First Physics Results from CMS experiment with LHC Collision Data of 2009

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✓ LHC is up and running

✓ CMS:
  • Is in physics commissioning mode
  • Detector performance is according to design

✓ First Collision on Monday, Nov. 23, 2009.

✓ Results of collisions at 900 and 2360 GeV (highest energy so far) from CMS experiment published (in JHEP).
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.) $\pm 0.02$ (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, $dN_{\text{ch}}/d\eta|_{|\eta|<0.5}$, 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.

*See Appendix A for the list of collaboration members
The number of created charged particles per unit of $\eta$ at $|\eta| \approx 0$ (denoted by $dN_{ch}/d\eta|_{\eta=0}$) provides constraints on particle production models, currently giving predictions at the LHC energies varying by 30-50%.

The measurement provides indirect information about the particle production mechanism and the energy density created in the collision.

These results will be important for measurements that receive a background from the underlying proton-proton collision and from the multiple interactions per beam crossing ("pileup") at higher luminosities, including future LHC upgrades.
Nature envelops LHC

2006: CMS detector tests magnet using Cosmics

~2500-strong CMS collaboration
~50 institutes from 38 countries
November, December 2009: Suspence, joy, tension, pride, ..

Almost 20 years since conception
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).
ρ-φ view of Detector

- 3.8 T Superconducting magnet
- Hermetic hadron Calorimeter, |η| ≤ 5.2
- HO planes
- Lead Tungstate E/M Calorimeter
- All Silicon Tracker
- Redundant Muon system (RPCS, Drift Tubes, Cathode Strip Chambers)
CMS has been ready: study of cosmics during last 2 years ➔ detector simulation is excellent ➔ 23 papers in JINST!

Work of Sunil Bansal, Monika Jindal, Chandigarh
LHC Start-up

- After the incident on September 19th, 2008 the LHC has started pp collisions on November 23th, 2009
  ~0.1 Hz collision, L~ few $10^{24}$ cm$^{-2}$ s$^{-1}$
  - Data taking: Dec. 12 and 14 (2x2 hours) ➔ CMS has collected,
    - 350 k minimum bias events at 900 GeV ($10 \mu b^{-1}$)
    - 20 k minimum bias events at 2360 GeV (< 1 $\mu b^{-1}$)
    - ~ 10 Hz collisions, L ~ few $10^{26}$ cm$^{-2}$ s$^{-1}$ (no pile-up)
    - Prob. of multiple collision in same event ~ $10^{-4}$
  - CMS has taken good quality data
  - All major parts of the detector are operating
  - High data taking efficiency (> 80%)
- LHC will resume operation soon, collisions by end-February
  - Run for 18 - 24 month at 7 TeV
    - 100 - 200 pb$^{-1}$ in 2010
    - 1 fb$^{-1}$ by the end of 2011

Ultimately, $10^9$ Hz collisions with L ~ $10^{34}$ cm$^{-2}$ s$^{-1}$, energy 14 TeV?
Trigger and Luminosity in CMS

**Trigger**: Beam Scintillator Counters (BSC) AND beam pickups (BPTX)

- Beam Scintillator Counters @ ± 10.86 m from IP, $3.23 \leq |\eta| \leq 4.65 \rightarrow$ measure hit and coincidence rates, resolution 3 ns, mip detection eff. ~ 96%
- Beam pick-up devices @ ± 175 m from IP \rightarrow precise information on bunch structure and timing of incoming beams

**On-line luminosity monitor Novel method**: Uses signals from Forward Hadron Calorimeter (HF)

- Independent of main CMS DAQ
- 2 online methods for measuring relative lumi.
- Measure avg. ET sum per tower
- Zero counting \( \Rightarrow \) Measure fraction of empty towers:

\[
\mathcal{L} \propto \langle E_T \rangle \\
\mathcal{L} \propto -\log(\langle f_0 \rangle)
\]
Events and data samples

Event selection:

>3 GeV on both sides of HF
+ Beam Halo rejection (BSC): reject events having scintillators hits on 2 sides with time difference < 73 ± 20 ns
+ Beam background rejection (reject events with large # pixel hits)
+ Collision vertex (reco eff. > 99%) → beam spot: use tracks with $p_T > 900$ MeV/c, $\sigma_{xy}: 0.5$ mm → z-position of primary vertex: use tracks of $p_T > 75\text{MeV/c}$, track within 2mm of beam spot

<table>
<thead>
<tr>
<th>Centre-of-mass Energy</th>
<th>0.9 TeV</th>
<th>2.36 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection</td>
<td>Number of Events</td>
<td></td>
</tr>
<tr>
<td>BPTX Coincidence + one BSC Signal</td>
<td>72 637</td>
<td>18 074</td>
</tr>
<tr>
<td>One Pixel Track</td>
<td>51 308</td>
<td>13 029</td>
</tr>
<tr>
<td>HF Coincidence</td>
<td>40 781</td>
<td>10 948</td>
</tr>
<tr>
<td>Beam Halo Rejection</td>
<td>40 741</td>
<td>10 939</td>
</tr>
<tr>
<td>Beam Background Rejection</td>
<td>40 647</td>
<td>10 905</td>
</tr>
<tr>
<td>Valid Event Vertex</td>
<td>40 320</td>
<td>10 837</td>
</tr>
</tbody>
</table>
Variety of proton-on-proton interaction

Diffraction: when one or both beam particles go to high mass state.

Diffractive events have much less charged multiplicity compared to non-diffractive collision.

Single diffractive events are very forward
Majority of p-p collisions are soft, elastic.

- no hard scattering of partonic constituents
- cannot be described well by perturbative QCD
- phenomenological models (hadronisation, fragmentation, ..) fitted to experimental data.

- LHC data, even at lower energies, crucial for extrapolation of behaviour of multiplicity and total cross-section from lower to higher energies.

- LHC experiments are meant for study of hard, inelastic scattering.
- At high lumi, interesting, rare events will be embedded in ~ 20 near-simultaneous minimum bias events!
- Event modelling must take into account minimum bias processes may need tweaking based on current LHC data.

- Minimum bias events in p-p collisions are also reference measurements for Heavy Ion interactions.
Relevance of hadron-hadron interaction models

- As of today, components of various processes differ in available event generator packages.

- Phojet describes large rapidity gap events.
- High-mass diffractive processes linked with non-diffractive process.
- Pomeron, Regge, soft-colour-reconnection phenomenologies revived with HERA, Tevatron data.

- Multi-parton interactions model described in Pythia explained UA2, UA5, Tevatron data (non-diffractive hadron production).

<table>
<thead>
<tr>
<th>Energy</th>
<th>PYTHIA</th>
<th></th>
<th></th>
<th>PHOJET</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.9 TeV</td>
<td>2.36 TeV</td>
<td>0.9 TeV</td>
<td>2.36 TeV</td>
</tr>
<tr>
<td>SD</td>
<td>22.5%</td>
<td>16.1%</td>
<td>21.0%</td>
<td>21.8%</td>
</tr>
<tr>
<td>DD</td>
<td>12.3%</td>
<td>35.0%</td>
<td>12.8%</td>
<td>33.8%</td>
</tr>
<tr>
<td>ND</td>
<td>65.2%</td>
<td>95.2%</td>
<td>66.2%</td>
<td>96.4%</td>
</tr>
<tr>
<td>NSD</td>
<td>77.5%</td>
<td>85.6%</td>
<td>79.0%</td>
<td>86.2%</td>
</tr>
</tbody>
</table>

Expected fractions before any selection and selection efficiencies from 2 models.

Exclusion of SD ➔ 95% pure sample.
Multiparton interactions and partonic cross-section

\[ \sigma(p_1 + p_2 \rightarrow j_1 + j_2 + X) = \int_0^1 dx_1 f(x_1, \mu^2) \otimes \] \[ \hat{\sigma}(x_1 p_1 + x_2 p_2 \rightarrow j_1 + j_2) \otimes f(x_2, \mu^2) \]

- partonic cross section varies faster than \( \frac{1}{p_{\perp \text{min}}^2} \)
- diverges with \( p_\perp \)
- calculate x-section as function of \( p_{\text{tmin}} \)

Eventually, partonic cross-section exceeds non-diffractive, total inelastic cross-section \( \Rightarrow \) Results in more than one interaction per event

Average number of interactions per event depends on how soft Interactions are treated, on parton densities, hadronisation, factorisation.

\# of interactions, \( n \), depend on \( p_{\text{tmin}} \). \( n \) is Poisson distributed.

\( \Rightarrow \) Study min. bias events thoroughly, with as soft particles as possible
Large uncertainties at present for soft hadron physics cross-section and multiplicities \(\rightarrow\) min.bias and underlying events measurements at LHC is very important for understanding of Standard Model and BSM physics.
• Bulk of Pt spectrum lies at low $p_T$, with peak below 200 MeV/c $\Rightarrow$ detectors have to be efficient in measuring low momentum tracks $\Rightarrow$ large effort has been devoted in CMS (and ATLAS).

• Measurement of track pseudorapidilty and $p_T$ spectra is based on (charged) track counting $\Rightarrow$ Threshold for track reconstruction reduced considerably from nominal 500 MeV/c. $\Rightarrow$ Use only innermost detector layers, drop requirement of many hits $\Rightarrow$ Require quality tracks and track-vertex association $\Rightarrow$ Removes most (~75%) of secondary tracks, but also some (~25%) primary tracks $\Rightarrow$ efficient track selection and vertexing needed.

• Dominant uncertainty due to alignment of detector element $\Rightarrow$ try to reduce dependency on detector alignment $\Rightarrow$ 2 complementary strategies developed in CMS: Hit Counting and Tracklet Reconstruction.
World’s largest silicon detector, at -10°C

- 1440 silicon pixel + 15148 silicon strip detectors (SST), \(|\eta| \leq 2.5\)
- Impact parameter resolution: 100 \(\mu\)m
- Transverse momentum resolution: 0.7% for 1 GeV/c ch. particles

Pixels: three 53.3 cm long barrel layers at radii 4.4, 7.3, 10.2 cm.
+ 2 forward disks between 6-15 cm, at \(z = 34.5, 46.5\) cm

SST: total 205 m\(^2\), 55 cm long, 10 layers between 22 to 110 cm from beam.

Precision in alignment obtained in advance with cosmics, for particle trajectories in bending plane: 3-4 \(\mu\)m

Status of detector during data taking:
- 98.4% Pixel + 97.2% SST channels operational.
- Fraction of noisy Pixel channels \(\leq 10^{-5}\)
- High Data taking efficiency (> 80%)
energy loss in the tracker layers well described by MC

vertex position distributions ➔ clean Gaussians, with no tails

Hits association with primary tracks

Correlation between the pseudorapidity position and ionization energy deposition in pixel modules.
Pixel Cluster Counting method

- Counting hits (clusters of pixels) in the pixel barrel layers
  - Measure $p_T$ upto 30 MeV/c, $|\eta| \leq 2$
- Cluster length $\sim |\sinh(\eta)|$
- Use pixel cluster size information:
  - estimate z position of interaction vertex
  - remove hits at high $\eta$ from non-primary sources

- Shorter clusters are eliminated (loopers, secondaries)
- Corrections for loopers, weak decays, secondaries.

- Independent result for all 3 layers
- Immune to detector misalignment
- Sensitive to beam background

Pixel cluster length along the beam direction as a function of $\eta$. The solid line shows the cut applied.

Obtain track multiplicity using hit-to-track correction function obtained from Monte Carlo.
PixelTracklet method

- Tracklets: pairs of clusters on different pixel barrel layers $\rightarrow$ measure $p_T$ down to 50 MeV/c, $|\eta| \leq 2$
- The $\Delta \eta$ and $\Delta \phi$ correlations are used to separate the signal
- A side-band in $\Delta \phi$ is used to subtract combinatorial background
- Independent result for all 3 layer pairs
- Less sensitive to detector response simulation and beam background.

Tracklets don’t provide much info on curvature, but correlation to the origin

$\Delta \eta$ distribution of the two clusters of the tracklets tails: due to combinatorial backgrounds.
Correction for event selection eff. + contribution from SD events = 8.3%.

# of clusters attached to reconstructed tracks in pixel detector with $|\eta| < 1$

Pythia predicts fewer particles with $p_T < 500$ MeV/c $\Rightarrow$ mismatch at low values, but does not affect final measurements.
Tracking method

- Uses all pixel and strip layers
  - requires ≥ 3 hits, 2 in pixels.
  - Pt threshold ~ 100 MeV/c, |η|≤2.4
  - Eff. > 80% for pions, p_T=250 MeV/c

- Builds particle trajectories iteratively
- Low fake rate achieved with cleaning based on cluster shapes
- 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

Differential yield of charged hadrons in the range, p_T > 100 MeV/c, |η|<2.4 The values with increasing η are successively shifted by four units along the vertical axis.

\[
\langle p_T \rangle = 0.46\pm0.01\pm0.01 \text{ GeV/c at } 0.9 \text{ TeV}, \\
\langle p_T \rangle = 0.50\pm0.01\pm0.01 \text{ GeV/c at } 2.36 \text{ TeV}.
\]
The transverse-momentum distribution of charged hadrons measured up to 4 GeV/c, $|\eta|< 2.4$

- systematic uncertainty 4%
- With increasing energy, the $p_T$-spectrum gets “harder”.

$$\frac{d^2 N}{dy \, dp_T} = \frac{E}{p} \frac{d^2 N}{d\eta \, dp_T}$$

$$E \frac{d^3 N}{dp^3} = \frac{d^3 N}{d\phi \, dy \, p_T \, dp_T} = \frac{1}{2\pi p_T} \frac{d^2 N}{dy \, dp_T}$$

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

Spectrum well fitted by the Tsallis-function: combines a low-$p_T$ characteristics by inverse slope parameter $T$ (at low energy ~Boltzmann distribution), with a high-$p_T$ tail described in terms of exponent $n$.

$$E_T(p_T) = \sqrt{m^2 + p_T^2} - m$$

$n, T$ parameters

$m=$ pion mass
Multiplicity distributions

$dN_{ch}/d\eta$ distributions obtained from three methods at 0.9 TeV and 2.36 TeV. The error bars represent systematic uncertainties excluding those common to all the methods.

$dN_{ch}/d\eta$ distributions averaged over the cluster counting, tracklet and global track methods. Shaded band represents systematic uncertainties. The error bars on the UA5 and ALICE data points are statistical only.
Features of Pseudorapidity distribution

- The rapidity distribution $dN/dY$, is expected to be flat for $Y\approx 0$.
- $\eta$ is not same as $Y$ for pions and kaons with $pt > 200$ MeV/c.
- The numerical difference between $Y$ and $\eta$ causes subtle wavy effect.

- More hadrons are produced per unit of rapidity at high energies than at lower energies, which is interesting given that peripheral nature of these collisions.

From the CMS data, $dN/d\eta = 3.48 \pm 0.02 \pm 0.13$ at 0.9 TeV and $dN/d\eta = 4.47 \pm 0.04 \pm 0.15$ at 2.36 TeV.

From ALICE measurements, $dN/d\eta = 3.10 \pm 0.13 \pm 0.22$ at 0.9 TeV

- increase of 28.4% is significantly more than the 18.5% predicted by a tuned version of PYTHIA, and the 14.5% predicted by PHOJET models.
Energy dependence

Collision energy dependence of average transverse momentum.
\[ \langle p_T \rangle = T \frac{2n}{n-3} \]

Charged particle pseudorapidity density as a function of collision energy, obtained as sum of differential yields for \( p_T = (0.1, 3.5) \) GeV/c + extrapolations to the lower and upper sides.
Discussion on energy dependence

- Comparison with lower energy measurements: ISR, FNAL, UA1, UA5, CDF verify whether $dN/d\eta$ at $\eta=0$ varies linearly with $\ln (s^{1/2})$ or not.

- Feynman→ the variation with center-of-mass energy should go as $\ln(s)$, but, actually, the rise is quadratic in $\ln(s)$.

- It is also worth noting that the difference between p+p and p+anti-p collisions is less than a couple of percent, again underscoring the soft, peripheral nature of these collisions.

- Strong, non-linear increase in $p_T$ expected.
- $p_T$ distribution flatter with increasing $N_{ch}$

The predictions of non-single diffraction $\text{NSD} = \text{HC} + \text{DD}$ depend on assumed value for DD/NSD.
- ALICE value of 0.094 ($\text{HC/NSD} = 0.906$) are the measured fractions from UA5.
- PYTHIA values are $\text{DD/NSD} = 0.156$ ($\text{HC/NSD} = 0.844$ → PYTHIA predicts more DD than UA5 measured.
**Systematic uncertainties in measurements**

<table>
<thead>
<tr>
<th>Source</th>
<th>Pixel Counting [%]</th>
<th>Tracklet [%]</th>
<th>Tracking [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correction on event selection</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0 (1.0)</td>
</tr>
<tr>
<td>Acceptance uncertainty</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Pixel hit efficiency</td>
<td>0.5</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>Pixel cluster splitting</td>
<td>1.0</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Tracklet and cluster selection</td>
<td>3.0</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Efficiency of the reconstruction</td>
<td>-</td>
<td>3.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Correction of looper hits</td>
<td>2.0</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Correction of secondary particles</td>
<td>2.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Misalignment, different scenarios</td>
<td>-</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Random hits from beam halo</td>
<td>1.0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Multiple track counting</td>
<td>-</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Fake track rate</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>$p_T$ extrapolation</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total, excl. common uncertainties</strong></td>
<td>4.4</td>
<td>3.7</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Total, incl. common uncert. of 3.2%</strong></td>
<td>5.4</td>
<td>4.9</td>
<td>4.0 (2.8)</td>
</tr>
</tbody>
</table>

- The uncertainties concern the acceptance and efficiency estimates and to what degree they depend on the phenomenological models. The net uncertainty is only 3%.

An additional 2-3% comes from reconstruction efficiencies, and 1% for knowledge of the tracker geometry.
Conclusion

• The first publication from CMS on collision data is submitted to JHEP
• The first published data at 2.36 TeV
• The results follow the trend indicated by earlier experiments.
• The energy-dependence of the multiplicity density is steeper than predicted by PYTHIA and PHOJET tunes used.
• The paper demonstrates the readiness of the CMS detector in the LHC startup in 2009.
• Excellent detector performance is shown and high quality data is taken.

This is the start of the long and exciting physics program of CMS at the LHC!
Backup
CMS Experiment at the LHC, CERN
Date Recorded: 2009-12-14 04:21:03 CEST
Run/Event: 124120/542515
Candidate multijet event at 2.36 TeV

PFJet 1 of 29.9 GeV

PFJet 2 of 24.2 GeV

PFJet 3 of 13.3 GeV

3 PFlow jets pT > 10 GeV
pT cut on tracks displayed > 0.4 GeV
• Select events with valid vertex as collision events

→ Clean event selection
CMS accumulated Lumi in 2009

Accumulated HF-online lumi

<table>
<thead>
<tr>
<th>Energy</th>
<th>Sample</th>
<th>Lumi</th>
</tr>
</thead>
<tbody>
<tr>
<td>900 GeV</td>
<td>Delivered</td>
<td>18.7 (\mu b^{-1})</td>
</tr>
<tr>
<td></td>
<td>Recorded</td>
<td>14.6 (\mu b^{-1})</td>
</tr>
<tr>
<td>2.36 TeV</td>
<td>Delivered</td>
<td>1.68 (\mu b^{-1})</td>
</tr>
<tr>
<td></td>
<td>Recorded</td>
<td>1.23 (\mu b^{-1})</td>
</tr>
</tbody>
</table>
CMS trigger strategy in 2009

• Adapt to rapidly changing conditions: beam splashes, circulating beams: stable/unstable, magnet on/off, tracker HV on/off

• Write out as many events as possible, do not reject unnecessarily.
• Capture as many bunches with protons as possible (rate 11-88 Hz)
• Capture all events with ANY detector activity (rate upto 600 Hz).

Early collision trigger menu: useability depends on bunch pattern and lumi. Zero bias (filled bunch coincidence), beam gas (unpaired bunch): Prescaled
Minimum bias: based on beam scintillators, HCAL, ECAL, pixels: unprescaled

Level1: accept any activity within ± 2 bunch crossings for filled bunches
High Level : catch anything which makes detector active or which L1 might have missed
Trigger rate for MB = 0.5 - 15 Hz, Efficiency > 90%