Diffractive production of open charm and bottom at the LHC

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Plan of the talk

- Introduction
- Single and central diffraction
  - theoretical framework
  - diffractive production of $c\bar{c}$ and $b\bar{b}$
- Hadronization of heavy quarks
- Diffractive production of open charm and bottom
- Conclusions
Production of heavy quarks

\[ h_1 + h_2 \rightarrow Q + \bar{Q} + X: \]

\[ \gamma + p \rightarrow Q + \bar{Q} + X: \]
Dominant mechanism

**LO collinear approach**

\[ h_1 \rightarrow \bar{Q} \]
\[ h_2 \rightarrow \bar{Q} \]

**\( k_t \)-factorization**

\[ h_1 \rightarrow \bar{Q} \]

\[ h_2 \rightarrow \bar{Q} \]

\[ \kappa_1^2 = 0 \text{ (kolinearne)} \]

\[ \kappa_1^2 \neq 0 \text{ (nasze podejście)} \]

\[ \kappa_2^2 = 0 \text{ (kolinearne)} \]

\[ \kappa_2^2 \neq 0 \text{ (nasze podejście)} \]
Formalism of collinear - factorization

\[
\frac{d\sigma}{dy_1 dy_2 d^2 p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2) |\mathcal{M}_{ij}|^2
\]

\(p_{1t} = p_{2t} = p_t\)

\[x_1 = \frac{m_t}{\sqrt{s}} \left( \exp(y_1) + \exp(y_2) \right),\]

\[x_2 = \frac{m_t}{\sqrt{s}} \left( \exp(-y_1) + \exp(-y_2) \right)\]
Single and central diffraction

Luszczak, Maciula, Szczurek, Phys. Rev. D84 (2011) 4018
In this approach (Ingelman-Schlein model) one assumes that the Pomeron has a well defined partonic structure, and that the hard process takes place in a Pomeron–proton or proton–Pomeron (single diffraction) or Pomeron–Pomeron (central diffraction) processes.

\[
\frac{d\sigma_{SD}}{dy_1 dy_2 dp_t^2} = K \frac{|M|^2}{16\pi^2 s^2} \left[ (x_1 \bar{q}_f^D(x_1, \mu^2) x_2 \bar{q}_f(x_2, \mu^2)) \right] \\
+ \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f(x_2, \mu^2) \right) \right],
\]

\[
\frac{d\sigma_{CD}}{dy_1 dy_2 dp_t^2} = K \frac{|M|^2}{16\pi^2 s^2} \left[ (x_1 q_f^D(x_1, \mu^2) x_2 \bar{q}_f^D(x_2, \mu^2) \right) \\
+ \left( x_1 \bar{q}_f^D(x_1, \mu^2) x_2 q_f^D(x_2, \mu^2) \right) \right] 
\]
The 'diffractive' quark distribution of flavour $f$ can be obtained by a convolution of the flux of Pomeron $f_P(x_P)$ and the parton distribution in the Pomeron $q_f/P(\beta, \mu^2)$:

$$q_f^D(x, \mu^2) = \int dx_P d\beta \delta(x - x_P \beta) q_f/P(\beta, \mu^2) f_P(x_P) = \int_x^1 \frac{dx_P}{x_P} f_P(x_P) q_f/P\left(\frac{x}{x_P}, \mu^2\right).$$

The flux of Pomeron $f_P(x_P)$:

$$f_P(x_P) = \int_{t_{min}}^{t_{max}} dt \ f(x_P, t),$$

with $t_{min}, t_{max}$ being kinematic boundaries.

Both pomeron flux factors $f_P(x_P, t)$ as well as quark/antiquark distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.
Absorption has been included by multiplying cross section by gap survival factors (violation of Regge factorization):

for RHIC: \text{dd} \times 0.06; \text{d}0 \text{ or } 0\text{d} \times 0.13

for LHC: \text{dd} \times 0.02; \text{d}0 \text{ or } 0\text{d} \times 0.05
Results (photon included)

have rapidity gap as single diffractive processes
Single diffractive production of $c\bar{c}$ and $b\bar{b}$

It is not completely clear where to cuts $P$ or $R$ contribution.
Single diffractive production of $c\bar{c}$ and $b\bar{b}$

$p p \rightarrow c\bar{c} X$ (SD) \quad $|s| = 14$ TeV

$p p \rightarrow b\bar{b} X$ (SD) \quad $|s| = 14$ TeV

$x_P < 0.1$

$x_R < 0.2$
Hadronization of heavy quarks

- phenomenology → fragmentation functions extracted from $e^+e^-$ data
- often used (older parametrizations): Peterson et al., Braaten et al., Kartvelishvili et al.
- more up-to-date: charm nonperturbative fragmentation functions determined from recent Belle, CLEO, ALEPH and OPAL data: Kneschke-Kniehl-Kramer-Schienbein (KKKS08) + DGLAP evolution!
- FONLL → Braaten et al. (charm) and Kartvelishvili et al. (bottom)
- GM-VFNS → KKKS08 + evolution

- numerically performed by rescaling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

$$\frac{d\sigma(y, p_t^M)}{dyd^2p_t^M} \approx \int \frac{D_Q\to M(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dyd^2p_t^Q} \, dz$$

where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- approximation:
  rapidity unchanged in the fragmentation process → $y_Q = y_M$
default set: Peterson FF with $\varepsilon_c = 0.05$ and $\varepsilon_b = 0.004$
values extracted by H1, ALEPH and OPAL experiments

Cacciari et al. (FONNL framework) ⇒ rather harder functions are suggested
BCFY FF with $r_c = 0.1$ and Kartvelishvili FF with $\alpha_b = 29.1$
our choice: Peterson FF with $\varepsilon_c = 0.02$ and $\varepsilon_b = 0.001$
## Predictions of integrated cross sections for LHC experiments

<table>
<thead>
<tr>
<th>Acceptance</th>
<th>Mode</th>
<th>Integrated cross sections, [nb]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>single-diffractive</td>
</tr>
<tr>
<td>ATLAS, $</td>
<td>y</td>
<td>&lt; 2.5$ ( p_\perp &gt; 3.5 \text{ GeV} )</td>
</tr>
<tr>
<td>LHCb, $2 &lt; y &lt; 4.5$ ( p_\perp &lt; 8 \text{ GeV} )</td>
<td>$D^0 + \overline{D^0}$</td>
<td>42663.7 (IR: 29%)</td>
</tr>
<tr>
<td>CMS, $</td>
<td>y</td>
<td>&lt; 2.4$ ( p_\perp &gt; 5 \text{ GeV} )</td>
</tr>
<tr>
<td>LHCb, $2 &lt; y &lt; 4.5$ ( p_\perp &lt; 40 \text{ GeV} )</td>
<td>$B^+ + B^-$</td>
<td>731.69 (IR: 26%)</td>
</tr>
<tr>
<td>LHCb, $2 &lt; y &lt; 4$ ( 3 &lt; p_\perp &lt; 12 \text{ GeV} )</td>
<td>$D^0\overline{D^0}$</td>
<td>220.47 (IR: 27%)</td>
</tr>
</tbody>
</table>

- **single-diffractive**: \( \frac{IR}{IP+IR} \approx 25\% 
- **central-diffractive**: \( \frac{IR}{IP+IR} \approx 10\% 
- **single–diffractive non–diffractive**: \( \approx 2 – 3\% 
- **central–diffractive non–diffractive**: \( \approx 0.03 – 0.05\% 

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Cross sections for $D^0$ mesons production (single-diffractive)

$p p \rightarrow D^0 X$

$\sqrt{s} = 14$ TeV

$|y_{D^0}| < 2.5$ ATLAS

$2.0 < y_{D^0} < 4.5$ LHCb

$\sigma$ (nb/GeV) = 0.02

Peterson FF, $\varepsilon = 0.02$
Cross sections for $D^0$ mesons production (central-diffractive)

$p p \rightarrow D^0 X$

$\sqrt{s} = 14$ TeV

$|y_{D^0}| < 2.5$ ATLAS

$2.0 < y_{D^0} < 4.5$ LHCb

$\sigma_d (nb/GeV) = 0.02$

Peterson FF, $\varepsilon_c = 0.02$
Cross sections for $B^\pm$ mesons production (single-diffractive)

$\sqrt{s} = 14$ TeV

$\frac{d\sigma}{dp_T}$ (nb/GeV)

$pp \to B^\pm X$

$|y_B^*| < 2.4$ CMS

$2.0 < y_B^* < 4.5$ LHCb

Peterson FF, $\epsilon_B = 0.001$

$pp \to B^\pm X$

$|y_B^*| < 2.4$ CMS

$2.0 < y_B^* < 4.5$ LHCb

Peterson FF, $\epsilon_B = 0.001$
Cross sections for $B^\pm$ mesons production (central-diffractive)

**CMS**

$$|y_{B^\pm}| < 2.4$$

**LHCb**

$$2.0 < y_{B^\pm} < 4.5$$

Peterson FF, $\varepsilon_b = 0.001$
Total cross sections for charmed meson-antimeson pair production for the LHCb detector

<table>
<thead>
<tr>
<th>Acceptance</th>
<th>Mode</th>
<th>Integrated cross sections, $\mu$b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CD</td>
</tr>
<tr>
<td>$2.0 &lt; y &lt; 4.5$</td>
<td>$D^0 + \bar{D}^0$</td>
<td>2.19</td>
</tr>
<tr>
<td>$p_\perp &lt; 8$ GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2.0 &lt; y &lt; 4.0$</td>
<td>$D^0\bar{D}^0$</td>
<td>0.009</td>
</tr>
<tr>
<td>$3 &lt; p_\perp &lt; 12$ GeV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table I: Total cross sections for charmed meson-antimeson pair production for the LHCb detector.
Cross sections for charmed meson-antimeson pair production for the LHCb detector
(single-diffractive)

\[ p p \rightarrow D^0 \bar{D}^0 X \]

\[ \sqrt{s} = 14 \text{ TeV} \]

- **single-diffractive**
- **pomeron**
- **reggeon**
- **sum**

**Peterson FF, \( \varepsilon_s = 0.02 \)**

- **\( 2.0 < y_{D^0} < 4.0 \) LHCb**
- **\( 3.0 < p_{\perp} < 12.0 \text{ GeV} \) LHCb**

\[ p \rightarrow p p = 14 \text{ TeVs} \]

**Single-diffractive**

**Pomeron**

**Reggeon**

**Sum**

\[ \sigma_d (\text{nb/GeV}) \]

\[ \sigma_d (\text{nb}) \]

\[ p_{\perp}^{D^0} \text{ (in } D^0\bar{D}^0 \text{ mode)} \text{ (GeV)} \]

\[ y_{D^0} \text{ (in } D^0\bar{D}^0 \text{ mode)} \]
Cross sections for charmed meson-antimeson pair production for the LHCb detector (central-diffractive)

\[ p p \to D^0 \overline{D}^0 X \]

\[ \sqrt{s} = 14 \text{ TeV} \]

- central-diffractive
- \( 2.0 < y_{D^0} < 4.0 \) LHCb
- \( 3.0 < p_{T} < 12.0 \text{ GeV} \) LHCb

\[ d\sigma/dp_{T}^0 \] (nb/GeV)

Peterson FF, \( \varepsilon_c = 0.02 \)

- pomeran
- reggeon
- sum

\[ d\sigma/dy_{D^0} \] (nb)

Peterson FF, \( \varepsilon_c = 0.02 \)
Results

\[ p p \rightarrow D^0 \bar{D}^0 X \]

**single-diffractive**

- 3.0 < \( p^*_T \) < 12.0 GeV

**Reggeon-glue**

- \( 3.0 < \sigma_d < 12.0 \text{ GeV} \)

**gluon-Pomeron**

- \( 5.0 < \sigma_d < 12.0 \text{ GeV} \)

**Pomeron-glue**

- \( 3.0 < \sigma_d < 12.0 \text{ GeV} \)

**Pomeron-Pomeron**

- \( 0.0 < \sigma_d < 12.0 \text{ GeV} \)

**Reggeon-reggeon**

- \( 0.0 < \sigma_d < 12.0 \text{ GeV} \)

**gluon-Reggeon**

- \( 0.0 < \sigma_d < 12.0 \text{ GeV} \)

**central-diffractive**

- \( 3.0 < \sigma_d < 12.0 \text{ GeV} \)
Conclusions

- Cross sections for single and central diffractive production of $c\bar{c}$ and $b\bar{b}$ have been calculated.
- Large and measurable cross section for charm single diffractive production.
- Cross sections for $D^0$ and $B^{\pm}$ mesons have been calculated for different experiments (cuts).
- LHCb wish to study such processes (G. Wilkinson).