Measurement of the Minimum Bias, Underlying Events and Double-Parton Scatterings

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Overview

Hadron-Hadron Collision $\rightarrow$ Hard scattering b/w partons $\oplus$ UE activity

Important to study soft & semi-hard interactions @ LHC

1. Recent Measurements from CMS @ 13 TeV $\rightarrow$ Different Aspects of Particle Production
2. Minimum Bias Data (MB) Analysis
   - BEC of Charged Hadrons (CDS Record 2318575)
3. UE Activity using Z Boson Events (arXiv:1711.04299)
4. DPS Studies using same-sign WW events (CDS Record 2257583)
5. Summary

Correct description of the data $\rightarrow$ Requires tuning of MC event generators $\rightarrow$ Precise physics predictions
Bose-Einstein Correlations (BEC) of Charged Hadrons (CDS Record 2318575)

- BEC: Probes the size and shape of the particle emitting region in high-energy collisions
- Correlation functions extracted using double ratios & two data-driven (cluster subtractions & hybrid cluster subtraction) methods
- Homogeneity lengths ($R_{inv}$) studied as a function of particle multiplicity ($N_{tracks}$) at the particle level, average pair transverse momentum ($k_T$) & mass ($m_T$)

- $R_{inv}$ increases with $\langle N_{tracks} \rangle$ & saturates at higher values
- $R_{inv}$ decreases with increasing $k_T$ → Emitting source was expanding prior to decoupling
Results: $m_T$ Dependence

Hydrodynamic Models

- Intercept connected with the geometrical size of the source (at freeze-out)
- Slope connected to the flow component, bigger slope (bigger flow) for lower multiplicities

Expansion in the low multiplicity region is faster than in the high multiplicity region
- Collective flow decreases with increasing multiplicity & saturates $\sim 80$
Charged Particle Spectra in MB events

- Diffraction → Exchange of color-neutral object
- Three event categories: Inelastic, NSD-enhanced, SD-enhanced

SD-One-Side enhanced sample → PYTHIA8 MBR4C described the measurements within uncertainties
Room for improvement in high multiplicity regions (dominated by MPI)
**Results**

- **Integrated** $p_T$ spectrum of charged particles → Sensitive to the transition b/w the non-perturbative & perturbative QCD regions

*Graphs showing data and MC predictions for different $p_T$ min values and SD/NSD selections*

- NSD-enhanced events: EPOS LHC gives the best description, with small fluctuations
- SD-enhanced events: Low $p_T$ region difficult to describe
- Transition b/w the region dominated by particle production from MPI & hard scattering evident from fast change of slope
UE activity using $Z \rightarrow \mu\mu$ events (arXiv:1711.04299)

- Experimentally clean signature & absence of QCD FSR \((Accepted by JHEP)\)
- **Observables:** Charged-particle density & $\sum p_T$ density

**Phase-space Regions**

- $|\Delta \phi(Z, \text{ch. particle})| < 60^\circ$: \textit{Towards} $\rightarrow$ Sensitive to MPI/UE
- $|\Delta \phi(Z, \text{ch. particle})| > 120^\circ$: \textit{Away}
- $60^\circ < |\Delta \phi(Z, \text{ch. particle})| < 120^\circ$: \textit{Transverse} $\rightarrow$ Sensitive to MPI/UE

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\[
\begin{align*}
\text{CMS} & \quad \text{(13 TeV)} \\
2.1 \text{ fb}^{-1} & \quad \text{pp} \rightarrow Z + X \rightarrow \mu^+\mu^- + X
\end{align*}
\]

<table>
<thead>
<tr>
<th>$p_T^\mu$ [GeV]</th>
<th>$1/\langle N_{\text{ch}}(\phi) \rangle$ [rad$^{-1}$]</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>1.0</td>
</tr>
<tr>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>2.0</td>
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<tr>
<td>60</td>
<td>2.5</td>
</tr>
<tr>
<td>80</td>
<td>3.0</td>
</tr>
<tr>
<td>100</td>
<td>3.5</td>
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**Charged particles**

- $|p_T| > 0.5 \text{ GeV}$, $|\eta| < 2$
- $81 < M_{\mu\mu} < 101$
Current results are compared with those at 1.96 TeV (CDF) & 7 TeV (CMS)
60–80% rise from 1.96 TeV to 7 TeV → Simulations predict a slower rise with $\sqrt{s}$
25–30% rise from 7 TeV to 13 TeV → Best described by POWHEG+PYTHIA8 & POWHEG+HERWIG++

Upper cut on $p_T^{\mu\mu}$ → UE activity mainly from MPI
Better description: POWHEG+PYTHIA8
POWHEG+HERWIG++ overestimates the data
Double-Parton Scattering (DPS) (CDS Record 2257583)

- Two hard parton-parton interactions in a single pp collision $\rightarrow$ **DPS**

\[
\sigma_{\text{DPS}}^{XY} = \frac{m \sigma_X \sigma_Y}{2 \sigma_{\text{eff}}} \Rightarrow \text{Assumed factorization of DPDFs}
\]

\[
\sigma_{\text{eff}} \Rightarrow \text{Predicted to be independent of process type & collision energy}
\]

**Importance of DPS Processes**

- Provide information about hadron structure in transverse plane
- Estimation of background contributions for interesting SM & BSM processes

**Channels**

- $W+2\text{jets}$ (JHEP03(2014)032)
- $\gamma+3\text{jets}$ (CDS Record 2007815)
- Double $J/\psi$ (JHEP09(2014)094)
- $4\text{jets}$ (Phys.Rev.D89(2014)092010)
- $2\text{bjet}+2\text{jet}$ (Phys.Rev.D94(2016)112005)
- Same-sign $WW$ (JHEP02(2018)032), (CDS Record 2257583)

**More Channels Waiting To Be Explored !!**

**Why DPS using Same-Sign WW**

\[
\sigma_{W^+W^-}^{\text{DPS}} \approx \sigma_{W^+W^-}^{\text{SPS}} \Rightarrow \text{a clean final state with leptonically decaying W bosons}
\]
DPS in Same-Sign WW Production

Event Selection

- 2 same-sign leptons (µµ or eµ): $p_T(l_1/2) > 25/20$ GeV
- $p_T^{miss} > 15$ GeV
- $N_{jets} < 2$ ($p_T > 30$ GeV)
- $N_{bjets} = 0$ ($p_T > 25$ GeV)
- Veto on additional leptons & τ_{had}

Signal & Background Processes

- **PYTHIA8 (CUETP8M1 TUNE) Signal sample**
- Backgrounds: WZ, Jet induced backgrounds, Diboson, Triboson & $Z \rightarrow \tau\tau$

BDTs trained against the WZ background process using 11 input variables

- $p_T l_{1,2}, p_T^{miss}, \eta_1 \times \eta_2, |\eta_1 + \eta_2|$
- $M_{T2}^{ll}, m_T(l_1, p_T^{miss}), m_T(l_1, l_2)$
- $\Delta\phi(l_1, l_2), \Delta\phi(l_2, p_T^{miss}), \Delta\phi(l_1 l_2, l_2)$
**Results**

- **Shapes of BDT → Fitted using a likelihood fit for** $e^+e^+, e^-e^-, \mu^+\mu^+, \mu^-\mu^-$

<table>
<thead>
<tr>
<th></th>
<th>expected</th>
<th>observed</th>
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<tbody>
<tr>
<td>$\sigma_{\text{pythia}}$</td>
<td>1.64 pb</td>
<td>1.09$^{+0.50}_{-0.49}$ pb</td>
</tr>
<tr>
<td>$\sigma_{\text{DPSWW}}$</td>
<td>0.87 pb</td>
<td></td>
</tr>
<tr>
<td>significance for $\sigma_{\text{pythia}}$</td>
<td>3.27 $\sigma$</td>
<td>2.23 $\sigma$</td>
</tr>
<tr>
<td>significance for $\sigma_{\text{DPSWW}}$</td>
<td>1.81 $\sigma$</td>
<td></td>
</tr>
<tr>
<td>UL in the absence of signal</td>
<td>&lt; 0.97 pb</td>
<td>&lt; 1.94 pb</td>
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**2$\sigma$ sensitivity → 1$^{\text{st}}$ time in WW DPS**

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Summary

- Unique measurements of charged-particle spectra in different event categories → Important input for MC tuning
- Consistent results from three different correlations functions (with different dependence on MC simulations) used to study BEC
- Homogeneity lengths increase with increasing track multiplicities → Consistent with hydrodynamical calculations
- Observed change in UE activity in Z boson events from 7 → 13 TeV → Best described by POWHEG + PYTHIA8 & POWHEG + HERWIG++
- Overall good description of UE activity by simulations → Universality of UE tunes
- $2\sigma$ sensitivity observed in DPS with same-sign WW analysis