Nuclear effect on charm production in pA in the CGC framework

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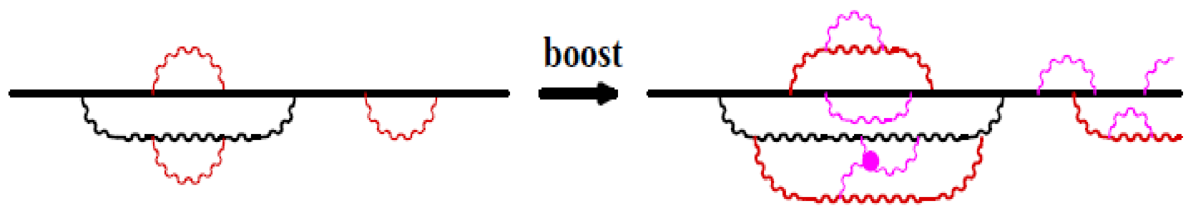
Outline

- Introduction
- CGC framework: MV model+BK evolution
- Open Charm
- Charmonium
- Summary and discussion

Introduction: CGC in A

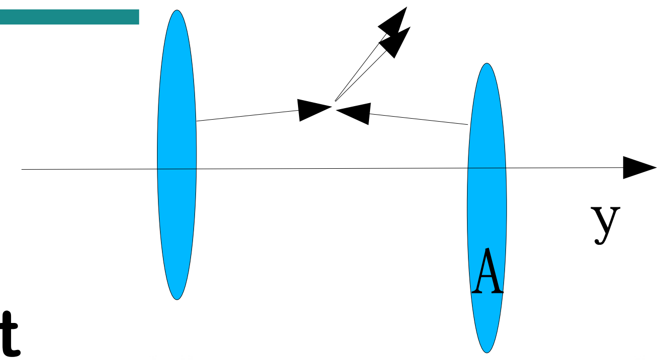
- Initial condition for AA collisions
  - Small-x partons: $\sqrt{s}\, x_A = k_1 e^{-y1} + k_2 e^{-y2}$
  - Color Glass Condensate in high E limit
    - Boost = seeing short time fluctuations

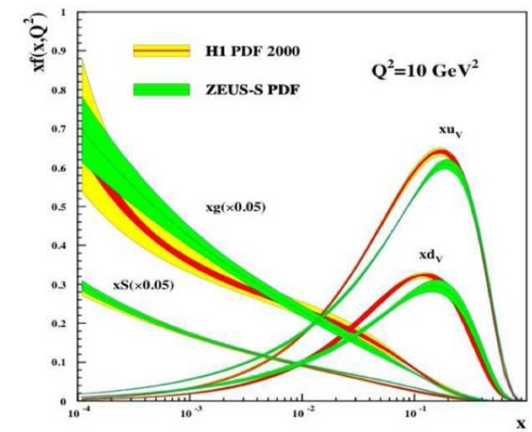
    ⇒ dense patonic system

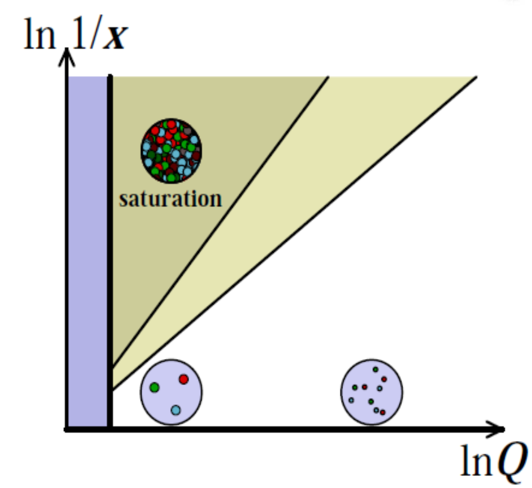


⇒ parton saturation

- In nuclei, larger *partons/trans area* by $A^{1/3}$
  - Earlier saturation than proton
  - Multiple scatterings in A

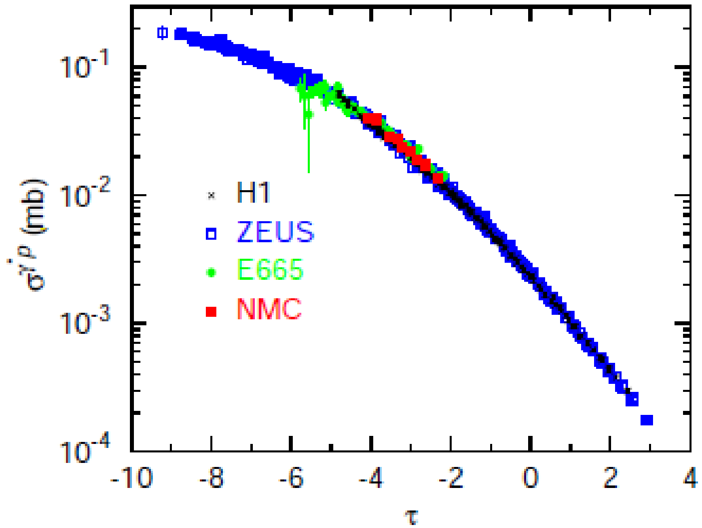




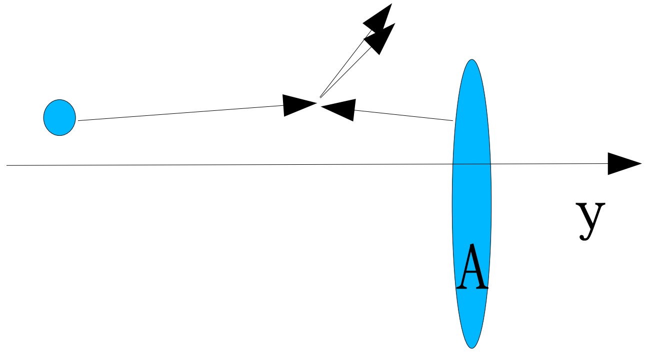


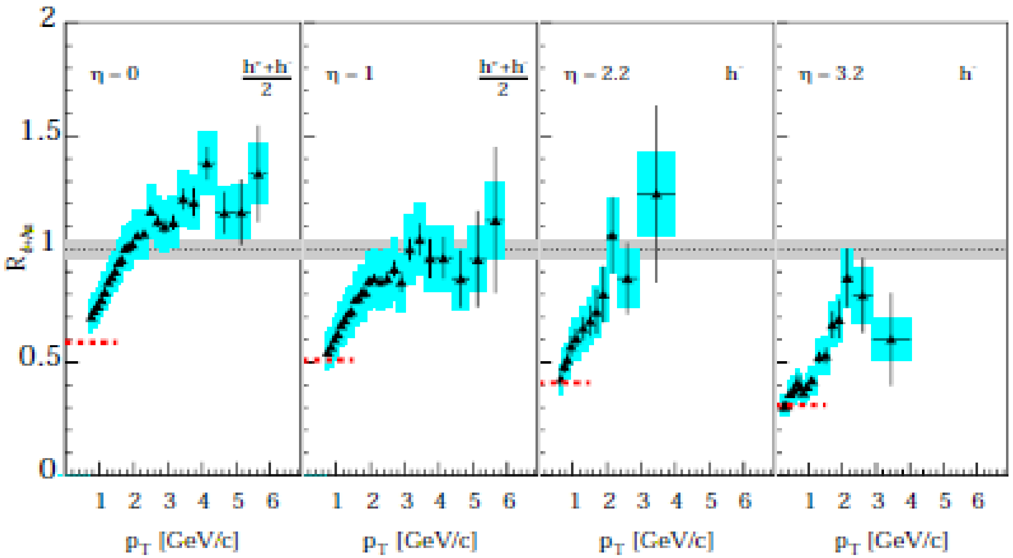
Introduction: CGC in A

- **Evidence of CGC**
  - **HERA (DIS) : $\tau \sim Q^2/Q_s^{\,2}(x)$**



  - **BRAHMS : $R_{dA}(y)$**
    - **Large xp and small xA**





Introduction: Charm

- Heavy flavors: $m_Q >> \Lambda_{QCD}$
  - initial hard productions only ⇒ pQCD predictions
  - Calibrated impurity probing medium property
  - Caveats: nuclear pdf, intrinsic kT, multiple scattering

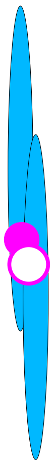
- Quarkonia:
  - Rare formation
  - Caveats: longer formation time $O(1/\alpha_s m^2)$

    formation mechanism not fully understood

    estimate for cold nuclear effects

Introduction: Why charm in CGC?

- Heavy flavors: $m_Q >> \Lambda_{QCD}$ but
  - Produced from gluon fusion
  - Multiple interactions possible at RHIC
    - $1/(2m) \sim 0.07$ fm/c vs $R_A/\gamma \sim 0.13$ fm
    - $1/(1/\alpha_s m^2) \sim 0.3$ fm/c



CGC framework

CGC framework: MV Gauss model

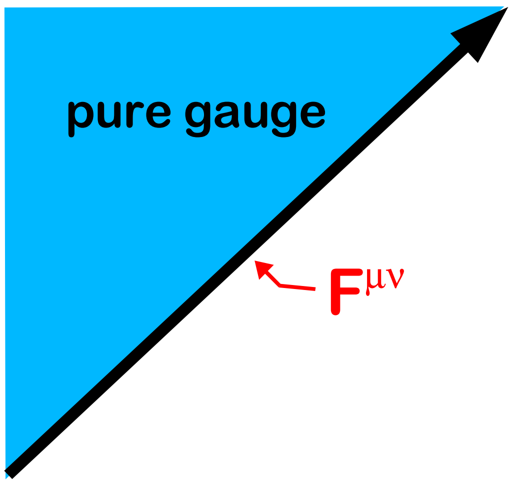
- "Valence" partons : random charge on x+ axis
- Small-x partons: classical field

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

- Compute observables $\mathcal{O}$ (ρ)
- Average over W the distribution of ρ

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

- McLerran-Venugopalan (MV) model
  - Gaussian : $W[\rho] = \exp\left[-\int d^2x\, \rho(x)_a^2 / 2\mu^2\right]$
  - $\mu^2 \sim Q_s^2$: mean charge density
  - valid for small x, but $\alpha_s \ln(1/x) < 1$ e.g., x~0.01

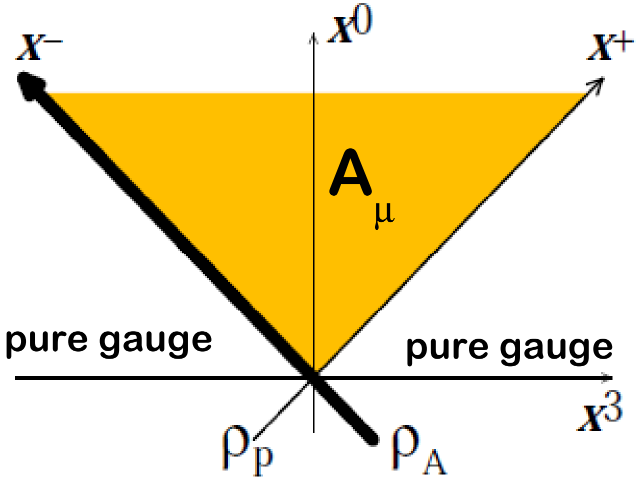


McLerran, Venugopalan (1994), Iancu, Leonidov, McLerran (2001)

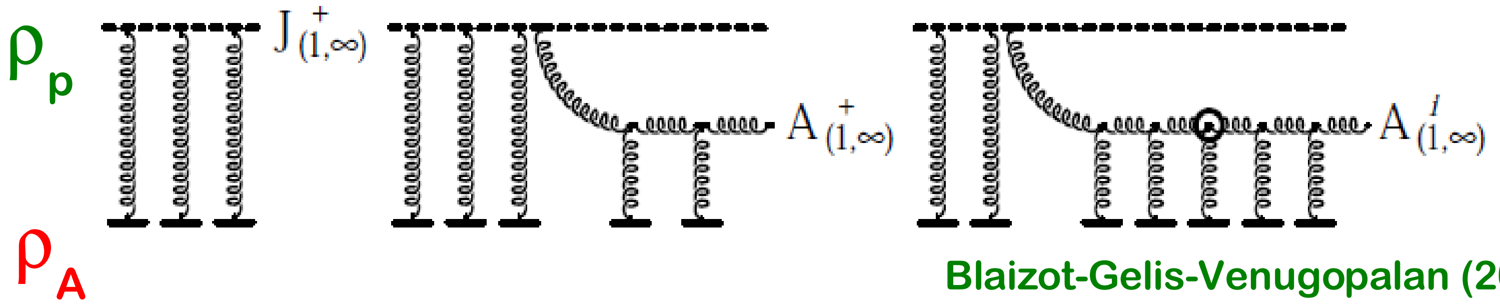
CGC framework: pA collision

- pA coll = two sources

$$[D_\nu, F^{\nu\mu}]_a = J_a^{\mu(0)}$$
$$J_a^{\nu(0)} = g\delta^{\nu +}\delta(x^-)\rho_{p,a}(\boldsymbol{x}_\perp) + g\delta^{\nu -}\delta(x^+)\rho_{A,a}(\boldsymbol{x}_\perp$$



- dilute+dense system: $g^2\rho_A$=O(1)
- Classical EoM sums tree graphs O(ρ_A^∞)
  - Multiple scatterings



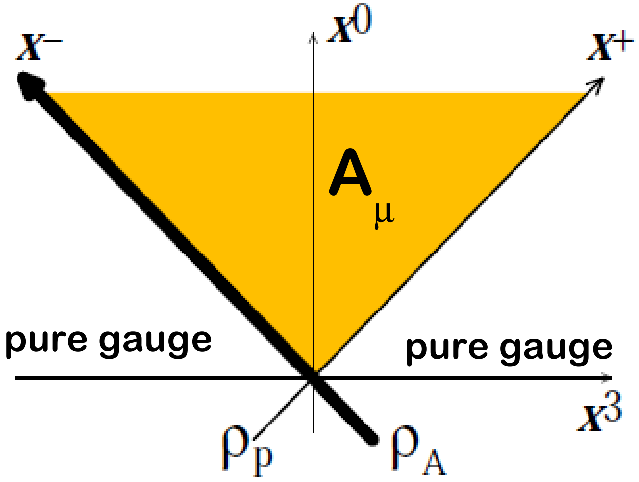
Blaizot-Gelis-Venugopalan (2004)

CGC framework: gluon production

- **x-section:**

$$\frac{d\overline{N}_g}{d^2\boldsymbol{q}_\perp dy} \sim \frac{\alpha_s}{q_\perp^2}\int_{\boldsymbol{k}_\perp} \varphi_p(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp)\phi_A^{gg}(\boldsymbol{k}_\perp)$$

- **"Unintegrated gluon dist.fn." (uGDF) includes multiple interactions**



$$\phi_A^{g,g} \sim \boldsymbol{k}_\perp^2\,\mathrm{FT}\,\langle U(\boldsymbol{x})\,U^\dagger(\boldsymbol{y})\rangle$$

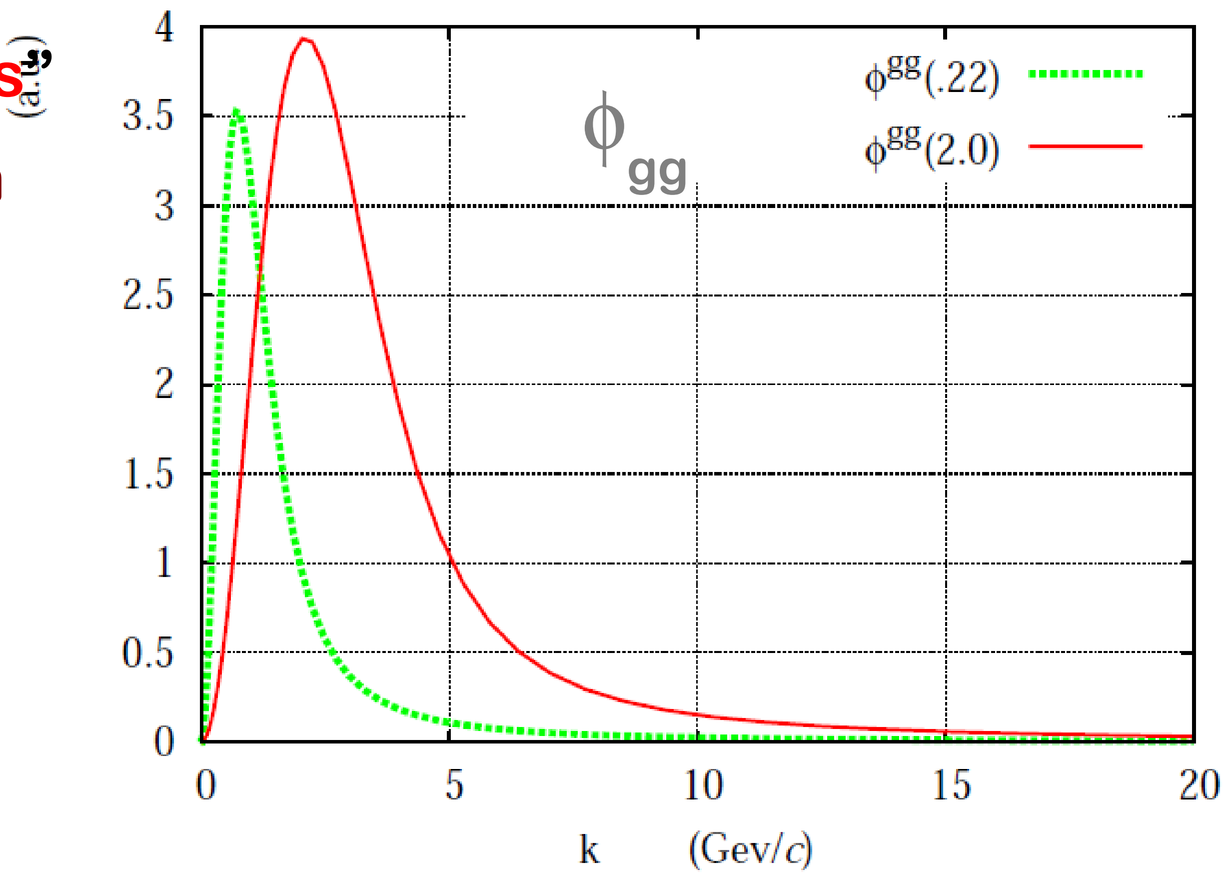
$$U(\boldsymbol{x}) \equiv \mathcal{P}\exp\left[ig^2\int dz^+(1/\nabla^2)\rho(z^+,\boldsymbol{x})\cdot T\right]$$

$$xg(x,Q^2) = \frac{1}{4\pi^3}\int dk_\perp^2\,\phi_A^{g,g}(x,k_\perp^2)$$

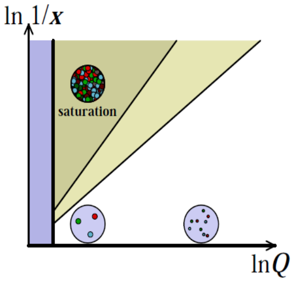
Blaizot-Gelis-Venugopalan (2004)

CGC Framework: uGDF

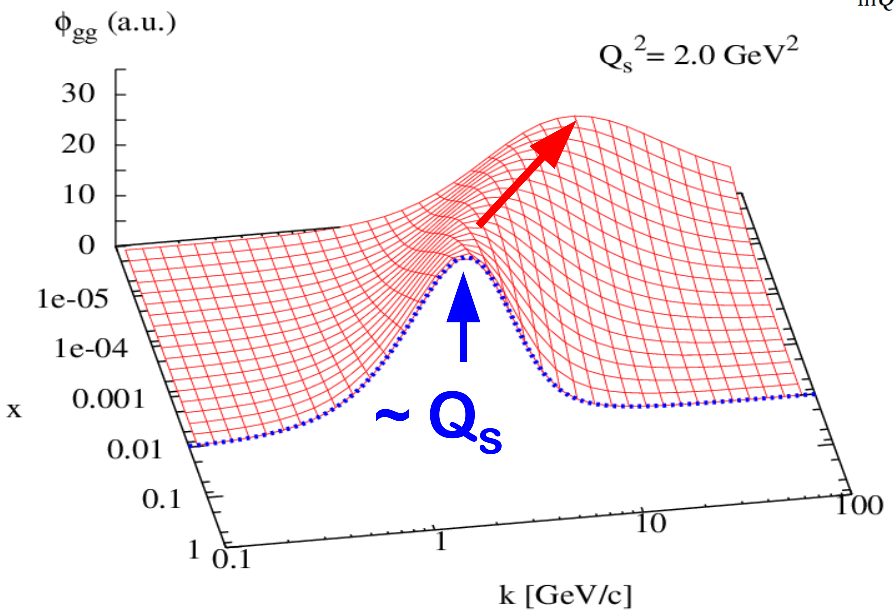
- MV model assumed at x~0.01
- scale $\mu^2 \sim Q_s^{\ 2} \sim A^{1/3}$ in the model characterizes targets
  - 0.22 GeV^2 …"proton"
  - 2.0 GeV^2 … "nucleus"
- intrinsic kT distribution
- $1/k^2$ – perturbative tail



CGC Framework: x-evolution



- BK equation (large N & A)
  - Evolve from x0=0.01
    - MV model for x>x0
  - Linear: BFKL sums up (α_s y)
  - Nonlinear: gluon fusion effect

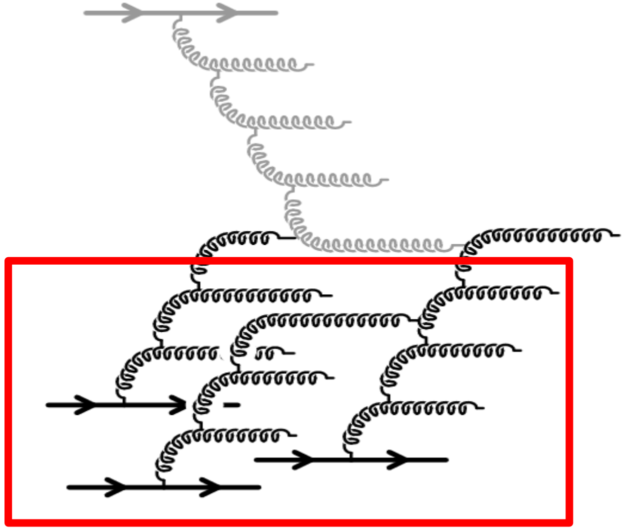


$$\frac{\partial}{\partial Y} T_Y(\boldsymbol{k}_\perp) = \bar{\alpha}_s \left[\chi(-\partial_L) T_Y(\boldsymbol{k}_\perp) - T_Y^2(\boldsymbol{k}_\perp) \right]$$

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

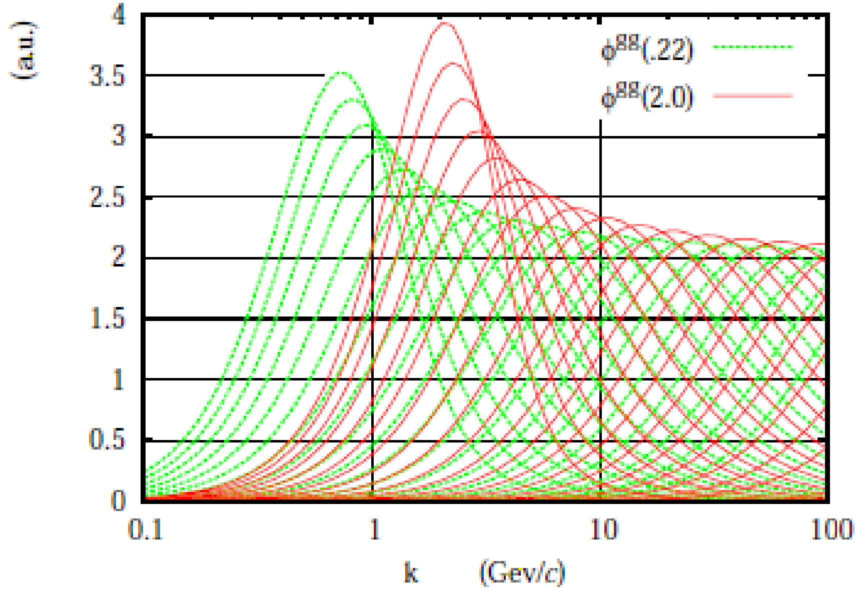
$\chi(\gamma) = 2\psi(1) - \psi(\gamma) - \psi(1-\gamma)$: BFKL kernel

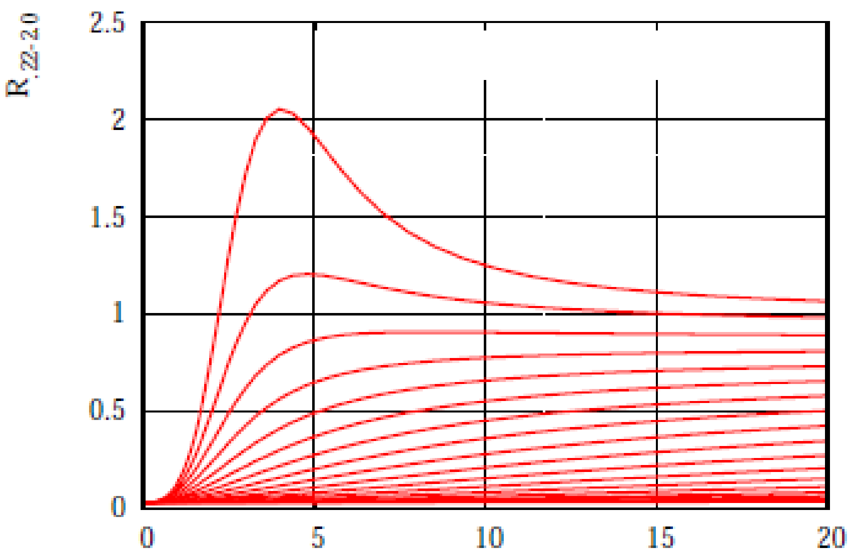
$T_Y(\boldsymbol{k}_\perp) = \int \frac{d^2 \boldsymbol{x}_\perp}{2\pi \boldsymbol{x}_\perp^2} (1 - \langle \tilde{U}\tilde{U}^\dagger \rangle) e^{i\boldsymbol{k}_\perp \cdot \boldsymbol{x}_\perp}$ $\quad \phi_{gg}(k_T, \ x) \quad =$



CGC Framework: x-evolution

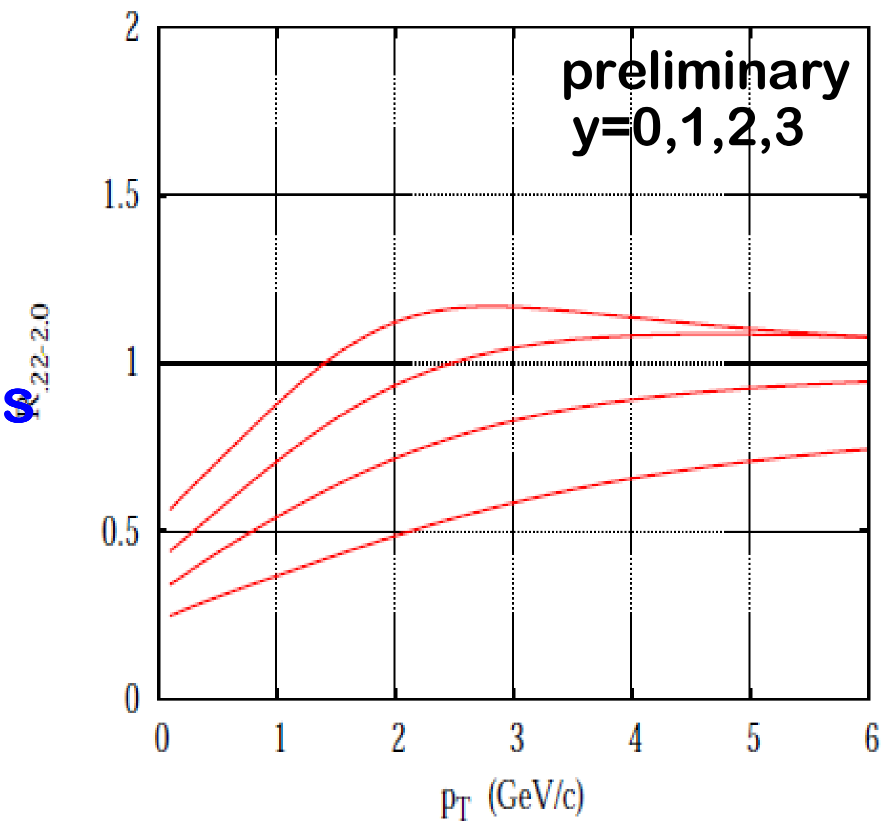
- BK equation (large N & A)
  - Evolve from x0=0.01
  - Nonlinear: gluon fusion effect
  - Peak moves to higher pT
  - RpA suppressed due to faster saturation for A





CGC Framework: x-evolution

- BK equation (large N & A)
  - Evolve from x0=0.01
  - Nonlinear: gluon fusion effect
  - Peak moves to higher pT
  - RpA suppressed due to faster saturation for A
  - Forward suppression for gluons similar to BRAHMS



Open charm production

Open charm production

- **Analytic formula to** $O(\rho_p^{\,1}\, \rho_A^{\,\text{infty}})$

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

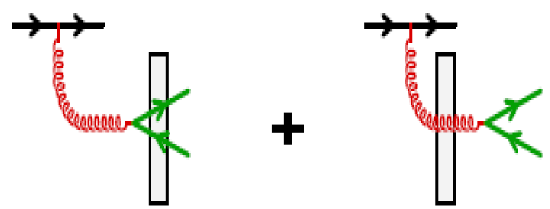
$$\times\Big\{ \int_{\vec{k}_\perp,\vec{k}'_\perp} \mathrm{tr}\Big[(\not{q}+m) T_{q\bar{q}}(\vec{k}_\perp)(\not{p}-m) T^*_{q\bar{q}}(\vec{k}'_\perp)\Big] \phi_A^{q\bar{q},q\bar{q}}(\vec{k}_{2\perp}|\vec{k}_\perp,\vec{k}'_\perp)$$

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

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

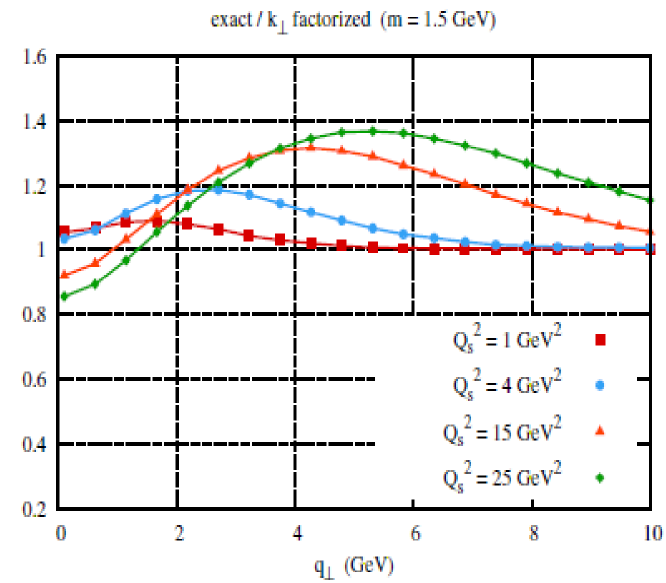
hard **nucleus** **proton**

2



- **kT factorization is broken, but small**
- **Collinear approx for proton may be OK**

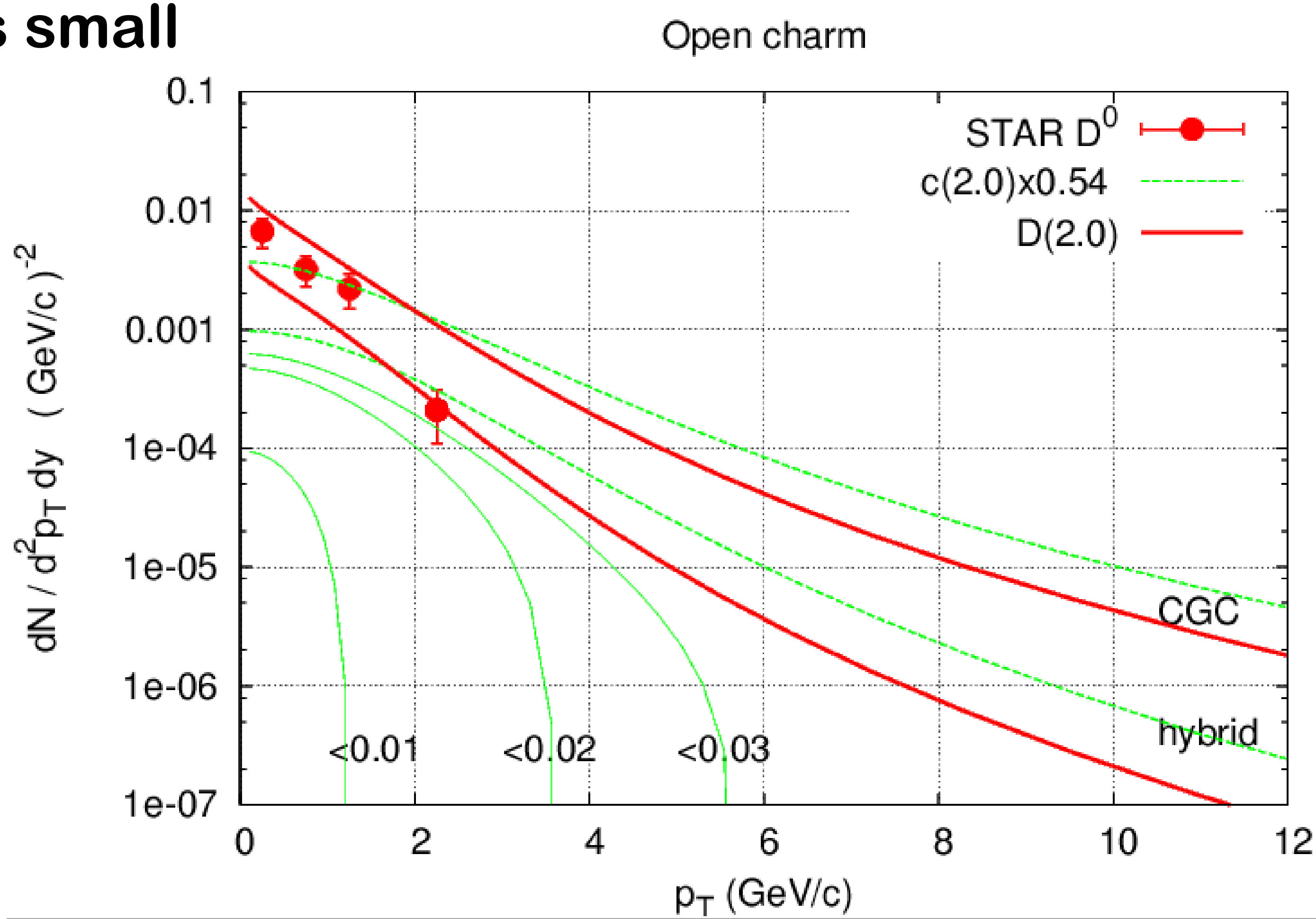
= hybrid ; cheaper numerical task



HF, Gelis, Venugopalan

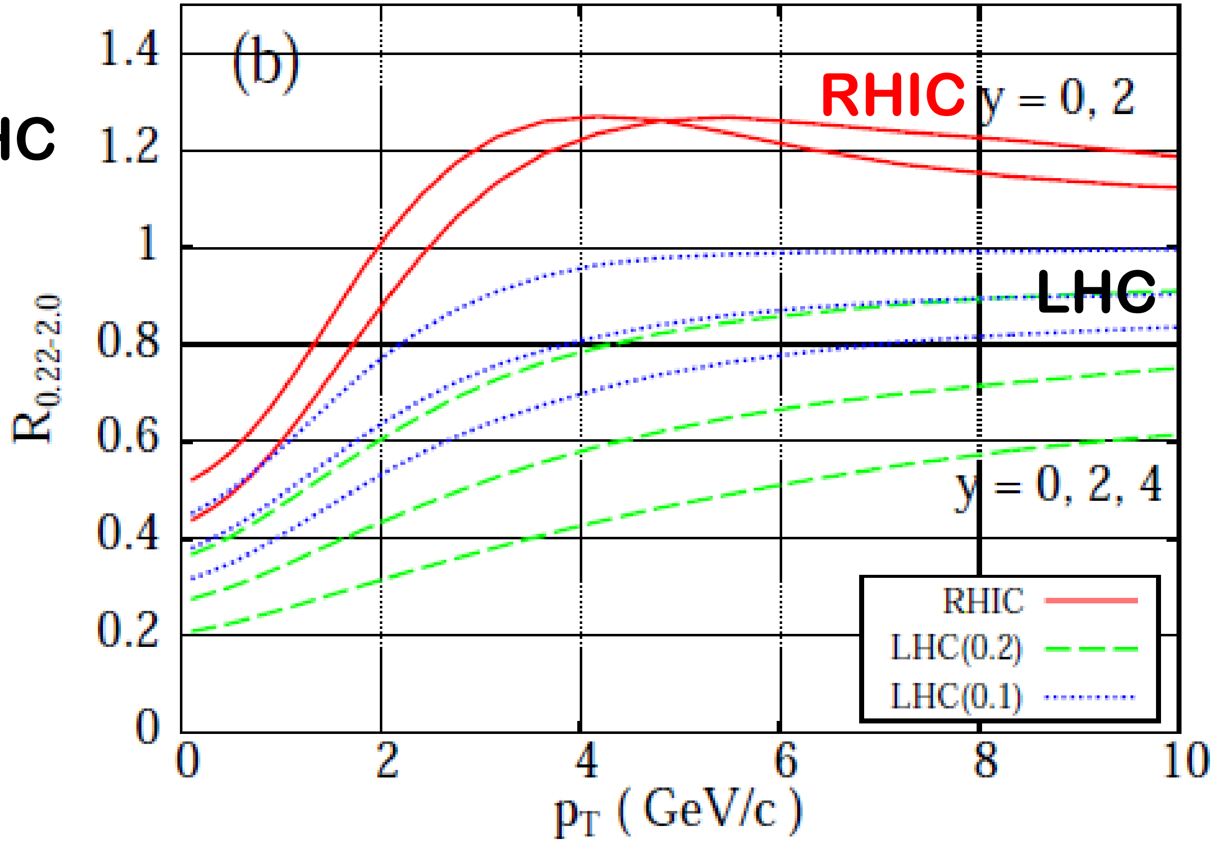
Open charm production

- **CGC** = uGDF for p & A ; **Hybrid** = uGDF for A and xG for p
  - Hard spectrum in medium- x region
  - Small-x contrib is small
  - Look forward



Open charm production

- Ratio of pA/pp
- Hybrid: R = "xG . uGDF(2.0)" / "xG . uGDF(0.22)"
  - Cronin enhancement @ RHIC
  - moves to higher pT w/ y
  - Large suppression @ LHC



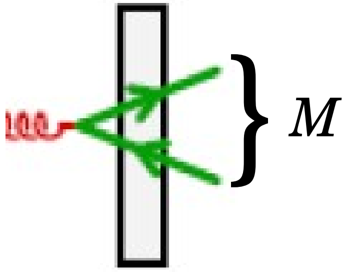
Charmonium

Charmonium in CEM

- **Color evaporation model:**

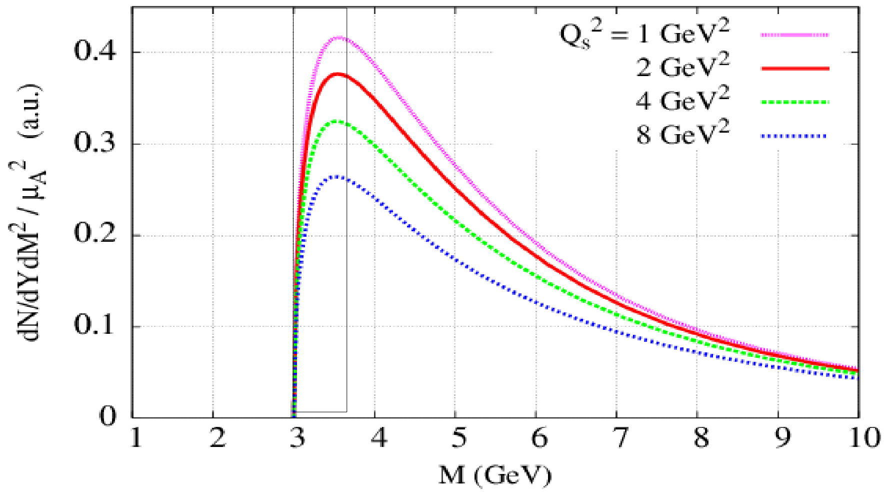
Assume separation of pair production and b.s. formations

$$\frac{dN_{J/\psi}}{dY d^2\boldsymbol{P}_\perp} \underset{CEM}{=} F_{J/\psi} \int_{4m^2}^{4m_D^2} dM^2 \frac{dN}{dY d^2\boldsymbol{P}_\perp dM^2}$$



- **Effects of dense gluons**
  - Initial gluon saturation
  - Multiple scatterings of cc pair

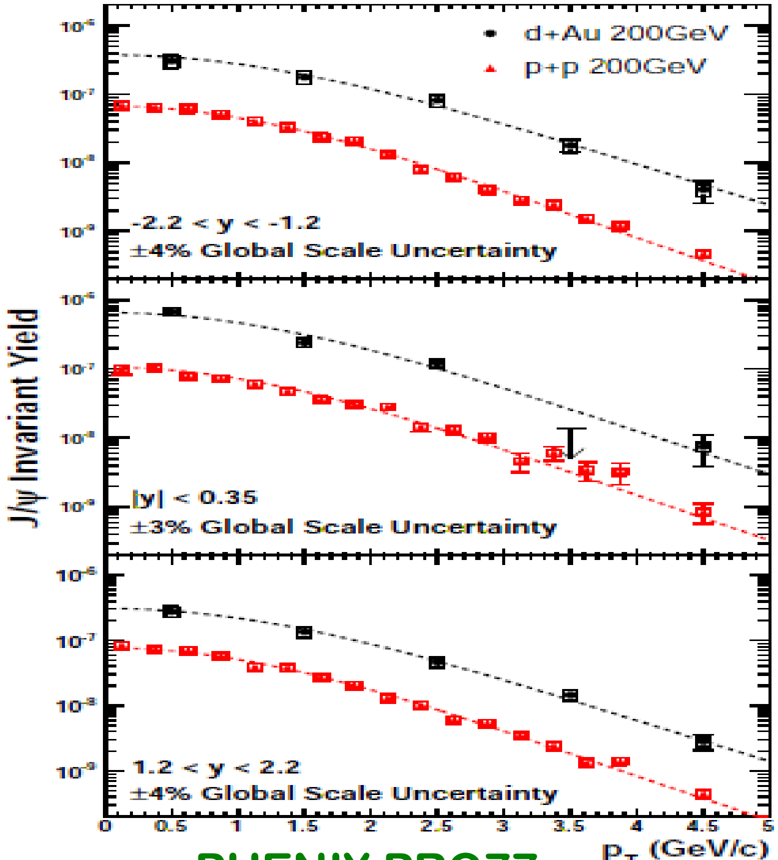
M-dist vs Qs2 (MV model)



Charmonium in CEM

- **Momentum distribution**
  - **Hardened too much**
  - **Difficulty of model?**

    hybrid=kT kick only from A or need improve medium-x?



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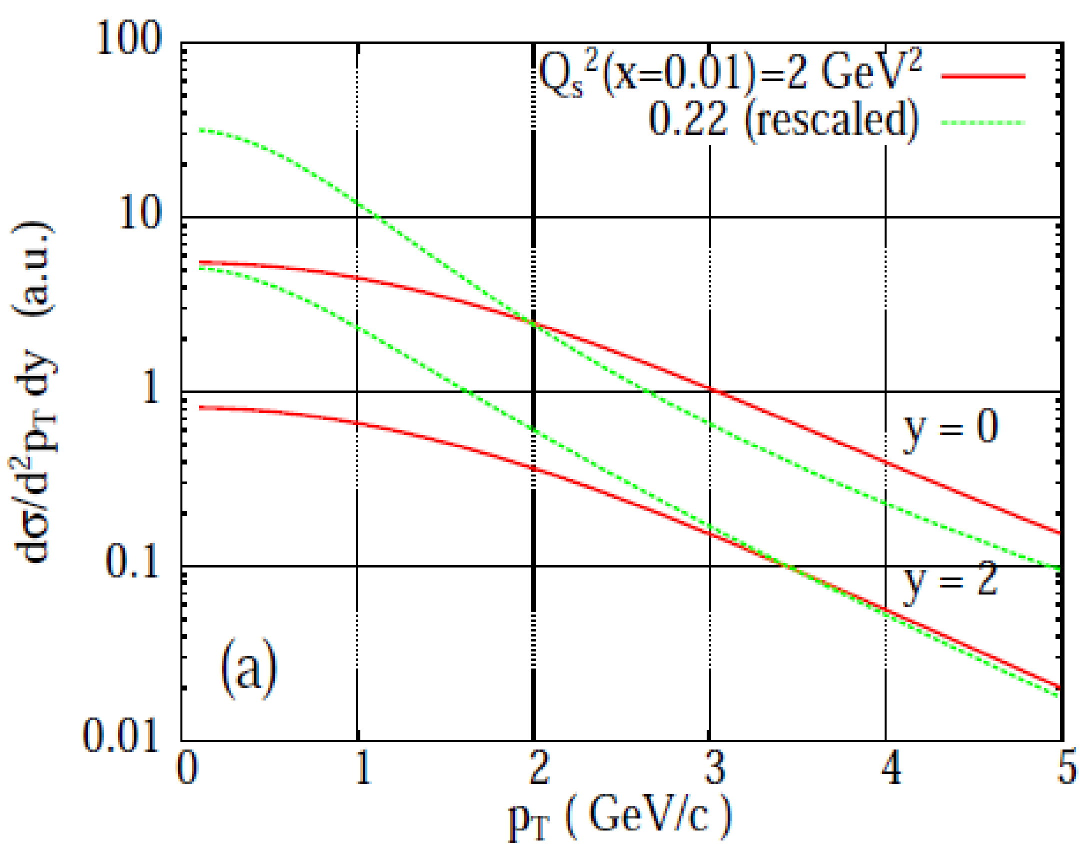
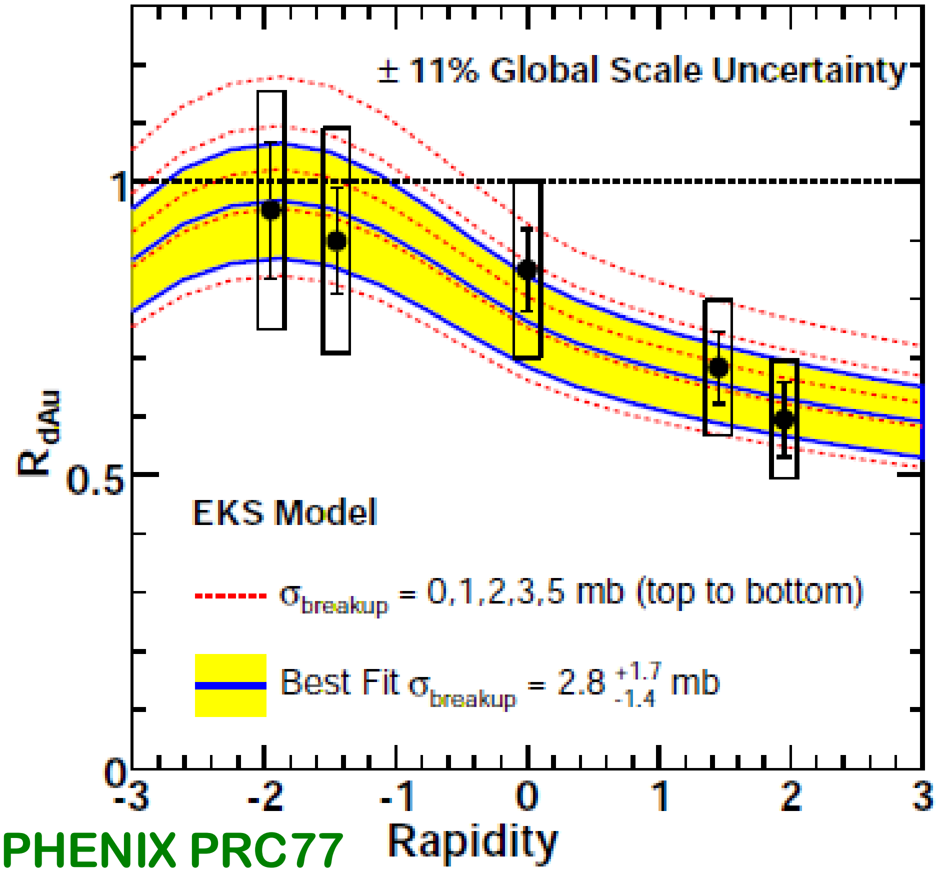


Charmonium in CEM

- **Rapidity dependence of RdA**



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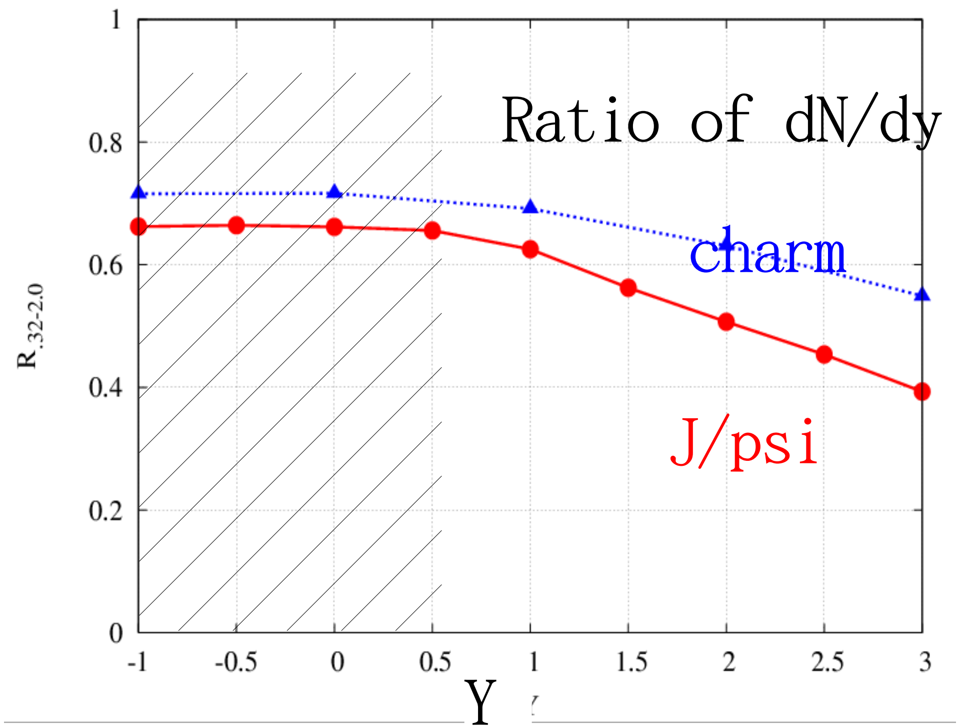

Summary and Discussion

- CGC model for cc production in pA is presented
  - LO(α_s), but O(ρ_A^∞)
  - Mid-rapidity at RHIC rather insensitive to small-x
    - Medium-x part is important
  - Saturation is reflected in forward rapidity
  - LHC will be best place to see the saturation
  - CGC model is still in primitive stage

Discussion

- More post-dictions and predictions
  - Improve the CGC model
    - medium-x pdf, onium formation, ..., etc
  - Centrality dep thru Qs(x,b)
  - AA at very forward y
  - Test the model; azimuthal correlation of cc
    - intrinsic kT & multiple scattering

Just preliminary