Gluon saturation and heavy flavors in p+A collisions at the LHC

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in collaboration with
K. Watanabe (heavy quarks)
J. Albacete, A. Dumitru, Y. Nara (rcBK phenom)
T. Deng, K. Itakura, Y. Nara (event gen)

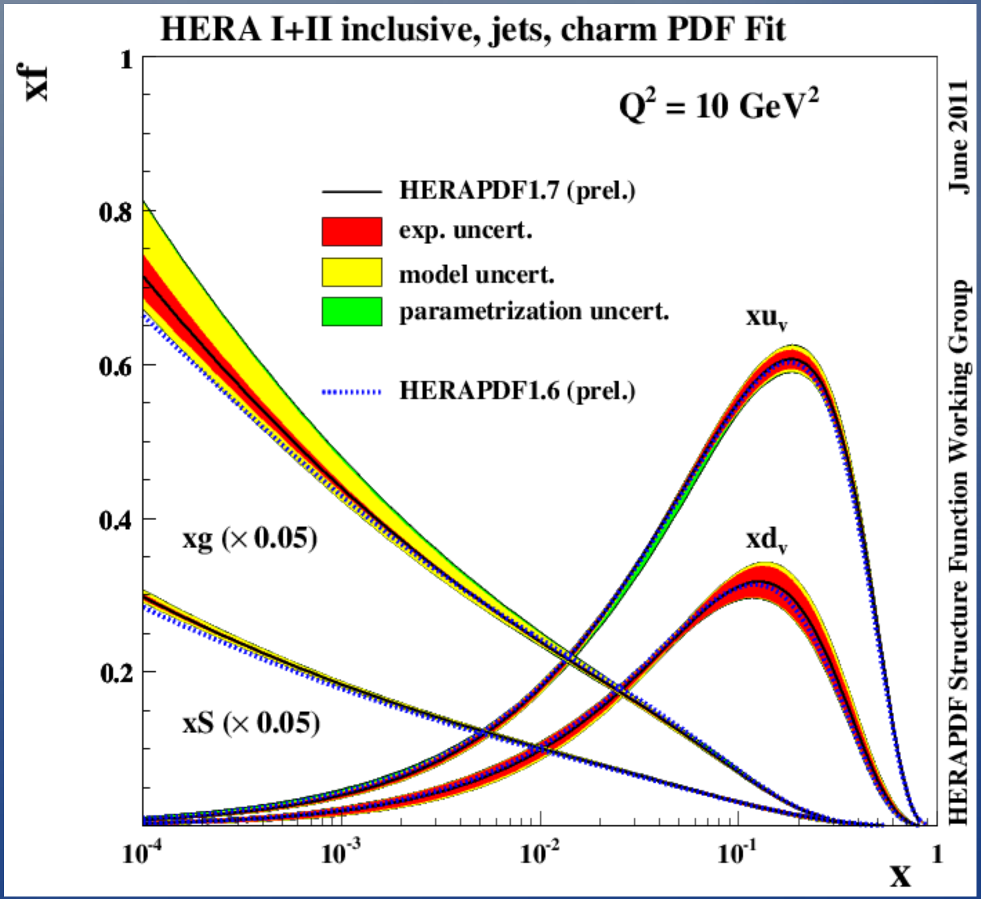
H.F and K. Watanabe, arXiv:1304.2221 [hep-ph]
J. Albacete, A. Dumitru, HF, Y. Nara, NPA897(2013)1

outline

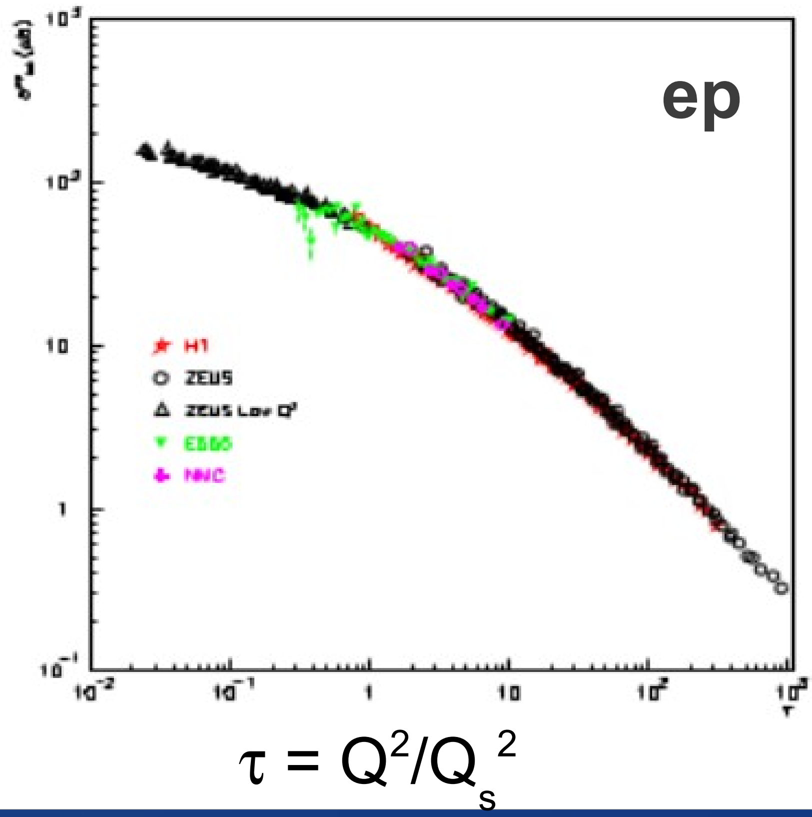
- Introduction
- rcBK phenomenology (review)
- Quarkonium
- Open heavy flavor (preliminary)
- Summary

Dense gluon and new scale

- Gluon number xG(x, Q) increases at small x
- A new scale, Qs^2, emerges

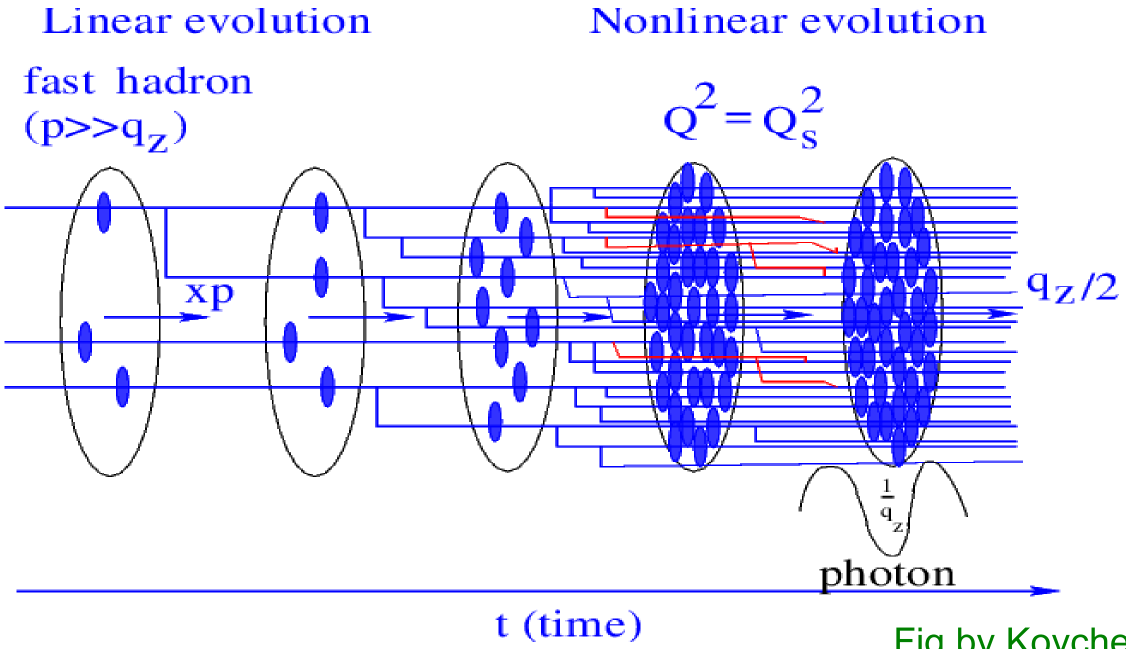


Stasto, Geloc-Bienat, Kwiecinski
PRL 86 (2001) 596



Intuitive picture of saturation

- The higher the energy is, the more partons join in color sources
- Recombination becomes important when $\boxed{Q_s^2(x) \sim \alpha_s \cdot \frac{xG(x,Q_s^2)}{\pi R_h^2}}$
- Qs^2 is enhanced by $A^{1/3}$ in a nucleus A
- Functional formulation: **JIMWLK eqn.**



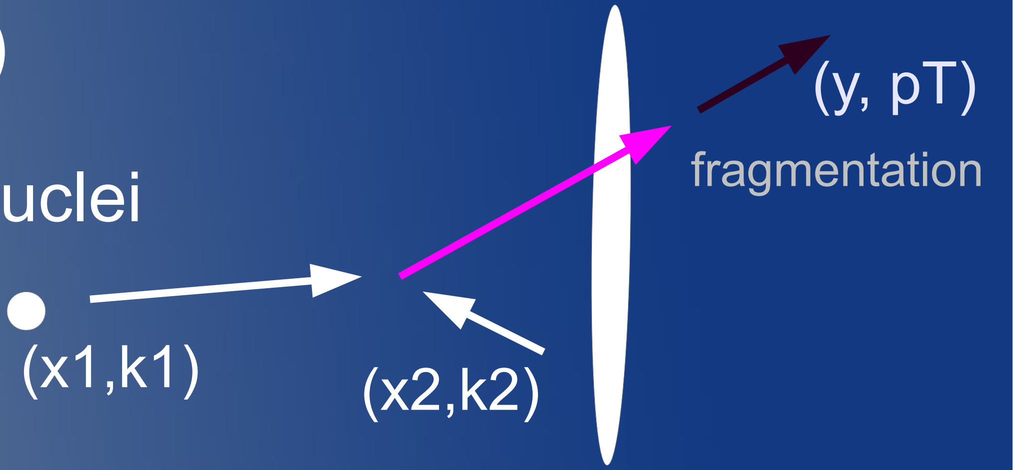
Phase space density

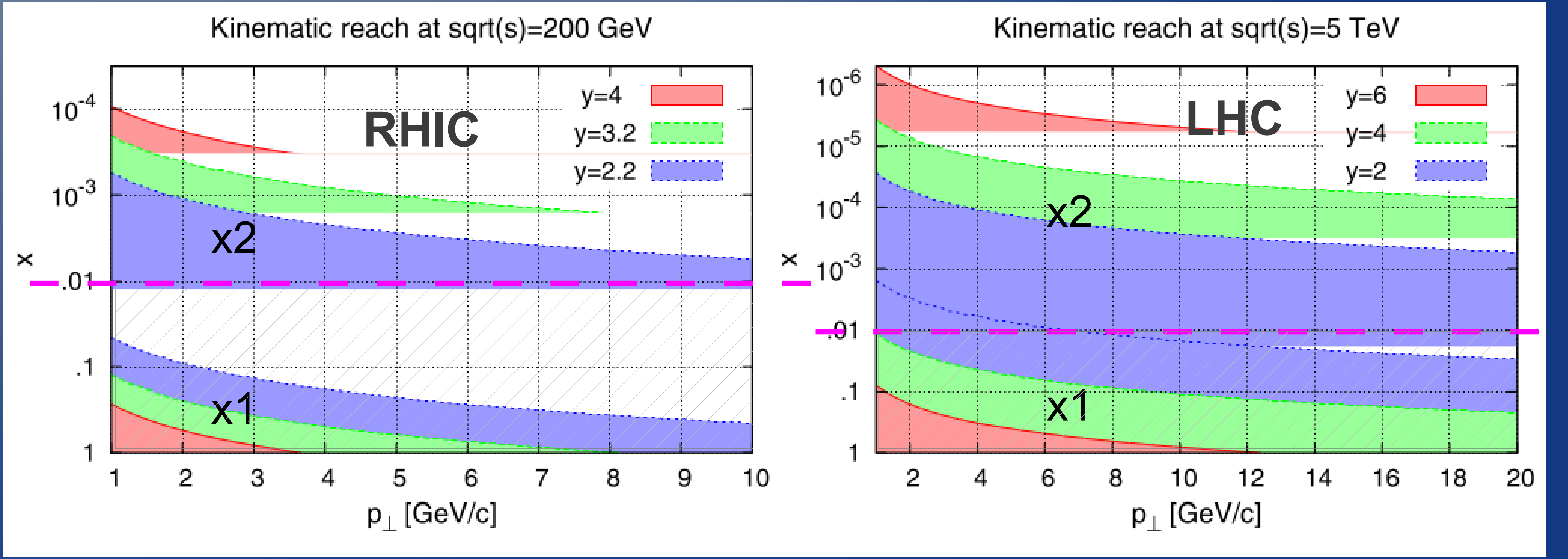
$$\frac{dN}{d^2r d^2p} \sim \frac{xG(x,Q_s^2)}{\pi R_h^2 Q_s^2(x)} \sim \frac{1}{\alpha_s}$$

Fig by Kovchegov-Levin

Kinetic coverage in pA at colliders

- $x_{1,2}$ ~ pT / sqrt(s) exp(+-y)
- assume “small” $x<x_0=0.01$ for nuclei





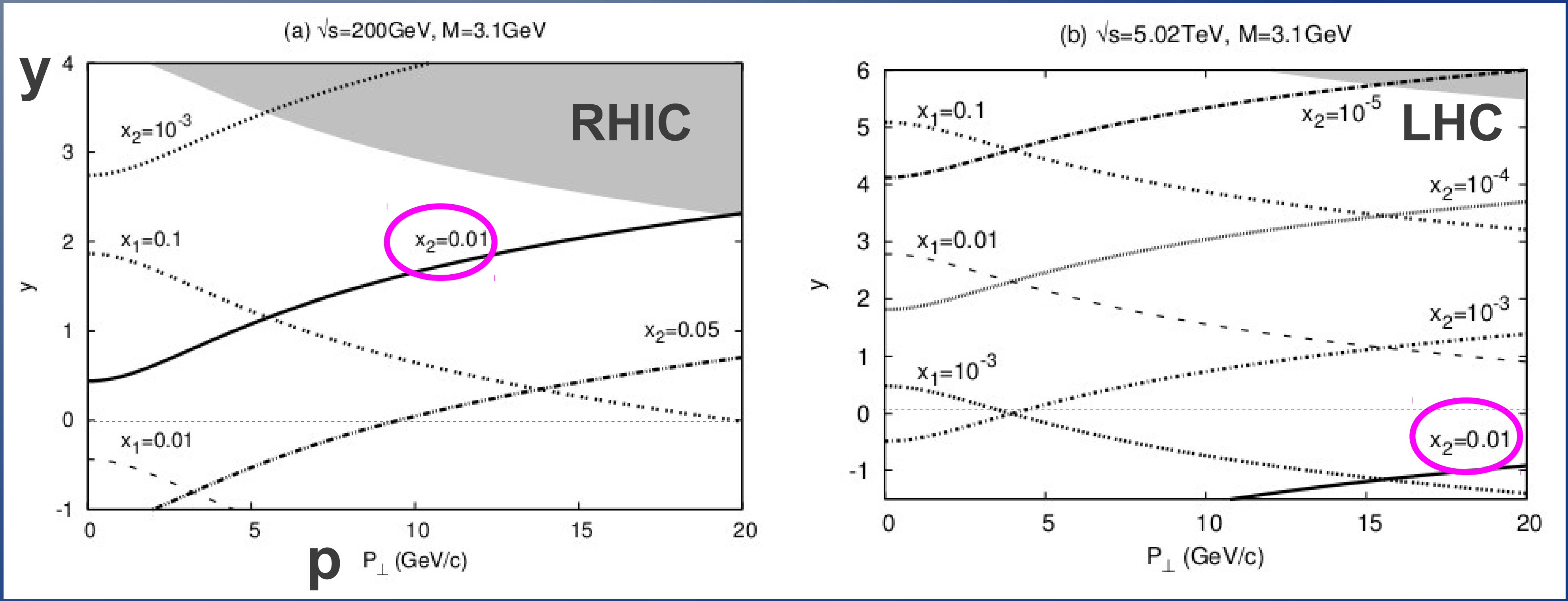
Aim of this work

- Take the rcBK eqn as a phenomenology tool, we evaluate saturation effects on heavy flavor observables in pA collisions

- Strategy:
  - take available particle production formulas in CGC framework (LO in α_s)
  - use numerical sol of rcBK for gluon dist. to improve energy (x-) dependence

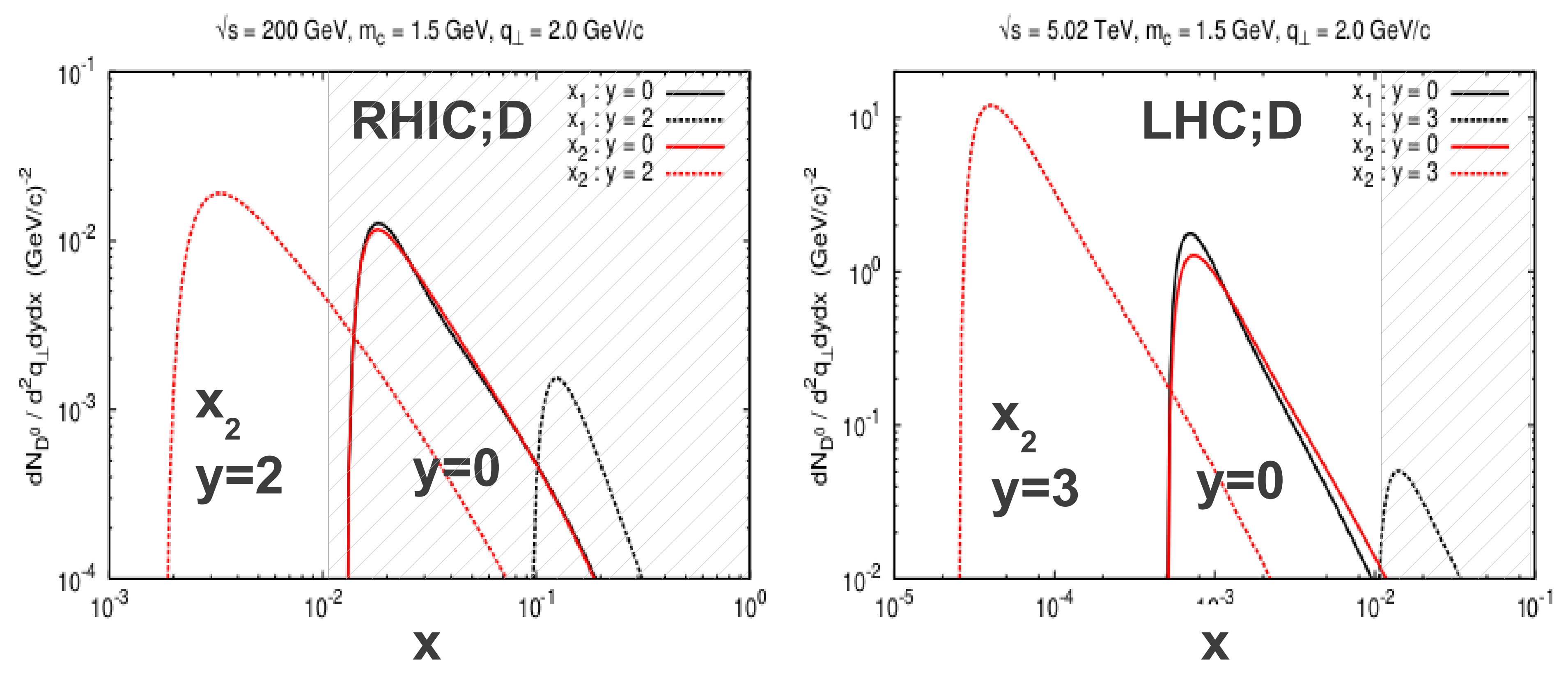
Heavy quarks are sensitive?

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



How about open heavy flavors ?

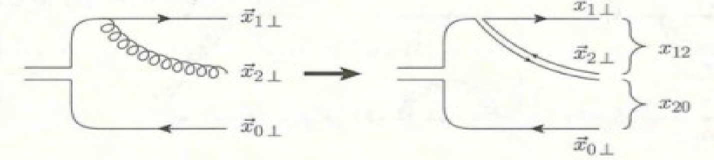
- c --> D
- at qT = 2 GeV



rcBK phenomenology

rcBK phenomenology

- In large N_c limit, evolution of dipole is closed

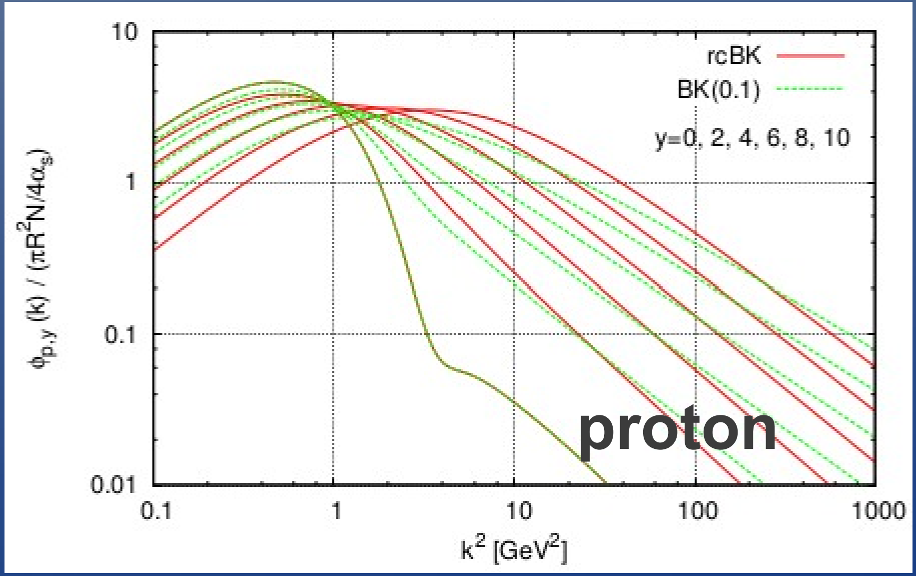


- BK eqn with running coupling in Balitsky's pres.

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

Evolution example

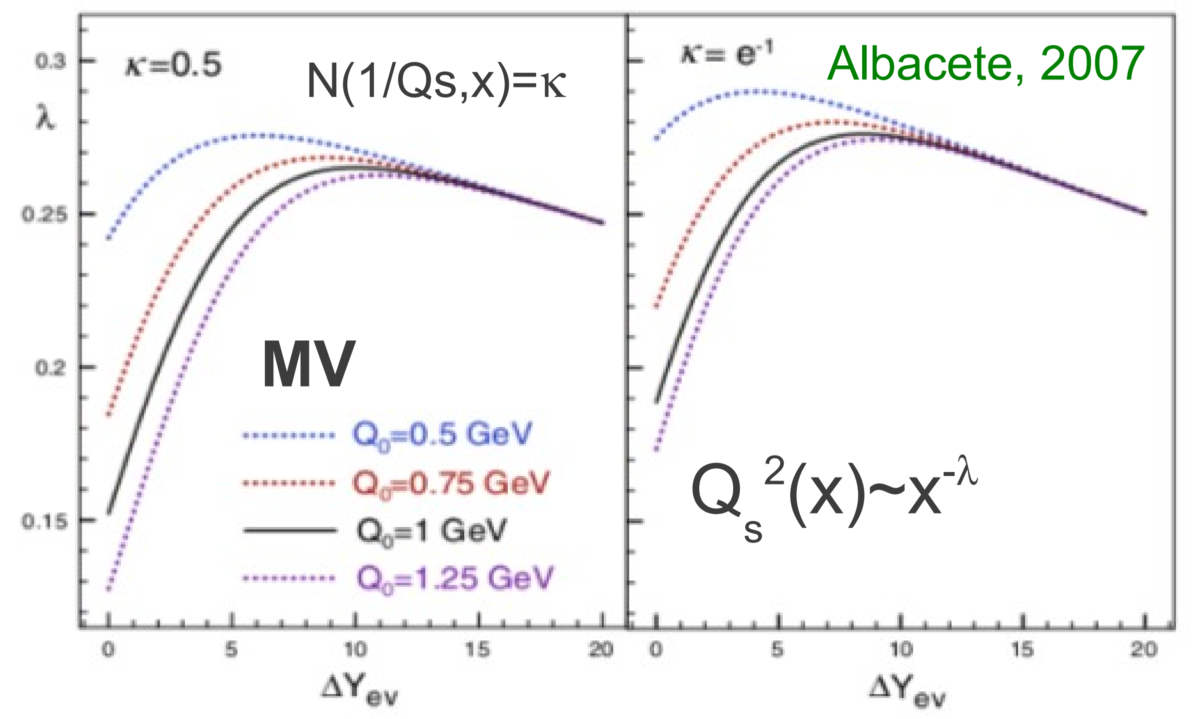
Kovchegov-Weigert (07), Balitsky-Chirilli (09)



rcBK phenomenology

- In large N_c limit, evolution of dipole is closed
- BK eqn with running coupling in Balitsky's pres.

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



$N(1/Qs,x)=\kappa$

Albacete, 2007

MV

$Q_s^2(x) \sim x^{-\lambda}$

Constraining uGD with DIS data

Initial condition and evolution

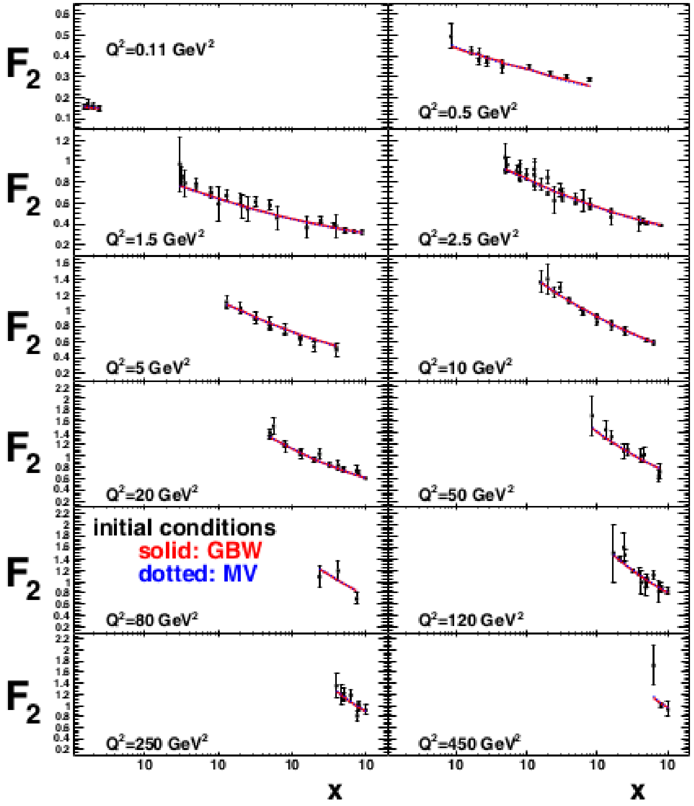
Albacete et al. PRD80

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

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

Fit to HERA-DIS data

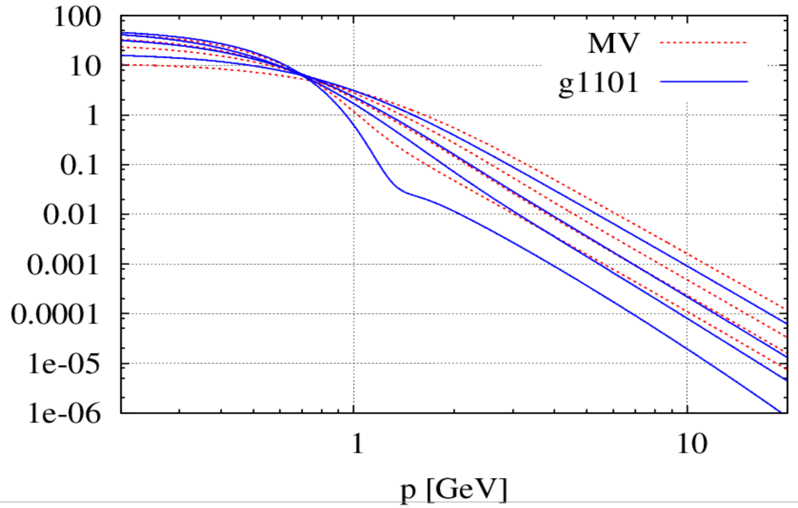
$$\sigma_{T,L}(x, Q^2) = \sigma_0 \int_0^1 dz \int d\mathbf{r} |\Psi_{T,L}(z, Q^2, \mathbf{r})|^2 \mathcal{N}(r, Y),$$



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

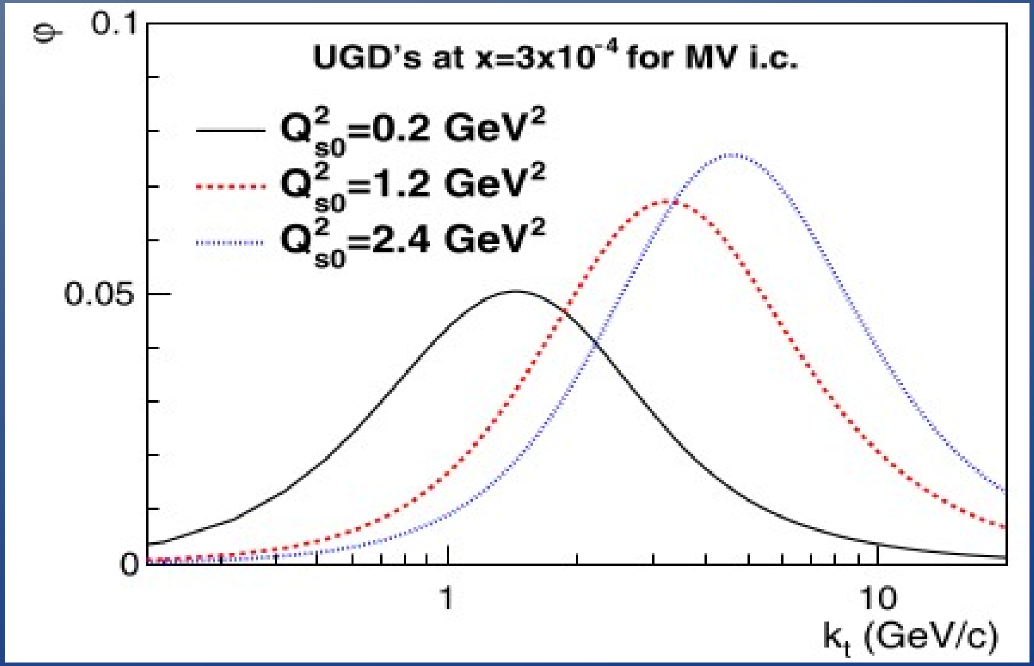
N(k,y), y=0, 1.5, 3, 6

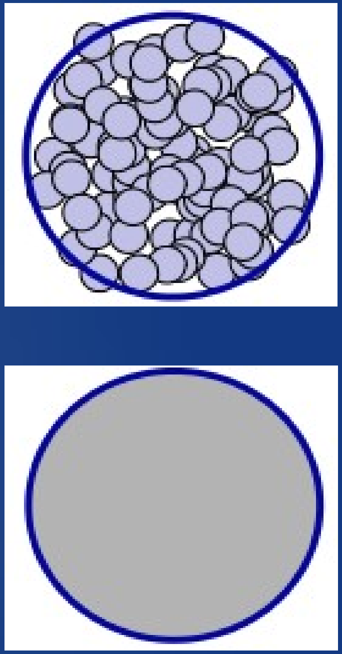


Modeling of nuclear target

$$Q_{s0A}^{2} = A^{1/3}\, Q_{s0}^{2}$$

- For hadron production, MC modeling with local $Qs^2(b)$
- For heavy quarks, uniform nucleus with effective Qs^2
- Low kT gluon dist is more suppressed





Hadron production

- INPUT: gluon dist from rcBK in large Nc

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

- kT-factorization formula for y ~ 0

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

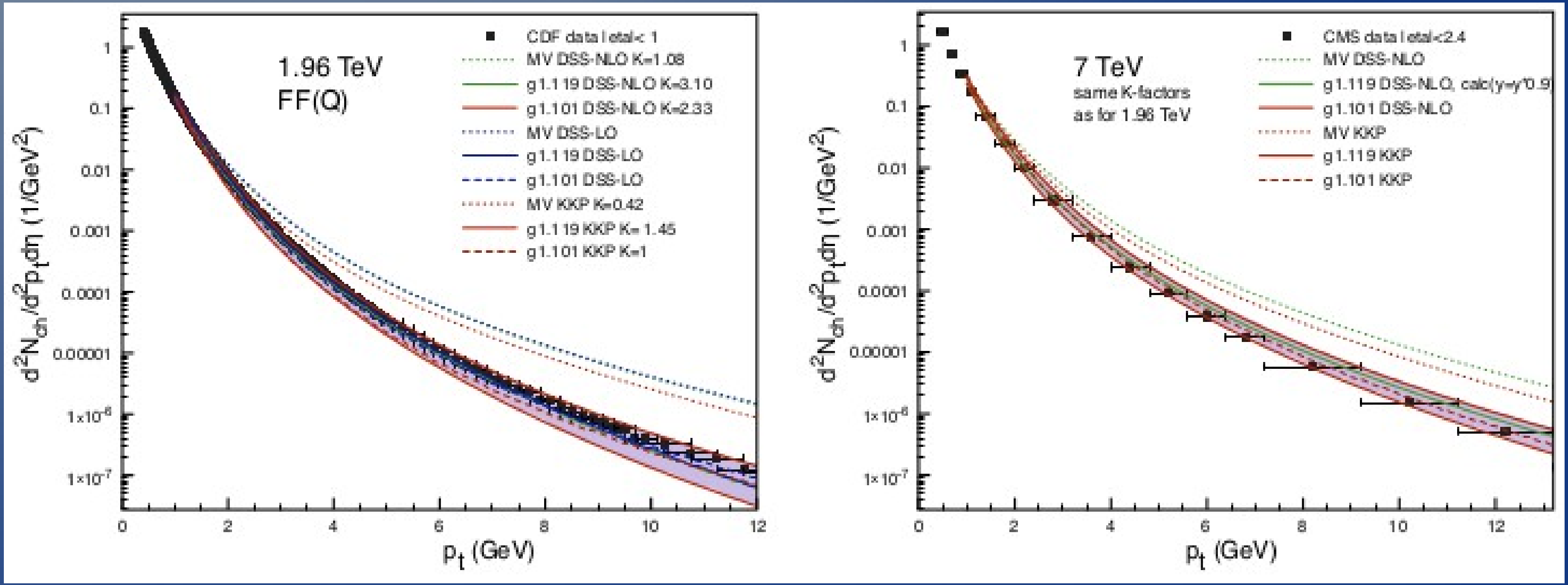
- DHJ *hybrid* formula for y > 0

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

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

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-dependence and pt-depndence



dN/dy in p-Pb collisions

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

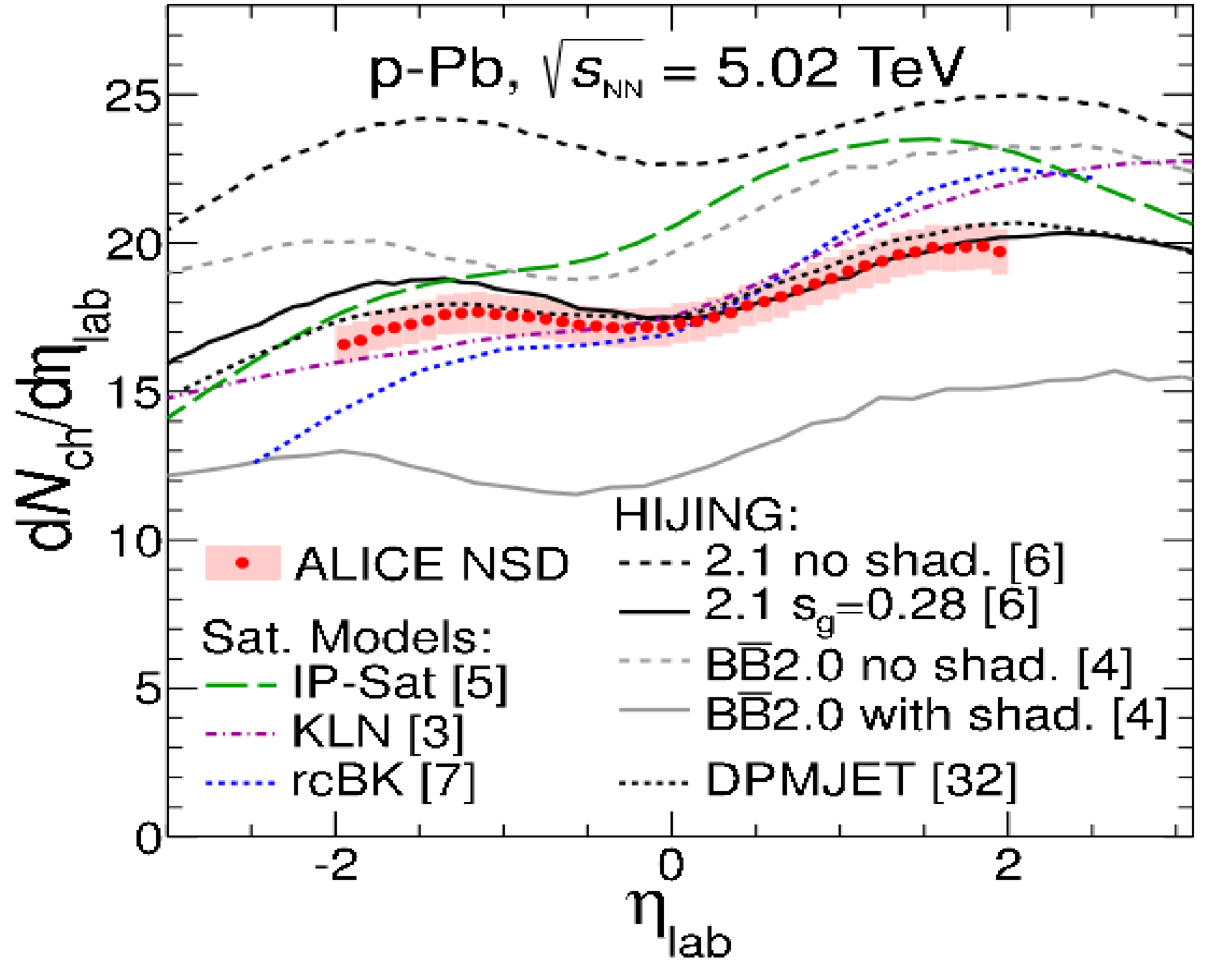
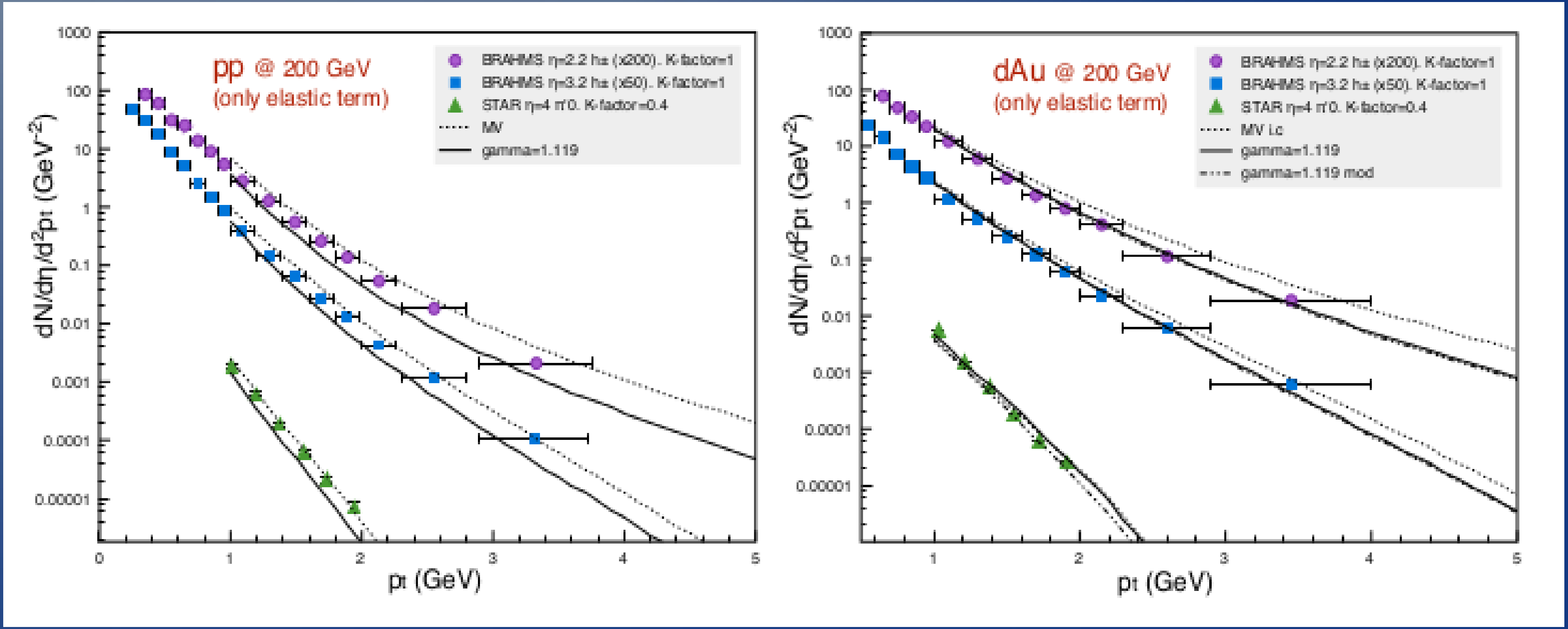


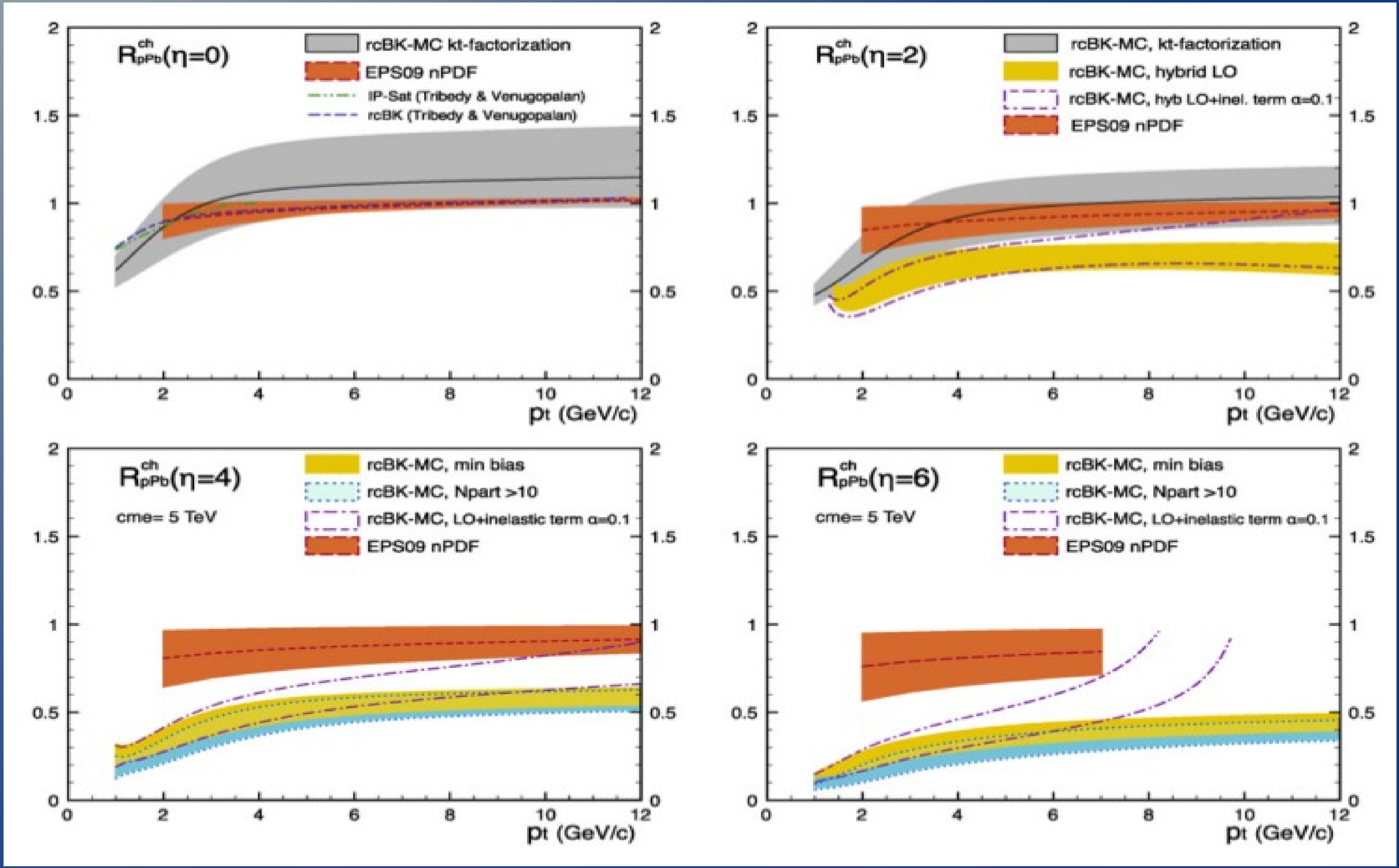
Fig. 1: Pseudorapidity density of charged particles measured in NSD p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to theoretical predictions [3–7]. The calculations [4, 5] have been shifted to the laboratory system.

Forward spectrum in dA at RHIC

- DHJ formula (CTEQ6, DSS)
- The same normalization chosen for pp and dA
  - particle dependent



y-dependence of RpA



Heavy flavor prodution in pA

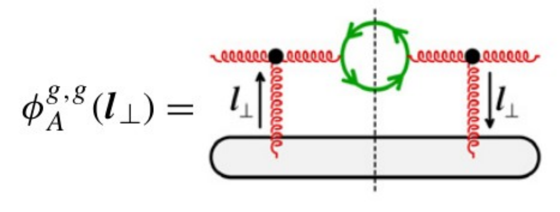
Quark pair production in pA

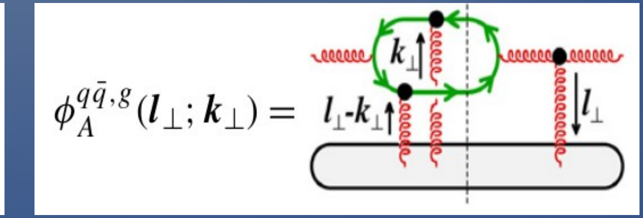
- Formula at $O(\rho_p\,\rho_A^{\infty})$ in large Nc limit

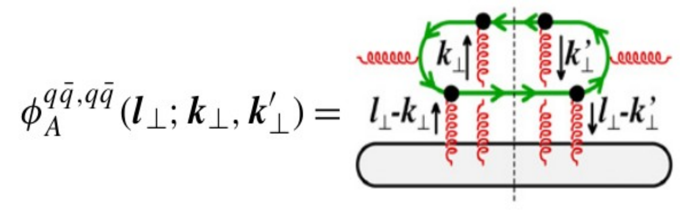
$$\frac{dN_{q\bar q}}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2}\frac{\alpha_s^2 N}{8\pi^4 d_A}\frac{1}{(2\pi)^2}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp} \frac{\Xi(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)}{\boldsymbol{k}_{1\perp}^2\,\boldsymbol{k}_{2\perp}^2}\,\phi_{A,y_2}^{q\bar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

Gelis-Blaizot-Venugopalan
HF-Gelis-Venugopalan

- Pair production --> multi-parton correlators







- We simplify them as a product of fundamental 2-pt funs in large Nc limit

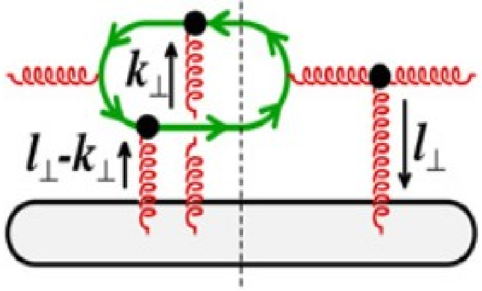
Quarkonium production

- Color Evaporation Model
  - the pair bounds with a constant probability

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

- Saturation effects:
  - depletion of lower-kT gluons in uGD
  - multiple scatterings of each quark of pair

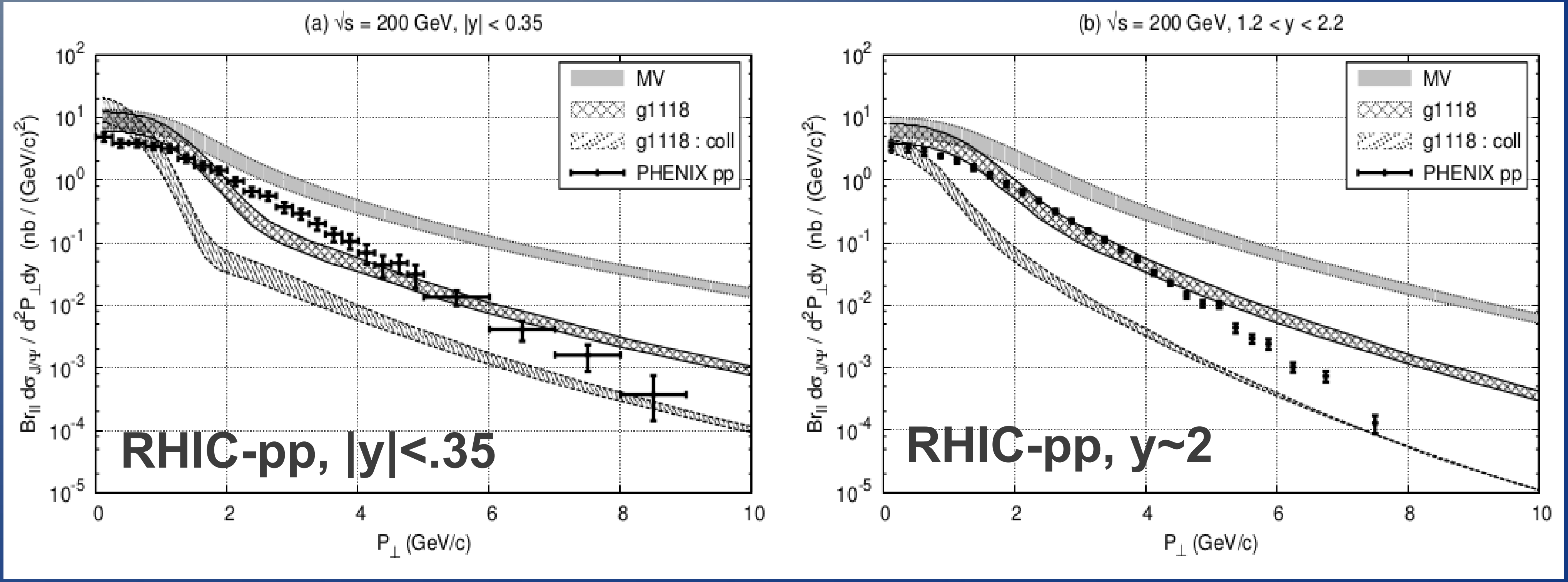
$$\phi_A^{q\bar{q},g}(\boldsymbol{l}_\perp;\boldsymbol{k}_\perp) =$$



J/psi production

- Color Evaporation Model

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



J/psi production

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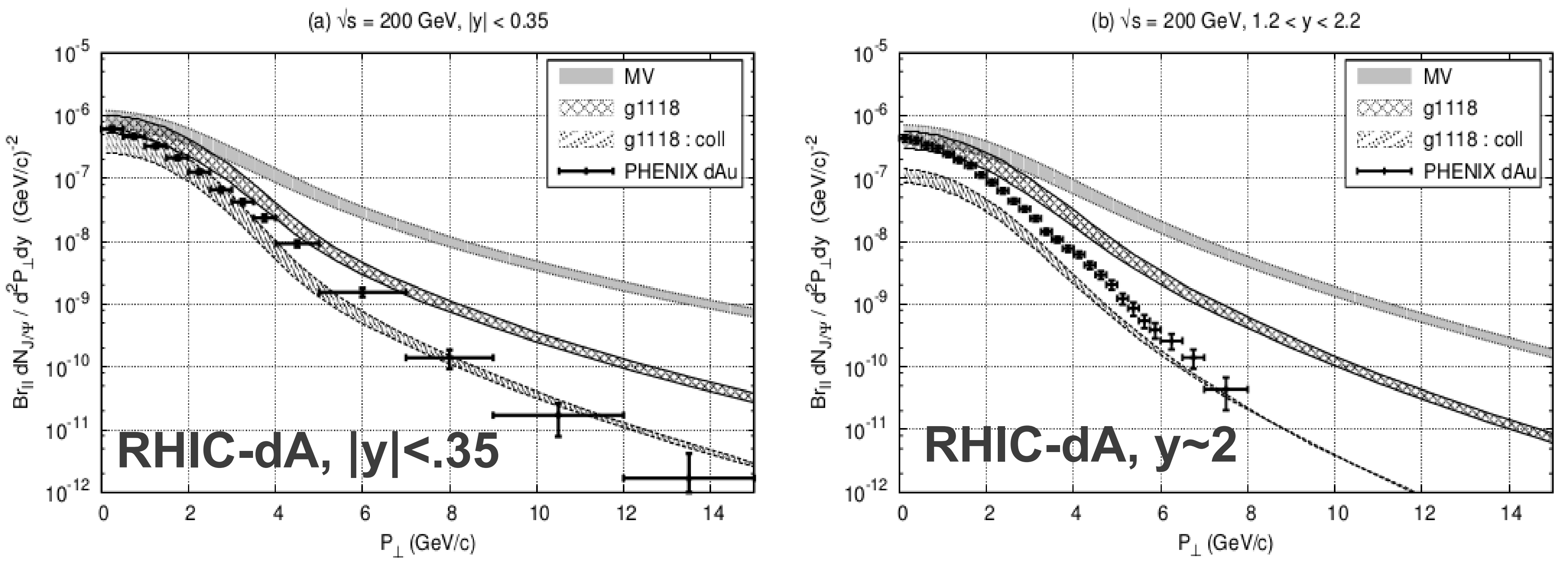
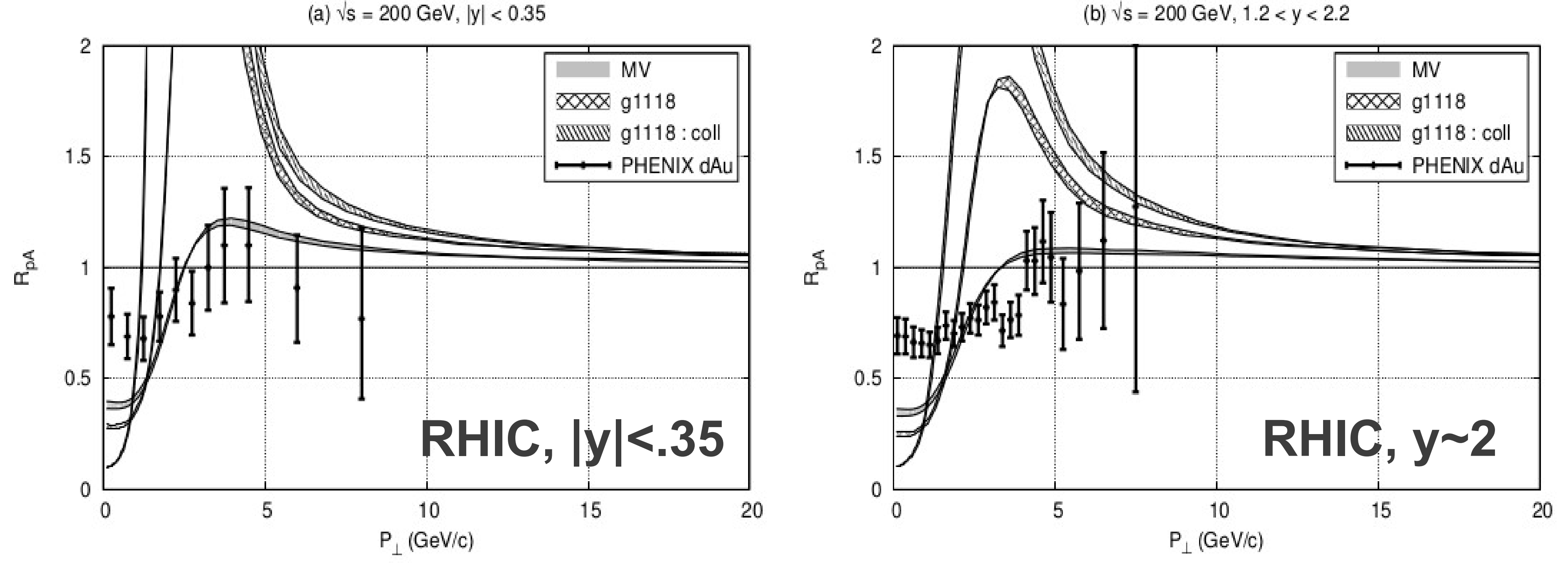


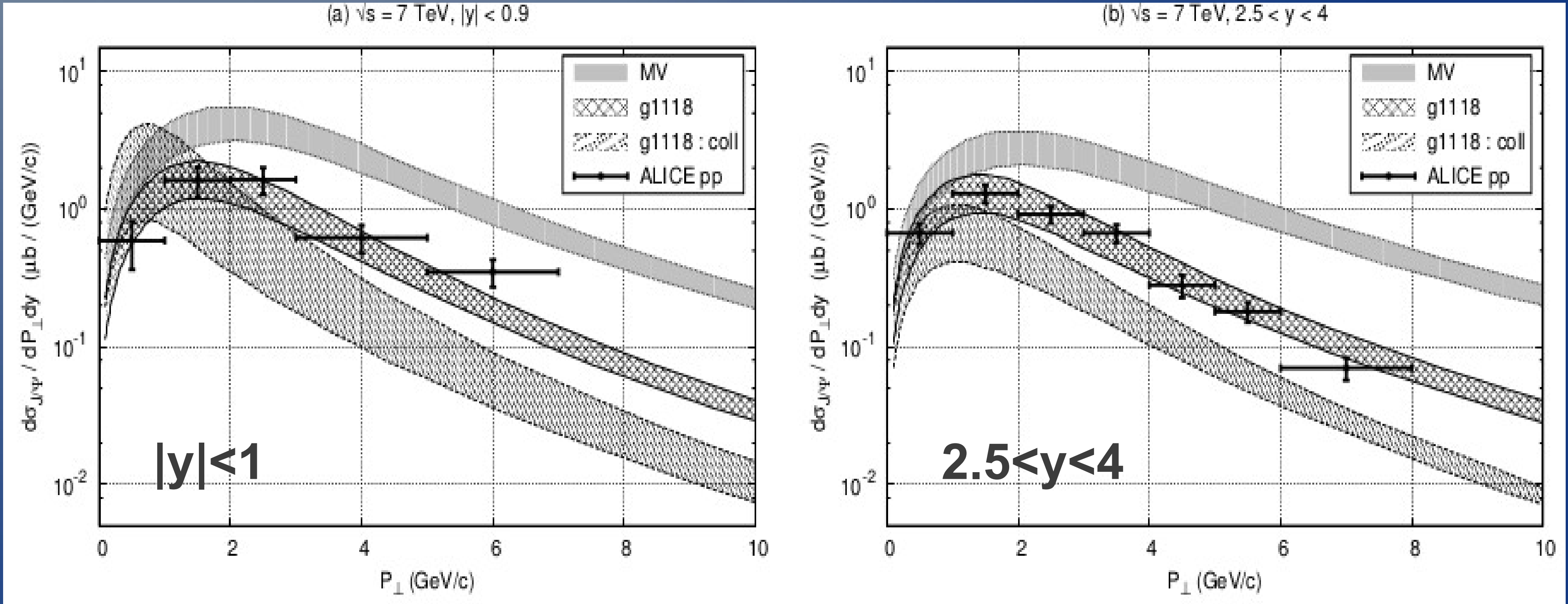
RpA of J/psi at RHIC

- Sensitive IC of uGD (in pp)
- “MV” shows reasonable behavior in the ratio



J/psi production at the LHC

- pp at sqrt(s)=7 TeV
- wider x-evolution from x0 (no dip)

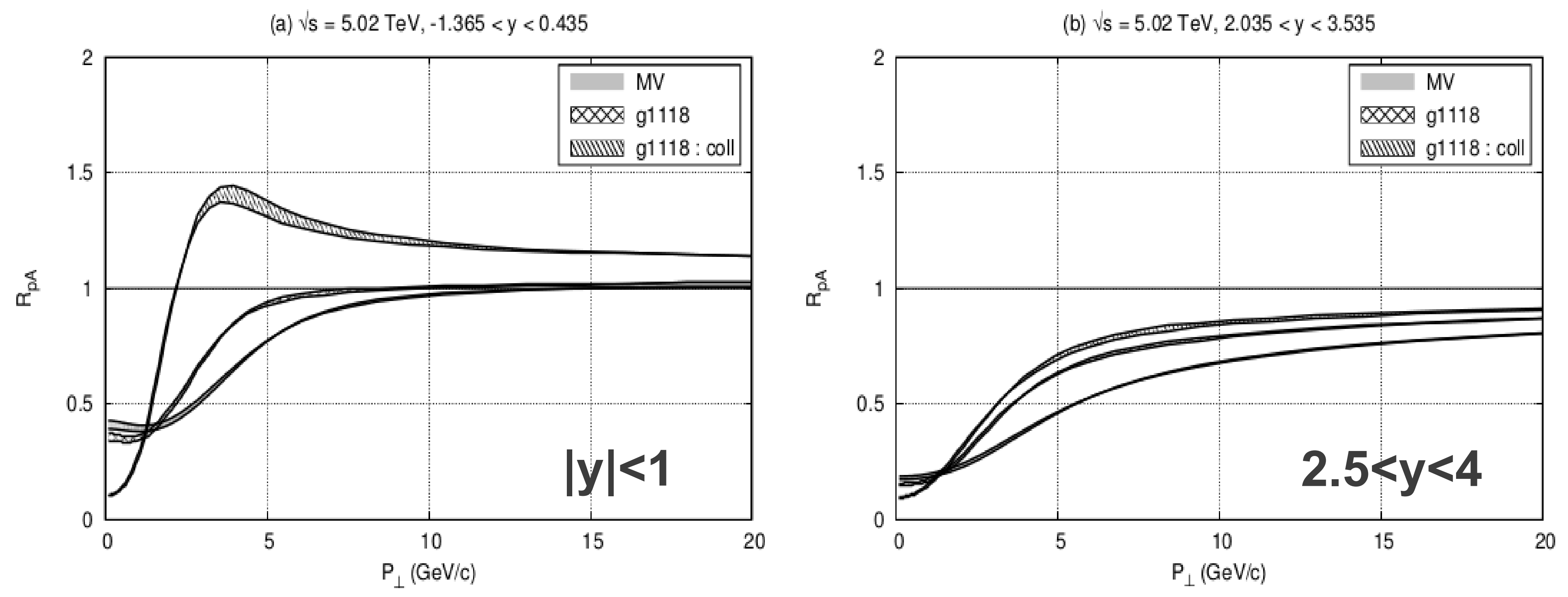


|y|<1

2.5<y<4

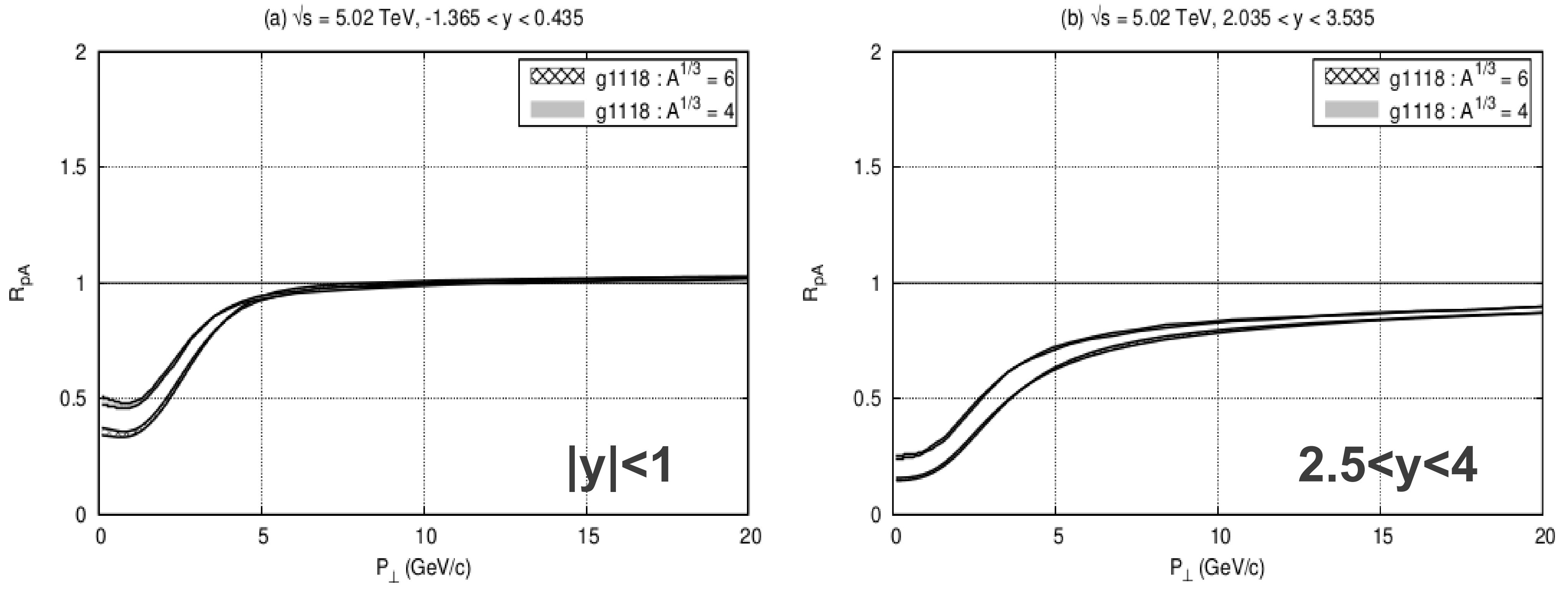
RpA of J/psi at the LHC

- RpA at sqrt(s)=5.02 TeV



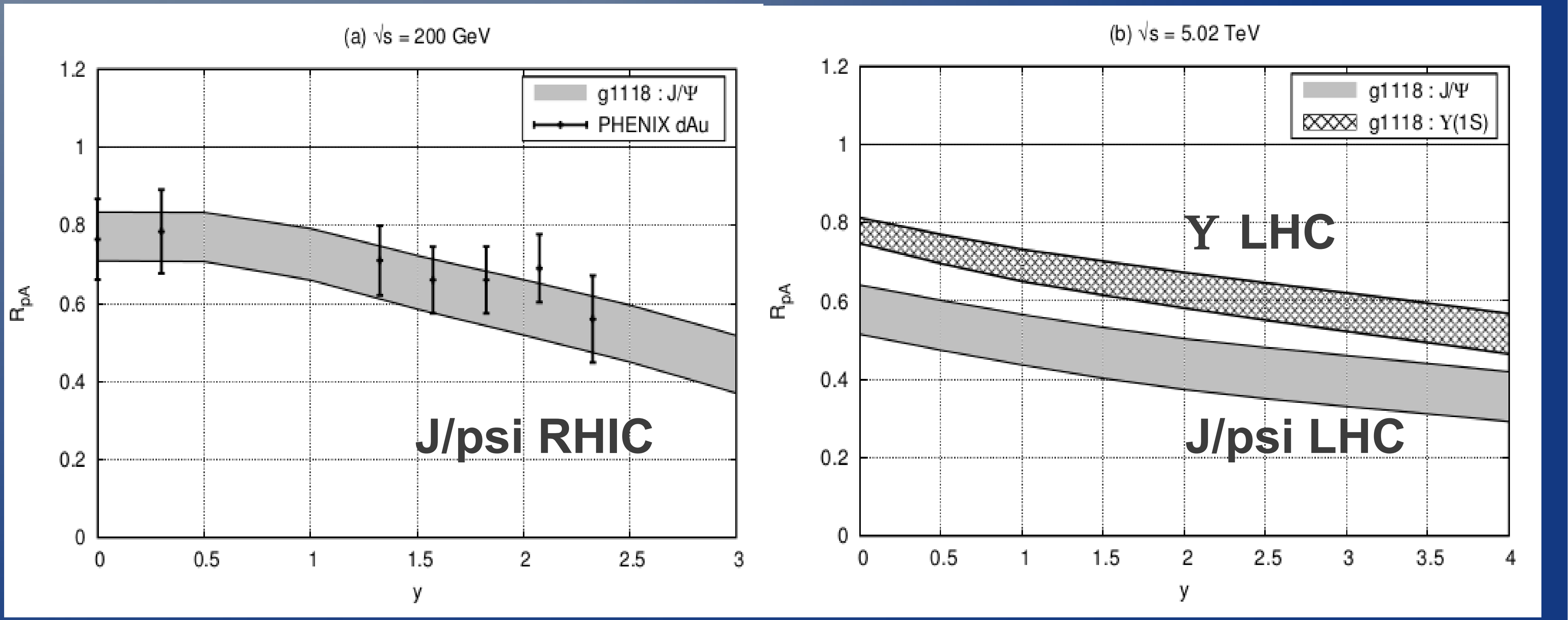
RpA of J/psi at the LHC

- RpA at sqrt(s)=5.02 TeV
- $Q_{s0A}^{2} = (4 – 6)\text{x}\ Q_{s0}^{2}$



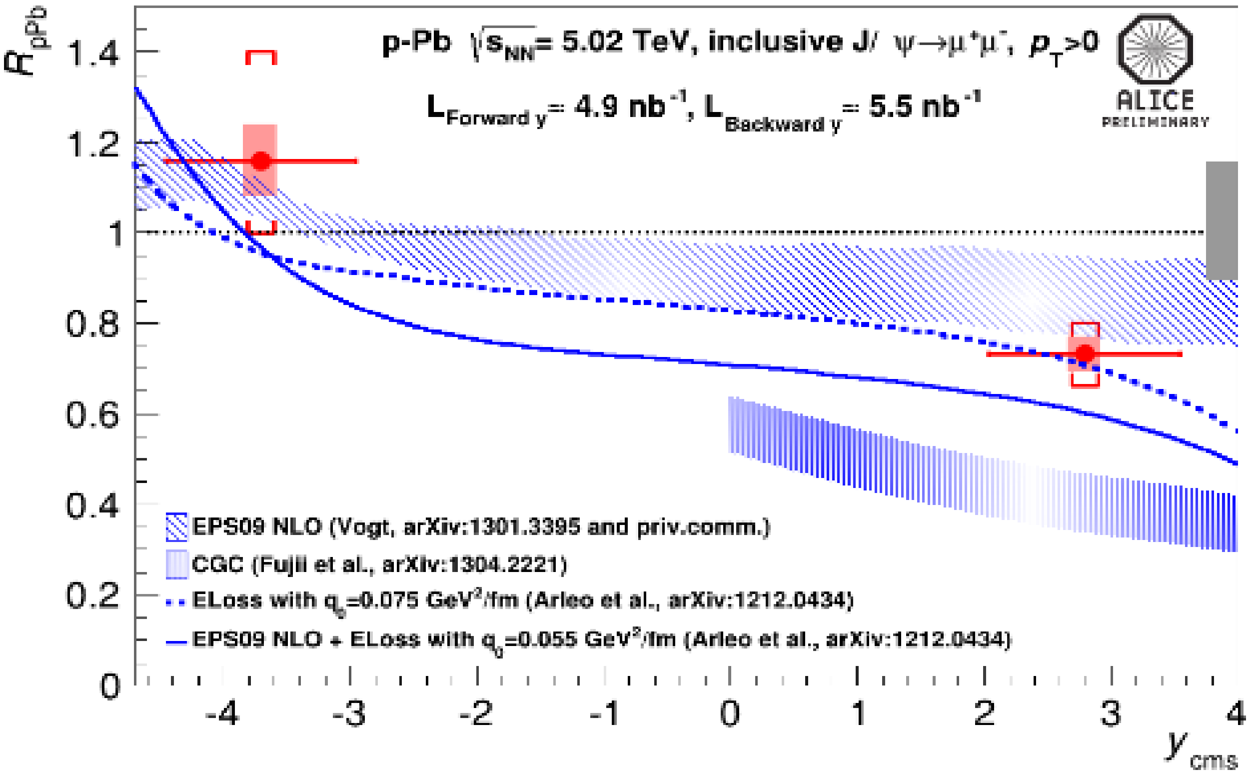
RpA(y) for J/psi at the LHC

- More suppression at the LHC than at RHIC
- Upsion also suppressed significantly at LHC



Nuclear modification factor: R_{pA}

from R. Arnaldi pA WS ECT* 9-May



- R_{pA} decreases towards forward y

Uncertainties:

- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

- dominant error source is due to the normalization to pp collisions

- Comparison with theoretical predictions shows reasonable agreement with:
  - shadowing EPS09 NLO calculations (R. Vogt)
  - models including coherent parton energy loss contribution (F. Arleo et al)

while CGC description ($Q^2_{s0,A}$ = 0.7-1.2 GeV/c², H. Fujii et al) seems not to be favoured

RpA for J/psi

- Similar suppression observed at RHIC and LHC
- Stronger suppression at the LHC in our calc.
    - impact parameter dependece important?
    - NLO contrib or multi-parton correlators?
    - other effects? (energy-loss of high-x1, ..., etc)

Open heavy flavor

- Integrate out one quark, convolute with frag func from

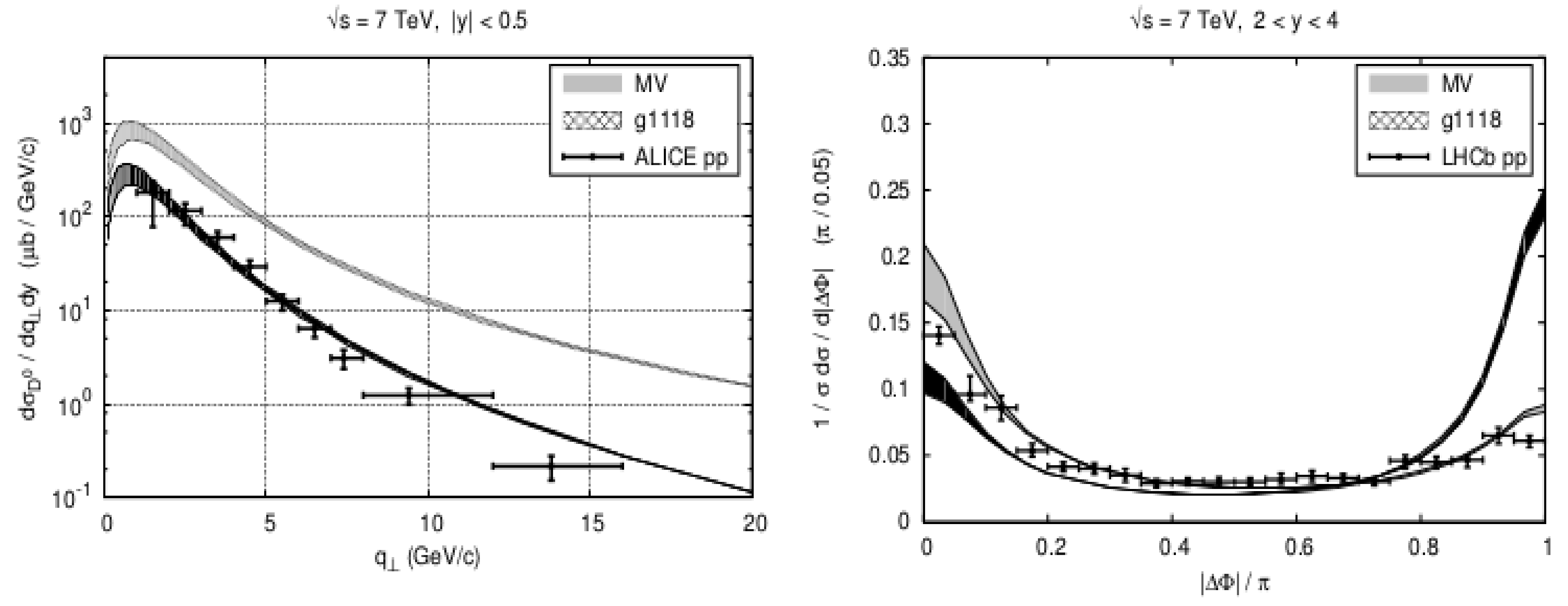
$$\frac{dN_{q\bar{q}}}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2}\frac{\alpha_s^2 N}{8\pi^4 d_A}\frac{1}{(2\pi)^2}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp}\frac{\Xi(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)}{\boldsymbol{k}_{1\perp}^2\boldsymbol{k}_{2\perp}^2}\,\phi_{A,y_2}^{q\bar{q},g}(\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

- Saturation effects
  - depletion of small kT gluon in nuclei
  - multiple scatterings of each quark – de-correlation

$$CP[\Delta\Phi] = \frac{1}{N_{\rm trig}}\int_{q_{h\perp},q_{\bar{h}\perp}}\frac{dN_{h\bar{h}}}{d^2\boldsymbol{q}_{h\perp}d^2\boldsymbol{q}_{\bar{h}\perp}dy_h dy_{\bar{h}}},$$

D spectrum and correlation in pp at the LHC

- Single particle spectrum reasonably reproduced with uGD set g1118
- Away-side correlation peak is not observed

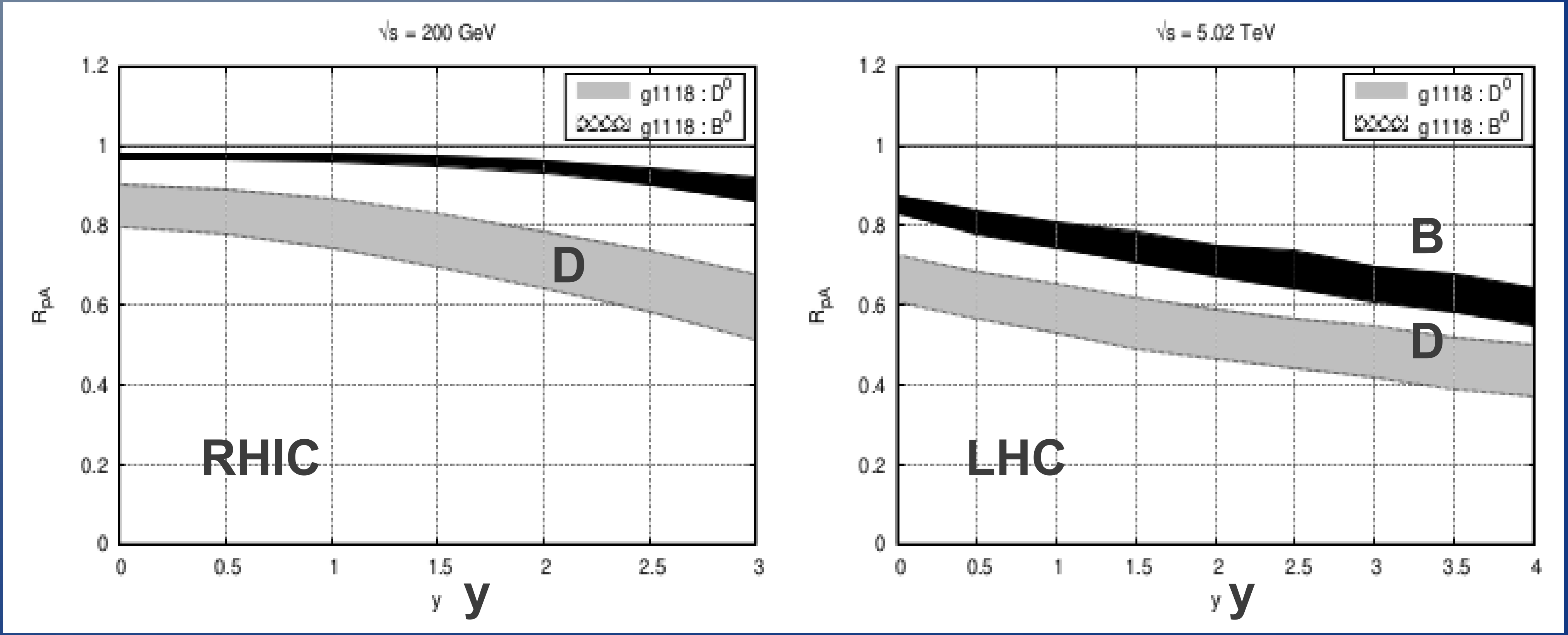


ALICE, JHEP 1201, 128 (2012

LHCb, JHEP 1206, 141 (2012)

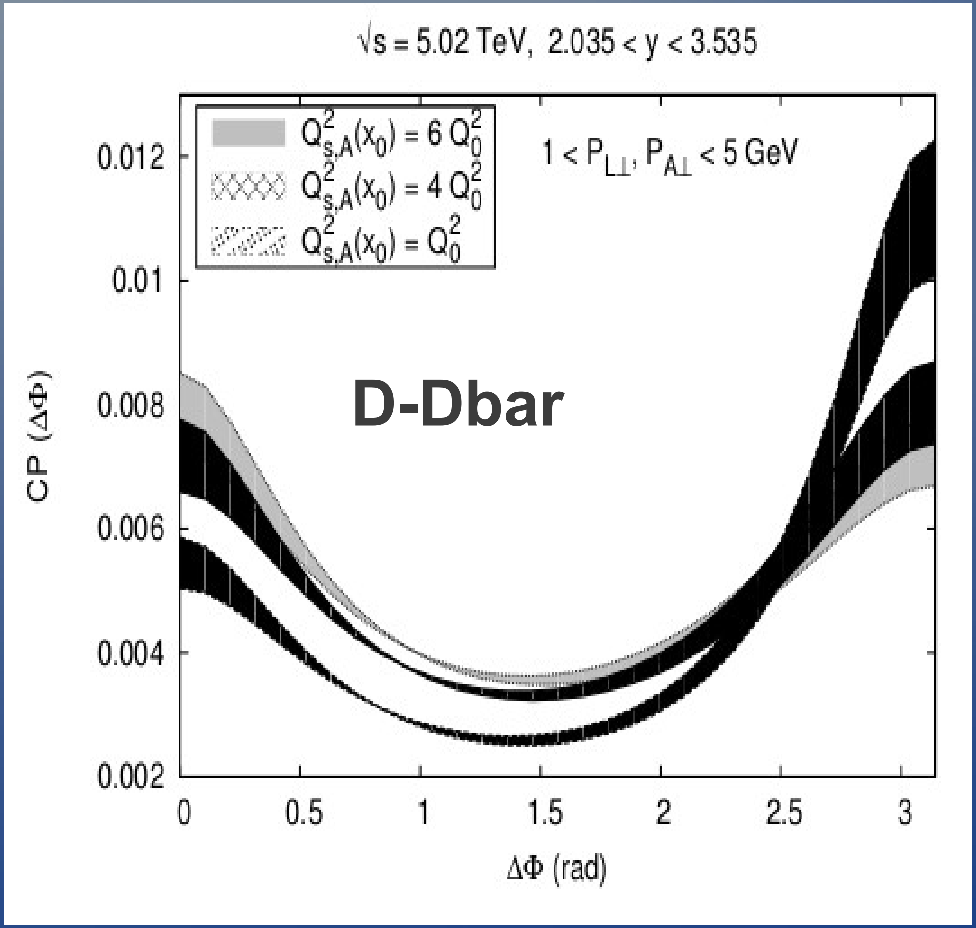
RpA(y) for D,B (prelim)

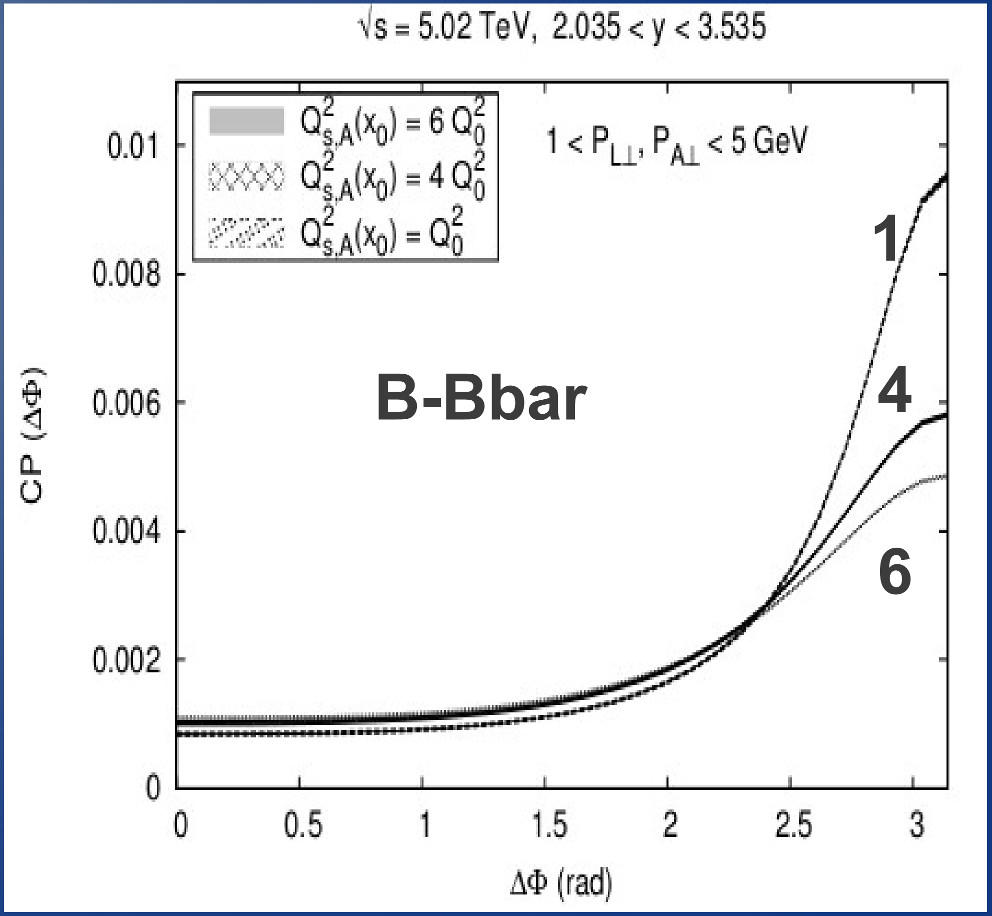
- Suppression due to saturation is seen



Heavy-meson correlation (prelim)

- away-side peak diminishes with Qs02
- near-side peak appears only for DDbar





Summary

- Hadron productions are compatible with CGC-rcBK description
- Heavy flavor production has been computed at LHC energy using gluon distribution from rcBK
  - $R_{pA}^{J\psi}$(y=3) looks more suppressed than ALICE
  - Open heavy flavor is also useful channnel
- Outlook:
  - NLO improvement for hadron production
  - Multi-point correlators
  - b-dependence in heavy quark production