Latest CMS Minimum Bias Results

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Introduction I

- Majority of the particles produced in pp collisions arise from soft interactions, which are only modeled phenomenologically
  - models must tuned/validated with experimental results

- Today, we will present a new set of results to be used as input to that modeling work and event generator tuning based on minimum bias data collected at CMS in pp collisions:
  1. Strange Particle Production at $\sqrt{s} = 0.9$ & 7 TeV
  2. Charged Particle Multiplicities at $\sqrt{s} = 0.9$, 2.36, & 7.0 TeV
  3. Charged Particle Transverse Momentum Spectra at 7 TeV
     ➔ Emphasis on large $p_T$
  4. Transverse-Momentum and Pseudorapidity Distributions of Charged Hadrons at $\sqrt{s} = 0.9$, 2.36 & 7 TeV
     ➔ $dN/d\eta$, $dN/dp_T$ and $<p_T>$ of charged hadrons
     ➔ Emphasis on low $p_T$
Data used has a natural admixture of soft, semi-hard, hard scatters and multiple particle interactions.

Not all soft processes are kept in the analyses to be discussed (1-4):

- elastic scattering
- single-diffractive
- double-diffractive
- non-diffractive

Single–Diffraction (SD) was observed with an independent analysis and results will be presented today as well.
CMS Detector

• 0.7% at $\eta = 0$
• 2% at $|\eta| = 2.5$

$\mathbf{p_T}$ resolution @ 1 GeV/c:

- CMS Tracker

3.8 T

CMS Detector

Hadronic Forward Calorimeter $HF(\pm)$
Minimum Bias Trigger and FW HCal

- **HCAL Forward**
  - HF: $2.9 \leq |\eta| \leq 5$.  
- **Beam Scintillator Counters**
  - BSC: $\pm 10.5$ m from IP 
  - $3.23 \leq |\eta| \leq 4.65$
- **Beam Pick-up Timing**
  - BPTX: $\pm 175$ m from IP

- **Trigger: Min Bias & Zero Bias**
  - L1 Beam Scintillator Counters “BSC”
  - L1 Trigger “BPTX”
- **Minimum Bias selection:**
  - BPTX+BSC(OR)+ vertex: $\epsilon \sim 90\%$
  - HF (E > 3 GeV both sides): $\epsilon \sim 90\%$
  - !(BSC Halo) + track quality for further rejection of beam gas interactions

*Main requirement to reject single-diffraction (SD) events and define Non-diffracting (NSD) signal*
Trigger and data selection NSD & rejection of SD

Checks with data

\[ \Sigma (E+p_z) = \Sigma E(1+\cos \Theta) = \Sigma (p_T e^n) \]

Checks with MC

- High NSD trigger acceptance \( > 85\% \)
- SD contamination after event selection 5-6\% 
- Difference between Phojet SD definitions and Pythia is at the level of 2\%
Tracker Performance

- The CMS silicon pixel and strip tracker detectors were used
- Pixels: three 53.3 cm long layers with radii 4.4, 7.3, 10.2 cm
- >97% of all channels were operational, hit efficiency optimized

The energy loss in the tracker layers well described by MC

The vertex position distributions are clean Gaussians, with no tails
Strange Particle Production

$K_s$, $\Lambda$ & $\Xi$

CMS PAS QCD-10-007
Strange Particles Decays

CMS Preliminary
$\sqrt{s} = 7$ TeV

Yield = 4285879 ± 2097
Mass = 497.653 ± 0.003 MeV/c²
$\sigma_1 = 4.27 ± 0.01$ MeV/c²
Fraction with $\sigma_1$: 0.669
$\sigma_2 = 11.13 ± 0.02$ MeV/c²
Statistical uncertainties only

CMS Preliminary
$\sqrt{s} = 7$ TeV

Yield: 18062.2 ± 163.3
Mean: 1322.06 ± 0.03 MeV/c²
Sigma: 3.25 ± 0.03 MeV/c²
Statistical uncertainties only

CMS Preliminary
$\sqrt{s} = 7$ TeV

Yield = 953652 ± 1009
Mass = 1115.967 ± 0.003 MeV/c²
$\sigma_1 = 1.67 ± 0.00$ MeV/c²
Fraction with $\sigma_1$: 0.604
$\sigma_2 = 4.35 ± 0.01$ MeV/c²
Statistical uncertainties only

CMS preliminary

$\sqrt{s} = 7$ TeV:
- $\Lambda^0$
- $K^0_S$
- $\Xi^-(X2)$
$\sqrt{s} = 900$ GeV:
- $\Lambda^0$
- $K^0_S$
- $\Xi^-(X2)$

Efficiency vs $p_T$ [GeV/c]
Strange Hadron Spectra

- Only NSD interactions
- Normalized to number of NSD
- Solid line is a fit to Tsallis function
- Band error due to normalization
Comparison with various generators

- All generators underestimate the amount of Strange Particles produces at both 0.9 and 7 TeV.
Comparison with previous experiments & event Generator

### Simulation

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\langle p_T\rangle_{\text{true}}$ (GeV/c)</th>
<th>$\langle p_T\rangle_{\text{Tallis}}$ (GeV/c)</th>
<th>$T$ (GeV)</th>
<th>$\langle p_T\rangle_{\text{true}}$ (GeV/c)</th>
<th>$\langle p_T\rangle_{\text{Tallis}}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PYTHIA 6 (D6T) $K_S^0$</td>
<td>0.579</td>
<td>0.581</td>
<td>0.156</td>
<td>0.753</td>
<td>0.754</td>
</tr>
<tr>
<td>PYTHIA 8 $K_S^0$</td>
<td>0.550</td>
<td>0.550</td>
<td>0.141</td>
<td>0.713</td>
<td>0.711</td>
</tr>
<tr>
<td>PYTHIA 6 (P0) $K_S^0$</td>
<td>0.582</td>
<td>0.585</td>
<td>0.150</td>
<td>0.730</td>
<td>0.726</td>
</tr>
<tr>
<td>PYTHIA 6 (D6T) $\Lambda^0$</td>
<td>0.756</td>
<td>0.756</td>
<td>0.152</td>
<td>1.064</td>
<td>1.069</td>
</tr>
<tr>
<td>PYTHIA 8 $\Lambda^0$</td>
<td>0.669</td>
<td>0.666</td>
<td>0.112</td>
<td>0.933</td>
<td>0.928</td>
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<tr>
<td>PYTHIA 6 (P0) $\Lambda^0$</td>
<td>0.694</td>
<td>0.695</td>
<td>0.124</td>
<td>0.921</td>
<td>0.910</td>
</tr>
<tr>
<td>PYTHIA 6 (D6T) $\Xi^-$</td>
<td>0.763</td>
<td>0.759</td>
<td>0.123</td>
<td>1.167</td>
<td>1.162</td>
</tr>
</tbody>
</table>

### Data

![Graph showing comparison between Simulation & Data](image)

### Simulation & Data

| Particle | $\frac{dN}{dy}|_{y=0}(7\text{TeV})$ | $\frac{dN}{dy}|_{y=0}(0.9\text{TeV})$ | $0.9$ TeV | $7$ TeV |
|----------|---------------------------------|---------------------------------|-----------|---------|
| $K_S^0$  | 1.41 ± 0.20 ± 0.39              | 1.41 ± 0.20 ± 0.39              | 0.72 ± 0.01 ± 0.06 | 0.72 ± 0.01 ± 0.06 |
| $\Lambda^0$ | 1.48 ± 0.26 ± 0.26             | 1.48 ± 0.26 ± 0.26             | 0.54 ± 0.01 ± 0.06 | 0.54 ± 0.01 ± 0.06 |
| $\Xi^-$    | 1.47 ± 0.27 ± 0.27             | 1.47 ± 0.27 ± 0.27             | 0.33 ± 0.02 ± 0.05 | 0.33 ± 0.02 ± 0.05 |
Charge Multiplicities

CMS PAS QCD-10-004
KNO Scaling and $C_q$ Moments

- Probability distributions $P_n(s)$ of producing $n$ particles at collision energy $s$:

$$P_n(s) = \frac{1}{\langle n(s) \rangle} \psi\left(\frac{n}{\langle n(s) \rangle}\right)$$

- Scaling function:

$$\Psi(z) = \langle n \rangle P_n, \text{ with } z = \frac{n}{\langle n \rangle}$$

- Moments:

$$C_q = \langle n^q \rangle / \langle n \rangle^q$$
Results for the Probability Distributions

\[ P_n = \frac{\sigma_n}{\sigma} \]

where \( \sigma \) normalization taken from NSD events

\[ p_T > 100 \text{ MeV}, \text{ then extrapolate to 0 MeV} \]

The fraction of charged hadrons that is added by extrapolation correction ranges between 5% and 7%
Comparison with Generators

Soft vs Semi hard scatters & Multi Parton Interactions
Scaling Functions Results

Difference in scaling between $|\eta| < 2.4$ and $|\eta| < 0.5$
Other useful distributions

2010 – Recent Theoretical work
$C_q$ moments increase nearly linearly with $\log(\sqrt{s})$ for $0.5 < |\eta| < 2.4$
Charged particle transverse momentum spectra

Jet Triggered: CMS PAS QCD-10-008
Minimum Bias: CMS PAPER QCD-10-006 (PRL)
High-$E_T$ jet triggers are employed to enhance yields at high $p_T$.
A robust prediction of pQCD hard processes is the power-law scaling of the inclusive invariant cross section with $x_T \equiv 2p_T/\sqrt{s}$

$E \frac{d^3 \sigma}{dp^3} = F(x_T)/p_T^n(x_T, \sqrt{s}) = F'(x_T)/\sqrt{s}^n(x_T, \sqrt{s})$

Expected to be valid for $p_T > 2\text{GeV}$
Comparison of Differential Yield with Generators including the low $p_T$

- The gray band corresponds to statistical plus systematic errors in quadrature.

- Pythia – 8 in reasonable agreement

- Jet Triggered data note: CMS PAS QCD-10-008
Differential Yield of Charged Hadrons @ low $p_T$

- Minimum $p_T$ 150 MeV
- Fit with Tsallis-Function:

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

- $y = 0.5 \ln [(E + p_z) / (E - p_z)]$, $E_T = \sqrt{m^2 + p_T^2} - m$

- Exponential at low $p_T$
  - Beam-beam remnant
- Power Law at high $p_T$
  - Hard parton-parton scattering

Based on Minimum Bias PRL
As expected: $p_T$ Spectrum gets harder at higher energies

Invariant differential yield for the new analysis (solid circles) & the previous CMS 7TeV measurement (stars) over the limited $p_T$ range of the earlier result. (Lower) Ratio of the new (solid circles) & previous (stars) CMS results to a Tsallis fit of earlier measurement.
Difference between "new" and "old" result...Further tuning of tracking in 3rd method

Pixel detector:
- 53.3 cm long,
- 3 layers with radii: 4.4, 7.3, 10.2 cm

\[
p_T > 30 \, \text{MeV/c}
\]
- Clusters per layer
- $|\eta| < 2$
- 3 measurements of $dN/d\eta$
- Immune to mis-alignment
- Simplest method
- Requires noise-free detector

\[
p_T > 75 \, \text{MeV/c}
\]
- 2 of 3 pixel layers
- $|\eta| < 2$
- 3 measurements of $dN/d\eta$
- Sensitive to mis-alignment

Over 50% Efficient for $p_T > 0.1, 0.2, 0.3 \, \text{GeV/c}$ for $\pi, K, p$

Full tracks (pixel and strips)
- $|\eta| < 2.4$
- $dN/d\eta$ and $dN/dp_T$
- Sensitive to mis-alignment
- Most complex
Average $p_T$ of Charged Hadrons

- The energy dependence of the average charged-hadron $p_T$ can be described by a quadratic function of $\ln(s)$.

- Minimum Bias: CMS PAPER QCD-10-006 (PRL)
Charged particle pseudorapidity distributions

Minimum Bias: CMS PAPER QCD-10-006 (PRL)
Rise of the particle density at 2.36 & 7 TeV steeper than in model predictions.
What is next for this type of measurements?

- Finish all the analysis requested by the MBUEWG for \( \text{dN/d}\eta \), \( \text{dN/dp}_T \), etc.

- Some of the main differences with analyses shown today:
  - Do not reject SD events
  - Minimum \( \text{p}_T \) of 500 MeV and require at least one track in the central region

- Still some open questions to WG
  - Definition/Correction of “primary” charged particles

⇒ More discussion in close section
Observation of diffraction in proton-proton collisions at 900 and 2360 GeV

CMS PAS FWD-10-001
Diffraction

- Diffractive reactions in $p \, p$ collisions: reactions $p \, p \rightarrow X \, Y$ in which the systems $X$ and $Y$ are separated by a Large Rapidity Gap

Single diffraction (SD)

$\xi \, s = M(X)^2$

Double Pomeron Exchange (DPE)

2 gluon exchange with vacuum quantum numbers “Pomeron”

$\xi_1 \, \xi_2 \, s = M(X)^2$

- Diffractive events contribute significantly to Minimum Bias data set ($\sim 30\%$ of the total $p \, p$ cross section)

- Modelling of soft diffraction is generator dependent

⇒ Info on proton structure (dPDFs and GPDs), discovery physics, MPI, …
Strategy for Single Diffraction Detection at CMS

No measurement of the proton → rely on Large Rapidity Gaps

### Single diffraction (SD)

- $\xi = \frac{M_x^2}{s}$
- $\sigma \approx \frac{1}{\xi}$
- $\Delta y \approx -\ln \xi$
- $\xi \approx \sum (E_i \pm p_{z,i})/\sqrt{s}$

#### Look for a SD peak @ low $\xi$:

- $\xi \approx \sum (E_i \pm p_{z,i})/\sqrt{s}$
- Sum runs over all the Calo Towers:

  $p_{z,i} = E_i \cos \vartheta_i$

### CONFIRM SD PEAK @ low $E_{HF\pm}$, $N_{HF\pm}$

- $E_{HF\pm} = $ energy deposition in HF$\pm$
- $N_{HF\pm} = $ multiplicity of towers above threshold in HF$\pm$

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Looking for a SD peak at low $\xi$:
- At 11.2m from interaction point
-rapidity coverage: $3 < |\eta| < 5$
- Steel absorbers/quartz fibers (Long + short fibers)
- $0.175 \times 0.175$ $\eta/\varphi$ segmentation
Observation of Single Diffraction at CMS
(Results at 7 TeV to become public in the near future)

900 GeV (10 μb⁻¹)
2360 GeV (0.4 μb⁻¹)

Systematic uncertainty dominated by energy scale
SD seen in ∑ E+pz distribution due to cross section peaking at small values of ξ

Acceptance for SD ~ 20%
For NSD ~80% (PYTHIA)
Observation of Single Diffraction at CMS

SD signature confirmed by the absence of forward hadronic activity (presence of a LRG)
Enriched SD Sample ➔ $E(\text{HF}+) < 8 \text{ GeV}$

**Requirement of low Activity in one side of CMS**

SD component of the data LRG in $z+$ direction
Concentrating on the fragmenting object $(X)$ boosted in $z$-direction

$$
\xi = \sum_i (E_i \pm p_{z,i})
$$
Conclusions...

- **Strange Particle:**
  - production at all energies is underestimated by available generator
  - …so is the relative increase between 0.9 and 7 TeV

- **Charged Particle Multiplicity**
  - Scaling violations observed - Cq grows linearly with log (√s)
  - Reasonable agreement with Pythia-8 for 0.9 and 2.36 TeV, but overestimates multiplicity at 7 TeV

- **Charged Particle Transverse momentum spectra at 7 TeV**
  - At high p_T behaves as expected by pQCD contrary to CDF results
  - At low p_T our new results are superseed previous CMS results

- **Charged Particle Pseudorapidity distributions**
  - Underestimated by current models, but empirical fit possible

- **SD unambiguously observed**

  ➔ Good references for MC tuning & for future suppression measurements in Dense QCD medium produced in PbPb collision are now available