Forward-central correlations in quarkonia production

Roman Pasechnik

THEP, Lund University

in cooperation with
Nuclear Physics Institute, Prague

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Contents

Challenges in heavy quarkonia studies

✓ **Quarkonia production in pp/pA, as well as high pT forward particle production in pA, traditionally are very important probes for QCD dynamics**
e.g. QCD factorisation, gluon resummations, higher order PT and non-PT effects, medium, CGC etc

★ *probe for QCD in heavy quark production*

heavy quarks provide a naturally hard enough scale to study the production mechanisms in perturbative QCD (factorisation breaking, CS vs CO etc)

★ *probe for large-distance evolution and formation*

Quarkonia are suppressed in a deconfined medium which is believed to be due to a Debye screening of the heavy quark potential (Matsui-Satz'86)

★ *Quarkonia are sensitive to all the stages, from early heavy quark production to late time evolution and bound states' formation*

✓ **Charmonia are very special!**

★ *Charm quark mass scale is at the boundary between pQCD and soft QCD*
★ *Specific for heavy ions production and destruction mechanisms*

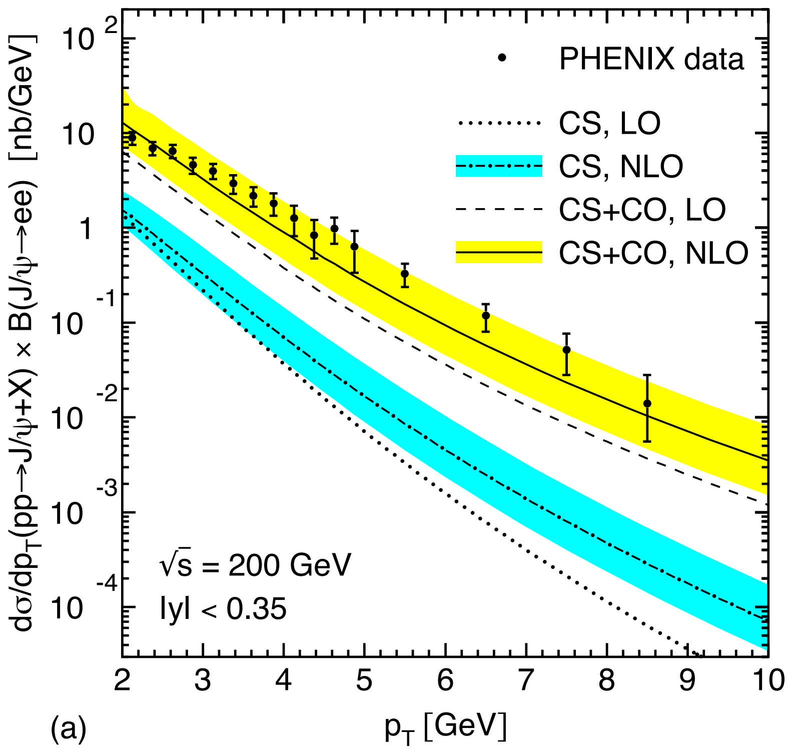
✓ **J/psi puzzle: highly uncertain production and evolution in hot environment**
What is the dominating QCD mechanism and role of the medium? why R_{pA} is close to one?

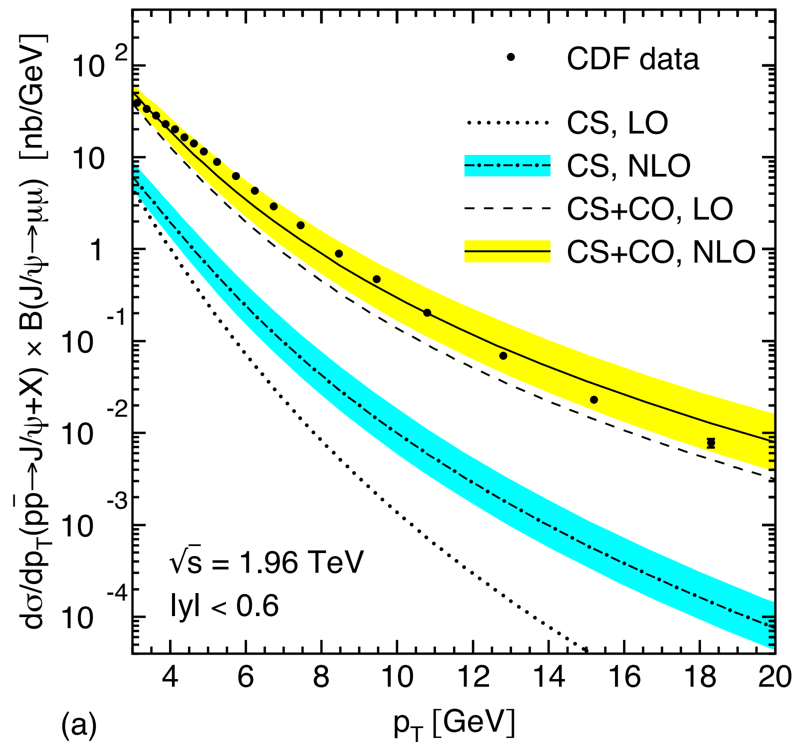
✓ *recombination of c-quarks (Braun-Munzinger, Stachel'00)*
✓ *sequential melting of excited states (Rafelski et al'09)*
✓ *modification of feeddown*
✓ *formation time effects (Karsch-Petronzio'88)*
✓ *cold nuclear matter effects (Vogt'05)*
✓ *shadowing and nuclear absorption (Noble'81, Tram-Arleo'09) etc*

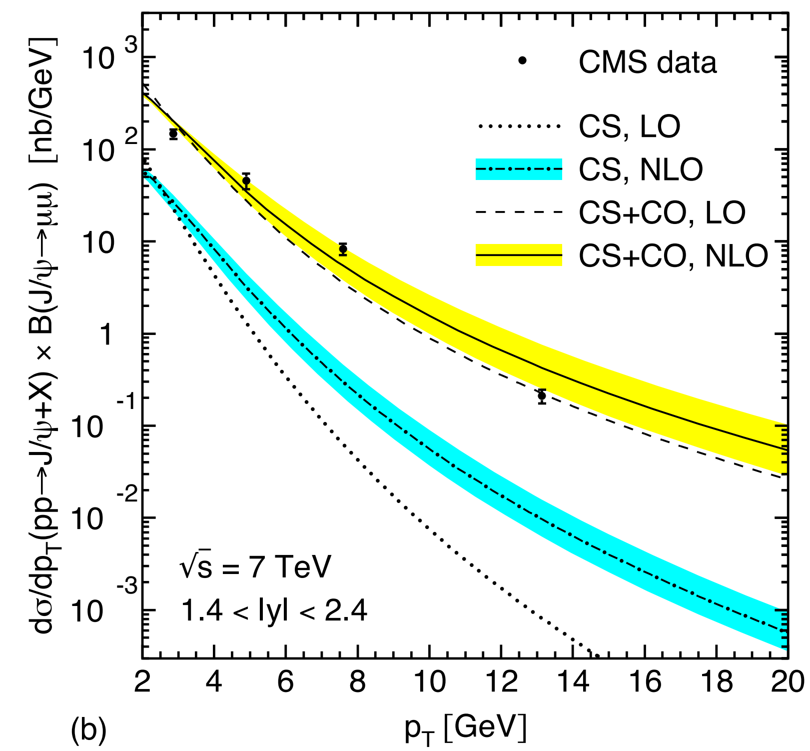
⇒ **Quantitative understanding of J/psi in pp/pA/AA at different energies is required!**

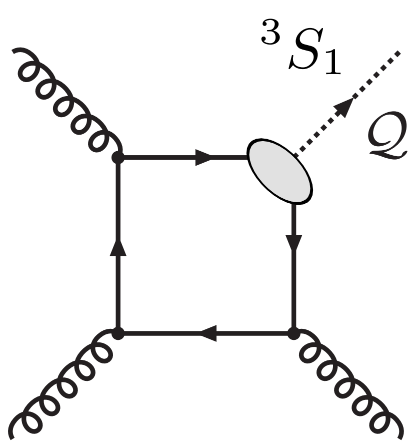
Deficiencies: Color-Singlet vs Color-Octet

for review, see Lansberg, Kramer etc **M. Butenschoen, B. Kniehl'10**

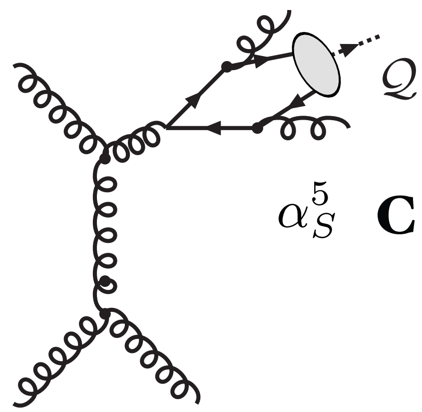




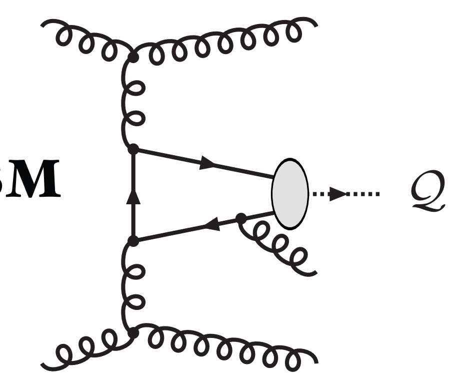


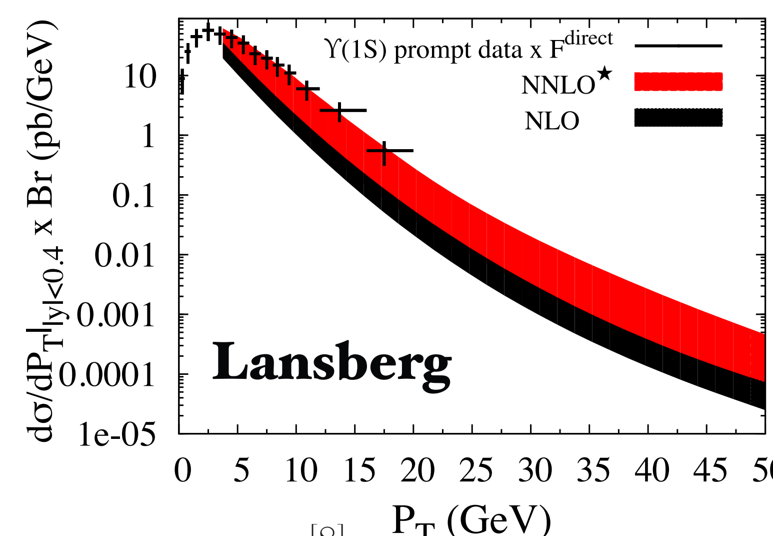


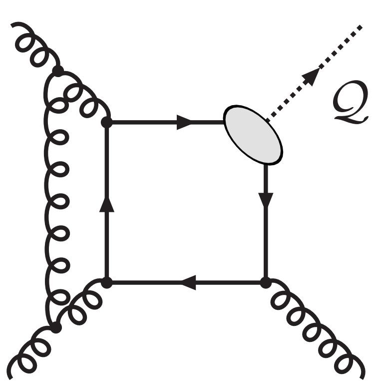
α_S^3 **CSM**

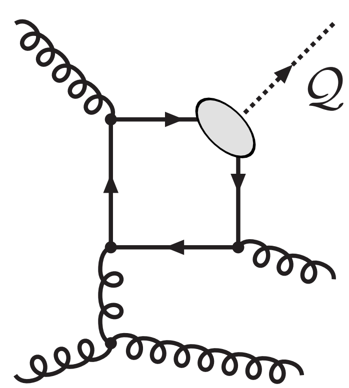


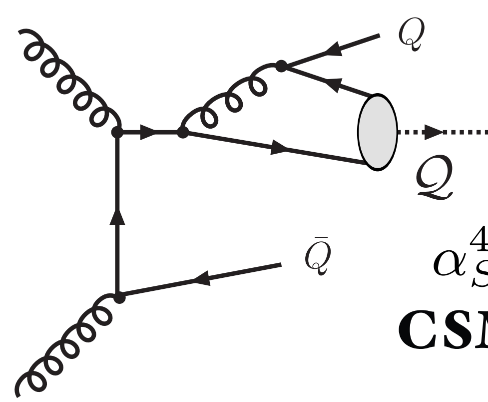
α_S^5 **CSM**











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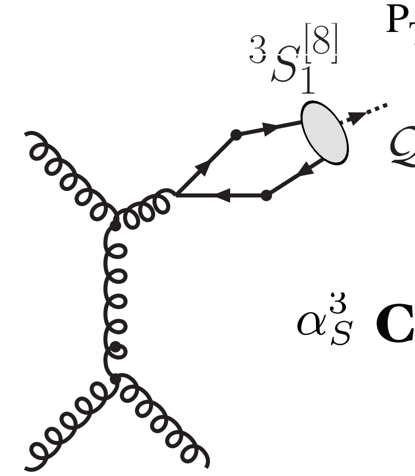
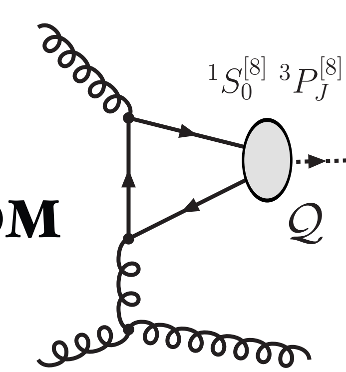


α_S^3 **COM**



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

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

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

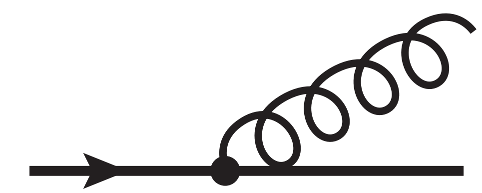
In most cases, a scattering cross section in the target rest frame can be represented in terms of three basic ingredients:

- **Gluon to quark-antiquark splitting amplitude:**

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

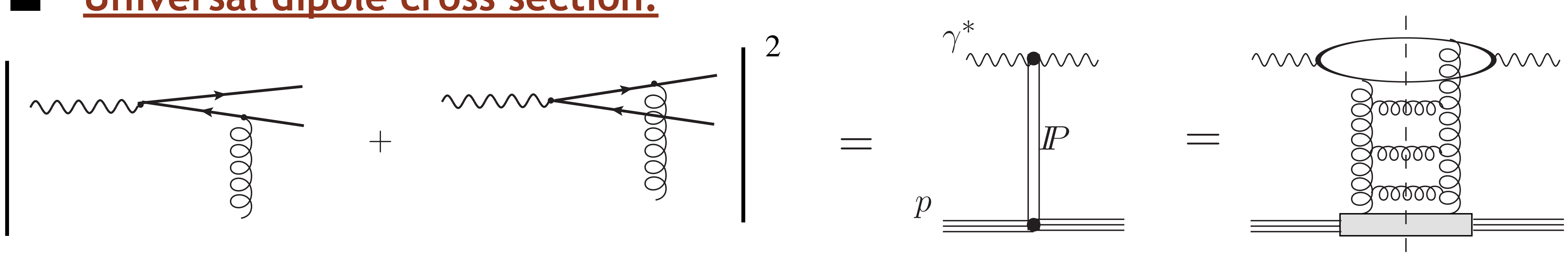
$$= \frac{\sqrt{\alpha_s}}{2\pi} (\xi^\mu_Q)^\dagger \Big\{ m_Q(\vec{e}_{ini}\cdot\vec{\sigma}) + i(1-2\beta)(\vec{\sigma}\cdot\vec{n})(\vec{e}_{ini}\cdot\vec{\nabla}_r) - (\vec{e}_{ini}\times\vec{n})\cdot\vec{\nabla}_r \Big\}\, \tilde{\xi}^{\bar{\mu}}_{\bar{Q}}\, K_0(\epsilon r)\,,$$

- **Gluon Bremsstrahlung off a quark:**

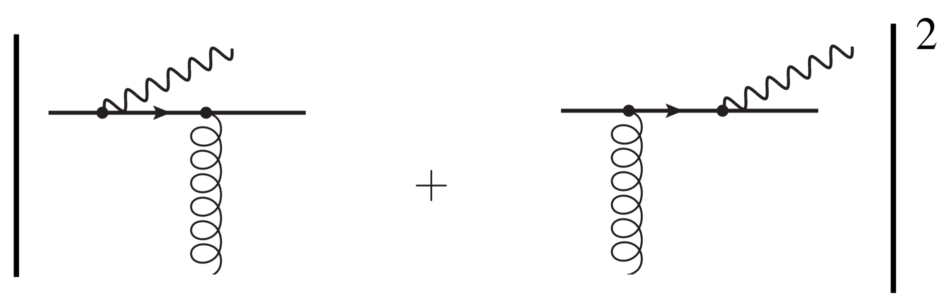


$$\Phi^T_{qG^*}(\alpha,\vec{\pi}) = \sqrt{\alpha_s}\,(\eta^s_Q)^\dagger \frac{(2-\alpha)(\vec{e}_*\cdot\vec{\pi}) + i m_q\alpha^2(\vec{n}\times\vec{e}_*)\cdot\vec{\sigma} - i\alpha(\vec{\pi}\times\vec{e}_*)\cdot\vec{\sigma}}{\vec{\pi}^2+\alpha^2 m_q^2}\, \eta^{s'}_Q$$

- **Universal dipole cross section:**



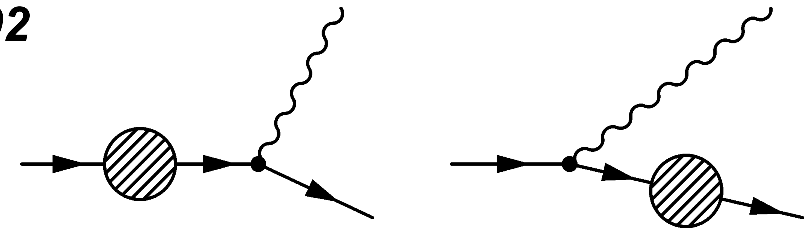
$\propto \quad \sigma_{q\bar{q}}(r,x)$



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

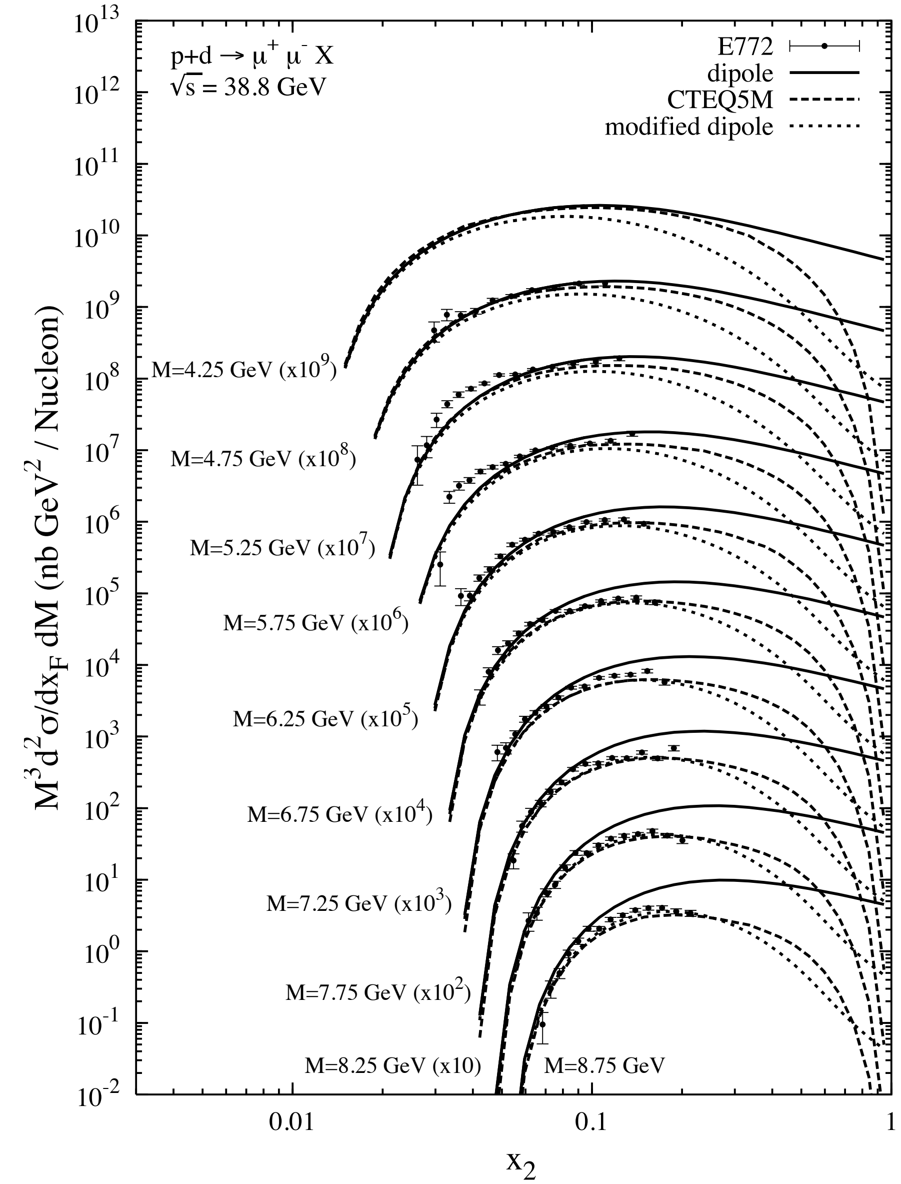
Dipole approach vs NLO QCD: Drell-Yan

J. Raufeisen et al, PRD66 2002

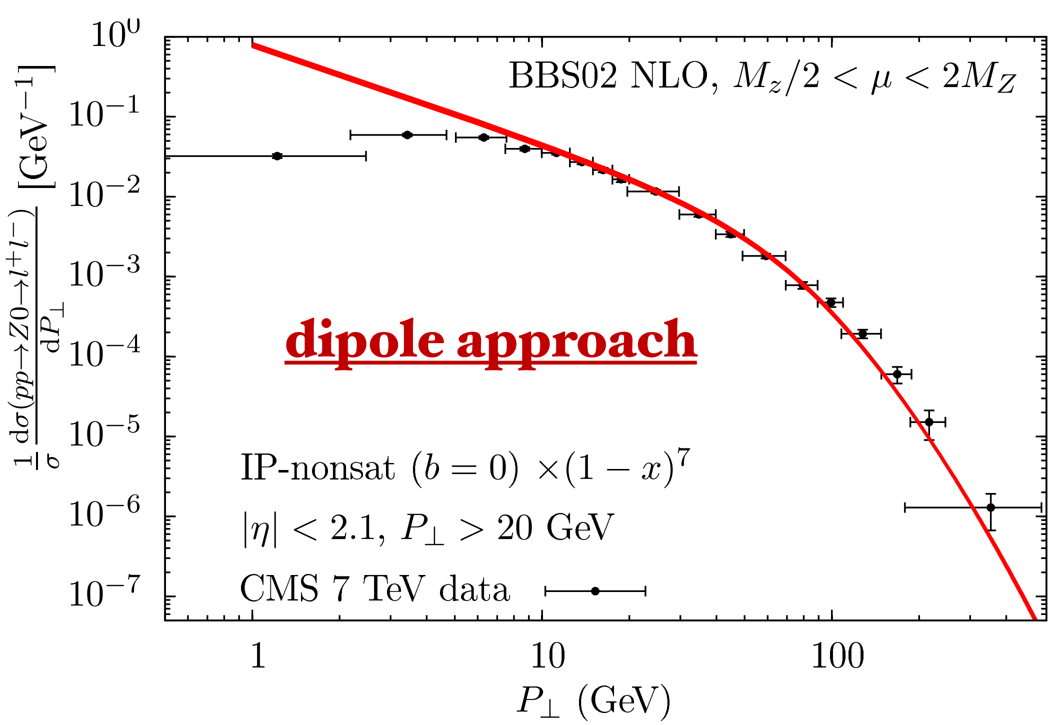


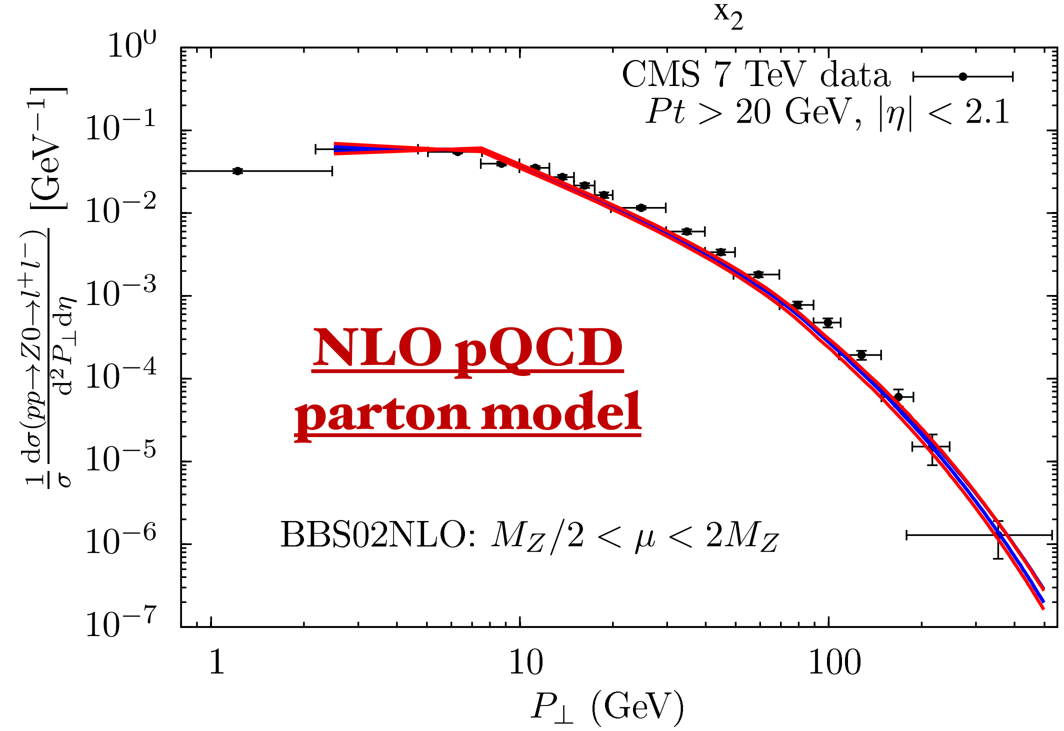
$$\frac{d\sigma(qN \to \gamma^* X)}{d\ln\alpha} = \int d^2\rho\, |\Psi_{\gamma^* q}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}}(\alpha\rho, x)$$

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



Dipole approach predictions effectively account for higher order QCD corrections!

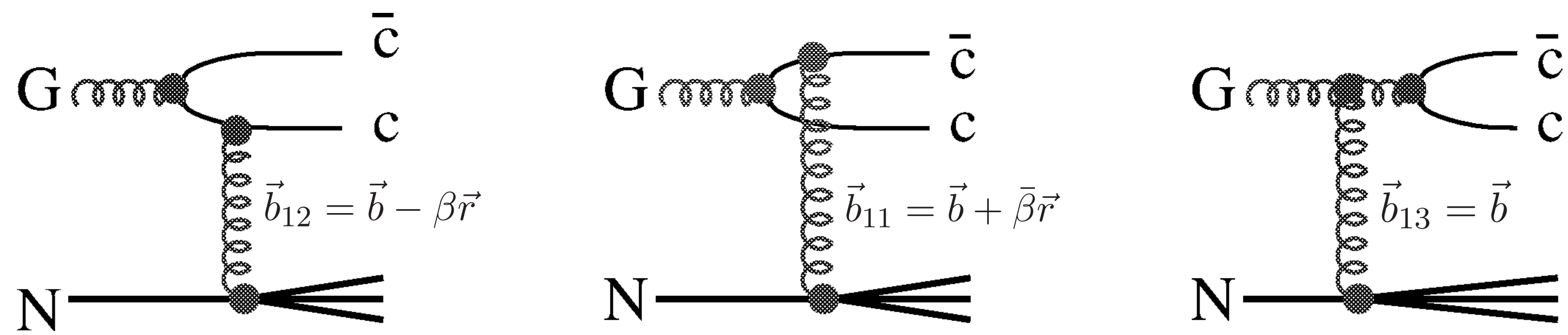




Dipole framework for heavy flavor production

"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

$$\sigma(G+p\to c\bar{c}+X) = \sum_{\mu\bar{\mu}}\int_0^1 d\beta\int d^2r\,\sigma_3(r,\beta,x_2)\,|\Phi_{Q\bar{Q}}(\vec{r},\beta)|^2$$

$$\sigma_3(r,\beta,x_2) = \frac{9}{8}\Big(\sigma_{\bar{q}q}(\bar{\beta}r,x_2)+\sigma_{\bar{q}q}(\beta r,x_2)\Big) - \frac{1}{8}\sigma_{\bar{q}q}(r,x_2)\,, \qquad x_2 = \frac{M^2_{c\bar{c}}}{2m_pE_G}$$

Gluon shadowing corrections and direct J/psi

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

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

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

gluon shadowing (NLO) corrections for

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

C-even 8^+

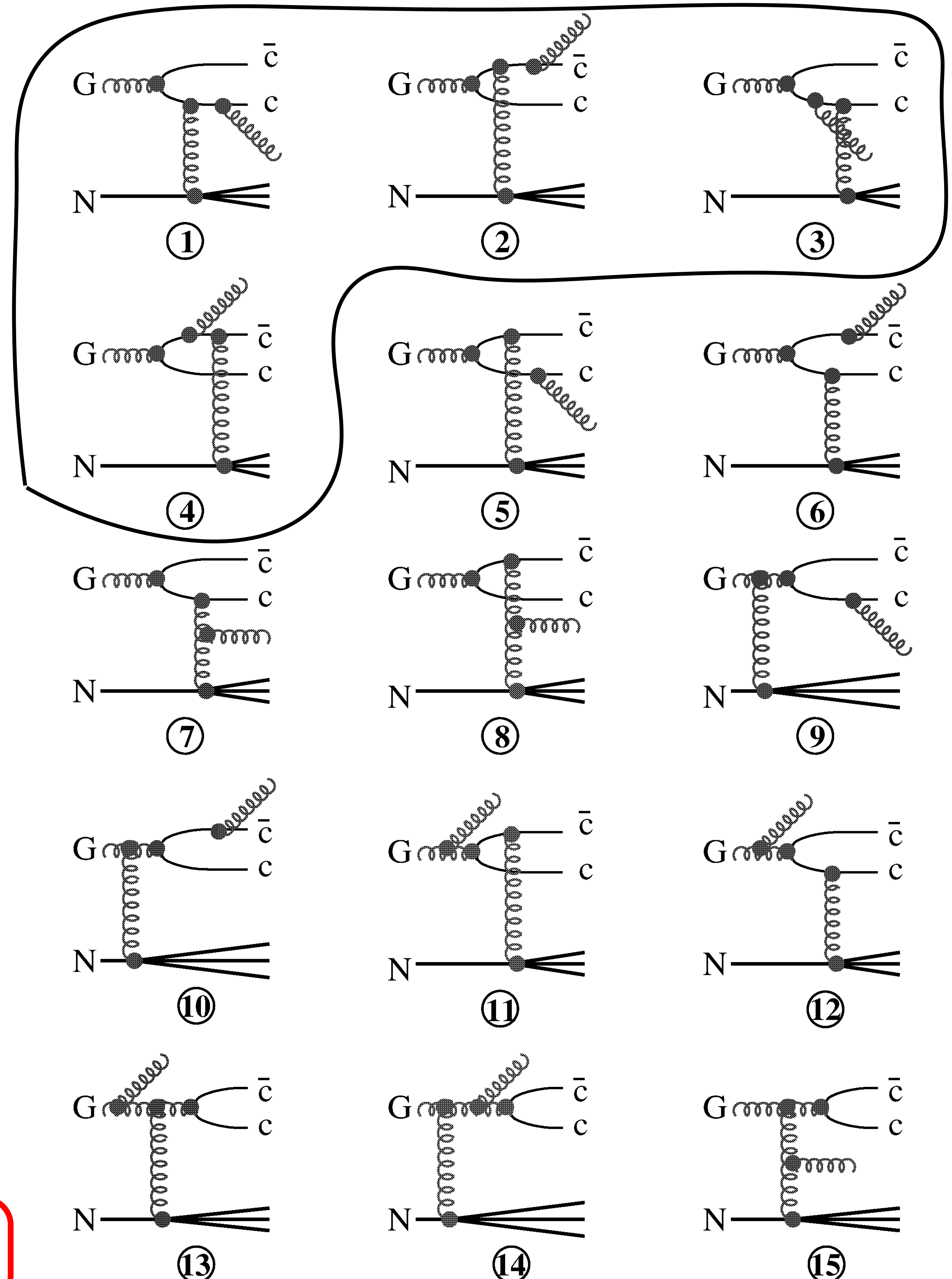
e.g. P-waves $\chi_{c,b}$

leading order for

C-odd 1^+

e.g. S-waves

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



DIS-like cross section

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

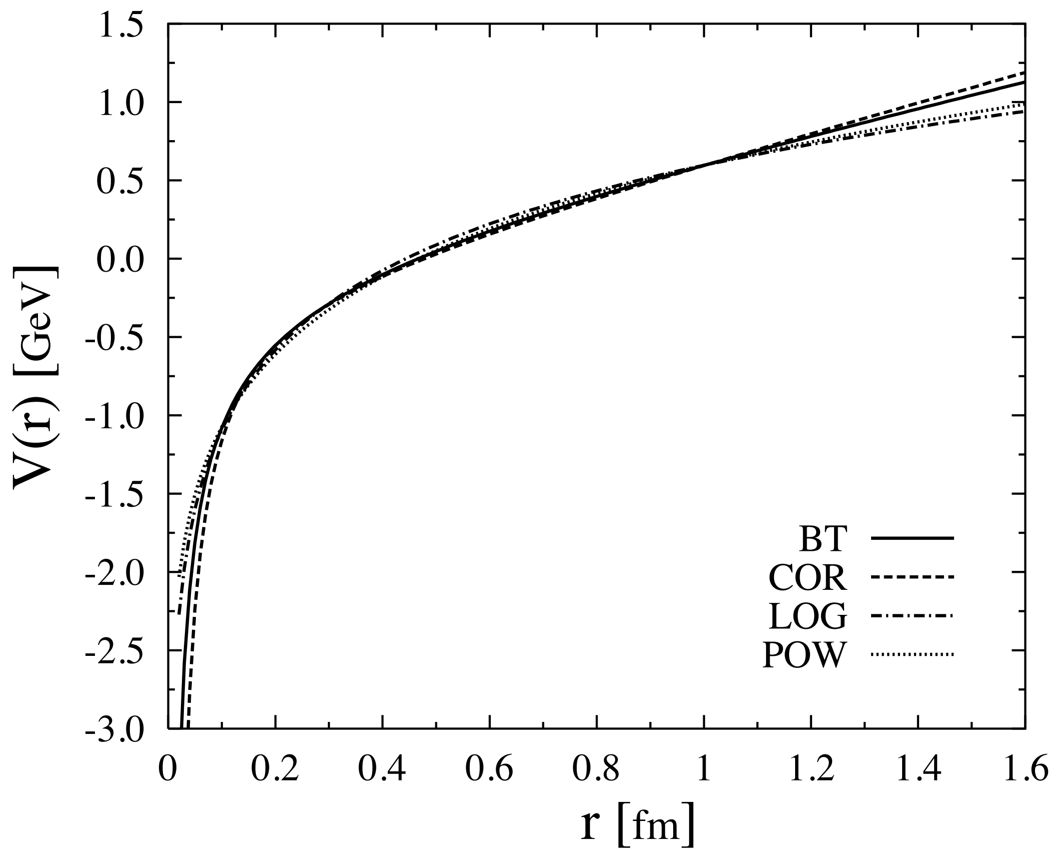
$$\Sigma_{1^-} = \Sigma_{8^-} = \Sigma_{8^+} = \frac{9}{4}\sigma_{\bar{q}q}(\rho)\,,\ \Sigma_{1^+} = \frac{5}{4}\sigma_{\bar{q}q}(\gamma\rho)$$

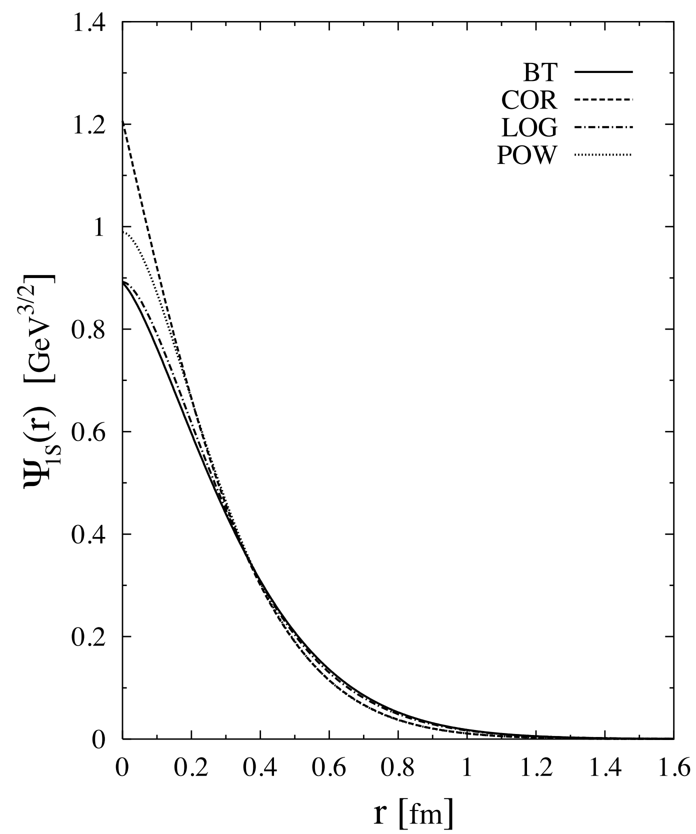
...dynamics of soft radiated gluon determines yields for gluon shadowing and J/psi

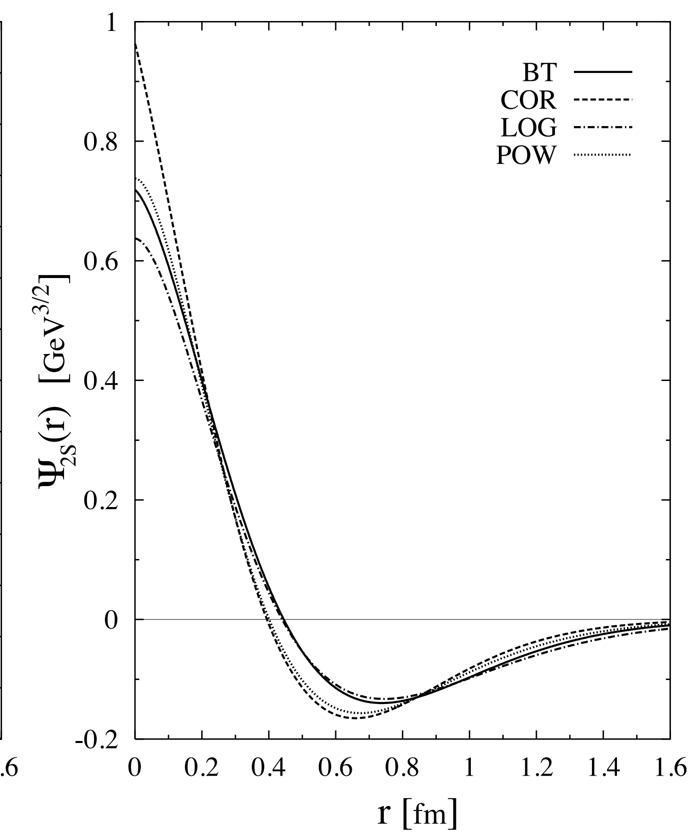
S- and P-wave quarkonia wave functions

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"

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

Melosh spin rotation

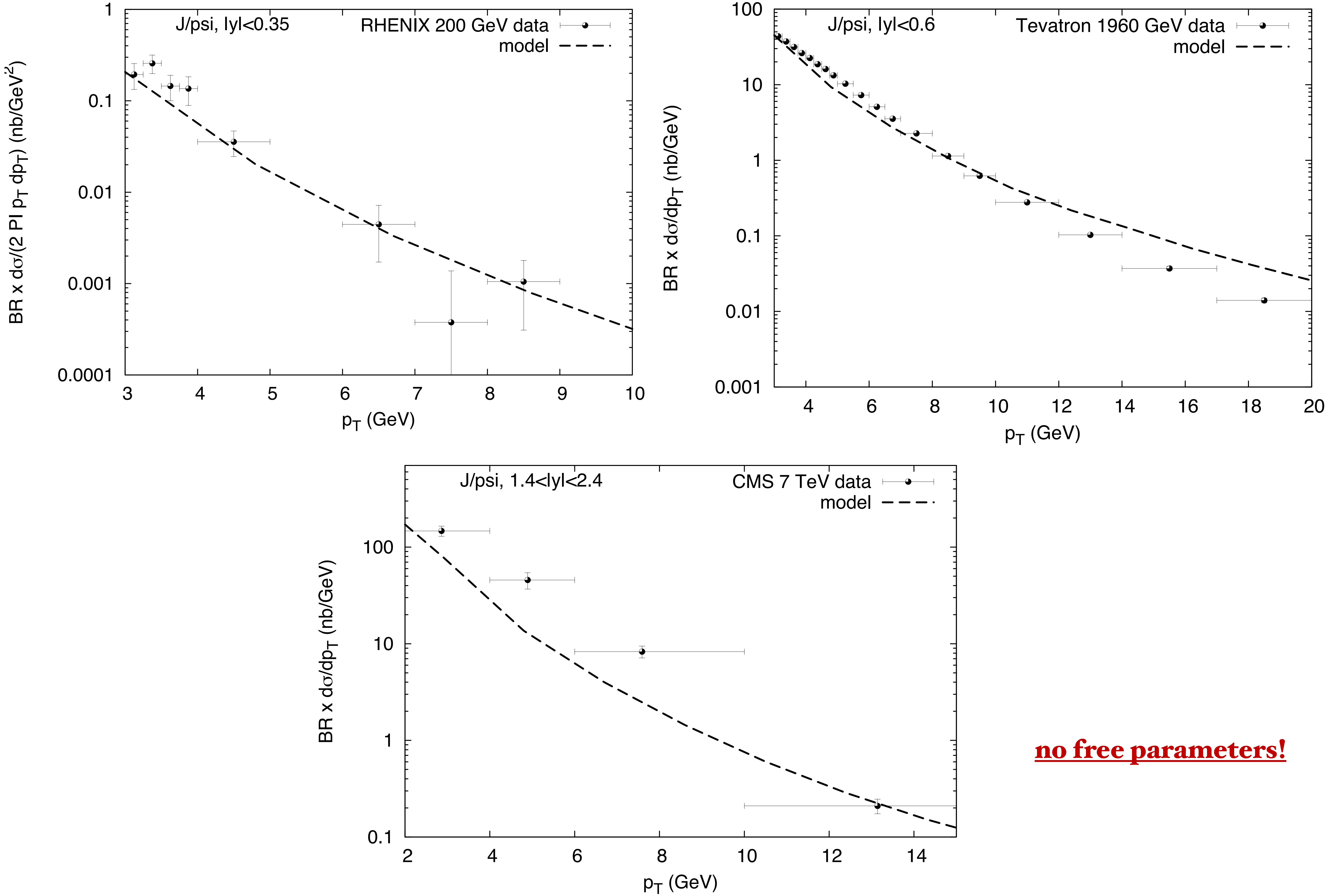
$$\overline{\chi}_{\mathbf{c}} = \widehat{R}(\alpha,\vec{p}_T)\,\chi_c\,, \quad \overline{\chi}_{\bar{\mathbf{c}}} = \widehat{R}(1-\alpha,-\vec{p}_T)\,\chi_{\bar{c}}\,,$$

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

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

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

Color-Singlet Model in the dipole picture: preliminary results



no free parameters!

Associated QQ-q: “Bremsstrahlung” vs “Fusion”

Gauge-invariant sub-sets of diagrams

B. Kopeliovich et al, PRD76 2007

”Bremsstrahlung” component

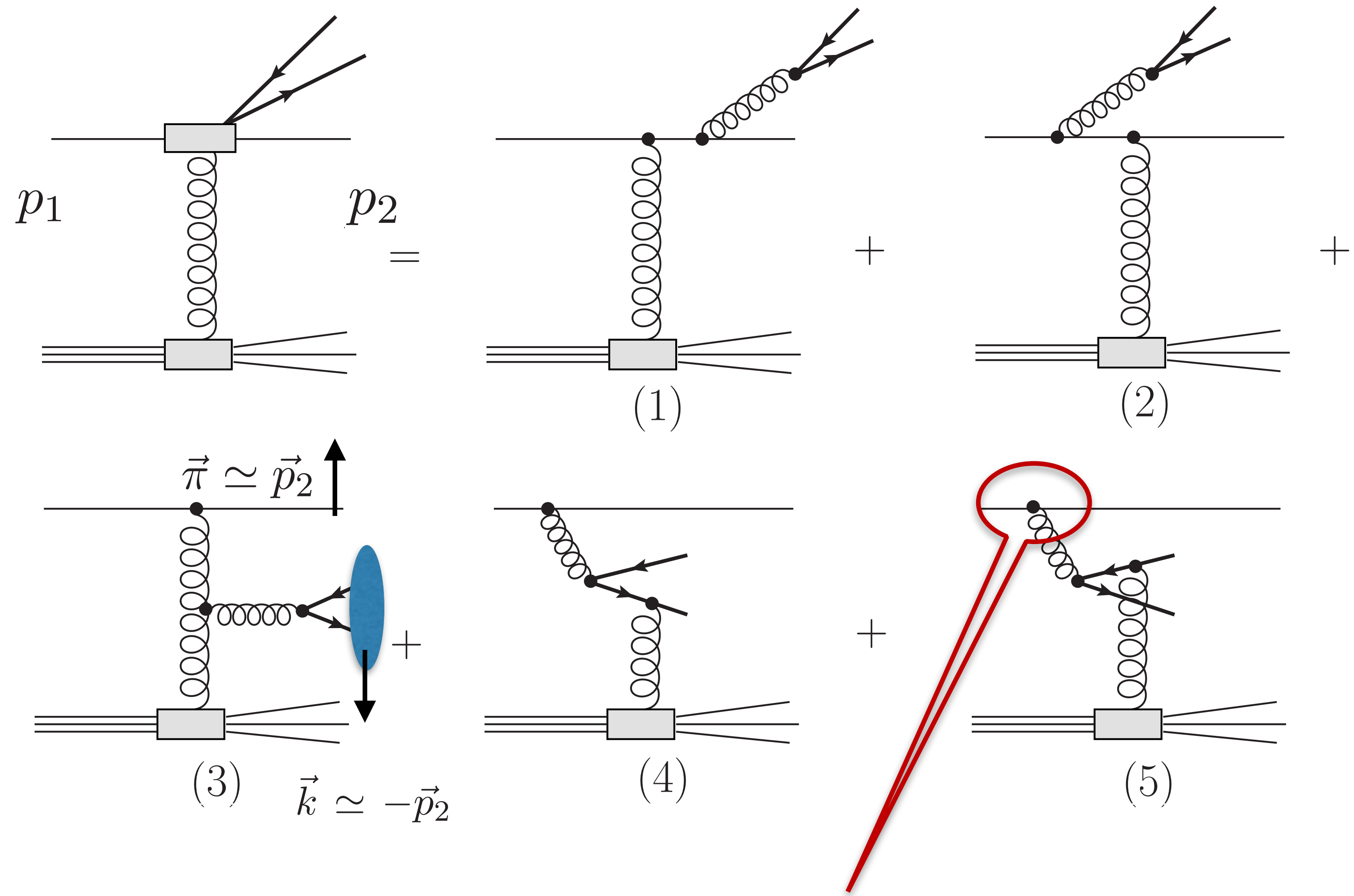
$$M^T_{\rm Br} = M^T_1 + M^T_2 + \frac{Q^2}{M^2+Q^2} M^T_3$$

suppressed by QQ mass!

”Fusion” component

$$M^T_{\rm Pr} = \frac{M^2}{M^2+Q^2} M^T_3 + M^T_4 + M^T_5$$

Dominates!



Gluon virtuality

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

$$\vec{\pi} = \alpha \vec{p}_2 - \bar{\alpha}\vec{k}\,, \qquad \vec{k} = \sum_i \vec{k}_i$$

Non-perturbative gluon distribution amplitude

$$\Psi_{qg}(\alpha, \vec{r}) = \frac{i\sqrt{\alpha_s}}{\pi}\,\frac{\vec{r}\cdot\vec{e}_*}{r^2}\,\exp(-r^2/2r_0^2)\,, \qquad \alpha \ll 1$$

...probing the “gluonic spots” $\quad r_0 \sim 0.3$ fm

Basis for heavy quarkonia production in association with a forward particle

Forward-central pion-J/psi correlations at RHIC

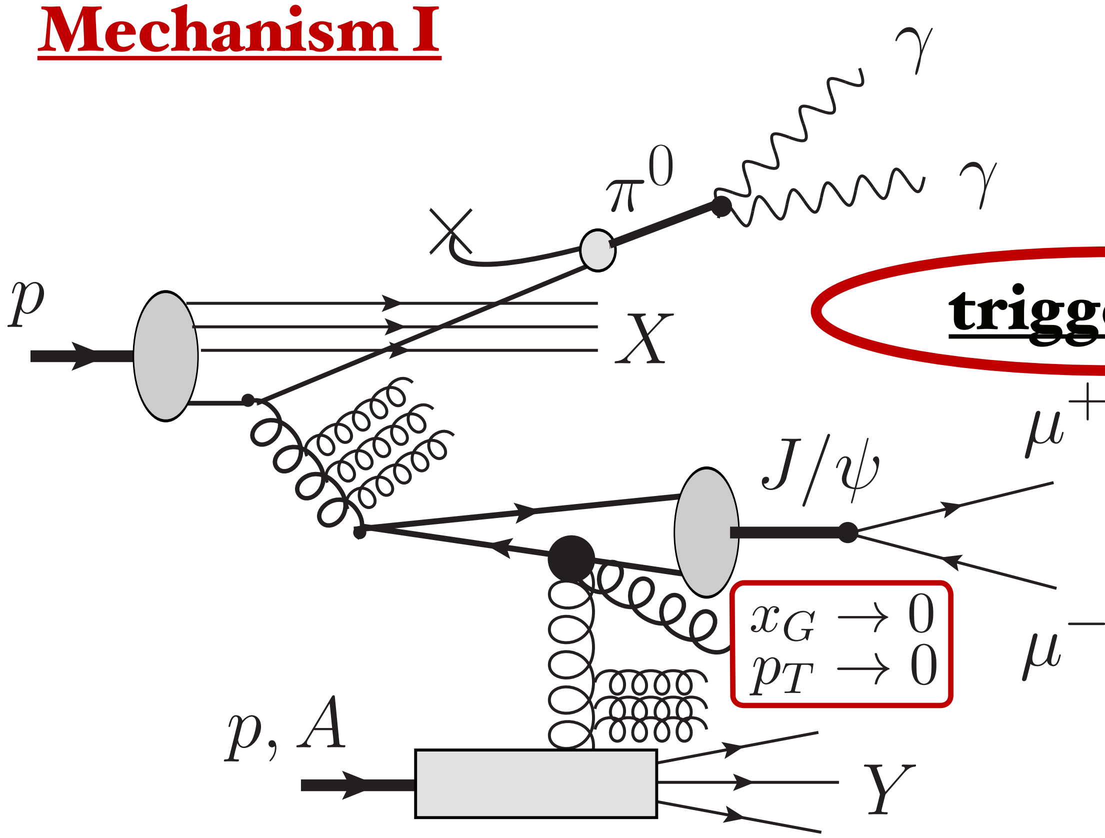
Differential correlations are usually more sensitive to troublesome soft QCD/medium effects than inclusive observables!

We propose a new measurement:

central J/psi or Upsilon production in association with forward high-pT leading pion

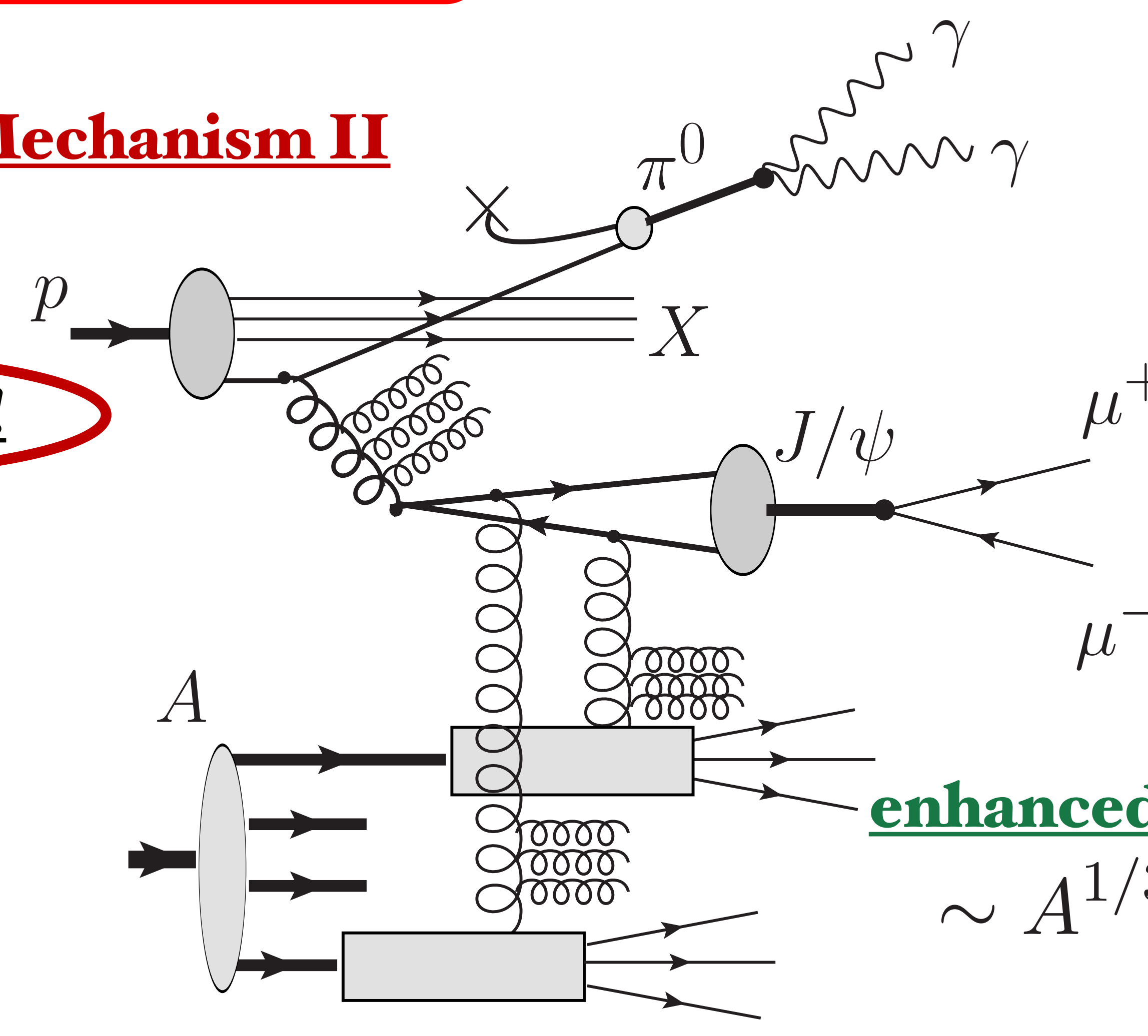
Two mechanisms for associated J/psi + pion production

Mechanism I



triggerable!

Mechanism II



enhanced as

$\sim A^{1/3}$

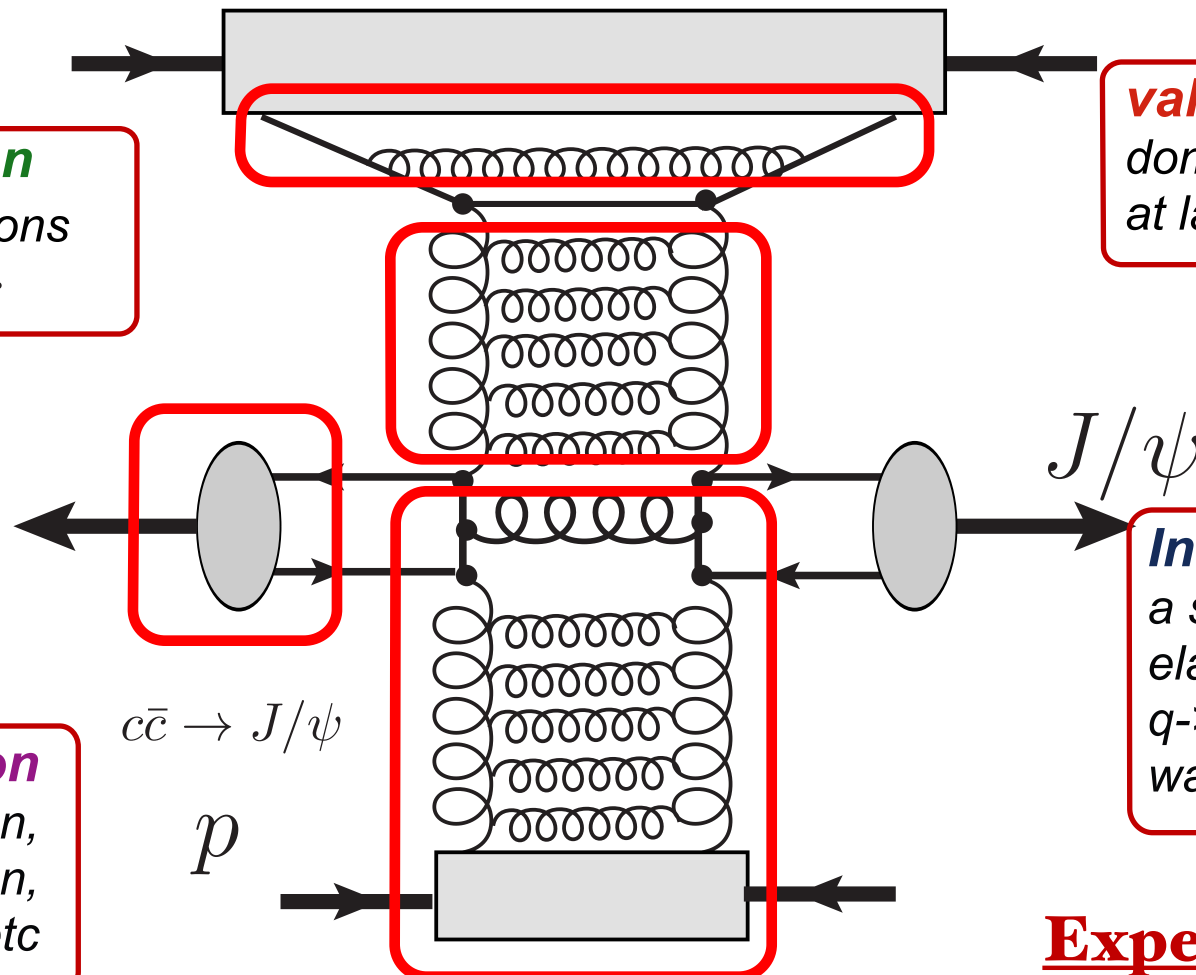
Physics motivation for forward-central correlations study

Mueller graph:

BFKL Pomeron
resummed low-x gluons
$\sim \alpha_s(\mu) \ln x$

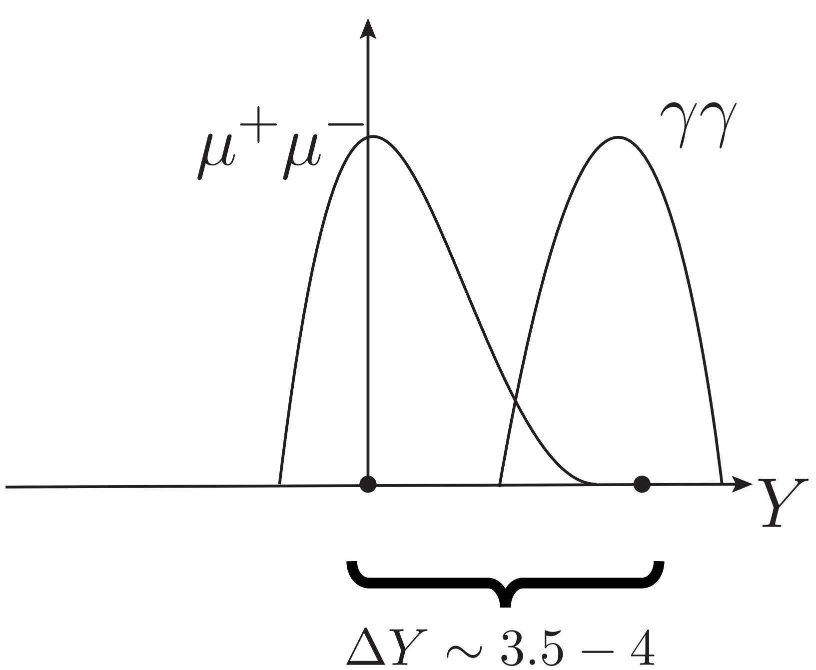
Pomeron** becomes **important for a large rapidity difference** between pion and quarkonium, but **less important for harder scale and lower energy

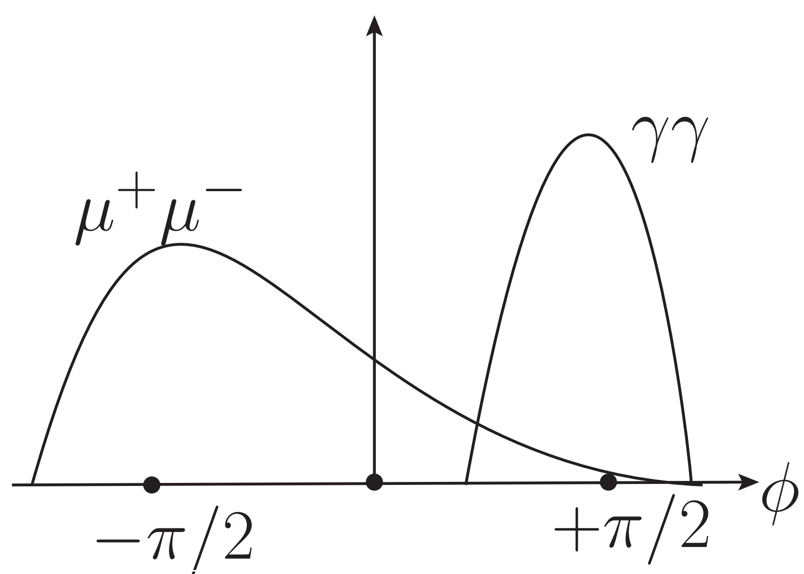
J/psi wave function
accounts for suppression, energy loss, polarisation, non-PT effects, etc



valence quark PDF
dominates the Reggeon at large x ~ 1

In the dipole approach:
a superposition of universal elastic dipole amplitudes times q->qG, G->ccbar and c->cG wave functions





Expectations:

- ✓ nearly back-to-back azimuthal correlation broadened by soft gluon emissions etc
- ✓ background due to Drell-Yan is strongly reduced due to a harder pion p_T spectrum
- ✓ uncertainties are cancelled in R_{pA}
- ✓ improved test of quarkonia production mechanisms

Feasibility study: forward quark pT distribution

hadron-level CS

$$pp \to q + J/\psi + X$$

$$\frac{d\sigma(pp \to q + J/\psi + X)}{dx_F} = \frac{x_1}{x_1 + x_2} \int_{x_1}^{1} \frac{d\alpha}{\alpha^2} \times \sum_q \left[\rho_q\Big(\frac{x_1}{\alpha}, \mu^2\Big) + \rho_{\bar q}\Big(\frac{x_1}{\alpha}, \mu^2\Big)\right] \frac{d\sigma(qp \to q + J/\psi + X)}{d\ln\alpha}$$

parton-level CS

$$q + p \to q + \{Q\bar{Q}\}G_b + X$$

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

Heavy quark pair in color singlet

$$\Psi^{1\pm}_{q\{Q\bar{Q}\}G} = \frac{1}{\sqrt{3}} (\tau_b)^l_m \delta^i_j \sum_{\lambda_*=L,T} \Phi^{\lambda_*}_{qG^*}(\alpha,\vec{\pi}) \Phi^{\lambda_*}_{Q\bar{Q}}(\vec{r},\beta) \Phi^{1\pm}_{QG}(\vec{r},\vec{\rho},\beta)$$

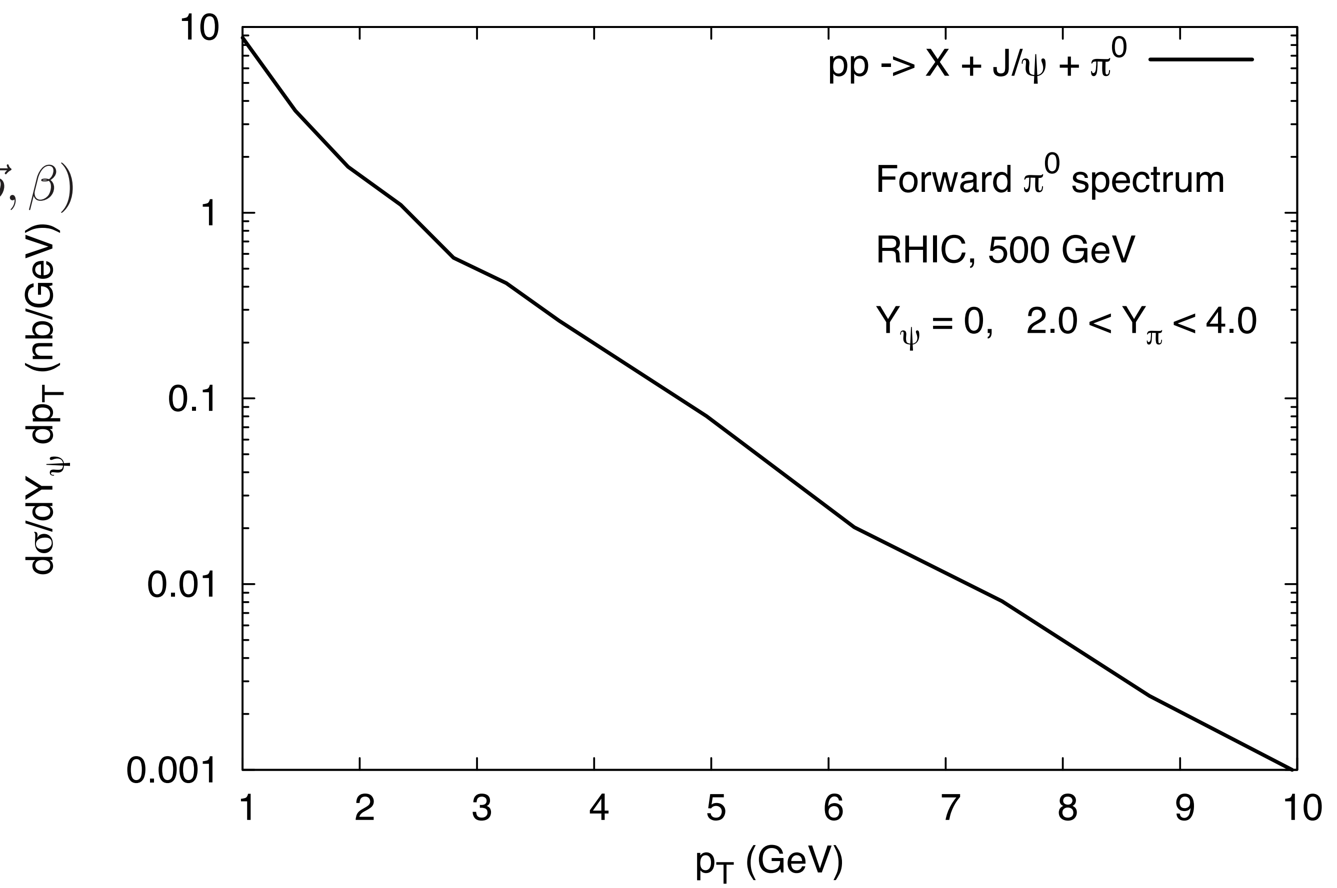
C-even/C-odd amplitudes

$$\Phi^{1-}_{QG}(\vec{r},\vec{\rho},\beta) = \Phi^{8-}_{QG}(\vec{r},\vec{\rho},\beta) = \Phi_{QG}(\vec{\rho}+\beta\vec{r}) - \Phi_{QG}(\vec{\rho}-\bar{\beta}\vec{r})$$

$$\Phi^{1+}_{QG}(\vec{r},\vec{\rho},\beta) = \frac{1}{2}\Big\{\frac{1}{\bar{\beta}}\Phi_{QG}(\vec{\rho}+\beta\vec{r}) + \frac{1}{\beta}\Phi_{QG}(\vec{\rho}-\bar{\beta}\vec{r})\Big\}$$

$$\Phi^{T}_{QG} = \frac{i\sqrt{\alpha_s}}{\pi} (\vec{e}_f \cdot \vec{\nabla}_\rho) K_0(\tau\rho)$$

$$\tau^2 = \lambda^2 + \gamma M^2_{Q\bar{Q}}\,, \qquad M^2_{Q\bar{Q}} = \frac{m_Q^2 + \kappa^2}{\beta\bar{\beta}} \qquad \gamma \ll \beta$$



J/psi production is driven by semi-soft dynamics!

Summary

✓ The dipole approach to semi-hard/semi-soft reactions such as gluon shadowing corrections to quarkonia production and J/psi production beyond QCD factorisation is justified

✓ New class of measurements of forward-central correlations both in pp and pA feasible at both RHIC experiments is proposed

✓ These observables enable to probe with high precision such QCD aspects as BFKL evolution, QCD factorisation, proton structure at low and large x, quarkonia production mechanisms and (potentially) polarisation and CNM effects

✓ The proposed measurement provides a good way to reduce backgrounds and uncertainties in studies of quarkonia production in pp/pA and thus allows to test higher order effects in pQCD at RHIC and disentangle them from e.g. CGC and other multi-particle effects.