Production of two heavy quark pairs in double parton scattering at LHC

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Two partons from the target scatter with two partons from the projectile.

\[ \alpha_S^2 \] suppressed by \( \alpha_S^2 \)

LHC: gluon density is huge

\[ G^2(x, \mu^2) \] enhanced by \( G^2(x, \mu^2) \)

May be seen in data as an excess of heavy pairs with respect to standard pQCD.
Motivation to study DPS

- Generalized and multiparton distributions
- Production of hadronic states with double charm in pp collisions

Double charm baryons

Double charm tetraquarks:


B factories

LHC
Double charm production in pp collisions

\[ \sigma_{h_1 h_2 \rightarrow Q_1 \bar{Q}_1 Q_2 \bar{Q}_2}^{DPS} = \left( \frac{m}{2} \right) \frac{\sigma_{^4S_3 P\Sigma h_1 h_2 \rightarrow Q_1 \bar{Q}_1}^{SPS}}{\sigma_{_{eff}}} \]

uncorrelated partons
independent scatterings

slow down the growth of DPS!

LHC: DPS = SPS!!!

Luszczak, Maciula, Szczurek,
arXiv:1111.3255

without saturation...

\[ \sigma_{_{tot}}(\sqrt{s}) \]

(SPS p p → c\bar{c} X vs. DPS p p → c\bar{c} c\bar{c} X)

CTEQ6 LO

GRV94 LO

GJR08 LO

MSTW08 LO

\( |y_c| \leq 8.0 \)

\( \sigma_{_{eff}} = 15 \text{ mb} \)

\( \mu_R^2 = \mu_F^2 = M_c^2 \)

LO: \( g g \rightarrow c\bar{c} \)

gluon saturation

affect the factorization formula!
Double parton scattering in the factorization approach

\[
\frac{d\sigma_{\text{double}}}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} = \frac{1}{C} \hat{\sigma}_1(x_1 \bar{x}_1) \hat{\sigma}_2(x_2 \bar{x}_2) \int d^2b \, F(x_1, x_2, b) F(\bar{x}_1, \bar{x}_2, b)
\]

\[
F(x_1, x_2, b) = f(x_1) f(x_2) g(b)
\]

\[
\frac{d\sigma_{\text{double}}}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} = \frac{1}{C} \frac{d\sigma_1}{dx_1 d\bar{x}_1} \frac{d\sigma_2}{dx_2 d\bar{x}_2} \frac{1}{\sigma_{\text{eff}}}
\]

\[
\sigma_{\text{eff}} = 15 \text{ mb}
\]

CDF 4 jets (1993)
CDF γ + 3 jets (1997)
Bähr et al. reanalysis (2013)
D0 γ + 3 jets (2009)
ATLAS W + 2 jets (2013)

LHCb (2012)
J/Ψ + D^0
J/Ψ + D^+
J/Ψ + D_s^+
J/Ψ + Λ_c^+
Gluon saturation

High energies
large number of gluons
gluon recombination

\[ g\ g \rightarrow \ g \]

Gluon recombination at very small $x$ tames the growth of the gluon distribution

Implementation: $k_T$ factorization + unintegrated pdfs or color dipole approach
Charm production in the color dipole approach

\[ \sigma\{ p \, p \rightarrow Q\bar{Q} \, X \} = 2 \int_{0}^{\ln(\sqrt{s}/2m_{Q})} d\gamma \int d\rho \, x_{1} G(x_{1}, \mu^{2}) \, \sigma\{ g \, p \rightarrow Q\bar{Q} \, X \} \]

\[ \sigma\{ g \, p \rightarrow Q\bar{Q} \, X \} = \int_{0}^{1} d\alpha \int d^{2}\rho \, |\Psi_{g\rightarrow Q\bar{Q}}(\alpha, \rho)|^{2} \sigma_{gq\bar{q}}(\alpha, \rho) \]

\[ |\Psi_{g\rightarrow Q\bar{Q}}(\alpha, \rho)|^{2} = \frac{\alpha_{s}(\mu^{2})}{(2\pi)^{2}} \left\{ m_{Q}^{2} K_{0}^{2}(m_{Q} \rho) + (\alpha^{2} + \bar{\alpha}^{2}) m_{Q}^{2} K_{1}^{2}(m_{Q} \rho) \right\} \]

\[ \sigma_{gq\bar{q}}(\alpha, \rho) = \frac{9}{8} [\sigma_{dp}(\alpha \rho) + \sigma_{dp}(\bar{\alpha} \rho)] - \frac{1}{8} \sigma_{dp}(\rho) \]

Kopeliovich, Tarasov
hep-ph/0205151
\[ \sigma_{d\rho}(x, \rho) = 2 \int d^2 b \, N(x, \rho, b) \quad \text{N}(x, \rho, b) = N(x, \rho) \, S(b) \]

\[ \sigma_{d\rho}(x, \rho) = \sigma_0 \, N(x, \rho) \]

**Input:**  
\[ G(x_1, \mu) = CTEQ6L \quad \mu^2 = m_c^2 \]

**Phenomenolog. parametrization of DIS data**  
Golec-Biernat Wüsthoff, PRD (1999)

\[ N(x, \rho) = 1 - \exp \left[ -\frac{1}{4} \left( \rho^2 Q_s^2 \right) \right] \]

\[ Q_s^2(x) = Q_0^2 \left( \frac{x_0}{x} \right)^\lambda \]

\[ \rho \to 0 \quad N \approx \frac{1}{4} \left( \rho^2 Q_s^2 \right) \quad \text{(linear limit)} \]

**Numerical solution of BK equation with running coupling corrections to the kernel: rcBK**

Albacete, Armesto, Milhano, Salgado, PRD (2009)
Numerical Results

Before ALICE

\[ \sigma_{c\bar{c}} (\mu b) \]

GBW

\[ s^{1/2} (GeV) \]

rcBK

C-Rays

nucl-ex/0607015

Merino et al. (2009)

KT fac

PHENIX

UA2

Cosmic Rays

Cazaroto, Gonçalves, Navarra, arXiv:1108.3143
Numerical Results

After ALICE

\[
\sigma_{DPS}^{h_1 h_2 \to Q_1 \bar{Q}_1 Q_2 \bar{Q}_2} = \left( \frac{m}{2} \right) \frac{\sigma_{SPS}^{h_1 h_2 \to Q_1 \bar{Q}_1} \sigma_{SPS}^{h_1 h_2 \to Q_2 \bar{Q}_2}}{\sigma_{eff}}
\]
Heavy quark production cross section

Total pp cross section

Giannini, Duraes, arxiv:1302.3765
without saturation effects

Luszczak, Maciula, Szczurek, arXiv:1111.3255

with saturation effects

(agreement between models within the uncertainties)
charm \{ \frac{DPS}{SPS} = 0.3 \quad \frac{DPS}{SPS} = 0.6 \} \\
bottom \{ \frac{DPS}{SPS} = 1 \}
Color dipole model for charm production still works!

Charm production at LHC: **DPS processes are comparable to SPS.** We confirm the results of Luszczac, Maciula and Szczurek.

**Saturation effects are visible!** They reduce 15% the SPS and 28% the DPS charm cross sections at $s^{1/2} = 14$ TeV.

**Enhancement in b production due to DPS (bc).**
Single parton scattering in pp collisions (SPS)

One gluon from the target scatters with one gluon from the projectile

Heavy quark pair in SPS

Two heavy quark pairs in SPS

Suppressed by $\alpha_s^2$
Double parton scattering in pp collisions (DPS)

Two gluons from the target scatter with two gluons from the projectile

Two heavy quark pairs in DPS

Landshoff, Polkinghorne, PRD (1978)

M. Diehl, arXiv:1306.6059

At LHC: gluon density is huge

Higher probability of DPS
Charm production in the color dipole approach

\[
\sigma_{h_1 h_2 \to Q \bar{Q} X} = \int_0^{1 - \ln(2m_Q/\sqrt{s})} dy \ x_1 \ G_{h_1}(x_1, \mu_F) \ \sigma(G h_2 \to \{Q \bar{Q}\}X)
\]

\[
\sigma(G h_2 \to \{Q \bar{Q}\}X) = \int_0^1 d\alpha \int d^2 \rho \ |\Psi_{G \to Q \bar{Q}}(\alpha, \rho)|^2 \ \sigma_{h_2}^{Q \bar{Q} G}(\alpha, \rho)
\]

\[
\sigma_{h_2}^{Q \bar{Q} G}(\alpha, \rho) = \frac{9}{8} [\sigma_{Q \bar{Q}}(\alpha \rho) + \sigma_{Q \bar{Q}}(\bar{\alpha} \rho)] - \frac{1}{8} \sigma_{Q \bar{Q}}(\rho)
\]
\[ T_{cc} = c \, c \, \bar{q} \, \bar{q} \]

“brother” of the

\[ X(3872) = c \, \bar{c} \, q \, \bar{q} \]

Tetraquark
diquark + antidiquark

Weakly bound

\[ \Lambda \approx \frac{1}{\Lambda_c} \]

“Atomic”

Strongly bound

D - D* molecule
Only gluon-gluon fusion

Higher order -> renormalization with K factor

Early works

Recent works

In Fig. 2 we compare cross sections for the single and double-parton scattering as a function of proton-proton center-of-mass energy. At low energies the conventional single-parton scattering dominates. For reference we show the proton-proton total cross section as a function of energy as parametrizes in Ref. [33]. At low energy the $c\bar{c}$ or $c\bar{c}c\bar{c}$ cross sections are much smaller than the total cross section. At higher energies the contributions dangerously approach the expected total cross section$^1$. This shows that inclusion of unitarity effect and/or saturation of parton distributions may be necessary. The effect of saturation in $c\bar{c}$ production has been included e.g. in Ref. [34] but not checked versus experimental data.

\[
\frac{d \sigma_{pp \rightarrow Q\bar{Q} X}}{d y} = x_1 G(x_1, \mu^2) \sigma_{g p \rightarrow Q\bar{Q} X}
\]
Minijet Model + KLN

$Q_0^2 = 1.00 \text{ GeV}^2; \quad \lambda = 0.29$

$Q_0^2 = 1.00 \text{ GeV}^2; \quad \lambda = 0.31$
DPS $p p \rightarrow c\bar{c}c\bar{c}X$, $\sqrt{s} = 7$ TeV

- LO: $g g \rightarrow c\bar{c}$
- CTEQ6 LO
- $\sigma_{eff} = 15$ mb

- $\mu^2 = \mu_F^2 = 4m_c^2$
- $\mu_R^2 = \mu_F^2 = M_{c\bar{c}}^2$
- $\mu_R^2 = \mu_F^2 = m_1^2$

- SPS $p p \rightarrow c\bar{c}X$

Graphs show distributions of $y_c$ and $y$, with legends indicating different processes and energies.
Dipole – proton cross section

Golec-Biernat - Wüsthoff \hspace{2cm} GBW \hspace{1cm} (1998)
Bartels - Golec-Biernat - Kowalski \hspace{1cm} BGK \hspace{1cm} (2002)
Kowalski - Teaney \hspace{1cm} IPsat \hspace{1cm} (2003)
Iancu - Itakura - Munier \hspace{1cm} IIM \hspace{1cm} (2004)
Kharzeev - Kovchegov - Tuchin \hspace{1cm} KKT \hspace{1cm} (2004)
Kowalski - Motyka - Watt \hspace{1cm} bCGC \hspace{1cm} (2006)
Dumitru - Hayashigaki - Jalilian-Marian \hspace{1cm} DHJ \hspace{1cm} (2006)
Gonçalves - Kugeratski - Machado - Navarra \hspace{1cm} GKMN \hspace{1cm} (2006)
Marquet - Peshanski - Soyez \hspace{1cm} MPS \hspace{1cm} (2007)
Boer - Utermann - Wessels \hspace{1cm} BUW \hspace{1cm} (2008)
Albacete - Armesto - Milhano - Salgado \hspace{1cm} rcBK \hspace{1cm} (2009)

(and others...sorry for omissions)
• Asymptotic limits:

**Without saturation:**

\[
\begin{align*}
\rho \to 0 & \quad N \approx \rho^2 \\
\rho \to \infty & \quad N \approx \rho^2 \to \infty
\end{align*}
\]

**With saturation:**

\[
\begin{align*}
\rho \to 0 & \quad N \approx \rho^2 \\
\rho \to \infty & \quad N \approx 1
\end{align*}
\]

• Model by Golec-Biernat and Wüsthoff (GBW) - 1999:

\[
N(x, \rho) = 1 - \exp \left[ -\frac{1}{4} (\rho^2 Q_s^2) \right]
\]

\[
\begin{align*}
\rho \to 0 & \quad N \approx \frac{1}{4} (\rho^2 Q_s^2) \\
\rho \to \infty & \quad N \approx 1
\end{align*}
\]