Underlying Event, Minimum Bias and Forward Energy Flow Measurements with CMS

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on behalf of CMS Collaboration

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CMS Experiment

Analysis presented are sensitive to pile-up and performed with low lumi

\[ p_T \text{ resolution @ 1 GeV/c:} \]

- 0.7% at \( \eta = 0 \)
- 2.0% at \( |\eta| = 2.5 \)

Beam Scintillator Counters
- \( \pm 10.86 \text{m} \) from interaction point
- Hit and coincidence rates (beam-halo rejection)

Beam Pick-up Timing for the eXperiments
- Bunch structure
- Timing of beam
  Time resolution better 2ns!
The Underlying Event

Everything except the hard scattering:
UE = MPI + BBR (+ ISR and FSR contamination)

→ Need to “tune” soft interactions MC model(s) to UE: previous and LHC data
The Underlying Event

Everything except the hard scattering:
UE = MPI + BBR (+ ISR and FSR contamination)

Identify in the event an energy scale (and direction) reflecting the hard scattering:
→ Di-jet events: Leading track-jet (cluster of tracks with highest pT)
→ Drell-Yan: di-muon final state

3 topological regions from the azimuthal difference w.r.t. the leading direction:
→ away (|Δφ| > 120°): hard scattering and radiation
→ transverse (60° < |Δφ| < 120°): suited for UE studies
→ towards (|Δφ| < 60°): same as “away” for track-jet approach
  suited for UE studies in DY process

Observables built from charged particles:
\[ d^2 N_{\text{chg}} / d\eta d(\Delta\phi) \] : charged multiplicity density
\[ d^2 \Sigma p_T / d\eta d(\Delta\phi) \] : scalar \( p_T \) sum density

900 GeV
UE transverse region: charge and $\Sigma p_T$ density

7 TeV and 900 GeV results for the reference charged multiplicity density and $\Sigma p_T$ density profiles including Z1 (solid) and 4C (dashed) predictions.

– 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 $\approx$ constant average number of selected particles and a slow increase of $\Sigma p_T$, in a saturation regime.

– Increase of the activity with $\sqrt{s}$ also corroborates MPIs (growth with PDFs).

– PYTHIA nicely re-tuned to describe the data, still differences of the order of 5 to 20% for different versions and tunes (even very recent PYTHIA8 tune 4C).
Comparison between 7 TeV and 900 GeV

- In the presence of a large energy scale, UE grows significantly with $\sqrt{s}$
- A factor 2 going from 900 GeV to 7 TeV to be compared with 1.7 for MB.
- MPI growth with $\sqrt{s}$ well described by Z1 and 4C, too pronounced in D6T.
Charge and $\Sigma p_T$ density: Drell-Yan Events

Activity as a function of $M_{\mu\mu}$: for events with small recoil activity by requiring $p_T^{\mu\mu} < 10$ GeV/c

→ close to true UE

- no dependence on energy scale ($M_{\mu\mu}$), as MPI saturates at these scale (also known from track-jet analysis).
- **Pythia-8 4C, Pythia-6 DW** and Z1 agrees with the measurements within 10-15%
Charge and $\Sigma p_T$ density: Drell-Yan Events

Activity as a function of $p_T^{\mu\mu}$: for events with $60 < M_{\mu\mu} < 120$ GeV/c$^2$

- MPI saturates and $p_T^{\mu\mu}$ dependence gives radiation evolution (mainly initial state radiation).
- Transverse region: qualitatively similar as towards but has higher activity due to spill-over contribution from away side hard component.
- Pythia-8 4C underestimate the activity (except at small $p_T^{\mu\mu}$), Pythia-6 tunes agree with the measurements within 10-15%
Single Charged Particle Spectra: $dN/d\eta$

**Event Selection:**
- MinBias trigger (BSC)
- At least 3 GeV in both HF
- primary vertex
  - Corrected to non-single diffraction (NSD)

**Charged Particle Selection:**
- $|\eta| < 2.5$
- corrected to $p_T > 0$ GeV/c
- 3 different methods

CMS measurements in agreement with other experiments.

However densities are higher than most models and pre-LHC MC at high energy.
Empirical $x_T = 2 p_T / \sqrt{s}$ scaling 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
Charged Particle Multiplicities

- Change in slope: multi-component structure
- Large multiplicity tail observed at 7 TeV
- $<p_T>$ vs $n$ scale with energy: weekly dependent on $\sqrt{s}$
- 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 (again PYTHIA 8 better)
- MC produce too few particles with low transverse momentum; PYTHIA 8 compensate for this by producing too many particle with high pT (semi hard MPI modelling)

KNO scaling: violate for $|\eta| < 2.4$ hold for $|\eta| < 0.5$
Strange Particle Production: $K^0_s$, $\Lambda$, $\Xi^-$

$K^0$, $\Lambda$, $\Xi^-$: long-lived particles ($c\tau > 1$ cm) identified from their decay products originating from a displaced vertex.

- the amount of strangeness suppression (w.r.t. $u$ and $d$ quarks) is an important component in MC models
- interesting for new physics (e.g. strange enhancement in QGP formation)

Production yields in function of rapidity $y$ and $p_T$:
- $<p_T>$ increasing with particle mass and $\sqrt{s}$: agreement with predictions
- $\sqrt{s}$ increase in production consistent with inclusive charged particles
- production ratios, $\Lambda / K^0$ and $\Xi^- / \Lambda$ (versus $y$ and $p_T$) independent of $\sqrt{s}$: no clear sign of QGP formation

MC underestimating total yield (both $\sqrt{s}$ 0.9 and 7TeV) and $\sqrt{s}$ scaling
Two-particles correlation in $\Delta \eta$ and $\Delta \phi$

Signal distribution
= Correlated and uncorrelated pairs from same event

Background distribution
= Uncorrelated pairs from mixing 2 events

$$R(\Delta \eta, \Delta \phi) = \left( N - 1 \right) \left( \frac{S_N(\Delta \eta, \Delta \phi)}{B_N(\Delta \eta, \Delta \phi)} - 1 \right)$$

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"
MinBias Results: Independent Cluster Model

**Independent Cluster Model (ICM)**

- Clusters are produced independently
- Each cluster decay isotropically into hadrons in its own c.m.s.
- Short range correlations in \( \Delta \eta \) can be characterized by 2 parameters:
  - cluster size \( K \rightarrow \) # correlated particles
  - cluster width \( \delta \rightarrow \Delta \eta \) correlation size

\[ \sqrt{s} = 900 \text{ GeV} \]

\[ \sqrt{s} = 7 \text{ TeV} \]

- \( K_{\text{eff}} \) increase with \( \sqrt{s} \) (more jets at high \( \sqrt{s} \) ?)
- \( \delta \) constant with \( \sqrt{s} \) (isotropic cluster decay)
- CMS results follow trend from lower \( \sqrt{s} \) data
- PYTHIA (D6T) shows similar energy dependencies for \( K_{\text{eff}} \) and \( \delta \) as data
- PYTHIA (D6T) predicts too low \( K_{\text{eff}} \)
High Multiplicity Results at $\sqrt{s} = 7$ TeV

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

MinBias

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

High Multiplicity: $N > 110$

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

→ Observation of a Long-Range, Near-Side angular correlations at high multiplicity in pp events at intermediate $p_T$ (Ridge at $\Delta \phi \sim 0$)

… not reproduced in PYTHIA 8 (and PYTHIA 6, HERWIG++, madgraph)
Multiplicity and $p_T$ dependence

→ Study dependence on $p_T$ and multiplicity for $2 < |\Delta \eta| < 4.8$ for $R(\Delta \phi)$:

\[
R(\Delta \phi) = \left( N - 1 \right) \left( \frac{\int_{2}^{4.8} S_N(\Delta \eta, \Delta \phi) d \Delta \eta}{\int_{2}^{4.8} B_N(\Delta \eta, \Delta \phi) d \Delta \eta} \right)_{N}^{-1}
\]

“Ridge” maximal for high multiplicity and intermediate $p_T$: $1 < p_T < 3$ eV/c

“Ridge” not reproduced by PYTHIA 8

See talk by Sara Alderweireldt
High energy collisions - large parton densities important:
→ MPI, low x physics and possible saturation effects.

Energy flow in the forward region
→ Information about color (re)connections to the proton remnant
→ High sensitivity to underlying events and important for the
tuning of MC generators

Forward particle production important in air shower models
→ Majority of the energy carried by the forward particles

→ Test of cosmic ray MC: QGSJET, SIBYLL and EPOS

See posters by Niladri Sen and Ann-Karin Sanchez
- Strong dependence of forward energy flow with $\sqrt{s}$ reproduced by all MC
- Strong contributions from MPI (PYTHIA6-no MI fails)
- PYTHIA 6 (Z2,CW,D6T,P0,..) and PYTHIA 8 with MPI fails at high $\eta$ (color reconnection)
- HERWIG++ describes the data (but different tunes for both $\sqrt{s}$)
Forward Energy Flow in di-jet Events

- Significantly higher forward energy flow in dijets events than in MinBias
- Activity increase ~2-3 as collision energy change from 900 GeV to 7 TeV.
- Good description by PYTHIA6 and PYTHIA8
- MPI required: PYTHIA6-no MI & CASCADE failing
- HERWIG++ describes the data (but different tunes for both $\sqrt{s}$)
→ High sensitivity to MC and tunes
Forward Energy Flow: cosmic ray generator

Cosmic ray generators providing a good description of data
Forward Energy Flow in W/Z Events

Correlation between central track multiplicity and energy deposit in forward region provide additional information for the understanding of MPI

- Identify the W and Z candidate with leptonic final state

- Central Track Multiplicity:
  \( p_T > 0.5 \text{ GeV/c}, 1 \text{ GeV/c} \)
  and \( |\eta| < 2.5 \) (excluding tracks from W/Z)

- Forward Energy: sum of tower deposit in HF with at least 4 GeV energy (to reduce the noise)

- Track multiplicity and forward energy is Sensitive to underlying event.
- Pythia6 Z2 provide good description of multiplicity
- large differences in small and large energy region
Forward Energy Flow in W/Z Events

Correlation between Forward Flow and Central Track Multiplicity

- track multiplicity, energy distribution in forward and backward region strongly correlated.
- energy spectra and correlations are not well modeled.
Summary

- Charged particle spectra measured at various energies.
- Missing strangeness in MCs.
- Unexpected long range correlation (similar to heavy-ion collisions). MCs don't describe this observation.

**Underlying Event:**
- Important to understand the UE modeling for precision measurements and new physics searches.
- Measurement performed at various energies and with different processes.

- Forward Energy Flow: important for understanding of the MPI and low-x physics. Energy flow measured using various processes i.e MinBias, dijet, W/Z.

*Many measurements are available and large MC tuning effort going on to describe these measurements*