

Diffractive processes at the LHC within k_t -factorization approach

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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

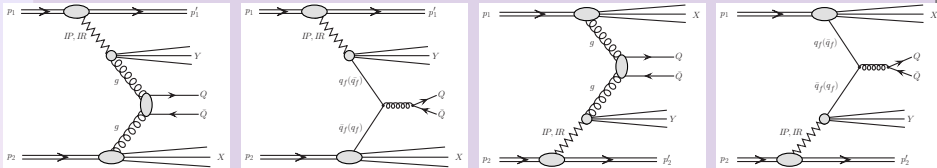
Based on:

M. Łuszczak, R. Maciuła and A. Szczurek, Phys. Rev. **D91**, 054024 (2015),
arXiv:1412.3132

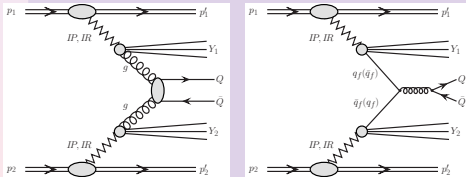
M. Łuszczak, R. Maciuła, A. Szczurek and M. Trzebinski,
a paper in preparation

Single- and central-diffractive production of heavy quarks

single- diffractive production



central- diffractive production



- leading-order gluon-gluon fusion and quark-antiquark annihilation 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.

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

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

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

- **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:

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

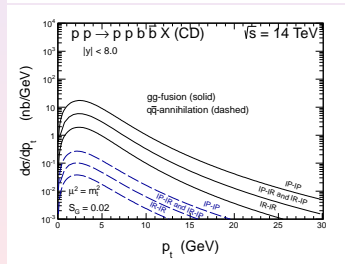
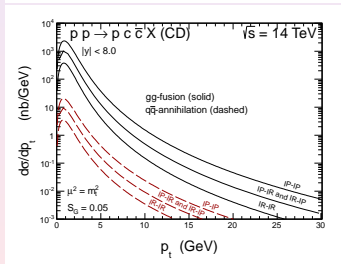
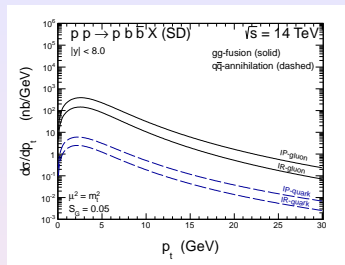
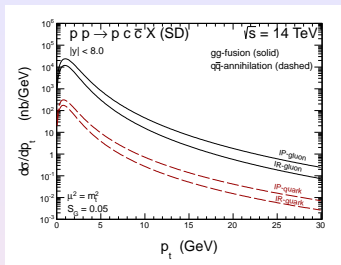
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

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

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

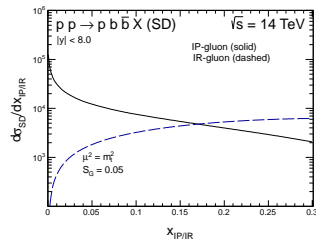
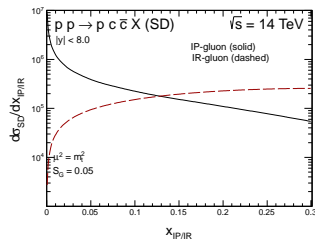
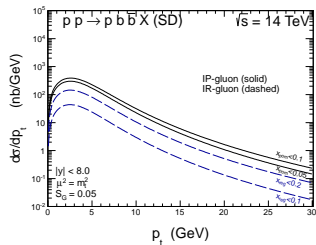
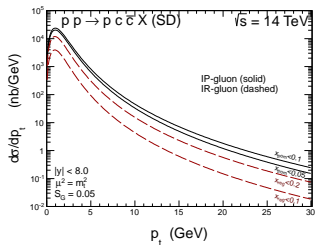
Both pomeron flux factors $f_{\mathbf{P}}(x_{\mathbf{P}}, t)$ as well as parton distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.

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



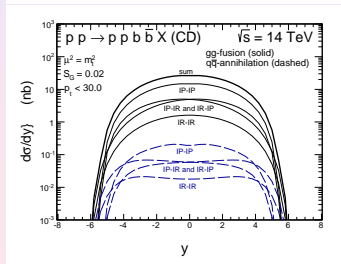
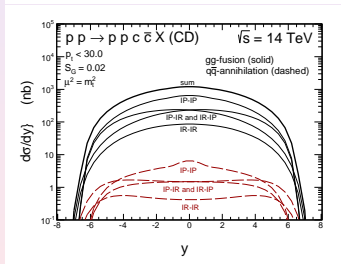
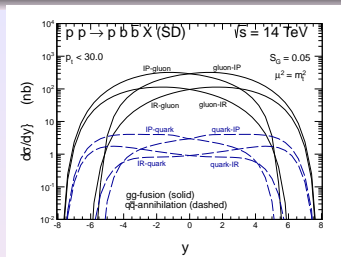
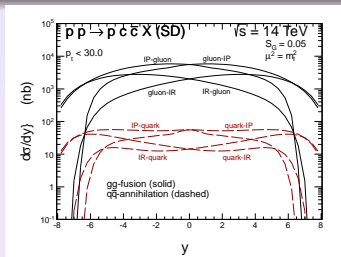
- the multiplicative factors are approximately $S_G = 0.05$ for single-diffractive production and $S_G = 0.02$ for central-diffractive one for the nominal LHC energy ($\sqrt{s} = 14$ TeV)

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



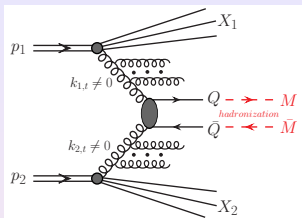
- in the case of pomeron exchange the upper limit in the convolution formula is taken to be 0.1 and for reggeon exchange 0.2 ($x_P < 0.1$, $x_R < 0.2$)
- the whole Regge formalism does not apply above these limits

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_P to $0.0 < x_P < 0.1$ and over x_R to $0.0 < x_R < 0.2$

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 rescaling 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>IR</i> : 25%)	177.35 (<i>IR</i> : 43%)	–
LHCb, $2 < y < 4.5$ $p_{\perp} < 8$ GeV	$D^0 + \overline{D}^0$	31442.8 (<i>IR</i> : 31%)	2526.7 (<i>IR</i> : 50%)	1488000 ± 182000
CMS, $ y < 2.4$ $p_{\perp} > 5$ GeV	$(B^+ + B^-)/2$	349.18 (<i>IR</i> : 24%)	14.24 (<i>IR</i> : 42%)	$28100 \pm 2400 \pm 2000$
LHCb, $2 < y < 4.5$ $p_{\perp} < 40$ GeV	$B^+ + B^-$	867.62 (<i>IR</i> : 27%)	31.03 (<i>IR</i> : 43%)	$41400 \pm 1500 \pm 3100$
LHCb, $2 < y < 4$ $3 < p_{\perp} < 12$ GeV	$D^0 \overline{D}^0$	179.4 (<i>IR</i> : 28%)	7.67 (<i>IR</i> : 45%)	$6230 \pm 120 \pm 230$

- single-diffraction: $\frac{IR}{IP+IR} \approx 24 - 31\%$

- central-diffraction: $\frac{IP\,IR+IR\,IP+IR\,IR}{IP\,IP+IP\,IR+IR\,IP+IR\,IR} \approx 42 - 50\%$

- $\frac{\text{single-diffractive}}{\text{non-diffractive}} \approx 2 - 3\%$ $\frac{\text{central-diffractive}}{\text{non-diffractive}} \approx 0.03 - 0.07\%$

k_t -factorization in non-diffractive charm production

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

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 $Q\bar{Q}$ correlations

- multi-differential cross section

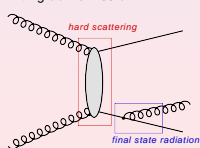
$$\frac{d\sigma}{dy_1 dy_2 d^2 p_{1,t} d^2 p_{2,t}} = \sum_{i,j} \int \frac{d^2 \kappa_{1,t}}{\pi} \frac{d^2 \kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \rightarrow Q\bar{Q}}|^2} \times \delta^2(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t})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

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

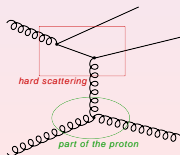
- **LO off-shell** $|\mathcal{M}_{g^* g^* \rightarrow Q\bar{Q}}|^2 \Rightarrow$ Catani-Ciafaloni-Hautmann (CCH) analytic formulae or QMRK approach with effective BFKL NLL vertices

- major part of **higher-order corrections effectively included**

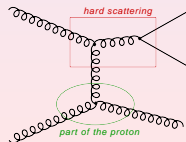
pair creation with gluon emission



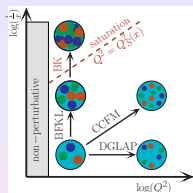
flavour excitation



gluon splitting



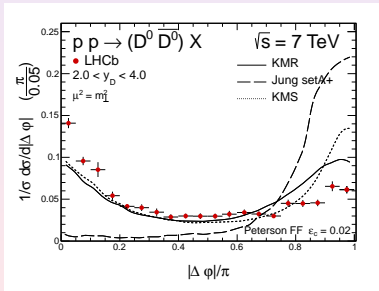
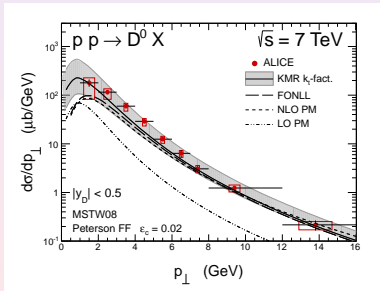
Unintegrated gluon distribution functions (UGDFs)



most popular models:

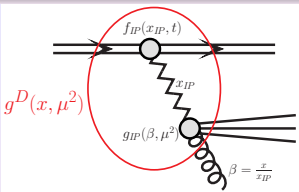
- Kwieciński, Jung (CCFM, wide range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x -values)
- Kutak-Staśto (BK, saturation, only small x -values)

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:

$$g^D(x, \mu^2) = \int dx_P d\beta \delta(x - x_P \beta) g_P(\beta, \mu^2) f_P(x_P) = \int_x^1 \frac{dx_P}{x_P} f_P(x_P) g_P\left(\frac{x}{x_P}, \mu^2\right)$$

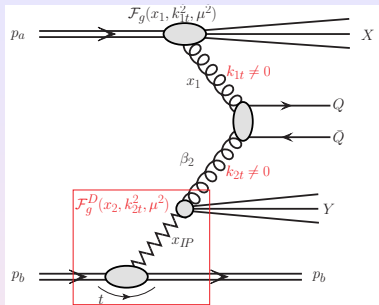
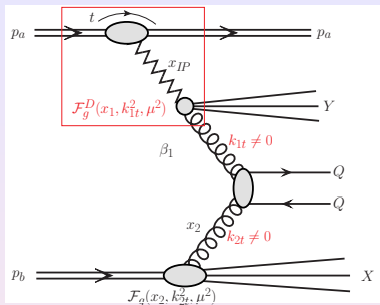
where the flux of pomerons: $f_P(x_P) = \int_{t_{min}}^{t_{max}} dt f(x_P, t)$

Second step \Rightarrow diffractive unintegrated gluon within [Kimber-Martin-Ryskin](#) method:

$$f_g^D(x, k_t^2, \mu^2) \equiv \frac{\partial}{\partial \log k_t^2} \left[g^D(x, k_t^2) T_g(k_t^2, \mu^2) \right] = T_g(k_t^2, \mu^2) \frac{\alpha_S(k_t^2)}{2\pi} \times \int_x^1 dz \left[\sum_q P_{gq}(z) \frac{x}{z} q^D\left(\frac{x}{z}, k_t^2\right) + P_{gg}(z) \frac{x}{z} g^D\left(\frac{x}{z}, k_t^2\right) \Theta(\Delta - z) \right]$$

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

Single-diffractive cross section

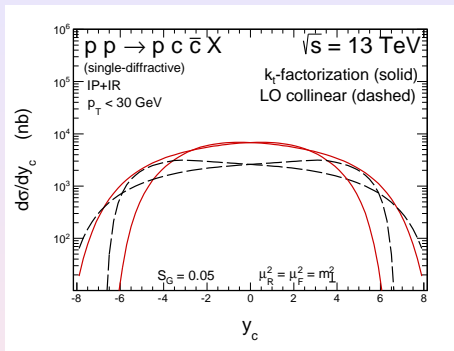
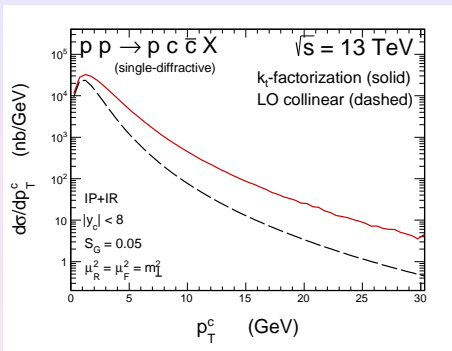


$$d\sigma^{SD(a)}(p_a p_b \rightarrow p_a c\bar{c} XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi} d\hat{\sigma}(g^* g^* \rightarrow c\bar{c}) \times \mathcal{F}_g^D(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g(x_2, k_{2t}^2, \mu^2)$$

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

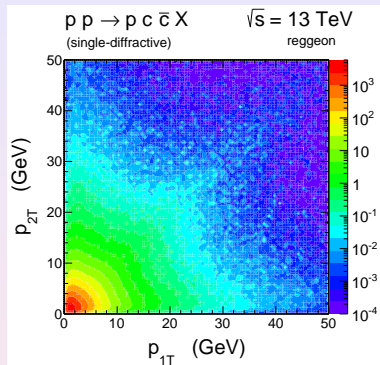
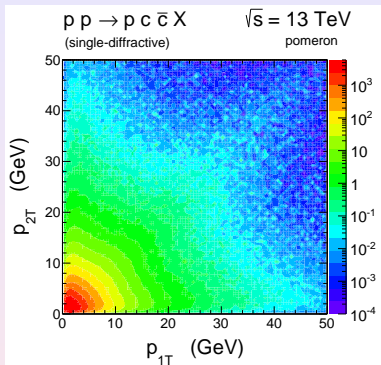
- \mathcal{F}_g are the conventional UGDs and \mathcal{F}_g^D are their diffractive counterparts
- elementary cross section with **off-shell** matrix element $|\mathcal{M}_{g^* g^* \rightarrow c\bar{c}}(k_1, k_2)|^2$
- influence of pomeron transverse momenta on initial gluon transverse momenta neglected,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

LO Parton Model vs. k_t -factorization approach



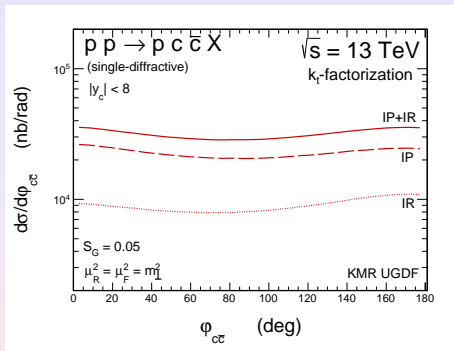
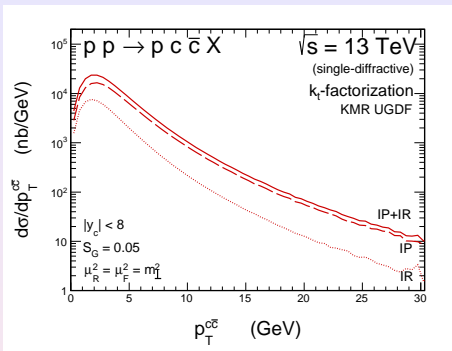
- significant differences between LO PM and k_t -factorization (similar as in the non-diffractive case)
- higher-order corrections very important

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



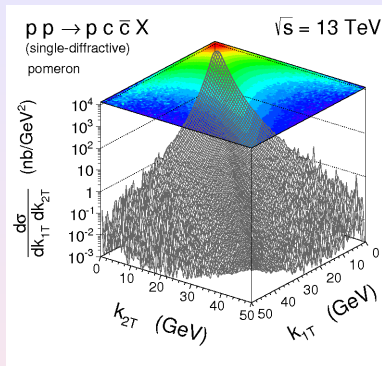
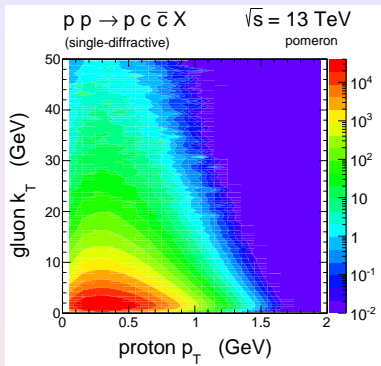
- transverse momenta of outgoing particles not balanced
- one p_t small and second p_t large \Rightarrow configurations typical for NLO corrections (in the PM classification)

Correlation observables



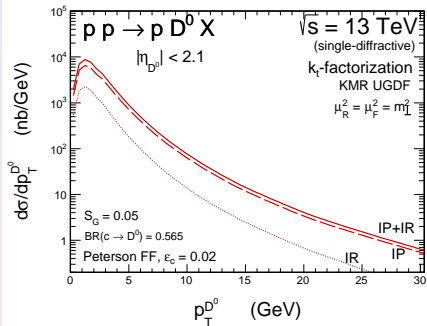
- quite large $c\bar{c}$ pair transverse momenta
- azimuthal angle correlations \Rightarrow almost flat distribution (similar shape in the case of inclusive central diffraction (DPE))
- exclusive central diffractive events \Rightarrow smaller $p_T^{c\bar{c}}$ and $\varphi_{c\bar{c}}$ much more correlated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

Initial gluon vs. outgoing proton transverse momenta



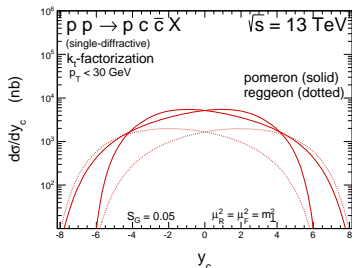
- the cross section concentrated in the region of proton p_T less than 1 GeV
- quite large gluon transverse momenta
- pomeron p_T should not really affect predicted distributions

D^0 meson transverse momentum spectra for ATLAS



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

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



- our predictions can be verified experimentally using the LHC data
- the $D^{*\pm}$ mesons were identified in $D^{*\pm} \rightarrow D^0 \pi^\pm \rightarrow (K^- \pi^+) \pi^\pm$ decay channel
- the decay length of the D^0 candidate, calculated as the transverse distance between the candidate vertex and the primary vertex projected along the total transverse momentum of the track pair, was required to be greater than zero
- finally, $D^{*\pm}$ meson candidates were reconstructed in the range of transverse momentum $p_T^D > 3.5$ GeV and pseudorapidity $|\eta^D| < 2.1$
- the background was reduced by requiring $p_T^D/E_T > 0.02$, where E_T is a sum of the transverse energy of stable particles (except neutrinos) generated within the range of ATLAS calorimeter ($|\eta| < 4.9$)

- 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.