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Validation of the CMS Full Simulation for the Tracker and Muon Systems

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Université de Notre Dame du Lac & Fermilab

Representing the CMS Collaboration

Overview

- Tracker Modeling and Performance
  - Material studies
    - photon conversions/nuclear interactions
  - Tracker dE/dx results
  - Issues with low energy hyperons

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

- Muon Systems Modeling and Performance
  - energy deposition & charge simulation
  - isolation variables

dE/dx modeling, muon interactions at high energy, shower models, material specification

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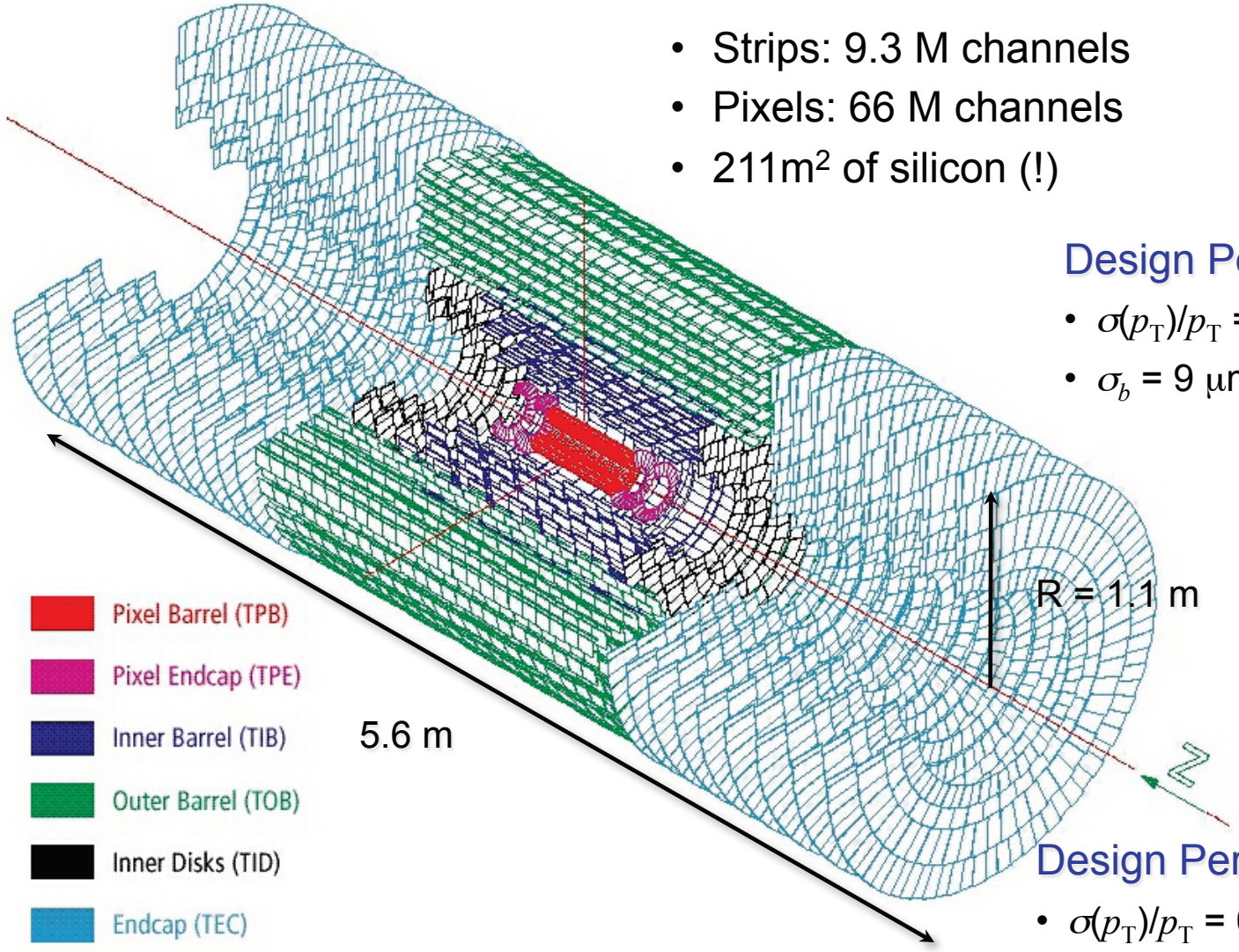
CMS Tracking System



- Strips: 9.3 M channels
- Pixels: 66 M channels
- 211m^2 of silicon (!)

B = 4T

Design Performance: $(\eta = 0)$

- $\sigma(p_T)/p_T$ = 0.015% × p_T (GeV)
- σ_b = 9 μm @ p_T = 1 TeV

Design Performance: $(\eta = 2.5)$

- $\sigma(p_T)/p_T$ = 0.07% × p_T (GeV)
- σ_b = 11 μm @ p_T = 1 TeV

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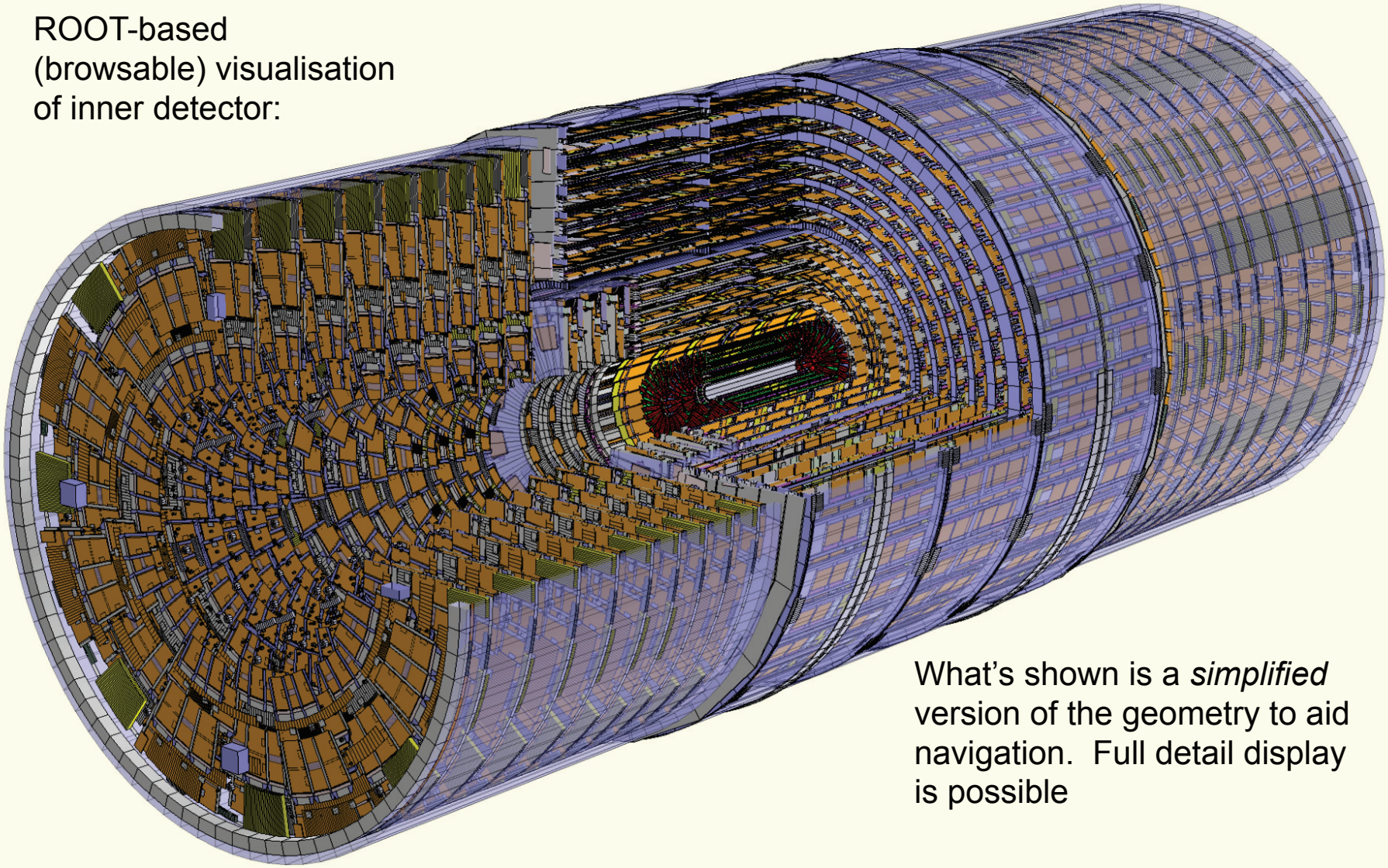
Overview of CMS Tracker

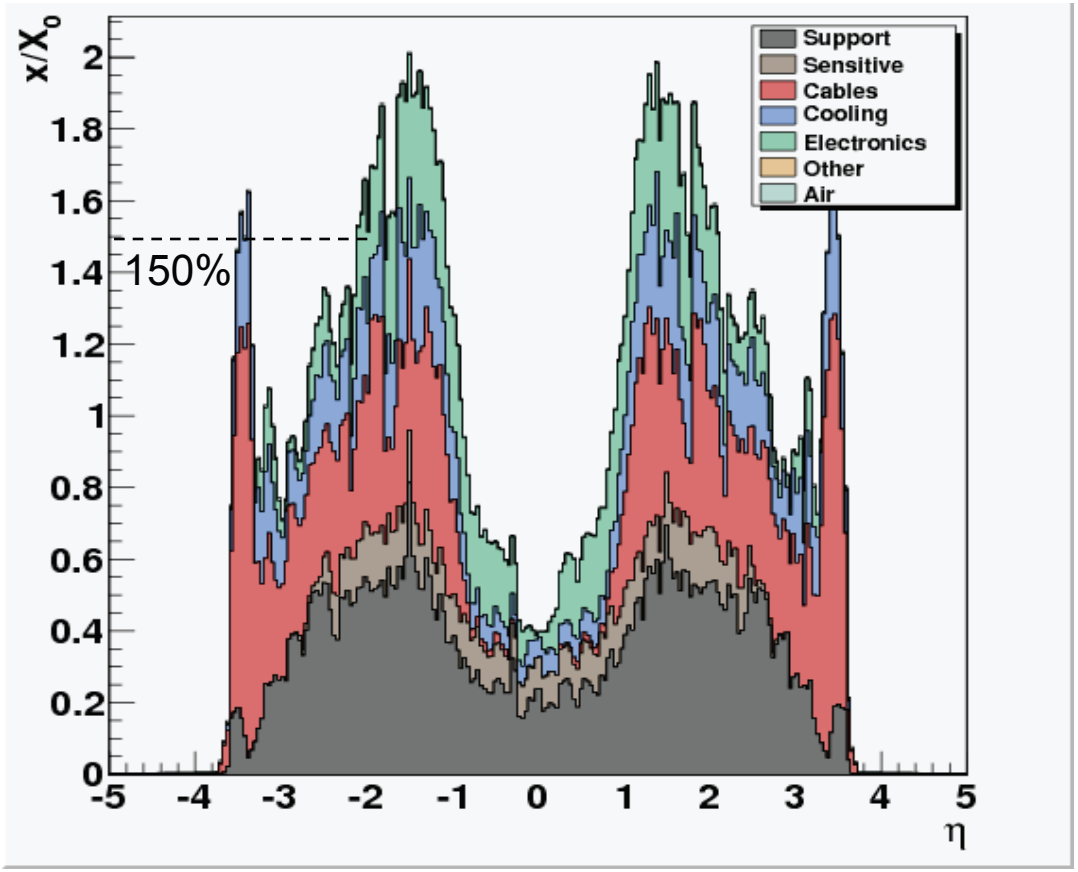
ROOT-based
(browsable) visualisation
of inner detector:



What's shown is a *simplified* version of the geometry to aid navigation. Full detail display is possible

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:

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

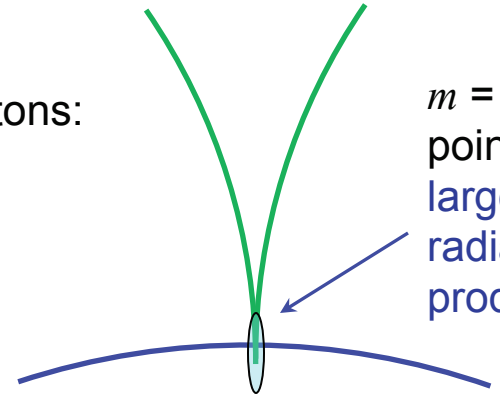
For Nuclear Interactions:

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

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

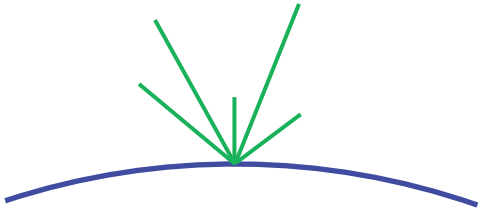
- Different reconstruction characteristics:

Photons:



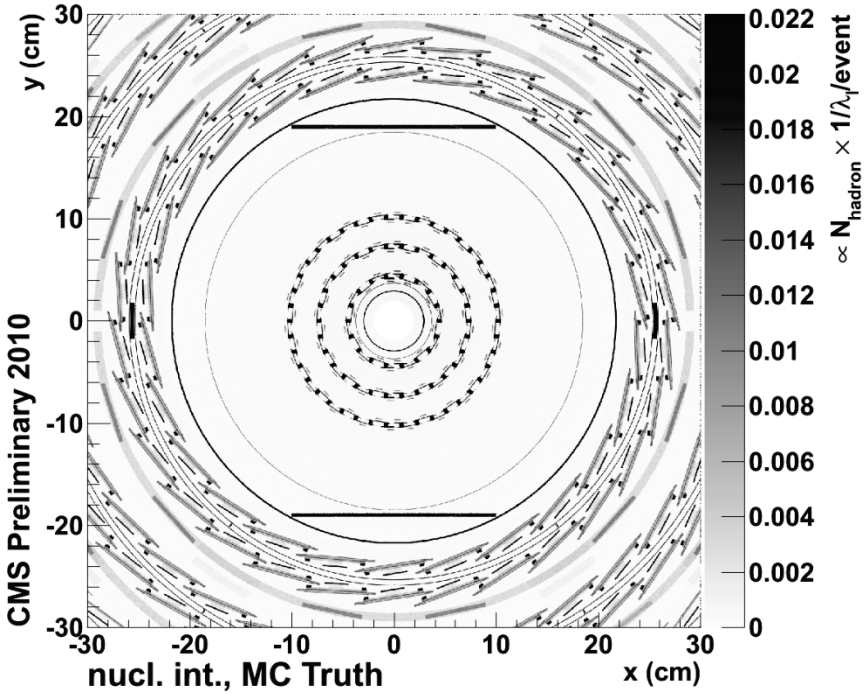
m = 0: tracks parallel at point of production ⇒ larger uncertainty in radial position of production point

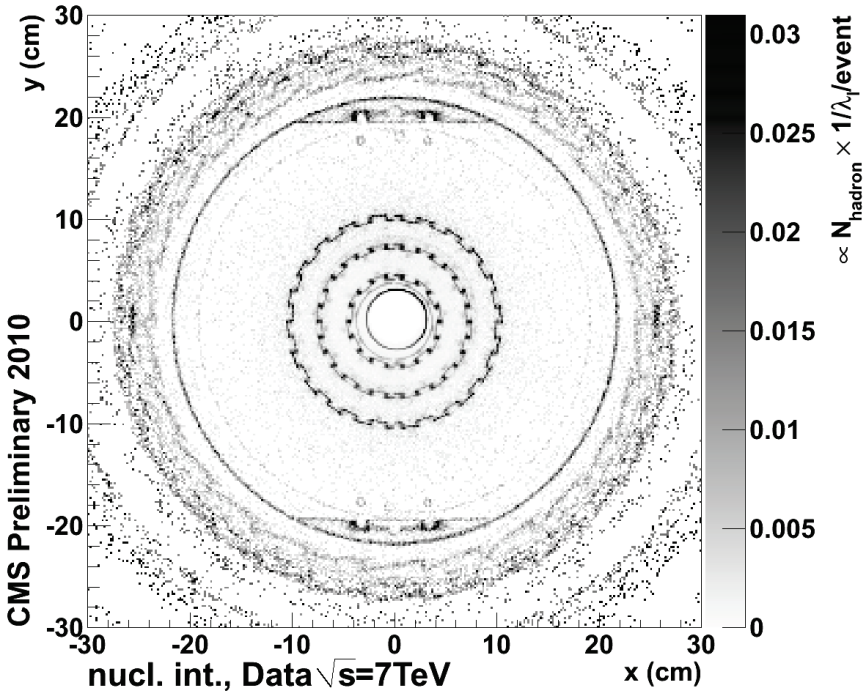
Nuclear interactions:



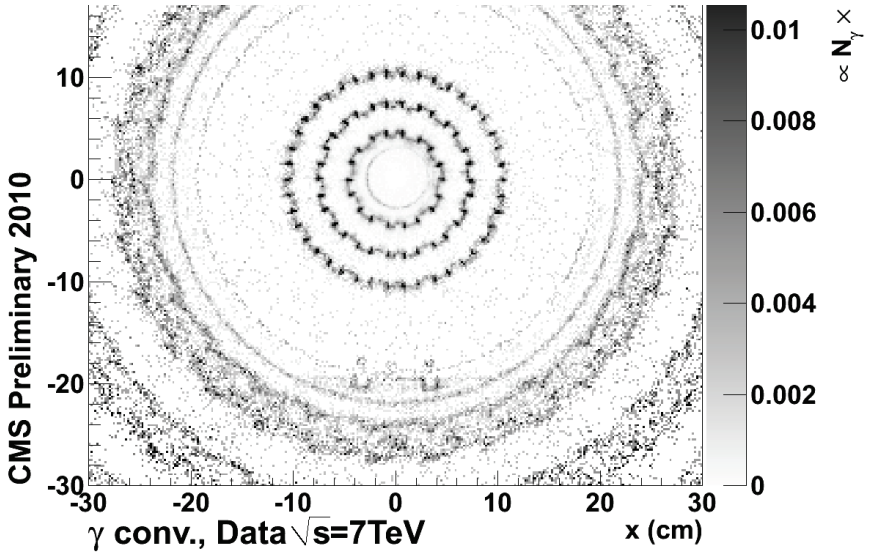
Good vertex resolution, many soft tracks with large impact parameters

Some examples:





Note the superior position resolution of the nuclear interaction data



The beampipe isn't centered!

CMS PAS: TRK-10-003

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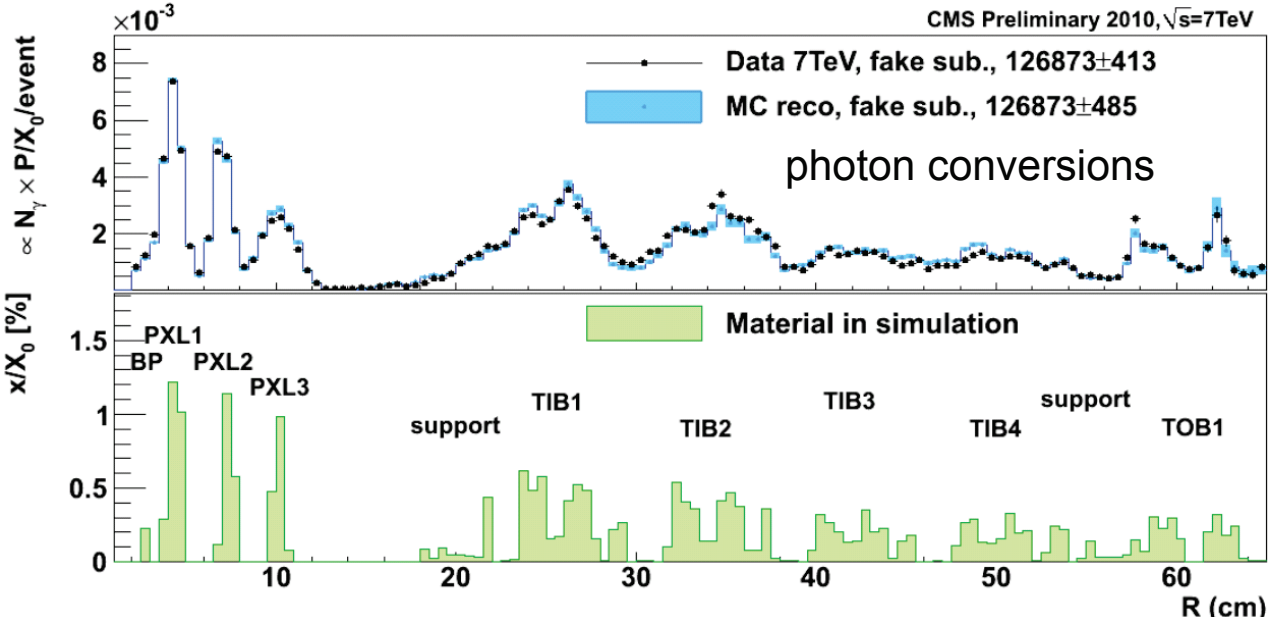
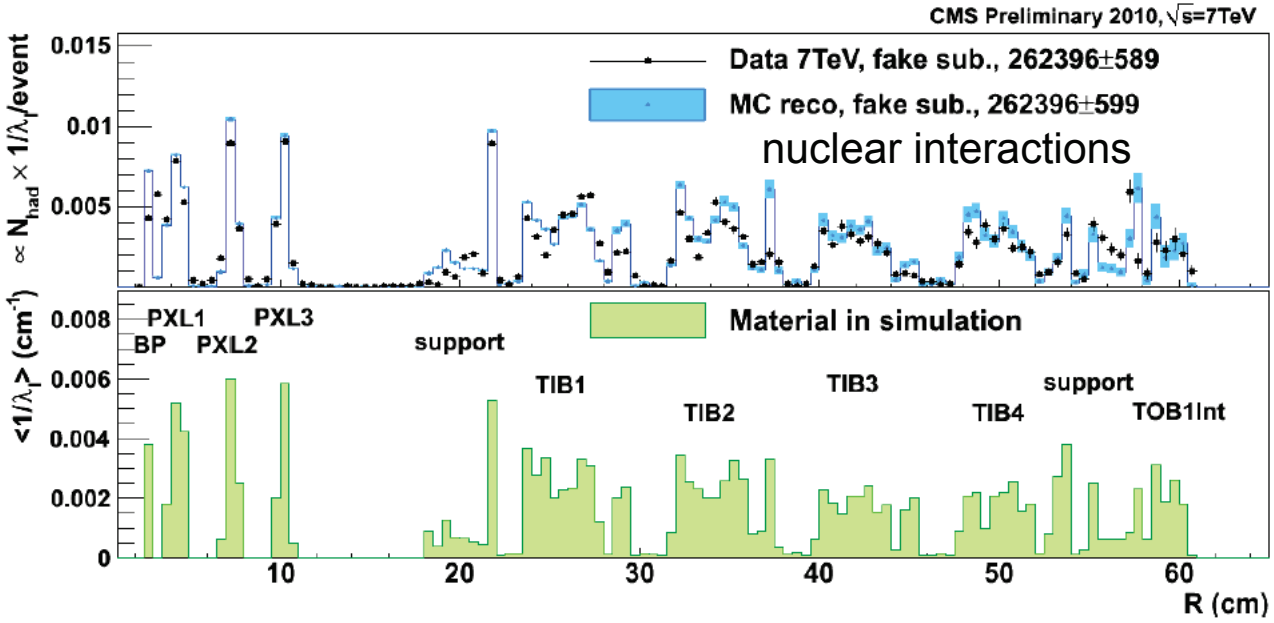
Extracting the material budget





can unfold this distribution using estimates of the photon position resolution

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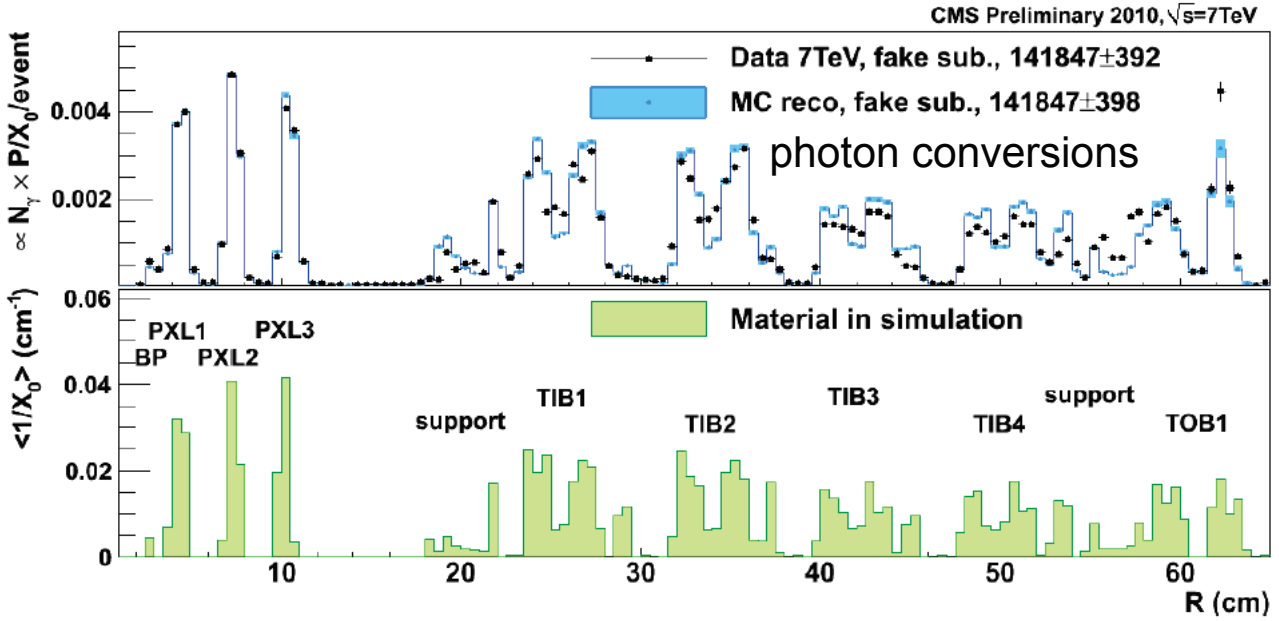
Extracting the material budget



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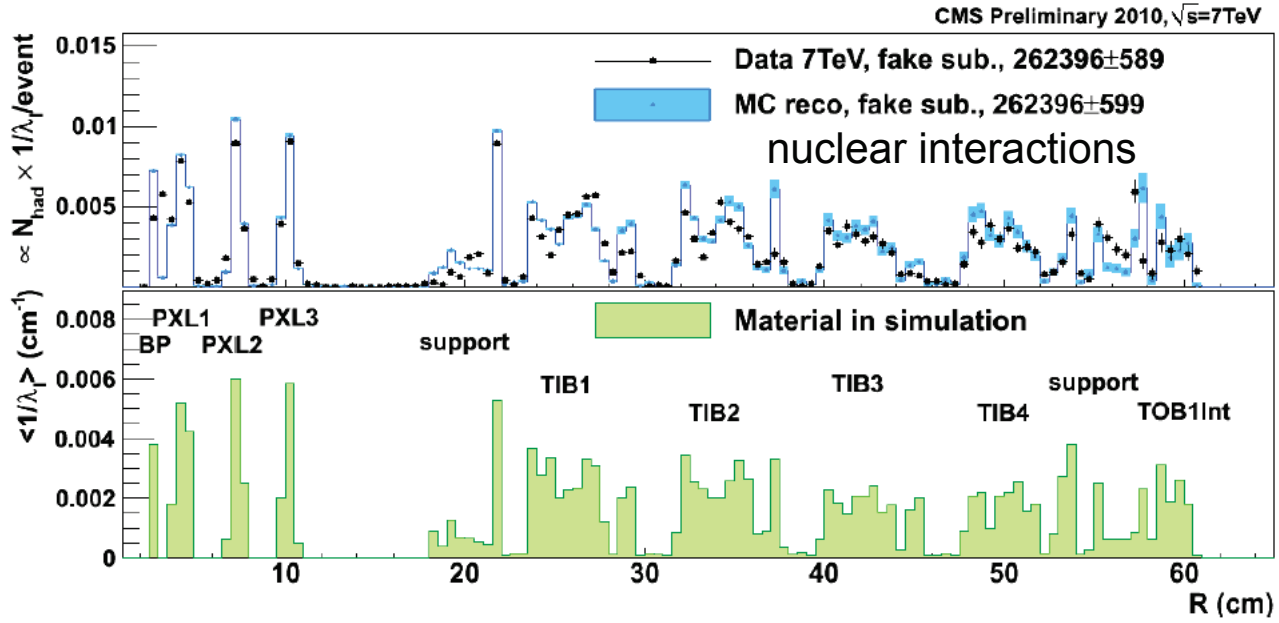

astonishingly good agreement between data and simulation

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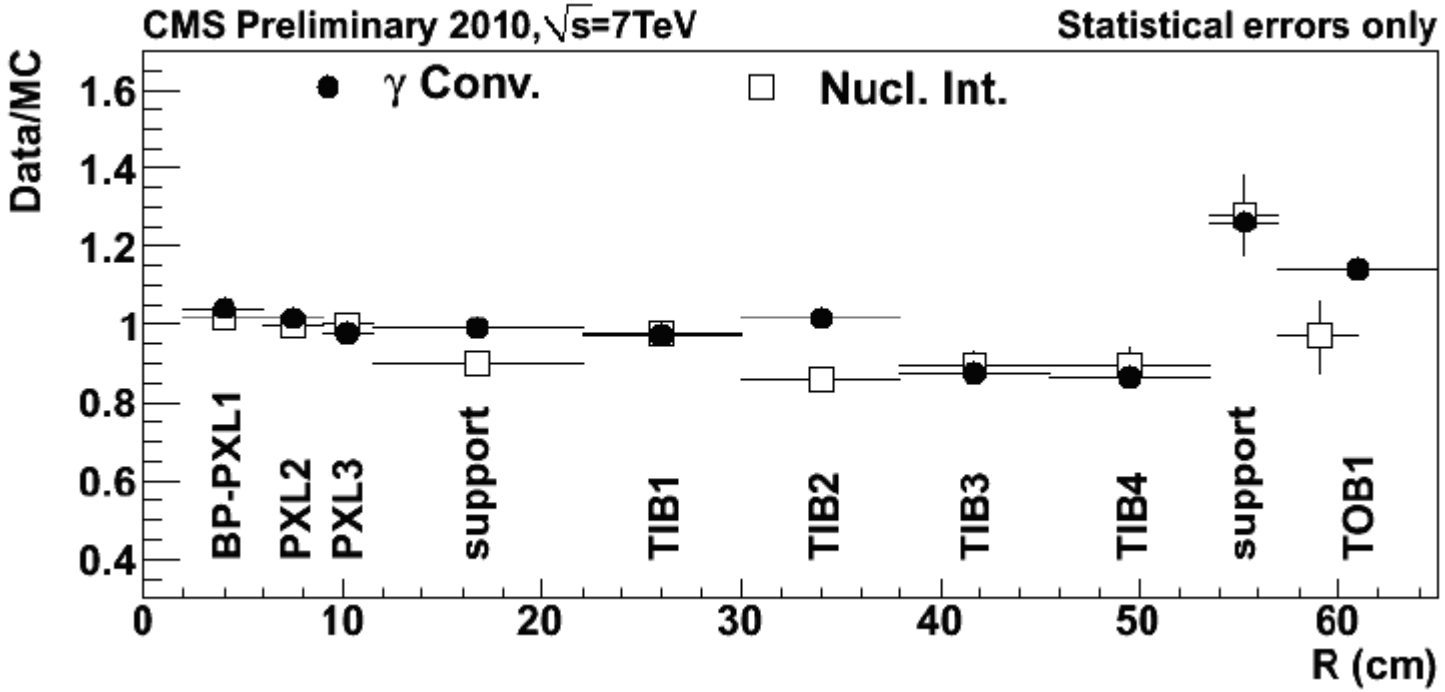
Extracting the material budget



- 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)

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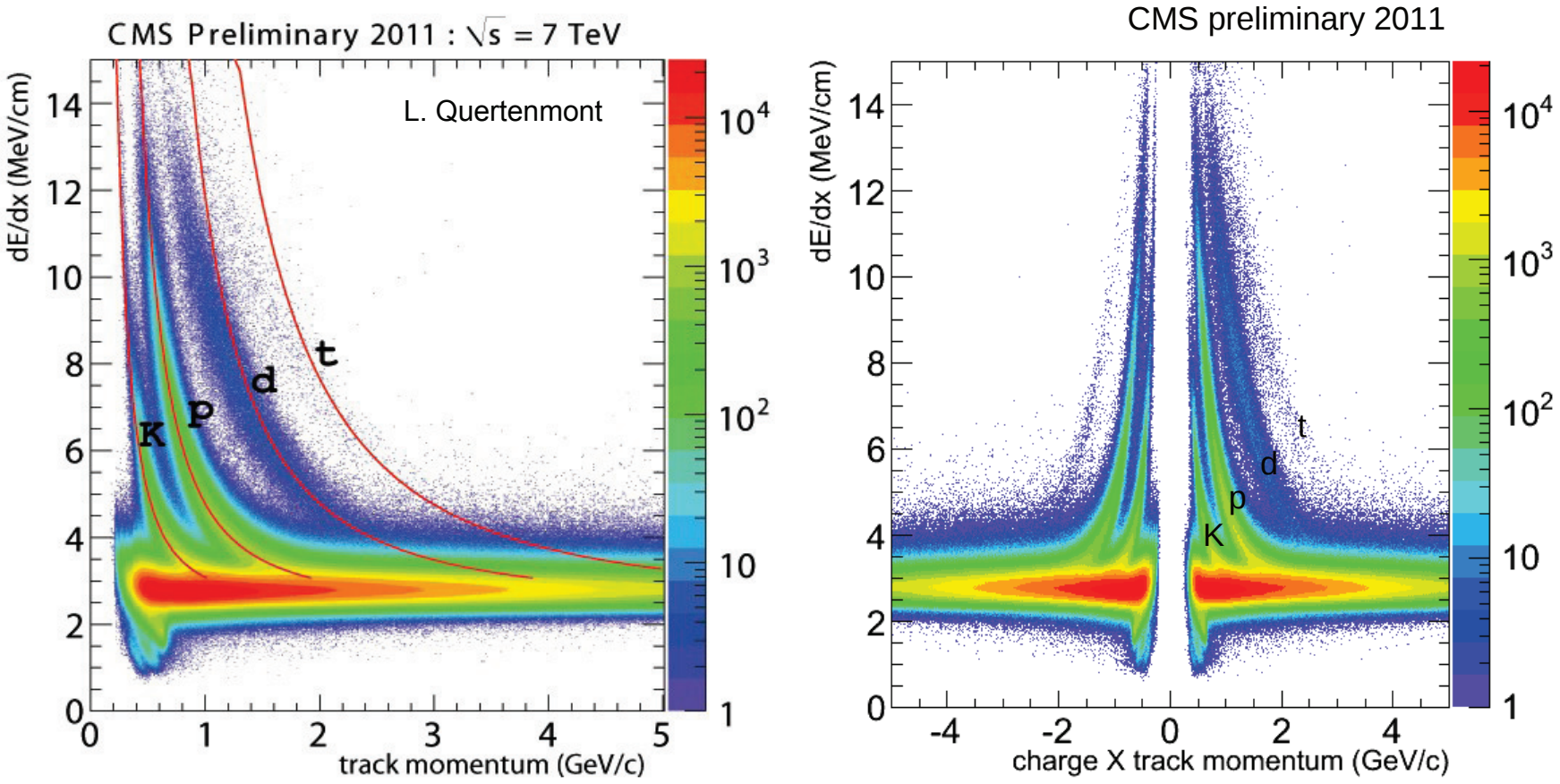
Tracker dE/dx Simulation



- 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

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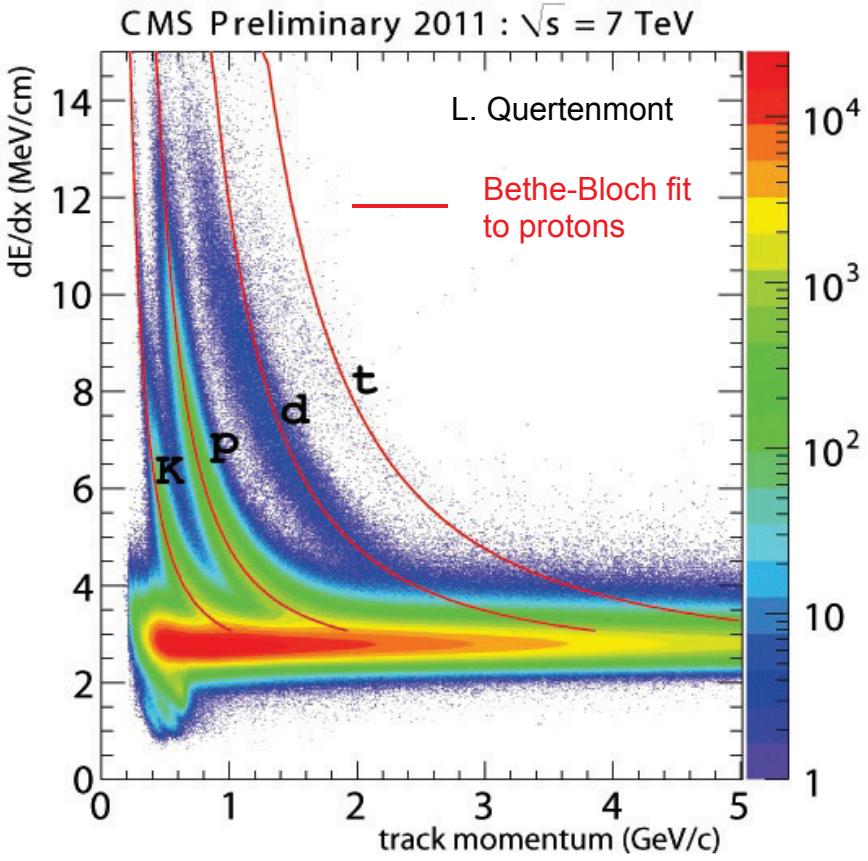
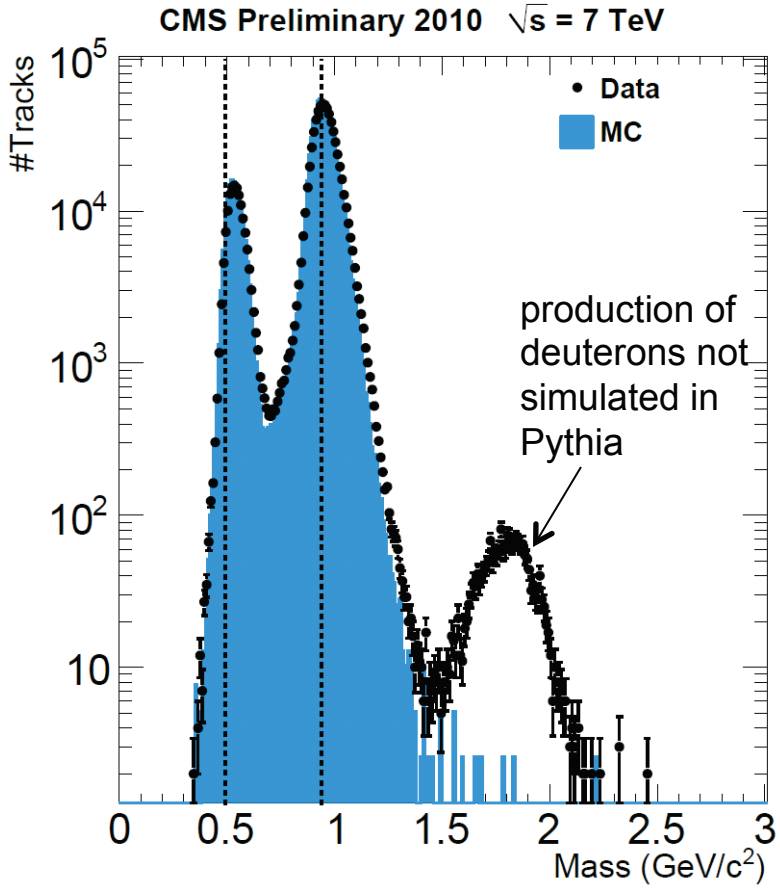
Tracker dE/dx Simulation





- Signal simulation in tracker includes charge propagation, charge collection efficiencies, saturation effects, and tracker noise modeling
  - tuned on cosmic data and early collisions
- also important for cluster splitting in high-occupancy environments (under study)

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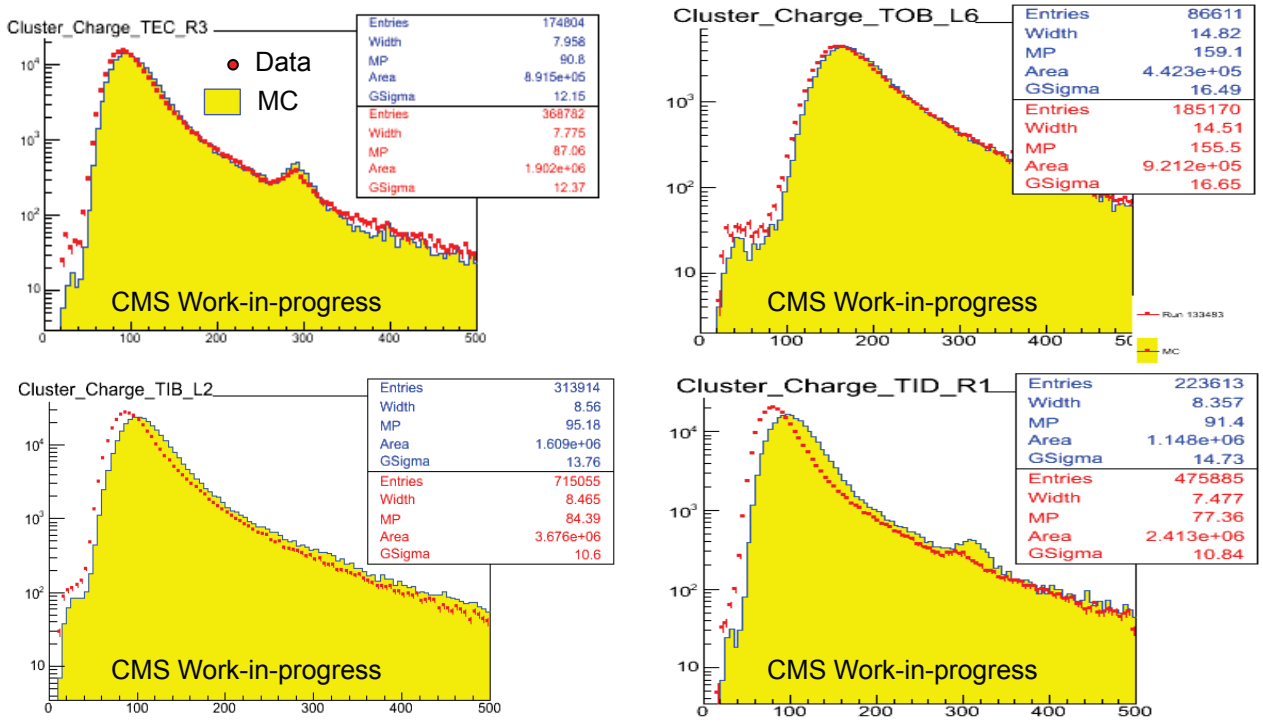
Tracker dE/dx Simulation

Distributions from Silicon Strip Tracker:

S. Gotra



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  - tuned on cosmic data and early collisions
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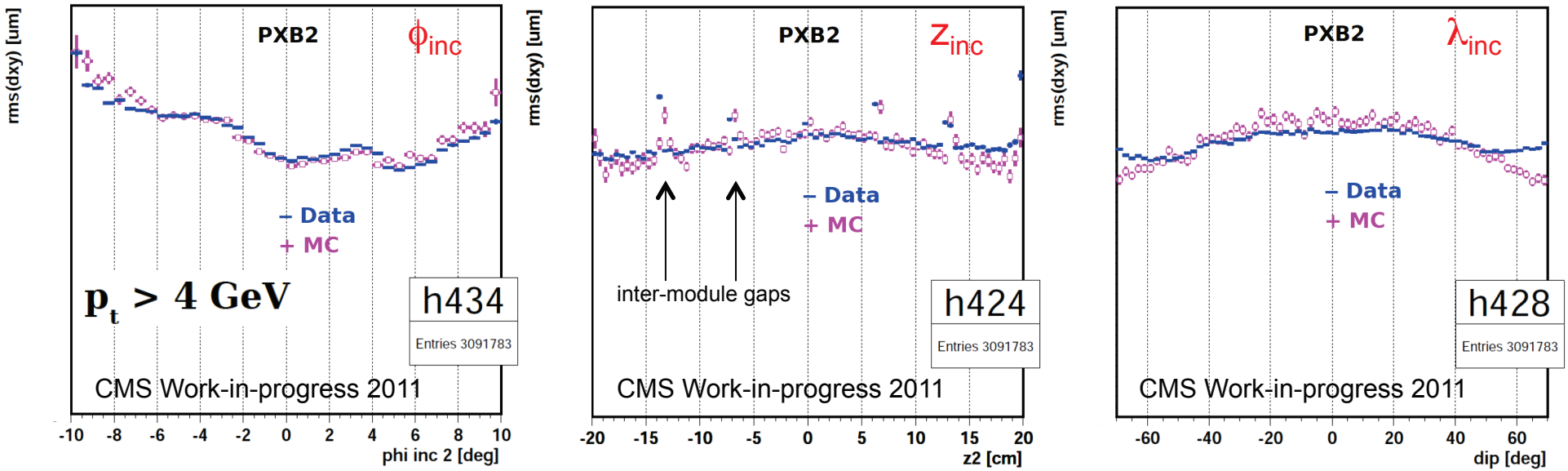
Pixel Tracker Resolutions & Geometry

- Dependence of resolution on incident angle, z, polar angle

D. Pitzl



- plots for Pixel Barrel 2, for tracks with p_T > 4 GeV
  - covers wide range of parameter space, fairly extreme incident angles
  - resolution deteriorates at inter-module gaps in z
  - well-modeled by simulation

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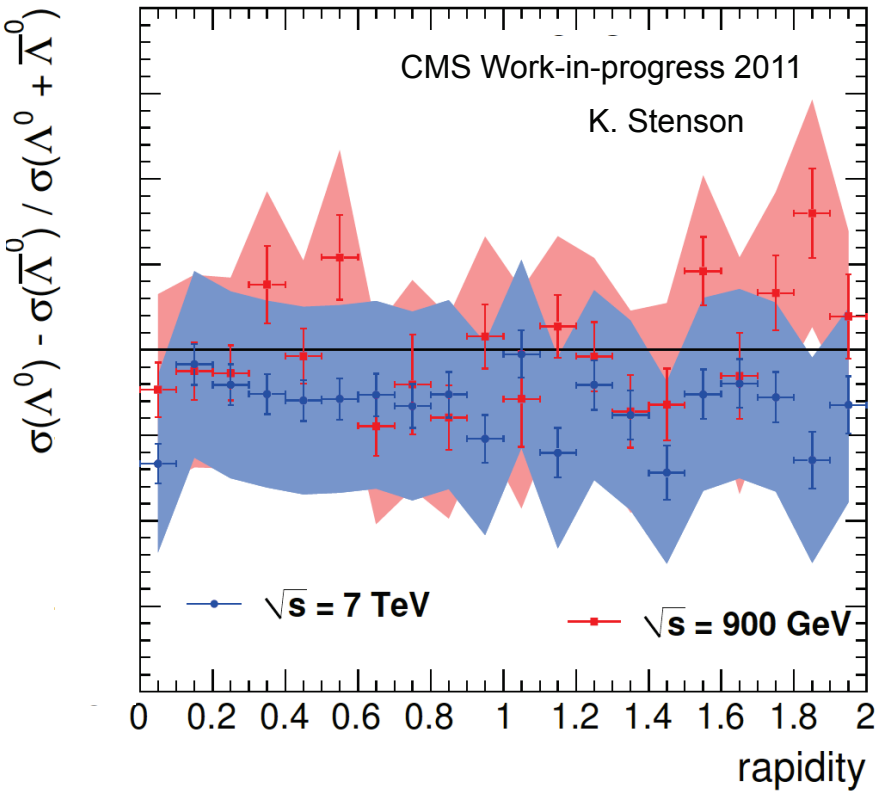
Low Momentum Hyperon Transport Issues

- Various particle production studies need to measure accurately the production cross sections and asymmetries in the production of K^0s, Λs, etc.
- Current GEANT4 implementation of low-energy cross sections not sufficient (see ALICE talk earlier today)
- E.g.:



- MC-corrected asymmetry in Λ-anti-Λ production is negative (unexpected)
- Have to correct for Λs that interact before decaying, and interaction rates of decay products
- large differences between data and G4 cross sections for these processes

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More on this issue

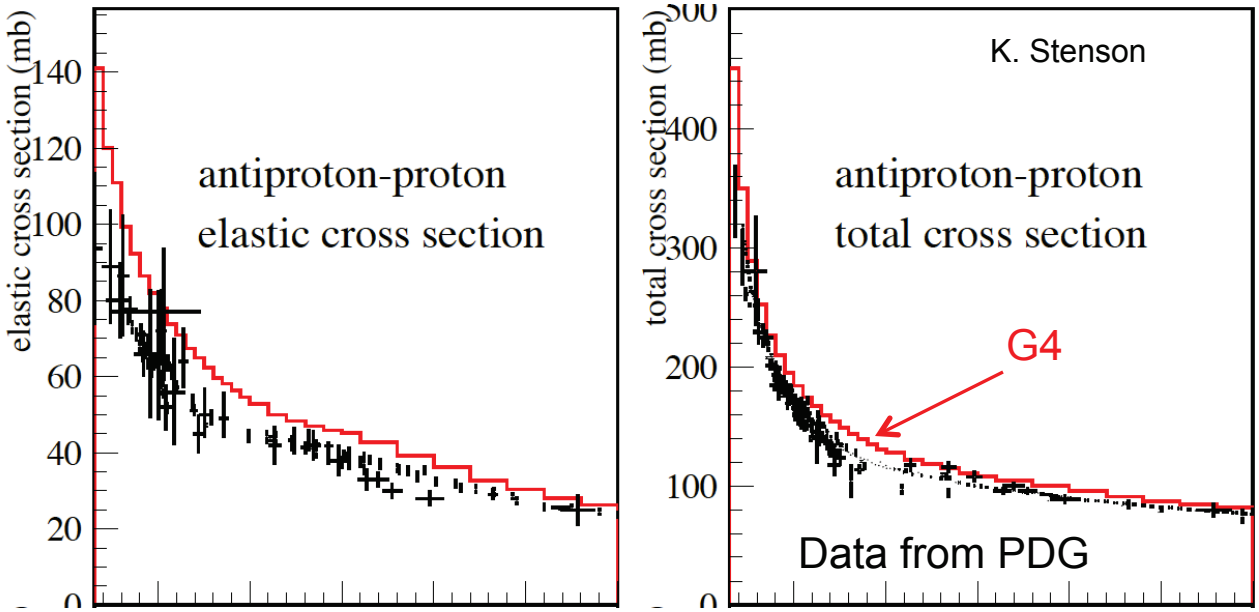
- Simple test of firing particles at a “mock up” of CMS tracker:
  - 1mm thick Be target followed by five 1mm thick silicon detectors, each separated by 4cm
    - looks like inner 25cm of tracker
  - compare CHIPS 4.9.4.b01 to “Standard” G4 for interaction probability in “tracker”

K. Stenson

Particle	Momentum (MeV/c)	Model	Interaction probability (%)
proton	310	“standard”	1.66
proton	1000	“standard”	0.72
pbar	310	“standard”	7.49
pbar	310	CHIPS	2.71
pbar	1000	“standard”	3.26
pbar	1000	CHIPS	1.64

Some comments

- Also pbar cross sections:



- Hyperons and Kaons have similar issues(?)
- Hadronic cross sections are separate from physics lists (except in CHIPS)
  - would be good to update these to have a uniform set of cross sections

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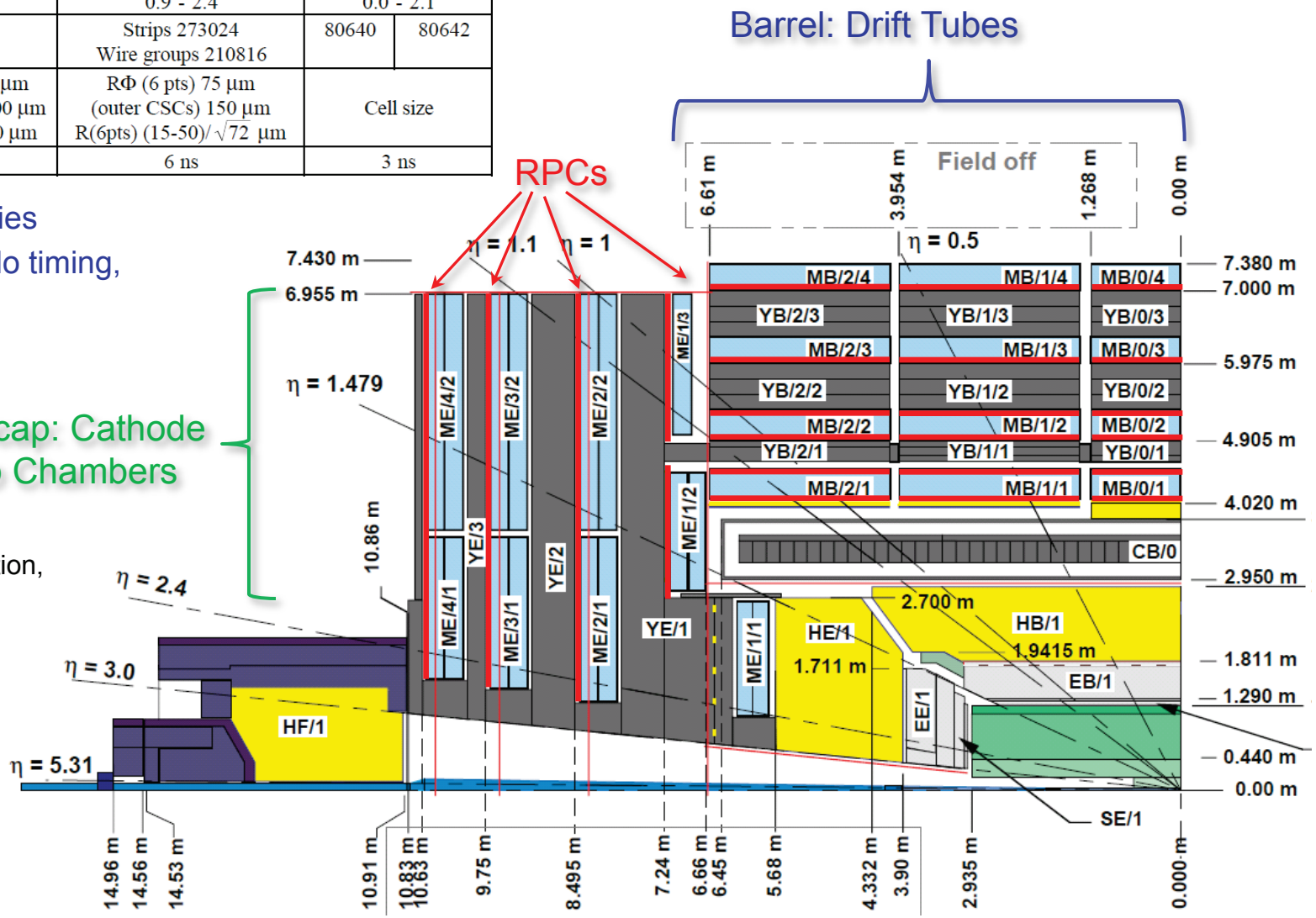
CMS Muon System: Overview

Detector	Drift Tubes	Cathode Strip Chambers	Resistive Plate	
Function	Tracking p_T trigger BXID	Tracking p_T trigger BXID	BXID p_T trigger Resolve tracking ambiguities	
η region	0.0 - 1.3	0.9 - 2.4	0.0 - 2.1	
Channels	195000	Strips 273024 Wire groups 210816	80640	80642
Spatial resolution (σ)	per wire 250 μm RΦ (6/8 pts) 100 μm Z (3/4 pts) 150 μm	RΦ (6 pts) 75 μm (outer CSCs) 150 μm R(6pts) (15-50)/$\sqrt{72}$ μm	Cell size	
Time resolution	5 ns	6 ns	3 ns	

- Three technologies
- all subsystems do timing, BX resolution
- 840k channels

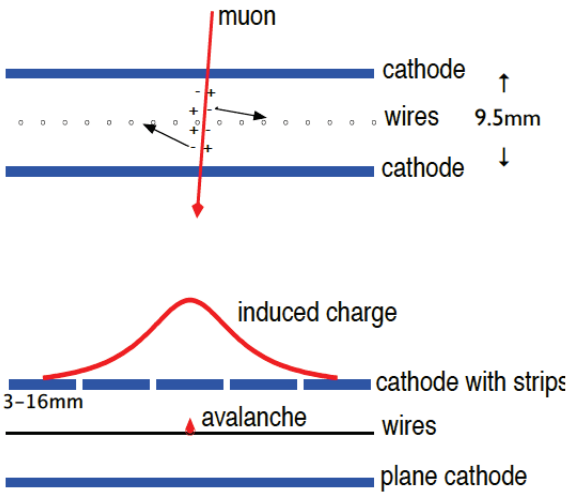
Endcap: Cathode Strip Chambers

steel for absorbtion, flux return

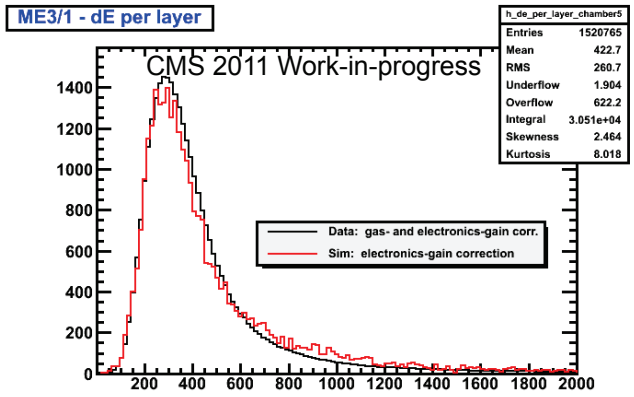


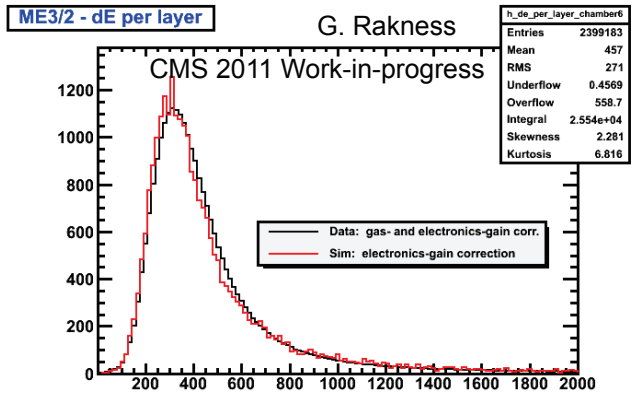
Muons: Local Charge Deposition

- Example: CSC Simulation



– Geant used to deposit energy in material layers described by detailed geometry
  - ionization models important
– Digitization includes full simulation of step-wise ionization of gas along the particle path, electron and ion drift, amplification by avalanche, and image charge deposition on the strips
– Detailed modeling of electronic pathways, amplification, pulse-shaping, etc.





– Recent results on ADC distributions from re-evaluation of simulation constants, including local gains measured in Data

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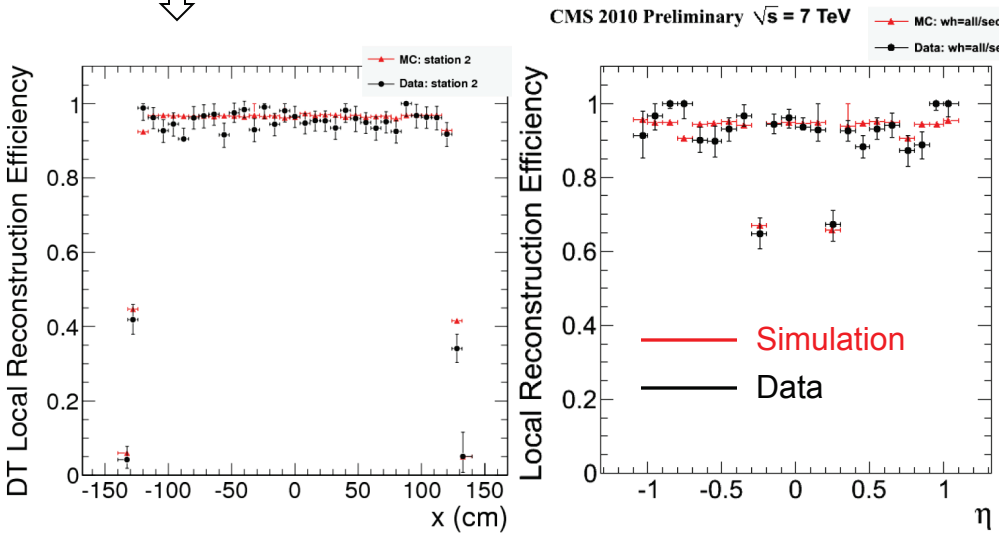
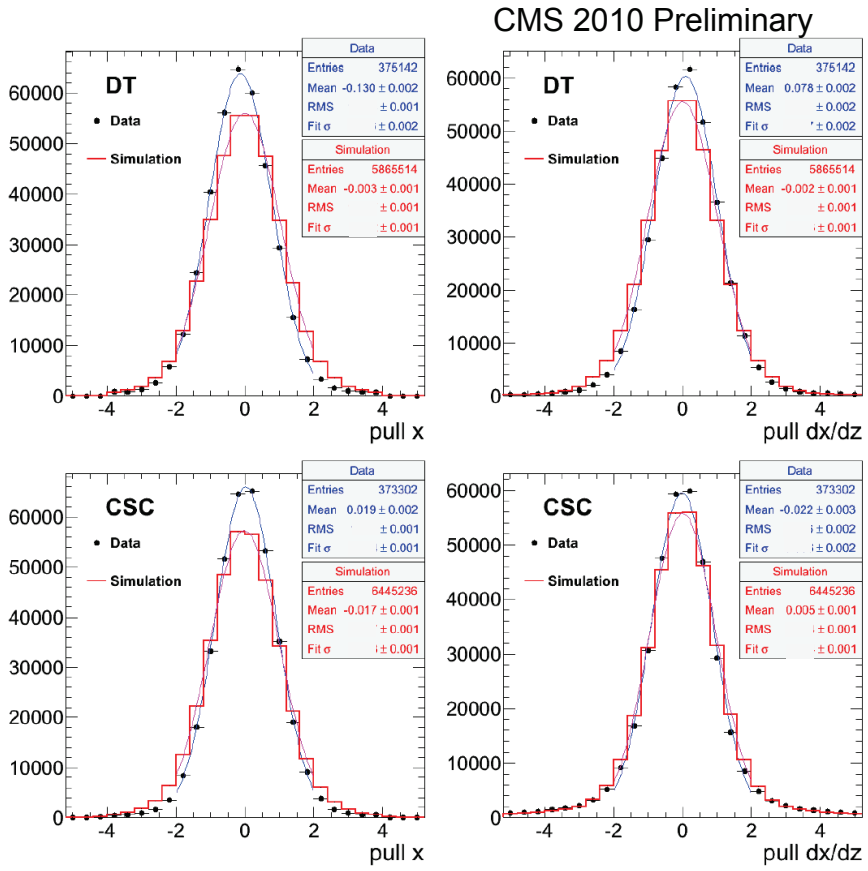
Muons: Local Resolution & Efficiency

- Performance of local muon reconstruction
  - Global tracks compared to muon-only segments
    - tag-and-probe method using muons from J/Ψ and Z^0 decays
    - p_T>10, 15 GeV (C, EC) to limit multiple-scattering effects
  - dead channels, effective alignment resolution included in MC





- Resolutions of extrapolations from central tracker to muon segments

  - checks proper implementation of material, multiple scattering through solenoid, absorber

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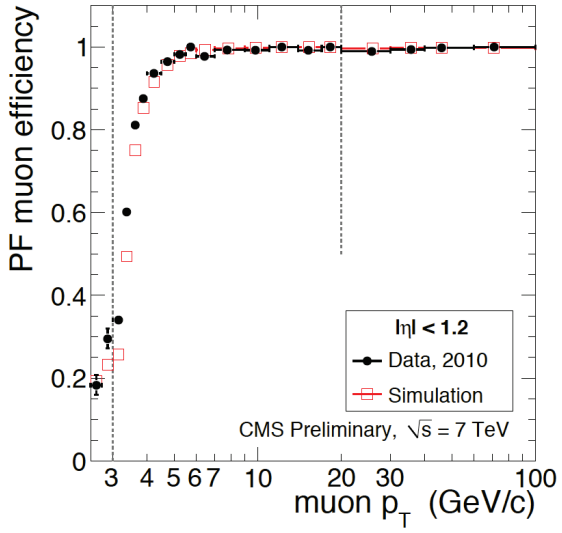
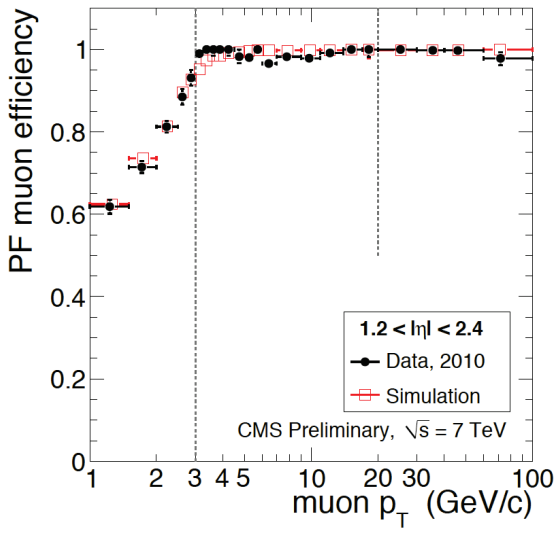
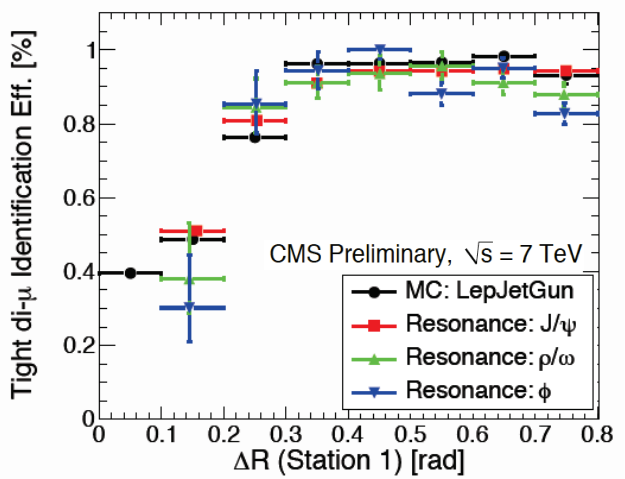
Muons: Global Efficiencies

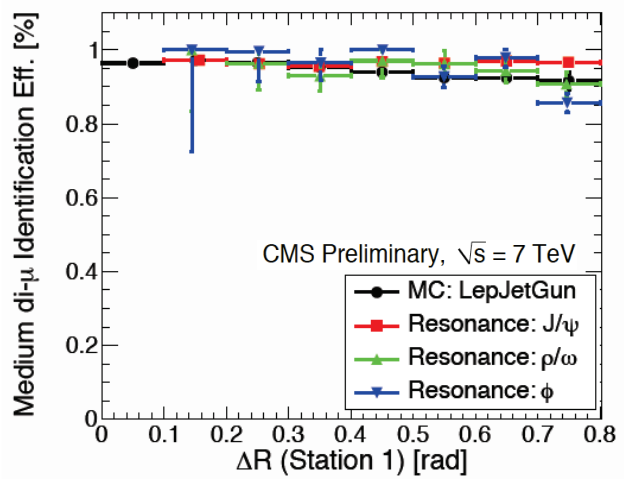
- Measured with Tag-and-Probe:





- Efficiencies for high-p_T muons in barrel and endcap measured with Z decays
- no (public) results yet at highest p_T





- Efficiency vs. angular separation of tracks at first barrel layer using many different muon sources

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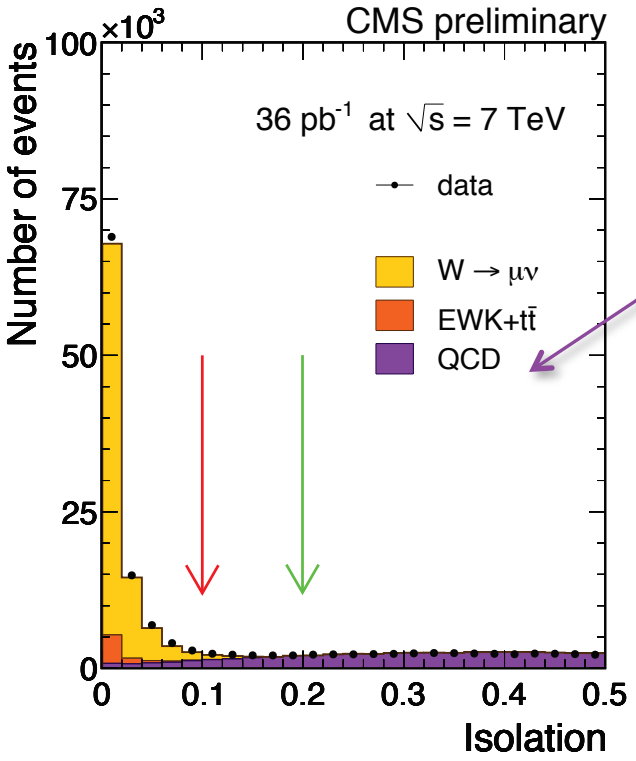
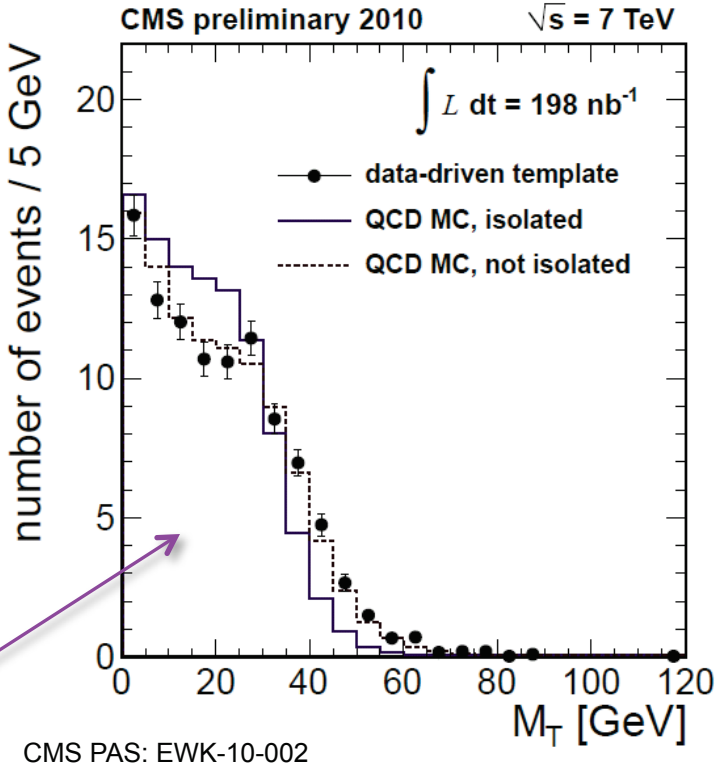
Muon System: Isolation

- 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

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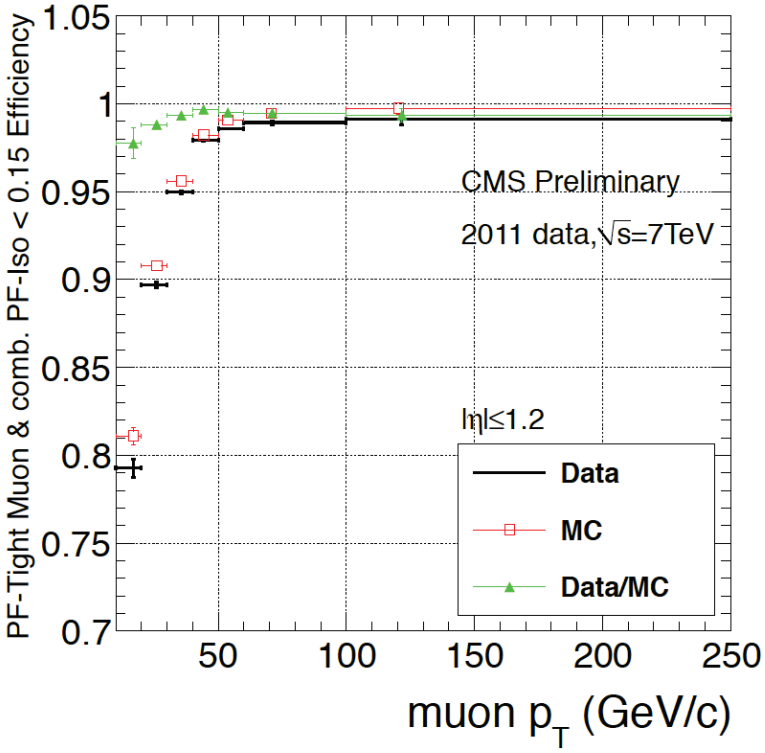
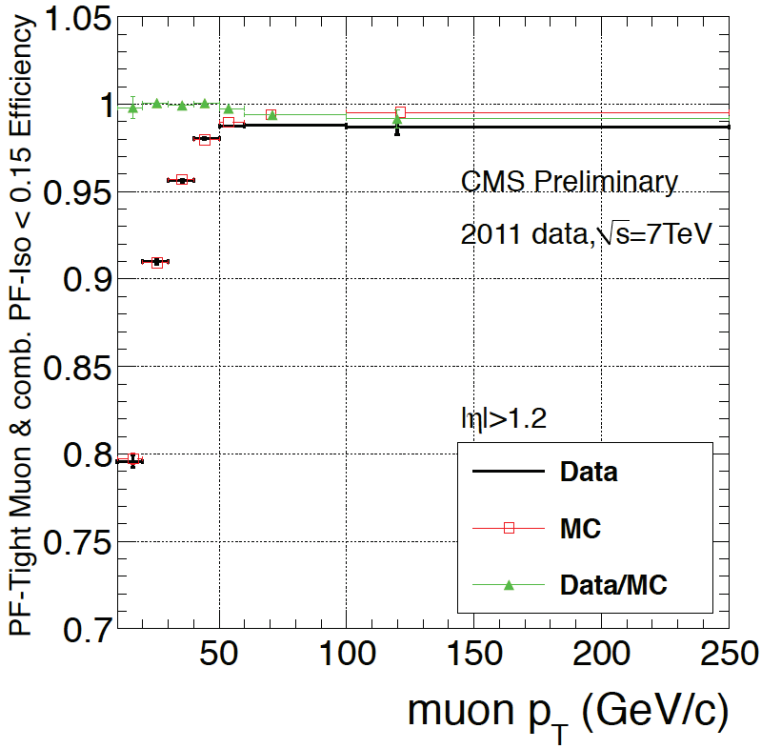
Muon System: Isolation

- 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
  - Efficiencies for isolation compared with Simulation:





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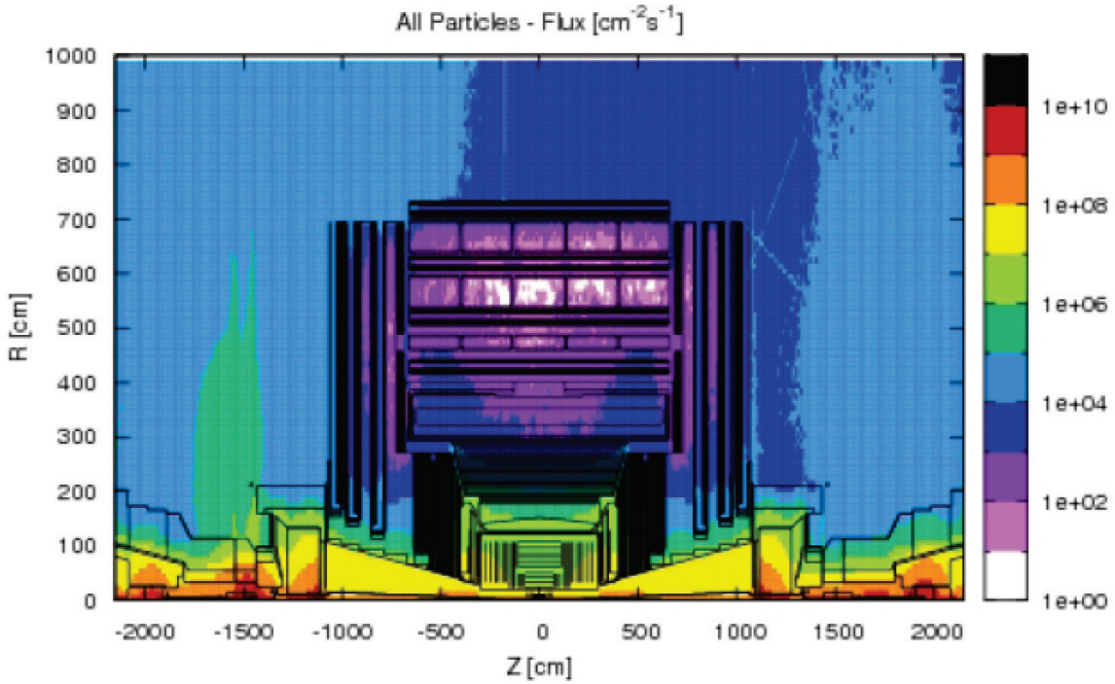
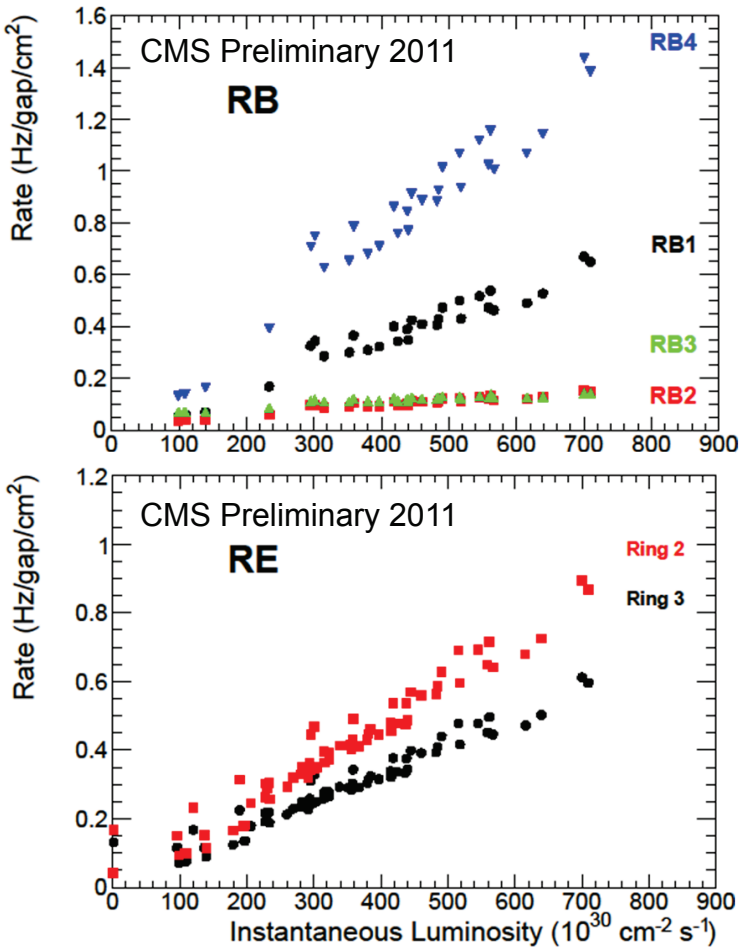
Cavern Backgrounds

- Not high enough yet for serious MC/Data Comparison
  - Simulated flux at 7 TeV:



Radial dependence of background rates in RPCs:



- Rates extrapolated to a luminosity of 10^{34} cm/s^2 are more or less consistent with expectations
- more analysis coming

Conclusions

- In general, no severe problems with basic simulations
  - n.b.: low energy nuclear cross sections
- Excellent MC/Data agreement for most distributions
  - result of a huge amount of work over many years by many people
- "Validation" and improvements ongoing
  - continual refinement as the dataset grows