Geant4 Error Propagation in CMS Track Reconstruction

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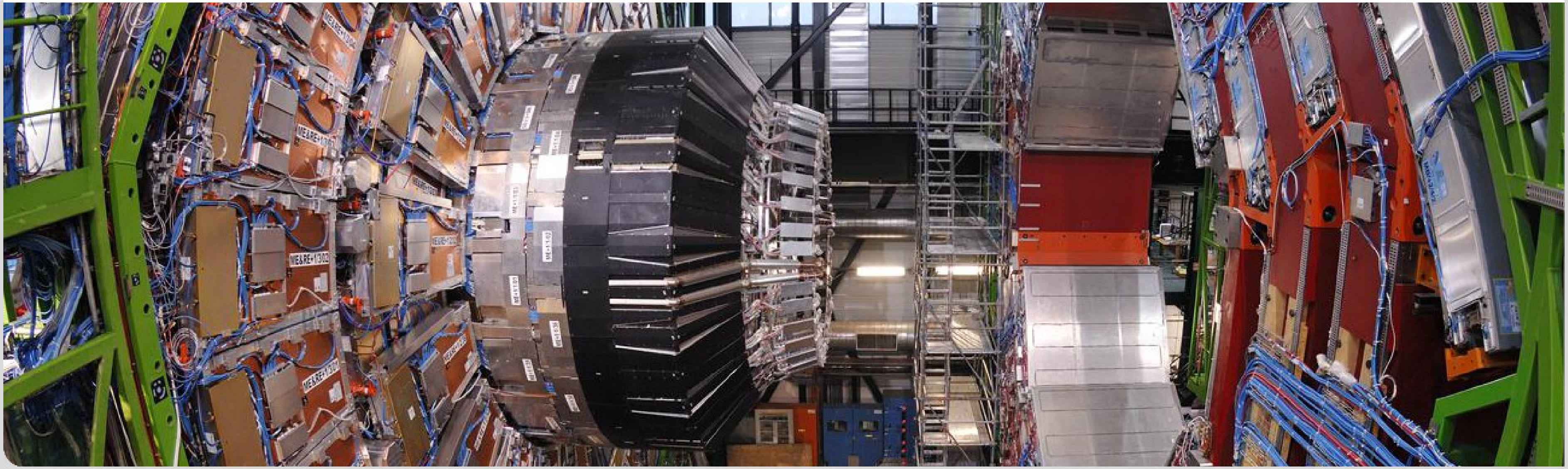


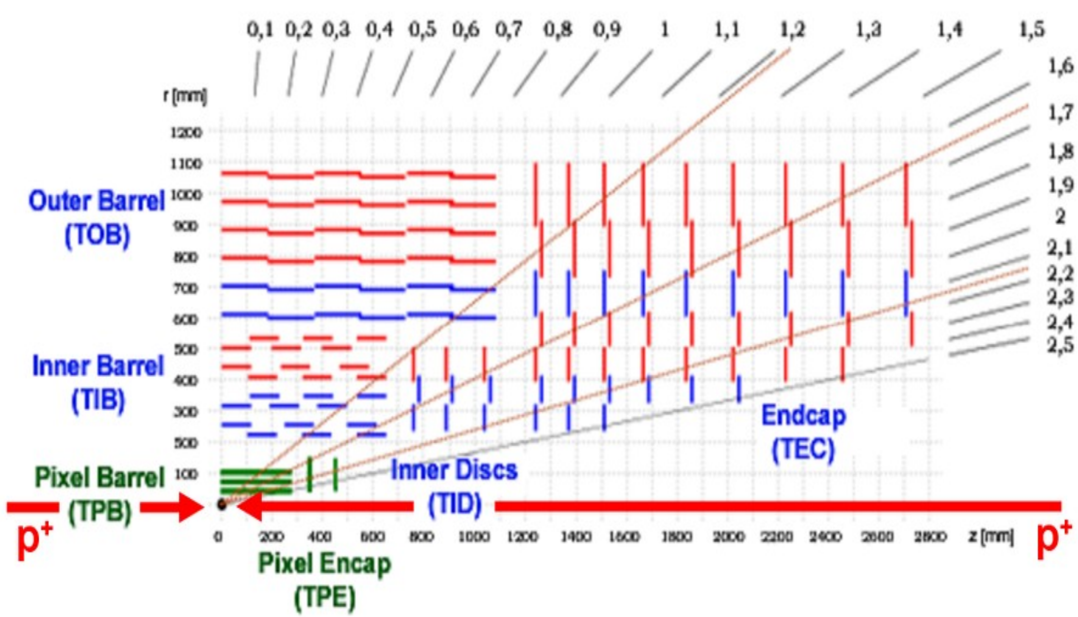
CMS Tracker Layout

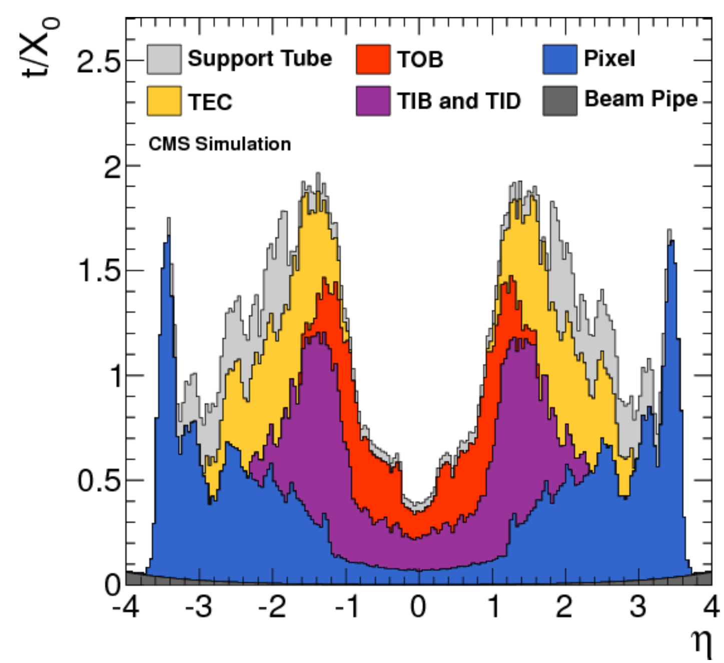
... at least 1/4th of it

The CMS Tracker is made up of a range of functional units:

- The innermost Pixel Tracker (1440 individual pixel modules)
- The outer strip detector parts (15184 individual strip modules):
  - TIB: Tracker Inner Barrel
  - TOB: Tracker Outer Barrel
  - TID: Tracker Inner Disc
  - TEC: Tracker Endcap

Material budget of the CMS tracker in units of radiation length X0





https://twiki.cern.ch/twiki/bin/view/CMSPublic/TrackerMaterialBudgetplots

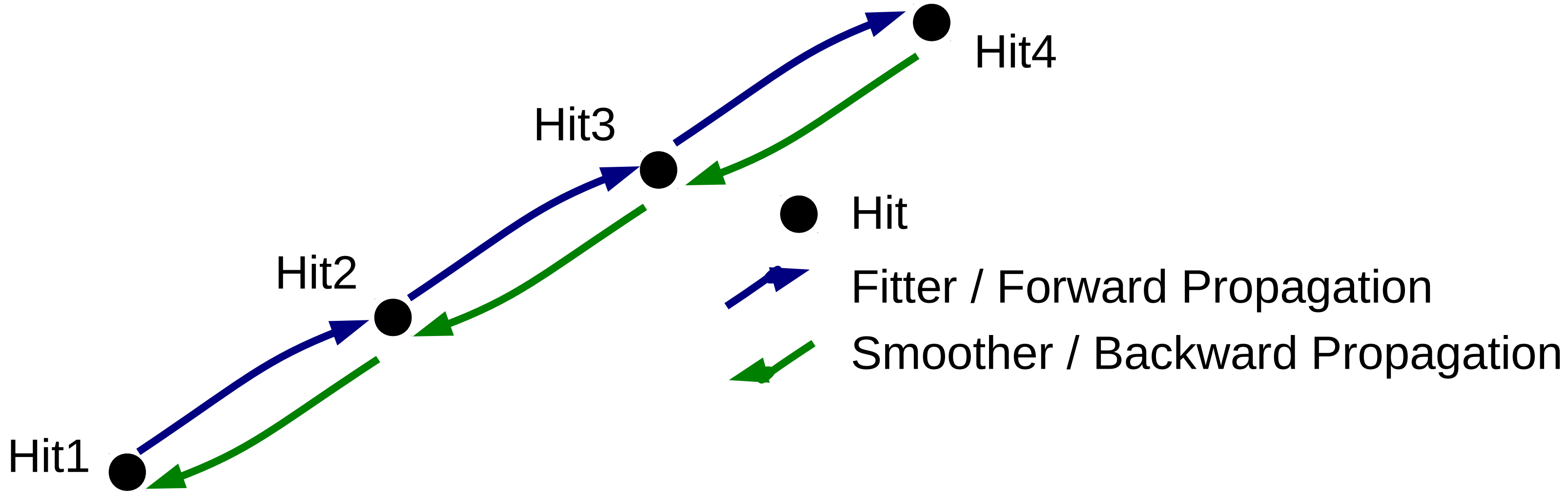
Introduction to Geant4 Error Propagation Package

- Geant4 contains an sophisticated error propagation package [1], short Geant4e
- The trajectory state of a particle is defined by:
  - Momentum
  - Position
  - Charge
  - Particle type
  - Trajectory error matrix
- This trajectory state can be propagated to any target surface, considering
  - The magnetic field defined in G4
  - The material defined in G4
- The physics list is limited when computing the energy loss along the trajectory with Geant4e:
  - No change of path due to multiple scattering
  - No random fluctuations for energy loss
  - No creation of secondary tracks
  - No hadronic processes

[1] http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/ch05s08.html

CMS Final Track Building

- After the tracks and associated hits have been found by the Kalman filter, a final track fit is performed
- All hits belonging to one track are used to update the track state starting from the inside of the tracker
- To perform the Kalman filter combination, the current track state is propagated to the detector surface where the next hit is located (forward propagation)
  - Energy loss and mulitple scattering contributions need to be included here !
- Once the most outer hit is reached, the procedure is repeated from the outside in
  - Before doing so, the errors are enlarged to have two independent fits (forward & backward)
- This step is called smoothing in CMSSW and uses the backward propagation method



Possible Applications for Geant4e in CMS Tracking

Although the full fledged Geant4e is probably too time consuming to run as default, there are some benefits in having this tool in hand:

- Systematic effects of the current material simulation can be studied
- The current material modeling in the reconstruction can be improved, if results of the Geant4e propagation show deficits in some regions
- Some particles can be selected to be reconstructed with the full Geant4e track propagation
- Detector alignment computations might benefit from the improved Geant4-based material description

Integration work of Geant4e into CMS Tracking

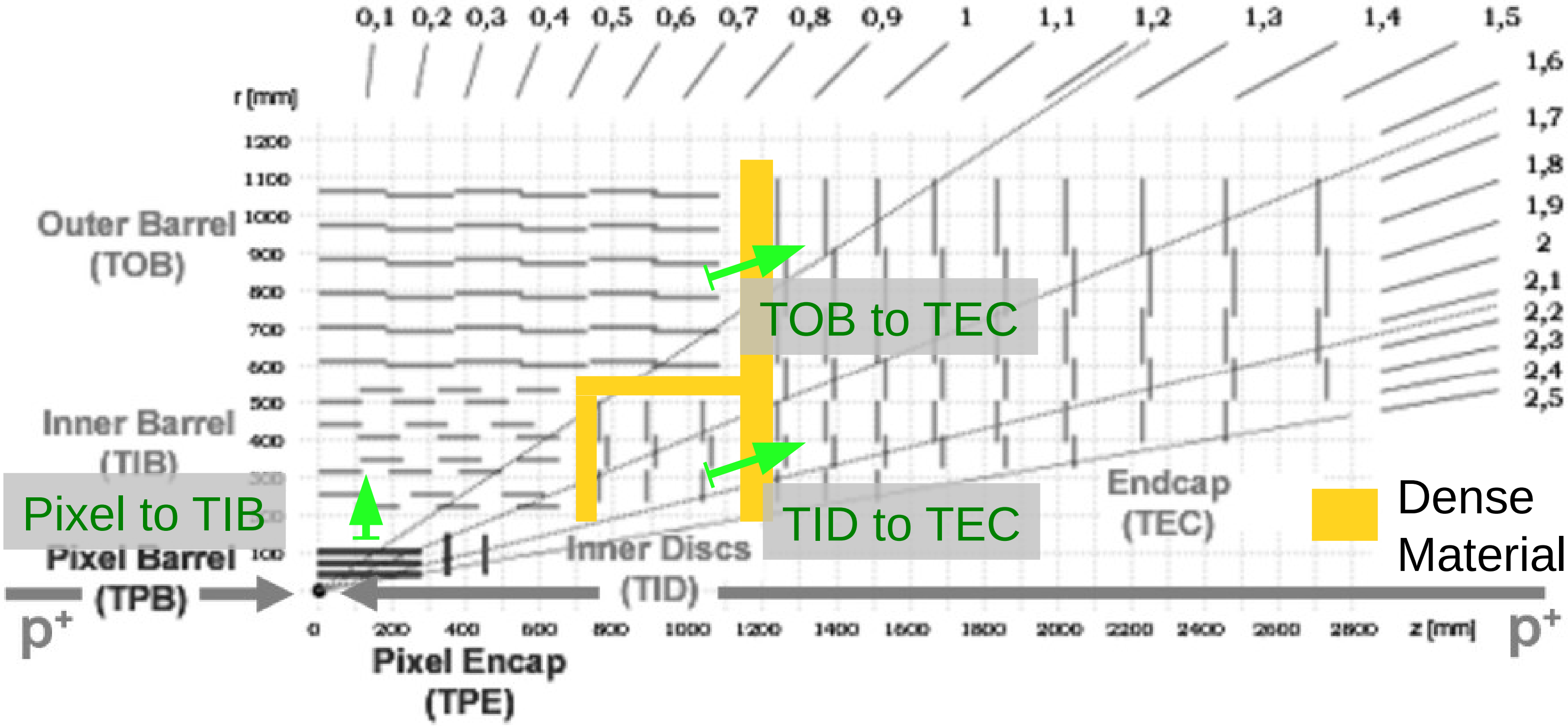
- **Fix for memory bug in Geant4e [1]**
  - The existence of a memory leak made it impossible to fit more than 1000+ tracks
  - A patch has been provided by me and is included since Geant 4.9.6 – patch 02
  - In my specific use case, fixing the memory leak also sped up the Geant4e propagation by a factor 3
  -
- **Loading of the Geant4 data**
  - Simulation Geant4 volumes and magnetic field needed to be loaded in reconstruction workflow
- **Manual transformation of error matrix during backward propagation**
  - The free trajectory state representation used as input to Geant4e is co-linear, according to the documentation [2]:

    `fYperp and fZperp are the coordinates of the trajectory in a local orthonormal reference frame with the X axis along the particle direction ...`
  - The associated error matrix is also defined in this reference frame
  - For a backward propagation, the momentum vector must be flipped by the user code before passing the trajectory state to the Geant4e code -> reference frame changed !
  - Important: the associated error matrix must be transformed, too

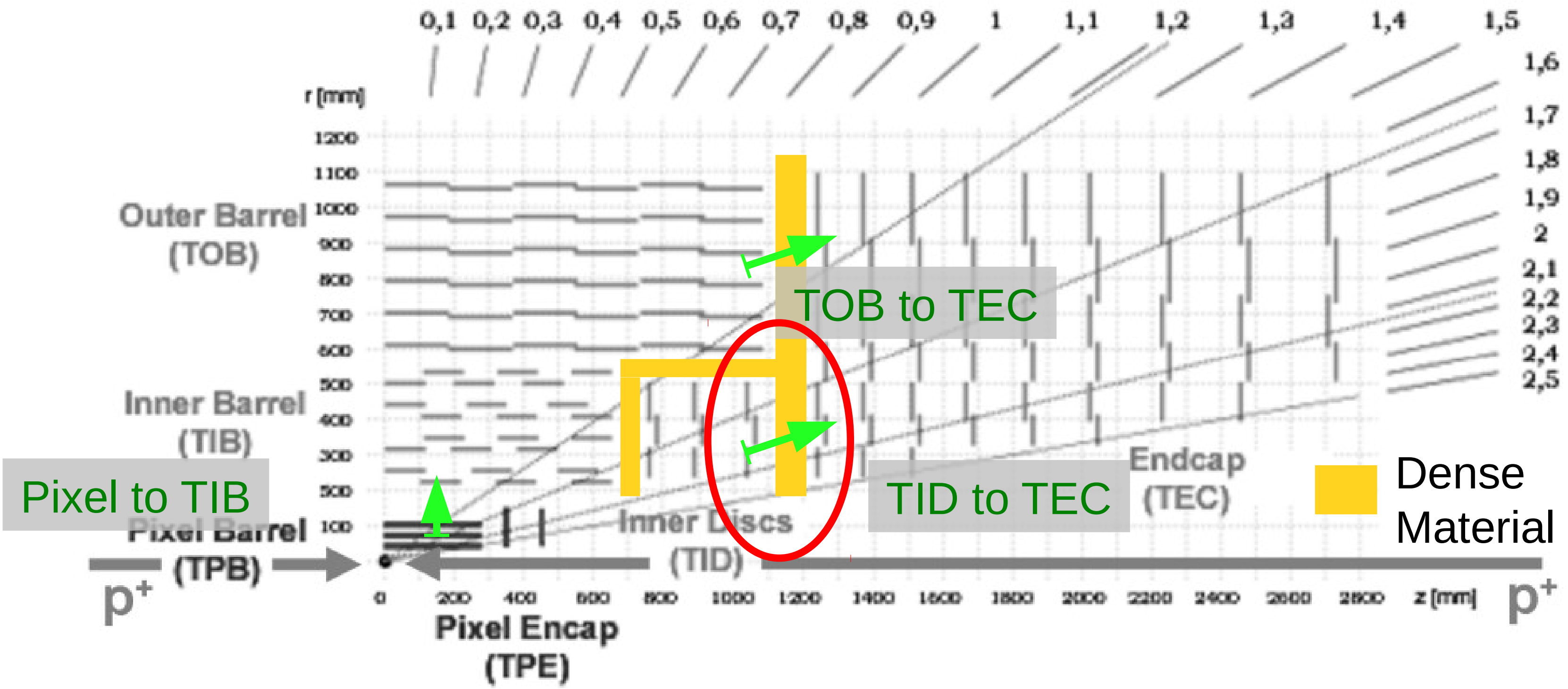
[1] http://bugzilla-geant4.kek.jp/show_bug.cgi?id=1466
[2] http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/ch05s08.html

Energy Loss Validation

- Compare the computed energy loss by Geant4e during reconstruction with the energy loss during the full Geant4 simulation
- Differences in details can be expected:
  - Geant4e does not consider random fluctuations for energy loss
  - During reconstruction, the track state is only known within the associated errors
- But: The overall mean energy loss averaged over many tracks should agree between both
- Single muon tracks with Pt = 1 GeV will be used as input for the reconstruction

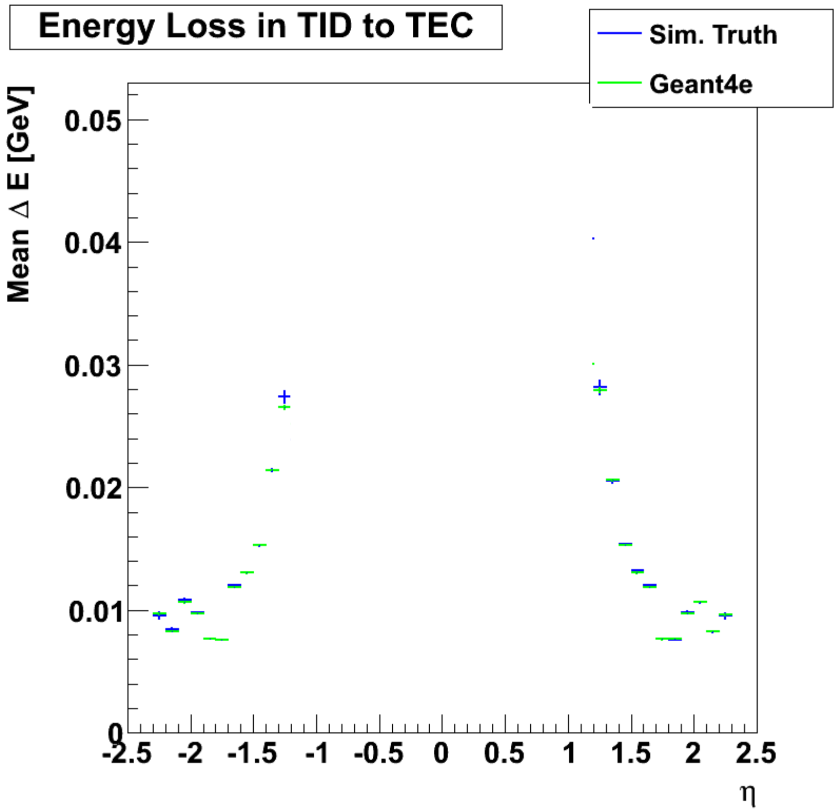


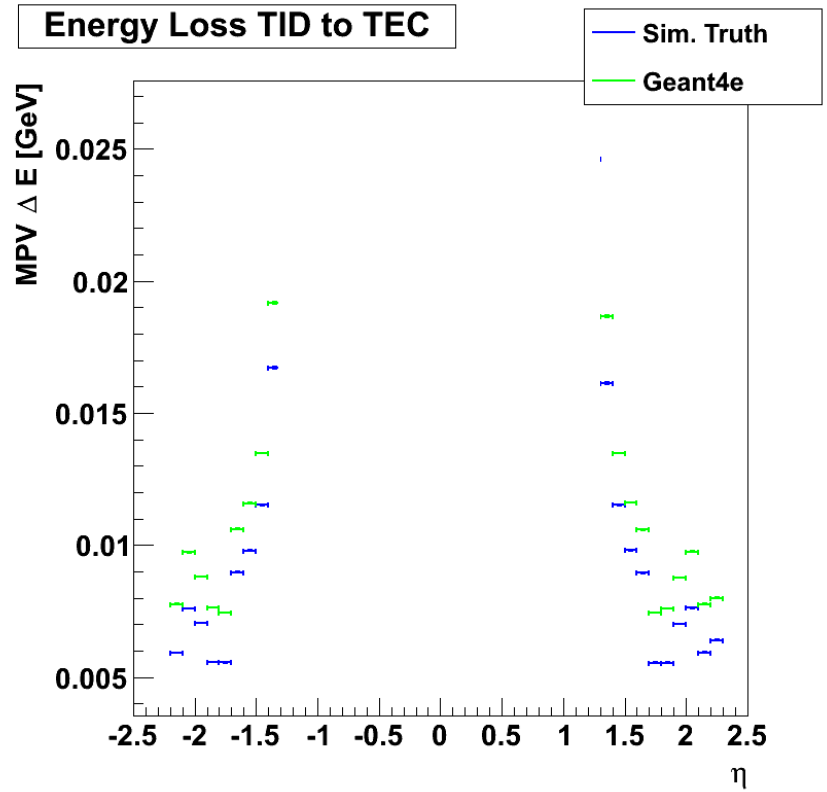
Transition is Endcap region
TID to TEC



Transition TID to TEC

- **Left plot:** Mean energy loss over Eta
- **Right plot:** Most probable value (MPV) of the energy loss distribution over Eta
  - The most probable value has been computed via a fit of ROOT's landau function to the distribution

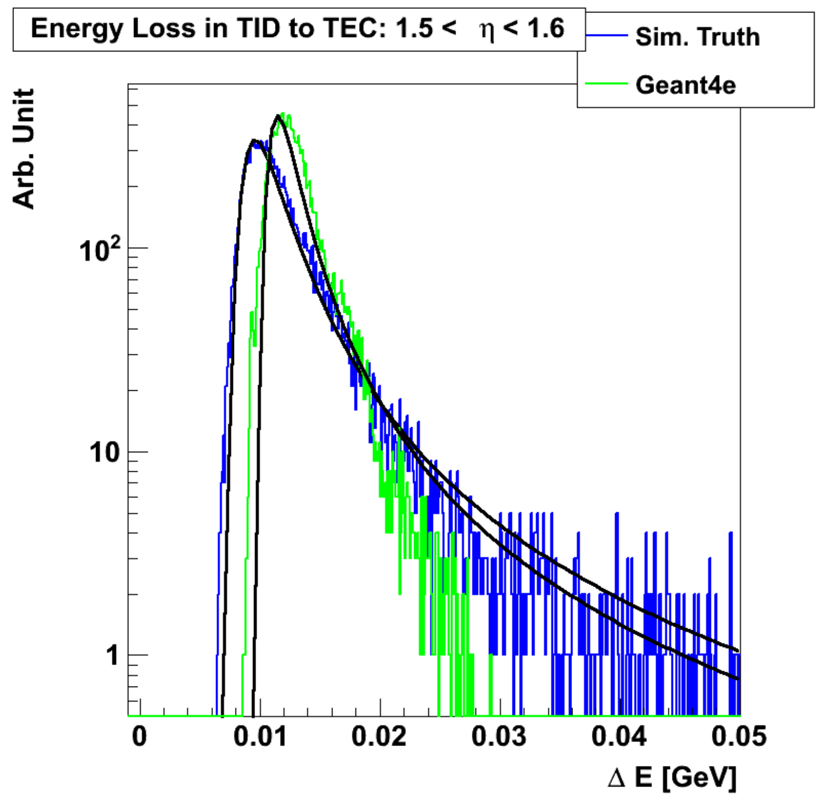




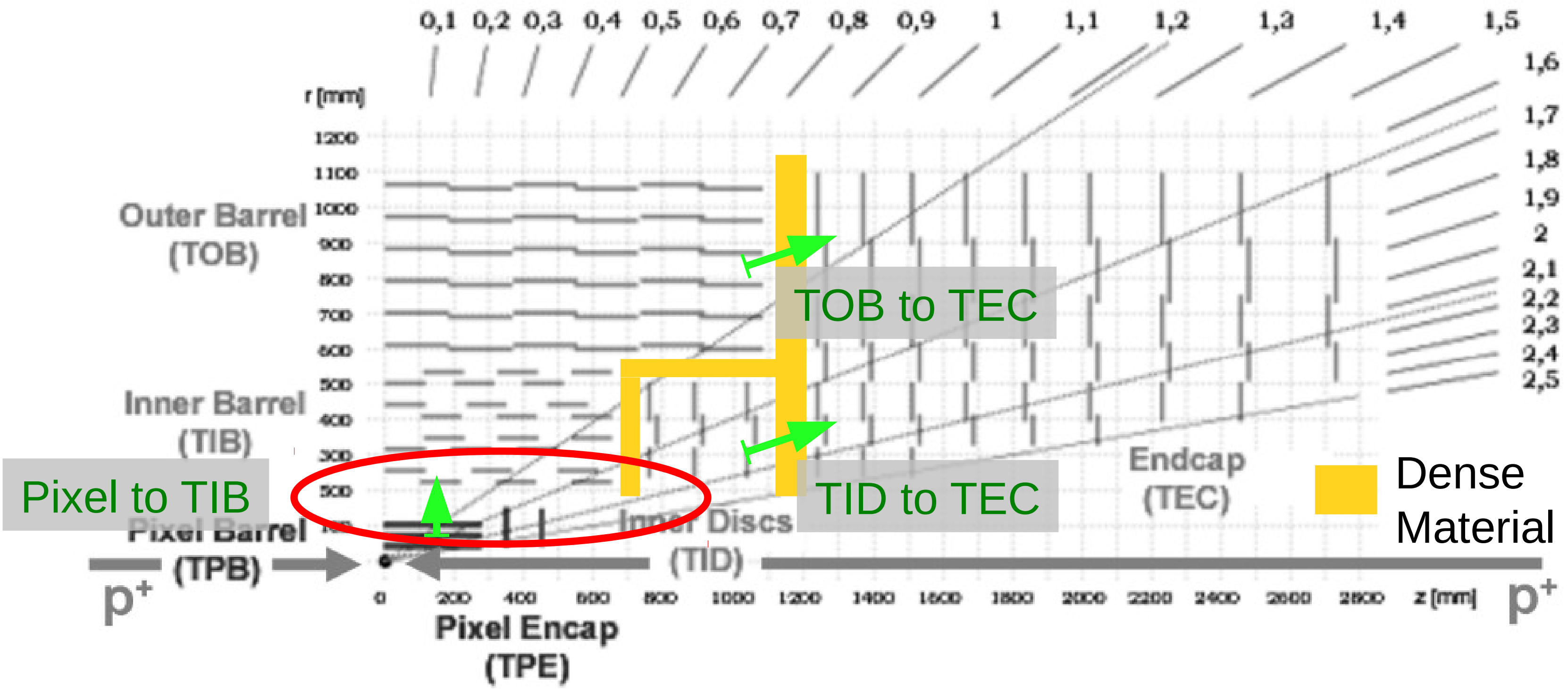
- Mean energy loss agrees very well
- MPV modeled slightly different in Geant4 simulation and Geant4e

Transition TID to TEC

- Energy loss distribution for one dedicated Eta bin: 1.5 < |Eta| < 1.6
- Both distributions have been fitted with ROOT's Landau function
- as expected: The Geant4e modeling diverts from the Landau model, especially in the tails
  - The Geant4e physics list does not include random fluctuations of a higher energy loss, therefore a reduced tail
- as seen before: The mean energy loss averaged over many tracks still agrees well

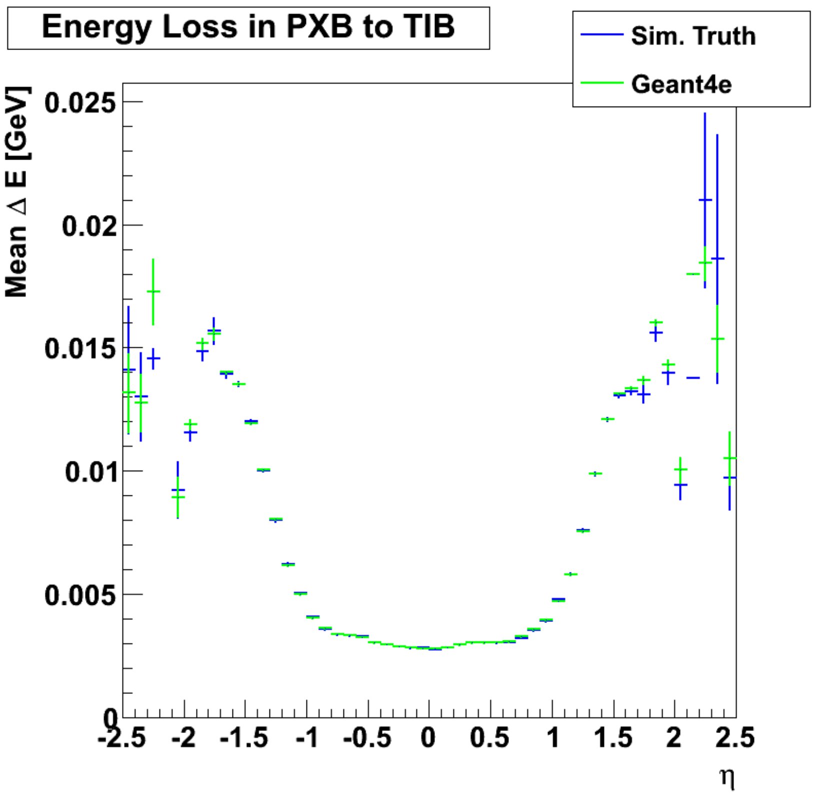


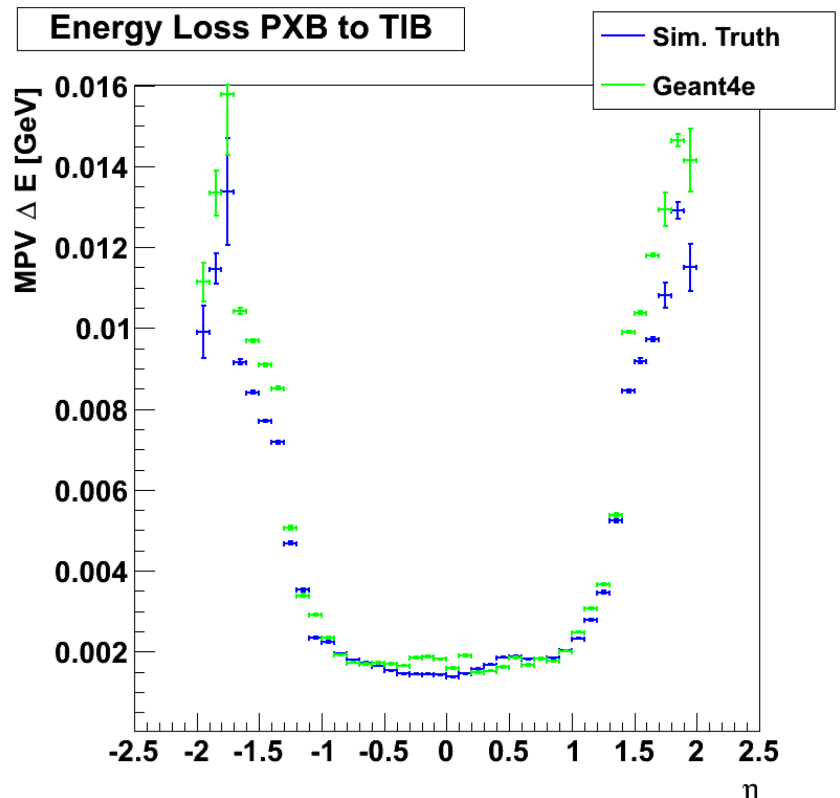
Transition is Barrel region
Pixel to TIB



Transition PXB to TIB

- **Left plot:** Mean energy loss over Eta
- **Right plot:** Most probable value (MPV) of the energy loss distribution over Eta
  - The most probable value has been computed via a fit of ROOT's landau function to the distribution
- The mean energy loss shows a good performance of Geant4e throughout Eta

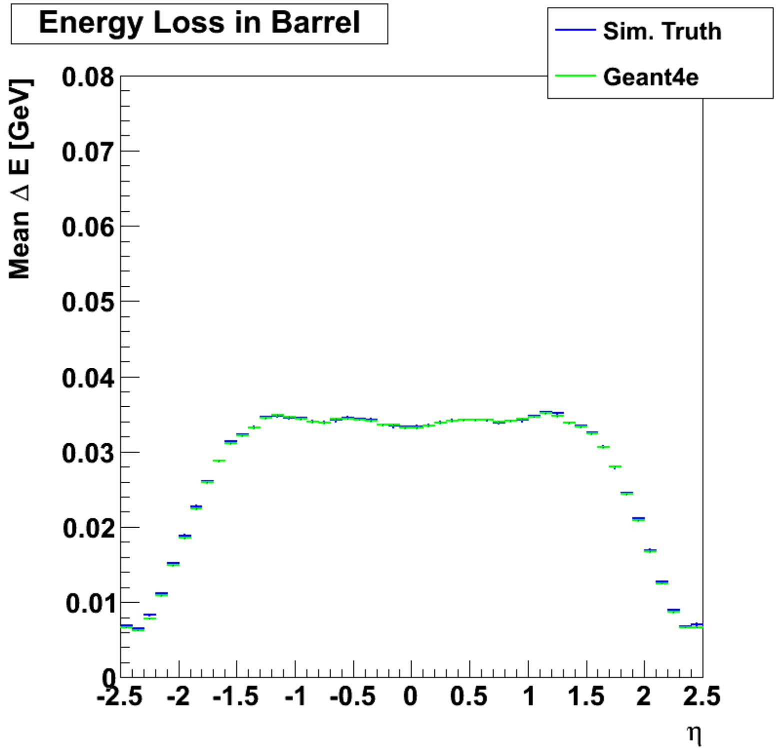


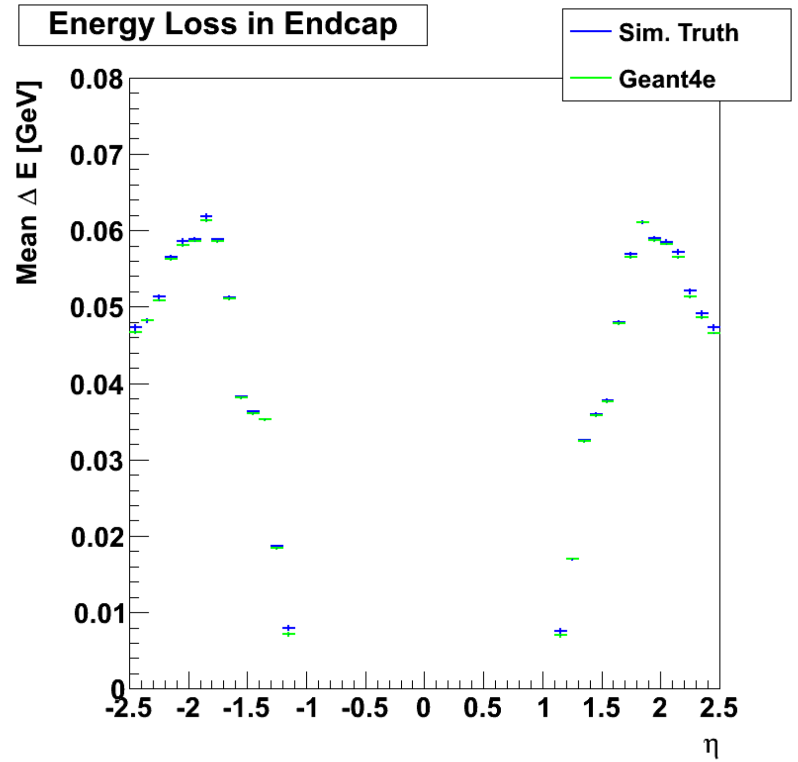


- The mean energy loss shows a good performance of Geant4e throughout Eta

Energy Loss in the whole detector

- The energy loss Geant4e computes for each track when passing through the complete detector is compared to the energy loss in simulation
- Here, only the mean energy loss is used for comparison
  - A landau distribution is not applicable any more, as the particle traverses through many different materials types and width
- Geant4e shows very good agreement, both for the barrel and endcap region





Test Setup for Track Fitting

- Re-fitting of single Muon tracks:
  - Pt = [0.9 – 1.1] GeV
  - Originating from the interaction point
  - Using all available tracker hits
  - Comparing the fit result of CMS energy loss model and Geant4e

- The default CMS energy loss model uses parametrization of the energy loss on a per detector module level:
  - Allows for very fast computation of energy loss effects

Two quantities for fit quality will be studied:

- **Pull distribution:**

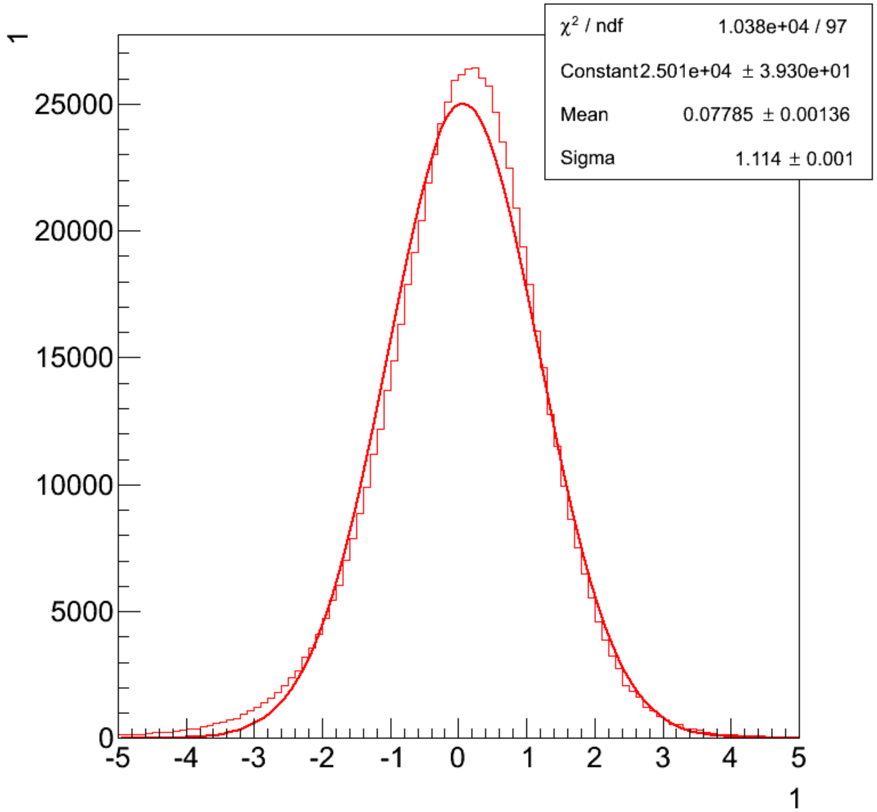
$$pull(val) = \frac{val_{reco} - val_{simulation}}{error(val_{reco})}$$

- **Residual plotted** over Eta (Eta is most sensitive to material changes):

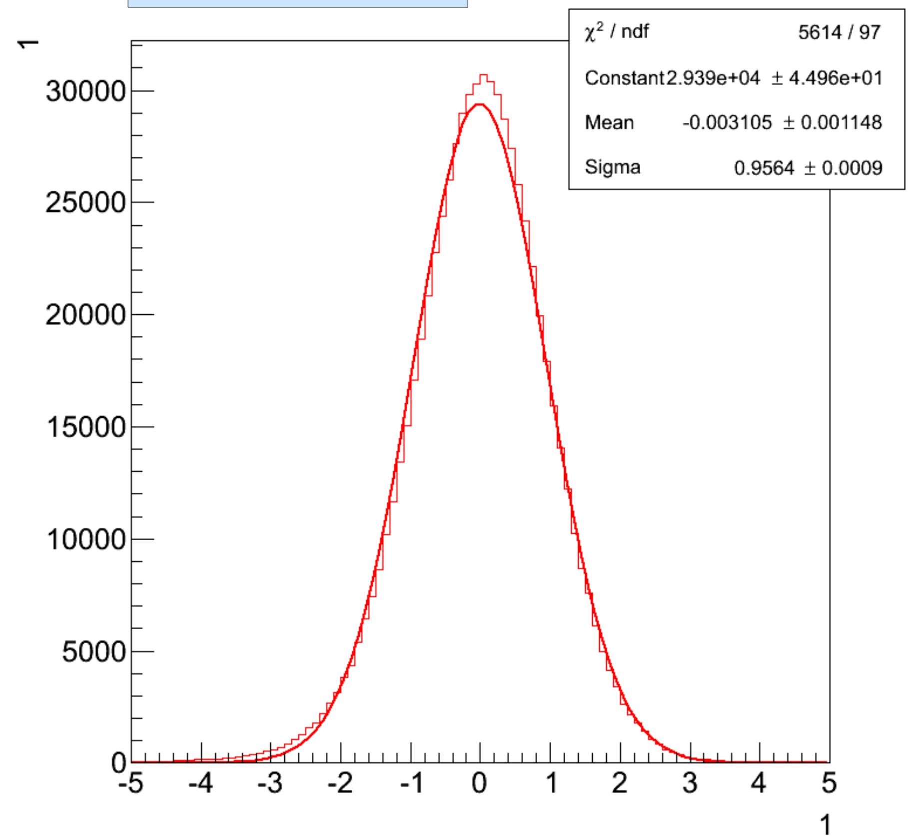
$$res(val) = val_{reco} - val_{simulation}$$

Pull of 1/P : Momentum Parameter

regular



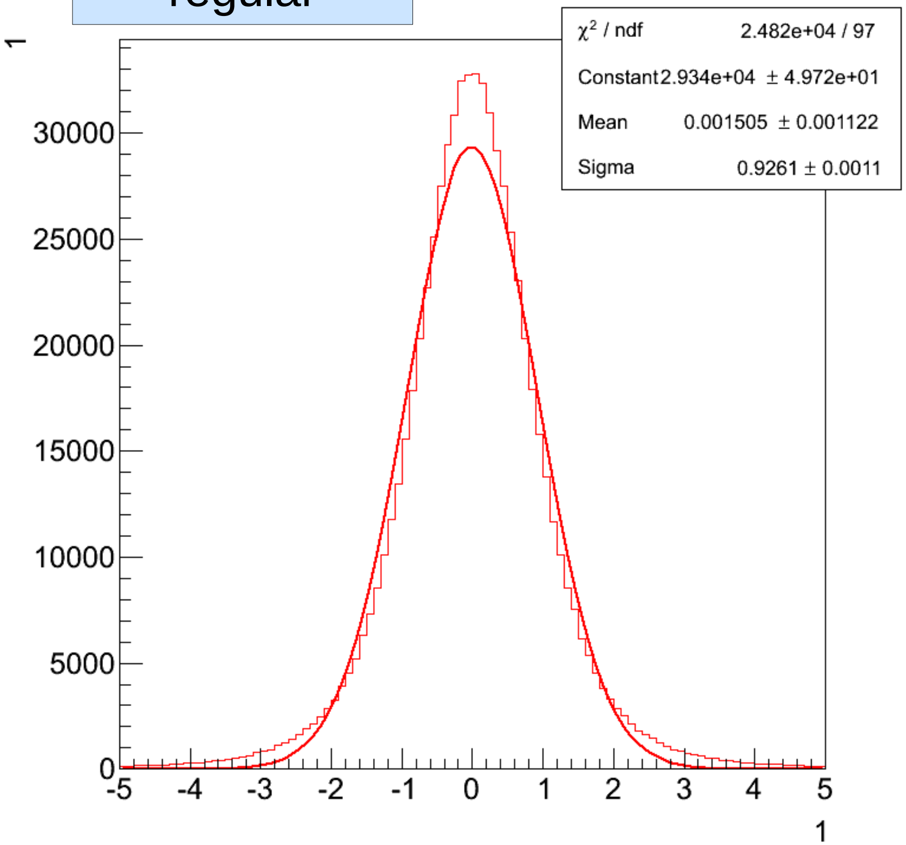
Geant4e



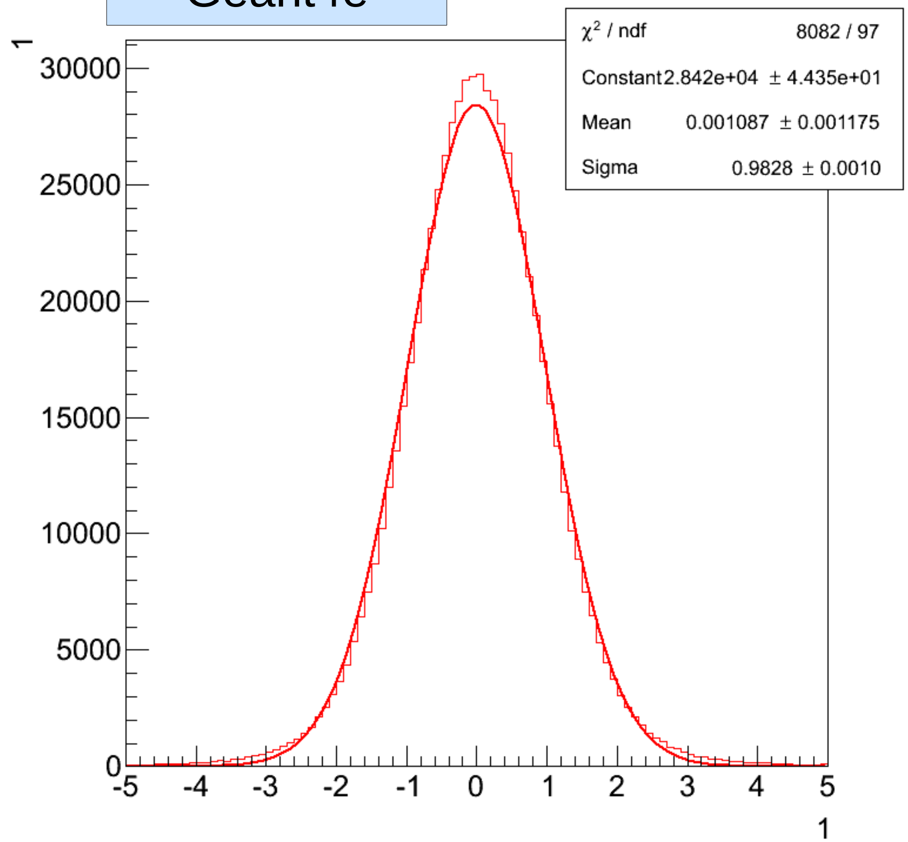
- The Geant4e material model is able to achieve a better mean (0.0779 vs. -0.0031) and sigma (1.114 vs. 0.9564) than the regular method
- In this momentum regime, errors on the momentum are modeled well

Pull of Theta

regular



Geant4e

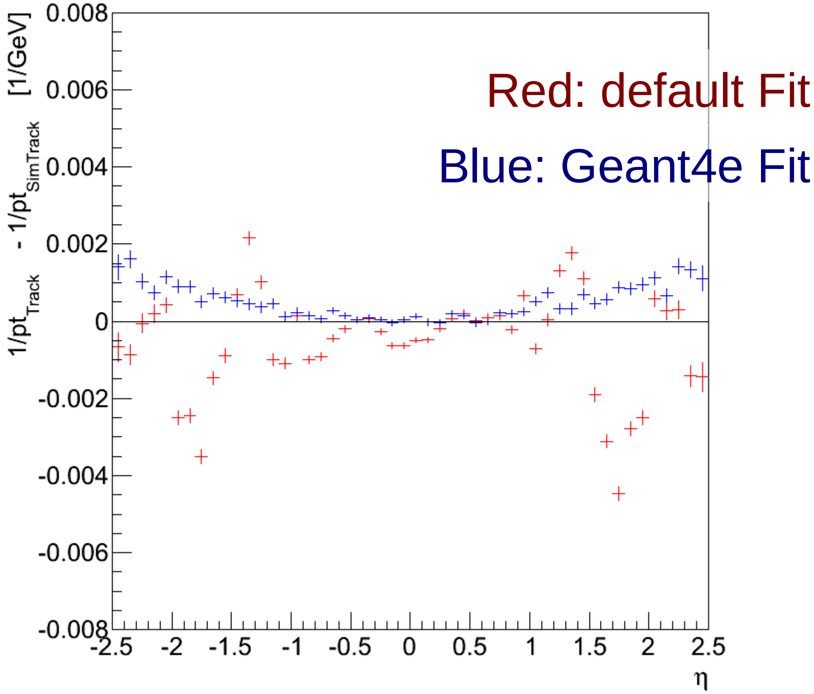


- The Geant4e material model is able to achieve a slightly better mean (0.0015 vs. -0.0010) and sigma (0.926 vs. 0.983) than the regular method

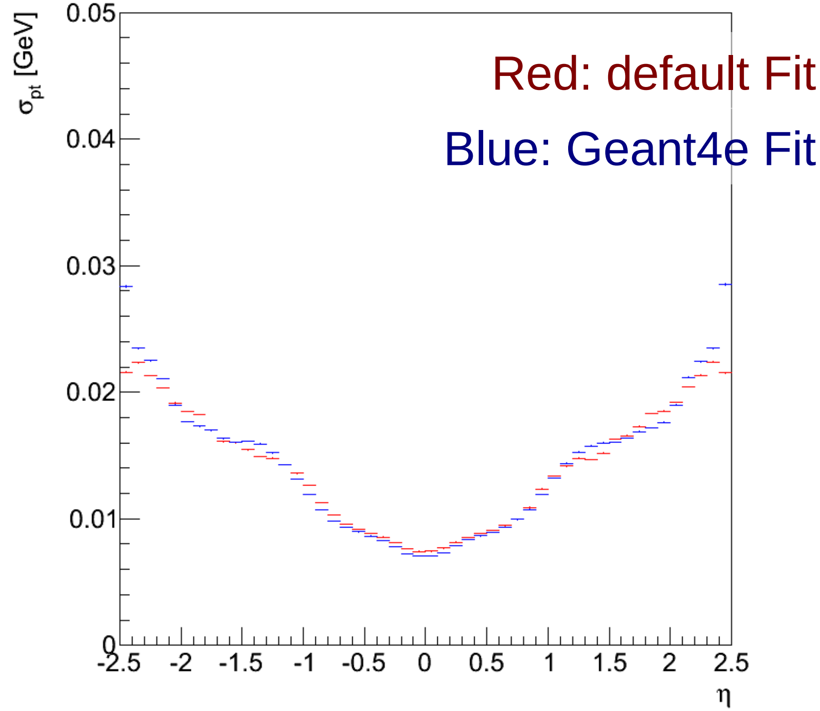
Muon Tracks: Pt Residual

- The quantity most influenced by the material modeling is the track momentum
- The left plot shows, that the Geant4e can improve the 1/pt residual compared to the regular method
  - The improvement is especially visible in the endcap regions(|Eta| > 1)
- The Geant4e material method shows as systematic shift going to high |Eta|
  - Further improvements possible

1/pt residual over Eta



Error on Pt over Eta



Conclusions and Next Steps

- A Geant4 material model-based track fit has been implemented for the CMS detector
- Energy loss studies shows a very good agreement between the Geant4 simulation and Geant4e used during the reconstruction
- Validation of the reconstruction procedure on artificial, Monte-Carlo generated muon tracks has been successfully performed
- The Geant4e-based reconstruction shows potential to improve the fit quality, especially in difficult Eta-regions

Next Steps

- Validate the method on resonance peaks (J/Psi, Kaon decay) in Monte Carlo samples and data
  - Quantify possible improvements to the mass reconstruction resolution
- Integrate into the CMSSW framework as one option for analysis users to refit their tracks

Wishes and Comments to Geant4 Community

- Geant4e is a great tool, it should be more easily accessible
- The code is in good shape, I can process millions of tracks without problems
- The documentation could be improved:
  - Explain how the propagator should be used in a Kalman fitter scenario (forward & backward) propagation
- Proposal: an automated mode to perform backward propagations in Geant4e:
  - Flip momentum
  - Take care of the error matrix transformation
  - Take care of the error handling

Thank you very much !