Single and double charmed meson production at the LHC

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Outline

1. Open charm production at the LHC
   - Theoretical framework within the $k_t$-factorization approach
   - Inclusive single $D$ meson spectra
   - Production of $D\bar{D}$ pairs and kinematical correlations

2. Mechanism of double-parton scattering (DPS)
   - Simple factorized theoretical model
   - Double charm ($DD$ pairs) production vs. LHCb data
   - DPS effects and inclusive $D$ meson spectra

Based on:
vanHameren, Maciuła, Szczurek, Phys. Rev. D89, 094019 (2014)
Open charm production at the LHC
Mechanism of double-parton scattering (DPS)

Summary

Theoretical framework within the \( k_t \)-factorization approach

Heavy quarks measurements in pp scattering at the LHC

- **direct**: open charm/bottom mesons \( \rightarrow \) reconstruction of all decay products
  \( (K^- \pi^+, K^+ K^- \pi^+, K^- \pi^+ \pi^+) \)

- **indirect**: nonphotonic electrons/muons \( \rightarrow \) leptons from semileptonic decays of heavy flavoured mesons


very small \( x \) region! (down to \( 10^{-5} \))

**ATLAS**, \(|\eta_D| < 2.1, p_\perp > 3.5 \text{ GeV}\), ATLAS-CONF-2011-017

wide rapidity interval
Dominant mechanisms of heavy quarks production

- **Leading order (LO) processes contributing to $Q\bar{Q}$ production:**
  
  ![LO diagrams](image)

- **Gluon-gluon fusion** dominant at high energies

- **Main classes of the next-to-leading order (NLO) diagrams:**
  - Pair creation with gluon emission
  - Flavour excitation
  - Gluon splitting

  ![NLO diagrams](image)  

- $\frac{NLO}{LO} \approx 3$ for $p_\perp \sim 0 - 3$ GeV and $y \sim 0$;

- $\frac{NLO}{LO} \geq 10$ for large $p'_\perp$ s or large $y$;
Standard approach of perturbative QCD

**collinear approximation** → transverse momenta of the incident partons are assumed to be zero (Wiezsacker-Williams method in QED)

- Quadruply differential cross section:
  \[
  \frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2s^2} \sum_{i,j} x_1 p_i(x_1, \mu^2) x_2 p_j(x_2, \mu^2) |M_{ij}|^2
  \]
- \( p_i(x_1, \mu^2), p_j(x_2, \mu^2) \) - standard collinear PDFs in the proton (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- NLO on-shell matrix elements well-known

**several approaches:** improved schemes of NLO collinear calculations

- **FONLL** (Cacciari et al.) JHEP 05 (1998) 007; JHEP 03 (2001) 006

**state-of-art:** \( \sigma_{tot} \) and inclusive single particle spectra

**BUT** cannot be applied in more exclusive studies of KINEMATICAL CORRELATIONS
Basic concepts of the $k_t$-factorization (semihard) approach

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


$\Rightarrow$ very efficient approach for $Q\bar{Q}$ correlations

- multi-differential cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \sum_{i,j} \int \frac{d^2 \kappa_{1,t}}{\pi} \frac{d^2 \kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} |M_{i^*j^*\to Q\bar{Q}}|^2$$

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

- **LO off-shell** $|M_{g^*g^*\to Q\bar{Q}}|^2$ $\Rightarrow$ Catani-Ciafaloni-Hautmann (CCH) analytic formulae or QMRK approach with effective BFKL NLL vertices

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

- major part of NLO corrections effectively included
  - pair creation with gluon emission
  - flavour excitation
  - gluon splitting
Open charm production at the LHC

Mechanism of double-parton scattering (DPS)

Summary

Theoretical framework within the $k_t$-factorization approach

Unintegrated gluon distribution functions (UGDFs)

most popular models:

- Kwieciński, Jung (CCFM, wide range of $x$)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of $x$)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small $x$-values)
- Kutak-Staśto (BK, saturation, small $x$-values)

already applied and tested in:

e.g. deep-inelastic structure function; inclusive charm and associated charm and jet photoproduction at HERA; dijets in photoproduction, hadroproduction and deep-inelastic scattering; electroweak boson production

charm quarks at LHC energies

$\Rightarrow$ only gluon-gluon fusion

and very small $x$-values down to $10^{-5}$

great test of many different UGDFs in so far unexplored kinematical regime
Open charm production at the LHC

Mechanism of double-parton scattering (DPS)

Theoretical framework within the $k_t$-factorization approach

2Dim-differential cross sections for charm quarks $\sqrt{s} = 7$ TeV

\[ p p \rightarrow c \bar{c} X \quad \sqrt{s} = 7 \text{ TeV} \]

\[ x \gtrsim 10^{-4} \quad \text{(ATLAS)} \]

\[ x \gtrsim 10^{-5} \quad \text{(LHCb)} \]

\[ \left| y_c \right| \leq 8 \]

LHCb:

\[ \log_{10}(x_1) \]

\[ \log_{10}(x_2) \]

charm quark $p_{\perp}$ (GeV)

charm antiquark $p_{\perp}$ (GeV)
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**Fragmentation functions technique**

- **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: 
  Kneesch-Kniehl-Kramer-Schienbein (KKKS08) + DGLAP evolution
  - FONLL $\rightarrow$ Braaten et al. (charm) and Kartvelishvili et al. (bottom) 
  - GM-VFNS $\rightarrow$ KKKS08 + evolution

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

\[
\frac{d\sigma(y, p_t^M)}{dy d^2p_t^M} \approx \int \frac{D_{Q\rightarrow M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2p_t^Q} dz
\]

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

- **Approximation**: 
  Rapidity unchanged in the fragmentation process $\rightarrow y_Q = y_M$
Inclusive single $D$ meson spectra

**Inclusive $D$ meson spectra**

- **ALICE, ATLAS, LHCb**

**$p p \rightarrow D^0 X$**  \( \sqrt{s} = 7 \text{ TeV} \)

- $|y_D| < 0.5$
- $\mu^2 = m_b^2$
- Peterson FF $\varepsilon_c = 0.05$

**$p p \rightarrow (D^+ + D^0) X$**  \( \sqrt{s} = 7 \text{ TeV} \)

- $2.0 < y_D < 4.5$
- $\mu^2 = m_b^2$
- Peterson FF $\varepsilon_c = 0.05$

- **LHCb Preliminary**

- **ATLAS Preliminary**

- **all of the UGDFs models underestimate experimental data points**

- **only the KMR UGDF gives results which are close to the measured values**
Open charm production at the LHC
Mechanism of double-parton scattering (DPS)
Summary

Inclusive single $D$ meson spectra

**Inclusive $D$ meson spectra**

**ALICE, ATLAS, LHCb**

1. Typical pQCD uncertainties: scales and quark mass
2. Only the upper limits of uncertainty bands for the KMR UGDF reasonably well describe the ALICE, ATLAS and LHCb data
3. $k_t$-factorization with the KMR UGDF consistent with the FONLL and NLO PM collinear predictions
**DD meson-antimeson correlations vs. LHCb data**

- **KMR and KMS UGDFs** ⇒ good description of the shapes
- **KMR UGDF** ⇒ absolute cross section well described
Double charm production (final state with two pairs of $c\bar{c}$)

Double-parton scattering (DPS)

Single-parton scattering (SPS)

**SINGLE CHARM vs. DOUBLE CHARM mechanism**

- **SPS** $p\;p \rightarrow c\bar{c}\;X$ vs. **DPS** $p\;p \rightarrow c\bar{c}\;c\bar{c}\;X$

- **SPS** $c\bar{c}$ vs. **DPS** $c\bar{c}c\bar{c}$: comparable total cross sections at LHC energies!

- **SPS** $c\bar{c}c\bar{c}$ negligible
Simple DPS picture and factorized Ansatz

process initiated by two simultaneous hard gluon-gluon scatterings in one proton-proton interaction ⇒

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

two subprocesses are not correlated and do not interfere

**analogy:** frequently considered mechanisms of double gauge boson production and double Drell-Yan annihilation

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

in more general form:

\[
\begin{align*}
d\sigma^{DPS}(pp \rightarrow c\bar{c}c\bar{c}X) &= \frac{1}{2} \cdot \Gamma_{gg}(b, x_1, x_2; \mu_1^2, \mu_2^2) \Gamma_{gg}(b, x_1', x_2'; \mu_1^2, \mu_2^2) \\
&\quad \times d\sigma_{gg \rightarrow c\bar{c}}(x_1, x_2', \mu_1^2) \cdot d\sigma_{gg \rightarrow c\bar{c}}(x_1', x_2, \mu_2^2) \ dx_1 dx_2 dx_1' dx_2' d^2 b
\end{align*}
\]

**DPDF** - emission of one parton with assumption that second parton is also emitted
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Simple factorized theoretical model

Double-parton distributions (DPDFs) and factorized Ansatz

\[ \Gamma_{ij}(b, x_1, x_2; \mu_1^2, \mu_2^2) = F_i(x_1, \mu_1^2) \cdot F_j(x_2, \mu_2^2) \cdot F(b; x_1, x_2, \mu_1^2, \mu_2^2) \]

- correlations between two partons

C. Flensburg et al., JHEP 06, 066 (2011)

In general:

\[ \sigma_{\text{eff}}(x_1, x_2, x_1', x_2', \mu_1^2, \mu_2^2) = \left( \int d^2 b F(b; x_1, x_2, \mu_1^2, \mu_2^2) \cdot F(b; x_1', x_2', \mu_1^2, \mu_2^2) \right)^{-1} \]

Factorized Ansatz:

- additional limitations: \( x_1 + x_2 < 1 \) oraz \( x_1' + x_2' < 1 \)

- DPDF in multiplicative form:
  \[ \Gamma_{gg}(b; x_1, x_2, \mu_1^2, \mu_2^2) = F_g(x_1, \mu_1^2) \cdot F_g(x_2, \mu_2^2) \cdot F(b) \]

- \( \sigma_{\text{eff}} = \left[ \int d^2 b \left( F(b) \right)^2 \right]^{-1} \), \( F(b) \) - energy and process independent

Phenomenology: \( \sigma_{\text{eff}} \Rightarrow \) nonperturbative quantity with a dimension of cross section, connected with transverse size of proton

\[ \sigma_{\text{eff}} \approx 15 \text{ mb} \] (\( p_\perp \)-independent)

A detailed analysis of \( \sigma_{\text{eff}} \):
Seymour, Siódmok, JHEP 10, 113 (2013)
How the DPS mechanism can be investigated?

Study of **MESON-MESON pairs** production:

* **DD** pairs - both containing c quarks or both containing $\bar{c}$ antiquark

  - impossible to produce within standard SPS single $c\bar{c}$ production mechanism
  - measurements of charm meson-meson pairs highly recommended at the LHC
  - larger rapidity differences between particles: **DD** pairs at ATLAS
  - same-sign nonphotonic lepton pairs, e.g. $\mu^+\mu^+$ at ALICE

Double open charm ($cc\bar{c}\bar{c}$)

Double hidden charm ($J/\Psi J/\Psi$)

**First clean signature of the DPS mechanism?**

**Double charm ($DD$ pairs) production vs. LHCb data**

![Graphs showing open charm production at the LHC](image)

**Summary**

Proper order of magnitude but still something is missing (about factor 2)
Double charm (DD pairs) production vs. LHCb data

What can be still missing?

Different class of the DPS diagrams ($3 \rightarrow 4$) ⇒ **perturbative parton splitting**

- LO calculations available using splitting DPDFs
  - J.Gaunt, JHEP, 01, 042 (2013)
- our first rough estimation: $\frac{DPS(3\rightarrow4)}{DPS(4\rightarrow4)} \approx 30–60\%$
- inclusion of the DPS($3 \rightarrow 4$) contributions in the LHCb data very difficult
  - (unknown $\sigma_{eff}^{3\rightarrow4}$; the LO collinear formalism is not sufficient for charm)
- more precise calculations, beyond the factorized Ansatz, are NOT possible
  - in the moment ⇒ more advanced framework have to be worked out
Does the DPS contribute to inclusive $D$ mesons spectra?
Conclusions

SPS \(c\bar{c}\):

- only KMR UGDF allows for results which are close to the LHC inclusive charm data 
  (rest of tested UGDFs seem to underestimate significantly experimental data)
- only upper limits of our theoretical predictions give quite reasonable description of the ALICE, 
  ATLAS and LHCb data (also true for FONLL)
- \(k_t\)-factorization approach together with KMR UGDF is very efficient for studying kinematical 
  correlations in less inclusive measurements of \(D\bar{D}\) pairs

DPS \(c\bar{c}c\bar{c}\):

- SPS \(c\bar{c}\) and DPS \(c\bar{c}c\bar{c}\) cross sections become comparable at LHC energies
- Production of double charm (\(DD\) pairs) is an extremely good testing ground 
  of double-parton scattering effects
- DPS mechanism can give a very important contribution to inclusive \(D\) meson distributions?

Thank You for attention!