Soft QCD Results from CMS

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for the CMS collaboration
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Outline

- Introduction
- Properties of Minimum Bias Events
  - Transverse momentum spectra and event-by-event multiplicity distributions of charged particles
  - Strangeness production and strange hadron spectra
- Particle Correlations
  - Short-range and long-range angular correlations in pp events at 0.9 and 7 TeV
  - Bose-Einstein Correlations measured at 0.9 and 7 TeV
- Underlying Events Measurements and MC Tunes
- Summary
Soft interactions at LHC

- **Collisions at LHC**
  - the majority of the pp collisions are soft, without hard parton scattering
  - no “perturbative” predictions, need to model them phenomenologically
  - Usually rely on Monte-Carlo (MC) description

- Early LHC data provide a unique chance to deepen the knowledge on soft QCD
  - PS, UE and hadronization models were tuned on previous data. Different models diverge at high energy predictions

- Will provide reference for high energy pp collisions and heavy ion physics

Understanding of soft QCD contributions is crucial for new physics searches and precision measurements of Standard Model processes
**Key detector components for soft QCD measurements**

\[ \eta = -\ln(\tan(\theta/2)) \]

**Silicon Tracker System:**
- **Strips:** 9.3M channels; **Pixels:** 66M channels. > 98% operational
- Extremely high granularity and resolution
- Coverage over \(|\eta| < 2.5\)

- **Pixels**
  - 3 barrel layers \((r = 4, 7, 11 \text{ cm})\)
  - 2 × 2 endcap disks
  - ~ 1 m\(^2\) Si sensor

- **Strips**
  - 10 barrel layers
  - 9 + 3 × 2 endcap disks
  - 200 m\(^2\) Si sensor

**Beam Pickup Timing for experiments (BPTX)**
\[ z = \pm 175 \text{ m}, \text{ time resolution } 0.2 \text{ ns} \]

**Beam Scintillator Counters (BSC)**
\[ z = \pm 10.86 \text{ m}, 3.23 < |\eta| < 4.65, \text{ time resolution: } 3 \text{ ns} \]
MinBias $p_T$ reach extended by jet triggers to ~100 GeV/c

Inclusive invariant cross-section

$x_T$ scaling curve

• Results at 7 TeV most compatible with PYTHIA 8 while PYTHIA 6 is worse
• Empirical $x_T = 2 \frac{p_T}{\sqrt{s}}$ unifies the differential cross sections from a wide range of collision energies onto a common curve at high $x_T$
  → Interpolated ($x_T$ and $p_T$ scaling) data provides a reference for PbPb studies of nuclear modification factors at LHC for $\sqrt{s}_{NN} = 2.76$ TeV

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

CMS QCD-10-008 arXiv:1104.3547
- Large multiplicity tail observed at 7 TeV (cf. $dN/d\eta$)
- $<p_T>$ vs $n$ scale with energy
- No Monte Carlo is able to describe all multiplicities at all energies (but PYTHIA 8 better)
- Most MC/tunes can not describe simultaneously the multiplicity and the $p_T$ dependence (PYTHIA 8 better)
Strangeness production ($K_S, \Lambda, \Xi$)

**$K_S$**

- **Candidates / 1 MeV/$c^2$**
- **$\sqrt{s} = 7$ TeV**
- **Yield:** $6534 \times 10^3$
- **Mean:** $497.8$ MeV/$c^2$
- **Avg $\alpha$:** $8.2$ MeV/$c^2$
- **$480 \mu b^{-1}$**

**$\Xi^{-}$**

- **Candidates / 2 MeV/$c^2$**
- **$\sqrt{s} = 7$ TeV**
- **Yield:** $34.4 \times 10^3$
- **Mean:** $1322.1$ MeV/$c^2$
- **Avg $\alpha$:** $4.1$ MeV/$c^2$
- **$480 \mu b^{-1}$**

**$K_S^0 - 4\pi$**

- **$480 \mu b^{-1}$**

- **$(1/N_{NSD}) dN/dp_T$ (GeV/c)$^{-1}$**
- **$K_S^0 p_T$ [GeV/$c$]**
- **$\sqrt{s} = 7$ TeV**
- **$\sqrt{s} = 0.9$ TeV**

- **$(1/N_{NSD}) dN/dy$**
- **$K_S^0$**
- **$\sqrt{s} = 7$ TeV**
- **$\sqrt{s} = 0.9$ TeV**

**$\Lambda\pi^{-}$**

- **$480 \mu b^{-1}$**

- **$(1/N_{NSD}) dN/dp_T$ (GeV/c)$^{-1}$**
- **$\Lambda\pi^{-} p_T$ [GeV/$c$]**
- **$\sqrt{s} = 7$ TeV**
- **$\sqrt{s} = 0.9$ TeV**

- **$(1/N_{NSD}) dN/dy$**
- **$\Xi^{-}$**
- **$\sqrt{s} = 7$ TeV**
- **$\sqrt{s} = 0.9$ TeV**

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Strangeness production(II)

Similar increase for strange as for charged particle with energy

→ PYTHIA fails again to match this increase!

Discrepancy larger for $\Xi^-$ at both energy and up to factor 3 at 7 TeV.

N stays approximately constant for both centre-of-mass energies.

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Two-particle correlation in $\Delta \eta$ and $\Delta \phi$

Signal distribution
= Correlated and uncorrelated pairs from same event

Background distribution
= Uncorrelated pairs from mixing 2 events

MinBias, $p_T > 0.1$ GeV/c, 7 TeV

"Away-side" ($\Delta \phi \sim \pi$) jet correlations:
Correlation of particles between back-to-back jets

Bose-Einstein correlations:
$(\Delta \phi, \Delta \eta) \sim (0,0)$

Momentum conservation:
$\sim -\cos(\Delta \phi)$

"Near-side" ($\Delta \phi \sim 0$) jet peak:
Correlation of particles within a single jet

Short-range correlations ($\Delta \eta < 2$): Resonances, string fragmentation, "clusters"

$R(\Delta \eta, \Delta \phi) = \frac{\langle N \rangle - 1}{\langle N \rangle} \frac{S_N(\Delta \eta, \Delta \phi)}{B_N(\Delta \eta, \Delta \phi)} - 1$
High multiplicity results at $\sqrt{s} = 7$ TeV

Intermediate $p_T : 1 < p_T < 3$ GeV/c

MinBias

High Multiplicity: $N > 110$

(b) MinBias, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

d) $N > 110$, $1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c}$

→ Near-Side angular correlations at high multiplicity at intermediate $p_T$

... not from short range correlations (resonances, near-side jet peaks, away side correlations of particles between back-to-back jets or Bose-Einstein correlations)

... not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)

The first surprise in LHC data, new testing ground for high density QCD physics!
When wave-function of identical bosons overlaps, Bose-Einstein statistic changes their dynamics

→ Production probability enhancement for identical light boson with similar momenta.

→ BEC measurements give information about size, shape and space-time development of emitting source.

**Observables:**

\[ R = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \]

- \( P(p_1, p_2) \): Joint probability of emission of a pair of bosons
- \( P(p_1), P(p_2) \): Individual probability of emission

→ Need to define a reference sample of non interfering boson pairs!

Assuming particle are mostly pions

\[ Q = \sqrt{- \left( p_1 - p_2 \right)^2} = \sqrt{M^2_{\text{inv}} - 4m^2_\pi} \]

**Parametrization:**

\[ R(Q) = C \left[ 1 + \lambda \Omega(Qr) \right] (1 + \delta Q) \]

- \( \Omega(Qr) \): Fourier transform of emission region of effective size \( r \)
- \( \lambda \): BEC strength
- \( \delta \): Long distance correlations
Bose-Einstein correlations (II)

Pairs of same-sign charged particles with $0.02 \text{ GeV} < Q < 2 \text{ GeV}$ are studied.

Double ratio defined to reduce biases

$$\mathcal{R}(Q) = \frac{R(Q)}{R_{MC}(Q)} = \left( \frac{\frac{dN_{signal}}{dQ}}{\frac{dN_{ref}}{dQ}} \right)$$

$$\Omega(Qr) = e^{-Qr}$$

→ BEC effective emission region grows with $\sqrt{s}$ while strength is similar

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→ This accounts for the grow with $\sqrt{s}$ (cf. $dN/d\eta$)

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The Underlying Event

The "underlying event" is everything except the outgoing hard scattered partons
UE = beam-beam remnants + initial and final-state radiation + multiple interactions

$\text{UE} = \text{beam-beam remnants} + \text{initial and final-state radiation} + \text{multiple interactions}$

$\rightarrow$ UE is what we need to correct for before comparison with hard scattering predictions

$\rightarrow$ Need to “tune” soft interactions MC model(s) to UE: previous and LHC data

**UE Observables**

Activity in transverse region:
- $d^2N_{\text{ch}}/d\eta d\phi$
- $d^2\Sigma p_T/d\eta d\phi$

for leading track/jet topologies

900 GeV

Leading Track Jet direction

Transverse

Away

Toward

**EPJ C70 (2010) 555**
Transverse region: charge and $\Sigma p_T$ density

Measurement of $dN_{ch}/d\eta d(\Delta\phi)$ and $d^2\Sigma p_T/d\eta d(\Delta\phi)$ in transverse region as a function of leading track-jet PT
→ Measure activity outside jet(s) → Underlying Event

Strong growth of underlying event activity with $\sqrt{s}$. PYTHIA Z1 describes the distributions and the $\sqrt{s}$ dependence well.

Fast rise for $P_T < 8$ GeV/c (4 GeV/c), attributed mainly to the increase of MPI activity, followed by a Plateau-like region with ≈ constant average number of selected particles and a slow increase of $\Sigma p_T$, in a saturation regime.

→ Increase of activity by a factor ~2 in data with $\sqrt{s}$ is more or less reproduced by PYTHIA 6 and PYTHIA 8
MC/DATA: 7 TeV. \( p_T \) track-jet > 20 GeV vs \( p_T \) track-jet > 20 GeV

**N\(_{ch}\), \( \Sigma p_T \) and \( p_T \) in the transverse region**

**7 TeV. \( p_T \) track-jet > 20 GeV vs \( p_T \) track-jet > 20 GeV**

CMS QCD-10-010

**MC/DATA: 7 TeV. \( p_T \) track-jet > 20 GeV**
Summary

- Various low pT QCD analyses with Minimum Bias events have been performed with CMS
  - Transverse momentum spectra and event-by-event multiplicity distributions of charged particles have been measured and compared to different Monte Carlo models.
  - Strange particle production in good agreement with empirical extrapolation from lower energies.
- Two particle correlation function has been measured at 0.9, 2.36 and 7 TeV.
  - A very novel feature has been observed of long range, near side two particle correlation. Not reproduced by any MC model.
- The BEC effect has been observed and quantified at 0.9 and 7 TeV.
  - The exponential parametrization has been shown better fit the data.
  - Various parameter dependences have been investigated.
- For the first time UEs have been analyzed at 7 TeV.
  - Many MC tunings have been compared to the data. None of them being in good agreement with data. New MPI model seem to help.
Backup slides
Trigger on High Multiplicity pp

Total integrated luminosity: 980 nb$^{-1}$

Two HLT thresholds:
- $N_{\text{online}} > 70$
- $N_{\text{online}} > 85$

$N_{\text{online}} > 85$ trigger un-prescaled for full 980 nb$^{-1}$ data set

~350K top multiplicity events (N>110) out of 50 billion collisions
Study dependence on $p_T$ and multiplicity for $2 < |\Delta \eta| < 4.8$ for $R(\Delta \phi)$:

- "Ridge" maximal for high multiplicity and intermediate $p_T$: $1 < p_T < 3$ eV/c
- "Ridge" not reproduced by PYTHIA 8
Ridge in high multiplicity pp

Interpretations:
Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections

Jet

Glasma tube

Color
Glass
Condensate

Hydrodynamic flow

Quark
Gluon
Plasma

EPOS model: pp

K. Werner, WWND2011