Saturation effect on heavy flavors in pA collisions

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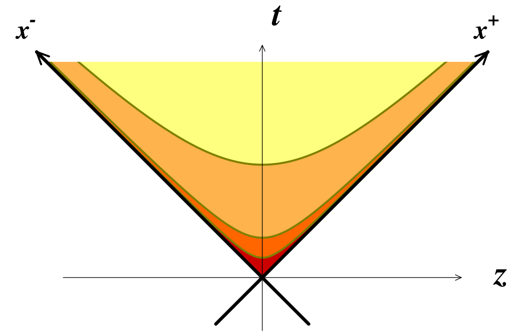
Outline

- CGC as HIC initial condition
  - small-x wavefunction
  - evolutoin
  - Color Glass Condensate
- Heavy flavors at HIC
- Quark production in pA collisions
  - Analytic solution from classical YM
  - Balitskii-Kovchegov (BK) evolution
- Numerical results
  - Open charm
  - Charmonium
- **HF, Gelis, Venugopalan, PRL95,162002(2005) , NPA780, 146 (2006) and in progress.**

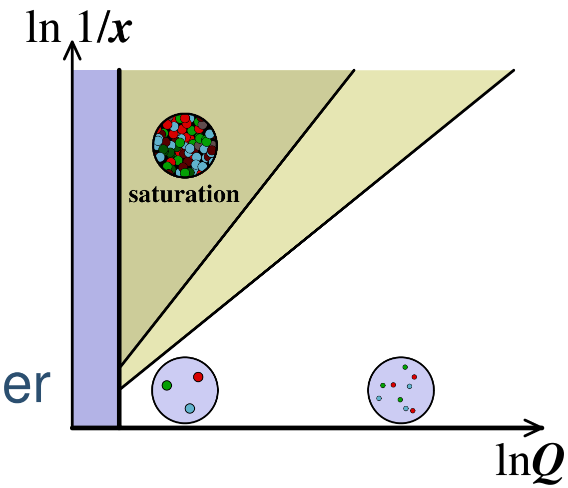
HIC and small-x WF

- HI exp's at RHIC/LHC explore properties of hot/dense matter
  - in the course of initial to final state
- The bulk of particles are produced at $\boldsymbol{p}_\perp \ll \sqrt{s}$
  - *i.e.* dominated by small x part of init WF

$$x \sim \boldsymbol{p}_\perp e^{-y}/\sqrt{s}$$

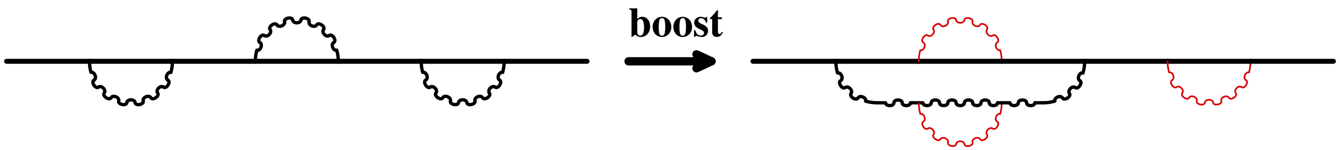


- Hadron WF has different aspects in (x, Q^2)
  - At large Q^2: dilute system of small partons
  - At small x: dense system of partons
  - At very small x: saturated system



- One immediate consequence to AA:
  - suppression of particle yield compared to sum of pp, as nucleus saturates earlier

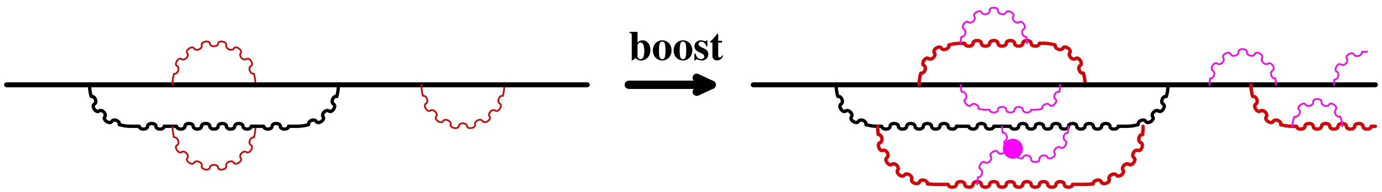
Small-x wavefunction



▷ at low energy, we see a constituent quark dressed with short-lived fluctuations

▷ at higher energy, due time dilatation, the fluctuations live long enough to become a source of other fluctuations (BFKL)

Small-x wavefunction



▷ at yet higher energy, shorter-lived fluctuations are emitted: system becomes very dense

▷ at some point, interactions between fluctuations become important: non-linearity & saturation

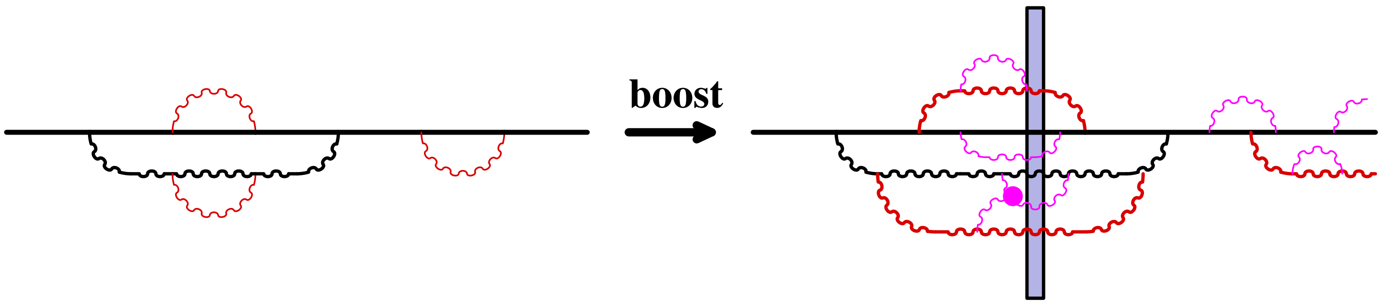
Balitsky, Kovchegov, JIMWLK

▷ Saturation scale $Q_s^2(x)$:

(area)×(density)= $\frac{\alpha_s}{Q_s^2} \times \frac{xG(x,Q_s^2)}{\pi R^2} \sim 1$

heavy nucleus is denser by a factor $A^{1/3} \sim 6$

Small-x wavefunction



▷ in a high energy reaction we take a snap-shot of these fluctuations generated from the frozen source

▷ frozen source may be treated statistically, since the moment of collision is arbitrary

Color glass condensate

McLerran, Venugopalan (1994), Iancu, Leonidov, McLerran (2001)

- Small x modes = classical color field
- Large x modes = "frozen" color sources ρ_a
- The classical field obeys Yang-Mills equations:

$$[D_\nu, F^{\nu\mu}]_a = \delta^{\mu +}\delta(x^-)\rho_a(\vec{\boldsymbol{x}}_\perp)$$

- The color sources ρ_a has random distribution $W_{x_0}[\rho]$ (x_0 separates between "small" and "large x")
- Observables are calculated in the presence of the classical field, and then averaged over the configurations of the sources ρ_a:

$$\langle \mathcal{O} \rangle = \int [D\rho_a]\, W_{x_0}[\rho_a]\, \mathcal{O}[\rho_a]$$

Applications to HIC

The CGC idea applied to HIC phenomenology

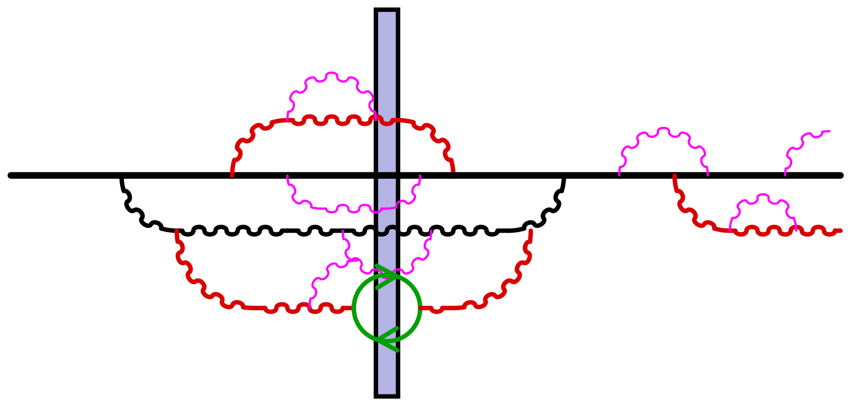
- AA – Kharzeev-Levin-Nardi, Krasniz-Nara-Venugopalan, Lappi, ...
- forward suppression – Albacete-Armesto-Kovner-Salgado-Wiedemann, Kharzeev-Levin-McLerran, ...
- dA – Kharzeev-Kovchegov-Tuchin, Dumitru-Hayashigaki-Jalilian-Marian, ...
- Limiting fragmentation – Jalilian-Marian, Gelis-Stasto-Venugopalan, ...
- Heavy Flavor – Kharzeev-Kovchegov-Tuchin, ...
- ...

Heavy flavor signal for QGP

Heavy flavors $\sim$ important baseline/signal for QGP

- Heavy $m_Q \gg \Lambda_{\mathrm{QCD}}$: pQCD calculation may apply
  - in-medium interaction will modify the final distributions
    large E-loss and non-zero v_2 for charm at RHIC?
    PHENIX
  - quarkonium melting in QGP
    Matsui-Satz, Kharzeev-Lorenco-Nardi-Satz, ...
    moderate suppression observed at RHIC
    where does it go at LHC?

Coherence in heavy flavor production



- Note: even $c\bar{c}$ fluctuation may live over the target thickness: $\gamma/2m_c > 2R$ at RHIC/LHC energies
  - ▷ Partonic multiple scattering of the pair in the target
  - ▷ Cold nuclear suppression of quarkonium – model studies

    Qiu-Vary-Zhuang, HF-Matsui, Glenn-Molnar-Nagle, ...

- Long-lived fluctuations and interactions ⇒ CGC framework
  - ▷ Indeed, $Q_s^2 \sim m_c^2$ at RHIC, and $Q_s^2 > m_c^2$ at LHC:

    $Q_s^2 \sim A^{1/3}(x_0/x)^{0.3} \sim 1$ GeV^2 at RHIC

    Kharzeev-Tuchin, HF-Gelis-Venugopalan, ...

Quark pair from the CGC in pA

Advantage of pA problem:

▷ analytically solved to weak source ρ_p^1 but to strong source ρ_A^∞

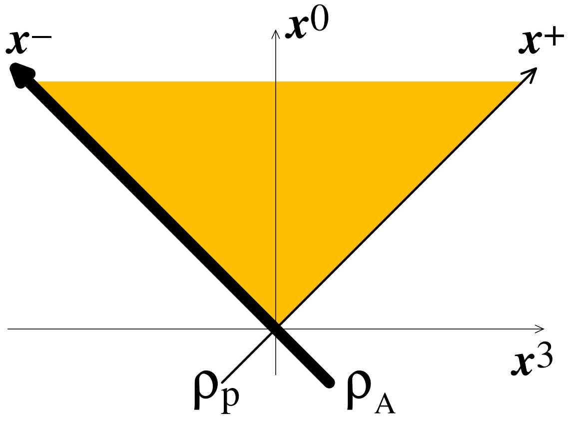
▷ written in (generalized) factorization form with "pdf" ϕ_A's

Blaizot-Gelis-Venugopalan

Strategy to computation:

(1) use the analytic expression, which includes re-scatterings

(2) evolve "pdf" ϕ_A's to treat quantum x-dependence (large N)



Expression for cross-section

- Quark pair: very complicated ...

$$\frac{d\sigma_{q\bar{q}}}{d^2\vec{\boldsymbol{p}}_\perp d^2\vec{\boldsymbol{q}}_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4 d_A} \int_{\vec{\boldsymbol{k}}_{1\perp},\vec{\boldsymbol{k}}_{2\perp}} \frac{\delta(\vec{\boldsymbol{p}}_\perp + \vec{\boldsymbol{q}}_\perp - \vec{\boldsymbol{k}}_{1\perp} - \vec{\boldsymbol{k}}_{2\perp})}{\boldsymbol{k}_{1\perp}^2 \boldsymbol{k}_{2\perp}^2}$$

$$\times\Big\{ \int_{\vec{\boldsymbol{k}}_\perp,\vec{\boldsymbol{k}}'_\perp} \mathrm{tr}\Big[(\not{q}+m)T_{q\bar{q}}(\vec{\boldsymbol{k}}_\perp)(\not{p}-m)T^*_{q\bar{q}}(\vec{\boldsymbol{k}}'_\perp)\Big]\phi_A^{q\bar{q},q\bar{q}}(\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp,\vec{\boldsymbol{k}}'_\perp)$$

$$+\int_{\vec{\boldsymbol{k}}_\perp} \mathrm{tr}\Big[(\not{q}+m)T_{q\bar{q}}(\vec{\boldsymbol{k}}_\perp)(\not{p}-m)\not{L}^* + \mathrm{h.c.}\Big]\phi_A^{q\bar{q},g}(\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp)$$

$$+\mathrm{tr}\Big[(\not{q}+m)\not{L}(\not{p}-m)\not{L}^*\Big]\phi_A^{g,g}(\vec{\boldsymbol{k}}_{2\perp})\Big\}\varphi_p(\vec{\boldsymbol{k}}_{1\perp})$$

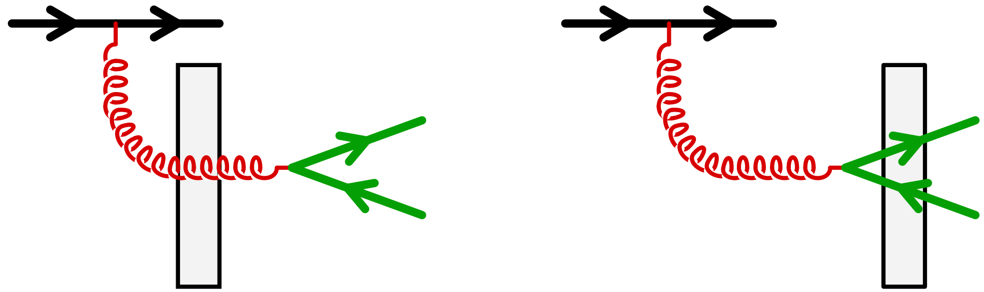
- Gluon:

$$\frac{d\sigma_g}{d^2\vec{\boldsymbol{q}}_\perp dy} = \frac{\alpha_s N}{\pi^4 d_A}\frac{1}{\boldsymbol{q}_\perp^2}\int_{\vec{\boldsymbol{k}}_\perp} \phi_A^{g,g}(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp)\varphi_p(\vec{\boldsymbol{k}}_{1\perp})$$

▷ simple $k_\perp$-factorization is violated for quarks, OK for gluons

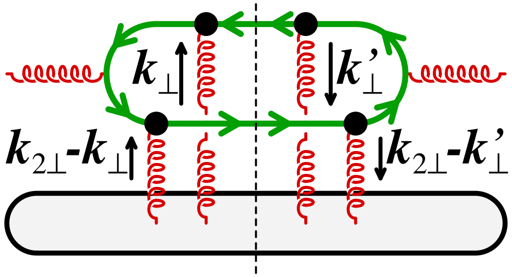
Expression for cross-section

- Pair $Q\bar{Q}$ breaks the $k_\perp$ factorization ansatz:



- We have three partonic correlators of the target: ϕ_A's e.g.,

$$\phi_A^{q\bar{q},q\bar{q}}(\vec{\boldsymbol{k}}_{2\perp}|\vec{\boldsymbol{k}}_\perp,\vec{\boldsymbol{k}}'_\perp) \quad \propto$$



Balitskii-Kovchegov equation

- In the large N limit, all ϕ_A's are obtained from

$$\phi^{q,\bar{q}}_{A,y}(\boldsymbol{k}_\perp) \sim \boldsymbol{k}_\perp^2 S_{A,y}(\boldsymbol{k}_\perp)$$

- BK evolution for $S_{A,y}(\boldsymbol{k}_\perp)$ justified in large N and A

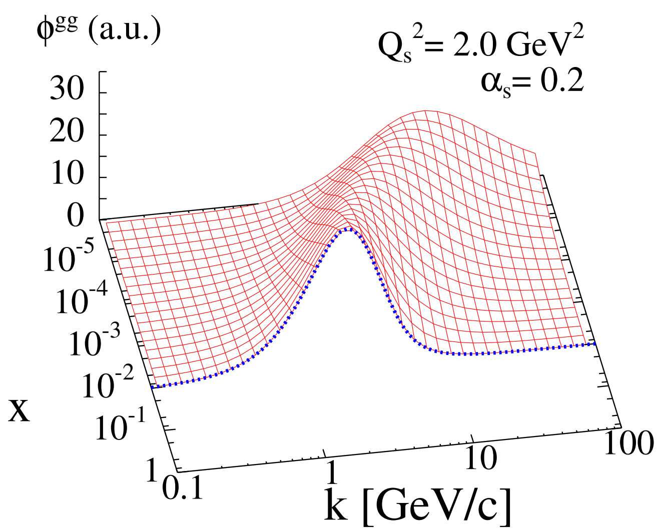
$$\frac{\partial}{\partial Y} T_Y(\boldsymbol{k}_\perp) = \bar{\alpha}_s \left[\chi(-\partial_L) T_Y(\boldsymbol{k}_\perp) - T_Y^2(\boldsymbol{k}_\perp)\right]$$

$\bar{\alpha}_s = \alpha_s N/\pi, \qquad L \equiv \ln(k_\perp^2/\Lambda^2)$

$\chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$: BFKL kernel

$S_Y(\boldsymbol{x}_\perp)$ is obtained from $T_Y(\boldsymbol{k}_\perp) = \int \frac{d^2\boldsymbol{x}_\perp}{2\pi \boldsymbol{x}_\perp^2}(1 - S_Y(\boldsymbol{x}_\perp)) e^{i\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp}$

- Parameters:
  - ▷ (x_0, Q_{s0}^2) for MV model
  - ▷ α_s for evolution

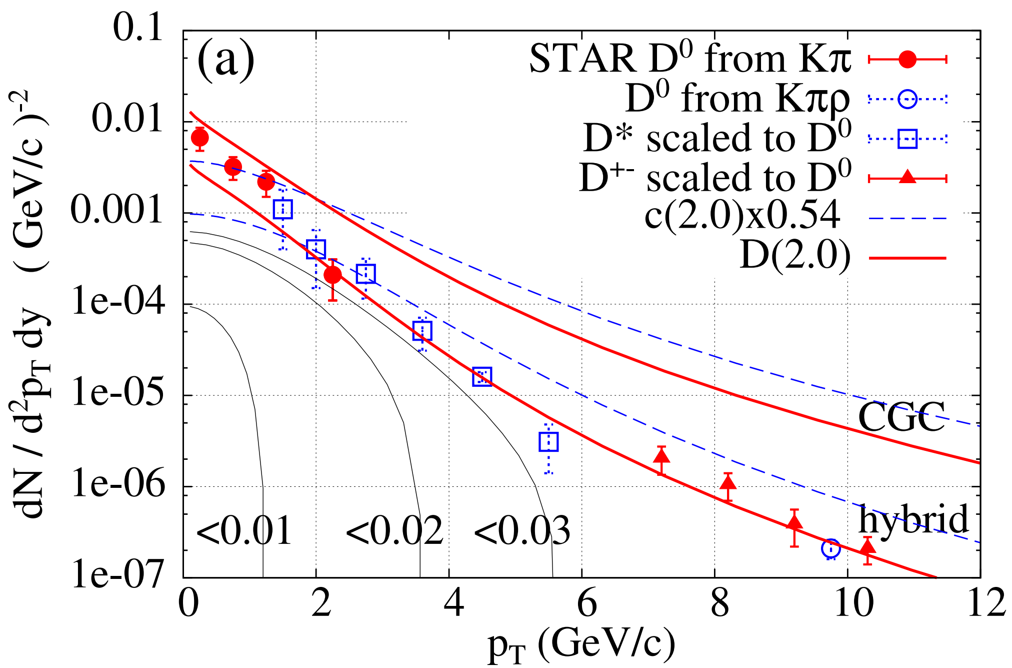


Open charm production

Open charm production in dA at RHIC at y=0

(1) CGC: our full result

(2) hybrid: collinear limit only on *deuteron*: $\boldsymbol{k}_{1\perp} \to 0$



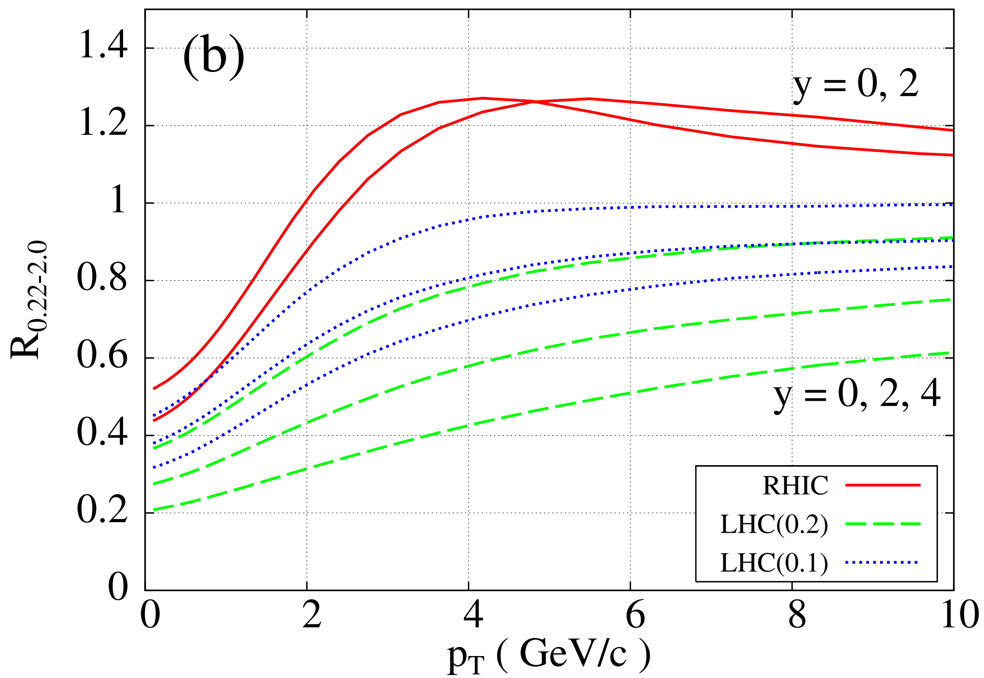
- hybrid result fits better the (preliminary) STAR data

  no b-contib included yet
- charm at $y = 0$ at RHIC has not much sensitivity to small x
- look forward !

Open charm production

Open charm production in dA at RHIC

in hybrid: pA = CTEQ$\otimes$(Q_s^2=2.0) vs pp = CTEQ$\otimes$(Q_s^2=.22)



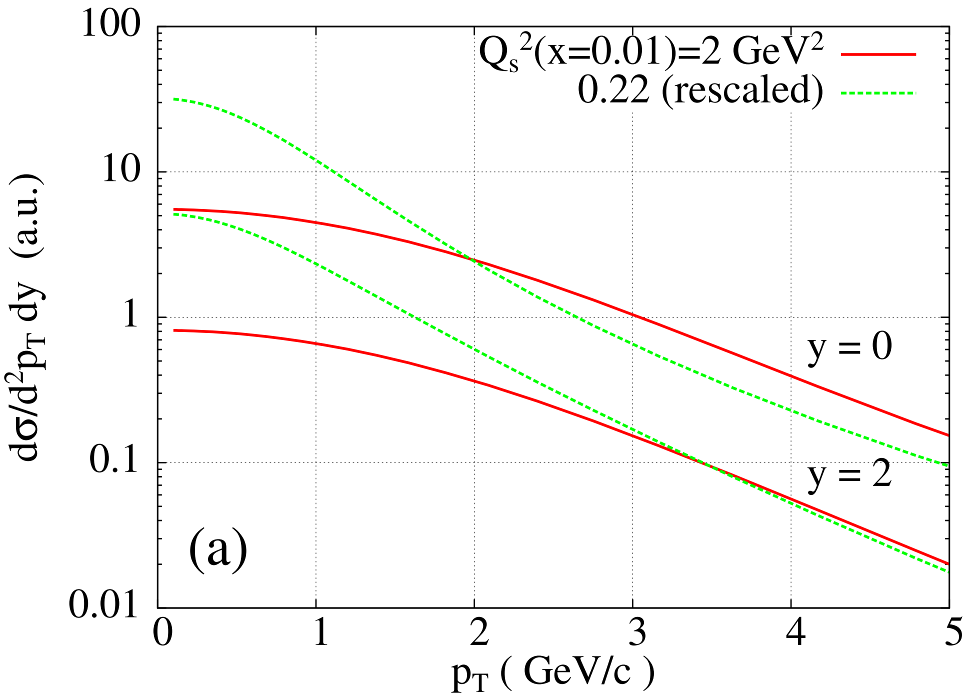
- a cronin-like peak is seen at RHIC even after convolution with FF
- large suppression at LHC, whose size depends on the value α_s
- Caveat: in hybrid treatment, $\boldsymbol{k}_\perp$-kick is included only from nuclear side; maybe easier to reflect the shape of $\phi_{A,y}(\boldsymbol{k}_\perp)$

Charmonium production

Charmonium estimated from Color Evaporation Model

hybrid:

pA = CTEQ$\otimes$(Q_s^2=2.0) vs pp = CTEQ$\otimes$(Q_s^2=.22)



- $p_\perp$ spectrum may be significantly affected in pA, compared to pp
- (preliminary) in the "full CGC" expression, the modification becomes much smaller
- Artifact of hybrid treatment?

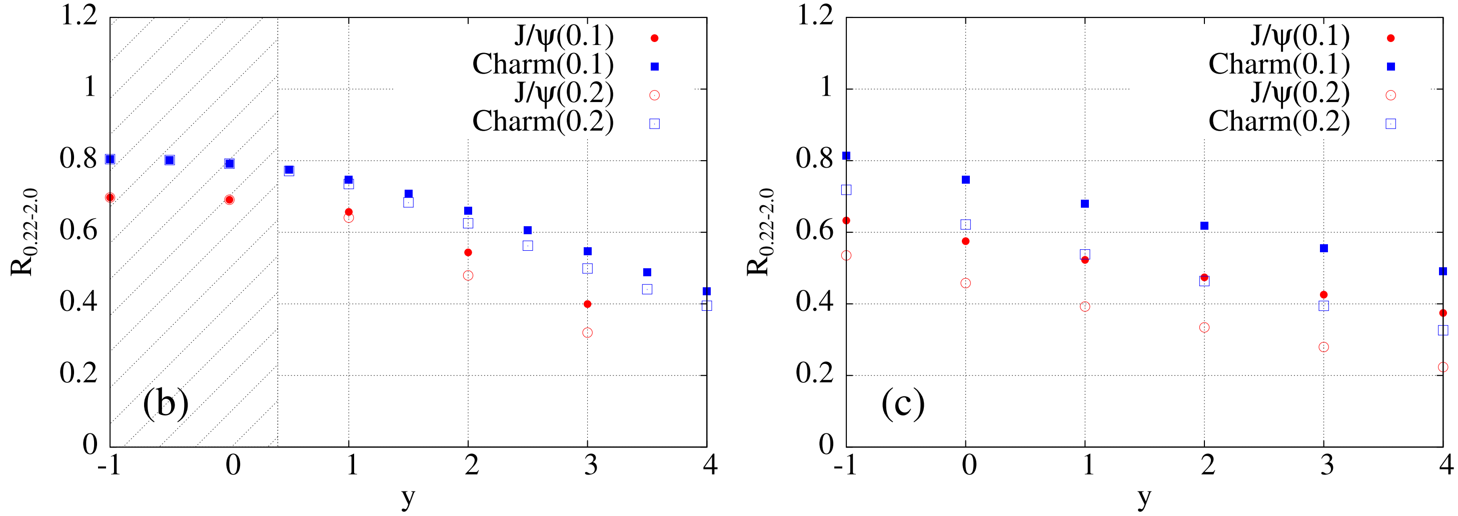
Rapidity dependence of R

hybrid: pA = CTEQ$\otimes$(Q_s^2=2.0) vs pp = CTEQ$\otimes$(Q_s^2=.22)

α_s=0.1, 0.2 fixed

blue = open charm, red= charmonium

RHIC LHC



- In forward region, both are more suppressed
- LHC has stronger saturation effect in wider range of y, as is should

Summary

- CGC framework to compute quark pair production in pA introduced
- Multiple scatterings are included in classical YM solution
- Quantum effects are treated in BK evolution for ϕ_A's
- We can numerically evaluate heavy flavor production in CGC framework
- Numerical results shown, mainly with hybrid approximation
- work in progress with “full” expression