Studies of double parton scattering and Monte Carlo tuning

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Work done within the CMS Collaboration

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Altarelli award
What is a proton-proton collision?

In general, it is a softer contribution but some MPI can be hard!

Double Parton Scattering (DPS)
Double parton scattering and experimental overview

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

→ What are the different pieces of this formula?

- \( m \): symmetry factor (equal to 1 or 2)
- \( \sigma_A, \sigma_B \): (partonic) inclusive cross sections for processes A and B
- \( \sigma_{\text{eff}} \): we can extract experimentally
Double parton scattering and experimental overview

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

Internal structure of the proton DPS background for any physics channel

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BUT... experimental issue: very difficult to define inclusive cross sections at parton level!

\( \sigma_{\text{eff}} \) value differs for different definitions of single cross sections!

Double parton scattering and experimental overview

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Example: \( \gamma+3 \) jets measured by CDF at 1.8 TeV

<table>
<thead>
<tr>
<th>Exclusive ( \sigma_A, \sigma_B )</th>
<th>Inclusive ( \sigma_A, \sigma_B )</th>
<th>Assuming unknown number of scatters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{eff}} \sim 14.5\pm1.7^{+1.7}_{-2.3} ) mb</td>
<td>( \sigma_{\text{eff}} \sim 10.3 ) mb</td>
<td>( \sigma_{\text{eff}} \sim 12.0\pm1.3^{+1.3}_{-1.5} ) mb</td>
</tr>
</tbody>
</table>

THERE IS AMBIGUITY!

Double parton scattering and experimental overview

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

\[ \rightarrow \text{Which channels have been used to look for DPS signals?} \]

<table>
<thead>
<tr>
<th>Experiment (energy, final state, year)</th>
<th>[\text{mb}]</th>
<th>[\text{mb}]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS ((\sqrt{s} = 7 \text{ TeV}, 4 \text{ jets}, 2016))</td>
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<tr>
<td>CDF ((\sqrt{s} = 1.8 \text{ TeV}, 4 \text{ jets}, 1993))</td>
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<tr>
<td>UA2 ((\sqrt{s} = 630 \text{ GeV}, 4 \text{ jets}, 1991))</td>
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<tr>
<td>AFS ((\sqrt{s} = 63 \text{ GeV}, 4 \text{ jets}, 1986))</td>
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<tr>
<td>DØ ((\sqrt{s} = 1.96 \text{ TeV}, 2\gamma+ 2 \text{ jets}, 2016))</td>
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<tr>
<td>DØ ((\sqrt{s} = 1.96 \text{ TeV}, \gamma+ 3 \text{ jets}, 2010))</td>
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<td>CDF ((\sqrt{s} = 1.8 \text{ TeV}, \gamma+ 3 \text{ jets}, 1997))</td>
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<tr>
<td>ATLAS ((\sqrt{s} = 8 \text{ TeV}, Z + J/\psi, 2015))</td>
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</tr>
<tr>
<td>CMS ((\sqrt{s} = 7 \text{ TeV}, W+ 2 \text{ jets}, 2014))</td>
<td></td>
<td></td>
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<tr>
<td>LHCb ((\sqrt{s} = 7/8 \text{ TeV}, \Upsilon(1S)D^{0,*}, 2015))</td>
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\[ \rightarrow \text{Many sensitive channels at various energies} \]

\[ \rightarrow \text{Scatter of values ranging between 10-25 mb} \]

\[ \rightarrow \text{Large uncertainties, mainly due to } \sigma_{\text{eff}} \text{ extraction method} \]
Double parton scattering and experimental overview

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

Internal structure of the proton
DPS background for any physics channel

→ Which channels have been used to look for DPS signals?

**In this presentation:**

- **four-jets**
- **two b-jets + two additional jets**
Physics of a four-jet scenario (I)

A four-jet final state may arise from one or two hard scatterings:

- the two additional jets may be produced via hard radiation or 2nd hard scattering

Discriminating observables:

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

\[
\Delta S = \arccos \left( \frac{\vec{p}_T(j_l, j_k) \cdot \vec{p}_T(j_j, j_i)}{|\vec{p}_T(j_l, j_k)| \cdot |\vec{p}_T(j_j, j_i)|} \right)
\]

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

Selection of a four-jet final state in generator level studies performed with PYTHIA8:

- two jets with $p_T > 50$ GeV
- two jets with $p_T > 20$ GeV

A SIMPLE scenario:
- SPS: MPI contribution switched off
- DPS-NO PS: Two hard scatterings at the parton level forced to happen w/o parton shower

$$\Delta S = \arccos \left( \frac{\vec{p}_T(j_l,j_k) \cdot \vec{p}_T(j_i,j_j)}{|\vec{p}_T(j_l,j_k)| \cdot |\vec{p}_T(j_i,j_j)|} \right)$$

**Discriminating power:**
- Different shapes of the two processes
- Specific regions filled by the two
Correlation observables: normalized cross sections

Kinematical topology of the jets of the final state in the transverse plane:

CMS, $\sqrt{s} = 7$ TeV, $L = 36$ pb$^{-1}$, $pp \rightarrow 4j+X$

| $|\eta| < 4.7$ | $1^{st}$, $2^{nd}$ jet: $p_T > 50$ GeV | $3^{rd}$, $4^{th}$ jet: $p_T > 20$ GeV |
|---|---|---|
| SHERPA | POWHEG+P6 Z2' | MADGRAPH+P6 Z2* |
| POWHEG+P6 Z2' | PYTHIA8 4C | HERWIG++ UE-EE-3 |
| Data | POWHEG+P6 Z2' MPI off | Total Uncertainty |

POWHEG w/o MPI is far below for $\Delta S$

$\Delta S$ sensitive to MPI contribution:

ROOM for DPS!

$\Delta S$ (soft,hard)

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

Correlation observables: normalized cross sections

Kinematical topology of the jets of the final state in the transverse plane:

\[ 3 \text{ pb}^{-1} (7 \text{ TeV}), \, pp \rightarrow 2 \text{ b} + 2 \text{ j} + X \]

- Predictions including MPI follow the trend of the data
- POWHEG w/o MPI is far below for \( \Delta S \): ROOM for DPS!

Light jets are expected to be produced also by a 2\(^{nd}\) scattering

PRD 94, 112005
How to determine the DPS contribution from exp. data?

**Used so far...**

**TEMPLATE METHOD**

Construction of two templates:
- SPS background
- DPS signal

**Some open issues..**

→ Definition of background and signal can be ambiguous
→ MC-dependent background template definition
→ Difficult to define experimentally $\sigma_A$ and $\sigma_B$ in pocket formula
→ Difficult to define partonic cross sections from particle-level ones
How to determine the DPS contribution from exp. data?

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**INCLUSIVE (TUNING) METHOD**
The inclusive method

Automatized generation of predictions with different UE parameters
Inclusive fits of DPS-sensitive observables \( O \)
Minimization of the binned \( \chi^2 = \sum O \sum b \in O \frac{(MC^b - DATA^b)^2}{\Delta^2 b} \)

\[ \rightarrow \] The UE parameters obtained from the best fit define the value of \( \sigma_{eff} \)

**ASSUMPTIONS:**
- ”Pocket formula”
- Uncorrelated uncertainties from data

**PROs:**
- No separation between signal and background
- Possibility to extract \( \sigma_{eff} \) from any model / Monte Carlo generator
Determination of $\sigma_{\text{eff}}$ in four-jet final states

Fit to the $\Delta S$ correlation observable

MC Generator: PYTHIA 8

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<th>$\sigma_{\text{eff}}$ (mb)</th>
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<tr>
<td>P8 4C</td>
<td>-</td>
<td>30.3</td>
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<tr>
<td>CDPSP8S-4j</td>
<td>0.751</td>
<td>19.0^{+4.7}_{-3.0}</td>
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$\Delta S$ (soft,hard)

4C MPI off: bad data description

4C: improved but not optimal agreement

CDPSP8S-4j: very good data description

EPJC 76 (2016) 155
Determination of $\sigma_{\text{eff}}$ in 2b2j final states

Fit to the $\Delta S$ correlation observable

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<td>CDPSP8S-2b2j</td>
<td>0.352</td>
<td>$23.2^{+3.3}_{-2.5}$</td>
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$\leftarrow$ P8 UE tune

$\leftarrow$ P8 DPS tune

Normalized $\Delta S$ in $pp \rightarrow 2b+2j+X$ in $|\eta| < 4.7$ at $\sqrt{s} = 7$ TeV

4C MPI off: bad data description

4C: improved but not optimal agreement

CDPSP8S-2b2j: very good data description

$\Delta S$ (light,bottom)

DESY-THESIS-15-010
Summary of DPS measurements

Waiting for values at 13 TeV!
Are soft and hard MPI described in the same framework?

Is the same set of UE parameters able to describe
- UE data
- DPS-sensitive measurements?

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<tr>
<td>P6 Z2*</td>
<td>33.0</td>
</tr>
<tr>
<td>CUETP8S1-CTEQ6L1</td>
<td>27.8+1.2 (-1.3)</td>
</tr>
<tr>
<td>CUETP8S1-HERAPDF1.5LO</td>
<td>29.0+2.3 (-2.0)</td>
</tr>
<tr>
<td>CDPSTP8S-4j</td>
<td>19.0+4.7 (-3.0)</td>
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<tr>
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Tension between UE-based and DPS-based tunes

Transverse $N_{\text{chg}}$ density vs. $p_{\perp}$, $\sqrt{s} = 7$ TeV

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

→ DPS "pocket" formula needs some improvement
i.e. Parton correlations in initial state
  • double/generalized PDF
  • "dynamic" value of $\sigma_{\text{eff}}$

→ Better understanding of the SPS background
  • $k_T$-factorization scheme

Further experimental measurements will constrain and refine the various approaches

The inclusive method can be used for any experimental measurement
DIS organization committee for this award
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Hannes Jung
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- Pierre Van Mechelen
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THANKS FOR YOUR ATTENTION