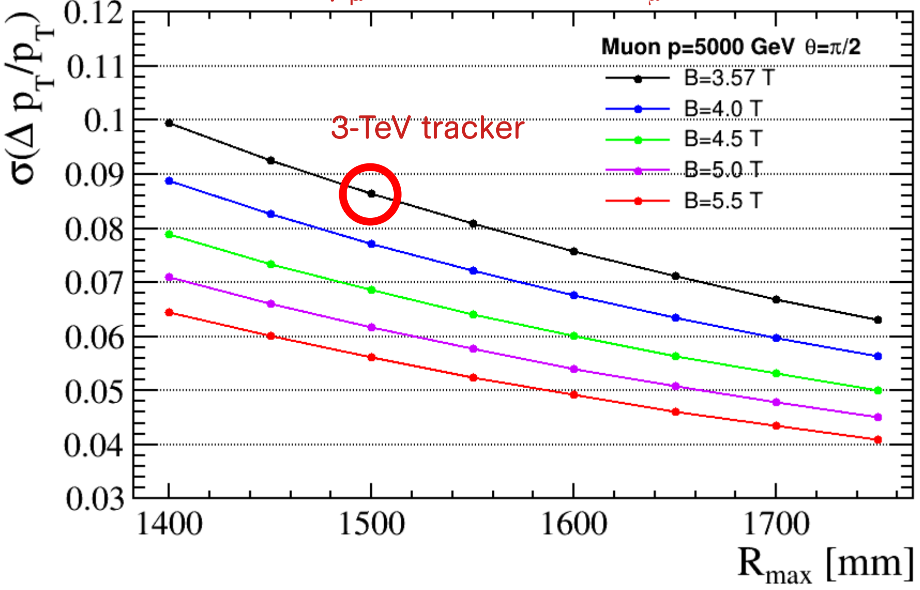
Z. Drasal and W. Riegler, NIM A 910 (2018) 127

- Increase the tracker size: cost limits, available space?
- Increase the B field intensity: technological limitations, magnet stability, cost?

p_μ = 100 GeV at θ_μ = 90°



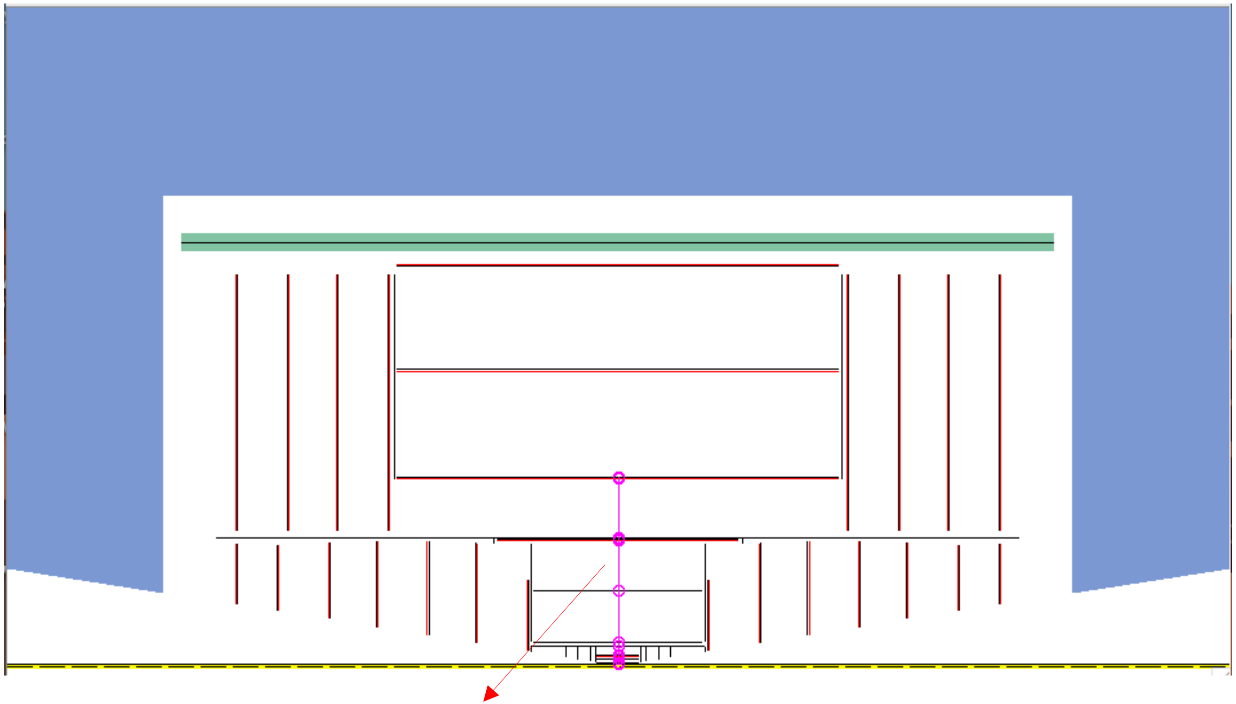
p_μ = 5000 GeV at θ_μ = 90°



Tracker geometry optimization

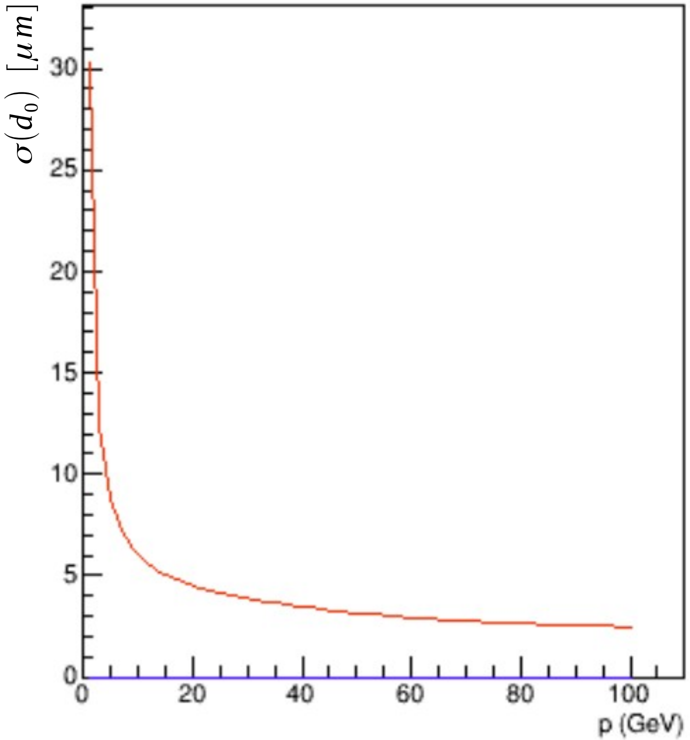
- Exploit a parametric tracker simulation written by F. Bedeschi and M. Selvaggi for FCC-ee.

p_T = 0.8 GeV at θ = 90° with B = 5 T



at B = 5 T particles with p_T < 1.1 GeV don't reach the tracker outer layer

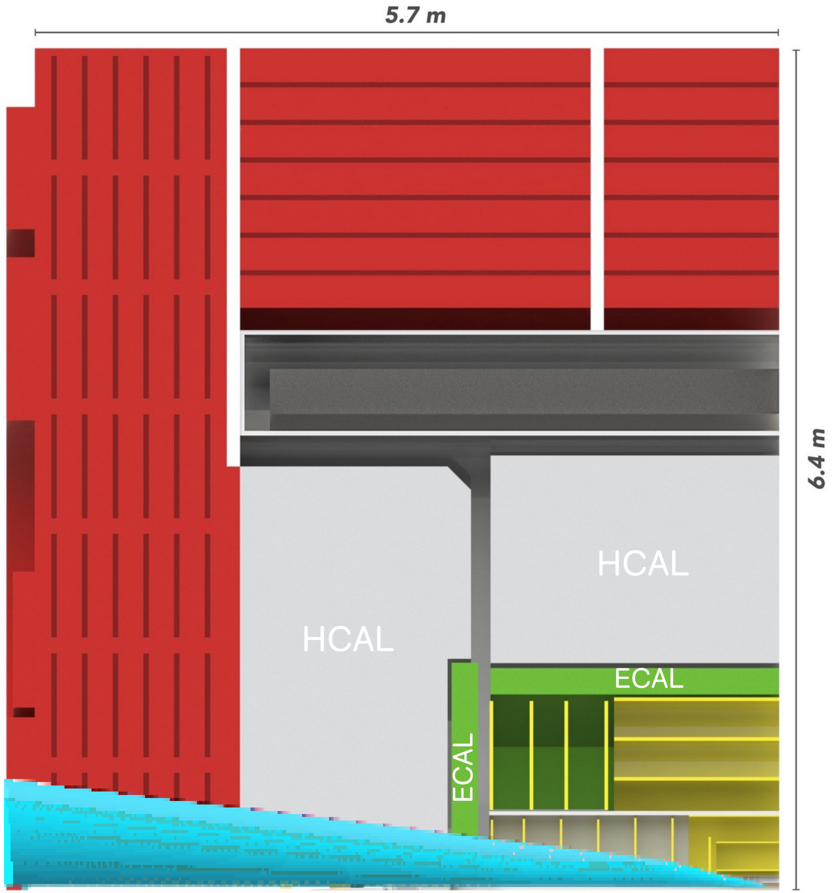
track impact parameter resolution



The calorimeters of the 3-TeV detector

Hadronic calorimeter (HCAL)

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



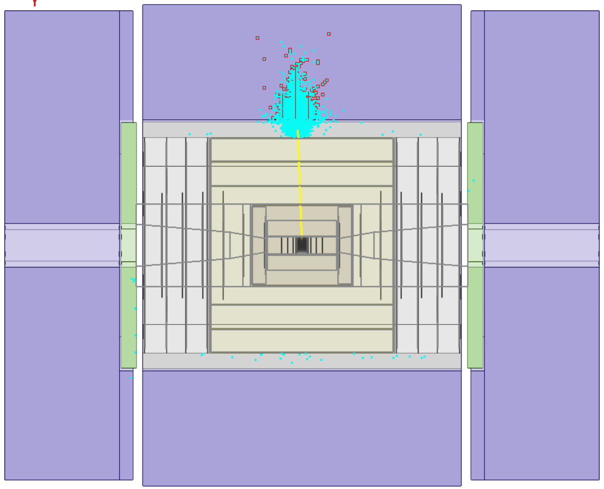
borrowed from CLIC

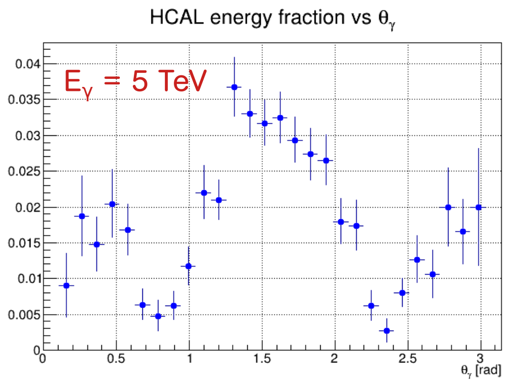
Electromagnetic calorimeter (ECAL)

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

Challenge: em and had showers containment

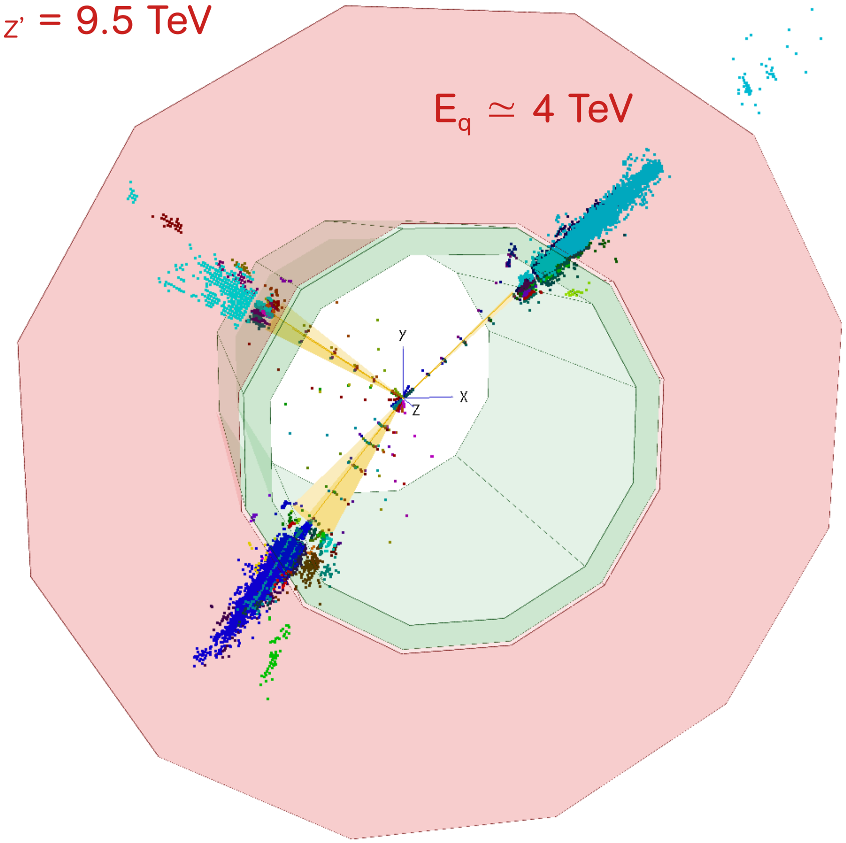
E_γ = 5 TeV





$\mu\mu \rightarrow Z' \rightarrow qq$

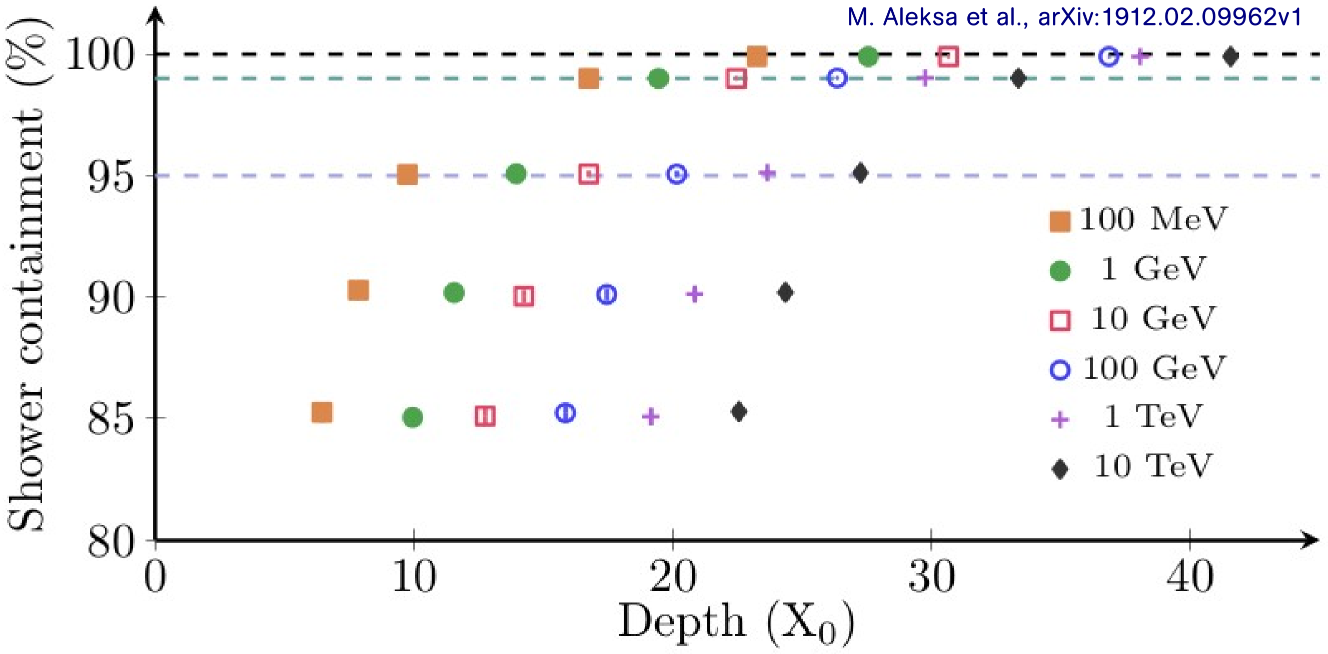
$M_{Z'}$ = 9.5 TeV



Need for deep calorimeters

- Need for deep calorimeters to contain the showers produced by very energetic particles, but also capable of reconstructing softer objects with energies below 100 GeV.

M. Aleksa et al., arXiv:1912.02.09962v1



Muon detectors

- The accomplishment of the muon collider physics programme will require the reconstruction and identification of muons from a few GeV up to a few TeV.

- Measuring the momentum as precisely as possible and determining the charge of very high-p_T muons will be challenging.

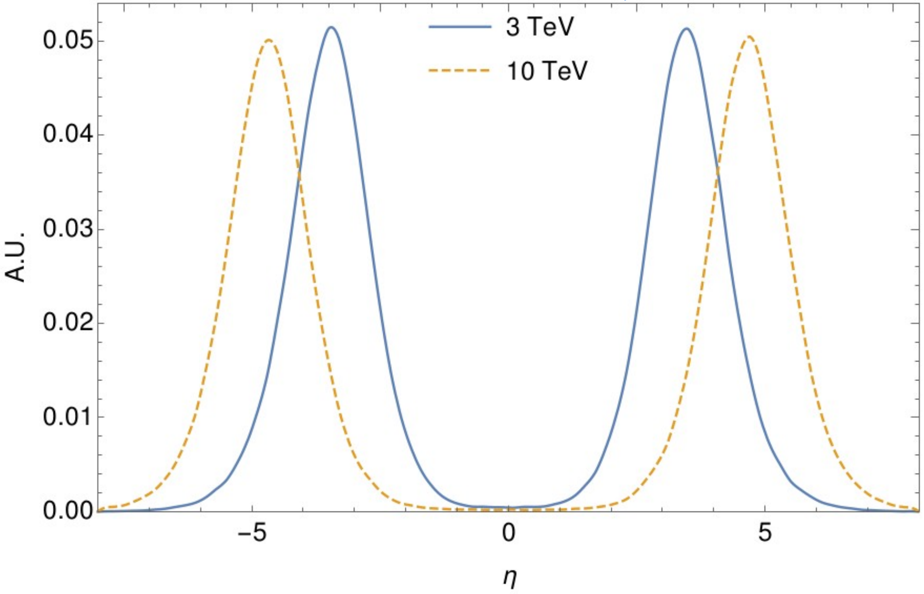
- A novel global approach will be needed which possibly combines information from the tracker, the calorimeters, and the muon detectors.

Forward muon detection

- As an addition to the central detector, the capability to detect the forward-scattered muons in ZZ-fusion processes would be a desideratum.

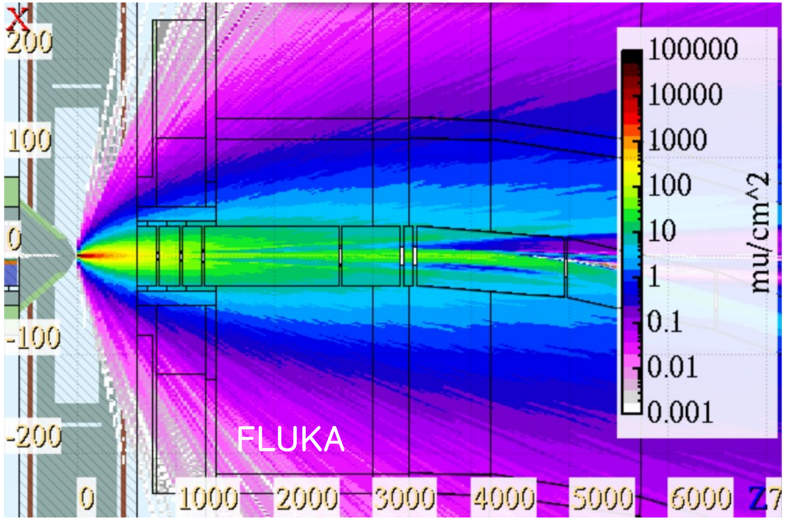
forward muon pseudorapidity in $\mu\mu \rightarrow H\mu\mu$

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



expected trajectories of forward muons

D. Calzolari, MDI Study Meeting on April 28, 2023



Final considerations (I)

- We need a detector capable of reconstructing efficiently and with high precision particles in a wide energy range.
- The background levels inside the detector are mainly determined by the nozzles material and shape.
- The longitudinal size of the detector is constrained by the position of the machine final focusing magnets ($L^* = 6$ m).
- As a first step, determine the most convenient configuration of the magnet system, then build around it the detector: vertex detector, tracker, calorimeters, muon detector.

Final considerations (II)

- The capability of detecting the forward-scattered muons of the ZZ-fusion process would be very desirable.
- How do we measure the luminosity?
- Concerning a dedicated PID detector, are we planning on doing flavour physics? Do we need it and is there room to fit it?

There are a lot of work ahead and plenty of options to be explored and tested by a limited bunch of people.

There are many possibilities to contribute.
Please join the endeavor!

Backup

d_0 resolution with the 3-TeV detector