Open charm meson production at LHC

Rafał Maciuła
Institute of Nuclear Physics (PAN), Kraków, Poland

12th International Workshop on Meson Production, Properties and Interaction,
KRAKÓW, POLAND, 31 May - 5 June 2012
Outline

1. Charm measurements at LHC
2. Hadroproduction of heavy quarks
   - parton model vs. $k_t$-factorization approach
   - unintegrated gluon densities for the proton
   - hadronization into open heavy mesons
3. Results vs. experimental data
   - $p_t$ spectra in different rapidity regions @ ALICE and LHCb
   - effects of hadronization and quark mass uncertainty
4. Open charm via Double Parton Scattering

Based on:
Łuszczak, Maciuła, Szczurek, Phys. Rev. D 79 (2009) 034009
Maciuła, Szczurek, Ślipek, Phys. Rev. D 83 (2011) 054014
Łuszczak, Maciuła, Szczurek, Phys. Rev. D 85, 094034 (2012)
Heavy quarks measurements at LHC

- **direct**: open charm/bottom mesons → reconstruction of all decay products ($K^-\pi^+$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+$)
- **indirect**: nonphotonic electrons/muons → leptons from semileptonic decays of heavy flavoured mesons

ALICE, $|y_D| < 0.5$, JHEP, 01 (2012) 128

LHCb, $2.0 < y_D < 4.5$, small $x$ region!
LHCb-CONF-2010-013

ATLAS, widest rapidity interval, $|\eta| < 2.5$
Dominant mechanisms of $Q\bar{Q}$ production

- Leading order processes contributing to $Q\bar{Q}$ production:
  
  - **gluon-gluon fusion** dominant at high energies
  - $q\bar{q}$ annihilation important only near the threshold
  - some of next-to-leading order diagrams:
    
    very important NLO contributions → factor 2
**collinear approximation** → transverse momenta of the incident partons are assumed to be zero

- quadruply differential cross section:

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

- \(p_i(x_1, \mu^2), p_j(x_2, \mu^2)\) - standard parton distributions in hadron (e.g. CTEQ, GRV, GJR, MRST, MSTW)

- NLO on-shell matrix elements well-known

**several packages:**

- **FONLL** (Cacciari et al.) - one particle distributions and total cross sections

- more exclusive tools - PYTHIA, HERWIG, MC@NLO
Charm measurements at LHC

Hadroproduction of heavy quarks

Results vs. experimental data

Open charm via Double Parton Scattering

parton model vs. $k_t$-factorization approach

$k_t$-factorization (semihard) approach

- charm and bottom quarks production at high energies
  $\rightarrow$ gluon-gluon fusion

- QCD collinear approach $\rightarrow$ only inclusive one particle
distributions, total cross sections

**LO $k_t$-factorization approach** $\rightarrow \kappa_{1,t}, \kappa_{2,t} \neq 0$

$\Rightarrow Q\bar{Q}$ correlations

- multi-differential cross section

\[
\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2(x_1 x_2 s)^2} |\mathcal{M}_{ij\rightarrow Q\bar{Q}}|^2
\]

\[
\times \delta^2 (\bar{\kappa}_{1,t} + \bar{\kappa}_{2,t} - \bar{p}_{1,t} - \bar{p}_{2,t}) \mathcal{F}_i(x_1, \kappa_{1,t}^2) \mathcal{F}_j(x_2, \kappa_{2,t}^2)
\]

- off-shell $|\mathcal{M}_{gg\rightarrow Q\bar{Q}}|^2$ $\rightarrow$ Catani, Ciafaloni, Hautmann (very long formula)

- major part of NLO corrections automatically included

- $\mathcal{F}_i(x_1, \kappa_{1,t}^2), \mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions

- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,

- $x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2)$, where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.
Different models of unintegrated parton distribution functions

- $k_t$-factorization $\rightarrow$ replacement: $p_k(x, \mu_F^2) \rightarrow F_k(x, \kappa_t^2, \mu_F^2)$
- PDFs $\rightarrow$ UPDFs

\[ xp_k(x, \mu_F^2) = \int_{0}^{\infty} d\kappa_t^2 F(x, \kappa_t^2, \mu_F^2) \]

- UPDFs - needed in less inclusive measurements which are sensitive to the transverse momentum of the parton

**gg-fusion dominance $\Rightarrow$ great test of existing unintegrated gluon densities!** especially at LHC (small-$x$)

several models:
- Kwiecinski, Jung (CCFM, wide $x$-range)
- Kimber-Martin-Ryskin (larger $x$-values)
- Kutak-Stasto, GBW (small-$x$, saturation effects)
- Ivanov-Nikolaev, KMS, etc.
Differential cross section for charm quarks

\[ \frac{d\sigma}{dp_1 t dp_2 t} \]

| Model          | charm quark $p_1$ (GeV) | charm antiquark $p_1$ (GeV) |
|----------------|-------------------------|-----------------------------|
| KMR            |                         |                             |
| Jung setA+     |                         |                             |
| Kutak-Stasto   |                         |                             |
| GBW            |                         |                             |
hadronization into open heavy mesons

**Fragmentation functions technique**

- **phenomenology → fragmentation functions extracted from $e^+ e^-$ data**
- **often used: Peterson et al., Braaten et al., Kartvelishvili et al.**
- **numerically performed by rescaling transverse momentum at a constant rapidity (angle)**

- from heavy quarks to heavy mesons:

\[
\frac{d\sigma(y, p_{tM}^M)}{dy d^2 p_{tM}^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_{tQ}^Q)}{dy d^2 p_{tQ}^Q} dz
\]

where: \( p_{tQ}^Q = \frac{p_{tM}^M}{z} \) and \( z \in (0, 1) \)

- **approximation:** rapidity unchanged in the fragmentation process \( \rightarrow y_Q = y_M \)
Different models of FFs

- **Peterson et al.**
  \[
  D_{Q \rightarrow M}(z) = N \frac{z}{z[1-(1/z)-\varepsilon_Q/(1-z)]}
  \]
  \[
  \varepsilon_c = 0.06, \varepsilon_b = 0.006 \text{ from PDG}
  \]

- **Braaten et al.**
  \[
  D_{Q \rightarrow M}(z) = N \frac{rz(1-z)^2}{(1-(1-r)z)^6} (F_1 + F_2)
  \]
  \[
  F_1 = 6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2
  \]
  \[
  F_2 = 3(1-r)^2(1-2r^2)z^4 - 2(1-r)(6-19r+18r^2)z^3
  \]
  \[
  r_c = 0.2, \ r_b = 0.07
  \]

- **Kartvelishvili et al.**
  \[
  D_{Q \rightarrow M}(z) = N(1-z)z^a
  \]
  \[
  a_c = 5.0, \ a_b = 14.0
  \]
Charm measurements at LHC

Hadroproduction of heavy quarks

Results vs. experimental data

Open charm via Double Parton Scattering

Various UGDFs models → crucial test of their applicability at high energies and small $x$-values

Only KMR model gives well description of the ALICE and LHCb data

Significant difference between LO parton model and LO $k_T$-factorization
Charm measurements at LHC

Hadroproduction of heavy quarks

Results vs. experimental data

Open charm via Double Parton Scattering

effects of hadronization and quark mass uncertainty
Consider \( pp \to (c\bar{c})(c\bar{c}) \) process, initiated by two hard (parton) scatterings in one proton-proton interaction.

Łuszczak, Maciuła, Szczurek, Phys. Rev. D 85, 094034 (2012)
in the analogy to frequently considered mechanisms of double gauge boson production or double Drell-Yan annihilation.
Formalism of theoretical DPS modelling

The double-parton scattering formalism assumes two single-parton scatterings so in a simple probabilistic picture the cross section for DPS can be written as:

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

The simple formula above can be generalized to include differential distributions:

\[
\frac{d\sigma}{dy_1dy_2d^2p_{1t}dy_3dy_4d^2p_{2t}} = \frac{1}{2\sigma_{\text{eff}}} \cdot \frac{d\sigma}{dy_1dy_2d^2p_{1t}} \cdot \frac{d\sigma}{dy_3dy_4d^2p_{2t}}
\]

- two subprocesses are not correlated and do not interfere
- \(\sigma_{\text{eff}} = 14.5 \pm 1.7^{+1.7}_{-2.3} \text{ mb} \Rightarrow \text{Tevatron, CDF, F.Abe et al., PRD 56 3811 (1997)}

- extra limitations for longitudinal momentum fractions of gluons:
  \(x_1 + x_2 < 1\) and \(x_1' + x_2' < 1\)
  cause the "second" emission must take into account that some momentum was used up in the "first" parton collision
double Parton Distribution Functions

A more general formula for the cross section in terms of so-called double-parton distributions (dPDFs):

\[ d\sigma^{DPS} = \frac{1}{2\sigma_{\text{eff}}} \cdot F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2) \cdot F_{gg}(x'_1x'_2, \mu_1^2, \mu_2^2) \times \\
\sigma_{gg\to c\bar{c}}(x_1, x'_1, \mu_1^2)\sigma_{gg\to c\bar{c}}(x_2, x'_2, \mu_2^2) \, dx_1 \, dx_2 \, dx'_1 \, dx'_2 \]

factorized form with standard PDFs

- \( F_{gg}(x_1, x_2, b) = g(x_1)g(x_2)F(b) \), where \( F(b) \) is an overlap of the matter distribution in the transverse plane
- \( 1/\sigma_{\text{eff}} = \int d^2bF^2(b) \Rightarrow \) universal factor (energy and process independent)

dPDFs from special evolution equations

- equal scales: \( \mu_1 = \mu_2 = \mu \) (Snigireev)
- unequal scales: \( \mu_1 \neq \mu_2 \) (Ceccioperi, Gaunt-Stirling)
LO collinear predictions for DPS charm production

- DPS mechanism gives a large contributions to inclusive charm production
- Dangerous approaching of the Donnachie-Landschoff parametrization of the total cross section \( \Rightarrow \) inclusion of unitarity effect and/or saturation of parton distributions may be necessary
inclusive double-scattering distributions in $y$ and $p_\perp$ are identical as for single-scattering

no difference between both prescriptions in the case of charm production
Invariant mass and rapidity difference spectra

- **DPS dominates** at large rapidity difference and/or large invariant masses

- unique feature of DPS: possible production of \(cc\) pairs \(\Rightarrow\) experimental signature \(D^0 D^0, D^0 D^+, D^+ D^+, D^+ D_s\)
Very recent news from CERN! LHCb-PAPER-2012-003 (V. Belayev)

\[
\begin{align*}
\frac{\sigma_{D^0D^0}}{\sigma_{D^0D^-}} & \sim 11\%, \\
\frac{\sigma_{D^0D^+}}{\sigma_{D^0D^-}} & \sim 13\%, \\
\frac{\sigma_{D^0D_s^+}}{\sigma_{D^0D_s^-}} & \sim 16\%, \\
\frac{\sigma_{D_s^+D^+}}{\sigma_{D_s^+D^-}} & \sim 12\%, \\
\frac{\sigma_{D_s^+D_s^+}}{\sigma_{D_s^+D_s^-}} & \sim 10\%.
\end{align*}
\]

SPS mechanism of $c\bar{c}c\bar{c}$ production can also contribute!

see Schafer, Szczurek, Phys. Rev. D 85, 094029 (2012)
D mesons from DPS mechanism (LO parton model)

TABLE I. The DPS cross section ($\sigma_{pp} + \sigma_{ppp}$)/2 in mb for the production of one meson in $\eta_1 \in (-2.5, 2.0)$ and the second meson in $\eta_2 \in (2.0, 2.5)$ (ATLAS, CMS), second column, and for $\eta_1, \eta_2 \in (-0.9, 0.9)$ (ALICE), third column, for different lower cuts on both mesons transverse momenta.

| $p_{T,\text{min}}$ (GeV) | ATLAS or CMS | ALICE | ALICE $p_{T,\text{DpDp}} > 4$ GeV |
|-------------------------|--------------|--------|----------------------------------|
| 0.0                     | $2.59 \times 10^{-3}$ | $0.66 \times 10^{-2}$ | $0.58 \times 10^{-3}$ |
| 1.0                     | $1.47 \times 10^{-4}$ | $2.48 \times 10^{-3}$ | $0.41 \times 10^{-3}$ |
| 2.0                     | $0.32 \times 10^{-5}$ | $2.93 \times 10^{-4}$ | $1.54 \times 10^{-4}$ |
| 3.0                     | $2.55 \times 10^{-7}$ | $0.35 \times 10^{-4}$ | $2.46 \times 10^{-5}$ |
| 4.0                     | $2.33 \times 10^{-8}$ | $0.62 \times 10^{-5}$ | $0.49 \times 10^{-5}$ |
Summary

- good description of the transverse momentum distributions of open charm mesons measured by ALICE and LHCb

- huge contribution to charm production cross section from Double-Parton-Scattering → application of the $k_t$-factorization approach in our next step

- waiting for ATLAS data from large rapidity interval $|\eta_D| < 2.5$ (5 units, large rapidity difference)

Thank You for attention!