Open charm meson production at RHIC within k_t-factorization approach and revision of their semileptonic decays

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Heavy Quark Physics in Heavy-Ion collisions: Experiments, Phenomenology and Theory

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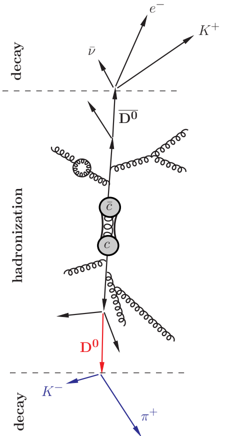
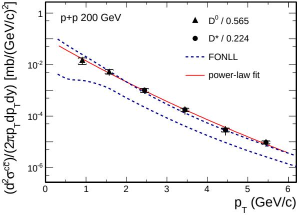
Outline

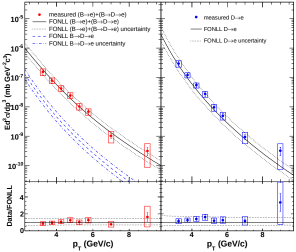
1. Charm production at RHIC
   - Theoretical framework within the k_t-factorization approach
   - Hadronization effects
   - Theoretical predictions vs. STAR open charm data
2. Nonphotonic electrons at RHIC
   - Revision of our previous calculations
3. Open charm at the LHC
   - Inclusive D meson spectra
   - Kinematical correlations

Heavy quark measurements in pp scattering at RHIC

- **indirect: nonphotonic electrons/muons** $\rightarrow$ leptons from semileptonic decays of heavy flavoured mesons; including separation of charm and bottom components $\rightarrow$ STAR, PHENIX @ $\sqrt{s} = 200$ GeV
- **direct: open charm meson** $\rightarrow$ reconstruction of all decay products ($K^-\pi^+$, $K^+K^-\pi^+$, $K^-\pi^+\pi^+$) $\rightarrow$ STAR @ $\sqrt{s} = 200, 500$ GeV



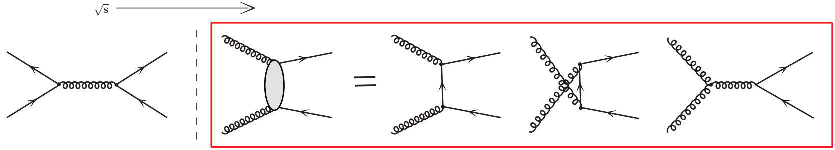




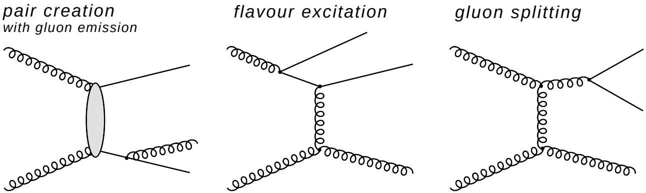
- nonphotonic electrons:
  Phys. Rev. Lett. 97 (2006) 252002; Phys. Rev. D83 (2011) 052006;
  Phys. Rev. Lett. 98 (2007) 192301, Erratum-ibid. 106 (2011) 159902
- open charm meson:
  200 GeV: Phys. Rev. D86 (2012) 072013
  500 GeV: next week on arXiv (D. Tlusty, private communication)

Dominant mechanisms of heavy quark production

- Leading order (**LO**) processes contributing to $Q\overline{Q}$ production:



- **gluon-gluon fusion** dominant at high energies
- main classes of the next-to-leading order (**NLO**) diagrams:



very important NLO corrections

- $\frac{NLO}{LO} \approx 3$ for $p_\perp \sim 0-3$ GeV and $y \sim 0$;
- $\frac{NLO}{LO} \gtrsim 10$ for large $p'_\perp s$ or large y;

Standard approach of perturbative QCD

collinear approximation $\rightarrow$ 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

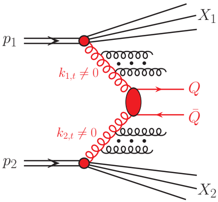
  Nason et al., Nucl. Phys. B303 (1988) 607; Nucl. Phys. B327 (1989) 49
  Beenakker et al., Phys. Rev. D40 (1989) 54; Nucl. Phys. B351 (1991) 505

several approaches: improved schemes of NLO collinear calculations

- **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

  state-of-art: σ_{tot} **and inclusive single particle spectra**
  BUT cannot be applied in a simple way in more exclusive studies
  of KINEMATICAL CORRELATIONS (Monte Carlo generators needed)

Basic concepts of the k_t-factorization (semihard) approach



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

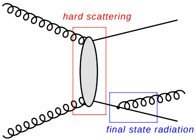
$\Rightarrow$ very efficient approach for $Q\bar{Q}$ correlations

- multi-differential cross section

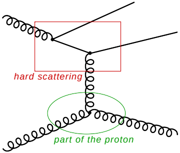
$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \sum_{i,j} \int \frac{d^2\kappa_{1,t}}{\pi} \frac{d^2\kappa_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathcal{M}_{i^* j^* \to Q\bar{Q}}|^2}$$
$$\times \; \delta^2 \left(\vec{\kappa}_{1,t} + \vec{\kappa}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}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

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

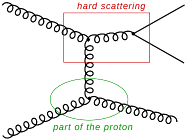
pair creation with gluon emission



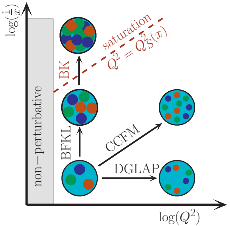
flavour excitation



gluon splitting

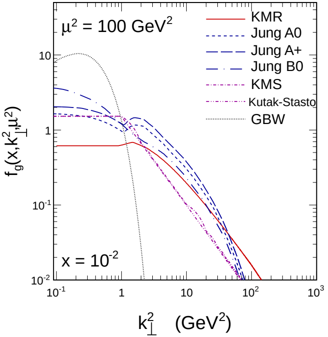


Unintegrated gluon distribution functions (UGDFs)



most popular models:

- Kimber-Martin-Ryskin (DGLAP-BFKL, wide range of x)
- Kwieciński-Martin-Staśto (BFKL-DGLAP, small x-values)
- Kutak-Staśto, Kutak-Sapeta (BK, saturation, small x-values)
- Jung (CCFM, wide range of x)
- new Jung-Hautmann 2013 (from high precision HERA data)



already applied and tested in:

e.g. deep-inelastic structure function; inclusive charm associated charm and jet photoproduction; dijets in photoproduction, hadroproduction and deep-inelastic scattering; electroweak boson production

charm quarks at different energies

$\Rightarrow$ only gluon-gluon fusion

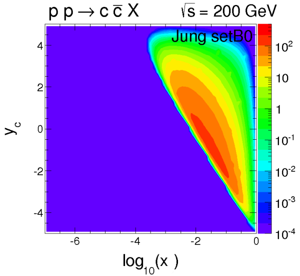
great test of many different UGDFs

in different kinematical regimes

LHC: very small x-values down to 10^{-5}

RHIC: large and intermediate x-values about 10^{-2} (10^{-3})

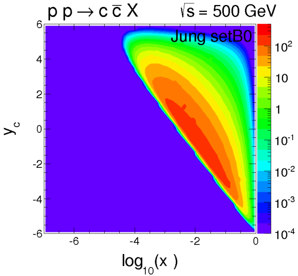
Kinematical regimes for charm quarks at high energies

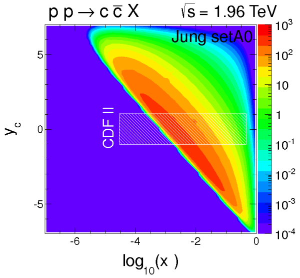


RHIC:

$\leftarrow x \gtrsim 10^{-2}$

$x \gtrsim 10^{-3} \rightarrow$

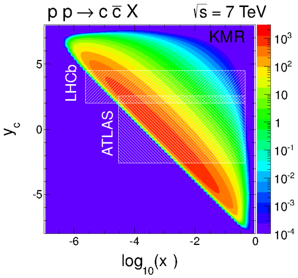




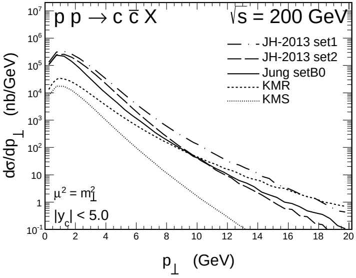
LHC:

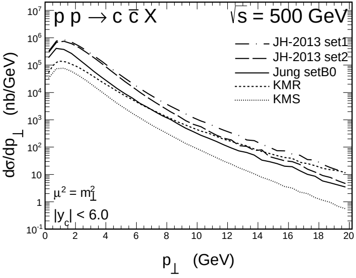
$x \gtrsim 10^{-4}$ (ATLAS)

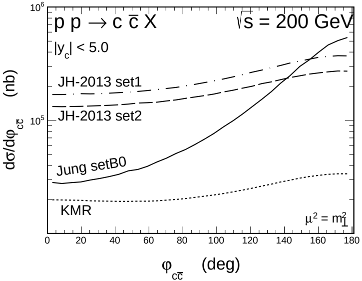
$x \gtrsim 10^{-5}$ (LHCb)



Charm quark cross section at RHIC

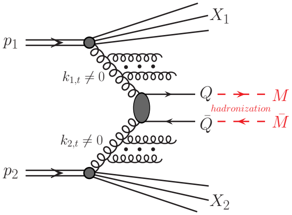






- different UGDFs give quite different results
- one needs to choose only those UGDFs which are dedicated to the considered kinematical regime (at RHIC the BFKL-based UGDFs are disfavoured)

Fragmentation of heavy quarks



- 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

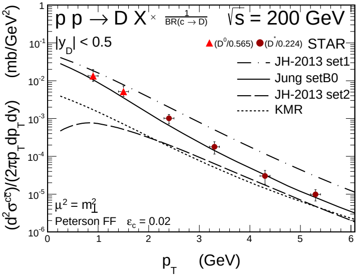
- numerically performed by rescalling transverse momentum at a constant rapidity (angle)
- from heavy quarks to heavy mesons:

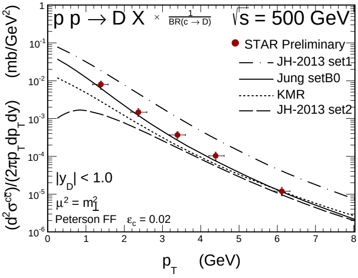
$$\frac{d\sigma(y,p_t^M)}{dyd^2p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y,p_t^Q)}{dyd^2p_t^Q} dz$$

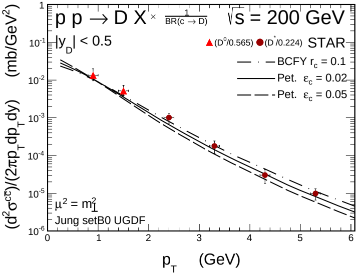
where: $p_t^Q = \frac{p_t^M}{z}$ and $z \in (0,1)$

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

Inclusive *D* meson spectra — RHIC

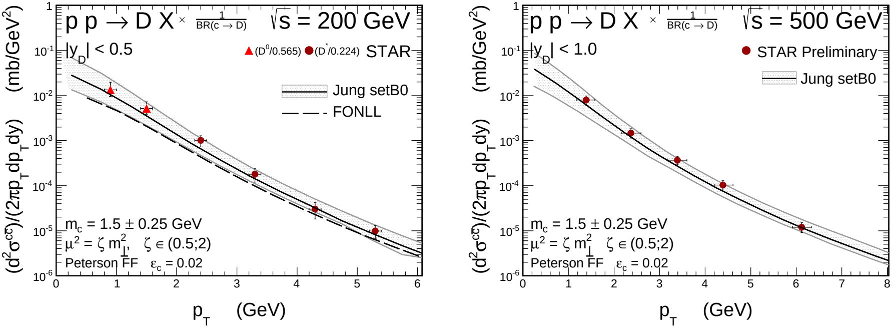






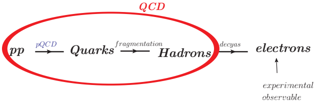
- very good description of the STAR data with the CCFM-based Jung setB0 UGDF
- main problem: most of the UGDF models from the literature fitted to the HERA data not always work in pp collisions
- not-negligible sensitivity to the choice of fragmentation model

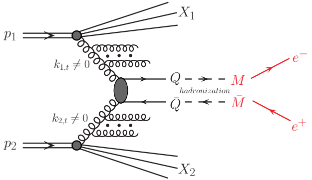
Comparison with the FONLL predictions



- typical pQCD uncertainties: renormalization/factorization scale and charm quark mass
- our central value gives sligthly better description of the STAR data with respect to the central value of FONNL
- both approaches consistent taking into account uncertainties

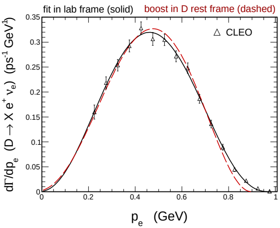
Experimental semileptonic decay functions

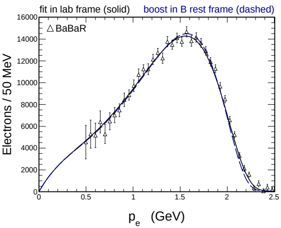




- **CLEO** $e^+e^- \rightarrow \Psi(3770) \rightarrow D\bar{D} \rightarrow Xe\nu$
  BR$(D^+ \rightarrow e^+\nu_e X)$=16.13±0.20(stat.)±0.33(syst.)%
  BR$(D^0 \rightarrow e^+\nu_e X)$=6.46±0.17(stat.)±0.13(syst.)%
- **BABAR** $e^+e^- \rightarrow \Upsilon(10600) \rightarrow B\bar{B} \rightarrow Xe\nu$
  BR$(B \rightarrow e\nu_e X)$=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%**

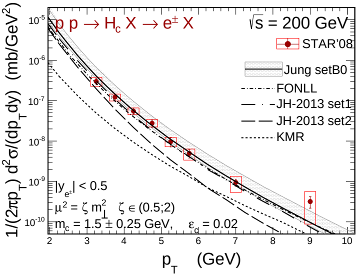
- Our input $\Longrightarrow$ **experimental decay functions:** $f_{CLEO}(p)$, $f_{BABAR}(p)$

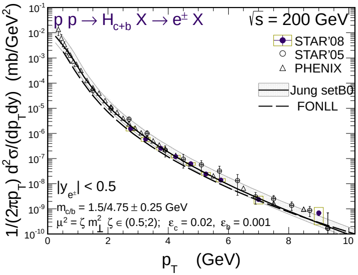


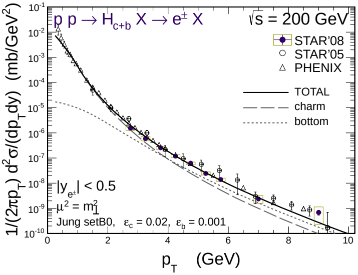


- including effects of the transformation of the spectrum in the D/B rest system to the CLEO/BABAR laboratory frame

Inclusive heavy-flavoured electron spectra RHIC

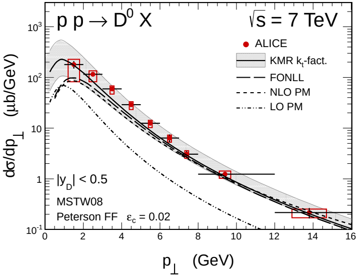


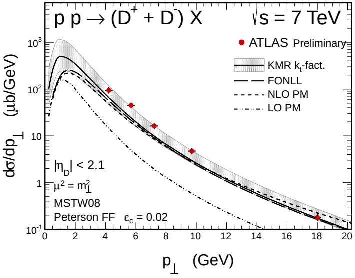


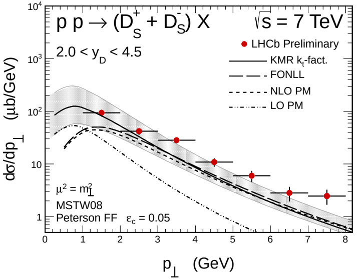


- Our previous results within the k_t-factorization: Łuszczak, Maciuła, Szczurek, Phys. Rev. D79 (2009) 034009 ⇒ some missing strength found due to the out-of-date UGDFs used
- NOW: very good description of the RHIC nonphotonic electron data
- cross point for charm and bottom contributions at $p_t \approx 4$ GeV (consistent with FONLL)

D meson transverse momentum spectra LHC

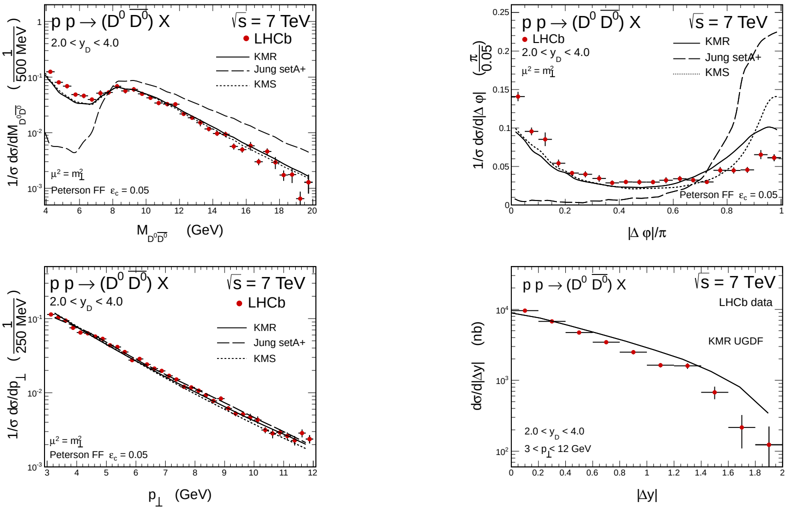






- Maciuła, Szczurek, Phys. Rev. D87 (2013) 094022 ⇒ only the upper limits of uncertainty bands reasonably well describe the LHC data
- k_t-factorization consistent with the FONLL
- LHC: new mechanism in charm sector: Double-Parton-Scattering (see talk by A. Szczurek)

$D\overline{D}$ meson-antimeson correlations vs. LHCb data



- k_t-factorization approach $\Rightarrow$ very efficient for kinematical correlation studies

Conclusions

- the k_t-factorization approach with the CCFM Jung UGDF gives a very good description of the open charm and nonphotonic electron RHIC data at both energies: $\sqrt{s} = 200$ and 500 GeV
- the k_t-factorization results consistent with the FONNL (our central value sligthly better describes the data)
- our theoretical predictions also give quite reasonable description of the LHC charm data (results consistent with FONLL)
  WARNING: Double-Parton-Scattering effects at the LHC!
- k_t-factorizaton approach is very efficient for studying kinematical correlations in less inclusive measurements of $D\overline{D}$ (or nonphotonic e^+e^-) pairs

Thank You for attention!