Tracker Material Budget Re-validation

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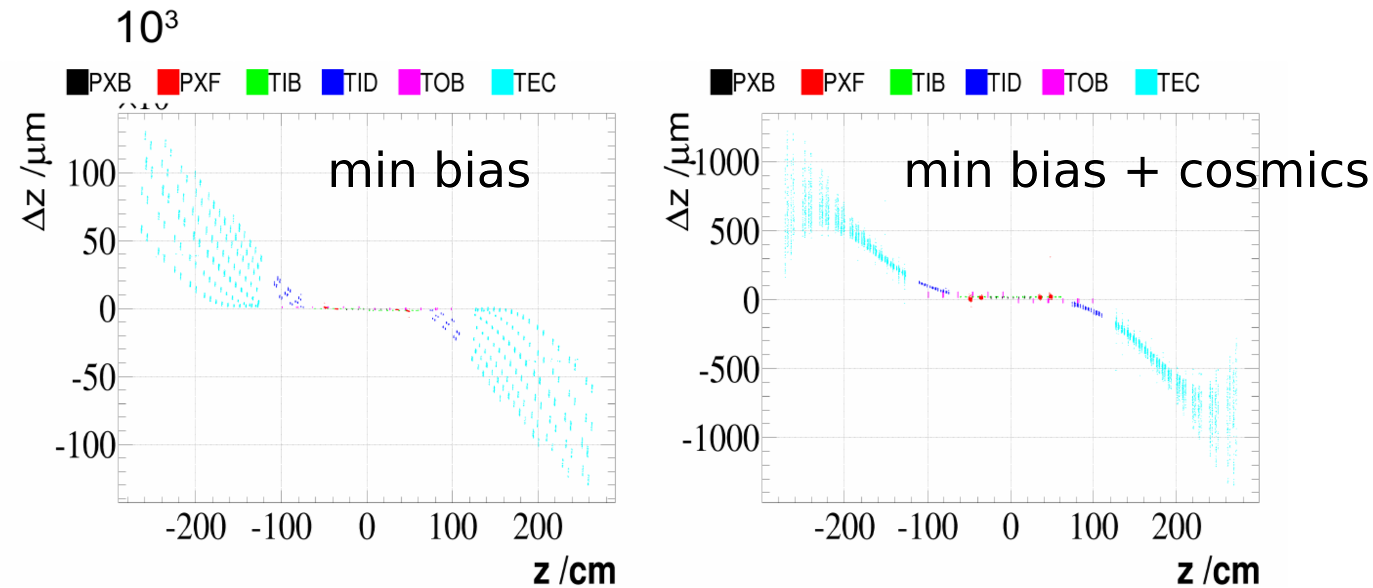
Problem: z expansion

- Z-dependent tracker alignment bias (know for a long time)
- Overview talk by Rainer Mankel (DESY) for the Tracker Alignment Group during CMS Week in June
  https://indico.cern.ch/event/827959/contributions/3467968/attachments/1868074/3072653/zExpansion-20190625.pdf
- Appears in simulation and real data
- Extra effort to keep z expansion under control, usually achieved by fine-tuned weighting of different event typologies
- Most pronounced in minimum bias events
- Only observed in TID and TEC modules
- Direction of effect must be independent of particle charge, otherwise netto effect would be zero

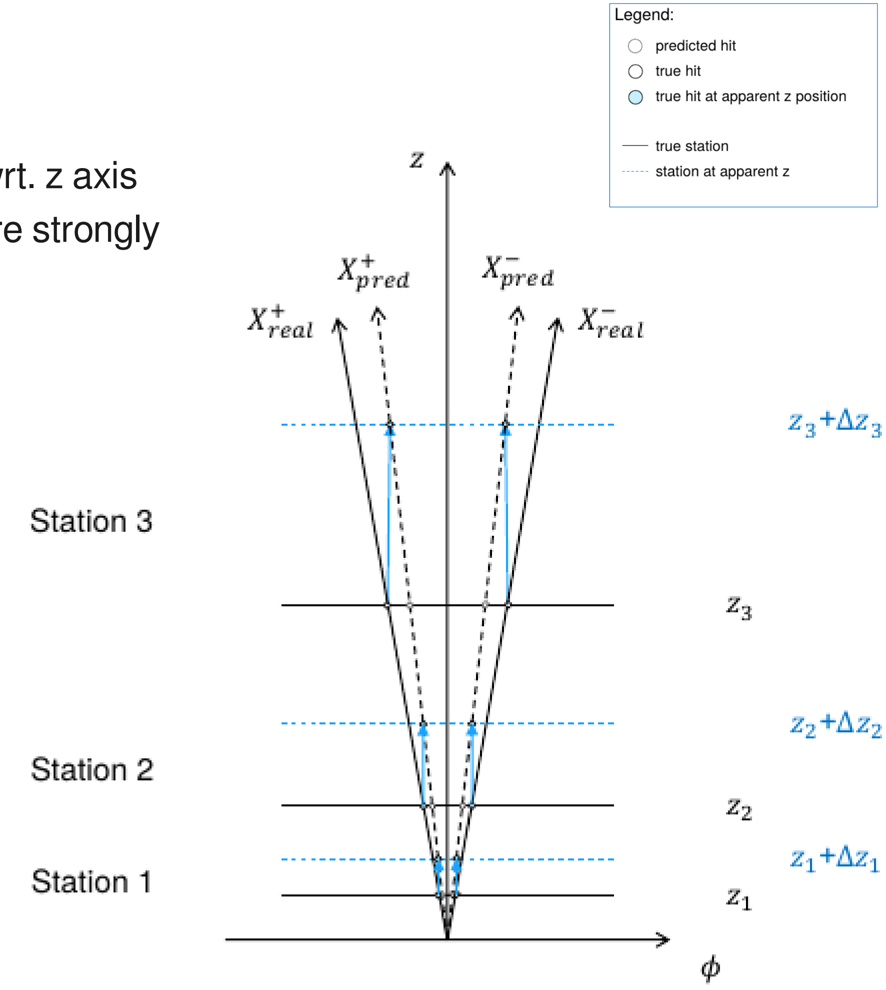


From: Matthias Schröder, Juan Grados, Nazar Stefaniuk, 2015
https://indico.cern.ch/event/389176/contributions/1821113/attachments/778085/1066964/Stefaniuk_Z_shr.pdf

Model for z expansion by Rainer Mankel

- In φz plane: helix is described by a straight line
- At fixed cot θ:
- lower pT (p) <=> lower curvature radius R <=> stronger inclination wrt. z axis
- If the "real" track has lower momentum than "predicted",it will be more strongly inclined wrt. z axis

- **Independent of the charge, the effect of the real local momentum being lower than the predicted, always leads to a z *expansion* trend $\Delta z = +2\,\Delta\, QR\, \varphi \cot\theta$**



Possible origins of momentum mis-modeling along the trajectory?

Material-related:

- Ionization energy loss in prominent dead material objects
- **Semi-continuous ionization energy loss, also in tracking stations (if underestimated in reconstruction)**
- Radiative energy loss (would only affect electrons)

Magnetic field-related:

- Mis-modeling of magnetic field

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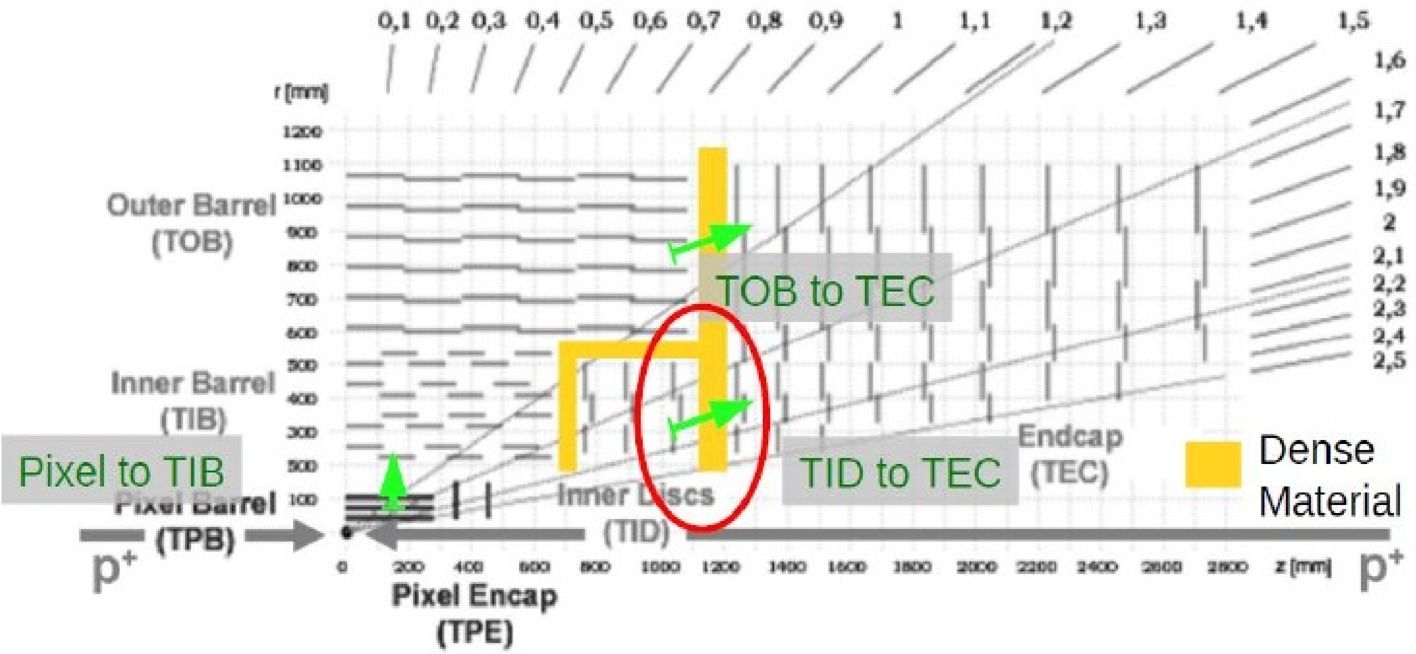
Relevant Material



- Big amounts of dense material in end cap regions, not directly associated to sensors
- Easily leads to momentum shifts between TID, TEC and the remaining tracker

Thomas Hauth (CERN) [2]: https://indico.cern.ch/event/279530/contributions/634997/attachments/511926/706535/Hauth_2014-03-LLPC.pdf

Task: Review of the assignement of material in the simulated CMS tracker

- At a given eta: total amount of material in reasonable agreement (reco to sim)
  [Studies of Tracker Material, CMS-PAS-TRK-10-003]
- Problem in treatment of passive localized material layers (such as services)
- Taking at look at:
  https://github.com/cms-sw/cmssw/blob/66cf5e6a8338b73321de8b373f99b17bb1b1b6d0/SimTracker/TrackerMaterialAnalysis/plugins/TrackingMaterialAnalyser.cc
- Along the full trajectory (at each position in the tracker) amount of crossed material must be known (multiple scattering etc.)
- Each track is split in segments, each associated to a *sensitive* detector in a detector layer,
  - a) assign each segment to the nearest layer e.g. all material *between* BPix 3 and TIB 1 will be split among the two
  - b) assign each segment to the the inner layer e.*g*. all material *between* BPix 3 and TIB 1 will go into the pixel barrel
  - c) assign each segment to the the outer layer e.g. all material *between* BPix 3 and TIB 1 will go into the TIB
- Default: a) nearest layer
- This splitting of material can be highly sub-optimal and lead to major biases in the trajectory in either directions
- **Review of material assignment necessary**
  e.g. sharing based on distance should be adopted, or introducing passive layers

First steps:

- Image material distribution of the detector with current material assignment (splitting modes)
  - Updated workflow for material budget analysis for Phase I geometry

  See: https://twiki.cern.ch/twiki/bin/viewauth/CMS/TrackingPOGRecoMaterialFromGeometry
- Generated sample of 10 000 single-neutrino events (neutrino gun)
- Passage of neutrinos through material of the simulated CMS detector is tracked in Geant4

Next steps...

- Find a good set of control plots/variables
- Include material budget comparison plots in them in the MTV workflow
- Redo sim. of tracker without big support structures

  (keep just material that is local to sensitive layers)
- Model of material with this “light-weighted” tracker version
- Compare / see if z expansion is cured
- Development of a weighted splitting mode (weight = distance from active layer?)
- Long term: inclusion of inactive layers in track propagation methods (e.g. ghost-layers with properly-flagged missing hits)

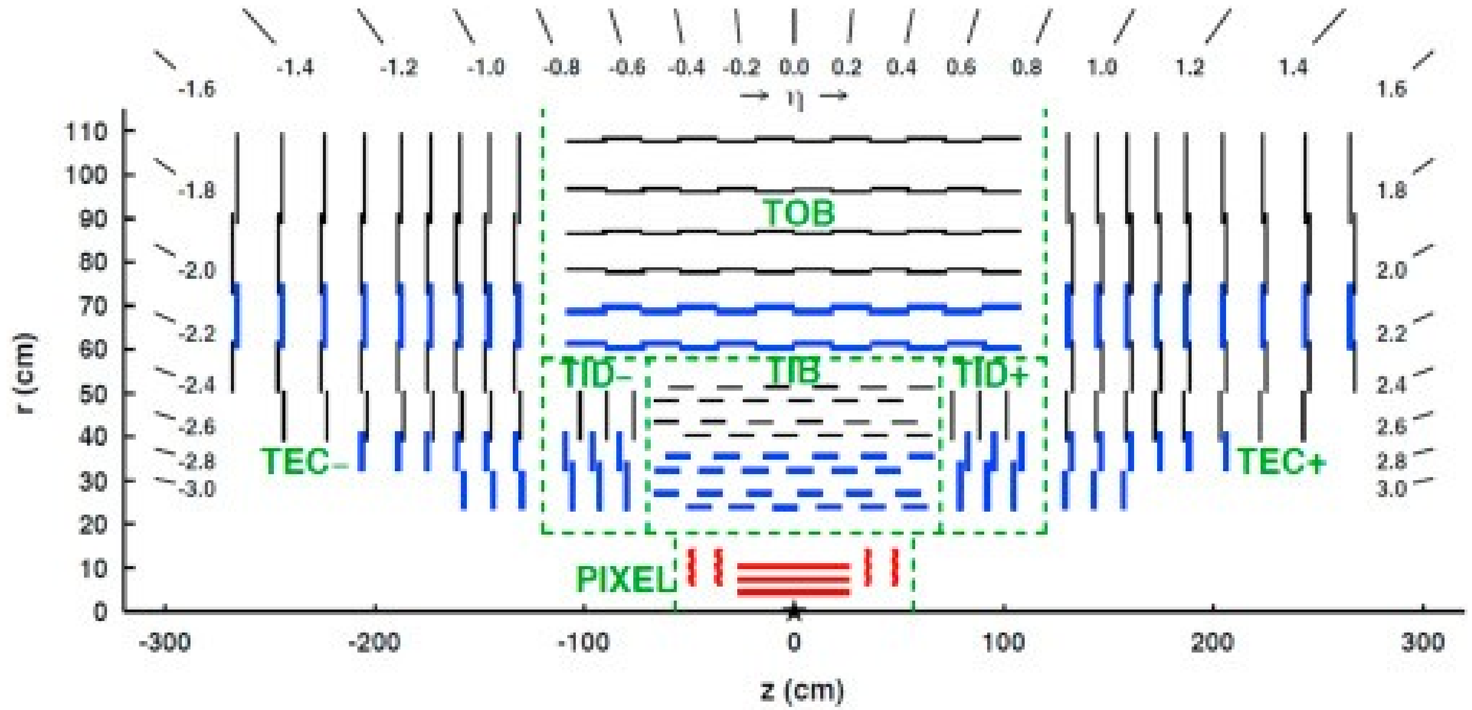
Thoughts / Remarks / Feedback always welcome!

Thanks to Marco Rovere for continuous help!

Thank you!

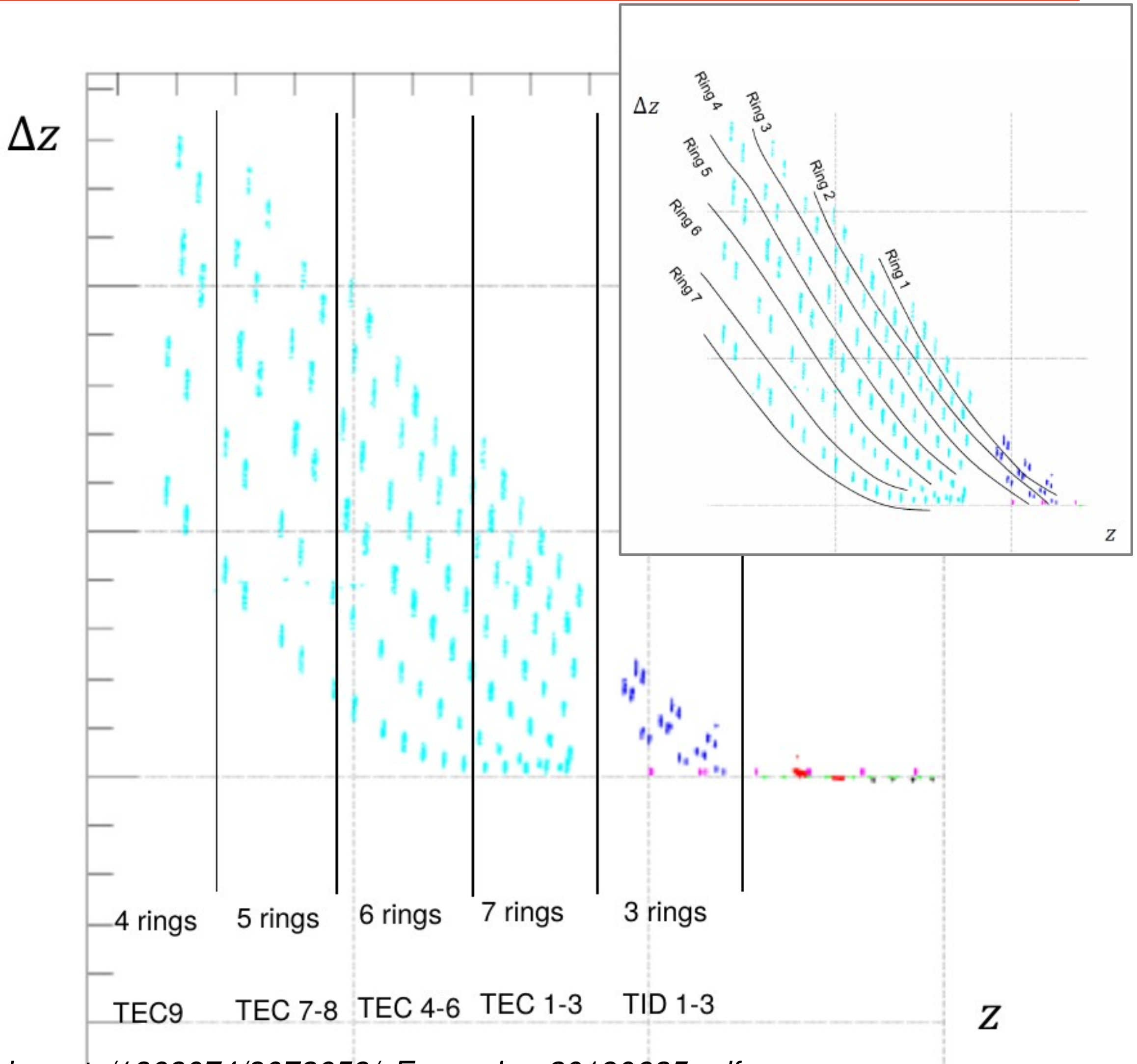
Backup

CMS Tracker (Phase 0)



Problem: z expansion

- Band structure
  can be easily associated to ring of modules
- Strongest for innermost ring, and weakest for outermost ring
- $\Delta z \propto 1/r$
- $\Delta z \propto z$
- $\Delta z \propto z/r = \cot(\theta)$
- Helix trajectory:
  $r = -2\, QR \sin\varphi$,
  z $= -2$ **QR** φ **$\cot\theta$**
  => **$\Delta z \propto \cot\theta, \ \propto \Delta(QR)\, \varphi \cot\theta$**
- An increasing Δ QR deviation along the trajectory might explain the effect
- e.g. mis-modeling of momentum (energy loss)
- Subdetectors with limited r resolution: TID, TEC



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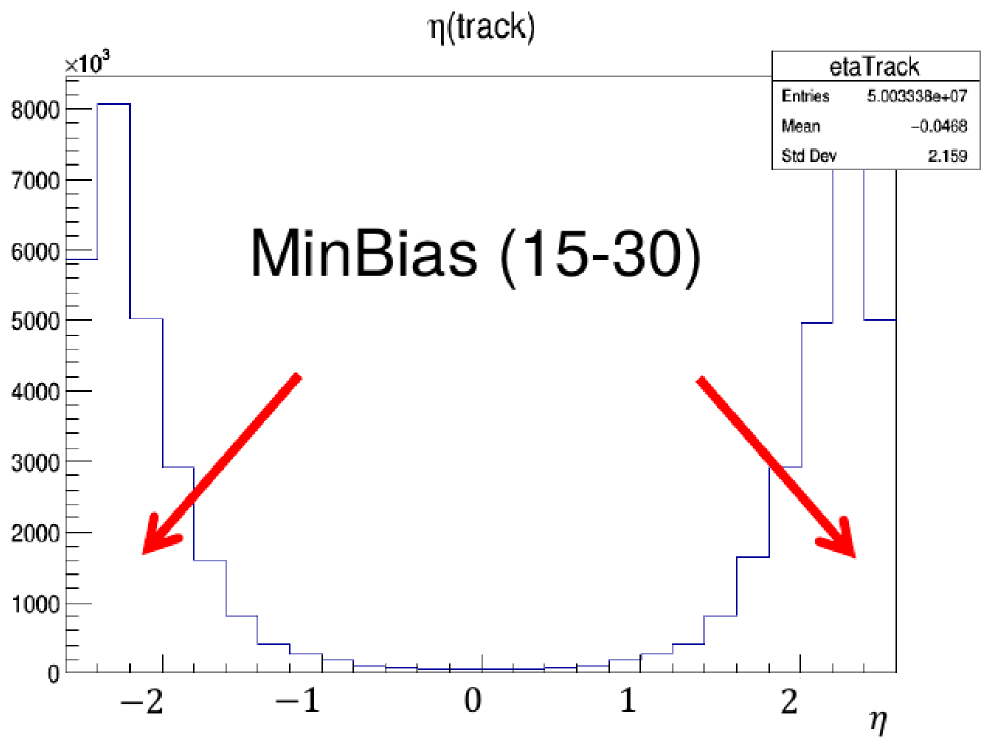
Model for z expansion: min bias events

- Minimum bias events have a unique coverage of the very forward region unlike other data sets
- Minimum bias is the main provider of tracks at large |cot θ|, would explain why it is a driver of z expansion



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Assumption: momentum mismodeling through wrongly estimated energy loss in tracking stations

Test1:

- Apply a tuning factor f = 4 to the energy loss correction (few MeV) in each tracking step within TID or TEC =>cures the twist and expansion
- Momentum corrections at the sub-permille level (few MeV cp. to some GeV track pt) in the end caps have a huge influence on z expansion

Test 2:

- Geant4 contains an error propagation package, named Geant4e [2]
- Trajectory state defined by: momentum, position, charge, particle type, error matrix
- Trajectory state can be propagated to any target surface, considering magnetic field and material defined in Geant4
- Situation improves roughly by ~factor 3, both z expansion and twist

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Task: Review of the assignement material in the simulated CMS tracker

- Geant4e propagation too costly for standard use
- Investigate possible improvements in the material description used by the standard re-fitters
- Problem is not in sim. material, but in material considerations in track propagation
  e.g. no inactive (dense) layers in Kalman Filter

First steps:

- Image material distribution of the detector
- Study current material assignment (i.e. dense material splitting mode), and available alternatives
- Find a better solution (split mode) for assignment of dense material (to active modules)

Imaging material distribution:

- For each step of the particle's spatial trajectory:
- Plot fraction of the total radiation length or total hadronic interaction length of its trajectory
- Breakdown into sub-detectors (TEC, TOB, TIB and TID and Pixel Phase 1)
- Beam pipe and support tube are included in the material budge

Validation process

- Neutrinos interact minimally with detector material and have straight trajectories
- Generated sample of **10 000 single-neutrino events** (neutrino gun)
- Passage of neutrinos through material of the simulated CMS detector is tracked in Geant4

- Each neutrino is incrementally stepped through the detector material
- Compute energy loss based on the electron density of the traversed material and its radiation length
- For step length x:
- $\langle dE \rangle = 0.5 * K * N_e * \Delta x / N_A$

  $K = 4 * pi * N_A * re^2 * m_e * c^2$ [MeV cm^2 / mol]

  N_A is Avogadro's number [1/mol]

  N_e is electron density (internally computed by Geant4)

- Calculate fractional radiation length / hadronic interaction length of that step for traversed material
- Compute final average radiation length and average energy loss
- Read out characteristic radiation length /hadronic interaction length of the simulated material (.txt file)

- Each material is classified in: Support, Sensitive, Cables, Cooling, Electronics, Air and Other
- Many materials belong to more than one category
- Their radiation length and hadronic interaction length are broken down according to the fractional contribution

Material budget in radiation length and hadronic interaction length