Inclusive heavy flavour production in the dipole picture

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Phenomenological dipole approach

Eigenvalue of the total cross section is
the universal dipole cross section

see e.g. B. Kopeliovich et al, since 1981

Eigenstates of interaction in QCD:
color dipoles

Dipole:
- cannot be excited
- experience only elastic scattering
- have no definite mass, but only separation
- universal – elastic amplitude can be extracted in one process and used in another

$$\sum_{h'} \frac{d\sigma_{sd}^{h\to h'}}{dt}\bigg|_{t=0} = \sum_{\alpha=1} |C_\alpha^h|^2 \frac{\sigma_\alpha^2}{16\pi} =$$ **SD cross section**

$$\int d^2 r_T |\Psi_h(r_T)|^2 \frac{\sigma^2(r_T)}{16\pi} = \frac{\langle \sigma^2(r_T)\rangle}{16\pi}$$

wave function of
a given Fock state

partonic interpretation of a scattering does depend on frame of reference!

total DIS cross section

$$\sigma_{tot}^{\gamma^* p}(Q^2, x_{Bj}) = \int d^2 r_T \int_0^1 dx \, |\Psi_{\gamma^*}(r_T, Q^2)|^2 \, \sigma_{\bar{q}q}(r_T, x_{Bj})$$

Theoretical calculation of the dipole CS is a challenge

BUT! *Can be extracted from data and used in ANY process!*

Example: Naive GBW parameterization of HERA data

$$\sigma_{\bar{q}q}(r_T, x) = \sigma_0 \left[1 - e^{-\frac{1}{4} r_T^2 Q_s^2(x)}\right]$$

saturates at
large separations

$$r_T^2 \gg 1/Q_s^2$$

color transparency $\sigma_{\bar{q}q}(r_T) \propto r_T^2 \quad r_T \to 0$

QCD factorisation $\sigma_{q\bar{q}}(r, x) \propto r^2 x g(x)$

A point-like colorless object does not interact with external color field!

ANY inclusive/diffractive scattering is due to an interference of dipole scatterings!

Gluon distribution amplitudes and dipole CS

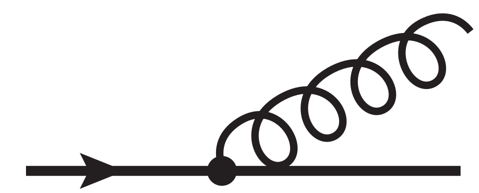
In most cases, a scattering cross section in the target rest frame can be represented in terms of three basic ingredients:

- Gluon to quark-antiquark splitting amplitude:

$$\Phi^T_{Q\bar{Q}} = \sqrt{\alpha_s} \int \frac{d^2\kappa}{(2\pi)^2}\, (\xi^\mu_Q)^\dagger \frac{m_Q(\vec{e}_{ini}\cdot\vec{\sigma}) + (1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_{ini}\cdot\vec{\kappa}) + i(\vec{e}_{ini}\times\vec{n})\cdot\vec{\kappa}}{\kappa^2+\epsilon^2}\, \tilde{\xi}^{\bar{\mu}}_{\bar{Q}}\, e^{-i\vec{\kappa}\vec{r}}$$

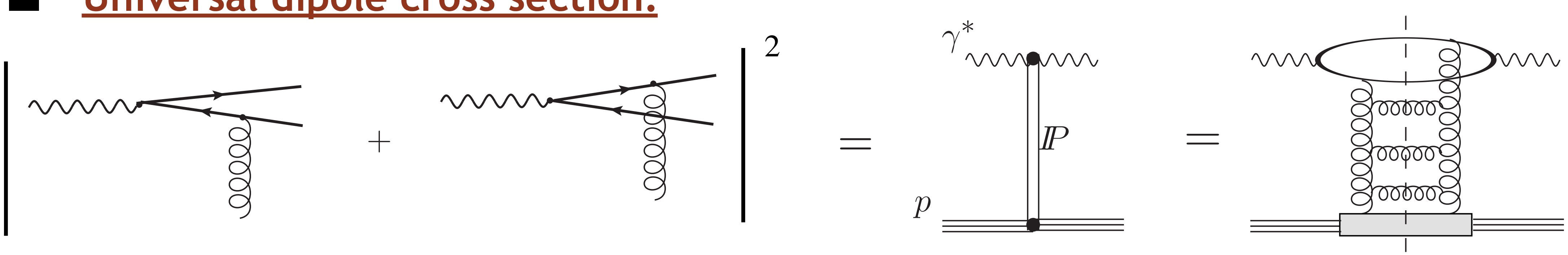
$$= \frac{\sqrt{\alpha_s}}{2\pi}\, (\xi^\mu_Q)^\dagger \Big\{ m_Q(\vec{e}_{ini}\cdot\vec{\sigma}) + i(1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_{ini}\cdot\vec{\nabla}_r) - (\vec{e}_{ini}\times\vec{n})\cdot\vec{\nabla}_r \Big\}\, \tilde{\xi}^{\bar{\mu}}_{\bar{Q}}\, K_0(\epsilon r)\,,$$

- Gluon Bremsstrahlung off a quark:

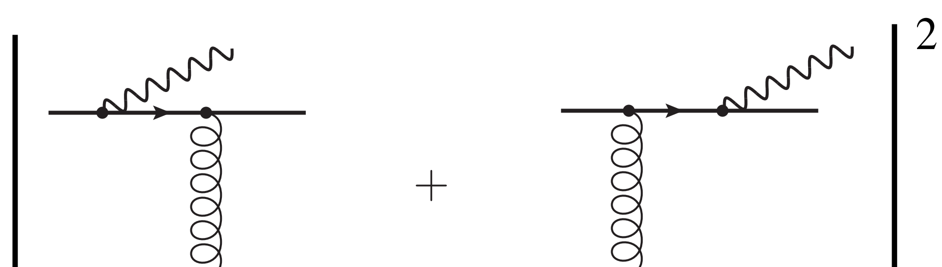


$$\Phi^T_{qG^*}(\alpha,\vec{\pi}) = \sqrt{\alpha_s}\, (\eta^s_Q)^\dagger \frac{(2-\alpha)(\vec{e}_*\cdot\vec{\pi}) + i m_q\alpha^2(\vec{n}\times\vec{e}_*)\cdot\vec{\sigma} - i\alpha(\vec{\pi}\times\vec{e}_*)\cdot\vec{\sigma}}{\vec{\pi}^2+\alpha^2 m_q^2}\, \eta^{s'}_Q$$

- Universal dipole cross section:



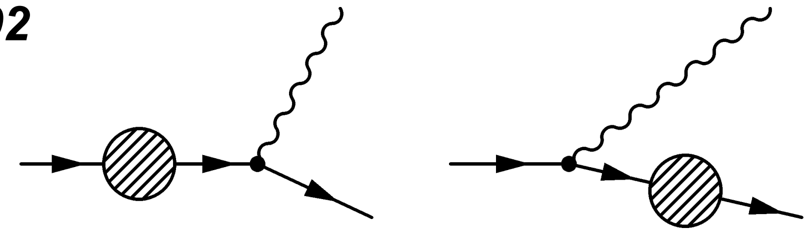
$\propto \quad \sigma_{q\bar{q}}(r,x)$



$\propto \quad \sigma_{q\bar{q}}(\alpha r,x)$

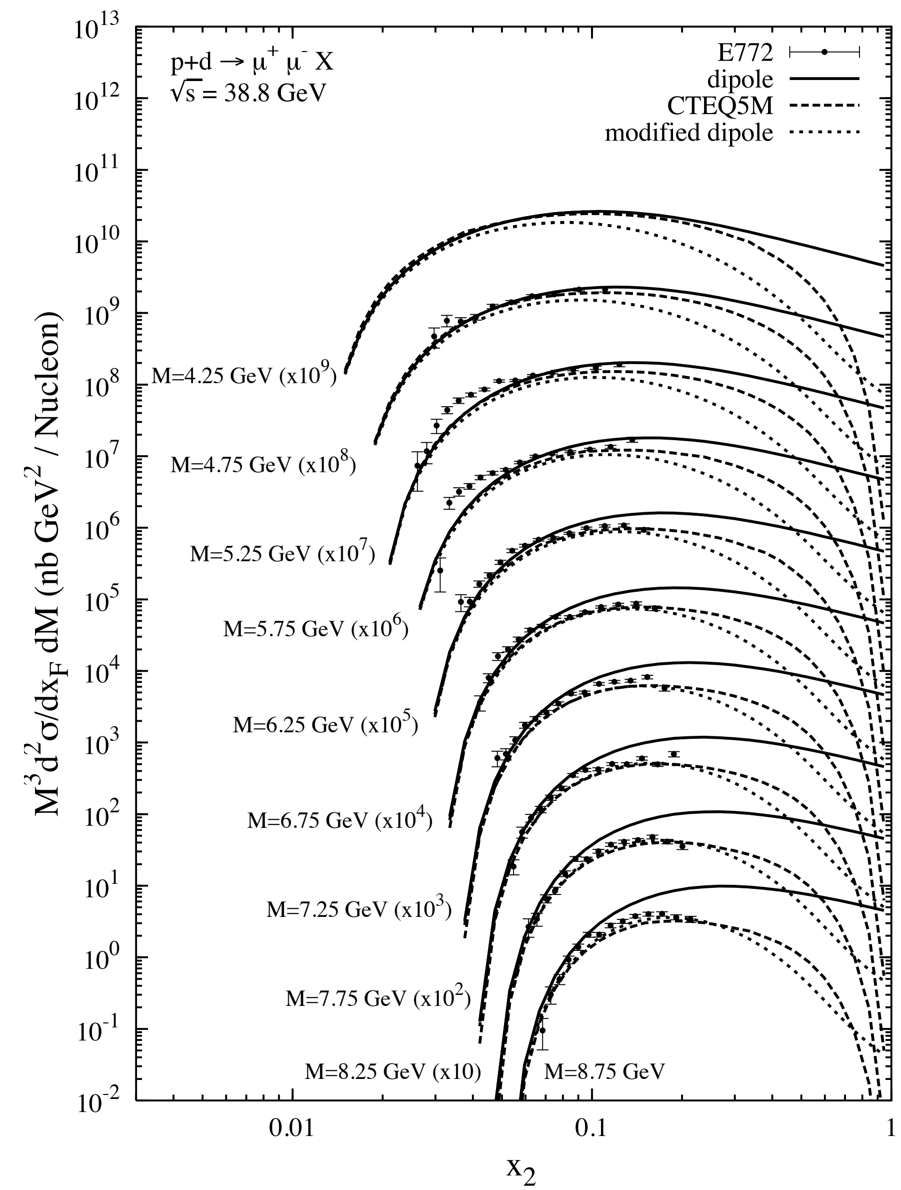
Dipole approach vs NLO QCD: Drell-Yan

J. Raufeisen et al, PRD66 2002

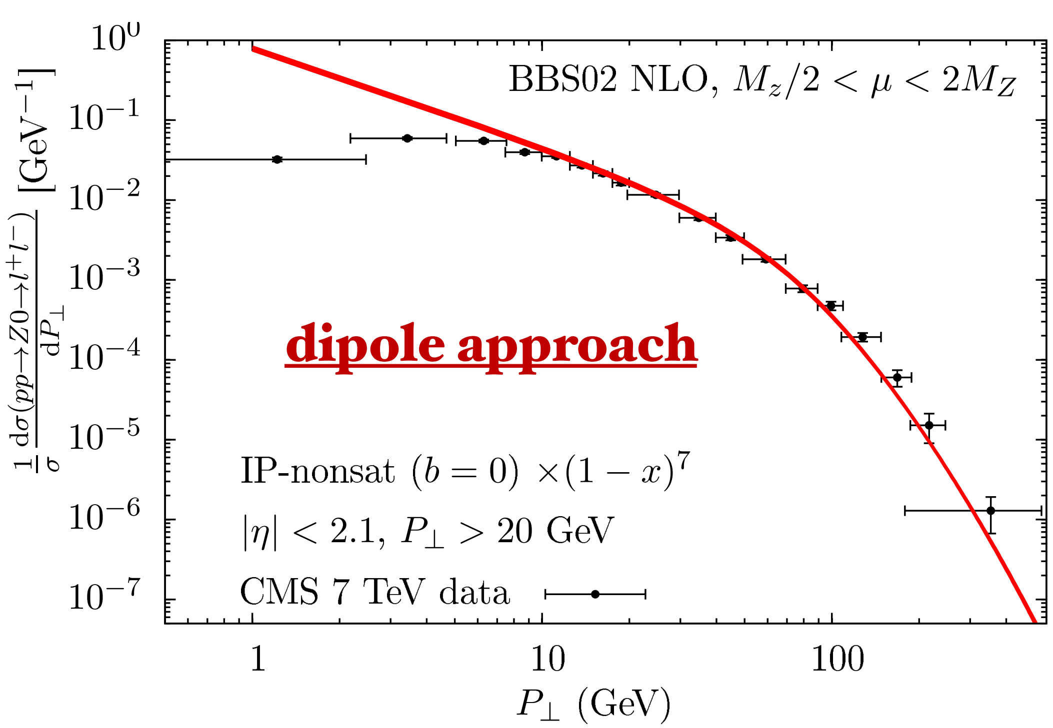


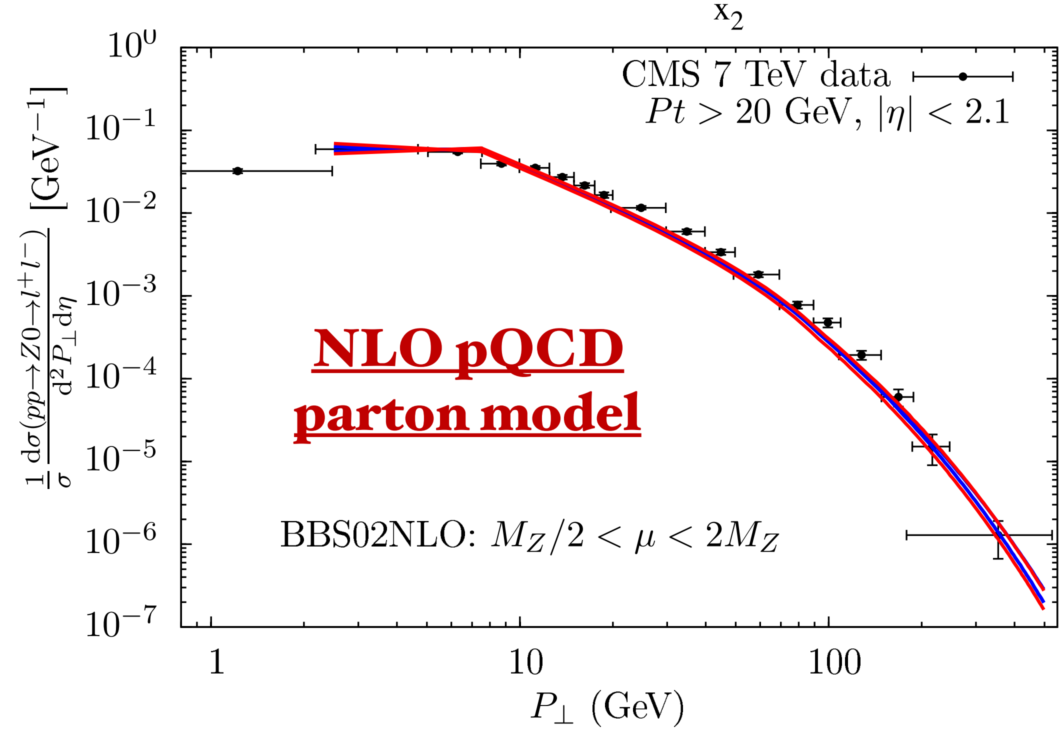
$$\frac{d\sigma(qN \to \gamma^* X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)$$

$$\frac{d^2\sigma(pN \to l^+l^- X)}{dM^2 dx_F} = \frac{\alpha_{em}}{3\pi M^2}\frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_{f=1}^{N_f} Z_f^2 \left[q_f\left(\frac{x_1}{\alpha},\widetilde{Q}\right)+\bar{q}_f\left(\frac{x_1}{\alpha},\widetilde{Q}\right)\right]$$
$$\times \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)\ .$$



Dipole approach predictions effectively account for higher order QCD corrections!





Heavy flavour production: Bremsstrahlung vs Fusion

Gauge-invariant sub-sets of diagrams

B. Kopeliovich et al, PRD76 2007

”Bremsstrahlung” component

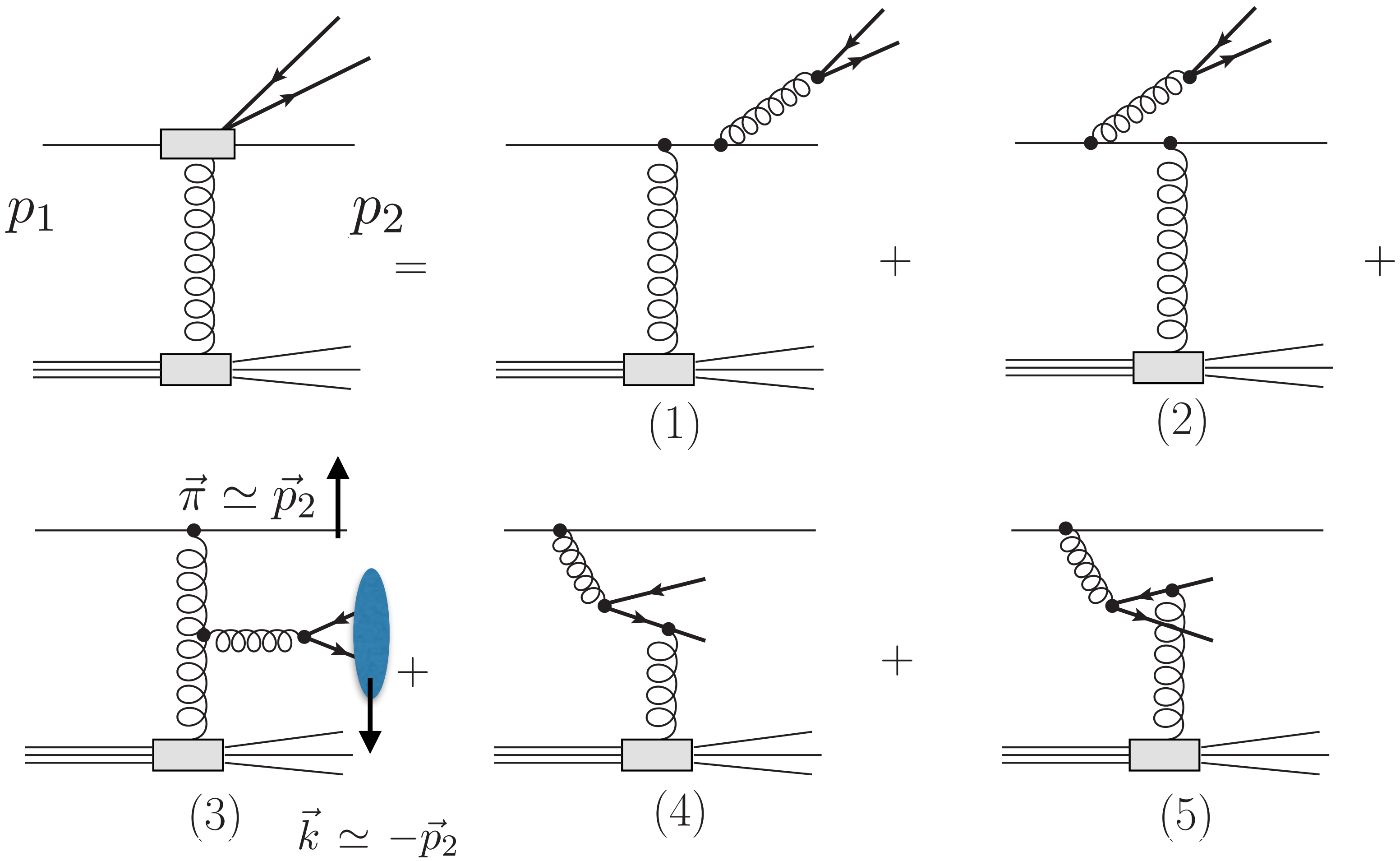
$$M_{\mathrm{Br}}^{T} = M_1^T + M_2^T + \frac{Q^2}{M^2+Q^2} M_3^T$$

suppressed by QQ mass!

”Fusion” component

$$M_{\mathrm{Pr}}^{T} = \frac{M^2}{M^2+Q^2} M_3^T + M_4^T + M_5^T$$

Dominates!



Gluon virtuality

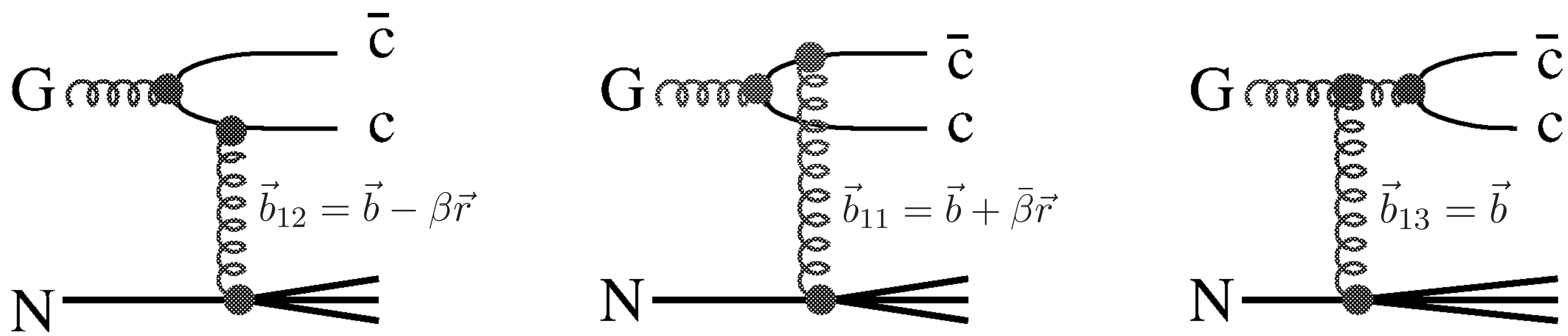
$$(p_2 - p_1)^2 \equiv -Q^2\,, \qquad Q^2 = \frac{\vec{\pi}^2 + \alpha^2 m_q^2}{\bar{\alpha}} \qquad \vec{\pi} = \alpha \vec{p}_2 - \bar{\alpha}\vec{k}\,, \qquad \vec{k} = \sum_i \vec{k}_i$$

Basis for heavy flavour production in the dipole picture

Dipole framework for heavy flavor production

"Fusion" components

$G + N \to \bar{c}c + X$



LC momenta

$$k_1 \simeq \bar{\beta}k - \kappa\,, \qquad k_2 \simeq \beta k + \kappa \qquad \vec{\kappa} = \bar{\beta}\vec{k}_2 - \beta\vec{k}_1$$

impact parameter representation

$$\hat{A}(\vec{s},\vec{r}) = \frac{1}{(2\pi)^4}\int d^2\vec{q}\, d^2\vec{\kappa}\; \hat{A}(\vec{q},\vec{\kappa})\, e^{-i\vec{q}\cdot\vec{s} - i\vec{\kappa}\cdot\vec{r}}$$

$$\hat{A} \simeq \frac{\sqrt{3}}{2}\sum_r \Big\{ \tau_r\,\tau_a \langle f|\hat{\gamma}_r(\vec{b}_{11})|i\rangle - \tau_a\,\tau_r\langle f|\hat{\gamma}_r(\vec{b}_{12})|i\rangle - i\sum_c f_{cra}\tau_c\langle f|\hat{\gamma}_r(\vec{b}_{13})|i\rangle \Big\}\Phi_{Q\bar{Q}}(\vec{r},\beta)\,,$$

$$|A|^2 \equiv \frac{1}{8}\frac{1}{2}\sum_{\lambda_*,\mu,\bar{\mu}} \langle \hat{A}^\dagger \hat{A}\rangle_{|3q\rangle_1}$$

$$\sum_X \langle i|\hat{\gamma}_a(\vec{b}_k)\hat{\gamma}_{a'}(\vec{b}_l)|i\rangle_{|3q\rangle_1} = \frac{3}{4}\delta_{aa'}S(\vec{b}_k,\vec{b}_l)$$

The universal dipole cross section

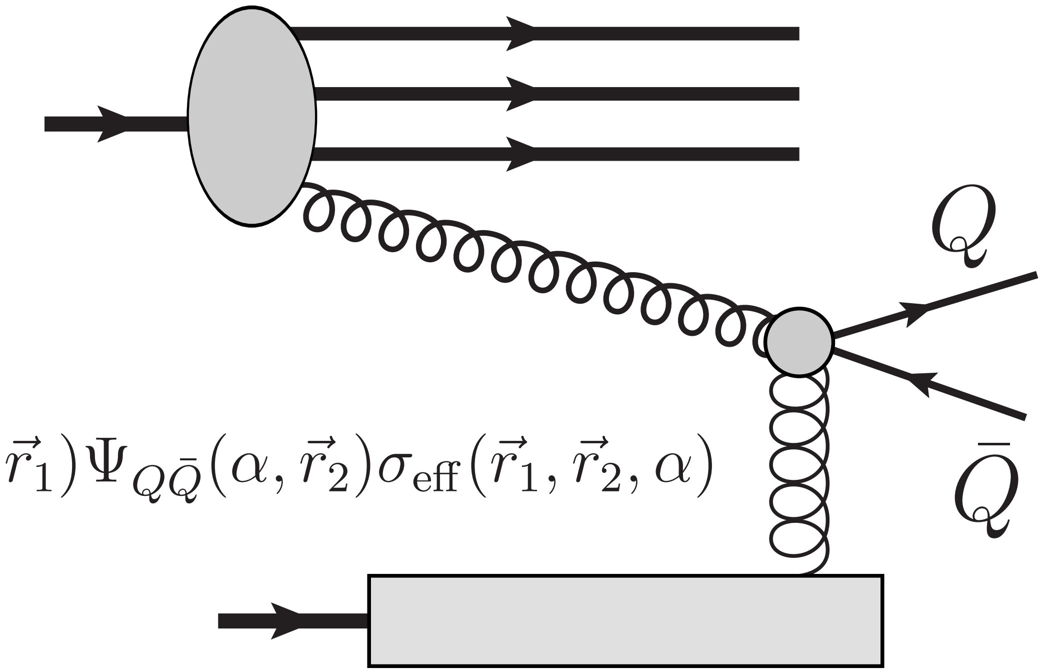
$$\sigma_{\bar{q}q}(\vec{r}_1 - \vec{r}_2) \equiv \int d^2b\Big[S(\vec{b}+\vec{r}_1,\vec{b}+\vec{r}_1) + S(\vec{b}+\vec{r}_2,\vec{b}+\vec{r}_2) - 2S(\vec{b}+\vec{r}_1,\vec{b}+\vec{r}_2)\Big]$$

The total cross section

$$\boxed{\begin{gathered}\sigma(G+p\to c\bar{c}+X) = \sum_{\mu\bar{\mu}}\int_0^1 d\beta \int d^2r\,\sigma_3(r,\beta,x_2)\,|\Phi_{Q\bar{Q}}(\vec{r},\beta)|^2 \\ \sigma_3(r,\beta,x_2) = \frac{9}{8}\Big(\sigma_{\bar{q}q}(\bar{\beta}r,x_2) + \sigma_{\bar{q}q}(\beta r,x_2)\Big) - \frac{1}{8}\sigma_{\bar{q}q}(r,x_2)\,, \qquad x_2 = \frac{M^2_{c\bar{c}}}{2m_pE_G}\end{gathered}}$$

Q-jet pT distribution in pp collisions: the dipole formula

$$G(x_1,\mu^2) \equiv x_1 g(x_1,\mu^2)$$



$$\frac{d\sigma^{pp}_{\rm incl}}{dY\, d\alpha d^2p_T} = G(x_1,\mu^2)\, \frac{d\sigma(Gp \to \bar{Q}Q + X)}{d\alpha d^2 p_T}$$

$$\frac{d^3\sigma(G\to Q\bar{Q}+X)}{d\alpha d^2p_T} = \frac{1}{(2\pi)^2}\int d^2r_1 d^2r_2 e^{ip_T\cdot(\vec{r}_1-\vec{r}_2)}\Psi^*_{Q\bar{Q}}(\alpha,\vec{r}_1)\Psi_{Q\bar{Q}}(\alpha,\vec{r}_2)\sigma_{\rm eff}(\vec{r}_1,\vec{r}_2,\alpha)$$

$$\begin{aligned}\Psi^*_{Q\bar{Q}}(\alpha,\vec{r}_1)\Psi_{Q\bar{Q}}(\alpha,\vec{r}_2) &= \frac{\alpha_s}{(2\pi)^2}\Big[m_Q^2 K_0(m_Q r_1)K_0(m_Q r_2) \\ &+(\alpha^2+\bar{\alpha}^2)m_Q^2\frac{\vec{r}_1\cdot\vec{r}_2}{r_1 r_2}K_1(m_Q\, r_1)K_1(m_Q\, r_2)\Big]\end{aligned}$$

$$\mu^2 \simeq M^2_{\bar{Q}Q} = \frac{m_Q^2+p_T^2}{\alpha\bar{\alpha}}$$

$$\begin{aligned}\sigma_{\rm eff}(\vec{r}_1,\vec{r}_2,\alpha) &= \frac{9}{16}\sigma_{q\bar{q}}(\alpha\vec{r}_1) + \frac{9}{16}\sigma_{q\bar{q}}(\bar{\alpha}\vec{r}_1) + \frac{9}{16}\sigma_{q\bar{q}}(\alpha\vec{r}_2) + \frac{9}{16}\sigma_{q\bar{q}}(\bar{\alpha}\vec{r}_2) \\ &- \frac{1}{16}\sigma_{q\bar{q}}(\bar{\alpha}\vec{r}_1+\alpha\vec{r}_2) - \frac{1}{16}\sigma_{q\bar{q}}(\alpha\vec{r}_1+\bar{\alpha}\vec{r}_2) \\ &- \frac{1}{2}\sigma_{q\bar{q}}(\alpha[\vec{r}_1-\vec{r}_2]) - \frac{1}{2}\ \sigma_{q\bar{q}}(\bar{\alpha}[\vec{r}_1-\vec{r}_2])\,.\end{aligned}$$

The dipole formula in momentum space

$$\sigma_{\bar{q}q}(\vec{r},x) = \frac{4\pi}{3}\int \frac{d^2\kappa_\perp}{\vec{\kappa}_\perp^4}\,(1-e^{i\vec{\kappa}_\perp\cdot\vec{r}})\,\alpha_s\,\mathcal{F}(x,\vec{\kappa}_\perp^2)$$

$$\frac{d^3\sigma(G\to Q\bar{Q}+X)}{d(\ln\alpha)d^2p_T} = \frac{1}{6\pi}\int\frac{d^2\kappa_\perp}{\kappa_\perp^4}\alpha_s^2\mathcal{F}(x,\kappa_\perp^2)\times$$
$$\left\{\left[\frac{9}{8}\mathcal{H}_0(\alpha,\bar{\alpha},p_T)-\frac{9}{4}\mathcal{H}_1(\alpha,\bar{\alpha},p_T,\kappa)+\mathcal{H}_2(\alpha,\bar{\alpha},p_T,\kappa)+\frac{1}{8}\mathcal{H}_3(\alpha,\bar{\alpha},p_T,\kappa)\right]+[\alpha\longleftrightarrow\bar{\alpha}]\right\}$$

$$\begin{aligned}
\mathcal{H}_0(\alpha,\bar{\alpha},p_T) &= \frac{m_Q^2+(\alpha^2+\bar{\alpha}^2)p_T^2}{(p_T^2+m_Q^2)^2}\,,\\
\mathcal{H}_1(\alpha,\bar{\alpha},p_T,\kappa) &= \frac{m_Q^2+(\alpha^2+\bar{\alpha}^2)\vec{p_T}\cdot(\vec{p_T}-\alpha\vec{\kappa})}{[(\vec{p_T}-\alpha\vec{\kappa})^2+m_Q^2](p_T^2+m_Q^2)}\,,\\
\mathcal{H}_2(\alpha,\bar{\alpha},p_T,\kappa) &= \frac{m_Q^2+(\alpha^2+\bar{\alpha}^2)(\vec{p_T}-\alpha\vec{\kappa})^2}{[(\vec{p_T}-\alpha\vec{\kappa})^2+m_Q^2]^2}\,,\\
\mathcal{H}_3(\alpha,\bar{\alpha},p_T,\kappa) &= \frac{m_Q^2+(\alpha^2+\bar{\alpha}^2)(\vec{p_T}+\alpha\vec{\kappa})\cdot(\vec{p_T}-\bar{\alpha}\vec{\kappa})}{[(\vec{p_T}+\alpha\vec{\kappa})^2+m_Q^2][(\vec{p_T}-\bar{\alpha}\vec{\kappa})^2+m_Q^2]}\,.
\end{aligned}$$

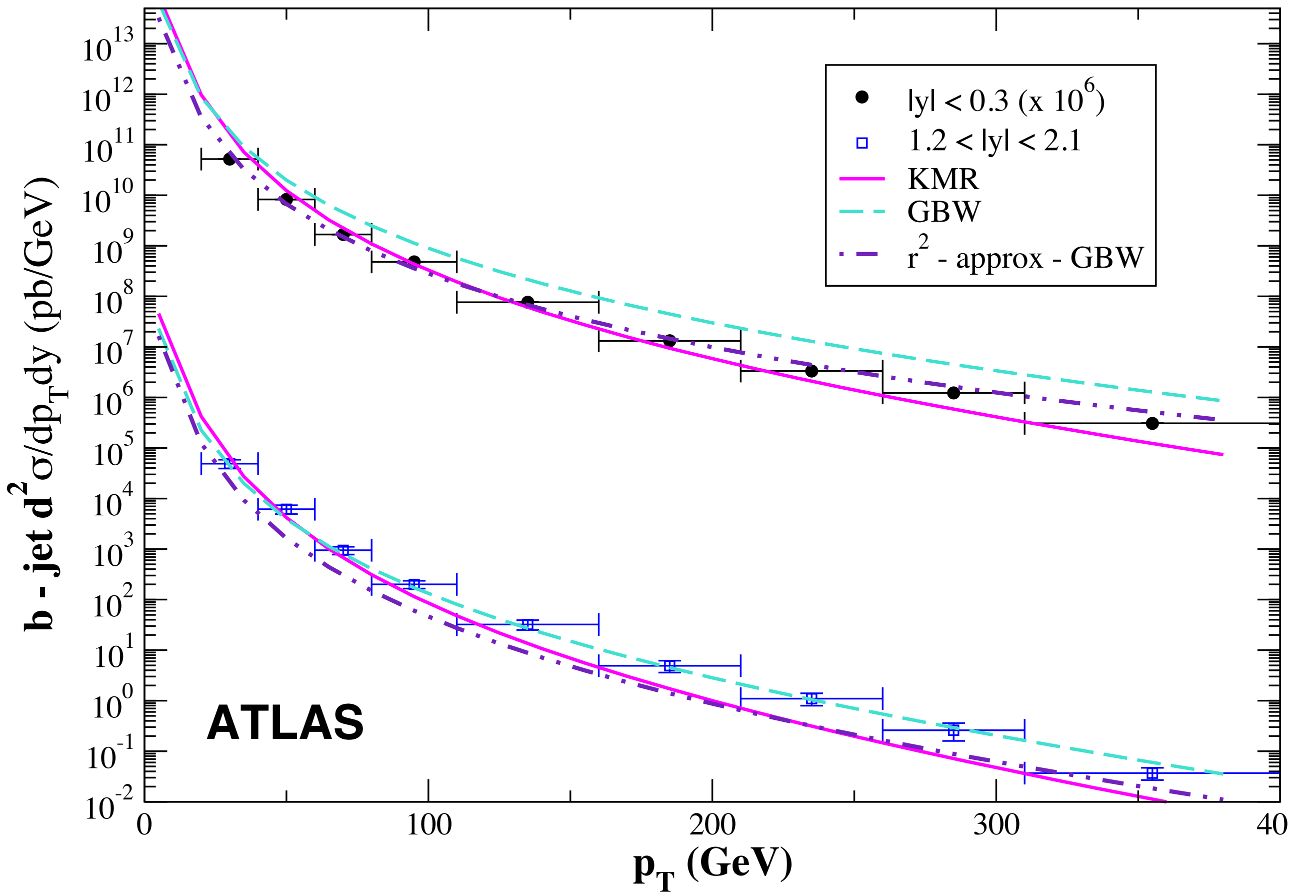
$$r^2 \ll R_0^2(x)$$

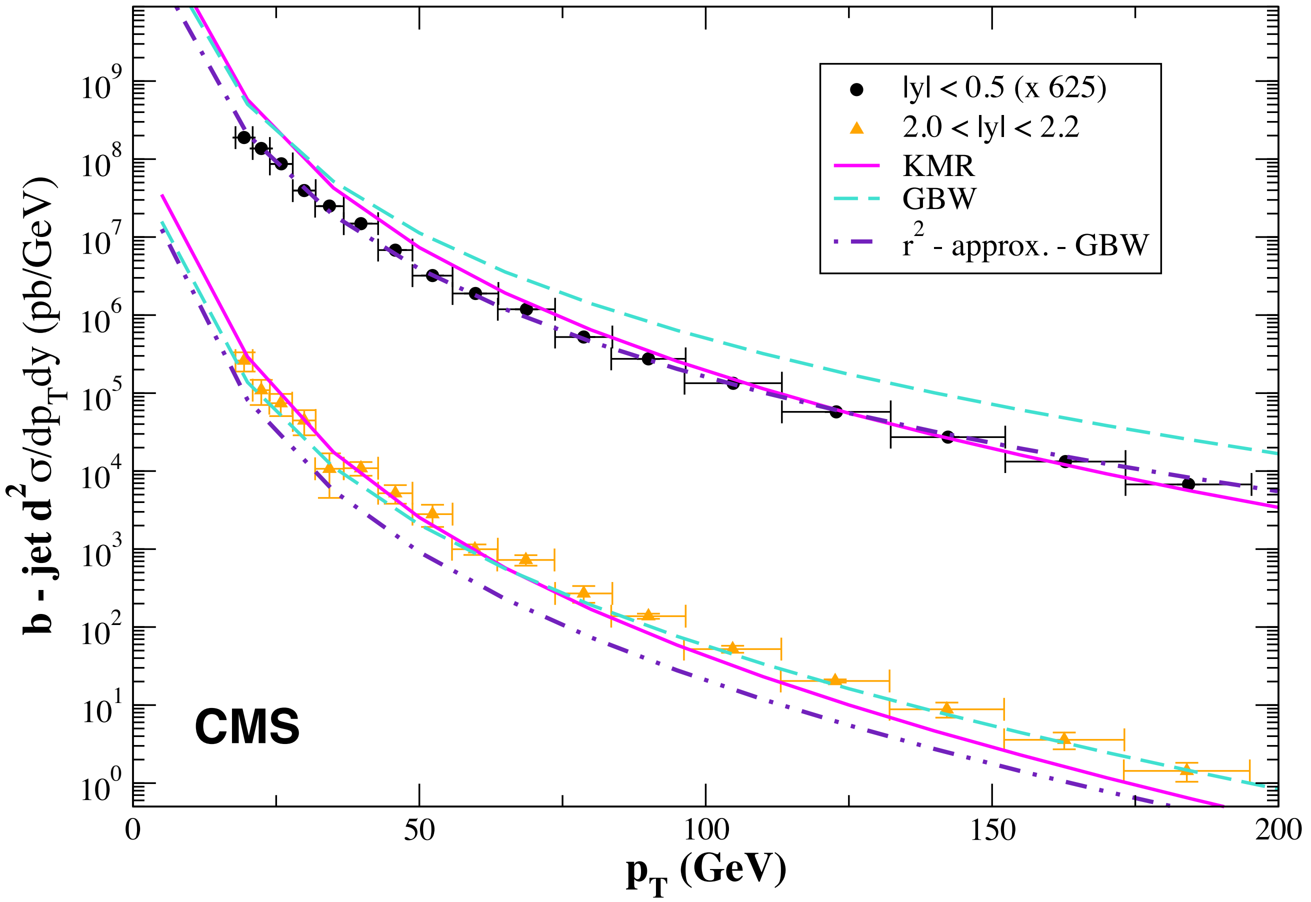
$$\sigma_{\bar{q}q}(x,\vec{r}) = \sigma_0\left[1-e^{-\frac{r^2}{R_0^2(x)}}\right] \simeq \sigma_0\,\frac{r^2}{R_0^2(x)}$$

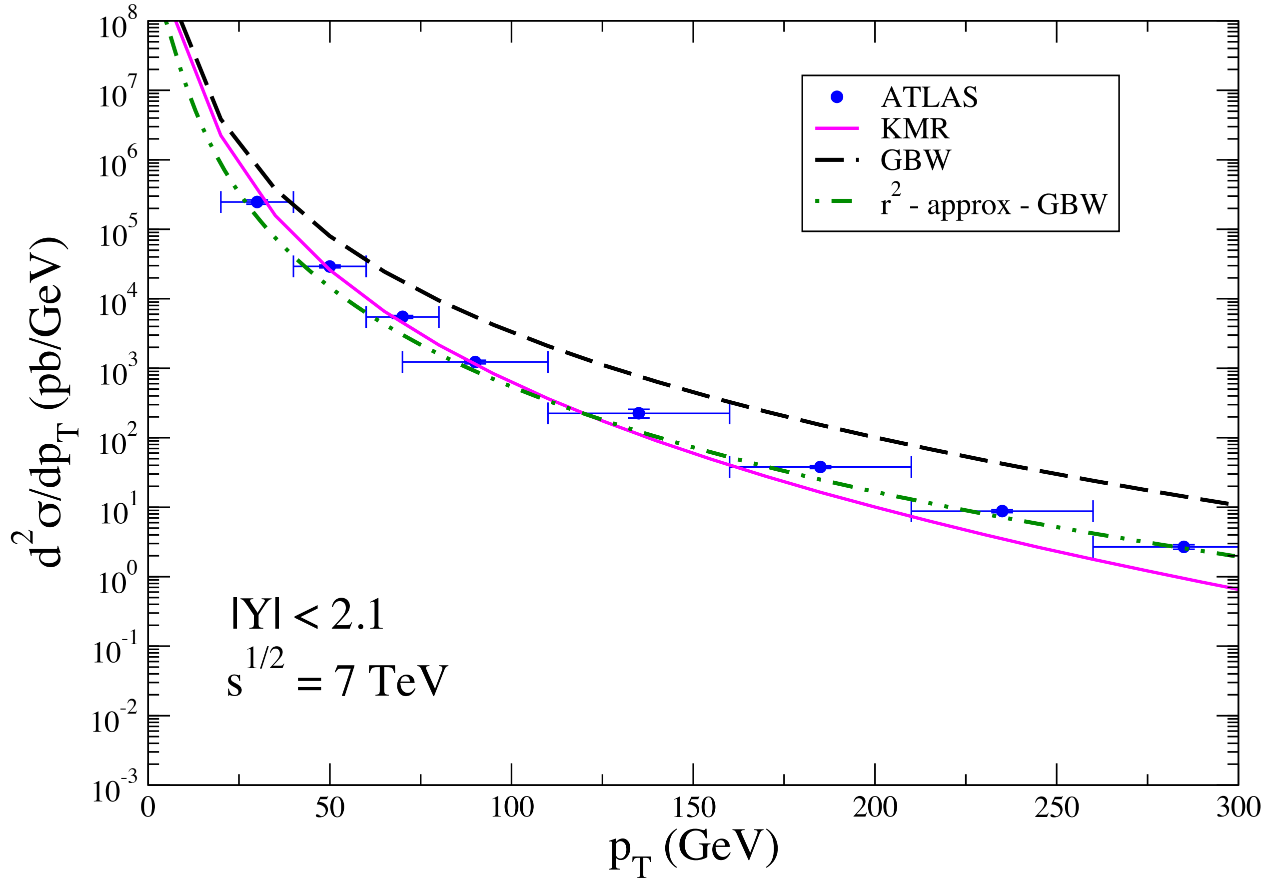
$$\sigma_{\rm eff}(\vec{r}_1,\vec{r}_2,\alpha) \approx \frac{\sigma_0}{R_0^2(x)}\left[\alpha^2+\bar{\alpha}^2-\frac{1}{4}\alpha\bar{\alpha}\right]\vec{r}_1\cdot\vec{r}_2$$

$$\frac{d^3\sigma(G\to Q\bar{Q}+X)}{d\alpha d^2p_T} = \frac{\alpha_s}{(2\pi)^2}\frac{\sigma_0}{R_0^2(x)}\left[\alpha^2+\bar{\alpha}^2-\frac{1}{4}\alpha\bar{\alpha}\right]\left\{\frac{4m_Q^2p_T^2}{(m_Q^2+p_T^2)^4}+(\alpha^2+\bar{\alpha}^2)\frac{2(m_Q^4+p_T^4)}{(m_Q^2+p_T^2)^4}\right\}$$

Q-jet pT distribution in pp collisions vs LHC data

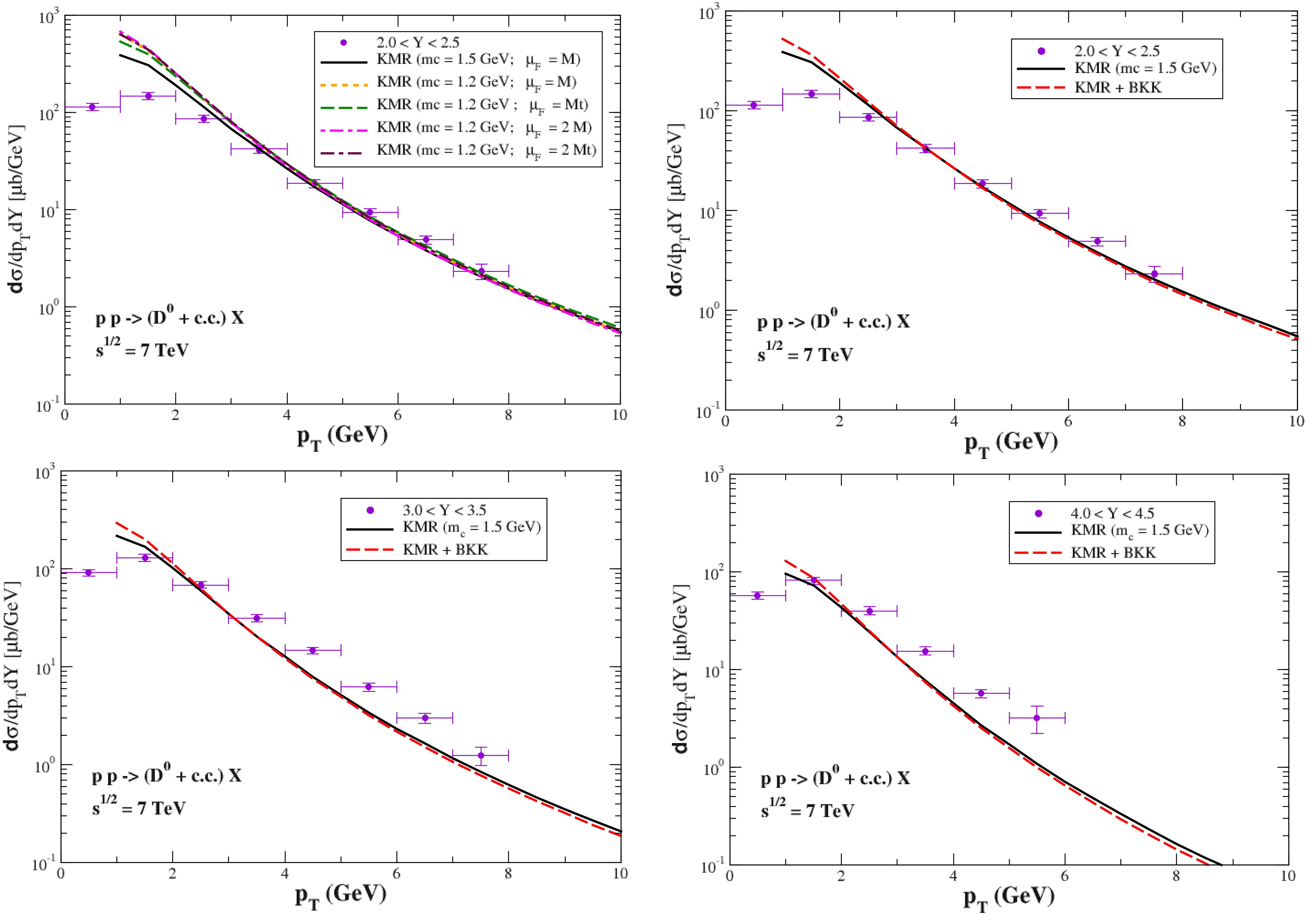




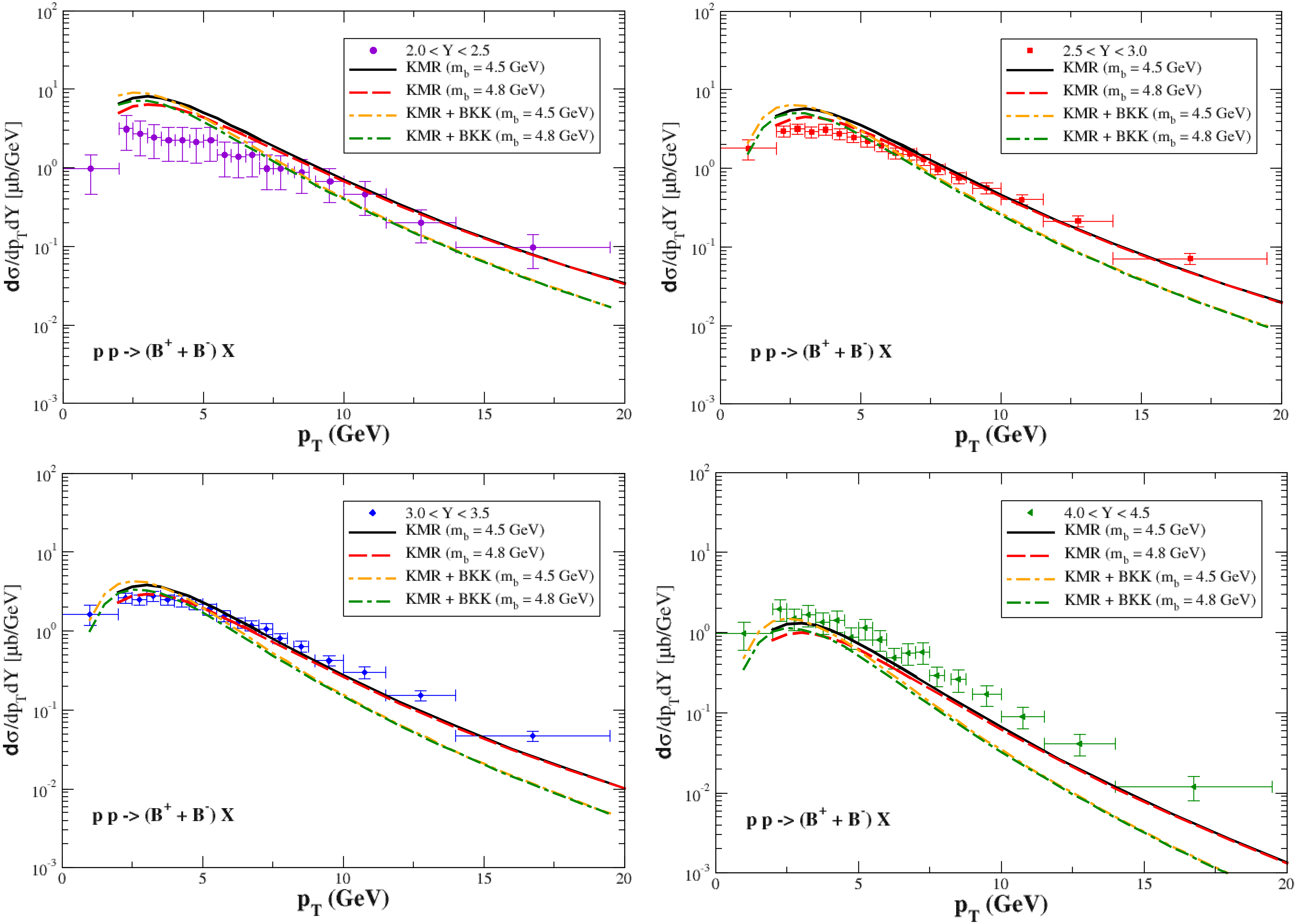


not worse than in NLO pQCD!

Open heavy flavour production vs LHC data: D-mesons



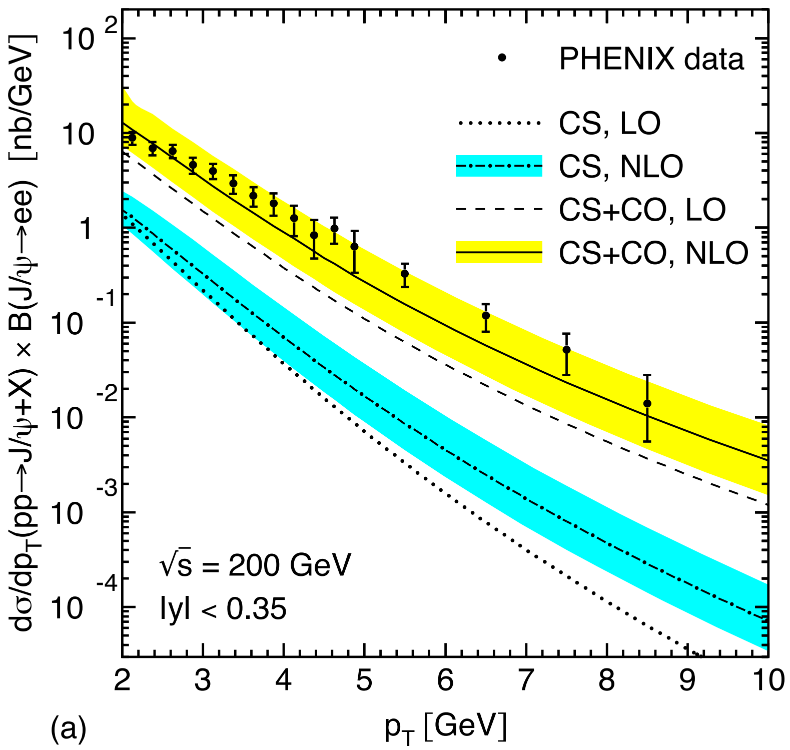
Open heavy flavour production vs LHC data: B-mesons

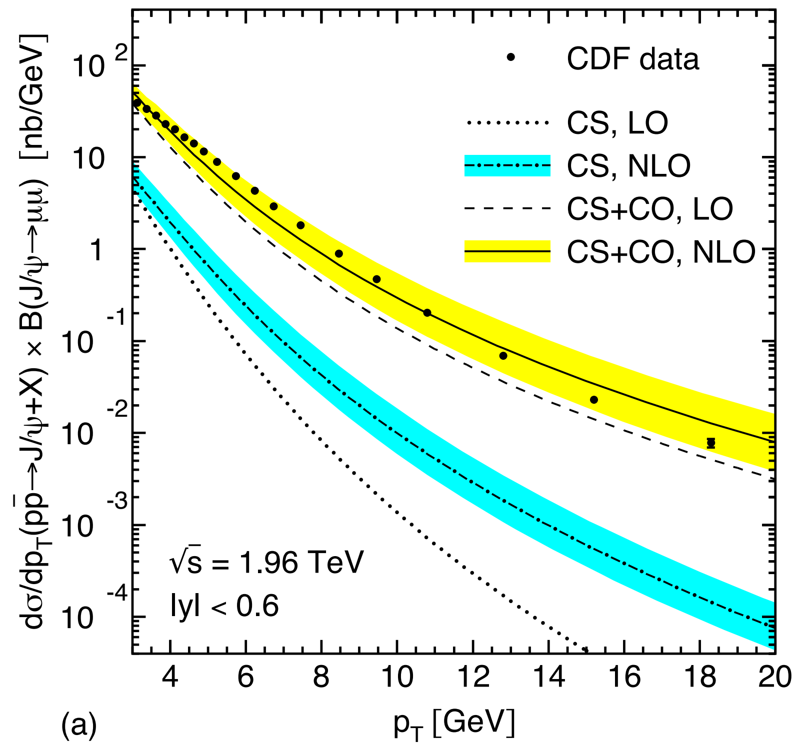


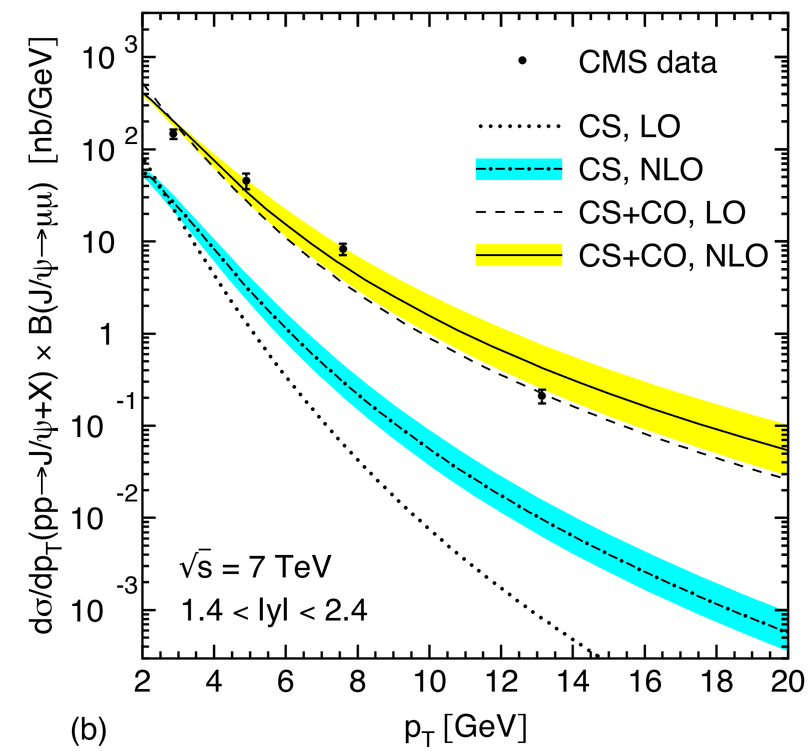
Quarkonia: Color-Singlet vs Color-Octet mechanisms

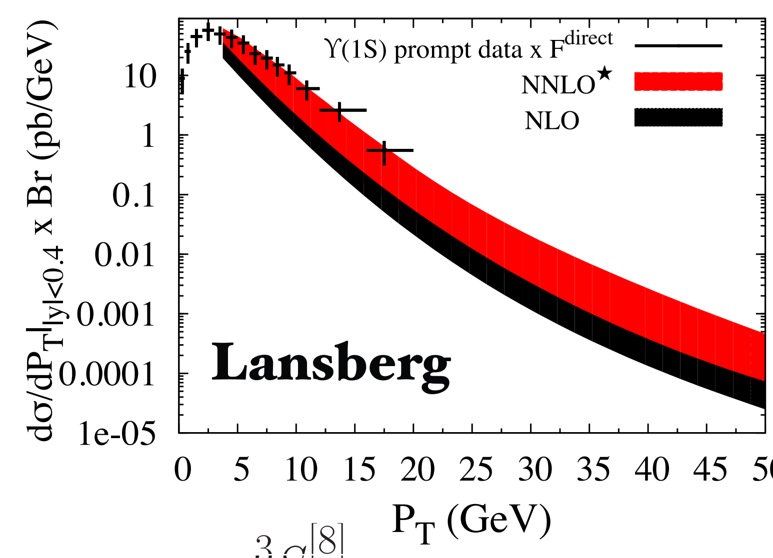
for review, see Lansberg, Kramer etc

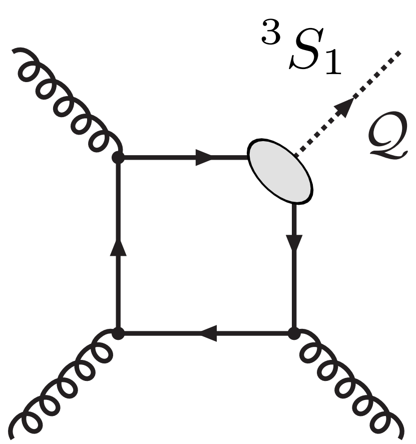
M. Butenschoen, B. Kniehl'10



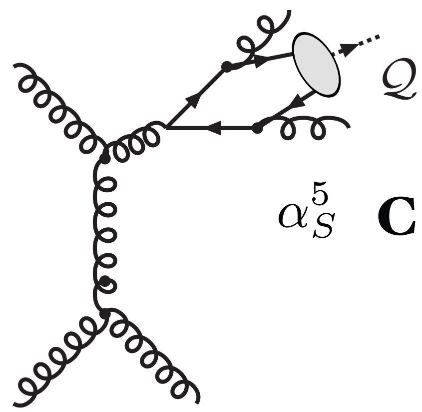




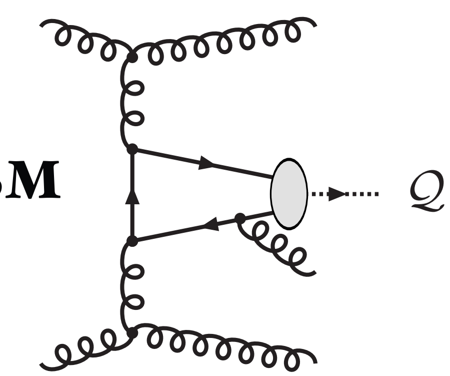


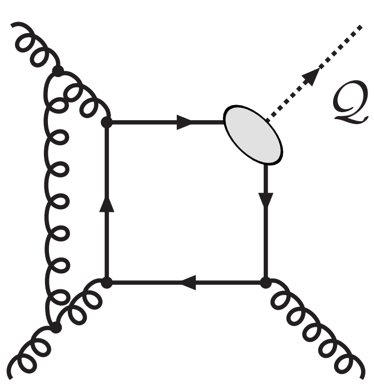


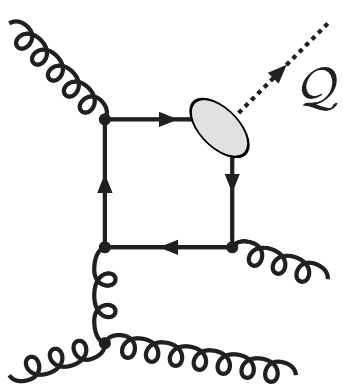
α_S^3 **CSM**

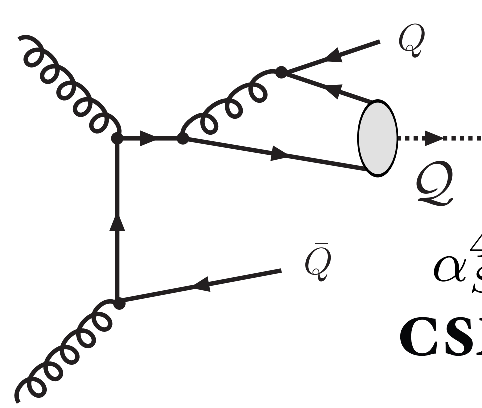


α_S^5 **CSM**

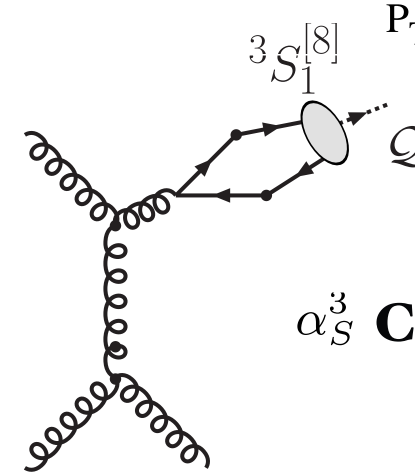




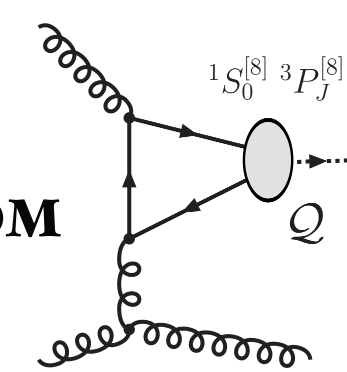




α_S^4 **CSM**



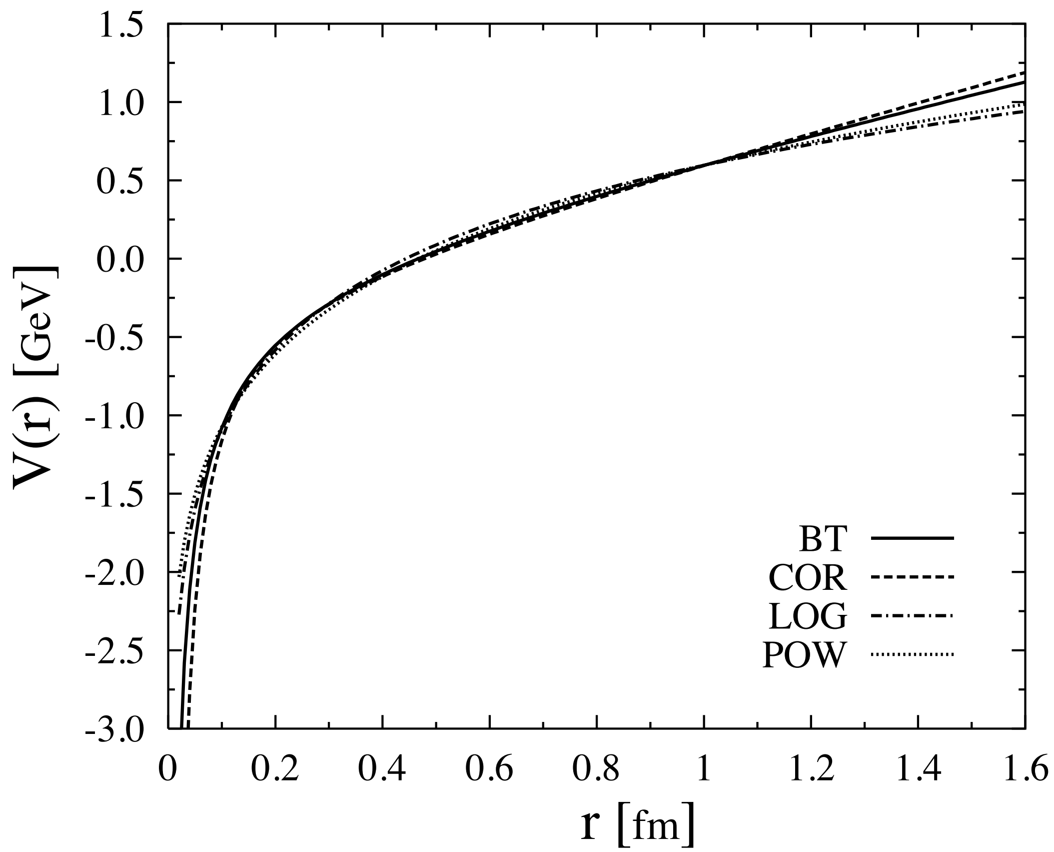
α_S^3 **COM**

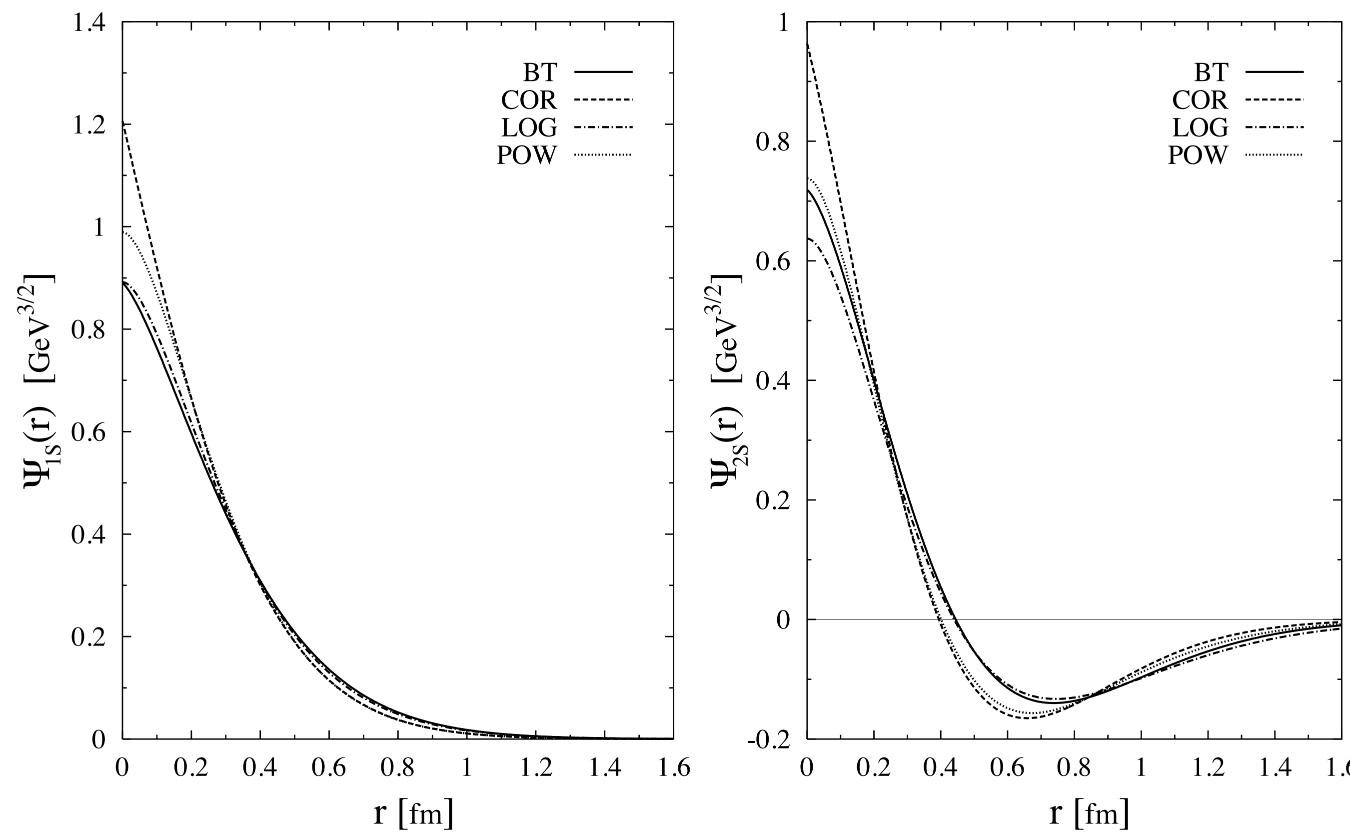


S- and P-wave quarkonia wave functions

Schrodinger equation for spatial ccbar wave function

$$\left(-\frac{\Delta}{m_c} + V(r)\right)\,\Psi_{nlm}(\vec{r}) = E_{nl}\,\Psi_{nlm}(\vec{r}) \qquad \Psi(\vec{r}) = \Psi_{nl}(r)\cdot Y_{lm}(\theta,\varphi)$$





..from the rest frame to the LC frame

$$\Psi(\vec{r}) \Rightarrow \Psi(\vec{p}) \qquad M^2 = 4(p^2 + m_c^2) = \frac{p_T^2 + m_c^2}{\alpha(1-\alpha)}$$

$$p_L = (\alpha - 1/2)M(p_T,\alpha)$$

"Terentiev trick"

$$\boxed{\Psi(\vec{p}) \Rightarrow \sqrt{2}\,\frac{(p^2+m_c^2)^{3/4}}{(p_T^2+m_c^2)^{1/2}}\cdot\Psi(\alpha,\vec{p}_T) \equiv \Phi_\psi(\alpha,\vec{p}_T)}$$

Melosh spin rotation

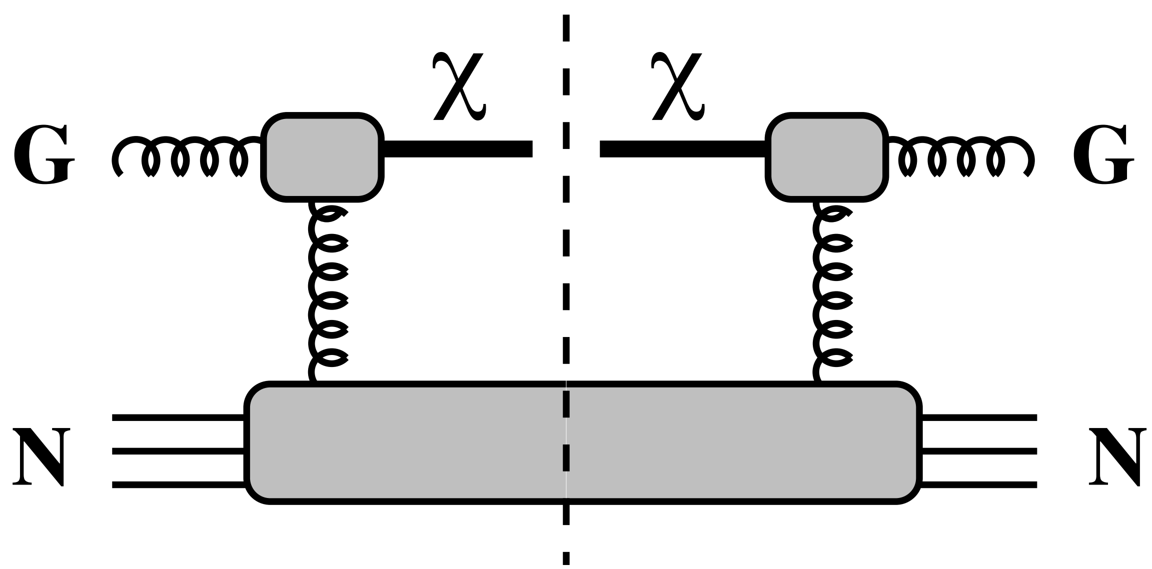
$$\overline{\chi}_{\mathbf{c}} = \widehat{R}(\alpha,\vec{p}_T)\,\chi_c\,, \quad \overline{\chi}_{\bar{\mathbf{c}}} = \widehat{R}(1-\alpha,-\vec{p}_T)\,\chi_{\bar{c}}\,,$$

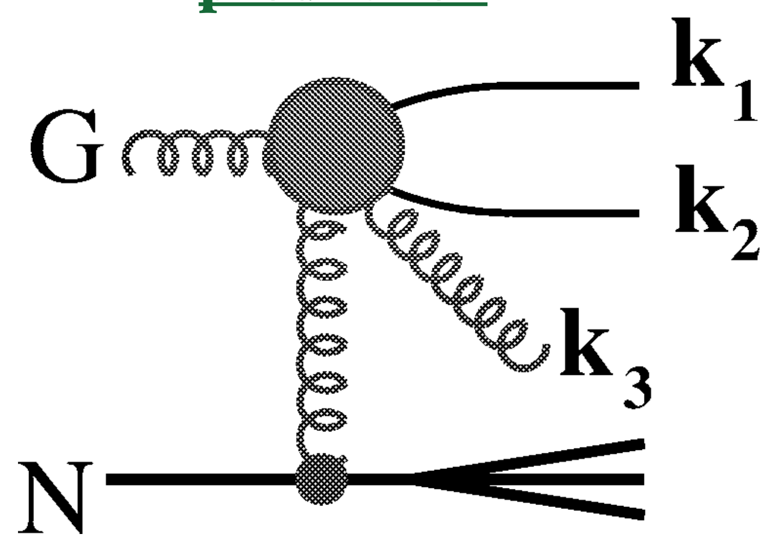
$$\widehat{R}(\alpha,\vec{p}_T) = \frac{m_c + \alpha M - i\,[\vec{\sigma}\times\vec{n}]\,\vec{p}_T}{\sqrt{(m_c+\alpha M)^2 + p_T^2}}$$

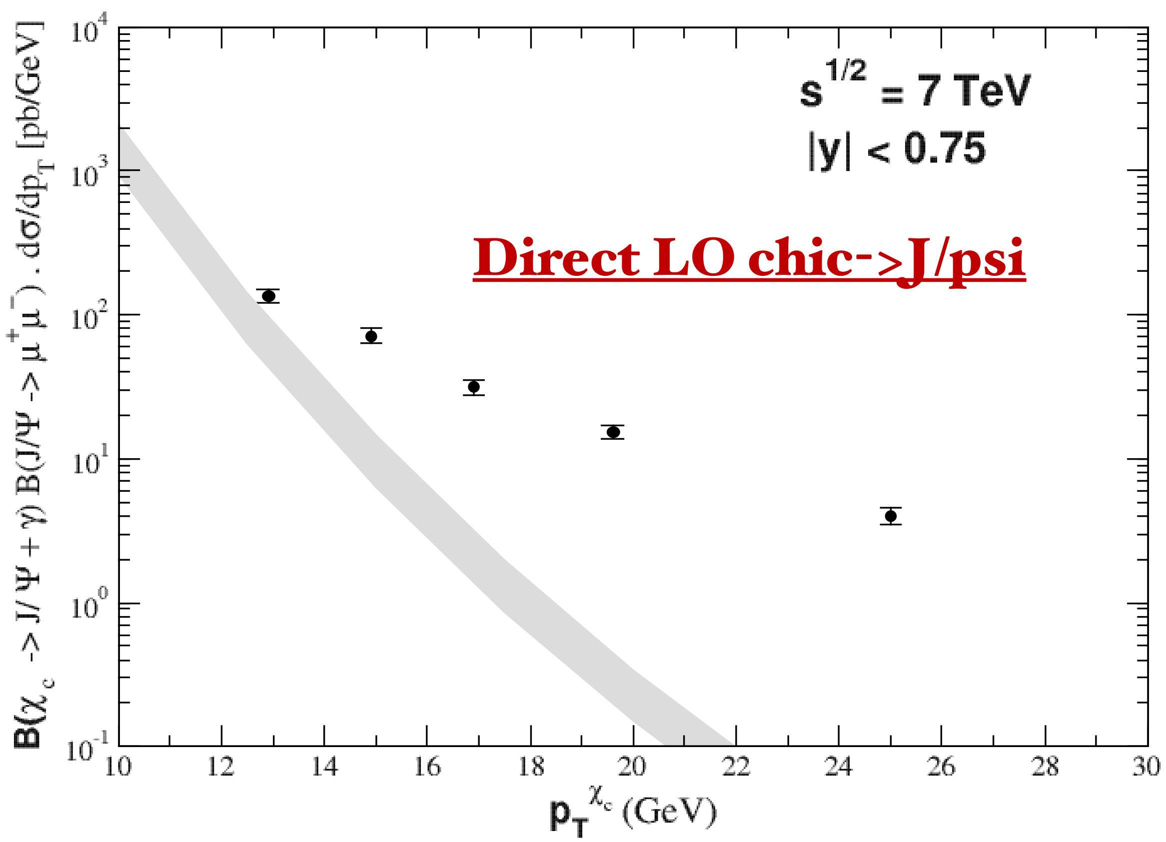
$$U^{(\mu,\bar{\mu})}(\alpha,\vec{p}_T) = \chi_c^{\mu\dagger}\,\widehat{R}^\dagger(\alpha,\vec{p}_T)\,\vec{\sigma}\cdot\vec{e}_\psi\,\sigma_y\,\widehat{R}^*(1-\alpha,-\vec{p}_T)\,\sigma_y^{-1}\,\tilde{\chi}_{\bar{c}}^{\bar{\mu}}$$

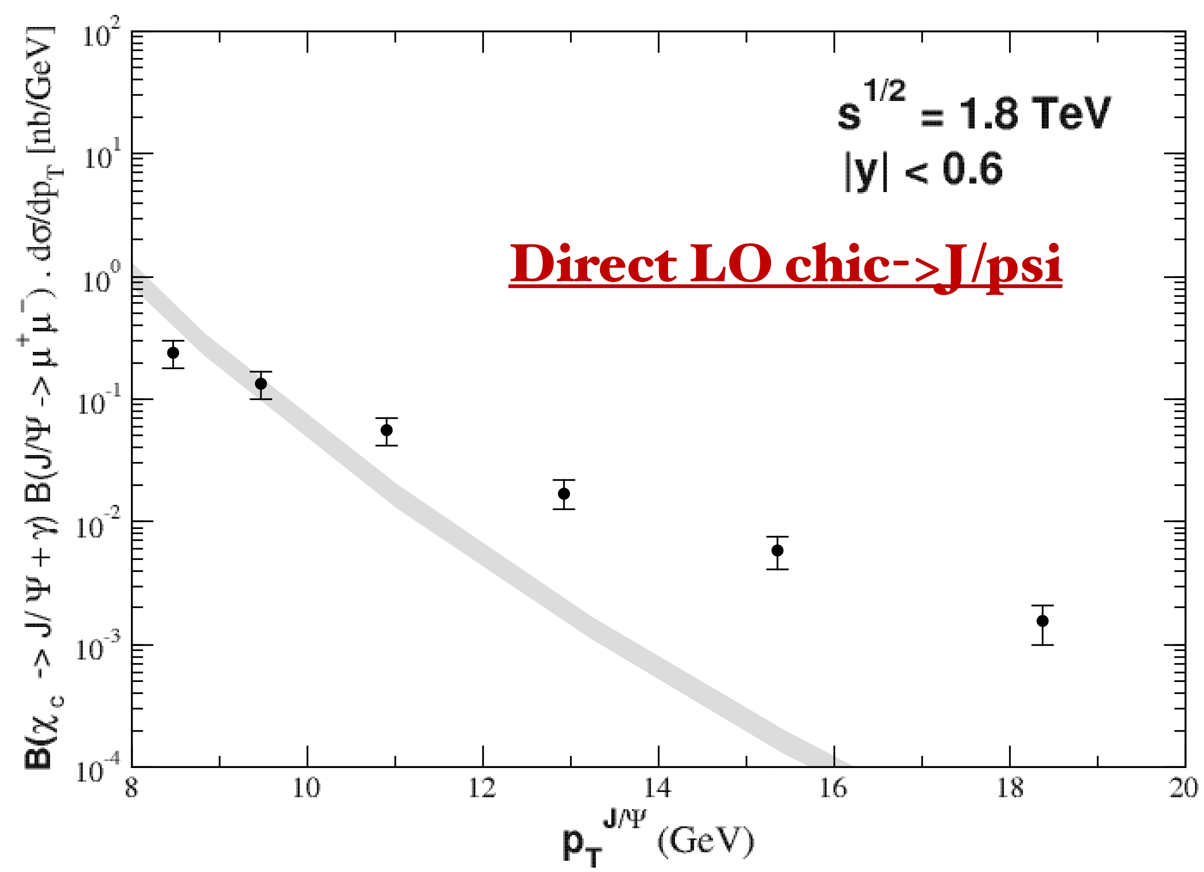
$$\boxed{\Phi_\psi^{(\mu,\bar{\mu})}(\alpha,\vec{p}_T) = U^{(\mu,\bar{\mu})}(\alpha,\vec{p}_T)\cdot\Phi_\psi(\alpha,\vec{p}_T)}$$

Color-Singlet chic -> J/psi production in the dipole picture









work in progress

Gluon shadowing corrections and direct J/psi

Direct J/psi (singlet/C-odd) production is not possible via

$$G + G \to Q\bar{Q}$$

$$\boxed{G + G \to Q\bar{Q} + G}$$

gluon shadowing (NLO) corrections for

C-even 1^- C-odd 8^-

C-even 8^+

e.g. P-waves $\chi_{c,b}$

leading order for

C-odd 1^+

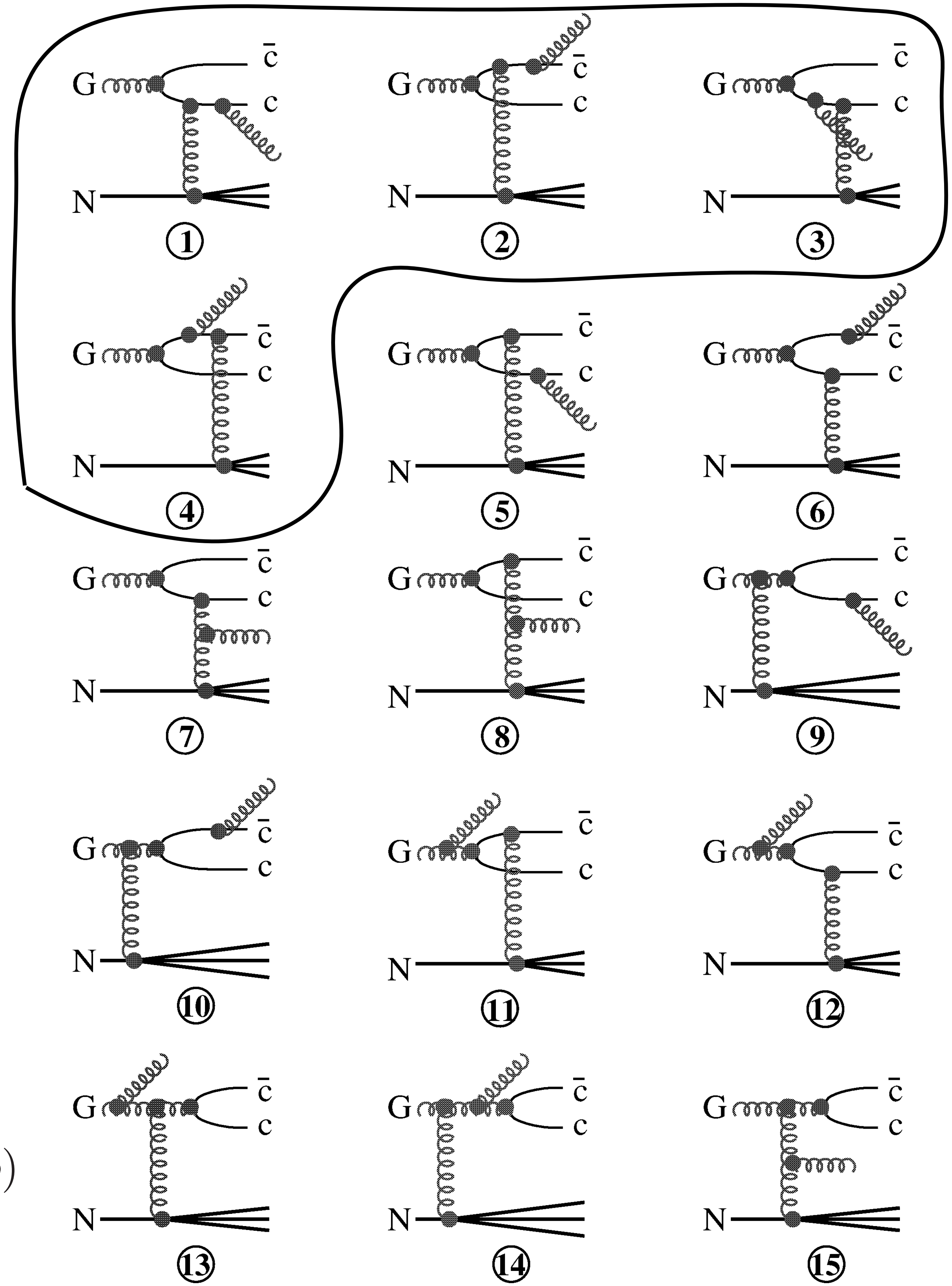
e.g. S-waves

$J/\psi,\ \psi',\ \Upsilon$

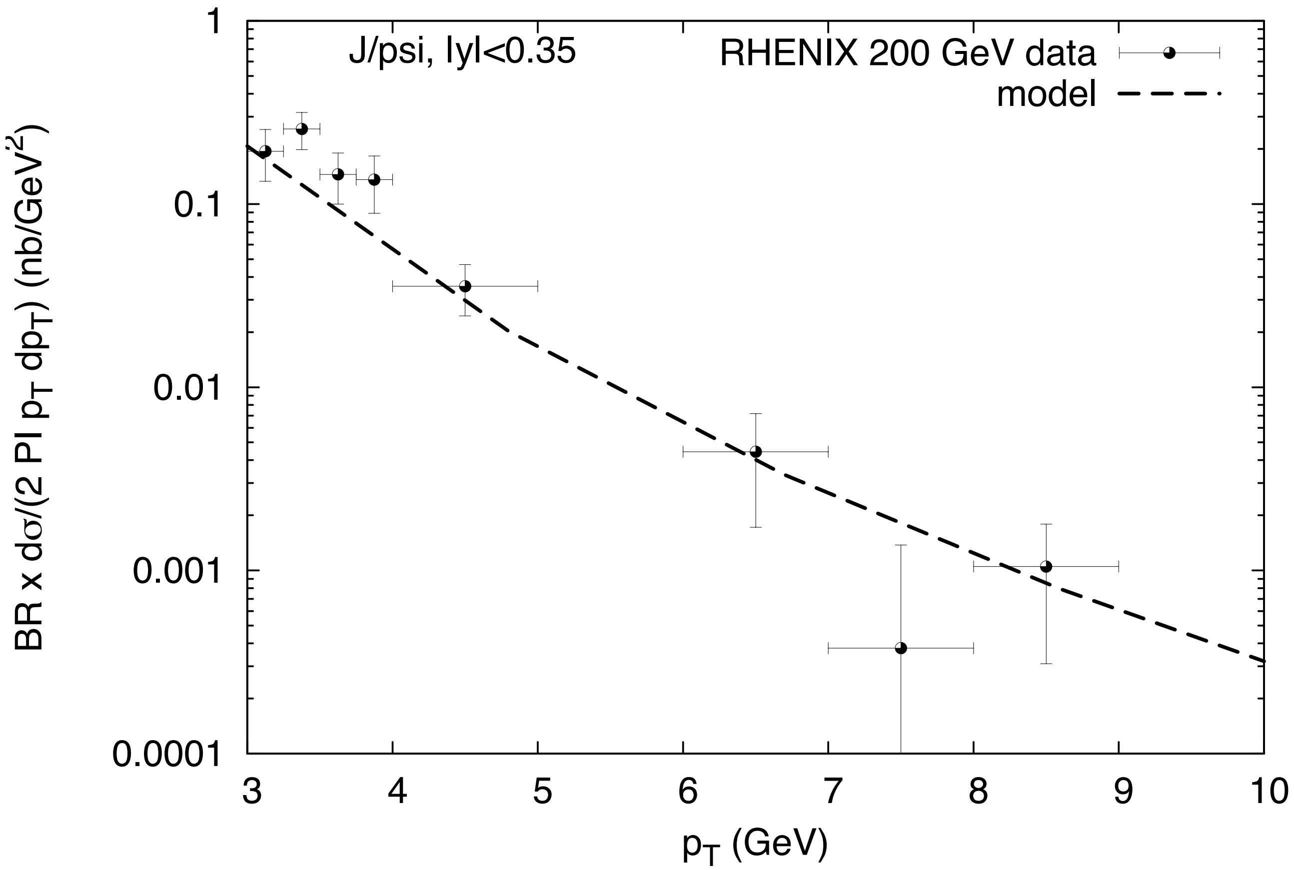
DIS-like cross section

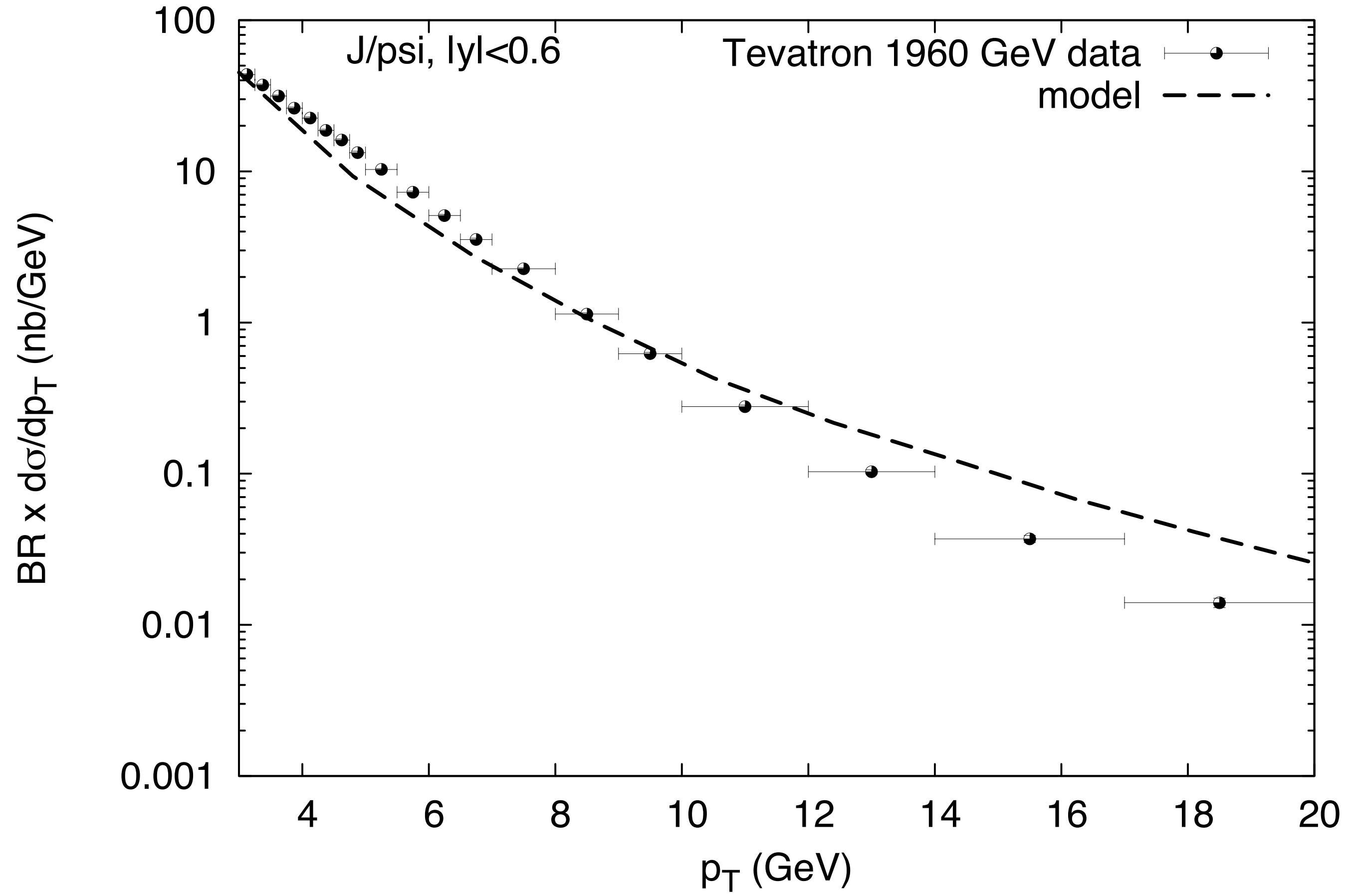
$$\frac{d\sigma}{d\beta\, d\ln\gamma} = \int d^2r d^2\rho \, |\Psi_{Q\bar{Q}G}(\beta,\gamma,\vec{r},\vec{\rho})|^2 \, \Sigma(\beta,\gamma,\vec{r},\vec{\rho})$$

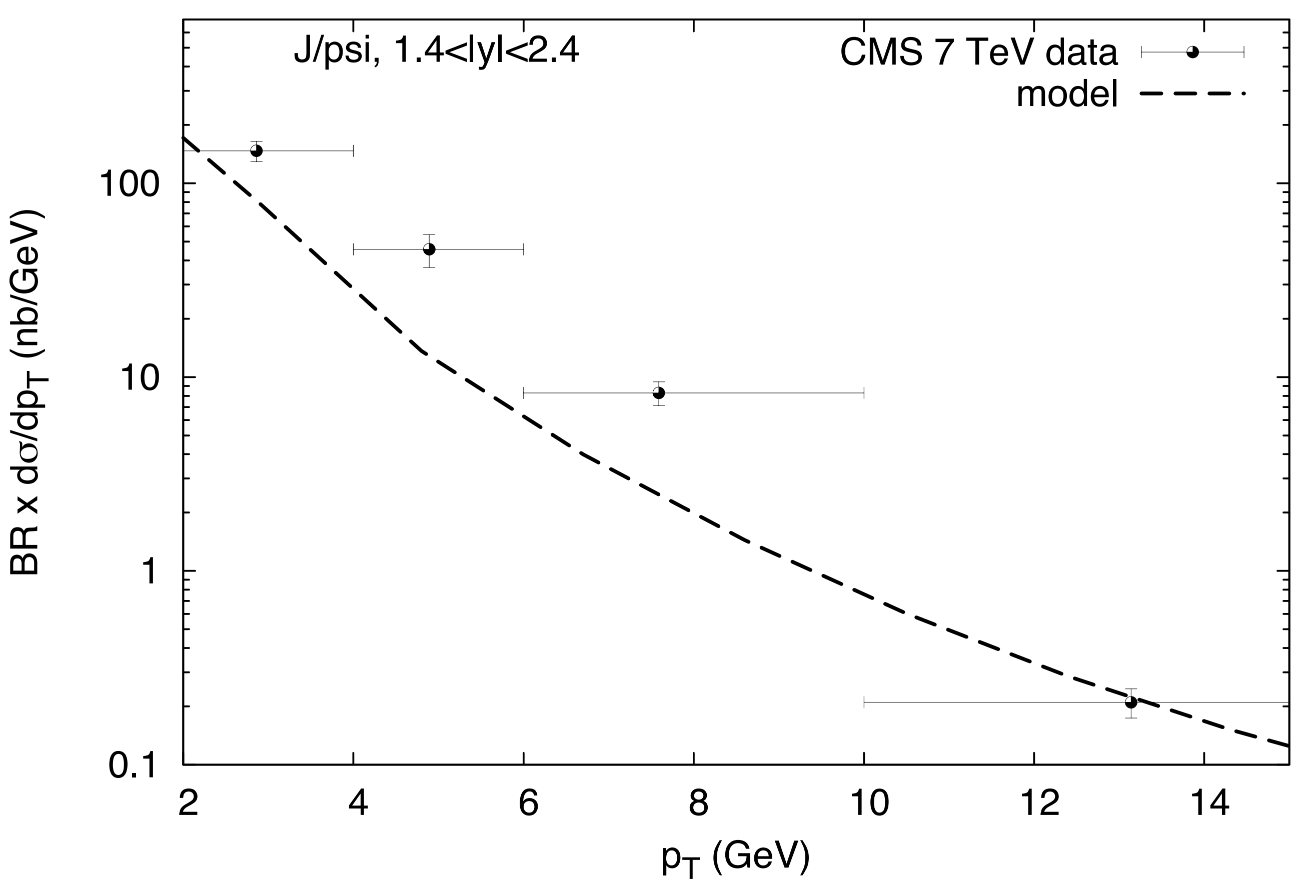
$$\Sigma_{1^-} = \Sigma_{8^-} = \Sigma_{8^+} = \frac{9}{4}\sigma_{\bar{q}q}(\rho)\,, \;\; \Sigma_{1^+} = \frac{5}{4}\sigma_{\bar{q}q}(\gamma\rho)$$



Color-Singlet direct J/psi production in the dipole picture







work in progress

Conclusions

- ✓ The dipole picture provides universal and robust means for studies the heavy flavour production processes (open HF and quarkonia) in both pp and pA collisions beyond QCD factorisation
- ✓ Recent inclusive b-jets, D- and B-meson production data in pp collisions at the LHC are well described in the framework of color dipole approach which effectively but correctly accounts for perturbative QCD effects
- ✓ Preliminary results on J/psi production exhibit a correct behaviour with transverse momentum and a dominance of the CS mechanism while chic data description at high pT's requires an account for an additional gluon radiation
- ✓ Residual sensitivity to the modelling of the universal dipole cross section, the fragmentation functions and quarkonia wave functions should provide model-independent constraints on these important ingredients