Heavy Flavor Production in Nuclear Collisions

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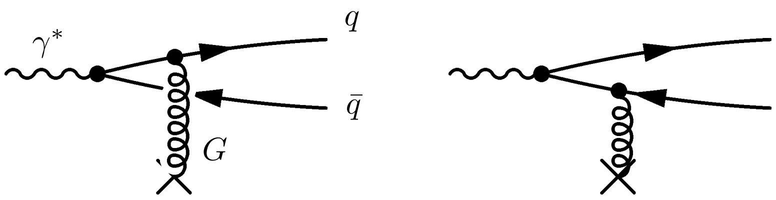
Introduction

- Measurements of heavy quark production are an invaluable source of information.
- Initial state:
  - Heavy quark production allows one to study the poorly known gluon distributions of protons and nuclei.
  - Hadroproduction of heavy quarks at high energies can be formulated in terms of the same dipole cross section as low-x DIS.
  - The advantage of the dipole formulation is that it is formulated in terms of interaction eigenstates. This simplifies the calculation of multiple scattering effects.
- Final state:
  - The theory of medium-induced gluon radiation can be written in terms of the dipole cross section. (B.G. Zakharov)
  - Use well-developed dipole phenomenology to estimate the contribution of radiative energy loss to quenching.

The Dipole Approach to DIS and k_T-Factorization



$$\rho = q\bar{q} \text{ transverse separation}$$
$$\alpha = p_q^+/q_{\gamma^*}^+ = \frac{1+\cos(\theta)}{2}$$
$$\varepsilon^2 = \alpha(1-\alpha)Q^2 + m_q^2$$

- At low x, photon-gluon fusion ($\gamma^* + G \to q + \bar{q}$) dominates over $\gamma^* + q \to q + G$ and the DIS cross section can be written as,

$$\frac{d\sigma_L^{\gamma^* p}}{d^2 p_T} = \frac{4\alpha_{em} e_f^2 Q^2}{\pi} \int d\alpha \alpha^2 (1-\alpha)^2 \int \frac{d^2 k_T}{k_T^4} \alpha_s \mathcal{F}(x, k_T) \left[\frac{1}{p_T^2 + \varepsilon^2} - \frac{1}{(\vec{p}_T - \vec{k}_T)^2 + \varepsilon^2} \right]^2$$
$$= \int d\alpha \int \frac{d^2\rho_1 d^2\rho_2}{2(2\pi)^2} \Psi^*(\alpha, \rho_1) \Psi(\alpha, \rho_2) e^{i\vec{p}_T \cdot (\vec{\rho}_1 - \vec{\rho}_2)} \left[\sigma_{q\bar{q}}(\rho_1) + \sigma_{q\bar{q}}(\rho_2) - \sigma_{q\bar{q}}(|\vec{\rho}_1 - \vec{\rho}_2|) \right]$$

with

$$\sigma_{q\bar{q}}(x, \rho) = \frac{4\pi}{3} \int \frac{d^2 k_T}{k_T^4} \alpha_s \mathcal{F}(x, k_T) \left[1 - e^{i\vec{k}_T \cdot \vec{\rho}} \right]$$

- The dipole cross section $\sigma_{q\bar{q}}(x, \rho)$ carries information about the k_T dependence of the gluon distribution.
- Probably, any process that probes $\mathcal{F}(x, k_T)$ can be written in terms of $\sigma_{q\bar{q}}(x, \rho)$.

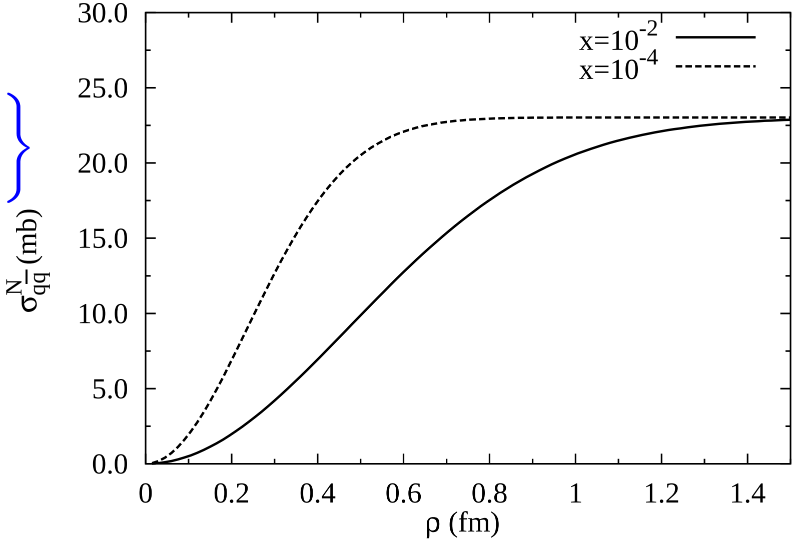
The Dipole Cross Section

- I use the DGLAP improved saturation model of Bartels, Golec-Biernat, Kowalski, Phys. Rev. D**66**: 014001, 2002 for $\sigma_{q\bar{q}}(x,\rho)$

$$\sigma^N_{q\bar{q}}(x,\rho) = \sigma_0 \left\{ 1 - \exp\left(-\frac{\pi^2 \rho^2 \alpha_s(\mu) x G(x,\mu)}{3\sigma_0} \right) \right\}$$

with

$$\sigma_0 = 23\,\text{mb}$$
$$\mu^2 = \frac{\lambda}{\rho^2} + \mu_0^2$$

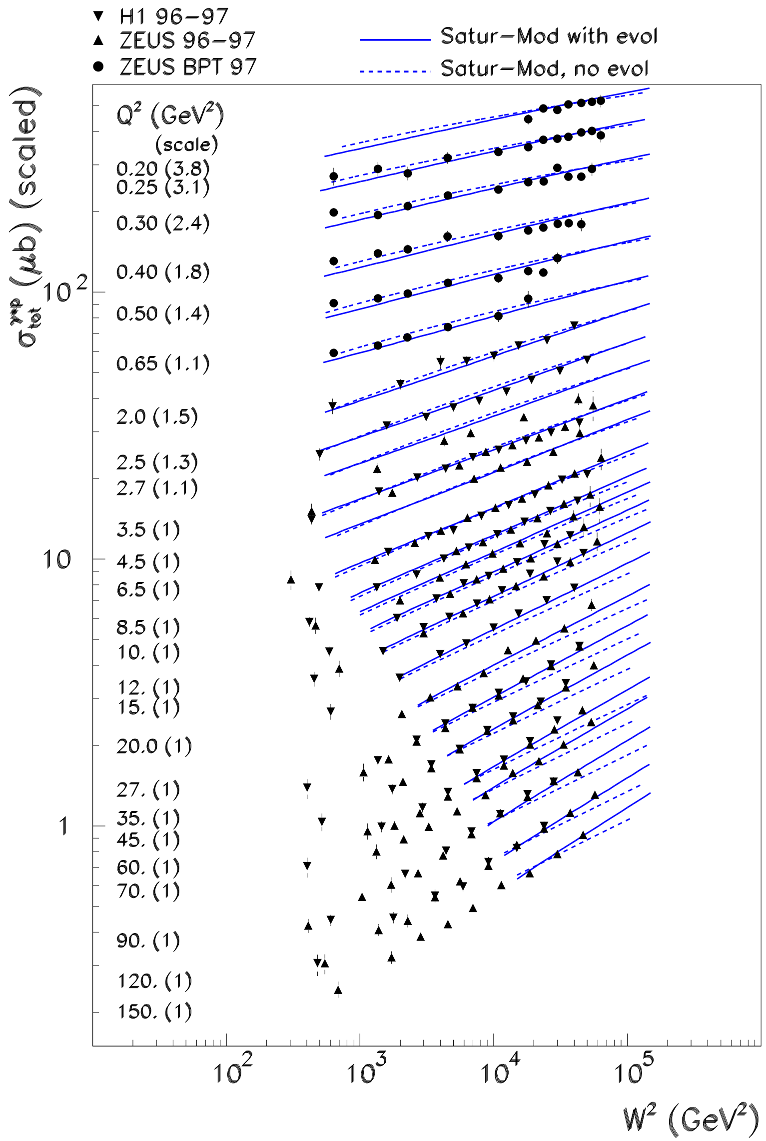


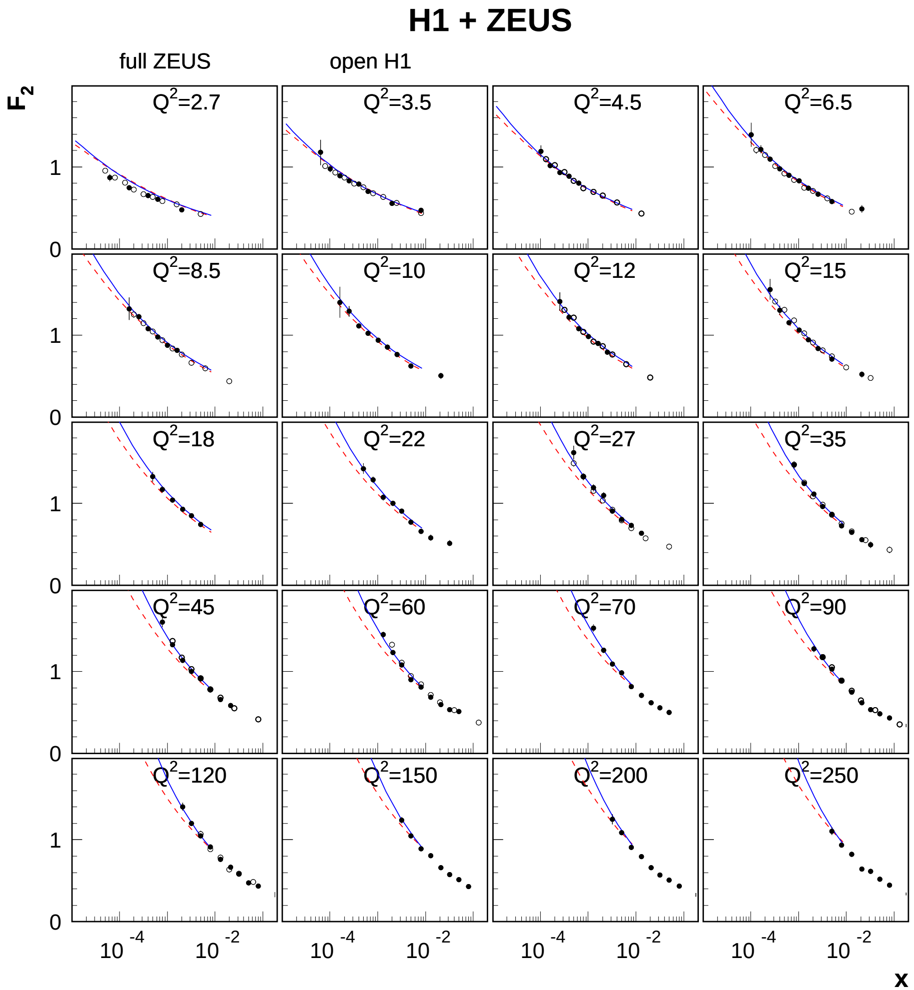
- The gluon density $xG(x,\mu)$ evolves according to DGLAP.
- The perturbative QCD result is recovered at small ρ:

$$\sigma^N_{q\bar{q}}(x,\rho) \to \frac{\pi^2}{3} \alpha_s(\mu) \rho^2 x G(x,\mu)$$

Blättel, Baym, Frankfurt, Strikman, Phys. Rev. Lett. **70**, 896, 1993.

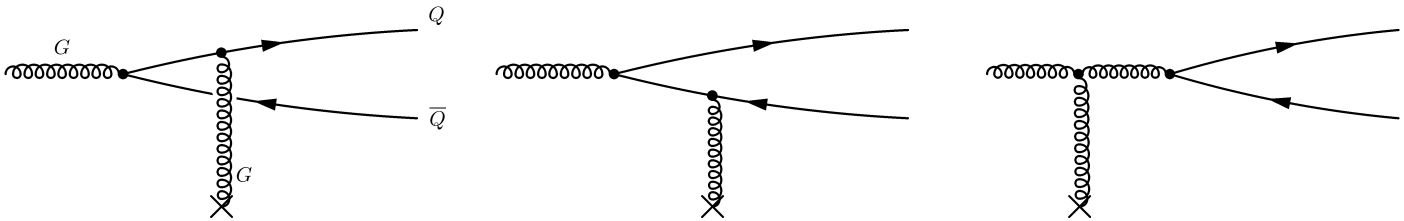
Fit to HERA Data (Bartels et al.)





Heavy Quark Production at High Energies

At high energies, heavy quark pairs ($Q\overline{Q}$) are predominantly produced through gluon-gluon fusion:



The amplitude reads (Kopeliovich, Tarasov, NPA710:180,2002)

$$\begin{aligned}\mathcal{A}^a_{ij}(\alpha,\vec{p}_T,\vec{k}_T) \;=\; \int d^2r d^2b e^{i\vec{p}_T\cdot\vec{\rho}-i\vec{k}_T\cdot\vec{b}}\Psi(\alpha,\rho)\Big\{&\delta_{ae}\delta_{ij}\left[\gamma^e(\vec{b}-\alpha\vec{\rho})-\gamma^e(\vec{b}+(1-\alpha)\vec{\rho})\right]\\ &+\frac{1}{2}d_{aeg}T^g_{ij}\left[\gamma^e(\vec{b}-\alpha\vec{\rho})-\gamma^e(\vec{b}+(1-\alpha)\vec{\rho})\right]\\ &+\frac{i}{2}f_{aeg}T^g_{ij}\left[\gamma^e(\vec{b}-\alpha\vec{\rho})+\gamma^e(\vec{b}+(1-\alpha)\vec{\rho})-2\gamma^e(\vec{b})\right]\Big\}\end{aligned}$$

with the profile function

$$\gamma^e(\vec{b})=\frac{\sqrt{\alpha_s}}{4\pi}\int\frac{d^2k_T}{k_T^2}e^{i\vec{k}_T\cdot\vec{b}}F^e_{GN\to X}(\vec{k}_T)\quad,\quad \sigma_{q\bar{q}}(\rho)=\int d^2b\sum_X\sum_{e=1}^{8}\left|\gamma^e(\vec{b}+\vec{\rho})-\gamma^e(\vec{b})\right|^2$$

The Dipole Approach to Heavy Quark Production

- The result for the $Q\overline{Q}$ cross section is, (Nikolaev, Piller, Zakharov, JETP **81**, 851, 1995):

$$\frac{d\sigma(pp \to Q\overline{Q} + X)}{dy_{Q\overline{Q}}} = x_1 G(x_1, \mu_F) \int_0^1 d\alpha d^2\rho \left|\Psi_{G\to Q\overline{Q}}(\alpha,\rho)\right|^2 \sigma_{q\bar{q}G}(x_2, \alpha, \rho)$$

  - α: Light-Cone momentum fraction of the heavy quark Q
  - ρ: transverse size of the $Q\overline{Q}$ pair
  - $\left|\Psi_{G\to Q\overline{Q}}(\alpha,\rho)\right|^2 = \alpha_s(\mu_R)/(4\pi^2)\left\{\left[\alpha^2 + (1-\alpha)^2\right] m_Q^2 K_1^2(m_Q\rho) + m_Q^2 K_0^2(m_Q\rho)\right\}$
  - and

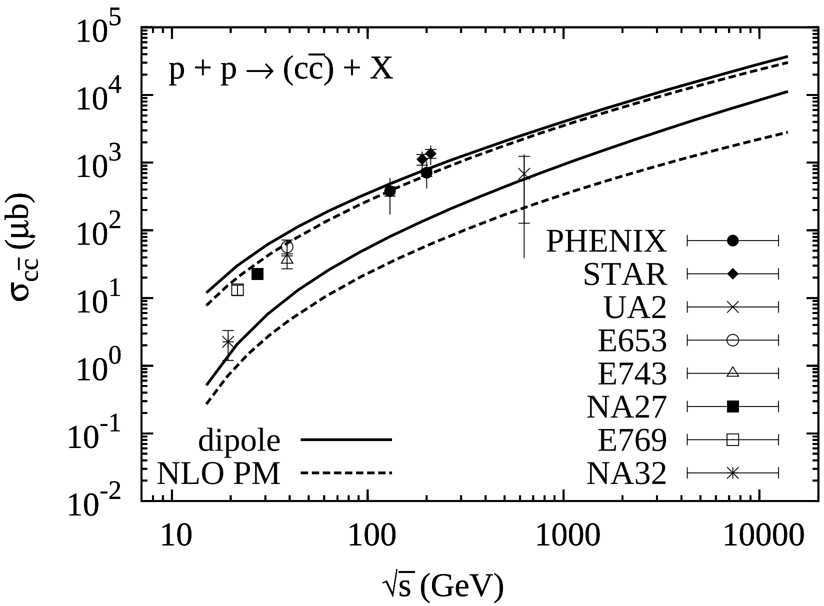
$$\sigma_{q\bar{q}G}(x_2,\alpha,\rho) = \frac{9}{8}\left[\sigma_{q\bar{q}}(x_2,\alpha\rho) + \sigma_{q\bar{q}}(x_2,(1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}(x_2,\rho).$$

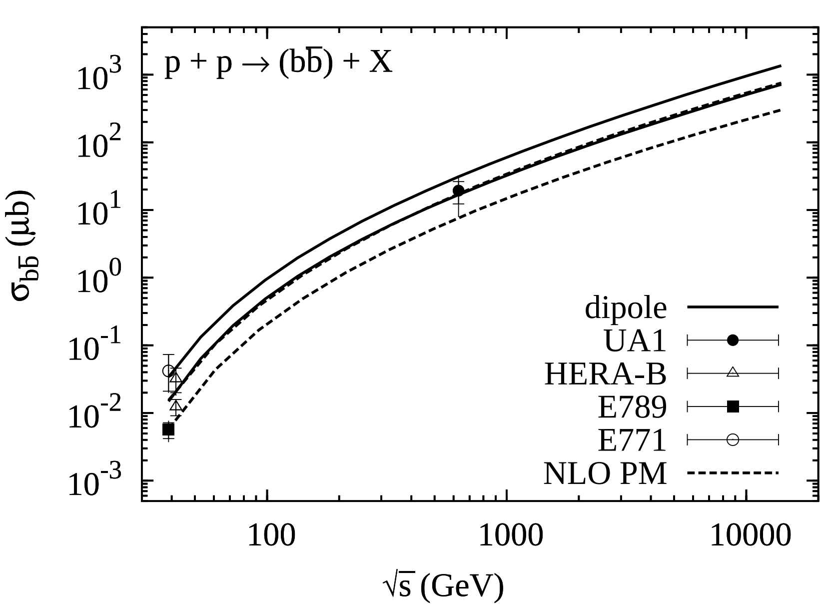
- General rule:

$$\sigma(a + N \to bcX) = \int d\Gamma \left|\Psi_{a\to bc}(\Gamma)\right|^2 \sigma^N_{bc\bar{a}}(\Gamma)$$

  - Γ: set of all internal variables of the (bc)-system
  - $\Psi_{a\to bc}$: Light-Cone wavefunction for the transition $a \to bc$
  - $\sigma^N_{bc\bar{a}}$: cross section for scattering the $bc\bar{a}$-system off a nucleon

Theoretical Uncertainties





JR, J.C. Peng, Phys. Rev. D**67**, 054008, 2003

- Large uncertainties for open charm production from choice of m_c

  $1.2\,\text{GeV} \le m_c \le 1.8\,\text{GeV}$, $m_c \le \mu_R \le 2m_c$, $\mu_F = 2m_c$

  $4.5\,\text{GeV} \le m_b \le 5.0\,\text{GeV}$, $m_b \le \mu_R, \mu_F \le 2m_b$

- Dipole Approach valid only at high energies (HERA-B energy too low)

Multiple Scattering and Nuclear Effects

- When switching from a proton to a nuclear target, the profile function $\gamma_N^a(b)$ for a nucleon needs to be replaced by the profile function for a nucleus $\gamma_A^a(b)$
- Hence $\sigma_{q\bar{q}}^N(\rho) \to \sigma_{q\bar{q}}^A(\rho)$ and

$$\sigma_{q\bar{q}G}^N(\rho) = \frac{9}{8}\left[\sigma_{q\bar{q}}^N(\alpha\rho) + \sigma_{q\bar{q}}^N((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}^N(\rho)$$

$$\to \sigma_{q\bar{q}G}^A(\rho) = \frac{9}{8}\left[\sigma_{q\bar{q}}^A(\alpha\rho) + \sigma_{q\bar{q}}^A((1-\alpha)\rho)\right] - \frac{1}{8}\sigma_{q\bar{q}}^A(\rho)$$

- The advantage of the (ρ, α) representation is, that one can calculate $\sigma_{q\bar{q}}^A(\rho)$ from $\sigma_{q\bar{q}}^N(\rho)$.
- In the limit of very high energy, all partons move along straight lines and pick up only a (color) phase factor as they move through the nucleus. Averaging over the target is done as in Glauber theory,

$$\sigma_{q\bar{q}}^A(\rho) = 2\int d^2b \left\{1 - \exp\left(-\frac{\sigma_{q\bar{q}}^N(\rho)T(b)}{2}\right)\right\}.$$

- At finite energy, one has to solve the Dirac (Klein-Gordon) equation for quarks (gluons) propagating through an external color field in the (non-abelian) Furry approximation: Terms of order $1/E$ are neglected, except in phase factors. This accounts for variations of the transverse size of partonic configurations.

Shadowing in DIS vs. Heavy Quark Shadowing

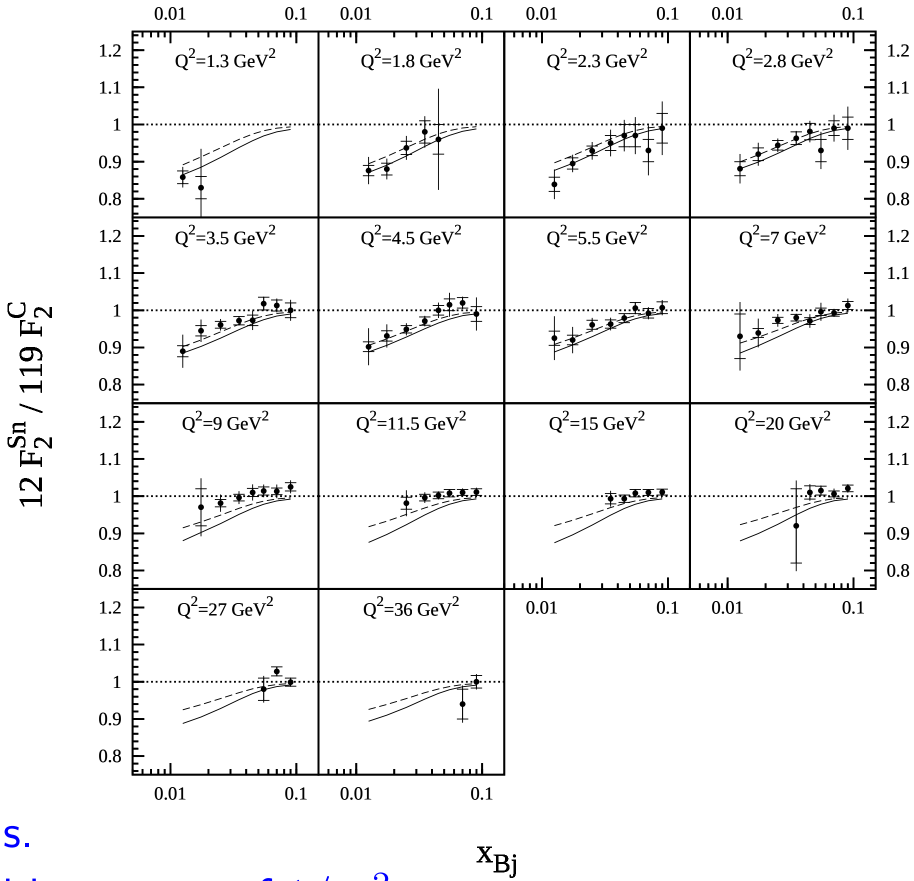
- In DIS, shadowing is caused by the aligned jet configurations, where either $\alpha \to 0$ or $\alpha \to 1$

  $$\left|\Psi_{\gamma^* \to q\bar{q}}(\alpha,\rho)\right|^2 \propto \exp(-2\varepsilon\rho).$$

  Extension parameter:

  $$\varepsilon^2 = \alpha(1-\alpha)Q^2 + m_q^2.$$

  These aligned jet configurations are shadowed even for $Q^2 \to \infty$.
  That is why shadowing in DIS is leading twist.



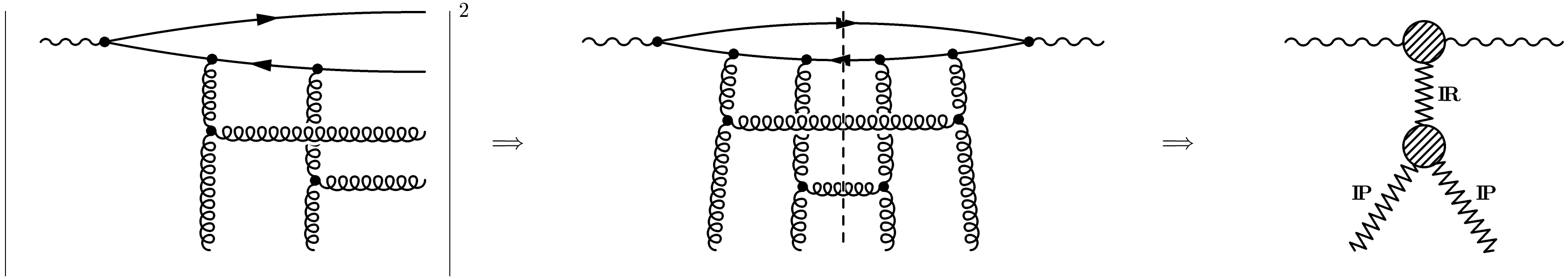
- In heavy quark production however

  $$\left|\Psi_{G \to Q\overline{Q}}(\alpha,\rho)\right|^2 \propto \exp(-2m_Q\rho).$$

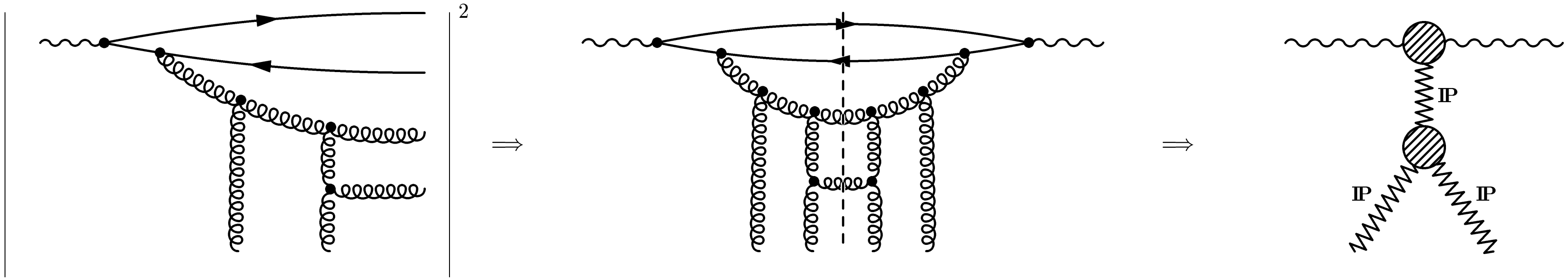
  The heavy quark mass cuts off large fluctuations.
  Multiple scattering of the $Q\overline{Q}$ pair is suppressed by powers of $1/m_Q^2$.
  Hence, eikonalization of $\sigma_{q\bar{q}}^N$ alone does not give the complete picture of heavy quark shadowing.

Mechanisms of Nuclear Suppression

- $Q\overline{Q}$ rescattering:



- $Q\overline{Q}G$ ($\approx GG$) rescattering:



Inclusion of Higher Fock States

- Higher Fock states are included in the parametrization of $\sigma_{q\bar{q}}^N(x,\rho)$.
- However, the rescattering of these higher Fock states is neglected in the eikonal approximation.
- This can be cured by the following recipe:

$$\sigma_{q\bar{q}}^A(x,\rho) = 2\int d^2b \left\{1 - \exp\left(-\frac{\sigma_{q\bar{q}}^N(x,\rho)\widetilde{T}(b)}{2}\right)\right\},$$

  where

$$\widetilde{T}(b) = T(b) R_G(x,b)$$

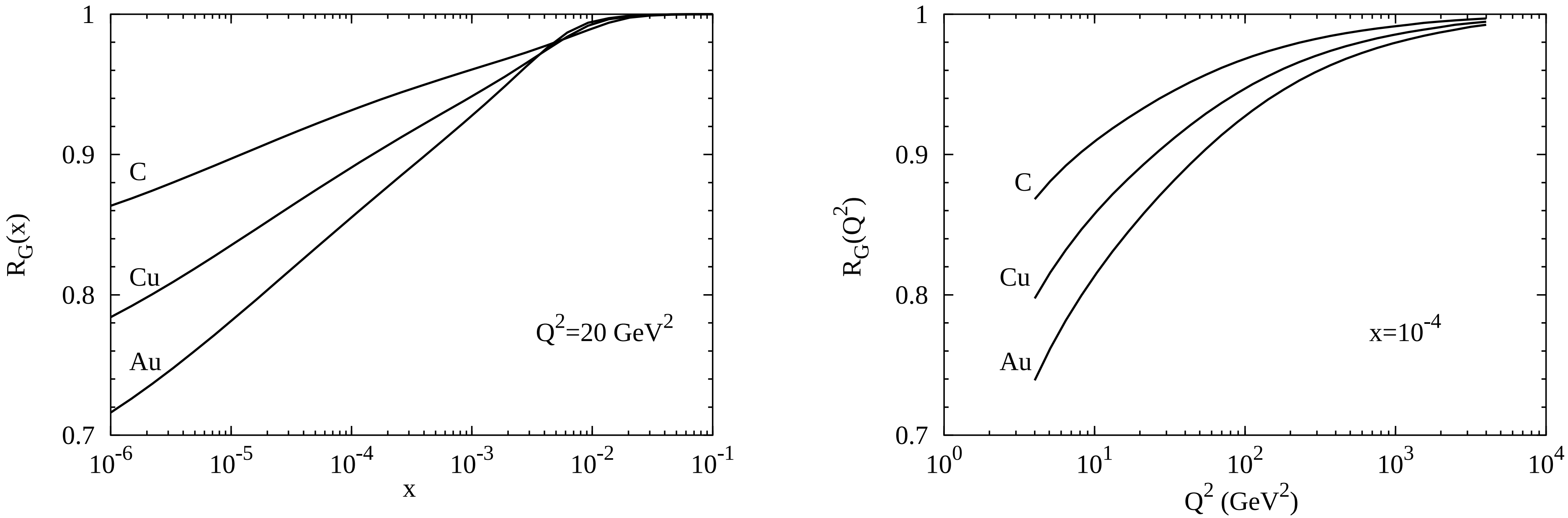
  and $R_G(x,b)$ is the leading twist gluon shadowing, calculated from the propagation of a GG dipole through a nucleus.

- Expansion of the nuclear dipole cross section:

$$\sigma_{q\bar{q}}^A(x,\rho) = \frac{\pi^2}{3}\alpha_s\rho^2 \int d^2b T(b) R_G(x,b) x G_N(x) - \frac{\pi^2\alpha_s^2}{36}\rho^4 \int d^2b \left[T(b) R_G(x,b) x G_N(x)\right]^2 + \ldots$$

  Already the single scattering term is suppressed due to gluon shadowing.

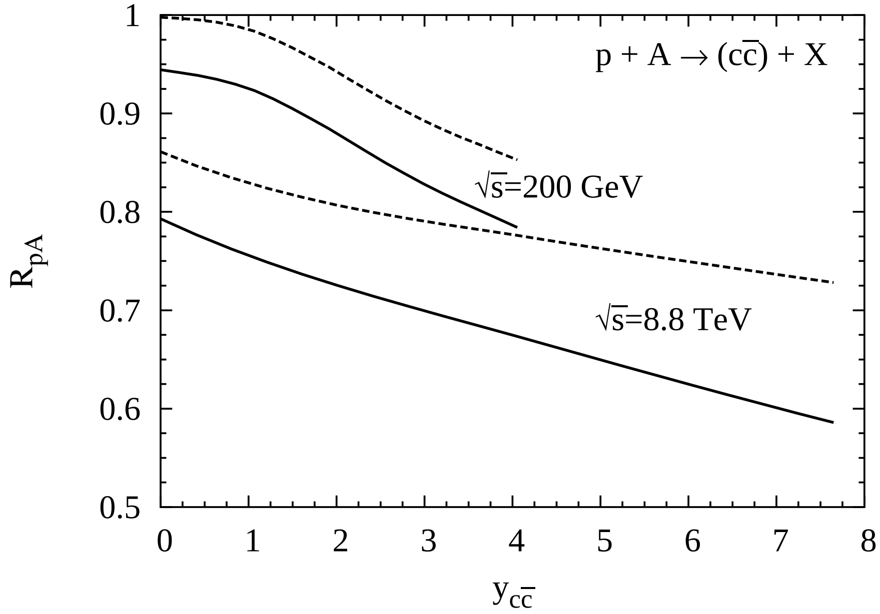
Gluon Shadowing

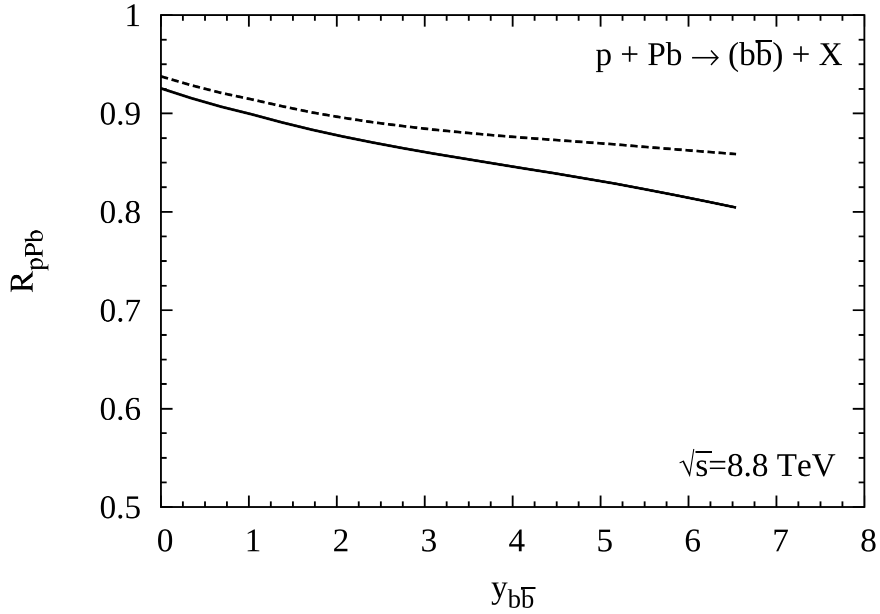


Kopeliovich, JR, Tarasov, Johnson, Phys. Rev. C**67**, 014903, 2003

- No gluon shadowing at $x_2 > 0.01$, because of short l_c.
- The dipole approach predicts much smaller gluon shadowing than most other approaches.
- The gluon can propagate only distances of order of a constituent quark radius (~ 0.3 fm) from the $Q\overline{Q}$-pair. This overcompensates the color factor $9/4$ in the interaction strength.
- The smallness of the gluon correlation radius is the only known way to explain the tiny Pomeron-proton cross section (≈ 2 mb).

Suppression of Open Charm and Bottom in pA Collisions





JR, J. Phys. G**30**(2004)S1159

- Dashed curves: Gluon Shadowing only
- Solid curves: Total suppression (including $Q\overline{Q}$ rescattering and Gluon Shadowing)
- Gluon Shadowing reduces the probability for $Q\overline{Q}$ rescattering.

Medium induced gluon radiation

- Distinguish 3 different regimes: Baier, Schiff, Zakharov, Ann. Rev. Nucl. Part. Sci. 50:37,2000
  1. $E < \omega_{BH} \sim$ few-hundred MeV: Bethe Heitler applies,
  $$-\left(\frac{dE}{dz}\right)_{BH} \sim \frac{\alpha_s C_R E}{\lambda_{free}}. \tag{1}$$
  2. $\omega_{BH} \ll E \ll \omega_{LPM} = \hat{q}L^2 \sim \begin{cases} 5\ \text{GeV (cold)} \\ 50\ \text{GeV (hot, longitudinally expanding medium)} \end{cases}$:
  $$-\left(\frac{dE}{dz}\right)_{LPM_1} \sim \alpha_s C_R \sqrt{\hat{q}E}. \tag{2}$$
  This is the same E dependence as for the LPM effect in QED.
  3. $\omega_{LPM} \ll E$:
  $$-\left(\frac{dE}{dz}\right)_{LPM_2} \sim \alpha_s C_R \hat{q} L. \tag{3}$$
  $\Rightarrow$ No effect from initial state energy loss expected at large $\sqrt{S}$.

Estimate of the BDMPS transport coefficient

- The transport coefficient $\hat{q}$ and the dipole cross section $\sigma_{q\bar{q}}(r_T^2) = Cr_T^2$ are both related to the average color-field strength $\langle F^2 \rangle$ in the medium JR, PLB557,184(2003),

$$C = \frac{\pi^2}{3}\alpha_s \langle F^2 \rangle \tag{4}$$

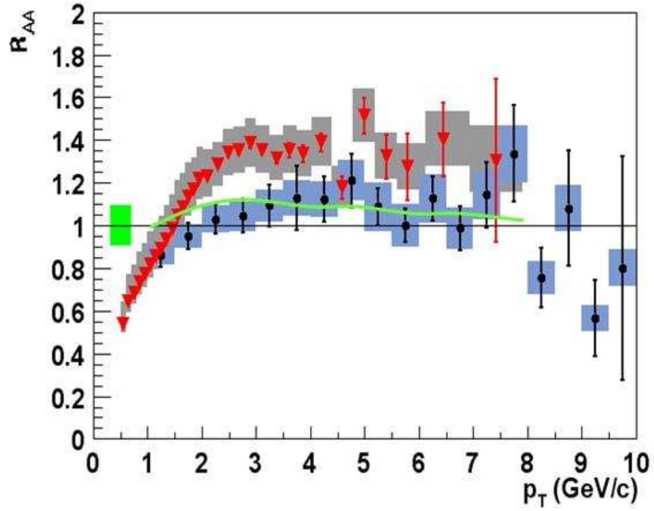
$$\hat{q} = 2\rho_A \frac{\pi^2}{3}\alpha_s \langle F^2 \rangle \tag{5}$$

- The dipole approach has a highly developed and successful phenomenology in DIS, Drell-Yan, heavy flavor production, total hadronic cross sections, color transparency . . . .
  Kopeliovich et al. PRL.88:232303,2002

- Use KST parameterization of $\sigma_{q\bar{q}}$ to determine $\hat{q}$.
  Kopeliovich et al. PRD62,054022(2000)

$$\hat{q} \approx 0.2 \frac{\text{GeV}}{\text{fm}^2}$$

Higher order corrections make $\hat{q}$ weakly energy dependent, $\hat{q} \propto E^{0.08}$.



The transport coefficient in heavy ion collisions

- In HIC, a medium with high energy density is created. Bjorken's estimate of the initial energy density at RHIC yields

$$\epsilon_{Bj} = \frac{\langle m_T \rangle}{\pi R_A^2 \tau_0} \left(\frac{dN}{dy} \right)_{y=0} \approx 10\,\text{GeV}/\,\text{fm}^3 \approx 60 \epsilon_{cold} \tag{6}$$

  at initial time $\tau_0 = 0.5$ fm.

- Because of the expansion of the medium, the hard parton sees an averaged transport coefficient,

$$\hat{q}^{med} = \frac{2\hat{q}}{L^2} \int_{\tau_0}^{\tau_0+L} d\tau (\tau - \tau_0) \frac{\tau_0}{\tau}. \tag{7}$$

  Salgado, Wiedemann, PRL89,092303(2002)

- The averaged transport coefficient is then

$$\hat{q}^{med} \approx 10 \hat{q}^{cold} \approx 2\,\text{GeV}/\,\text{fm}^2. \tag{8}$$

  $\hat{q} \gtrsim 20\,\text{GeV}/\,\text{fm}^2$ is needed to reproduce pion quenching at RHIC.
  (Armesto et al, hep-ph/0511257)

Summary

- At high energies, heavy quark production can be formulated in terms of the same color dipole cross section as low-x DIS.
- The cross section for heavy quark production in pp collision is well described in this approach.
- The dipole cross section is an eigenvalue of the diffraction amplitude operator $\Rightarrow$ easy calculation of multiple scattering effects.
- The dipole approach takes into account both, leading twist gluon shadowing and higher twist rescattering of the $Q\overline{Q}$ pair.
- Initial state effects yield $\sim 10\%$ suppression at RHIC.
- Initial state energy loss is irrelevant at RHIC energy.
- Estimates of the BDMPS transport coefficient suggest that induced gluon radiation account only for a small part of quenching for light and heavy flavors.