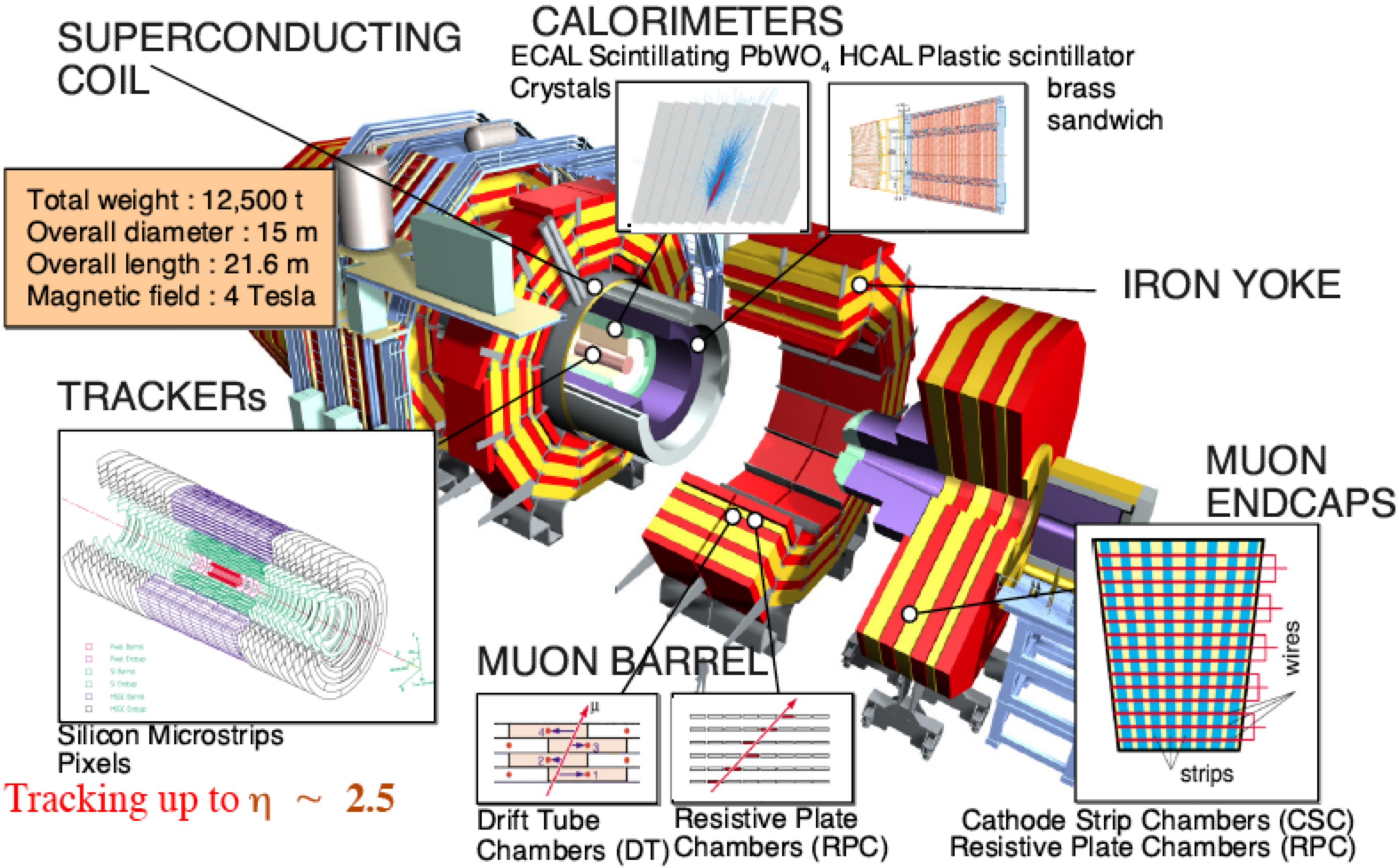
First Collisions with the CMS Detector at LHC

Alexei Raspereza
DESY Hamburg

The CMS detector



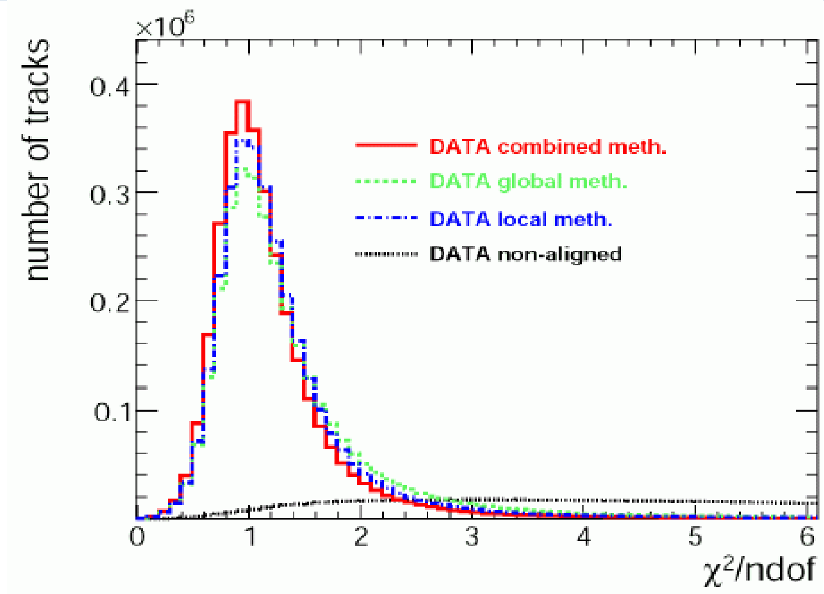
➼ Tracking up to $\eta \sim 2.5$

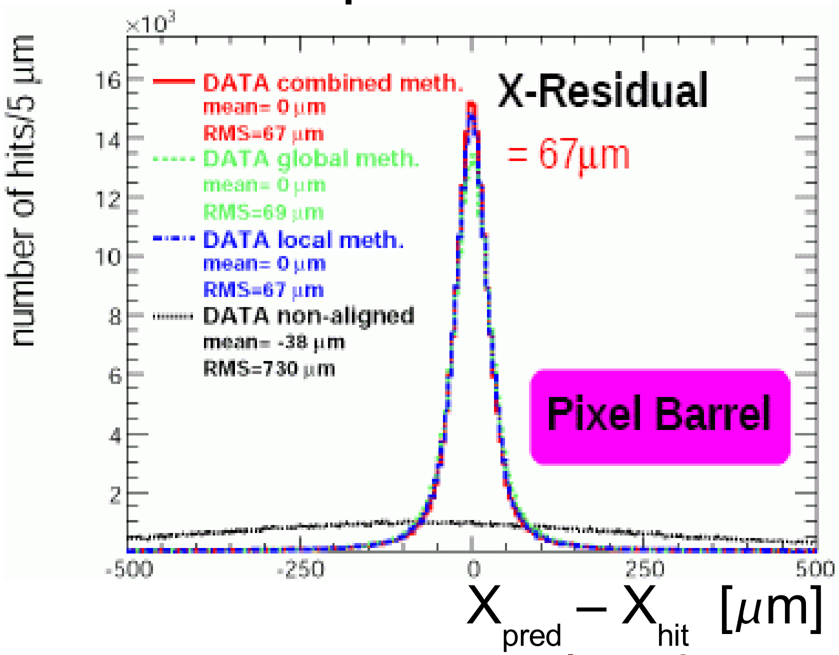
Preparation for the First Collisions

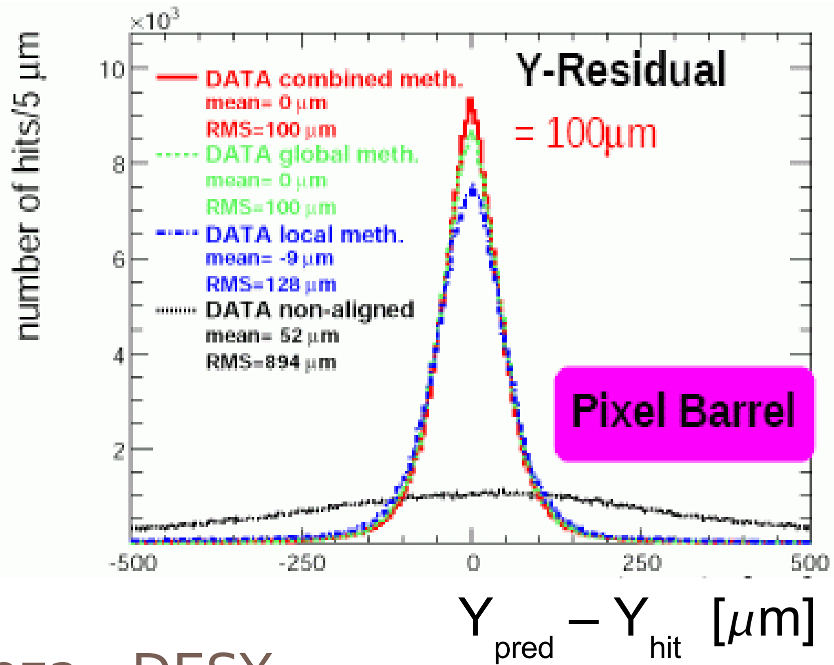
- **LHC and CMS operations in 2009 were preceded by extensive preparatory work**
  - Sub-detector test-beam and commissioning campaigns prior to data taking
  - Detector alignment and calibration with cosmic data
- **<u>DESY and UH contributions</u>**
  - Development of Data Quality Monitor
  - Alignment of the CMS tracker with cosmic data (UH + DESY Hamburg)
  - Commissioning of CASTOR calorimeter (DESY Hamburg)
  - Commissioning of Beam Condition Monitor (DESY Zeuthen , DESY Hamburg)

Tracker alignment for 2009

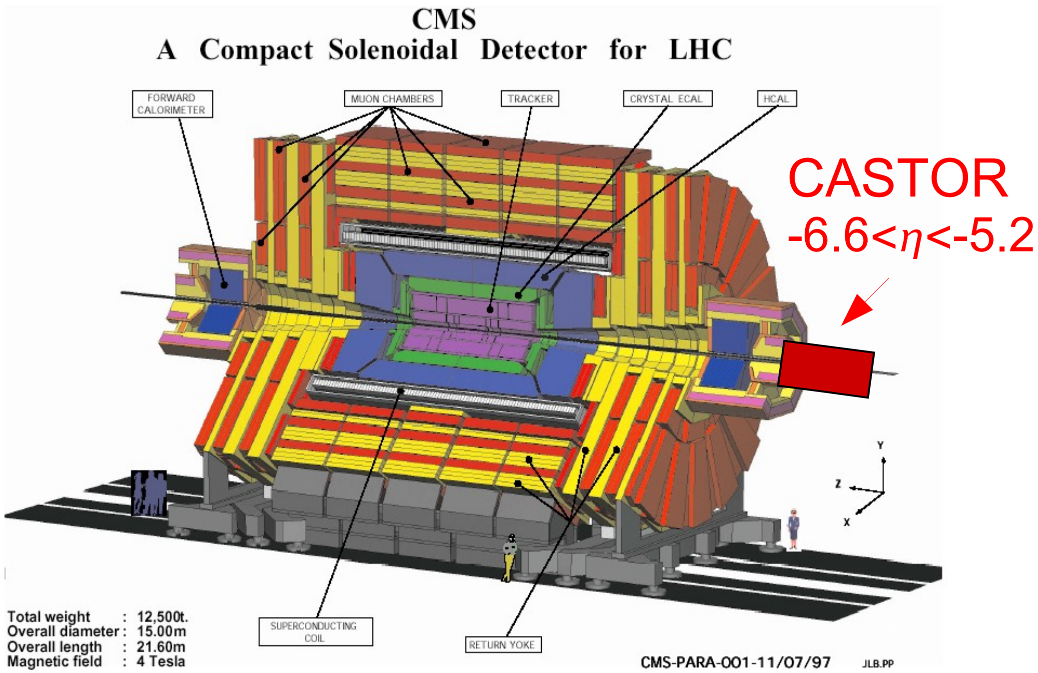
- Alignment performed by minimizing track residuals (x_{hit} - x_{track}) at single module level
- Requires very large track sample
  - 3.2M cosmic tracks used (CRAFT' 08 data)
- Clear improvement in residual width (bottom plots)
- Already aligned to 3-4 μm in barrel, 3-14 μm in endcaps

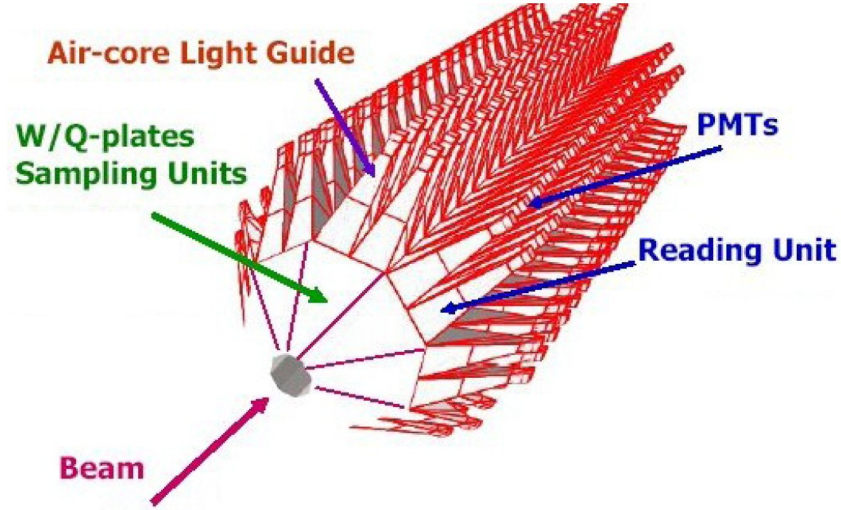






CASTOR Testbeam and Installation





- 14 segments in length of 1.6m,
- 16 segments in Φ for radius of 0.3m
- 2 EM segments: 2x10 X_0 → 0.77 λ
- 12 HAD segments: 12x0.77λ → 9.24λ
- 224 channels in total, 10λ
- **Installation within CMS completed**
  - Fully equipped (> 99% of channels give signal, 92% see LED)
  - DAQ system integrated into CMS Hcal data stream

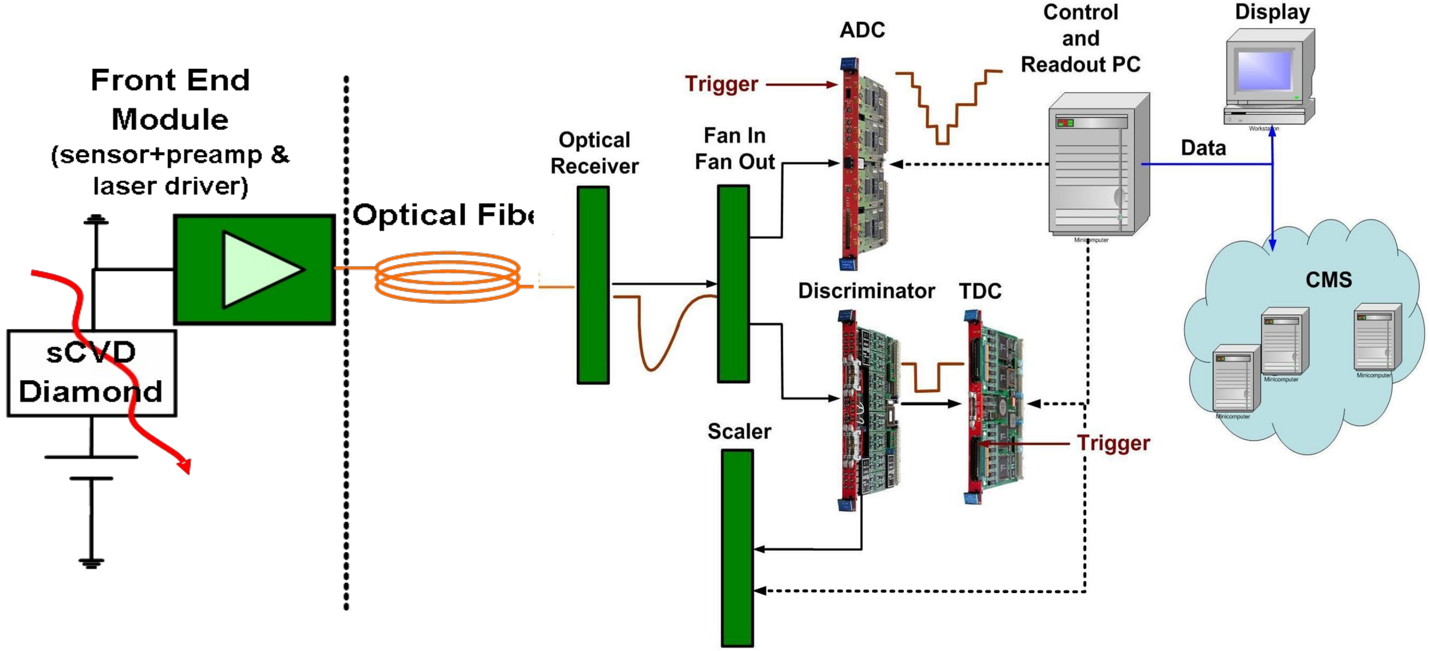
2008 Testbeam at CERN

- Studies with muon beams (inter-calibration, response uniformity checks, light collection study)
- PMT studies (pedestals at different HV)
- Response to electron/pion beams (linearity, resolution)

BCM1F (Fast Beam Condition Monitor)

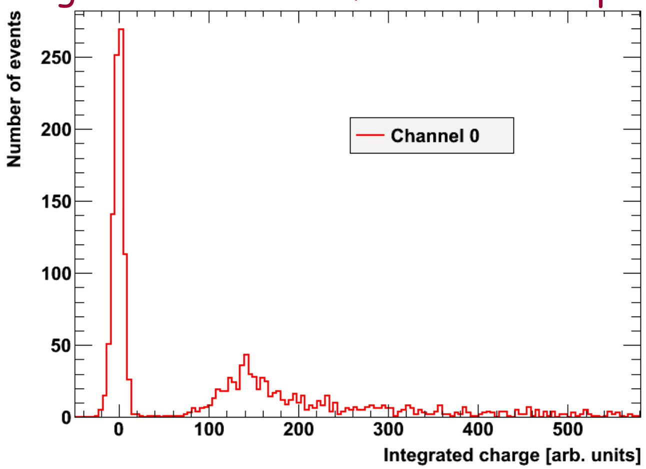
single crystal diamond sensors near the pixel detector to monitor beam halo flux

- Location : ±1.8 m from IP
- Four sensors around beam-line
- Readout independent from CMS DAQ and LHC UPS
- Sampling time : sub(bunch)-by-bunch
- Function : monitoring + protection, post-mortem analysis (*e.g.* after beam loss)

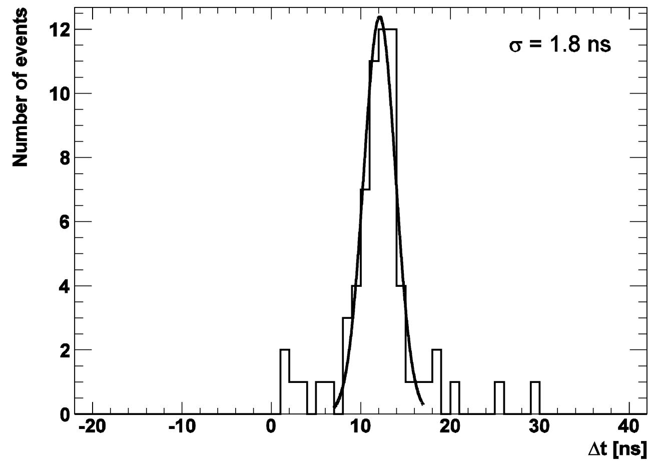


Performance plots from 2008

Signal distribution for beam halo particles



time resolution measured with the 8 bit 500 MS/s ADC

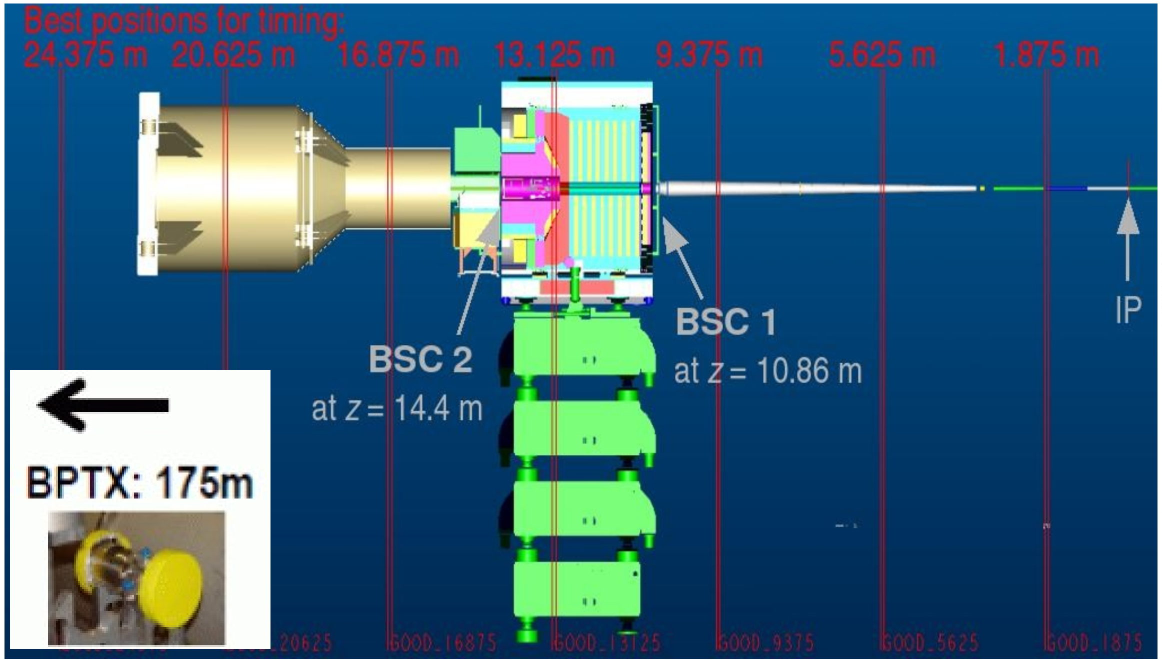


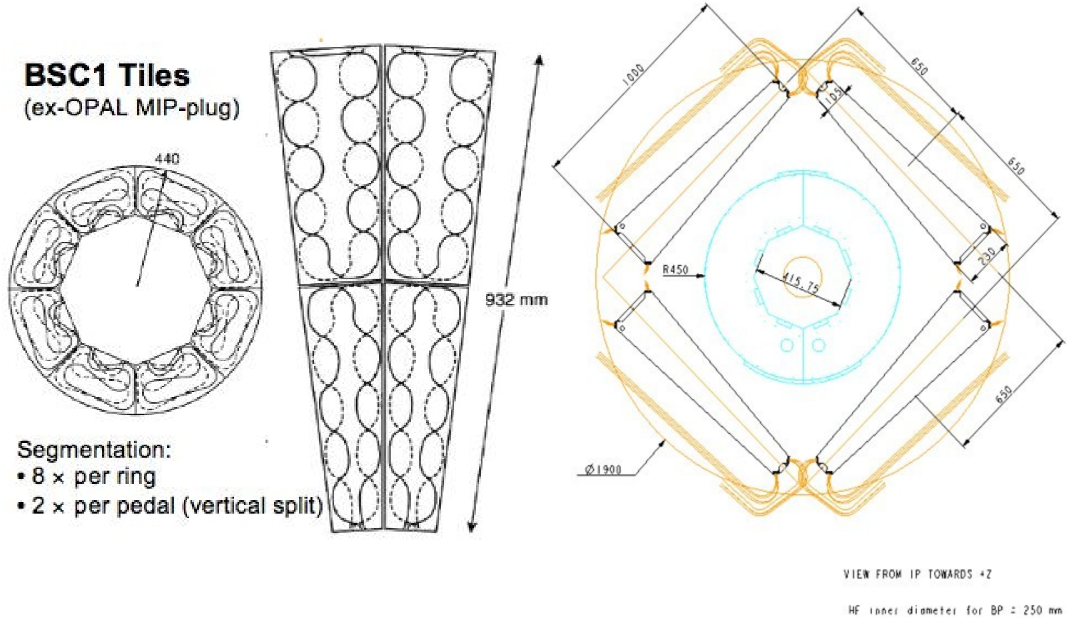
LHC Run Nov-Dec 2009 : Event Chronology

- 2009 LHC running. Event Chronology
  - Nov 7 – 9 : first beams since 2008, “splash” events, a lot of data to digest
  - Nov 17 – Nov 23 : LHC restarts, capturing beams with RF system
  - Nov 23 : two beams with > 10^9 protons/beam, first collisions @ 900GeV
  - Dec 5 – Dec 6 : beams are back, 4x4 bunches, collisions @ 900 GeV seen in fully operational CMS detector!
  - Dec 8 – Dec 14 : from first collisions to routine operations
  - Dec 14 : collisions @ 2.36 TeV (world record!)
  - Dec 14 : 16 bunches in each beam, intensity > 10^{11} protons/beam, more data
  - Dec 16 – end of 2009 LHC running, time to scrutinize data!
    - 10 μb^{-1} of pp collision data taken at 900 GeV
    - 0.4 μb^{-1} at 2.36 TeV

Recording Collision Data. Minimal Bias Trigger

- First collision data are taken with loose trigger conditions ⇒ minimal bias events
  - Min bias trigger : hit in any Beam Scintillator Counters (BSC1) (inner ring) in coincidence with a signal from the two Beam Pick-Up Timing for eXperiments (BPTX) ⇒ two bunches crossing IP



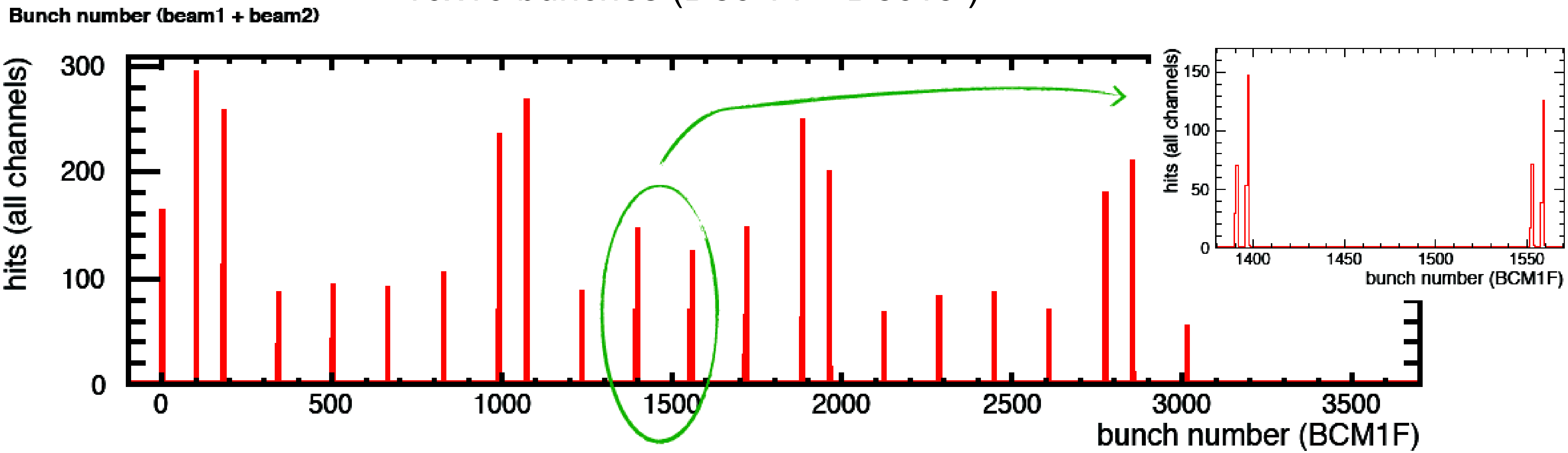


  - Any two hits from the BSC1 outer pedals on opposite sides of IP, consistent with the time difference of 73 ns (twice distance from BSC1 to IP) are used as a beam halo veto

Monitoring Beam Structure with BCM1F during Collision Runs

- Excellent time resolution allows BCM1F to tag single bunches!

16x16 bunches (Dec 14 – Dec15)

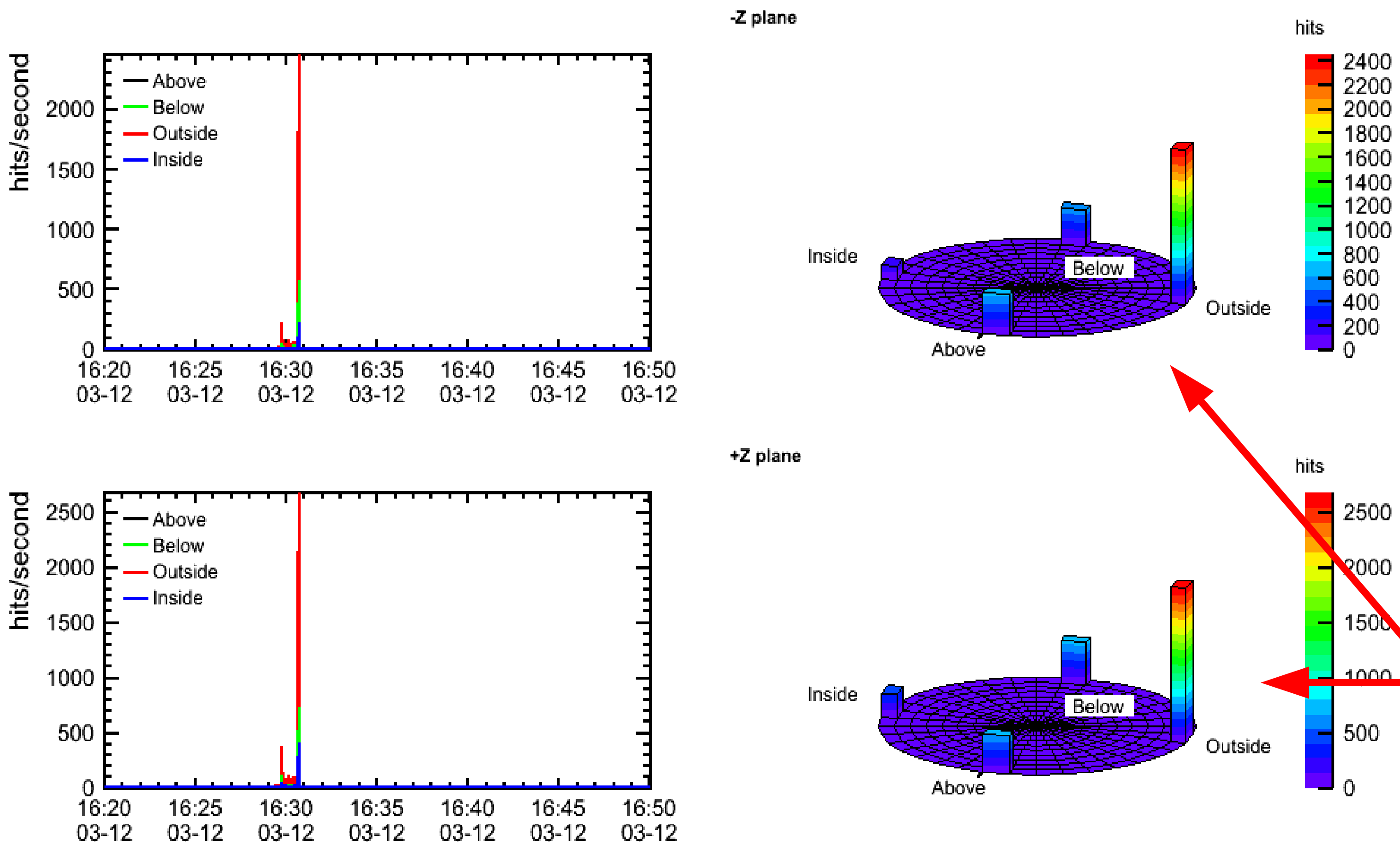


Bunch number = (TDC_time[ns] - 6275[ns])/24.95

- TDC_time is time provided by TDCs in [ns]
- 6275 [ns] – time of bunch #1 w.r.t. orbit trigger
- 24.95 ns – time between bunches as foreseen for design operational conditions

Beam Movement Detected by BCM1F during Collision Run

- Relative response of the four diamond sensors placed at ϕ=0°, 90°, 180°, 270° around beam-pipe is sensitive to beam movements



Equal response of all sensors ⇒ beam @ nominal position (center of beam pipe)

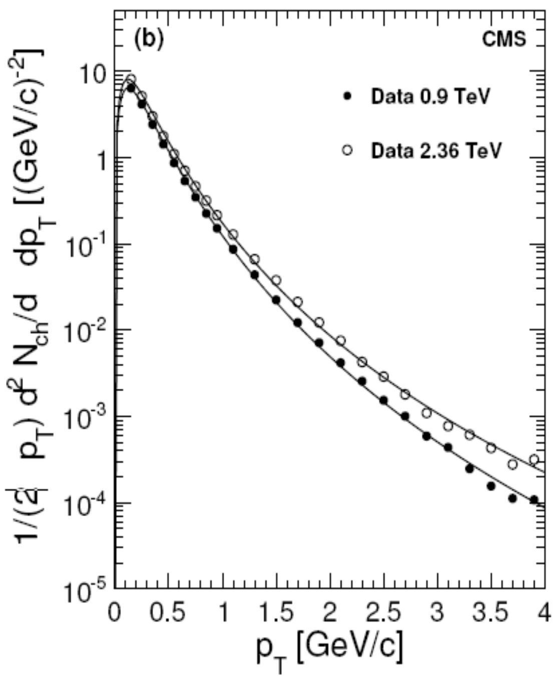
Increased response in one of the sensors compared to others indicates movement of beam towards this sensor

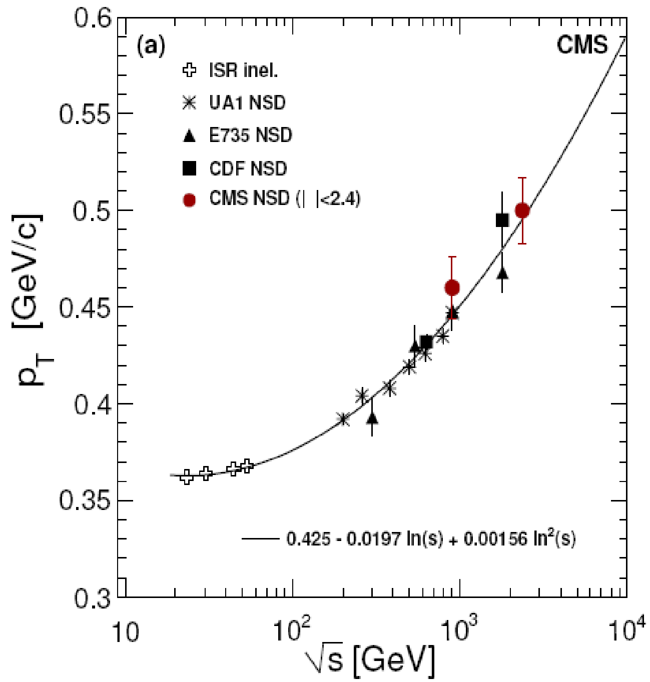
Beam moved away from LHC ring center

http://www.desy.de/~rasp/bcm1f_beam_movement.gif

First CMS Paper Covering Collision Results

- At design luminosity signal events will overlay with more than 20 near-simultaneous min bias collisions
  - First LHC collisions collected with min bias trigger are valuable data to study characteristics of these events
  - Kinematic properties of collision products in min bias events => topic of the first CMS publication





Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV

CMS Collaboration

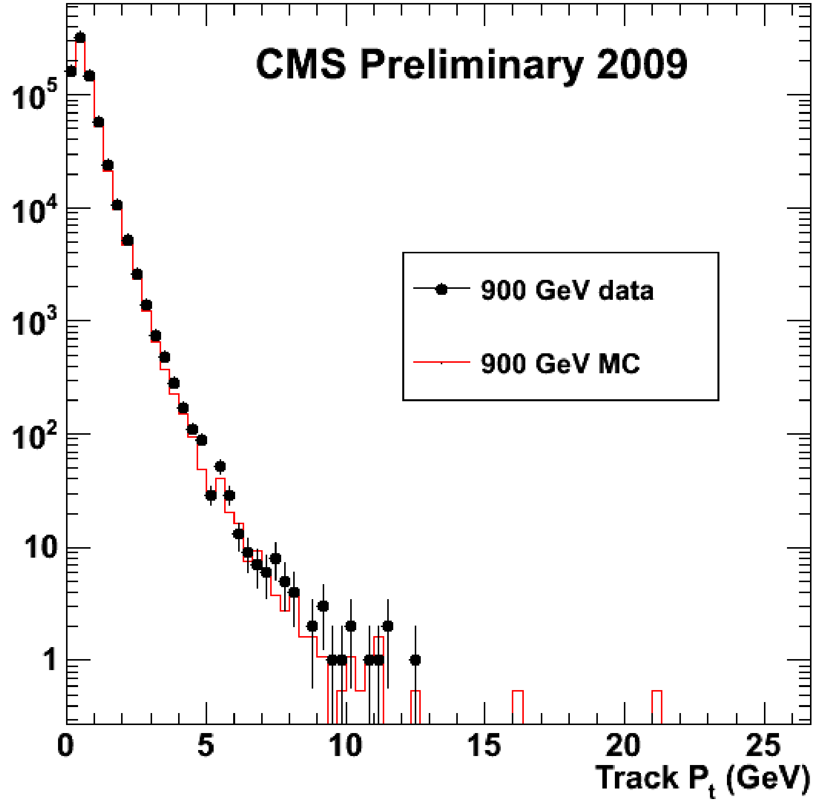
Abstract: Measurements of inclusive charged-hadron transverse-momentum and pseudorapidity distributions are presented for proton-proton collisions at $\sqrt{s} = 0.9$ and 2.36 TeV. The data were collected with the CMS detector during the LHC commissioning in December 2009. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be 0.46 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 0.9 TeV and 0.50 ± 0.01 (stat.) $\pm$ 0.01 (syst.) GeV/c at 2.36 TeV, for pseudorapidities between -2.4 and $+2.4$. At these energies, the measured pseudorapidity densities in the central region, $dN_{ch}/d\eta|_{|\eta|<0.5}$, are 3.48 ± 0.02 (stat.) $\pm$ 0.13 (syst.) and 4.47 ± 0.04 (stat.) $\pm$ 0.16 (syst.), respectively. The results at 0.9 TeV are in agreement with previous measurements and confirm the expectation of near equal hadron production in $p\bar{p}$ and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

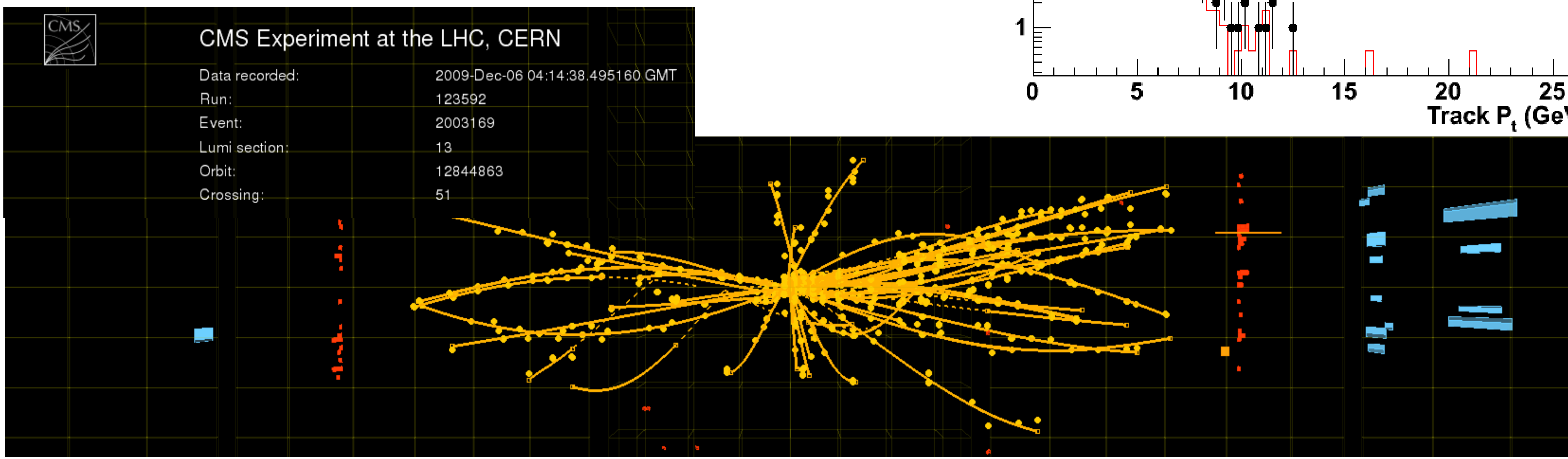
Keywords: Hadron-Hadron Scattering

JHEP02(2010)041

Track Reconstruction

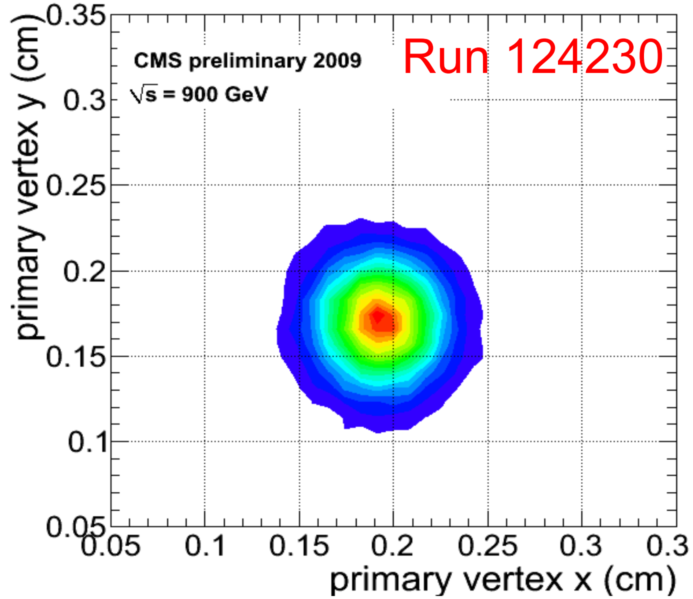
- Charged tracks reconstructed with Kalman filter technique
  - Difficult task in dense environment
- Algorithm shown to have high efficiency on cosmic tracks and MC
- p_T distribution in agreement with MC
  - $p_T/\sigma(p_T) > 10$, ≥ 8 tracker hits

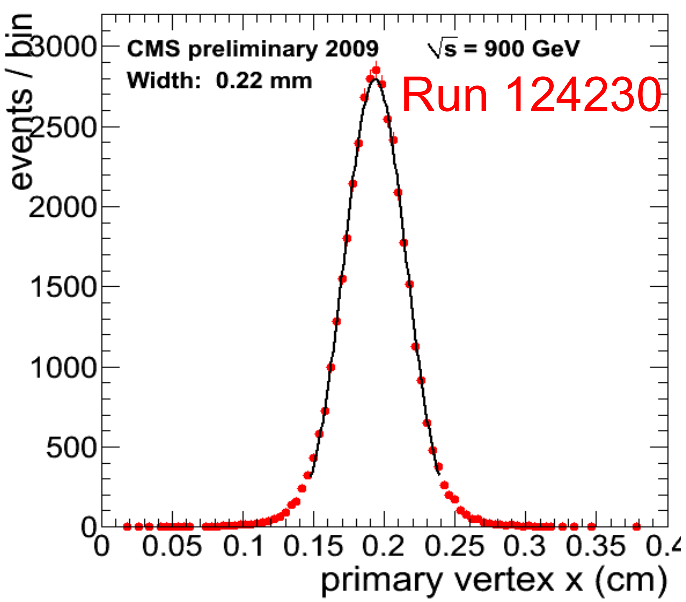


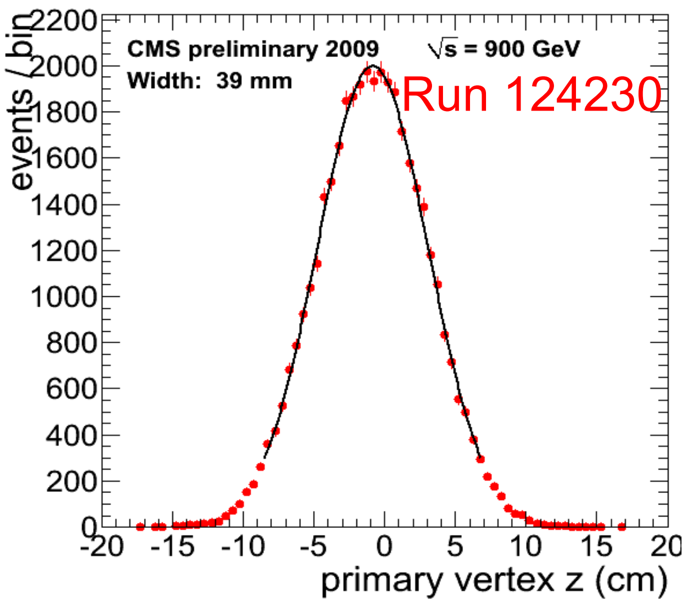


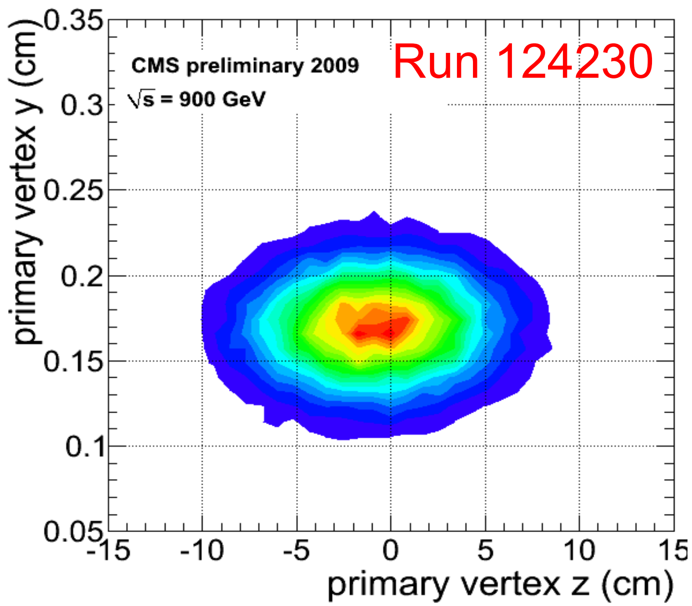
Primary Vertex Reconstruction

- Primary vertex is reconstructed from filtered tracks
  - Cuts on # pixel hits, # SST hits, χ^2/ndof, distance to beam
  - track quality criteria for 0.9(2.36) TeV data are looser compared to the nominal criteria optimized for high energy collisions
- Adaptive Vertex Fitter
  - tracks assigned weights based on their compatibility with common vertex ⇨ reduced effect of outliers on the reconstructed vertex



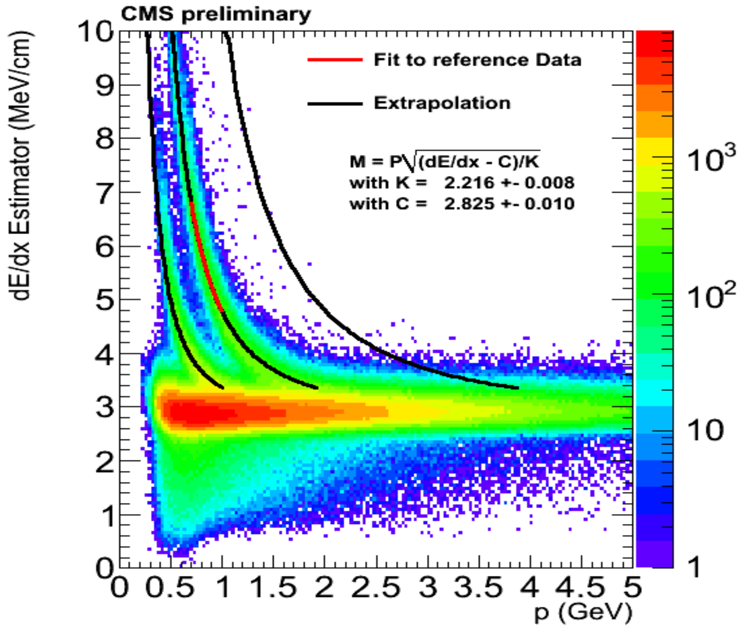


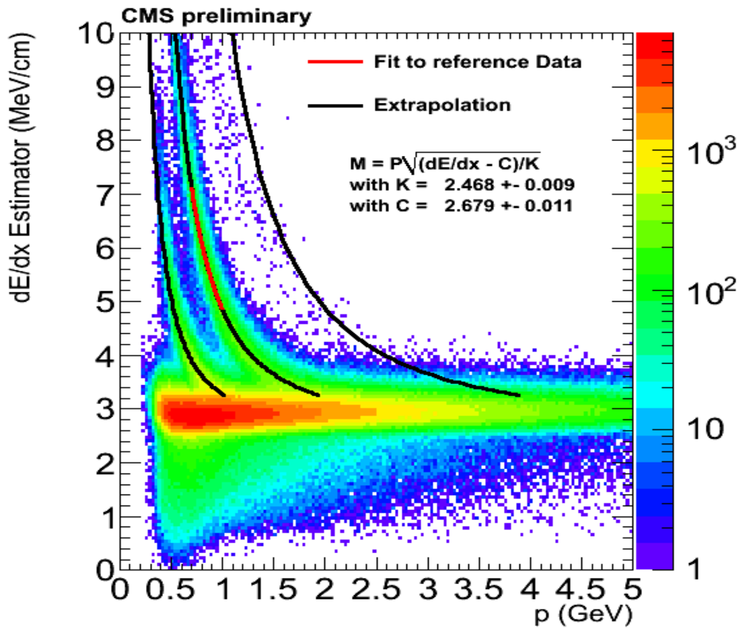


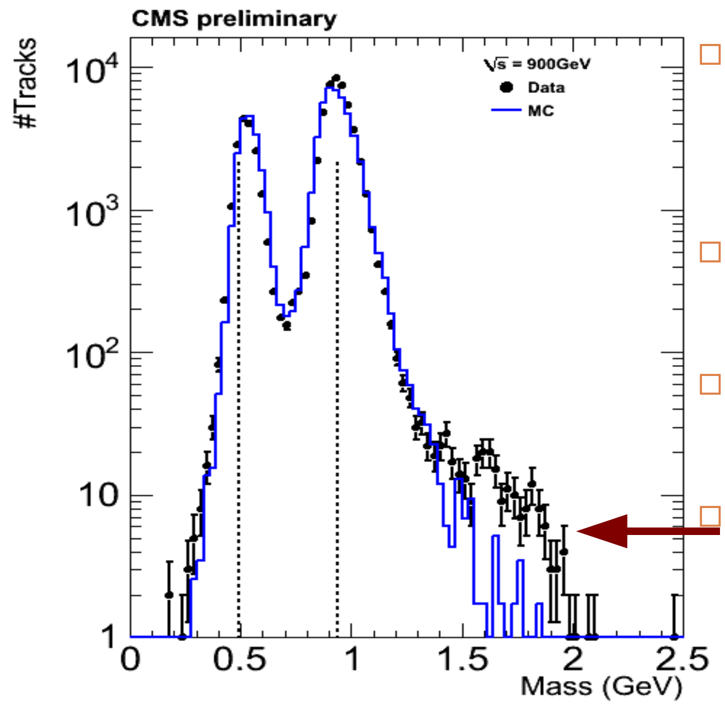


dE/dx Measurements

- motivation : search for Heavy Stable (Long-lived) Charged States
- $\frac{dE}{dx} = K\frac{m^2}{p^2} + C$ reproduces Bethe-Bloch with accuracy better than 1% for $0.4<\beta<0.9$
- Parameters *K* and *C* are regarded as universal
  - extracted from the fit to the proton line
  - momentum restricted to [0.7,1.0] GeV/c





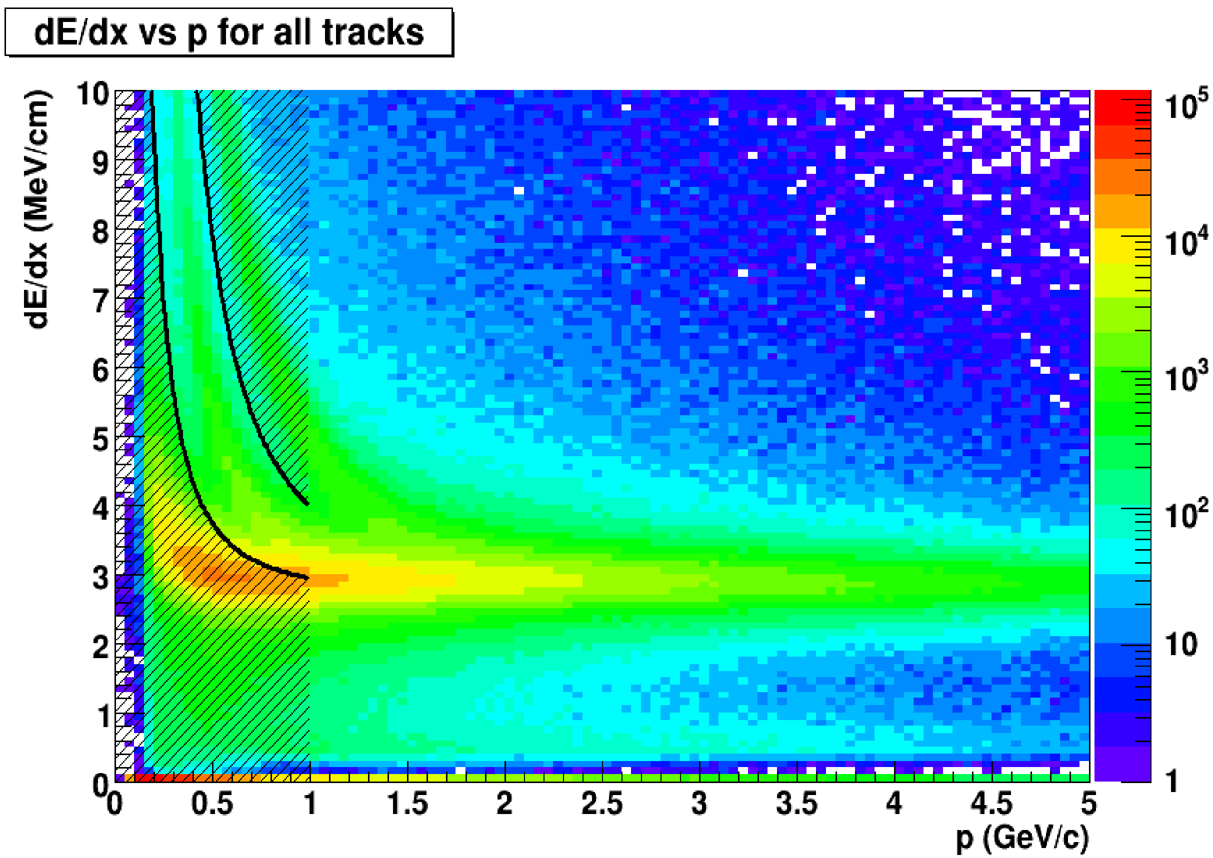


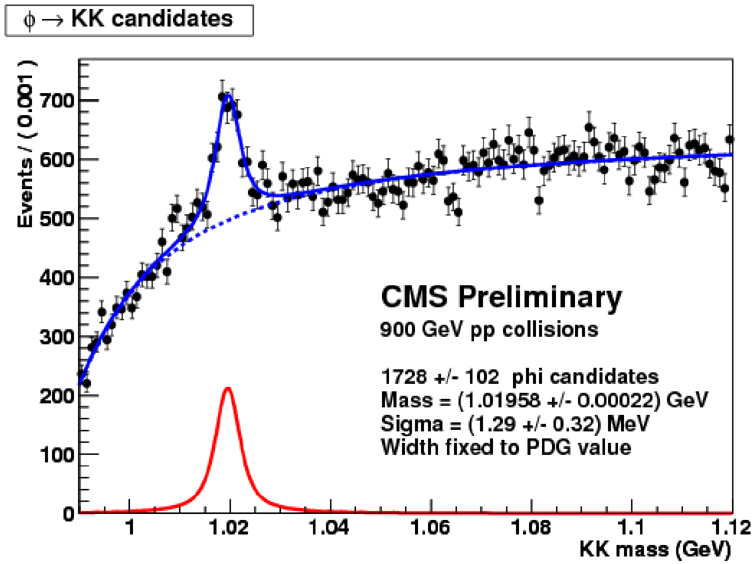
- Mass reconstructed from dE/dx measurement
  - p<2GeV, dE/dx>4.1 MeV/cm
- Separately fitted *K* and *C* for data and MC
- Clear peaks corresponding to kaons and protons
- Additional peak attributed to deutrons (not visible in Monte Carlo)

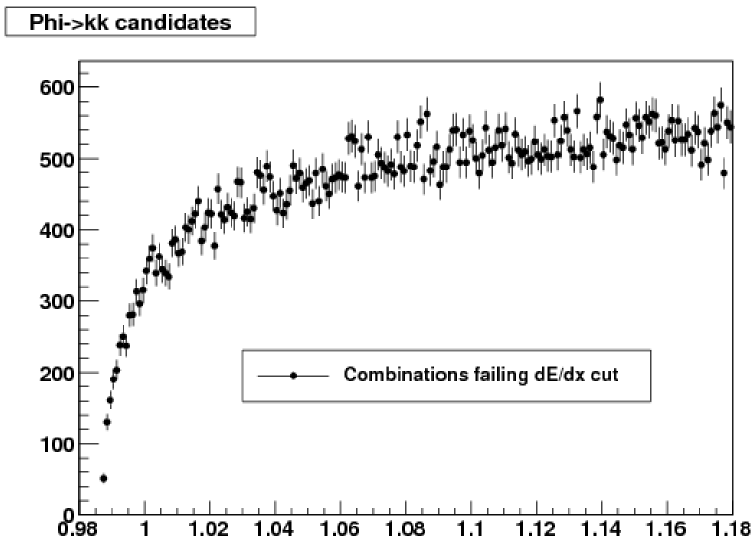
Application of dE/dx Measurement

- dE/dx application nicely illustrated by search for $\phi \rightarrow K^{+}K^{-}$
- $K^{\pm}$ identification ⇒ • $p > 1\,\mathrm{GeV}$ OR $K(M_K^{min}/p_k)^2 + C < dE/dx < K(M_K^{max}/p_K)^2 + C$

  Compatibility window ±200 MeV/c² of M_K

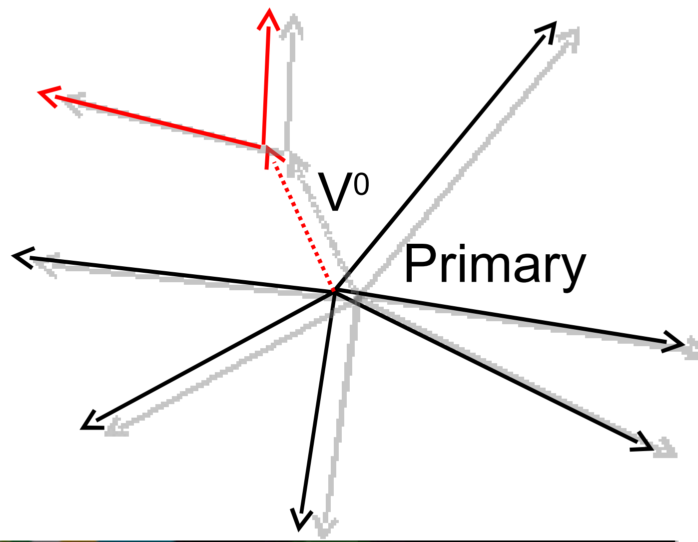


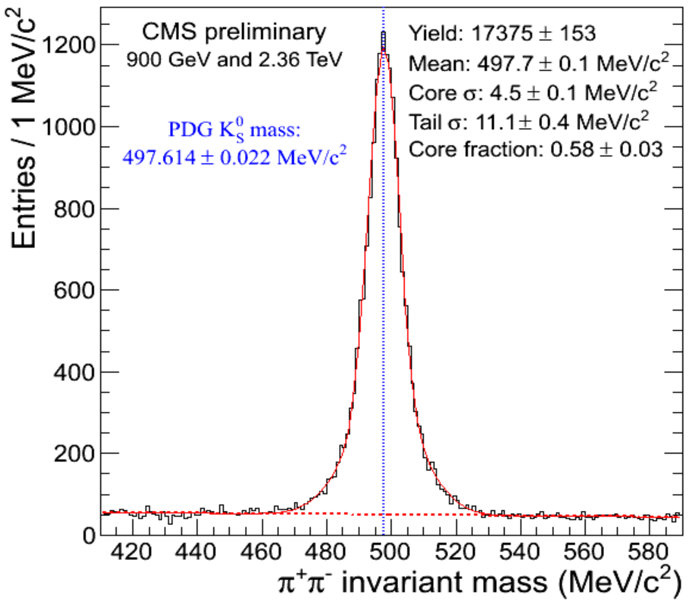


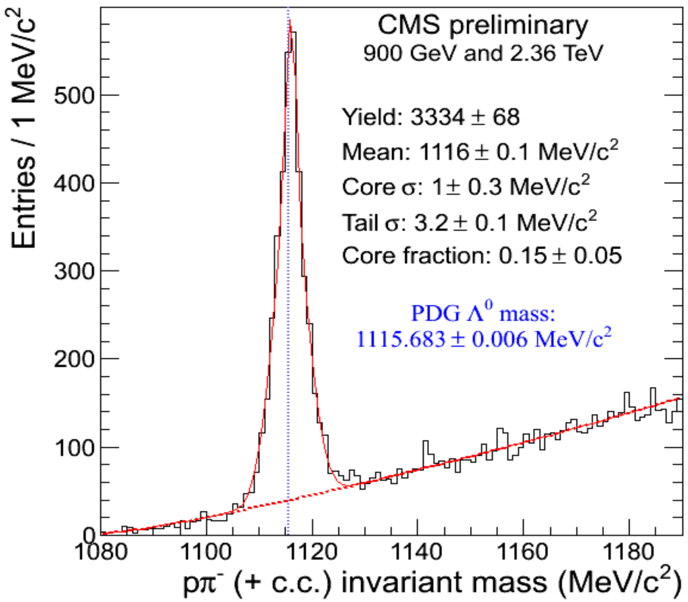


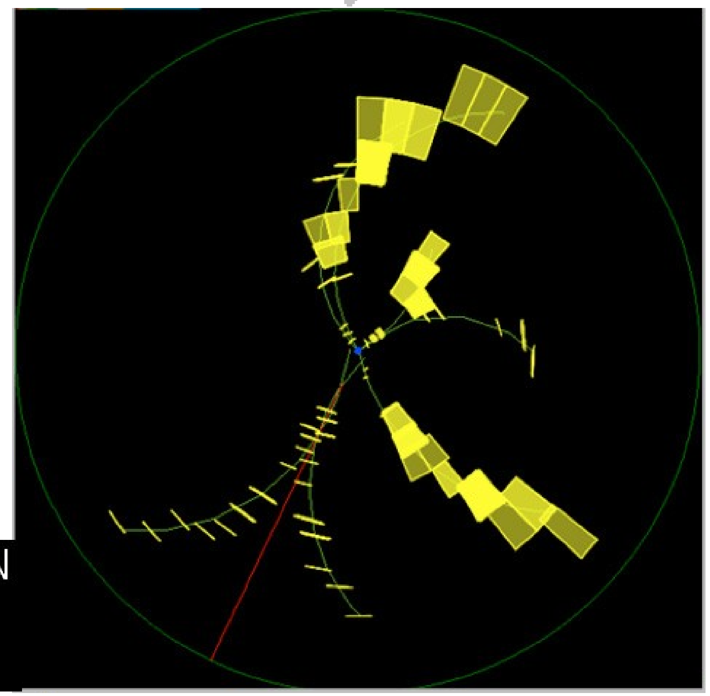
K^0_S and Λ reconstruction

- Two opposite charge tracks compatible with common vertex (V^0)
- Transverse distance from V^0 to beamspot $> 10\sigma$ to avoid fake V^0's composed from the primary vertex tracks



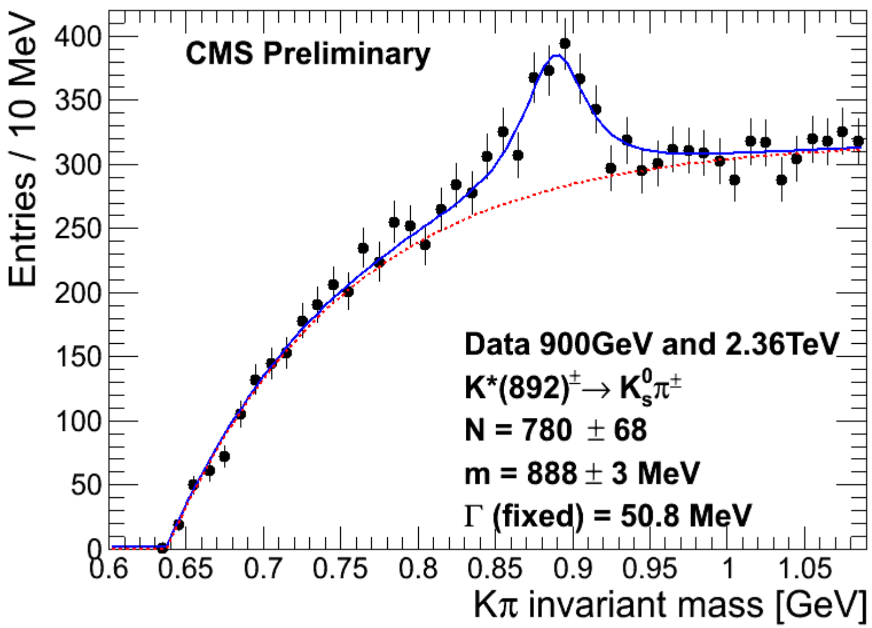




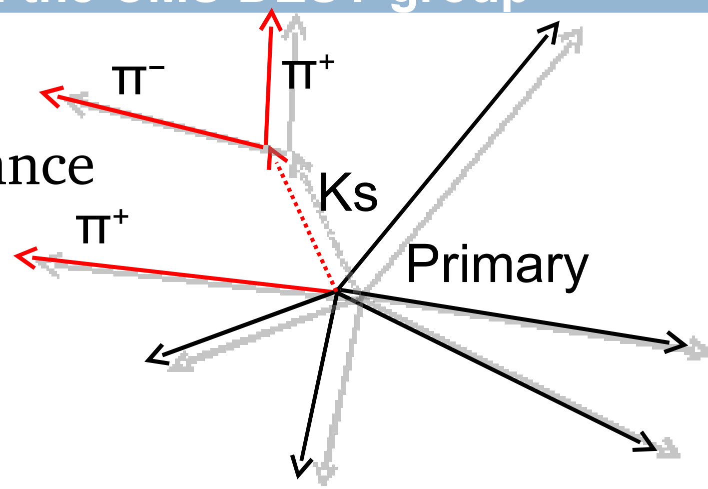


$K^*(892)^\pm$ and $\Xi^\pm$ Signals

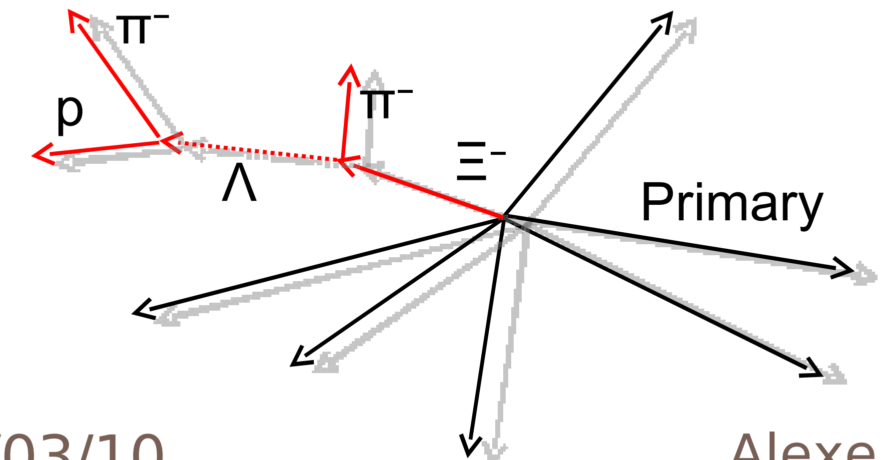
Contribution from the CMS DESY group

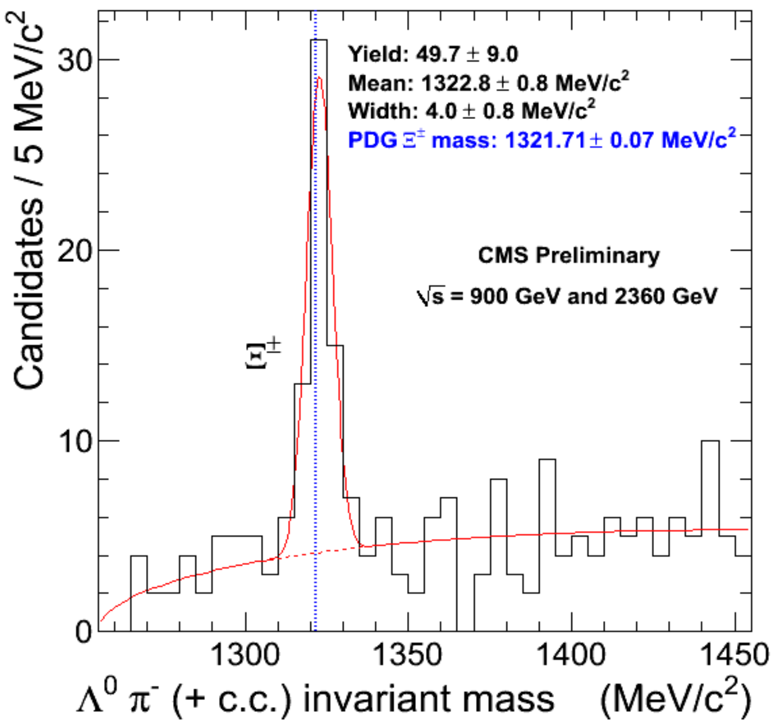


Decay of strong resonance
$K^*(892)^\pm \rightarrow Ks + \pi^\pm$



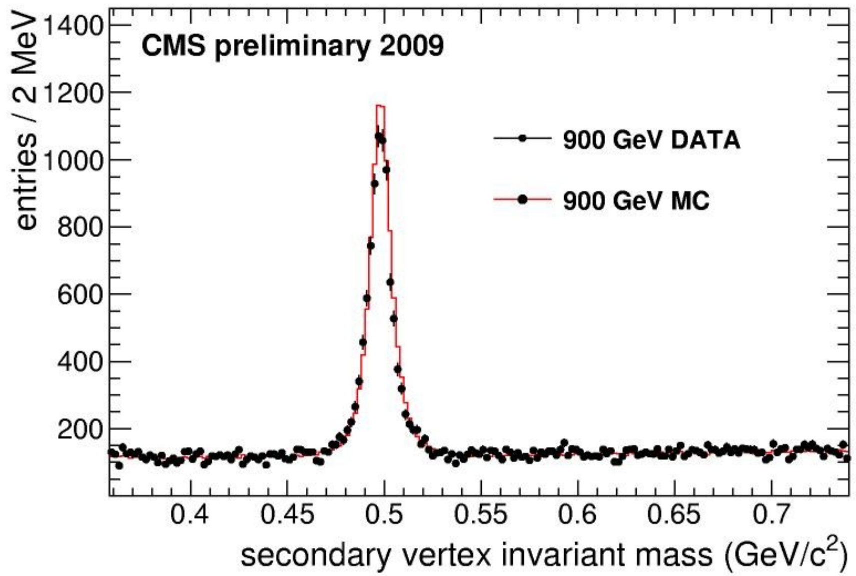
Cascade decay of doubly strange baryon Ξ



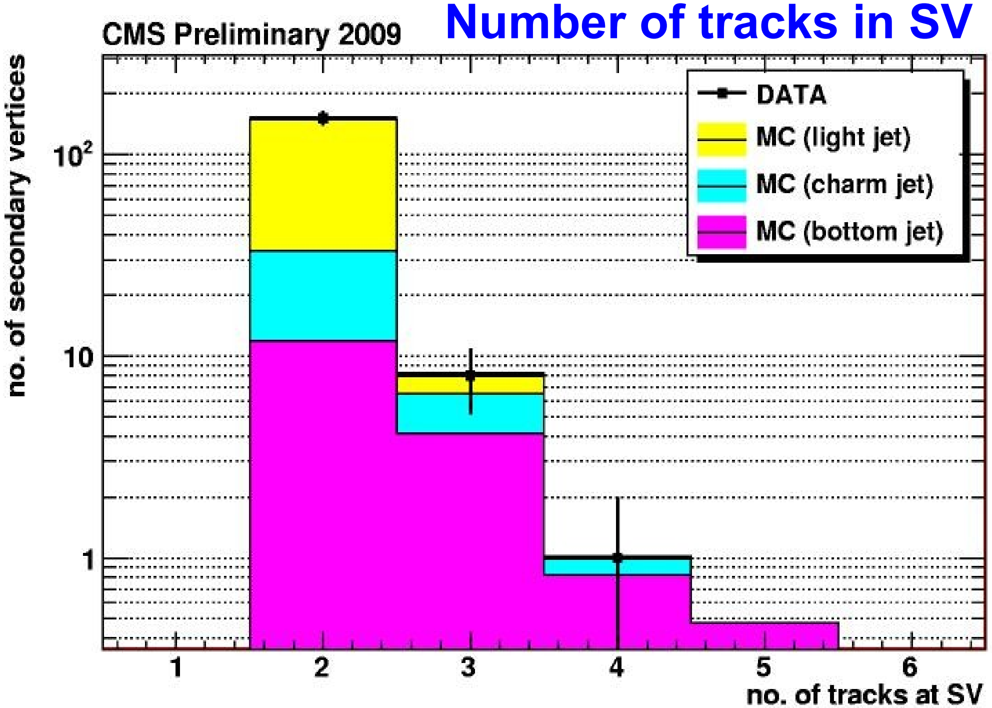


Secondary Vertices (SV) in First Collisions

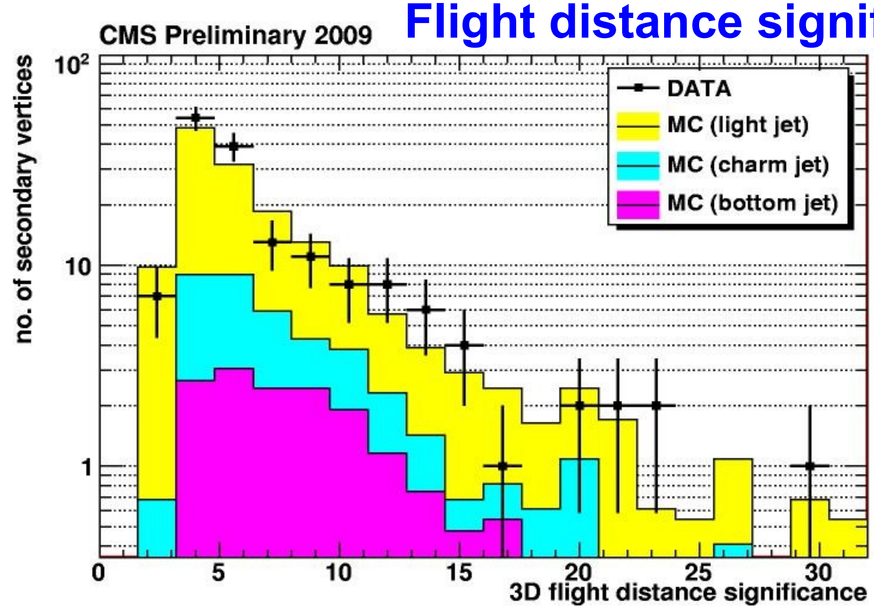
- ***$K^0 s$*** mass peak obtained with relaxed cuts on SV indicates that inclusive SV finding works well for b-tagging
- Tighter selection criteria to reject V0's, nuclear interactions and fakes => nice agreement between data and simulations



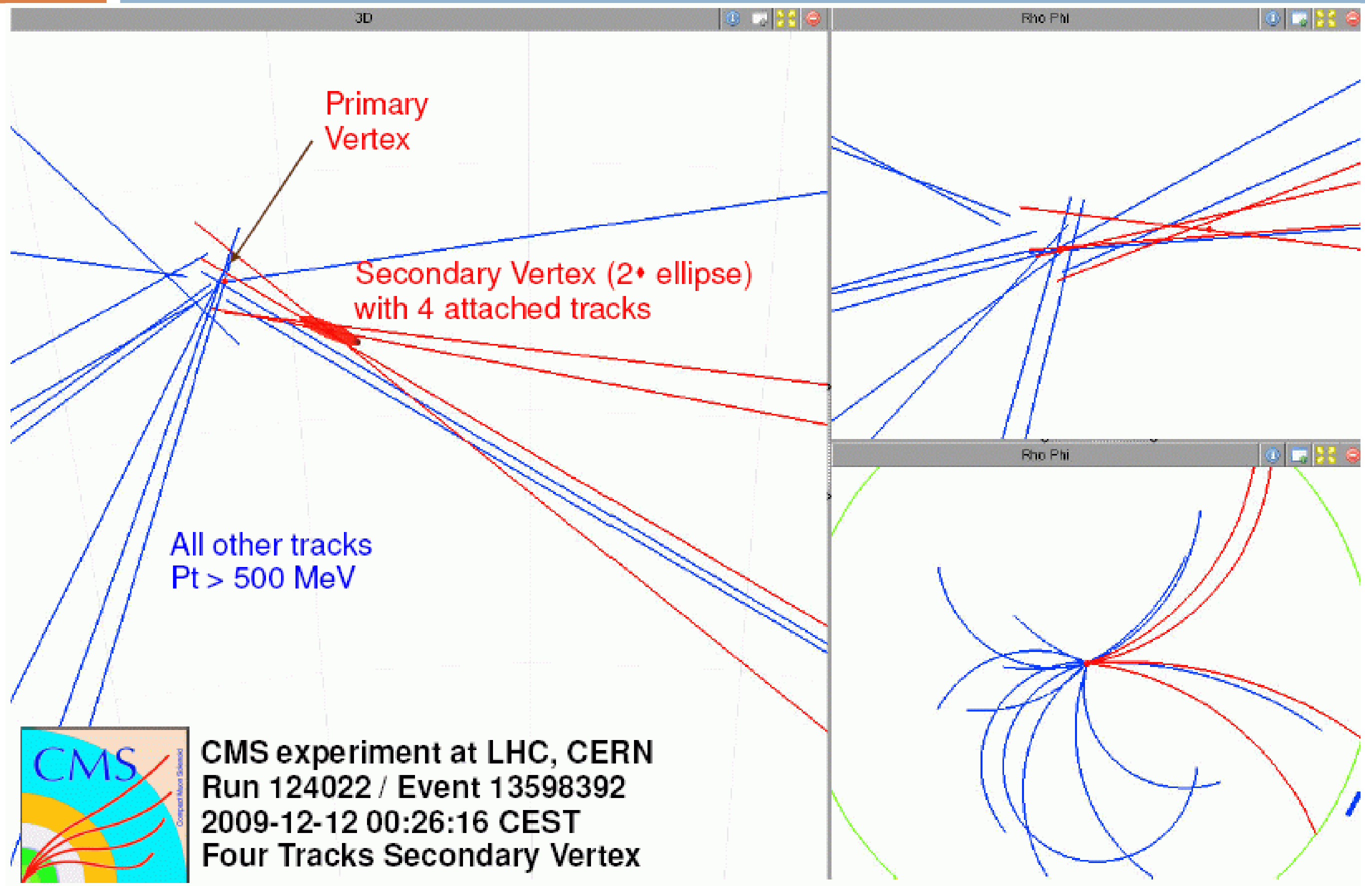
Number of tracks in SV



Flight distance significance



Secondary Vertex Candidate



- Four tracks making the secondary vertex:

pt[GeV]	#pix hits	#hits	χ^2/ndf	dzsig	dxysig	IP3Dsig	σ(IP)
1.11	2	9	16.1/23	-3.94	-0.08	3.82	18μm
1.26	3	9	17.4/19	-3.86	-2.6	4.21	9μm
1.39	3	9	38.6/25	1.47	2.68	2.87	10μm
2.04	3	14	16.5/33	1.72	0.27	1.56	8μm

- **Recorded @ $\sqrt{s}$ = 900 GeV**
- **AntiKt0.7 PF jet**
  - $p_T = 10\ GeV/c$
  - $\eta = -1.42,\ \varphi = 0.20$
- **18 tracks @ primary vertex**
- **Vertex χ^2/ndof = 1.67/5**
- **Vertex mass = 1.64 GeV**
- **L_{xy}/σ = 0.12/0.019 [cm] = 6.6**
- **L3D/σ = 0.26/0.037 [cm] = 7**

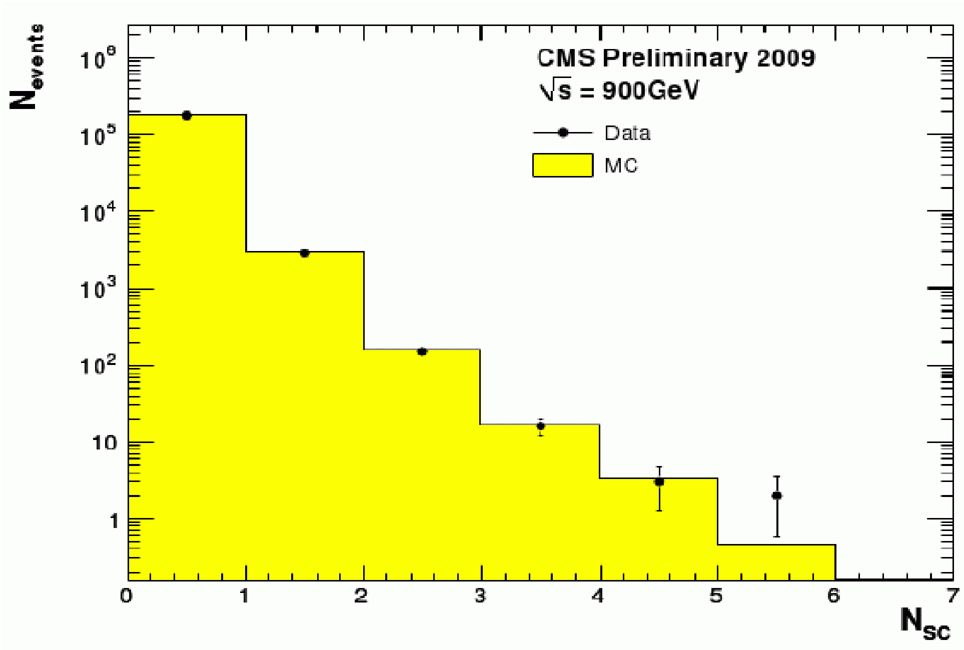
Electromagnetic Objects in First Collisions

- Low luminosity, relaxed quality criteria – most of EM objects due to fakes
- Nonetheless, first collisions verified functioning of algorithms and simulation of detector response : tracker, ECal, Preshower (in front of Endcap)
- Bremsstrahlung, conversions + strong magnetic field ⇨ energy reaching ECal spread in azimuth

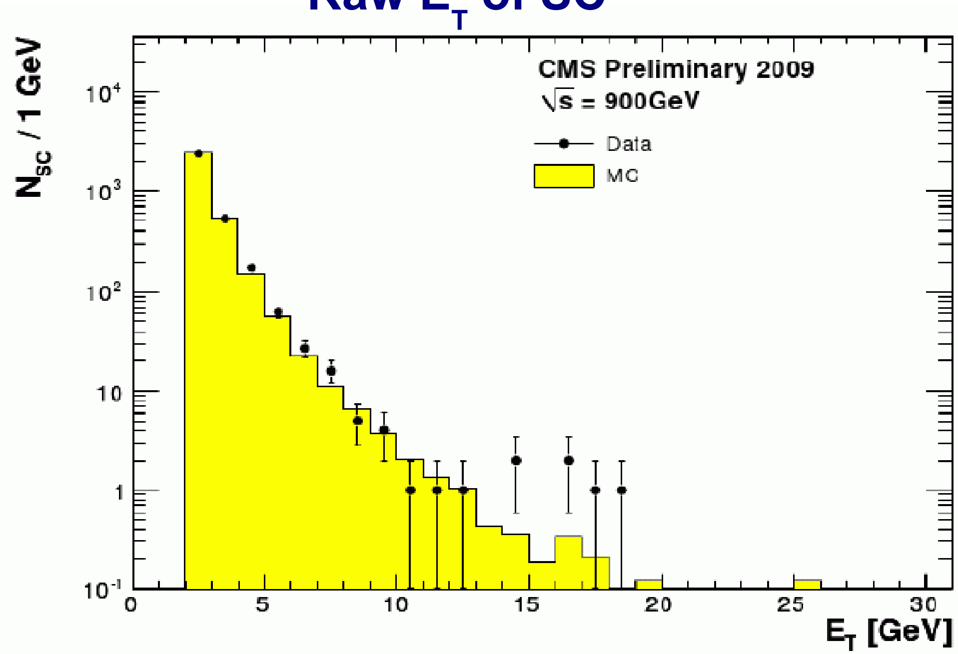
  Concept of Supercluster (SP) : set of clusters extended in ϕ

  - Minimized variations of cluster containment due to electromagnetic interactions in tracker

Number of SC/event

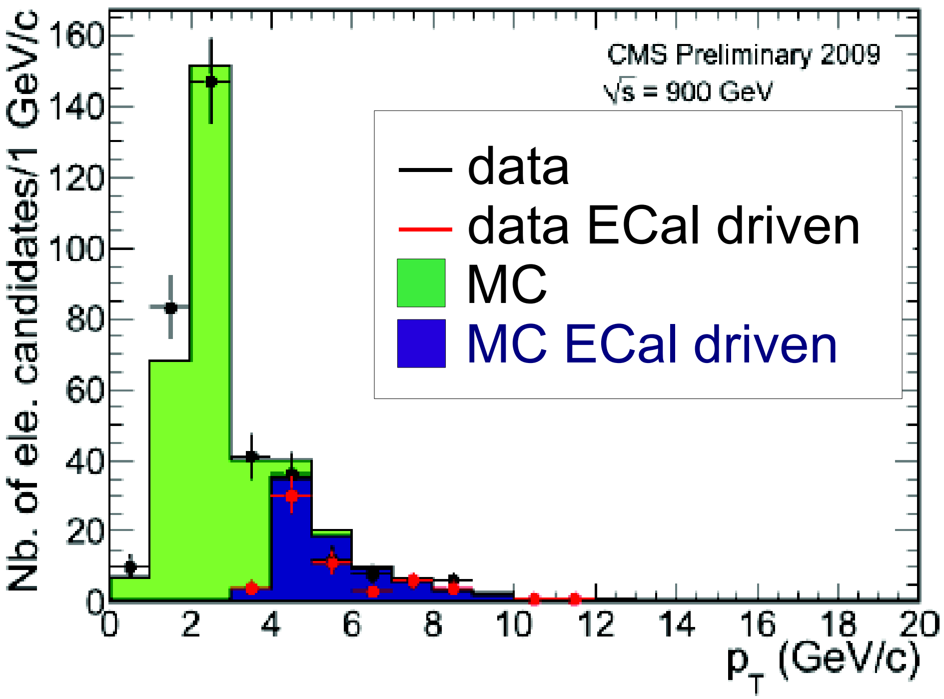


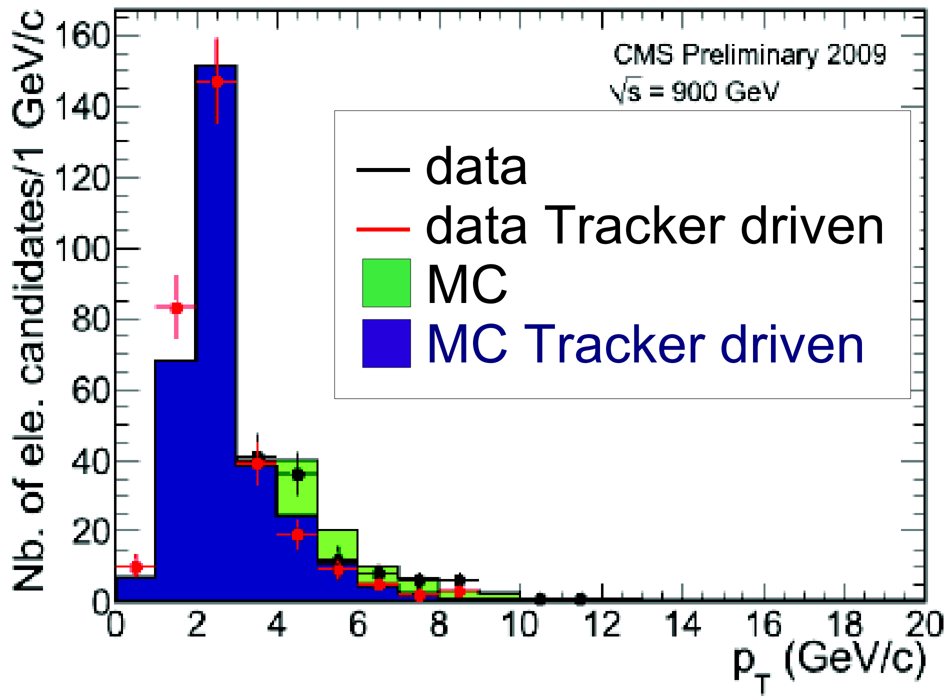
Raw E_T of SC



Electrons in First Collisions

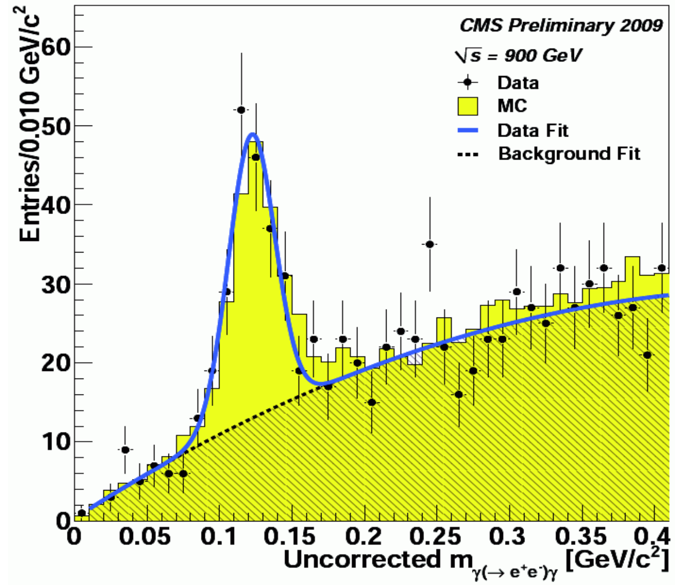
- Main source of electrons in first collisions are conversions (very low p_T)
- Gaussian Sum Fit (GSF) – algorithm for electron track reconstruction – takes into account non-Gaussian energy loss due to bremsstrahlung
  - ECal driven reconstruction – seeded by SC with E_T > 4GeV – optimized for isolated electrons in p_T range elevant for Z and W decays and down to 5 GeV/c
  - Tracker driven reconstruction – pixel seeded – suitable for low p_T electrons (inside jets)

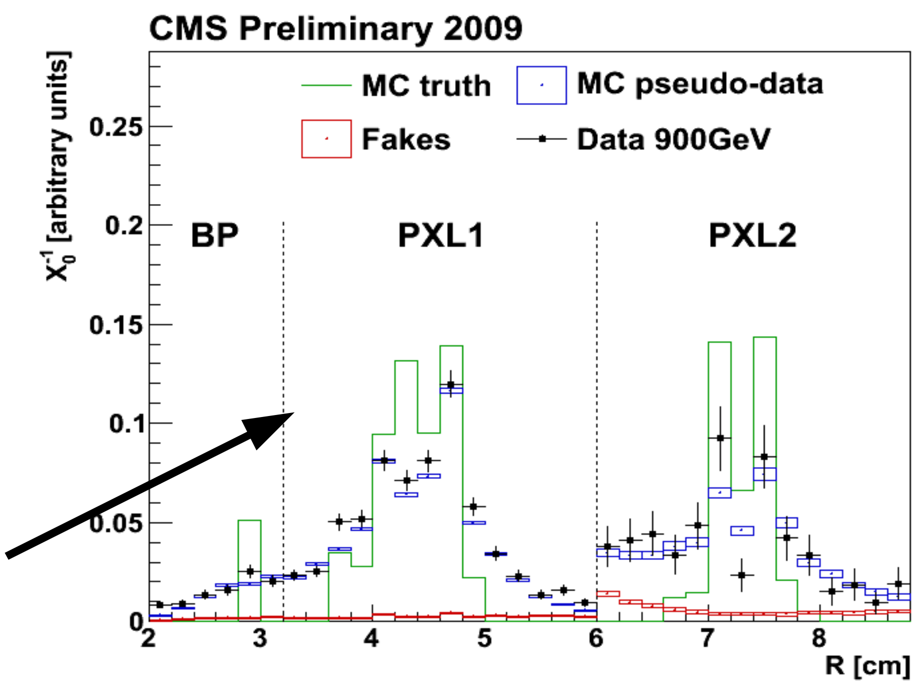




$\pi^0 \to (e^+e^-)\gamma$ Signal and Radiography of the CMS Detector

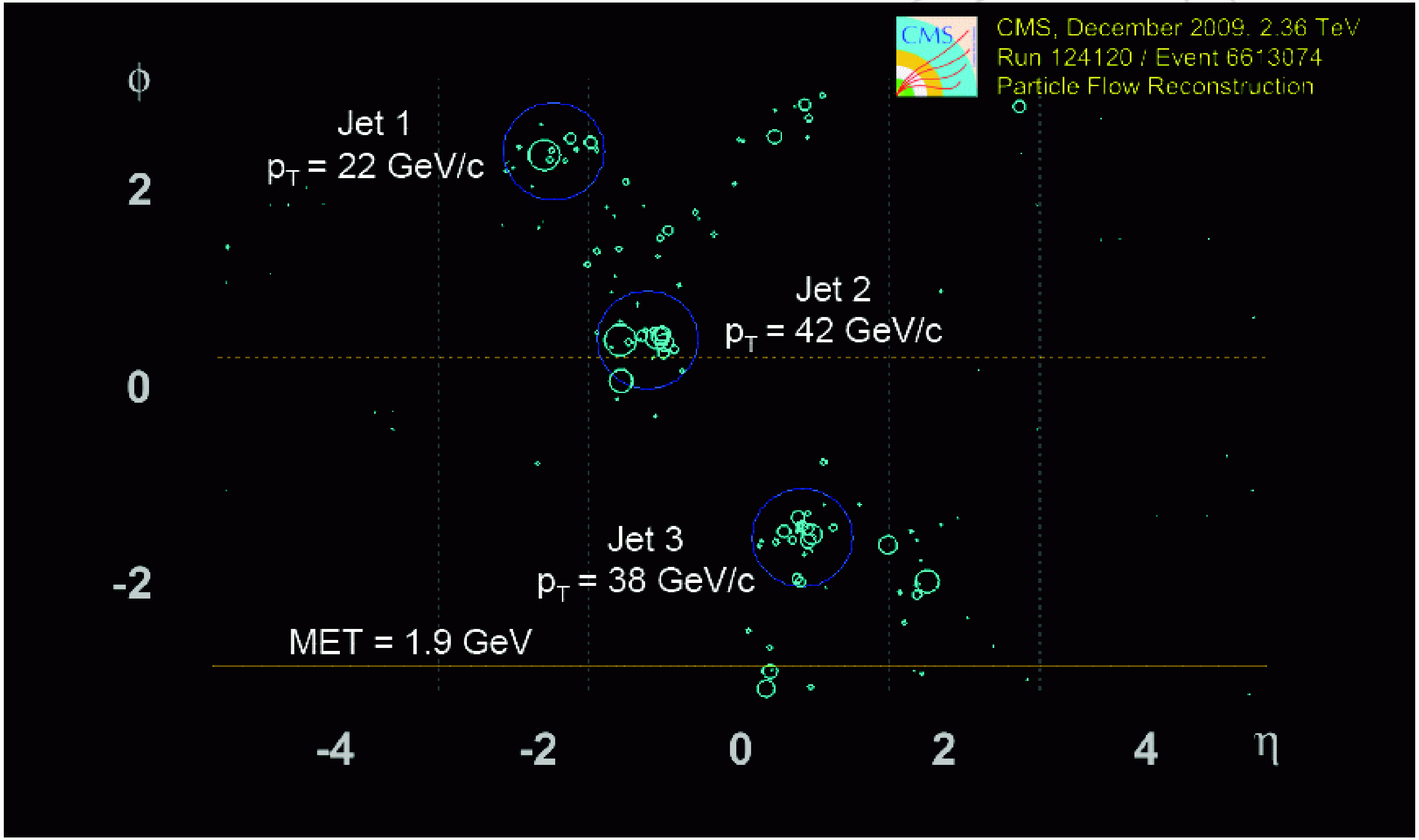
- $\pi^0 \to (e^+e^-)\gamma$, one photon is detected in ECal, another is reconstructed as conversion
- Conversions :
  - 2 opposite charge tracks compatible with common vertex
  - parallel at vertex position
- Photons :
  - ECal cluster in barrel, $E_T > 300$MeV
  - No HCal activity behind ECal cluster
  - Primary vertex and ECal cluster position define photon momentum vector
- $P_T(\pi^0) > 1.2$ GeV/c
- Nice example of complementary performance of the CMS sub-detectors (ECal + tracker)
- Conversions ⇒ radiography of CMS detector study of material budget distribution





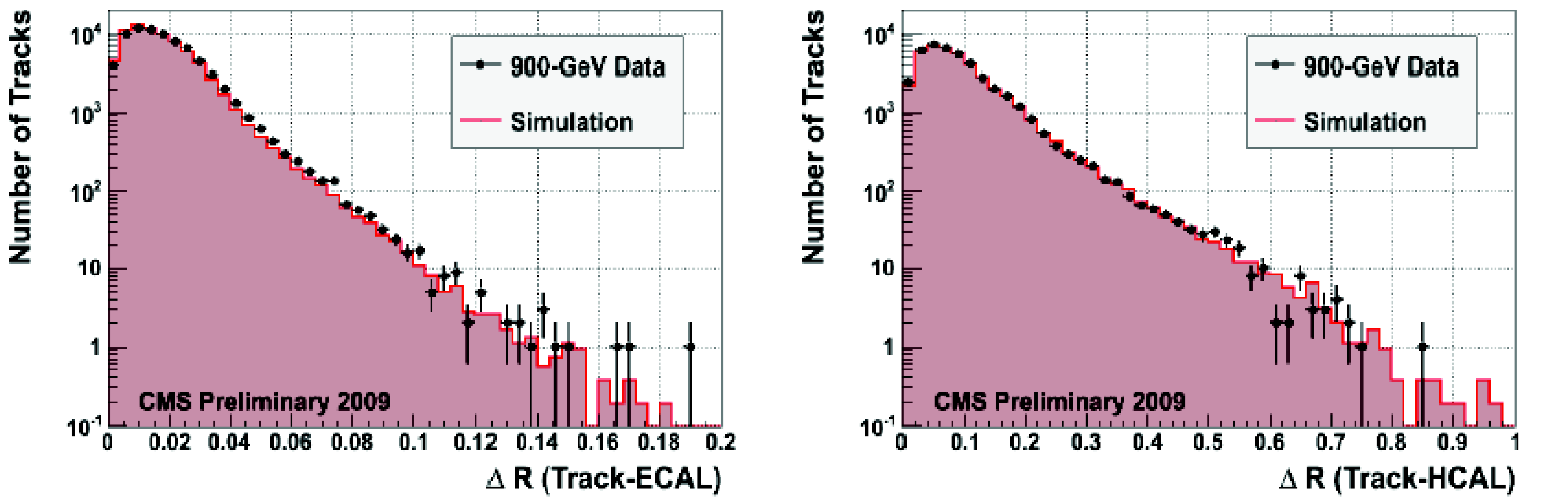
Particle Flow Commissioning

- Particle Flow concept : reconstruction of individual particles based on complementary information from all sub-detectors



Particle Flow Commissioning

- Particle Flow provides most accurate jet and measurement
- Charged hadrons (≈65% of jet energy) [track+Ecal+HCal] : measured with tracker
- Photons (≈20% of jet energy) [ECal or tracks+ECal for conversions] : measured with ECal or tracker for conversions
- Neutral hadrons (≈15%) [ECal+HCal] : measured with calorimeters
- Efficient track-cluster association is prerequisite to avoid double-counting of energy!



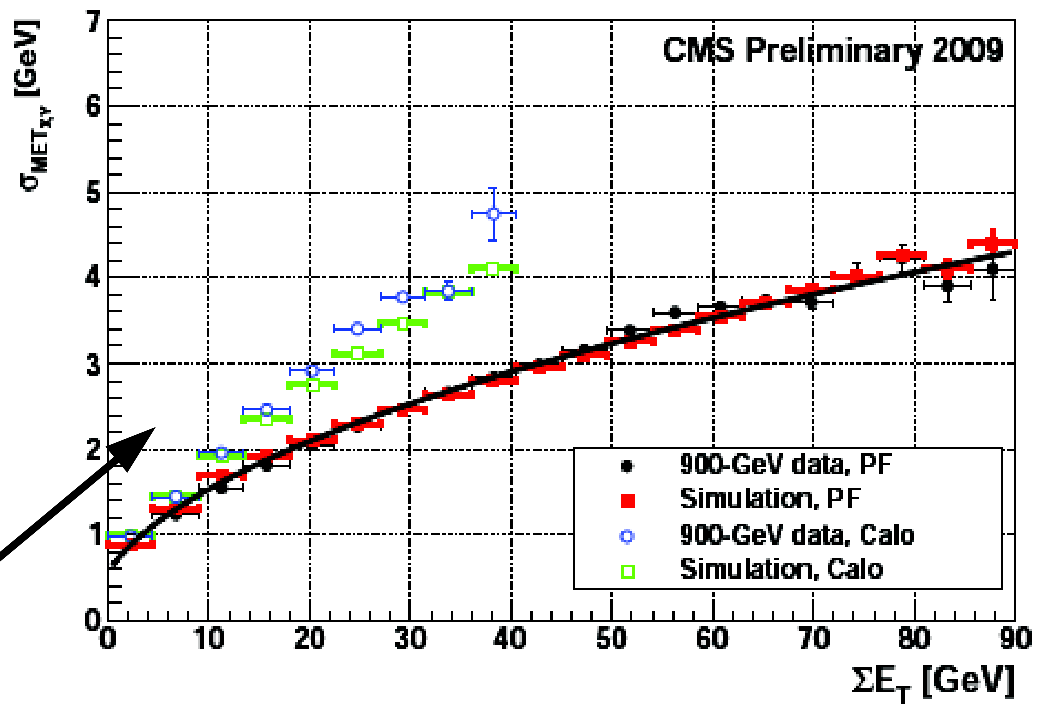
Agreement with simulation validates track cluster link efficiency, alignment between tracker and calorimeters and energy sharing between Ecal and HCal!

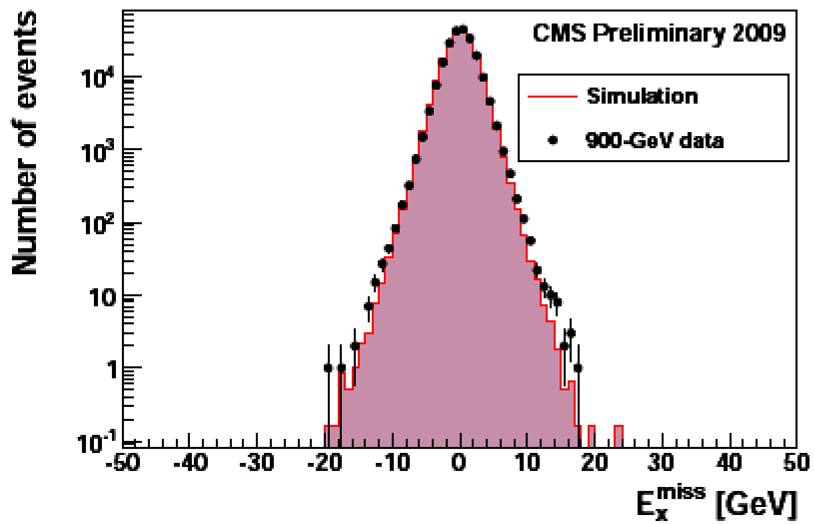
Missing E_T with Particle Flow

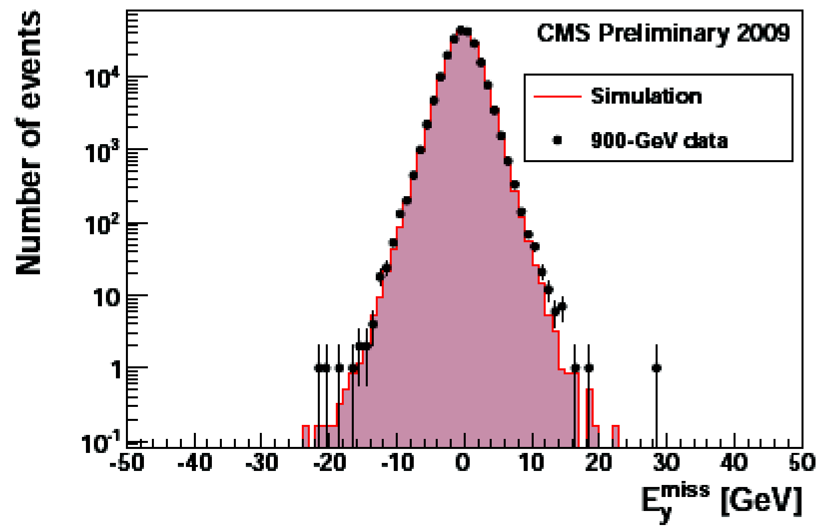
- Minimal bias events : small E_T^{miss} is expected
  - ideal sample for testing resolution on E_T^{miss}
- Resolution is studied with the E_x^{miss} and E_y^{miss} distributions
- Parameterized as function of $\sum E_T$

$$\sigma(E_{x,y}^{miss}) = a \oplus b\sqrt{\sum E_T}$$

- Considerable improvement compared to calorimeter based E_T^{miss} reconstruction



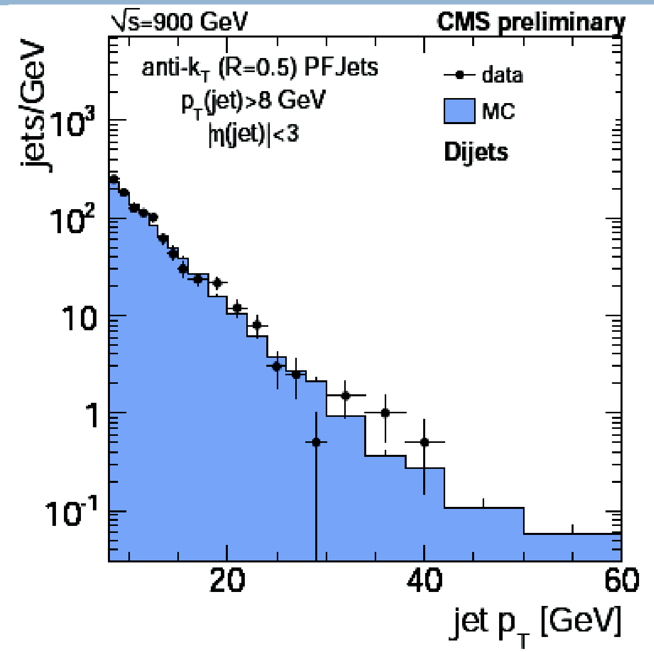


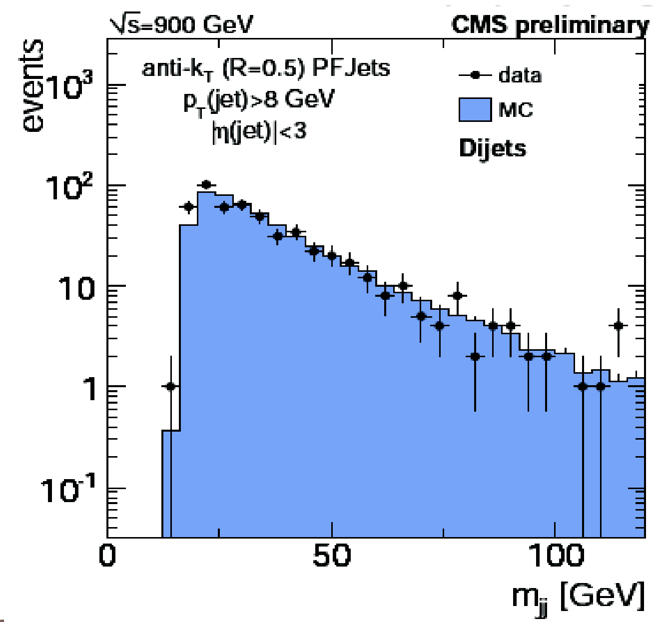


Di-Jets in First Collisions

- Di-jets : two leading jets
  - balanced in p_T
  - Back-to-back
- Clean sample dominated by real jets
  - Fakes are unlikely to have balancing counter-part
  - Loose jet ID compared to inclusive jet sample can be used to enhance statistics

⇒ Selected sample tests :
  - jet modeling in Monte Carlo
  - jet reconstruction procedure
  - relative jet calibration (p_T balance of jets w.r.t. control central region ⇒ flattened response in η)
- Types of jets studied
  - Calorimeter jets
  - Track corrected jets
  - Particle Flow jets

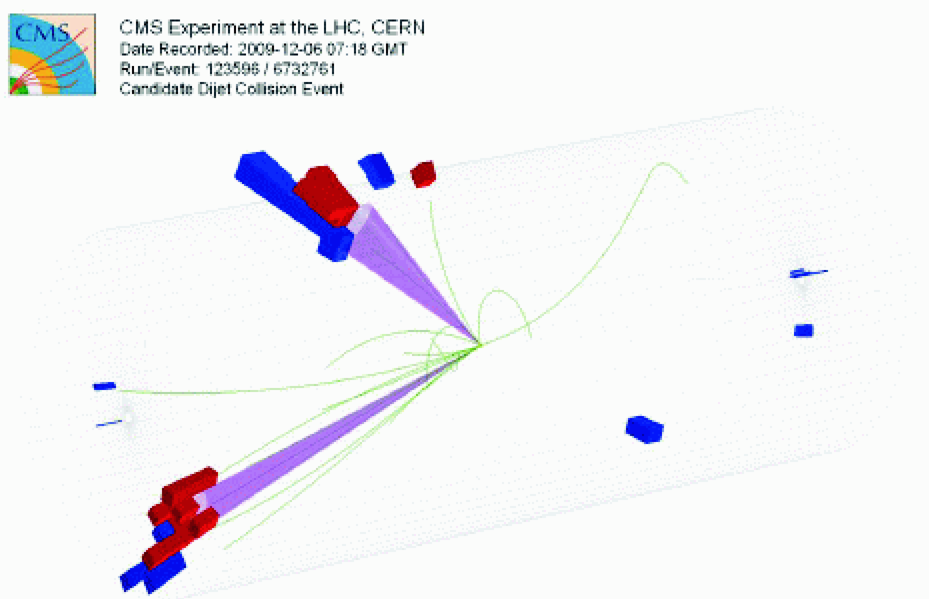


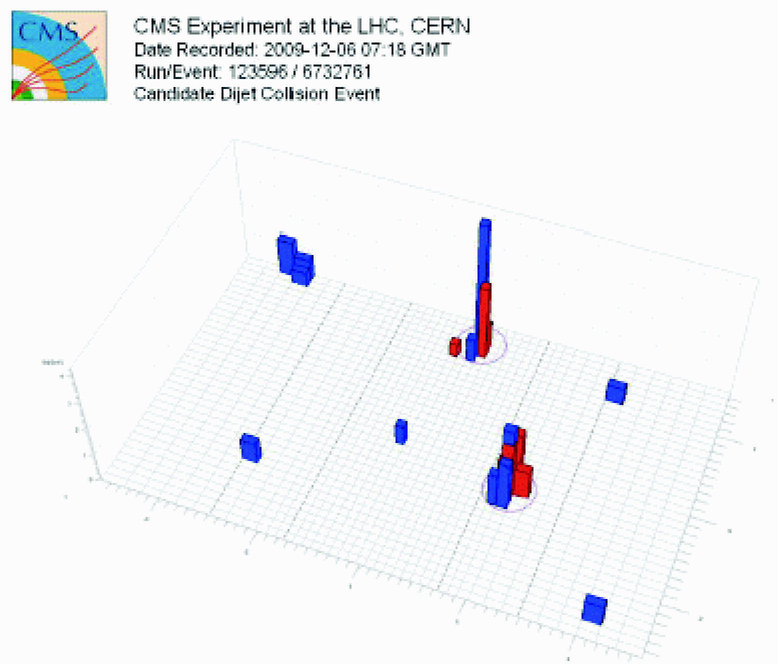


Candidate Di-jet Event

Anti-K_T algorithm with cone size R=0.7

	Jet 1	Jet 2
Corrected p_T (GeV)	24	26
η	0.3	2.0
ϕ	2.5	-0.7
EM Energy Fraction	0.5	0.6

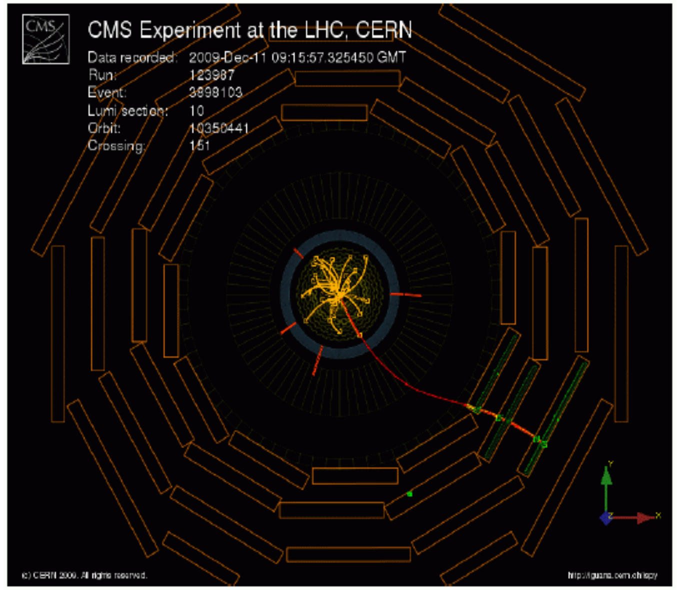


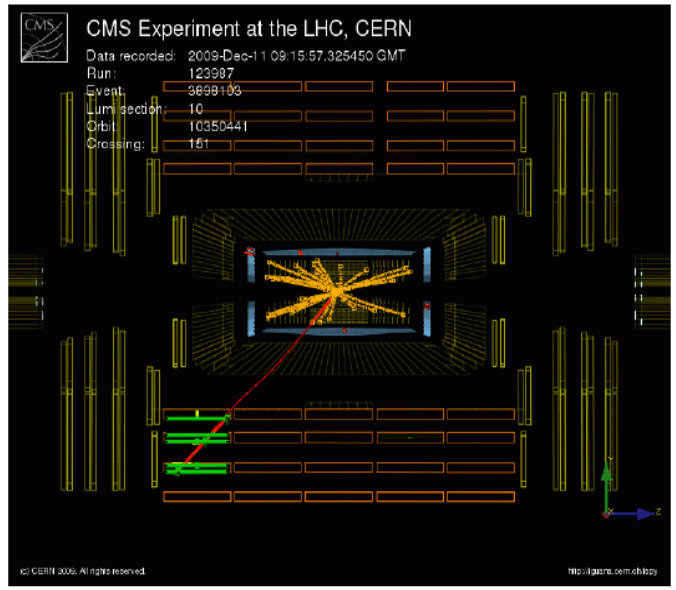


Muons in the CMS Detector

- Compact **Muon** Solenoid – detector is particularly efficient in muon reconstruction : muons are expected to be the best understood high-level objects
- Global muons are of primary interest
  - Relevant for *W*- *Z*- decays, as well as leptonic decays of the heavy flavour hadrons in jets (crucial for b-tagging)
  - Constituents:
    - Standalone muon – track reconstructed in the muon system
    - Matched to the track in the inner tracker
    - Calorimeter signal compatible with MIP
- Main source of muons in the first collisions
  - on-flight decays of $K^{\pm}$ and $\pi^{\pm}$
  - Cosmics in-time with collisions (but tracks are likely displaced from primary vertex)

Barrel muon candidate





Dimuons in First Collisions

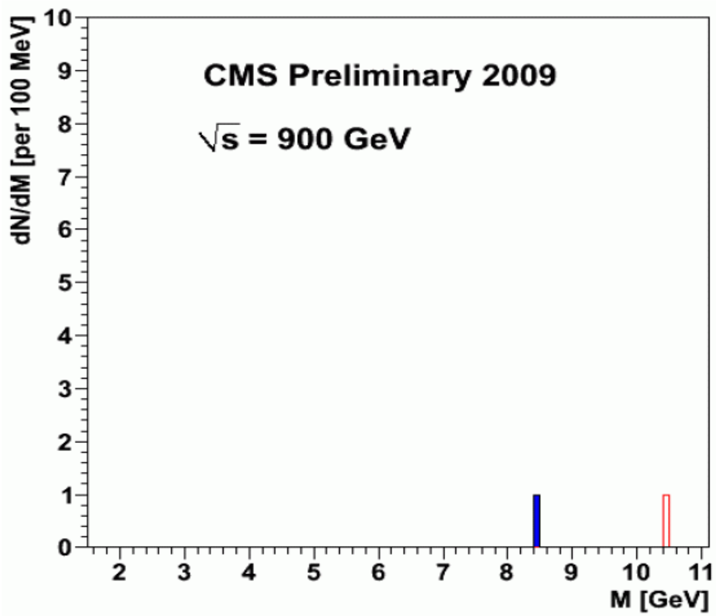
- Expectation of dimuon events in the first collisions
  - Global muons alone 2 GeV < $m_{\mu\mu}$ < 4 GeV
    - 0.07 dimuons @ 900 GeV
    - 0.01 dimuons @ 2.36 TeV
- Considering only global muons, S/B in the mass window 3.0-3.2 GeV is 14/1
- If we see opposite sign muon pair with 3.0 GeV < $m_{\mu\mu}$ < 3.2 GeV it is likely to be J/Ψ candidate rather than background muon pair

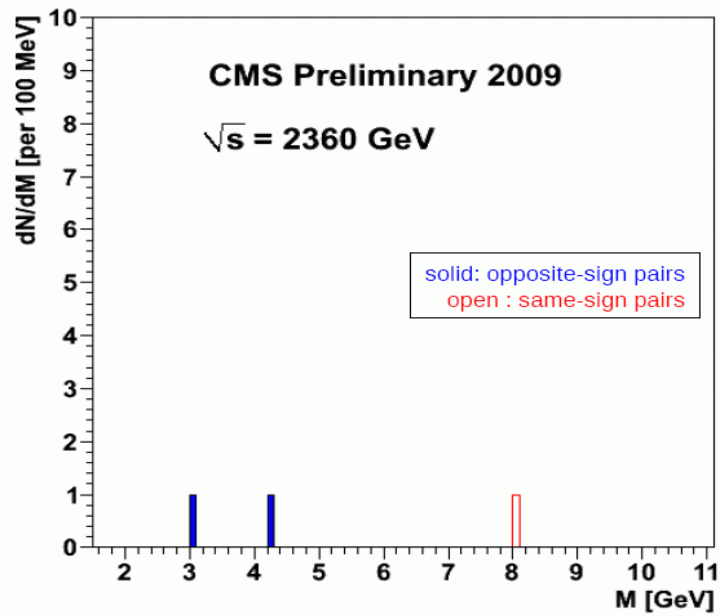
Three opposite sign muon pairs are observed after dedicated selection

One dimuon has mass 3.04 GeV

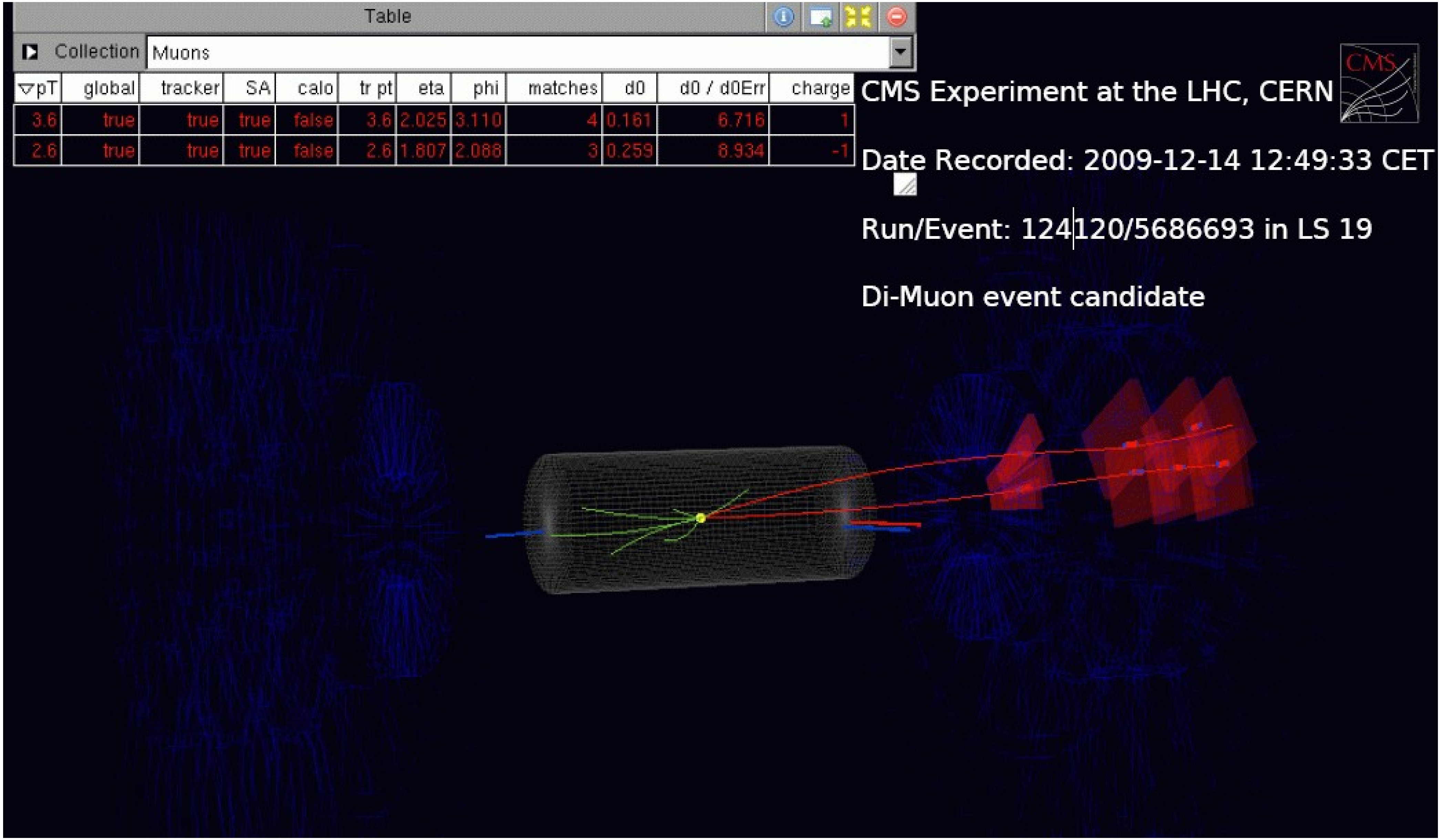
Vertex fit probability = 57%

first muon : global muon, χ^2/ndf= 0.97
second muon : global muon, χ^2/ndf= 0.46





J/Ψ Candidate



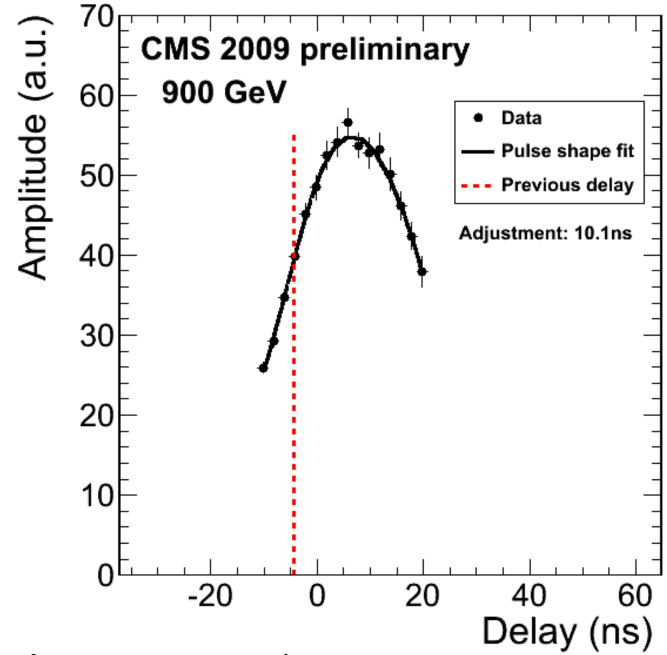
Summary

- First collision data have been collected by CMS in the fall 2009
- These data are of utmost value, allowing for:
  - Initial studies of underlying event (first CMS publication with collision data)
  - Commissioning of physics objects and reconstruction algorithms
  - Monte Carlo tuning
  - Detector calibration
- CMS detector and software are in excellent shape
- Surprisingly good agreement between data and simulation is observed ⇒ efforts invested in development of the full detector simulation software pay back
- Looking forward to first data @ 7 TeV and preparing for **electroweak** and **top physics** commissioning!

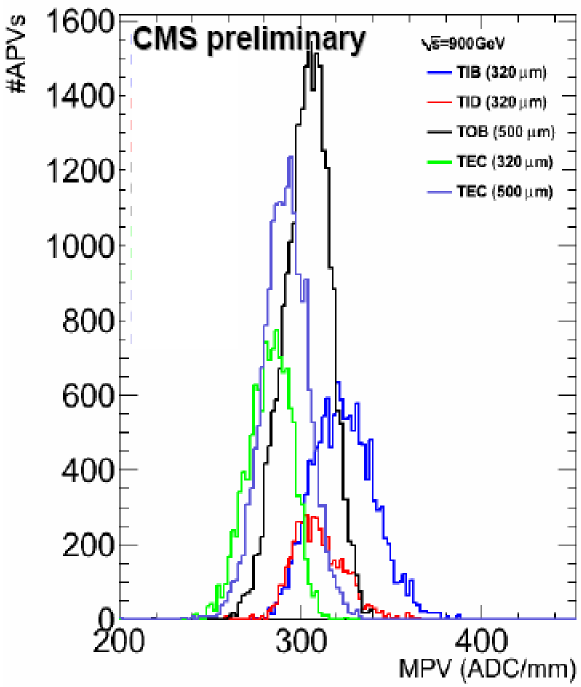
Backup slides

Silicon Strip Tracker

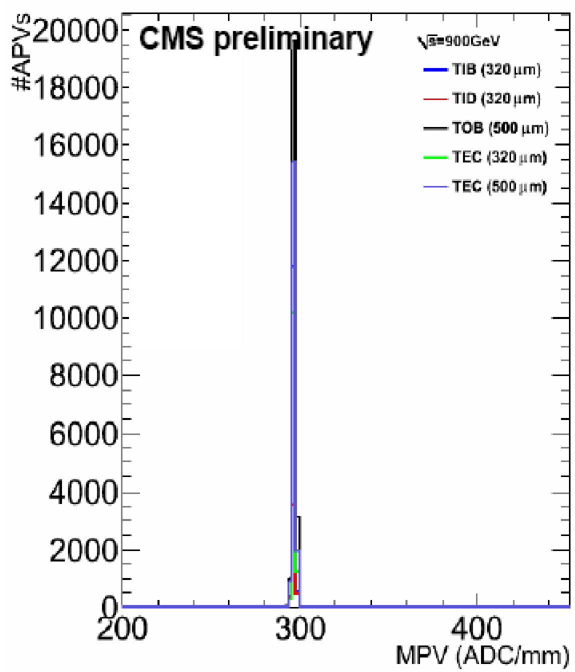
- Time delay scan to determine maximum charge collection
- Sensor efficiency measured with reconstructed tracks
  - >99.9% excluding known bad modules
- Cluster Signal/Noise ratios measured
  - High (19-24) and in agreement with expectation



Before Calibration



After Calibration



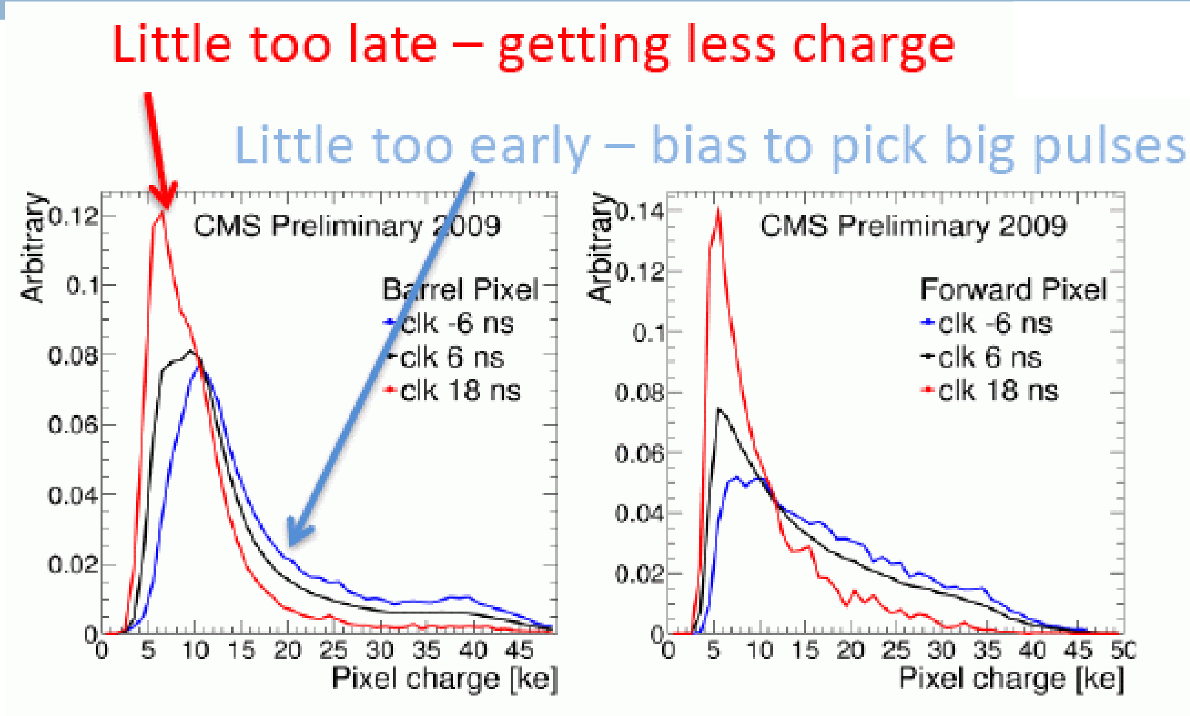
- Calibration procedure
  - For every module: fit normalized cluster charge distribution by Landau (use only tracks with pT>1GeV and at least 8 hits)

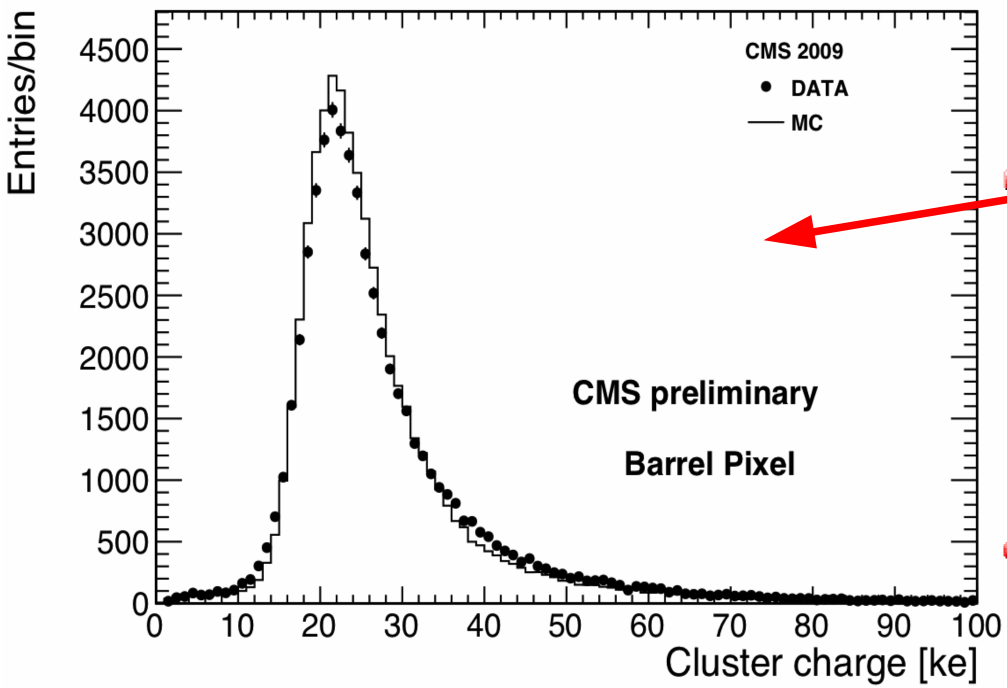
    Extract MPV from the fit and compute the gain : G = MPV/300

    Conversion factor (ADC/mm ⇒ MeV/cm) from cosmic data

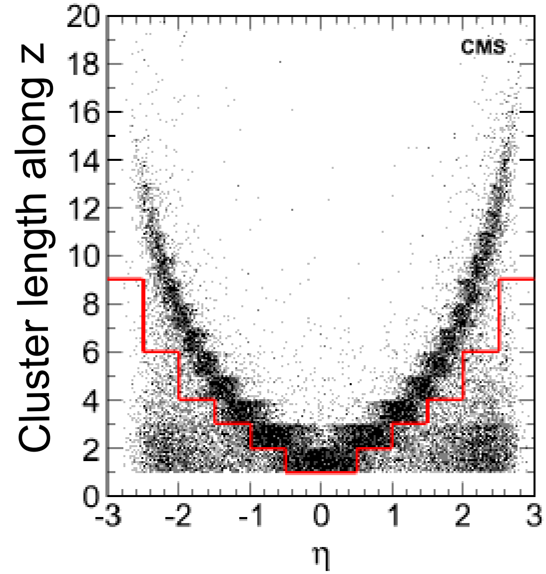
Silicon Pixel Detector

- Charge collection must be synchronized with bunch crossings
  - Pixel charge sampled @ 25 ns
- Timing scan
  - Optimize signal shape
  - Avoid biased selection



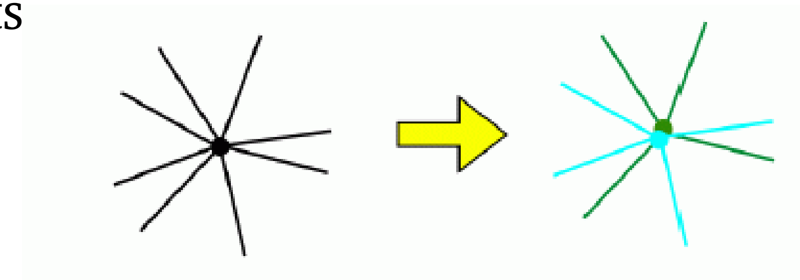


- Charge corrected for track incident angle
  - clusters above red line are likely from IP; below – background
- Good agreement with simulation

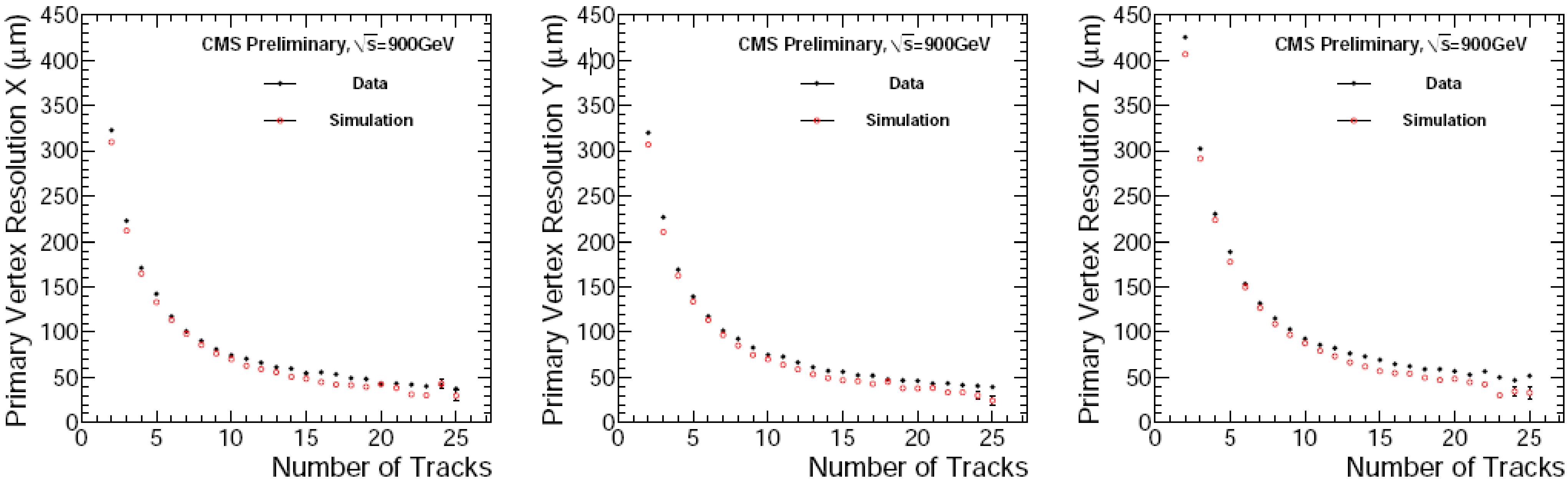


Primary Vertex Resolution

- Data-driven “two-vertex” method to measure PV resolution
  1) Split tracks belonging to PV into two independent sets
  2) Reconstruct vertex separately for each set
  3) Compare two fitted vertices and compute
     - Resolution : σ of Gaussian fit to $\frac{x_1 - x_2}{\sqrt{2}}$



Resolution as function of number of tracks



B-Tagging Related Variables

- Very limited # of b-jets in first collisions (Anti-K_T algorithm with cone size=0.7 is used)
  - Few well-defined jets/tracks with momenta appropriate for b-tagging @ high √s

    Impact parameters and secondary vertices are mainly studied to understand bkgd and fakes
- 3-dimensional impact parameter:
  - First track above charm : 4-vector sum is updated by adding tracks in decreasing order of 3D IP Significance (pion mass hypothesis is assumed) until invariant mass ⩾1.5GeV