New mechanisms of charm production

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Plan of the talk

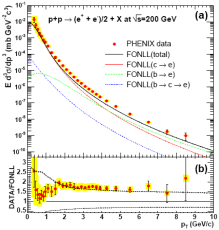
Based on:

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

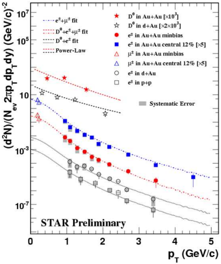
Maciuła, Szczurek, Ślipek, Phys. Rev. D 83 (2011) 054014

Heavy quarks measurements at BNL RHIC

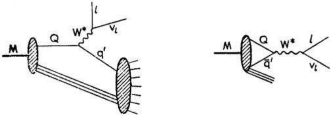
Phys. Rev. Lett. 97, 252002 (2006)



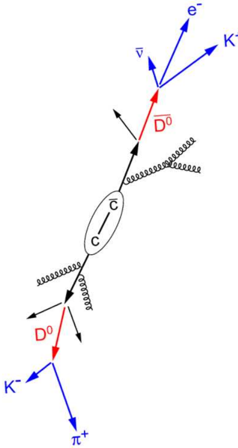
Phys. Rev. Lett. 98, 192301 (2007)



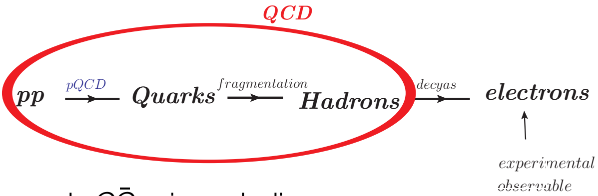
- direct: reconstruction of all decay products
- indirect: charm and bottom electrons/muons



- **nonphotonic electrons** → leptons from semileptonic decays of heavy flavoured mesons: D or B → X e(μ) υ
- pp collisions, $\sqrt{s} = 200$ GeV, $p_t > 0.2$ GeV, $|y| \leq 0.35$, PHENIX, STAR

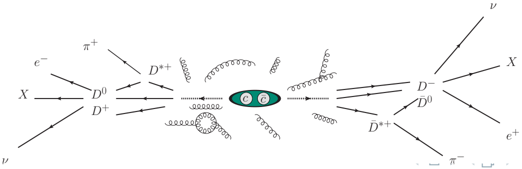


3-step process



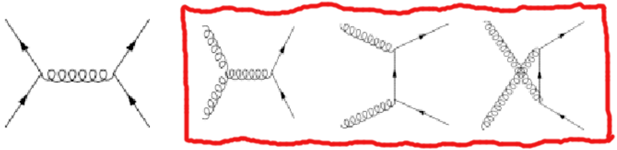
1. Heavy quarks $Q\bar{Q}$ pairs production
   - $m_c = 1.5$ GeV, $m_b = 4.75$ GeV $\longrightarrow$ perturbative QCD
2. Heavy quarks hadronization (fragmentation)
3. Semileptonic decays of D and B mesons

$$\frac{d\sigma^e}{dyd^2p} = \frac{d\sigma^Q}{dyd^2p} \otimes D_{Q\to H} \otimes f_{H\to e}$$

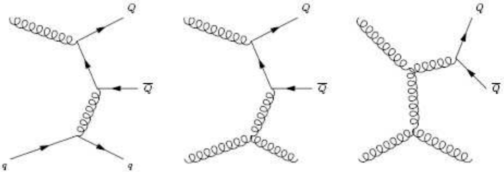


Dominant mechanisms of $Q\bar{Q}$ production

- Leading order processes contributing to $Q\bar{Q}$ production:



- **gluon-gluon fusion** dominant at high energies
- $q\bar{q}$ anihilation important only near the threshold
- some of next-to-leading order diagrams:



very important NLO contributions $\rightarrow$ factor 2

pQCD standard approach

collinear approximation → transverse momenta of the incident partons are assumed to be zero

- quadrupuly differential cross section:

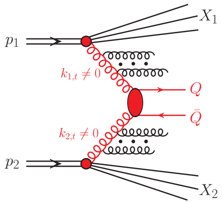
$$\frac{d\sigma}{dy_1 dy_2 d^2p_t} = \frac{1}{16\pi^2\hat{s}^2} \sum_{i,j} x_1 p_i(x_1, \mu^2)\; x_2 p_j(x_2, \mu^2)\; \overline{|\mathcal{M}_{ij}|^2}$$

- $p_i(x_1, \mu^2), p_j(x_2, \mu^2)$ - standard parton distributions in hadron (e.g. CTEQ, GRV, GJR, MRST, MSTW)
- NLO on-shell matrix elements well-known

several packages:

- **FONLL** (Cacciari *et al.*) - one particle distributions and total cross sections
- more exclusive tools - PYTHIA. HERWIG, MC@NLO

k_t-factorization (semihard) approach



- charm and bottom quarks production at high energies $\longrightarrow$ gluon-gluon fusion
- QCD collinear approach $\rightarrow$ only inclusive one particle distributions, total cross sections

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

- multi-differential cross section

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

- off-shell $\overline{|\mathcal{M}_{gg\to Q\bar{Q}}|^2} \longrightarrow$ Catani, Ciafaloni, Hautmann (very long formula)
- major 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
- $x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2)$,

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

Unintegrated parton distribution functions

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

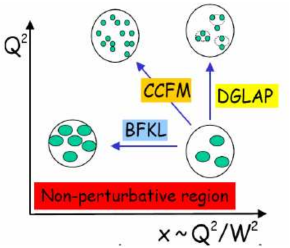
$$xp_k(x,\mu_F^2) = \int_0^\infty d\kappa_t^2 \mathcal{F}(x,\kappa_t^2,\mu_F^2)$$

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

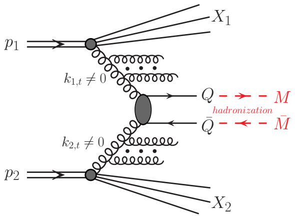
gg-fusion dominance ⇒ great test of existing unintegrated gluon densities!
especially at LHC (small-x)

several models:

- Kwiecinski (CCFM, wide x-range)
- Kimber-Martin-Ryskin (higher x-values)
- Kutak-Stasto (small-x, saturation effects)
- Ivanov-Nikolaev, GBW, Karzeev-Levin, etc.



Fragmentation functions technique



- fragmentation functions extracted from e^+e^- data
- often used: Braaten et al., Kartvelishvili et al., Peterson et al.
- rescalling transverse momentum
  at a constant rapidity (angle)

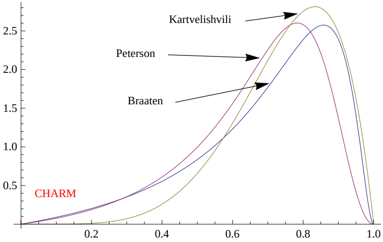
- from heavy quarks to heavy mesons:

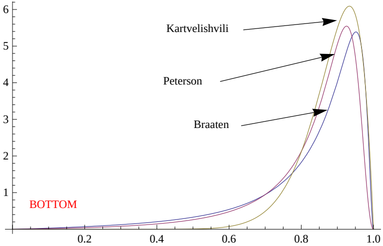
$$\frac{d\sigma(y, p_t^M)}{dy d^2 p_t^M} \approx \int \frac{D_{Q\to M}(z)}{z^2} \cdot \frac{d\sigma(y, p_t^Q)}{dy d^2 p_t^Q} dz$$

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

- **approximation:**
  rapidity unchanged in the fragmentation process $\to y_Q \approx y_M$

Different models of FFs





- **Peterson et al.**

  $$D_{Q\to M}(z) = \frac{N}{z[1-(1/z)-\varepsilon_Q/(1-z)]}$$

  $\varepsilon_c = 0.06$, $\varepsilon_b = 0.006$ from PDG

- Braaten et al.

  $$D_{Q\to M}(z) = N\frac{rz(1-z)^2}{(1-(1-r)z)^6}(F_1 + F_2)$$

  $$F_1 = 6 - 18(1-2r)z + (21 - 74r + 68r^2)z^2$$

  $$F_2 = 3(1-r)^2(1-2r_2r^2)z^4 - 2(1-r)(6-19r+18r^2)z^3$$

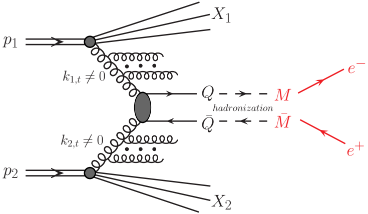
  $r_c = 0.2$, $r_b = 0.07$

- Kartvelishvili et al.

  $$D_{Q\to M}(z) = N(1-z)z^a$$

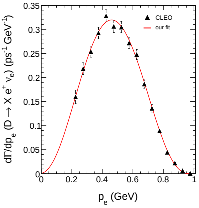
  $a_c = 5.0$, $a_b = 14.0$

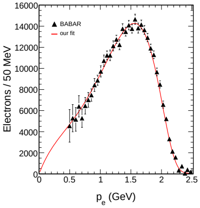
Experimental decay functions and Monte Carlo approach



- **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.)%

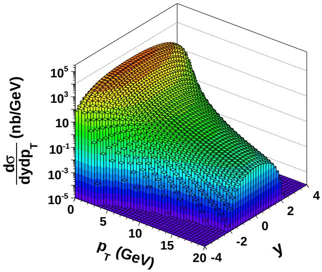
- Monte Carlo $\Longrightarrow$ directions and lengths of outgoing leptons momenta
- Our input $\Longrightarrow$ experimental decay functions: $f_{CLEO}(p)$, $f_{BABAR}(p)$

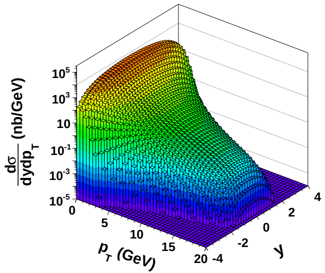


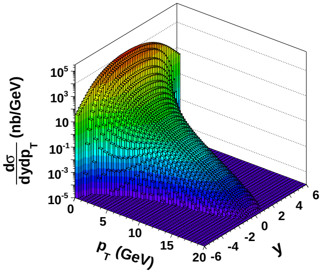


- approximation:
  D mesons $(D^{\pm}, D^0, \bar{D}^0, D_S^{\pm}, D^{*0}, D^{*\pm}, D_S^{*\pm})$
  B mesons $(B^{\pm}, B^0, \bar{D}^0, B_S^0, \bar{B}_S^0, B^*, B_S^*)$
  BR(D and $B \longrightarrow X\ e\ \nu \approx 10\%$)

Effects of hadronization and decay

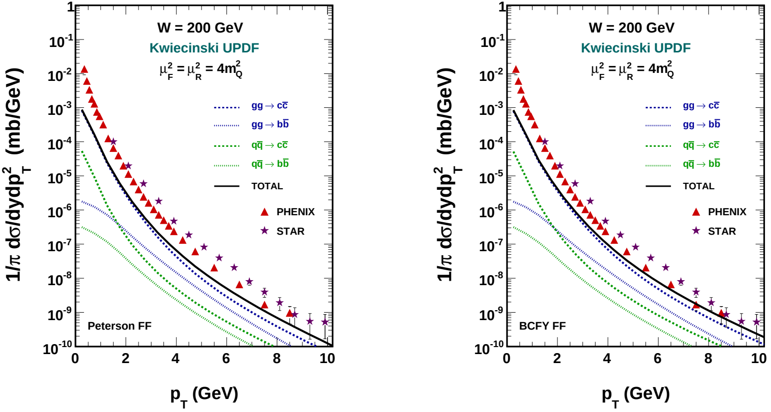






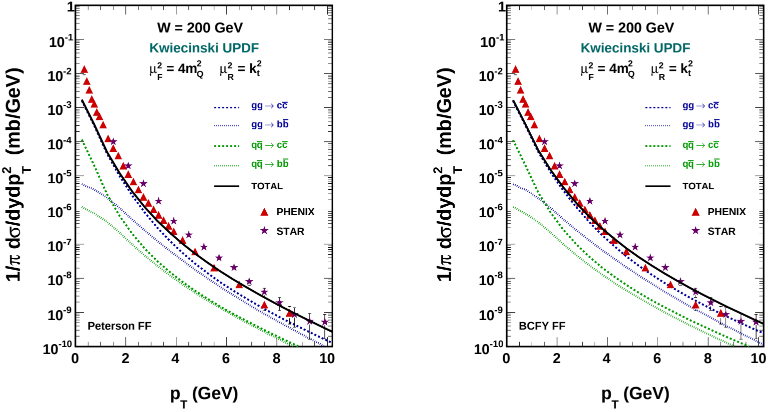
- degradation of transverse momentum, much softer spectra for electrons
- broader distributions in rapidity at small transverse momenta

p_t distributions vs. PHENIX and STAR data



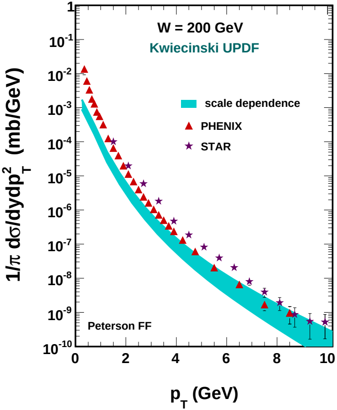
- $q\bar{q}$ contributions are negligible

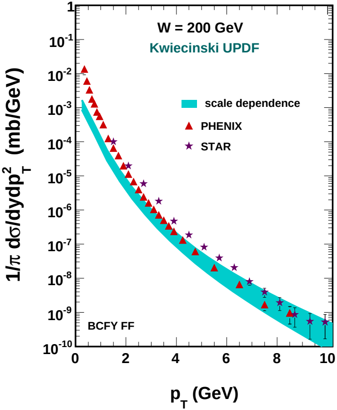
p_t distributions vs. PHENIX and STAR data



- very strong dependence on μ_R and μ_F

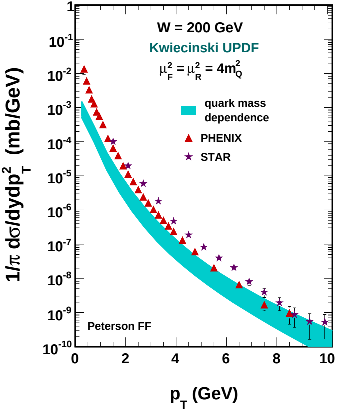
Uncertainties due to factorization and renormalization scales

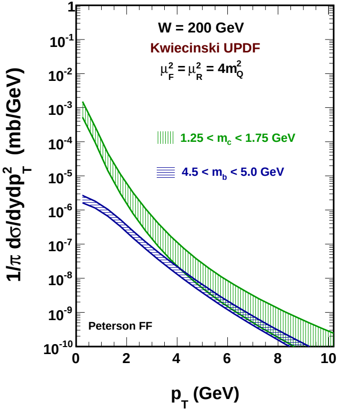




- upper limit: $\mu_R^2 = k_t^2$ and $\mu_F^2 = 4m_Q^2$
- lower limit: $\mu_R^2 = \mu_F^2 = m_{1t}^2 + m_{2t}^2$

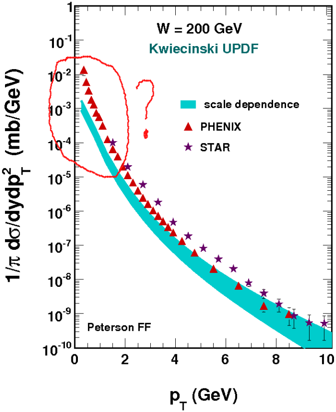
Uncertainties due to heavy quarks masses



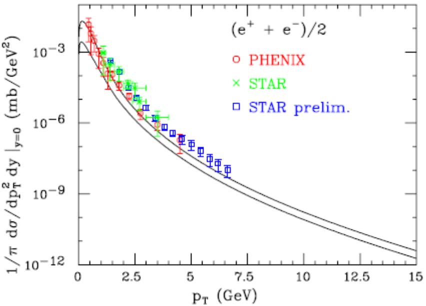


- charm quarks are much more sensitive to the m_Q value

LO k_t-factorization vs. FONLL

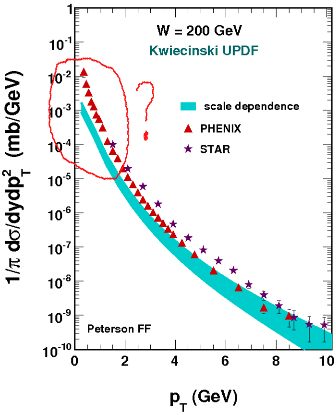


Phys. Rev. Lett. 95, 122001 (2005)



- large uncertainties $\rightarrow$ good description only with upper limits
- LO k_t-factorization results comparable with FONLL at $p_t > 2$ GeV
  BUT some missing strength at low transverse momenta

How to improve LO k_t-factorization?



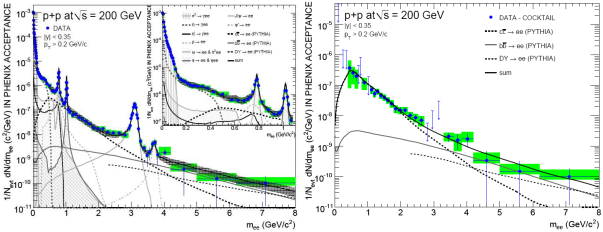
- to apply other UGDFs (KMR, Kutak-Stasto)
- some of mechanisms (e.g. flavour excitation) which are automatically included in NLO processes should be included by hand to improve LO calculations
- single quark production in the k_t-factorization

- large uncertainties → good description only with upper limits
- LO k_t-factorization results comparable with FONLL at $p_t > 2$ GeV BUT some missing strength at low transverse momenta

Inclusive measurements of e^+e^- pairs

- **e^+e^- pair invariant mass spectrum** (0 – 8 GeV)

  PHENIX, p+p @ $\sqrt{s} = 200$ GeV, A. Adare, et al., Phys. Lett. **B 670** (2009), 313-320



- dielectron mass spectrum dominated by semileptonic decays of charm and bottom mesons → nonphotonic electrons
- alternative method → dielectron correlations
- a new tool for testing pQCD techniques, fragmentation functions and semileptonic decays of D and B mesons

Cross section for nonphotonic e^+e^- pairs production

- multi-differential cross section:

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

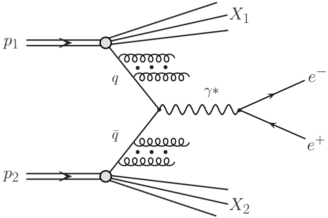
- hadronization of the quark/antiquark pair:

$$\frac{d\sigma(y_1, p_{1t}^M, y_2, p_{2t}^M, \phi)}{dy_1 dp_{1t}^M dy_2 dp_{2t}^M d\phi} \approx \int \frac{D_{Q\to M}(z_1)}{z_1} \cdot \frac{D_{\bar{Q}\to \bar{M}}(z_2)}{z_2} \cdot \frac{d\sigma(y_1, p_{1t}^Q, y_2, p_{2t}^Q, \phi)}{dy_1 dp_{1t}^Q dy_2 dp_{2t}^Q d\phi} dz_1 dz_2$$

where: $p_{1t}^Q = \frac{p_{1t}^M}{z_1}$, $p_{2t}^Q = \frac{p_{2t}^M}{z_2}$ and $z_1, z_2 \in (0,1)$

- the same experimental decay functions with proper normalization: $BR(M \to e) \cdot BR(M \to e) \approx 0.01$
- new differential distributions: $\varphi_{e^+e^-}$, $M_{e^+e^-}$, $p_{t,sum}$

Related processes: Drell-Yan mechanism



- Szczurek, G. Ślipek
  Phys. Rev. **D 78** (2008) 114007
- k_t-factorization approach with Kwieciński UPDFs
- 0-th and 1-st order $q\bar{q}$-anihilation and 1-st order Compton scattering

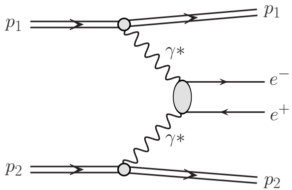
- 0-th order Drell-Yan cross section

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \sum_f \int \frac{d^2\kappa_{1t}}{\pi} \frac{d^2\kappa_{2t}}{\pi} \frac{1}{16\pi^2(x_1x_2s)^2} \delta^2\left(\vec{\kappa}_{1t}+\vec{\kappa}_{2t}-\vec{p}_{1t}-\vec{p}_{2t}\right)$$
$$\left[\mathcal{F}_{q_f}(x_1,\kappa_{1t}^2,\mu_F^2)\,\mathcal{F}_{\bar{q}_f}(x_2,\kappa_{2t}^2,\mu_F^2)\,\overline{|M(q\bar{q}\to e^+e^-)|^2}\right.$$
$$\left.+\,\mathcal{F}_{\bar{q}_f}(x_1,\kappa_{1t}^2,\mu_F^2)\,\mathcal{F}_{q_f}(x_2,\kappa_{2t}^2,\mu_F^2)\,\overline{|M(q\bar{q}\to e^+e^-)|^2}\,\right]$$

- **unintegrated quark distributions**

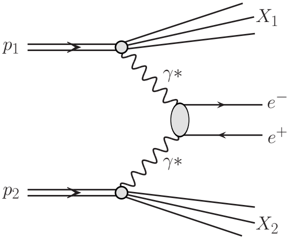
Related processes: elastic and inelastic $\gamma\gamma \to e^+e^-$ reactions

- $pp \to ppe^+e^-$



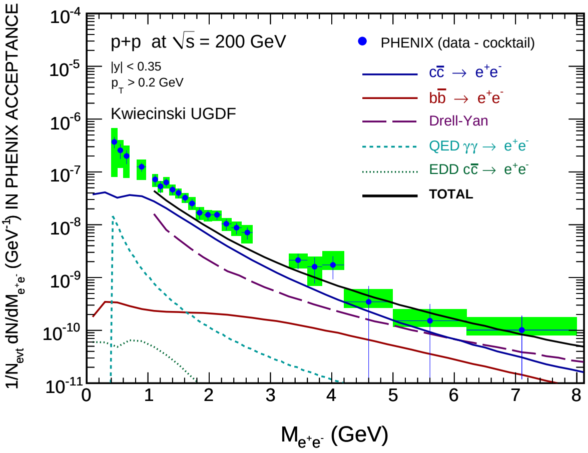
- exact momentum space calculations with 4-body phase space
- consistent with LPAIR Monte Carlo package

- $pp \to X_1X_2e^+e^-$



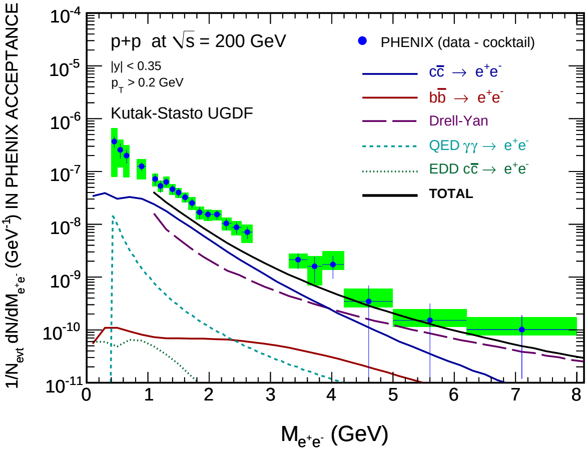
- collinear kinematics
- MRST 2004 (Martin-Roberts-Stirling-Thorne) photon distributions in nucleon

Dilepton invariant mass spectrum



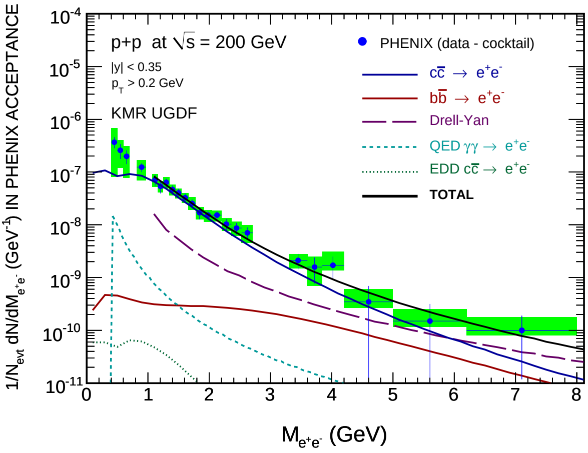
- similar description of the data like in the single lepton case

Dilepton invariant mass spectrum



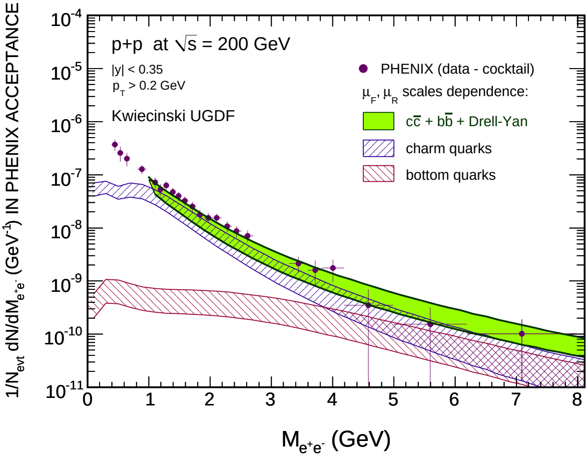
- Kutak-Stasto UGDF dedicated for smaller *x*-values

Dilepton invariant mass spectrum

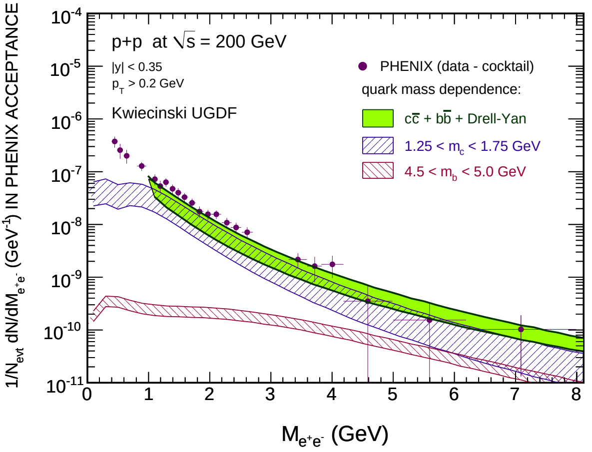


- very good description of the data even at small invariant masses

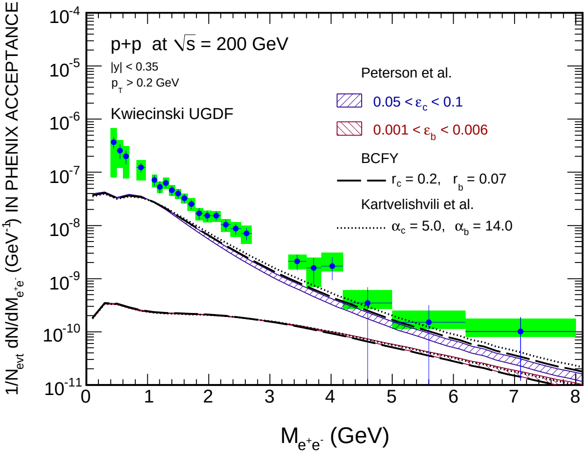
Uncertainties - μ_F, μ_R scale dependence



Uncertainties - quark mass dependence

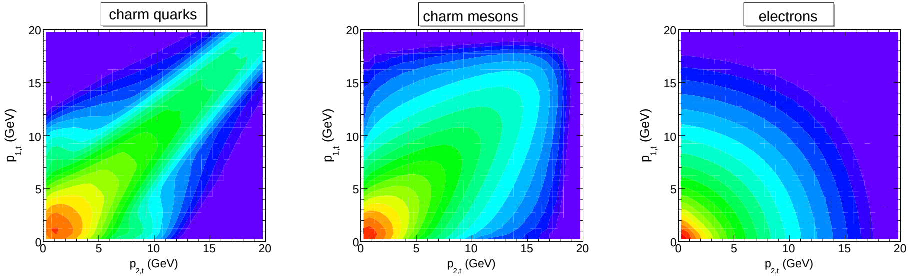


Sensitivity to the fragmentation function



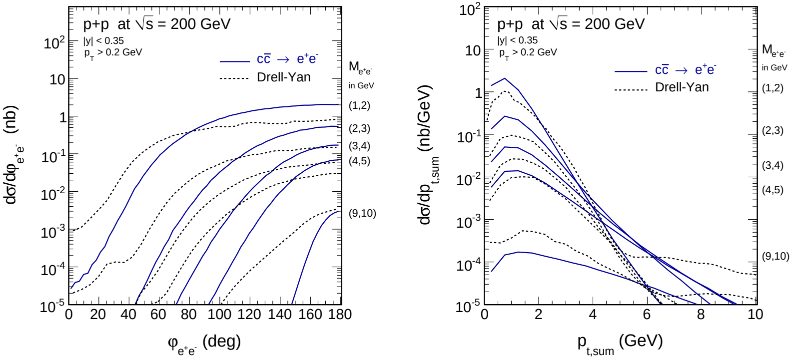
- this source of uncertainties can be neglected, especially at low-p_t

Transverse momenta correlations



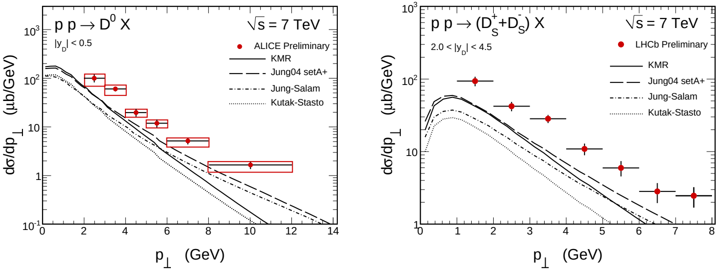
- e^+e^- decorrelation during each step of calculation

Azimuthal and $p_{t,sum}$ correlations



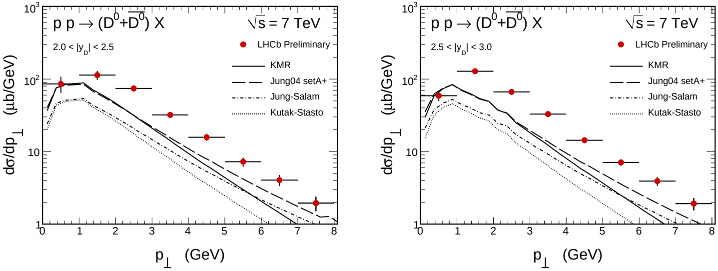
- azimuthal angle between outgoing leptons
- $\overrightarrow{p_{t,sum}} = \overrightarrow{p_{1t}} + \overrightarrow{p_{2t}}$

LHC, charmed mesons



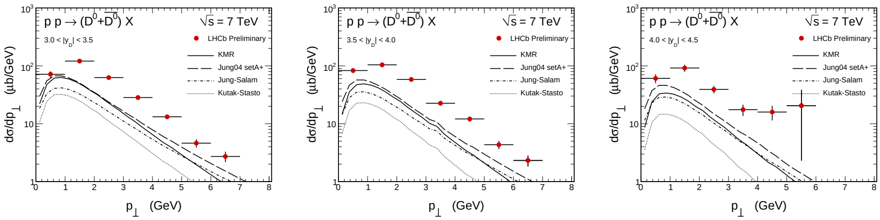
ALICE, LHCb (LHCb-CONF-2010-013)

LHC, charmed mesons



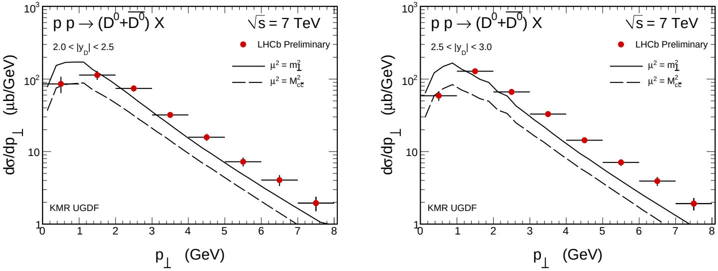
Kimber-Martin-Ryskin, Jung, Kutak-Stasto UGDF

LHC, charmed mesons



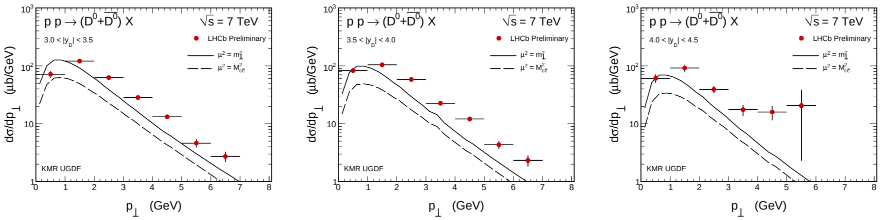
something missing?

KMR UGDF, scale dependence



$\mu^2 = M^2_{c\bar{c}}$ or m_t^2

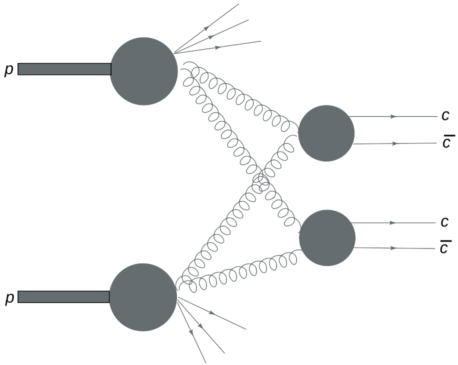
KMR UGDF, scale dependence



$\mu^2 = M_{c\bar{c}}^2$ or m_t^2

Production of two $c\bar{c}$ pairs in double-parton scattering

Consider two hard (parton) scatterings



Luszczak, Maciula, Szczurek, arXiv:1111.3255

Formalism

Consider reaction: $pp \to c\bar{c}c\bar{c}X$

Modeling double-parton scattering

Factorized form:

$$\sigma^{DPS}(pp \to c\bar{c}c\bar{c}X) = \frac{1}{2\sigma_{eff}}\sigma^{SPS}(pp \to c\bar{c}X_1) \cdot \sigma^{SPS}(pp \to c\bar{c}X_2).$$

The simple formula can be generalized to include differential distributions

$$\frac{d\sigma}{dy_1 dy_2 d^2p_{1t} dy_3 dy_4 d^2p_{2t}} = \frac{1}{2\sigma_{eff}} \cdot \frac{d\sigma}{dy_1 dy_2 d^2p_{1t}} \cdot \frac{d\sigma}{dy_3 dy_4 d^2p_{2t}} \, .$$

σ_{eff} is a model parameter (12-15 mb)

Formalism

$$d\sigma^{DPS} = \frac{1}{2\sigma_{eff}} F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2) F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$$
$$d\sigma_{gg \to c\bar{c}}(x_1, x_1', \mu_1^2) d\sigma_{gg \to c\bar{c}}(x_2, x_2', \mu_2^2) \; dx_1 dx_2 dx_1' dx_2' \, .$$

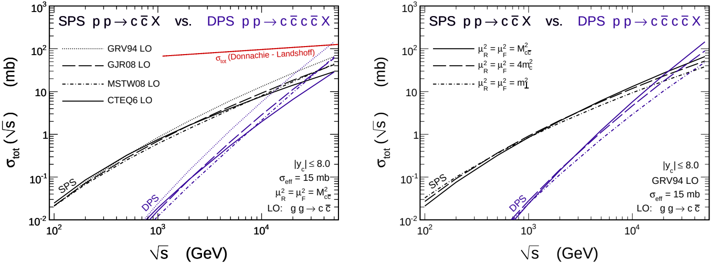
$F_{gg}(x_1, x_2, \mu_1^2, \mu_2^2)$, $F_{gg}(x_1' x_2', \mu_1^2, \mu_2^2)$
are called double parton distributions

dPDF are subjected to special evoultion equations

single scale evolution: Snigireev

double scale evolution: Ceccopieri, Gaunt-Stirling

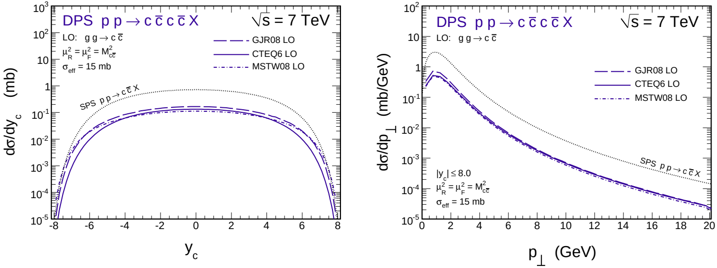
DPS results



Inclusive cross section more difficult to calculate

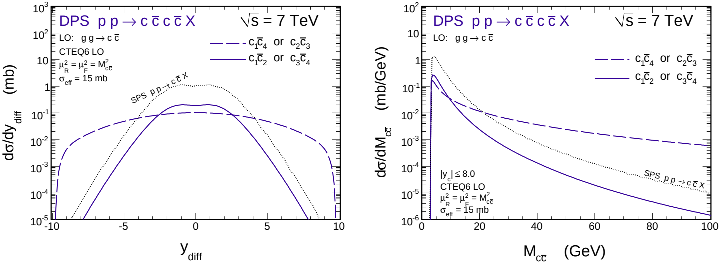
$\sigma_{SS}, 2\sigma_{DS} < \sigma_c^{inclusive} < \sigma_{SS} + 2\sigma_{DS}$

DPS results



In the factorized model inclusive double-scattering distributions in y and p_t are identical as for single scattering.

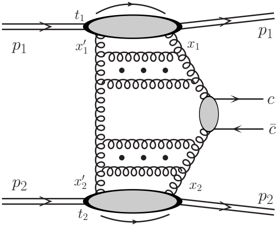
DPS results



DPS: large rapidity differences, large invariant masses

- Not possible for quarks (antiquarks)
- Difficult for mesons
- Nonphotonic electrons (muons) ?

Kaidalov-Khoze-Martin-Ryskin approach



The amplitude for $p\,p \to p\,p\,Q\,\bar{Q}$:

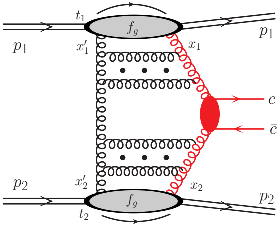
$$\mathcal{M}_{\lambda_q \lambda_{\bar{q}}} = s \cdot \pi^2 \frac{1}{2} \frac{\delta_{c_1 c_2}}{N_c^2 - 1} \Im \int d^2 q_{0\perp} V^{c_1 c_2}_{\lambda_q \lambda_{\bar{q}}}$$

$$\times \frac{f_g^{\rm off}(x', x_1, q_{0\perp}^2, q_{1\perp}^2, t_1) f_g^{\rm off}(x', x_2, q_{0\perp}^2, q_{2\perp}^2, t_2)}{q_{0\perp}^2\, q_{1\perp}^2\, q_{2\perp}^2}$$

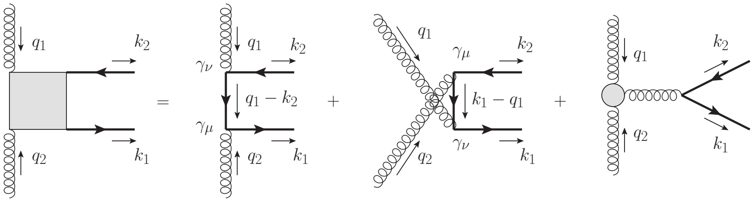
- k_t-factorization approach with exact **off-shell** $g^* g^* \to Q\bar{Q}$ matrix element (without any approximations and selection rules)
- off-diagonal unintegrated gluon distributions
- genuine 4-body reaction with exact kinematics in the full phase space:

$$d\sigma = \frac{1}{2s} |\mathcal{M}_{2\to4}|^2 (2\pi)^4 \delta^4(p_a + p_b - p_1 - p_2 - p_3 - p_4) \frac{d^3 p_1}{(2\pi)^3 2E_1} \frac{d^3 p_2}{(2\pi)^3 2E_2} \frac{d^3 p_3}{(2\pi)^3 2E_3} \frac{d^3 p_4}{(2\pi)^3 2E_4}$$

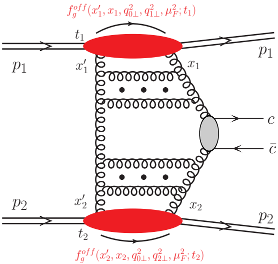
$g^* g^* \to Q\bar{Q}$ matrix element



- gluon-gluon fusion dominant at high energies
- Effective vertex in QMRK approach
- 3-gluon vertex drops out in projection to the color singlet final state



Off-diagonal unintegrated gluon distributions



- **KMR method** based on Shuvaev et al. prescription for collinear off-diagonal PDFs $(x' \ll x_{1,2})$

$$f_g^{\rm off}(x', x_{1,2}, q_{1/2\perp}^2, q_{0\perp}^2, \mu_F^2) \simeq R_g(x') \cdot f_g(x_{1,2}, q_{1/2\perp}^2, \mu_F^2)$$

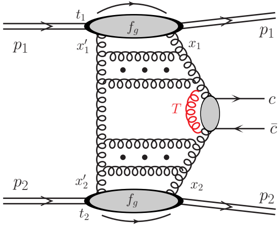
- two gluons $\Rightarrow$ one gluon effective kinematics $Q_{1,2t}^2 = min(q_{0t}^2, q_{1,2t}^2)$

$$f_g^{KMR}(x, x', Q_t^2, \mu^2; t) = R_g \frac{\partial}{\partial \ln q_t^2} \left[xg(x, q_t^2) \sqrt{T_g(q_t^2, \mu^2)} \right]_{q_t^2 = Q_t^2} F(t)$$

- R_g: *accounts for skewed effect*
- $\frac{\partial}{\partial \ln q_t^2}[xg(x,q_t^2)]$: *integrated density, defined at $Q_t > Q_0$*
- $\sqrt{T_g(q_t^2,\mu^2)}$: *Sudakov f.f. (ensures the purity of rapidity gaps)*
- $F(t)$: *effective f.f.* $F(t) = \exp(bt/2)$, $b = 4\,GeV^{-2}$

- $R_g = \frac{2^{2\lambda+3}}{\sqrt{\pi}} \frac{\Gamma(\lambda+5/2)}{\Gamma(\lambda+4)} \approx 1.2 - 1.3$ at high energies

Sudakov form factor and gap survival probability



- suppresion of real emissions from the active gluon during the evolution so the rapidity gap survive (probability of not emitting any extra partons)

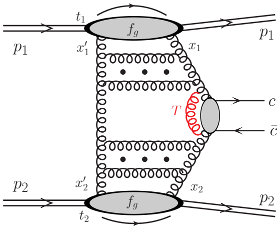
$$T_g(q_\perp^2, \mu^2) = \exp\left(-\int_{q_\perp^2}^{\mu^2} \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2} \frac{\alpha_s(k_\perp^2)}{2\pi} \times \right.$$

$$\times \left. \int_0^{1-\Delta} \left[zP_{gg}(z) + \sum_q P_{qg}(z) \right] dz \right)$$

$$\Delta = \frac{k_\perp}{k_\perp + M_{q\bar{q}}}$$

- crucial **sensitivity to upper and lower scales** $q_\perp^2$, μ^2

Sudakov form factor and gap survival probability



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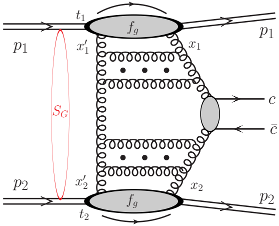
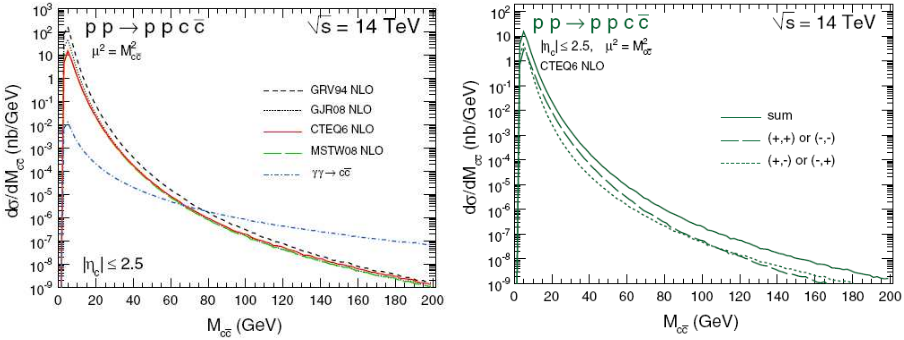


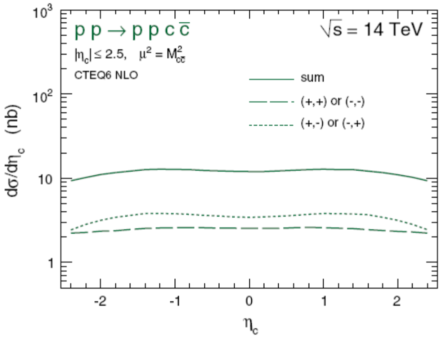
- **absorption corrections** (soft rescattering effects between interacting protons)
- not universal value → depends on collision energy and typical proton transverse momenta
- $S_g^{LHC} = 0.03$, $S_g^{TEV} = 0.1$, $S_g^{RHIC} = 0.15$

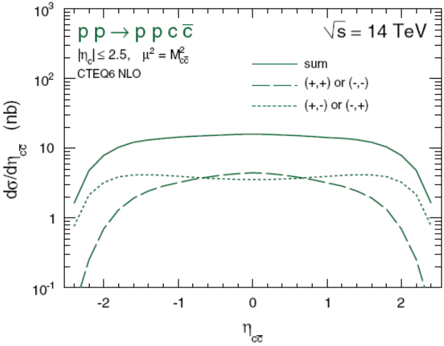
LHC @ $\sqrt{s} = 14$ TeV



- some uncertainties due to PDFs
- different quark helicity states

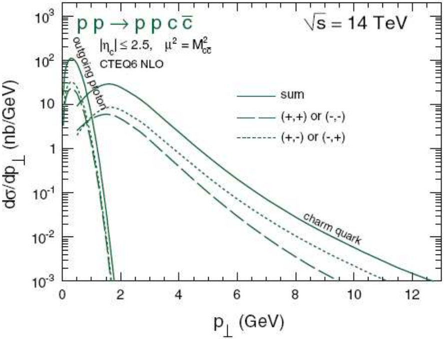
LHC @ $\sqrt{s} = 14$ TeV

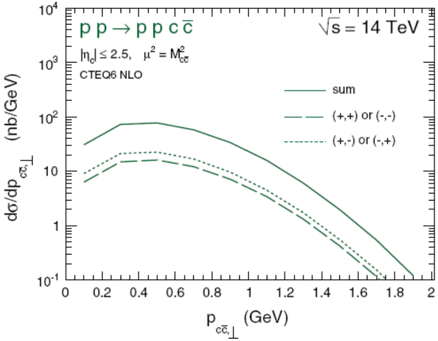




- rather flat pseudorapidity distributions

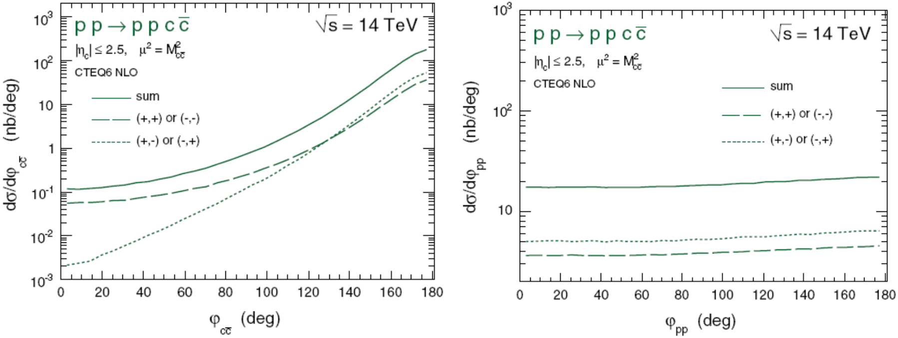
LHC @ $\sqrt{s} = 14$ TeV





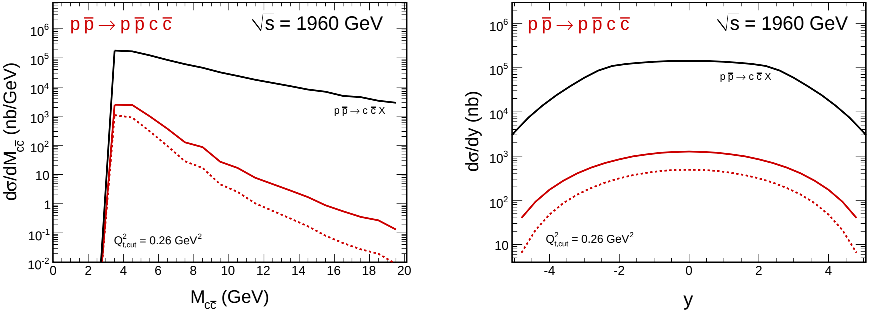
- quark distributions fully perturbative, opposite sign helicities dominates at large transverse momenta
- proton distributions much narrower (below 1 GeV) and controlled by non-perturbative proton form factor $\rightarrow$ sensitive to internal structure of the proton

LHC @ $\sqrt{s} = 14$ TeV



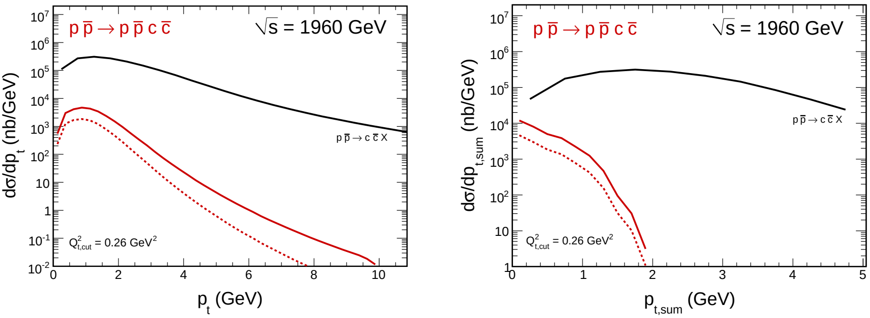
- quarks preference for the back-to-back configuration, opposite helicities much more correlated
- protons almost decorrelated

Tevatron @ $\sqrt{s} = 1.96$ TeV



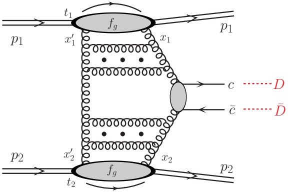
- exclusive/inclusive $\sim 0.1 - 1\%$
- $M_{c\bar{c}}$, p_t, $p_{t,sum}$ distributions much steeper, narrower

Tevatron @ $\sqrt{s} = 1.96$ TeV



- exclusive/inclusive $\sim 0.1 - 1\%$
- $M_{c\bar{c}}$, p_t, $p_{t,sum}$ distributions much steeper, narrower

Fragmentation functions (FF) technique



- phenomenology $\rightarrow$ fragmentation functions extracted from e^+e^- data
- often used: Braaten et al., Kartvelishvili et al., Peterson et al.
- numerically performed by rescalling transverse momentum at a constant rapidity (angle)

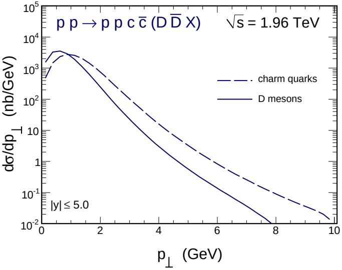
- from heavy quarks to heavy mesons:

$$\frac{d\sigma(y_1, p_{1t}^M, y_2, p_{2t}^M, \phi)}{dy_1 dp_{1t}^M dy_2 dp_{2t}^M d\phi} \approx \int \frac{D_{Q\rightarrow M}(z_1)}{z_1} \cdot \frac{D_{\bar{Q}\rightarrow \bar{M}}(z_2)}{z_2} \cdot \frac{d\sigma(y_1, p_{1t}^Q, y_2, p_{2t}^Q, \phi)}{dy_1 dp_{1t}^Q dy_2 dp_{2t}^Q d\phi} dz_1 dz_2$$

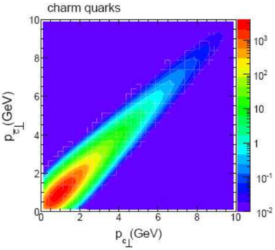
where: $p_{1t}^Q = \frac{p_{1t}^M}{z_1}$, $p_{2t}^Q = \frac{p_{2t}^M}{z_2}$ and $z_{1,2} \in (0,1)$

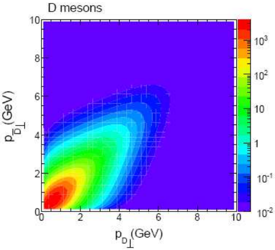
- **approximation:**
  rapidity unchanged in the fragmentation process $\rightarrow y_Q = y_M$

Numerical effects of the fragmentation

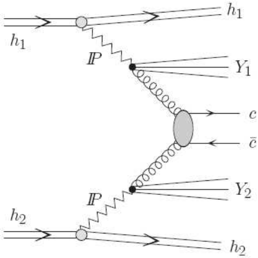


- sufficient approach for rough predictions before having exclusive Monte Carlo hadronization
- decorrelation during fragmentation process
- work in progress:
  $c \to D^+ \to K^-\pi^+\pi^+$ (BF $\sim$ 9.51%)
  $c \to D^0 \to K^-\pi^+$ (BF $\sim$ 3.80%)
  $c \to D^0 \to$ 2-prongs (BF $\sim$ 67.0%)
  $c \to D_s^+ \to K^+K^-\pi^+$ (BF $\sim$ 5.2%)





Inclusive Double Pomeron Exchange



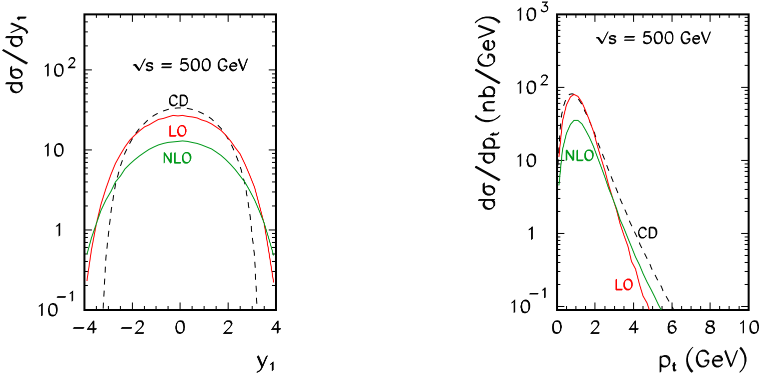
- Ingelman and Schlein approach
- well defined partonic structure of Pomeron
- hard process takes place in a Pomeron-Pomeron interactions

$$\frac{d\sigma_{DD}}{dy_1\, dy_2\, dp_t^2} = K \frac{\left|M\right|^2}{16\pi^2 \hat{s}^2} \left[\left(x_1 q_f^D(x_1,\mu^2)\, x_2 \bar{q}_f^D(x_2,\mu^2) \right) + \left(x_1 \bar{q}_f^D(x_1,\mu^2)\, x_2 q_f^D(x_2,\mu^2) \right) \right]$$

$$q_f^D(x,\mu^2) = \int dx_{I\!P}\, d\beta\, \delta(x - x_{I\!P}\beta) q_{f/I\!P}(\beta,\mu^2)\, f_{I\!P}(x_{I\!P}) = \int_x^1 \frac{dx_{I\!P}}{x_{I\!P}}\, f_{I\!P}(x_{I\!P}) q_{f/I\!P}\left(\frac{x}{x_{I\!P}},\mu^2\right) \tag{1}$$

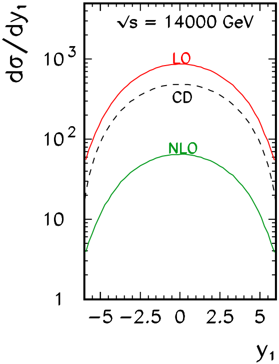
convolution of the flux of Pomerons $f_{I\!P}(x_{I\!P})$ and the parton distribution in the Pomeron $q_{f/I\!P}(\beta,\mu^2)$

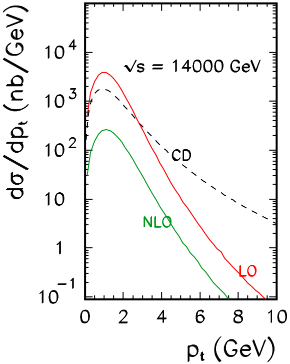
RHIC @ $\sqrt{s} = 500$ GeV



- dashed black - inclusive central diffraction
- solid red and green - exclusive central diffraction

LHC @ $\sqrt{s} = 14$ TeV

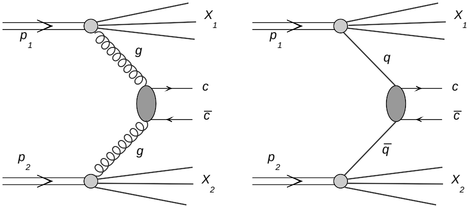




- huge difference between LO or NLO PDFs for exclusive mechanism
  $\Rightarrow$ good description of the exclusive dijets data with NLO PDFs

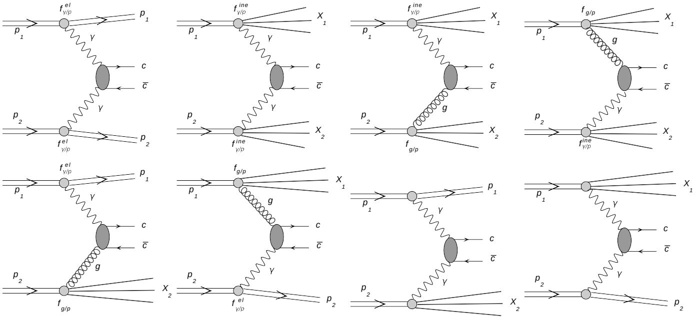
QCD mechanisms

Standard QCD LO mechanisms:



Let us considered photon-induced mechanisms

Photon-induced mechanisms

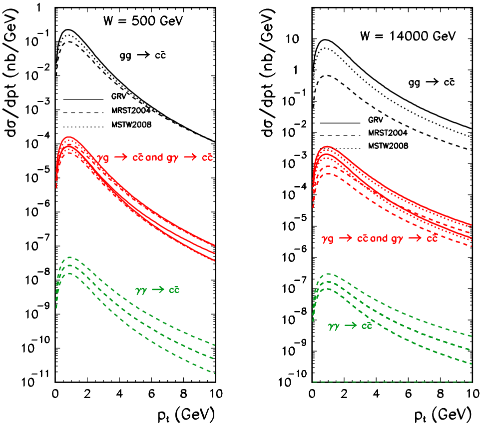


Photon as a parton of the proton

The factorization of the QED-induced collinear divergences leads to QED-corrected evolution equations for the parton distributions of the proton.

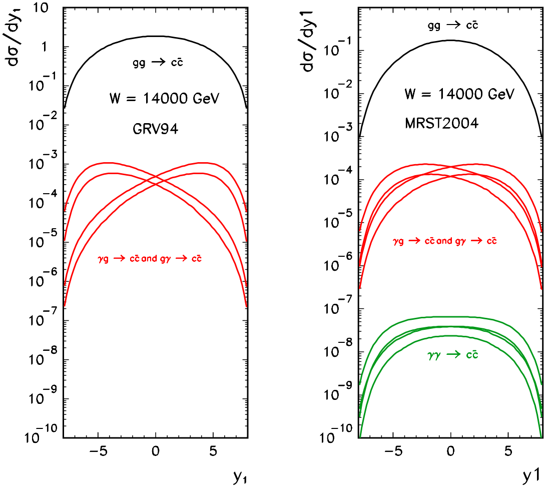
$$
\begin{aligned}
\frac{\partial q_i(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{qq}(y)\; q_i\left(\frac{x}{y},\mu^2\right) + P_{qg}(y)\; g\left(\frac{x}{y},\mu^2\right) \right\} \\
&+ \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ \tilde{P}_{qq}(y)\; e_i^2 q_i\left(\frac{x}{y},\mu^2\right) + P_{q\gamma}(y)\; e_i^2 \gamma\left(\frac{x}{y},\mu^2\right) \right\} \\
\frac{\partial g(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha_S}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{gq}(y)\; \sum_j q_j\left(\frac{x}{y},\mu^2\right) + P_{gg}(y)\; g\left(\frac{x}{y},\mu^2\right) \right\} \\
\frac{\partial \gamma(x,\mu^2)}{\partial \log \mu^2} &= \frac{\alpha}{2\pi} \int_x^1 \frac{dy}{y} \left\{ P_{\gamma q}(y)\; \sum_j e_j^2\; q_j\left(\frac{x}{y},\mu^2\right) + P_{\gamma\gamma}(y)\; \gamma\left(\frac{x}{y},\mu^2\right) \right\},
\end{aligned}
$$

Distributions in transverse momentum

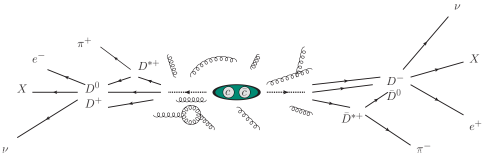


Luszczak, Maciula, Szczurek, Phys. Rev. **D84** (2011) 4018

Distributions in rapidity



Off-shell quarks and antiquarks



$$
\begin{aligned}
\sigma_{pp\to ppQ\bar{Q}} &= \int dm_1 dm_2\, \rho(m_1)\rho(m_2) \int dy_1 dy_2 d^2p_t \\
const & \Big[x_1 g_1(x_1,\mu_F^2) x_2 g_2(x_2,\mu^2) |\mathcal{M}_{gg\to Q\bar{Q}}(m_1,m_2)|^2 \\
&+ x_1 q_1(x_1,\mu_F^2) x_2 \bar{q}_2(x_2,\mu_F^2) |\mathcal{M}_{q\bar{q}\to Q\bar{Q}}(m_1,m_2)|^2 \\
&+ x_1 \bar{q}_1(x_1,\mu_F^2) x_2 q_2(x_2,\mu_F^2) |\mathcal{M}_{q\bar{q}\to Q\bar{Q}}(m_1,m_2)|^2 \,.
\end{aligned}
$$

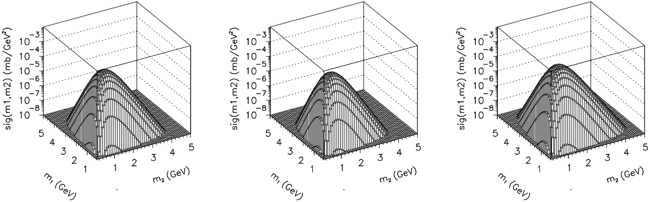
$\rho(m_1), \rho(m_2)$ distribution of quark(antiquark) mass

(2)

We take log-normal distributions

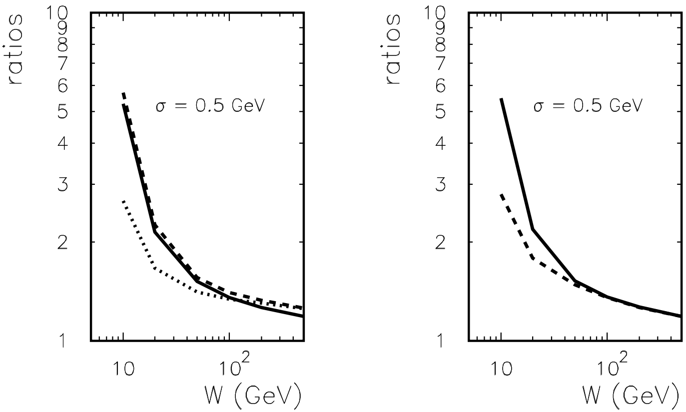
Off-shell quarks

Now we have two-dim distribution in quark (m_1) and antiquark (m_2) masses



left: gg midle: $q\bar{q}(pp)$ right: $q\bar{q}(p\bar{p})$
W =20 GeV

Off-shell quarks

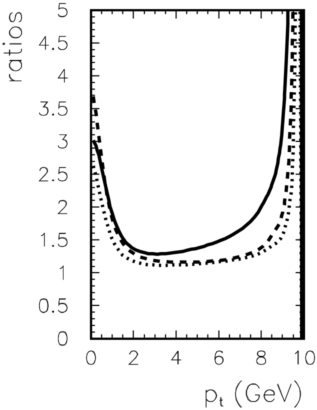


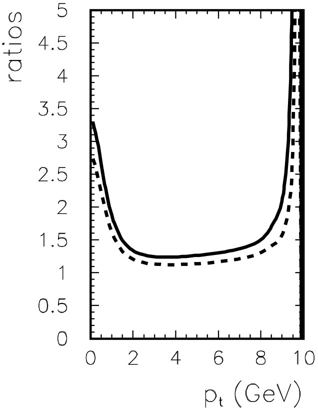
left: gg, $q\bar{q}(pp)$, $q\bar{q}(p\bar{p})$

right: pp (solid), $p\bar{p}$ (dashed)

large effect at small energies

Off-shell quarks





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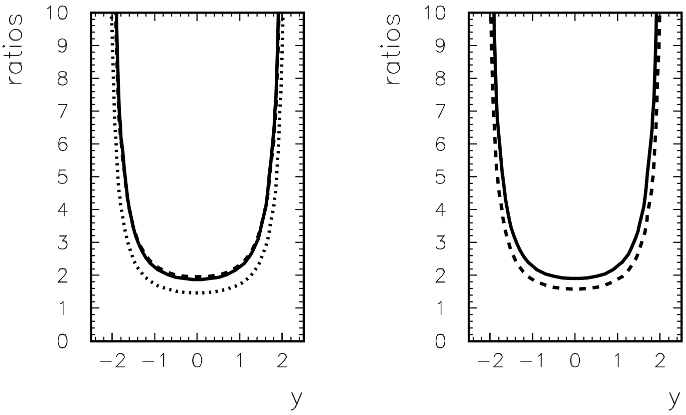
Off-shell quarks



left: gg, $q\bar{q}(pp)$, $q\bar{q}(p\bar{p})$
W =20 GeV

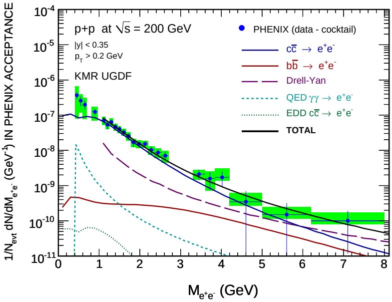
right: pp (solid), $p\bar{p}$ (dashed)

charm/bottom cross section at LHC

Conclusions:

- very good agreement with PHENIX data using KMR UGDFs
- electron-hadron correlations → way to separate charm and bottom contributions

A. Mischke, Phys. Lett. B 671 (2009) 361



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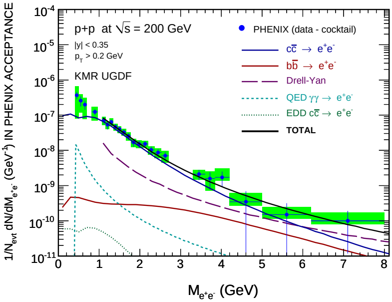
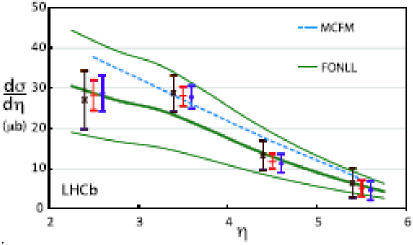


LHC era:

- nonphotonic electrons at LHC ⇒ selection of UGDFs at much smaller x-values
- charm and bottom at LHCb in unique kinematical region: $2 \leq |\eta| \leq 6$, $\sqrt{s} = 7$ TeV ⇒ very small x region!!!



Conclusions

- Huge contribution of double-parton scattering for $pp \to (c\bar{c})(c\bar{c})X$.
  Go to mesons and nonphotonic electrons (muons).
- $pp \to p(c\bar{c})p$ requires Monte Carlo studies to understand whether it can be measured.
- Single and central diffractive production should be measured.
- Photon-induced contributions are small ($\sim$ 1 %).
- off-shell $c\bar{c}$ production $\Rightarrow$ systematic studies at low energies (RHIC low-energy scan?)

Thank You for attention!