Multiple Heavy Quarks production: experiment

Vanya Belyaev (ITEP, Moscow)
High energy hadron gluon collision

- Heavy flavour production at LHC is dominated by gg-fusion process
- Quarkonia: reasonably (rapidly improving) agreement with NR QCD
  - $J/\psi$, $\psi'$, $\eta_c$, $\chi_{c1,2}$, $\chi_{b1,2}(nP)$, ....
- Open flavour, charm and beauty:
  - CDF, ATLAS, ALICE, LHCb,... vs FONLL, POWHEG, GMVFNS,...

JHEP 1603(2016) 159
JHEP 1201(2012) 128
JHEP 1207(2012) 191
NPB 907 (2016) 717

- Good job: both experimental and the theory!

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Single particle spectra

- Not so many observables ...
- Relatively low sensitivity to high-order effects for open-flavour hadrons
- Correlations of two hadrons: much more variables!
- Direct probe for various subprocesses
Multiple HQ?

$\sigma(J/\psi\psi)/\sigma(J/\psi) = (3.0\pm1.0) \times 10^{-4}$

- $\pi Pt$: 13 $J/\psi J/\psi$
- $p Pt$: 15±4 $J/\psi J/\psi$

Compare with uncorrelated model

Compare with $qq \rightarrow \psi \psi$, $gg \rightarrow \psi \psi$, $BB \rightarrow \psi \psi$
Multiple HQ? Open flavour

WA75
• 350 GeV/c π⁻
• emulsion
• 2 events
• 200 D candidates
...not so rare

Discussion and conclusions. For both the events reported above, the most natural interpretation is the simultaneous emission and the subsequent decay of four charmed particles, assumed hereafter to be D mesons. In both cases a rather energetic D⁻ is seen.

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Why multiple HQ?

- More observables, large sensitivity to QCD corrections
- $2\times J/\psi, J/\psi + \Upsilon$: good way to probe the role of Colour Octet
- $2\times J/\psi$: palette of theory calculations
  - incomplete NLO* Colour Singlet
  - LO + $k_T$
  - LO CO
  - full NLO
  - $J/\psi, \Upsilon + (c\bar{c})$
  - NRQCD, $k_T$, CO, ...
  - $2\times(c\bar{c}) : k_T$

+ Double Parton Scattering
DPS: simple paradigm

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

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

\( m=1,2 \)

Pocket formula

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

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

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- **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 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

\( \sigma_{\text{eff}} \sim \frac{1}{4} \sigma_{\text{in}} \) production of cross-section for A+B is enhanced with **factor of four** with respect to naive model

- Large role at "low" \( p_T \), decreases with \( p_T \)
  - with HQ, the measurements can be performed at low \( p_T \), up to 0

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Is $\sigma_{\text{eff}}$ really a constant?

- There is calculable contribution from $1+2$
- Correlations, large dependency on scale
  - Stabilization for low $x$-processes
  - Probing of universality of $\sigma_{\text{eff}}$ is important for understanding of proton structure and QCD at high parton densities

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2\times J/\psi signals after \ (>30\ \text{years of silence}

Signal \sim 100

PLB 707 (2012) 52

Signal \sim 400

JHEP 1409 (2014) 094

Signal \sim 55

PRD 90 (2014) 111101R

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2×J/ψ signals after >30 years of silence

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2×J/ψ in numbers

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>CMS</th>
<th>D0</th>
<th>ATLAS</th>
<th>LHCb</th>
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<tbody>
<tr>
<td>√s</td>
<td>7TeV</td>
<td>7TeV</td>
<td>1.96TeV</td>
<td>8TeV</td>
<td>13TeV</td>
</tr>
<tr>
<td>Lumi</td>
<td>38pb⁻¹</td>
<td>4.73fb⁻¹</td>
<td>8.10fb⁻¹</td>
<td>1.41fb⁻¹</td>
<td>279pb⁻¹</td>
</tr>
<tr>
<td>y(J/ψ)</td>
<td>2&lt;y&lt;4.5</td>
<td></td>
<td></td>
<td></td>
<td>2&lt;y&lt;4.5</td>
</tr>
<tr>
<td>p_T(J/ψ)</td>
<td>&lt;10 GeV/c</td>
<td>&gt;4.5 GeV/c</td>
<td>&gt;4.0 GeV/c</td>
<td>&gt;8.5 GeV/c</td>
<td>&lt;10 GeV/c</td>
</tr>
<tr>
<td>Signal</td>
<td>141±19</td>
<td>446±23</td>
<td></td>
<td>1160±70</td>
<td>(1.05±0.05)×10³</td>
</tr>
<tr>
<td>f_DPS</td>
<td>O(10%)</td>
<td>(42±12)%</td>
<td></td>
<td>(9.2±2.1±0.5)%</td>
<td>(50–100)%</td>
</tr>
</tbody>
</table>

- 4 muon final state:
  - easy to trigger, low background, high efficiency
- Complementary acceptances: (very) different x-regions
- No vs high-\(p_T\) cut: different DPS contamination

None of LHC experiments used full Run-I/Run-II dataset

Significant increase in statistic could be expected
$\sigma(2\times J/\psi) = 5.1 \pm 1.0 \pm 1.1 \text{ nb}

not enough precision to disentangle

SPS LO: $4.0 \pm 1.2 \text{ nb}$  Berezhnoy et al PRD84 (2011) 094023

SPS LO: $4.6 \pm 1.1 \text{ nb}$  Sun et al. PRD 94 (2016) 074033

SPS NLO: $5.4^{+2.7}_{-1.4} \text{ nb}$  Sun et al. PRD 94 (2016) 074033

DPS: $3.8 \pm 1.3 \text{ nb}$

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$\sigma(2\times J/\psi) = 1.49\pm0.07\pm0.13 \text{ nb}$

$p_T(2\times J/\psi), \Delta y(2\times J/\psi), m(2\times J/\psi)$ distributions are analysed by Lansberg&Shao NLO* CS

- Importance of $\alpha_s^3$
- No large CO contribution
- To accommodate large $\Delta y$
  
  $\sigma_{\text{eff}} = 11\pm2.9\text{mb}$
$2\times J/\psi$  D0 @ 1.96TeV

$\sigma(2\times J/\psi) = 129\pm 11\pm 37$ fb

- **SPS**: $59\pm 6\pm 22$ fb
- **DPS**: $70\pm 6\pm 22$ fb

Prediction:
- **SPS LO**: 51.9 fb  Qiao, Sun, CPC37 (2013) 033105
- **SPS kT**: 55.1 fb  Baranov, PRD87 (2013) 034035
- **SPS NLO**: $90^{+180}_{-50}$ fb  Lansberg, Shao, PRL 111(2013) 122001
- **DPS**: 17.6 $\pm 13$ fb

$\sigma_{\text{eff}} = 4.8\pm 0.5\pm 2.5$ mb
$2 \times J/\psi$ ATLAS @ 8 TeV

\[ \sigma(2 \times J/\psi) = 160 \pm 12 \pm 14 \text{ pb} \]

- **Model-independent SPS vs DPS separation**

- **DPS:** $14.8 \pm 3.5 \pm 1.5 \text{ pb} \]

\[ \sigma_{\text{eff}} = 6.3 \pm 1.6 \pm 1.0 \text{ mb} \]

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\[ \sigma(2 \times J/\psi) = 15.2 \pm 1.0 \pm 0.9 \text{ nb} \]

**SPS predictions:**
- **LO CS 1.3 nb**  
  Likhoded *et al.*, PRD94 (2016) 054017
- **LO CO 0.45 nb**  
  Shao, PC 184 (2013) 2562
- **NLO* CS 15 nb**  
  Lansberg, Shao, PLB751 (2015) 479
- **NLO CS 12 nb**  
  Sun, Han, Chao, PRD94 (2016) 074033
- **DPS: 8.1 nb**

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# 2×J/ψ LHCb @ 13TeV

## Table

<table>
<thead>
<tr>
<th>Variable</th>
<th>LO CS</th>
<th>LO $k_T$</th>
<th>NLO* CS'</th>
<th>NLO* CS'' $\langle k_T \rangle = 2$ GeV/c</th>
<th>NLO* CS'' $\langle k_T \rangle = 0.5$ GeV/c</th>
<th>NLO CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(J/\psi J/\psi)$</td>
<td>—</td>
<td>78 ± 3</td>
<td>—</td>
<td>88 ± 56</td>
<td>81 ± 7</td>
<td>—</td>
</tr>
<tr>
<td>$y(J/\psi J/\psi)$</td>
<td>83 ± 39</td>
<td>—</td>
<td>75 ± 37</td>
<td>68 ± 34</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>$m(J/\psi J/\psi)$</td>
<td>76 ± 7</td>
<td>74 ± 7</td>
<td>—</td>
<td>78 ± 7</td>
<td>77 ± 7</td>
<td>—</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>$</td>
<td>59 ± 21</td>
<td>61 ± 18</td>
<td>—</td>
<td>63 ± 18</td>
</tr>
</tbody>
</table>

## f\(_{\text{DPS}}\) [%]

<table>
<thead>
<tr>
<th>Variable</th>
<th>LO CS</th>
<th>LO $k_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(J/\psi J/\psi)$</td>
<td>—</td>
<td>75 ± 24</td>
</tr>
<tr>
<td>$y(J/\psi J/\psi)$</td>
<td>—</td>
<td>73 ± 8</td>
</tr>
<tr>
<td>$m(J/\psi J/\psi)$</td>
<td>—</td>
<td>57 ± 20</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>$</td>
</tr>
</tbody>
</table>

## σ\(_{\text{eff}}\) [mb]

<table>
<thead>
<tr>
<th>Variable</th>
<th>LO $k_T$</th>
<th>NLO* CS'' $\langle k_T \rangle = 2$ GeV/c</th>
<th>NLO* CS'' $\langle k_T \rangle = 0.5$ GeV/c</th>
<th>NLO CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(J/\psi J/\psi)$</td>
<td>11.3 ± 0.6</td>
<td>10.1 ± 6.5</td>
<td>10.9 ± 1.2</td>
<td>—</td>
</tr>
<tr>
<td>$y(J/\psi J/\psi)$</td>
<td>—</td>
<td>11.9 ± 7.5</td>
<td>10.0 ± 5.0</td>
<td>—</td>
</tr>
<tr>
<td>$m(J/\psi J/\psi)$</td>
<td>10.6 ± 1.1</td>
<td>10.2 ± 1.0</td>
<td>10.4 ± 1.0</td>
<td>—</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>$</td>
<td>12.5 ± 4.1</td>
<td>12.2 ± 3.7</td>
</tr>
</tbody>
</table>

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J/ψ+ϒ DØ @ 1.96TeV

• Very interesting final state: no SPS LO CS diagrams!

\[ \sigma(J/ψ+ϒ) = 27\pm9\pm7 \text{ nb} \]

• Uniform \( Δφ \) suggest DPS dominance

\[ \sigma_{\text{eff}} = 2.2\pm0.7\pm0.9 \text{mb} \]
Fiducial cross-section: \(68.8 \pm 12.7 \pm 7.4 \pm 2.8 \, \text{pb}\)

\[\sigma_{\text{eff}} = 2.2 - 6.6 \, \text{mb}\]
Measurements with open charm hadrons

- Unique feature of LHCb experiment:
  - Infinite statistics of charm mesons
  - Low background
  - Hadron identification
  - Efficient trigger

... and even better for Run-II
J/\psi+c\bar{c} and 2\times c\bar{c} LHCb @7TeV


\[ J/\psi D^0 \ 4875 \pm 86 \]
\[ J/\psi D^+ \ 3323 \pm 71 \]
\[ J/\psi D_0^- \ 328 \pm 22 \]
\[ J/\psi \Lambda_c \ 116 \pm 14 \]

D^0D^0 \ 1087 \pm 37
D^0D^+ \ 1177 \pm 39
D^0D_s \ 111 \pm 12
D^0\Lambda_c \ 41 \pm 8

Berezinoy et al, Baranov, Lansberg, Macula and Szczurek

\[ \sqrt{s}=7\text{TeV}, 355\text{pb}^{-1} \]
Signals

<table>
<thead>
<tr>
<th></th>
<th>( \Upsilon(1S) )</th>
<th>( \Upsilon(2S) )</th>
<th>( \Upsilon(3S) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 )</td>
<td>980 ± 50</td>
<td>184 ± 27</td>
<td>60 ± 22</td>
</tr>
<tr>
<td>( D^+ )</td>
<td>556 ± 35</td>
<td>116 ± 20</td>
<td>55 ± 17</td>
</tr>
<tr>
<td>( D_s^+ )</td>
<td>31 ± 7</td>
<td>9 ± 5</td>
<td>6 ± 4</td>
</tr>
<tr>
<td>( \Lambda_c^+ )</td>
<td>11 ± 6</td>
<td>1 ± 4</td>
<td>1 ± 3</td>
</tr>
</tbody>
</table>

Predictions:
SPS: (0.1-0.6)%
DPS O(10%)%

Expected:
DPS: 25%

\[ B_{\mu+\mu^-} \times \sigma_{\Upsilon(1S)D^0 \sqrt{s}=7 \text{ TeV}} = 155 \pm 21 \text{ (stat)} \pm 7 \text{ (syst)} \text{ pb}, \]
\[ B_{\mu+\mu^-} \times \sigma_{\Upsilon(1S)D^+ \sqrt{s}=7 \text{ TeV}} = 82 \pm 19 \text{ (stat)} \pm 5 \text{ (syst)} \text{ pb}, \]
\[ B_{\mu+\mu^-} \times \sigma_{\Upsilon(1S)D^0 \sqrt{s}=8 \text{ TeV}} = 250 \pm 28 \text{ (stat)} \pm 11 \text{ (syst)} \text{ pb}, \]
\[ B_{\mu+\mu^-} \times \sigma_{\Upsilon(1S)D^+ \sqrt{s}=8 \text{ TeV}} = 80 \pm 16 \text{ (stat)} \pm 5 \text{ (syst)} \text{ pb}, \]

\[ \frac{\sigma_{\Upsilon(1S)\Upsilon(1S)}}{\sigma_{\Upsilon(1S)\sqrt{s}=7 \text{ TeV}}} = (7.7 \pm 1.0) \%, \]
\[ \frac{\sigma_{\Upsilon(1S)\Upsilon(1S)}}{\sigma_{\Upsilon(1S)\sqrt{s}=8 \text{ TeV}}} = (8.0 \pm 0.9) \%, \]

\[ B_{2/1} \times \frac{\sigma_{\Upsilon(2S)D^0 \sqrt{s}=7 \text{ TeV}}}{\sigma_{\Upsilon(2S)D^0 \sqrt{s}=8 \text{ TeV}}} = (13 \pm 5) \%, \]
\[ B_{2/1} \times \frac{\sigma_{\Upsilon(2S)D^0 \sqrt{s}=7 \text{ TeV}}}{\sigma_{\Upsilon(2S)D^0 \sqrt{s}=8 \text{ TeV}}} = (20 \pm 4) \%, \]

\[ B_{2/1} \times \frac{\sigma_{\Upsilon(2S)D^+ \sqrt{s}=7 \text{ TeV}}}{\sigma_{\Upsilon(2S)D^+ \sqrt{s}=8 \text{ TeV}}} = (22 \pm 7) \%, \]
\[ B_{2/1} \times \frac{\sigma_{\Upsilon(2S)D^+ \sqrt{s}=7 \text{ TeV}}}{\sigma_{\Upsilon(2S)D^+ \sqrt{s}=8 \text{ TeV}}} = (22 \pm 6) \%, \]
JHEP 1607 (2016) 052

ALL differential distributions in excellent agreement with DPS

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B_c pure SPS \ c\bar{c} + b\bar{b} 

- Very special case:
  - Large signals, properties are well measured:
    - Mass, lifetime,
    - Ratios of Brs
  - Differential rates in excellent \( O(1-5\%) \) agreement with \( \alpha_s^4 \) calculations
  - Overall rate is largely "unknown": no measured Br

Puzzle:
- where are double heavy baryons \( \Xi_{cc} \) & \( \Xi_{bc} \)?
  - also pure SPS
  - essentially the same matrix element
No obvious pattern

Double quarkonium is a bit lower

$2 \times c\bar{c}$ is a bit higher

Only one real outlier $\Upsilon J/\psi$

"reference" $\sigma_{eff}$ from multi-jet events by CDF
Summary

- Studies of multiquark production awaked after 30-35 years pause
- A lot of precise measurement suitable for QCD tests
- SPS: very important role of high order effect
  - Quarkonia: Color Octet contribution is small
- DPS with HQ is well established phenomenon
  - Allows DPS tests up to $p_T \sim 0$
  - DPS as expected is dominant at relatively low $p_T$
  - The most precise measurement of $\sigma_{\text{eff}}$
    - But even better precision is needed to probe universality of $\sigma_{\text{eff}}$
- None of LHC experiments analysed full Run-I/Run-II dataset yet: one can expect much better precision!
  - e.g. LHCb for $2\times J/\psi$: 4%, 0%, 18% of 7, 8 and 13TeV data
- Next step: multi HQ with open beauty?
- Next step: Triple Parton Scattering at Run-II?
  - Even larger multiplicity of charm and beauty!

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Thank you!
~40% of heavy quarks in <4% of $4\pi$

RICH Detectors:
95% $\varepsilon(K^\pm)$ @5% $\pi\rightarrow K$ misID

pp-interaction point

Vertex Locator
$O(50fs)$ resolution for $B$
The most precise $\tau(B)$

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

Muon:
$\varepsilon(\mu^+) = 97\% @ 1-3\% \pi\rightarrow \mu$ misID

ECAL:
$\sigma_m(\pi^0) = 7$ MeV/$c^2$

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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 \( \theta(1 - x_1 - x_2) \) 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 \( p^+jets \) cross-sections in Tevatron case
  - Up to 30-50% for certain kinematical ranges

- For processes with (very) small \( x \) only factorization is fine

\[
\Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2)F_g(x_2, \mu_2^2)F(b; x_1, x_2, \mu_1^2, \mu_2^2),
\]
\[
\sigma_{eff}(x_1, x_2, x'_1, x'_2, \mu_1^2, \mu_2^2) = \left( \int d^2bF(b; x_1, x_2, \mu_1^2, \mu_2^2)F(b; x'_1, x'_2, \mu_1^2, \mu_2^2) \right)^{-1}.
\]