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

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E.R. Cazaroto, V.P. Goncalves, F.S. Navarra, arXiv:1306.4169

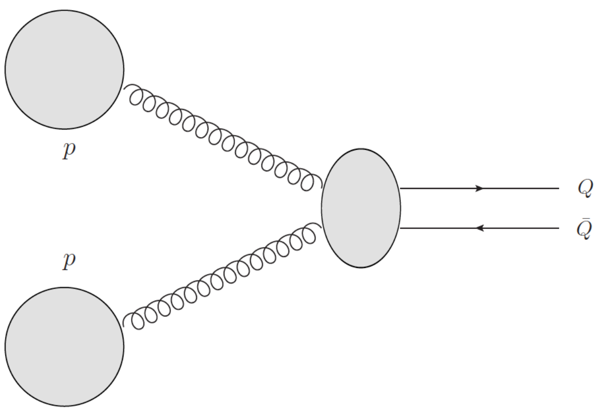
Double parton scattering in pp collisions (DPS)

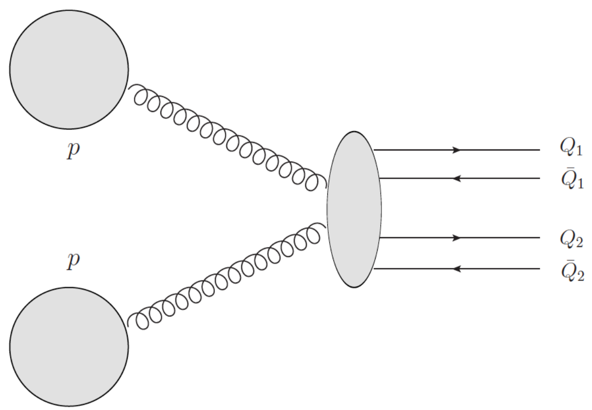
Two partons from the target scatter with two partons from the projectile

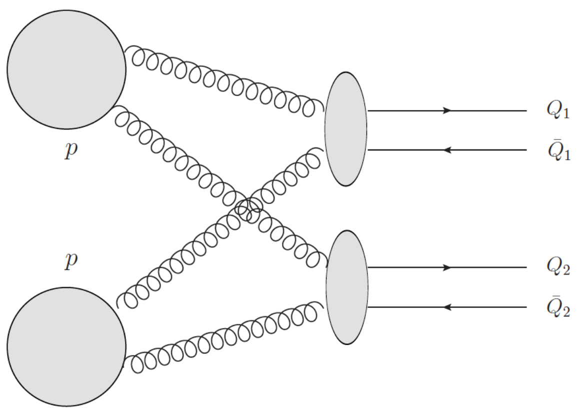
Landshoff, Polkinghorne, PRD (1978) → M. Diehl, arXiv:1306.6059

Single parton scattering

Double parton scattering







suppressed by α_s^2

enhanced by $G^2(x,\mu^2)$

LHC: gluon density is huge

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

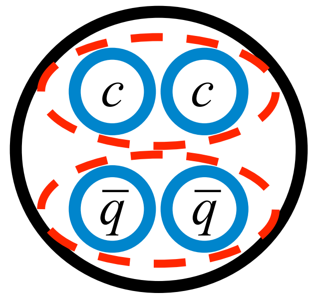
Motivation to study DPS

- Generalized and multiparton distributions

- Production of hadronic states with double charm in pp collisions

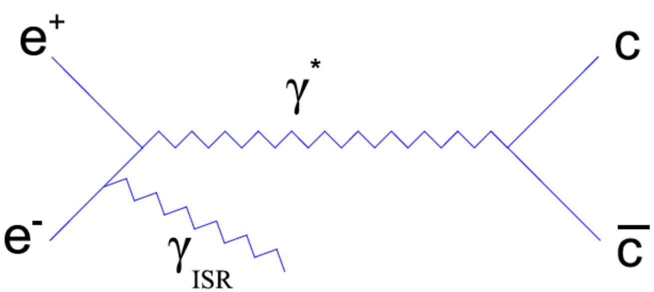
Double charm baryons

Double charm tetraquarks:

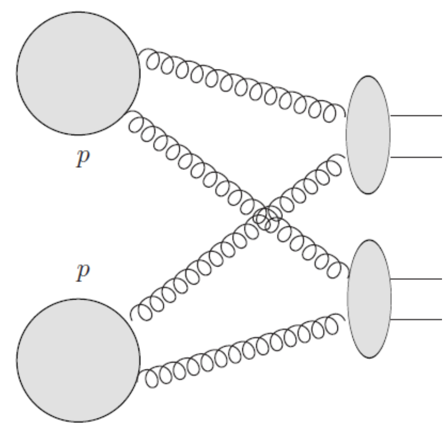


T_{cc}

Nielsen,Navarra,Lee,
Phys. Rept. (2010)
arXiv:0911.1958



B factories



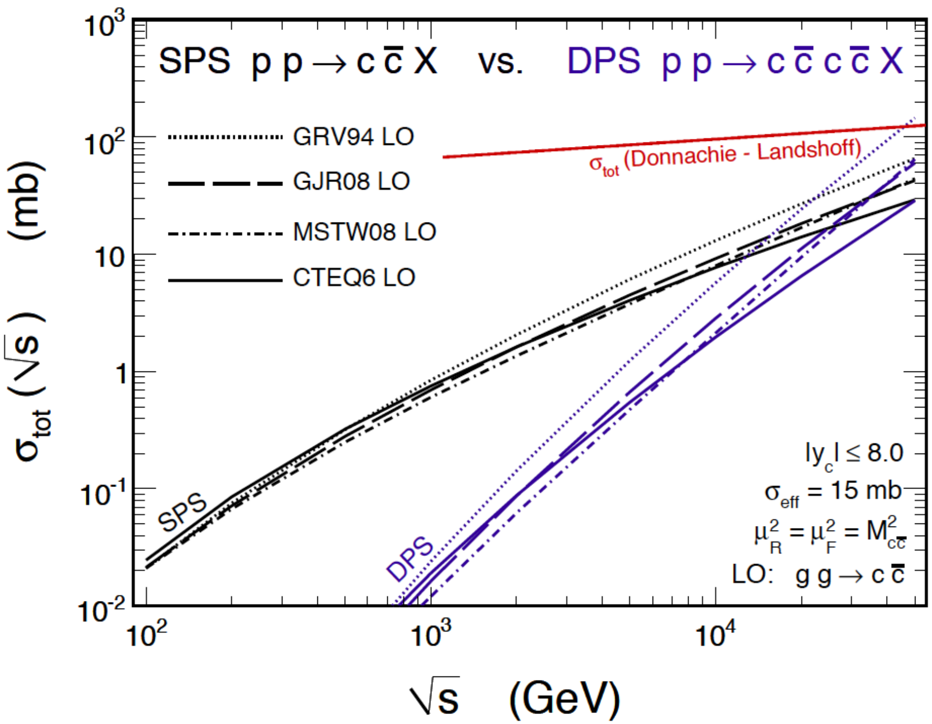
LHC

Double charm production in pp collisions

- uncorrelated partons
- independent scatterings

→

$$\sigma^{DPS}_{h_1 h_2 \to Q_1 \bar{Q}_1 Q_2 \bar{Q}_2} = \left(\frac{m}{2}\right) \frac{\sigma^{SPS}_{h_1 h_2 \to Q_1 \bar{Q}_1} \sigma^{SPS}_{h_1 h_2 \to Q_2 \bar{Q}_2}}{\sigma_{eff}}$$



LHC: DPS = SPS !!!

Luszczak, Maciula, Szczurek, arXiv:1111.3255

without saturation…

gluon saturation
- slow down the growth of DPS !
- affect the factorization formula !

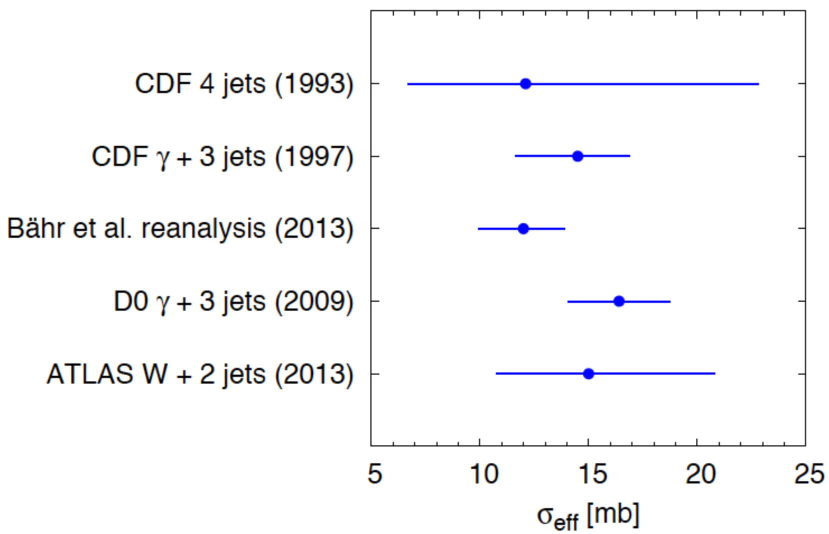
Double parton scattering in the factorization approach

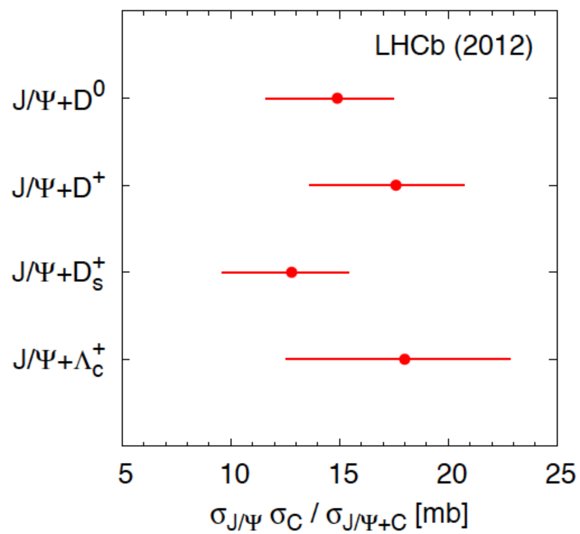
$$\frac{d\sigma_{\rm double}}{dx_1\,d\bar{x}_1\,dx_2\,d\bar{x}_2} = \frac{1}{C}\,\hat{\sigma}_1(x_1\bar{x}_1)\,\hat{\sigma}_2(x_2\bar{x}_2)\int d^2\mathbf{b}\,F(x_1,x_2,\mathbf{b})\,F(\bar{x}_1,\bar{x}_2,\mathbf{b})$$

$$F(x_1,x_2,b) = f(x_1)\,f(x_2)\,g(b)$$

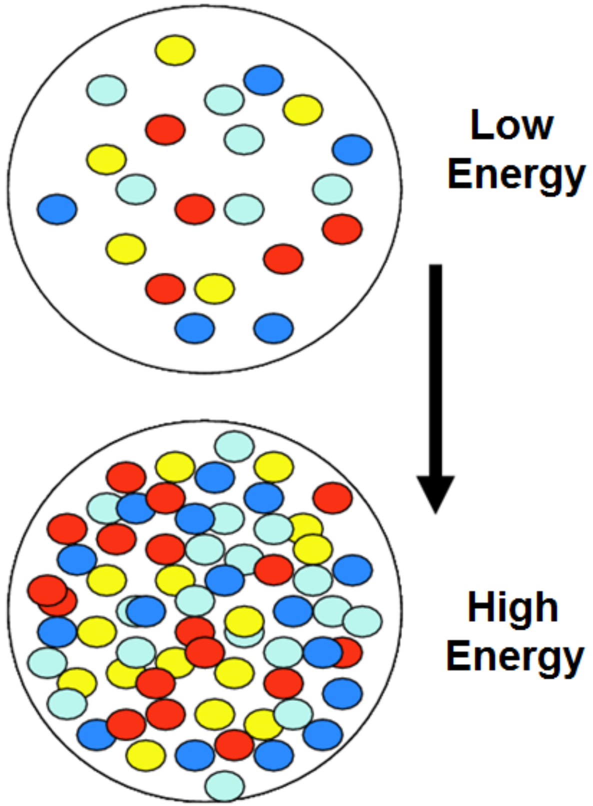
$$\frac{d\sigma_{\rm double}}{dx_1\,d\bar{x}_1\,dx_2\,d\bar{x}_2} = \frac{1}{C}\,\frac{d\sigma_1}{dx_1\,d\bar{x}_1}\,\frac{d\sigma_2}{dx_2\,d\bar{x}_2}\,\frac{1}{\sigma_{\rm eff}}$$

$$\sigma_{eff} = 15\,mb$$





Gluon saturation



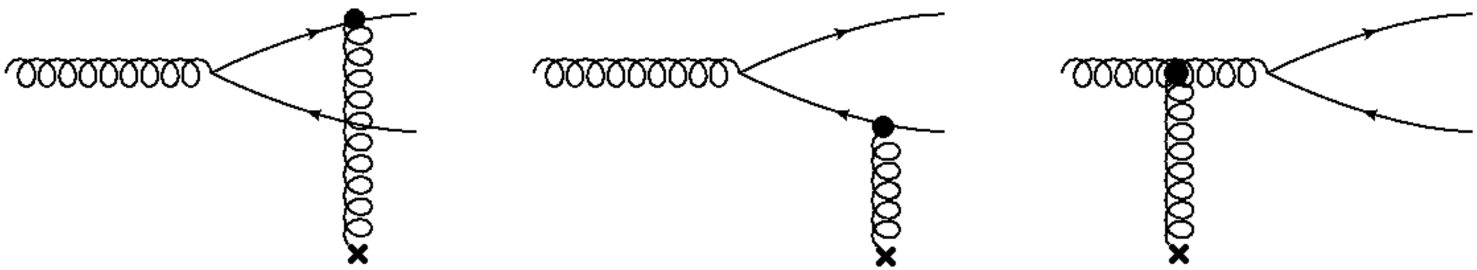
high energies
large number of gluons
gluon recombination

$$g\,g \rightarrow g$$

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



$$\sigma\{p\,p \to Q\bar{Q}\,X\} = 2\int_0^{\ln(\sqrt{s}/2m_Q)} dy\; x_1\, G(x_1,\mu^2)\;\sigma\{g\,p \to Q\bar{Q}\,X\}$$

Kopeliovich, Tarasov
hep-ph/0205151

$$\sigma\{g\,p \to Q\bar{Q}\,X\} = \int_0^1 d\alpha \int d^2\rho\;|\Psi_{g\to Q\bar{Q}}(\alpha,\rho)|^2\,\sigma_{gq\bar{q}}(\alpha,\rho)$$

$$|\Psi_{g\to Q\bar{Q}}(\alpha,\rho)|^2 = \frac{\alpha_s(\mu^2)}{(2\pi)^2}\{m_Q^2\,K_0^2(m_Q\,\rho) + (\alpha^2+\bar{\alpha}^2)\,m_Q^2\,K_1^2(m_Q\,\rho)\}$$

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

$$x_1 = \frac{2\,m_Q\,e^{y}}{\sqrt{s}}$$

$$x_2 = \frac{2\,m_Q\,e^{-y}}{\sqrt{s}}$$

$$y = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$

$$\sigma_{dp}(x,\rho) = 2\int d^2b\, N(x,\rho,b) \qquad N(x,\rho,b) = N(x,\rho)\, S(b)$$

$$\sigma_{dp}(x,\rho) = \sigma_0\, N(x,\rho)$$

Input: $G(x_1,\mu) = CTEQ6L \qquad \mu^2 = m_c^2 \qquad N(x,\rho)$

Phenomenolog. parametrization of DIS data

Golec-Biernat Wüsthoff, PRD (1999)

$$N(x,\rho) = 1 - \exp\left[-\frac{1}{4}\left(\rho^2 Q_S^2\right)\right] \qquad Q_s^2(x) = Q_0^2\left(\frac{x_0}{x}\right)^{\lambda}$$

$$\rho \to 0 \qquad N \approx \frac{1}{4}\left(\rho^2 Q_S^2\right)$$

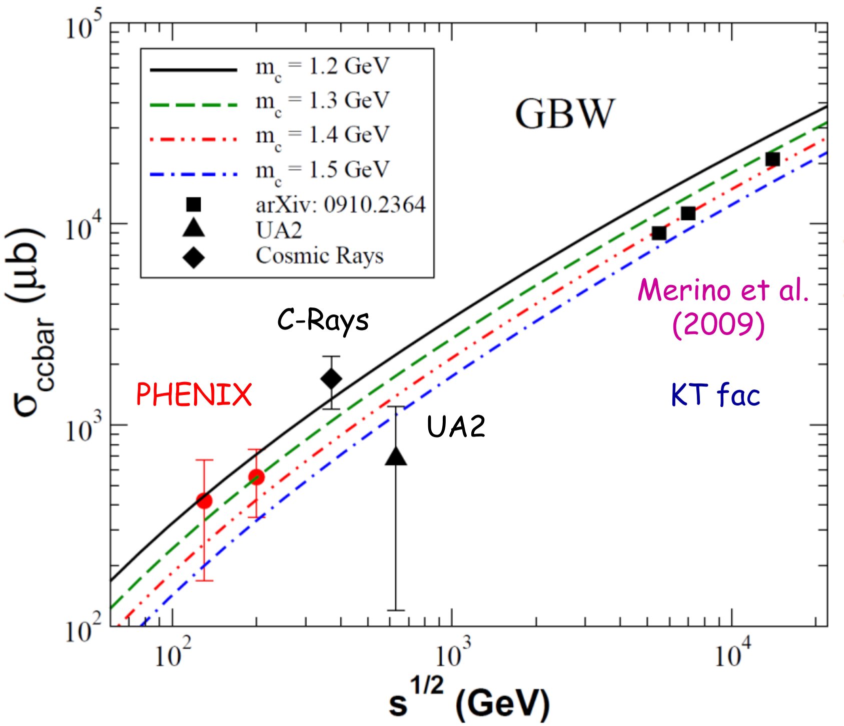
(linear limit)

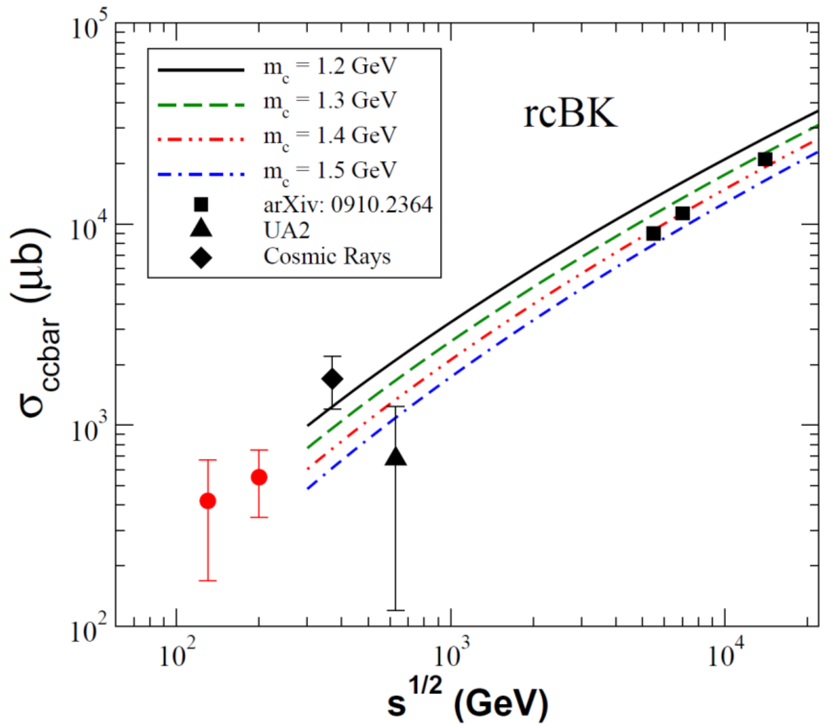
Numerical solution of BK equation with running coupling corrections to the kernel: rcBK

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

Numerical Results

Before ALICE



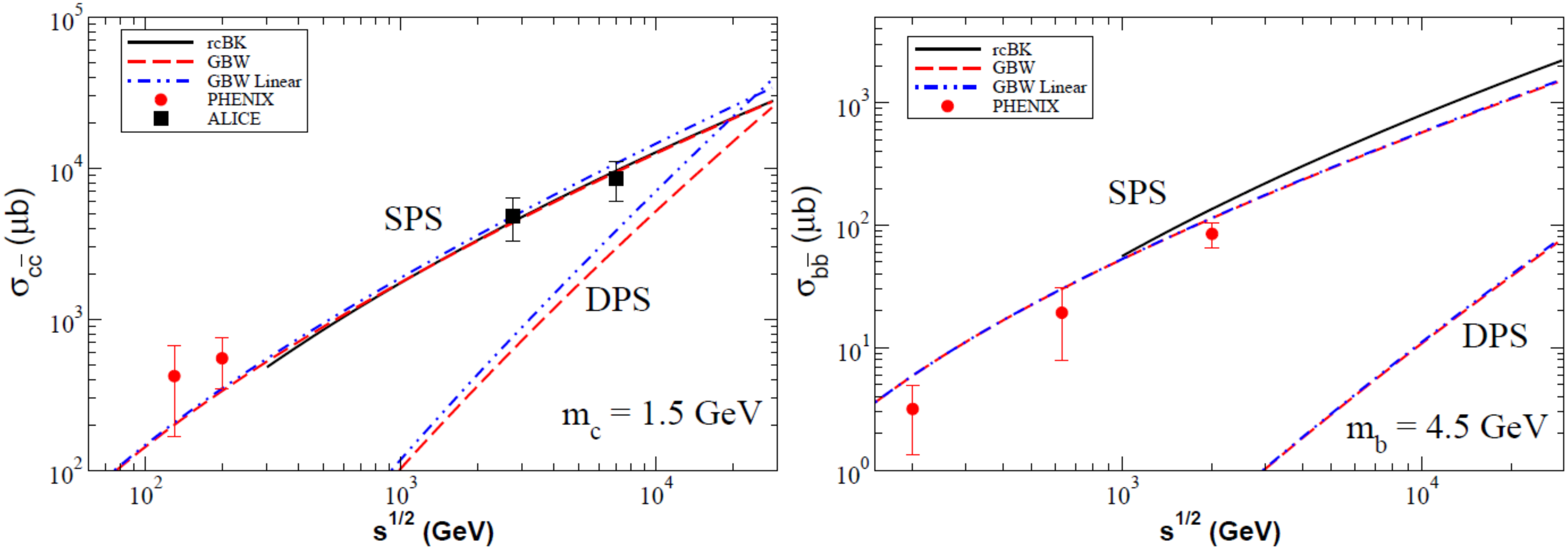


C-Rays
nucl-ex/0607015

Cazaroto,Gonçalves,Navarra,
arXiv:1108.3143

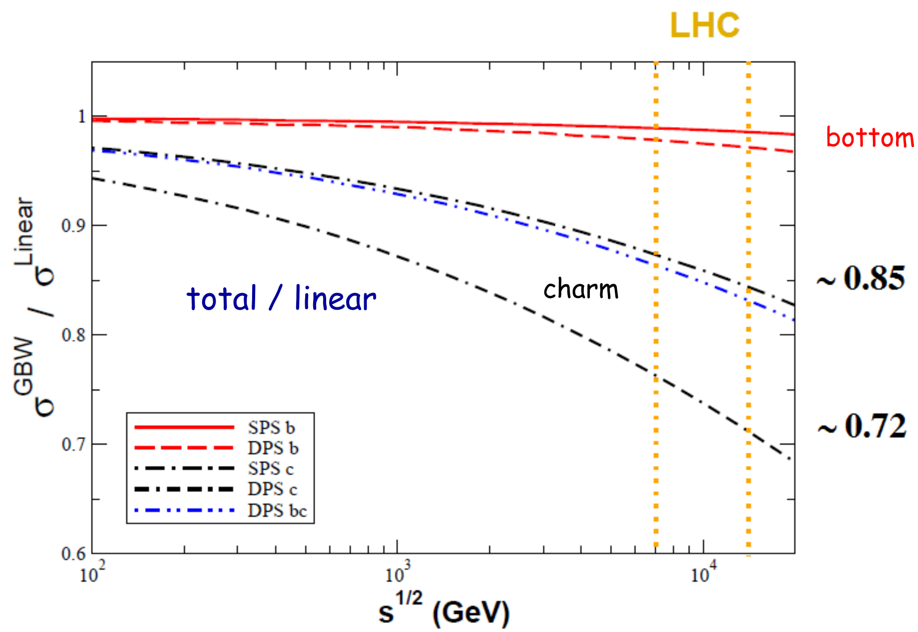
Numerical Results

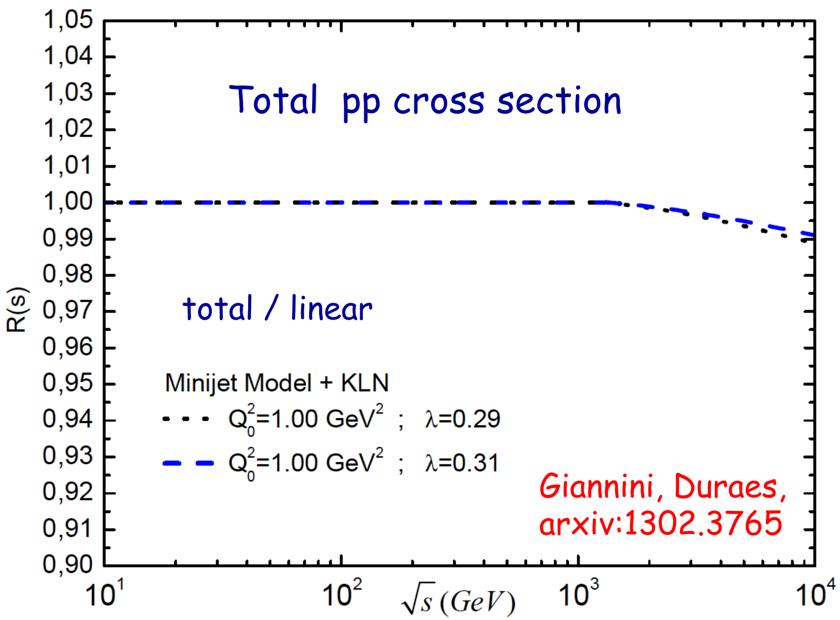
After ALICE



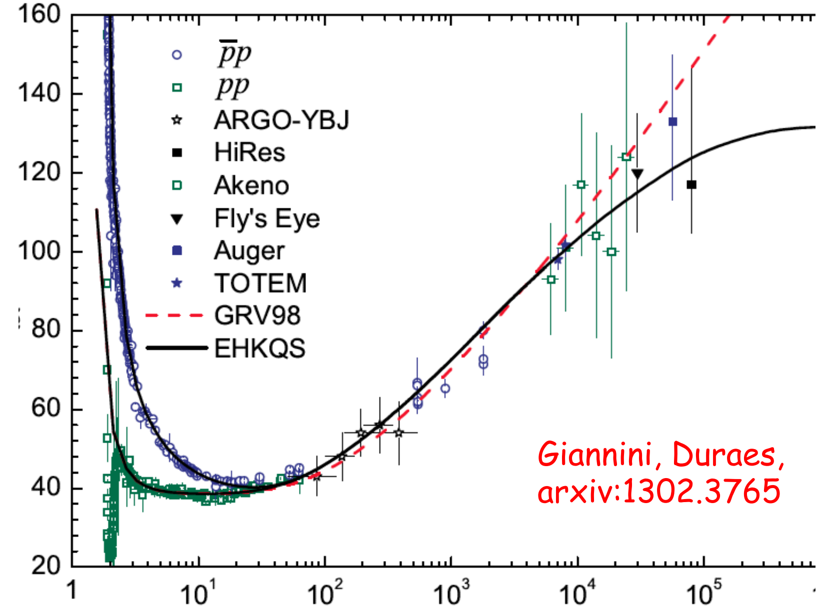
$$\sigma^{DPS}_{h_1h_2\to Q_1\bar{Q}_1Q_2\bar{Q}_2} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{h_1h_2\to Q_1\bar{Q}_1}\,\sigma^{SPS}_{h_1h_2\to Q_2\bar{Q}_2}}{\sigma_{eff}}$$

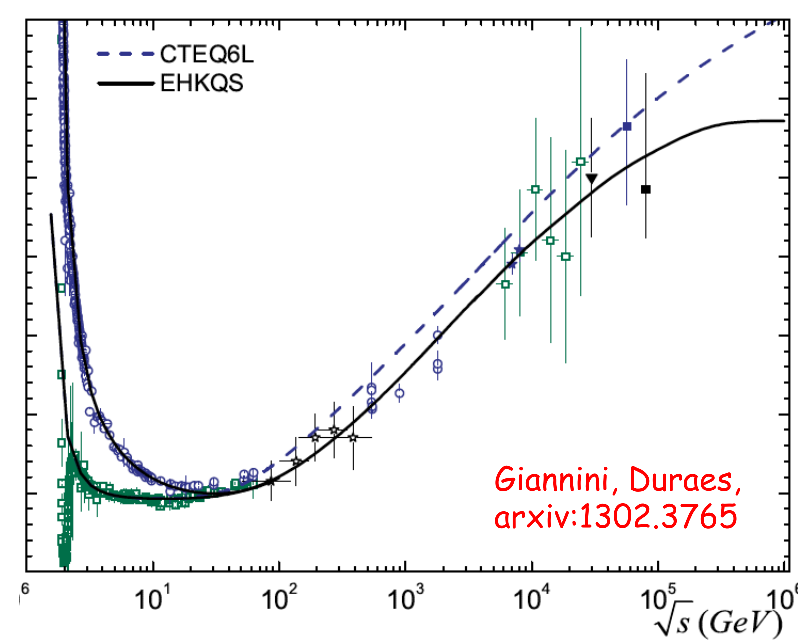
Heavy quark production cross section

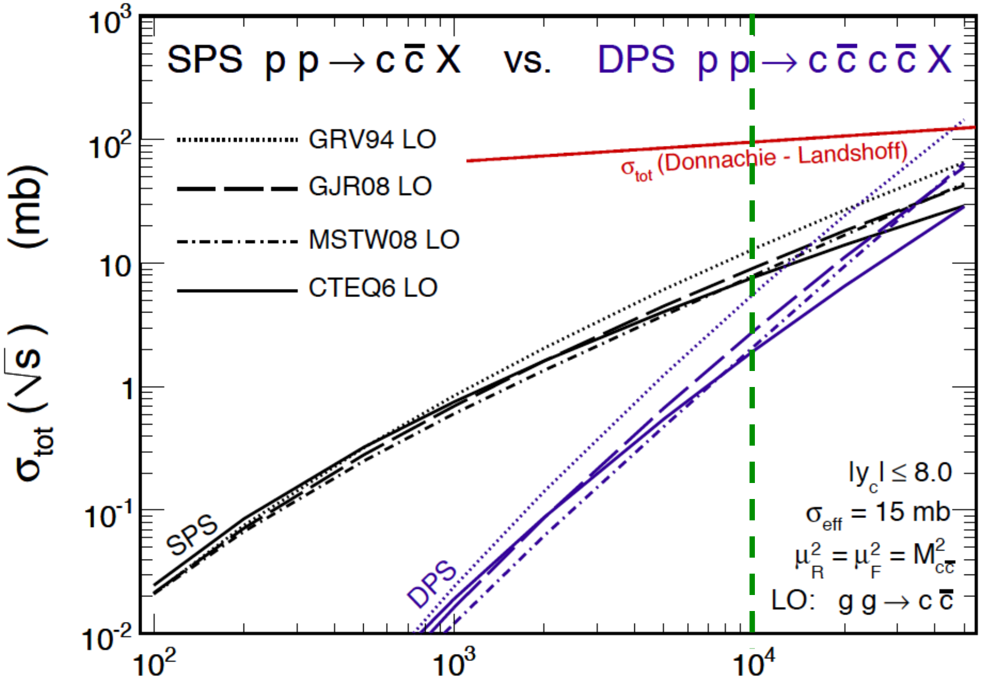




Total pp cross section

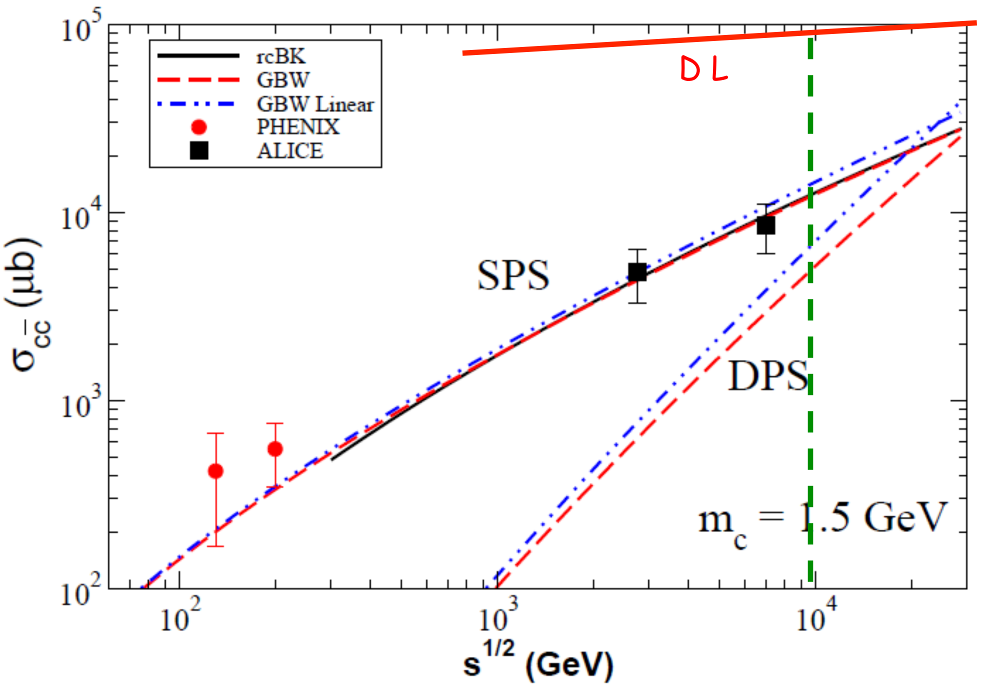






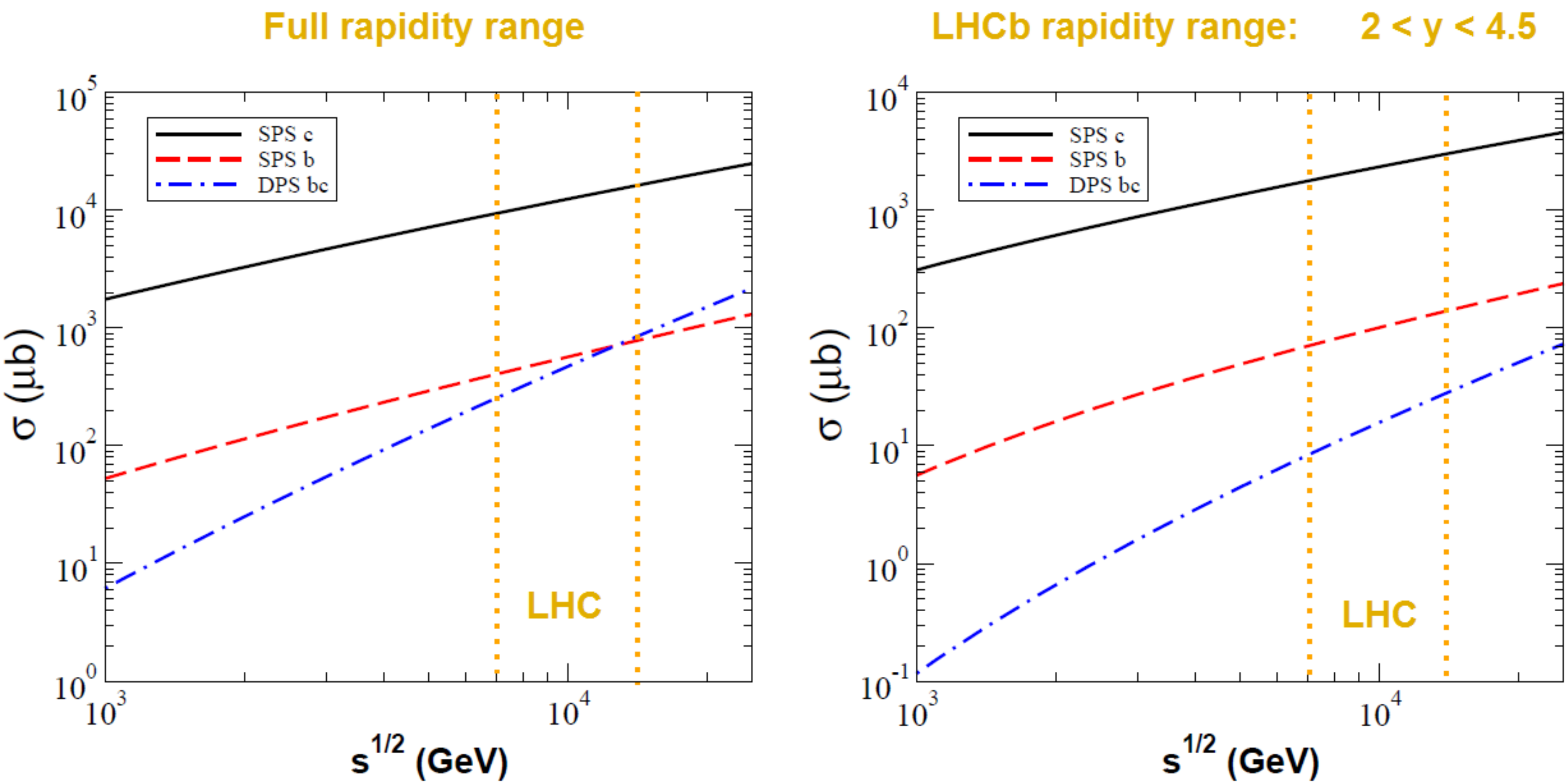
without saturation effects

Luszczak, Maciula, Szczurek, arXiv:1111.3255

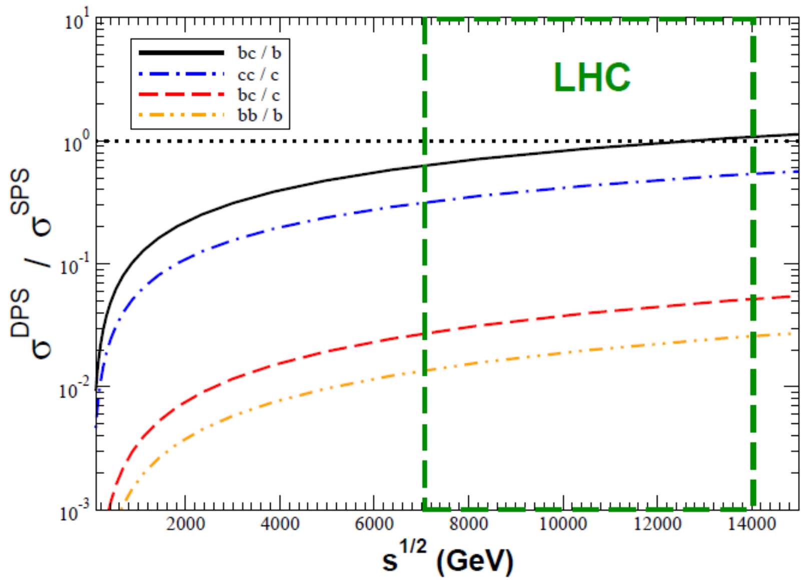


with saturation effects

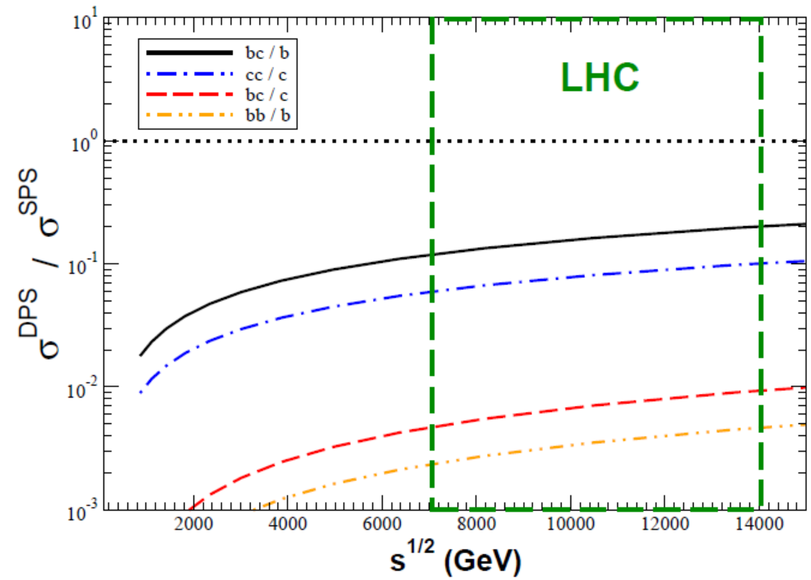
(agreement between models within the uncertainties)


Full rapidity range
LHCb rapidity range: 2 < y < 4.5
SPS c
SPS b
DPS bc
LHC
σ (μb)
s^1/2 (GeV)

Full rapidity range



LHCb rapidity range: $2 < y < 4.5$



charm

$$\frac{DPS}{SPS} = 0.3 \qquad \frac{DPS}{SPS} = 0.6 \qquad \frac{DPS}{SPS} = 0.06 \qquad \frac{DPS}{SPS} = 0.1$$

bottom

$$\frac{DPS}{SPS} = 1$$

Summary

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.

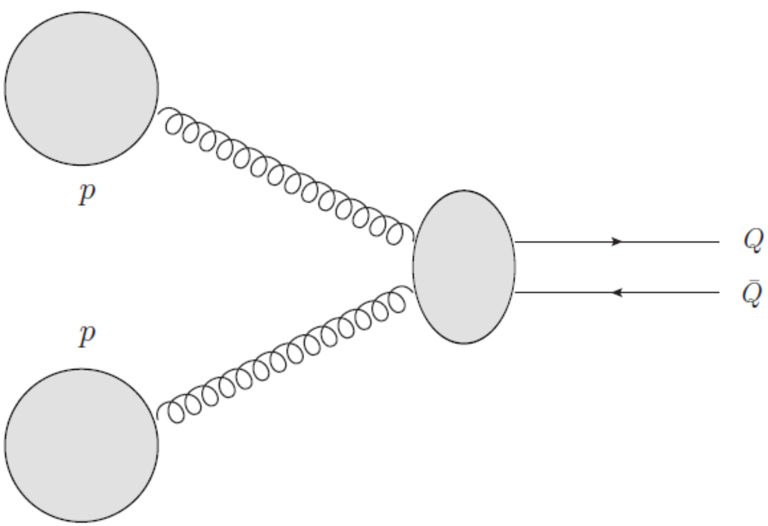
Saturation effects are visible !
They reduce 15% the SPS and 28% the DPS charm cross sections at $s^{1/2}$ = 14 TeV.

Enhancement in b production due to DPS (bc).

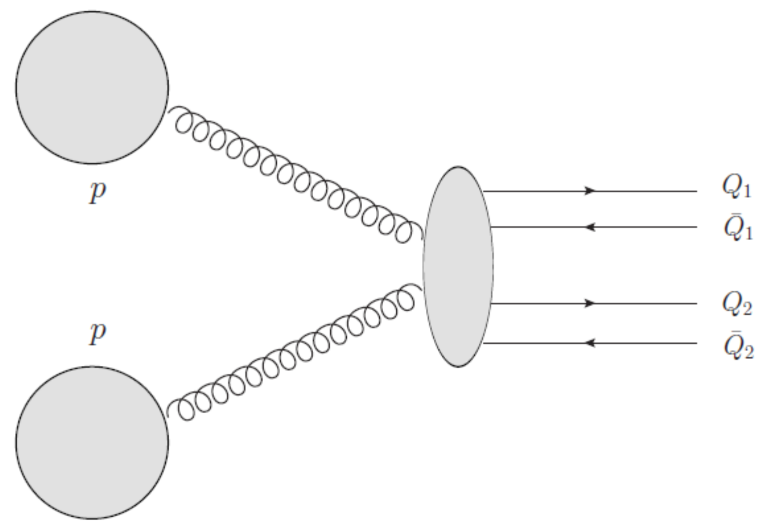
Single parton scattering in pp collisions (SPS)

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 α_S^2

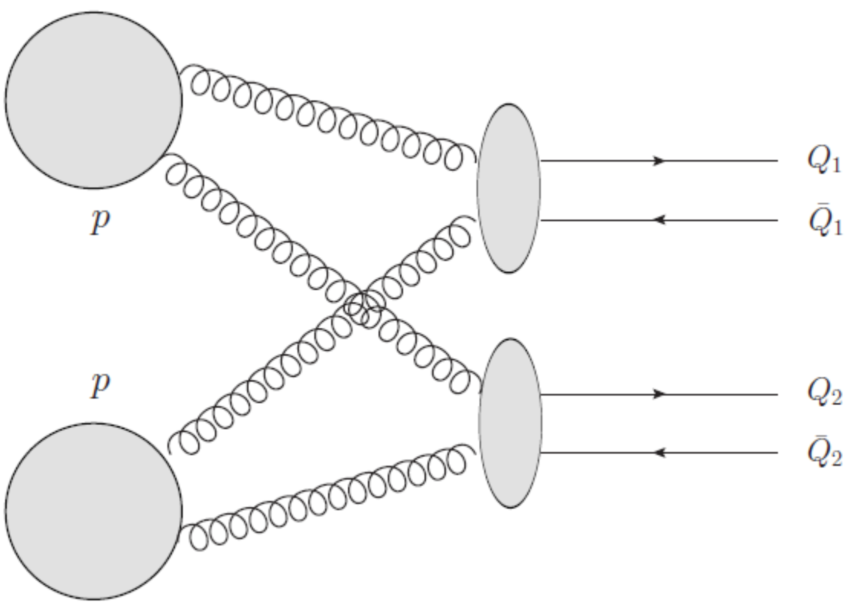
Double parton scattering in pp collisions (DPS)

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

Landshoff, Polkinghorne, PRD (1978)

M. Diehl, arXiv:1306.6059

Two heavy quark pairs in DPS

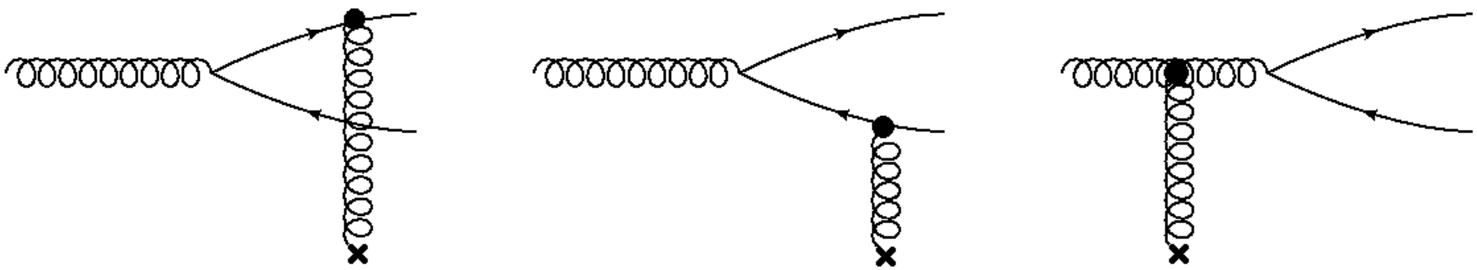


At LHC: gluon density is huge

Higher probability of DPS

Charm production in the color dipole approach

$$\sigma^{DPS}_{h_1h_2\to Q_1\bar{Q}_1Q_2\bar{Q}_2} = \left(\frac{m}{2}\right)\frac{\sigma^{SPS}_{h_1h_2\to Q_1\bar{Q}_1}\sigma^{SPS}_{h_1h_2\to Q_2\bar{Q}_2}}{\sigma_{eff}}$$



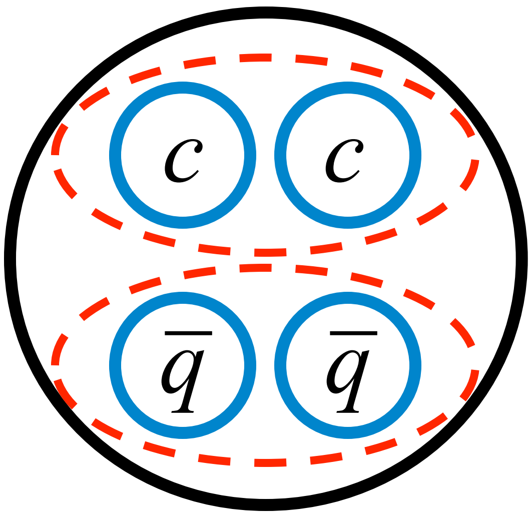
$$\sigma(h_1h_2\to\{Q\bar{Q}\}X) = 2\int_0^{-ln(2m_Q/\sqrt{s})} dy\, x_1\, G_{h_1}(x_1,\mu_F)\,\sigma(Gh_2\to\{Q\bar{Q}\}X)$$

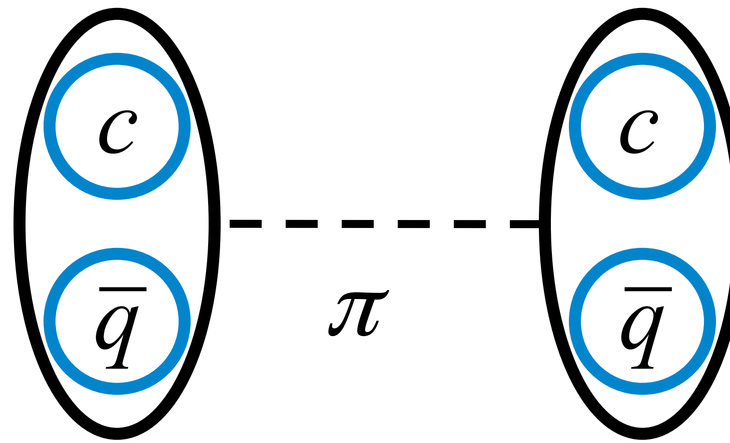
$$\sigma(Gh_2\to\{Q\bar{Q}\}X) = \int_0^1 d\alpha \int d^2\rho\, |\Psi_{G\to Q\bar{Q}}(\alpha,\rho)|^2\, \sigma^{h_2}_{Q\bar{Q}G}(\alpha,\rho)$$

$$\sigma^{h_2}_{Q\bar{Q}G}(\alpha,\rho) = \frac{9}{8}[\sigma_{Q\bar{Q}}(\alpha\rho)+\sigma_{Q\bar{Q}}(\bar{\alpha}\rho)] - \frac{1}{8}\sigma_{Q\bar{Q}}(\rho)$$

Tcc

$T_{cc} = c\,c\,\bar{q}\,\bar{q}$ “brother” of the $X(3872) = c\,\bar{c}\,q\,\bar{q}$



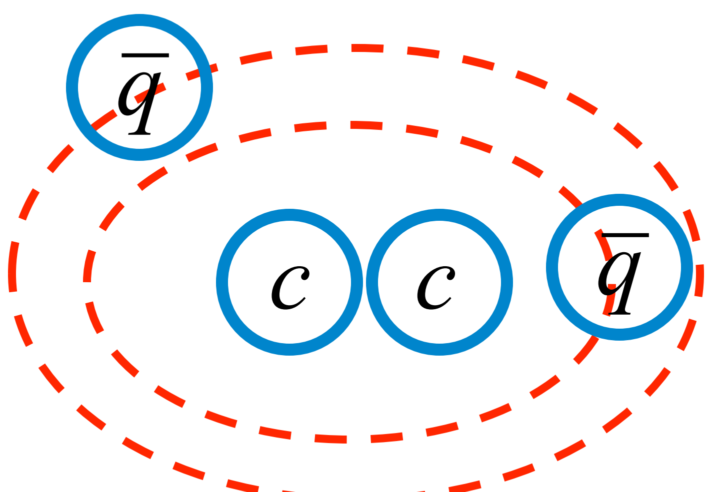


Tetraquark

diquark + antidiquark

Weakly bound

D – D* molecule



“Atomic” $\approx \bar{\Lambda}_c$

Strongly bound

Only gluon-gluon fusion

Higher order -> renormalization with K factor

Early works

[1] P.V. Landshoff and J.C. Polinghorne, Phys. Rev. **D18** (1978) 3344.

[2] F. Takagi, Phys. Rev. Lett. **18** (1979) 1296.

[3] C. Goebel and D.M. Scott and F. Halzen, Phys. Rev. **D22** (1980) 278

[4] B. Humpert, Phys. Lett. **B131** (1983) 461.

[5] N. Paver and D. Treleani, Phys. Lett. **B146** (1984) 252.

[6] N. Paver and D. Treleani, Z. Phys. **C28** (1985) 187.

[7] M. Mekhfi, Phys. Rev. **D32** 2371; M. Mekhfi, Phys. Rev. **D32** 2380.

[8] B. Humpert and R. Oderico, Phys. Lett. **B154** (1985) 211.

[9] T. Sjöstrand and M. van Zijl, Phys. Rev. **D36** (1987) 2019.

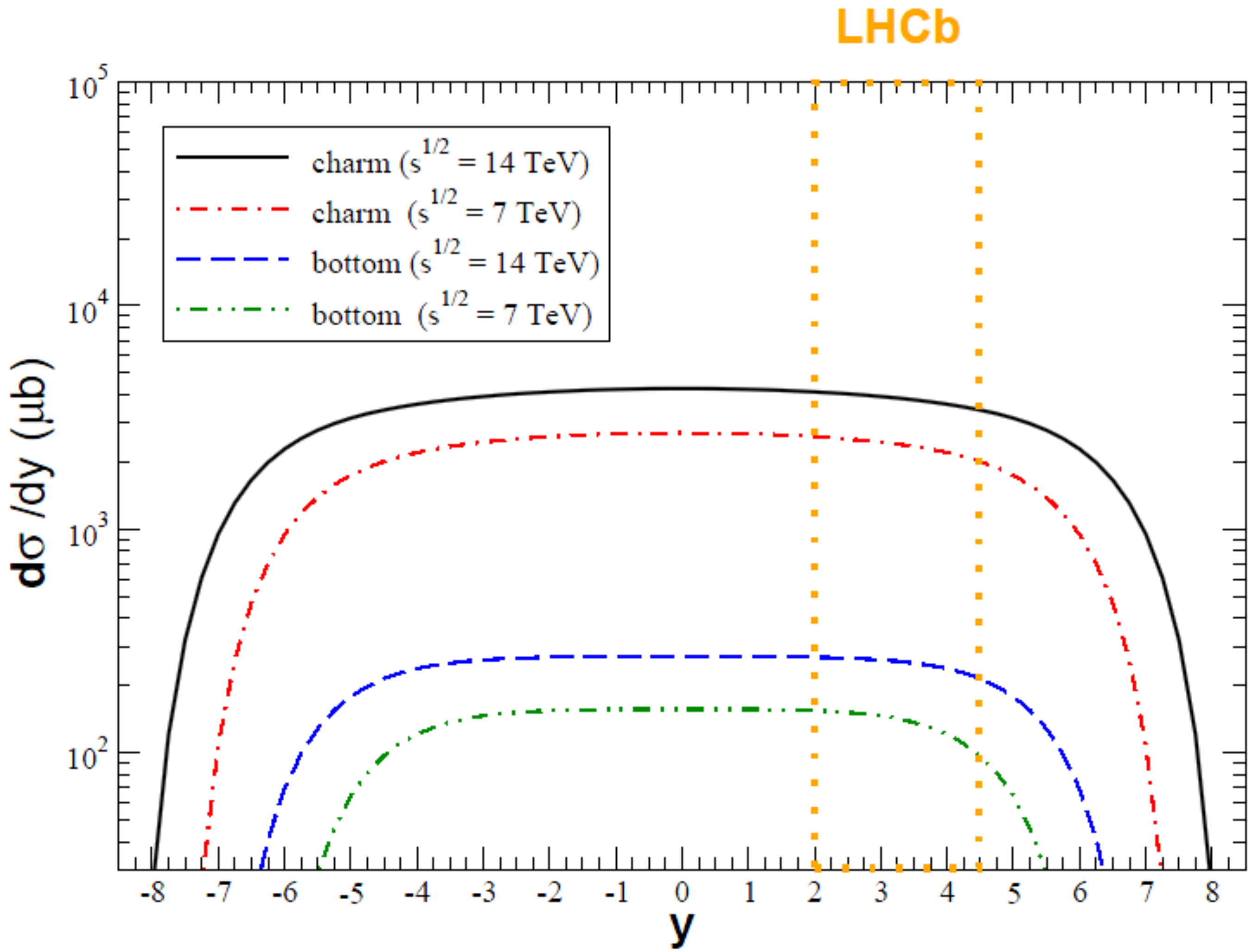
P.V. Landshoff and J.C. Polinghorne, Phys. Rev. **D18** (1978) 3344.

Recent works

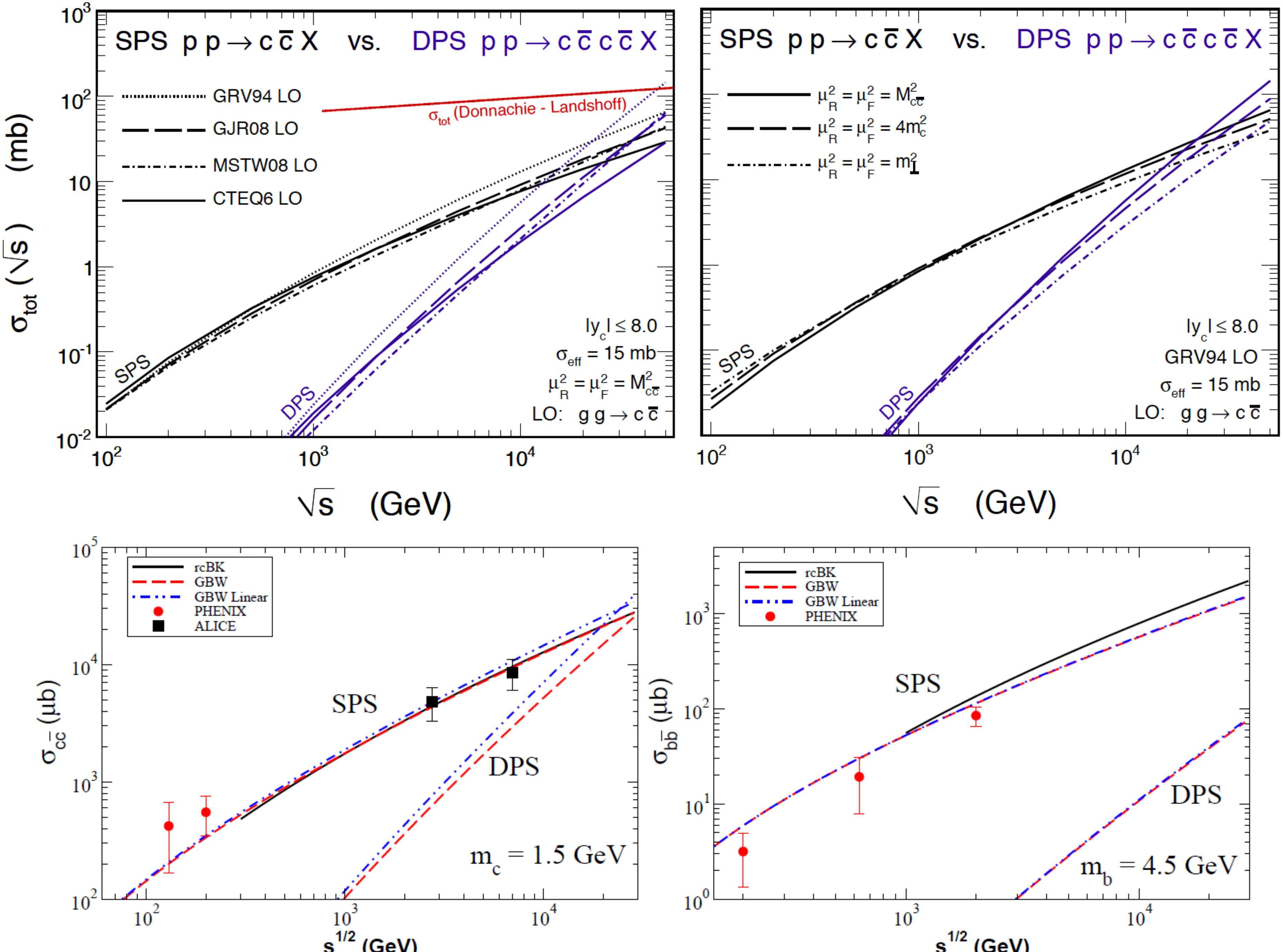
[10] M. Drees and T. Han, Phys. Rev. Lett. **77** (1996) 4142.
[11] A. Kulesza and W.J. Stirling, Phys. Lett. **B475** (2000) 168.
[12] A. Del Fabbro and D. Treleani, Phys. Rev. **D66** (2002) 074012.
[13] E.L. Berger, C.B. Jackson and G. Shaughnessy, Phys. Rev. **D81** 014014 (2010).
[14] J.R. Gaunt, C-H. Kom, A. Kulesza and W.J. Stirling, arXiv:1003.3953.
[15] M. Strikman and W. Vogelsang, Phys. Rev. **D83** (2011) 034029.
[16] B. Blok, Yu. Dokshitzer, L. Frankfurt and M. Strikman, Phys. Rev. **D83** (2011) 071501.
[17] C.H. Khom, A. Kulesza and W.J. Stirling, Phys. Rev. Lett. **107** (2011) 082002.
[18] S.R. Baranov, A. M. Snigirev and N.P. Zotov, arXiv:1105.6279.
[19] A.M. Snigirev, Phys. Rev. **D68** (2003) 114012.
[20] V.L. Korotkikh and A.M. Snigirev, Phys. Lett. **B594** (2004) 171.
[21] T. Sjöstrand and P.Z. Skands, JHEP **0403** (2004) 053.
[22] J.R. Gaunt and W.J. Stirling, JHEP **1003** (2010) 005.
[23] J.R. Gaunt and W.J. Stirling, JHEP **1106** (2011) 048.
[24] M. Diehl and A. Schäfer, Phys. Lett. **B698** (2011) 389.
[25] M.G. Ryskin and A.M. Snigirev, Phys. Rev. **D83** (2011) 114047.
[26] M. Diehl, D. Ostermeier and A. Schäfer, arXiv:1111.0910.

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.

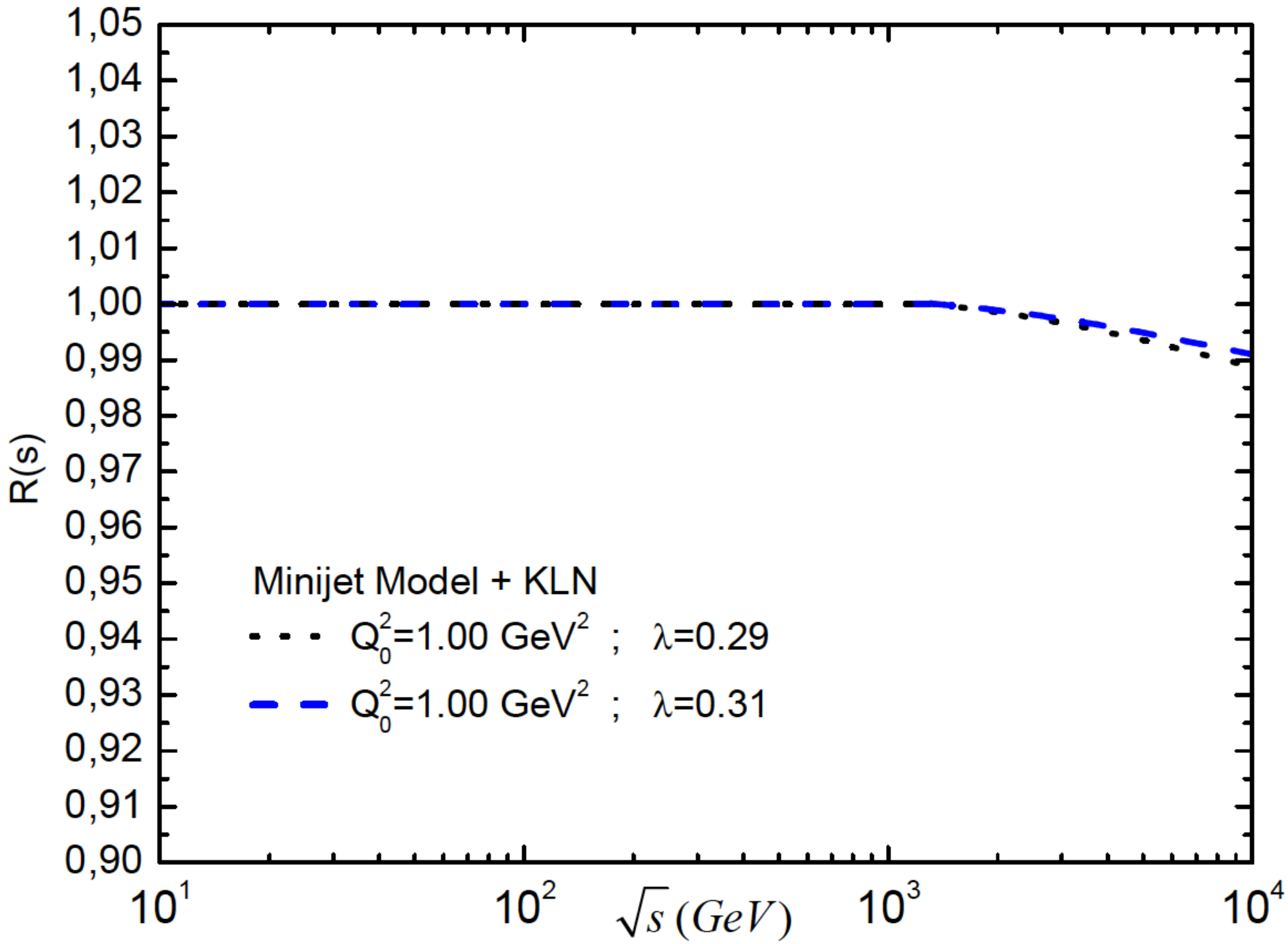
$$\frac{d\sigma\{p\,p \to Q\bar{Q}\;X\}}{d\,y} = x_1\,G(x_1,\mu^2)\;\;\sigma\{g\;p \to Q\bar{Q}\;X\}$$



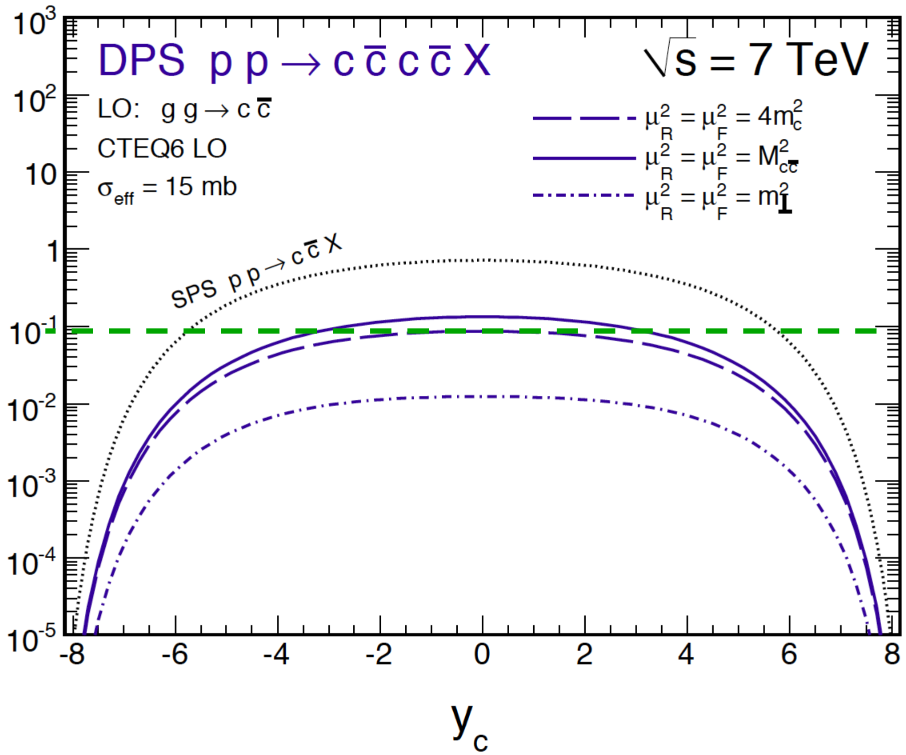
LHCb
charm ($s^{1/2}$ = 14 TeV)
charm ($s^{1/2}$ = 7 TeV)
bottom ($s^{1/2}$ = 14 TeV)
bottom ($s^{1/2}$ = 7 TeV)
dσ /dy (μb)
y

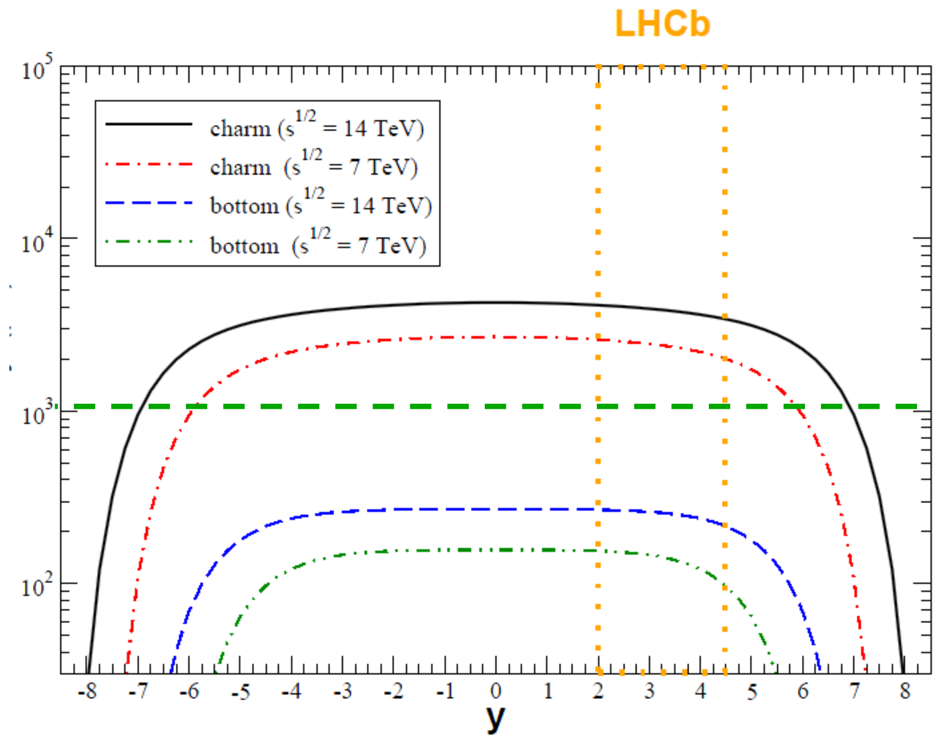


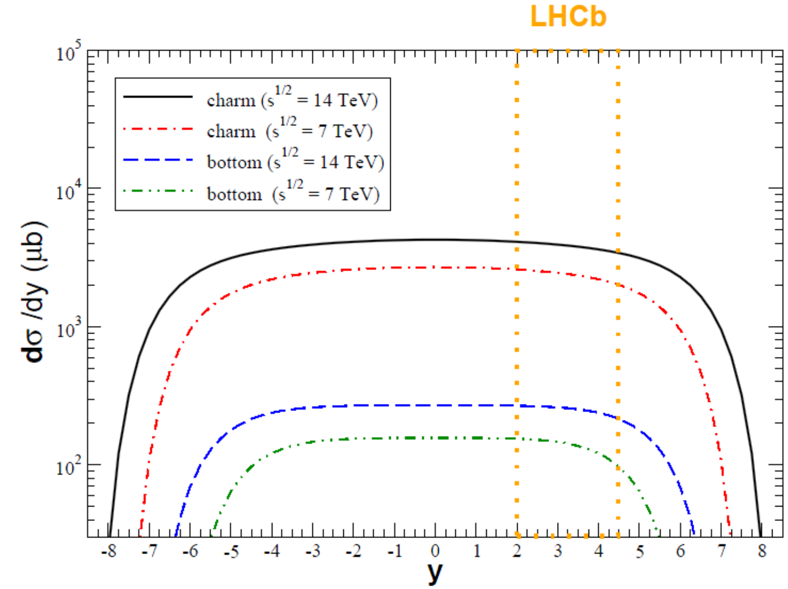
SPS p p → c c̄ X vs. DPS p p → c c̄ c c̄ X
GRV94 LO
GJR08 LO
MSTW08 LO
CTEQ6 LO
σ_tot (Donnachie - Landshoff)
|y_c| ≤ 8.0
σ_eff = 15 mb
μ_R^2 = μ_F^2 = M_cc̄^2
LO: g g → c c̄
SPS
DPS
σ_tot (√s) (mb)
√s (GeV)
μ_R^2 = μ_F^2 = 4m_c^2
μ_R^2 = μ_F^2 = m_⊥^2
GRV94 LO
rcBK
GBW
GBW Linear
PHENIX
ALICE
σ_cc̄ (μb)
m_c = 1.5 GeV
s^1/2 (GeV)
σ_bb̄ (μb)
m_b = 4.5 GeV



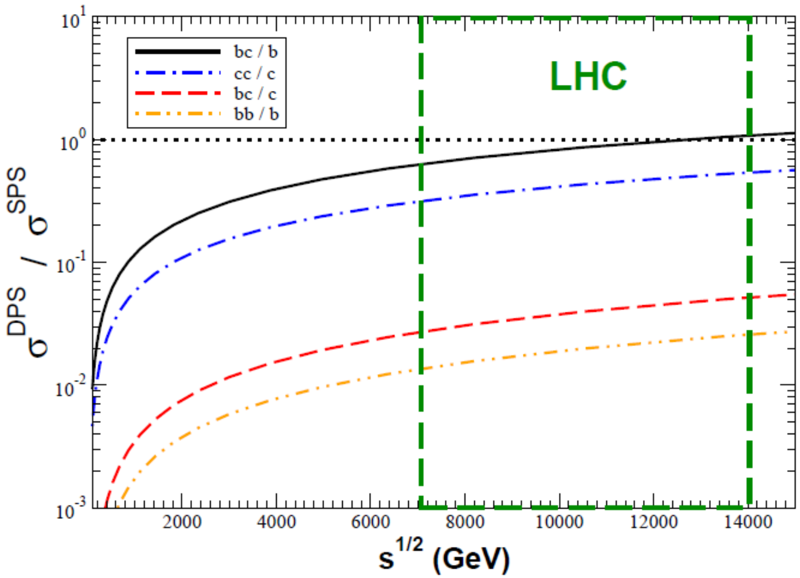
R(s)
1,05
1,04
1,03
1,02
1,01
1,00
0,99
0,98
0,97
0,96
0,95
0,94
0,93
0,92
0,91
0,90
Minijet Model + KLN
Q_0^2=1.00 GeV^2 ; λ=0.29
Q_0^2=1.00 GeV^2 ; λ=0.31
10^1
10^2
10^3
10^4
$\sqrt{s}\,(GeV)$


DPS p p → c c̄ c c̄ X
√s = 7 TeV
LO: g g → c c̄
CTEQ6 LO
σ_eff = 15 mb
μ_R^2 = μ_F^2 = 4m_c^2
μ_R^2 = μ_F^2 = M_cc̄^2
μ_R^2 = μ_F^2 = m_T^2
SPS p p → c c̄ X
y_c

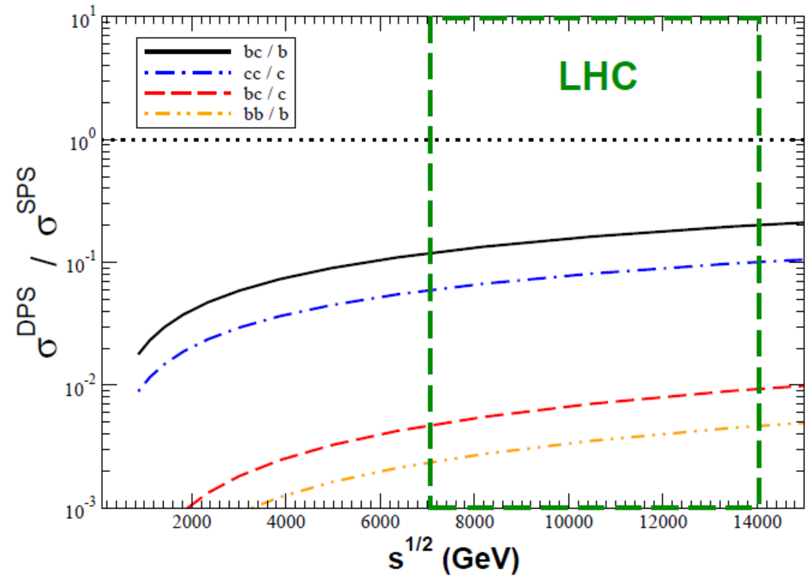

LHCb
charm (s^1/2 = 14 TeV)
charm (s^1/2 = 7 TeV)
bottom (s^1/2 = 14 TeV)
bottom (s^1/2 = 7 TeV)
y



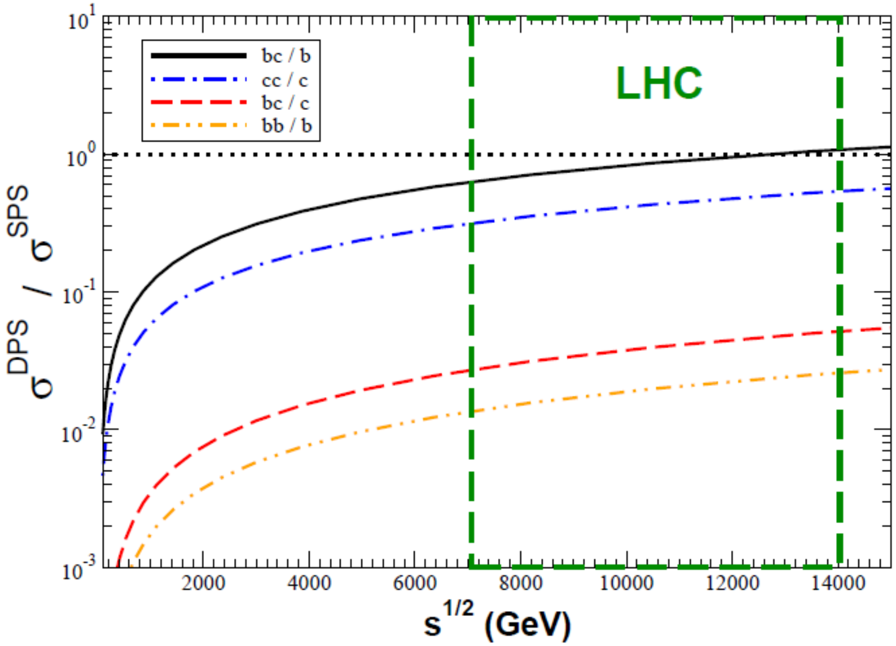
Full rapidity range



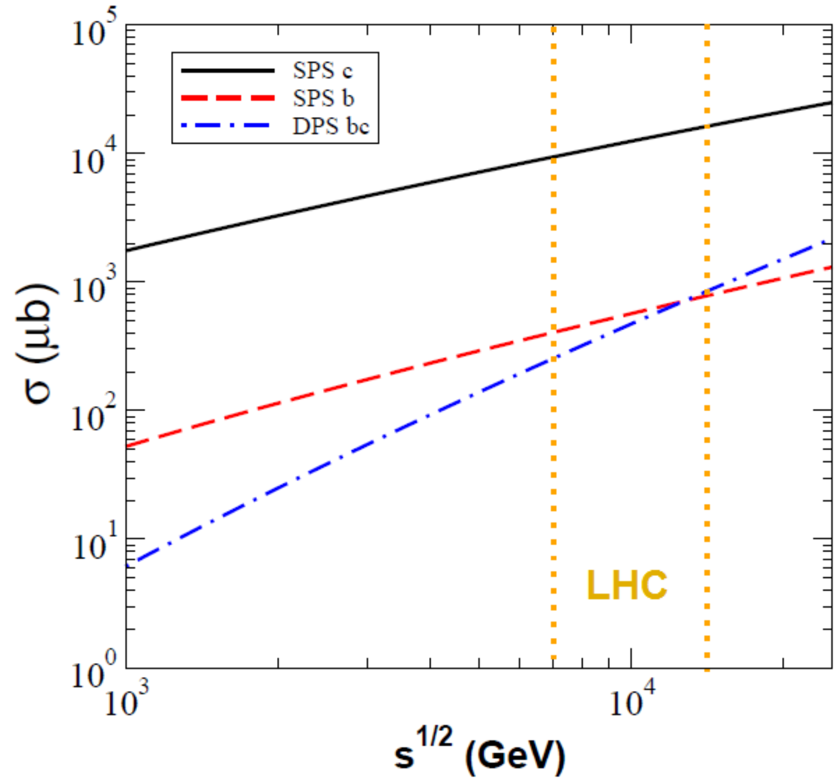
LHCb rapidity range: 2 < y < 4.5



Full rapidity range



Full rapidity range



Dipole – proton cross section

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

(and others...sorry for omissions)

- Asymptotic limits:

Without saturation:

$$\begin{cases} \rho \to 0 & N \approx \rho^2 \\ \rho \to \infty & N \approx \rho^2 \to \infty \end{cases}$$

With saturation:

$$\begin{cases} \rho \to 0 & N \approx \rho^2 \\ \rho \to \infty & N \approx 1 \end{cases}$$

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

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

$$\begin{cases} \rho \to 0 & N \approx \frac{1}{4}\left(\rho^2 Q_S^2\right) \\ \rho \to \infty & N \approx 1 \end{cases}$$