Double Parton Scattering @ LHCb

Vanya Belyaev (ITEP/Moscow)
Two independent hard scattering processes
Relations through (unknown) double PDF

\[
\Gamma_{ij}(x_1, x_2; b_1, b_2; Q_1^2, Q_2^2) = D^{ij}_h(x_1, x_2; Q_1^2, Q_2^2) f(b_1) f(b_2).
\]

Assume factorization of double PDFs

\[
D^{ij}_h(x_1, x_2; Q_1^2, Q_2^2) = D^{i}_h(x_1; Q_1^2) D^{j}_h(x_2; Q_2^2).
\]

(Can’t be true for all \(x, Q^2\))

Easy to make predictions!
And the predictions are easy to test

Universal (energy and process independent) factor)

\[
\frac{1}{\sigma_{eff}} = \int d^2 b F^2(b)
\]

Pocket formula

\[
\sigma_{DPS}^{AB} = \frac{m}{2} \frac{\sigma_{SPS}^A \sigma_{SPS}^B}{\sigma_{eff}}.
\]

\(m=1,2\)

\[
\sigma_{eff}^{DPS} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb}
\]

CDF, F.Abe et al., PDR 56 3811 (1997)
DPS

- Simple pattern, a lot of powerful consequences and interesting predictions
- **Pocket formula is also valid for differential cross-sections**

\[
\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{\text{eff}}} \sigma^{SPS}(pp \rightarrow c\bar{c}X_1) \cdot \sigma^{SPS}(pp \rightarrow c\bar{c}X_2).
\]

\[
\frac{d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t} dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}} = \frac{1}{2\sigma_{\text{eff}}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_1)}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} \cdot \frac{d\sigma^{SPS}(pp \rightarrow c\bar{c}X_2)}{dy_3 dy_4 d^2 p_{3,t} d^2 p_{4,t}}.
\]

- The cross-section is **larger** than in naïve model
  \[\sigma_{\text{eff}} = 15\text{mb} \text{ vs } \sigma_{\text{in}} = 55\text{mb}\]

- The effective cross-section is a property of proton (integral over transverse degrees of freedom)
  - Smaller than "proton size": \[\pi R^2 \approx 50\text{mb}\]
  - It is universal: **energy and process independent**
    - easy to compare Tevatron, GPD and LHCb

- Easy to extend to \(pA\) and \(AA\) collisions with interesting predictions
  - Large enhancement for certain processes

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Too simple?

• Validity of factorization anzatz:

\[
D_h^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_h^i(x_1; Q_1^2)D_h^j(x_2; Q_2^2).
\]

• This anzatz allow \( x_1 + x_2 > 1 \):
  • energy non-conservation. Need to suppress such configurations: at least \( \theta(1-x_1x_2) \) factor is needed
  • Makes integration impossible
• Numerical studies within Lund dipole cascade model shows violation of factorization at large \( Q_1^2 \) and/or \( Q_2^2 \)
  • up to 20% deviation from factorization in \( p^+\text{jets} \) cross-sections in Tevatron case
  • Up to 30-50% for certain kinematical ranges
• For processes with (very) small \( x \) only factorization is fine

\[
\Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2)F_g(x_2, \mu_2^2)F(b, x_1, x_2, \mu_1^2, \mu_2^2),
\]

\[
\sigma_{\text{eff}}(x_1, x_2, x_1', x_2', \mu_1^2, \mu_2^2) = \left( \int d^2b F(b; x_1, x_2, \mu_1^2, \mu_2^2) F(b; x_1', x_2', \mu_1^2, \mu_2^2) \right)^{-1}.
\]
• Need to measure $\sigma_{\text{eff}}$
  • validate independence on energy and process
  • ... or measure the dependence
• Validate/probe the pocket formula for differential cross-sections
  • Due to $\theta(1-x_1-x_2)$ insert the differential formula dies the first
• ”A” and ”B” have larger rapidity separation with respect to uncorrelated case...

\[
D_{h}^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_{h}^{i}(x_1; Q_1^2) D_{h}^{j}(x_2; Q_2^2).
\]
DPS importance

• Can easily mimic crucial signals

• DPS importance grows with energy/gluon density (smaller x)

• Interparton correlations

• First observed long time ago:
  • 4-jets AFS@ISR
  • 3-jets+γ CDF, D0, …

• @ LHC
  • ATLAS, CMS: 4-jets, W+jets, 2×J/ψ, W+J/ψ, Z+J/ψ, …
  • LHCb: 2×J/ψ, Z+D, double charm, ….

\[ \sigma_{\text{eff}} \text{ is important QCD parameter:}
\]
Energy independent (?)
Process independent (?)

TEST IT!
Energy/process independent?
~40% of heavy quarks in <4% of 4π

RICH Detectors:
95% ε(K±) @5% π→K misID

Muon:
ε(μ±)=97% @1-3% π→μ misID

pp-interaction point

Vertex Locator
O(50fs) resolution for B
The most precise τ(B)

ECAL: σ_m(π^0)=7MeV/c^2

Tracking:
Δp/p =0.5-0.6% for 5<p<100 GeV/c
The most precise B-masses

19 May 2015 DESY

Vanya Belyaev, "DPS@LHCB"
Run I

1 fb^{-1}@7TeV
2 fb^{-1}@8TeV
3.3 pb^{-1}@2.76TeV
1.6 nb^{-1} pA \& Ap

Thanks to LHC accelerator team for the excellent performance of machine

19 May 2k+15 DESY

Vanya Belyaev, "DPS@LHCb"
\[ J/\psi \to \mu^+\mu^- \] @ LHCb

- High trigger efficiency
  - Dimuon trigger
  - No \( p_T(J/\psi) \) cut
- Excellent \( \mu\)ID
- Very low background
- Resolution \(~13\text{MeV}/c^2\)
- High yield: \(~150\text{M}/\text{fb}^{-1}\)
- Cross-section is measured at \(\sqrt{s}=7,8 \text{ & } 2.76\text{TeV}\)

\( \sqrt{s}=7\text{TeV}, \ 355\text{pb}^{-1} \)

19 May 2k+15 DESY

\textbf{Vanya Belyaev, "DPS@LHCb"}
Prompt open charm at LHCb

- Dedicated charm triggers
  - Further improvement for 2012, and even further for Run II
- Excellent hadron ID
  - RICH detectors
- Excellent mass-resolution
  \( O(5\text{MeV/c}^2) \)
- "background-free" signals \( p_t > 3\text{GeV/c} \)
  - \( D^0 \rightarrow K^-\pi^+ \) 200M/\( \text{fb}^{-1} \)
  - \( D^+ \rightarrow K^-\pi^+\pi^+ \) 100M/\( \text{fb}^{-1} \)
  - \( D_s \rightarrow \phi\pi^+ \) 10M/\( \text{fb}^{-1} \)
  - \( \Lambda_c \rightarrow pK^-\pi^+ \) 2M/\( \text{fb}^{-1} \)
- Measured cross-section at \( \sqrt{s} = 7\text{TeV} \)

\( \sqrt{s} = 7\text{TeV}, 355\text{pb}^{-1} \)

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Vanya Belyaev, "DPS@LHCb"
$J/\psi +$ open charm signals

$J/\psi D^0$ $4875 \pm 86$

$J/\psi D^+$ $3323 \pm 71$

$J/\psi D_s$ $328 \pm 22$

$J/\psi \Lambda_c$ $116 \pm 14$

$\sqrt{s} = 7\text{TeV}$, 355pb$^{-1}$

Clear signals, Small background, Significances $>7\sigma$

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2\times open charm signals

$\sqrt{s}=7\text{TeV}, 355\text{pb}^{-1}$

Small background Significances for 6 modes exceed 5\sigma

\begin{align*}
\text{D}^0\text{D}^0 &\quad 1087\pm37 \\
\text{D}^0\text{D}^+ &\quad 1177\pm39 \\
\text{D}^+\text{D}^+ &\quad 249\pm19 \\
\text{D}^+\text{D}_s &\quad 52\pm9 \\
\end{align*}
### Production cross-sections

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma_{J/\psi C}/\sigma_{J/\psi}$ [10^{-3}]</th>
<th>$\sigma_{J/\psi C}/\sigma_C$ [10^{-4}]</th>
<th>$\sigma_{J/\psi C}/\sigma_{J/\psi C}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi D^0$</td>
<td>16.2 ± 0.4 ± 1.3^{+3.4}_{-2.5}</td>
<td>6.7 ± 0.2 ± 0.5</td>
<td>14.9 ± 0.4 ± 1.1^{+2.3}_{-3.1}</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>5.7 ± 0.2 ± 0.6^{+1.2}_{-0.9}</td>
<td>5.7 ± 0.2 ± 0.4</td>
<td>17.6 ± 0.6 ± 1.3^{+2.8}_{-3.7}</td>
</tr>
<tr>
<td>$J/\psi D^+_s$</td>
<td>3.1 ± 0.3 ± 0.4^{+0.6}_{-0.5}</td>
<td>7.8 ± 0.8 ± 0.6</td>
<td>12.8 ± 1.3 ± 1.1^{+2.0}_{-2.7}</td>
</tr>
<tr>
<td>$J/\psi \Lambda_c^+$</td>
<td>4.3 ± 0.7 ± 1.2^{+0.9}_{-0.7}</td>
<td>5.5 ± 1.0 ± 0.6</td>
<td>18.0 ± 3.3 ± 2.1^{+2.8}_{-3.8}</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\sigma$ [mb]</th>
<th>$\sigma_{CC}/\sigma_{C\bar{C}}$ [%]</th>
<th>$\sigma_{C_1 C_2}/\sigma_{C_1 C_2}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 D^0$</td>
<td>690 ± 40 ± 70</td>
<td>10.9 ± 0.8</td>
<td>2 × (42 ± 3 ± 4)</td>
</tr>
<tr>
<td>$D^0 D^0$</td>
<td>6230 ± 120 ± 630</td>
<td>10.9 ± 0.8</td>
<td>2 × (47 ± 1 ± 0.4)</td>
</tr>
<tr>
<td>$D^0 D^+$</td>
<td>520 ± 80 ± 70</td>
<td>12.8 ± 2.1</td>
<td>47 ± 7 ± 4</td>
</tr>
<tr>
<td>$D^0 D^-$</td>
<td>3990 ± 90 ± 500</td>
<td>12.8 ± 2.1</td>
<td>6.0 ± 0.2 ± 0.5</td>
</tr>
<tr>
<td>$D^0 D^+ _s$</td>
<td>270 ± 50 ± 40</td>
<td>15.7 ± 3.4</td>
<td>36 ± 8 ± 4</td>
</tr>
<tr>
<td>$D^0 D^0 _s$</td>
<td>1680 ± 110 ± 240</td>
<td>15.7 ± 3.4</td>
<td>5.6 ± 0.5 ± 0.6</td>
</tr>
<tr>
<td>$D^0 \Lambda_c^+$</td>
<td>2010 ± 280 ± 600</td>
<td>—</td>
<td>9 ± 2 ± 1</td>
</tr>
<tr>
<td>$D^+ D^+$</td>
<td>80 ± 10 ± 10</td>
<td>9.6 ± 1.6</td>
<td>2 × (66 ± 11 ± 7)</td>
</tr>
<tr>
<td>$D^+ D^-$</td>
<td>780 ± 40 ± 130</td>
<td>9.6 ± 1.6</td>
<td>2 × (6.4 ± 0.4 ± 0.7)</td>
</tr>
<tr>
<td>$D^+ D^+_s$</td>
<td>70 ± 15 ± 10</td>
<td>12.1 ± 3.3</td>
<td>50 ± 15 ± 6</td>
</tr>
<tr>
<td>$D^+ D^-_s$</td>
<td>550 ± 60 ± 90</td>
<td>12.1 ± 3.3</td>
<td>7 ± 1 ± 1</td>
</tr>
<tr>
<td>$D^+ \Lambda_c^+$</td>
<td>60 ± 30 ± 20</td>
<td>10.7 ± 5.9</td>
<td>140 ± 70 ± 20</td>
</tr>
<tr>
<td>$D^+ \Lambda_c^-_s$</td>
<td>530 ± 130 ± 170</td>
<td>10.7 ± 5.9</td>
<td>15 ± 4 ± 2</td>
</tr>
</tbody>
</table>

$\sqrt{s}=7$TeV, 355pb$^{-1}$

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2$<y(D)<4$, 2$<y(J/\psi)<4$, $p_T(D)>3$GeV/c

SPS fraction 1-5% Extremely clean DPS!

Berezhnoy et al, Baranov Lansberg, Macula and Szczurek
• Measured cross-sections significantly \((\times 30-100)\) larger than theory predictions for SPS

• DPS process with purity in excess of 97% ???

• Really unique

Test differential distributions

Most precise \(\sigma_{\text{eff}}\)

\(J/\psi C\) agrees perfectly with CDF DD closer to \(~20\text{mb}\)

\(\sqrt{s}=7\text{TeV, 355pb}^{-1}\)

\begin{align*}
D^0D^0 & \\
D^0D^+ & \\
D^0D_s^+ & \\
D^+D^+ & \\
D^+D_s^+ & \\
D^+\Lambda_c^+ & \\
J/\psi D^0 & \\
J/\psi D^+ & \\
J/\psi D_s^+ & \\
J/\psi \Lambda_c^+ & \\
\end{align*}

\(\sigma_{\text{eff}}\) [mb]


Vanya Belyaev, "DPS@LHCb"
Correlations: $\Delta \phi$, $\Delta y$, $m$


$\sqrt{s}=7\text{TeV}$, $355\text{pb}^{-1}$

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Just for comparison: $D\bar{D}$
$p_T$-spectra: puzzle?

Fit with exponent for $p_T>3\text{GeV/c}$

$\sqrt{s}=7\text{TeV}, 355\text{pb}^{-1}$
Other processes?  $2 \times J/\psi$

Theory
DPS $\sigma = 2.3 \text{nb}$
SPS (LO CS) $\sigma = 4 \text{nb (30%) }$
$\chi_c$ feeddown, CO, ... 

Not too conclusive.
Update for full statistic (x80) is in process

PLB707(2012) 52

Luminosity:
37.5 pb$^{-1}$ (2010 data)
significance $> 6\sigma$
• 139 18 events
• 672 129 eff-corrected

$$\sigma_{J/\Phi J/\Phi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb},$$
$$\sigma_{J/\Phi J/\Phi} / \sigma_{J/\Phi} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4},$$

Berezhnoy et al, PRD84 (2011) 094023
Try harder scale: $Z+c\bar{c}$

More data is needed.

Very interesting region: 30-90% violation of factorization formula is expected

$\sigma_{Z\rightarrow \mu^+\mu^-D^0}$
$\sigma_{Z\rightarrow \mu^+\mu^-D^+}$

| $Z + D^0$ | $2.50 \pm 1.12 \pm 0.22$ |
| $Z + D^+$ | $0.44 \pm 0.23 \pm 0.03$ |

| $\text{MCFM massless}$ | $0.85^{+0.12}_{-0.07}^{+0.11}_{-0.17} \pm 0.05$ |
| $\text{MCFM massive}$ | $0.64^{+0.01}_{-0.01}^{+0.08}_{-0.13} \pm 0.04$ |

| $\text{DPS}$ | $3.28^{+0.68}_{-0.58}$ |
| $\text{DPS}$ | $1.29^{+0.27}_{-0.23}$ |

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Next steps?

• **Something + c\bar{c} at LHCb**

\[
\sigma(X+c\bar{c})_{DPS} = \frac{\sigma(X) \times \sigma(c\bar{c})}{\sigma_{\text{eff}}} \approx 10\% \sigma(X)
\]

• 10% of “hard” events has additional charm!

• Choice of “X” defines the process scale, vary from soft c\bar{c} to hard Z/W, ...

• Intermediate scales?

• Large statistic allows precise differentia measurements

• Probe pocket formula and search for factorization violations

\[
\sigma(c\bar{c})_{pT<8 \text{ GeV/c}, 2.0<y<4.5} = 1419 \pm 12 \text{ (stat)} \pm 116 \text{ (syst)} \pm 65 \text{ (frag) \mu b}
\]

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Summary ("Towards TPS")

- DPS is actively explored at LHC by ATLAS, CMS and LHCb
  - Great degree of complementarity:
    - large variety of processes
    - different kinematics range
    - different DPS purity
  - Testing the basic principles of DPS paradigm
  - ... and search for factorization violation
  - Charm and multiple charm production is very good DPS probe
  - DPS processes have different energy dependence from SPS
    - data at $\sqrt{s}=13$ TeV will be very useful for better DPS understanding
    - for $\sqrt{s}=13$ TeV for some processes, e.g. $c\bar{c}$, one probably can speculate also about *Triple Parton Scattering*
Energy/process independent?
Compare with CDF’2k+6

- CDF: azimuthal correlations for $D^{(0,+) \ D^*_-}$
- Large gluon splitting contribution

Very different kinematical region

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