First studies for a 10 TeV Muon Collider detector

Laura Buonincontri, Luca Giambastiani, Alessandro Montella

Tracker and Calo meeting - 13 Sept. 2022

Outlook

- Tracking system
  - p_T resolution
  - Requirement on B decay vertex
- Electromagnetic calorimeter design
- Hadronic calorimeter (very first studies)

Tracking system

Goals:

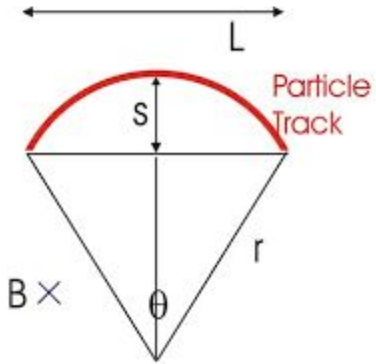
- Apply the formulas for the momentum resolution to the 3 TeV case
- Check difference between formulas and tracking with BIB
- Study how the resolution varies at different p_T

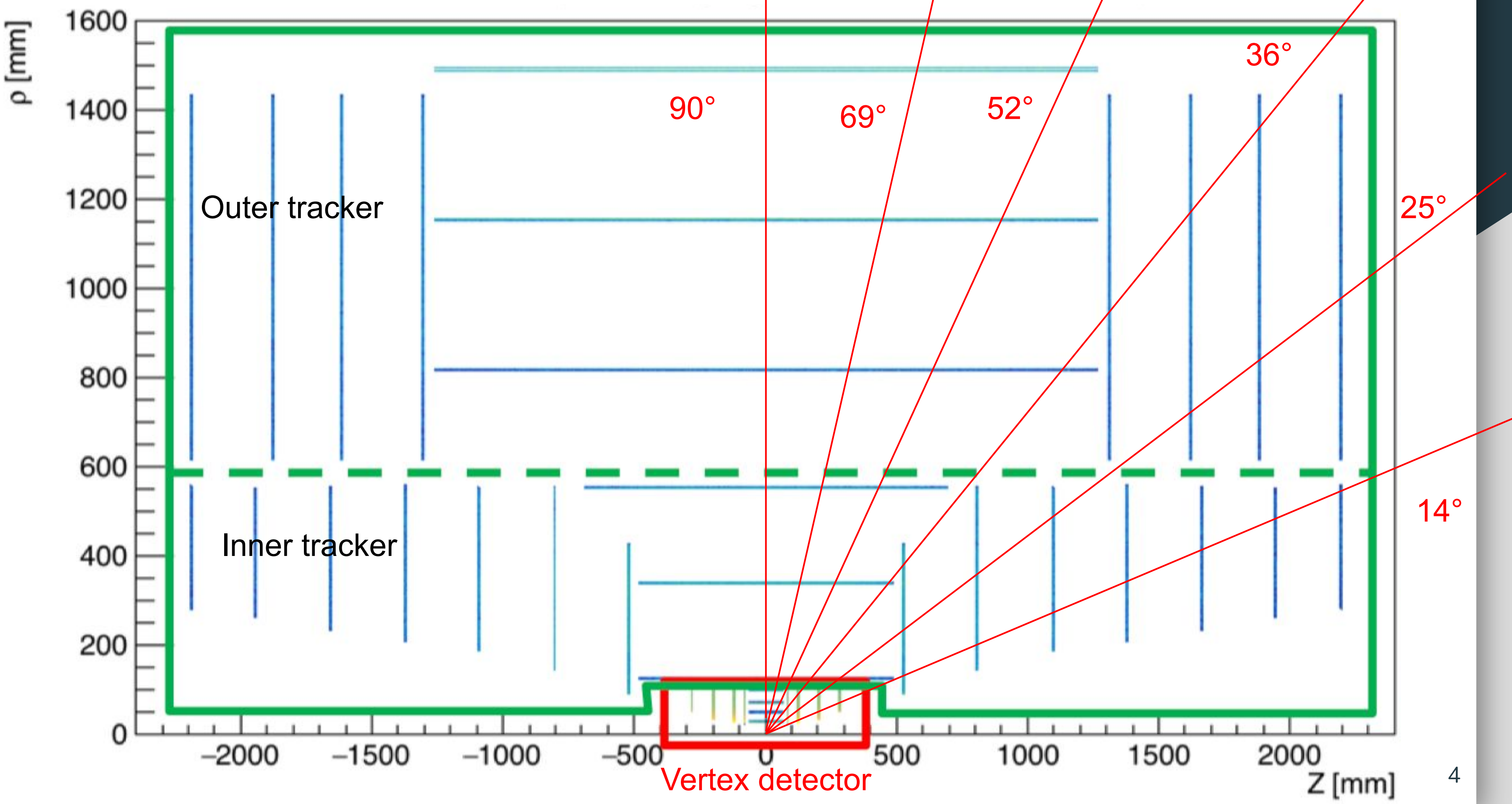
$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{\sigma[\mathrm{m}]\, p_T[\mathrm{GeV/c}]}{0.3\, B[\mathrm{T}]\, L[\mathrm{m}]^2}\sqrt{\frac{720}{N+4}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.014}{\beta\, 0.3\, B[\mathrm{T}]\, L[\mathrm{m}]}\sqrt{\frac{x_{\mathrm{tot}}}{X_0}}\left(1 + 0.038 \ln \frac{x_{\mathrm{tot}}}{N\, X_0}\right)$$

Procedure:

- Assume the same magnetic field (3.57 T), dimensions and material budget of the 3 TeV detector
- Assume a hit resolution of 7 μm in the transverse plane
- Select 6 polar angles with respect to the beam pipe
- Count the number of layers that a particle have to cross at different angles
- Apply formulas to determine the resolution for particles of various energies





ρ [mm]
1600
1400
1200
1000
800
600
400
200
0
−2000
−1500
−1000
−500
0
500
1000
1500
2000
Z [mm]
Outer tracker
Inner tracker
Vertex detector
90°
69°
52°
36°
25°
14°

- B = 3.57 T
- Spatial hit resolution: 7 µm

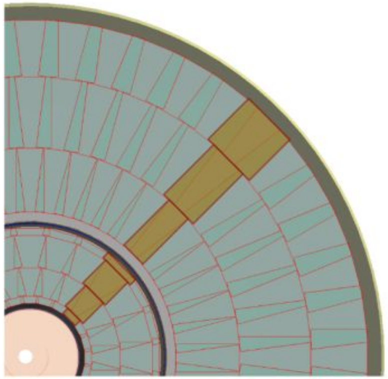
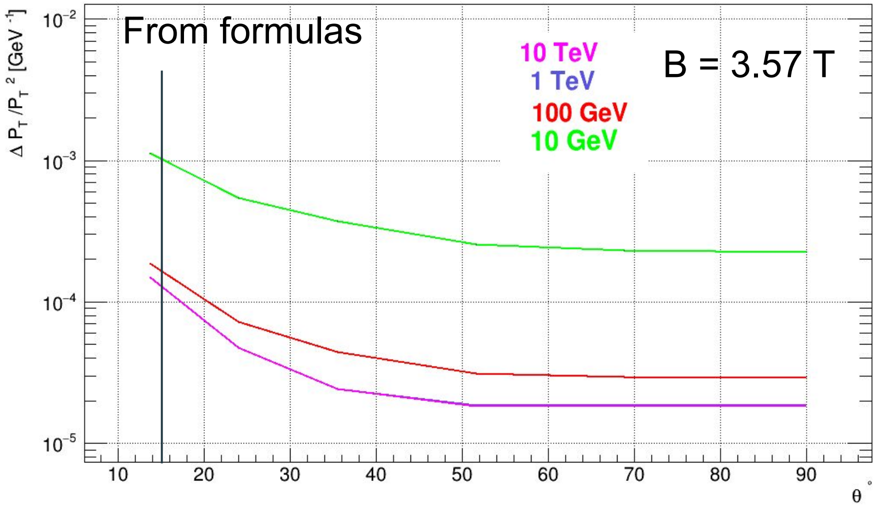
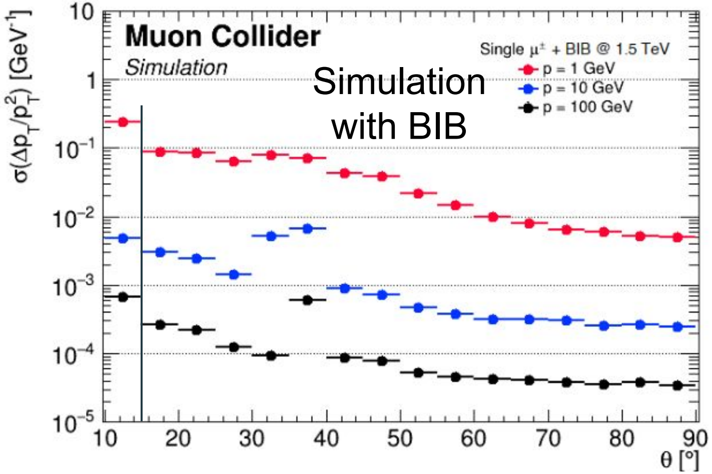


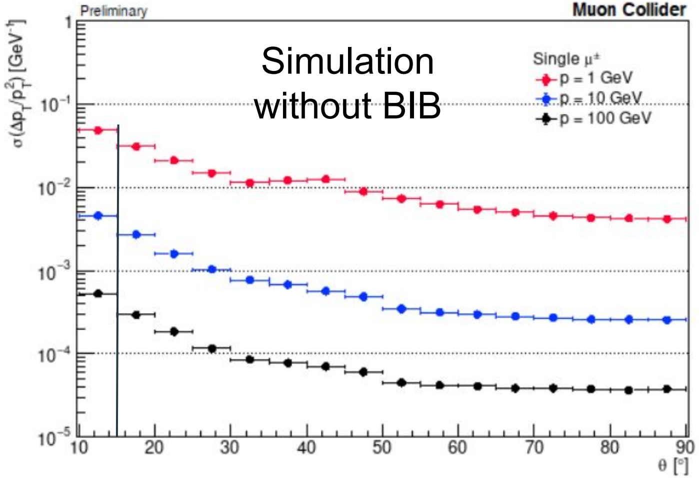
Figure 26: Transverse view of the sixth inner disk and the third outer tracker disk.

Polar Angle [°]	x/X^0	L [m]	N layers (double layers are double counted)
14	0.24	0.550	11
25	0.22	0.950	13
36	0.205	1.350	12
52	0.125	1.500	14
69	0.105	1.500	14
90	0.1	1.500	14

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







- 10 TeV and 1 TeV curves from formulas overlap because the spatial resolution dominates over mult. scattering: divided by p_T^2, spatial resolution is independent from p_T , while multiple scattering goes down with p_T
- At 90° the efficiencies are comparable in all three cases (central region of the detector, less affected by BIB)
- Simulations show that in the forward region (15°)
  - at 10 GeV both with and w/o BIB ~3 10^{-3}
  - at 100 GeV both with and w/o BIB ~4 10^{-4}
- Formulas show:
  - 1 10^{-3} at 10 GeV
  - 2 10^{-4} at 100 GeV

Contributions to resolution ($\Delta P_T/P_T^2$) for two angles

25 °

P_T	Multiple scattering	Single point resolution	Total resolution $\Delta P_T/P_T^2$ ($\Delta P_T/P_T$)
10 GeV	5.5e-4	4.7e-5	**5.5e-4 (0.55%)**
100 GeV	5.4e-5	4.7e-5	**7.2e-5 (0.72%)**
1 TeV	5.4e-6	4.7e-5	**4.7e-5 (4.7%)**
10 TeV	5.4e-7	4.7e-5	**4.7e-5 (47%)**

69 °

P_T	Multiple scattering	Single point resolution	Total resolution $\Delta P_T/P_T^2$ ($\Delta P_T/P_T$)
10 GeV	2.3e-4	1.8e-5	**2.3e-4 (0.23%)**
100 GeV	2.3e-5	1.8e-5	**2.9e-5 (0.29%)**
1 TeV	2.3e-6	1.8e-5	**1.9e-5 (1.9%)**
10 TeV	2.3e-7	1.8e-5	**1.8e-5 (18%)**

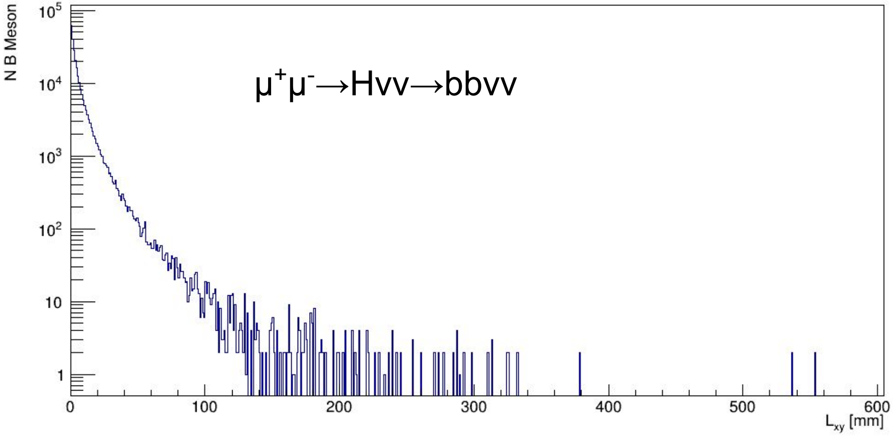
- With the current layout the formulas results are not very far from the simulation (especially in the central region)
- Above 1 TeV p_T multiple scattering contribution is negligible
  - Optimize material budget is useful only at low energy (<~ 1 TeV)
  - Can increase magnetic field, hit resolution and tracker dimension

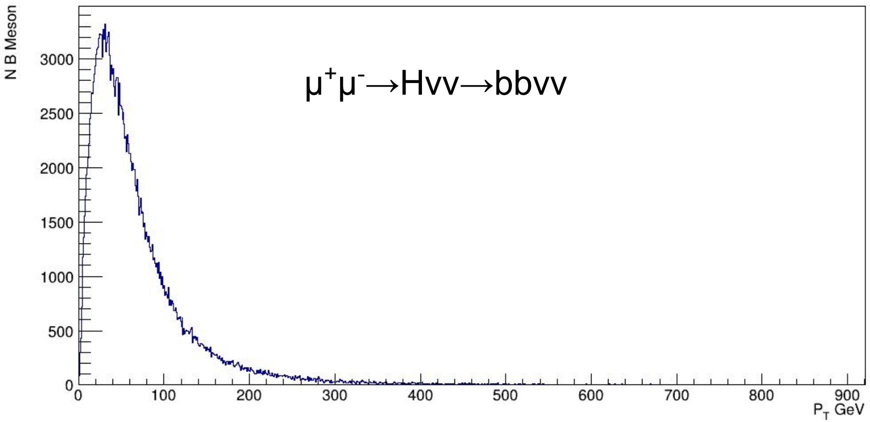
$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{\sigma[\mathrm{m}]\, p_T[\mathrm{GeV/c}]}{0.3\, B[\mathrm{T}]\, L[\mathrm{m}]^2}\sqrt{\frac{720}{N+4}}$$

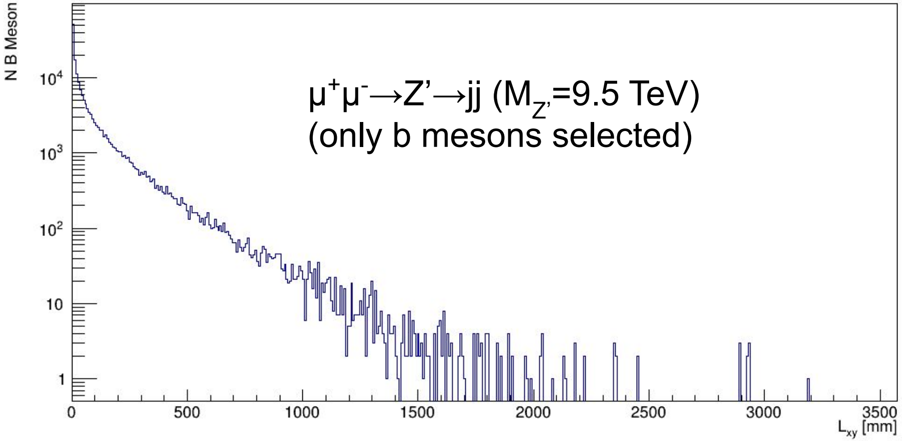
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.014}{\beta\, 0.3\, B[\mathrm{T}]\, L[\mathrm{m}]}\sqrt{\frac{x_{\mathrm{tot}}}{X_0}}\left(1+0.038\ln\frac{x_{\mathrm{tot}}}{N\, X_0}\right)$$

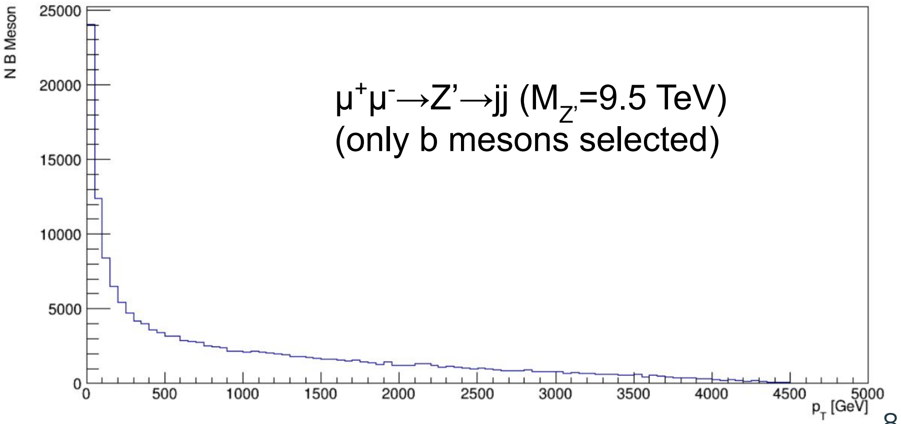
B decay vertex in the tracking system

B^+ B^- and B^0 with $|\eta| < 2.44$









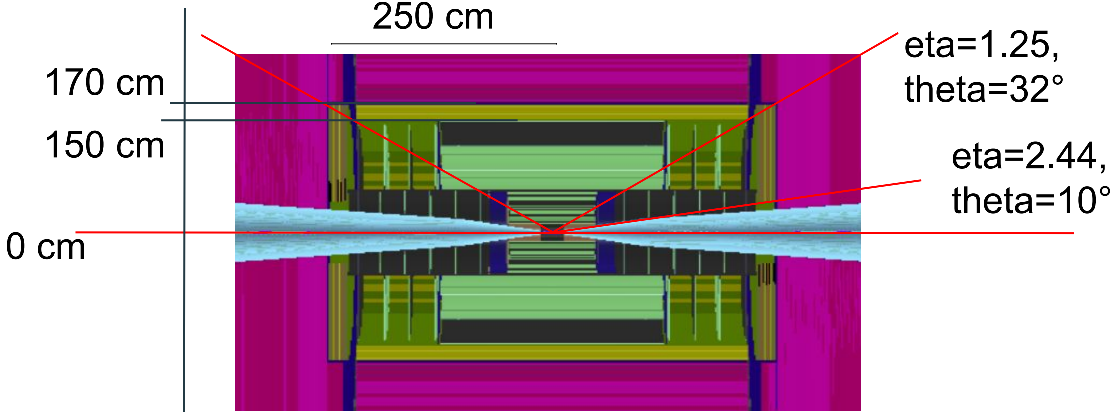
Layer Number	Radius [mm]	Ratio in H -> bb	Ratio in Z’ -> jj
Layer 1	31	0.97	0.51
Layer 2	51	0.990	0.60
Layer 3	74	0.998	0.68
Layer 4	104	1	0.74
Layer 5	127	1	0.78
Layer 6	340	1	0.93
Layer 7	554	1	0.97
Layer 8	819	1	0.991
Layer 9	1153	1	0.997
Layer 10	1486	1	0.999

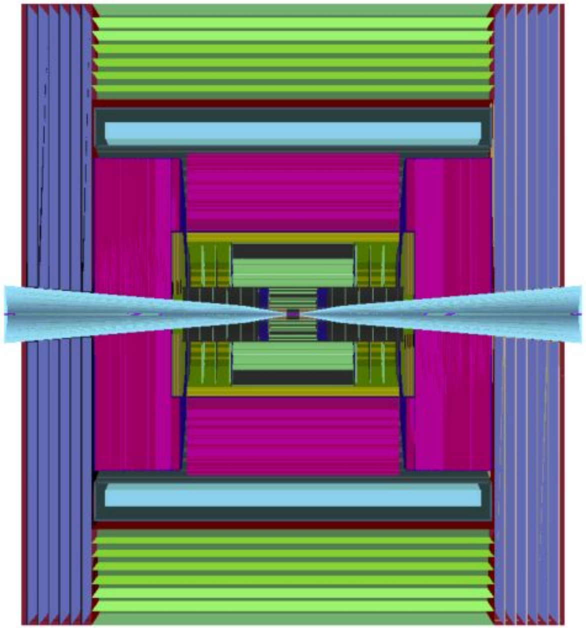
Ratio of B^+ B^- and B^0 with $|\eta| < 2.44$, that decay before the N-th layer

Half of the B meson decay within the first layer for the Z’

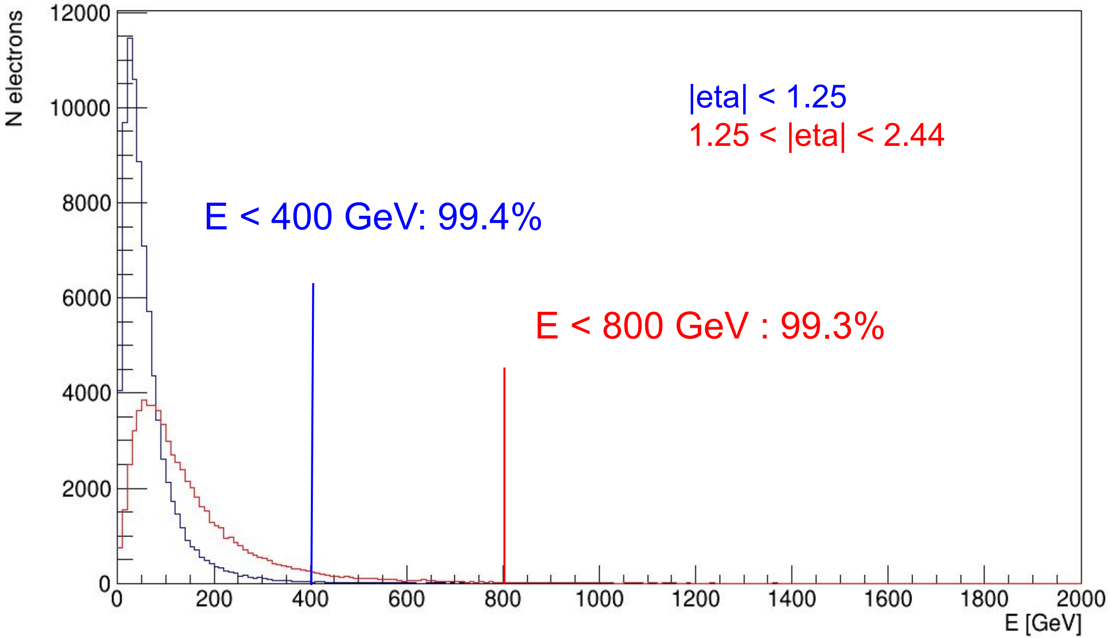
Electromagnetic calorimeter

- Study of electrons energy spectrum from the processes:
  - $\mu^+\mu^- \rightarrow H\nu\nu \rightarrow ZZ\nu\nu \rightarrow l^+l^- jj\nu\nu$
  - $\mu^+\mu^- \rightarrow Z' \rightarrow e^+e^-$ ($M_{Z'}$ =9.5 TeV)
- Separate central/forward electrons
- Run of a Geant4 simulation





Electron energy for $\mu^+\mu^- \to H\nu\nu \to ZZ\nu\nu \to l^+l^-jj\nu\nu$



Electron energy for $\mu^+\mu^- \to Z' \to e^+e^-$ at 10 TeV: all at 5 TeV

Simulation with Geant4

- ECAL setup for 3 TeV: 40 layers for a total of 20 cm, corresponding to 22 X_0
- Simulation of the Si+W ECAL calorimeter in order to understand how many radiation lengths are necessary to contain ~99% of the energy of 200 electrons with E = 400 GeV, 800 GeV and 5 TeV

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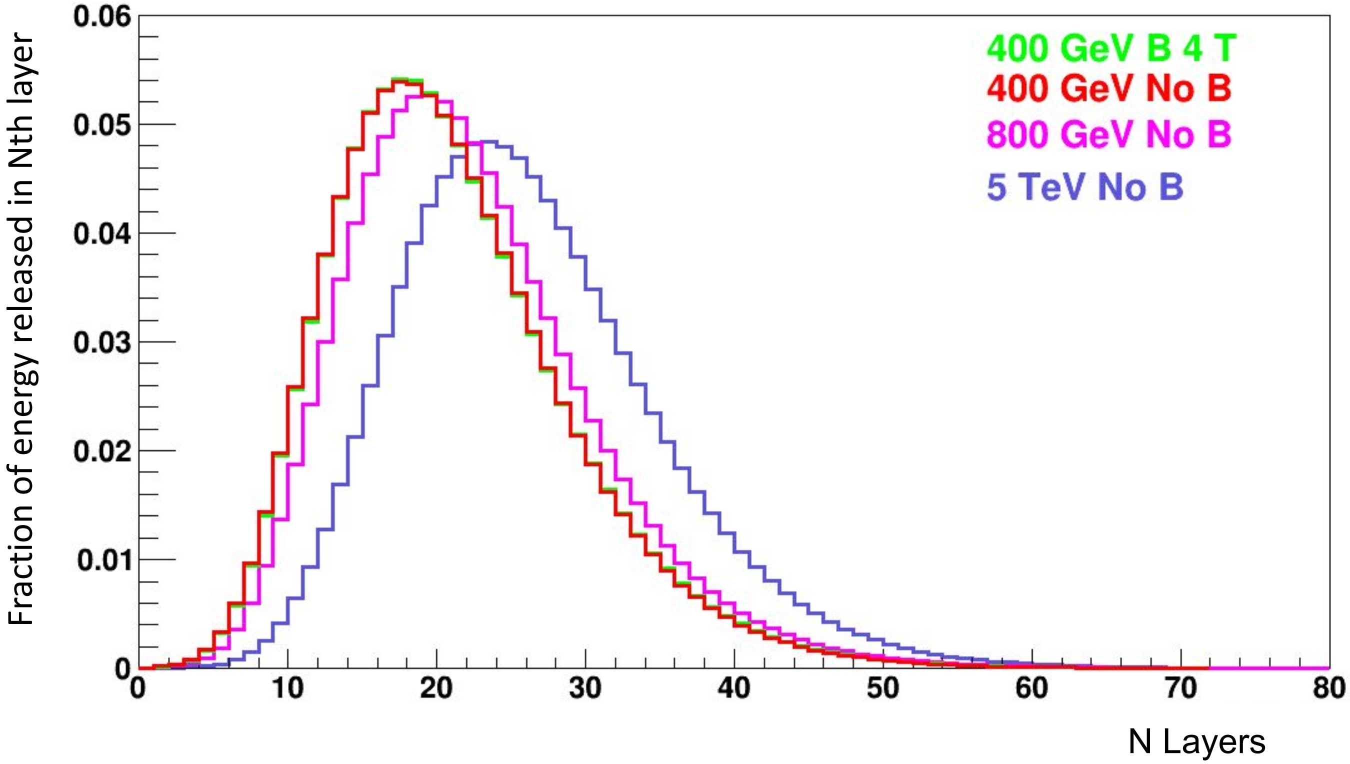
```

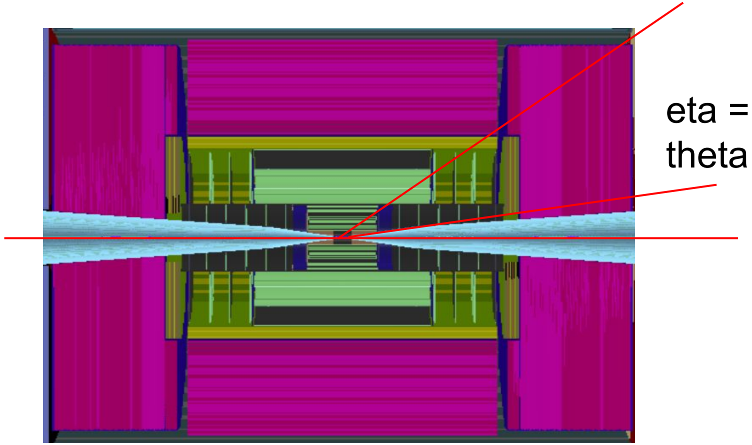
E	Number of X_0	Number of Layers	ECAL length	λ_I	B (z)
400 GeV	27.1	45	22.73 cm	1.20	0 T
400 GeV	27.1	45	22.73 cm	1.20	4 T
800 GeV	28.3	47	23.73 cm	1.26	0 T
5 TeV	30.8	51	25.76 cm	1.36	0 T

Plot from the simulation



Hadronic Calorimeter

- 3 TeV HCAL: 60 layers of steel absorber and plastic scintillating tiles, 159 cm corresponding to 7.5 λ_I
- Study of energy spectrum for positive pions and protons from the process $\mu^+\mu^- \rightarrow Z' \rightarrow jj$
- Divide central (|eta| < 1.06) and forward (1.06 < |eta| < 2.44) regions

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     Steel235:    500 um   ---> sum =      6 cm  =  3.398 Radl  = 0.3541 NuclearInteractionLength
     Steel235:    1.9 cm   ---> sum =   2.28 m   =  129.1 Radl  =  13.45 NuclearInteractionLength
 G4_POLYSTYRENE:      3 mm   ---> sum =     36 cm  = 0.8714 Radl  = 0.5236 NuclearInteractionLength
       Copper:    100 um   ---> sum =    1.2 cm  = 0.8359 Radl  = 0.07698 NuclearInteractionLength
          PCB:    700 um   ---> sum =    8.4 cm  = 0.4798 Radl  = 0.1737 NuclearInteractionLength
     Steel235:    500 um   ---> sum =      6 cm  =  3.398 Radl  = 0.3541 NuclearInteractionLength
       Air_MC:    2.7 mm   ---> sum =   32.4 cm  = 0.001061 Radl  = 0.0004545 NuclearInteractionLength
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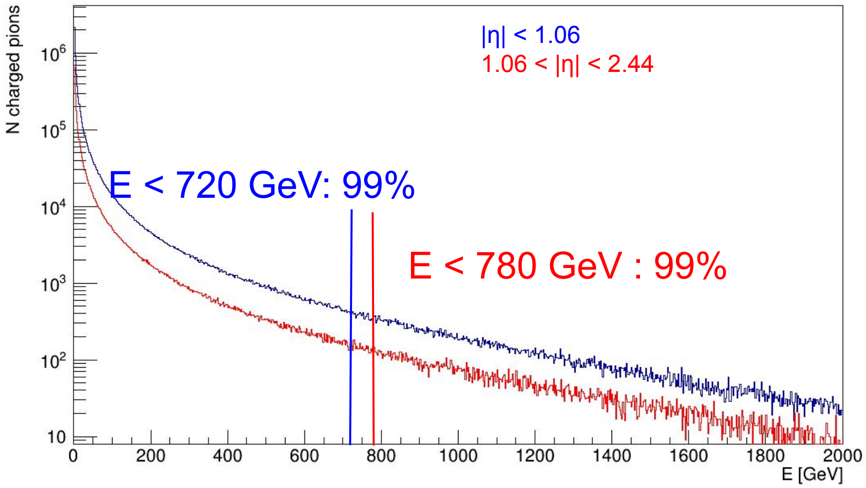
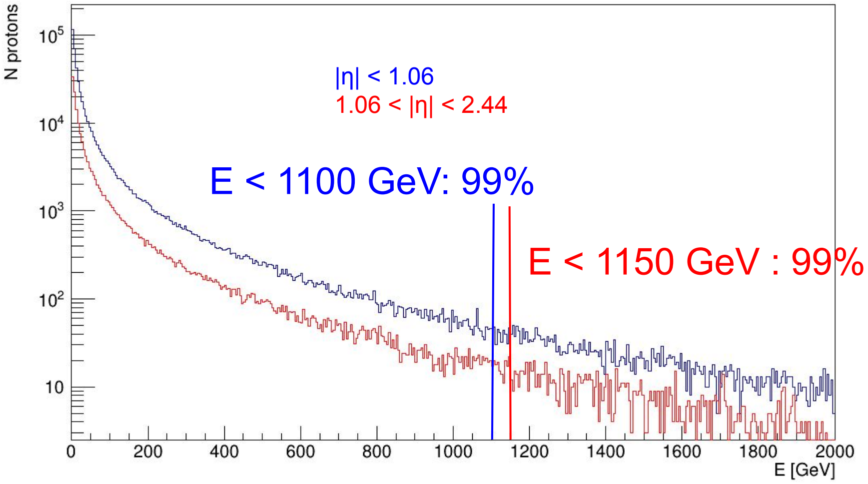
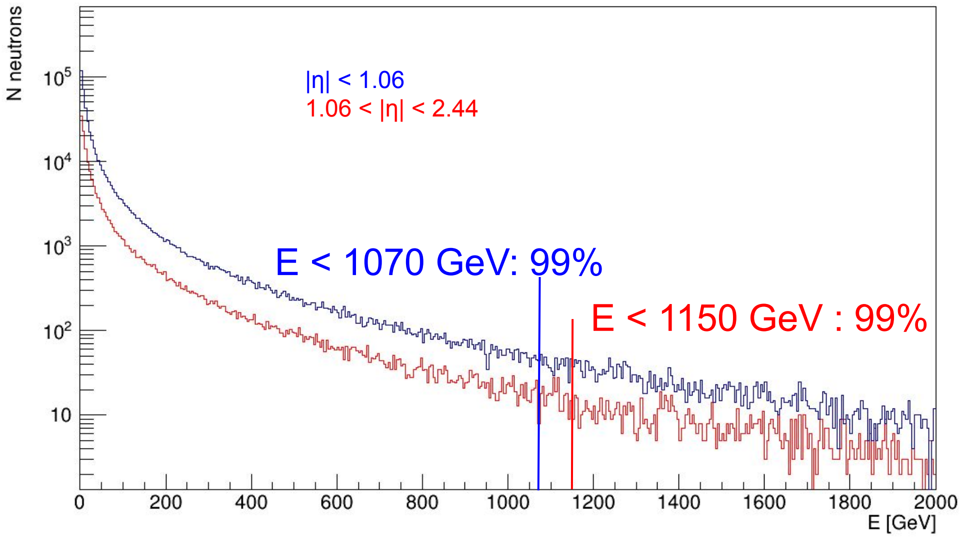


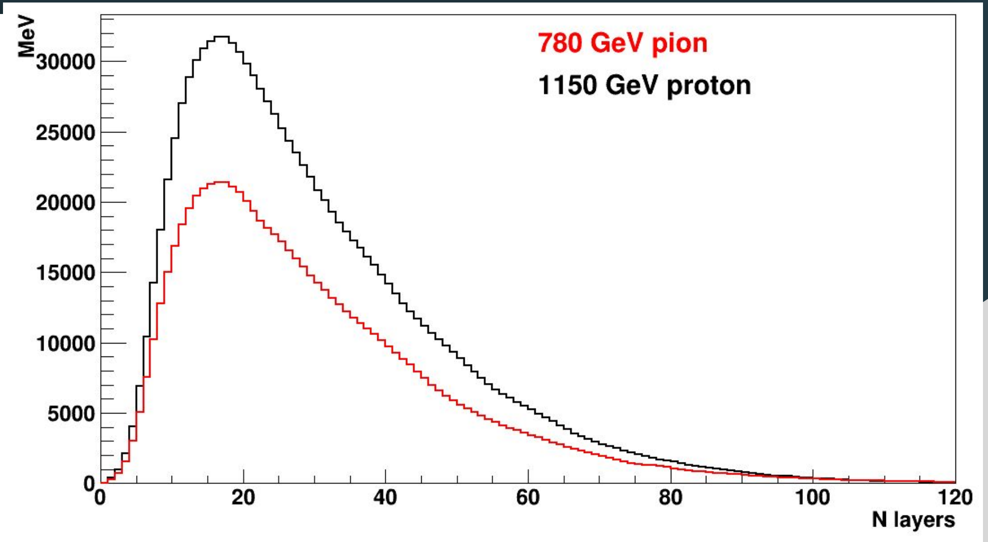




$\mu^+\mu^- \rightarrow Z' \rightarrow jj$, $M_{Z'}$ = 9.5 TeV

First attempts: only HCAL

- The two showers have very similar profile
- Unable to absorb 100% of energy: 6% is missing with very large number of layers
  - Lost neutrinos?
  - Slow neutrons?
- Should include ECAL in front of HCAL



Particle	Energy [GeV]	N layers to lose 90% E_{TOT}	N layers to lose 80% E_{TOT}	Energy released in 51 ECAL layers
Pion (+)	780 GeV	69 layers (8.6 λ_I)	48 Layer	24%
Proton	1150 GeV	69 layers (8.6 λ_I)	48 layers	20%

Summary

- Tracking resolution from formulas is close to values from simulation
  - A factor 2-3 underestimate in the forward region
  - Discuss on how to modify in order to better suit 10 TeV collisions
    - It already gives values similar to FCC-hh in the central region
    - To optimize for high-energy particles, can increase B, dimension or get better hit spatial resolution
    - To-do: apply resolution from formulas to H->$\mu^+\mu^-$ and tune parameters to get a certain invariant mass resolution
- ECAL thickness of 51 layers (vs 40 of 3 TeV detector) is enough to absorb 99% of energy from a 5 TeV electron
- HCAL thickness of 69 layers (vs 60 of 3 TeV detector) can absorb 90% of energy from 780 GeV positive pions and 1150 GeV protons (99th percentile with $\mu^+\mu^-\rightarrow Z'\rightarrow jj$)

Backup

Comparison with FCC-hh

69° (Compare with η=0 in the plot)

P_T	Multiple scattering	Single point resolution	Total resolution $\Delta P_T/P_T^2$ ($\Delta P_T/P_T$)
10 GeV	2.3e-4	1.8e-5	**2.3e-4 (0.23%)**
100 GeV	2.3e-5	1.8e-5	**2.9e-5 (0.29%)**
1 TeV	2.3e-6	1.8e-5	**1.9e-5 (1.9%)**
10 TeV	2.3e-7	1.8e-5	**1.8e-5 (18%)**

25° (η=1.5)

P_T	Multiple scattering	Single point resolution	Total resolution $\Delta P_T/P_T^2$ ($\Delta P_T/P_T$)
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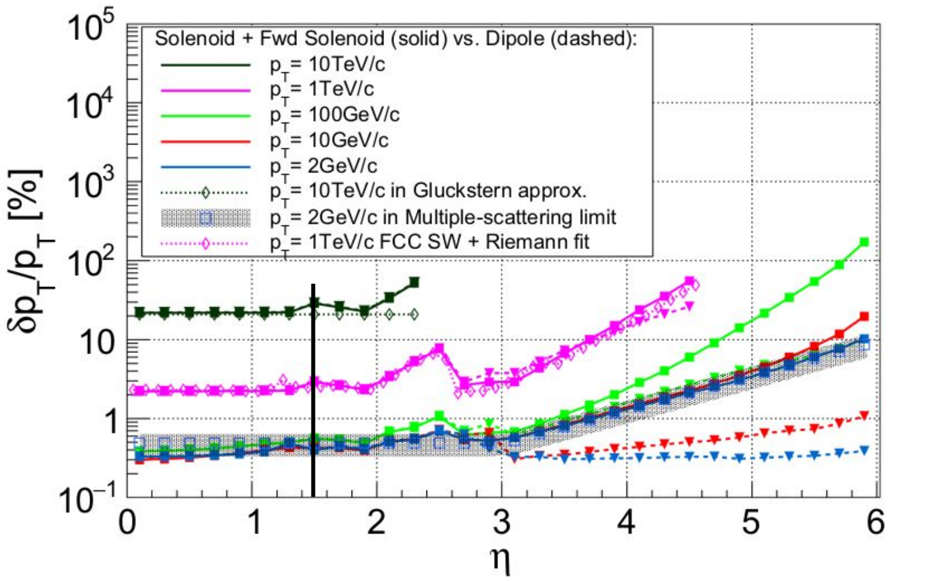
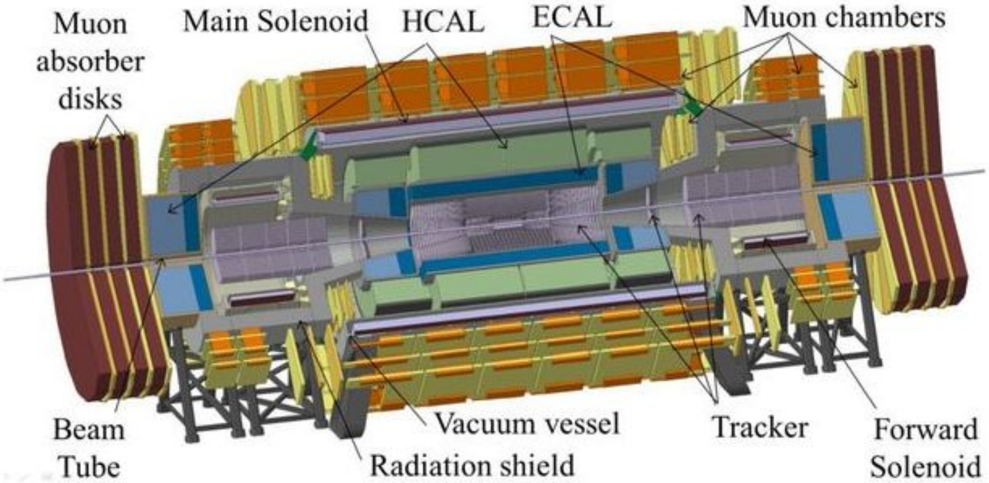


- 12 detector layers
- Transverse path length (L=1.55 m)
- σ = 7 μm in the r-φ plane
- B = 4 T
- $x/X_0 = 0.2$

FCC week 2017: New FCC-hh Detector Baseline



Main solenoid:

- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) on outside of main and forward solenoids
- Assembly and Services see next talk

Forward solenoid:

- Tracker inside solenoid
- Forward calorimeters after forward solenoids
- Enclosed by radiation shield

(to shield muon chambers from neutrons emanating from forward calorimeters)

Material Budget