Study of high $p_T$ particle production from Double Parton Scatterings

Paolo Gunnellini on behalf of the CMS collaboration
Outline

1. Introduction
2. Choice of sensitive observables
3. Choice of physics channels
4. Summary of recent DPS measurements
5. Extraction of the DPS contribution
6. Other DPS-sensitive measurements
7. Summary and conclusion
Introduction: the Underlying Event

Hard scattering
Initial and Final State
Radiation
Multiple Parton Interaction (MPI)
Beam-beam remnants

In general, the UE is a softer contribution but... some MPI can be hard!

Double Parton Scattering

\[
P_A = \frac{\sigma_A}{\sigma_{pp}^{tot}}
\]

\[
P_B = \frac{\sigma_B}{\sigma_{pp}^{tot}}
\]

\[
\sigma_{DPS}^{AB} \propto \frac{m}{2} P_A P_B \sigma_{pp}^{tot}
\]

\[
\sigma_{DPS}^{AB} = \frac{m \sigma_A \sigma_B}{2 \sigma_{eff}}
\]

\[
\sigma_{eff} \ll \sigma_{pp}^{tot}
\]

Need for correlations!
Choice of sensitive observables (I): a four-jet scenario

A four-jet final state may arise from one or two chains:
- the two additional jets may be produced via PS or a 2nd hard scattering

Various kinematical observables can discriminate the two processes:

\[ \Delta_{\text{soft}}^\text{rel} p_T = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|} \]

\[ \Delta S = \arccos \left( \frac{\vec{p}_T(j^i, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(j^i, j^k)| \cdot |\vec{p}_T(j^l, j^m)|} \right) \]

! Selection of jet pairs at different scales helps the jet association!
Which regions of the phase space are interesting for DPS detection?

Studies of SPS and DPS contributions performed with PYTHIA8:

Selection of a four-jet final state in $|\eta| < 4.7$ at two different $p_T$ thresholds (20 and 50 GeV)

A SIMPLE scenario:
- SPS: MPI contribution switched off
- DPS: Two hard scatterings at the parton level forced to happen w/o parton shower

Different regions of the phase space are filled by the two processes

Discriminating power
Choice of physics channels

Benchmarks for the detection of the DPS

- $W(\mu\nu) + W(\mu\nu)$
- $W(\mu\nu) + bb$
- $Z(\mu\mu) + bb$
- $bb + jj$
- $\gamma + 3j$
- $4j$
- $W(\mu\nu) + jj$
- $Z(\mu\mu) + jj$

Double $J/\Psi$

- Semi-hard (Minimum Bias)
- $j + UE$
- $W + UE$
- $Z(\mu\mu) + UE$

See Diego's talk

Scale of secondary scatter(s) vs. Scale of primary scatter
Measurement of a four-jet final state

Event selection

Exactly four jets in the final state in $|\eta| < 4.7$:
- 2 jets: $p_T > 50$ GeV (hard), 2 jets: $p_T > 20$ GeV (soft)

$\Delta S$ and $\Delta_{soft}^{rel} p_T$ sensitive to MPI contribution: $\rightarrow$ ROOM for DPS!
Measurement of a four-jet final state with b-jets

Event selection

Selection of at least four jets with $p_T > 20$ GeV:
- 2 b-jets: $|\eta| < 2.4$
- 2 other jets: $|\eta| < 4.7$

Additional jets may be produced also by DPS

Sensitivity to higher orders.. ..but also to MPI!
Measurement of a $W+$dijet final state

**Event selection**

Presence of a muon with $p_T > 35$ GeV in $|\eta| < 2.1$ and $E_{\text{miss}}^{\text{miss}} > 50$ GeV + at least 2 jets: $p_T > 20$ GeV in $|\eta| < 2.0$

$\Delta_{\text{soft}p_T} = \frac{|p_T(j_i, j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$

$\Delta = \arccos \left( \frac{\vec{\rho}_T(W) \cdot \vec{\rho}_T(j^l, j^m)}{|\vec{\rho}_T(W)| \cdot |\vec{\rho}_T(j^l, j^m)|} \right)$

The jets are expected to be produced also by a 2$^{nd}$ scattering

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Sensitivity to DPS!
Measurement of a final state with $\gamma + 3$ jets

Event selection

Selection of a photon and at least three jets in $|\eta| < 2.5$:

- $\gamma + 1$ jet: $p_T > 75$ GeV
- 2 jets: $p_T > 20$ GeV

$\Delta^\text{rel}_{soft} p_T = \frac{|p_T(j_i \cdot j_k)|}{|p_T(j_i)| + |p_T(j_k)|}$

$\Delta S = \arccos \left( \frac{\vec{p}_T(\gamma, j^k) \cdot \vec{p}_T(j^l, j^m)}{|\vec{p}_T(\gamma, j^k)| \cdot |\vec{p}_T(j^l, j^m)|} \right)$

Soft jets are expected to be produced also by a 2$^{nd}$ scattering

No difference between predictions with and w/o MPI

Need for improving sensitivity!
How can one extract the DPS contribution from the measured observables?
How to extract $\sigma_{\text{eff}}$: the template method

- Measurement of DPS-sensitive observables
- Definition of signal and background
- Fit the relative fraction of signal and background
- The signal fraction translates into a value for $\sigma_{\text{eff}}$

$\sigma_{\text{eff}}$ from Ramandeep Kumar

$W + \text{jets channel}$

$$\sigma_{\text{eff}} = \frac{\sigma_A \cdot \sigma_B}{\sigma_{\text{DPS}}}$$

$$\sigma_{\text{eff}} = \frac{N^e_v_A}{N^e_v_{A+B(\text{DPS})}} \cdot \sigma_B$$

$$\sigma_{\text{eff}} = \frac{N^e_A}{f_{\text{DPS}} \cdot N^e_{A+B}} \cdot \sigma_B$$
Extraction of $\sigma_{eff}$ from W+dijet final state (CMS)

**CONSIDERED OBSERVABLES:** normalized $\Delta S$ and $\Delta^{rel} p_T$

**BACKGROUND:** MADGRAPH+P8 with hard MPI above 15 GeV excluded

**SIGNAL:** Two mixed independent scatterings generated with P8 and MG+P8

**DRIVING UNCERTAINTY:** model dependence

\[
\frac{1}{N_{ev}} \frac{dN_{ev}}{d(\Delta^{rel} p_T)} \Rightarrow \frac{\sigma_{eff}}{N_{W+0j}} \cdot f_{DPS} \cdot \sigma_{2j} \\
N_{W+0j} = 27.8, \quad f_{DPS} = 5.5\%,
\]

\[
\sigma_{eff} = 20.7 \pm 0.8 \text{ (stat.)} \pm 6.6 \text{ (syst.)} \text{ mb}
\]
Experimental difficulties of the template method

→ **How to define the background?**
  - Good to exclude hard MPI..but no such possibility in some generators

→ **How to define exclusive and inclusive events?**
  - $N_{W+0j}$ and $N_{W+2j}$ are sensitive to the jet scales

→ These issues have an impact on the systematic uncertainty!

**Is there a way out?**

The inclusive fit method

- Run predictions for different choices of UE parameters
- Fit the MC predictions to the considered observables
- Improve the data description with the examined model
- (..look at the corresponding $\sigma_{\text{eff}}$..)
Extraction of $\sigma_{\text{eff}}$ in four-jet final states

Minimization of the binned $\chi^2 = \sum_O \sum_{b \in O} \frac{(MC^b - DATA^b)^2}{\Delta^2_b}$

Normalized $\Delta S$ in pp $\rightarrow$ 4j in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV

Normalized $\Delta_{\text{soft}} p_T$ in pp $\rightarrow$ 4j in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV

$\sigma_{\text{eff}} = 19.0^{+4.7}_{-3.0}$ mb

LEFT: $\Delta S$  
RIGHT: $\Delta_{\text{soft}} p_T$
Where do we stand now?

- Observables sensitive to DPS measured in various final states
- Values of $\sigma_{\text{eff}}$ extracted in $W+dijet$, four-jet and $WW$
- Ongoing extraction for the other channels

Channel dependence
Scale dependence
Flavour dependence

Investigation of various models
Large uncertainties

STILL MUCH TO DO!

..and it’s not all!

No extraction of a value of $\sigma_{\text{eff}}$ but indication of need for DPS!

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MPI@LHC2015 23rd November 2015
Inclusive double $J/\psi$ production

**Event selection**

Presence of two pairs of opposite-charge muons in $|\eta| < 2.2$; the two pairs must have invariant mass close to $J/\psi$

$$\sigma(J/\psi J/\psi + X) = 1.49 \pm 0.07 \pm 0.13 \text{ nb}$$

**Correction and phase-space extrapolation assuming unpolarized production**

SPS background should dominate the fall at low $\Delta y$

DPS expected to fill the high $\Delta y$ region

Useful baseline for building reliable models of $J/\psi$ production before extracting DPS signal

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CMS

Unpolarized $J/\psi$

- Stat. unc.
- Stat. and syst. unc.

J/ψ phase space:
- $p_t > 6.5 \text{ GeV/c for } |y| < 1.2$
- $p_t > 4.5 \text{ GeV/c for } 1.2 < |y| < 1.43$
- $p_t > 4.5 \text{ GeV/c for } 1.43 < |y| < 2.2$

$\sqrt{s} = 7 \text{ TeV, L = 4.7 fb}^{\dagger}$
What to do next?

$\rightarrow$ Measurements for LHC Run 2

- Energy dependence
  - Channel dependence
  - Scale dependence
  - Flavour dependence

- more statistics
- double differential distributions
- access to diboson final states
- DPS with Higgs

Benchmark for the detection of the DPS

- $W(\mu\nu)+W(\mu\nu)$
- $W(\mu\nu)+bb$  $Z(\mu\mu)+bb$
- $bb+jj$  $\gamma+3j$
- $4j$  $W(\mu\nu)+jj$  $Z(\mu\mu)+jj$

Double J/$\Psi$

- Semi-hard (Minimum Bias)  $j+UE$
- $W+UE$  $Z(\mu\mu)+UE$

Scale of secondary scatter(s)

Scale of primary scatter

Joined effort between phenomenological and experimental community

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MPI@LHC2015 23rd November 2015
Important to study first the sensitivity of the physics channel and the considered observables

Important to produce unfolded results in order to be able to compare predictions from any model

Double parton scattering is essential for proton structure as well as for background to physics searches

Several final states can be used for DPS detection
  - $W+\text{jets}$, four-jets, two $b$- + two other jets...

The measured final states clearly indicate the need for DPS for describing the experimental results

Future: measure energy dependence
  - get a unified picture of DPS with UE- and MB-sensitive measurements
Personal remarks and summary

- **Important to study first the sensitivity of the physics channel and the considered observables**
- **Important to produce unfolded results in order to be able to compare predictions from any model**

- Double parton scattering is essential for proton structure as well as for background to physics searches
- Several final states can be used for DPS detection
  - \( W + \text{jets, four-jets, two } b^- + \text{two other jets, } \gamma^+ \text{three jets, } WW... \)

- **The measured final states clearly indicate the need for DPS for describing the experimental results**
- **Future: measure energy dependence**
  - get a unified picture of DPS with UE- and MB-sensitive measurements

**THANK YOU!**
BACK-UP SLIDES
Determination of $\sigma_{\text{eff}}$ in the four-jet channel

Tuning the four-jet observables (Phys. Rev., D89, 2014) with PYTHIA8

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CDPSTP8S1-4j</th>
<th>CDPSTP8S2-4j</th>
<th>4C</th>
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<tbody>
<tr>
<td>MultipleInteractions:expPow</td>
<td>1.16</td>
<td>0.6921</td>
<td>2.0</td>
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<tr>
<td>MultipleInteractions:ecmPow</td>
<td>0.19*</td>
<td>0.345</td>
<td>0.19</td>
</tr>
<tr>
<td>MultipleInteractions:pT0ref</td>
<td>2.09*</td>
<td>2.125</td>
<td>2.09</td>
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<tr>
<td>BeamRemnants:reconnectRange</td>
<td>1.5*</td>
<td>6.526</td>
<td>1.5</td>
</tr>
<tr>
<td>$\chi^2$/NdF</td>
<td>0.75</td>
<td>0.42</td>
<td>-</td>
</tr>
</tbody>
</table>

$\sigma_{\text{eff}}$ (mb) $= 21.3^{+1.7}_{-1.3}$ mb $\rightarrow \sigma_{\text{eff}}$ (Tune 4C) $\sim 30.3$ mb

DPS-based tune propagated to MADGRAPH ME

Simulation of UE independent on the used matrix element

LEFT: $\Delta S$  
RIGHT: $\Delta_{\text{soft}p_T}$

CMS-GEN-14-001
Choice of sensitive observables

...but also the phase space thresholds matter!!

LEFT: four jets selected applying the same $p_T$

RIGHT: four jets with a rapidity cut applied between the most remote jets

arXiv 1503.08022

pp → 4 jets + X \quad √s = 7 TeV

$p_T > 20$ GeV, $|y_{jet}| < 4.7$
D0 DPS analysis: $\gamma+3$jets and $\gamma+b/c$ jet+2jets

**SELECTION 1:** $p_T^{\gamma} > 26$ GeV, $p_T^{lead} > 35$ GeV, $15 < p_T^{other} < 35$ GeV in $|\eta| < 2.5$

**SELECTION 2:** $p_T^{\gamma} > 26$ GeV, $p_T^{b} > 35$ GeV, $15 < p_T^{other} < 35$ GeV in $|\eta| < 2.5$

**CONSIDERED OBSERVABLES:** normalized $\Delta S$ btw $\gamma$-j and dijet systems

**BACKGROUND:** SHERPA sample with MPI simulation off

**SIGNAL:** Two independent events recorded from data

**DRIVING UNCERTAINTY:** model dependence (only samples with MPI off!)

\[
\sigma_{\text{eff}} \propto \frac{N_{DI}}{N_{DP}} \cdot \frac{\epsilon_{DP}}{\epsilon_{DI}} \cdot \sigma_{\text{hard}}
\]

with $f_{DP}^{\gamma+3j} = 21\%$ and $f_{DP}^{\gamma+b/cj+2j} = 17\%$

\[
\begin{align*}
\sigma_{\text{eff}} &= 12.7 \pm 0.2 \pm 1.3 \text{ mb} \\
\sigma_{\text{eff}} &= 14.6 \pm 0.6 \pm 3.2 \text{ mb}
\end{align*}
\]

Recommendations for DPS extraction

<table>
<thead>
<tr>
<th>Background and signal should cover the full phase space</th>
<th>CMS</th>
<th>ATLAS</th>
<th>D0/CDF</th>
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</thead>
<tbody>
<tr>
<td>✓ ✓</td>
<td>✓</td>
<td>✓</td>
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</table>

<table>
<thead>
<tr>
<th>Use more than one MC event generator to correctly evaluate the model dependence and the systematic uncertainty</th>
<th>CMS</th>
<th>ATLAS</th>
<th>D0/CDF</th>
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</thead>
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<td>✓ ✓ ✓</td>
<td>✓</td>
<td>✓</td>
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<table>
<thead>
<tr>
<th>Use more than one variable for the DPS determination</th>
<th>CMS</th>
<th>ATLAS</th>
<th>D0/CDF</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
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</table>

**BUT..** difficult to define the background template in the same way with different generators!
The proposed new approach

A FEW REMARKS WHEN USING THE TUNING METHOD:

1. Investigation of the contribution of different matrix elements used with the same UE simulation
2. Use more than one MC event generator to study the DPS contribution needed in different models
3. Use more than one variable for the DPS determination
4. Check if the new set of parameters spoil description of more inclusive distribution
How does the new tune perform in the UE description?

Measurement of charged particle mult. and $p_T$ sum in hadronic events


<table>
<thead>
<tr>
<th>Tune</th>
<th>$\sigma_{\text{eff}}$ (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P8 4C</td>
<td>30.3</td>
</tr>
<tr>
<td>CDPSTP8S2</td>
<td>$19.0^{+4.7}_{-3.0}$</td>
</tr>
</tbody>
</table>

A tension appears between the description of "softer" and "harder" MPI within the same framework

Charged particle multiplicity (top) and $p_T$ sum (bottom) for transverse (left) and toward (right) regions

CMS-GEN-14-001
How to fix this?

→ Attempt to implement in a tune a value of $\sigma_{\text{eff}}$ compatible with experimental measurements

**HERWIG++ case:** $\sigma_{\text{eff}} = \frac{28\pi}{\mu}$, with $\mu$ inverse proton radius

Tune UE-EE-5C (arXiv:1307.5015) : $\sigma_{\text{eff}} = 15$ mb (CDF)

Slight underestimation of the low $\Delta S$ region

**LEFT:** $\Delta S$

**RIGHT:** $\Delta_{\text{soft}p_T}^{rel}$

Another approach:
Dynamical approach to MPI contribution (arXiv:1503.08246)

- Introduction of $x$- and scale-dependence for values of $\sigma_{\text{eff}}$
- Inclusion of $1 \times 2$ mechanisms
ATLAS Coll. Associated production of prompt $J/\psi$ mesons and $W$ boson JHEP 04 (2014) 172

LHCb Coll. Prompt charm production in pp collisions HEP 1206 (2012) 141


LHCb Coll. Study of forward $Z+jet$ production in pp collisions JHEP 01 (2014) 033

CMS Coll. Measurement of the cross section and angular correlations for associated production of a $Z$ boson with $b$ hadrons JHEP 12 (2013) 039


No extraction of a value of $\sigma_{eff}$ but clear indication of need for DPS !
Cross section measurements sensitive to DPS

ATLAS Collaboration:
"Measurements of W+prompt J/ψ in pp collisions at 7 TeV"
JHEP 04 (2014) 172

ATLAS Collaboration:
"Measurement of the cross-section for W boson production in association with b-jets"

Measurements compatible with a DPS contribution with $\sigma_{\text{eff}} \sim 15$-$20$ mb
Keypoints of the choice of variables

- **Observables which consider the whole final state are more sensitive to DPS**
  - $\Delta S$, sum of transverse momenta, energy of the four objects

- **A large phase space for additional radiation reduces the DPS sensitivity**
  - Better selection with objects close in transverse momentum
  - **BUT**...more complicated migration effects (and unfolding procedure)
CMS strategy for the DPS measurement

1st step
Corrected distributions
DPS-sensitive variables

2nd step
Data interpretation and unambiguous definition of signal and background templates

3rd step
Extraction of the DPS fraction and study of the process dependence

Compare the data to your own favourite predictions!

4th (future) step: differential distributions with high luminosities..
Choice of the physics channel

\[ \sigma_{AB}^{DPS} = \frac{m \sigma_A \sigma_B}{2 \sigma_{\text{eff}}} \]

→ Which channels can be used to look for DPS signals?

- Benchmark for the detection of the DPS:
  - \( W(\mu\nu) + W(\mu\nu) \)
  - \( W(\mu\nu) + bb \) \( Z(\mu\mu) + bb \)
  - \( bb + jj \) \( \gamma + 3j \)
  - \( 4j \) \( W(\mu\nu) + jj \) \( Z(\mu\mu) + jj \)

- Double \( J/\psi \):
  - Semi-hard (Minimum Bias) \( j + UE \)
  - \( W + UE \) \( Z(\mu\mu) + UE \)

Published by CMS and/or ATLAS

Published by D0 and/or CDF

How can DPS be detected?
The Compact Muon Solenoid experiment

- Silicon tracker immersed in a 3.8 T magnetic field
- Wide calorimeter coverage
- Excellent jet energy resolution and muon detection efficiency
- Particle Flow technique for jet reconstruction
Angular correlations in $Z+b$-hadrons final states

Event selection

Presence of two leptons with $p_T > 20$ GeV in $|\eta| < 2.4$ with invariant mass close to the $Z$ peak and two $b$-hadrons with $p_T > 15$ GeV in $|\eta| < 2$

$$\Delta \phi = |\Delta \phi_{b1} - \Delta \phi_{b2}|$$

$$\Delta R = \sqrt{\Delta \phi_{b1}^2 + \Delta \eta_{b2}^2}$$

Data compatible with predictions at parton level with DPS contribution ($\sigma_{\text{eff}} \sim 25$-30 mb) included