Charmed mesons and leptons from semileptonic decays at the LHC

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Outline

1. Heavy flavours measurements at the LHC
2. Hadroproduction of Heavy Quarks
   - Parton model (collinear approx.) vs. k_t-factorization approach
   - Unintegrated gluon densities for the proton
   - Hadronization into open heavy mesons
3. Open charmed mesons
   - Transverse momentum distributions of various D mesons
   - $D\bar{D}$ pairs production and kinematical correlations
4. Leptons from semileptonic decays
   - Semileptonic decays of open charm and bottom
   - Transverse momentum distributions of electrons/muons
5. Summary

Previous papers:

Łuszczak, Maciuła, Szczurek, Phys. Rev. D 79 (2009) 034009

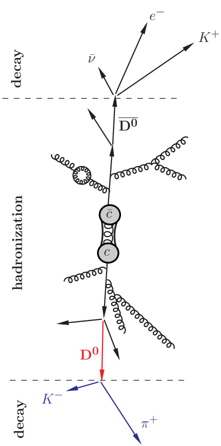
Maciuła, Szczurek, Ślipek, Phys. Rev. D 83 (2011) 054014

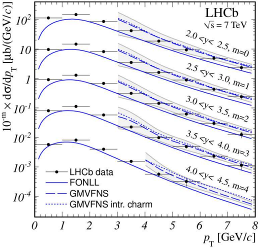
Based on:

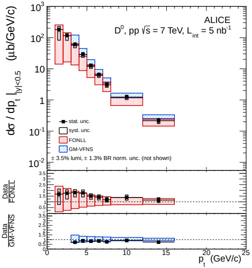
Maciuła, Szczurek, arXiv:1301.3033 (hep-ph)

Heavy Quarks measurements in pp scattering at the LHC

- **direct: open charm/bottom mesons** → reconstruction of all decay products ($K^-\pi^+$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+$)
- indirect: nonphotonic electrons/muons → leptons from semileptonic decays of heavy flavoured mesons



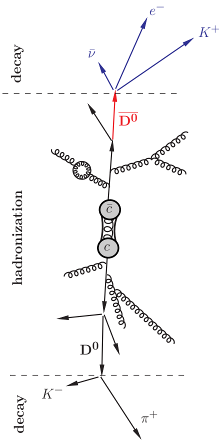


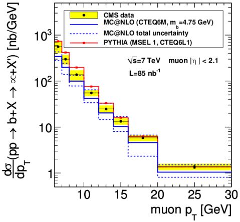


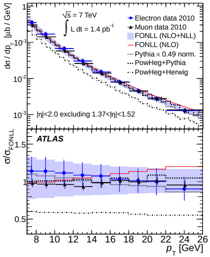
- ALICE, $|y_D| < 0.5$, JHEP 01 (2012) 128; Phys. Lett. B718 (2012) 279
- LHCb, $2.0 < y_D < 4.5$, $p_\perp < 8$ GeV, Nucl. Phys. B871 (2013) 1-20
  very small x region! (up to 10^{-5})
- ATLAS, $|\eta_D| < 2.1$, $p_\perp > 3.5$ GeV, ATLAS-CONF-2011-017
  wide rapidity interval

Heavy Quarks measurements in pp scattering at the LHC

- direct: open charm/bottom mesons → reconstruction of all decay products ($K^-\pi^+$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+$)
- **indirect: nonphotonic electrons/muons** → leptons from semileptonic decays of heavy flavoured mesons



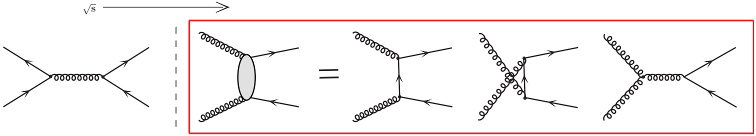




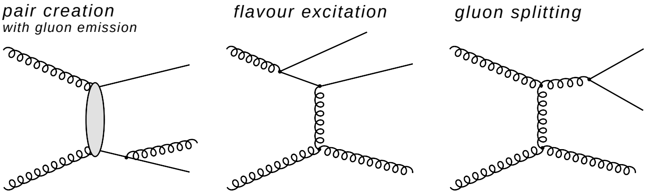
- ALICE, $|y_e| < 0.5(0.8), 0.5(1.0) < p_\perp < 8$ GeV,
  Phys. Rev. D86 (2012) 112007, Phys. Lett. B721 (2013) 13
  $2.5 < y_\mu < 4.0$, Phys. Lett. B708 (2012) 265
- CMS, $|\eta_\mu| < 2.0$, $p_\perp > 6$ GeV, JHEP, 06 (2012) 110
- ATLAS, $|\eta_e| < 2.0$, $7 < p_\perp < 26$ GeV, Phys. Lett. B707 (2012) 438

Dominant mechanisms of $Q\bar{Q}$ production

- leading order (LO) processes contributing to $Q\bar{Q}$ production:



- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
(or at extremely forward rapidities and very large invariant masses of $Q\bar{Q}$ system)
- some of next-to-leading order (NLO) diagrams:



very important NLO contributions $>$ factor 2 (total cross sections, $p_{\perp}$-dependence)

pQCD standard approach

collinear approximation → transverse momenta of the incident partons are assumed to be zero (Wiezsacker-Williams method in QED)

- quadrupuly differential cross section:

$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2 \hat{s}^2} \sum_{i,j} x_1 p_i(x_1,\mu^2)\; x_2 p_j(x_2,\mu^2)\; \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1,\mu^2)$, $p_j(x_2,\mu^2)$ - standard collinear PDFs in the proton

  (e.g. CTEQ, GRV, GJR, MRST, MSTW)

- NLO on-shell matrix elements well-known

  Nason et al., Nucl. Phys. B303 (1988) 607; Nucl. Phys. B327 (1989) 49
  Beenakker et al., Phys. Rev. D40 (1989) 54; Nucl. Phys. B351 (1991) 505

several approaches: improved schemes of NLO collinear calculations

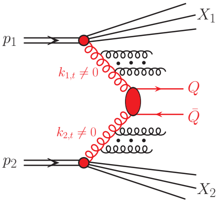
states of art in the respect of one particle distributions and total cross sections

- **FONLL** (Cacciari *et al.*) JHEP 05 (1998) 007; JHEP 03 (2001) 006
- **GM-VFNS** (Kniehl, Kramer *et al.*) Phys. Rev. D71 (2005) 014018; Phys. Rev. D79 (2009) 094009

more exclusive tools:

- PYTHIA, HERWIG, MC@NLO

k_t-factorization (semihard) approach



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

Catani-Ciafaloni-Hautmann, Nucl. Phys. B366 (1991) 135,
Collins-Ellis, Nucl. Phys. B360 (1991) 3,
Ball-Ellis, JHEP 05 (2001) 053

$\Rightarrow$ efficient for $Q\bar{Q}$ correlations

- Charm and Bottom Quarks production at high energies $\longrightarrow$ gluon-gluon fusion

considered by many authors $\rightarrow$ e.g. Zotov, Lipatov, Jung, Baranov, Teryaev
e.g. JHEP 01 (2011) 085; Phys. Rev. D85 (2012) 034035

- multi-differential cross section

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

- **off-shell** $\overline{|\mathcal{M}_{g^* g^* \to Q\bar{Q}}|^2}$ $\longrightarrow$ Catani-Ciafaloni-Hautmann or from BFKL NLL effective vertices (QMRK approach)
- some part of NLO corrections automatically included!
- $\mathcal{F}_i(x_1, \kappa_{1,t}^2)$, $\mathcal{F}_j(x_2, \kappa_{2,t}^2)$ - unintegrated parton distributions (k_t dependent)
- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,

  $x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2)$, where $m_{i,t} = \sqrt{p_{i,t}^2 + m_Q^2}$.

Different models of UGDFs

- k_t-factorization → replacement: $p_k(x,\mu_F^2) \longrightarrow \mathcal{F}_k(x,\kappa_t^2,\mu_F^2)$
- PDFs ⟶ UPDFs

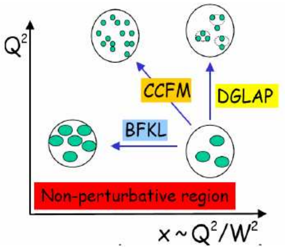
$$xp_k(x,\mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x,\kappa_t^2,\mu_F^2)$$

- **UPDFs** - needed in less inclusive measurements which are sensitive to the transverse momentum of the incident parton

gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!
at the LHC especially in the case of charm production → very small-x values

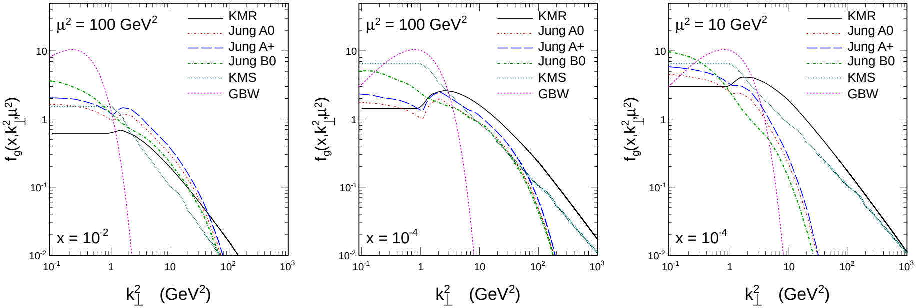
several models:

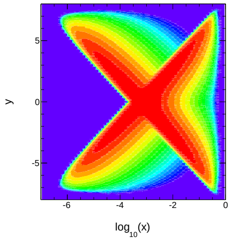
- Kwieciński, Jung (CCFM, wide x-range)
- Kimber-Martin-Ryskin (larger x-values)
- KMS, Kutak-Staśto (small-x, saturation effects)



already applied and tested in: e.g. deep-inelastic structure function; inclusive charm and associated charm and jet photoproduction at HERA; dijets in photoproduction, hadroproduction and deep-inelastic scattering; electroweak boson production

Different models of UGDFs

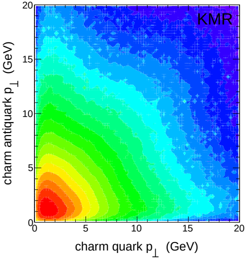


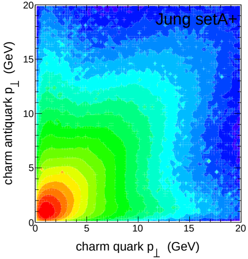


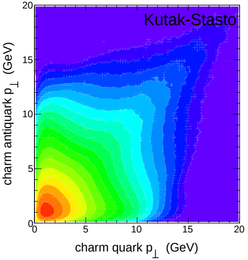
- significant differences between various UGDFs models
- crucial test of their applicability at high energies and small x-values
  $\longrightarrow$ charm cross section
- typical x-values:
  from 10^{-2} to 10^{-4} at ALICE, ATLAS
  full range up to 10^{-5} at LHCb

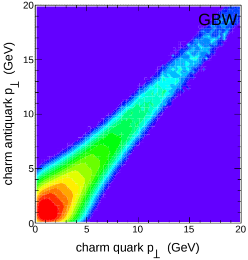
Differential cross section for charm quarks

$$\frac{d\sigma}{dp_{1t}dp_{2t}}$$

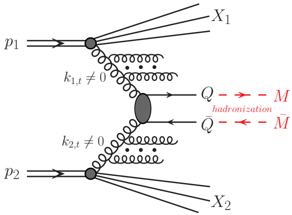








Fragmentation functions technique



- phenomenology → 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 → Braaten et al. (charm) and Kartvelishvili et al. (bottom)
  GM-VFNS → KKKS08 + evolution

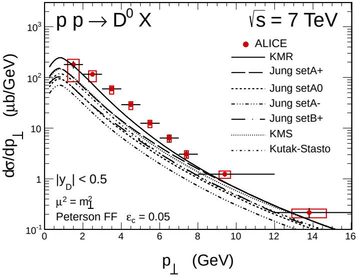
- numerically performed by rescalling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

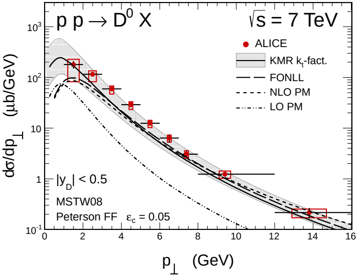
$$\frac{d\sigma(y, p_t^M)}{dyd^2p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dyd^2p_t^Q} dz$$

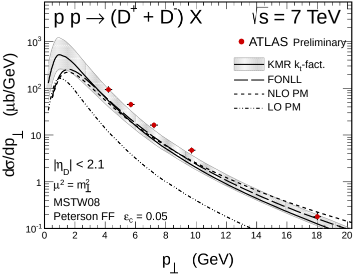
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0, 1)$

- **approximation:**
  rapidity unchanged in the fragmentation process → $y_Q = y_M$

ALICE and ATLAS data with predictions for D^0 and $D^\pm$

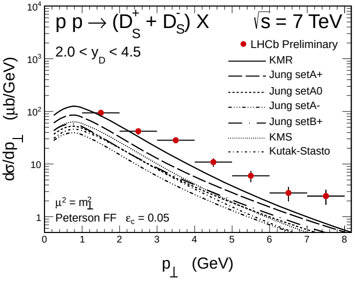


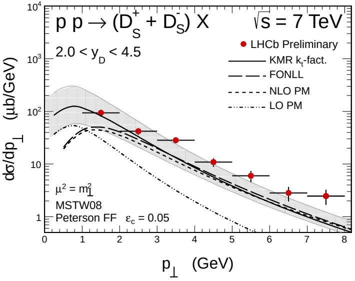


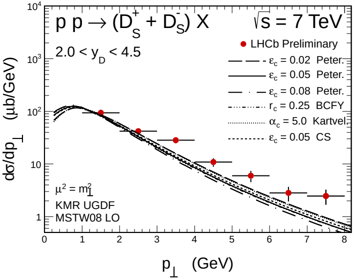


- only KMR (with uncertainties) gives quite reasonable description of the ALICE data
- k_t-factorization with KMR UGDF consistent with the FONLL and NLO PM predictions; significantly larger cross sections than from the LO PM
- ATLAS data poorly described only with the very upper limit of the predicted uncertainties (due to scales and quark mass)

LHCb data and predictions with uncertainties for $D_S^{\pm}$

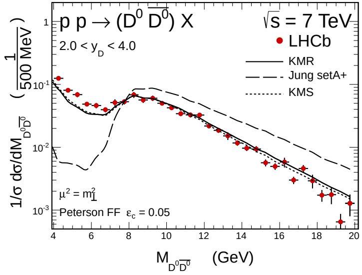


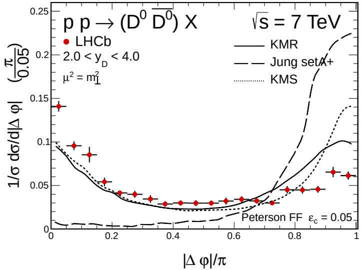


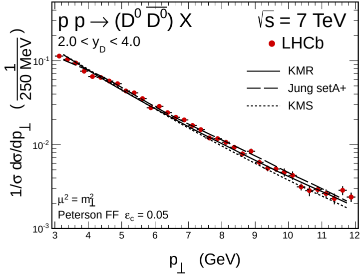


- LHCb data can be described only with KMR model and only with upper limits of the obtained uncertainty band
- Fragmentation Functions → source of uncertainties especially important at larger p_t's of mesons; rather harder (smaller ε_c) functions are suggested by the analysis

LHCb data and correlation observables: $M_{D^0\bar{D}^0}$, $\varphi_{D^0\bar{D}^0}$ and $p_{\perp}^{D^0(\bar{D}^0)}$







- very good description of shapes of the differential $M_{D^0\bar{D}^0}$ and p_t cross sections with KMR and KMS UGDFs
- azimuthal angle distributions → small missing strength at small angles (incomplete reconstruction of gluon splitting contribution)

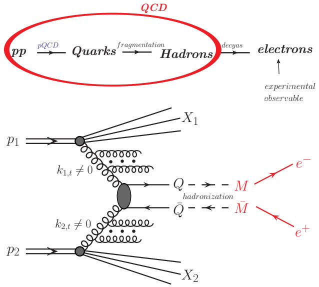
Total cross sections for different $D\bar{D}$ modes

Table: Integrated cross sections for the two mesons modes specified in the table below within the LHCb detector.

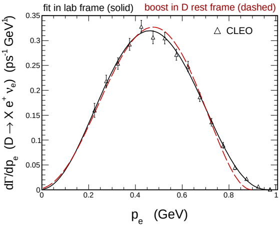
Mode	σ_{tot}^{EXP} (nb)	σ_{tot}^{THEORY} (nb) KMR $^{+}_{-}(\mu)$ $^{+}_{-}(m_c)$		Jung setA+		KMS	
		$\varepsilon_c = 0.05$	$\varepsilon_c = 0.02$	$\varepsilon_c = 0.05$	$\varepsilon_c = 0.02$	$\varepsilon_c = 0.05$	$\varepsilon_c = 0.02$
$D^0\bar{D}^0$	$6230 \pm 120 \pm 630$	$5193\,^{+1346}_{-879}\,^{+654}_{-576}$	6971	4532	5814	2895	3894
D^0D^-	$3990 \pm 90 \pm 500$	$4155\,^{+1076}_{-704}\,^{+523}_{-461}$	5577	3626	4652	2316	3115
$D^0D_S^-$	$1680 \pm 110 \pm 240$	$1471\,^{+381}_{-249}\,^{+185}_{-163}$	1974	1284	1647	820	1103
D^+D^-	$780 \pm 40 \pm 130$	$831\,^{+215}_{-141}\,^{+105}_{-92}$	1115	725	930	463	623
$D^+D_S^-$	$550 \pm 60 \pm 90$	$588\,^{+152}_{-99}\,^{+74}_{-65}$	790	513	659	328	441
$D_S^+D_S^-$	–	$104\,^{+27}_{-17}\,^{+13}_{-11}$	139	91	117	59	78

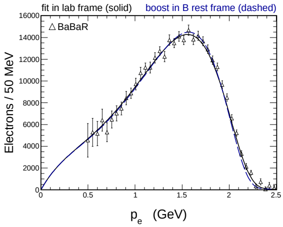
- only KMR model within uncertainties (which are quite large) well describes experimental cross sections
- due to the LHCb particular acceptance → important sensitivity of the predicted total cross sections to the applied fragmentation scheme (harder functions give results closer to the experimental values)

Experimental decay functions and Monte Carlo approach



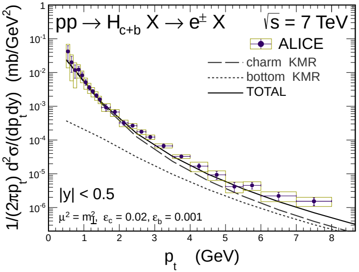
- **CLEO** $e^+e^- \to \Psi(3770) \to D\bar{D} \to Xe\nu$
  BR($D^+ \to e^+\nu_e X$)=16.13±0.20(stat.)±0.33(syst.)%
  BR($D^0 \to e^+\nu_e X$)=6.46±0.17(stat.)±0.13(syst.)%
- **BABAR** $e^+e^- \to \Upsilon(10600) \to B\bar{B} \to Xe\nu$
  BR($B \to e\nu_e X$)=10.36±0.06(stat.)±0.23(syst.)%
- **Monte Carlo** $\Longrightarrow$ directions and lengths of outgoing leptons momenta
- D mesons ($D^\pm, D^0, \bar{D}^0, D_S^\pm, D^{*0}, D^{*\pm}, D_S^{*\pm}$); B mesons ($B^\pm, B^0, \bar{D}^0, B_S^0, \bar{B}_S^0, B^*, B_S^*$)
  approximation: **BR(D and $B \longrightarrow X\ e\ \nu$) ≈ 10%**
- Our input $\Longrightarrow$ **experimental decay functions**: $f_{CLEO}(p)$, $f_{BABAR}(p)$

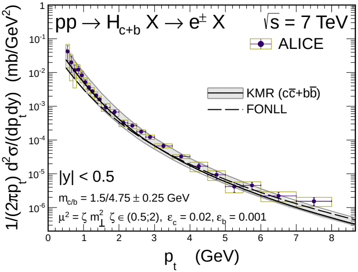


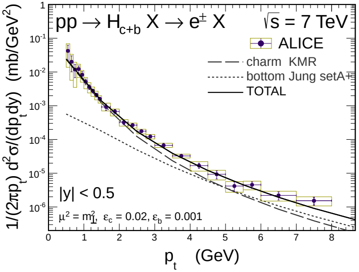


- including effects of the transformation of the spectrum in the D/B rest system to the CLEO/BABAR laboratory frame

ALICE data for charm and bottom flavoured electrons

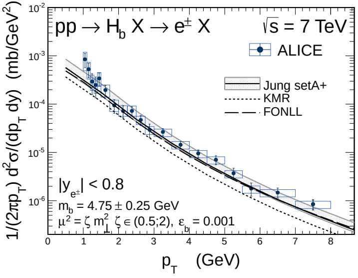


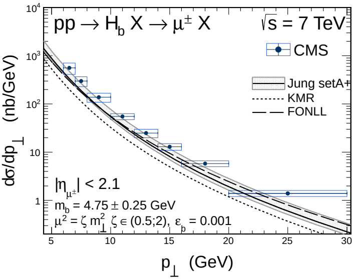


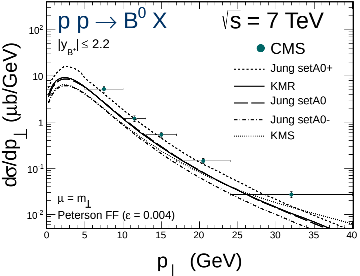


- very good description of the ALICE data using KMR UGDFs (charm + bottom)
- k_t-factorization results consistent with FONLL predictions
- bottom contribution very important for the region of larger ($>$ 4 GeV) $p'_\perp s$
(Jung UGDF seems to be more suitable for electrons from bottom decays)

Bottom flavoured leptons versus ALICE and CMS data

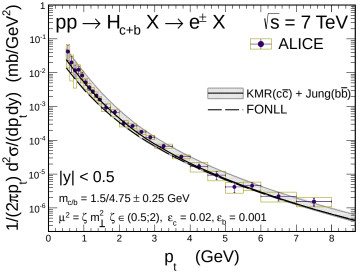


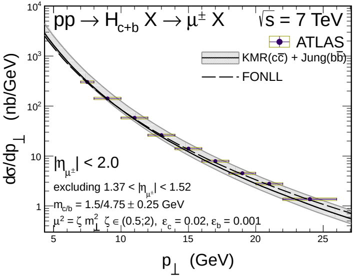


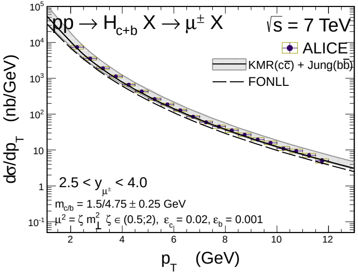


- in the case of bottom falvoured leptons KMR model underestimate significantly spectra measured by ALICE and CMS
- k_t-factorization with Jung UGDF works much better for bottom production and is consistent with FONLL predictions
- the same conclusions come from the direct meson-level analysis

Nonphotonic leptons with improved bottom contribution







- very good description of the ALICE and ATLAS data
- within the k_t-factorization approach separate treatment of charm and bottom production is needed:
  charm → KMR UGDF
  bottom → Jung UGDF
- There is no unique model of UGDFs to describe simultaneously charm and bottom production at the LHC

Summary

Charmed mesons:

- only KMR UGDF allows for results which are close to the LHC inclusive charm data (rest of tested UGDFs seem to underestimate significantly experimental data)
- the k_t-factorizaton approach together with KMR UGDF is consistent with mostly used FONLL and NLO PM predictions for charmed mesons production at the LHC and is very efficient for studying kinematical correlations in less inclusive measurements of $D\bar{D}$ pairs
- only upper limits of our theoretical predictions give quite reasonable description of the ALICE, ATLAS and LHCb inclusive charm data
  what can be missing in this type of analysis? $\longrightarrow$
  see A. Szczurek talk on Wednesday (15:00, WG4/5) about double-parton scattering contribution to charm cross section

Heavy flavoured leptons:

- very good description of the ALICE, ATLAS and CMS data for nonphotonic electrons and muons production
- at the LHC energies, for theoretical predictions within k_t-factorization approach, different models of UGDFs have to be used for charm (KMR) and bottom (Jung) respectively

Thank You for attention!