Double Parton Scattering @ LHCb

Vanya Belyaev (ITEP/Moscow)
DPS: simple paradigm

Two independent hard scattering processes
Relations through (unknown) double PDF

\[ \Gamma_{ij}(x_1, x_2; b_1, b_2; Q^2_1, Q^2_2) = D_{ij}^h(x_1, x_2; Q^2_1, Q^2_2) f(b_1) f(b_2). \]

Assume factorization of double PDFs

\[ D_{ij}^h(x_1, x_2; Q^2_1, Q^2_2) = D_{ij}^h(x_1; Q^2_1) D_{ij}^h(x_2; Q^2_2). \]

(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

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

m=1,2

Pocket formula

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

CDF, F.Abe et al., PDR 56 3811 (1997)
• Simple pattern, a lot of powerful consequences and interesting predictions

• **Pocket formula is also valid for differential cross-sections**

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

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

• The cross-section is **larger** than in naïve model

\[\sigma_{\text{eff}} = 15\text{mb} \quad \text{vs} \quad \sigma_{\text{in}} = 55\text{mb}\]

• 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:**
  \[
  D^{ij}_{h}(x_1, x_2; Q_1^2, Q_2^2) = D^{i}_{h}(x_1; Q_1^2)D^{j}_{h}(x_2; Q_2^2).
  \]

- This anzatz allows \(x_1 + x_2 > 1\):
  - 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...

$$D_{ij}^{ij}(x_1, x_2; Q_1^2, Q_2^2) = D_i^h(x_1; Q_1^2) D_j^h(x_2; Q_2^2).$$
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, ...
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

Tracking:
<table>
<thead>
<tr>
<th>(p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-0.6% for 5&lt;p&lt;100 GeV/c</td>
</tr>
</tbody>
</table>

The most precise B-masses

ECAL:
σ_m(π⁰)=7MeV/c²

Muon:
e(μ±)=97%@1-3% π→μ misID

pp-interaction point

Vertex Locator
O(50fs) resolution for B

The most precise τ(B)
Run I

1 fb⁻¹ @ 7 TeV
2 fb⁻¹ @ 8 TeV
3.3 pb⁻¹ @ 2.76 TeV
1.6 nb⁻¹ pA & Ap

Thanks to LHC accelerator team for the excellent performance of machine

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$J/\psi \to \mu^+\mu^- @ LHCb$

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

$dN/dm_{\mu^+\mu^-}$

$m_{\mu^+\mu^-}$ [GeV/c^2]

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

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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 $p_T>3\text{GeV}/c^2$
  - $D^0 \to K^-\pi^+$ 200M/ fb$^{-1}$
  - $D^+ \to K^-\pi^+\pi^+$ 100M/ fb$^{-1}$
  - $D_s \to \phi\pi^+$ 10M/ fb$^{-1}$
  - $\Lambda_c \to pK^-\pi^+$ 2M/ fb$^{-1}$
- Measured cross-section at $\sqrt{s}=7\text{TeV}$

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

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J/ψ + open charm signals

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

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2× open charm signals

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


$D^0D^0$ 1087±37

$D^0D^+$ 1177±39

$D^-D^*$ 249±19

$D^*\Lambda_c$ 52±9

$D^D\Lambda_c$ 111±12

$D^0\Lambda_c$ 41±8

$D^*\Lambda_c$ 21±5

Small background Significances for 6 modes exceed 5$\sigma$

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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>$16.2 \pm 0.4 \pm 1.3_{-2.5}^{+3.4}$</td>
<td>$6.7 \pm 0.2 \pm 0.5$</td>
<td>$14.9 \pm 0.4 \pm 1.1_{-3.1}^{+2.3}$</td>
</tr>
<tr>
<td>$J/\psi D^+$</td>
<td>$5.7 \pm 0.2 \pm 0.6_{-0.9}^{+1.2}$</td>
<td>$5.7 \pm 0.2 \pm 0.4$</td>
<td>$17.6 \pm 0.6 \pm 1.3_{-3.7}^{+2.8}$</td>
</tr>
<tr>
<td>$J/\psi D^{+}_{s}$</td>
<td>$3.1 \pm 0.3 \pm 0.4_{-0.5}^{+0.6}$</td>
<td>$7.8 \pm 0.8 \pm 0.6$</td>
<td>$12.8 \pm 1.3 \pm 1.1_{-3.8}^{+2.0}$</td>
</tr>
<tr>
<td>$J/\psi \Lambda^+_c$</td>
<td>$4.3 \pm 0.7 \pm 1.2_{-0.7}^{+0.9}$</td>
<td>$5.5 \pm 1.0 \pm 0.6$</td>
<td>$18.0 \pm 3.3 \pm 2.1_{-3.8}^{+2.8}$</td>
</tr>
</tbody>
</table>

**SPS fraction 1-5%**

Extremely clean DPS!

Berezhnoy et al,
Baranov
Lansberg,
Macula and Szczurek

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

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Pure DPS?

- Measured cross-sections significantly (×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 ~20mb

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

$\sigma_{\text{eff}}$

$D^0D^0$
$D^0D^+$
$D^0D_s^+$
$D^+D^+$
$D^+D_s^+$
$D^+\Lambda_c^+$

$J/\psi D^0$
$J/\psi D^+$
$J/\psi D_s^+$
$J/\psi \Lambda_c^+$


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Correlations: $\Delta \phi, \Delta y, m$

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

Just for comparison: $D\bar{D}$


$\sqrt{s}=7\text{TeV}, 355\text{pb}^{-1}$
$p_T$-spectra: puzzle?

Fit with exponent for $p_T > 3$ GeV/c


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

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Other processes? $2 \times J/\psi$

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

Not too conclusive.
Update for full statistic ($\times 80$) is in process

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

$$\sigma^{J/\Psi J/\Psi} = 5.1 \pm 1.0 \pm 1.1 \text{ nb},$$

$$\frac{\sigma^{J/\Psi J/\Psi}}{\sigma^{J/\Psi}} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4},$$

Berezhnoy et al, PRD84 (2011) 094023

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Try harder scale: $Z + c\bar{c}$

More data is needed.

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

<table>
<thead>
<tr>
<th>$\sigma_{Z \to \mu^+\mu^- D^0}$</th>
<th>measured</th>
<th>MCFM massless</th>
<th>MCFM massive</th>
<th>DPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z + D^0$</td>
<td>$2.50 \pm 1.12 \pm 0.22$</td>
<td>$0.85^{+0.12}<em>{-0.07}^{+0.11}</em>{-0.17} \pm 0.05$</td>
<td>$0.64^{+0.01}<em>{-0.01}^{+0.08}</em>{-0.13} \pm 0.04$</td>
<td>$3.28^{+0.68}_{-0.58}$</td>
</tr>
<tr>
<td>$Z + D^+$</td>
<td>$0.44 \pm 0.23 \pm 0.03$</td>
<td>$0.37^{+0.05}<em>{-0.03}^{+0.05}</em>{-0.07} \pm 0.03$</td>
<td>$0.28^{+0.01}<em>{-0.01}^{+0.04}</em>{-0.06} \pm 0.02$</td>
<td>$1.29^{+0.27}_{-0.23}$</td>
</tr>
</tbody>
</table>
Next steps?

- **Something + c\bar{c} at LHCb**

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

- 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 differential measurements**

- **Probe pocket formula and search for factorization violations**

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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?

![Graph showing energy/probess independence](graph.png)
Compare with CDF’2k+6

CDF: azimuthal correlations for $D^{(0,+)} D^{*-}$

Large gluon splitting contribution

Very different kinematical region

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