Treatment of charm production in higher-orders at tree-level within k_T-factorization approach

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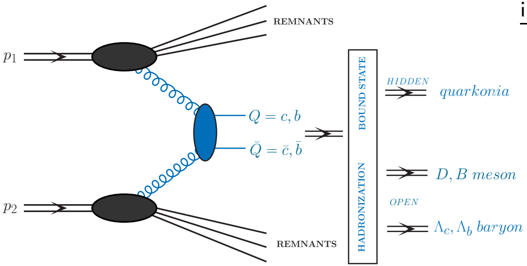
Heavy-Quark Hadroproduction from Collider to Astroparticle Physics, MITP Program

7-11 October 2019, Mainz, Germany

Heavy Flavours at high energies

Heavy-flavours (HF) $\Rightarrow$ open or hidden charm and beauty $\Rightarrow$ study of QCD

- among the most important tools in high-energy *pp*, *pA* and *AA* collisions

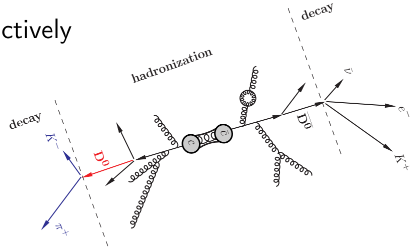


in proton-proton interactions:

- important tests of our understanding of various aspects of QCD quarkonium bound state $\Rightarrow$ non-perturbative aspects of QCD calculations
- heavy quark mass $\Rightarrow$ perturbative QCD
- B and D mesons and/or Λ-baryons $\Rightarrow$ non-perturbative aspects of hadronization in QCD

Production of HFs is one of the most actively studied topics at the LHC

- **indirect method** $\Rightarrow$ leptons from semileptonic decays of heavy flavours
- **direct method** $\Rightarrow$ open heavy mesons or heavy baryons
- charm at the LHC at central (ALICE) and forward rapidities (LHCb)



Studies of charm production at the LHC

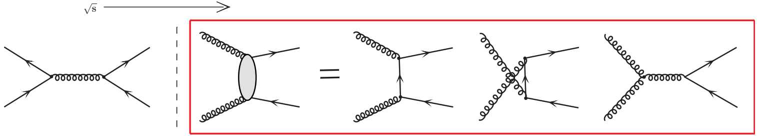
our last years activity in Heavy Flavours in pp-collisions

- model of calculations of charm cross section at high energies:
  the standard k_T-factorization approach $\Rightarrow$
  $2 \to 2$ pQCD mechanisms with off-shell partons and unintegrated PDFs
  $+$ independent parton fragmentation picture
  - inclusive D (p_T and rapidity distributions) Phys.Rev.D87 (2013) no.9, 094022
  - $D\bar{D}$-pair production (correlation studies) Phys.Rev.D87 (2013) no.9, 094022
  - nonphotonic leptons (semileptonic decays) PoS DIS2013 (2013) 169
  - double charm production (DPS) Phys.Rev.D87 (2013) no.7, 074039
  - triple charm production (MPI) Phys.Lett.B772 (2017) 849-853
  - D associated with one and two jets (DPS) Phys.Rev.D96 (2017) no.7, 074013
  - associated D and B (DPS) Phys.Rev.D97 (2018) no.9, 094010
  - inclusive Λ_c (ALICE and LHCb) Phys.Rev.D98 (2018) no.1, 014016
  - inclusive J/ψ (color evaporation model) Phys.Rev.D99 (2019) no.5, 054014

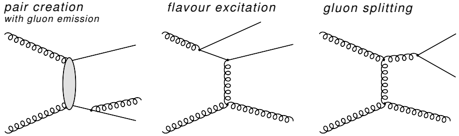
<u>in this talk</u>: A new scheme of the k_T-factorization calculations of charm cross section with the higher-order $2 \to 3$ and $2 \to 4$ mechanisms
Phys.Rev.D100 (2019) no.5, 054001

Charm cross section at high energies

- The leading-order (LO) partonic processes for $Q\overline{Q}$ production $\Rightarrow$ gluon-gluon fusion dominant at high energies



- Main classes of the next-to-leading order (NLO) diagrams:



the NLO/NNLO corrections of a special importance for charm production!

the observables of the interest $\Rightarrow$ single-particle transverse momentum (inclusive spectra)
correlation observables (less inclusive $\Delta\varphi$, M_{inv}, pair p_T)

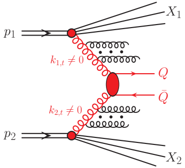
collinear approach:

- stat of the art for single particle spectra at NLO (FONLL, GM-VFNS)
- MC@NLO+PS for correlations
- NNLO not available for charm/bottom

k_T-factorizaton:

- exact kinematics from the very beginning
- correlation observables directly calculable
- some contributions even beyond the NLO available (also differentially)

k_T-factorization (high-energy factorization) approach



off-shell initial state partons $\Rightarrow$

initial transverse momenta explicitly included $k_{1,t}$, $k_{2,t} \neq 0$

- additional hard dynamics coming from transverse momenta of incident partons (virtualities taken into account)
- very efficient for less inclusive studies of kinematical correlations
- more exclusive observables, e.g. pair transverse momentum or azimuthal angle very sensitive to the incident transverse momenta

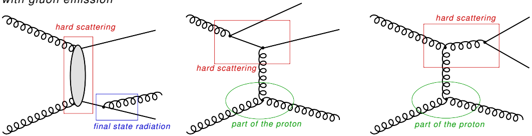
multi-differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{g^*g^* \to Q\bar{Q}}|^2}$$

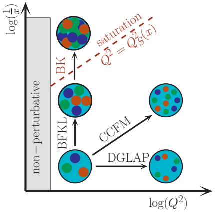
$$\times \quad \delta^2 \left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t} \right) \mathcal{F}_g(x_1, k_{1,t}^2, \mu)\, \mathcal{F}_g(x_2, k_{2,t}^2, \mu)$$

- $\mathcal{F}_g(x, k_t^2, \mu)$ - (unintegrated) transverse momentum dependent PDFs
- the LO off-shell matrix elements $\overline{|\mathcal{M}_{g^*g^* \to Q\bar{Q}}|^2}$ available (analytic form)
- the higher-order matrix elements only at tree-level (KaTie Monte Carlo generator)
- part of higher-order (real) corrections might be effectively included in uPDF

pair creation with gluon emission | *flavour excitation* | *gluon splitting*



Unintegrated parton distribution functions (uPDFs)

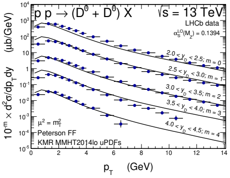


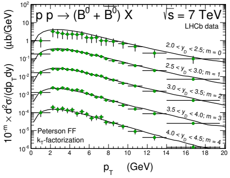
Most popular models:

- Jung, Salam, Hautmann (CCFM, broad range of x)
- Jung, Hautmann, et al. (DGLAP + PB, broad range of x)
- Kimber-Martin-Ryskin (DGLAP-BFKL, broad range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, rather small x-values)
- Kutak-Staśto, Kutak-Sapeta (BK+saturation, only small x-values)

As a default set: Kimber-Martin-Ryskin (KMR) approach:

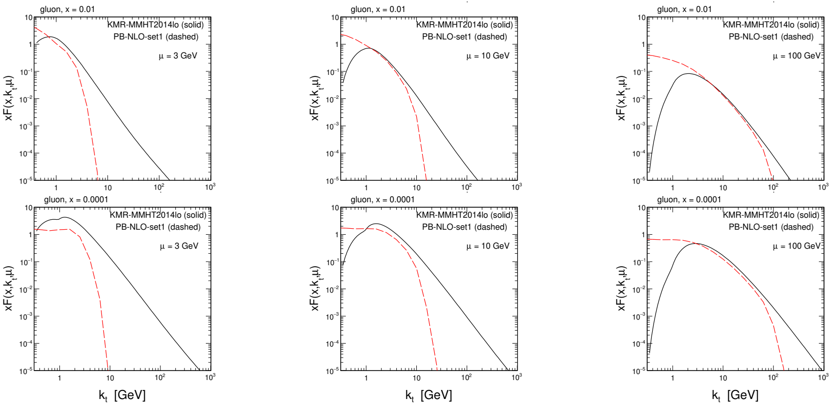
- calculated from collinear PDFs (most up-to-date PDF sets can be used)
- the unique feature: $k_t > \mu$ included $\Rightarrow$ hard emissions from the uPDF
- in fact, only the KMR model effectively includes real higher-order contributions that correspond, e.g. for charm, to associated production with one (NLO) and two (NNLO) jets (or minijets)





k_T-factorization + KMR uPDF works very well for inclusive open charm and bottom mesons at the LHC (as well as for correlation observables)

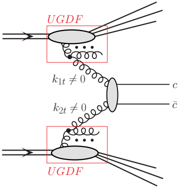
Unintegrated parton distribution functions (uPDFs)



- both models are similar only at intermediate k_T's
- region of $k_T \leq 1$ GeV $\Rightarrow$ completely artificial
- KMR-MMHT2014lo $\Rightarrow$ large $k_t > \mu$ contributions included (the only model in the literature)
- PB-NLO-set1 $\Rightarrow$ $k_t > \mu$ strongly suppressed (as in the case of all other models of uPDFs from the literature)

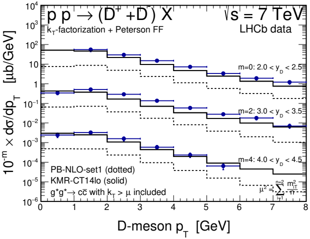
The k_T-factorization approach and the typical procedure

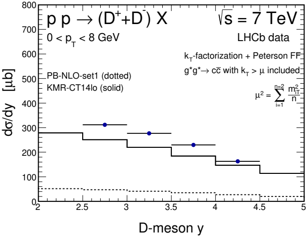
Standard calculations of charm production within the leading-order $2 \to 2$ mechanism:



- off-shell hard matrix element: $g^* g^* \to c\bar{c}$ mechanism only
- extra soft emissions from the uPDFs included
- extra hard emissions from the uPDFs allowed (but in fact present only in the KMR uPDFs)
- part of (real) higher-order corrections effectively included (but only within the KMR uPDFs)

Open charm meson at the LHCb experiment:



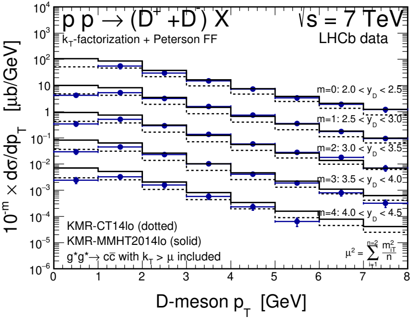


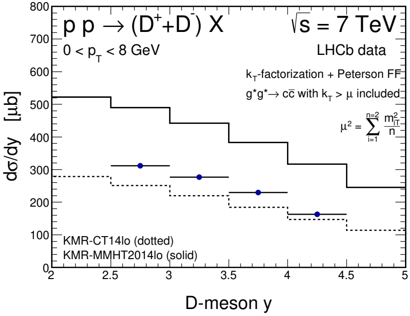
- PB-NLO-set1 $\Rightarrow$ the data points significantly underestimated
- KMR-CT14lo $\Rightarrow$ very good description of the LHCb data!

The k_T-factorization approach and the typical procedure

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF with $k_T > \mu$ + Peterson FF for $c \to D$

Uncertainties due to the collinear PDFs (different models)



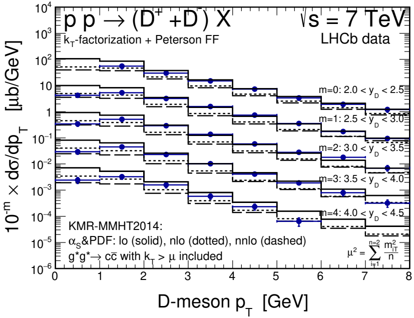


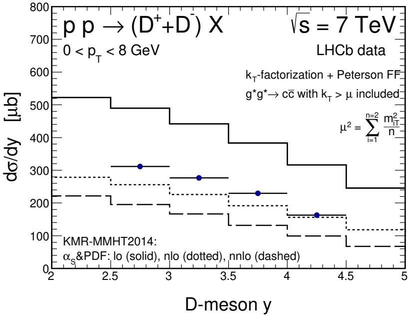
- here we compare MMHT2014lo and CT14lo PDFs
- visible differences for different models of PDFs used in the KMR calculations
- low-p_T data better described by the KMR-CT14lo uPDF

The k_T-factorization approach and the typical procedure

k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF with $k_T > \mu$ + Peterson FF for $c \to D$

Uncertainties due to the collinear PDFs (different orders)



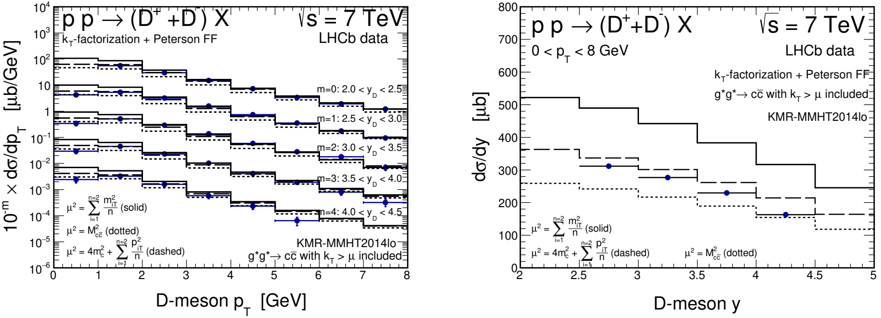


- here we compare MMHT2014lo, MMHT2014nlo and MMHT2014nnlo PDF fits
- again visible differences for the three different PDF fits: LO, NLO and NNLO
- it is not clear in the k_T-factorization which of them is the most appropriate
- low-p_T data better described by the NLO and NNLO MMHT2014 fits

The k_T-factorization approach and the typical procedure

k_T-factorization: $g^* g^* \to c\bar{c}$ + KMR uPDF with $k_T > \mu$ + Peterson FF for $c \to D$

Uncertainties due to the scales

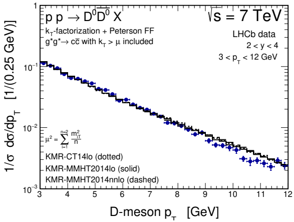


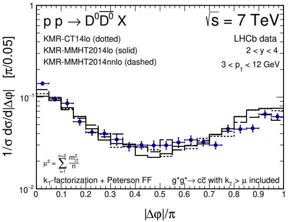
- we set the scales $\mu = \mu_R = \mu_F$ in three different ways
- here we show only results for the central values of these choices
- visible differences obtained at low transverse momenta

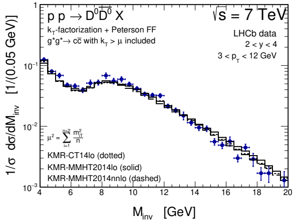
The k_T-factorization approach and the typical procedure

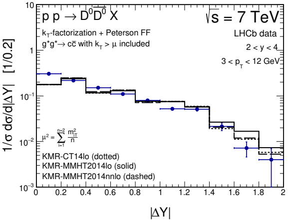
k_T-factorization: $g^* g^* \to c\bar{c}$ + KMR uPDF with $k_T > \mu$ + Peterson FF for $c \to D$

Shapes of the correlation distributions for $D\bar{D}$ pair production







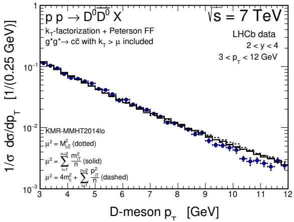


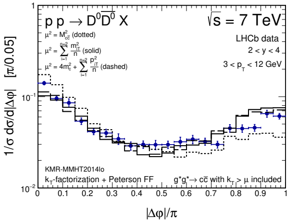
- different PDF sets $\Rightarrow$ similar quality description of the LHCb data

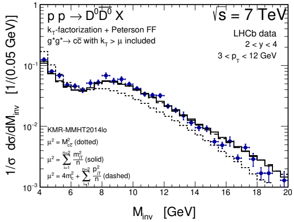
The k_T-factorization approach and the typical procedure

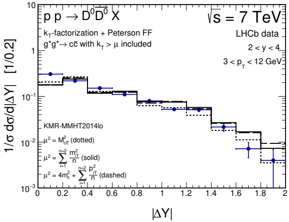
k_T-factorization: $g^*g^* \to c\bar{c}$ + KMR uPDF with $k_T > \mu$ + Peterson FF for $c \to D$

Shapes of the correlation distributions for $D\bar{D}$ pair production







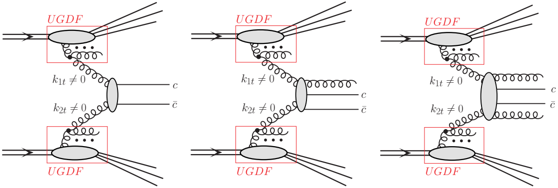


- Invariant mass and azimuthal angle distributions sensitive to the choice of the scales

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:
The main idea is to include higher-order corrections at the level of hard matrix elements with simultaneous limiting of the corresponding contributions incorporated in the uPDFs

- Due to the lack of the full NLO and/or NNLO framework of the k_T-factorization, within the present methods this can be done only at tree-level



We include and sum up:

- LO: $g^* g^* \to c\bar{c}$
- NLO: $g^* g^* \to gc\bar{c}$
- NNLO: $g^* g^* \to ggc\bar{c}$

The $2 \to 3$ and $2 \to 4$ mechanisms with PYTHIA regularization for minijets:
$F_{sup}(p_T) = p_T^4/(p_{T0}^2 + p_T^2)^2$

- the higher-orders with hard extra emissions come from the higher-order matrix elements, while only the softer extra emissions are included via the uPDF
- the limitations of the emissions from uPDFs $\Rightarrow$ merging LO, NLO and NNLO
- a special conditions are introduced to avoid a possible double-counting

Double counting exclusion (DCE) cuts:

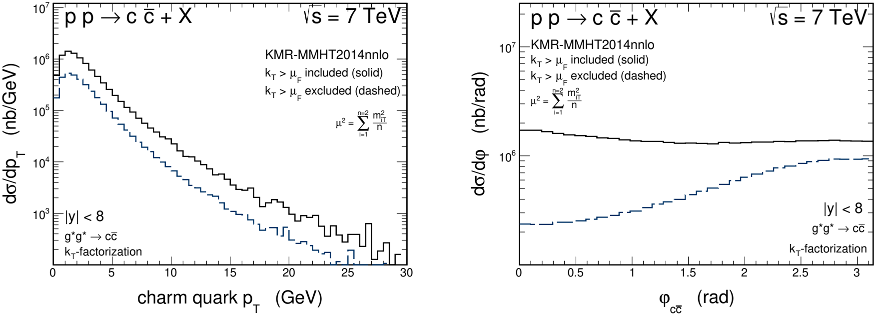
- $k_T < \mu_F$ for $g^* g^* \to c\bar{c}$, where μ_F is the factorization scale,
- $k_T < p_T$ of the minijet for $g^* g^* \to gc\bar{c}$,
- $k_T < p_T^{\mathrm{min}}$ of the two minijets for $g^* g^* \to ggc\bar{c}$.

transverse momenta of (mini)jets from the uPDF are constrained to be always subleading

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:

Role of the DCE cuts (limiting emissions from the uPDFs)



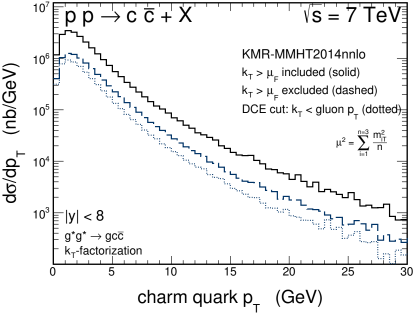
2 → 2 mechanism + KMR-MMHT2014nnlo uPDF:

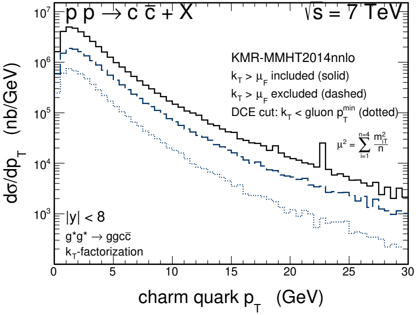
- damping of the cross section
- change of the azimuthal angle distribution

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:

Role of the DCE cuts (limiting emissions from the uPDFs)





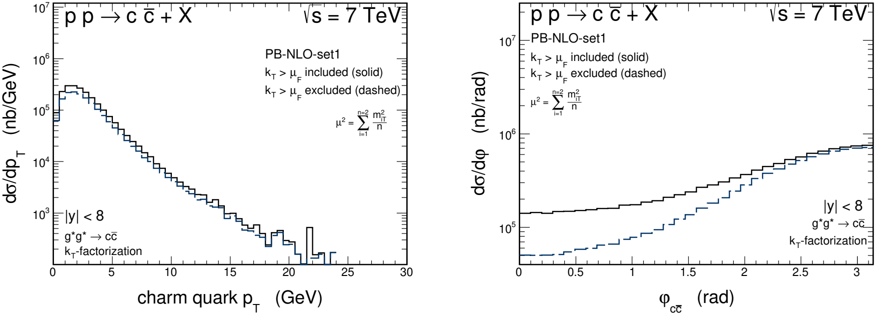
$2 \to 3$ and $2 \to 4$ mechanisms + KMR-MMHT2014nnlo uPDF:

- a huge damping of the cross section
- DCE cuts stronger than the pure $k_T < \mu_F$ limitation
- large double counting in $2 \to 4$ than in $2 \to 3$ case

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:

Role of the DCE cuts (limiting emissions from the uPDFs)



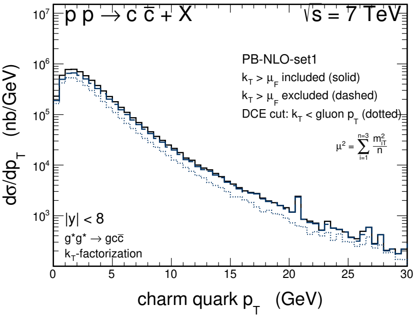
2 → 2 mechanism + PB-NLO-set1 uPDF:

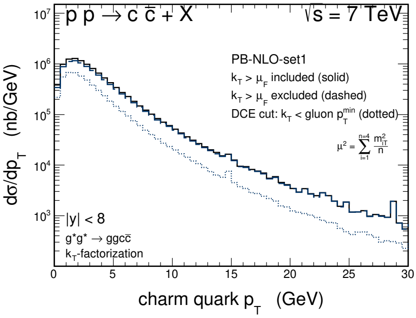
- much smaller effect (almost negligible) than in the case of the KMR uPDF
- still small change of the azimuthal angle distribution (small angles)

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:

Role of the DCE cuts (limiting emissions from the uPDFs)





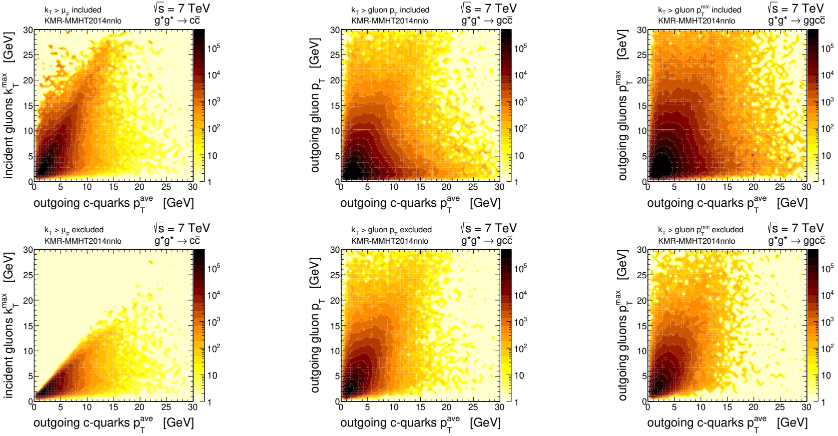
$2 \to 3$ and $2 \to 4$ mechanisms + PB-NLO-set1 uPDF:

- smaller double counting than in the case of the KMR uPDF

The k_T-factorization approach and the new scheme

An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:

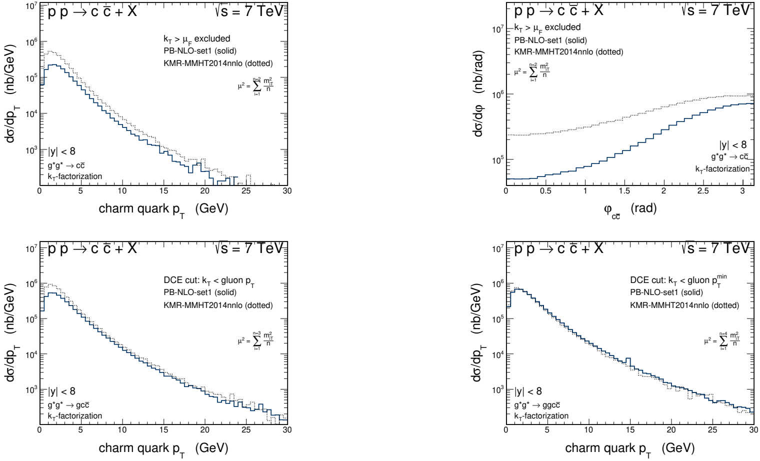
Numerical illustration of the DCE cuts (KMR uPDF)



- incident or outgoing gluon p_T vs. averaged p_T of the c-quark and $\bar{c}$-antiquark

The k_T-factorization approach and the new scheme

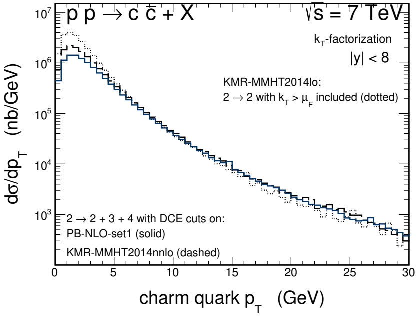
An alternative scheme of the calculation of the HF cross sections in the k_T-factorization:
KMR-MMHT2014nnlo vs. PB-NLO-set1 (DCE cuts included)

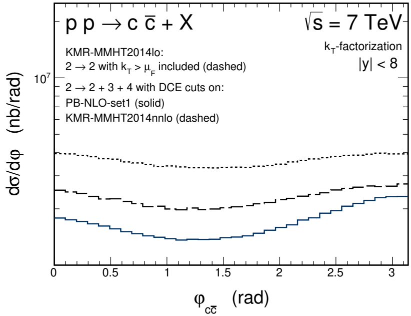


- $2 \to 2 \Rightarrow$ visible (rather small) differences in results for the two uPDF models
- $2 \to 3$ and $2 \to 4 \Rightarrow$ results for both uPDFs almost coincide

The k_T-factorization approach

Comparison of the standard and the new scheme of the k_T-factorization calculations:
$2 \to 2$ with $k_T > \mu$ vs. $2 \to 2+3+4$ with DCE cuts



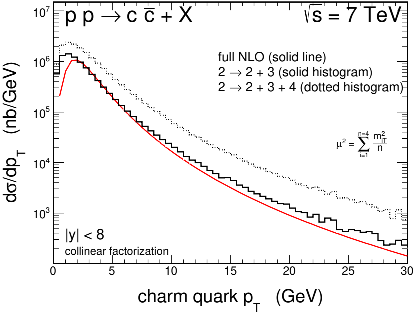


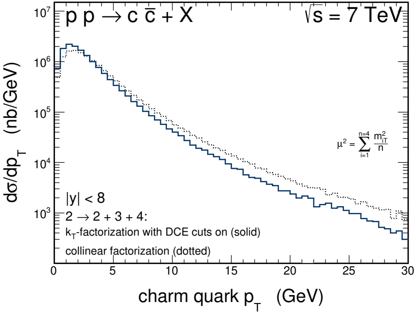
- both prescriptions coincide for $p_t > 3$ GeV
- the differences at small transverse momenta may be driven by the differences in collinear PDFs taken as an input for the calculation of the unintegrated PDFs
- both prescriptions lead to similar shapes of the azimuthal angle distribution (differences in the normalization comes from the region of small p_T's)

The k_T-factorization approach vs. collinear approach

Hypothesis:

Large NNLO corrections to the transverse momentum distribution

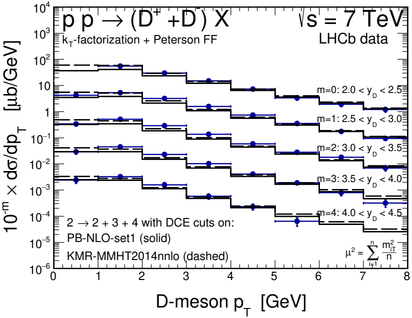


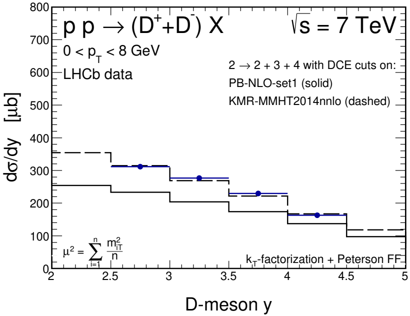


- no loops $\Rightarrow$ do not look at small transverse momenta
- at larger p_T's tree-level collinear $2 \to 2 + 3$ very similar to the full collinear NLO
- simple model predicts large NNLO effects on the p_T-slope in the collinear approach
- these collinear predictions are similar to the k_T-factorization results (even with the standard scheme for the k_T-factorization calculations)

The k_T-factorization approach

Comparison of the new scheme of the k_T-factorization calculations with the LHCb data:
$2 \to 2 + 3 + 4$ with DCE cuts (KMR-MMHT2014nnlo and PB-NLO-set1 uPDFs)

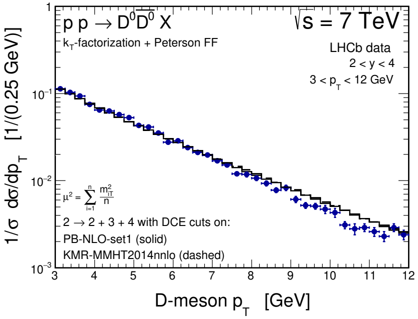


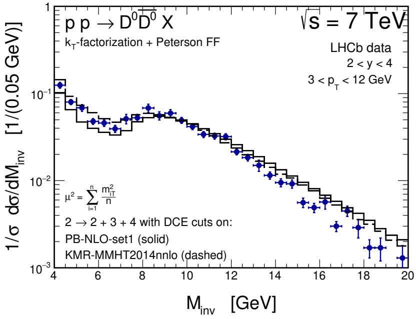


- within the new scheme we significantly improve description of the LHCb data (including correlations) with the PB-NLO-set1 uPDF
- here the PB-NLO-set1 uPDF is used only as an example, similar conclusions can be drawn for other (non KMR type) models of uPDFs from the literature
- (at present) proposed scheme is the only way to describe LHC charm data within the k_T-factorization approach when the uPDF different than the KMR is used

The k_T-factorization approach

Comparison of the new scheme of the k_T-factorization calculations with the LHCb data:
$2 \to 2 + 3 + 4$ with DCE cuts (KMR-MMHT2014nnlo and PB-NLO-set1 uPDFs)





- correlation distributions also very well described with the new scheme and PB-NLO-set1 uPDFs

The k_T-factorization approach

Comparison of the new scheme of the k_T-factorization calculations with the LHCb data:
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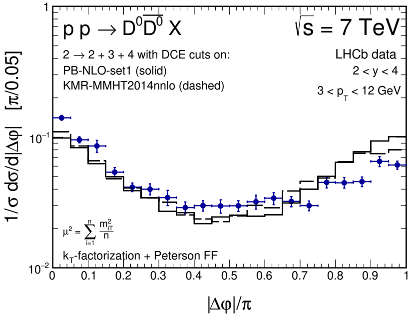

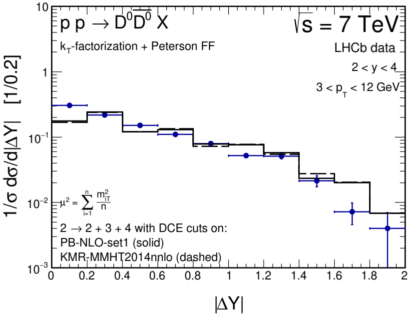

- correlation distributions also very well described with the new scheme and PB-NLO-set1 uPDFs

Conclusions

- We have considered charm production at the LHC within the k_T-factorization approach beyond the standard leading-order $g^* g^* \to c\bar{c}$ partonic mechanism
- For the first time we have included in this context next-to- and next-to-next-to-leading order mechanisms for the differential distributions
- We have proposed a new scheme for calculating the charm quark cross section including in addition the $2 \to 3$ and $2 \to 4$ higher-order contributions at the tree-level
- To the best of our knowledge this is first attempt to study the charm cross section at the LHC differentially beyond the NLO

One of the open question from Sven-Olaf Moch slides:
What can calculations beyond collinear factorization for heavy-quark production in k_T-factorization provide?

- k_T-factorization does not help to reduce uncertainties of the theoretical predictions for charm production
- some extra informations relevant for charm at the LHCb can be extracted from less inclusive studies of correlation observables for which k_T-factorization is very efficient
- the kinematical regime relevant for prompt neutrino flux that corresponds to the very forward production at high energies (linking very small x_1 and very large x_2) certainly is not the regime for which the k_T-factorization is dedicated to and where the k_T-factorization is expected to be valid

Let me show one more slide...

Our activity in prompt neutrino flux calculations

... and let me give you references to our papers which are strictly connected to the subject of prompt neutrino flux:

- V.P. Goncalves, R. Maciuła, R. Pasechnik, and A. Szczurek
  Mapping the dominant regions of the phase space associated with $c\bar{c}$ production relevant for the prompt atmospheric neutrino flux
  Phys. Rev. D96 (2017) no.9, 094026
- R. Maciuła, and A. Szczurek
  D-meson production asymmetry, unfavoured fragmentation, and consequences for prompt atmospheric neutrino production
  Phys. Rev. D97 (2018) no.7, 074001
- V.P. Goncalves, R. Maciuła, and A. Szczurek
  From $D_s^{\pm}$ production asymmetry at the LHC to prompt ν_τ at IceCube
  Phys. Lett. B794 (2019) 29-35
- R. Maciuła, A. Szczurek, J. Zaremba, and I. Babiarz
  Production asymmetry of ν_τ neutrinos and $\overline{\nu}_\tau$ antineutrinos from a fixed target experiment SHiP
  arXiv:1910.01402 [hep-ph]

Hopefully, some of our results might be interesting for you and worth to notice

Thank You for attention!