Diffractive production of heavy mesons at the LHC within k_t - factorization approach

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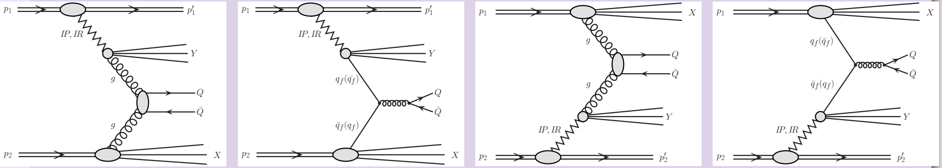
Plan of the talk

- 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

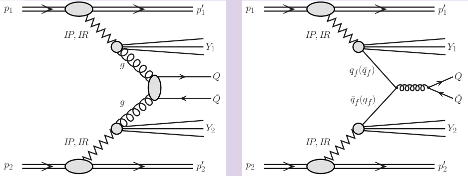
Based on:
M. Łuszczak, R. Maciuła and A. Szczurek, Phys. Rev. D**91**, 054024 (2015), arXiv:1412.3132
M. Łuszczak, R. Maciuła, A. Szczurek and M. Trzebinski,
a paper in preparation

Single- and central-diffractive production of heavy quarks

single- diffractive production



central- diffractive production



- leading-order gluon-gluon fusion and quark-antiquark 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:

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

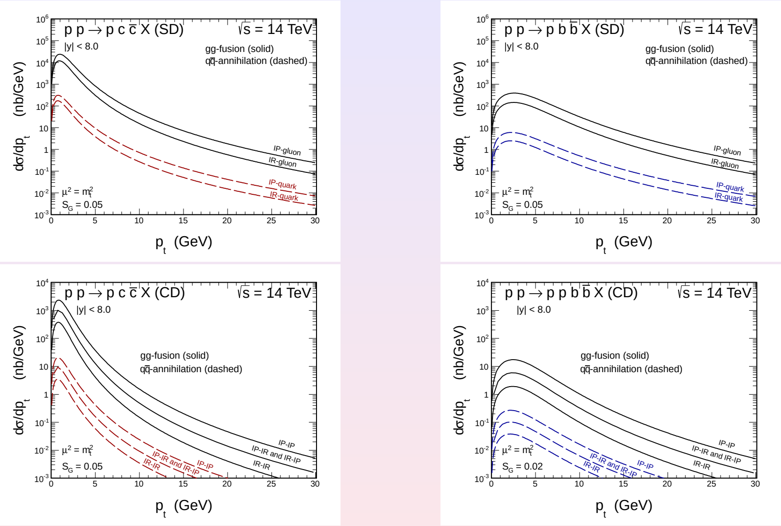
The flux of Pomerons $f_{\mathbf{P}}(x_{\mathbf{P}})$:

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

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

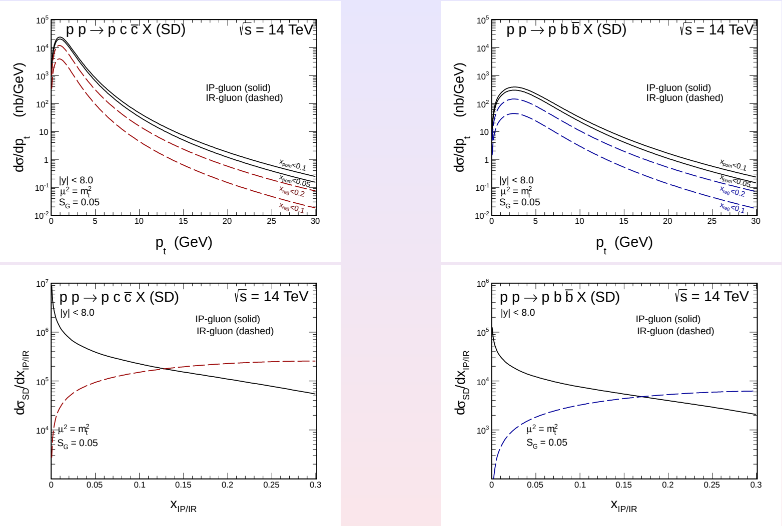
Both pomeron flux factors $f_{\mathbf{P}}(x_{\mathbf{P}},t)$ as well as parton distributions in the pomeron were taken from the H1 collaboration analysis of diffractive structure function at HERA.

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



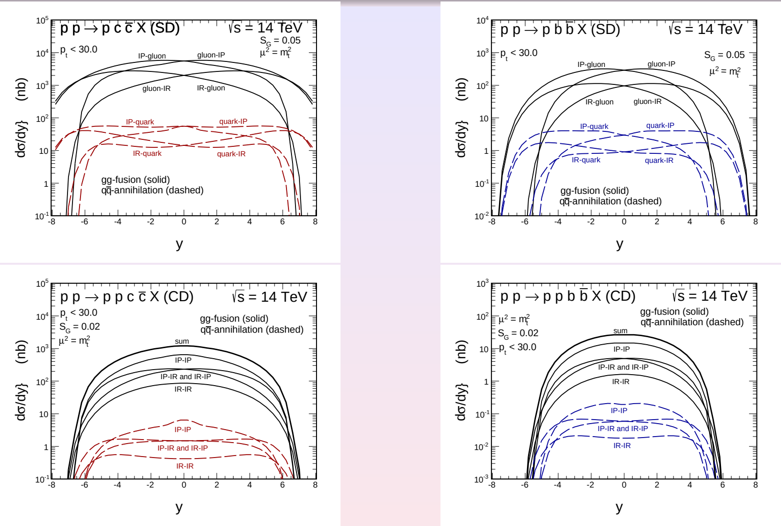
- the multiplicative factors are approximately $S_G = 0.05$ for single-diffractive production and $S_G = 0.02$ for central-diffractive one for the nominal LHC energy ($\sqrt{s} = 14$ TeV)

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



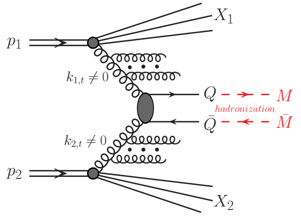
- in the case of pomeron exchange the upper limit in the convolution formula is taken to be 0.1 and for reggeon exchange 0.2 ($x_{\mathbb{P}} < 0.1$, $x_{\mathbb{R}} < 0.2$)
- the whole Regge formalism does not apply above these limits

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:

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

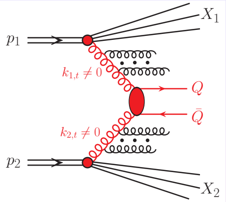
  where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$
- **approximation:**
  rapidity unchanged in the fragmentation process $\rightarrow y_Q = y_M$

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



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

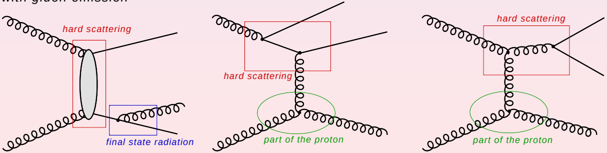
$$\frac{d\sigma}{dy_1\,dy_2\,d^2p_{1,t}\,d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to Q\bar{Q}}|^2}$$
$$\times \quad \delta^2\left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right)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

- $\mathcal{F}_i(x_1, \kappa^2_{1,t})$, $\mathcal{F}_j(x_2, \kappa^2_{2,t})$ - 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

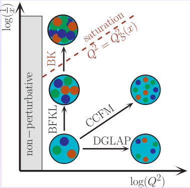
pair creation
with gluon emission

flavour excitation

gluon splitting



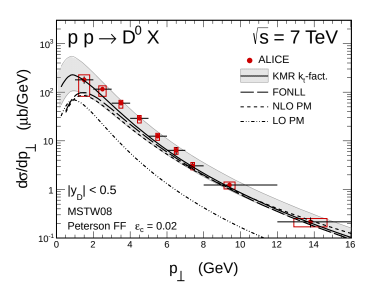
Unintegrated gluon distribution functions (UGDFs)

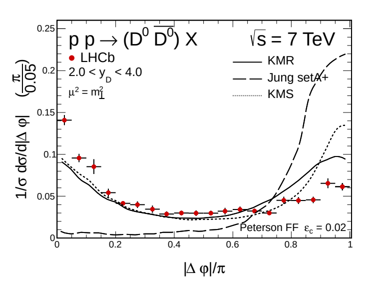


most popular models:

- 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)

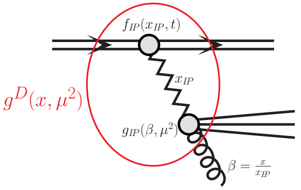
Lesson from non-diffractive charm production at the LHC:





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

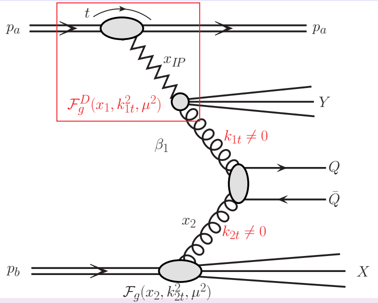
Second step $\Rightarrow$ diffractive unintegrated gluon within Kimber-Martin-Ryskin method:

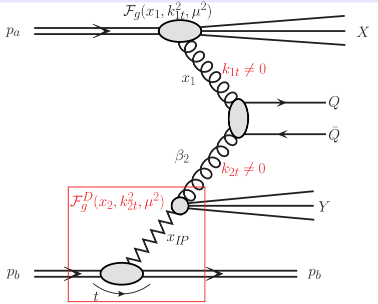
$$f_g^D(x, k_t^2, \mu^2) \equiv \frac{\partial}{\partial \log k_t^2}\left[g^D(x, k_t^2)\, T_g(k_t^2, \mu^2)\right] = T_g(k_t^2, \mu^2)\, \frac{\alpha_S(k_t^2)}{2\pi} \times$$

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

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

Single-diffractive cross section



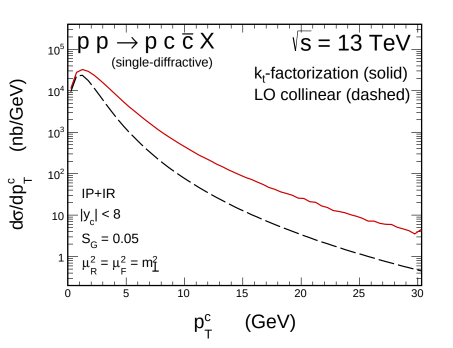


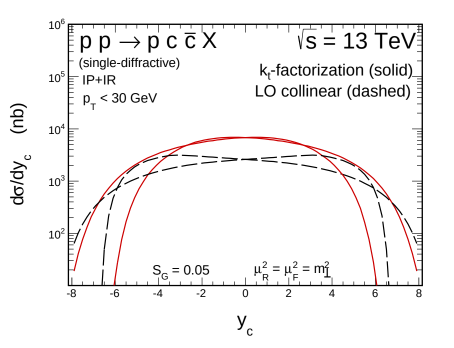
$$d\sigma^{SD(a)}(p_a p_b \to p_a c\bar{c}\, XY) = \int dx_1 \frac{d^2 k_{1t}}{\pi} dx_2 \frac{d^2 k_{2t}}{\pi}\, d\hat{\sigma}(g^* g^* \to c\bar{c}) \times \mathcal{F}_g^D(x_1, k_{1t}^2, \mu^2) \cdot \mathcal{F}_g(x_2, k_{2t}^2, \mu^2)$$

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

- $\mathcal{F}_g$ 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)

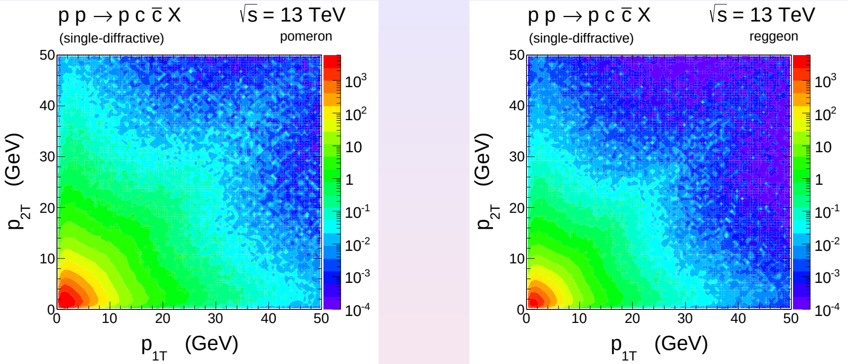
LO Parton Model vs. k_t-factorization approach





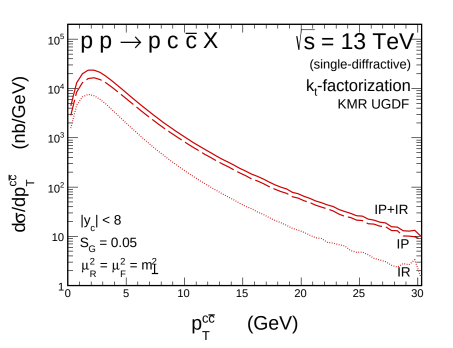
- significant differences between LO PM and k_t-factorization (similar as in the non-diffractive case)
- higher-order corrections very important

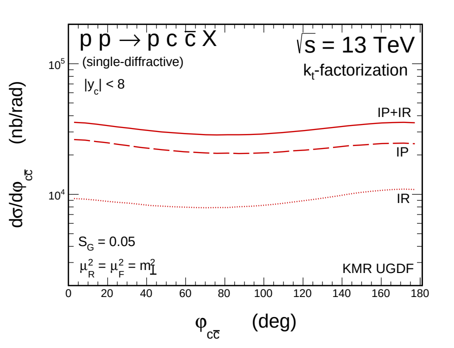
2Dim-distribution in transverse momenta of c and $\bar{c}$



- 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)

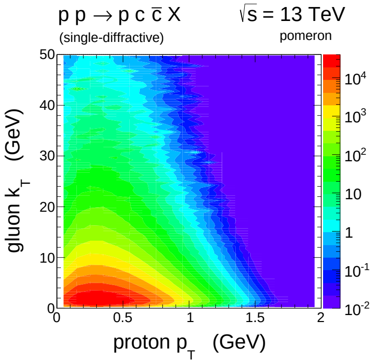
Correlation observables

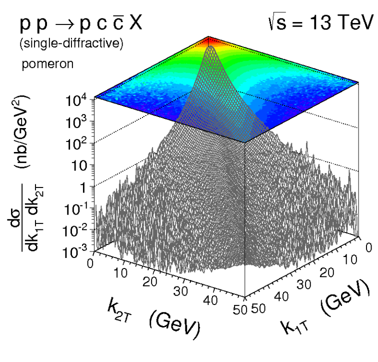




- quite large $c\bar{c}$ pair transverse momenta
- azimuthal angle correlations ⇒ almost flat distribution (similar shape in the case of inclusive central diffraction (DPE))
- exclusive central diffractive events ⇒ smaller $p_T^{c\bar{c}}$ and $\varphi_{c\bar{c}}$ much more correlated (peaked at π)

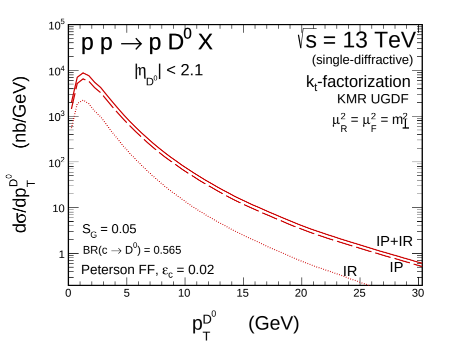
Initial gluon vs. outgoing proton transverse momenta





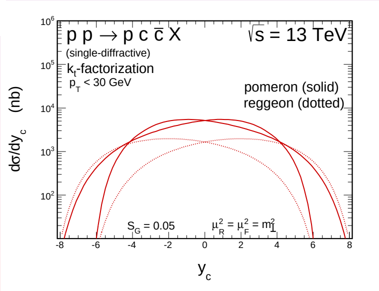
- the cross section concentrated in the region of proton p_T less than 1 GeV
- quite large gluon transverse momenta
- pomeron p_T should not really affect predicted distributions

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

- sizeable cross section for single-diffractive production of open charm at the LHC calculated for the first time within the k_t-factorization approach
- useful model for unintegrated diffractive PDFs
- very important higher-order corrections
- kinematical correlations avalaible