Double Parton Scattering at the LHC – Characteristics and Estimates

Edmond L Berger
Argonne National Laboratory

Outline

1. What is Double Parton Scattering (DPS)?
2. Aim: identify signature kinematic variables and characteristic concentrations in phase space that distinguish DPS events from the usual single parton scattering SPS events
3. Establish a methodology to measure the size of DPS
4. Once the cross section for DPS is established in a well-defined process, here, $pp \rightarrow b\bar{b}jjX$, then one can calculate its contributions in other final states
5. Possibly important for background estimates in new physics searches
6. Conclusions
What is double parton scattering?

- Two hard collisions per $pp$ interaction

- Does it exist as a discernable contribution?

- What are its characteristics, allowing its measurement?

- Heuristic cross section for $pp \rightarrow b\bar{b}j_1j_2X$

$$d\sigma^{DPS}(pp \rightarrow b\bar{b}j_1j_2X) = \frac{d\sigma^{SPS}(pp \rightarrow b\bar{b}X)d\sigma^{SPS}(pp \rightarrow j_1j_2X)}{\sigma_{eff}}$$
Several assumptions

\[ d\sigma^{DPS}(pp \rightarrow b\bar{b}j_1j_2X) = \frac{d\sigma^{SPS}(pp \rightarrow b\bar{b}X)d\sigma^{SPS}(pp \rightarrow j_1j_2X)}{\sigma_{eff}} \]

• \( \sigma_{eff} \)
  • Given one hard-scatter, \( \sigma_{eff} \) measures the effective size of the core in which accompanying partons are confined
  • Bounded by the transverse size of a proton
  • Different for \( gg \) and \( qq \) subprocesses? Energy dependent?

• Factorization/independent hard scatters cannot be strictly true, certainly not if any parton \( x > 0.5 \)

• Large dynamic range of LHC offers opportunity to explore this phenomenology; measure \( \sigma_{eff} \)
$pp \rightarrow b\bar{b}jjX \text{ at the LHC}$

Bottom quark pair production plus two jets

- Large rate over a wide kinematic range
- $b$ tagging provides a clean signal
- Relatively unambiguous which final objects to pair: $b$ with $\bar{b}$ and $j$ with $j$

Calculation

- Generate DPS $4 \rightarrow 4$ events with Madgraph/Madevent
- Generate SPS $2 \rightarrow 4$ events with ALPGEN (faster)
- Look for kinematic distributions that show discrimination between DPS and SPS

Assume, for illustration, $\sigma_{\text{eff}} = 12 \text{ mb}$; event rates quoted for $\sqrt{s} = 10 \text{ TeV}$ and $10 \text{ pb}^{-1}$ integrated luminosity
Double parton contributions

• At LO, the only contribution is: \((ij \rightarrow b\bar{b}) \otimes (kl \rightarrow jj)\)

• \(\otimes\): combine one event from \(b\bar{b}\) and one from \(jj\)

• NLO effects modeled with

\[
\begin{align*}
&b\bar{b}(j) \otimes jj, \quad b\bar{b}j \otimes (j)j, \quad b\bar{b}j \otimes j(j) \\
&b\bar{b} \otimes (j)jj, \quad b\bar{b} \otimes j(j)j, \quad b\bar{b} \otimes jj(j)
\end{align*}
\]

• \((j)\) indicates \(j\) is undetected

Single parton contributions

• LO : 2 \(\rightarrow\) 4 process \(ij \rightarrow b\bar{b}jj\)

• NLO modeled with contributions from the 5-jet final states:

\[
\begin{align*}
&b\bar{b}(j)jj, \quad b\bar{b}j(j)j, \quad b\bar{b}jj(j).
\end{align*}
\]
Simulation details

- Acceptance cuts
  
  \[ p_{T,j} \geq 25 \text{ GeV}, \ |\eta_j| \leq 2.5 \]
  \[ p_{T,b} \geq 25 \text{ GeV}, \ |\eta_b| \leq 2.5 \]
  \[ \Delta R_{jj} \geq 0.4, \ \Delta R_{bb} \geq 0.4 \]

- \[ \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

- Include detector resolution effects
  
  \[ \frac{\delta E}{E} = \frac{a}{\sqrt{E/\text{GeV}}} \oplus b, \]

  \[ a = 50\% \text{ and } b = 3\% \text{ for jets} \]

- Assume a \( b \)-tagging rate of 60\% for \( b \)-quarks with \( p_T > 20 \text{ GeV} \) and \( |\eta_b| < 2.0 \)

- Hard scale choice
  
  \[ \mu^2 = \sum_i p_{T,i}^2 + m_i^2 \]
DPS → uncorrelated (sub)events

- $\Phi$: angle between the planes defined by $\bar{b}b$ and $jj$ systems
- Uncorrelated scatters: the DPS $\Phi$ distribution flat
- In SPS, $a + b \rightarrow \bar{b}bjjX$, many diagrams contribute; spin and kinematic correlations expected between the planes

![Graph showing the DPS and SPS distributions for $\Phi$.]
Transverse momentum of leading jet

- $p_T$ of the leading jet in $pp \rightarrow b\bar{b}jjX$, either a $b$ or a light $j$

- DPS fills in the lower $p_T$ region

- Sum does not allow us to establish a DPS signal; cross-over set by $\sigma_{\text{eff}}$
**Distinguishing Variables - \( \Delta \phi_{jj} \) and \( S_\phi \)**

- Topology of DPS events includes two \( 2 \rightarrow 2 \) hard scatters
  - Expect 2 pairs of jets to be individually roughly back-to-back (up to effects of extra real radiation)
  - \( \rightarrow \Delta \phi_{jj} \sim \pi \) and \( \Delta \phi_{b\bar{b}} \sim \pi \)
- Even better is variable \( S_\phi \) that combines this information from both \( b\bar{b} \) and \( jj \) systems

\[
S_\phi = \frac{1}{\sqrt{2}} \sqrt{\Delta \phi(b_1, b_2)^2 + \Delta \phi(j_1, j_2)^2}
\]


\( p\bar{p} \rightarrow \gamma + 3jX \) at \( \sqrt{s} = 1.96 \) TeV
Distinguishing Variables - $S_\phi$

\[ S_\phi = \frac{1}{\sqrt{2}} \sqrt{\Delta \phi(b_1, b_2)^2 + \Delta \phi(j_1, j_2)^2} \]

- DPS events are clustered near $S_\phi \sim \pi$, well separated from the total
- SPS events are fairly uniformly distributed
**Distinguishing Variables** - $p_T(j_1, j_2)$ and $S'_{pT}$

- Topology of DPS events includes two $2 \rightarrow 2$ hard scatters
  - Expect 2 pairs of jets to be individually roughly back-to-back (up to effects of extra real radiation)
  - At LO for a $2 \rightarrow 2$ process, the vector sum of the transverse momenta of the final state pair is zero:
    \[ p_T(b_1, b_2) \sim 0 \text{ and } p_T(j_1, j_2) \sim 0 \]
  - NLO radiation and momentum mismeasurement smear the expected peak near zero

- Scaled variable $S'_{pT}$ combines this information from both $b\bar{b}$ and $jj$ systems

\[
S'_{pT} = \frac{1}{\sqrt{2}} \sqrt{\left( \frac{|p_T(b_1, b_2)|}{|p_T(b_1)| + |p_T(b_2)|} \right)^2 + \left( \frac{|p_T(j_1, j_2)|}{|p_T(j_1)| + |p_T(j_2)|} \right)^2}
\]

Distinguishing Variables - $S'_{p_T}$

$$S'_{p_T} = \frac{1}{\sqrt{2}} \sqrt{\left( \frac{|p_T(b_1, b_2)|}{|p_T(b_1)| + |p_T(b_2)|} \right)^2 + \left( \frac{|p_T(j_1, j_2)|}{|p_T(j_1)| + |p_T(j_2)|} \right)^2}$$

- DPS events produce a clear peak near $S'_{p_T} = 0$, well separated from the total
- SPS events are away from back-to-back (gluon splitting)
Two-dimensional distribution

Clear separation of DPS from SPS in the 2-D $\Phi$ and $S'_{pT}$ plane
Methodology/Strategy

Start with clean process $pp \rightarrow b\bar{b}jjX$

- Look at events in the 2-D $\Phi$ and $S'_{pT}$ plane
- Expect a concentration of events near $S'_{pT} = 0$ that are distributed uniformly in the inter plane angle $\Phi$. These are the DPS events
- Valley of low density between $S'_{pT} \sim 0.1$ and $0.4$ should allow a cut that enhances DPS
- This enhanced DPS sample should show a more rapid drop of the cross section vs $p_T$ of the leading jet
- Measure $\sigma_{\text{eff}}$
- Examine other processes, e.g., $pp \rightarrow 4\text{jets}X$; is the extracted $\sigma_{\text{eff}}$ roughly the same?
Conclusions

- Developed the phenomenology of double scattering for $pp \rightarrow \bar{b}bjjX$ at LHC energies
- Identified distinct regions of phase space in which DPS should be relatively clean
- LHC operates in a different region of Bjorken $x$ from the Tevatron: wider dynamic range provides opportunity to explore characteristics of DPS – factorization, process independence, ....
- Would be valuable to establish a DPS signal in early LHC runs and measure $\sigma_{\text{eff}}$
- Once $\sigma_{\text{eff}}$ is measured in a clean process, and dynamical features are established in a clean process (or two), then estimates can be made for possibly important backgrounds to Higgs and new physics processes
BACKUPS
Parton $x$ values for DPS and SPS

- Distributions in the parton $x$ values for DPS and SPS contributions to $pp \rightarrow b\bar{b}jjX$ at LHC
- DPS events tend to have small values of $x$ ($x < 0.2$)
- Momentum fraction carried by the beam remnant is $1. - x_1 - x_2$ for DPS and $1. - x$ in SPS: very similar
Past searches for DPS

- Good to have a process with a large rate and relatively clean signal
- Early searches focussed on 4 jet and $\gamma$ plus jets

Table 1: DPS analyses by AFS, UA2, and CDF Collaborations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>Final state</th>
<th>$p_T^{\text{min}}$ (GeV)</th>
<th>$\eta$ range</th>
<th>$\sigma_{\text{eff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFS ($pp$), 1986</td>
<td>63</td>
<td>4 jets</td>
<td>$p_T^{\text{jet}} &gt; 4$</td>
<td>$</td>
<td>\eta^{\text{jet}}</td>
</tr>
<tr>
<td>UA2 ($p\bar{p}$), 1991</td>
<td>630</td>
<td>4 jets</td>
<td>$p_T^{\text{jet}} &gt; 15$</td>
<td>$</td>
<td>\eta^{\text{jet}}</td>
</tr>
<tr>
<td>CDF ($p\bar{p}$), 1993</td>
<td>1800</td>
<td>4 jets</td>
<td>$p_T^{\text{jet}} &gt; 25$</td>
<td>$</td>
<td>\eta^{\text{jet}}</td>
</tr>
<tr>
<td>CDF ($p\bar{p}$), 1997</td>
<td>1800</td>
<td>$\gamma + 3$ jets</td>
<td>$p_T^{\text{jet}} &gt; 6$</td>
<td>$</td>
<td>\eta^{\gamma}</td>
</tr>
</tbody>
</table>

- Wide range of values of $\sigma_{\text{eff}}$

- Recent study by D0 of $p\bar{p} \rightarrow \gamma + \text{jets} + X$ at $\sqrt{s} = 1.96$ TeV

$\sigma_{\text{eff}}^{\text{ave}} = 16.4 \pm 0.3(\text{stat}) \pm 2.3(\text{syst}) \text{ mb}$