Open charm production at high energies and the quark Reggeization hypothesis

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Plan

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2. **Effective vertices in the QMRK approach**
3. **Fragmentation model**
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5. D**-meson production at the Fermilab Tevatron**
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QMRK approach and the particle Reggeization hypothesis

Regge limit of QCD: $\Lambda_{QCD} \ll \mu \ll \sqrt{S} \Rightarrow x = \mu/S \ll 1 \Rightarrow$

$\Rightarrow$ large contributions of the type $[\alpha_s \ln(1/x)]^n$,
described by BFKL(-like) evolution equations
for unintegrated PDFs $\Phi^p_{g(q)}(x, |\boldsymbol{q}_T|^2, \mu^2)$.

Numerical calculations:

- the Kimber-Martin-Ryskin (KMR) prescription for UPDFs;
- input: collinear densities by Martin-Roberts-Stirling-Thorne (MRST).

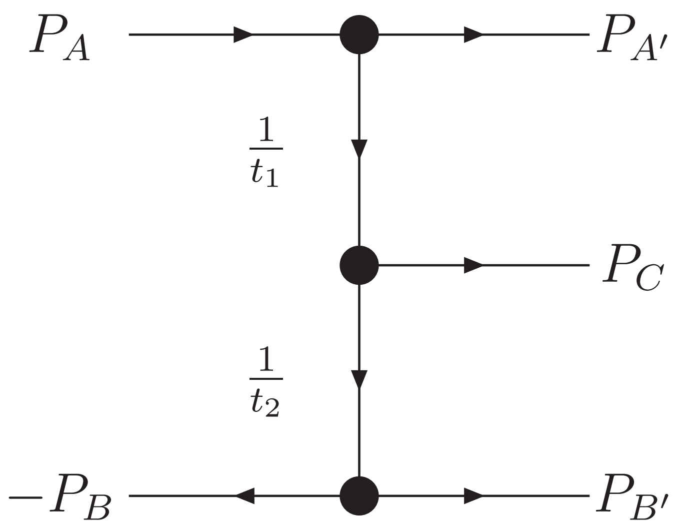
QMRK approach and the particle Reggeization hypothesis

1. Electron Reggeization in QED:
   M. Gellmann, M. L. Goldberger, F. E. Low, E. Marx, and
   F. Zachariasen, 1964.

2. Gluon Reggeization in QCD:
   E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, 1976;
   I. I. Balitsky and L. N. Lipatov, 1978.

3. Quark Reggeization in QCD:
   V. S. Fadin and V. E. Sherman, 1976.

QMRK approach and the particle Reggeization hypothesis



$$S_{AB} = (P_A + P_B)^2, \quad S_{A'C} = (P_{A'} + P_C)^2, \quad S_{B'C} = (P_{B'} + P_C)^2$$

$$S_{A'C},\, S_{B'C},\, P_C^2,\, P_{C_T}^2 \ll S_{AB}, \quad (P_A \cdot P_{A'}) \ll (P_A \cdot P_C) \ll (P_A \cdot P_{B'})$$

$$y_{A'} \gg y_C \gg y_{B'}$$

QMRK approach and the particle Reggeization hypothesis

$$P_1 = E_1(1,0,0,1), \quad P_2 = E_2(1,0,0,-1), \quad S = 4E_1E_2$$

$$(n^+)^\mu = \frac{P_1^\mu}{E_1}, \quad (n^-)^\mu = \frac{P_2^\mu}{E_2}, \quad k^\pm = k \cdot n^\pm = k^\mu n_\mu^\pm$$

$$k_1 = x_1 P_1 + k_{1T}, \qquad k_2 = x_2 P_2 + k_{2T}$$

$$t_1 = -k_1^2 = -k_{1T}^2, \qquad t_2 = -k_2^2 = -k_{2T}^2$$

$$x_1 \ll 1, \qquad x_2 \ll 1$$

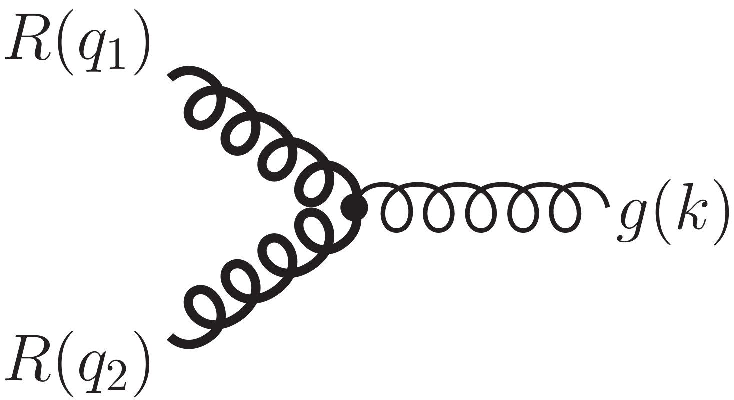
Effective vertices in the QMRK approach

The QMRK approach is based on the effective quantum field theory implemented with the non-abelian gauge-invariant action:

Reggeized gluons (R), L. N. Lipatov, 1995,
Reggeized quarks (Q), L. N. Lipatov and M. I. Vyazovsky, 2001

Feynman rules for the effective theory:
E. N. Antonov, L. N. Lipatov, E. A. Kuraev, and I. O. Cherednikov, 2005
L. N. Lipatov and M. I. Vyazovsky, 2001

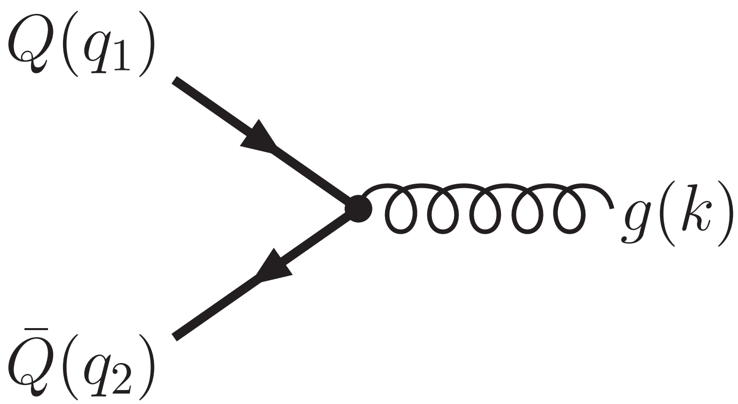
Effective vertices in the QMRK approach



$$C_\mu^{RR\to g}(q_1,q_2) = 2g_s f^{abc}\left((q_1-q_2)_\mu-(n^+)_\mu(q_1^- + \frac{q_1^2}{q_2^+} + (n^-)_\mu(q_2^- + \frac{q_2^2}{q_1^-})\right)\times\frac{x_1x_2E_1E_2}{\sqrt{t_1t_2}}$$

$$k = q_1 + q_2$$

Effective vertices in the QMRK approach

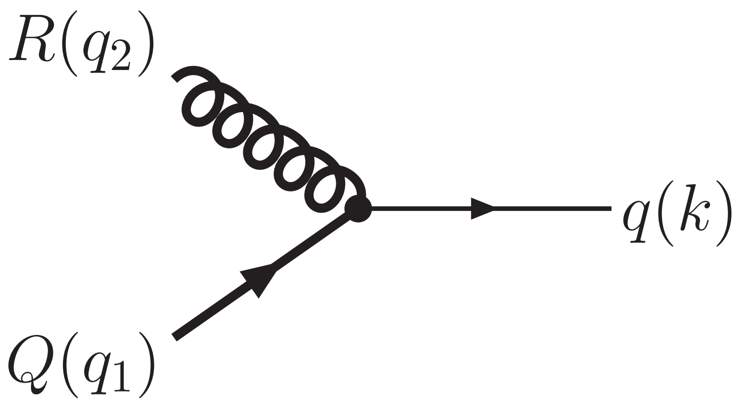


$$C_\mu^{Q\bar{Q}\to g}(q_1,q_2) = -ig_s T^a \gamma_\mu^{(+-)}(q_1,-q_2)$$

$$\gamma_\mu^{(+-)}(q_1,q_2) = \gamma_\mu - \hat{q}_1 \frac{(n^-)_\mu}{k^-} + \hat{q}_2 \frac{(n^+)_\mu}{k^+}$$

$$k = q_1 + q_2$$

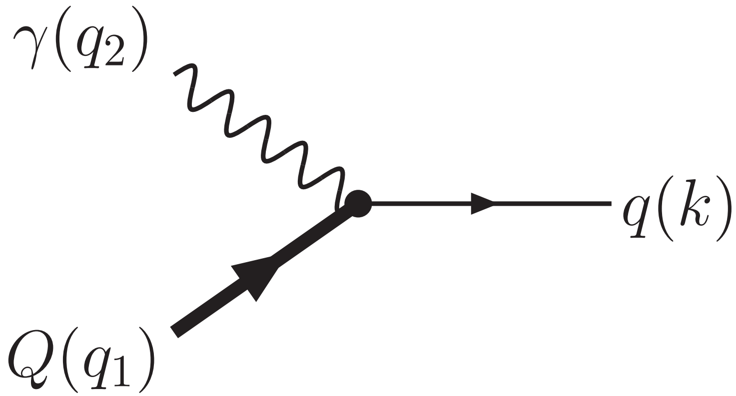
Effective vertices in the QMRK approach



$$C^{RQ\to q}(q_1,q_2) = -ig_s T^a \gamma_\mu^{(-)}(q_1,q_2)\Pi_T^{(+)\mu}(q_2)$$

$$\Pi_T^{(+)\mu}(q_2) = \frac{q_{2T}^\mu}{|\vec{q}_{2T}|}, \quad \Pi_T^{(+)\mu}(q_2) = -\frac{x_2 E_2 (n^+)^\mu}{|\vec{q}_{2T}|}$$

Effective vertices in the QMRK approach



$$C^{\gamma Q \to q}(q_1, q_2) = -iee_q \gamma_\mu^{(-)}(q_1, q_2)$$

$$\gamma_\mu^{(+)}(q,k) = \gamma_\mu + \hat{q}\frac{n_\mu^+}{k^+} = \gamma_\mu + \hat{q}\frac{P_{2\mu}}{P_2 \cdot k}, \quad \gamma_\mu^{(-)}(q,k) = \gamma_\mu + \hat{q}\frac{n_\mu^-}{k^-} = \gamma_\mu + \hat{q}\frac{P_{1\mu}}{P_1 \cdot k}$$

Fragmentation model

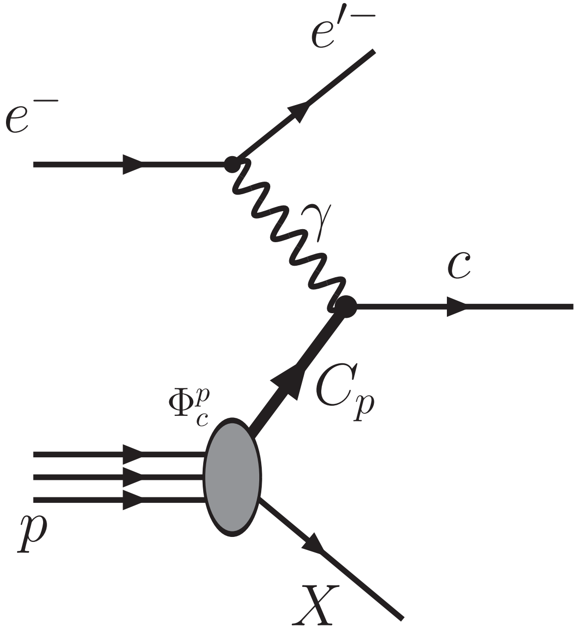
- Fragmentation approach: $p_T \gg M_D$.
- D-meson production cross section:

$$d\sigma(p\bar{p}(e) \to DX) = \int d\sigma(p\bar{p}(e) \to cX) D_{c\to D}(z, \mu^2) dz$$

$$\mu = \sqrt{p_T^2 + M_D^2}.$$

- B. A. Kniehl, G. Kramer, Phys. Rev. D **74**, 037502 (2006): universal non-perturbative fragmentation functions, obtained by fitting the OPAL Collaboration e^+e^--annihilation data at CERN LEP1.

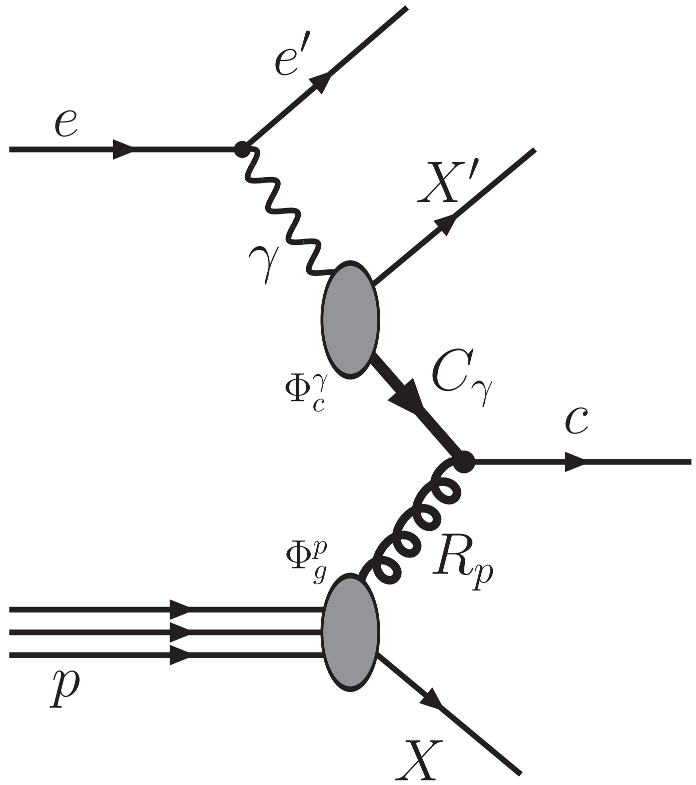
D-meson photoproduction at HERA: QMRK subprocesses



Direct: $\gamma + C \to c$

$$\overline{|M(\gamma C \to c)|^2} = 4\pi\alpha e_c^2 \vec{k}_T^2.$$

D-meson photoproduction at HERA: QMRK subprocesses



Resolved: $R_p + C_\gamma \to c$ and

$$R_\gamma + C_p \to c$$

$$\overline{|M(C_{p(\gamma)}R_{\gamma(p)} \to c)|^2} =$$

$$= \frac{2}{3}\pi\alpha_s(\mu^2)\vec{k}_T^2$$

D-meson photoproduction at HERA

The master formula for the direct production:

$$p_T^3 \frac{d\sigma}{dp_T} = 2\pi \int d\eta \int dz D_{c\to D}(z,\mu^2) z^2 \; y f_{\gamma/e}(y) \Phi_c^p(x_1, t_1, \mu^2) \overline{|M(\gamma C_p \to c)|^2},$$

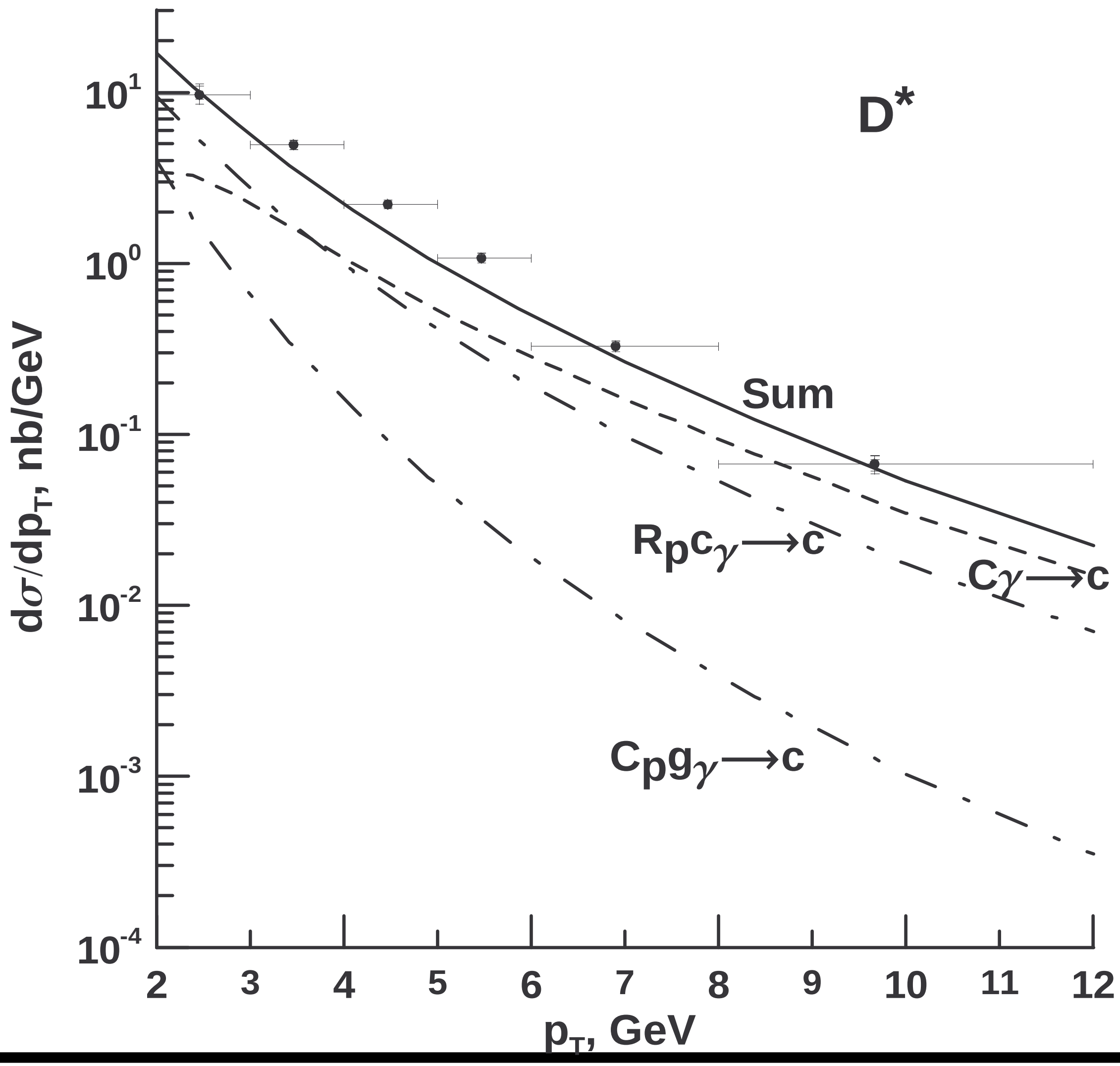
$$x_1 = \frac{p_T e^{\eta}}{2zE_p},\; y = \frac{p_T e^{-\eta}}{2zE_e},\; k_T = \frac{p_T}{z},\; t_1 = \vec{k}_T^2.$$

The master formula for the resolved production:

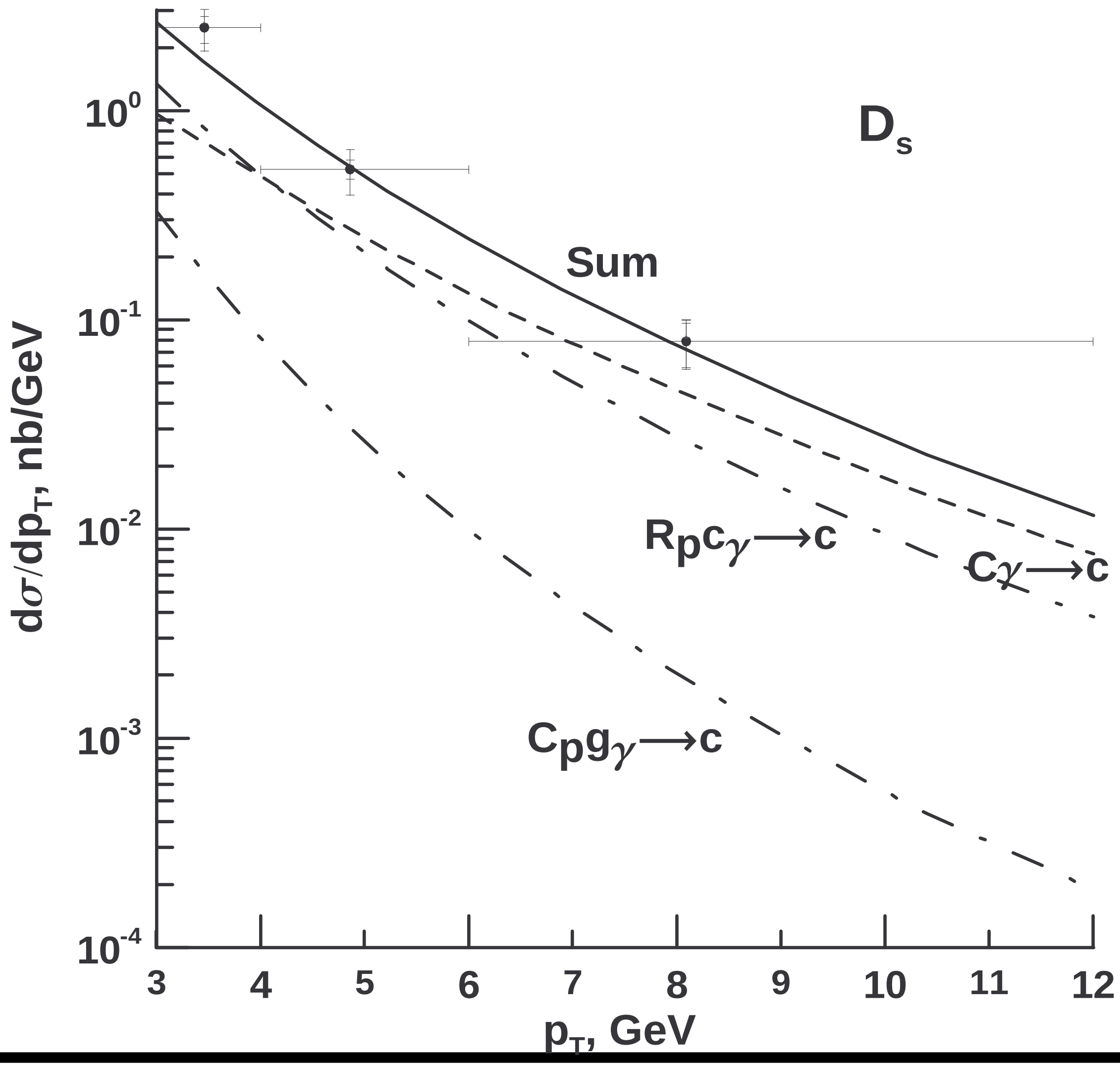
$$p_T^3 \frac{d\sigma}{dp_T} = \int d\eta \int dz \int dy \int dt_2 \int d\phi_2 D_{c\to D}(z,\mu^2) z^2 \; f_{\gamma/e}(y) \; \times$$
$$\times \quad \Phi_c^p(x_1, t_1, \mu^2) \Phi_g^{\gamma}(x_2, t_2, \mu^2) \overline{|M(C_p R_\gamma \to c)|^2},$$

$$x_1 = \frac{p_T e^{\eta}}{2zE_p}, \quad x_2 = \frac{p_T e^{-\eta}}{2zyE_e}, \quad t_1 = t_2 - 2|\vec{k}_T|\sqrt{t_2}\cos\phi_2 + \vec{k}_T^2, \quad k_T = \frac{p_T}{z}.$$

D^*-meson photoproduction at HERA



D_s-meson photoproduction at HERA



D-meson production at the Fermilab Tevatron

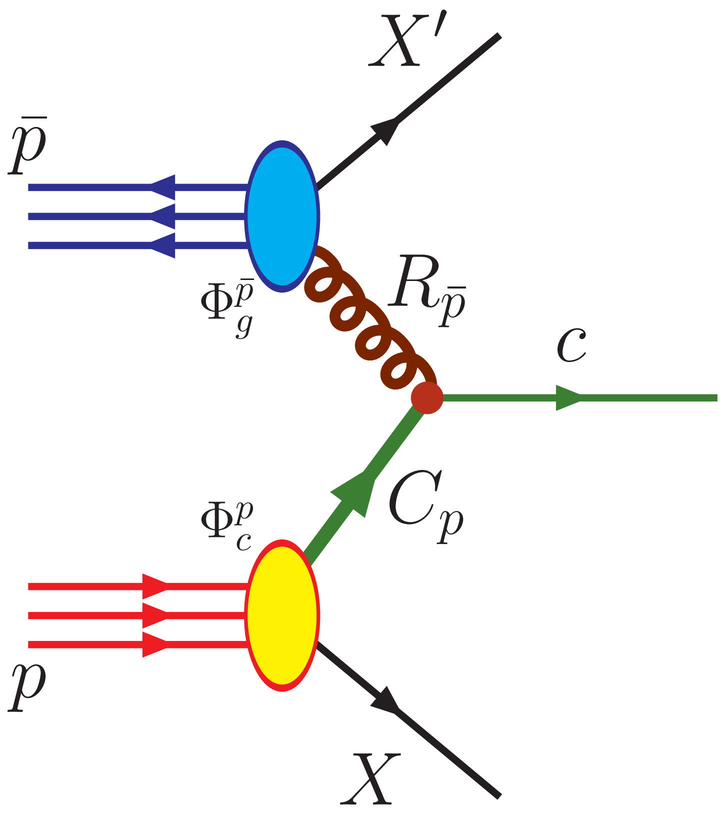
CDF Collaboration:
$d\sigma/dp_T$ for prompt D-meson production
in $p\bar{p}$ collisions at $\sqrt{S} = 1.96$ TeV
in the central rapidity region $|y| < 1$.

QMRK subprocesses

1. $R + C \to c$
2. $R + R \to c + \bar{c}$
3. $Q + \bar{Q} \to c + \bar{c}$, where $Q = U, D$ and S.

D-meson production at the Fermilab Tevatron

QMRK subprocess $\boldsymbol{R + C \to c}$



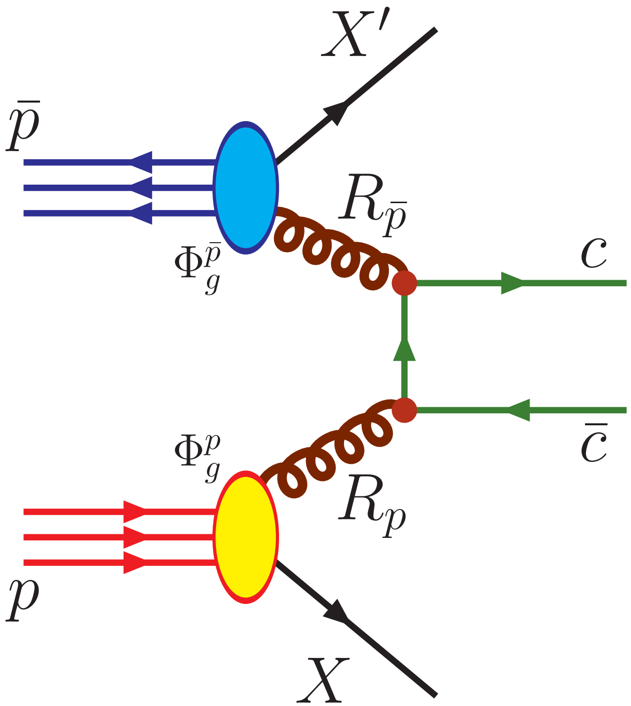
$$\boxed{C_p + R_{\bar{p}} \to c}$$

$$\overline{|M(C_p R_{\bar{p}} \to c)|^2} = \frac{2}{3}\pi\alpha_s(\mu^2)\vec{k}_T^2$$

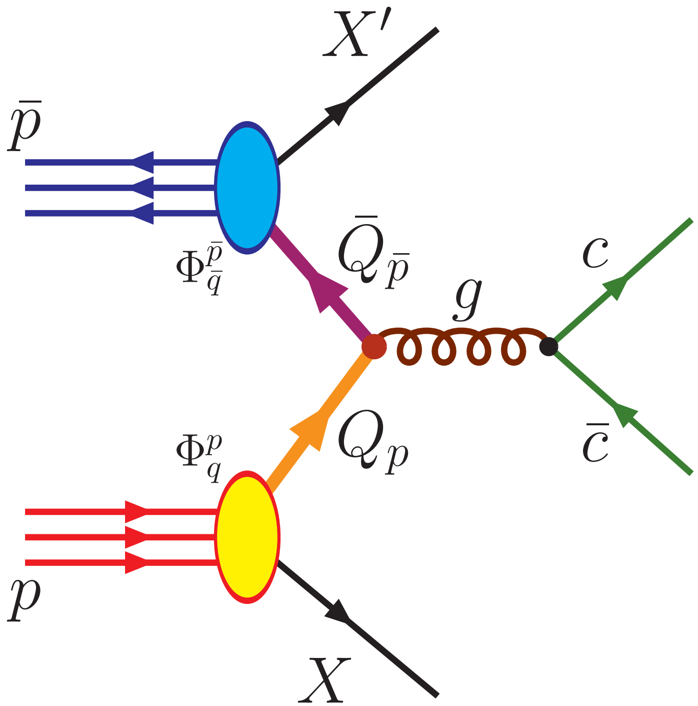
D-meson production at the Fermilab Tevatron

QMRK subprocesses $\boldsymbol{R + R \to c + \bar{c}}$ and $\boldsymbol{Q + \bar{Q} \to c + \bar{c}}$

$R_p + R_{\bar{p}} \to c + \bar{c}$



$Q_p + \bar{Q}_{\bar{p}} \to c + \bar{c}$



D-meson production at the Fermilab Tevatron

QMRK subprocess $R + R \to c + \bar{c}$

$$\overline{|M(R+R\to c+\bar{c})|^2} = \frac{1}{8}\cdot\frac{1}{8}\cdot\frac{k_1^- k_2^+}{16\,t_1 t_2}\left[12\,M_{11}+\frac{16}{3}\big(M_{22}+M_{33}\big)+2\big(6\,(M_{12}+M_{13})-\frac{2}{3}\,M_{23}\big)\right]$$

$$k_{1T} = |\vec{k}_{1T}|, \qquad k_{2T} = |\vec{k}_{2T}|, \qquad T = t - m^2, \qquad U = u - m^2$$

$$\begin{aligned} M_{11} &= \frac{8g_s^4}{s^2}\Bigg\{-\Bigg[k_{1T}^2 - k_{2T}^2 + T - U - 2\Bigg(\Big(\frac{k_{1T}^2}{k_2^+} - k_1^-\Big)k_3^+ - \Big(\frac{k_{2T}^2}{k_1^-} - k_2^+\Big)k_3^-\Bigg)\Bigg]^2 + \\ &+ s^2 + 4s\frac{k_{1T}^2 k_{2T}^2}{k_1^- k_2^+}\Bigg\} \\ M_{22} &= \frac{32g_s^4}{T^2}k_3^+(k_3^- - k_1^-)\big(T - k_3^+(k_3^- - k_1^-)\big) \\ M_{33} &= \frac{32g_s^4}{U^2}k_3^-(k_3^+ - k_2^+)\big(U - k_3^-(k_3^+ - k_2^+)\big) \end{aligned}$$

D-meson production at the Fermilab Tevatron

QMRK subprocess $R + R \to c + \bar{c}$

$$
\begin{aligned}
M_{12} &= \frac{16 g_s^4}{sT}\Big\{k_3^+ \frac{k_{1T}^2}{k_2^+}(T + k_{2T}^2) - k_3^- \frac{k_{2T}^2}{k_1^-}(T + k_{1T}^2) + T(k_3^- k_2^+ - k_3^+ k_1^- + U + k_{2T}^2) + \\
&+ k_3^+(k_3^- - k_1^-)\Big[k_{1T}^2 - k_{2T}^2 + T - U - 2\Big(\big(\frac{k_{1T}^2}{k_2^+} - k_1^-\big)k_3^+ - \big(\frac{k_{2T}^2}{k_1^-} - k_2^+\big)k_3^-\Big)\Big]\Big\} \\
M_{13} &= \frac{16 g_s^4}{sU}\Big\{k_3^- \frac{k_{2T}^2}{k_1^-}(U + k_{1T}^2) - k_3^+ \frac{k_{1T}^2}{k_2^+}(U + k_{2T}^2) + U(k_3^+ k_1^- - k_3^- k_2^+ + T + k_{1T}^2) - \\
&- k_3^-(k_3^+ - k_2^+)\Big[k_{1T}^2 - k_{2T}^2 + T - U - 2\Big(\big(\frac{k_{1T}^2}{k_2^+} - k_1^-\big)k_3^+ - \big(\frac{k_{2T}^2}{k_1^-} - k_2^+\big)k_3^-\Big)\Big]\Big\} \\
M_{23} &= \frac{16 g_s^4}{TU}\{k_{1T}^2 k_{2T}^2 - TU - T k_2^+ k_3^- - U k_3^+ k_1^- + \\
&+ k_3^+ k_3^- \big(T + U - 2(k_3^- - k_1^-)(k_3^+ - k_2^+)\big)\}
\end{aligned}
$$

D-meson production at the Fermilab Tevatron

QMRK subprocess $Q + \bar{Q} \to c + \bar{c}$

$$\begin{aligned}
\overline{|M(Q+\bar{Q}\to c+\bar{c})|^2} &= \frac{1}{4}\cdot\frac{1}{9}\cdot 2\cdot\frac{8g_s^4}{s^2}\Big[8(a_{13}-a_{23})^2 - s(T+U) + \\
&+ 4a_{13}(T+k_{1T}^2) + 4a_{23}(U+k_{2T}^2) + 4a_{12}m^2 - \\
&- \frac{4}{a_{12}}\left(a_{13}^2k_{1T}^2 + a_{23}^2k_{2T}^2 + a_{13}a_{23}(T+U)\right)\Big] \\
a_{ij} &= k_{i||}k_{j||}
\end{aligned}$$

D-meson production at Tevatron

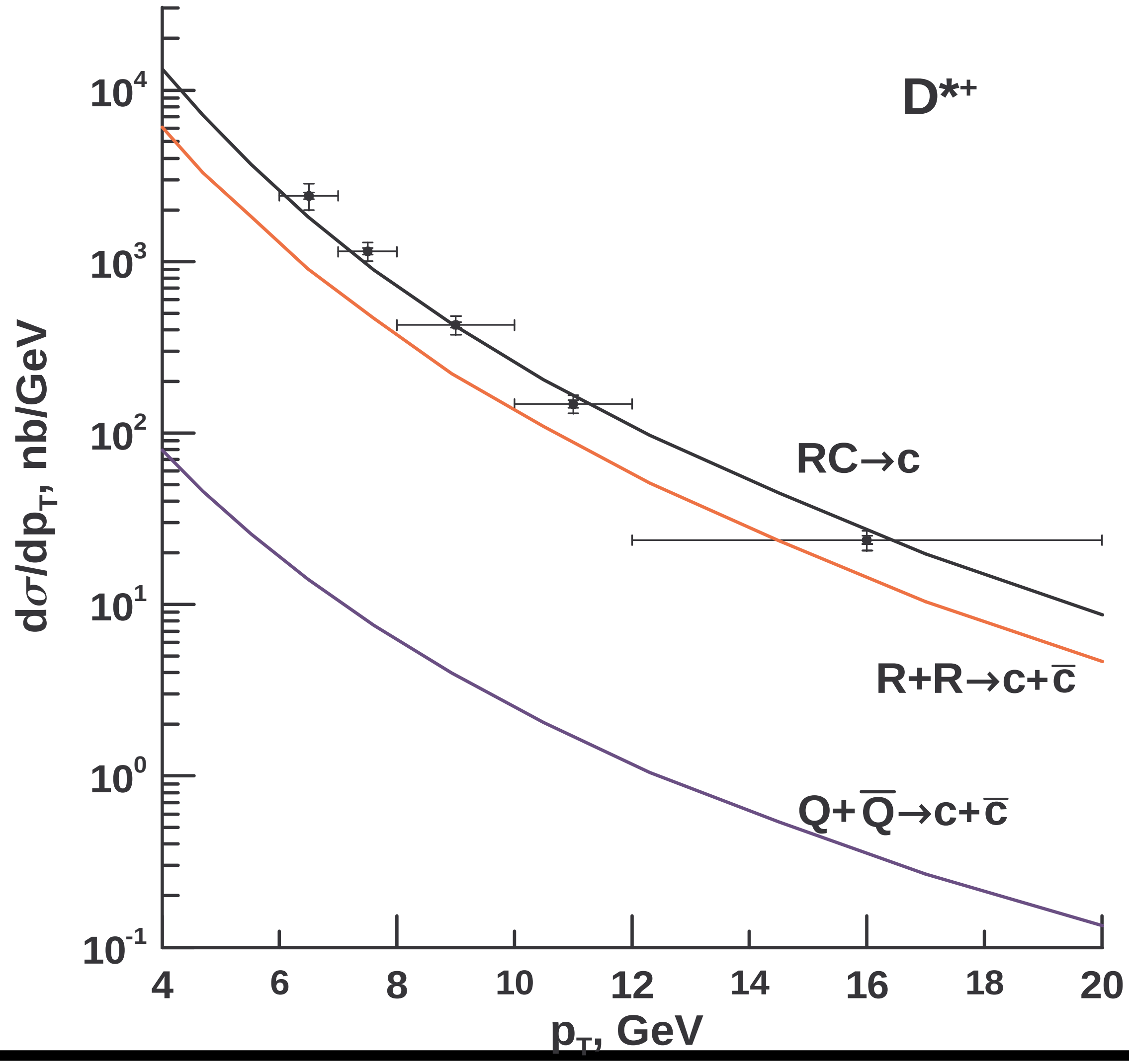
QMRK subprocess: $R + C \to c$

The master formula:

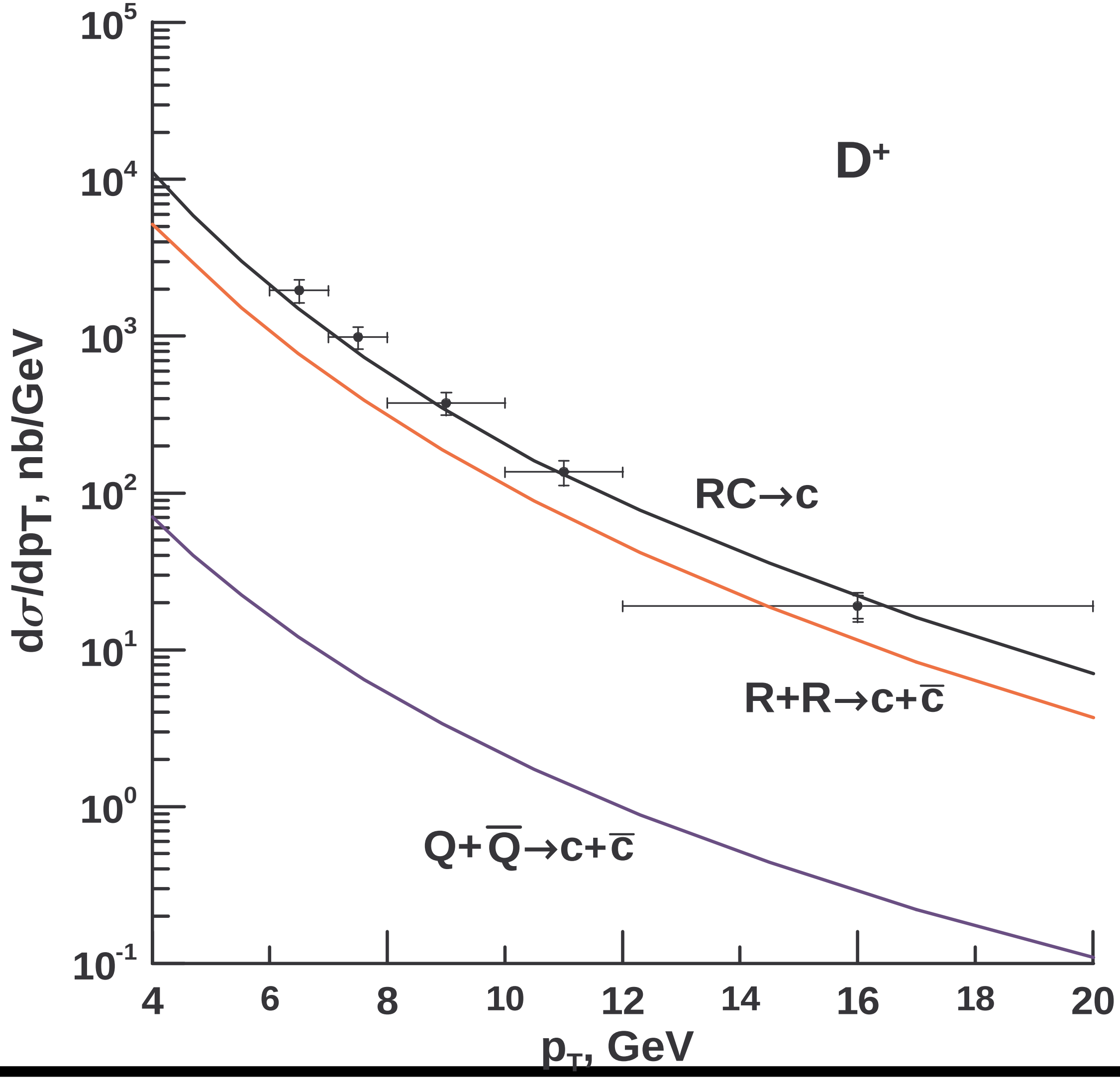
$$p_T^3 \frac{d\sigma}{dp_T} = \int dy \int dz \int dt_1 \int d\phi_1 D_{c\to D}(z,\mu^2) z^2 \times$$
$$\times \quad \Phi_c^p(x_1,t_1,\mu^2)\Phi_g^{\bar p}(x_2,t_2,\mu^2)\overline{|M(C_p R_{\bar p} \to c)|^2},$$

$$x_1 = \frac{p_T e^y}{z\sqrt{S}}, \quad x_2 = \frac{p_T e^{-y}}{z\sqrt{S}}, \quad t_2 = t_1 - 2\frac{p_T}{z}\sqrt{t_1}\cos\phi_2 + \frac{p_T^2}{z^2}.$$

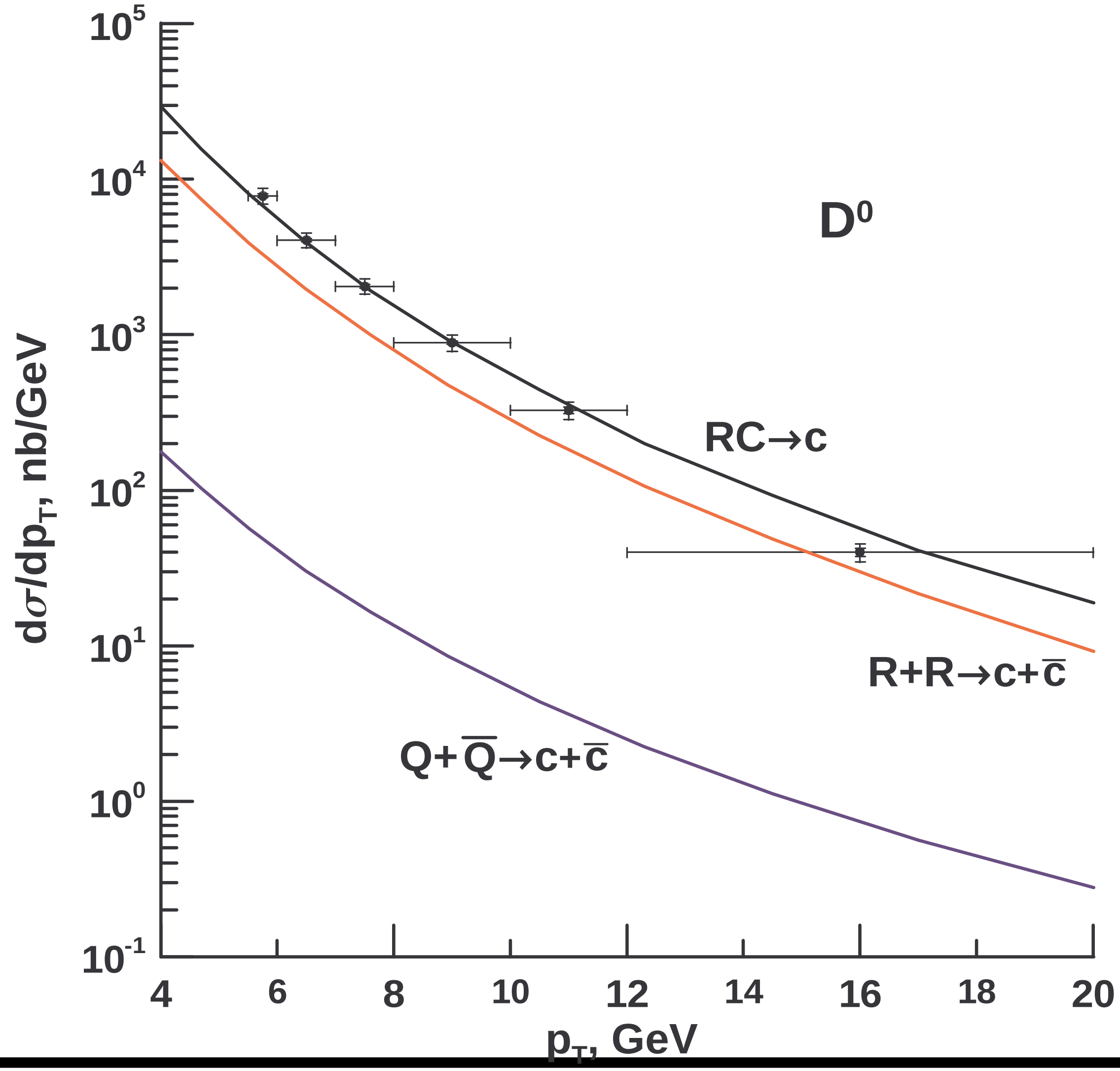
D^{*+}-meson production at Tevatron



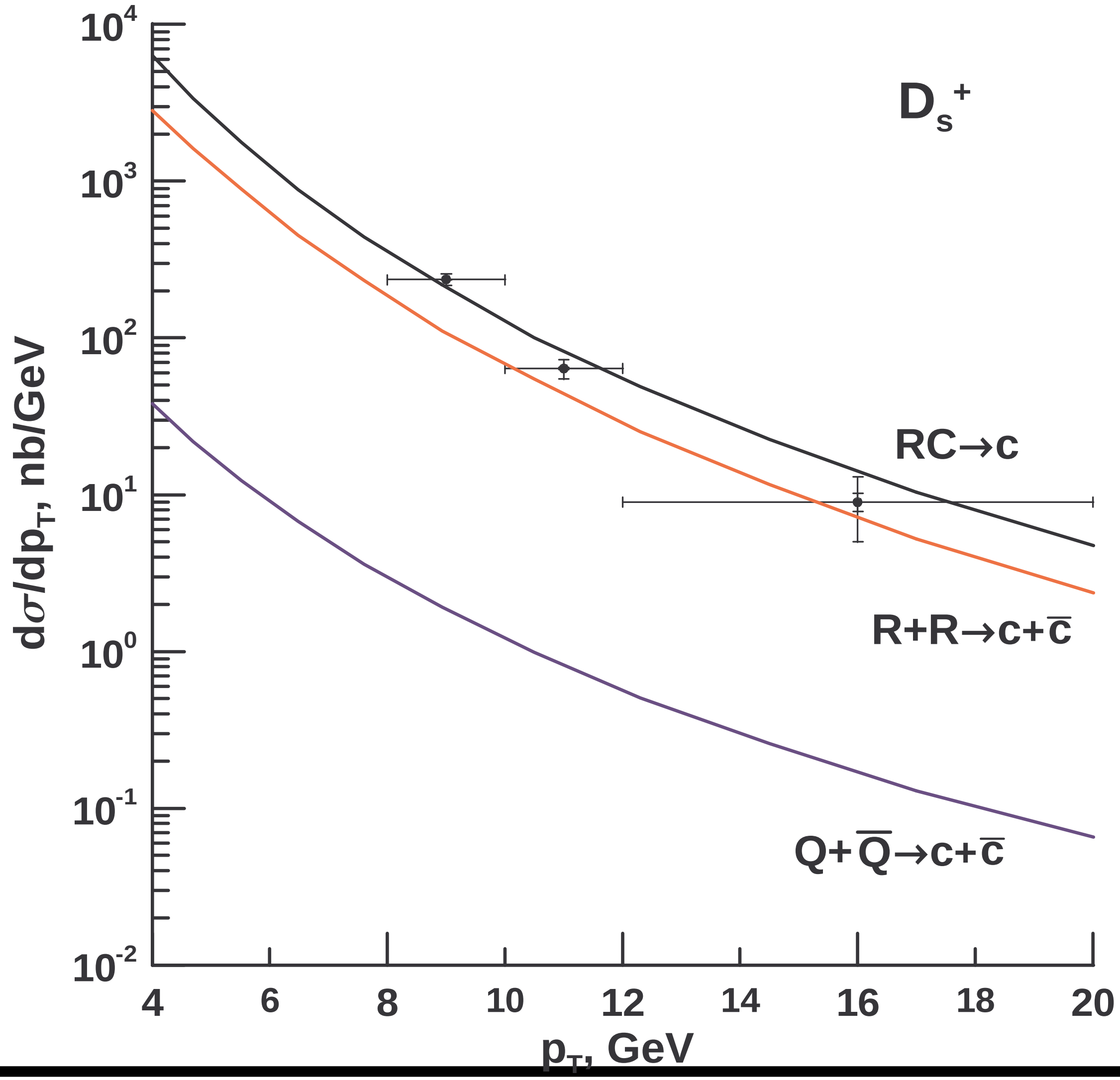
D^+-meson production at Tevatron



D^0-meson production at Tevatron



D_s^+-meson production at Tevatron



Conclusion

1. Working in the above mentioned approach and fragmentation model we calculated the p_T-spectra of D^*-, D_s-meson photoproduction at HERA Collider and obtained a satisfactory agreement at high p_T between the our results for the production via LO QMRK subprocess $\gamma C \to c$ and the experimental data.
2. We also calculated in this approach the p_T-spectra of D-meson production at Tevatron and obtained a good coincidence between our results and the experimental data.

Conclusion

Taking into consideration pointed out coincidences between analytical calculations and experimental data, we conclude:

1. The quark Reggeization hypothesis justify itself when one admits it because of correct describing the experimental data for cross sections of D-meson production in different reactions even at LO.

2. The Kimber-Martin-Ryskin-Watt unintegrated c-quark and gluon distribution functions in a proton seem to be correct because of successful using them for calculations of D-meson production in different reactions.

3. The details of the calculations are published in the work B. A. Kniehl, A. V. Shipilova, V. A. Saleev arXiv:0812.3376.

Thank you for attention.