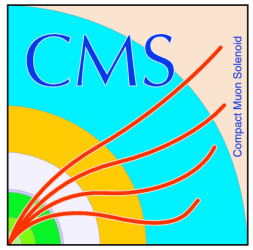
Status of the CMS Experiment
&
First Results

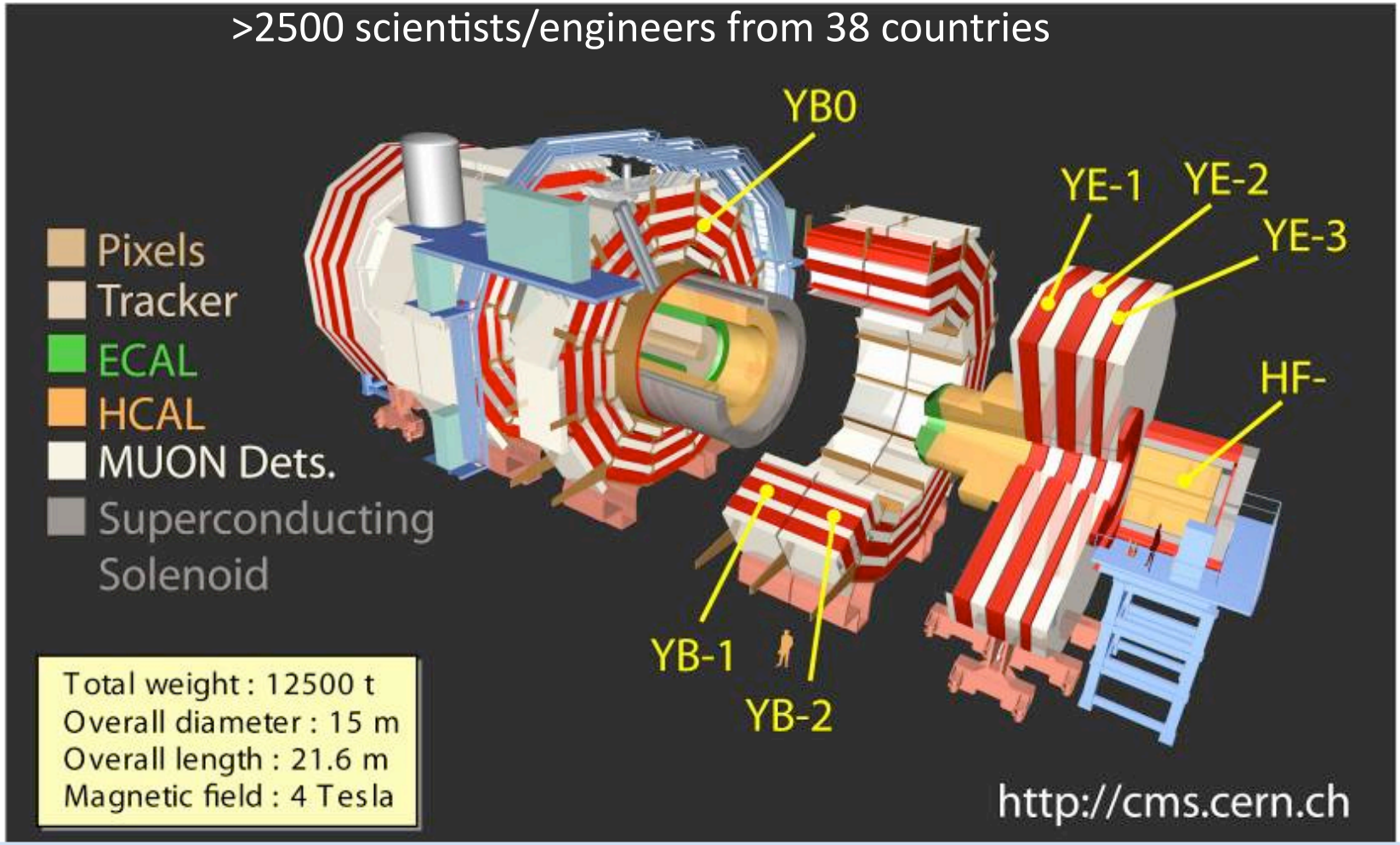


Tulika Bose
(Boston University)

On behalf of the CMS Collaboration

LHC@BNL
Brookhaven National Laboratory
February 8th, 2010

The CMS Detector



CMS comprises 66M pixel channels, ~10M Si microstrip ch, ~75k crystals, 150k Si preshower ch, ~15k HCAL ch, 250 DT chambers (170k wires), 450 CSC chambers (~200k wires), ~ 500 Barrel RPCs and ~ 400 endcap RPCs, muon and calorimeter trigger system, 50 kHz DAQ system (~ 10k CPU cores), Grid Computing (~ 50 k cores), offline (> 2M lines of source code).

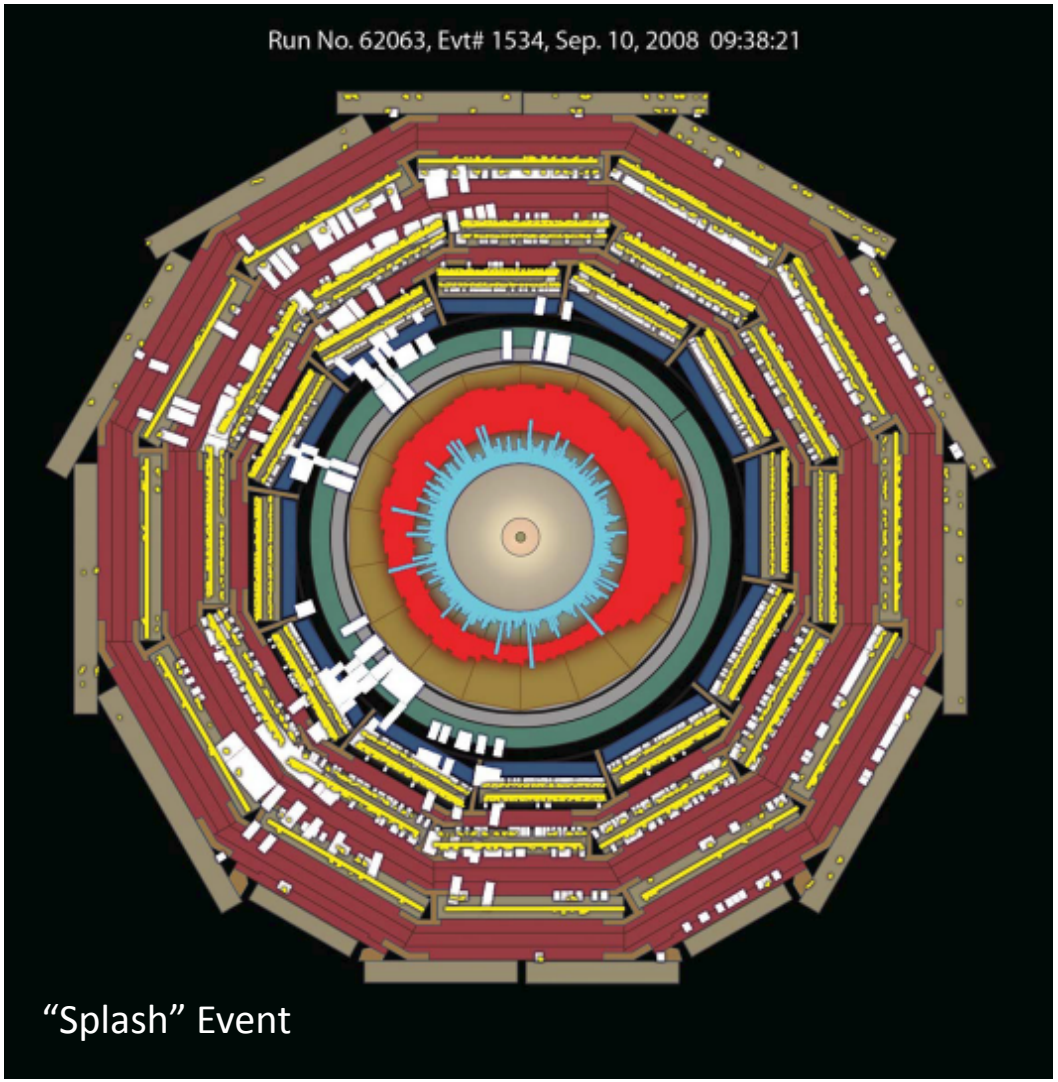
Closure of CMS prior to Beam in 2008

After almost 20 years, from conception, design, construction and commissioning CMS became a working experiment in September 2008

First LHC Beam in 2008

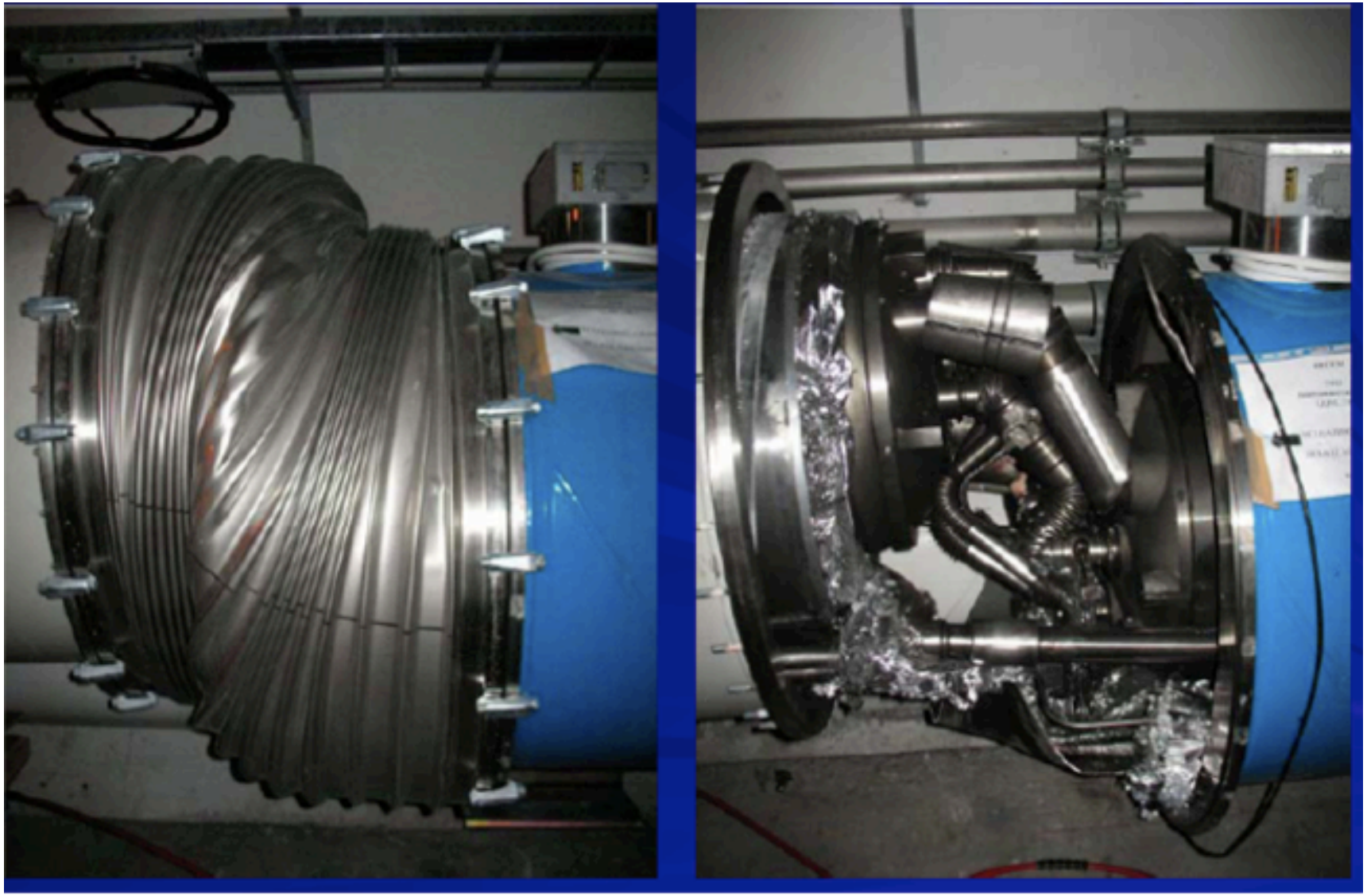
Data-taking with LHC beam.

- **Wed, 10 Sept. 2008**
  - "Splash" events observed when beam (450 GeV, 4×10^9 p) struck collimators 150m upstream of CMS
  - Halo muons observed once beam (uncaptured and captured) started passing through CMS



"Splash" Event

The Sep. 19th incident



CRAFT

The September 19th incident was followed by Cosmics Runs at Operating Field (Oct '08, Aug '09)

CRAFT*: Cosmics Run at Four Tesla

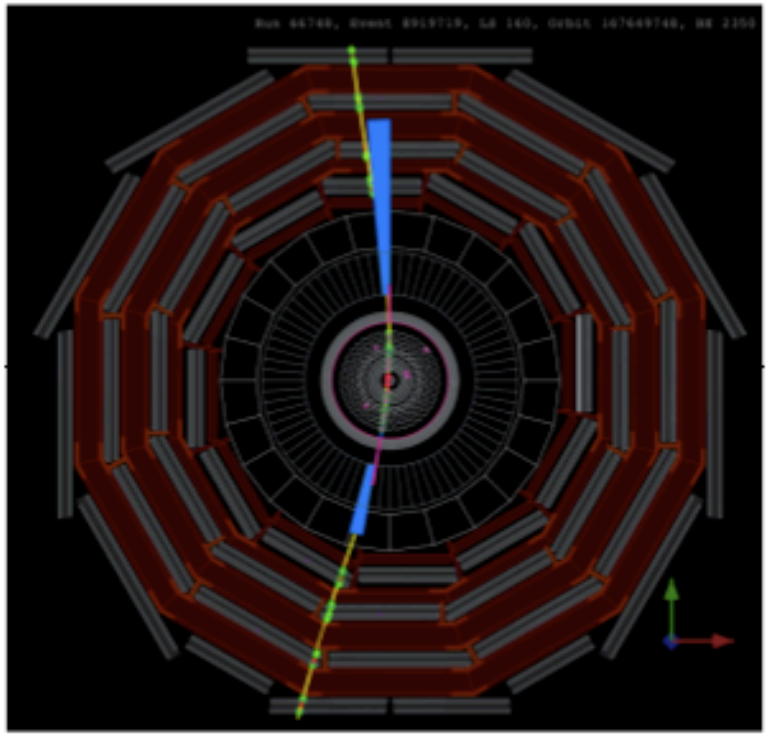
* Operating field of CMS is 3.8T

Wealth of data collected – for ascertaining health and performance of detector, detector cleanup studies (e.g. for alignment - equivalent to >10 pb^{-1}!)

23 papers submitted to JINST
(17 papers already accepted)

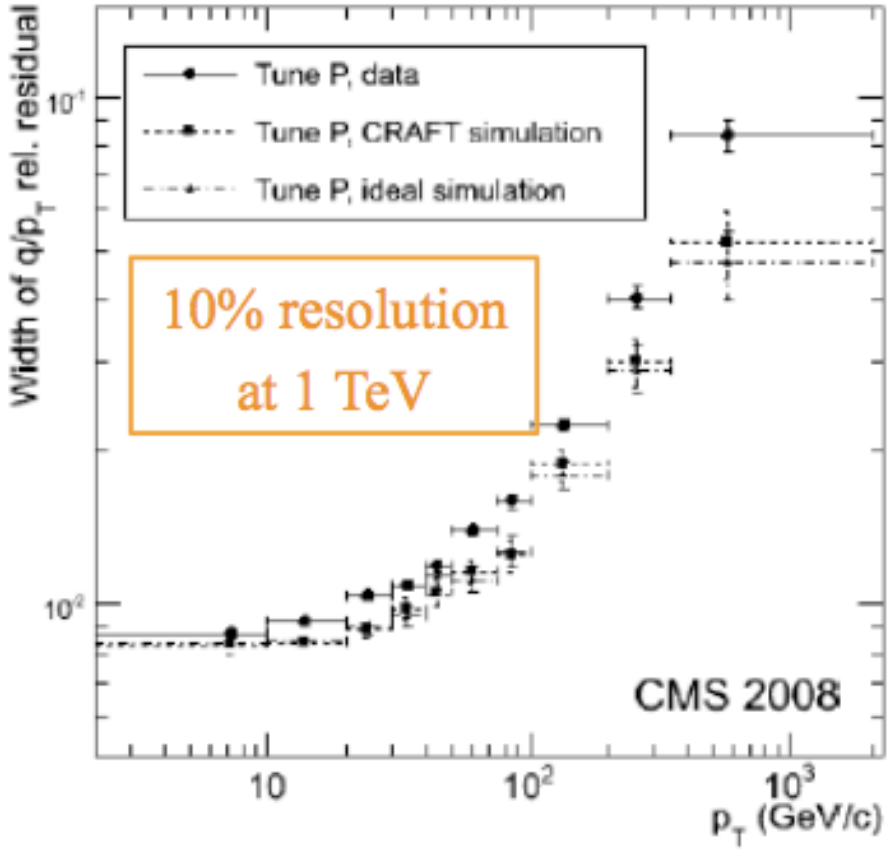
Extensive documentation of detector performance
Feedback into realistic simulation

Muon p_T resolution (cosmics)



$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}}$$

Compare muon p_T in upper, lower detector halves to evaluate resolution



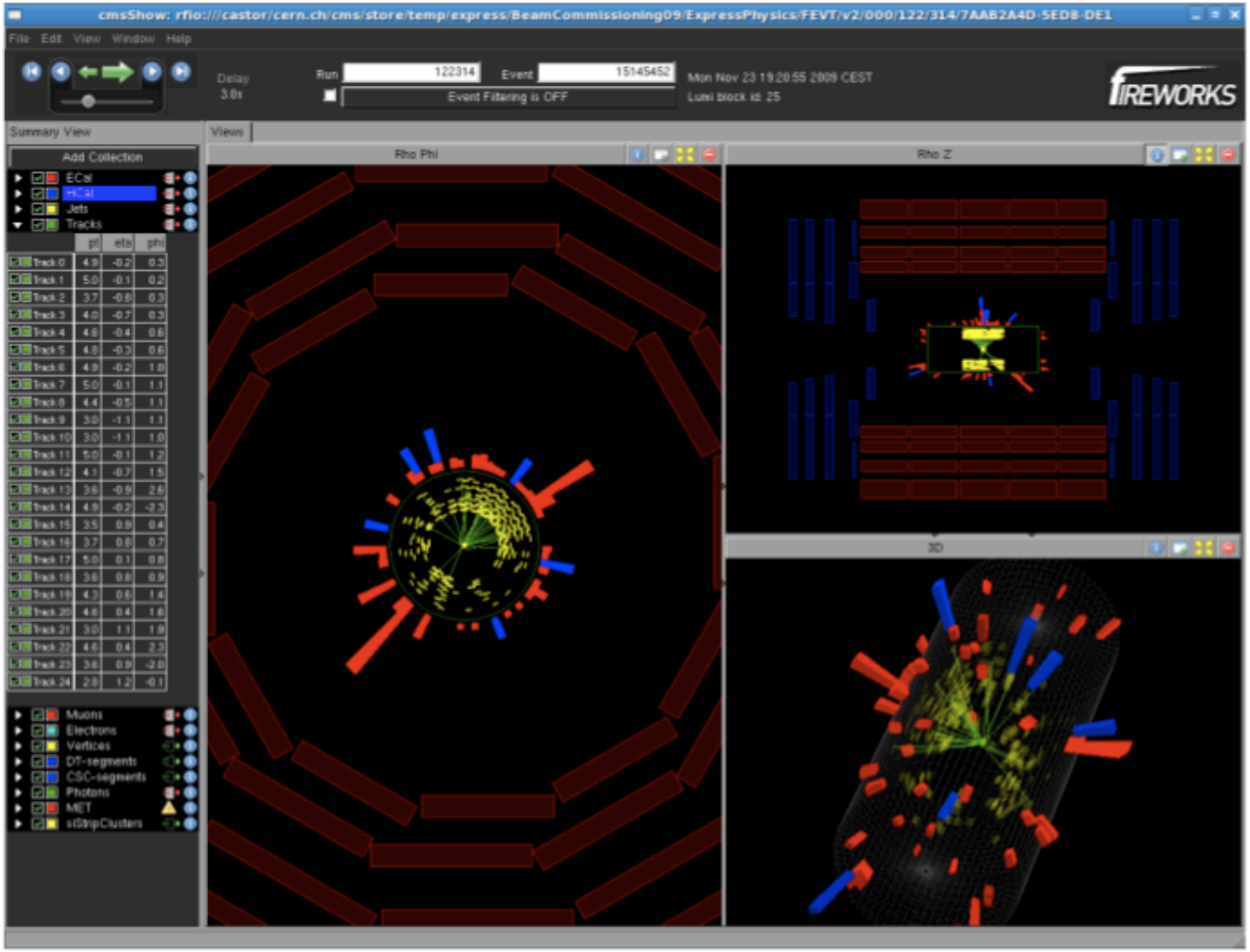
600 M events of mostly muon cosmic events collected during CRAFT make muons the most well-understood object group in CMS

The Nov/Dec 2009 Revolution

- Collision data taken at
  - 900 GeV (350 k minimum bias events or 10 μb^{-1})
  - 2.36 TeV (20 k minimum bias events or < 1 μb^{-1})
    - Highest collider energy in the world!

- CMS has taken good quality data
  - Almost all detector channels operational
  - high data-taking efficiency (> 85%)
  - Data can be analyzed very quickly
    - reconstructed data available for analysis within 15 minutes of data-taking!

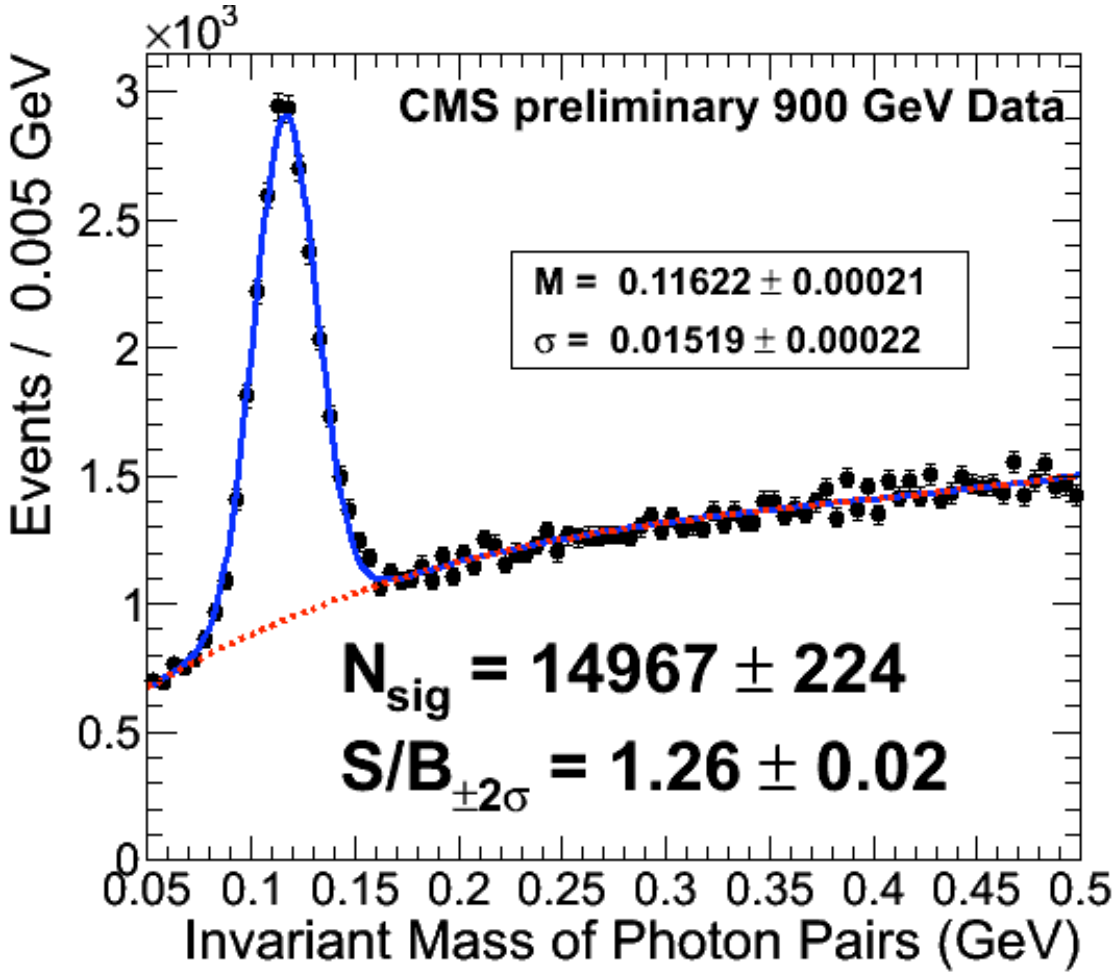
First collisions in CMS!



Nov 23rd, 2009

And only two days later…

First CMS results shown publicly at CERN – 26th November, 2009



And only 2 months later…

CMS PAPER QCD-09-010

CMS Paper

2010/02/03

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

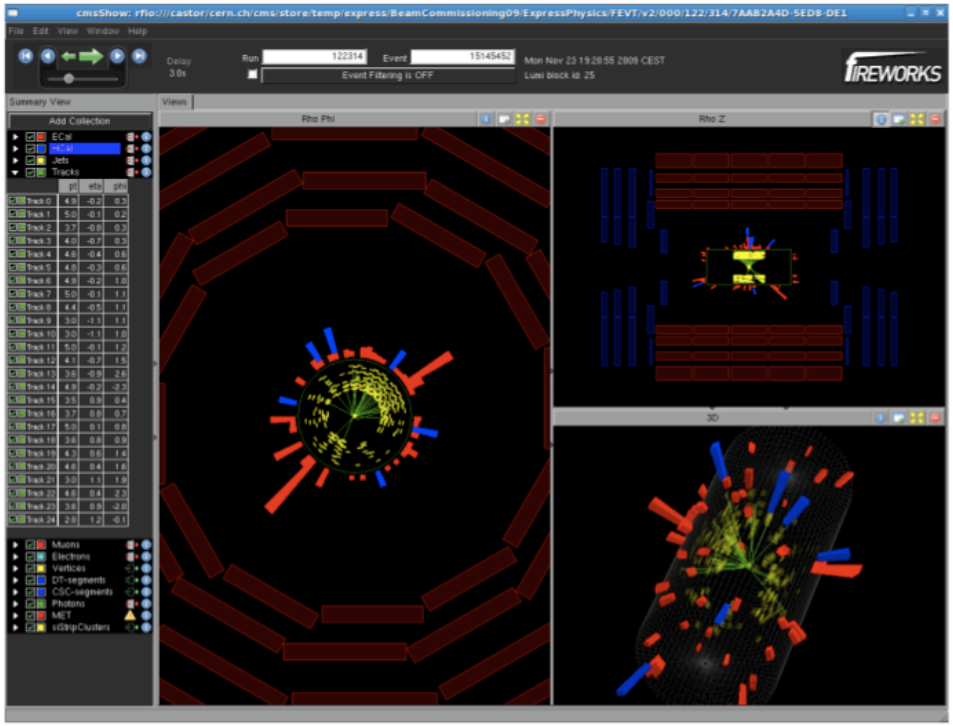
The CMS Collaboration*

arXiv:1002.0621v1 [hep-ex] 3 Feb 2010

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.

How did we go from



CMS PAPER QCD-09-010

CMS Paper

2010/02/03

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

The CMS Collaboration*

arXiv:1002.0621v1 [hep-ex] 3 Feb 2010

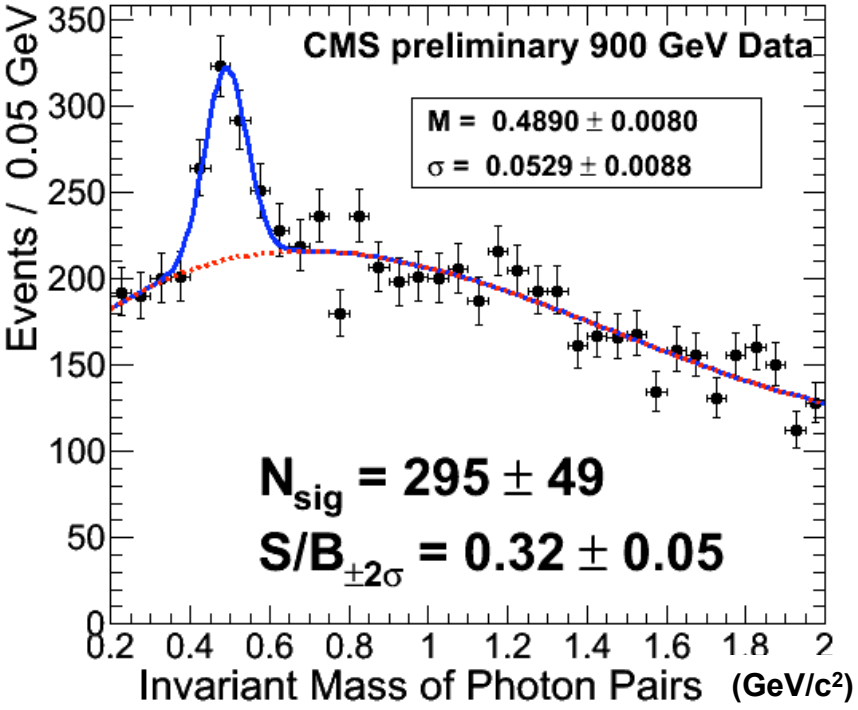
Abstract

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 pp and pp collisions. The results at 2.36 TeV represent the highest-energy measurements at a particle collider to date.

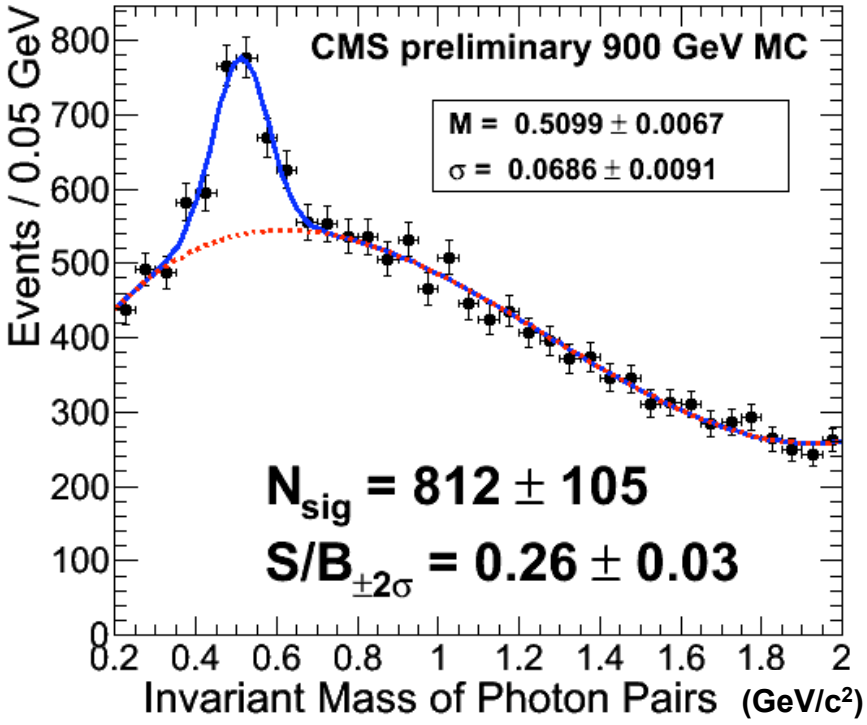
Detector Performance: Calorimetry & Jets

Calorimetry: $\eta \rightarrow \gamma\gamma$

DATA

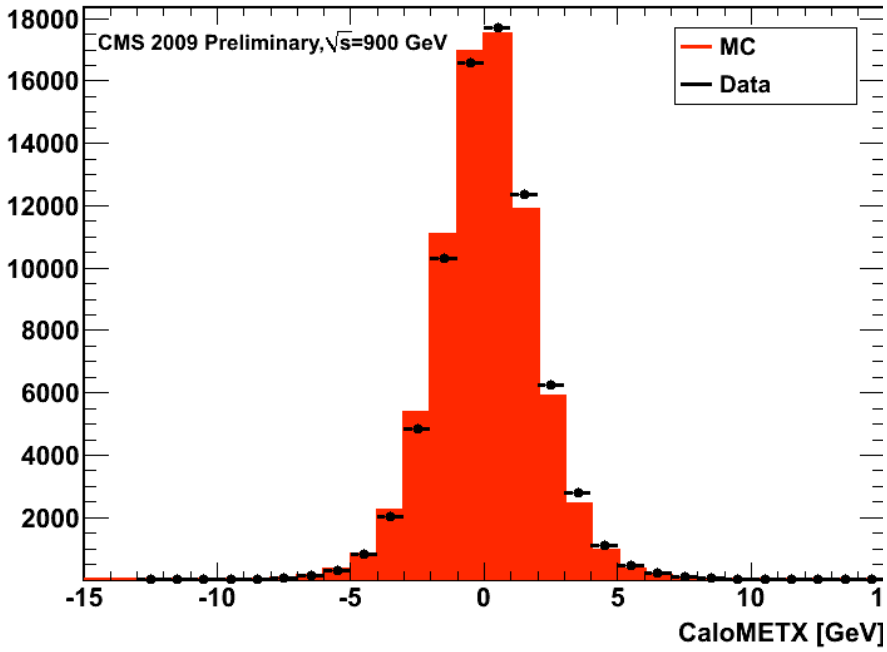


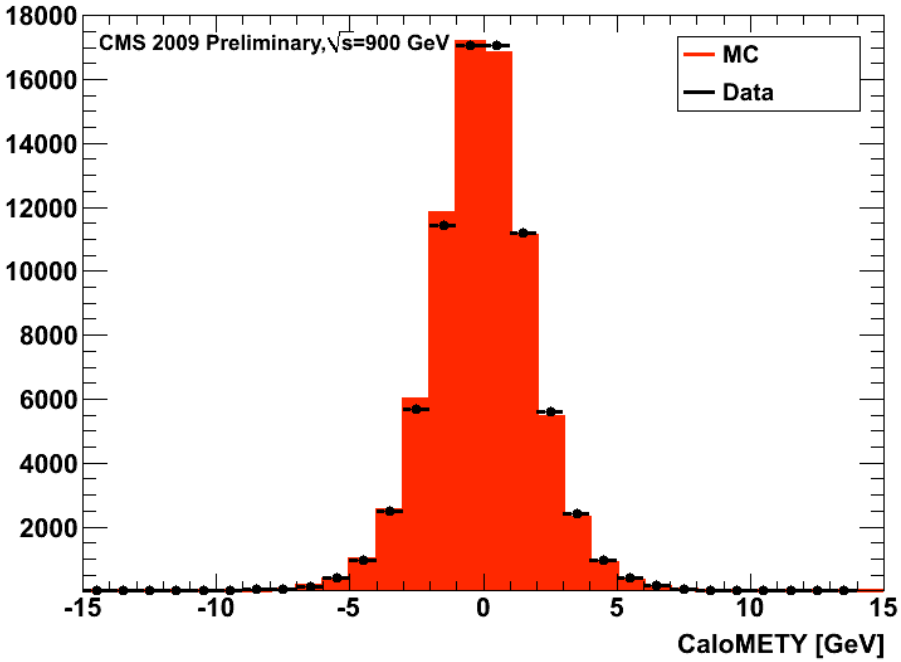
MC



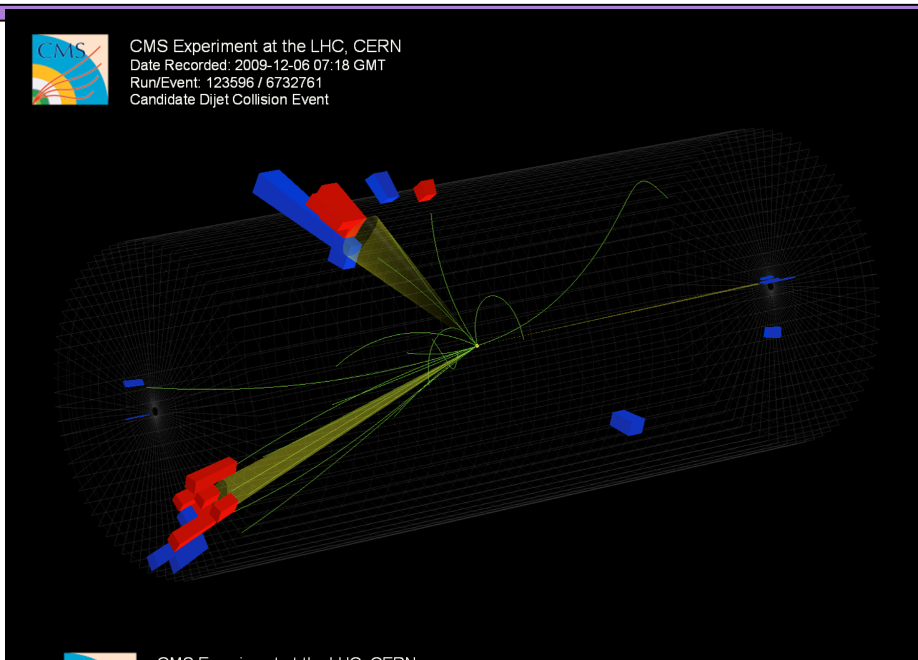
- Mass and width compatible with MC
- η yield scale as expected (π^0 candle)
  - $N(\eta) / N(\pi^0) = 0.020 \pm 0.003$ DATA
  - $N(\eta) / N(\pi^0) = 0.021 \pm 0.003$ MC

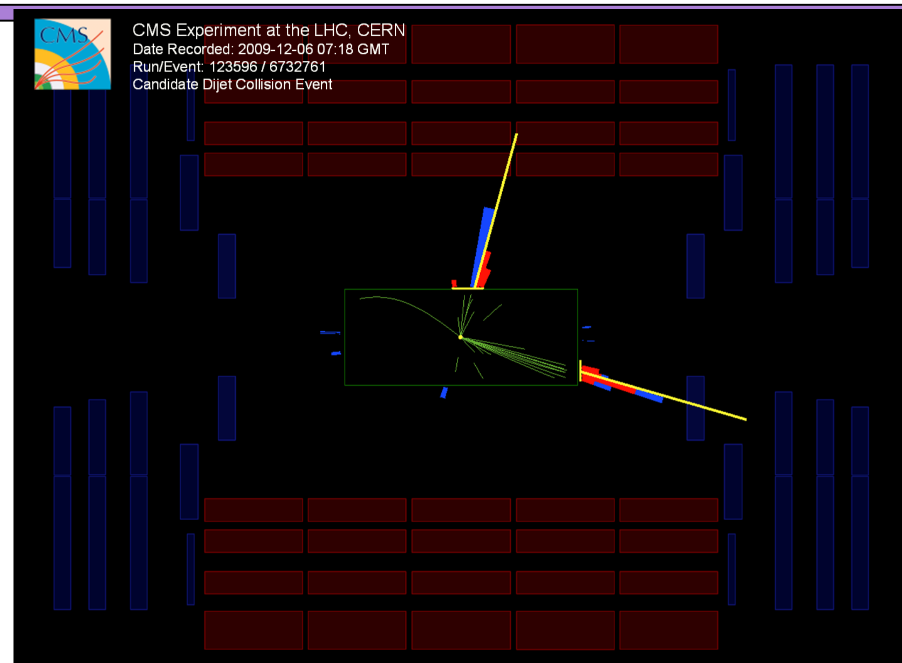
Calorimetry: Missing ET

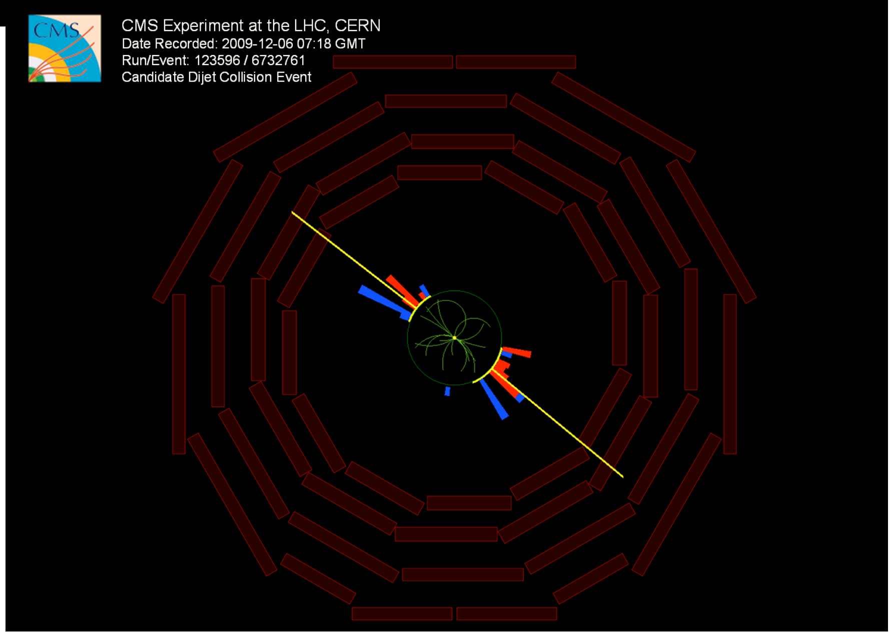


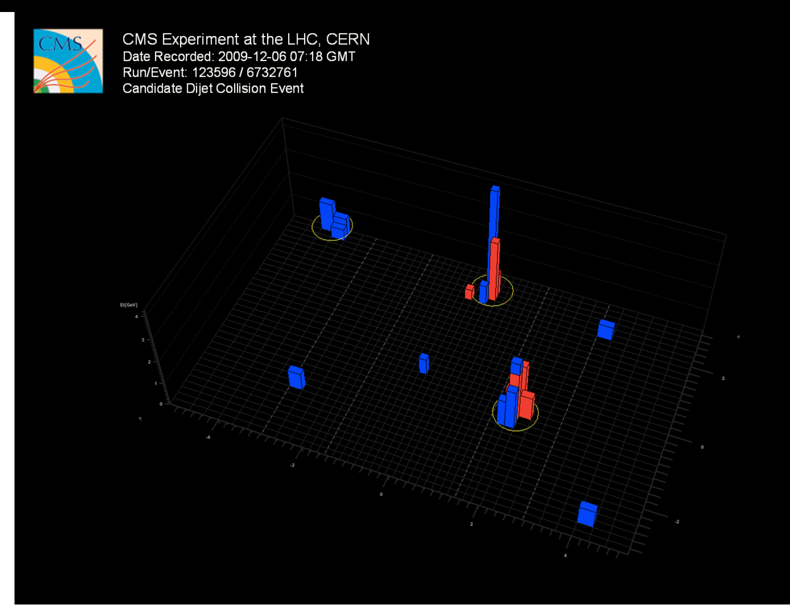


Dijet Candidate

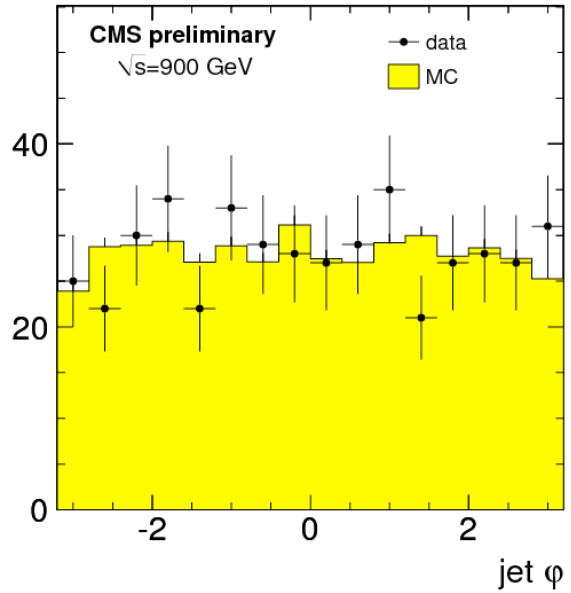


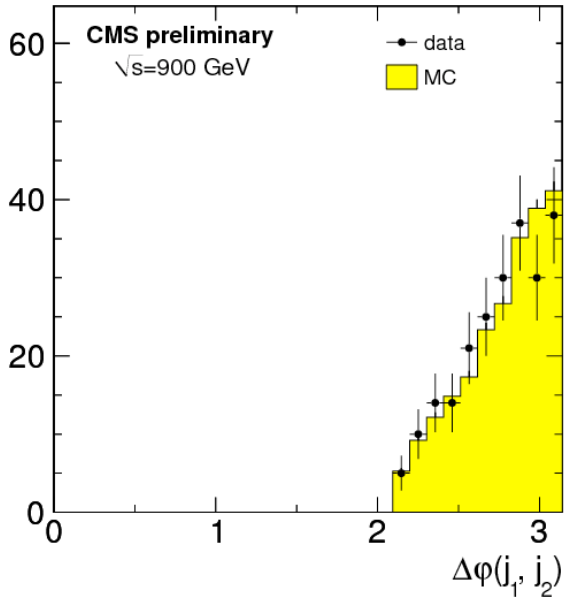


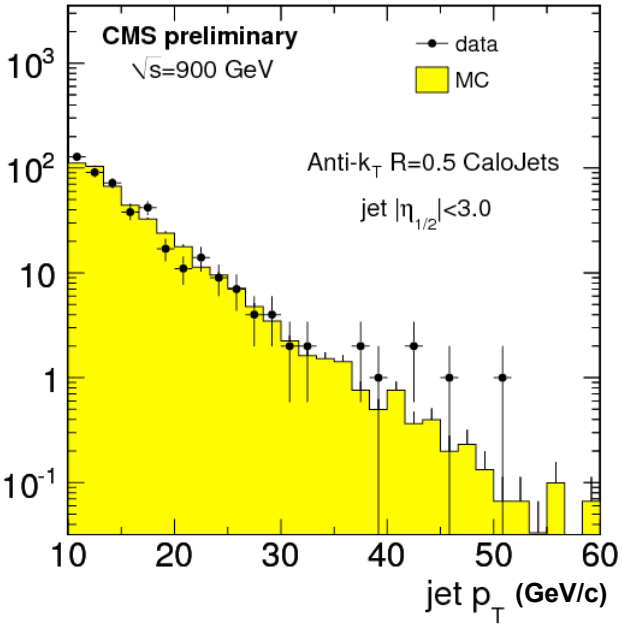


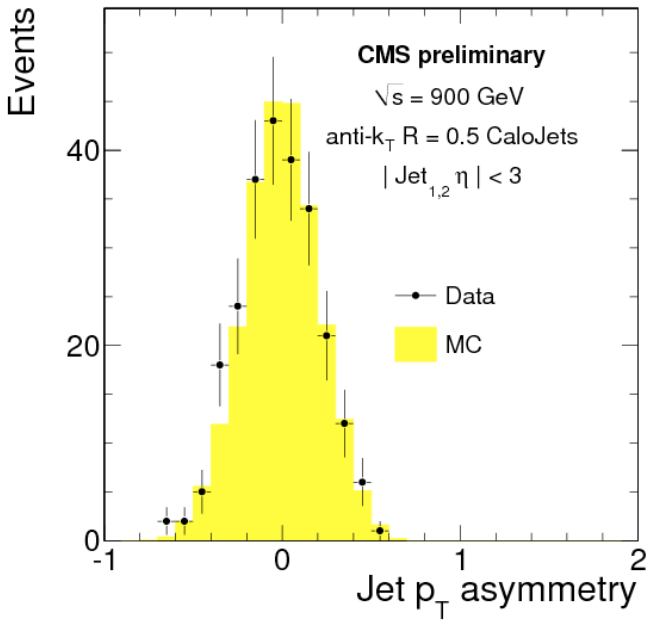


Calorimetric dijet events

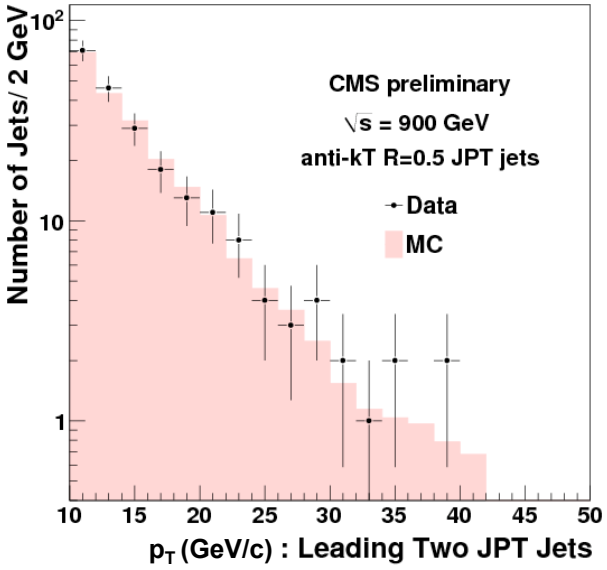


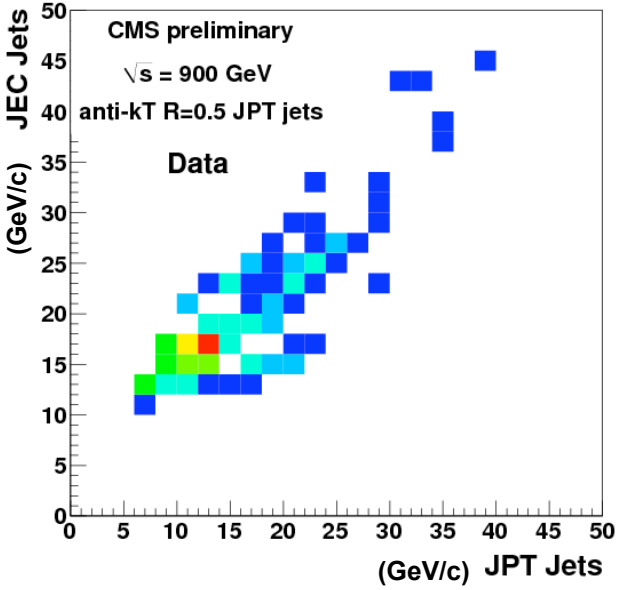


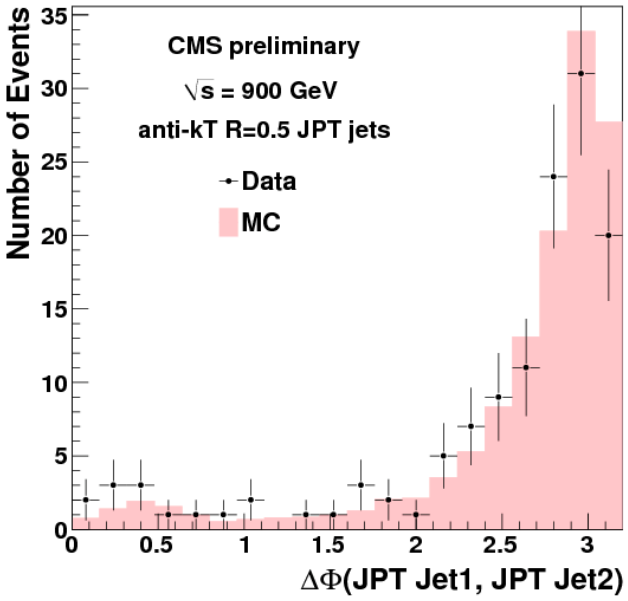


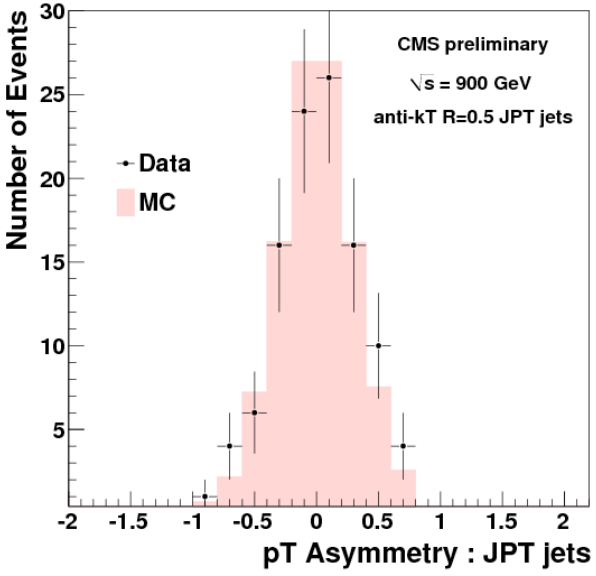


Calorimetric dijet events plus tracks





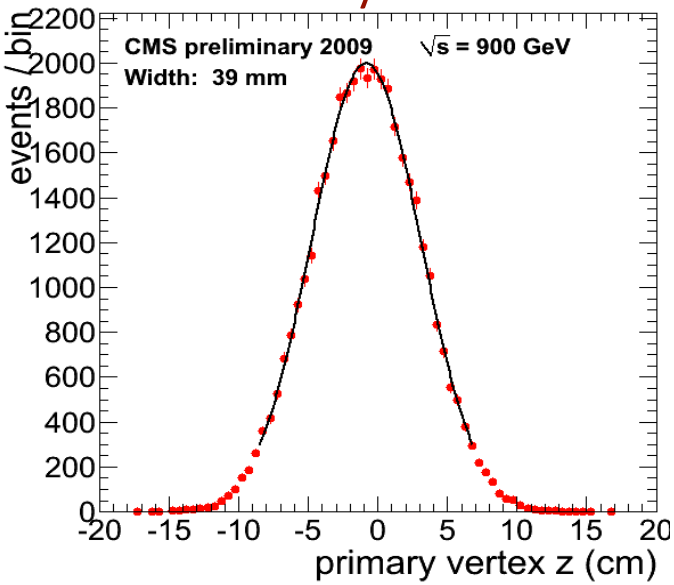


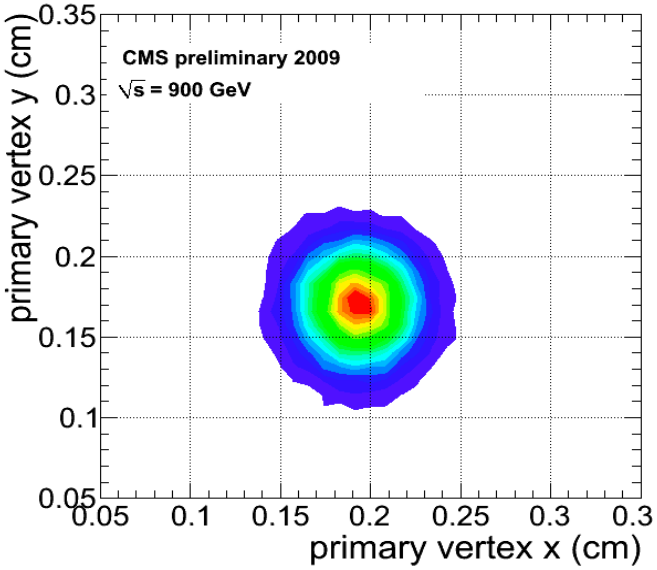


Tracking & Particle ID

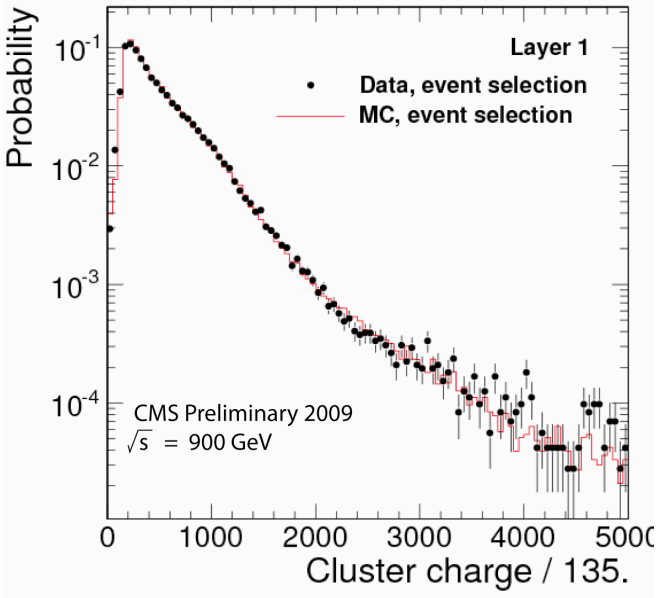
Tracking performance

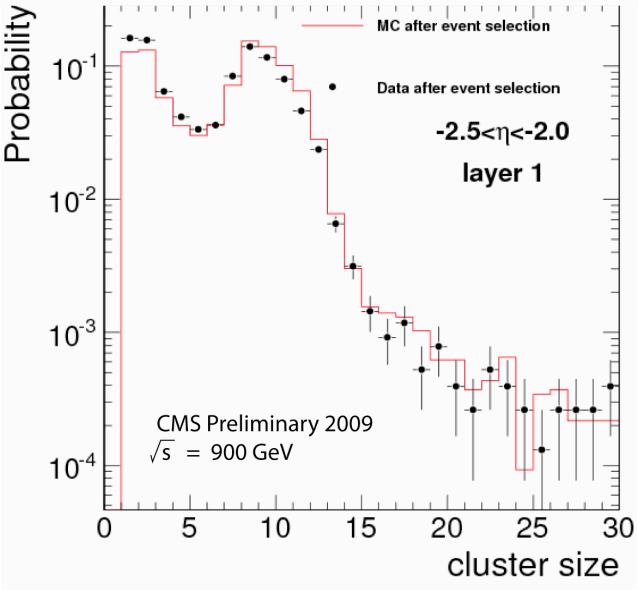
Primary Vertex





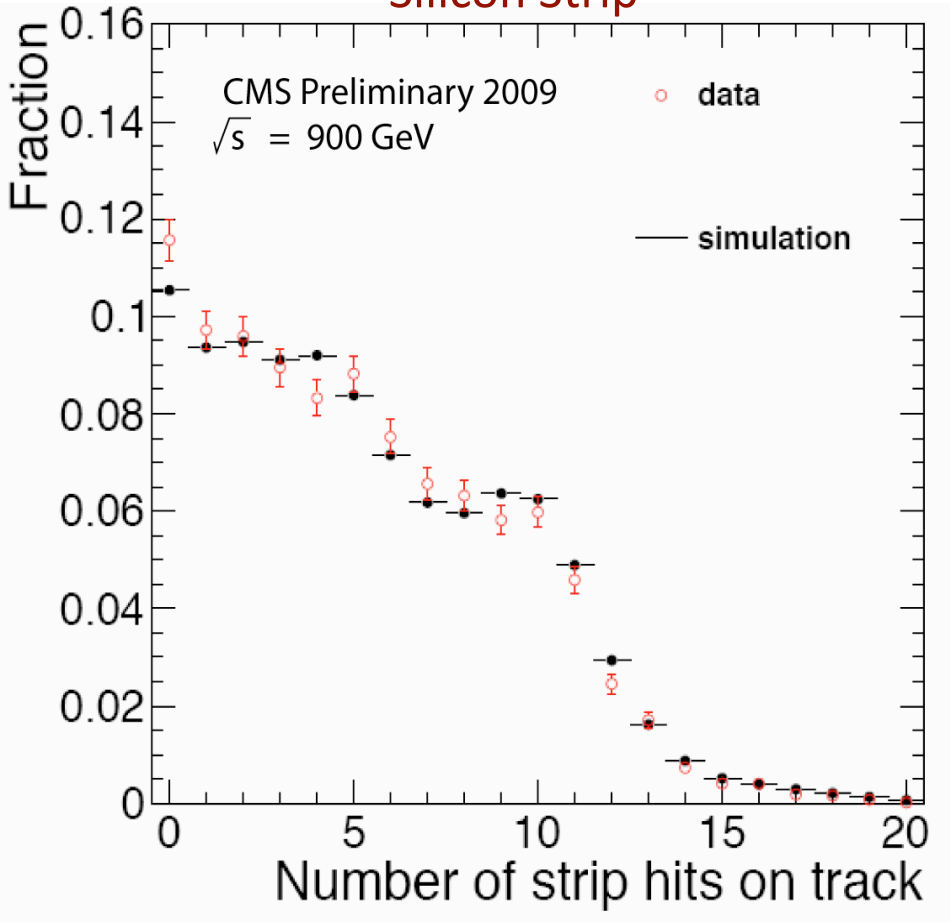
Pixel Clusters



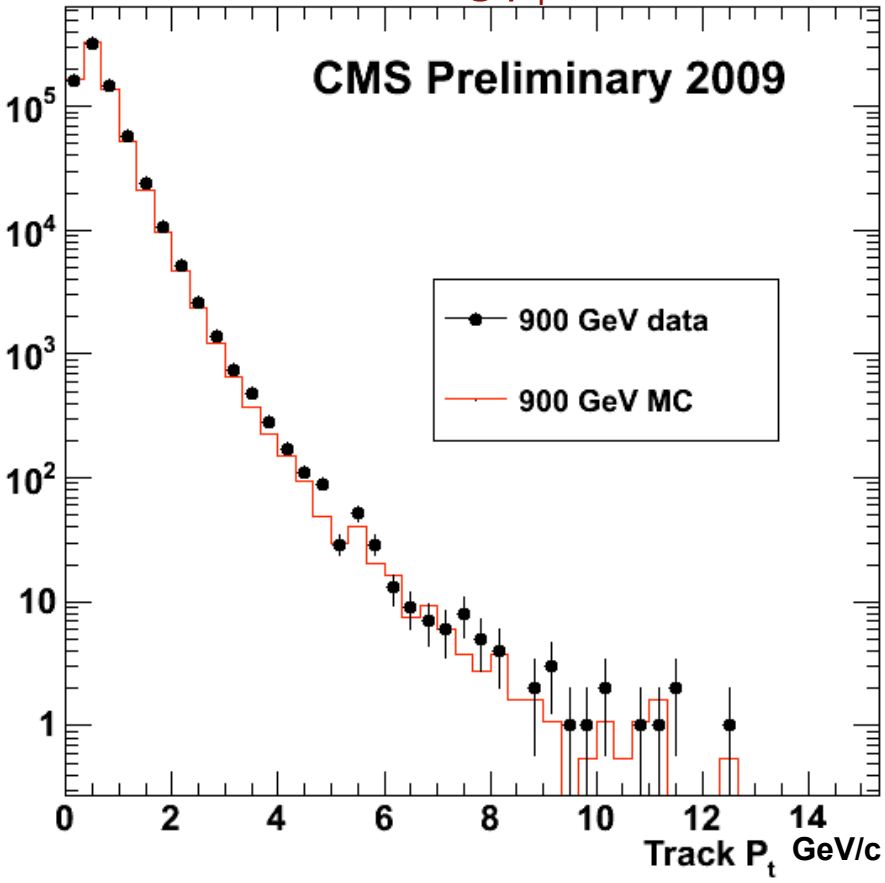


Tracking performance

Silicon Strip



Tracking p_T

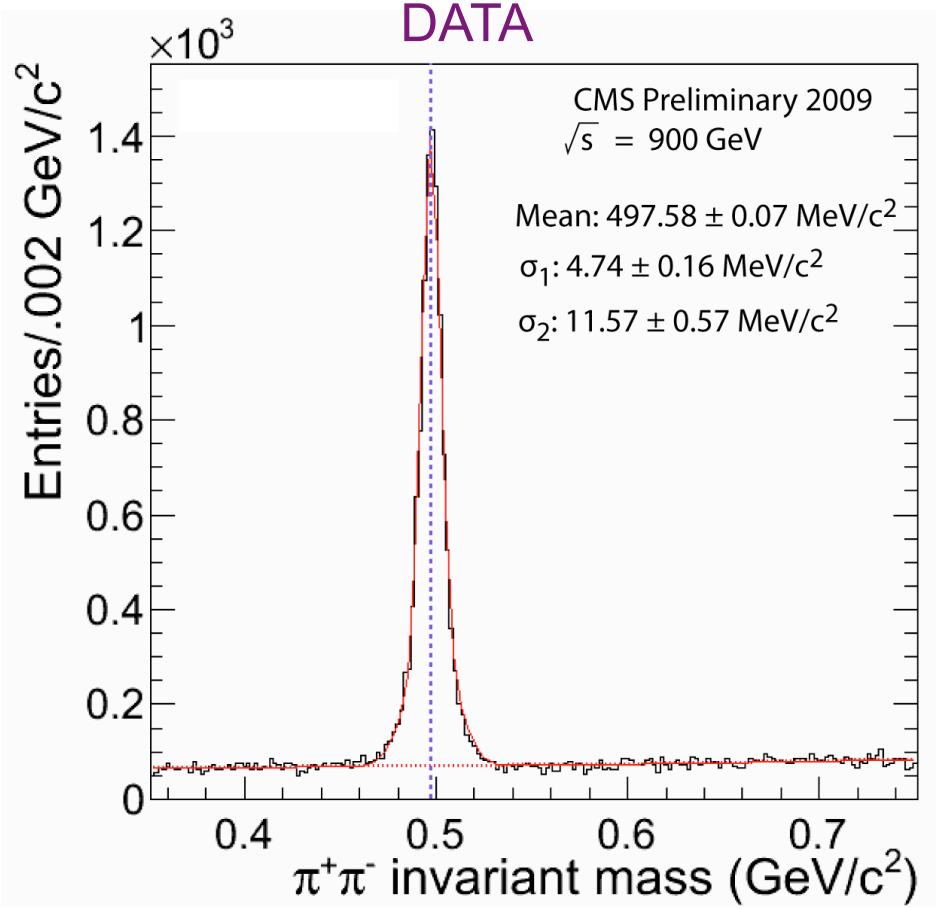


Events with 5 to 100 tracks:

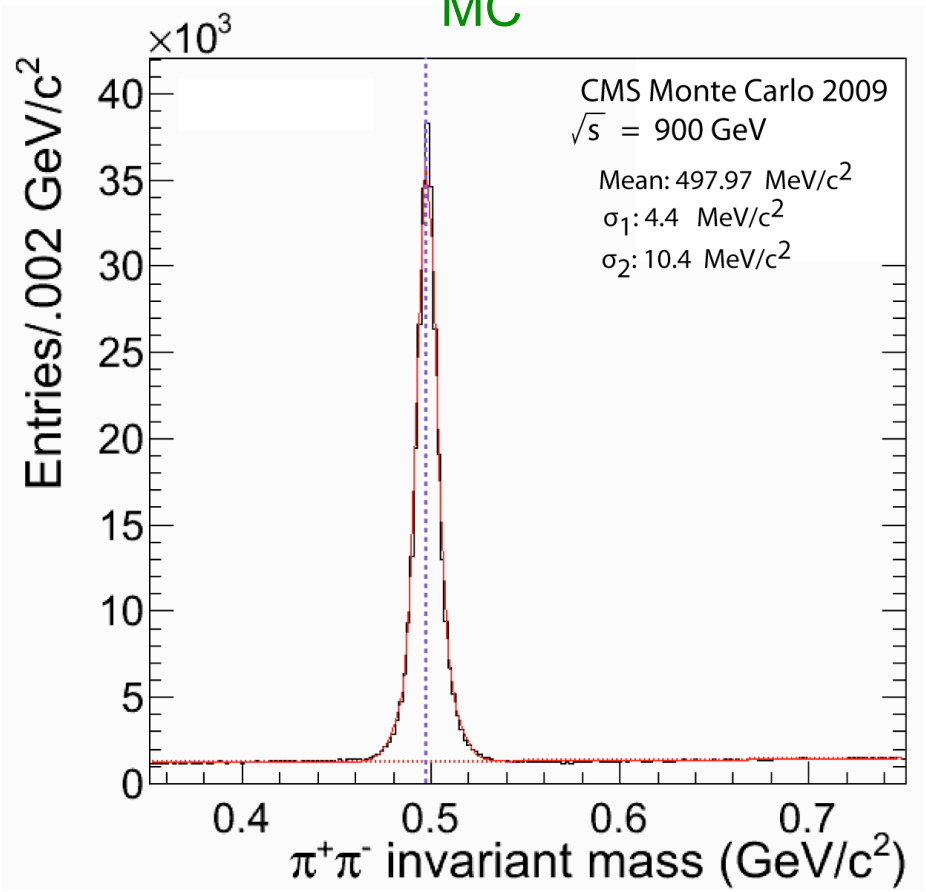
- Tracks with "highPurity" flag
  - at lease 8 hits
  - relative error on p_T < 10%
- No cut on η or p_T

K_s

DATA

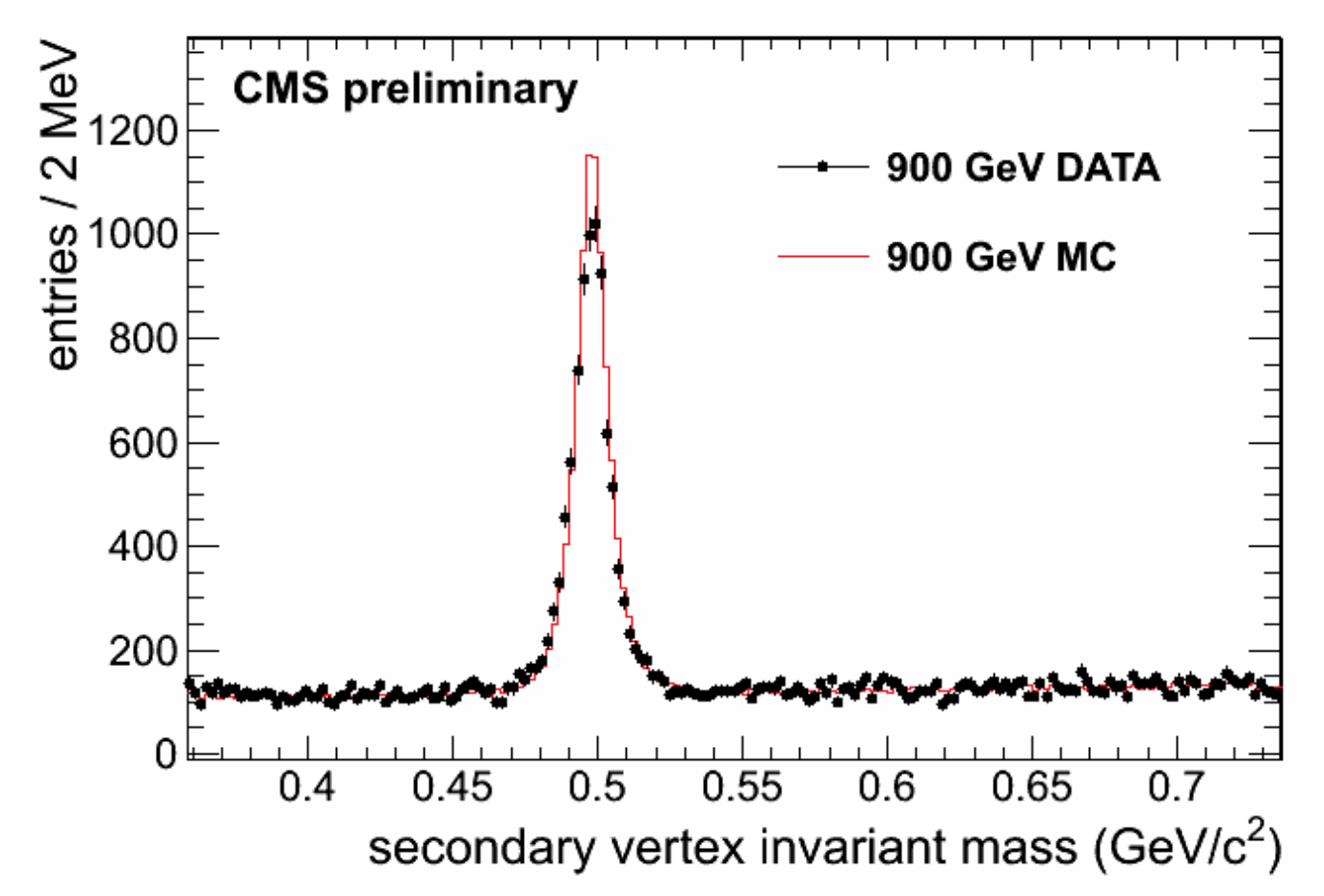


MC



Double Gaussian fits (from a sample of ~240 million minimum bias events)

K_s

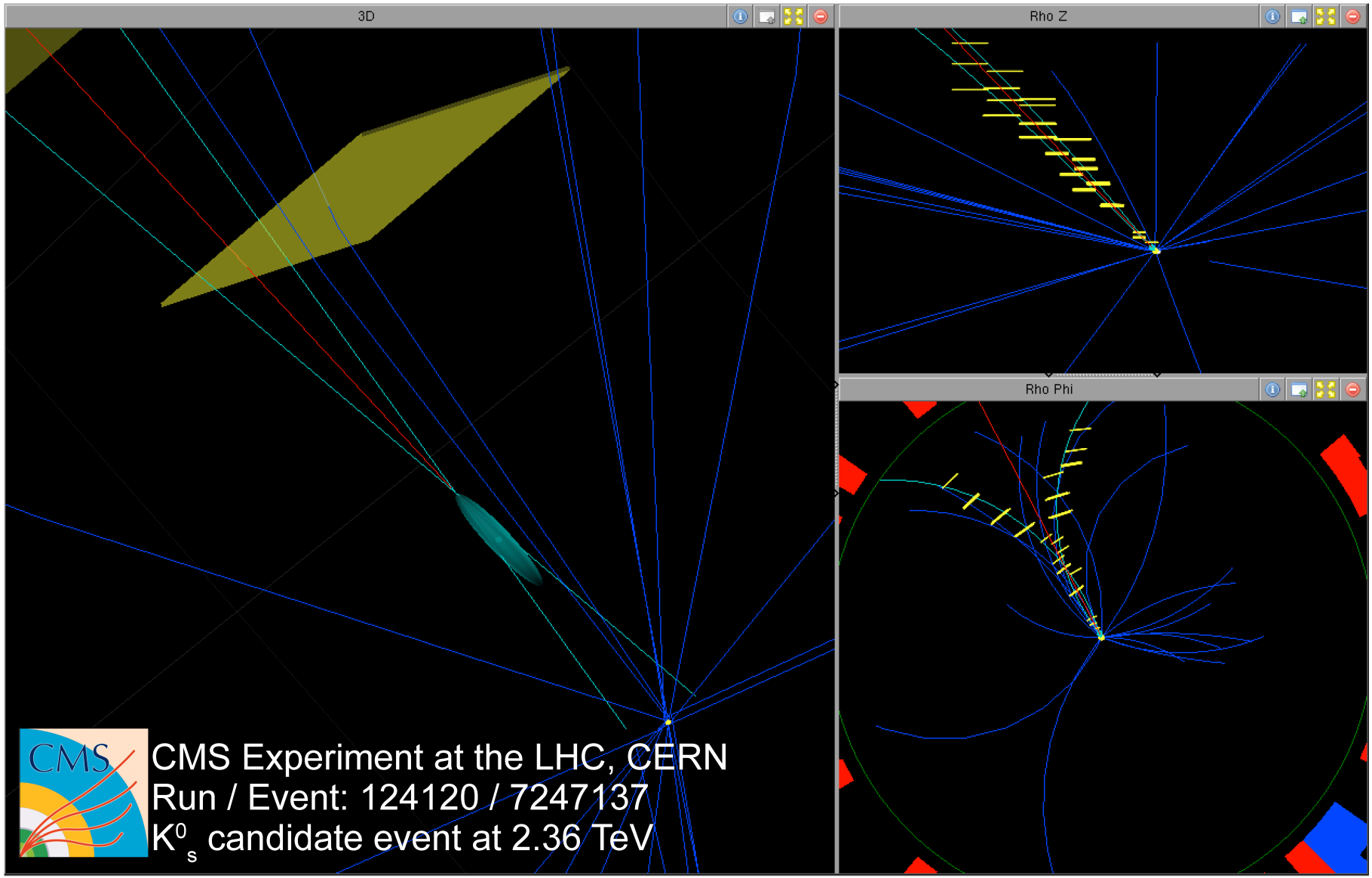


K_s : can be used as a vertexing and b-tagging commissioning tool

Invariant mass of ≥2 track vertices found by the secondary vertex B tagger

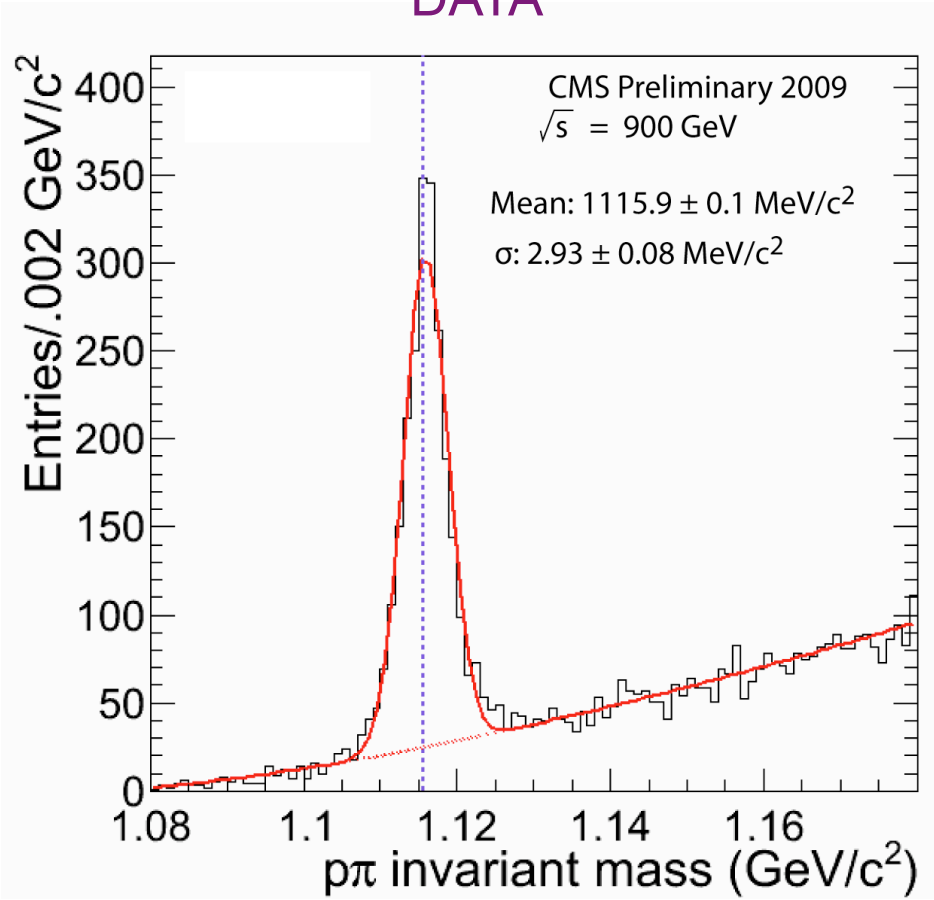
Clear K_s peak with low background (=> low mistag rate)

Candidate K_s event (2.36 TeV)

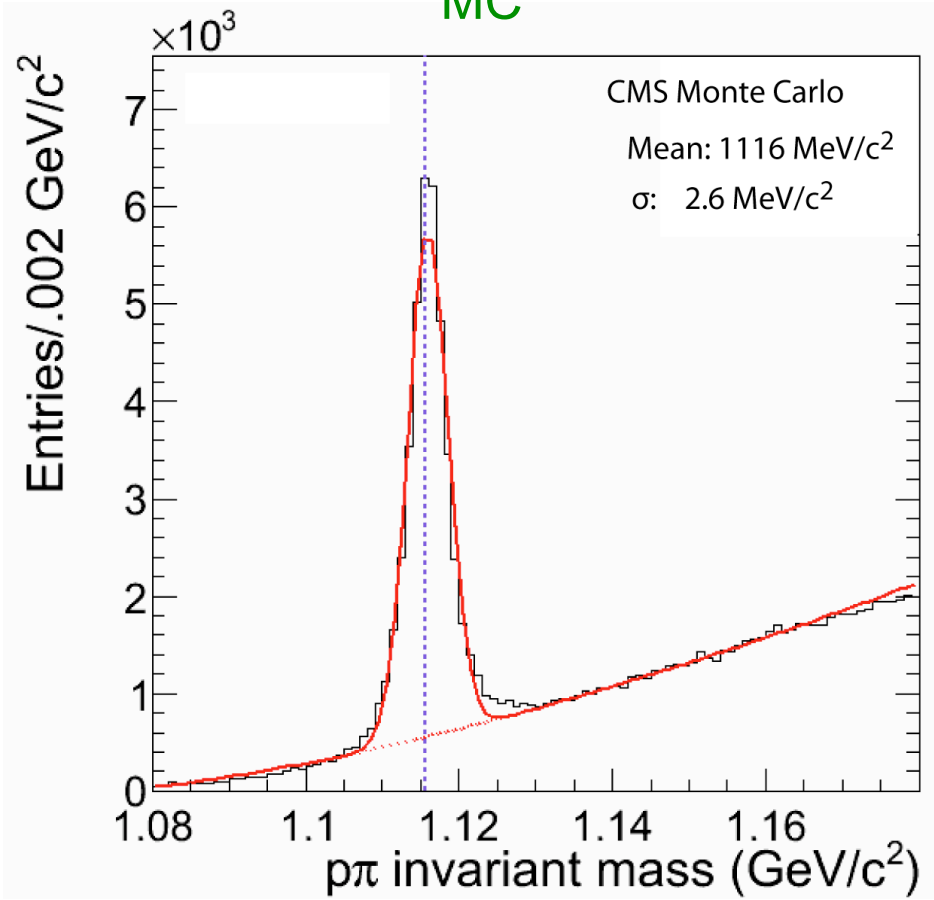


Λ

DATA



MC



Single Gaussian fits (from a sample of ~240 million minimum bias events)

$\phi \rightarrow KK$

CMS Preliminary: 900 GeV pp collisions

$m = 1.01937 \pm 0.00030$ GeV/c^2

$\sigma = 1.69 \pm 0.50$ MeV/c^2

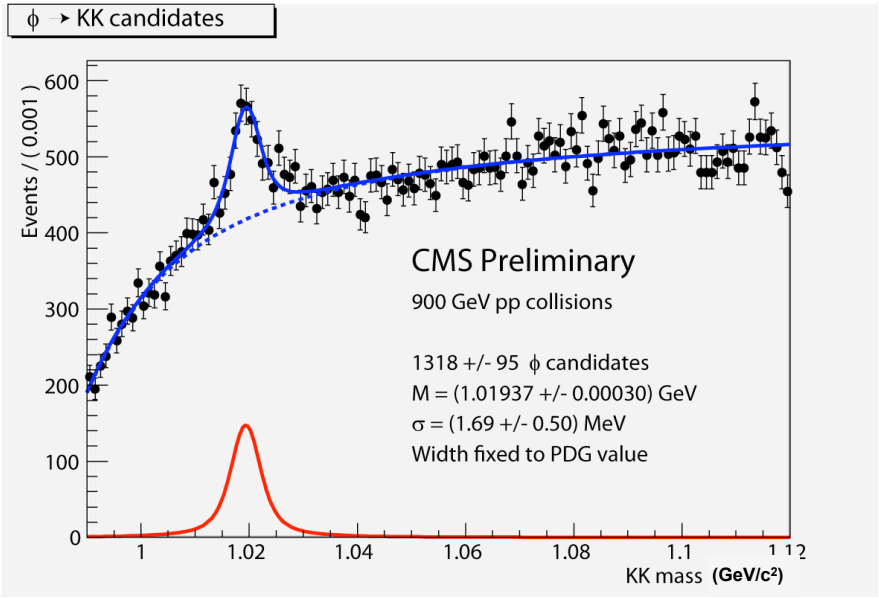
Γ fixed at 4.26 MeV/c^2 (PDG2009 value)

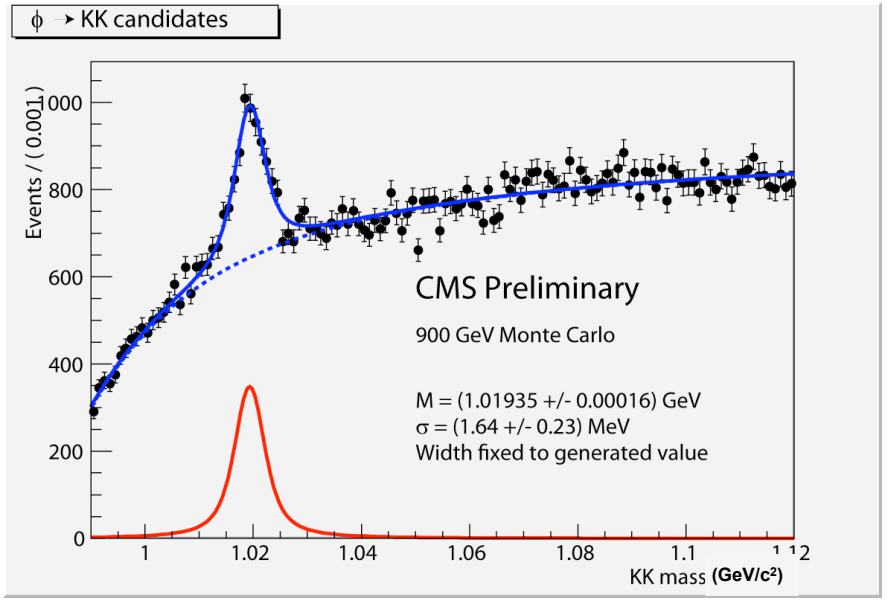
CMS Preliminary: 900 GeV Monte Carlo

$m = 1.01935 \pm 0.00016$ GeV/c^2

$\sigma = 1.64 \pm 0.23$ MeV

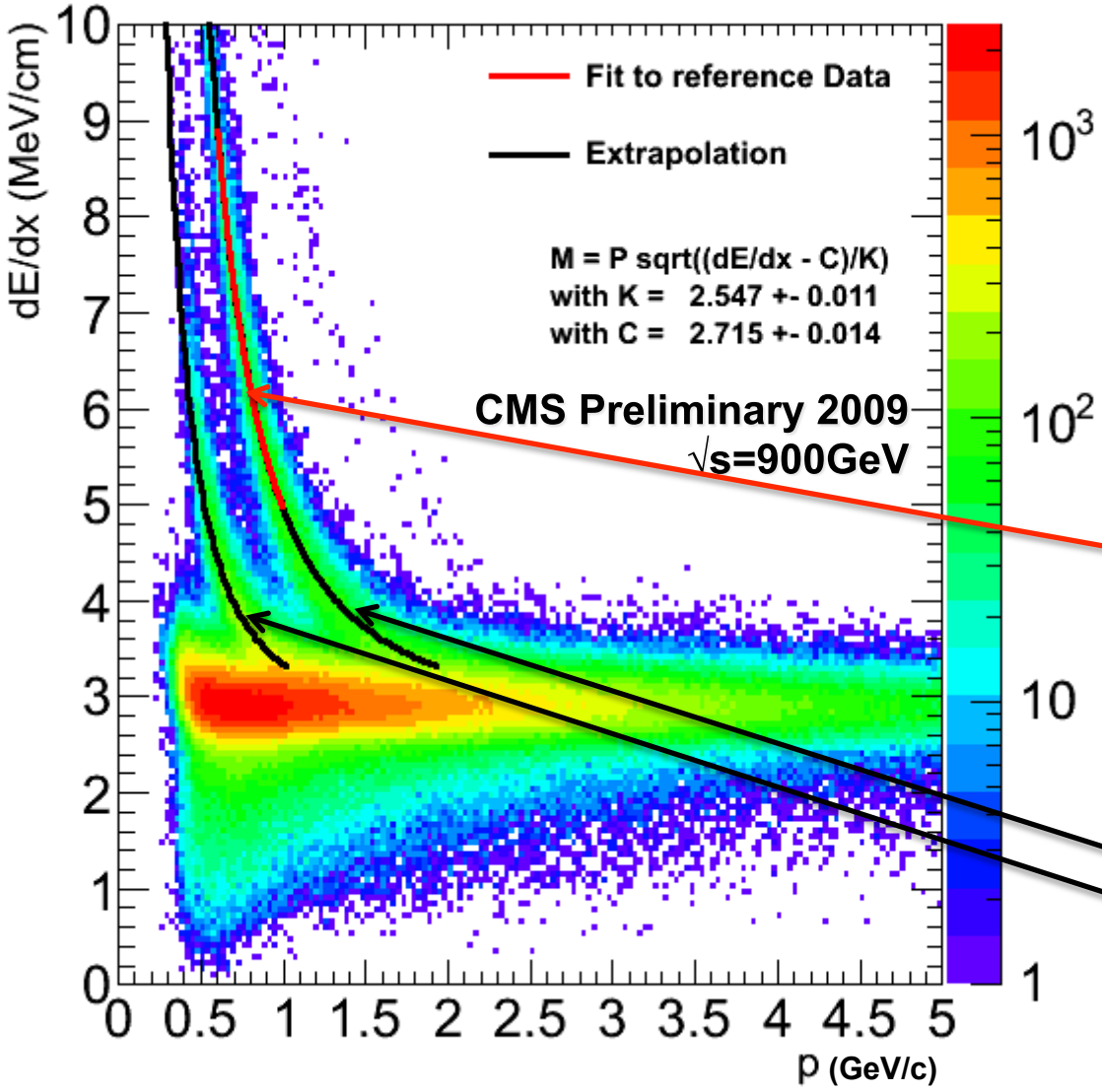
Γ fixed at 4.458 MeV/c^2 (PDG2001 value used to generate MC)





Gaussian convoluted with Breit-Wigner in fit

Tracker dE/dx

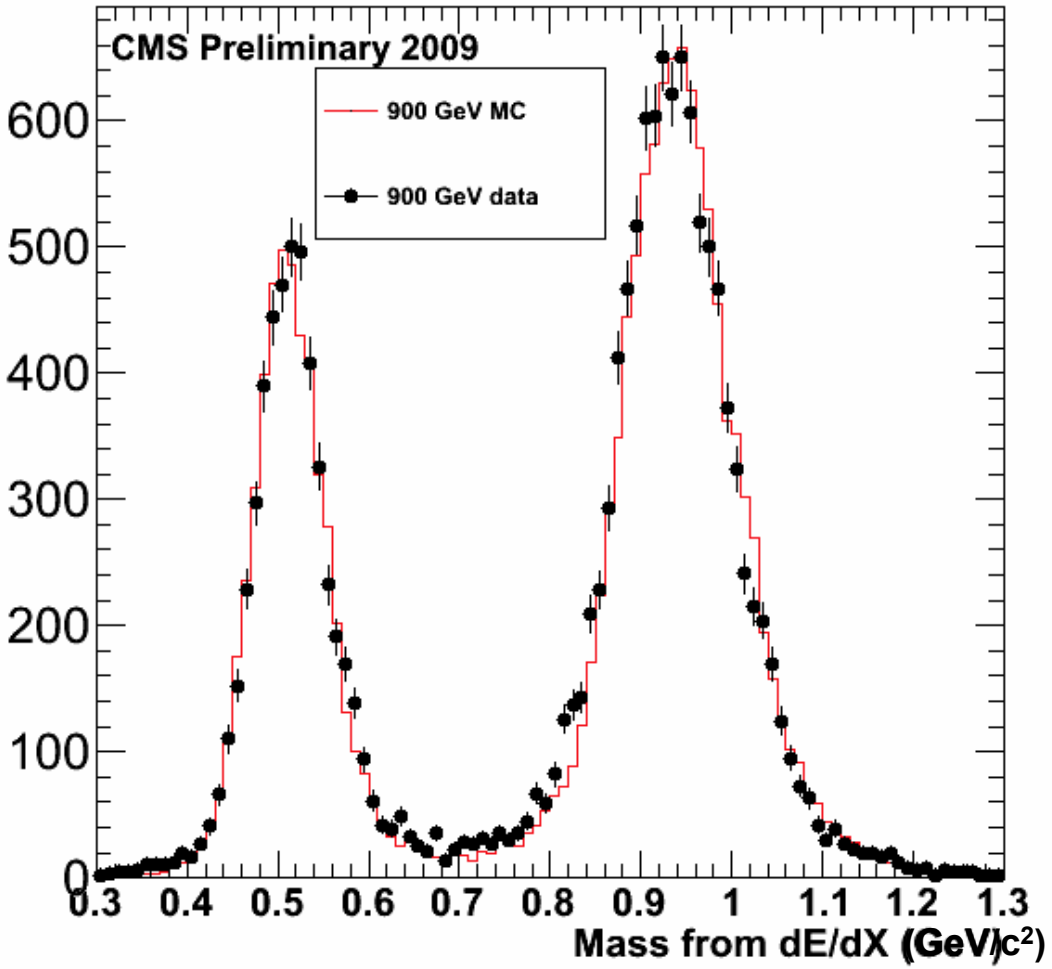


- dE/dx distributions can be fitted for various particles
  - (protons, pions, kaons)

$$\frac{dE}{dx} = K\frac{M^2}{p^2} + C$$

- Use reference data for protons (red line)
- Extrapolate behavior for protons at high momentum and kaons (black lines)
- Calculate mass by using dE/dX, p and reverting formula

Particle ID with tracker dE/dx



$$M = p\sqrt{\left(\frac{dE}{dx} - C\right)K^{-1}}$$

Track Selection:

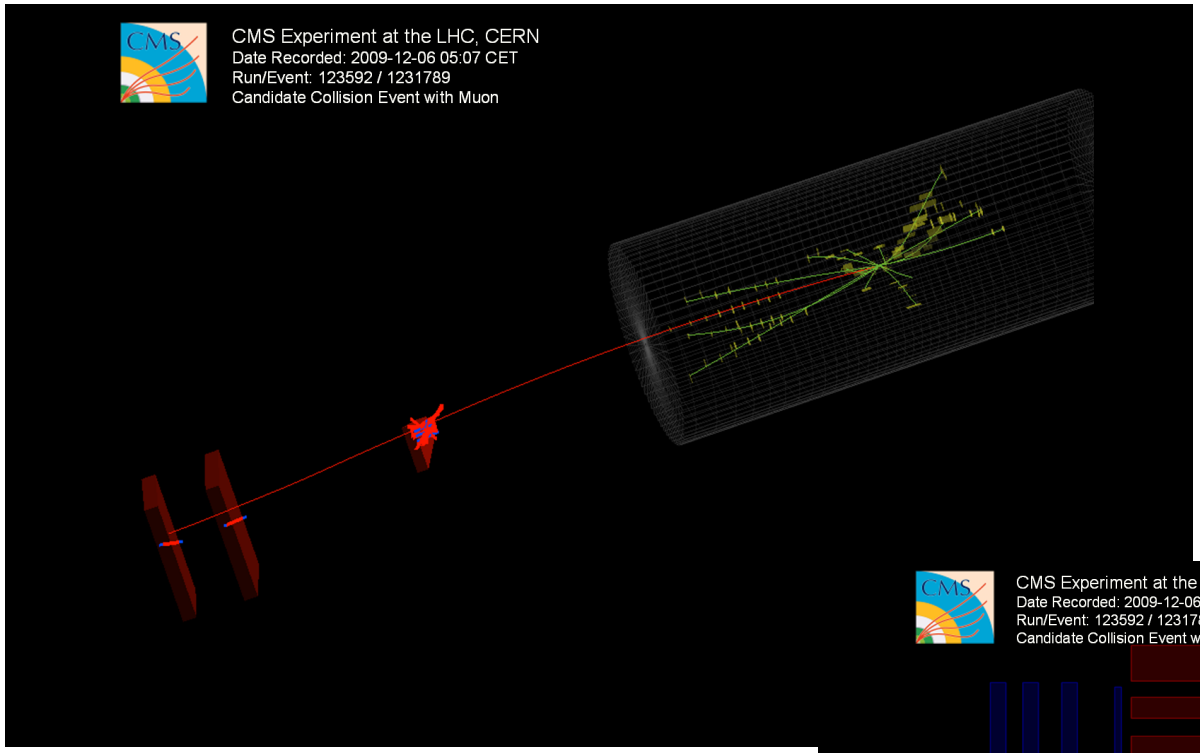
- p < 2 GeV
- At least 10 Silicon strip hits
- $|d_0|$<=2 cm && |dz|<=15cm

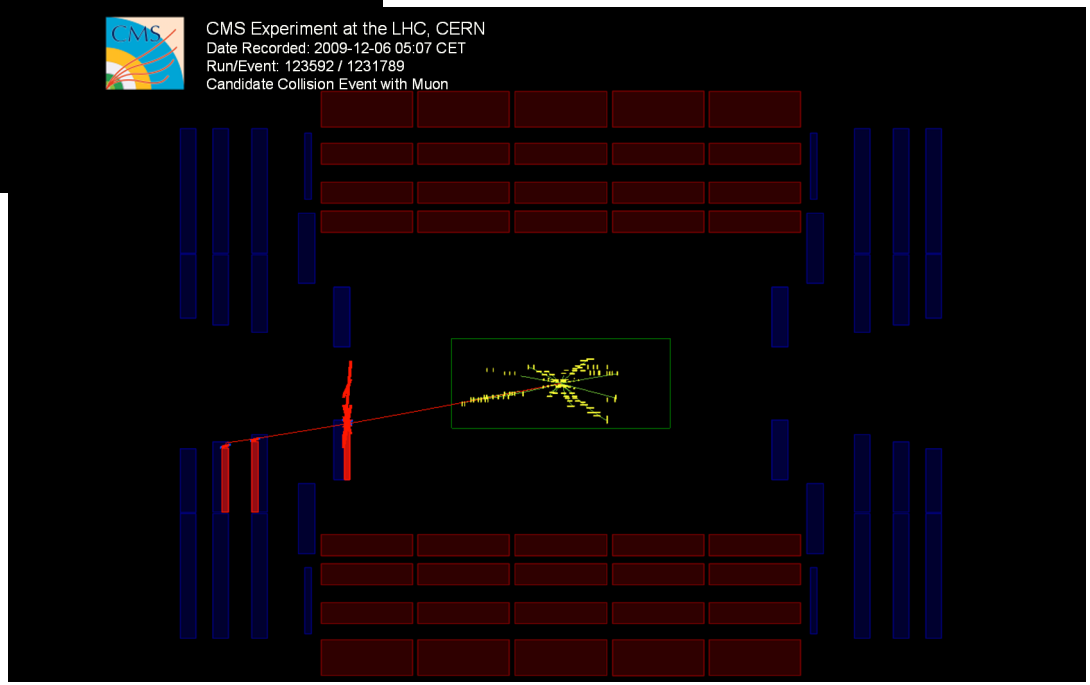
Mass distribution of particles with dE/dx > 4.15 MeV/cm

Proton and Kaons are clearly separated

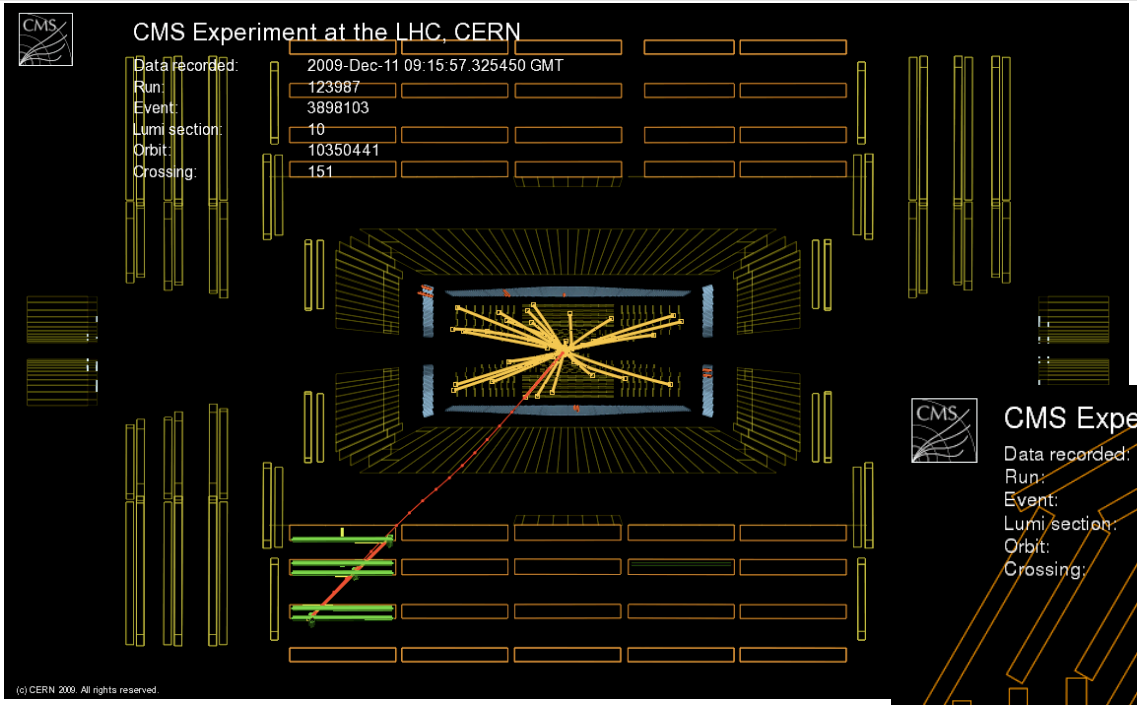
Muons

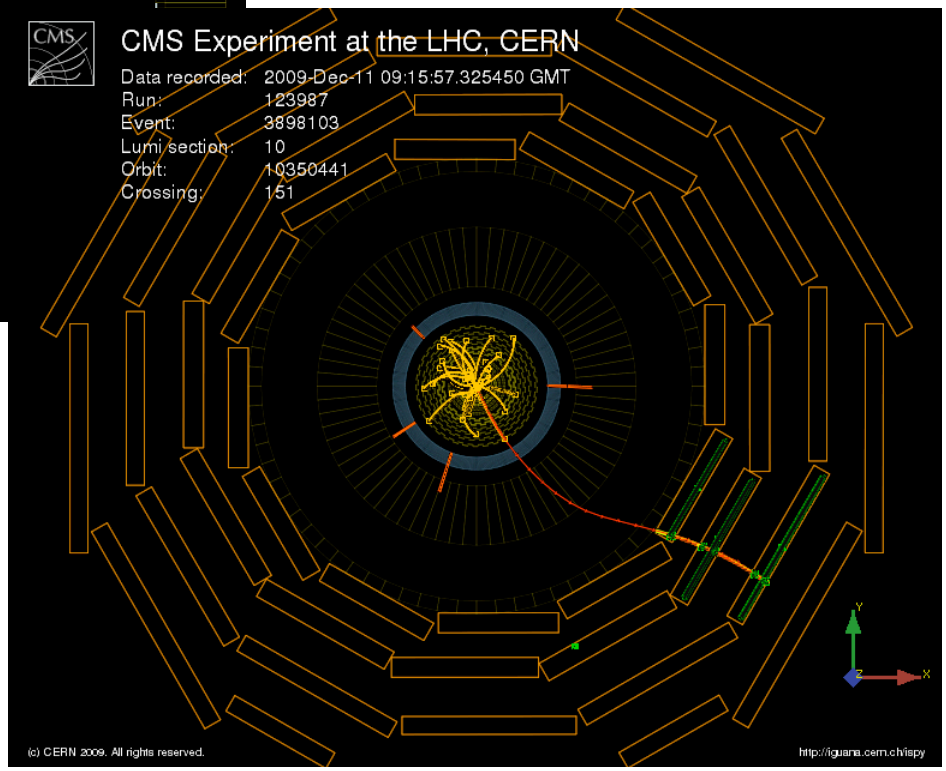
Endcap Muon Candidate



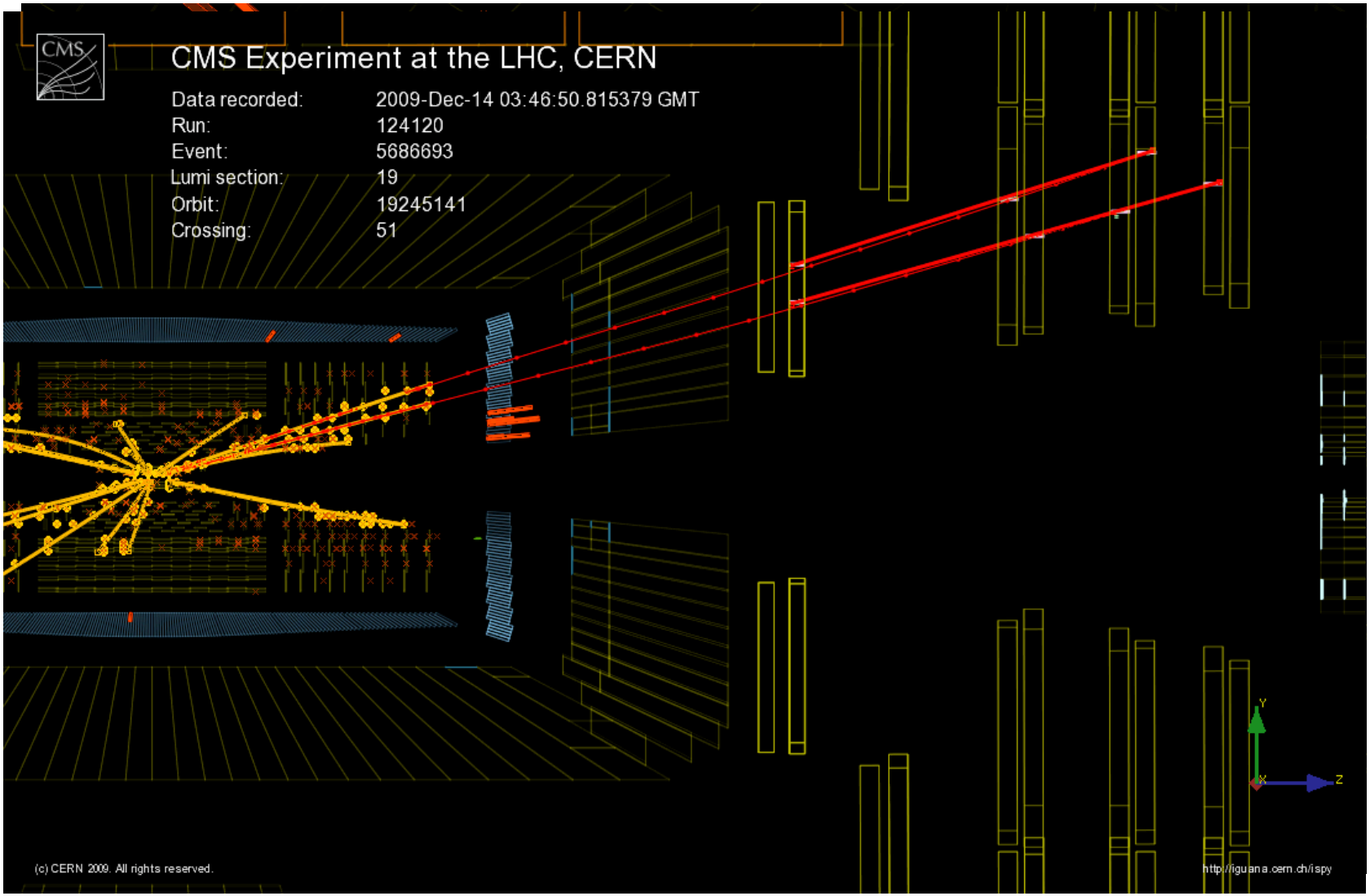


Barrel Muon Candidate



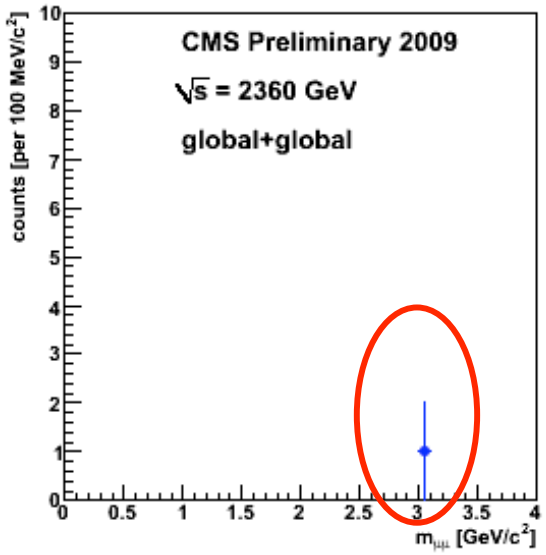


Di-muon event @ 2.36 TeV



$p_T(\mu_1)$ = 3.6 GeV/c, $p_T(\mu_2)$ = 2.6 GeV/c, $m(\mu\mu)$= 3.03 GeV/c^2

Di-muon event @ 2.36 TeV



Expected one J/ψ → μμ event in 500k min-bias events @ 2.36 TeV

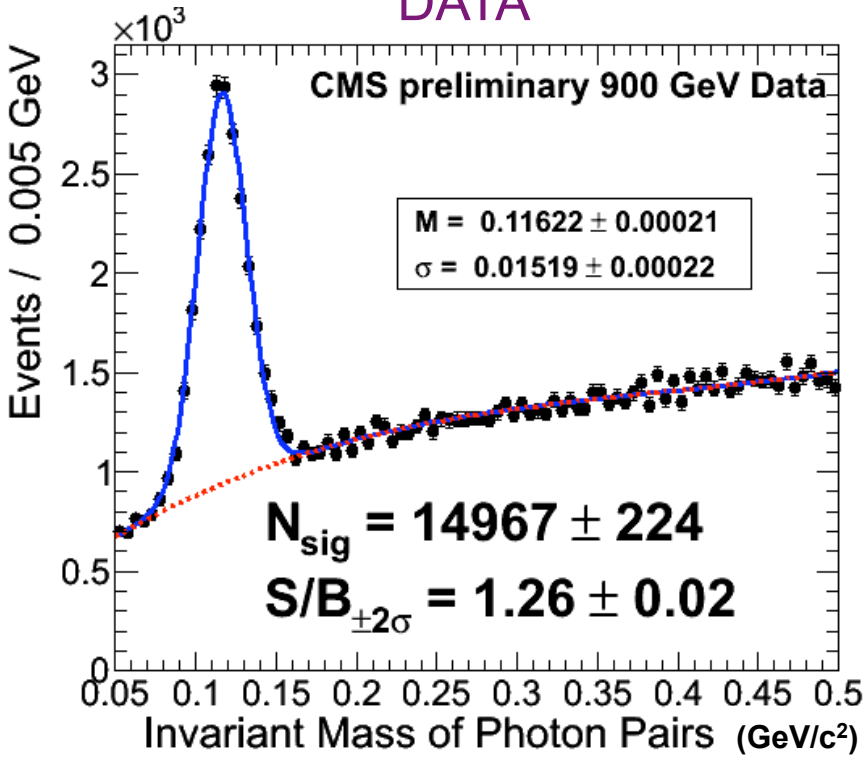
We see one J/ψ → μμ candidate event in 20k events

S/B ratio: 16/1 in [3.0, 3.2] GeV/c^2 region (background ~ 0)

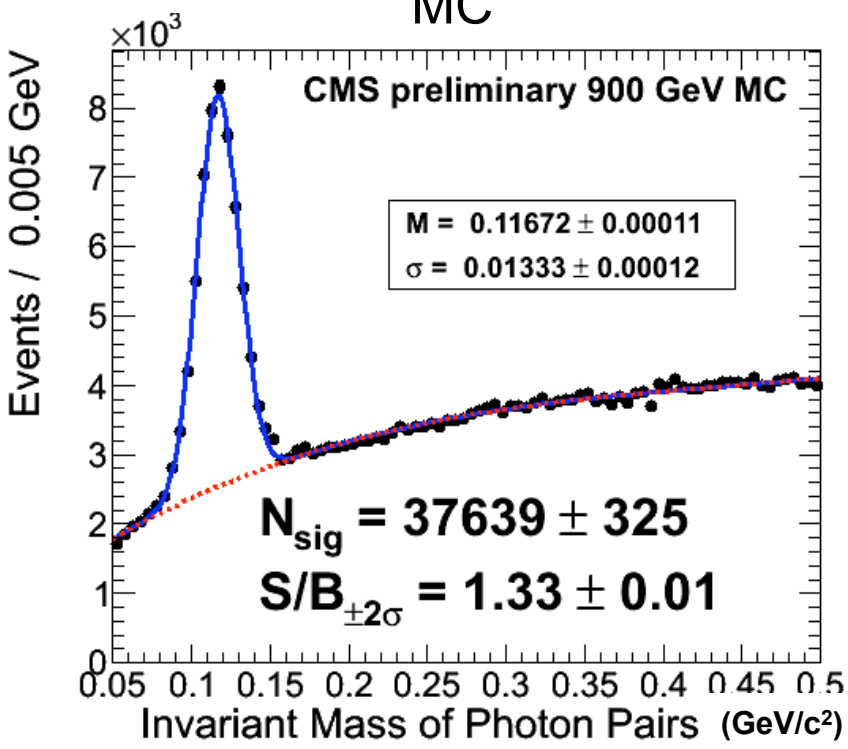
Electrons/Photons

$\pi^0 \rightarrow \gamma\gamma$

DATA



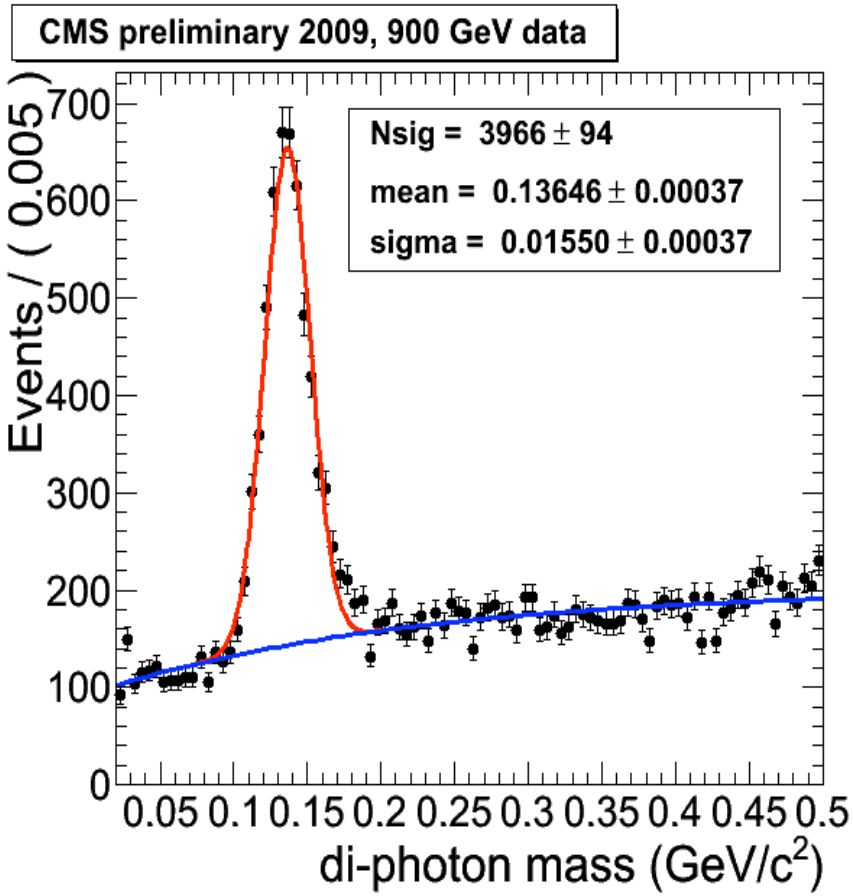
MC



Data and MC comparison (uncorrected distributions)

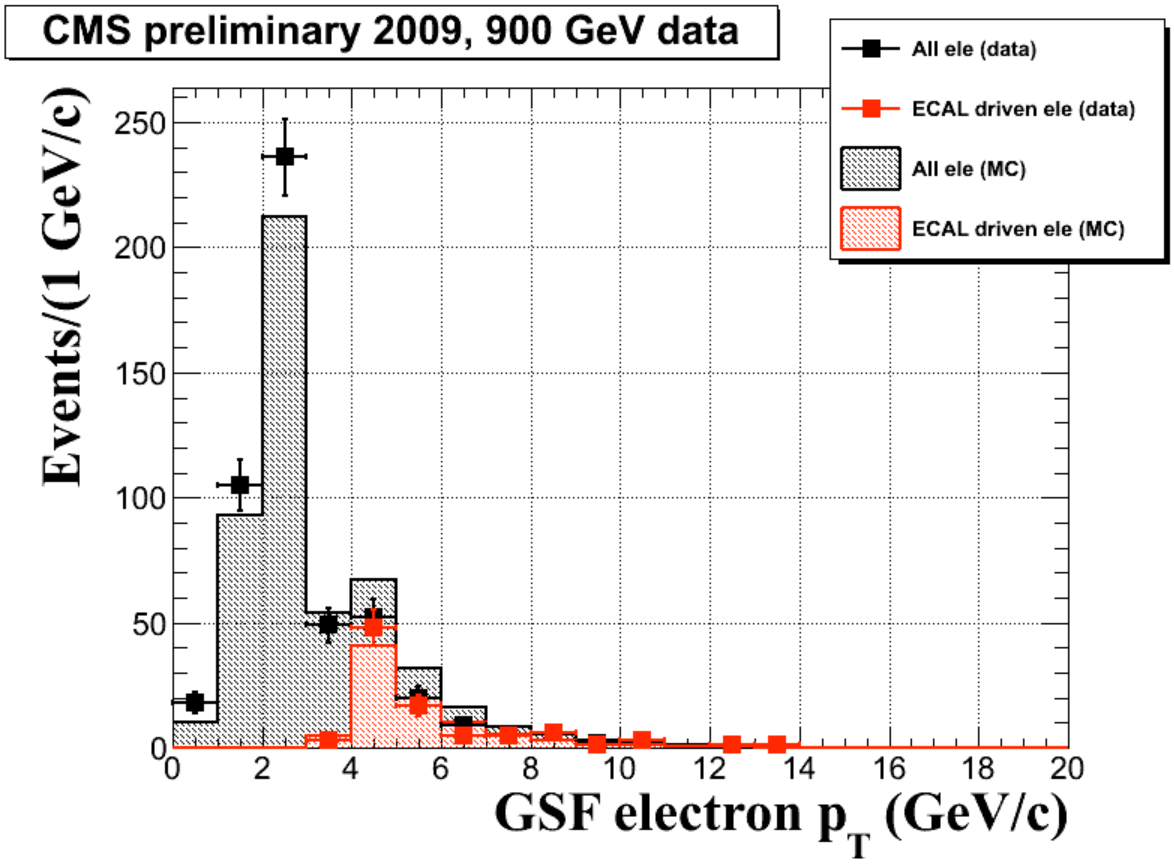
- Almost identical S/B, mass and width compatible
- M(π^0) is low in both data and MC
  - Mostly due to the readout threshold (100 MeV/Crystal) and conversions

$\pi^0 \rightarrow \gamma\gamma$



Using "out of the box" MC corrections to account for low readout threshold (100 MeV/crystal) and conversions

Electron p_T



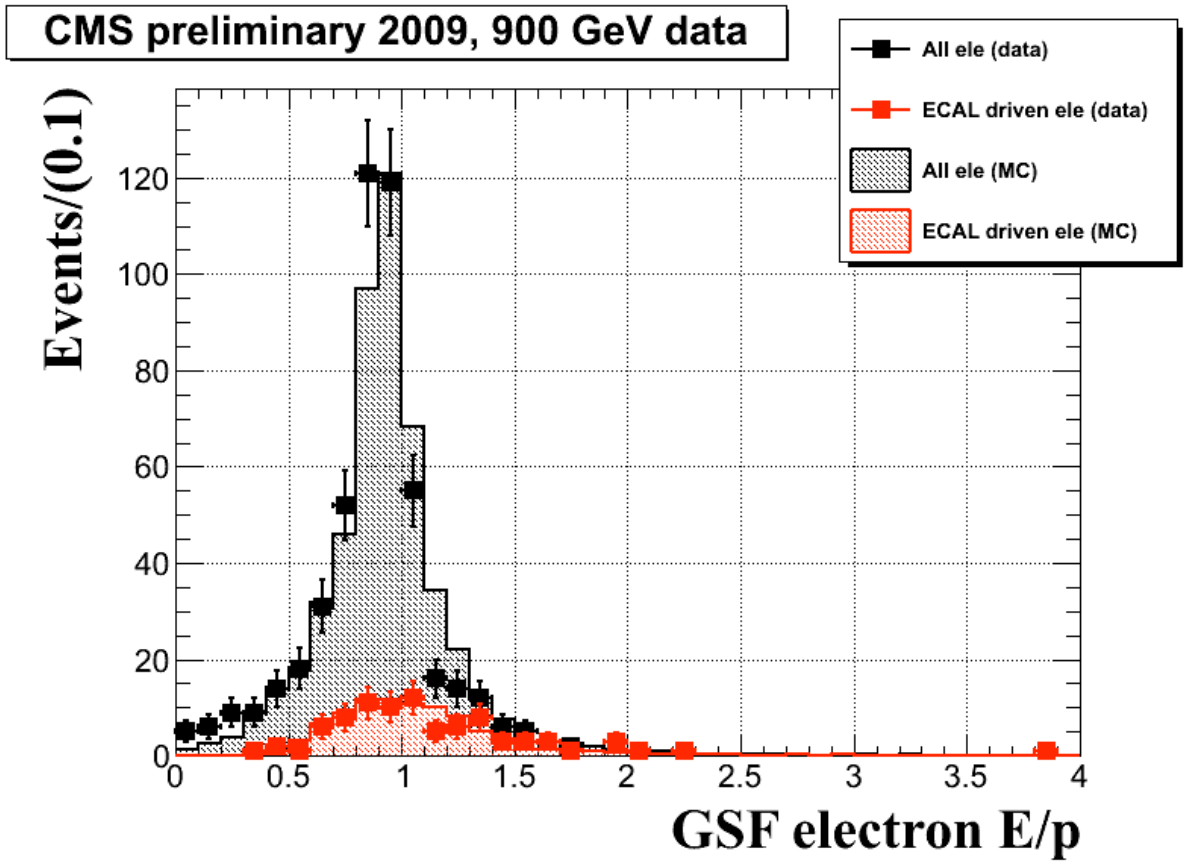
Electron transverse momentum as reconstructed in 900 GeV data (points) and 900 GeV MC (filled histos)

In black all electrons (tracker driven + ECAL driven)
In red only ECAL driven

MC is normalized to the same number of entries

Gaussian Sum Filter: R. Frühwirth, T. Speer: Nucl. Instrum. Methods Phys. Res., A 534 , 1-2 (2004) 217-221

Electron E/p



Electron E/p as reconstructed in 900 GeV data (points) and 900 GeV MC (filled histos)

In black all electrons (tracker driven + ECAL driven)
In red only ECAL driven

MC is normalized to the same number of entries

Gaussian Sum Filter: R. Frühwirth, T. Speer: Nucl. Instrum. Methods Phys. Res., A 534 , 1-2 (2004) 217-221

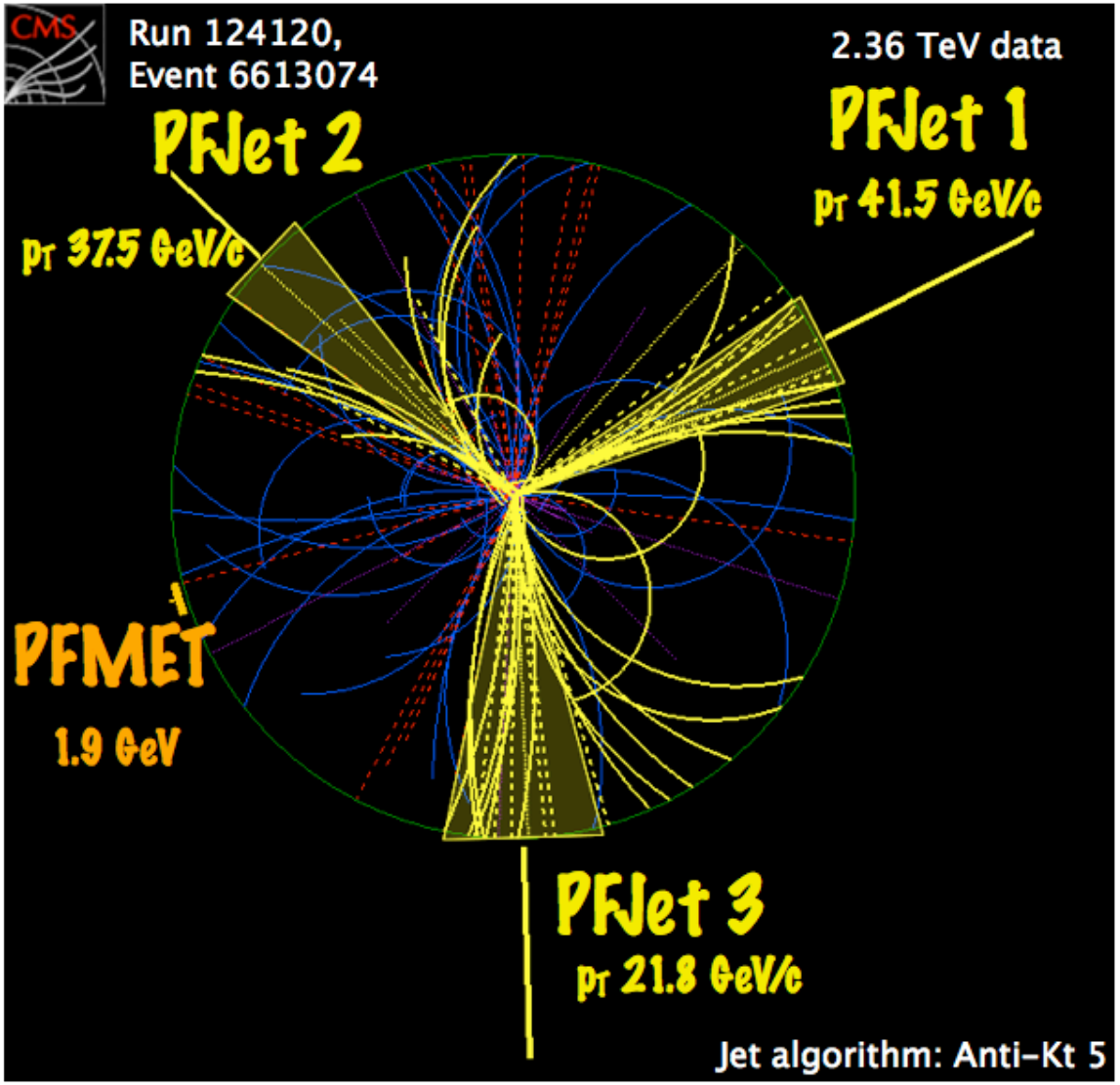
Particle Flow

Particle Flow

- Particle Flow: Full event reconstruction combining information from multiple sub-detectors
  - Topological matching between charged particle momenta measured using tracker with clusters in calorimeter
  - Corrects for energy loss along trajectories
  - Better precision, full event information

- The design of CMS detector is almost ideally suited to particle-flow:
  - Strong magnetic field to separate tracks
  - Excellent tracker with high tracking efficiency and low fake rate,
  - Fine granularity electromagnetic calorimeter (0.017 x 0.017)

Multi jet event @ 2.36 TeV



PFJets with (uncorrected) p_T > 20 GeV/c

Particle inside the jet:

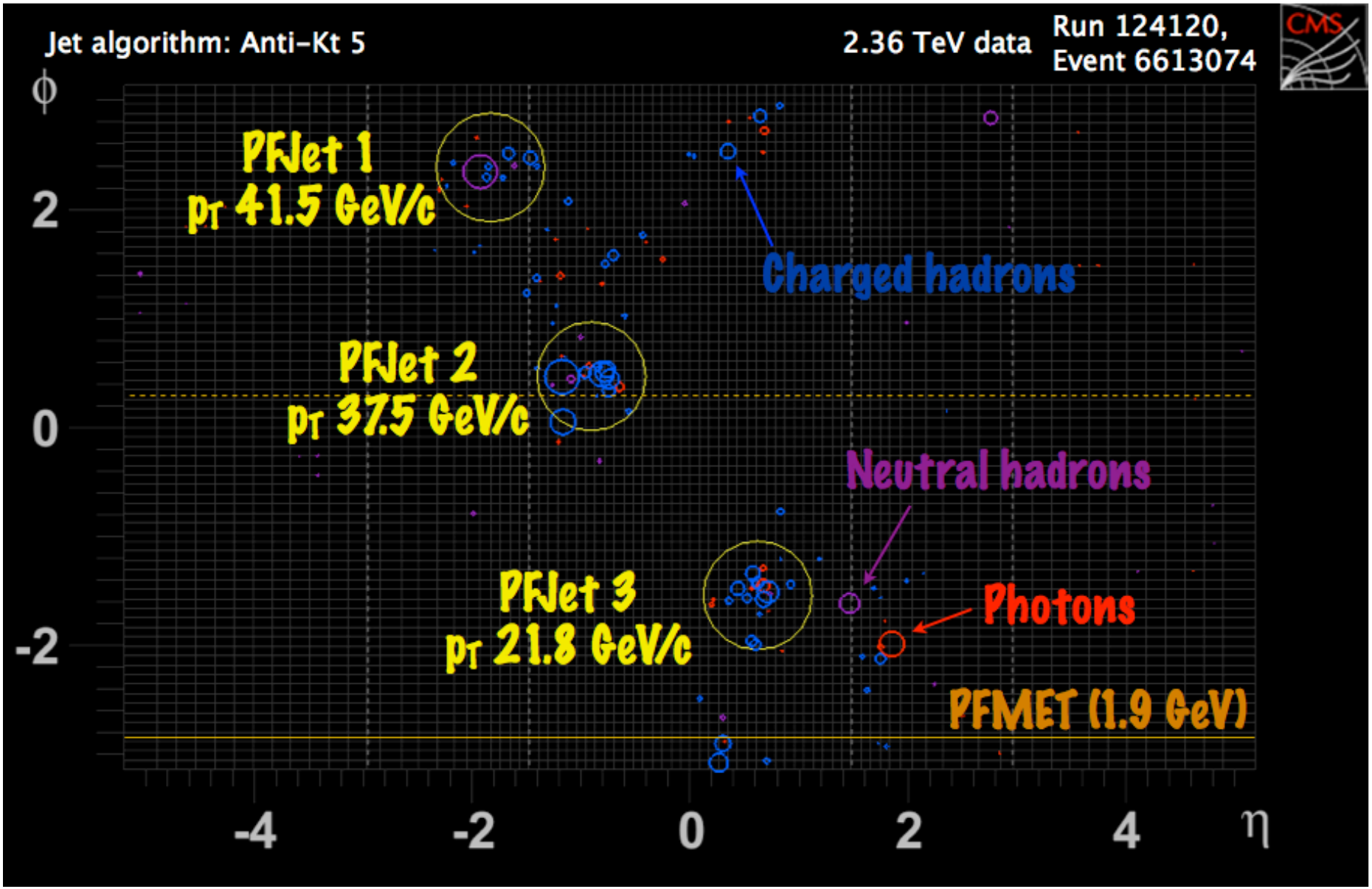
- Charged hadrons
- Photons
- Neutral hadrons

Particles outside the jet:

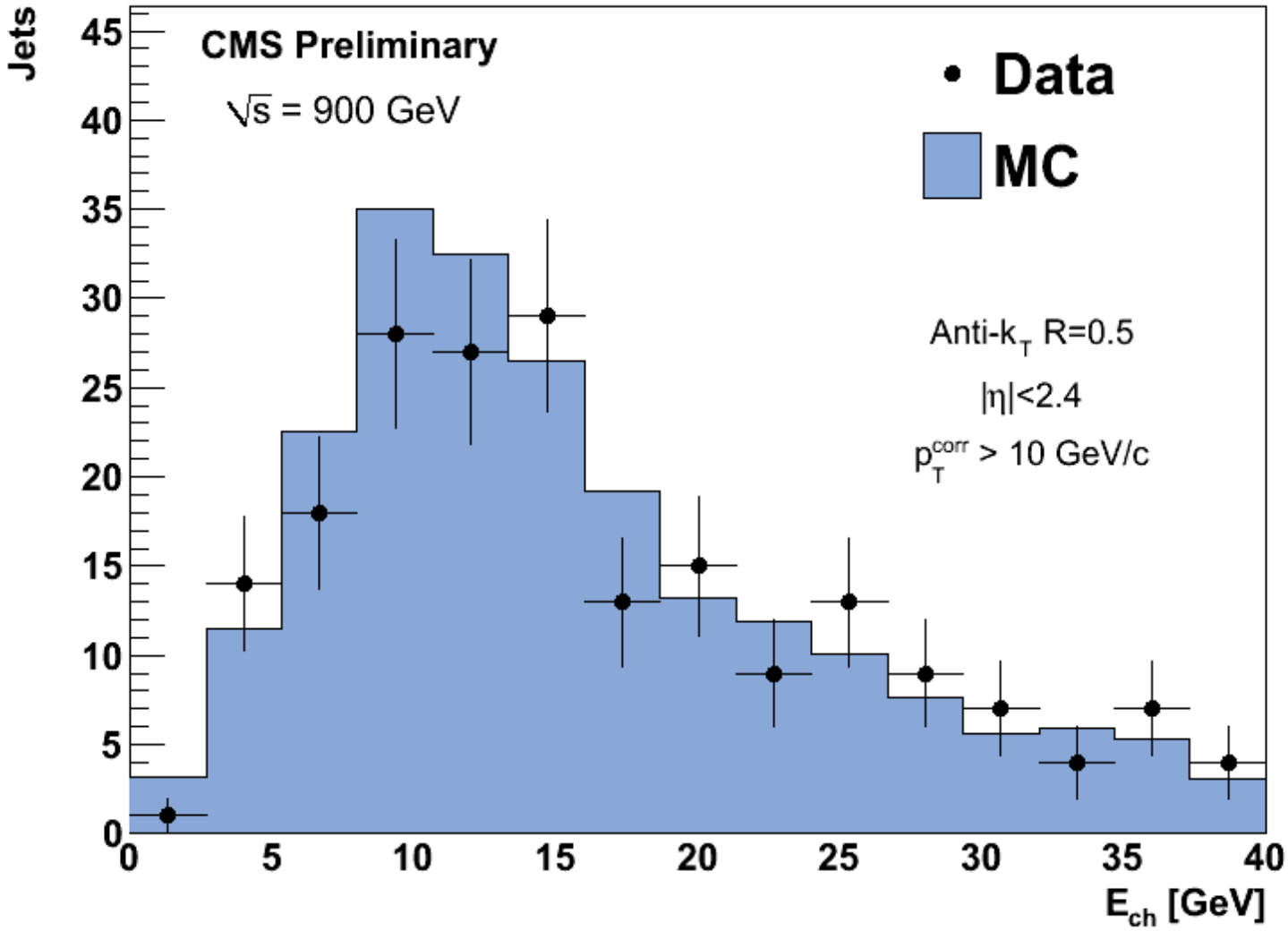
- Charged hadrons
- Photons
- Neutral hadrons

PFMET (1.9 GeV)

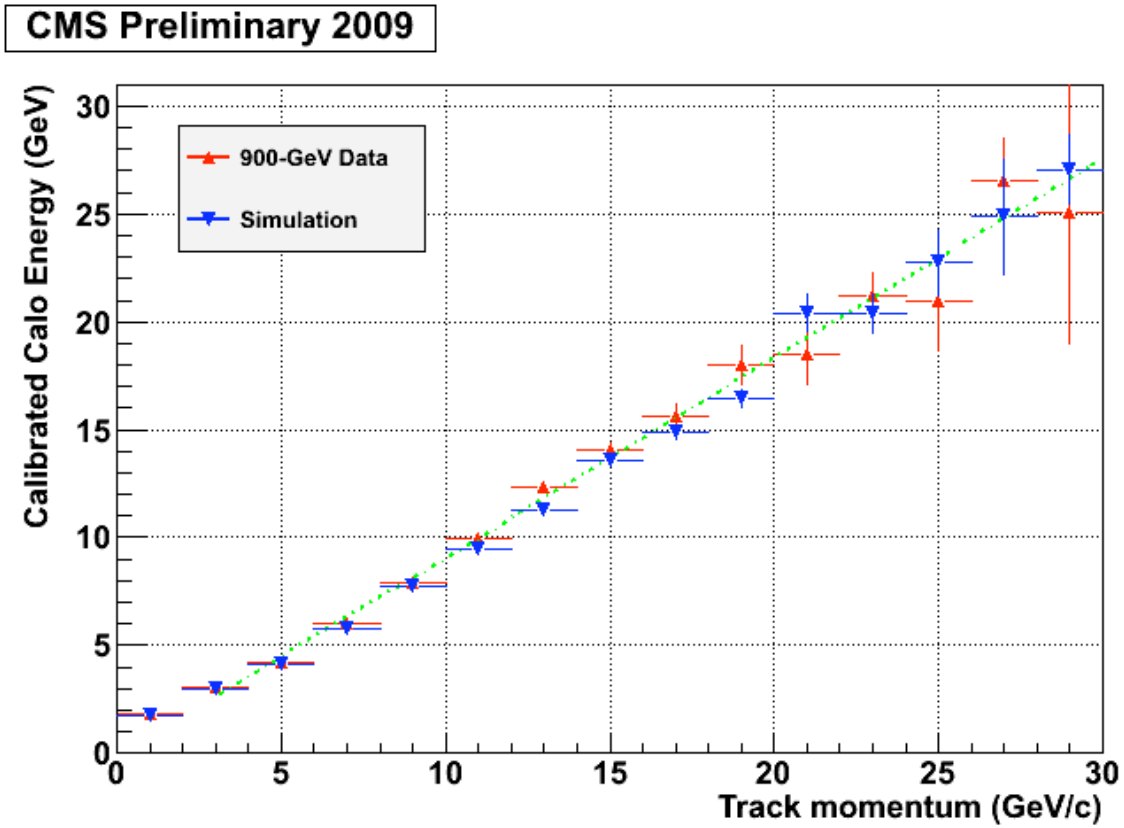
Multi jet event: η-φ view



Pflow Jet Composition



Charged hadron response



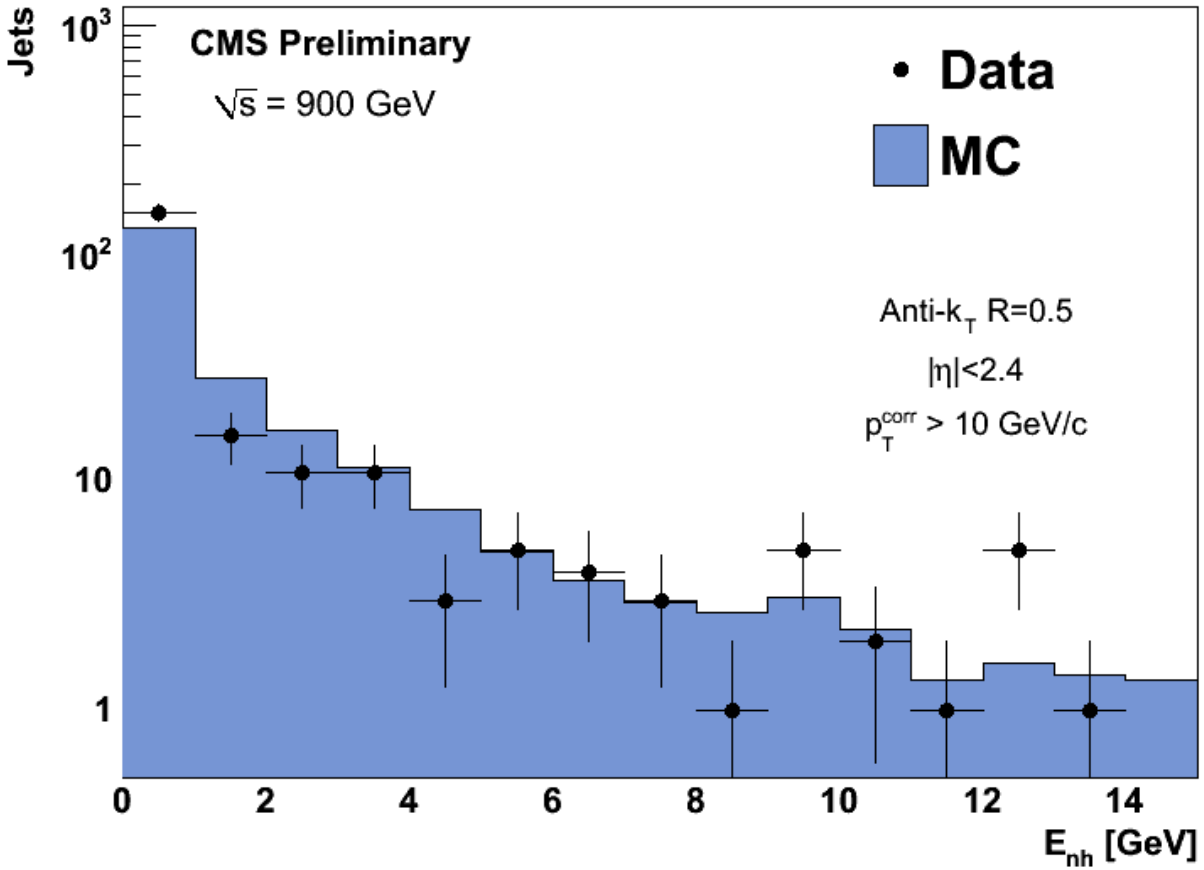
Selections:

- Track p_T > 1 GeV/c and $|\eta|$ < 2.4
- # hits > 14 and # pixel hits > 1
- HCAL hits linked to the track
- Only one track associated with jet

Linear fit to the data above 3 GeV

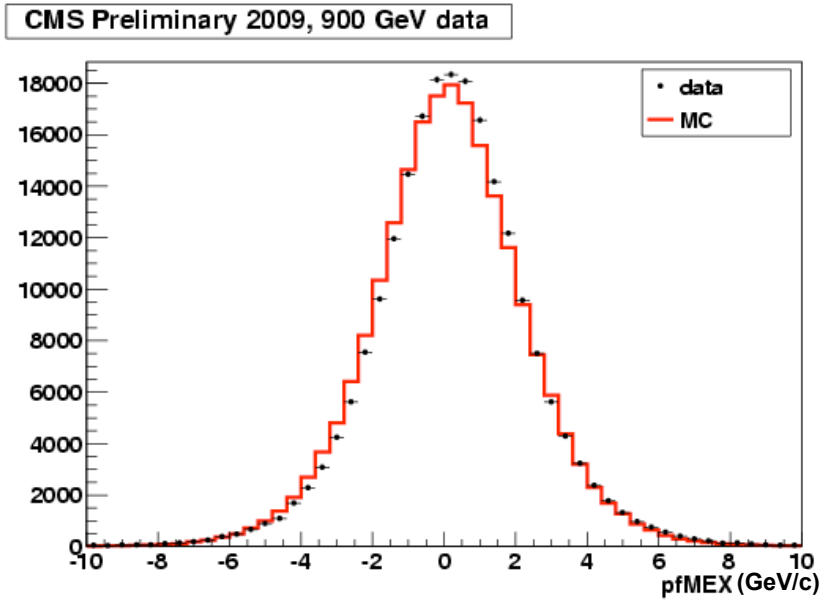
MC based calibration is validated

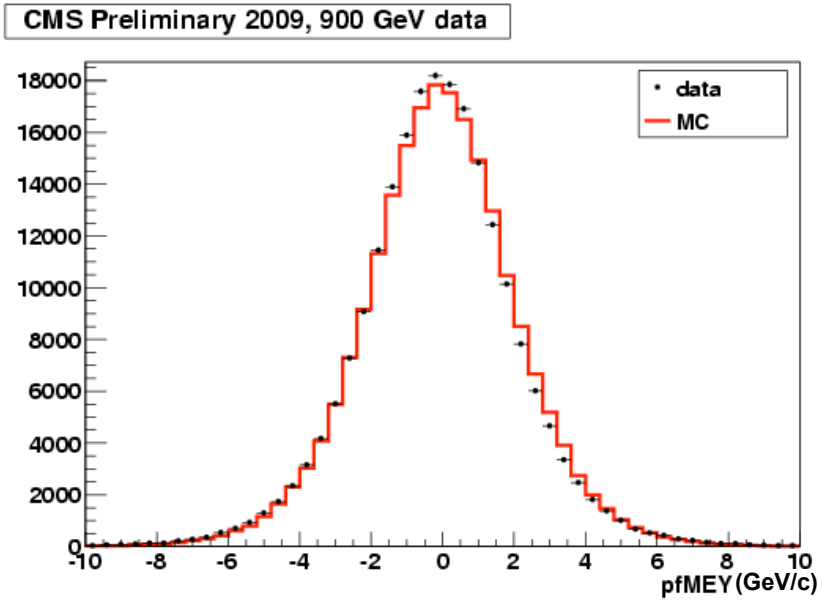
Neutral hadron energy distribution in jets

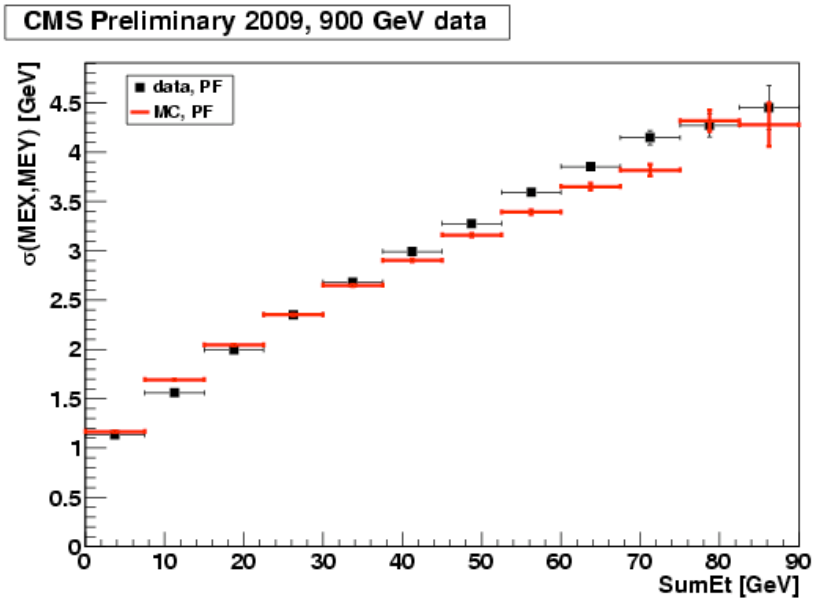


A calibrated calorimeter provides the possibility to extract the neutral hadron composition of jets using particle flow.

Particle Flow MET







Primary Charged Hadron Multiplicity Measurements

First CMS physics paper submitted (and accepted) for publication:
http://arxiv.org/abs/1002.0621

Minimum Bias at LHC

- Majority of pp collisions are soft (i.e. no hard parton scattering)

- Particle production in soft collisions is modeled using the different pp scattering processes

$$\sigma_{tot} = \sigma_{elas} + \sigma_{sd} + \sigma_{dd} + \sigma_{nd}$$

NSD

- Minimum bias @ LHC traditionally defined as Non-single Diffractive (NSD) events
  - enables comparison with previous experiments

- Measurements of charged particle multiplicity densities:
  - help understand mechanisms of hadron production and relative roles of hard and soft scattering @ LHC
  - are needed to understand the properties of inelastic events as they will be background due to pile-up at high luminosities
  - reference for heavy ion collisions

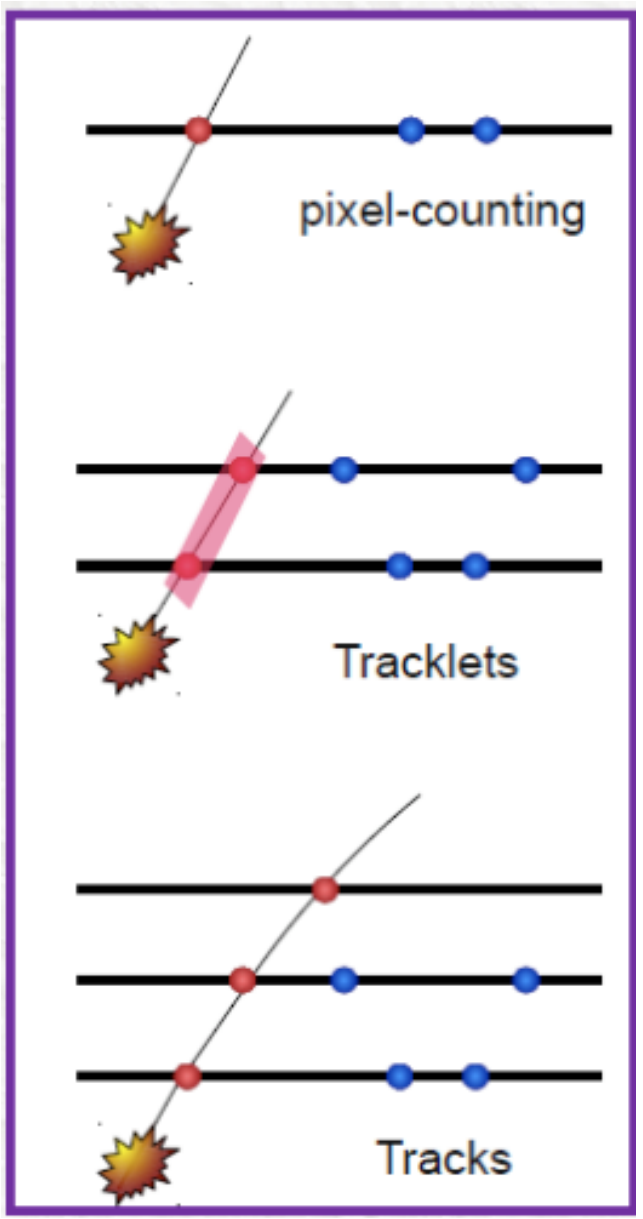
Analysis Techniques

Charged hadron observables:

- Particle multiplicities
- Average charged-particle p_T vs η
- Charged-particle p_T spectrum

Techniques:

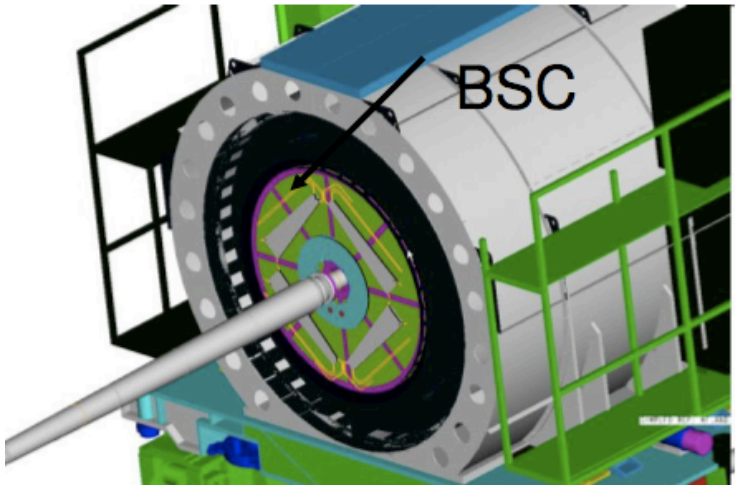
- Use (cluster) hits in pixel detector
- Use “primitive” tracks (“tracklets”) formed by correlating hits in two layers of the pixel detector projected to the vertex
- Use fully reconstructed tracks

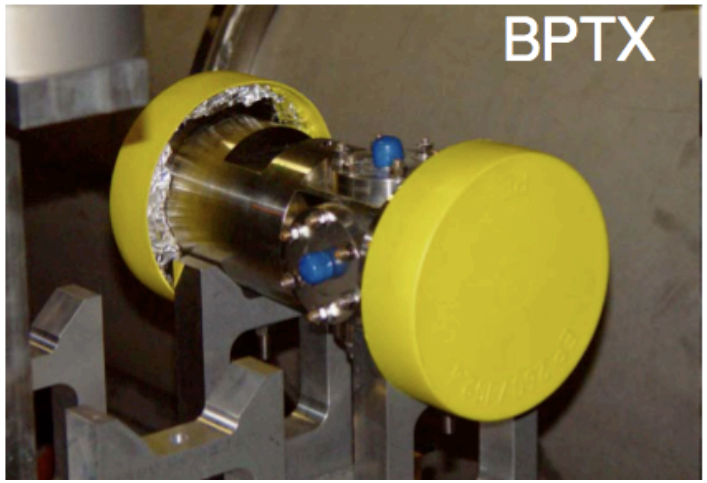


Triggers

- Beam Scintillation Counters (BSC)
  - located at ± 10.86 m from the nominal IP ($|\eta|$: 3.23 – 4.65)
  - each BSC is a set of 16 scintillator tiles
  - time resolution of 3 ns & ave. MIP detection eff. 96.3%
  - provide hit & coincidence rates
- Beam Pick-up Timing for the eXperiments devices (BPTX)
  - located around the beam-pipe at ± 175 m from the IP
  - better than 0.2 ns time resolution
  - provide precise info on bunch structure and timing of beam

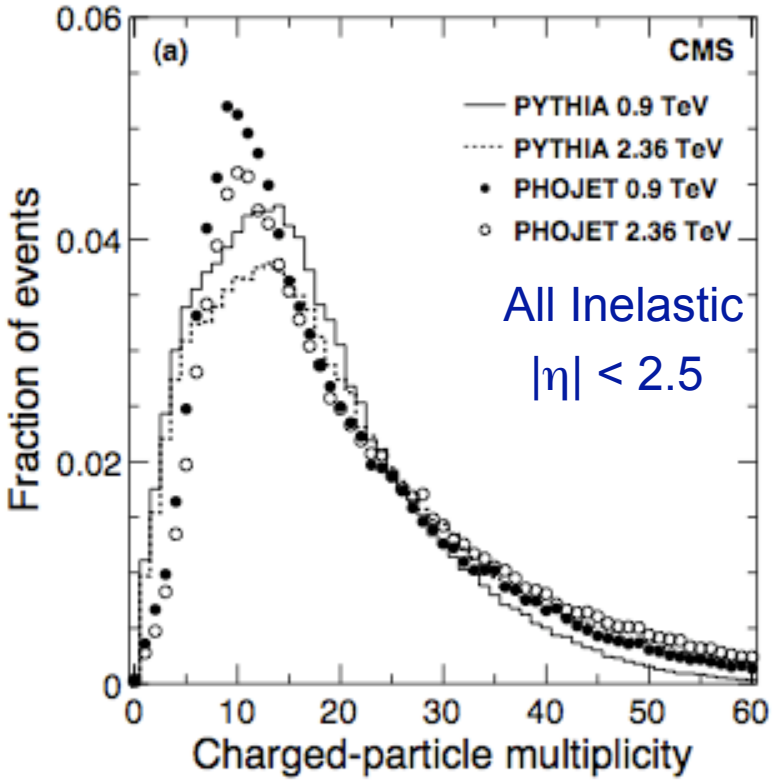
Trigger: signal in BSC coincident with signal from either BPTX device
BSC trigger efficiency > 98%

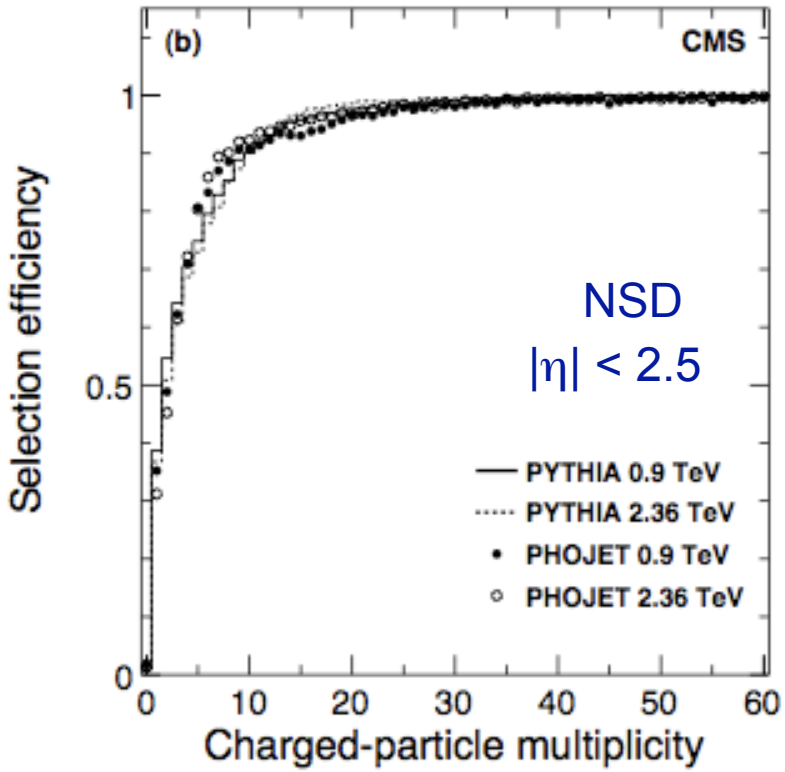




Event Selection

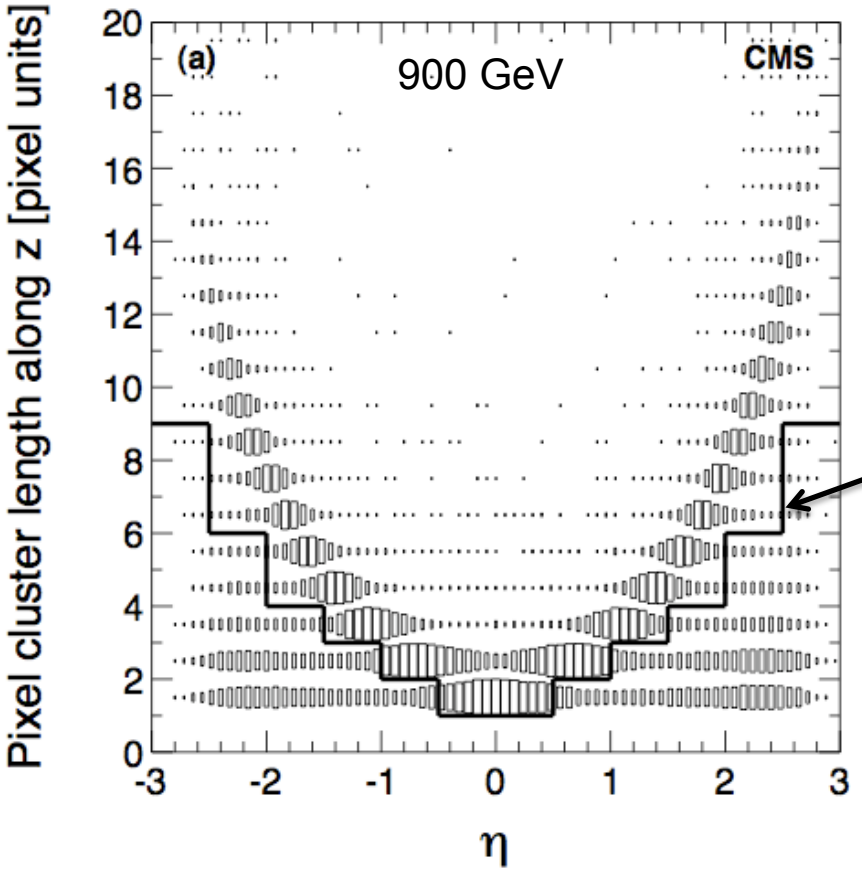
- Require BPTX signals from both beams passing the IP
- ≥ 1 reconstructed charged particle trajectory in the pixel detector
- >3 GeV on both sides of the Forward Calorimeter (HF)
- Beam-halo and beam-induced background rejection
- ≥ 1 reconstructed primary vertex





Cluster counting

- Cluster counting method
  - correlates the observed pixel-cluster length along z with the expected path length traveled by a primary particle at a given η value

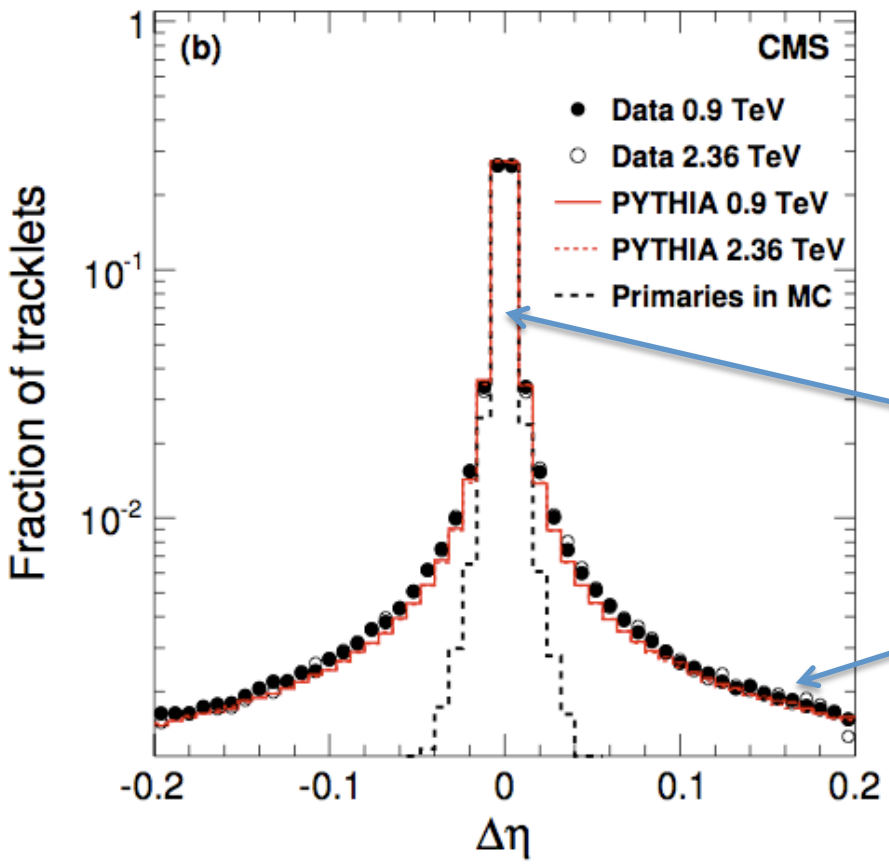


- Cluster length ~ |sinh(η)|
- Independent result for all 3 layers
- Immune to detector misalignment
- Sensitive to beam background
- Note: our detector is noise-free!

Selection cut:
removes clusters due to loopers, secondary particles and daughters of long-lived hadrons

Pixel Tracklets

- Pixel Tracklets
  - constructed from combinations of two pixel hits in any two pixel layers
  - calculate difference in the angular positions of the two clusters with respect to the PV, $\Delta\eta$ and $\Delta\phi$



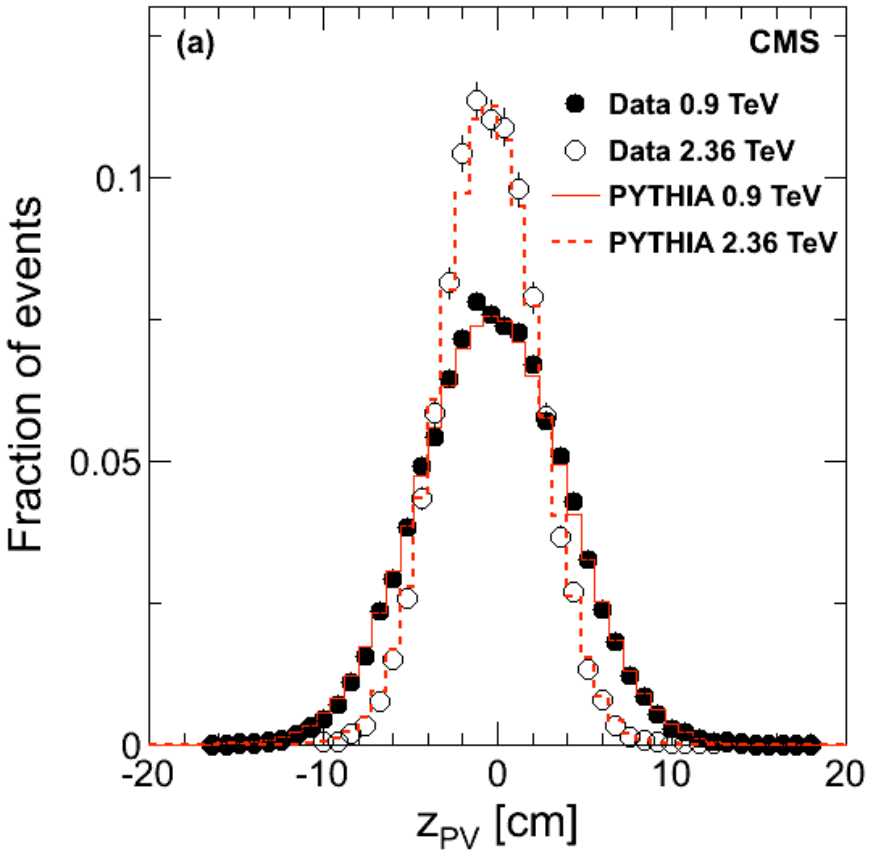
• The $\Delta\eta$ and $\Delta\varphi$ correlations are used to separate the signal
• Independent result for all 3 layer pairs
• Less sensitive to beam background
• side-band in $\Delta\varphi$ is used to subtract combinatorial background

Tracklets from primary particles

Combinatorial background

Tracking Method

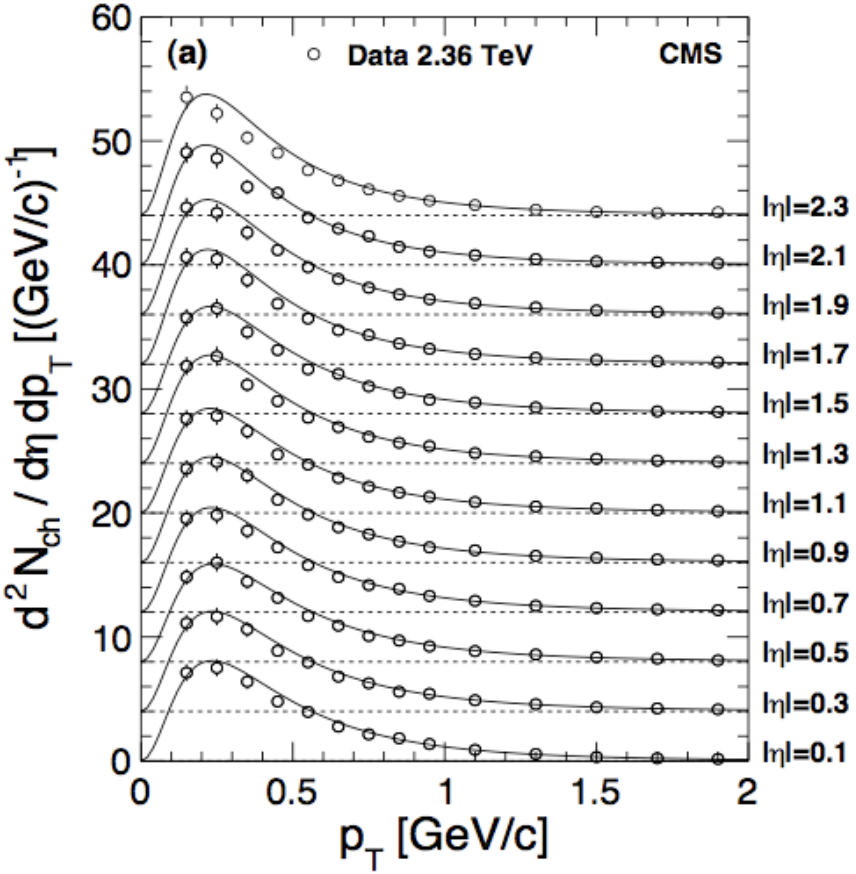
- Tracking method
  - Uses all pixel and strip layers
  - Builds particle trajectories iteratively



- Primary vertex reconstructed from tracks
- Compatibility with beam spot and primary vertex required
- Immune to background
- More sensitive to beam spot position and detector alignment

The vertex position distributions are clean Gaussians, with no tails

Average Charged Hadron Yield



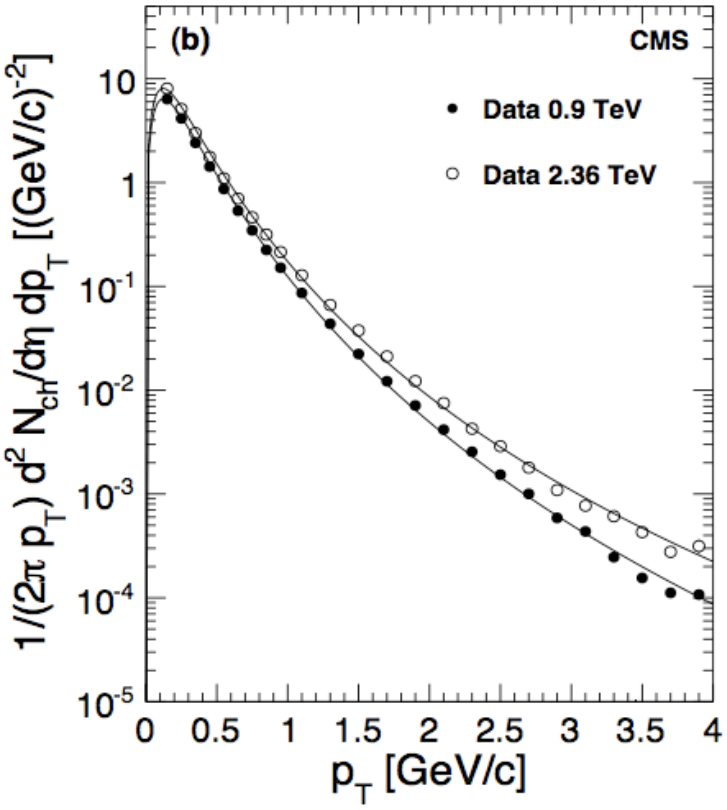
Differential yield of charged hadrons in the range $|\eta|<2.4$
The values with increasing η are successively shifted by four units along the vertical axis.

Distribution fit to Tsallis function:

$$E\frac{d^3N_{ch}}{dp^3} = \frac{1}{2\pi p_T}\frac{E}{p}\frac{d^2N_{ch}}{d\eta dp_T} = C(n,T,m)\frac{dN_{ch}}{d\eta}\frac{E}{p}\left(1+\frac{E_T}{nT}\right)^{-n}$$

C(n, T, m): normalization constant; m: charged pion mass; $E_T = \sqrt{m^2+p_T^2} - m$

p_T spectrum



- The transverse-momentum distribution of charged hadrons was measured up to 4 GeV/c.

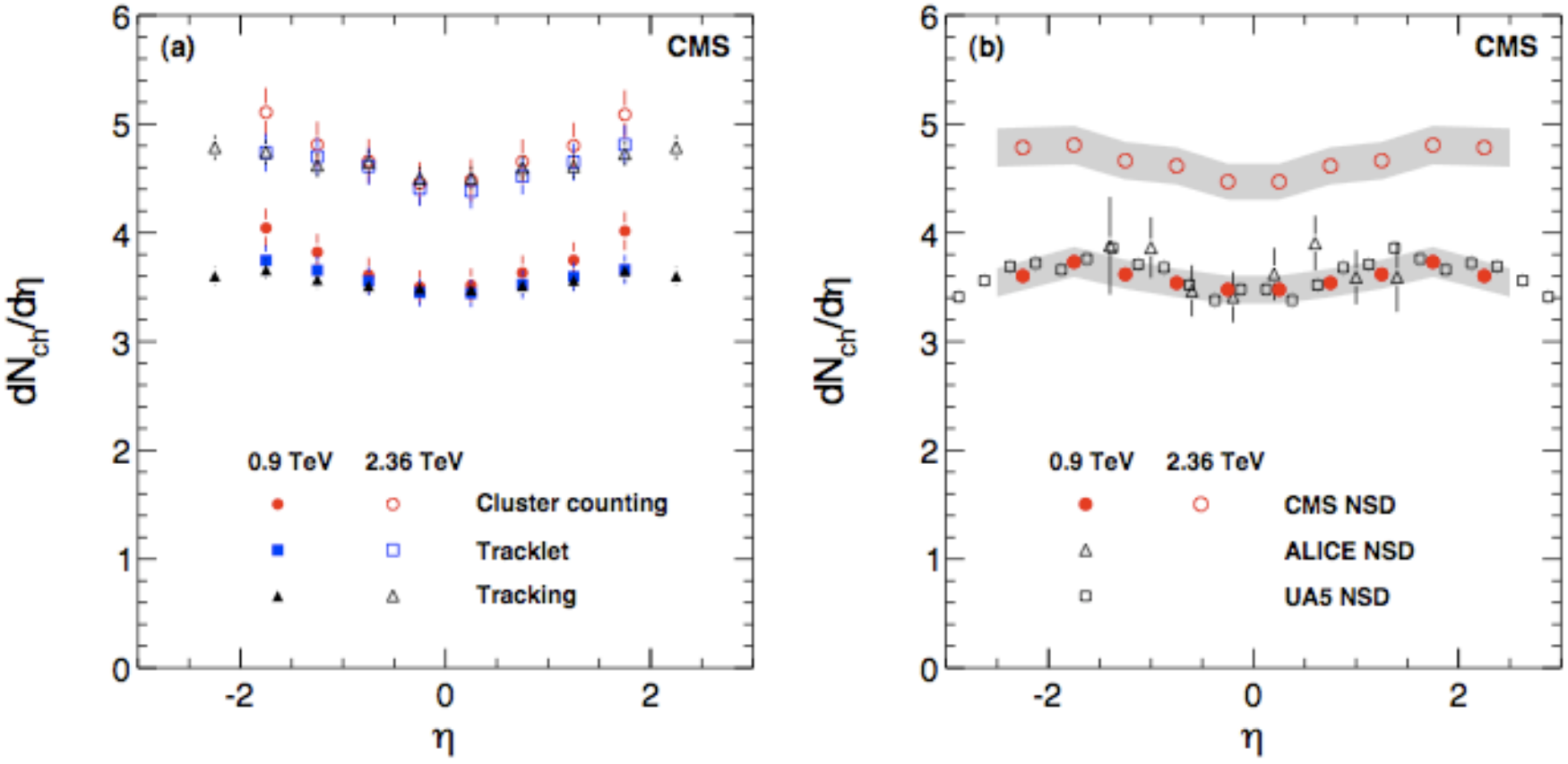
- With increasing energy, the p_T-spectrum gets "harder" as expected

$|\eta| < 2.4$:

$$\langle p_T \rangle = 0.46 \pm 0.01\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{GeV/c @ 0.9 TeV}$$

$$\langle p_T \rangle = 0.50 \pm 0.01\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{GeV/c @ 2.36 TeV}$$

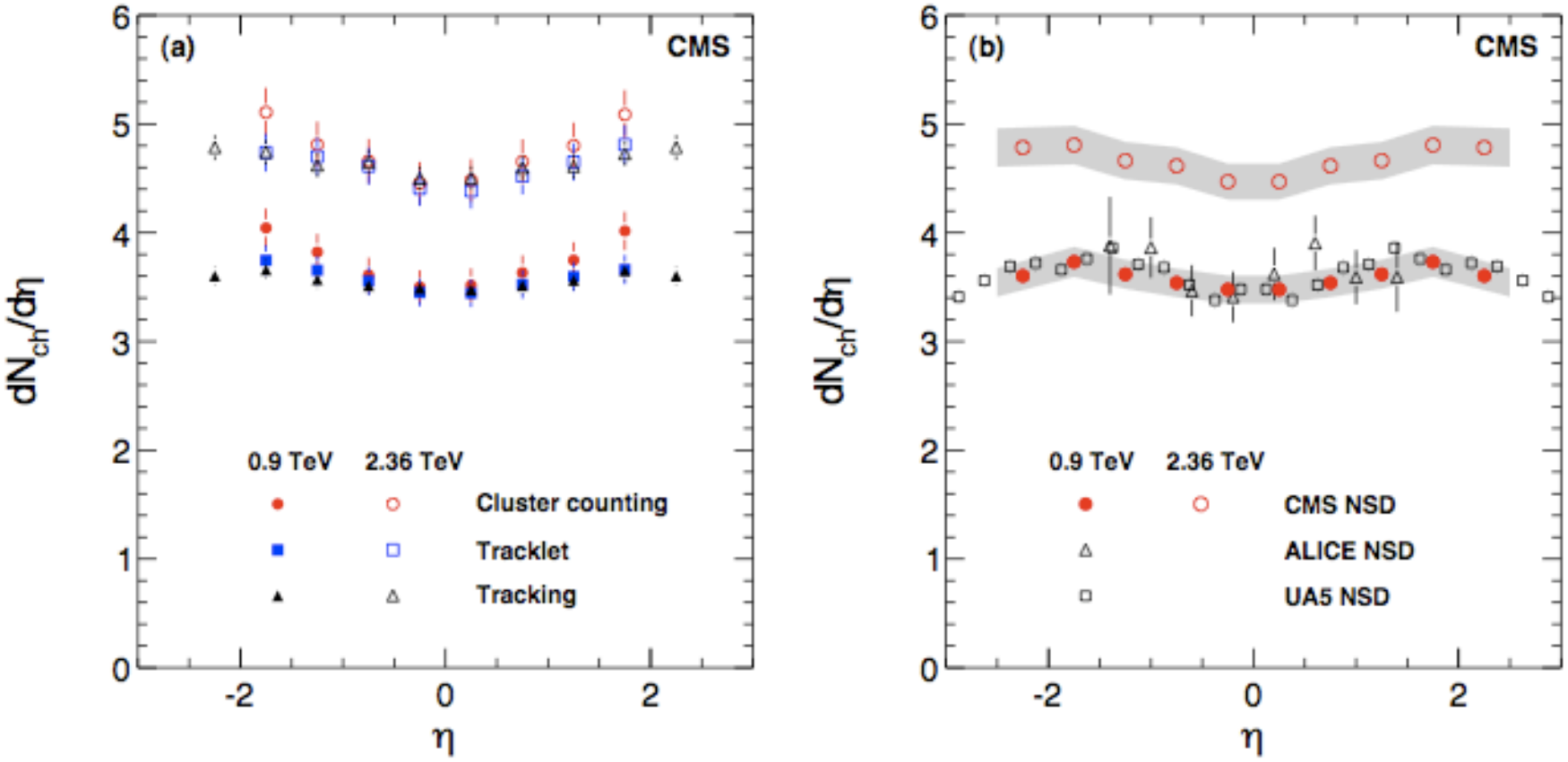
$dN_{ch}/d\eta$ distributions



Systematic uncertainties included for CMS:

-- contributions from event selection, acceptance, reconstruction efficiency, tracklet and cluster selection, correction for loopers, secondary particles, etc

$dN_{ch}/d\eta$ distributions

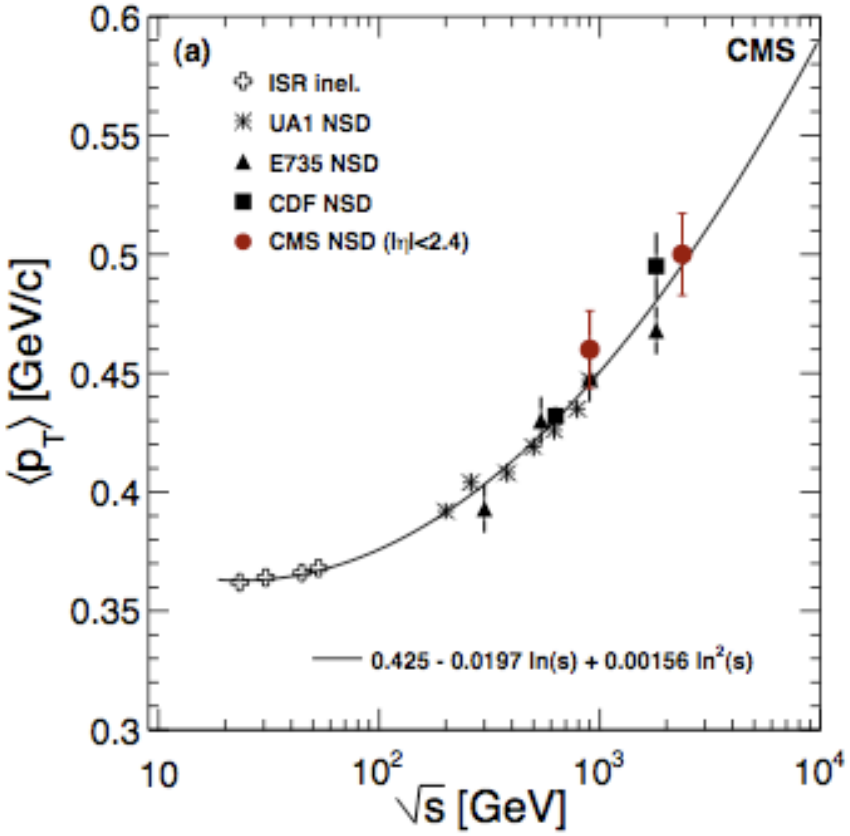


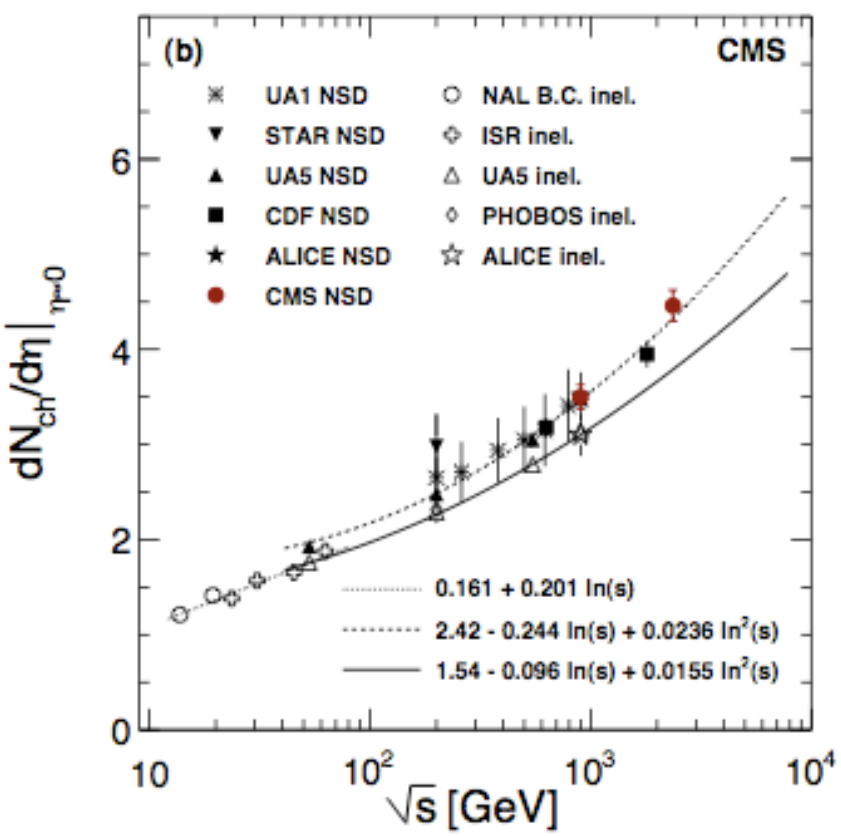
For $|\eta| < 0.5$

$$dN_{ch}/d\eta = 3.48 \pm 0.02\ (\text{stat.}) \pm 0.13\ (\text{syst.})\ \text{GeV/c @ 0.9 TeV}$$

$$dN_{ch}/d\eta = 4.47 \pm 0.04\ (\text{stat.}) \pm 0.16\ (\text{syst.})\ \text{GeV/c @ 2.36 TeV}$$

Comparisons





New measurements consistent with previous trends

Summary & Outlook

- The CMS detector is performing beautifully
  - performance is according to design
  - performance can be reproduced in Monte Carlo simulation
  - unprecedented level of understanding for such an early commissioning phase

- CMS has already made measurements of inclusive charged-hadron transverse momentum and pseudorapidity distributions @ 0.9 and 2.36 TeV
  - Results are in agreement with previous 0.9 TeV measurements
  - Confirm expectation of near equal hadron production in pp and $p\bar{p}$ collisions
  - Results at 2.36 TeV are the highest energy measurements at a particle collider to date

- Stay tuned for new results (and hopefully discoveries) in 2010-2011 !