Diffractive production of heavy mesons at the LHC

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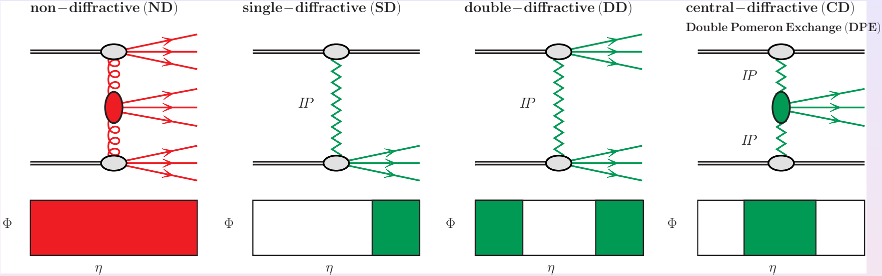
Plan of the talk

- Introduction
- Diffractive production of $c\bar{c}$ and $b\bar{b}$
- Hadronization of heavy quarks
- Diffractive production of open charm and bottom
- Diffractive charm production within k_t-factorization approach
- Conclusions

Based on:
M. Łuszczak, R. Maciuła and A. Szczurek, Phys. Rev. D**91**, 054024 (2015), arXiv:1412.3132
M. Łuszczak, R. Maciuła, A. Szczurek and M. Trzebinski,
a paper in preparation

Inelastic diffractive scatterings can be classified into three different species.



Single-diffraction (SD)

is the process initiated by exchange of pomeron between interacting protons, whereby one proton remains intact and second proton is destroyed and proton remnants appear in the detector. This broken proton gives rise to a bunch of final particles or to a resonance with the same quantum numbers. On the side of survived proton a rapidity gap appears, which separate the proton from remnants.

Double-diffraction (DD)

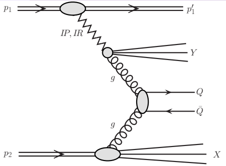
is similarly initiated but here both protons do not survive the collision. In this case rapidity gap is located in the central rapidity region.

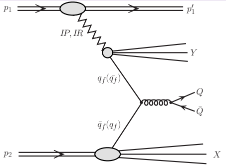
Central-diffraction (CD) called also Double-Pomeron-Exchange (DPE)

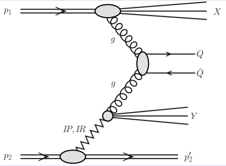
is governed by pomeron-pomeron interaction. Here, both colliding protons remain intact and some central system of particles, is produced. In these events two outgoing protons are separated from central objects by two rapidity gaps.

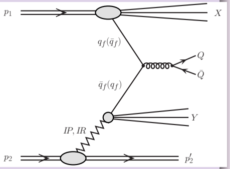
Single- and central-diffractive production of heavy quarks

single- diffractive production

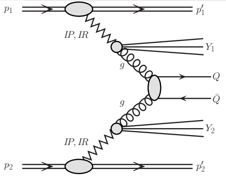


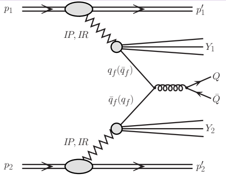






central- diffractive production





- leading-order gluon-gluon fusion and quark-antiquark anihilation partonic subprocesses are taken into consideration
- the extra corrections from subleading reggeon exchanges are explicitly calculated

Theoretical framework

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.

$$
\begin{aligned}
\frac{d\sigma_{SD^{(1)}}}{dy_1\, dy_2\, dp_t^2} &= \frac{1}{16\pi^2 \hat{s}^2} \times \Big[|\mathcal{M}_{gg\to Q\bar{Q}}|^2 \cdot x_1 g^D(x_1,\mu^2) x_2 g(x_2,\mu^2) \\
&+ |\mathcal{M}_{q\bar{q}\to Q\bar{Q}}|^2 \cdot \Big(x_1 q^D(x_1,\mu^2) x_2 \bar{q}(x_2,\mu^2) + x_1 \bar{q}^D(x_1,\mu^2) x_2 q(x_2,\mu^2) \Big) \Big], \\
\frac{d\sigma_{SD^{(2)}}}{dy_1\, dy_2\, dp_t^2} &= \frac{1}{16\pi^2 \hat{s}^2} \times \Big[|\mathcal{M}_{gg\to Q\bar{Q}}|^2 \cdot x_1 g(x_1,\mu^2) x_2 g^D(x_2,\mu^2) \\
&+ |\mathcal{M}_{q\bar{q}\to Q\bar{Q}}|^2 \cdot \Big(x_1 q(x_1,\mu^2) x_2 \bar{q}^D(x_2,\mu^2) + x_1 \bar{q}(x_1,\mu^2) x_2 q^D(x_2,\mu^2) \Big) \Big], \\
\frac{d\sigma_{CD}}{dy_1\, dy_2\, dp_t^2} &= \frac{1}{16\pi^2 \hat{s}^2} \times \Big[|\mathcal{M}_{gg\to Q\bar{Q}}|^2 \cdot x_1 g^D(x_1,\mu^2) x_2 g^D(x_2,\mu^2) \\
&+ |\mathcal{M}_{q\bar{q}\to Q\bar{Q}}|^2 \cdot \Big(x_1 q^D(x_1,\mu^2) x_2 \bar{q}^D(x_2,\mu^2) + x_1 \bar{q}^D(x_1,\mu^2)\, x_2 q^D(x_2,\mu^2) \Big) \Big],
\end{aligned}
$$

- standard collinear MSTW08LO parton distributions
  (A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt)
- diffractive distribution function (diffractive PDF)

Theoretical framework

The diffractive distribution function (diffractive PDF) can be obtained by a convolution of the flux of pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$ in the proton and the parton distribution in the pomeron, e.g. $g_{\mathbf{P}}(\beta,\mu^2)$ for gluons:

$$g^D(x,\mu^2) = \int dx_{\mathbf{P}}\, d\beta\, \delta(x - x_{\mathbf{P}}\beta) g_{\mathbf{P}}(\beta,\mu^2)\, f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_x^1 \frac{dx_{\mathbf{P}}}{x_{\mathbf{P}}}\, f_{\mathbf{P}}(x_{\mathbf{P}}) g_{\mathbf{P}}(\frac{x}{x_{\mathbf{P}}},\mu^2)\,.$$

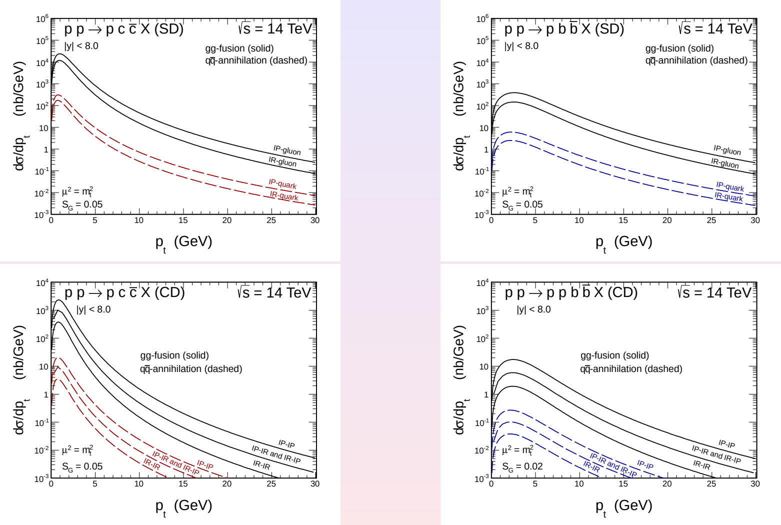
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

$$f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_{t_{min}}^{t_{max}} dt\, f(x_{\mathbf{P}},t)\,,$$

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

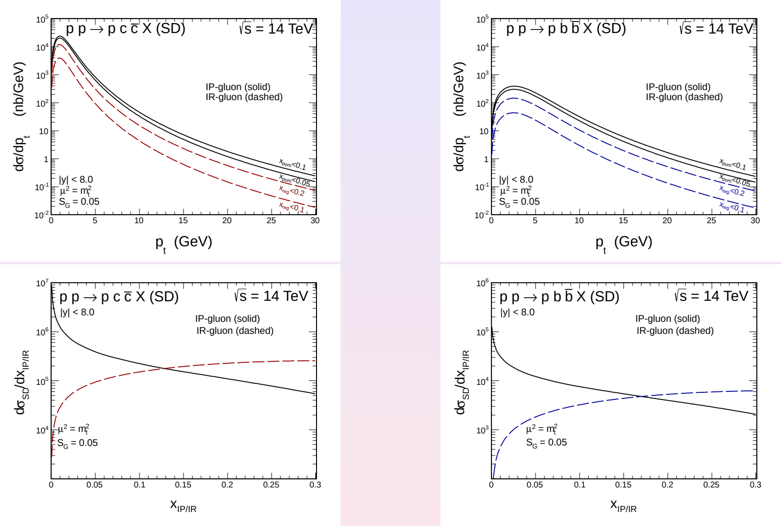
Both pomeron flux factors $f_{\mathbf{P}}(x_{\mathbf{P}},t)$ as well as parton distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.

Results for $c\bar{c}$ and $b\bar{b}$



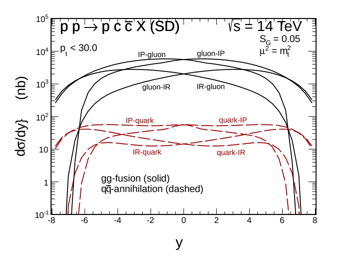
- the multiplicative factors are approximately $S_G = 0.05$ for single-diffractive production and $S_G = 0.02$ for central-diffractive one for the nominal LHC energy ($\sqrt{s} = 14$ TeV)

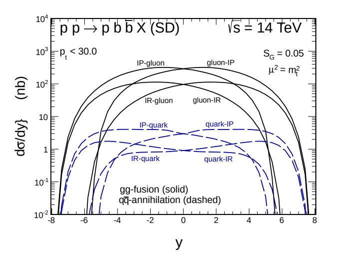
Results for $c\bar{c}$ and $b\bar{b}$

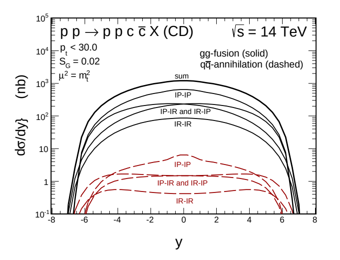


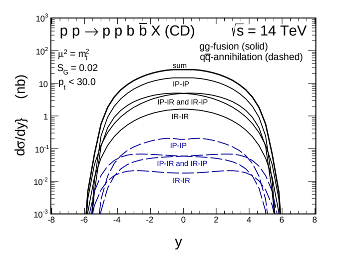
- in the case of pomeron exchange the upper limit in the convolution formula is taken to be 0.1 and for reggeon exchange 0.2 ($x_{\mathbb{P}} < 0.1$, $x_{\mathbb{R}} < 0.2$)
- the whole Regge formalism does not apply above these limits

Results for $c\bar{c}$ and $b\bar{b}$



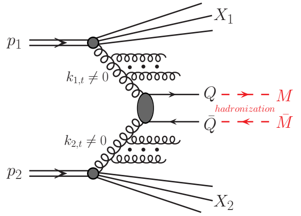






- the individual single-diffractive mechanisms have maxima at large rapidities, while the central-diffractive contribution is concentrated at midrapidities.
  This is a consequence of limiting integration over $x_{\mathbb{P}}$ to $0.0 < x_{\mathbb{P}} < 0.1$ and over $x_{\mathbb{R}}$ to $0.0 < x_{\mathbb{R}} < 0.2$

Hadronization of heavy quarks



- phenomenology $\rightarrow$ 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 rescalling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

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

  where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$
- **approximation:**
  rapidity unchanged in the fragmentation process $\rightarrow y_Q = y_M$

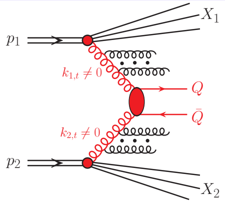
Predictions of integrated cross sections for LHC experiments

TABLE I: Integrated cross sections for diffractive production of open charm and bottom mesons in different measurement modes for ATLAS, LHCb and CMS experiments at $\sqrt{s} = 14$ TeV.

Acceptance	Mode	Integrated cross sections, [nb]		
		single-diffractive	central-diffractive	non-diffractive EXP data
ATLAS, $\|y\| < 2.5$, $p_\perp > 3.5$ GeV	$D^0 + \overline{D^0}$	3555.22 ($I\!R$: 25%)	177.35 ($I\!R$: 43%)	–
LHCb, $2 < y < 4.5$, $p_\perp < 8$ GeV	$D^0 + \overline{D^0}$	31442.8 ($I\!R$: 31%)	2526.7 ($I\!R$: 50%)	1488000 ± 182000
CMS, $\|y\| < 2.4$, $p_\perp > 5$ GeV	$(B^+ + B^-)/2$	349.18 ($I\!R$: 24%)	14.24 ($I\!R$: 42%)	$28100 \pm 2400 \pm 2000$
LHCb, $2 < y < 4.5$, $p_\perp < 40$ GeV	$B^+ + B^-$	867.62 ($I\!R$: 27%)	31.03 ($I\!R$: 43%)	$41400 \pm 1500 \pm 3100$
LHCb, $2 < y < 4$, $3 < p_\perp < 12$ GeV	$D^0\overline{D^0}$	179.4 ($I\!R$: 28%)	7.67 ($I\!R$: 45%)	$6230 \pm 120 \pm 230$

- single-diffraction: $\frac{I\!R}{I\!P + I\!R} \approx 24 - 31\%$
- central-diffraction: $\frac{I\!PI\!R + I\!RI\!P + I\!RI\!R}{I\!PI\!P + I\!PI\!R + I\!RI\!P + I\!RI\!R} \approx 42 - 50\%$
- $\frac{single-diffractive}{non-diffractive} \approx 2 - 3\%$ $\quad$ $\frac{central-diffractive}{non-diffractive} \approx 0.03 - 0.07\%$

k_t-factorization in non-diffractive charm production



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

Collins-Ellis, Nucl. Phys. B360 (1991) 3;
Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135;

Ball-Ellis, JHEP 05 (2001) 053

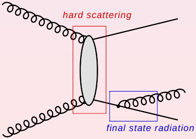
$\Rightarrow$ very efficient approach for $Q\overline{Q}$ correlations

- multi-differential cross section

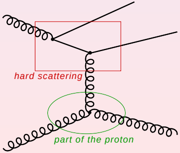
$$\frac{d\sigma}{dy_1\, dy_2\, d^2p_{1,t}\, d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to Q\bar{Q}}|^2}$$
$$\times\ \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right)\ \mathcal{F}_i(x_1, \kappa_{1,t}^2)\ \mathcal{F}_j(x_2, \kappa_{2,t}^2)$$

- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated (k_t-dependent) gluon distributions
- **LO off-shell** $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2} \Rightarrow$ Catani-Ciafaloni-Hautmann (CCH) analytic formulae or QMRK approach with effective BFKL NLL vertices
- major part of higher-order corrections effectively included

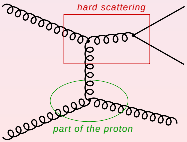
pair creation
with gluon emission



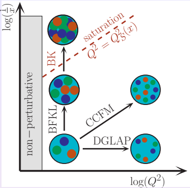
flavour excitation



gluon splitting



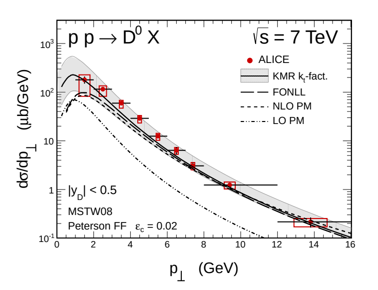
Unintegrated gluon distribution functions (UGDFs)

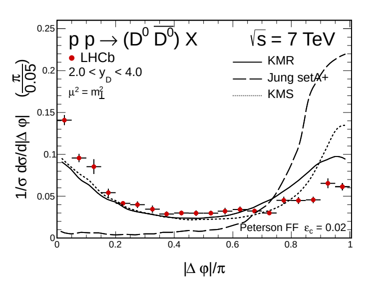


most popular models:

- 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, only small x-values)

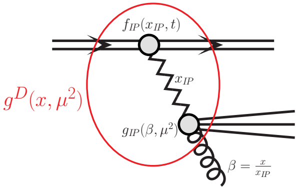
Lesson from non-diffractive charm production at the LHC:





- KMR UGDF works very well (single particle spectra and correlation observables)
- may be applied for hard diffractive processes

Model for diffractive UGDF



Resolved pomeron model (Ingelman-Schlein model):

- convolution of the flux of pomerons in the proton and the parton distribution in the pomeron
- both ingredients known from the H1 Collaboration analysis of diffractive structure function and diffractive dijets at HERA

First step $\Rightarrow$ diffractive collinear PDF:

$$g^D(x, \mu^2) = \int dx_{\mathbf{P}} d\beta\, \delta(x - x_{\mathbf{P}}\beta) g_{\mathbf{P}}(\beta, \mu^2)\, f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_x^1 \frac{dx_{\mathbf{P}}}{x_{\mathbf{P}}} f_{\mathbf{P}}(x_{\mathbf{P}}) g_{\mathbf{P}}(\frac{x}{x_{\mathbf{P}}}, \mu^2)$$

where the flux of pomerons: $f_{\mathbf{P}}(x_{\mathbf{P}}) = \int_{t_{min}}^{t_{max}} dt\, f(x_{\mathbf{P}}, t)$

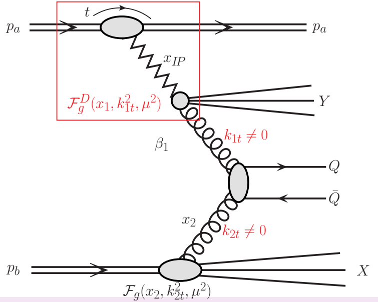
Second step $\Rightarrow$ diffractive unintegrated gluon within Kimber-Martin-Ryskin method:

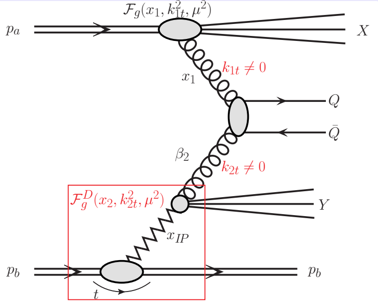
$$f_g^D(x, k_t^2, \mu^2) \equiv \frac{\partial}{\partial \log k_t^2}\left[g^D(x, k_t^2)\, T_g(k_t^2, \mu^2)\right] = T_g(k_t^2, \mu^2)\, \frac{\alpha_S(k_t^2)}{2\pi} \times$$

$$\int_x^1 dz \left[\sum_q P_{gq}(z) \frac{x}{z}\, q^D\left(\frac{x}{z}, k_t^2\right) + P_{gg}(z) \frac{x}{z}\, g^D\left(\frac{x}{z}, k_t^2\right) \Theta\left(\Delta - z\right)\right]$$

- $T_g(k_t^2, \mu^2)$ - Sudakov form factor

Single-diffractive cross section



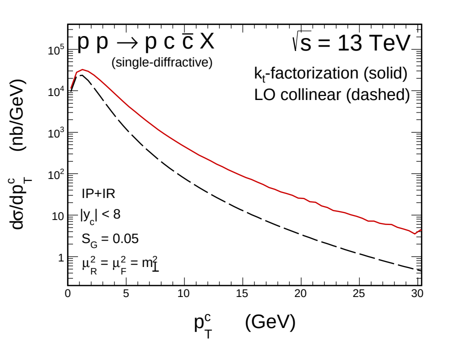


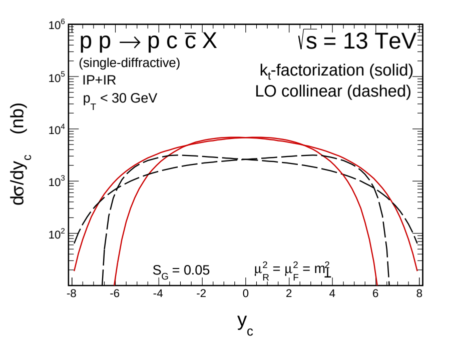
$$d\sigma^{SD(a)}(p_a p_b \to p_a c\bar{c}\, XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi}\, d\hat{\sigma}(g^* g^* \to c\bar{c}) \times \mathcal{F}_g^D(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g(x_2, k_{2t}^2, \mu^2)$$

$$d\sigma^{SD(b)}(p_a p_b \to c\bar{c} p_b\, XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi}\, d\hat{\sigma}(g^* g^* \to c\bar{c}) \times \mathcal{F}_g(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g^D(x_2, k_{2t}^2, \mu^2)$$

- $\mathcal{F}_g$ are the conventional UGDFs and $\mathcal{F}_g^D$ are their diffractive counterparts
- elementary cross section with off-shell matrix element $\overline{|\mathcal{M}_{g^* g^* \to c\bar{c}}(k_1, k_2)|^2}$
- influence of pomeron transverse momenta on initial gluon transverse momenta neglected, we assume: gluon $k_t >> p_T$ of pomeron (or outgoing proton)

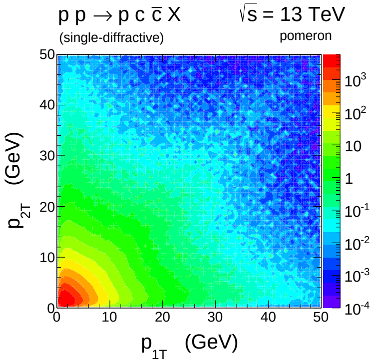
LO Parton Model vs. k_t-factorization approach

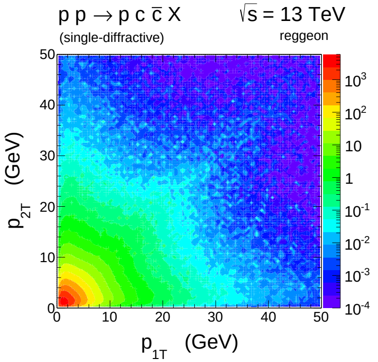




- significant differences between LO PM and k_t-factorization (similar as in the non-diffractive case)
- higher-order corrections very important

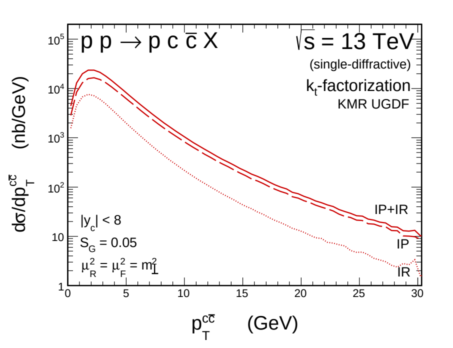
2Dim-distribution in transverse momenta of c and $\bar{c}$

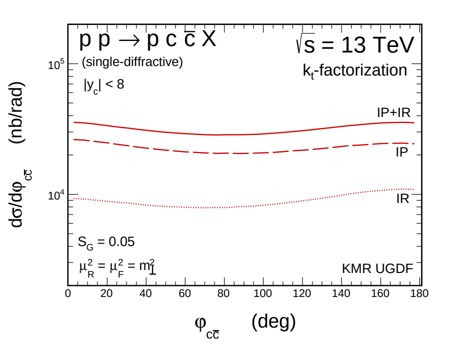




- transverse momenta of outgoing particles not balanced
- one p_t small and second p_t large $\Rightarrow$ configurations typical for NLO corrections (in the PM classification)

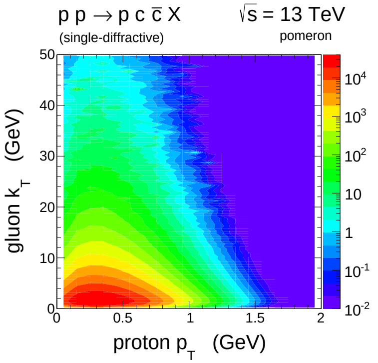
Correlation observables

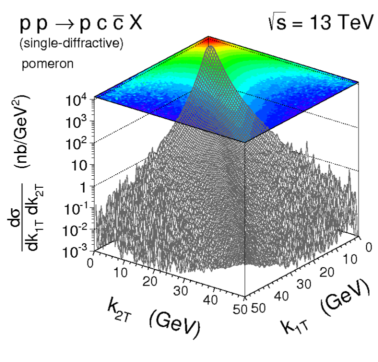




- quite large $c\bar{c}$ pair transverse momenta
- azimuthal angle correlations $\Rightarrow$ almost flat distribution (similar shape in the case of inclusive central diffraction (DPE))
- exclusive central diffractive events $\Rightarrow$ smaller $p_T^{c\bar{c}}$ and $\varphi_{c\bar{c}}$ much more correlated (peaked at π)

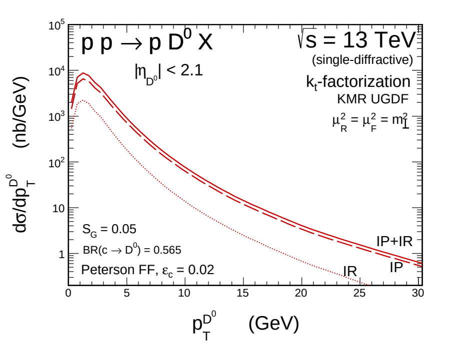
Initial gluon vs. outgoing proton transverse momenta





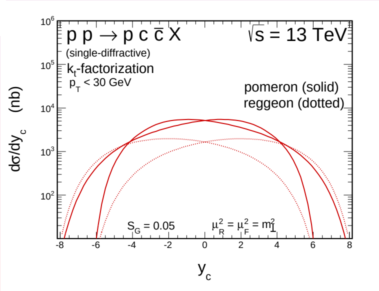
- the cross section concentrated in the region of proton p_T less than 1 GeV
- quite large gluon transverse momenta
- pomeron p_T should not really affect predicted distributions

D^0 meson transverse momentum spectra for ATLAS



- hadronization effects included via fragmentation function technique (Peterson FF)
- ATLAS: $|\eta| < 2.1$, $0.015 < x_{IP}(x_{IR}) < 0.15$
- $S_G = 0.05$; $\mathrm{BR}(c \to D^0) = 0.565$

- reggeon contribution may become more important in the forward rapidity region, e.g. in the LHCb detector



Conclusions

- The obtained cross sections for diffractive production of charmed mesons are fairly large and the statistics seems not to be any problem
- Rather possible backgrounds and the way how the diffractive contribution is defined and/or extracted is an important issue.
- We have presented a first application of the k_t-factorization to hard diffractive production (very important higher-order corrections).
- Azimuthal angle correlation between c and $\bar{c}$, and $c\bar{c}$ pair transverse momentum could be obtained for the first time.