Heavy Quark Production and Gluon Shadowing at RHIC and LHC

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Introduction

Heavy Quark production is one of the most interesting processes to be studied at RHIC and LHC:

- The reaction evolves over large longitudinal distances:

$$\sigma \sim \int |\mathcal{M}|^2 \, d(P.S.)$$

$\hookrightarrow \ln \frac{M^2}{S} \gg 1$ can compensate smallness of α_s

$\rightarrow$ pronounced nuclear effects make it possible to study space-time evolution of heavy quark production

- Saturation:
  for $M^2 < Q_s^2$, gluon recombination leads to nonlinear terms in the evolution equation:

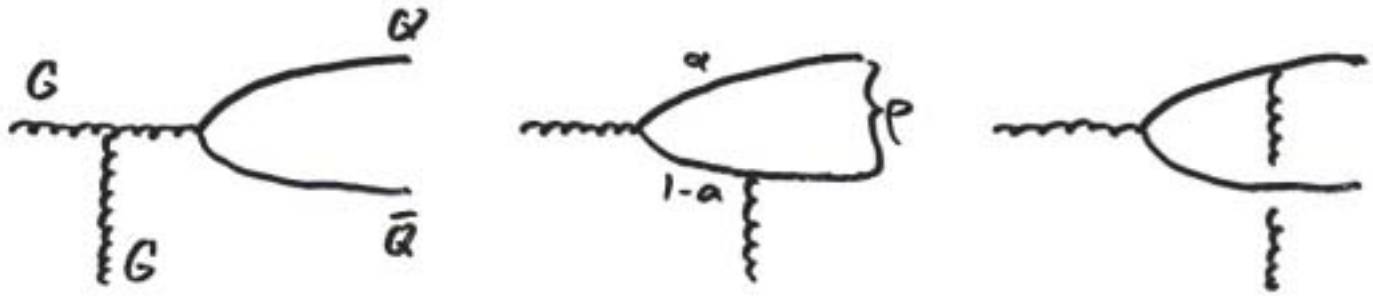
$$Q_s \sim \begin{cases} 1 \text{ GeV at RHIC} \\ 1.5 \text{ GeV at LHC} \end{cases} \qquad Q_s^2 \sim A^{1/3}$$

new hard scale $\rightarrow \frac{Q_s^2}{M^2} \sim O(1)$

$\rightarrow$ no twist expansion possible

Dipole Approach to Heavy Quark Production

Nikolaev, Piller, Zakharov, JETP 81 (95) 851
Kopeliovich, Tarasov, hep-ph/0205151
NPA 710 (02) 190



$$\frac{d\sigma_{Q\bar{Q}}}{dy} = x_1\, G(x_1,\mu) \int_0^1 d\alpha \int d^2\rho\, |\Psi_{G\to Q\bar{Q}}(\alpha,\rho)|^2\, \sigma^N_{q\bar{q}G}(x_2,\alpha,\rho)$$

$$\mu \sim m_Q$$

General rule:

$$\sigma(aN \to bcX) = \int d\Gamma\, |\Psi_{a\to bc}(\Gamma)|^2\, \sigma^N_{bc\bar{q}}(\Gamma)$$

Γ : set of all internal variables of the (bc)-system

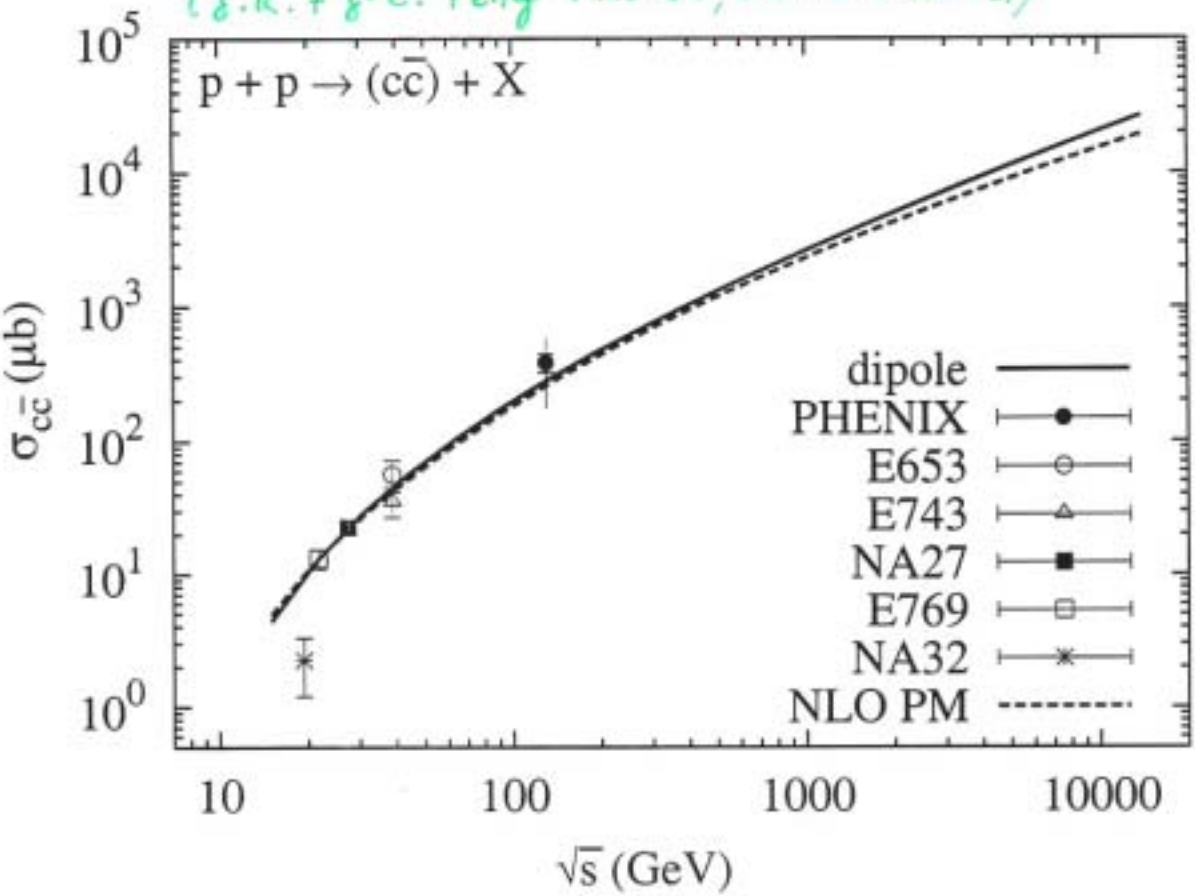
$\Psi_{a\to bc}$: LC wavefunctions for the transition $a \to bc$

$\sigma^N_{bc\bar{q}}$: cross section for scattering the $(bc\bar{q})$-system on a nucleon

The total $c\bar{c}$-pair cross section

Check validity of dipole approach in pp before application to nuclei

(J.R. + J-C. Peng PRD 67, 054008 (2003))



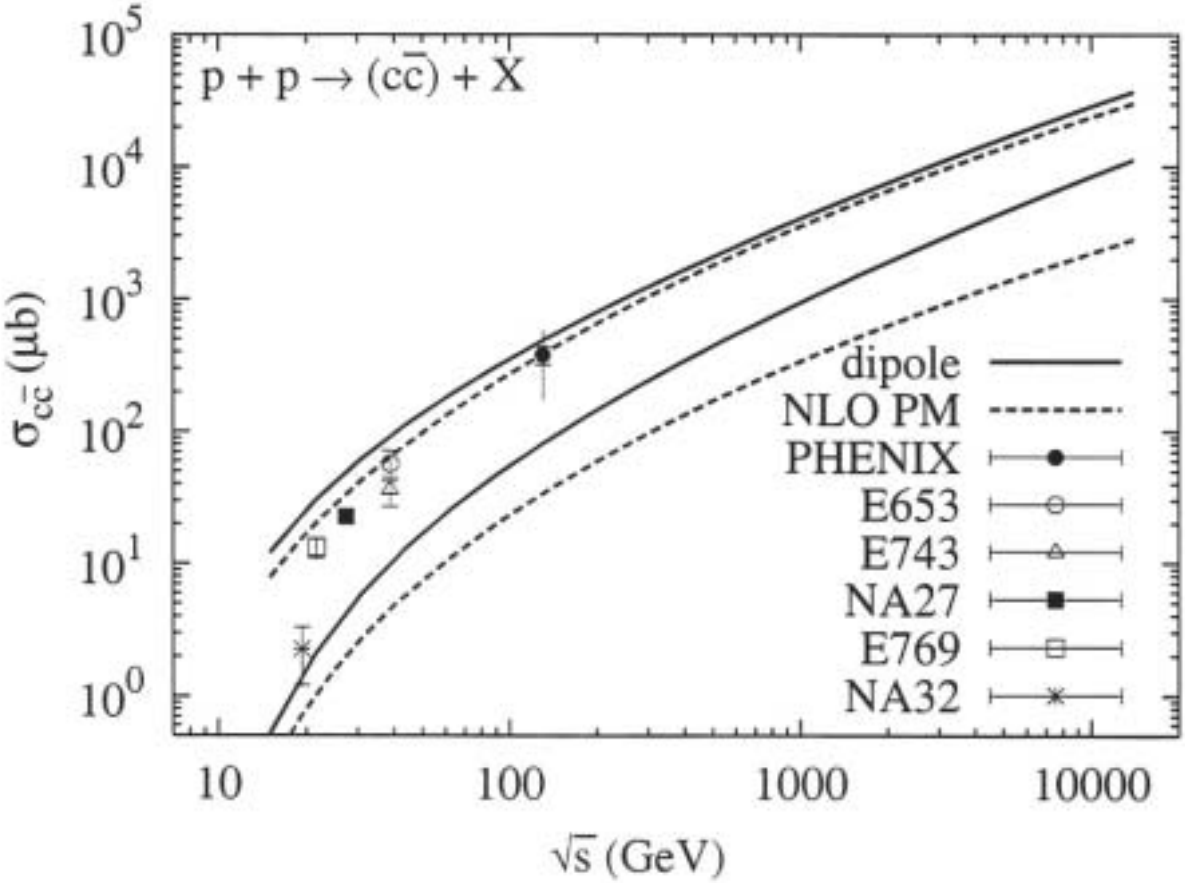
α_s^3 PM calculation from

Nason, Dawson, Ellis, NPB 303 (88) 607
NPB 327 (89) 49

Mangano, Nason, Ridolfi, NPB 373 (92) 295

- Dipole approach describes all data, even at low $\sqrt{s}$.
- No significant difference between dipole approach and parton model despite $m_c \sim Q_s$

Theoretical uncertainties



Uncertainties arise from the choice of

i) charm quark mass m_c

ii) renormalization scale μ_R (enters α_s)

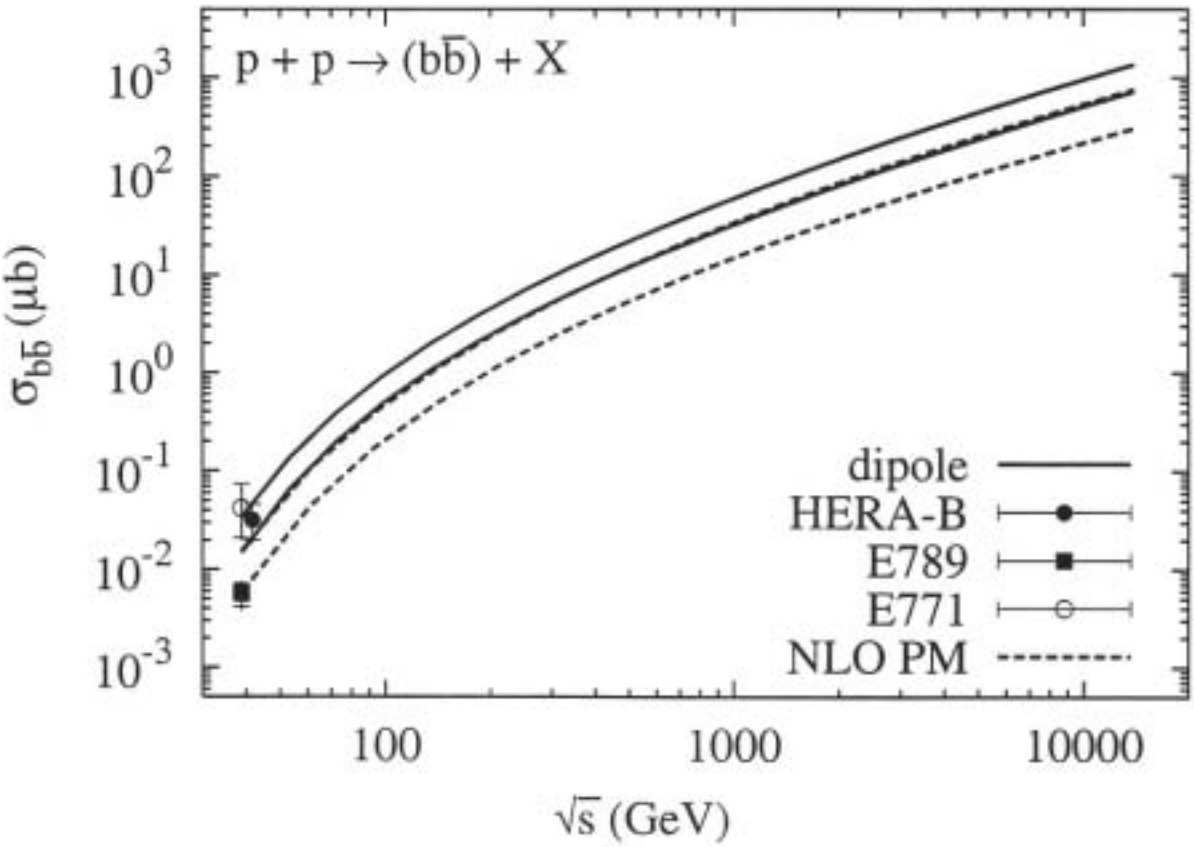
iii) factorization scale μ_F (enters PDFs)

$1.2\ \text{GeV} \leq m_c \leq 1.8\ \text{GeV}$, $\quad m_c \leq \mu_R \leq 2m_c$

$\mu_F = 2m_c$ fixed

fix parameters to describe data

The total $b\bar{b}$-pair cross section



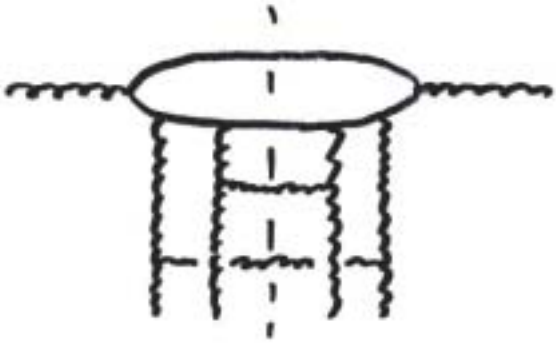
$4.5\ \text{GeV} \leq m_b \leq 5\ \text{GeV}$ $\quad m_b \leq \mu_R \mu_F \leq 2 m_b$

- For $b\bar{b}$ production, one needs the DGLAP improved saturation model of Bartels et al., PRD66:014001,(2002)
- The dipole approach tends to predict higher values than the next-to-leading order parton model.

Nuclear Shadowing in Open Charm Production

Two contributions to shadowing:

1) rescattering of $c\bar{c}$ - Fock state



$c\bar{c}$ - separation $\rho \sim \frac{1}{m_c}$

$\rightarrow$ higher twist shadowing

but $\frac{\Delta G}{G} \sim \frac{A^{1/3} Q_s^2(x)}{m_c^2}$

not negligible

(Kopeliovich, Tarasov, hep-ph/0205151)
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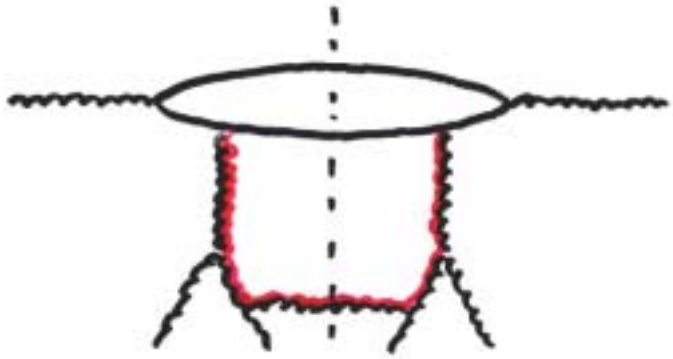
2) rescattering of higher Fock states
(Gluon Shadowing)



single scattering $c\bar{c}$ sees reduced gluon density

double scattering of $c\bar{c}G$ Fock state leads to the leading twist gluon shadowing

Nuclear Shadowing in the Dipole Formulation

Consider very low x_2 : $x_2 \ll 0.1\, A^{-1/3}$

→ $Q\bar{Q}$ pair exists over very large longitudinal distances:

$$\ell_c \gg R_A$$

→ Partonic configurations with fixed transverse separations are interaction eigenstates:

$$\sigma^A_{q\bar{q}G} = 2\int d^2b \left\{ 1 - e^{-\frac{1}{2}\sigma^p_{q\bar{q}G}\tilde{T}(b)} \right\}$$

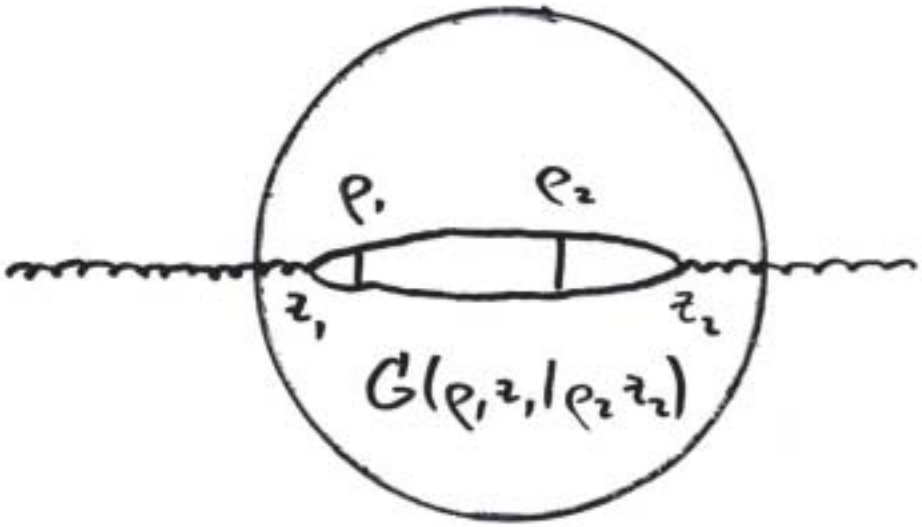
(Eikonalization gives only higher twist shadowing for HQ.)

→ The leading twist gluon shadowing R_G reduces the effective nuclear thickness:

$$\tilde{T}(b) = T(b)\, R_G(b)$$

Green function technique

Under realistic conditions, the size of the $Q\bar{Q}$-pair is not completely frozen (finite coherence length)



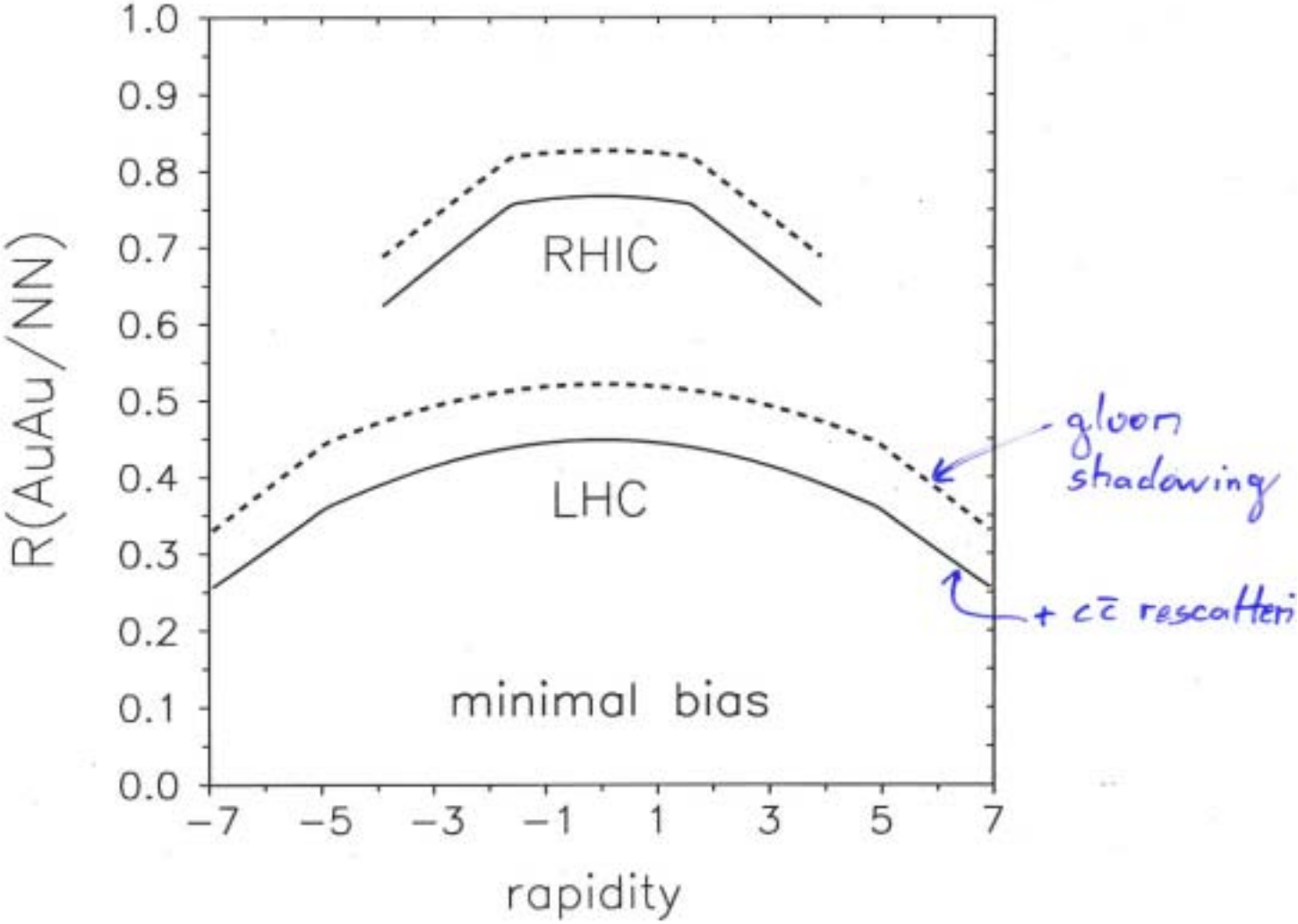
The lifetime of the $Q\bar{Q}G$-fluctuation is even shorter.

Describe propagation of $Q\bar{Q}$ (or $Q\bar{Q}G$) through the nucleus by Green function G

Limits: "Eikonal" for $x_2 \mapsto 0$

PP (single scattering) for $x_2 \to 0.1$

Nuclear suppression of open charm



Kopeliovich, Tarasov NPA 710 (2002) 180

p_T-Broadening at small and not-so-small x_2

$$\delta\langle p_T^2\rangle = \langle p_T^2\rangle_{hA} - \langle p_T^2\rangle_{hp} \geq 0 \quad \text{for DY, } J/\psi, \Upsilon$$

- very small x_2: broadening = color filtering
  The fluctuation containing the DY or J/ψ is formed far upstream, but the nucleus filters out large (i.e. small p_T) fluctuations.
  $\Rightarrow$ increase of $\langle p_T^2\rangle$

  (Kopeliovich, Raufeisen, Tarasov, Johnson, PRC 67 (2003) 014303)

- larger $x_2 \sim 0.1$:
  Broadening is due to multiple rescattering of the projectile parton.

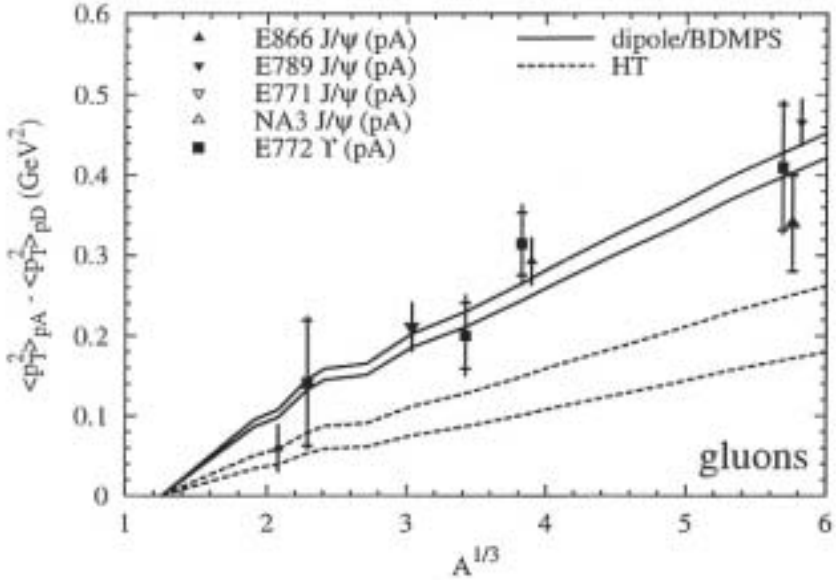
$$\delta\langle p_T^2\rangle = \underbrace{\frac{\pi^2}{3}\alpha_s(\delta\langle p_T^2\rangle)\langle F^2\rangle}_{C = \frac{d}{d\rho^2} G_{q\bar{q}}(s,\rho^2)\Big|_{\rho^2\to 0}} \cdot \langle T\rangle$$

Johnson
Kopeliovich, Tarasov, PRC 63 (2001) 035203

Mean transverse color field strength:

$$\langle F^2\rangle = \frac{1}{2\pi p^+}\int dy^- \langle N|F_a^{+\omega}(y^-)F_{a\,\omega}^{+}(0)|N\rangle$$

p_T-broadening at fixed target energies



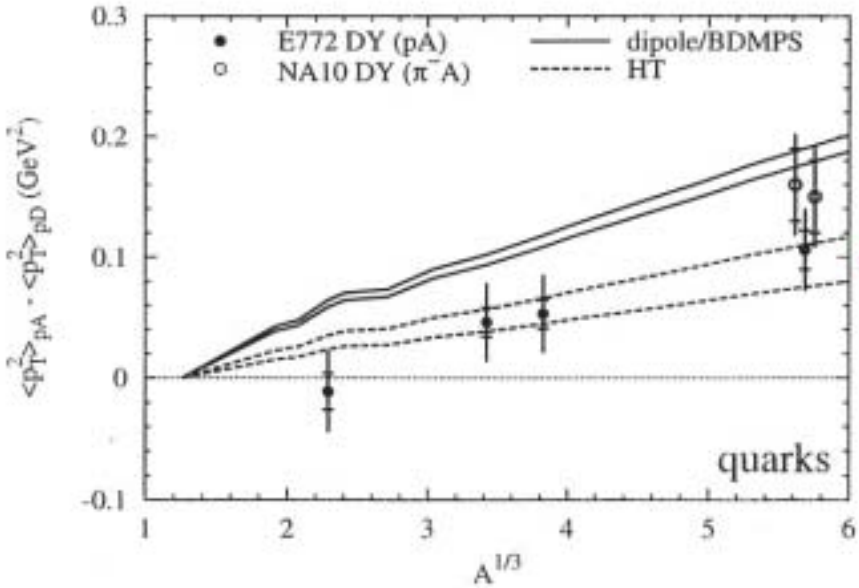
$$\delta\langle p_T^2\rangle = \left(\frac{9}{4}\right) G \left\{\langle T_A\rangle - \langle T_D\rangle\right\}$$

$$G = \frac{d}{dq^2} G_{q\bar{q}}(q^2, s)\Big|_{q^2\to 0}$$

BDMPS transport coefficient:

$$q_A(\sqrt{s} = 10\ \text{GeV}) \approx 0.08\ \frac{\text{GeV}^2}{\text{fm}}$$

$$q_A(\sqrt{s} = 22\ \text{GeV}) \approx 0.1\ \frac{\text{GeV}^2}{\text{fm}}$$



Upcoming E866 data might yield larger $\delta\langle p_T^2\rangle$

J. Raufeisen, PLB 557 (2003) 184

Summary

- At high energies, heavy quark production can be formulated in terms of the same color dipole cross section as low-x DIS. We tested this approach in pp.

- All nuclear effects are then predicted: no remaining free parameters.

- The dipole approach also includes higher twist contributions to nuclear effects in heavy quark production. (important for charm)

- Nuclear broadening can be calculated in the dipole approach as well:
  - $\delta\langle p_T^2\rangle$ well reproduced for J/ψ and Υ
  - Drell-Yan data overestimated by factor ~2

- The parameter free calculation of $\delta\langle p_T^2\rangle$ provides an independent estimate of the BDMPS transport coefficient.