New Frontiers in QCD 2013
--- Insight into QCD matter from heavy-ion collisions ---

Heavy quarks from CGC in p+A collisions

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with K. Watanabe

HF and K. Watanabe NPA915 (2013) 1 [arXiv:1304.2221[hep-ph]]
NPA920 (2013) 78 [arXiv:1308.1258[hep-ph]]

Motivation

- Heavy quarks produced from gluons only in initial hard interactions
- Heavy quarks in pA collisions at the LHC
  - probe small-x gluons
  - crucial baseline for calibration of AA collisions

Outline

- Introduction:

  Gluon distribution at small x in CGC (rcBK)

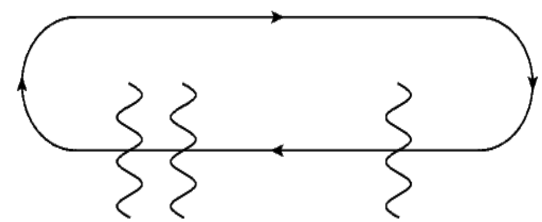
- Quark pair production in pA
  - quakonium
  - open charm

- Summary & Outlook

Gluon distribution at small x

- "Gluon distribution" is related to $1 - \mathcal{N}(r, y) = \frac{1}{N_c} \mathrm{tr} \left\langle \tilde{U}(r_1) \tilde{U}^\dagger(r_2) \right\rangle$

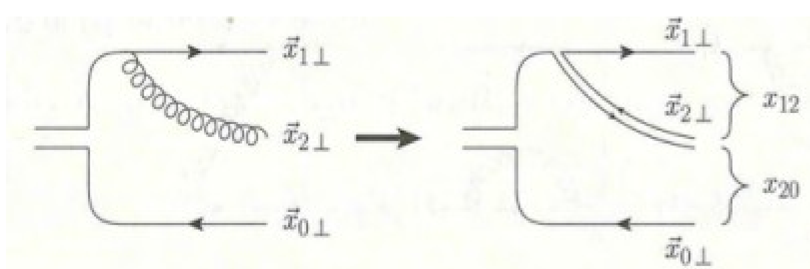
$$\phi(\boldsymbol{k}, y) \sim -\boldsymbol{k}^2 \mathrm{F.T.} \mathcal{N}(r, y)$$



- x-dependence is described by BK eqn in large N_c

Kovchegov-Weigert, Balitsky-Chirilli

$$\frac{\partial \mathcal{N}(r,y)}{\partial y} = \int d^2 \boldsymbol{r}_1 \, K^{\mathrm{run}} \left[\mathcal{N}(r_1, y) + \mathcal{N}(r_2, y) - \mathcal{N}(r, y) - \mathcal{N}(r_1, y) \mathcal{N}(r_2, y) \right]$$



Constraining N with DIS data (AAMQS)

Initial condition and evolution

$$\mathcal{N}_F(r, x=x_0) = 1 - \exp\left[-\frac{(r^2 Q^2_{s0,\mathrm{proton}})^\gamma}{4} \ln\left(\frac{1}{\Lambda r} + e\right)\right]$$

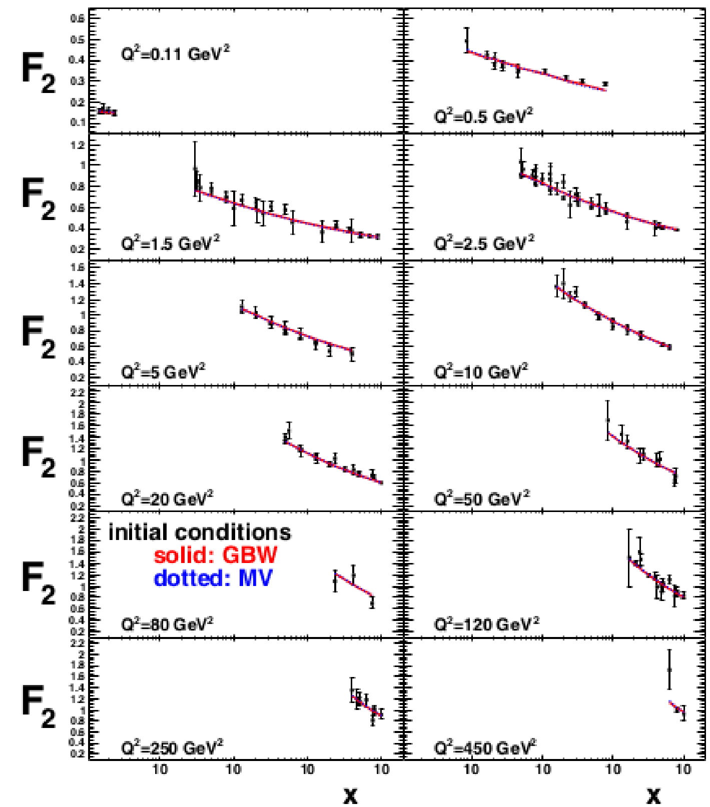
$$\alpha_s(r) = 1/[b_0 \ln(4C^2/r^2\Lambda^2 + a)]$$

other parametrization, Lappi et al.arXiv:1309.6963

Albacete et al. PRD80

Fit to HERA-DIS data

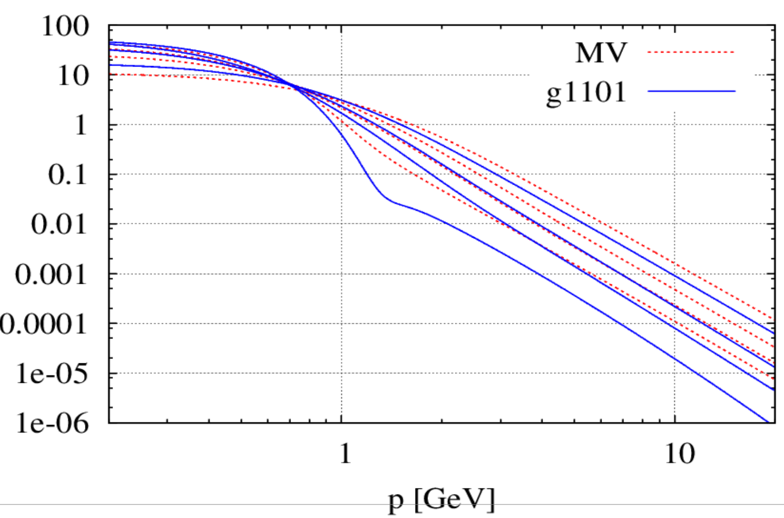
$$\sigma_{T,L}(x, Q^2) = \sigma_0 \int_0^1 dz \int d\mathbf{r} |\Psi_{T,L}(z, Q^2, \mathbf{r})|^2 \mathcal{N}(r, Y)$$



Parameter set

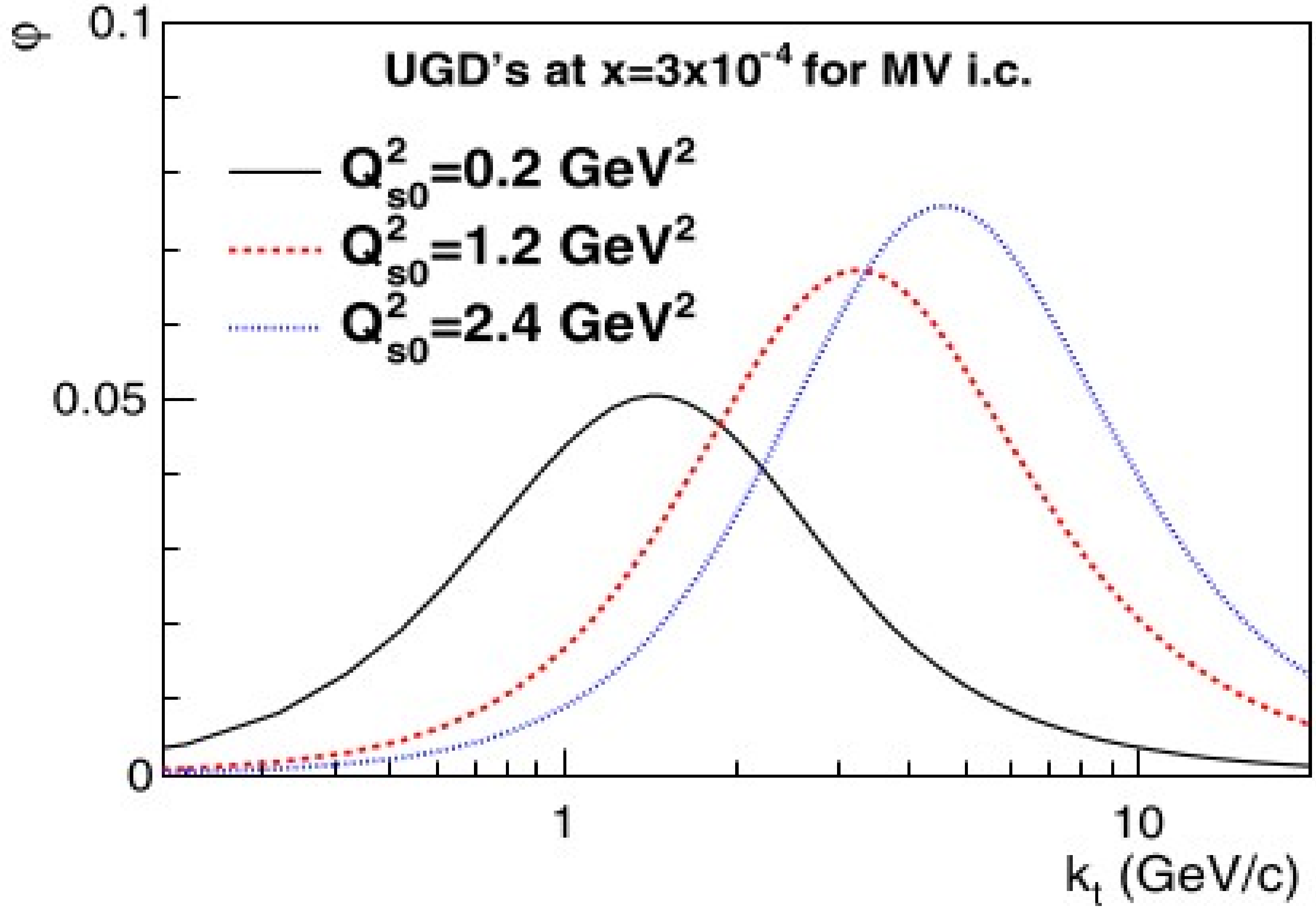
UGD Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ	α_{fr}	C
MV	0.2	1	0.5	1
g1.119	0.168	1.119	1.0	2.47
g1.101	0.157	1.101	0.8	1

N(k,y), y=0, 1.5, 3, 6



Gluon distributions for p and A

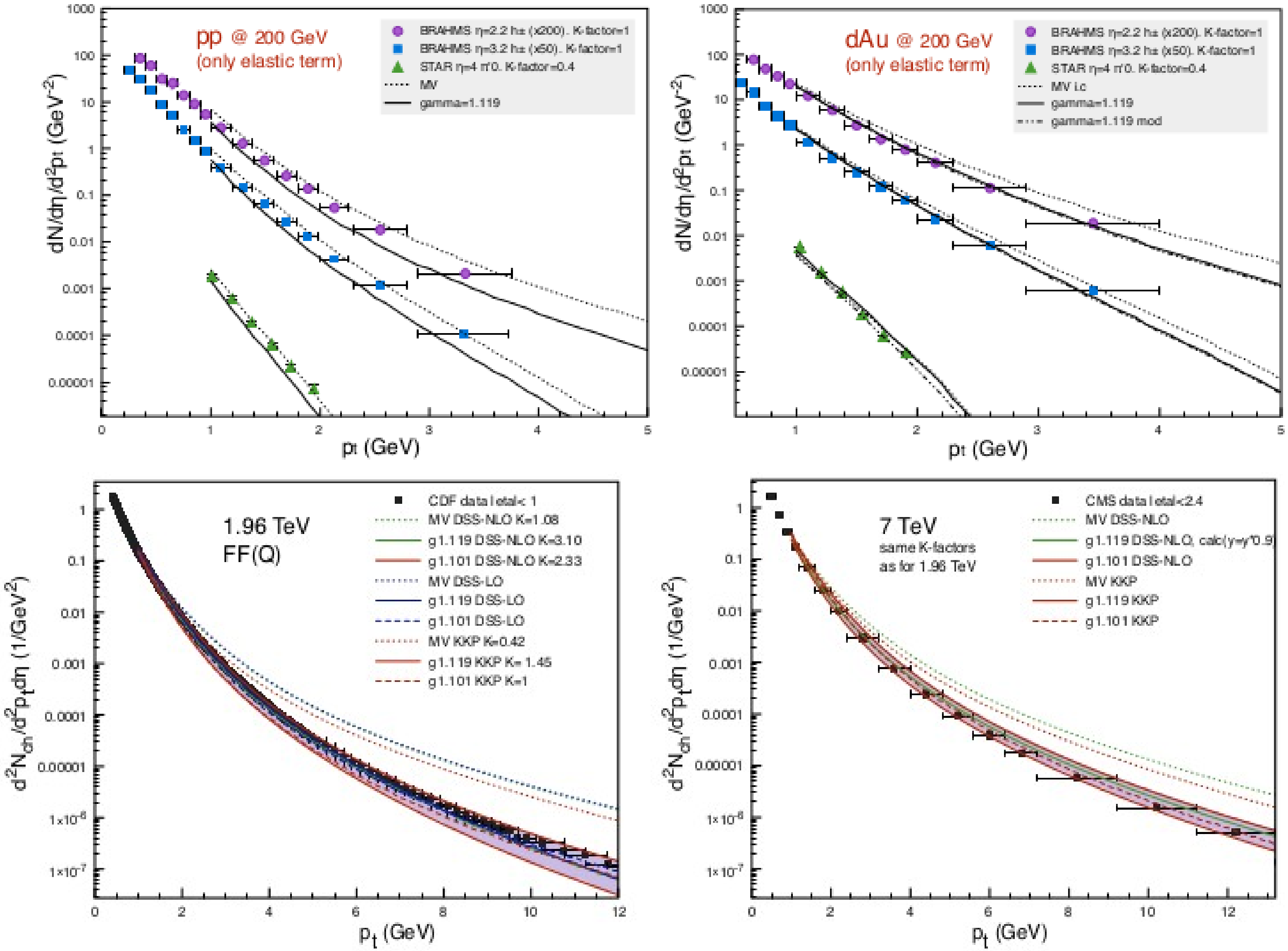
$Q_{sA}{}^2 = A^{1/3}\, Q_{sp}{}^2$
or MC



Hadron spectrum at RHIC, Tevatron, LHC

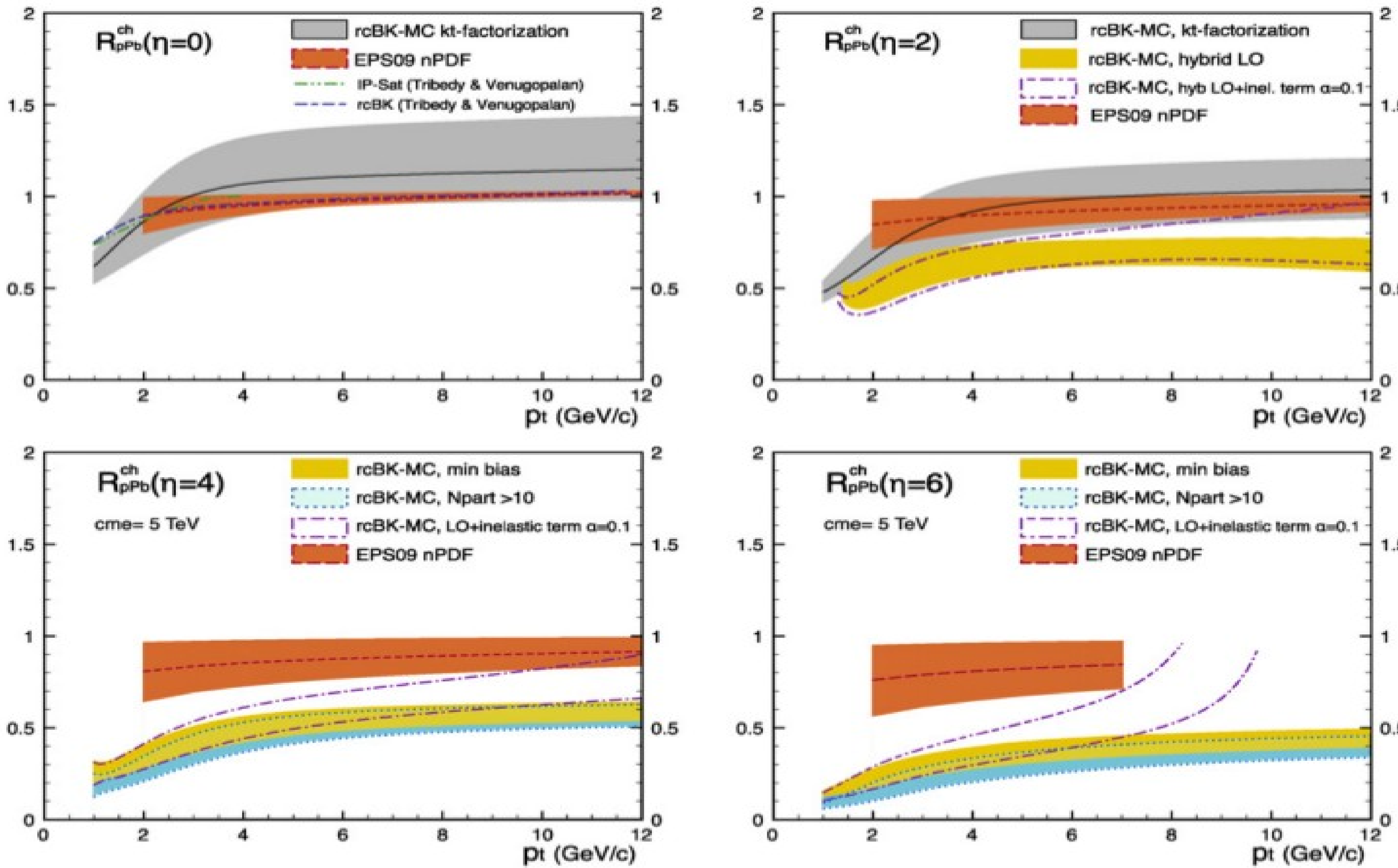
k_T factorization ($y\sim0$), DHJ ($y>0$) formulae

$Q_{sA}{}^2 = A^{1/3}\, Q_{sp}{}^2$
or MC



Albacete-Dumituru-HF-Nara, NPA897(2013)

RpA(pT) of single hadron at y=0,2,4,6 at the LHC



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- **Quark pair production in pA**
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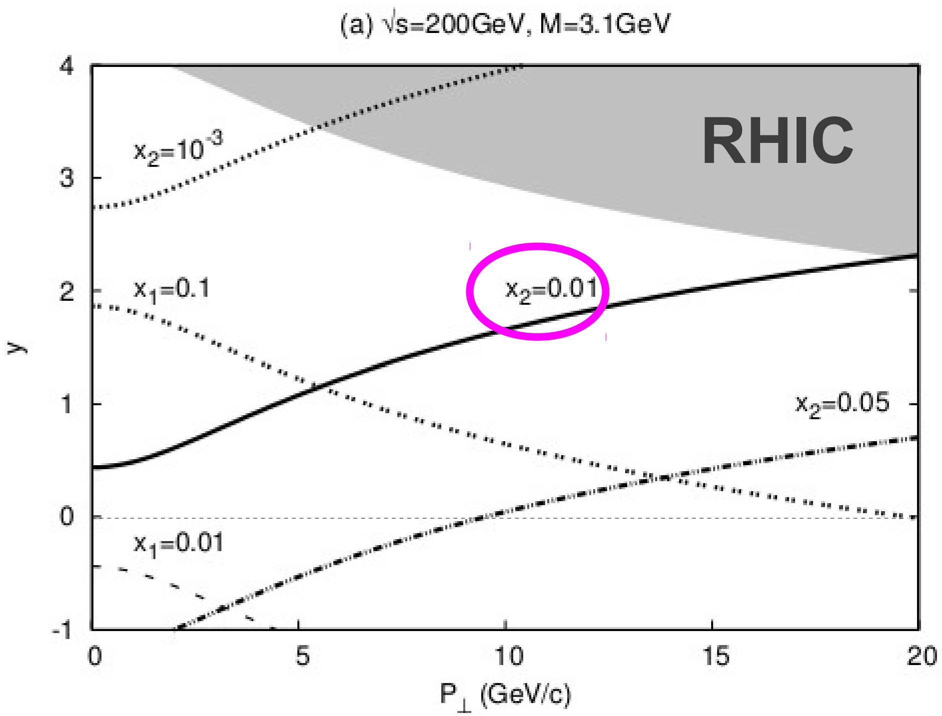
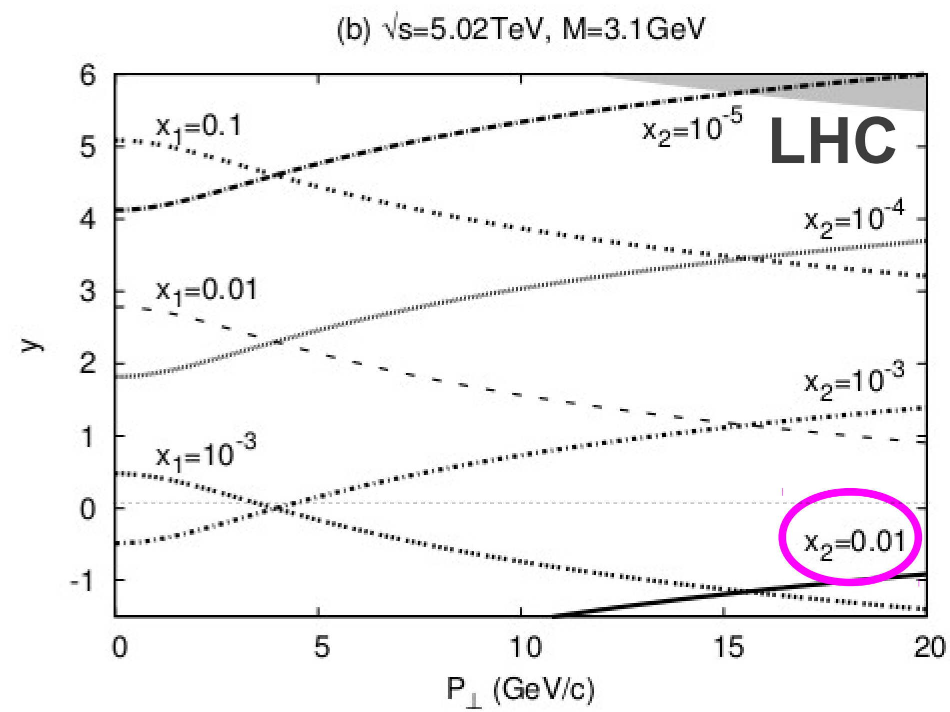
Heavy quarks sensitive small x?

- Quarkonium; gg --> J/ψ
- maybe at RHIC, while must be at the LHC



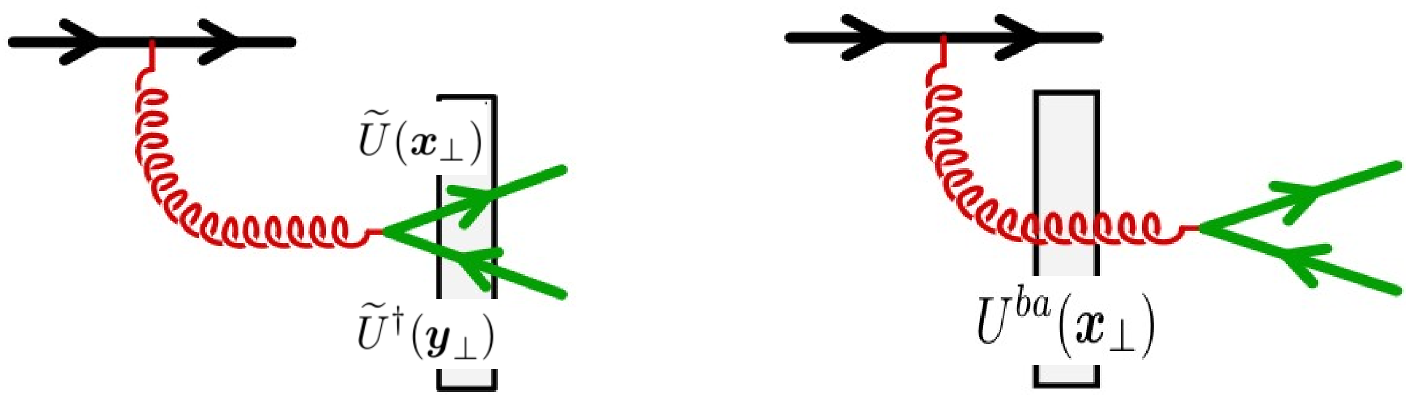


Quark pair production amplitude

Blaizot-Gelis-Venugopalan (2004)

$$\mathcal{M}_F(\boldsymbol{q},\boldsymbol{p}) = g^2 \int \frac{d^2\boldsymbol{k}_{1\perp}}{(2\pi)^2}\frac{d^2\boldsymbol{k}_{\perp}}{(2\pi)^2}\frac{\rho_{p,a}(\boldsymbol{k}_{1\perp})}{k_{1\perp}^2}\int d^2\boldsymbol{x}_\perp d^2\boldsymbol{y}_\perp e^{i\boldsymbol{k}_\perp\cdot\boldsymbol{x}_\perp} e^{i(\boldsymbol{p}_\perp+\boldsymbol{q}_\perp-\boldsymbol{k}_\perp-\boldsymbol{k}_{1\perp})\cdot\boldsymbol{y}_\perp}$$

$$\times\overline{u}(\boldsymbol{q})\left\{T_{q\bar{q}}(\boldsymbol{k}_{1\perp},\boldsymbol{k}_\perp)[\widetilde{U}(\boldsymbol{x}_\perp)t^a\widetilde{U}^\dagger(\boldsymbol{y}_\perp)] + T_g(\boldsymbol{k}_{1\perp})[t^b U^{ba}(\boldsymbol{x}_\perp)]\right\}v(\boldsymbol{p}) \; ,$$

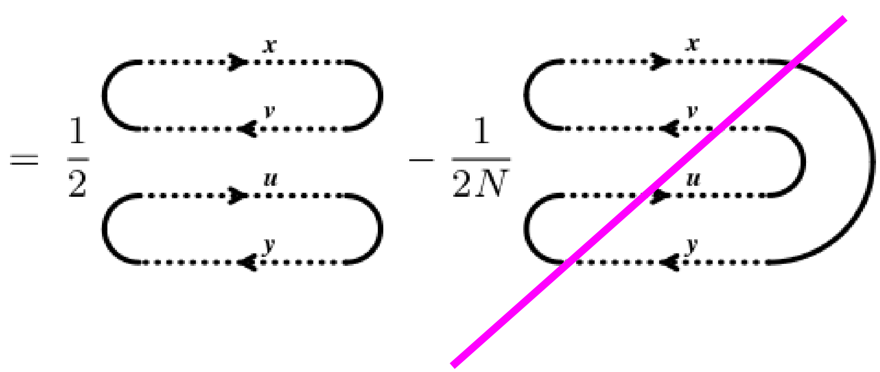


Cross-section in large N

$$\frac{dN_{q\bar{q}}}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2}\frac{\alpha_s^2 N}{8\pi^4 d_A}\frac{1}{(2\pi)^2}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp}\frac{\Xi(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2}\,\phi_{A,y_2}^{q\bar{q},g}(\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)\,\varphi_{p,y_1}(\boldsymbol{k}_{1\perp})$$

- Need 4-pt function (kT fact breaking)
- but, in large N limit, it reduces to a product of dipole amplitudes

$$C(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp;\boldsymbol{u}_\perp,\boldsymbol{v}_\perp) \equiv \mathrm{tr_c}\langle \widetilde{U}(\boldsymbol{x}_\perp)t^a\widetilde{U}^\dagger(\boldsymbol{y}_\perp)\widetilde{U}(\boldsymbol{u}_\perp)t^a\widetilde{U}^\dagger(\boldsymbol{v}_\perp)\rangle$$



Quarkonium in Color Evaporation Model (CEM)

$$\frac{dN_{\mathrm{J}/\psi}}{d^2\boldsymbol{P}_\perp\, dy} = F_{\mathrm{J}/\psi} \int_{4m_c^2}^{4M_D^2} dM^2 \, \frac{dN_{c\bar{c}}}{d^2\boldsymbol{P}_\perp\, dM^2\, dy}$$

- Assumption:

  Pair bounds to J/psi non-perturbatively, irrespective of its color, outside the nucleus

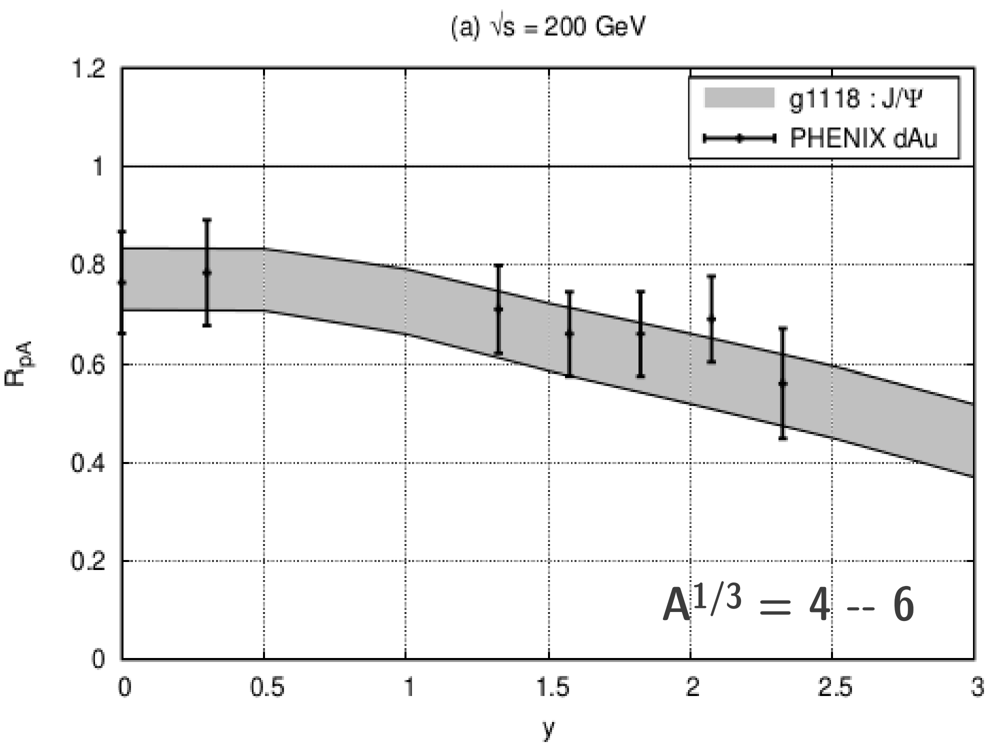
- Cold Nuclear Effect = Initial gluon saturation + multiple scatterings of pair

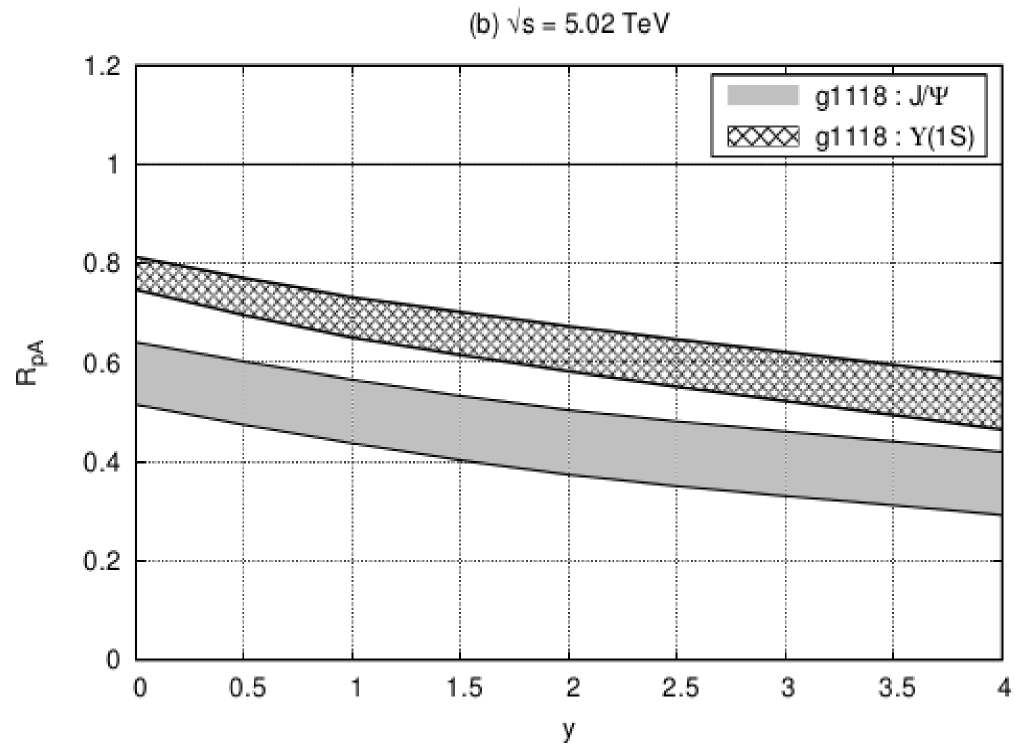
- Open charm production is evaluated with Fragmentation Func

RpA(y) for J/psi at RHIC & LHC

$$R_{\mathrm{pA}} = \frac{dN_{\mathrm{J}/\psi}/d^2P_\perp\, dy|_{\mathrm{pA}}}{N_{\mathrm{coll}}\, dN_{\mathrm{J}/\psi}/d^2P_\perp\, dy|_{\mathrm{pp}}} \qquad N_{\mathrm{coll}} = A^{\gamma/3}$$

- expect stronger suppression at LHC than at RHIC

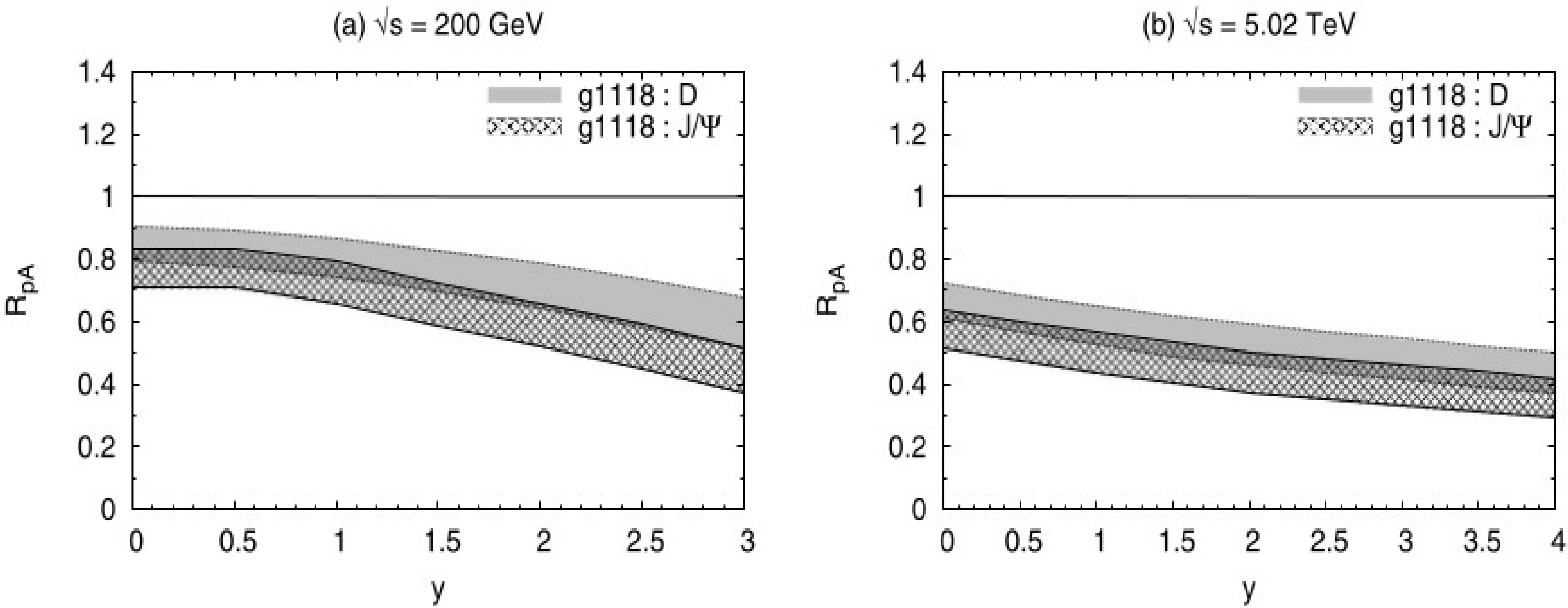




HF, Watanabe, NPA915,1, 2013

Comparison: quarkonium vs open charm

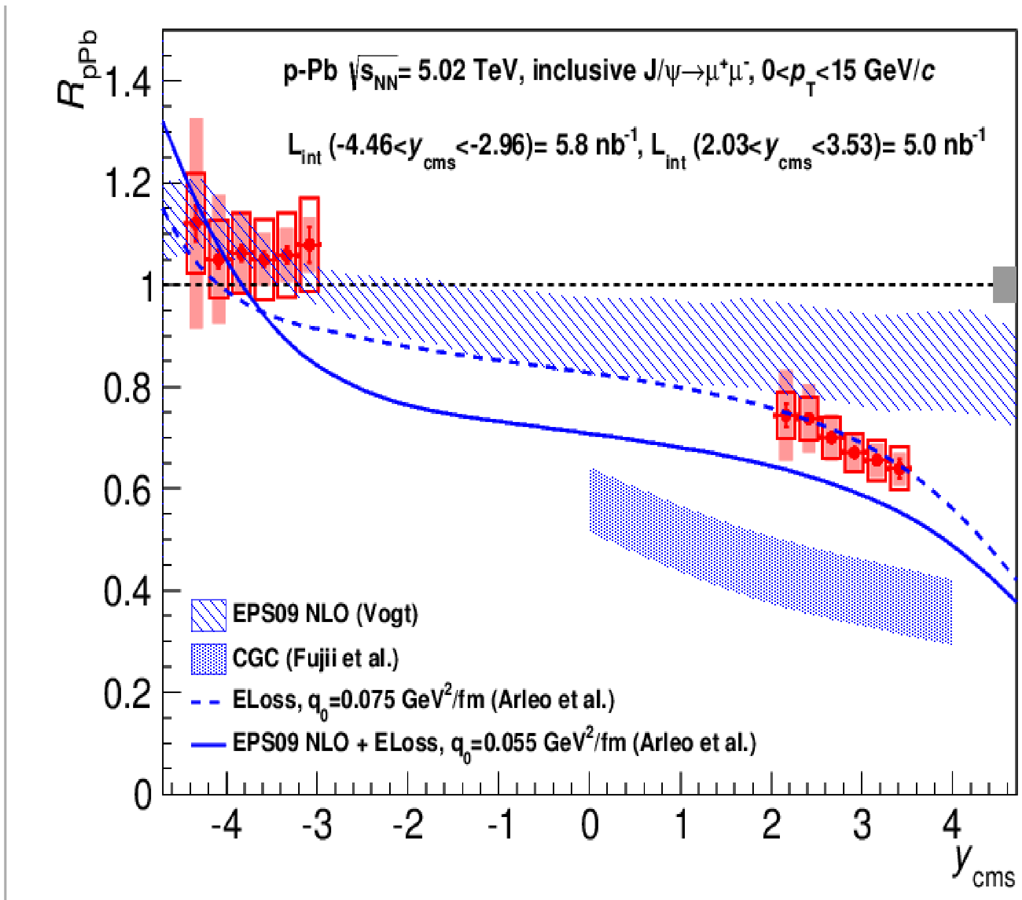
- Saturation is stronger at forward rapidity (smaller x)
- Multiple scattering increases the pair's invariant mass, which more suppresses quarkonium formation in CEM



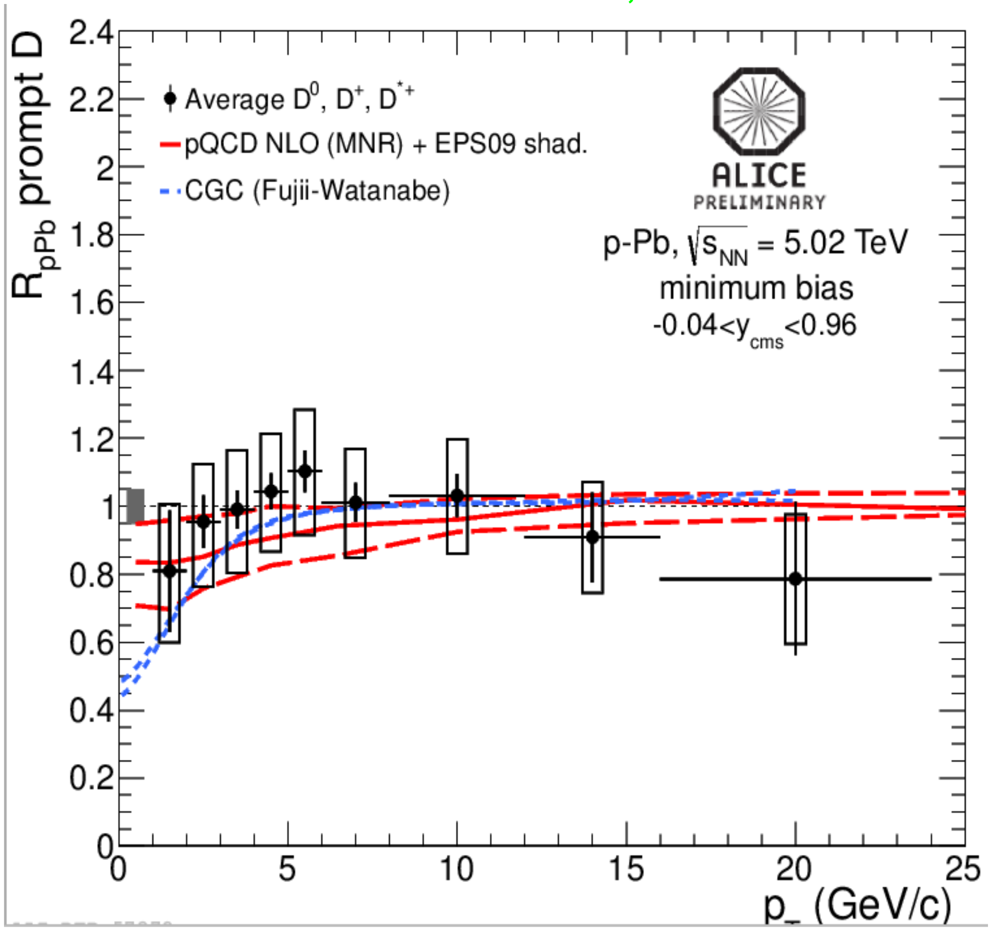
HF, Watanabe, NPA920 (2013)

Comparison with data

ALICE, 1308.6726



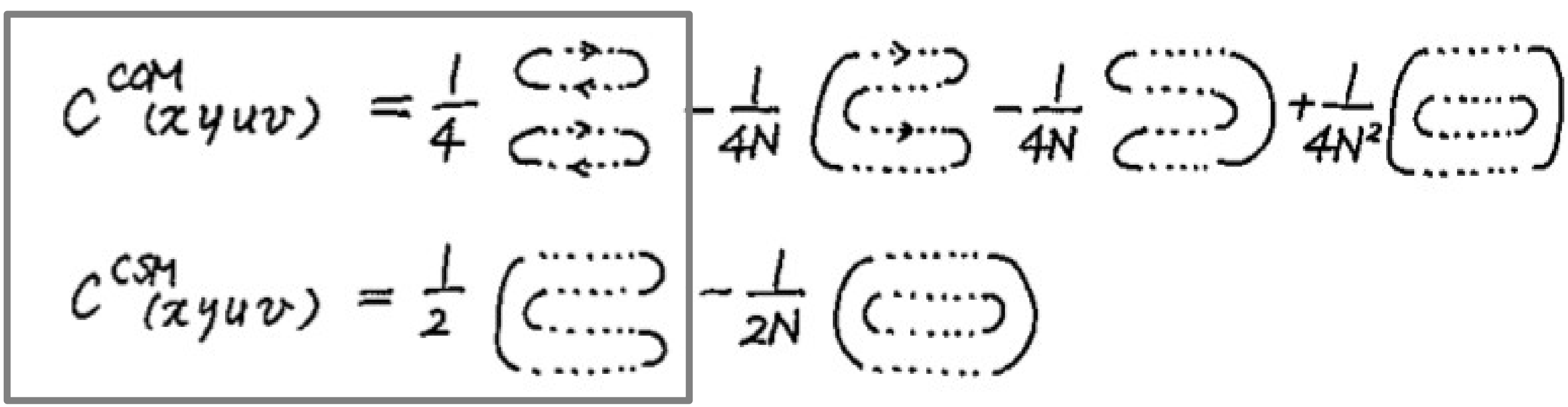
ALICE, 1310.1714



Hadronization mechanism

- Octet and/or Singlet?
  - COM correlator dominates in CEM in large N
  - CSM picks up a new type of 4pt correlation
  - NRQCD provides a systematic framework

Kang et al, 1309.7337
Qiu et al, 1310.2230
HF-Watanabe, work in progress



Summary & outlook

- QQbar production is expressed with known gluon distribution, constrained by rcBK phenomenology
- J/psi & D productions are obtained by CEM & FF
- RpA of J/psi is over-suppressed than ALICE data
- RpA of D is almost consistent with data
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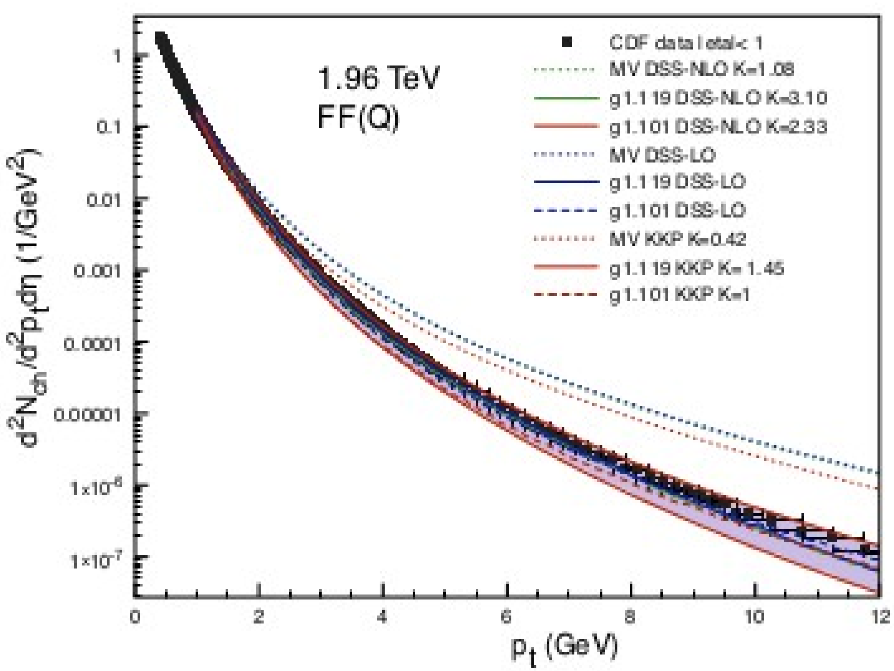
Summary & outlook

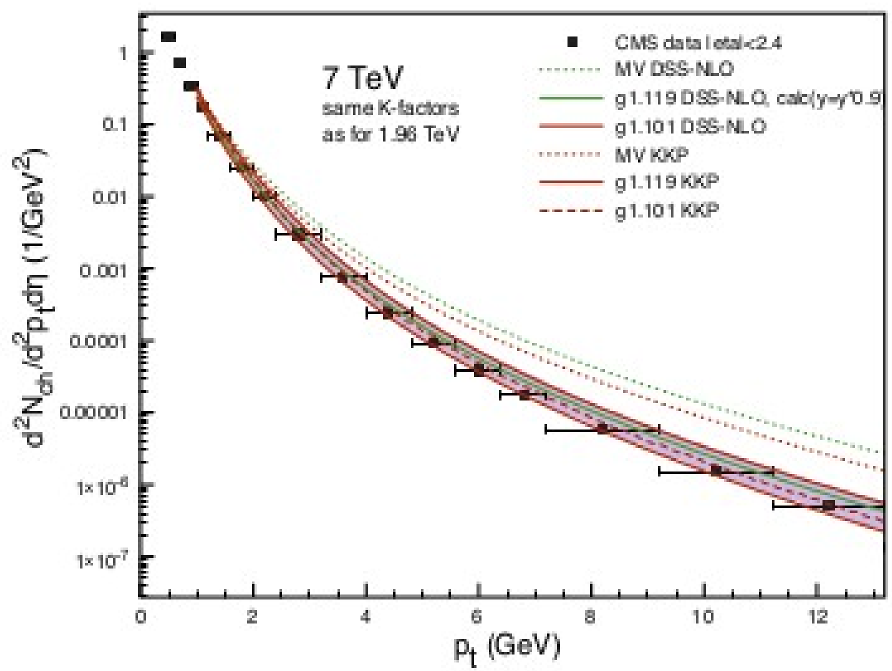
- QQbar production is expressed with known gluon distribution, constrained by rcBK phenomenology
- J/psi & D productions are obtained by CEM & FF
- RpA of J/psi is over-suppressed than ALICE data
- RpA of D is almost consistent with data
- Outlook
  - LHC gives new information on J/psi production process
  - CGC+NRQCD; needs new 4pt gluon correlator
  - NLO?

See Bowen's talk for NLO factorization in single hadron production

Hadron spectrum at pp colliders

- **kT-factorized formula**
  - **Normalized at pT=1 GeV for sqrt(s)=1.96 TeV**
  - uGD set ($\gamma \sim 1.1$) **describes energy and pt dependences**





dN/dy in p-Pb collisions

ALICE:
Phys.Rev.Lett. 110 (2013) 032301

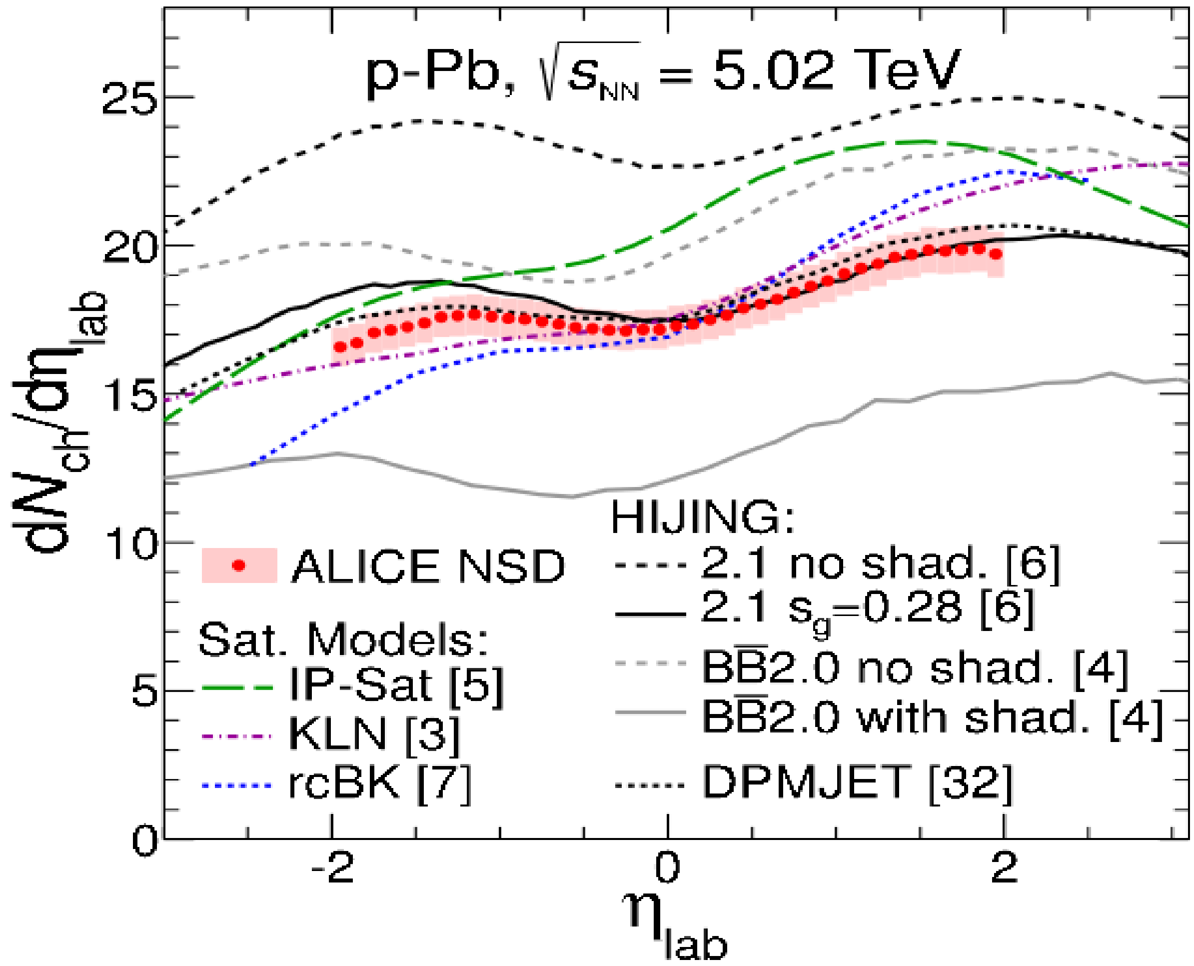


Fig. 1: Pseudorapidity density of charged particles measured in NSD p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV compared to theoretical predictions [3–7]. The calculations [4, 5] have been shifted to the laboratory system.

Hadron production

- **INPUT: gluon dist from rcBK in large Nc**

  $\phi(k,y) \sim k^2 N_A(k,y)$, $1-N_A = (1-N_F)^2$

- **kT-factorization for small x1,2 (y ~ 0)**

$$\frac{d\sigma^{A+B\to g}}{dy\, d^2p_t\, d^2R} = K^k \frac{2}{C_F} \frac{1}{p_t^2} \int^{p_t} \frac{d^2k_t}{4} \times \int d^2b\, \alpha_s(Q) \varphi_P\left(\frac{|p_t+k_t|}{2}, x_1; b\right) \varphi_T\left(\frac{|p_t-k_t|}{2}, x_2; R-b\right)$$

- **DHJ *hybrid* formula for small x2 for y > 0**

$$\left[\frac{dN_h}{d\eta\, d^2k}\right]_{\rm el} = \frac{1}{(2\pi)^2} \int_{x_F}^{1} \frac{dz}{z^2} \left[\sum_q x_1 f_{q/p}(x_1, Q^2) \tilde{N}_F\left(x_2, \frac{k}{z}\right) D_{h/q}(z, Q^2) + x_1 f_{g/p}(x_1, Q^2) \tilde{N}_A\left(x_2, \frac{k}{z}\right) D_{h/g}(z, Q^2)\right],$$

Dumitru-Hayashigaki-Jalilian-Marian,
Nucl. Phys. A 765, 464 (2006).

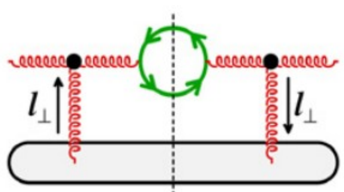
Quark pair production in pA

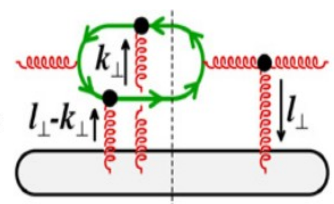
- Formula at $O(\rho_p\ \rho_A^{\infty})$ in large Nc limit

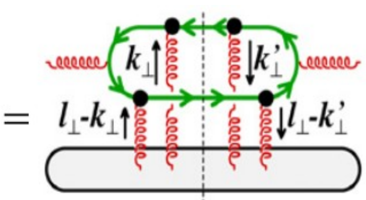
$$\frac{dN_{q\bar{q}}}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2}\frac{\alpha_s^2 N}{8\pi^4 d_A}\frac{1}{(2\pi)^2}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp}\frac{\Xi(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2}\ \phi_{A,y_2}^{q\bar{q},g}(\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)\ \varphi_{p,y_1}(\boldsymbol{k}_{1\perp})$$

Gelis-Blaizot-Venugopalan
HF-Gelis-Venugopalan

- Pair production --> multi-parton correlators

$\phi_A^{g,g}(\boldsymbol{l}_\perp) =$ 

$\phi_A^{q\bar{q},g}(\boldsymbol{l}_\perp;\boldsymbol{k}_\perp) =$ 

$\phi_A^{q\bar{q},q\bar{q}}(\boldsymbol{l}_\perp;\boldsymbol{k}_\perp,\boldsymbol{k}'_\perp) =$ 

- 4-pt & 3-pt functions simplify to a product of fundamental 2-pt funs in large Nc limit