Status of the CMS Experiment & First Results

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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, $4 \times 10^9$ p) struck collimators 150m upstream of CMS
  - Halo muons observed once beam (uncaptured and captured) started passing through CMS
The Sep. 19\textsuperscript{th} incident
CRAFT

The September 19\textsuperscript{th} incident was followed by Cosmics Runs at Operating Field (Oct ‘08, Aug ‘09)

\begin{center}
\textbf{CRAFT*: Cosmics Run at Four Tesla}
\end{center}

* 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 $>10 \text{ pb}^{-1}$!)

23 papers submitted to JINST
(17 papers already accepted)

Extensive documentation of detector performance
Feedback into \underline{realistic} simulation
Muon $p_T$ resolution (cosmics)

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 – 26\textsuperscript{th} November, 2009
And only 2 months later...

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

The 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 $0.46 \pm 0.01$ (stat.) $\pm 0.01$ (syst.) GeV/c at 0.9 TeV and $0.50 \pm 0.01$ (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, $dN_{\mathrm{d}}/d\eta|_{|\eta|<0.5}$, are $3.48 \pm 0.02$ (stat.) $\pm 0.13$ (syst.) and $4.47 \pm 0.04$ (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.
How did we go from

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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 2006. For non-single-diffractive interactions, the average charged-hadron transverse momentum is measured to be $0.36 \pm 0.01$ (stat.) $\pm 0.01$ (syst.) GeV/c at 0.9 TeV and $0.50 \pm 0.01$ (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, $dN/d\eta|_{|\eta|<0.5}$, are $3.48 \pm 0.02$ (stat.) $\pm 0.13$ (syst.) and $4.47 \pm 0.09$ (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: $\eta \rightarrow \gamma \gamma$

- Mass and width compatible with MC
- $\eta$ yield scale as expected ($\pi^0$ candle)
  - $N(\eta) / N(\pi^0) = 0.020 \pm 0.003$  \hspace{1em} DATA
  - $N(\eta) / N(\pi^0) = 0.021 \pm 0.003$  \hspace{1em} MC
Calorimetry: Missing ET

[Histograms showing CaloMETX and CaloMETY distributions for CMS 2009 Preliminary, \( \sqrt{s} = 900 \) GeV, with red lines for MC and black lines for Data.]
Calorimetric dijet events

 CMS preliminary
\sqrt{s}=900 \, \text{GeV}

jet $\phi$

jet $p_T$ (GeV/c)

Anti-$k_T$, $R=0.5$ CaloJets
jet $|\eta_{1,2}| < 3.0$

Events

CMS preliminary
\sqrt{s} = 900 \, \text{GeV}
anti-$k_T$, $R=0.5$ CaloJets
$|\text{Jet}_{1,2} \eta | < 3$

Jet $p_T$ asymmetry
Calorimetric dijet events plus tracks
Tracking & Particle ID
Tracking performance

Primary Vertex

CMS preliminary 2009
\( \sqrt{s} = 900 \text{ GeV} \)
Width: 39 mm

Pixel Clusters

Layer 1

CMS Preliminary 2009
\( \sqrt{s} = 900 \text{ GeV} \)

Probability

- Data, event selection
- MC, event selection

CMS Preliminary 2009
\( \sqrt{s} = 900 \text{ GeV} \)

Probability

- Data after event selection
- MC after event selection

-2.5<\( |\eta| <2.0 \)

layer 1
Tracking performance

Events with 5 to 100 tracks:
- Tracks with "highPurity" flag
  - at least 8 hits
  - relative error on $p_T < 10\%$
- No cut on $\eta$ or $p_T$
Double Gaussian fits (from a sample of \(\sim\)240 million minimum bias events)
**$K_s$**

Invariant mass of $\geq 2$ track vertices found by the secondary vertex B tagger. Clear $K_s$ peak with low background ( => low mistag rate )

**CMS preliminary**

- **900 GeV DATA**
- **900 GeV MC**

**$K_s$**: can be used as a vertexing and b-tagging commissioning tool
Candidate $K_s$ event (2.36 TeV)
Single Gaussian fits (from a sample of ~240 million minimum bias events)
CMS Preliminary: 900 GeV pp collisions

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

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

$\Gamma$ 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

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

Gaussian convoluted with Breit-Wigner in fit
dE/dx distributions can be fitted for various particles

- (protons, pions, kaons)

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

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

$M = p \sqrt{(dE/dx - C)/K}$

with $K = 2.547 \pm 0.011$

with $C = 2.715 \pm 0.014$
Particle ID with tracker $dE/dx$

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

Proton and Kaons are clearly separated

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

Track Selection:
- $p < 2$ GeV
- At least 10 Silicon strip hits
- $|d_0| \leq 2$ cm && $|dz| \leq 15$ cm
Muons
Endcap Muon Candidate
Barrel Muon Candidate
Di-muon event @ 2.36 TeV

\[ p_T(\mu_1) = 3.6 \text{ GeV/c}, \quad p_T(\mu_2) = 2.6 \text{ GeV/c}, \quad m(\mu\mu) = 3.03 \text{ GeV/c}^2 \]
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/c² region (background ~ 0)
Electrons/Photons
Data and MC comparison (uncorrected distributions)

- Almost identical $S/B$, mass and width compatible
- $M(\pi^0)$ is low in both data and MC
  - Mostly due to the readout threshold (100 MeV/Crystal) and conversions
Using “out of the box” MC corrections to account for low readout threshold (100 MeV/crystal) and conversions

CMS preliminary 2009, 900 GeV data

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

Nsig = 3966 ± 94
mean = 0.13646 ± 0.00037
sigma = 0.01550 ± 0.00037
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

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

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

PFJet 1
pt 41.5 GeV/c
PFJet 2
PT 37.5 GeV/c
PFJet 3
PT 21.8 GeV/c
PFMET (1.9 GeV)

Particle inside the jet:
- Charged hadrons
- Photons
- Neutral hadrons

Particles outside the jet:
- Charged hadrons
- Photons
- Neutral hadrons

PFJets with (uncorrected) PT > 20 GeV/c
Multi jet event: $\eta$-$\varphi$ view

Jet algorithm: Anti-$K_t$ 5

PFJet 1
$p_T$ 41.5 GeV/c

PFJet 2
$p_T$ 37.5 GeV/c

PFJet 3
$p_T$ 21.8 GeV/c

PFMET (1.9 GeV)

Charged hadrons

Neutral hadrons

Photons
Pflow Jet Composition

CMS Preliminary
\( \sqrt{s} = 900 \text{ GeV} \)

- Data
- MC

Anti-\( k_T \), R=0.5
|\( \eta |<2.4
\( p_T^{corr} > 10 \text{ GeV/c} \)
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.
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

\[ \sigma_{tot} = \sigma_{elas} + \sigma_{sd} + (\sigma_{dd} + \sigma_{nd}) \text{ NSD} \]

• 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 $\eta$
• 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 $\pm 10.86$ 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 $\pm 175$ 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
- $\geq 1$ 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
- $\geq 1$ reconstructed primary vertex

All Inelastic $|\eta| < 2.5$

NSD $|\eta| < 2.5$
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 $\eta$ value

Cluster length $\sim |\sinh(\eta)|$
• 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 $\Delta \phi$ correlations are used to separate the signal
- Independent result for all 3 layer pairs
- Less sensitive to beam background
- side-band in $\Delta \phi$ is used to subtract combinatorial background

![Graph showing distribution of tracklets](image)

- **Tracklets from primary particles**
- **Combinatorial background**
There is a graph showing the vertex position distributions for different energy levels (0.9 TeV and 2.36 TeV) and for PYTHIA simulations. The distributions are described as clean Gaussians with no tails.

The tracking method used:

- 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 $\eta$ are successively shifted by four units along the vertical axis.

Distribution fit to Tsallis function:

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

$C(n, T, m)$: normalization constant; $m$: charged pion mass;

$$ E_T = \sqrt{m^2 + p_T^2} - m $$
• 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.

$|\eta| < 2.4$:  
\[
\langle p_T \rangle = 0.46 \pm 0.01 \text{ (stat.)} \pm 0.01 \text{ (syst.) GeV/c @ 0.9 TeV}
\]
\[
\langle p_T \rangle = 0.50 \pm 0.01 \text{ (stat.)} \pm 0.01 \text{ (syst.) GeV/c @ 2.36 TeV}
\]
Systematic uncertainties included for CMS:
-- contributions from event selection, acceptance, reconstruction efficiency, tracklet and cluster selection, correction for loopers, secondary particles, etc
\[ dN_{\text{ch}} / d\eta = 3.48 \pm 0.02 \text{ (stat.)} \pm 0.13 \text{ (syst.) GeV/c @ 0.9 TeV} \]
\[ dN_{\text{ch}} / d\eta = 4.47 \pm 0.04 \text{ (stat.)} \pm 0.16 \text{ (syst.) GeV/c @ 2.36 TeV} \]
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!