Validation and Tuning of the CMS Full Simulation

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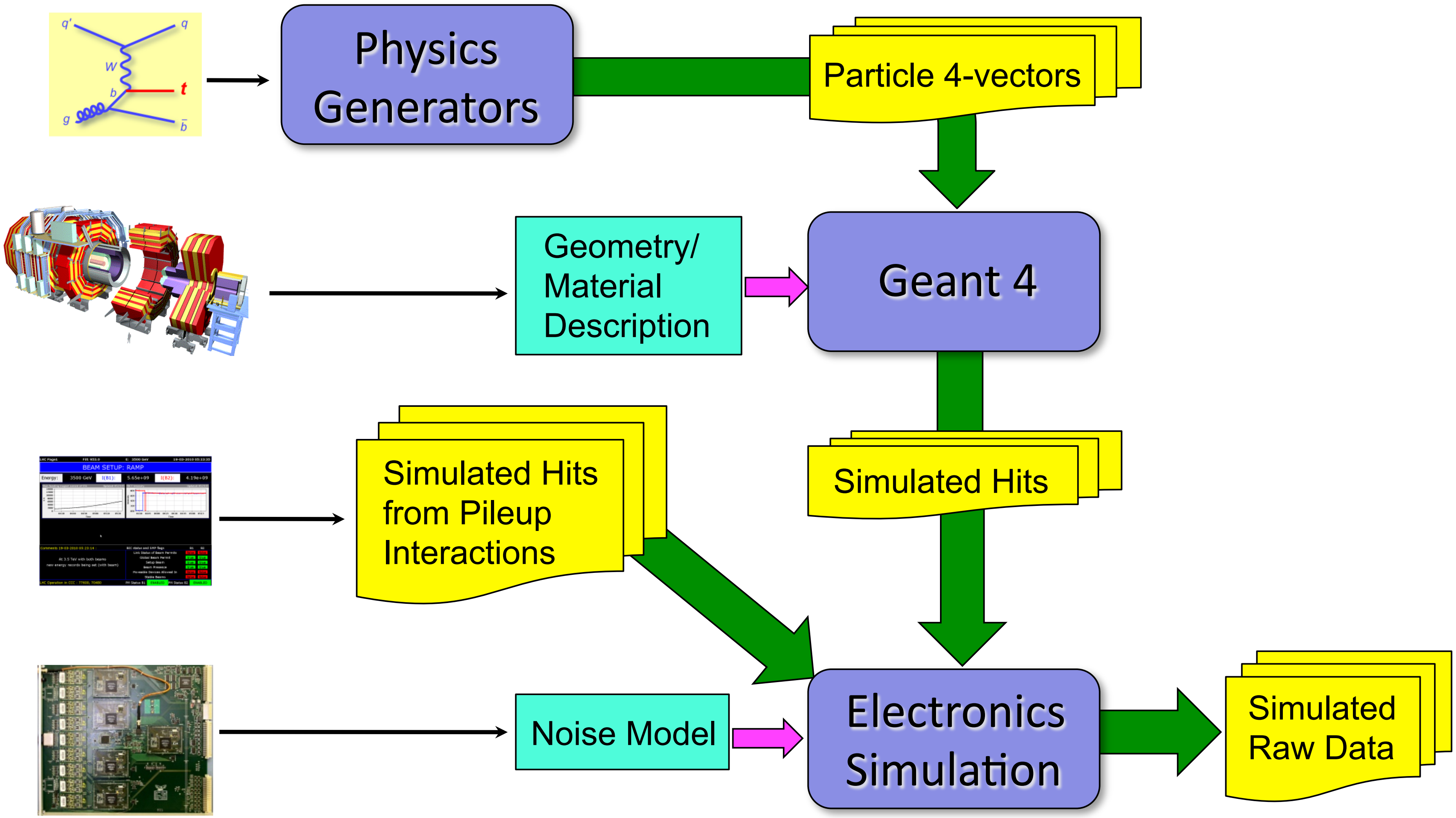
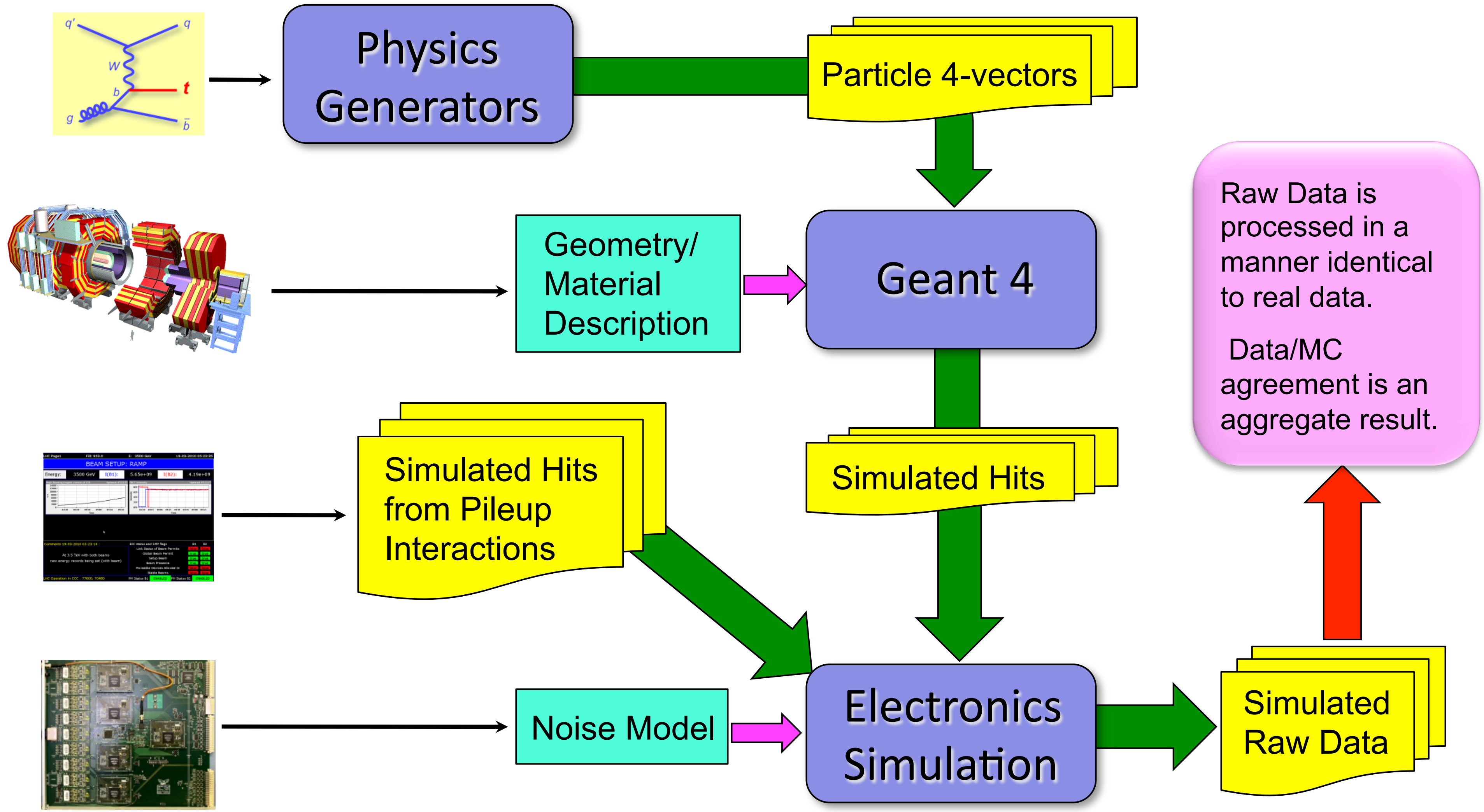
Representing the CMS Collaboration

Overview of CMS Simulation



Overview of CMS Simulation



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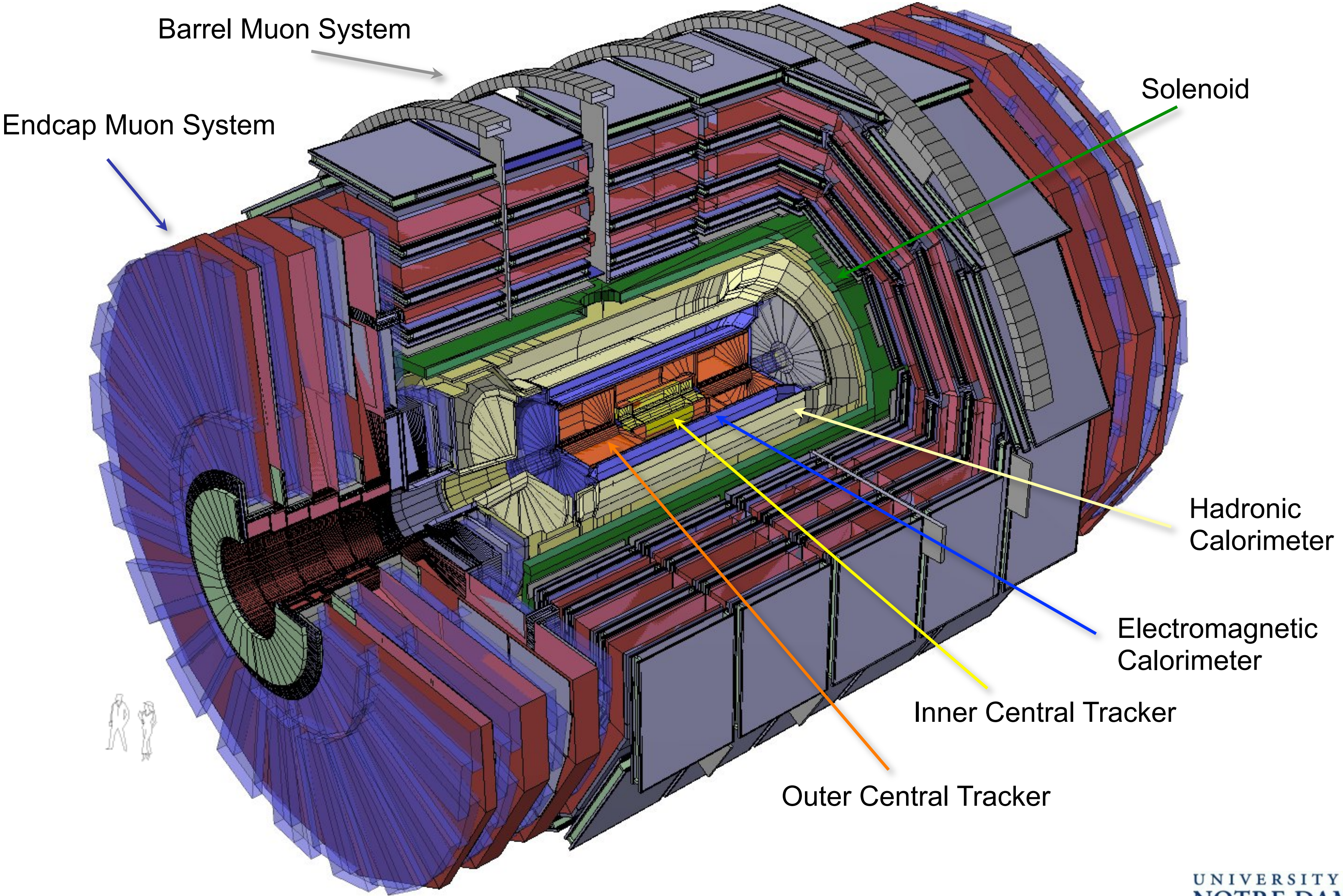
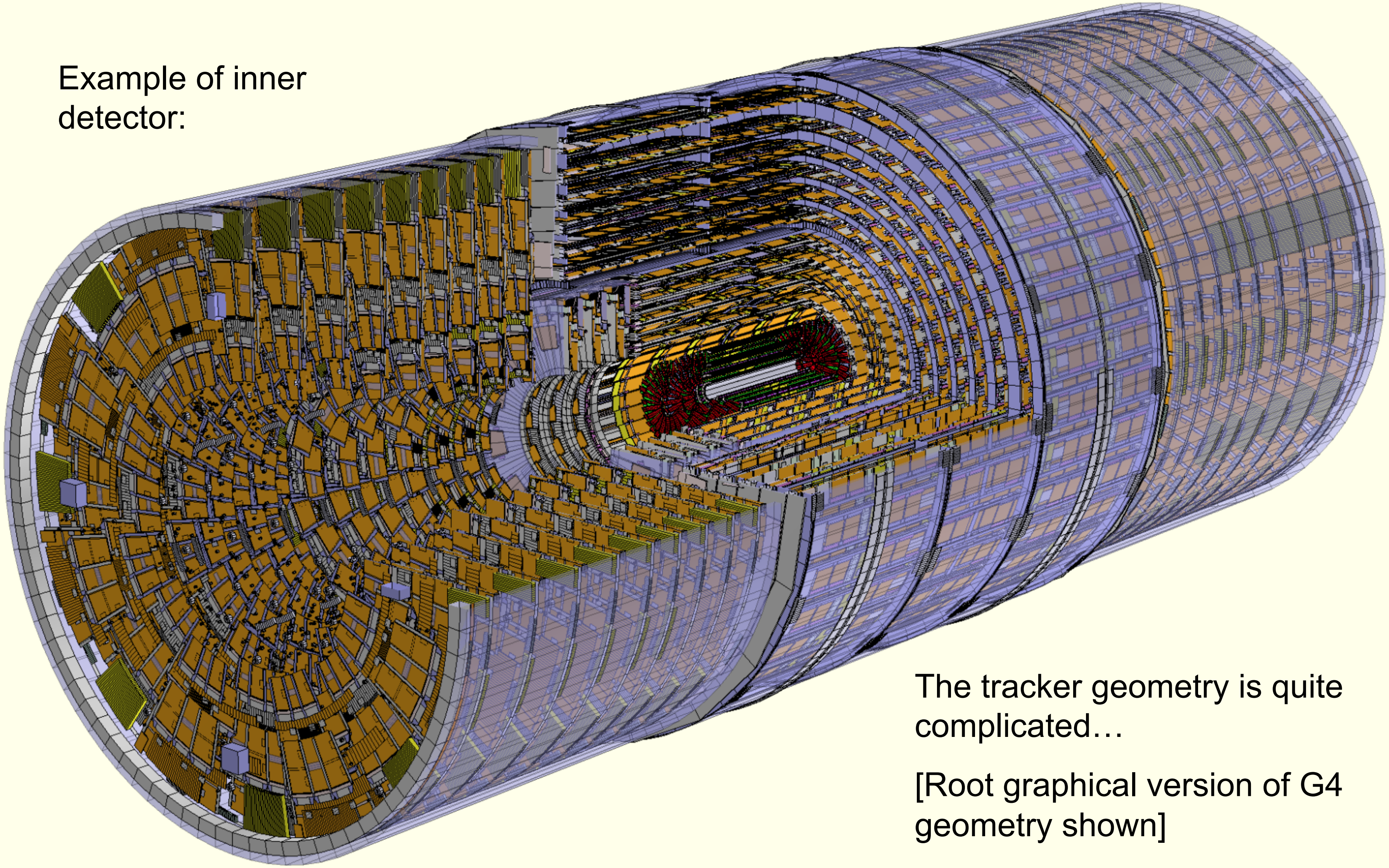
Overview of CMS



Overview of CMS

Example of inner detector:



The tracker geometry is quite complicated…

[Root graphical version of G4 geometry shown]

Overview

- Status of Tracker Geometry & Material Description
  - Material studies
    - photon conversions/nuclear interactions
  - Tracker dE/dx results
  - Track distributions

  } low energy nuclear and EM modeling, accuracy of material specification, low p_T generator physics

- Calorimeter Modeling
  - Electron bremsstrahlung
  - Jet and Missing Energy studies

  } material specification, physics models in particle showers, calorimeter noise models

- Muon System
  - Hit patterns and isolation variables

  } material specification, neutron transport, shower models

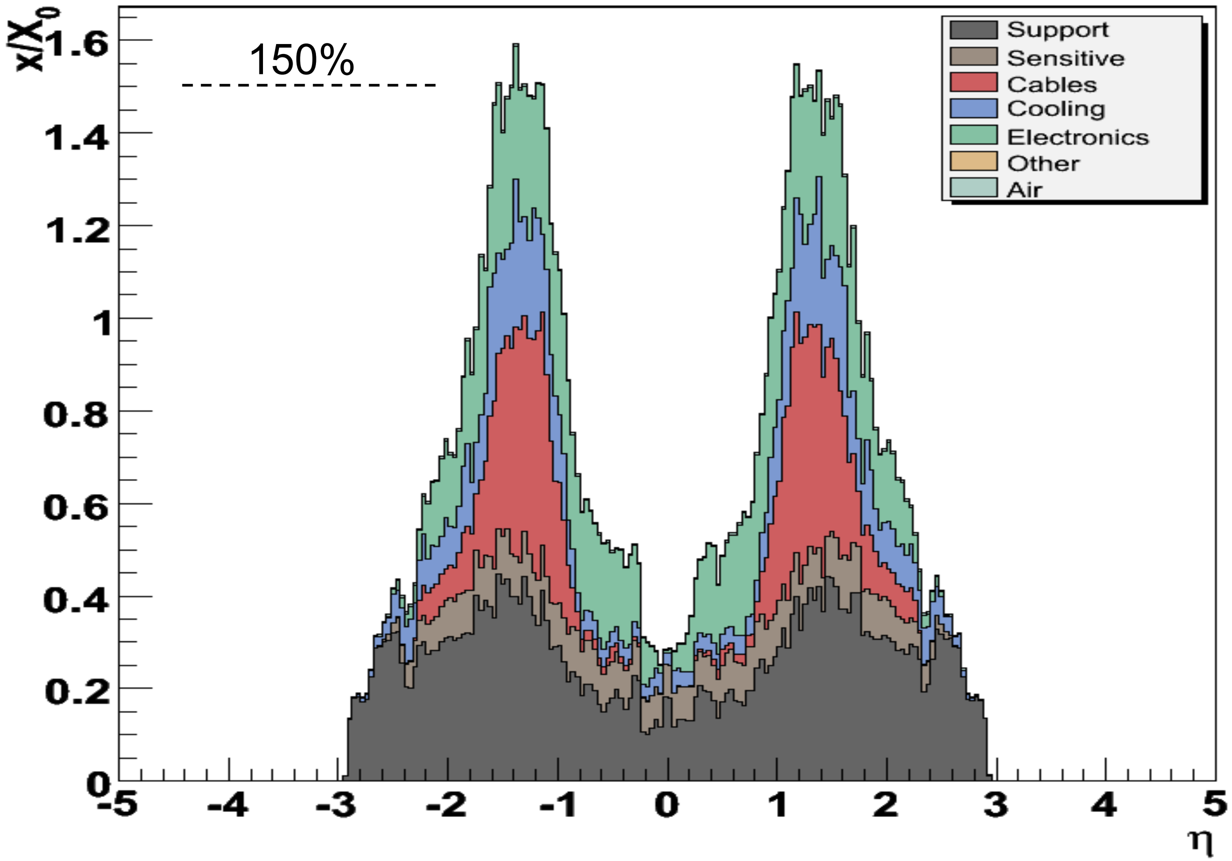
- Future Prospects

For other results, see:

Validation of Geant4 Physics Models with LHC Collision Data (PS08-1-170), Sunanda Banerjee

Detector Material Budget

Material distribution in current CMS Tracker (estimated):



- Very large photon conversion probability
- large effects of multiple-scattering
- must test with data to validate simulation

potentially large physics consequences

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Detector Material Studies

Reconstruction of Photon Conversions and Nuclear Interactions allow a mapping of the material distribution in the detector

Reminder - Photon conversion probability in a thin cylindrical shell:

$$dN_{conv} = N_{\gamma}(R,\theta,\phi) \cdot R^2 \sin\theta \, d\theta \, d\phi \frac{P}{X_0} dR \qquad N_{\gamma}(R,\theta,\phi) \propto 1/R^2 \sin\theta$$

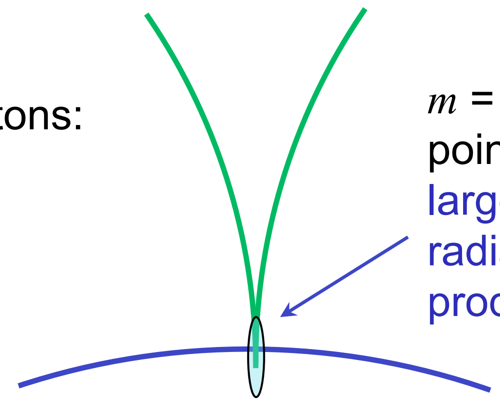
For Nuclear Interactions:

– swap P(photons) ~7/9 to P = 1, $X_0 \rightarrow \lambda_0$

(But, X_0 and λ_0 are sensitive to different physics)

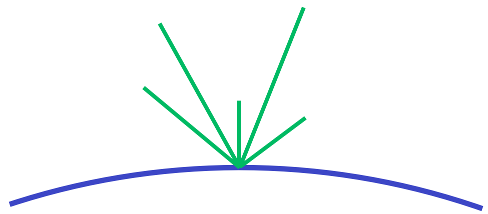
- Different reconstruction characteristics:

Photons:



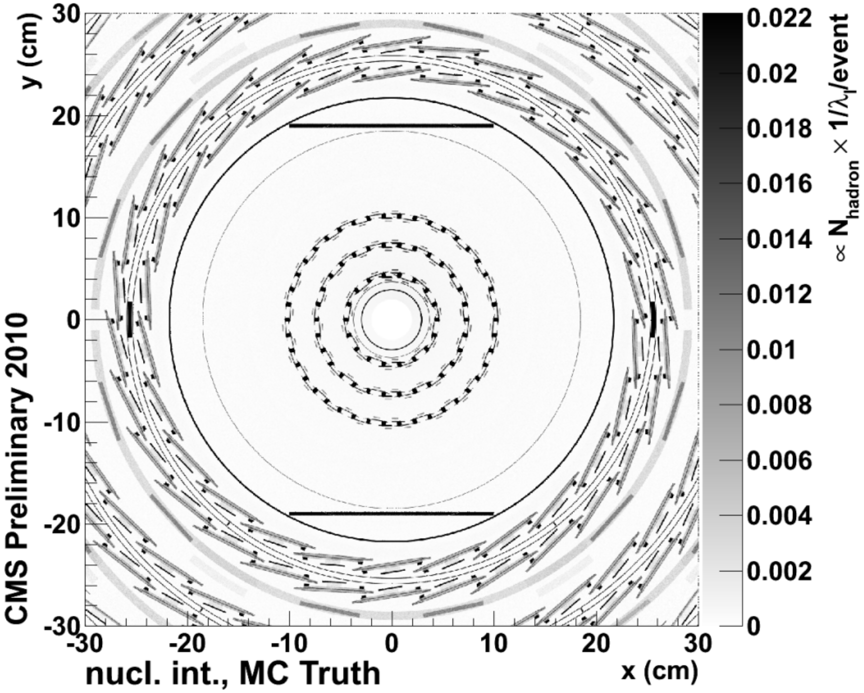
m = 0: tracks parallel at point of production ⇒ larger uncertainty in radial position of production point

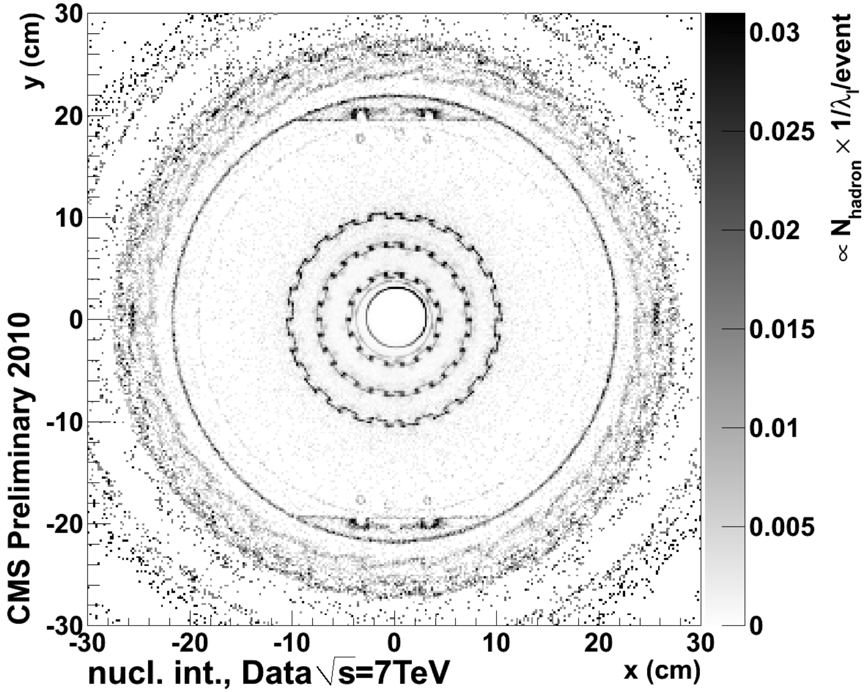
Nuclear interactions:



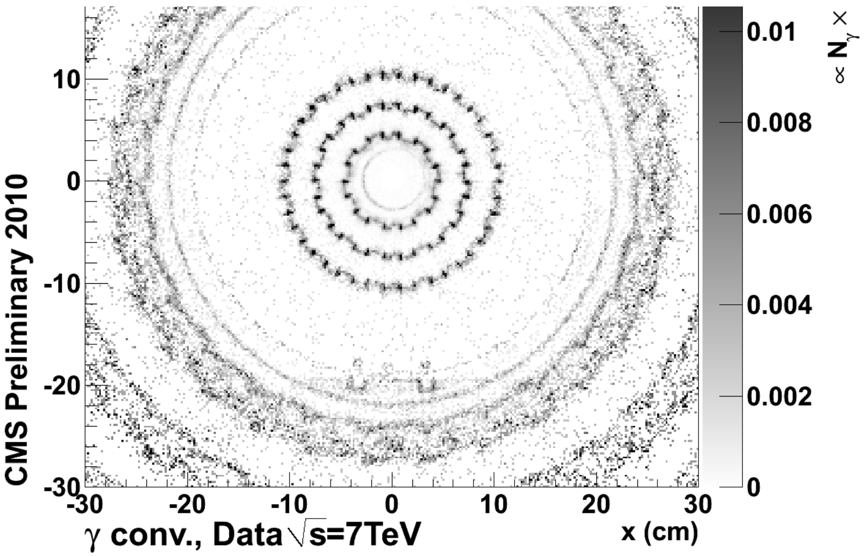
Good vertex resolution, many soft tracks with large impact parameters

Some examples:





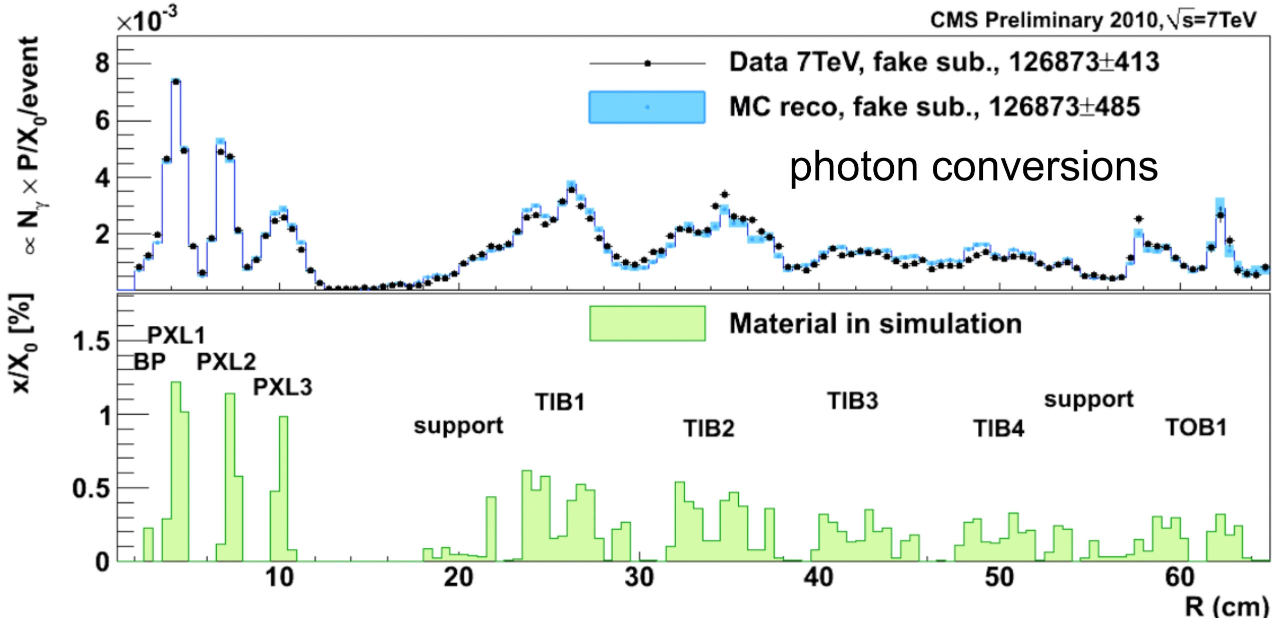
Note the superior position resolution of the nuclear interaction data



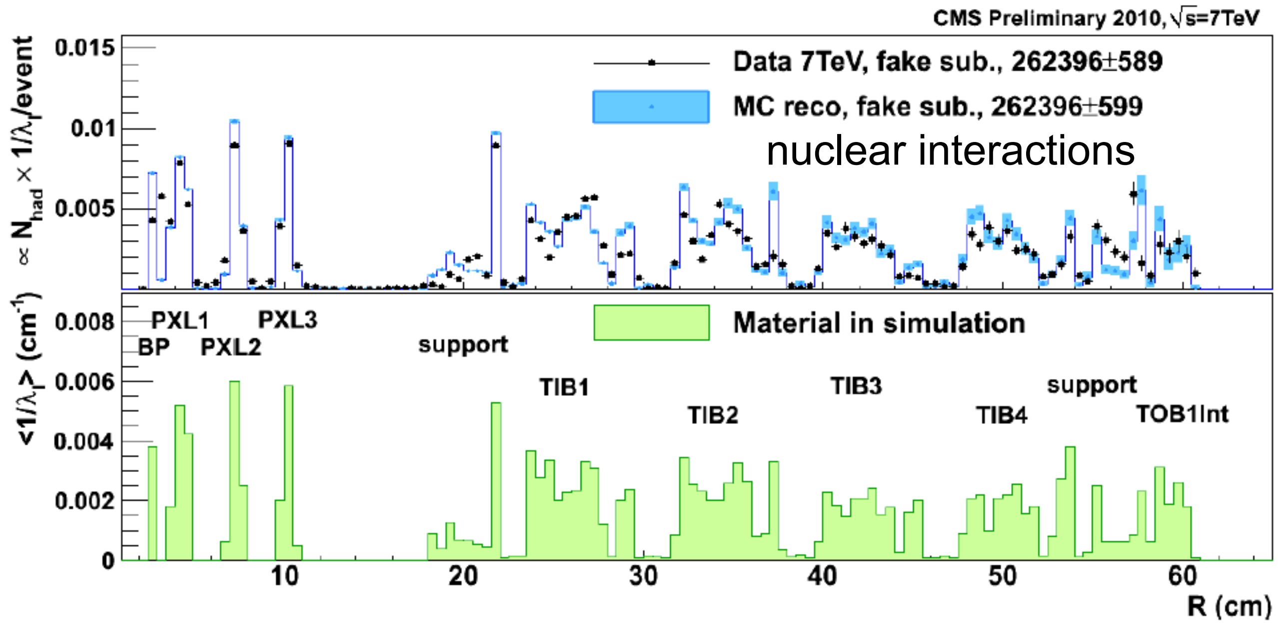
The beampipe isn't centered!

CMS PAS: TRK-10-003

Extracting the material budget



can unfold this distribution using estimates of the photon position resolution



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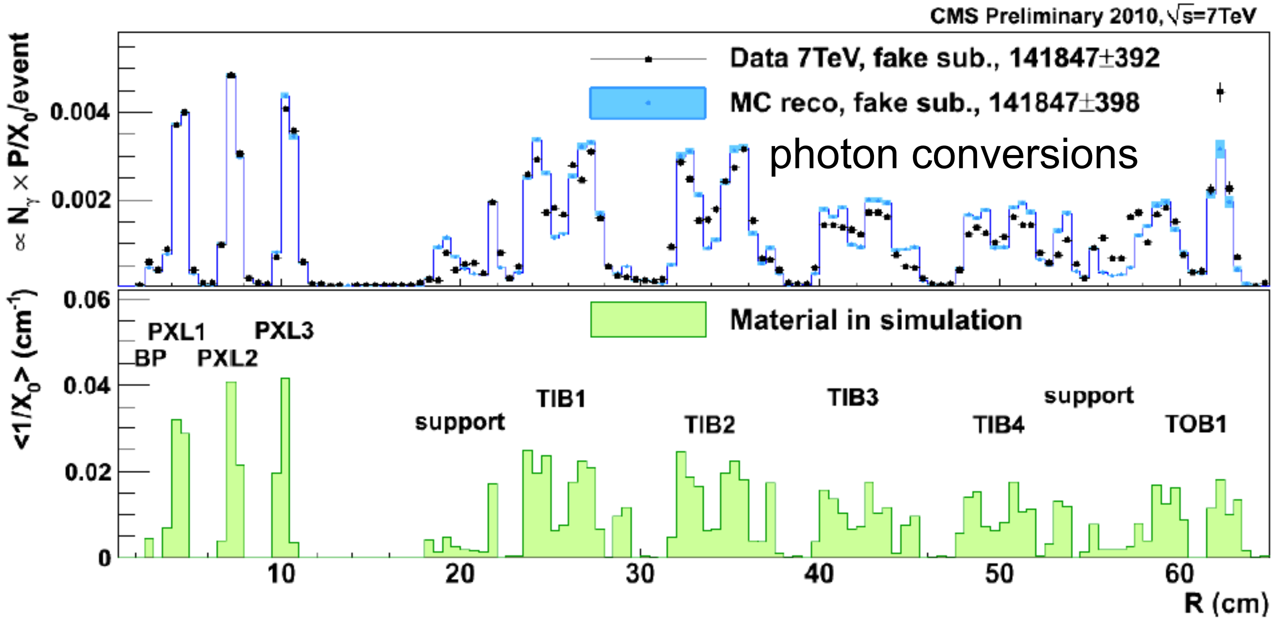

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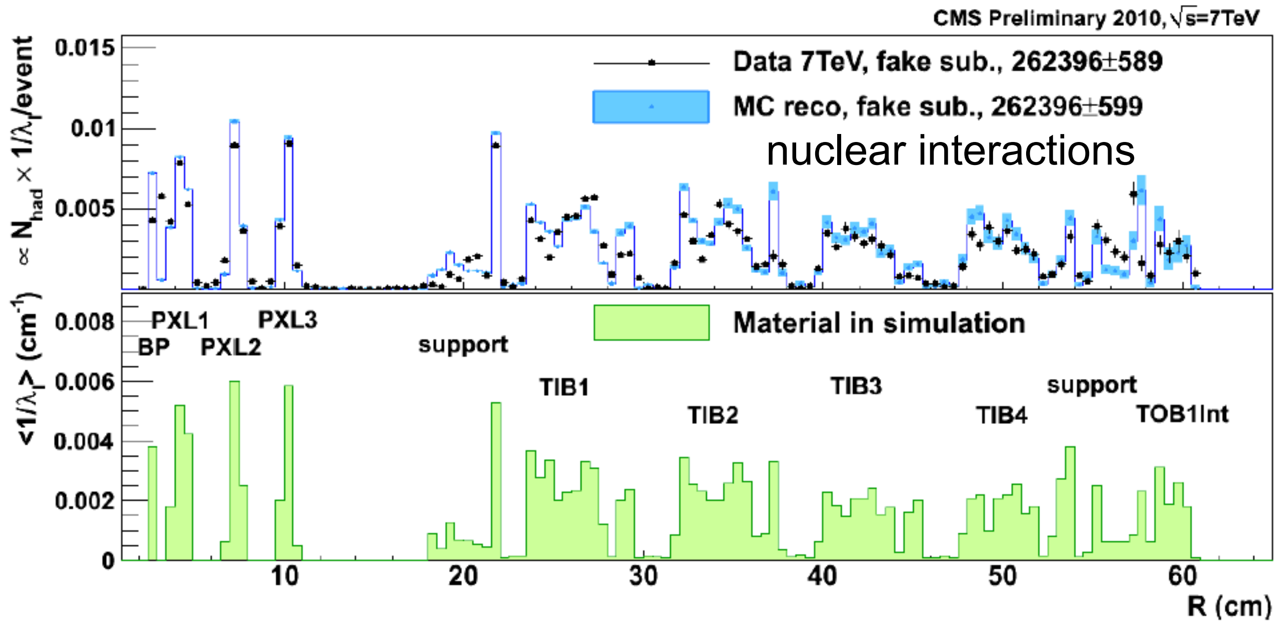

astonishingly good agreement between data and simulation

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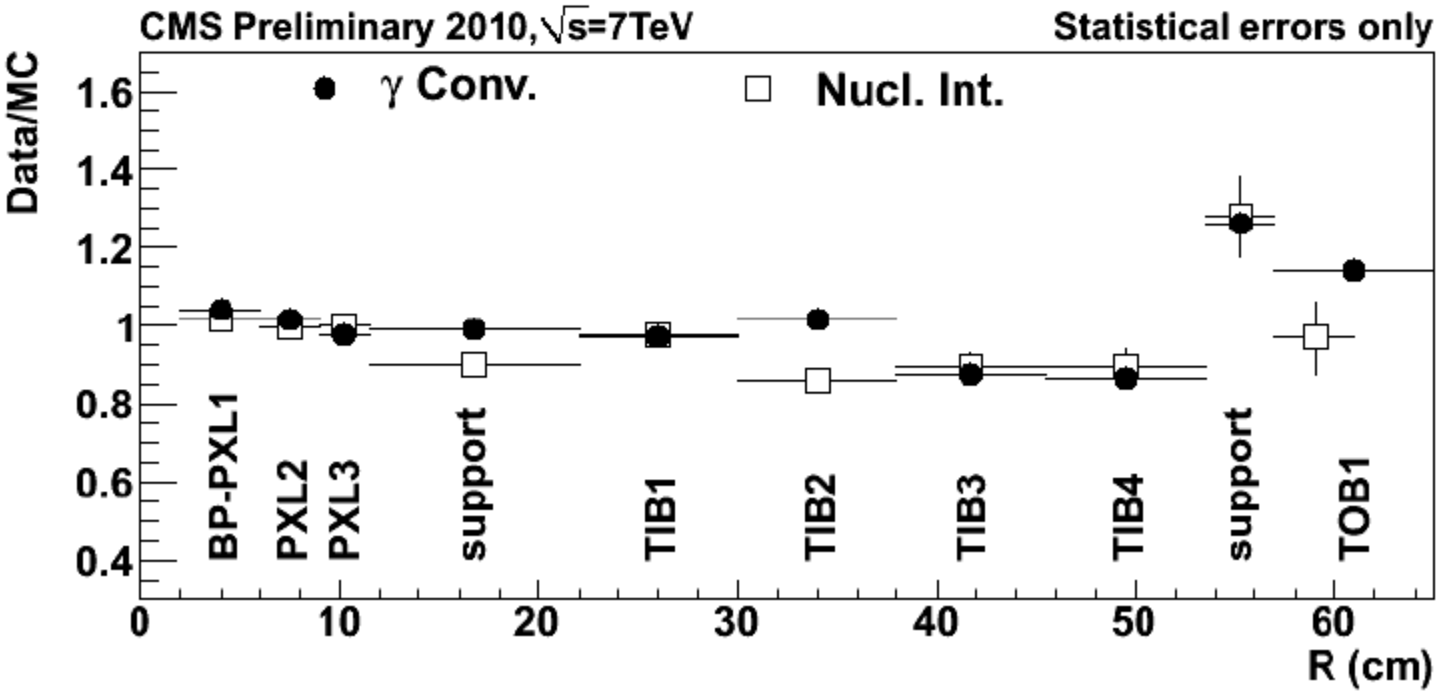
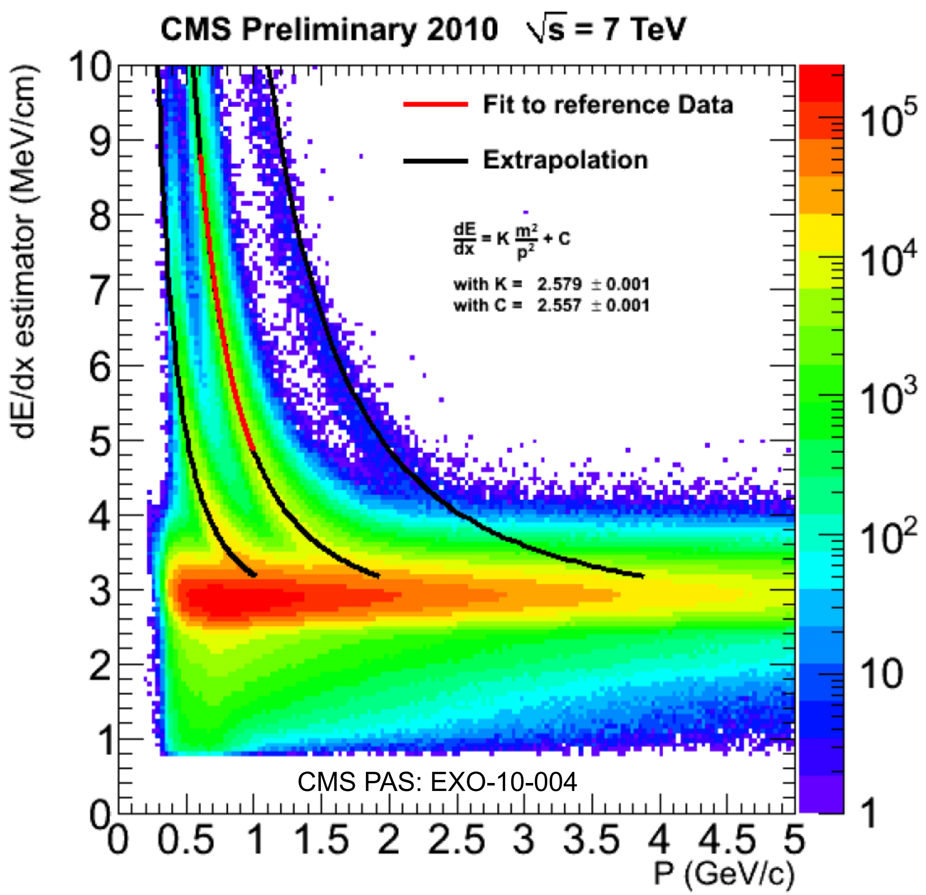
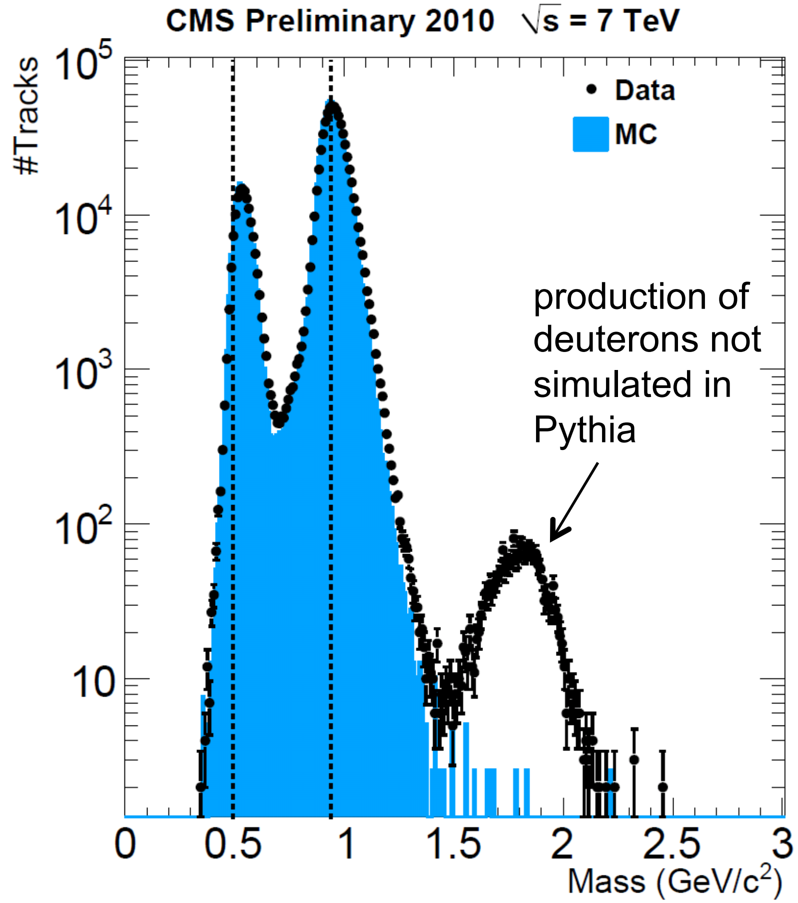
Extracting the material budget



- Other methods also employed:
  - track multiple scattering, momentum scale, etc.
- Agreement between photon conversions and nuclear interactions on the location and composition of materials gives us good confidence that the simulation geometry is an accurate representation of the real detector
- Uncertainties in the amount of material and its distribution are estimated to of order 5% (CMS PAS: TRK-10-003)

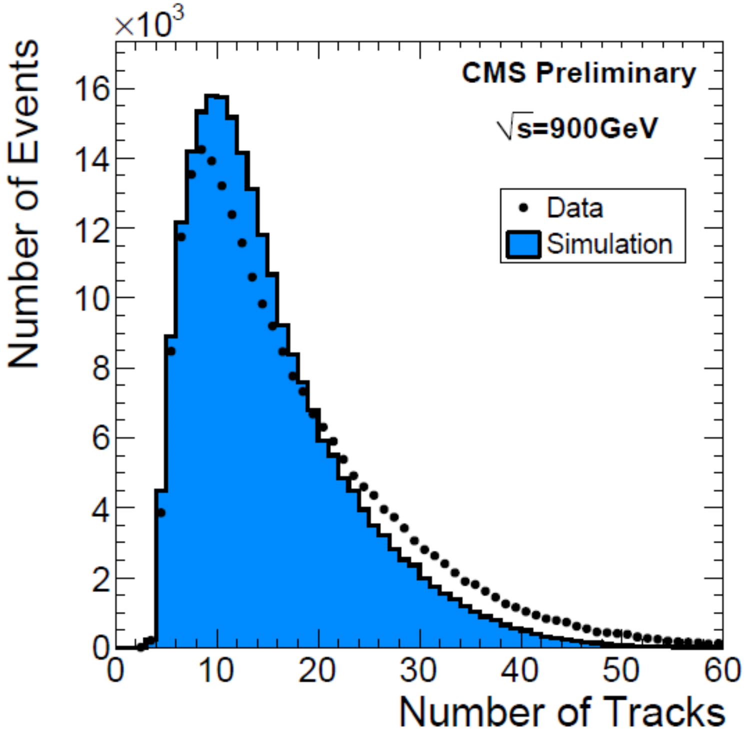
Tracker dE/dx Simulation

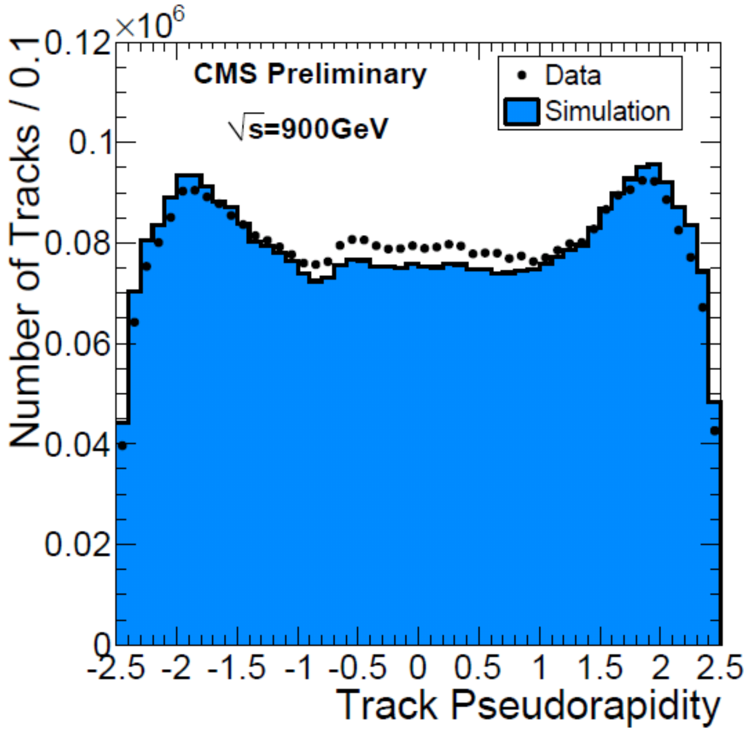




- Signal simulation in tracker includes charge propagation, charge collection efficiencies, saturation effects, and tracker noise modeling
  - tuned on cosmic data and early collisions
- detailed test of Geant4 descriptions of energy loss mechanisms in tracker material

Charged particle multiplicity

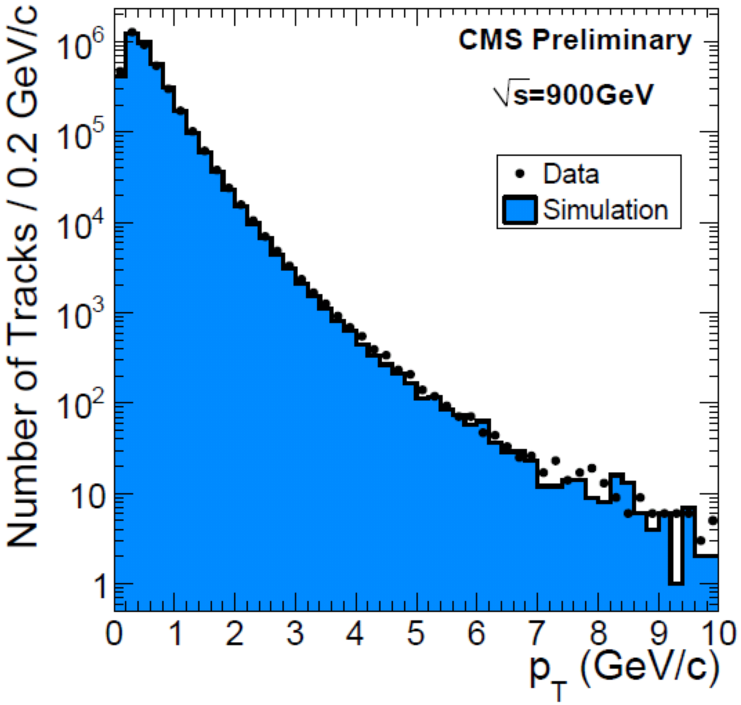


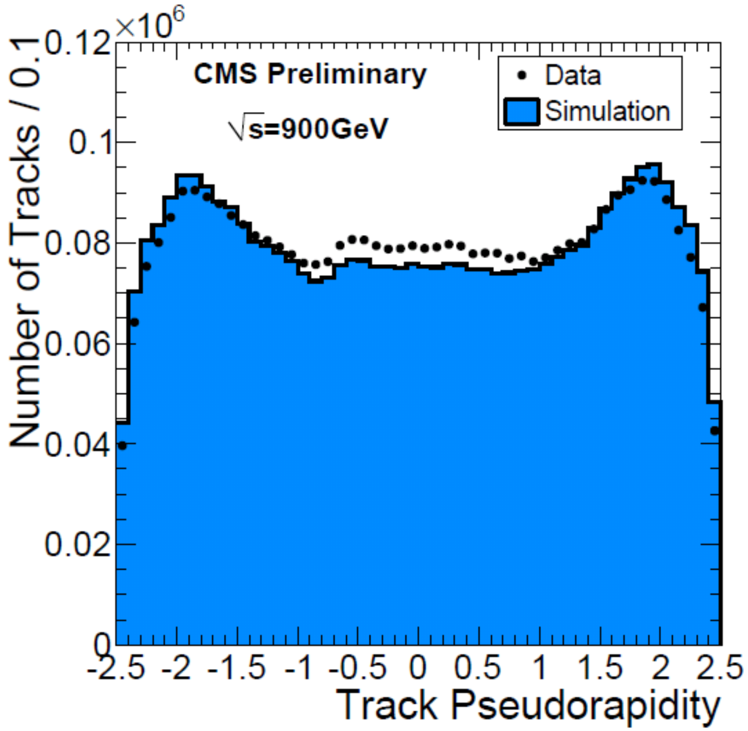


- Minimum Bias events
- Original Pythia 6.4 tunes largely divergent from Data distributions (tune D6T)
  - charged particle multiplicity very different
  - Surprising, given previous Tevatron studies

CMS PAS: TRK-10-001

Charged particle multiplicity





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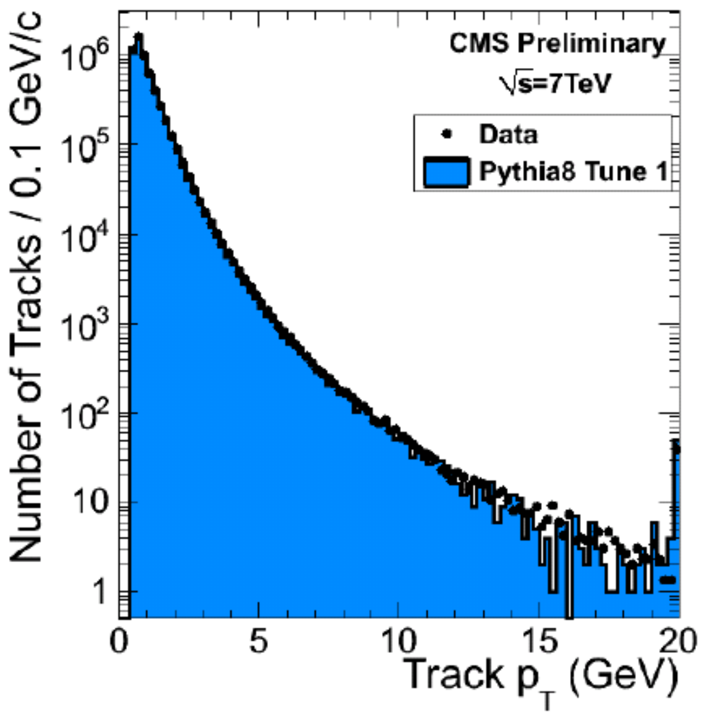
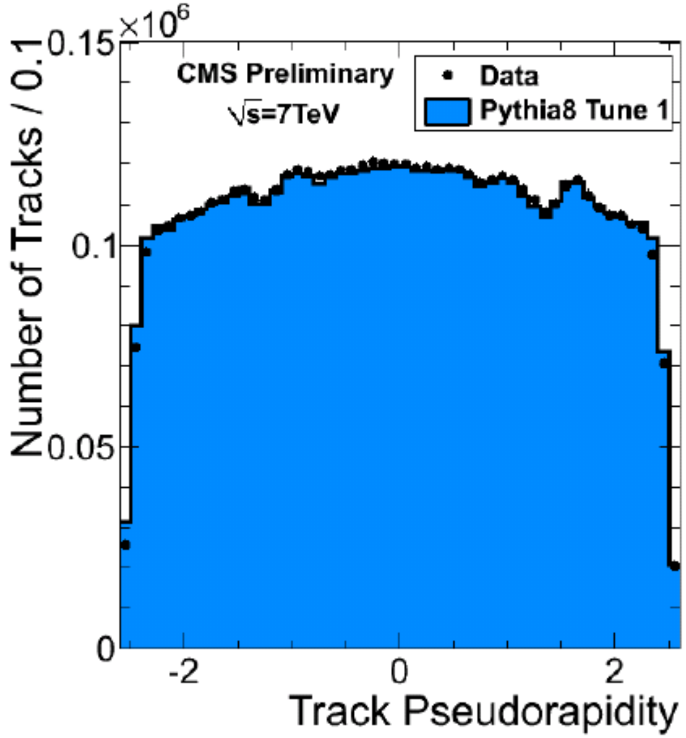


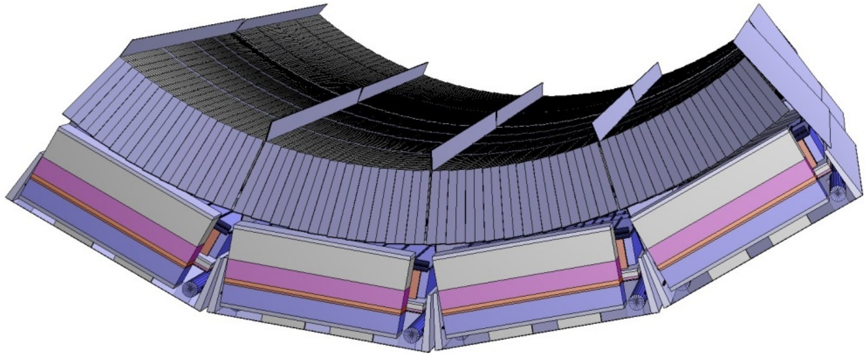


- Minimum Bias events
- Original Pythia 6.4 tunes largely divergent from Data distributions (tune D6T)
  - charged particle multiplicity very different
  - Surprising, given previous Tevatron studies
- New Pythia 8, Tune 1 gives much better agreement
  - new: hard scattering in diffractive interactions
    - relative increase in population of high-p_T, "forward" regions

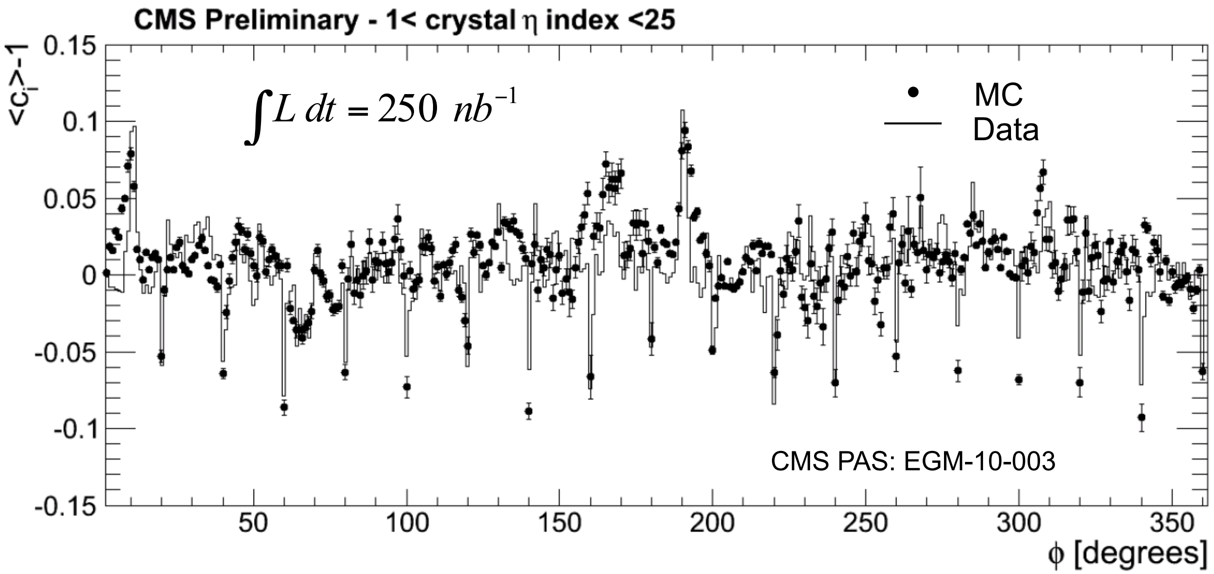
CMS PAS: TRK-10-005

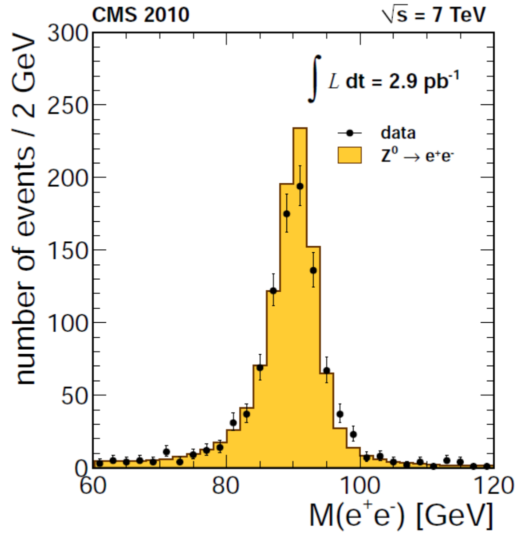
Electromagnetic Calorimeter Calibration

- Based on expected ϕ symmetry of energy deposition in minbias events
- Non-uniformity of response correction caused by inter-module gaps and different distributions of material in front of the calorimeter



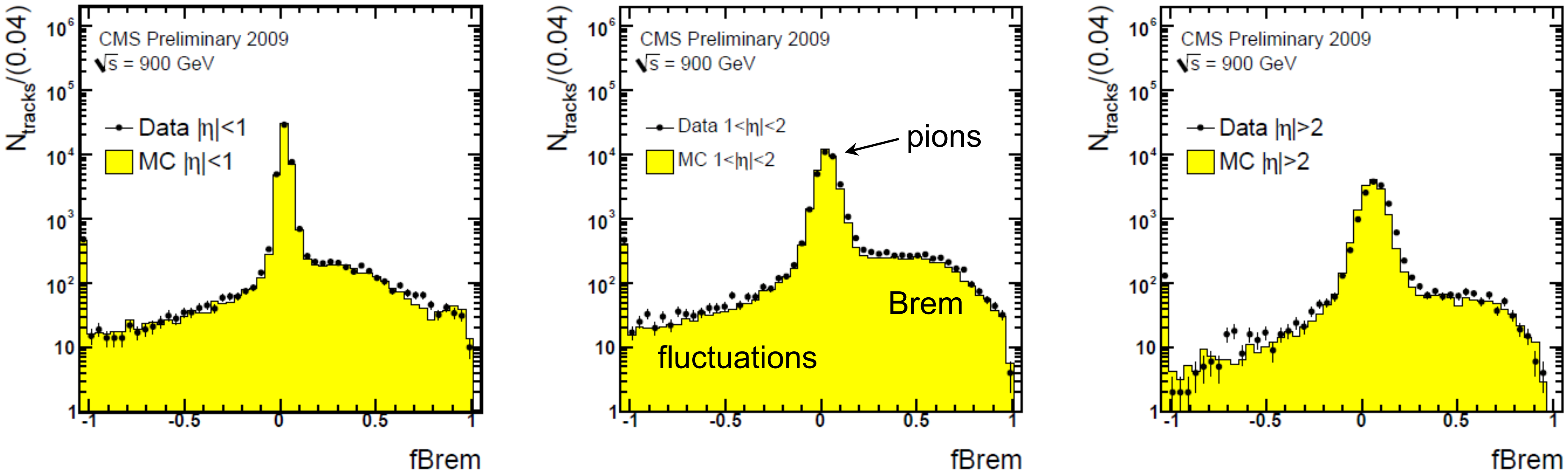
- Here: response correction for each calorimeter module:





Electromagnetic Interactions

- Fraction of energy loss in the Ecal for different ranges in η: $f_{\mathrm{Brem}} = (p_{\mathrm{in}} - p_{\mathrm{out}})/p_{\mathrm{in}}$
  - inclusive distributions based on high-purity track selection
    - Gaussian Sum Filter track fit to account for energy loss



- MC Minbias events; again remarkable MC/Data agreement

CMS PAS: EGM-10-001

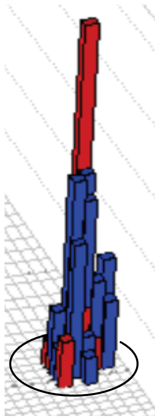
- depends on accurate modeling of:
  - material distributions
  - showers
  - correct distribution of particle types in Data and MC

Jet-Finding at CMS

• Calorimeter Jets

Jets clustered from ECAL and HCAL deposits (Calorimeter Towers)

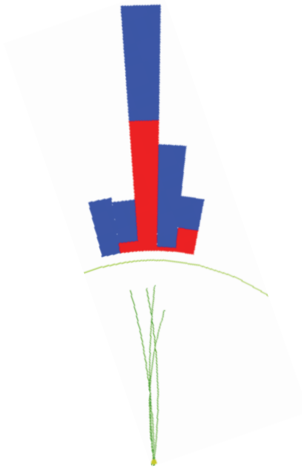
Correspondingly: Calo MET



• Jet-Plus-Track Jets (JPT)

Subtract average calorimeter response from CaloJet and replace it with the track measurement

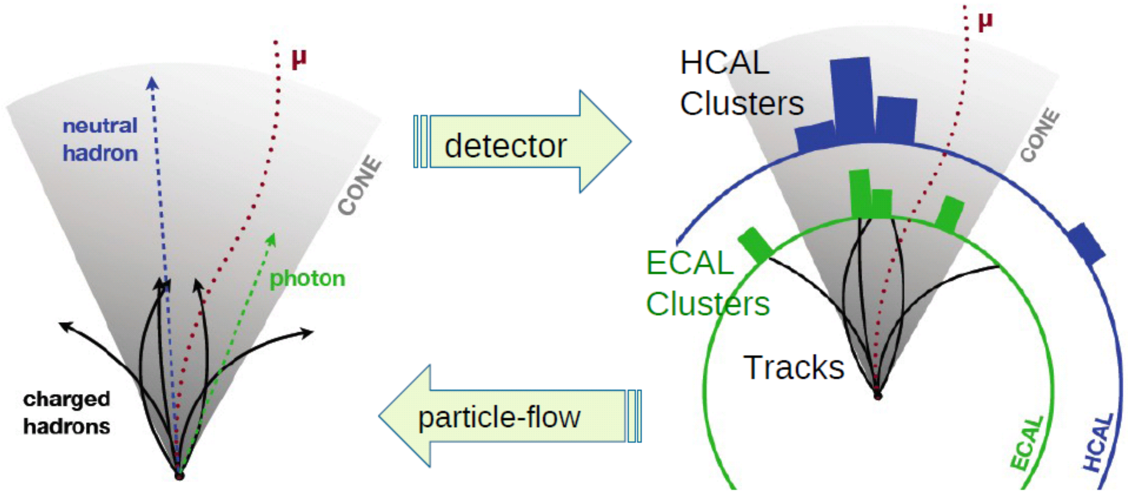
Correspondingly: Tc MET



• Particle Flow Jets (PF)

Cluster derived Particle Flow objects: unique list of calibrated "particles" representing "generator level" information

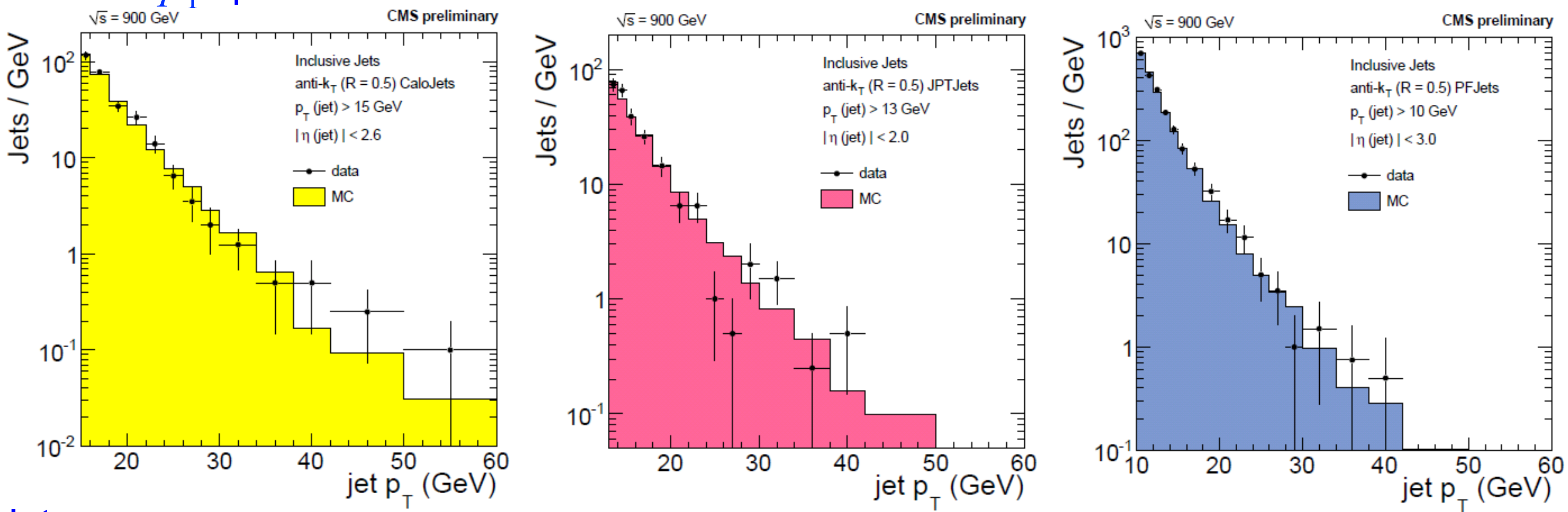
Correspondingly: PFMET



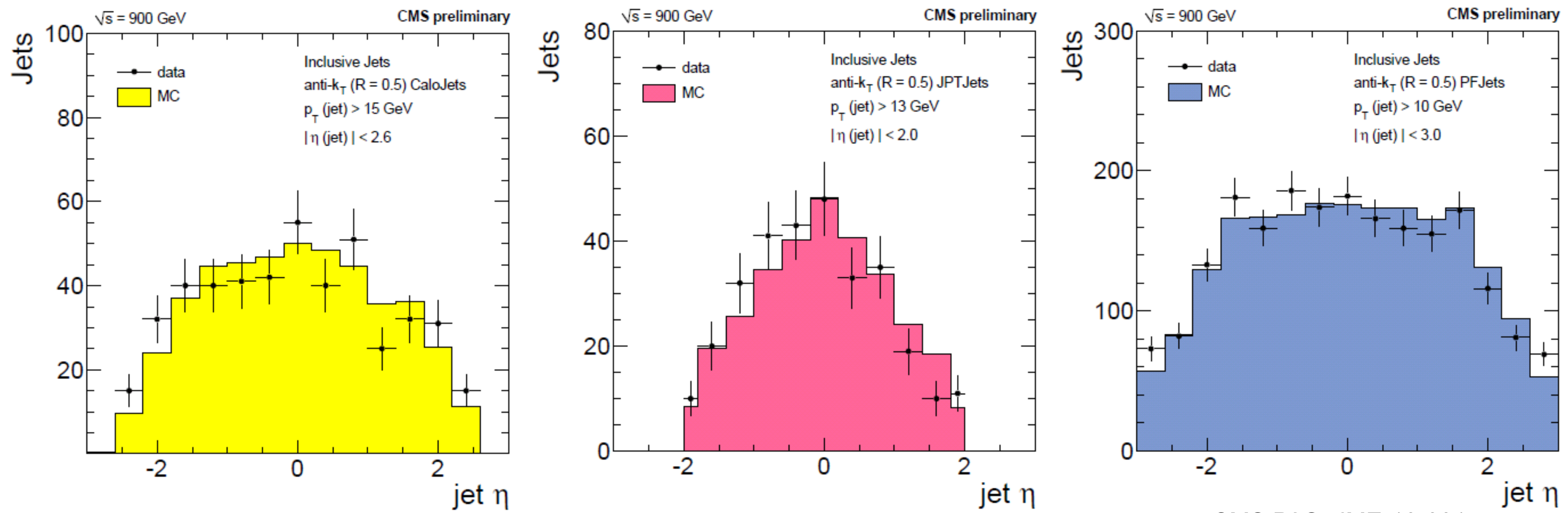
Default jet clustering algorithm: Anti-k_T with R = 0.5

Jet Variables

- Inclusive p_T spectrum

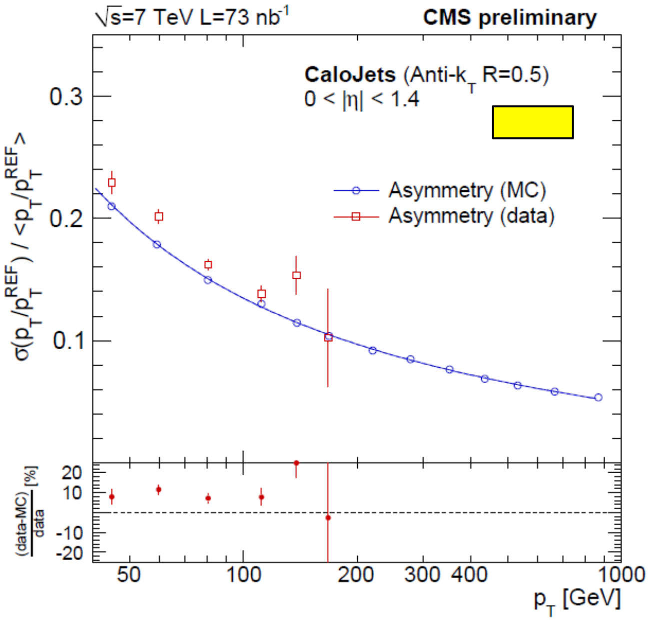


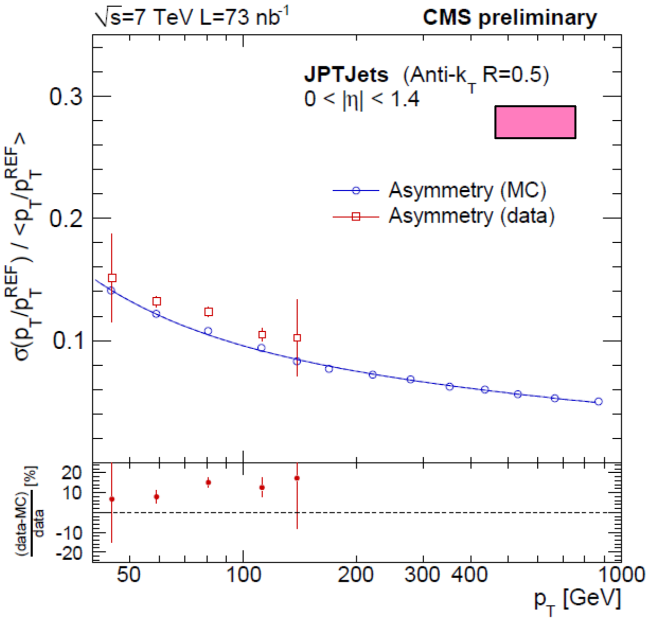
- Jet η



CMS PAS: JME-10-001

Jet Resolutions

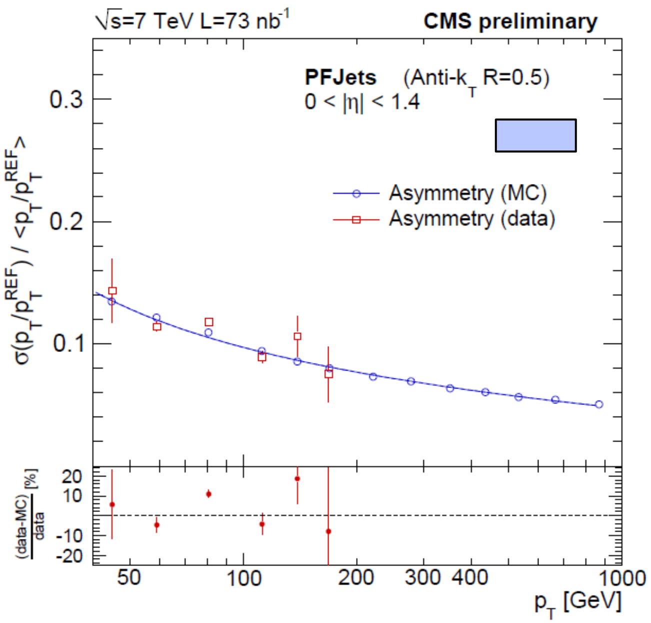




Di-jet Asymmetry Method:

$$A = \frac{p_T^{jet1} - p_T^{jet2}}{p_T^{jet1} + p_T^{jet2}}$$

$$\Rightarrow \frac{\sigma(p_T)}{p_T} = \sqrt{2}\sigma_A$$



- Resolution as a function of average p_T
  - extrapolated to zero additional activity in each bin by measuring σ_A at decreasing values of the third jet p_T^{jet3}
  - same treatment applied to QCD MC
  - within 10% agreement for all three jet algorithms
  - validates combination of generators, material description, shower models

CMS PAS: JME-10-003

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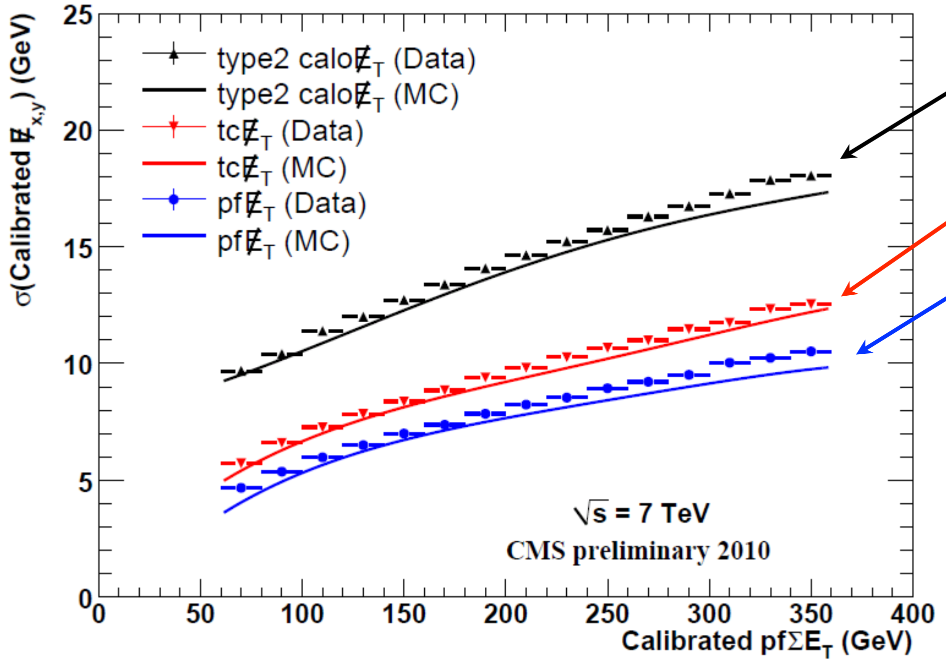
Missing E_T: Resolution Studies

- MET provides a stringent test of noise simulation, showering, and resolution modeling ⇒ all elements have to be correct



Calorimeter MET

Track-corrected MET

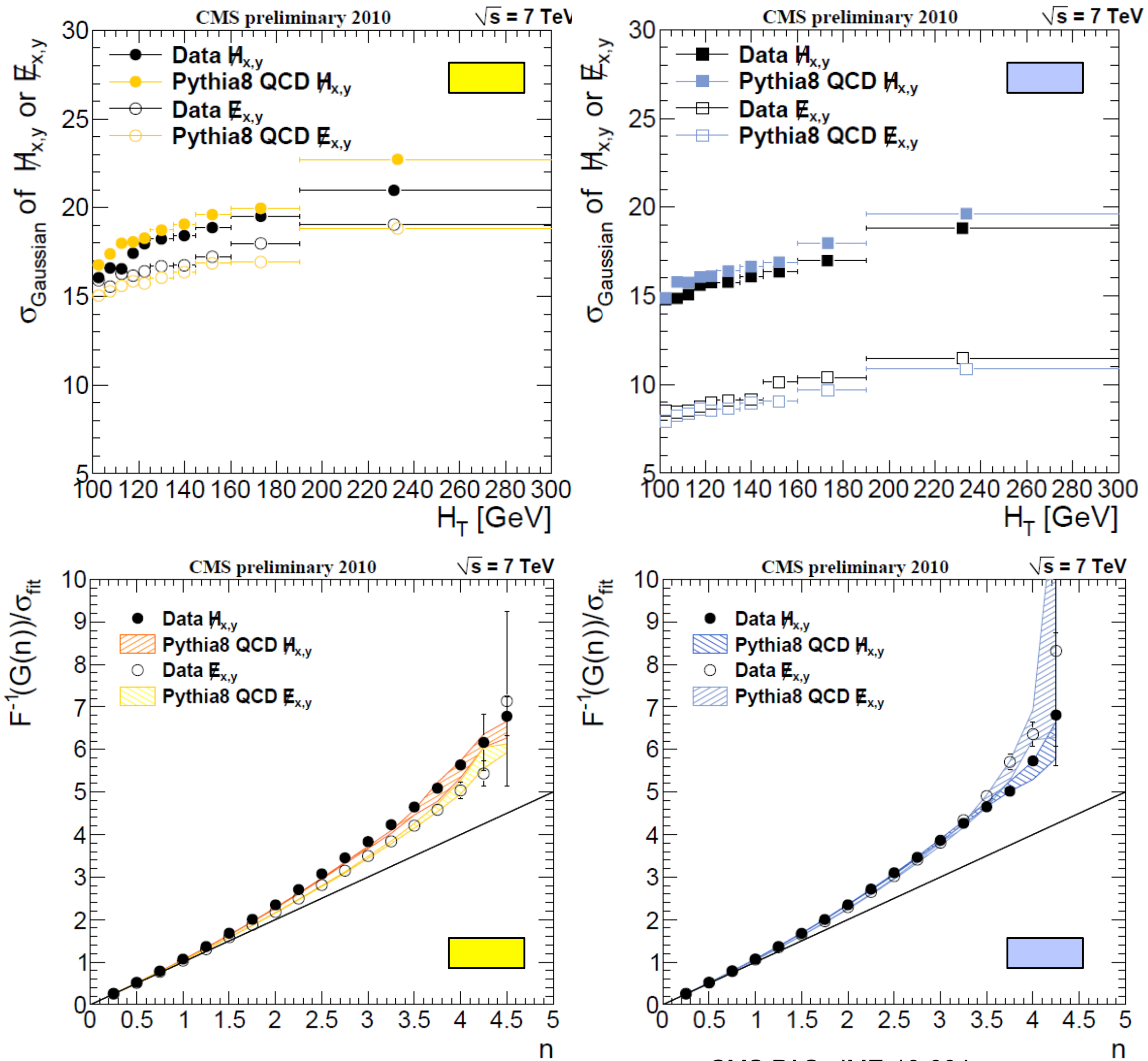
Particle Flow MET

(Jet Energy Scale corrections are applied to all jets with p_T>30 GeV; remaining unclustered energy is corrected using a scale derived from the hadronic recoil opposite Z → ee events)

- Here, $\not{E}_T$ resolution is measured using the width of the $\not{E}_x$, $\not{E}_y$ distributions
  - overall $\not{E}_T$ calibration from transverse energy balance in γ+jet events
  - at least two jets of p_T > 25 GeV required
  - identical MC/Data treatment

CMS PAS: JME-10-004

Comparisons of Calorimeter Resolutions



CMS PAS: JME-10-004

- Resolution of MET and H_T (total jet transverse energy) for Calorimeter Jets and Particle Flow Jets
  - H_T potentially more robust
  - multi-jet events
    - leading jet p_T > 40 GeV
  - width of central gaussian in $\not{H}_x, \not{H}_y$ and $\not{E}_x, \not{E}_y$
- Characterization of the non-Gaussian nature of the tails:
  - important for searches
  - plot shows width of data distributions (in sigma) containing nσ of a gaussian
  - deviation from gaussian form outside of 2σ

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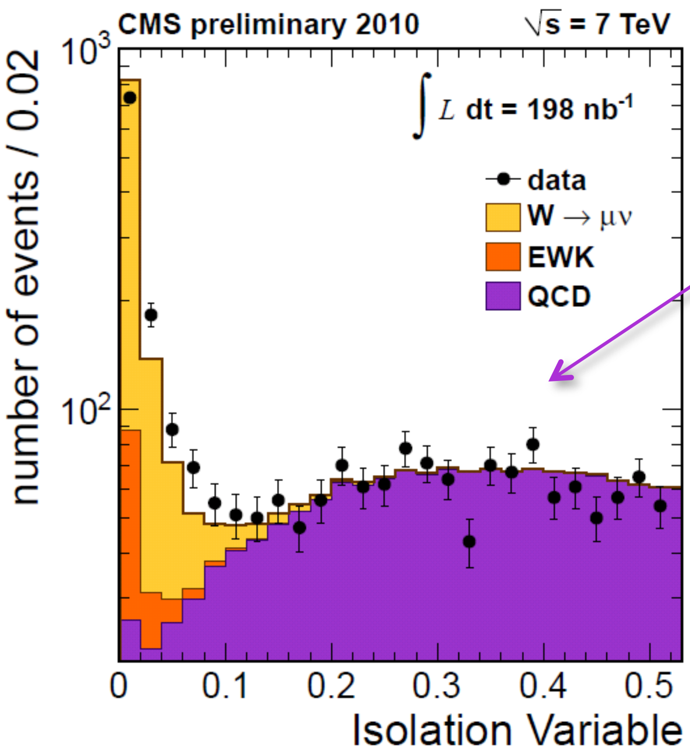
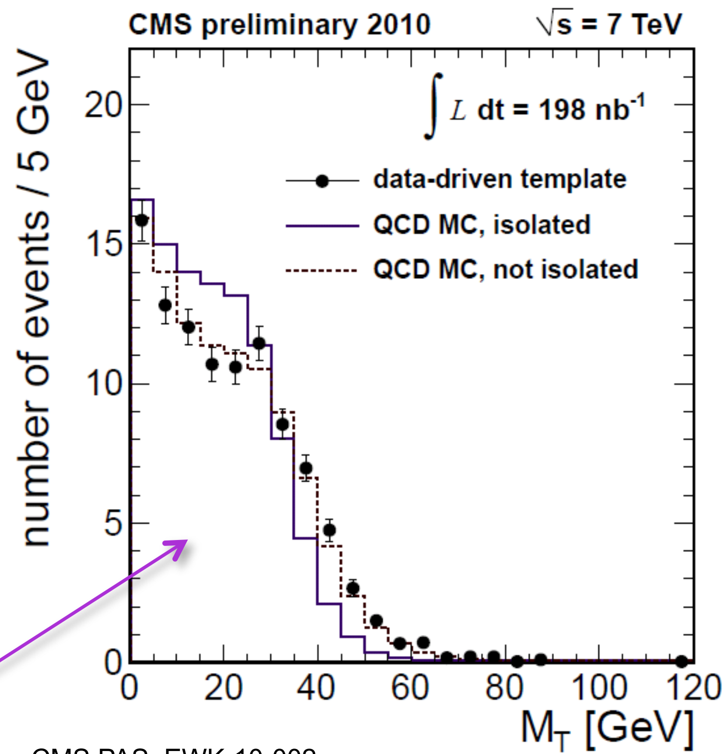
Muon System

- Energy deposition characterized by proper modeling of the absorber interaction lengths
  - punch-through, decays in flight account for much of the fakes
    - isolation variable critical to differentiate signal from QCD
  - future: significant backgrounds from neutron interactions



Sum of track, Ecal, Hcal energy in cone of $\Delta R < 0.3$ around muon

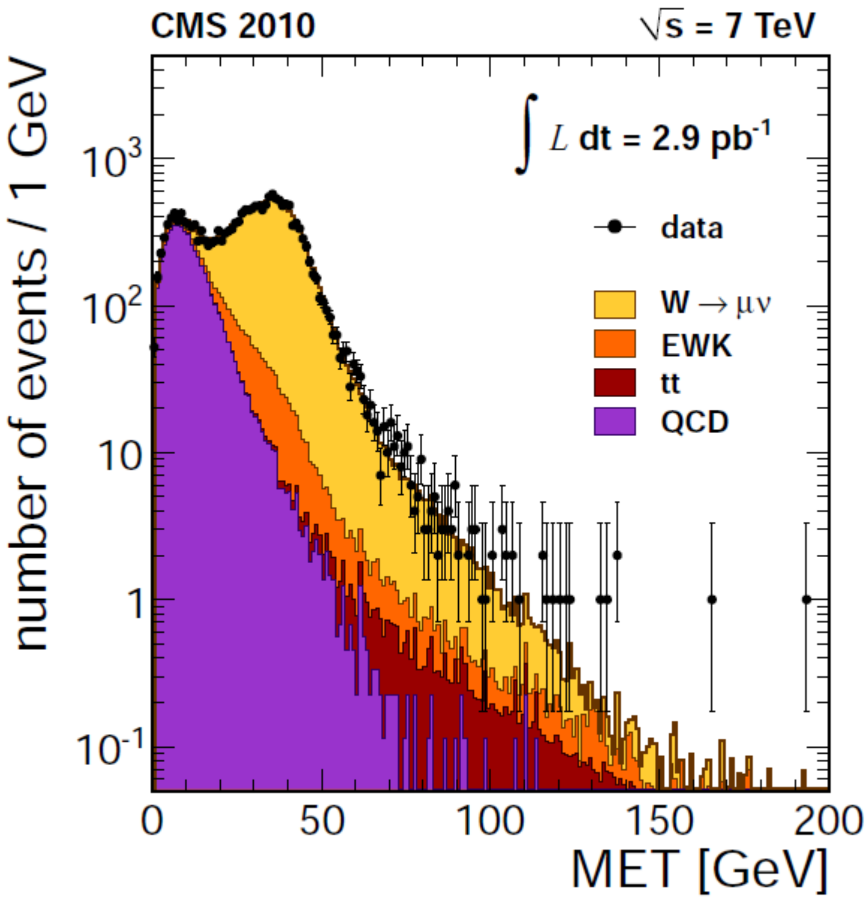
Comparison of isolation-inverted data sample with expectations from QCD MC

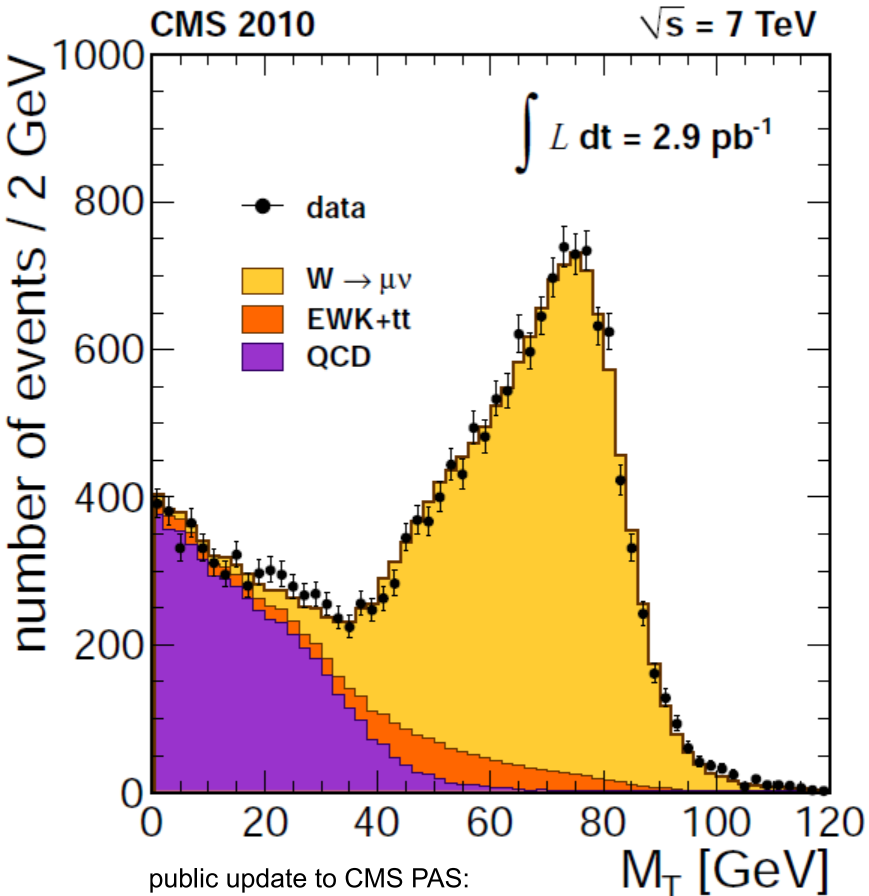


CMS PAS: EWK-10-002

Electroweak Distributions

- MET also well-modeled in $W \rightarrow \mu\nu$ events





public update to CMS PAS: EWK-10-002

- Here: combination of intrnisic resolution and generator models

Conclusions

- “Tuning” of CMS Simulation has been a multi-year process
  - based on Test Beam data, extensive Cosmic running
  - improved by comparisons using collision data
    - no substitute for the real thing…
- “Validation” ongoing
  - continual refinement as the dataset grows
    - higher statistics comparisons possible for a growing number of studies
- Current (excellent) level of Data/MC agreement is a product of a huge amount of work over many years by many people
  - not an accident!