Cosmic Muon Analysis with the CMS Detector

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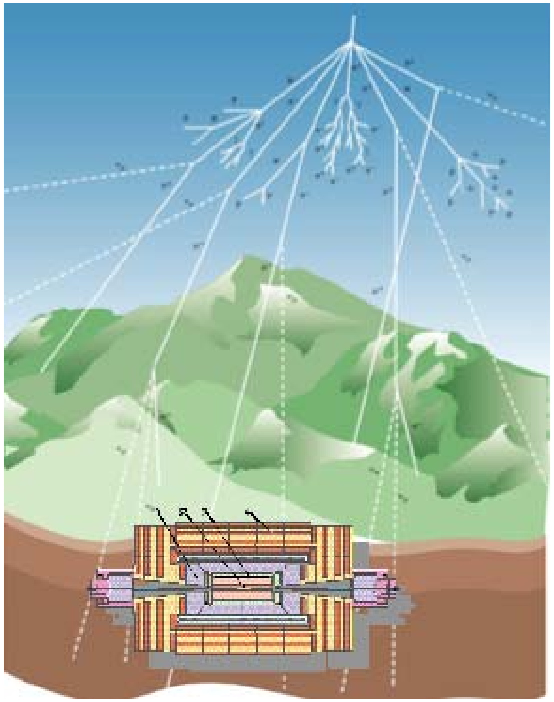
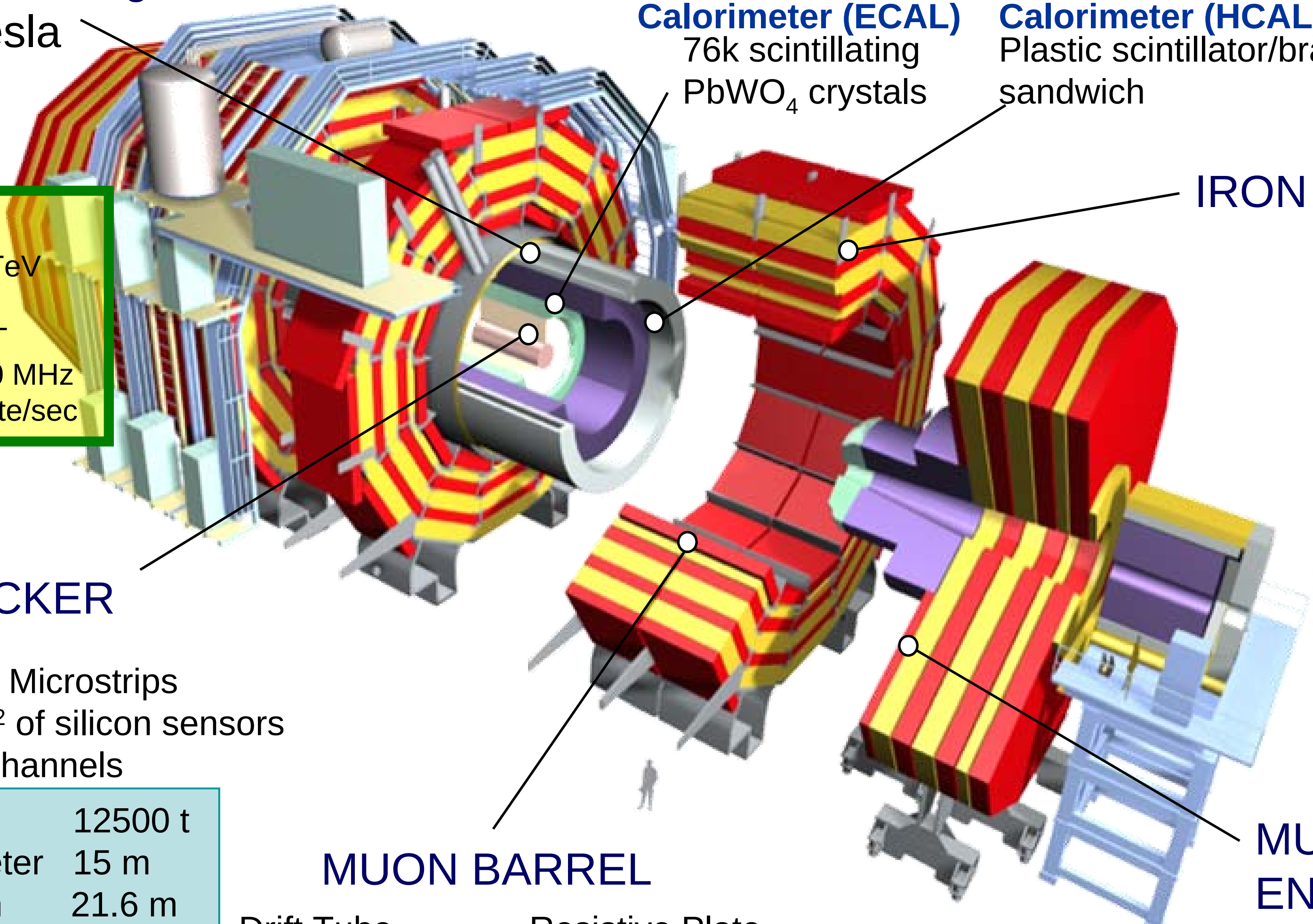
Outline

- The CMS detector at the LHC
- Cosmic Run at Four Tesla (CRAFT)
- Cosmic Rays
- Detector Performance
- Physics Analyses
- Summary



Compact Muon Solenoid



Superconducting Coil, 4 Tesla

CALORIMETERS

Electromagnetic Calorimeter (ECAL)
76k scintillating $PbWO_4$ crystals

Hadronic Calorimeter (HCAL)
Plastic scintillator/brass sandwich

IRON YOKE

LHC
Energy: 14 TeV/10 TeV
Length: 27 km
Magnetic Field: 8.3 T
Bunch Crossings: 40 MHz
Data Rate: 1 Terabyte/sec

TRACKER
Pixels
Silicon Microstrips
210 m^2 of silicon sensors
9.6M channels

Total weight	12500 t
Overall diameter	15 m
Overall length	21.6 m

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Cosmic Ray Muons

While waiting for LHC collisions

Cosmic ray muons are used as probe of detector performance during (no beam!)

Total rate is about 350 Hz at 100 m depth (about 1% of rate on surface of Earth)

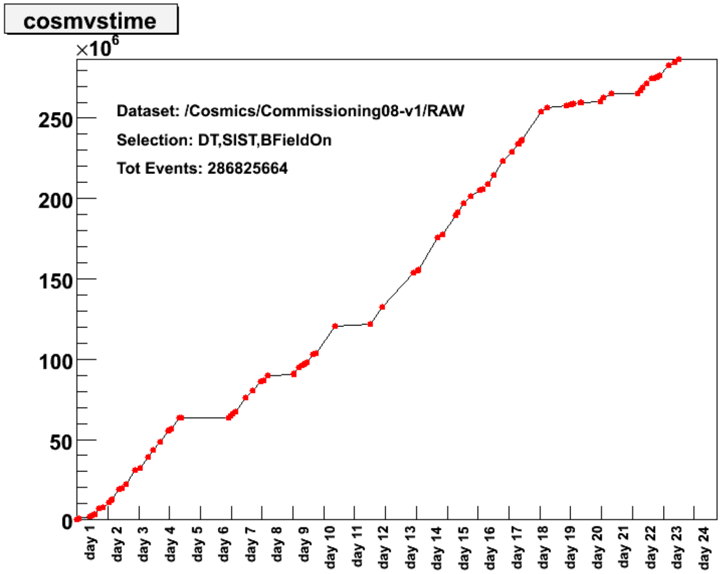
Cosmic rays are continuously bombarding Earth's atmosphere with far more energy than protons will have at the LHC, so cosmic rays would produce everything LHC can produce.

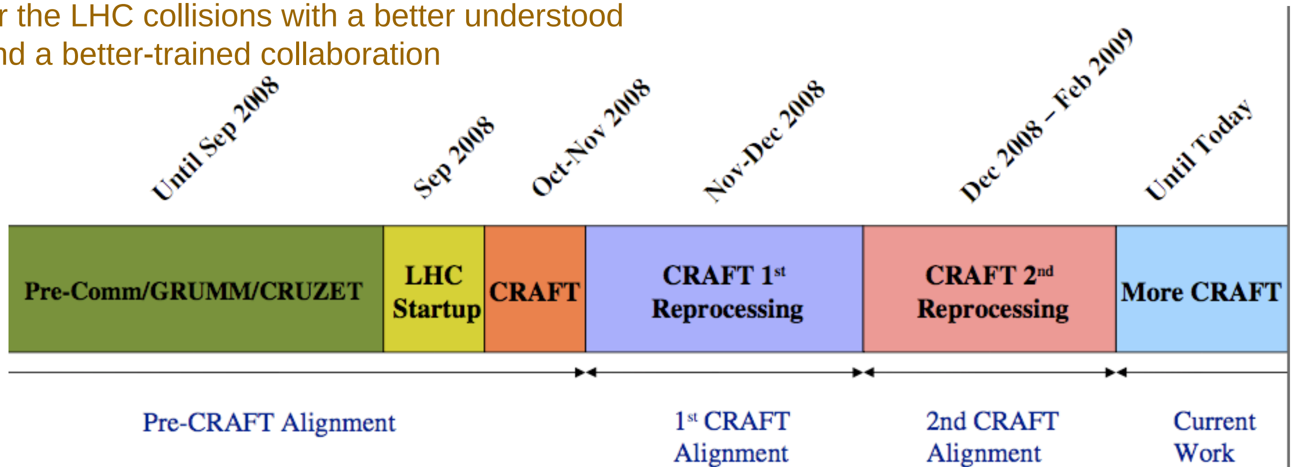
They have done so throughout the 4.5 billion years of the Earth's existence, and the Earth is still here!

The LHC just lets us see these processes in the lab (though at a much lower energy than some cosmic rays).

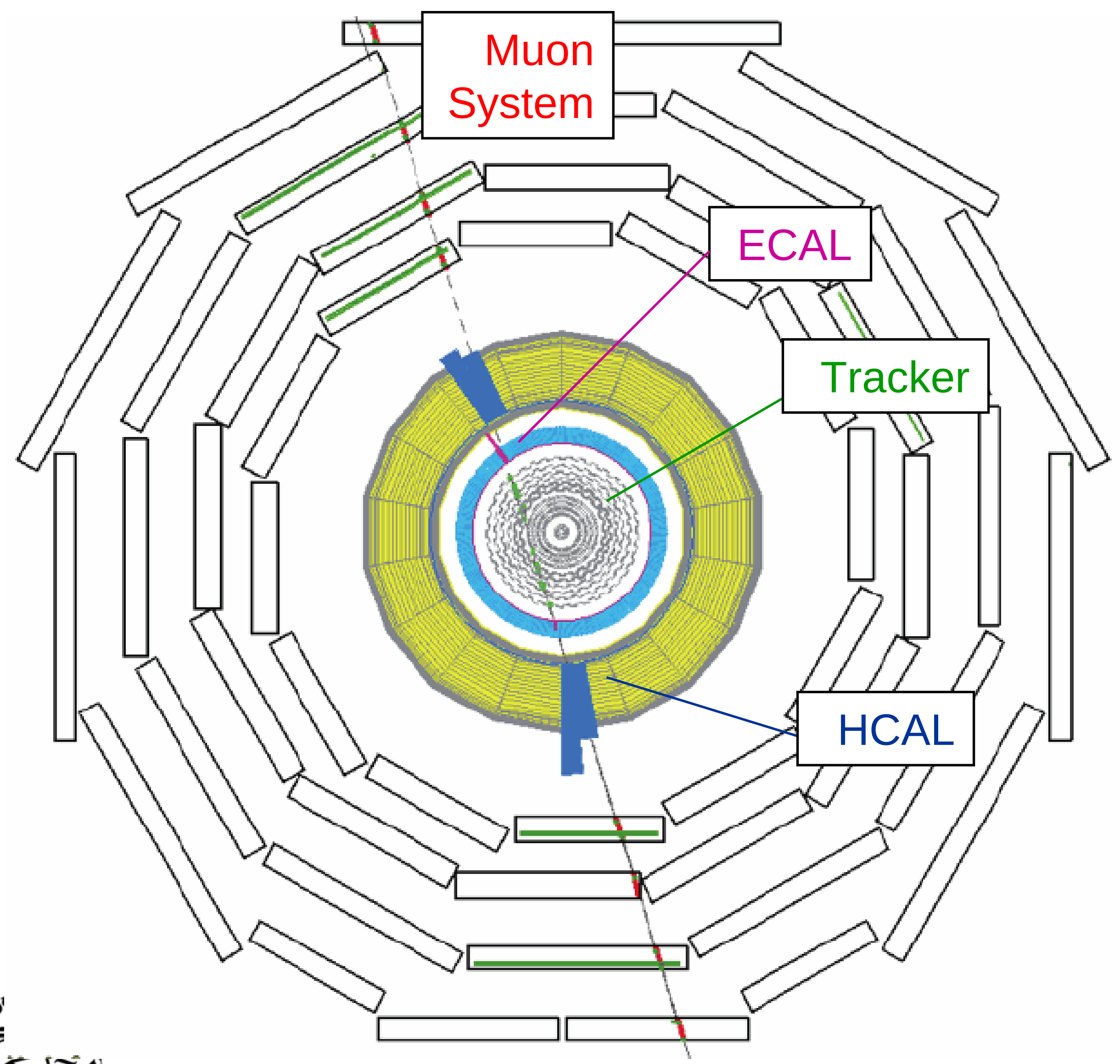
Cosmic Run at Four Tesla

- September 2008
  - CMS was ready for the first LHC beam
  - Sep 10: first beam in LHC was successfully steered around the full 27 km tunnel
  - Sep 19: a fault occurred in the electrical bus connection which caused mechanical damage and release of helium from the magnet cold mass into the tunnel
- October & November 2008
  - Commissioned CMS detector to collect cosmic ray data (collisions from universe instead of LHC)
  - About 300 million events were recorded with the magnetic field 3.8 T on within 4 weeks
  - Full rehearsal of everything from the data collection to physics analysis
  - Cosmic data are as important as collision data to enhance the detector and software quality
- 2009?
  - Prepare for the LHC collisions with a better understood detector and a better-trained collaboration





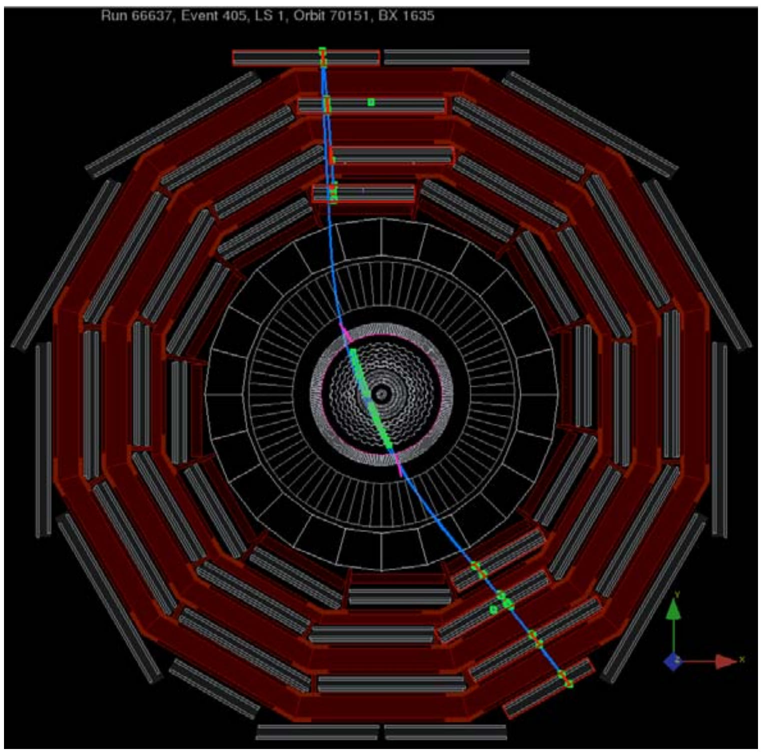
Global Detector Readout



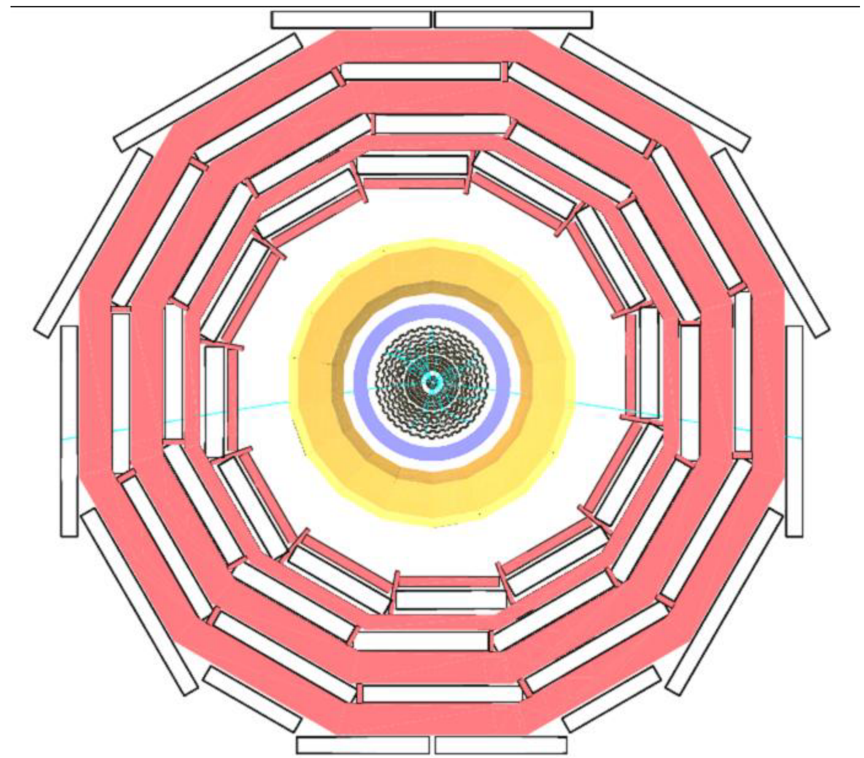
- Muon signals traced through
  - muon system
  - Strip Tracker (and pixels when close to beam pipe)
  - ECAL
  - HCAL
- Requires synchronization of all electronic signals
- Global track fit can be used for alignment and detector performance studies

Detection of Cosmic Rays

- Detecting cosmic rays needs different techniques (synchronization, reconstruction,…)
  - Cosmic rays arrive at the detector at random time and random direction
  - Particles from collisions have more strict timing and pattern of tracing (always from inside out and pass the detector components in certain sequence)



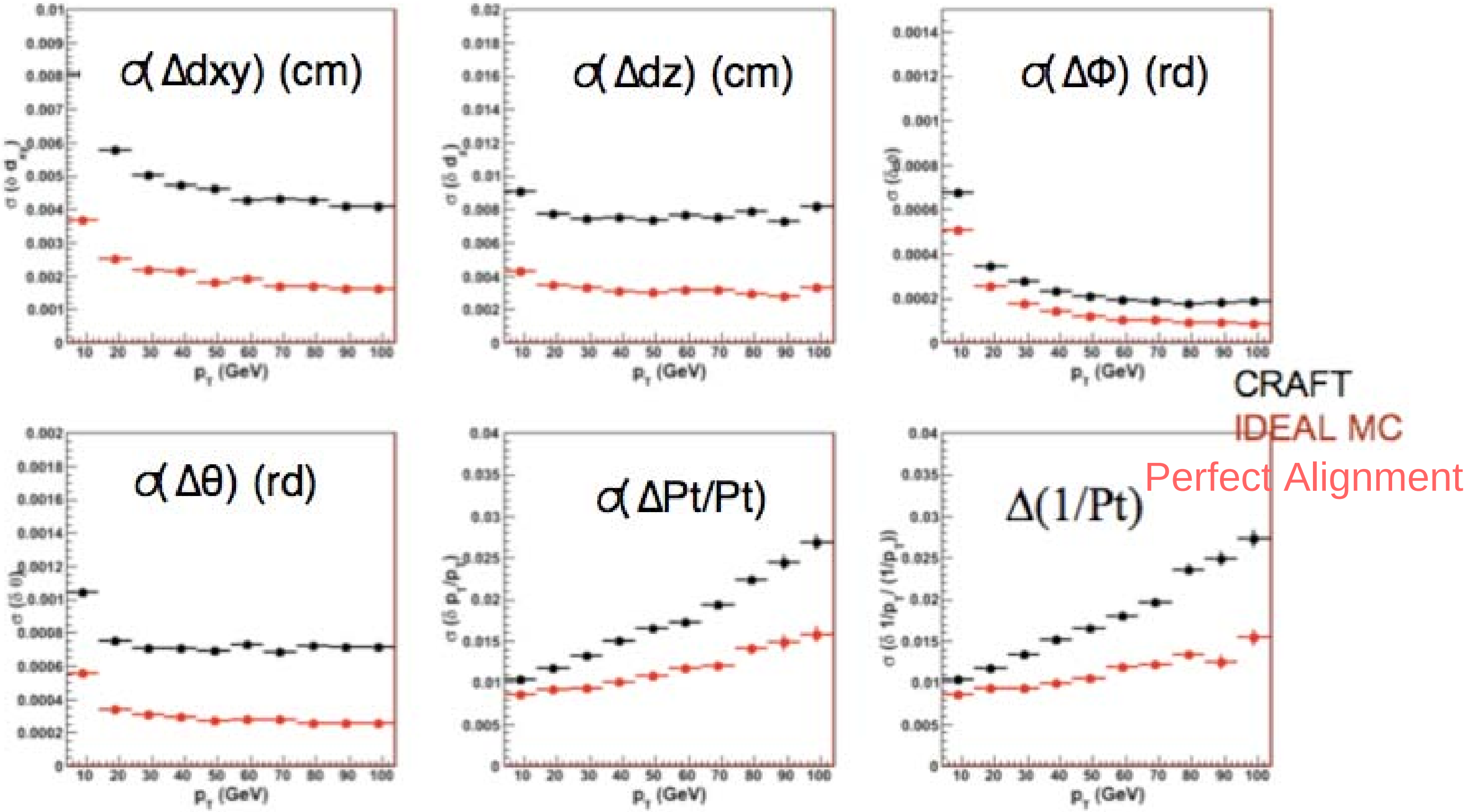
Cosmic muons



Simulated Drell-Yan event from LHC

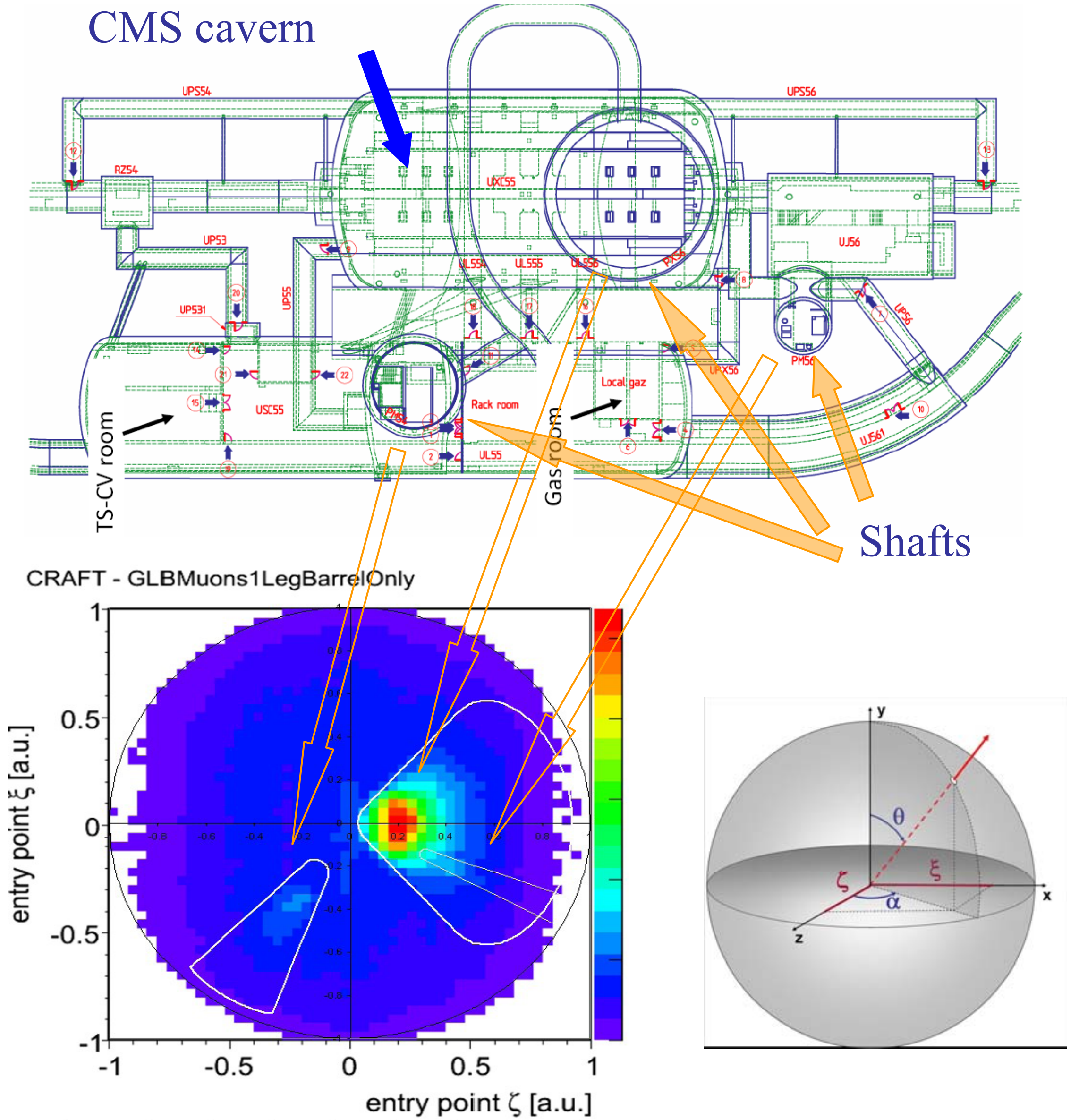
Reconstruction Resolutions

- 1 cosmic muon may leave 2 legs on the top half and bottom half
- Resolutions are estimated by comparing the 2 reconstructed tracks at the point of closest approach to the beam line



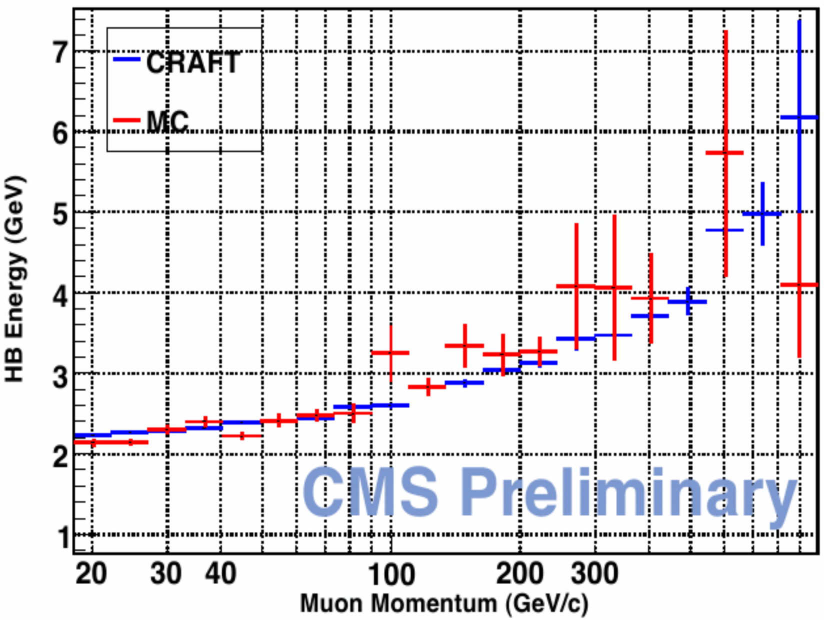
Angular Distribution of Cosmics

- Reconstructed angles of cosmic rays indicate increased acceptance through the 3 access shafts of CMS
  - CMS is located about 100 m underground

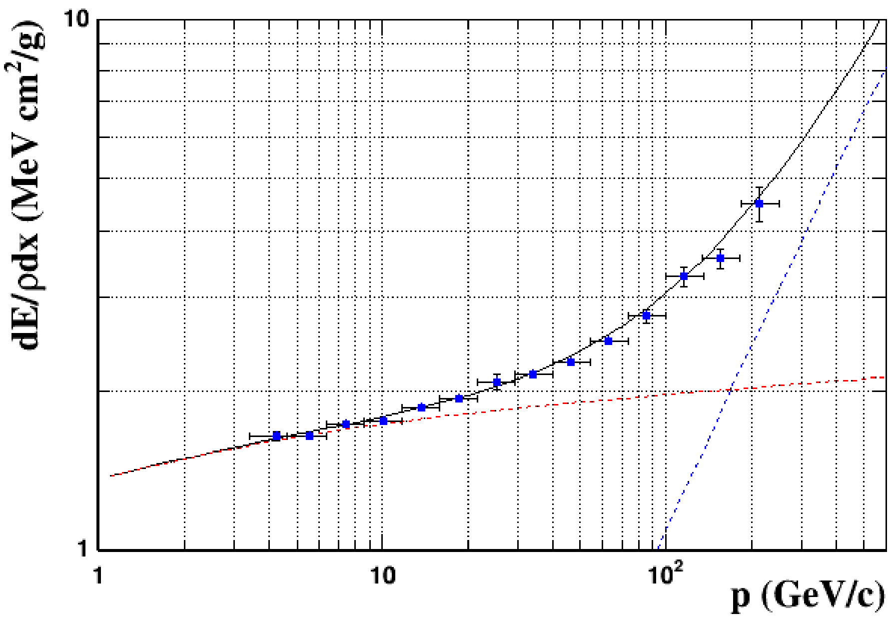


Energy Loss

- Energy loss
- Using energy deposit in HCAL barrel towers
- Experimental data (blue) is compared with Monte Carlo

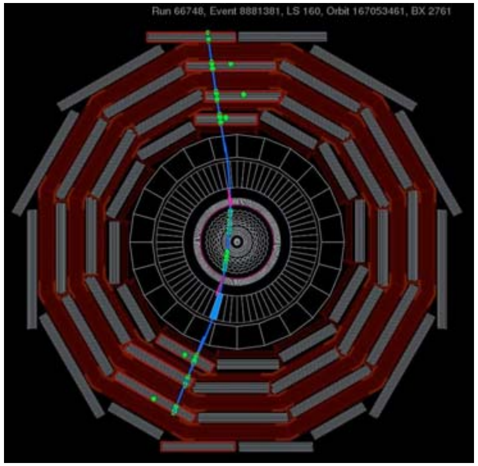


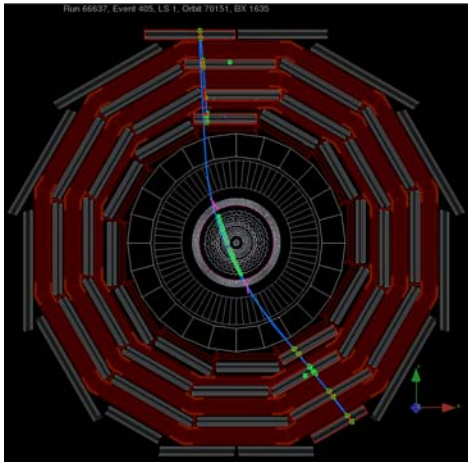
- Stopping power
- Correlation of the energy deposit measured in ECAL and the muon momentum measured in tracker
- Experimental data (dots) is compared with prediction (black line). Red and blue lines are ionization loss and radiation loss respectively.
- Error bars are statistical only



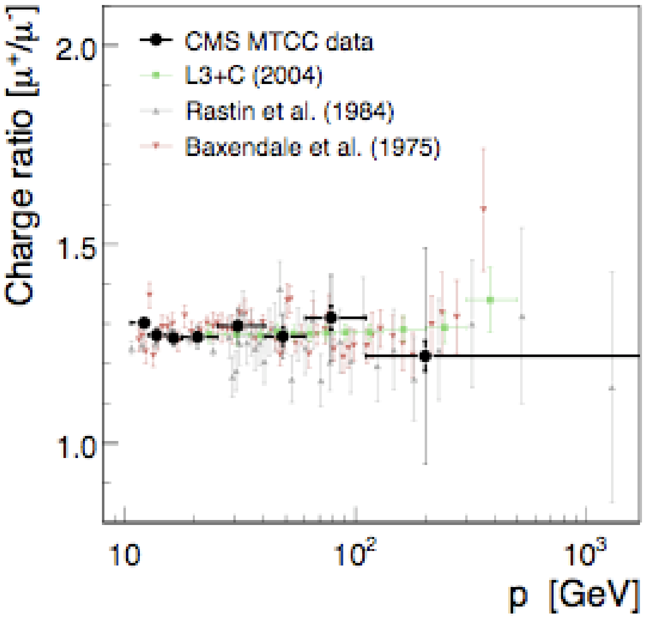
Atomospheric Muon Charge Ratio

- Atmospheric muon charge ratio
  - Muons with opposite charge are bent in different directions





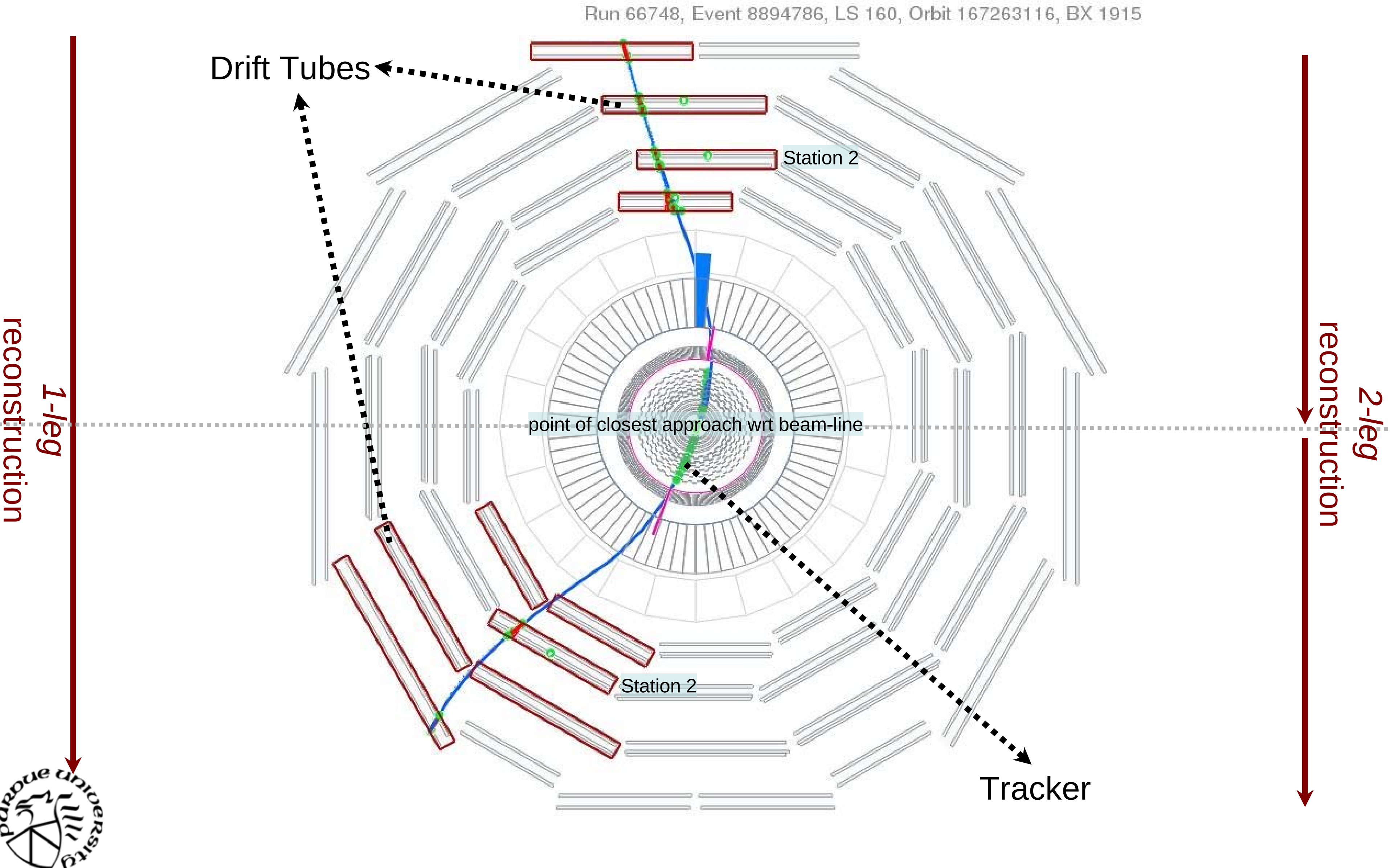
First CMS Physics
Measurement 2006



Challenge for Cosmic Physics Analysis

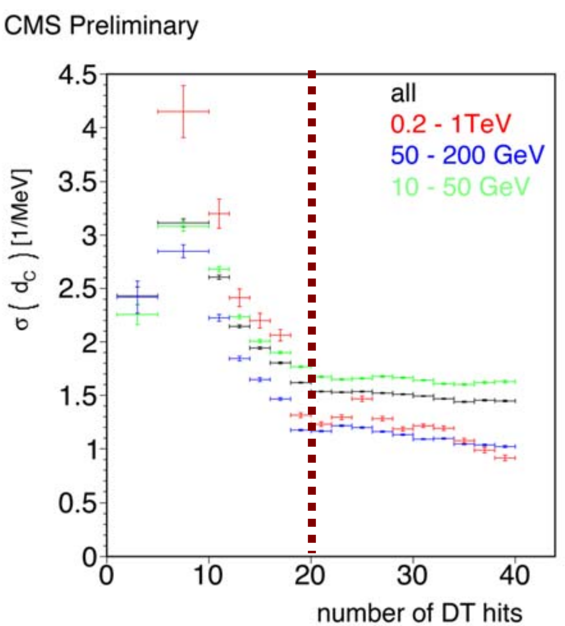
- CMS is not designed as a cosmic ray detector
  - beneath 100 m of concrete / molasse
  - the amount of material over CMS changes across the detector cross section
  - trigger and read-out timing have been designed for particles from the beam spot
  - magnetic field makes $\mu+$ and $\mu-$ traverse different trajectories
  - the tracker system is a small target for cosmic rays

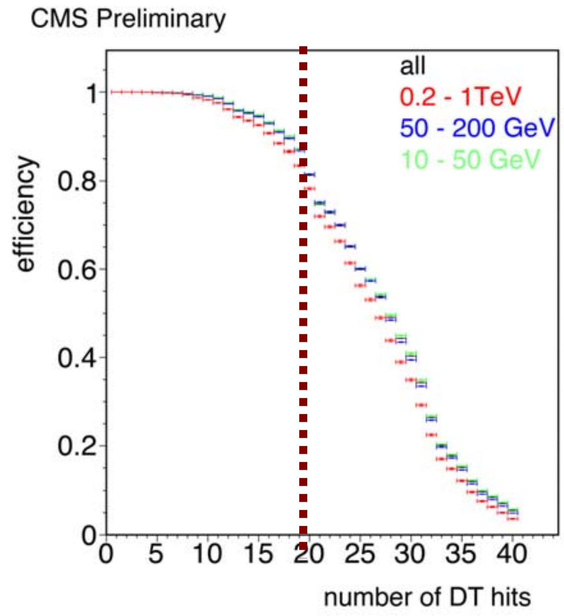
Analysis Components (1-leg vs 2-leg)

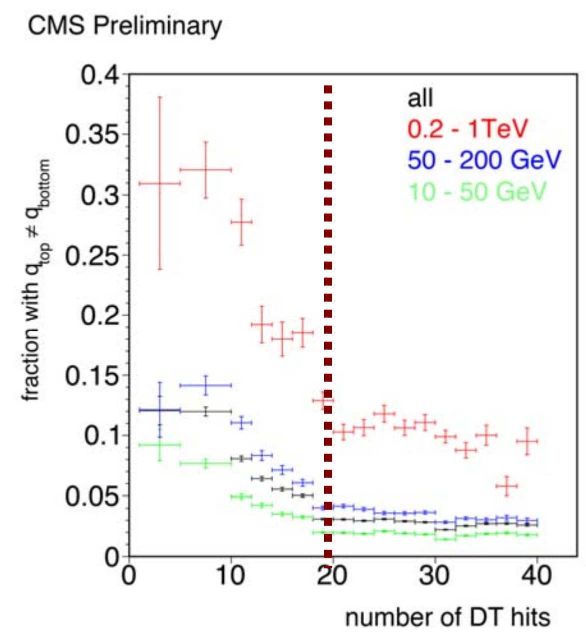


Unbiased Selection

- look for variables that don't bias the curvature distribution
- choose the cut value based on stability, staying efficient



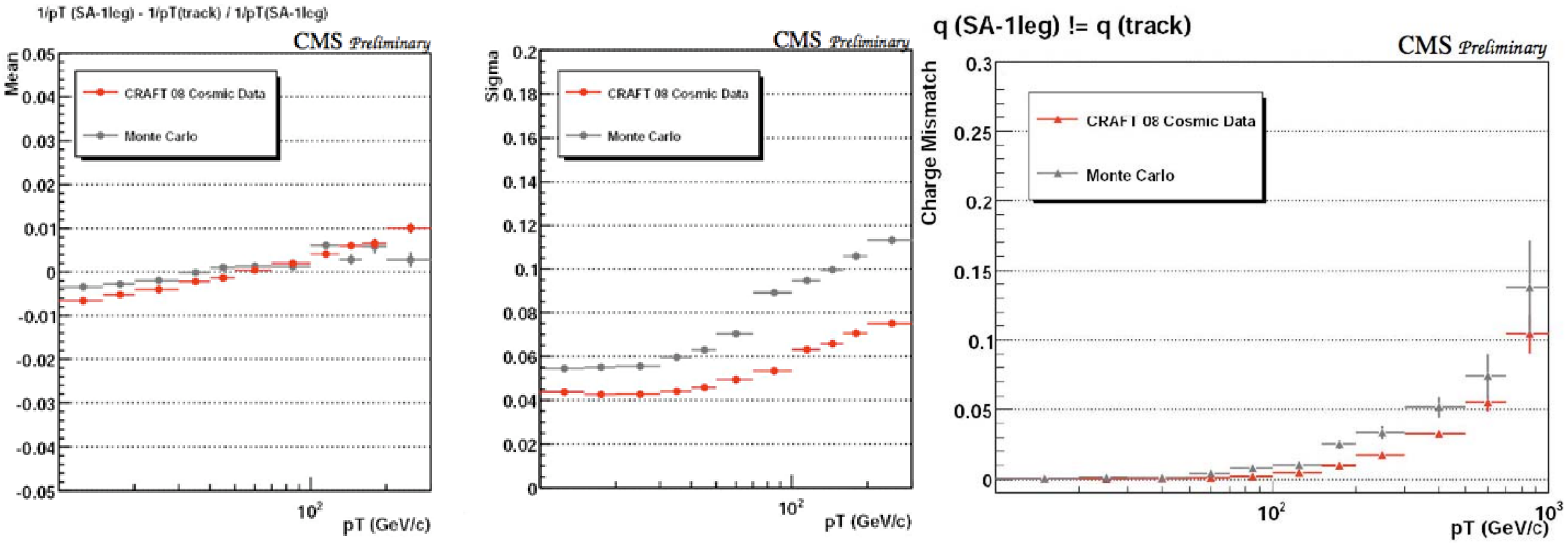




1-leg Analysis

- based on the **muon Drift Tubes** information
- a cosmic muon is reconstructed as a single muon object
  - different from LHC reconstruction ➠ split it in two muon legs
  - a single muon has longer lever arm
- higher statistics compared to tracker analysis
  - DT volume >> tracker volume
- good resolution at high *pt* thanks to long lever arm

1-leg Resolution and Charge Id

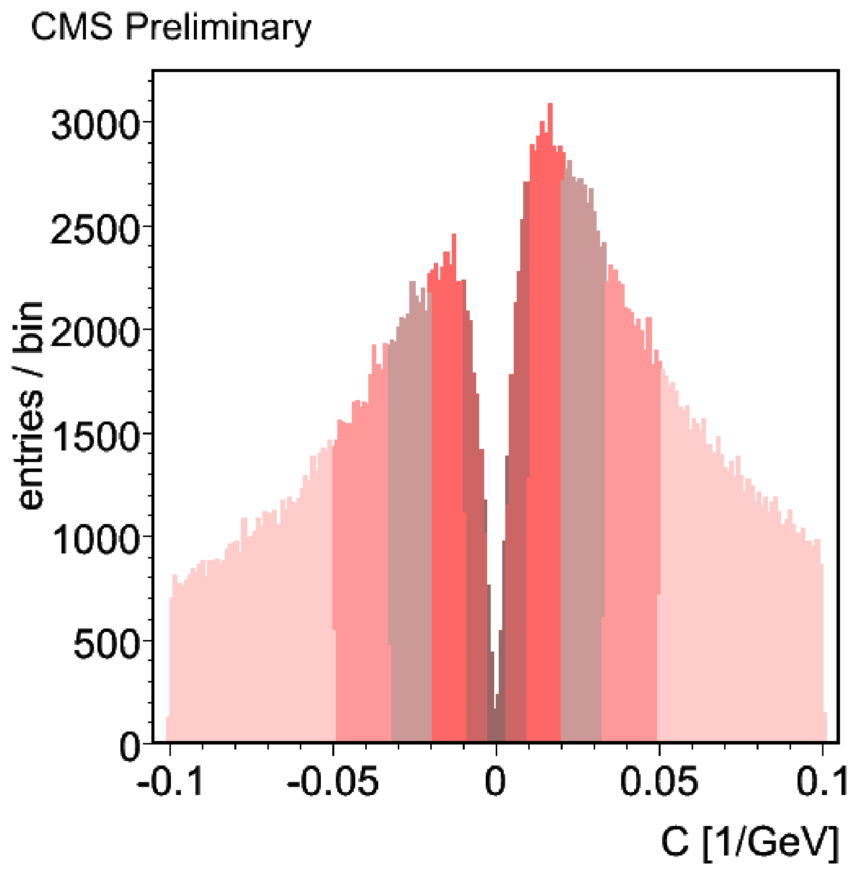


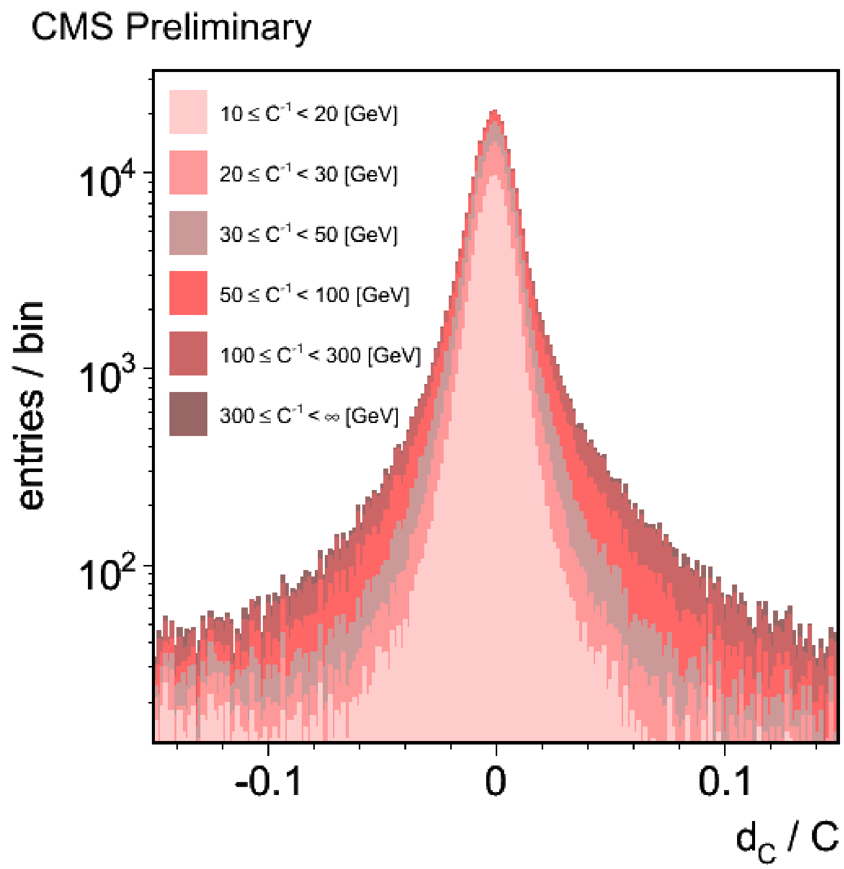
- compare DT *pt* with that from the tracker
  - DT – tracker scale within 1% for data and Monte Carlo
  - better resolution in data
- compare DT charge with that from the tracker
  - fraction below 5% up to *pt = 500 GeV*

2-leg Analysis

- completely data-driven approach
  - no Monte Carlo correction involved
  - however Monte Carlo can help to validate technique
- based on the **Tracker** information
- measure the charge ratio vs average *curvature*
  - $C \equiv 1/2 \cdot (q^{up} / pt^{up} + q^{low} / pt^{low})$
- measure the resolution from *curvature* difference
  - $d_C \equiv 1/2 \cdot (q^{up} / pt^{up} - q^{low} / pt^{low})$
- performance closer to that from LHC reconstruction
  - handle on goodness of TeV LHC tracks

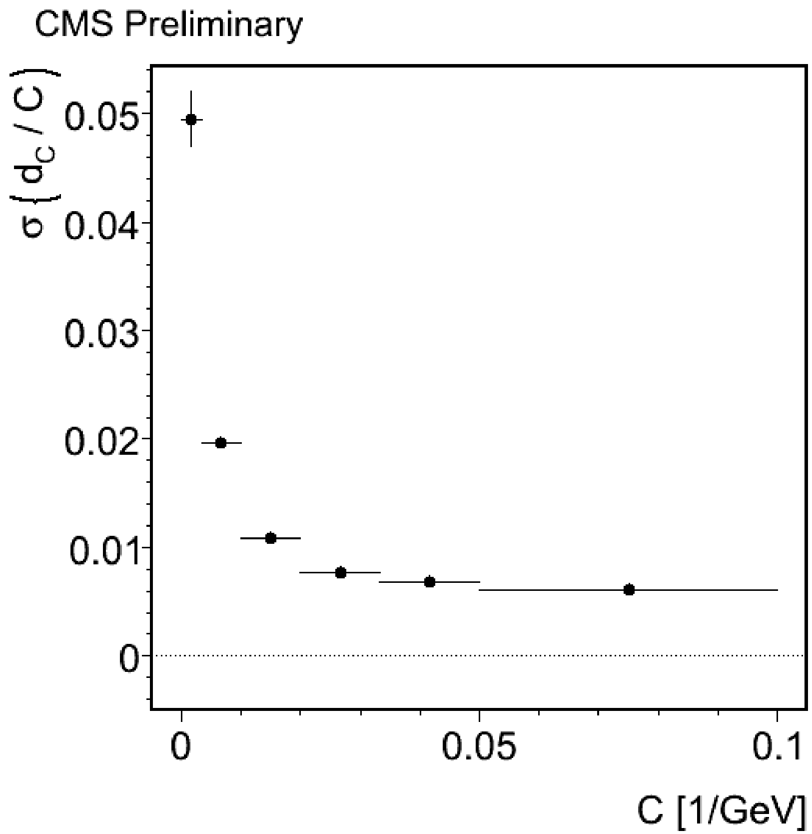
Curvature and Resolution

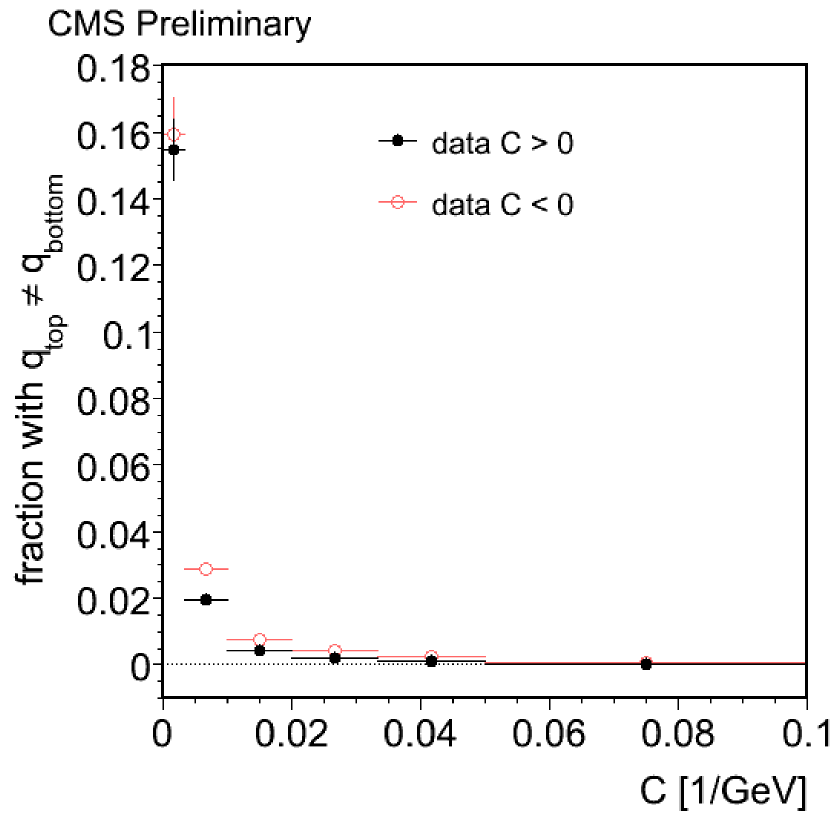




- curvature (left) and resolution (right) after selection
  - darker red corresponds to higher transverse momentum $pt \equiv 1 / |C|$
  - can see resolution getting worse with increasing *pt*

2-leg Resolution & Charge Id





- Gaussian fits of d_C/C core
  - excellent resolution, below 5% in all the curvature spectrum
- Mis-id fraction below 3% for *pt < 300 GeV*

Systematics

- selection
  - the goal was selecting high quality muons without introducing any bias
  - we have checked the impact of removing each cut
  - systematic uncertainty $\leqslant$ 1% in all *pt* range
- resolution function
  - splitting a cosmic muon in two legs provides a fully data-driven approach
  - from MC, d_C is an excellent proxy of the curvature resolution
- wrong tracker-muon matching
  - sometimes the tracker track is matched to the wrong muon
  - it affects less than 0.02% of the selected events
- magnetic field
  - the *B field* in the tracker region was known with great precision (<0.1%) before CRAFT
  - more complex field in the iron layers of the return yoke (muon spectrometer)
  - with CRAFT we probed for the first time the *B field* in the iron of the yoke directly
  - compare the effect of different field maps in the analysis ~ 3% at high *pt*
- trigger
- alignment
  - curvature sensitive to muon, tracker and muon-tracker relative alignments
  - impact of different alignments up to 5% at high *pt*

Conclusions

- Cosmic data are a goldmine for the detector commissioning before LHC collisions
- Detector performance was estimated and enhanced, lessons learned
- Physics with cosmic rays are studied, and results are coming soon
- CMS has its first physics results with real data before the LHC collisions

- Expecting the first real data from collisions!