Toward 10 TeV detector studies

Muon Collider Collaboration - Annual meeting

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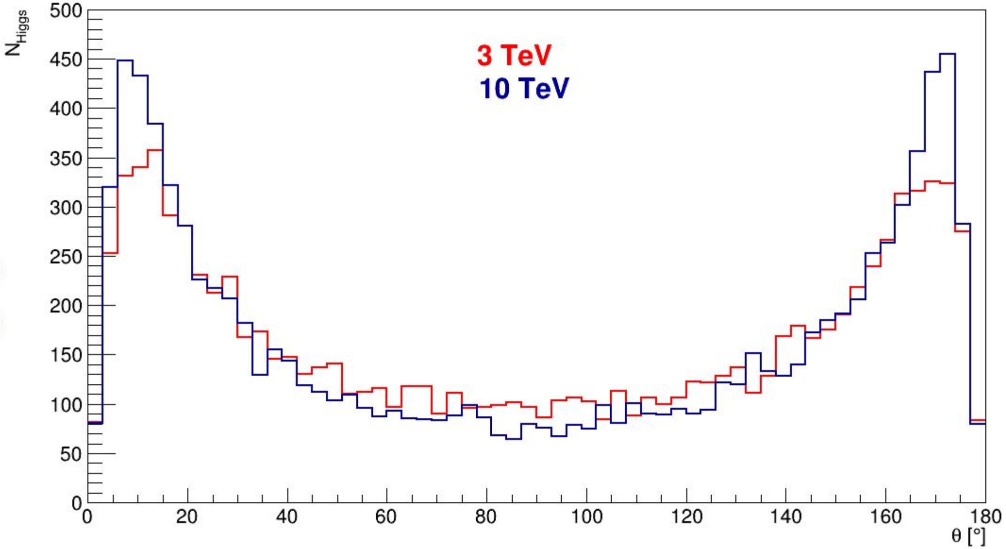
Overview

- Generator-level study of Standard Model and Beyond the Standard Model processes to understand the characteristics of processes at 10 TeV muon collider
- Madgraph Monte Carlo has been used to:
  - generate Standard Model samples at 3 and 10 TeV:
    - $\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu$, $H \to b\bar{b}$
  - Beyond the Standard Model at 10 TeV:
    - $\mu^+\mu^- \to Z\nu_\mu\bar{\nu}_\mu$, $Z \to jj\ (l^+l^-)$, (m_Z = 5 TeV)
    - $\mu^+\mu^- \to Z' \to jj(l^+l^-)$, $m_{Z'}$ = 9.5 TeV
- First studies on tracking system and calorimeter requirements at a 10 TeV muon collider

Higgs at 10 TeV vs 3 TeV: polar angle

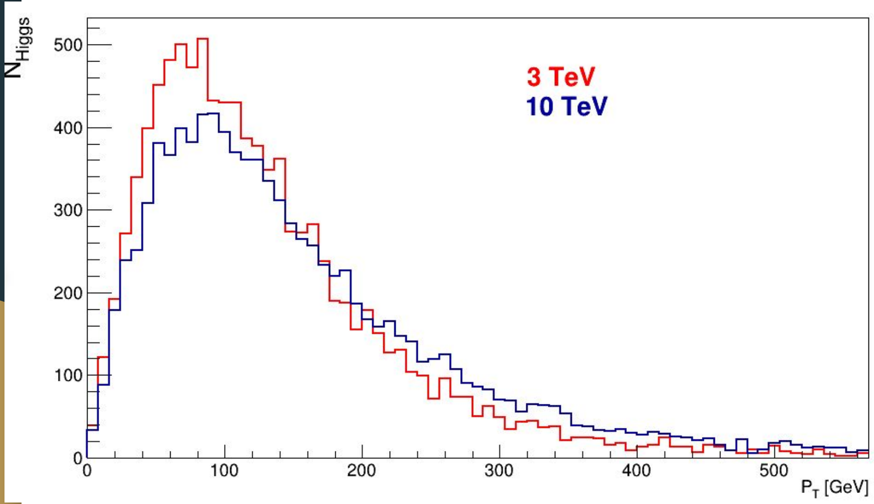
- $\mu^+ \mu^- \rightarrow H\nu_\mu \bar{\nu}_\mu \rightarrow b\bar{b}\nu_\mu \bar{\nu}_\mu$ process produced with Madgraph at 3 and 10 TeV (generator level requirements on both b quarks: η<3, P_T > 5 GeV)
- Higgs at 10 TeV are more forward with respect to 3 TeV



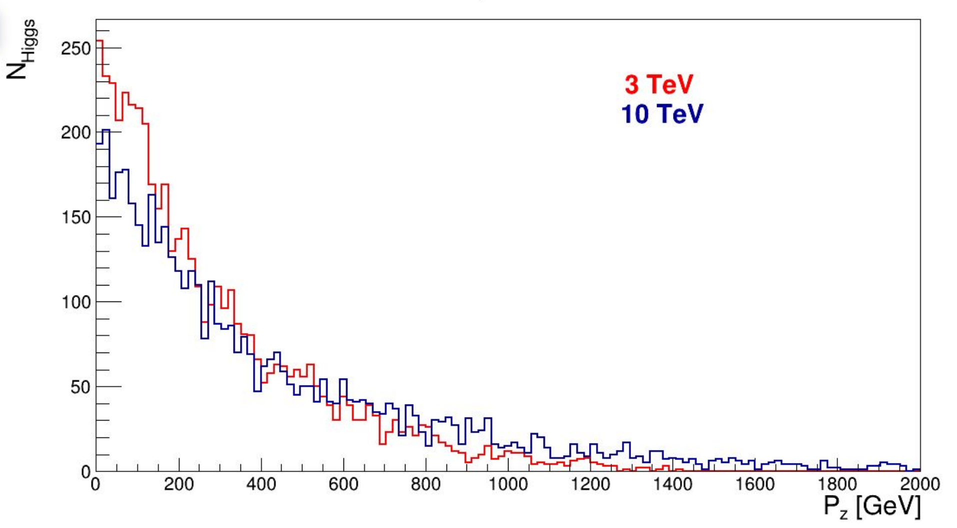
Higgs polar angle

Higgs at 10 TeV vs 3 TeV: momentum distributions

- Longer tails in P_T and P_Z at high longitudinal and transverse momentum at 10 TeV



Higgs transverse momentum [GeV]



Higgs longitudinal momentum [GeV]

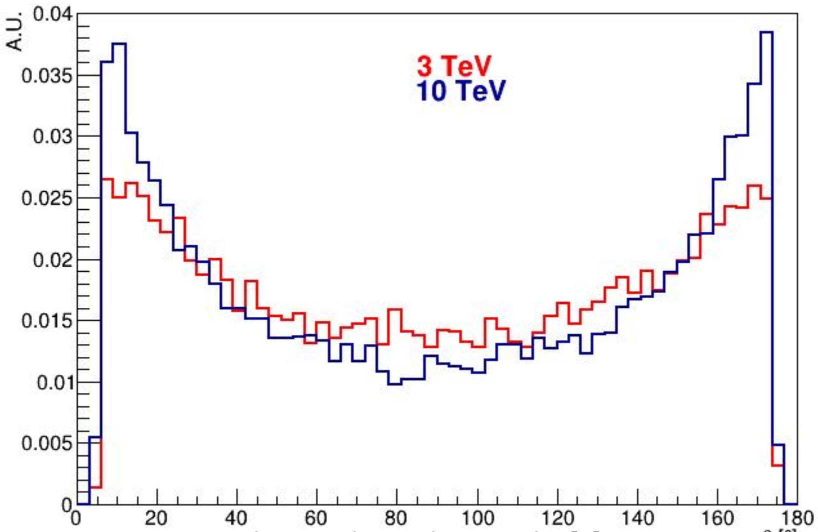
b quarks in $\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu$, $H \to b\bar{b}$: 10 TeV vs 3 TeV

- 10 TeV b quarks from the Higgs decay are more forward
- Aperture between two b quark comparable between 3 and 10 TeV

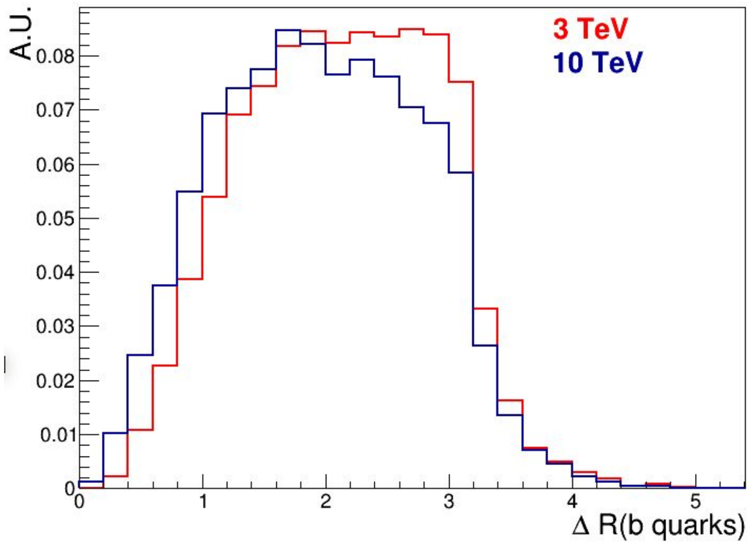
$\sigma(\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu \to bb\nu_\mu\bar{\nu}_\mu)$ = 263 fb at 3 TeV
$\sigma(\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu \to bb^{-}\nu_\mu\bar{\nu}_\mu)$ = 365 fb at 10 TeV

Within the 3 TeV acceptance:
N_{Hbb}(3 TeV, L=1 ab^{-1})=227 k events
N_{Hbb}(10 TeV, L=10 ab^{-1})=3.0 M events

$\Delta R = \sqrt{(\Delta\varphi^2 + \Delta\eta^2)}$

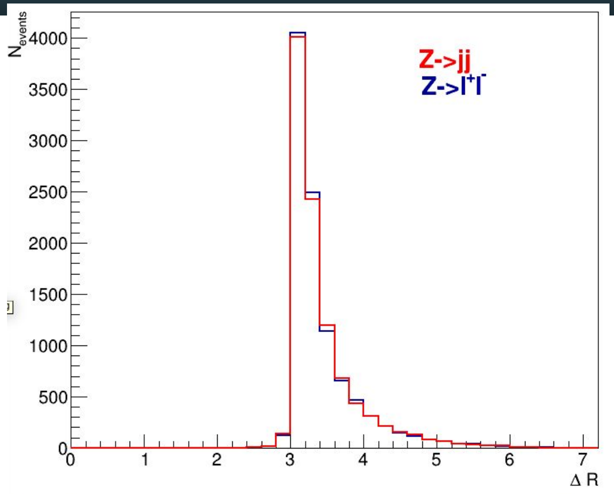


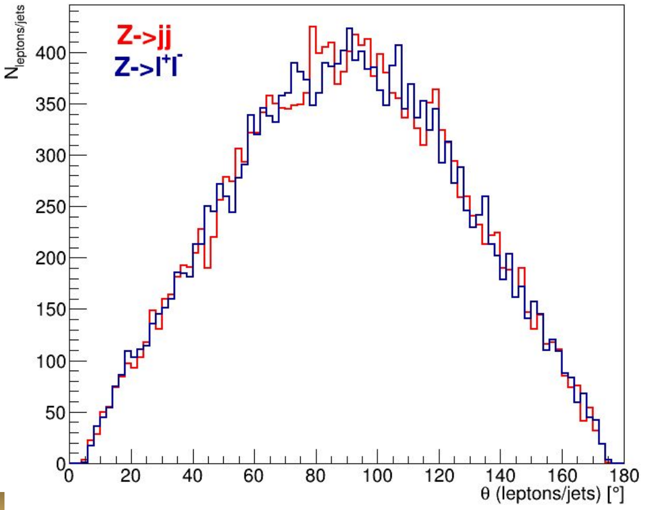
b quarks polar angle [°]

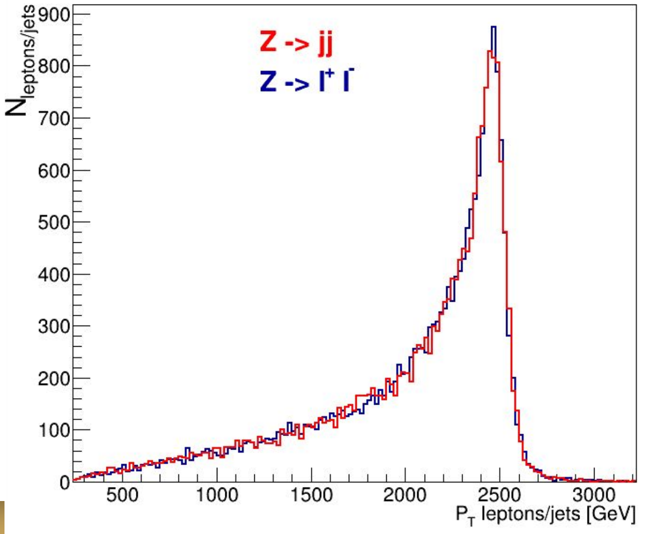


Beyond the Standard Model processes: heavy states via VBF

- $\mu^+\mu^- \to Z\nu_\mu\bar{\nu}_\mu, Z \to jj$ or l^+l^-, (m_Z = 5 TeV) at 10 TeV
- heavy Z are central in the detector
- Large aperture between final states jets/leptons pairs

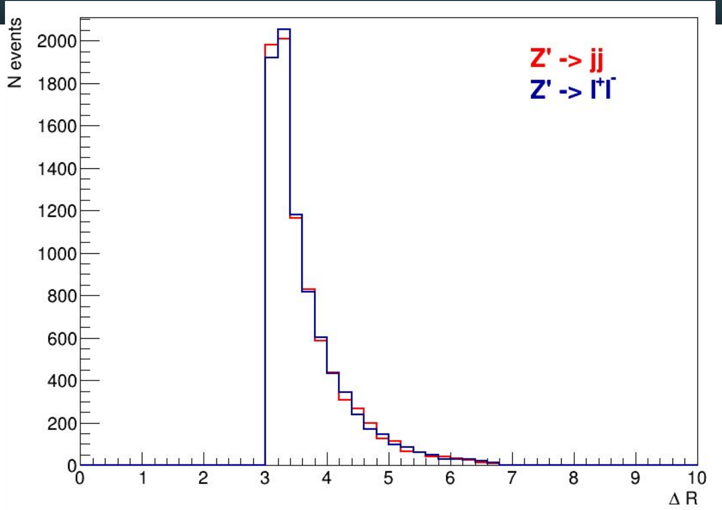


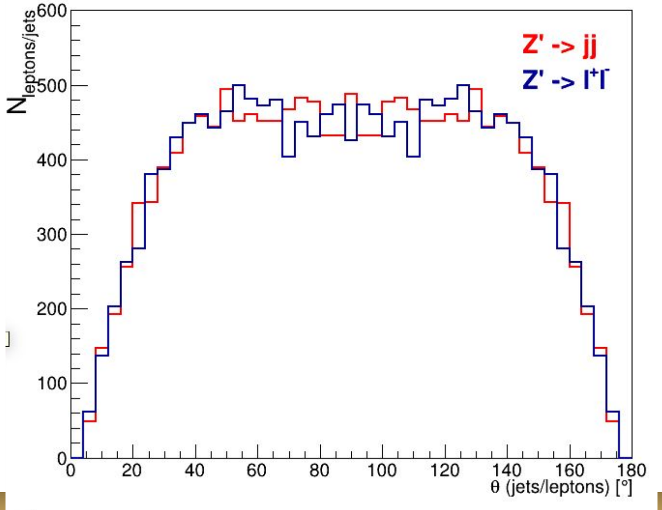


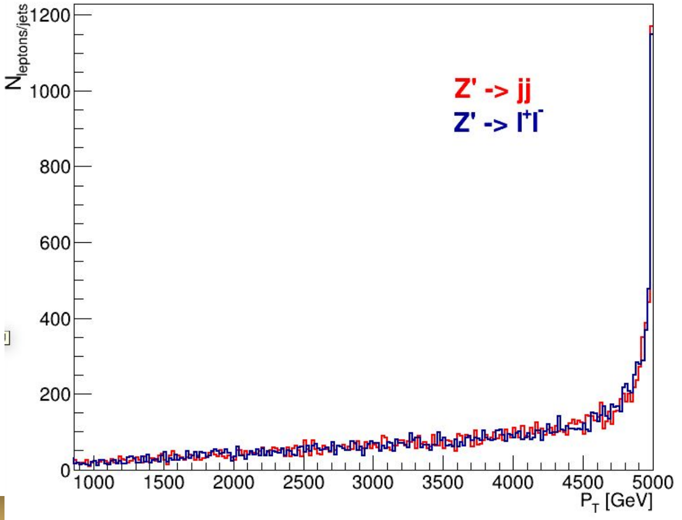


Beyond the Standard Model processes: heavy states s channel

- $\mu^+ \mu^- \rightarrow$ Z'$\rightarrow$ jj(l^+l^-), $m_{Z'}$ = 9.5 TeV at 10 TeV
- Z' final state particles are central in the detector
- Large aperture between final states jets/leptons pairs







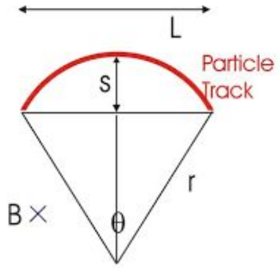
Tracking studies

- Goal: evaluate of the track momentum resolution for high p_T tracks as a function of the polar angle
- Understand how the momentum resolution can affect invariant mass distributions at 10 TeV
- Momentum resolution as a function of the polar angle are calculated with the formulas:

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

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

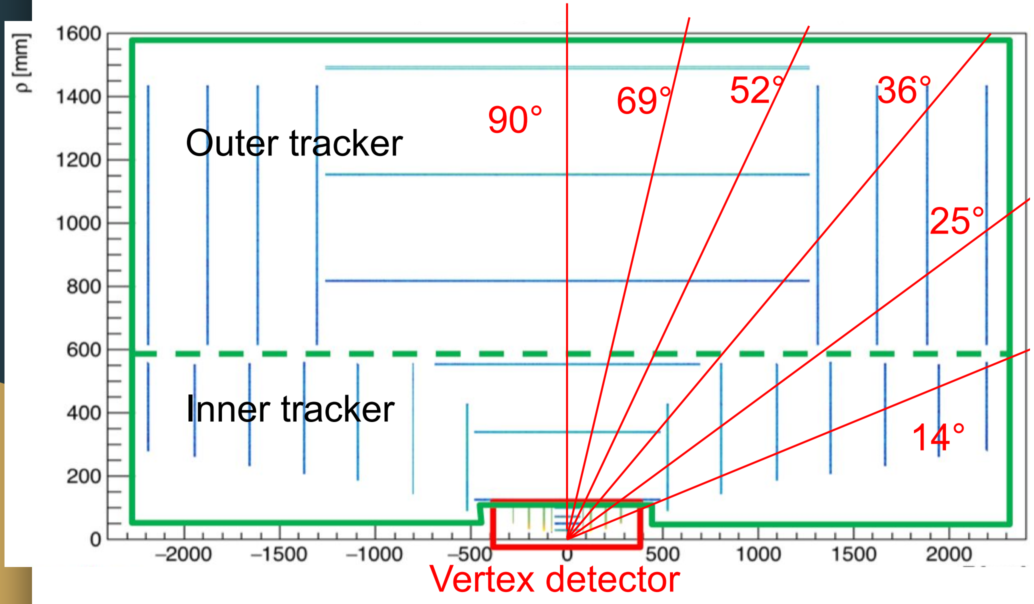
- *B*: magnetic field
- σ is the single point resolution
- x_{tot}/X_0: material budget
- *N*: number of layers
- *L*: distance between the first and the last point in the transverse plane

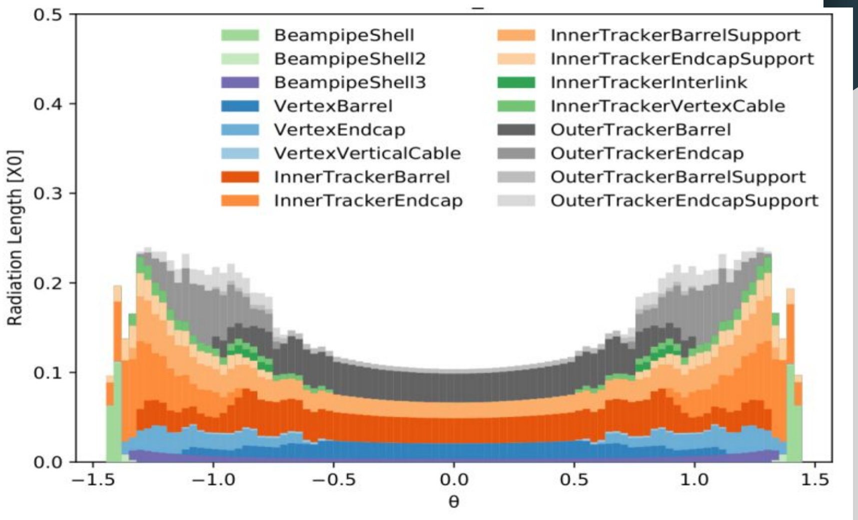


Formulas compared with the momentum resolutions obtained at 3 TeV:

- At 3 TeV: B=3.57 T, dimensions and material budget of the 3 TeV detector

Tracking studies

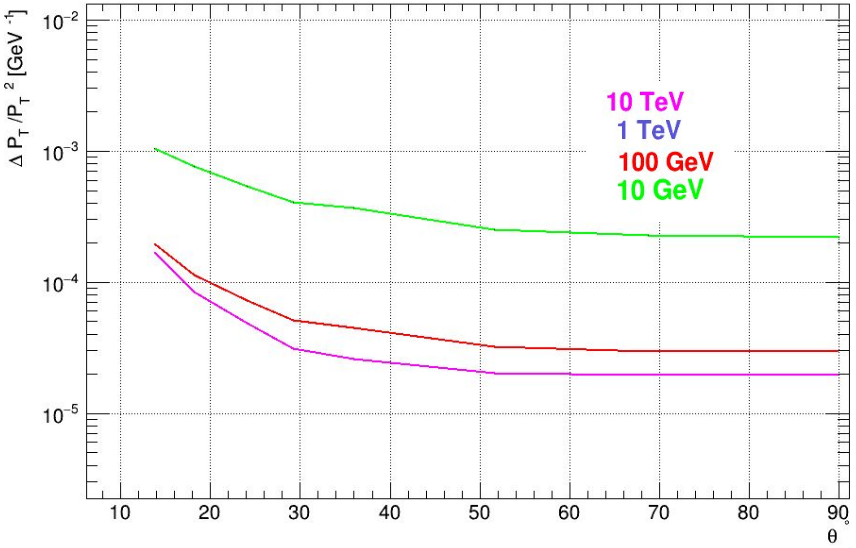


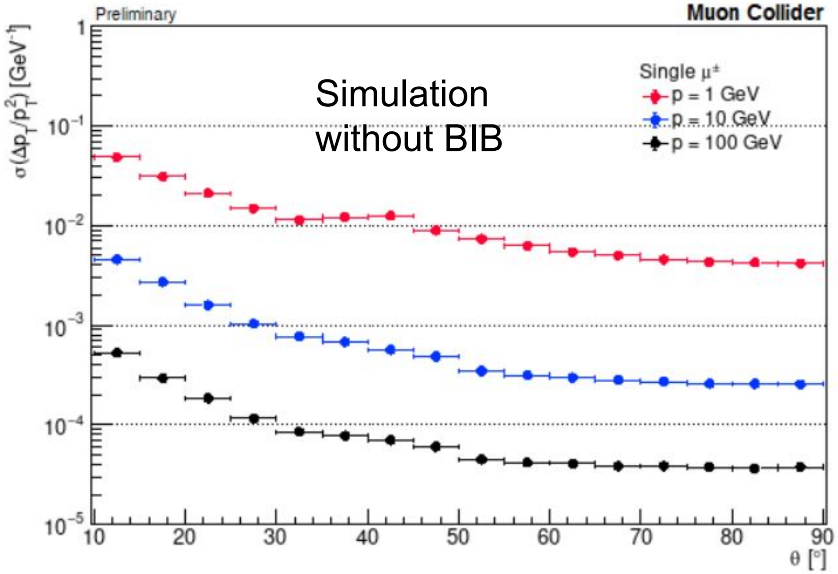


- L, N, material budget depend on the track polar angle

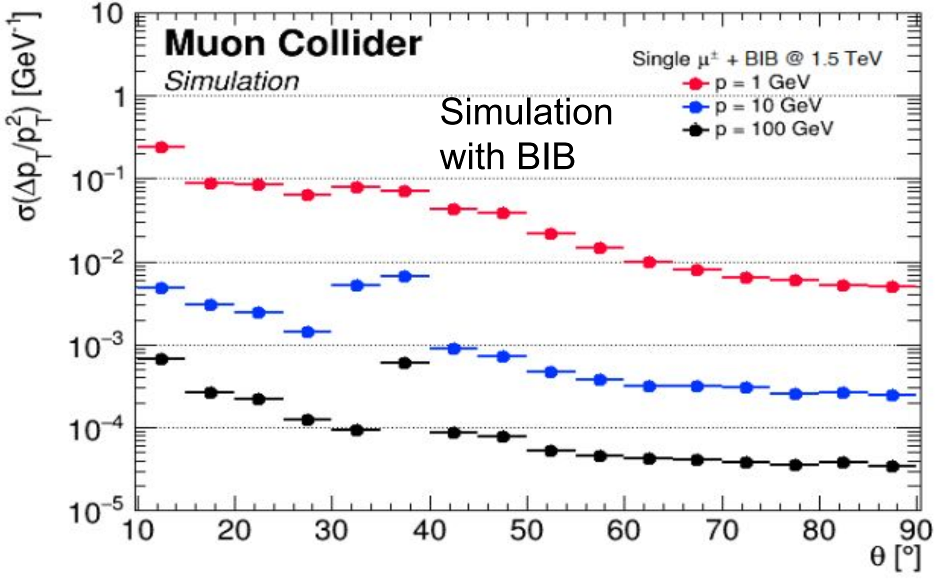
Comparison with 3 TeV: P_T resolution

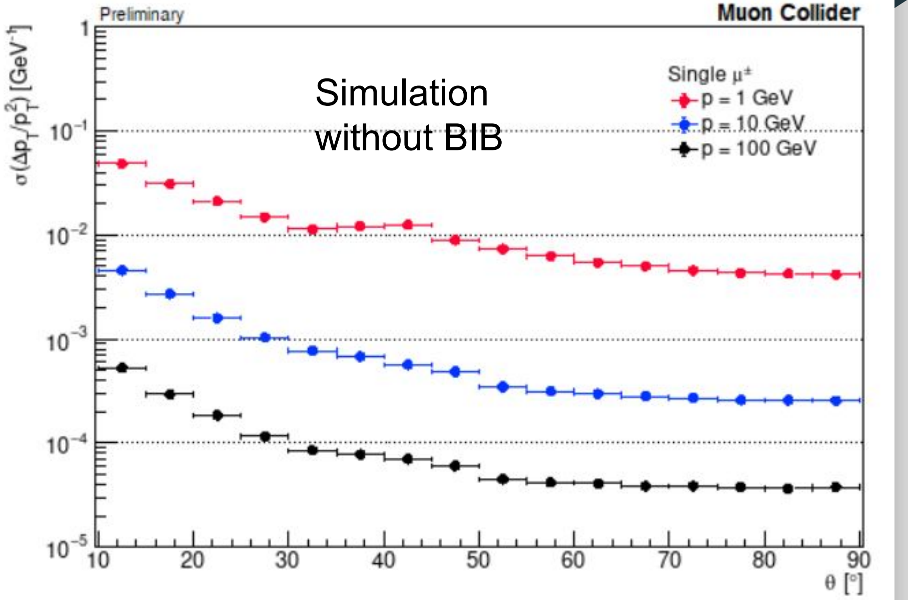
- Results not very far from the simulation (especially in the central region)
- Above 1 TeV p_T multiple scattering contribution is negligible:
  - Optimize material budget is useful only at low energy (<~ 1 TeV)
  - Magnetic field, hit resolution and tracker dimension can be tuned to reach the desired resolution





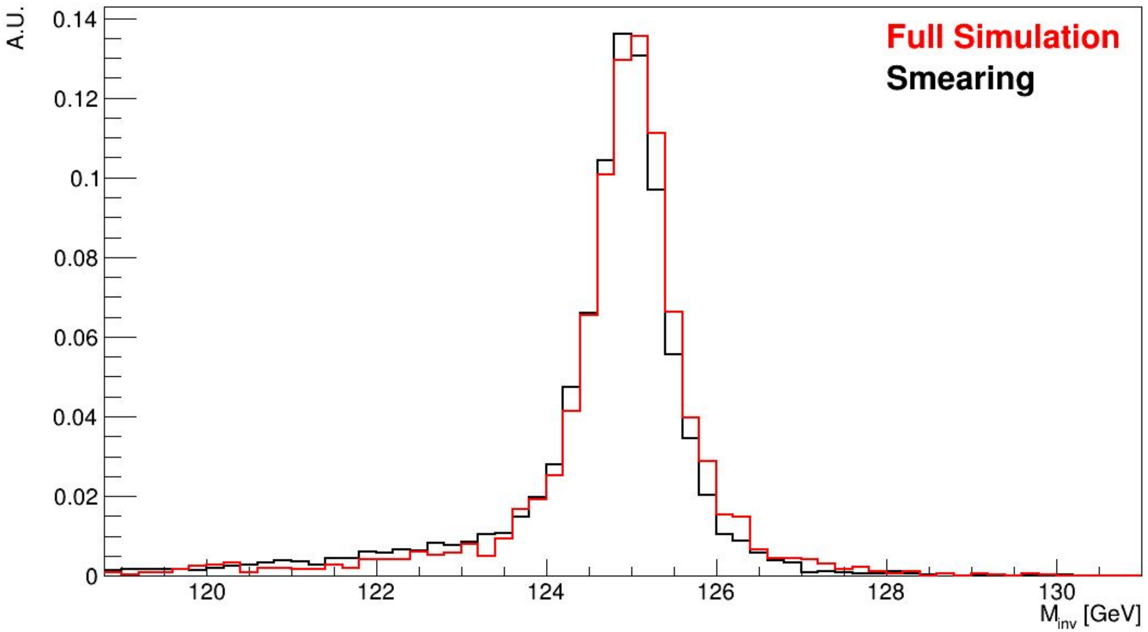
Comparison p_T resolutions with and without BIB





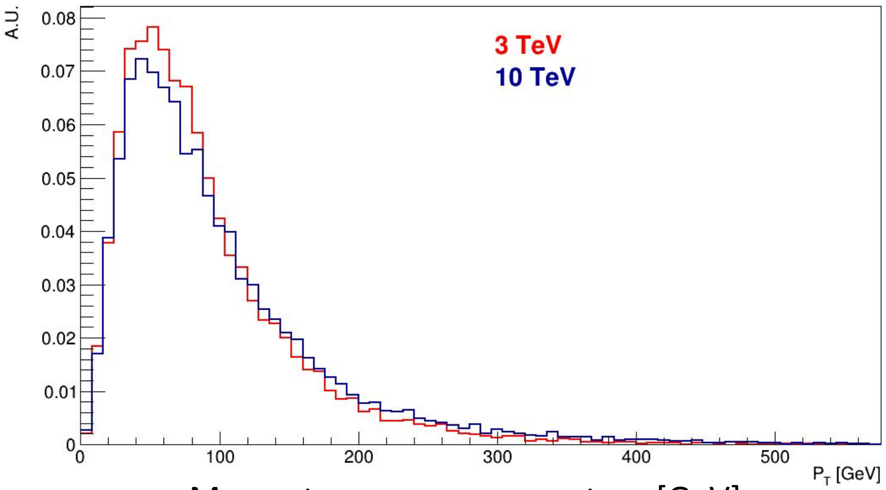
Comparison of formulas with full simulation at 3 TeV

- $\mu^+\mu^- \rightarrow H\nu\nu \rightarrow \mu^+\mu^-\nu\nu$ processes generated with Madgraph at 3 TeV
- Invariant mass resolution compared between:
  - Reconstructed particles with **full simulation (Marlin) without BIB**
  - Monte Carlo muons **smeared with the formulas**

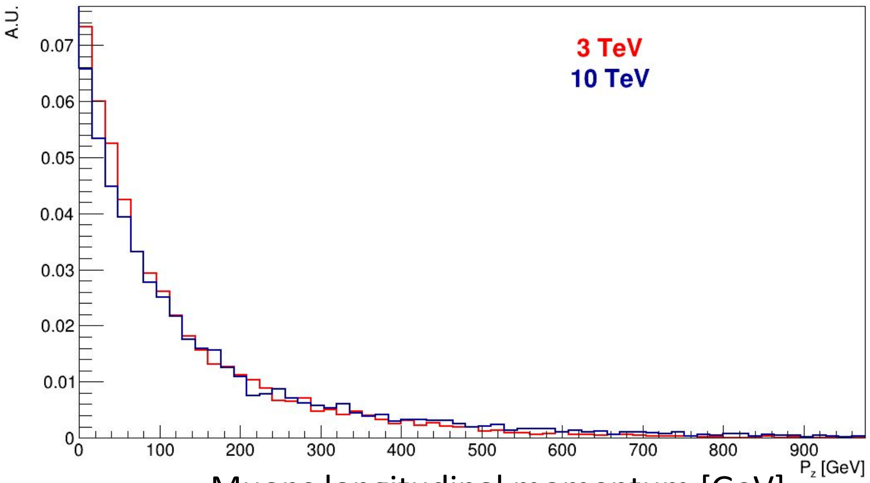


Muons distribution in the process $\mu^+\mu^-\to H\nu\nu\to\mu^+\mu^-\nu\nu$

- $\mu^+\mu^-\to H\nu\bar{\nu}\to\mu^+\mu^-\nu\bar{\nu}$ processes generated with Madgraph at 3 TeV and 10 TeV
- Within the 3 TeV acceptance, the distributions of P_T and P_Z of final state muons are similar at 10 and 3 TeV
  - **Cross checks** by using other Monte Carlo are ongoing to verify these distributions
  - **Next step** will be to apply the formulas for the momentum smearing to this and BSM processes and evaluate the resolution on the invariant mass



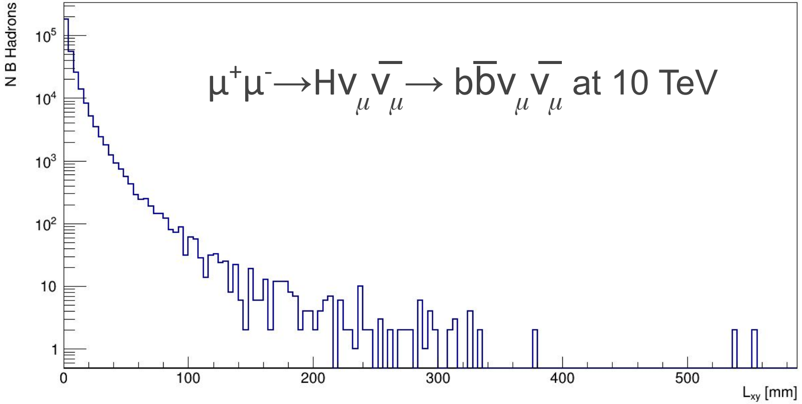
Muons transverse momentum [GeV]

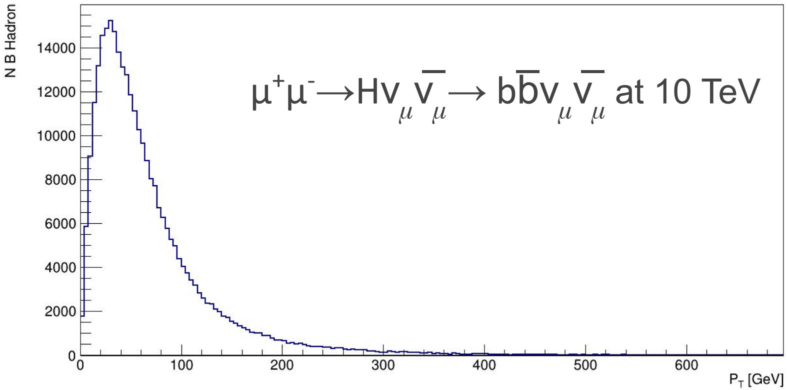


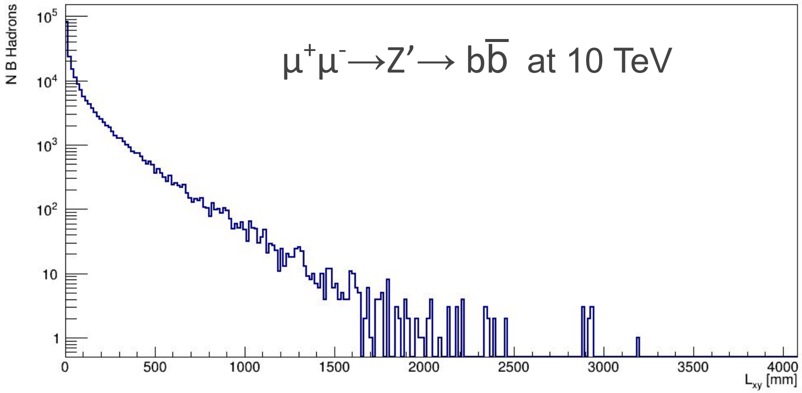
Muons longitudinal momentum [GeV]

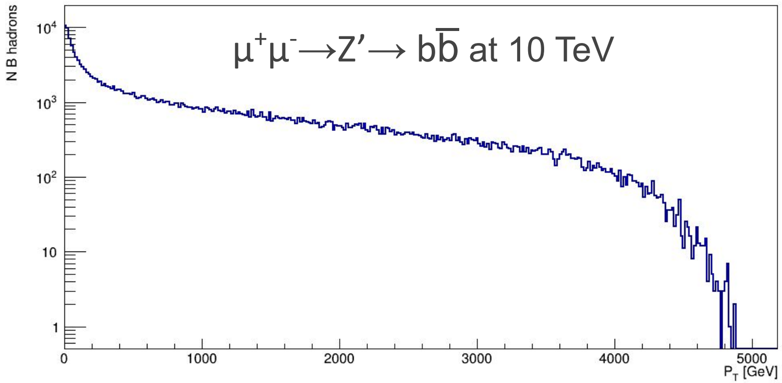
B hadrons decay in the tracking system

- P_T of B hadrons for H to bb and Z' to bb
- Distance travelled by b hadrons in the transverse plane









B decay vertex in the tracking system

- All b hadrons from Higgs decay inside the first layers

Layer Number	radius[mm]	Ratio in Hbb	Ratio in Z’ into b
Layer 1	31	0.97	0.51
Layer2	51	0.990	0.60
Layer3	74	0.998	0.68
Layer4	104	1.	0.74
Layer5	127	1.	0.78
Layer6	340	1.	0.93
Layer7	554	1.	0.97
Layer8	819	1.	0.991
Layer9	1153	1.	0.997
Layer10	1486	1.	0.999

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

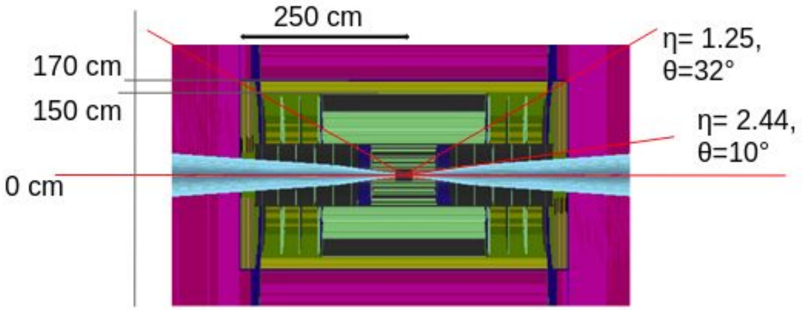
Secondary vertex resolution is driven by the resolution on the tracks impact parameter that depends on:

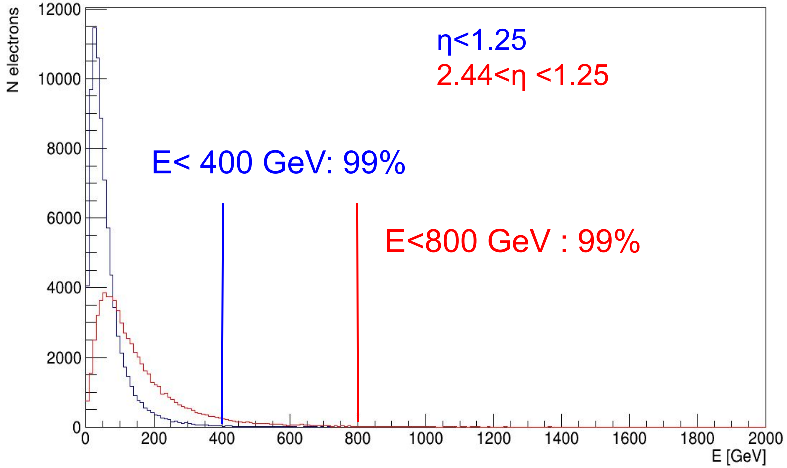
- number of layers
- radius of the closest layer to the beam pipe

➔ The required resolution on tracks coming from heavy BSM particles have to be discussed

Electromagnetic calorimeter studies

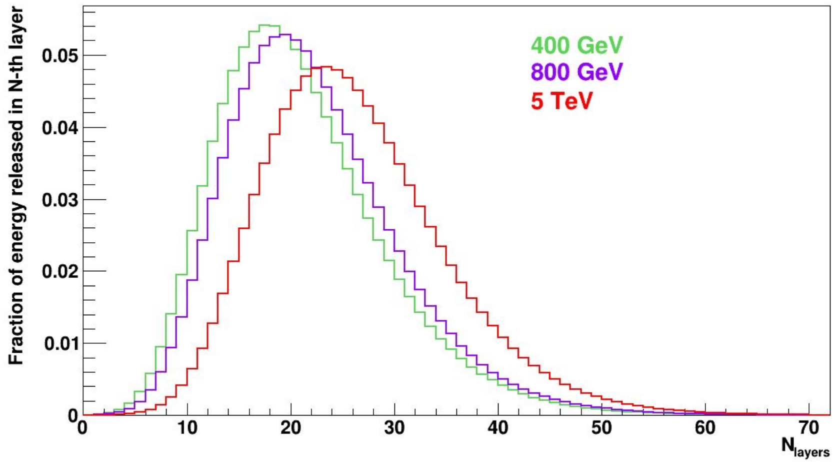
- ECAL setup for 3 TeV: 40 layers for a total of 20 cm, corresponding to 22 X_0
- Study of electrons energy spectrum from the processes at 10 TeV:
  - $\mu^+ \mu^- \rightarrow H\bar{\nu}_\mu \nu_\mu \rightarrow ZZ\bar{\nu}_\mu \nu_\mu$ ($Z \rightarrow e^+ e^-$) at 10 TeV
    - 99% electrons have E<400 GeV in the central region
    - 99% electrons have E<800 GeV in the forward region
  - $\mu^+ \mu^- \rightarrow Z' \rightarrow e^+ e^-$ ($M_{Z'}$ =9.5 TeV)
    - all electrons at 5 TeV





Simulation with Geant4

- 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



E	Number of X_0	N Layers	ECAL length	λ_I
400 GeV	27.1	45	22.73 cm	1.20
800 GeV	28.3	47	23.73 cm	1.26
5 TeV	30.8	51	25.76 cm	1.36

Preliminary studies on the hadronic calorimeter

- Current setup of the HCAL: 60 layers for a total of 159 cm, corresponding to 7.5 λ_I
- Simulation of the current steel absorber and plastic scintillating tiles HCAL calorimeter
- Materials and layers geometry taken from the HCAL geometry files
  - Implementation of specific materials/elements in Geant4
- From the simulation: particles in jets in $\mu^+\mu^- \to Z'\nu\bar{\nu} \to jj\nu\bar{\nu}$ at 10 TeV
  - Example: protons energy around 1150 GeV
- The current simulation do not include the ECAL in front of the HCAL

Particle	Energy [GeV]	N layers to lose 90% E_{TOT}
Proton	1150 GeV	~70 layers (8.6 λ_I)

Conclusions

From generator level studies:

- Standard Model Higgs events will be more forward at 10 TeV with respect to 3 TeV
- Heavy BSM processes are more central in the detector

Studies on the detector:

- Formulas for the calculation of the tracks momentum resolution as a function of the polar angle are checked at 3 TeV
- The next step is to apply these formulas to smear final state tracks momentum in Standard Model and BSM processes, as a function of the angular distribution
    - Which benchmark process can be used? Which resolution is required?
- Electromagnetic calorimeter depth will have to be increased to study heavy particles (of ~6 cm)
- For the hadronic calorimeter studies are still preliminary, next steps will be:
    - finalize the Geant4 simulation by including the electromagnetic calorimeter in front of the hadronic
    - simulate the shower of other particles/jets

BACKUP

Values used for the Muon Collider

- B=3.57 T
- Spatial resolution
  - 7 µm

	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	$5\mu m \times 5\mu m$	$7\mu m \times 90\mu m$	$7\mu m \times 90\mu m$

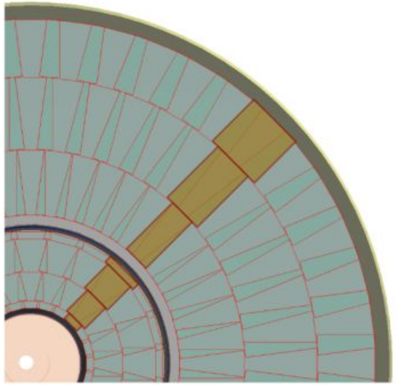


Figure 26: Transverse view of the sixth inner disk and the third outer tracker disk.