# CGC approach in p+A collisions

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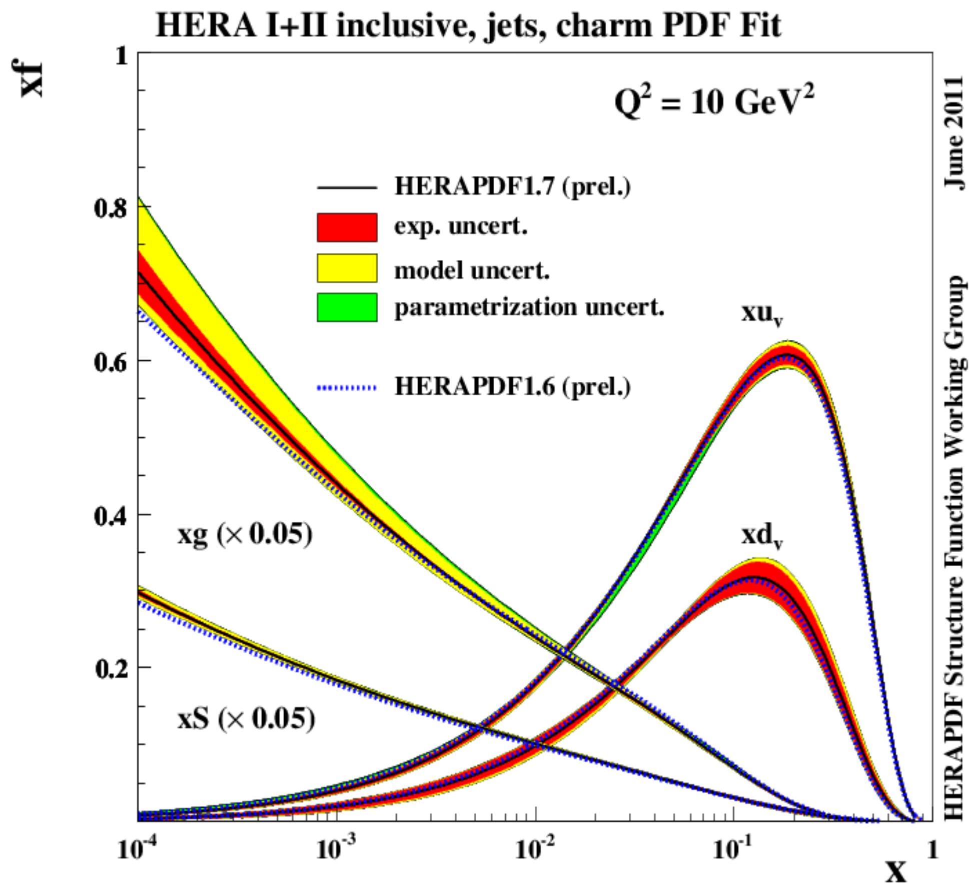
HF and K. Watanabe, arXiv:1304.2221[hep-ph]
J. Albacete, A. Dumitru, HF, Y. Nara, NPA897(2013)1
and others works

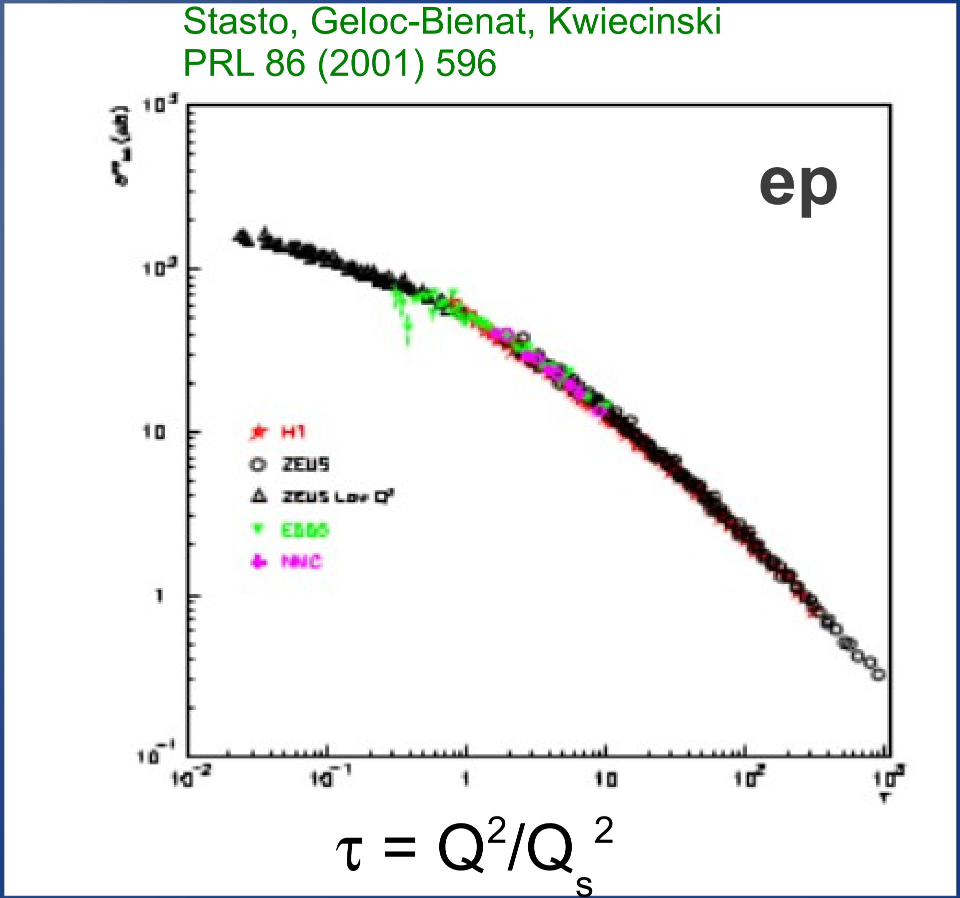
# Outline

- Introduction
- rcBK phenomenology
  - single hadron production in forward region
  - heavy flavors
- Challenges
  - multi-point correlators
  - NLO extension
- Summary

# Dense gluon and new scale

- Gluon number xG(x, Q) increases at small x
- A new scaling suggests a new scale, $Q_s^2$



# Intuitive picture of saturation

- The higher the energy is, the more parton fluctuations emerge
- Recombination becomes important when $$Q_s^2(x) \sim \alpha_s \cdot \frac{xG(x,Q_s^2)}{\pi R_h^2}$$

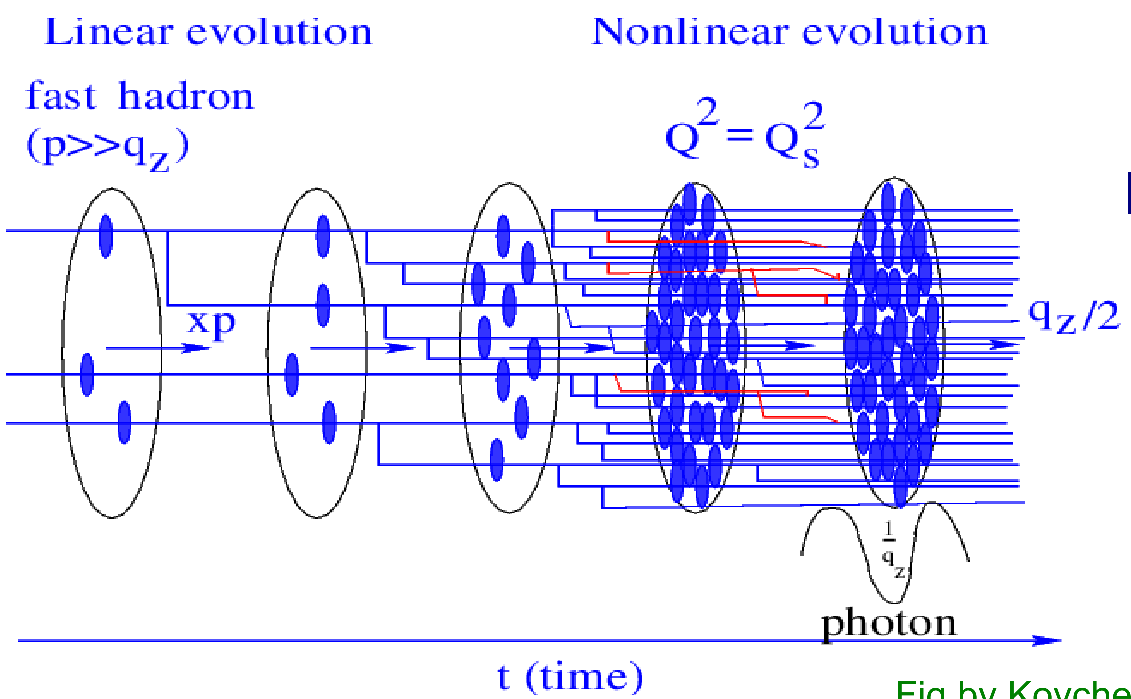



Fig by Kovchegov-Levin

Phase space density

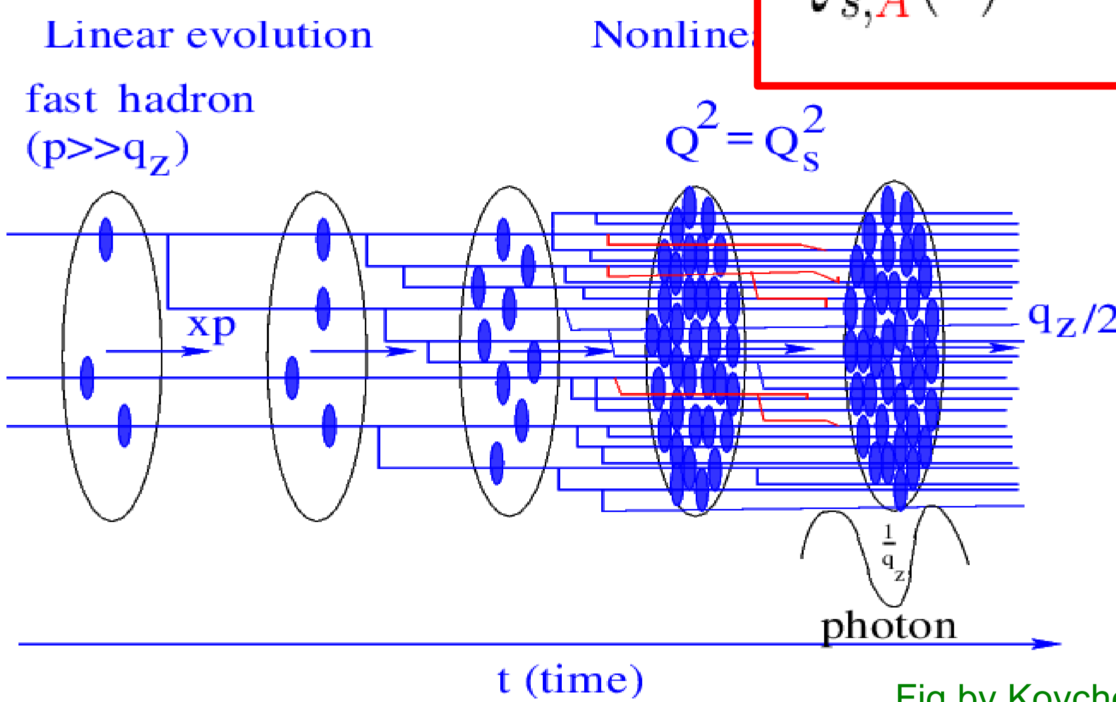
$$\frac{dN}{d^2r d^2p} \sim \frac{xG(x,Q_s^2)}{\pi R_h^2 Q_s^2(x)} \sim \frac{1}{\alpha_s}$$

# Intuitive picture of saturation

- The higher the energy is, the more parton fluctuations appear
- Recombination becomes important when

$$Q^2(x) \sim \alpha_s \cdot \frac{xG(x,Q_s^2)}{\ldots}$$

$$Q^2_{s,A}(x) \sim \alpha_s \cdot \frac{A\,xG(x,Q_s^2)}{A^{2/3}\pi R_0^2} = A^{1/3} Q^2_{s,p}$$




Phase space density

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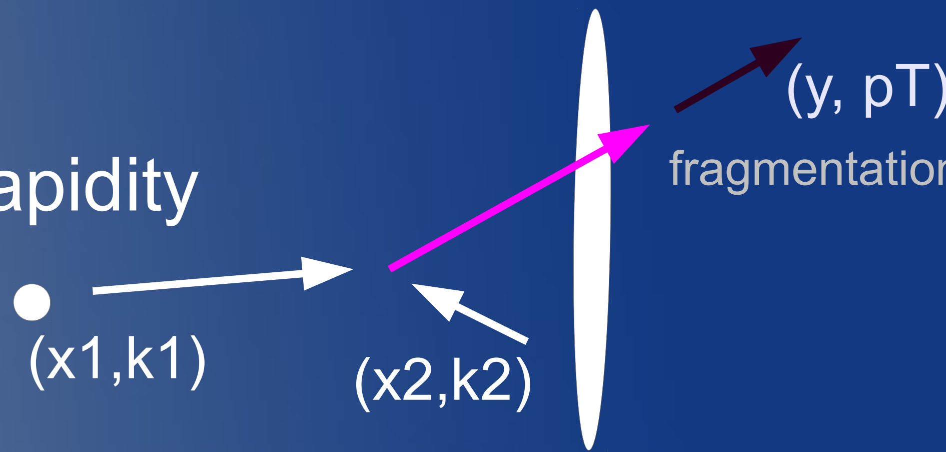
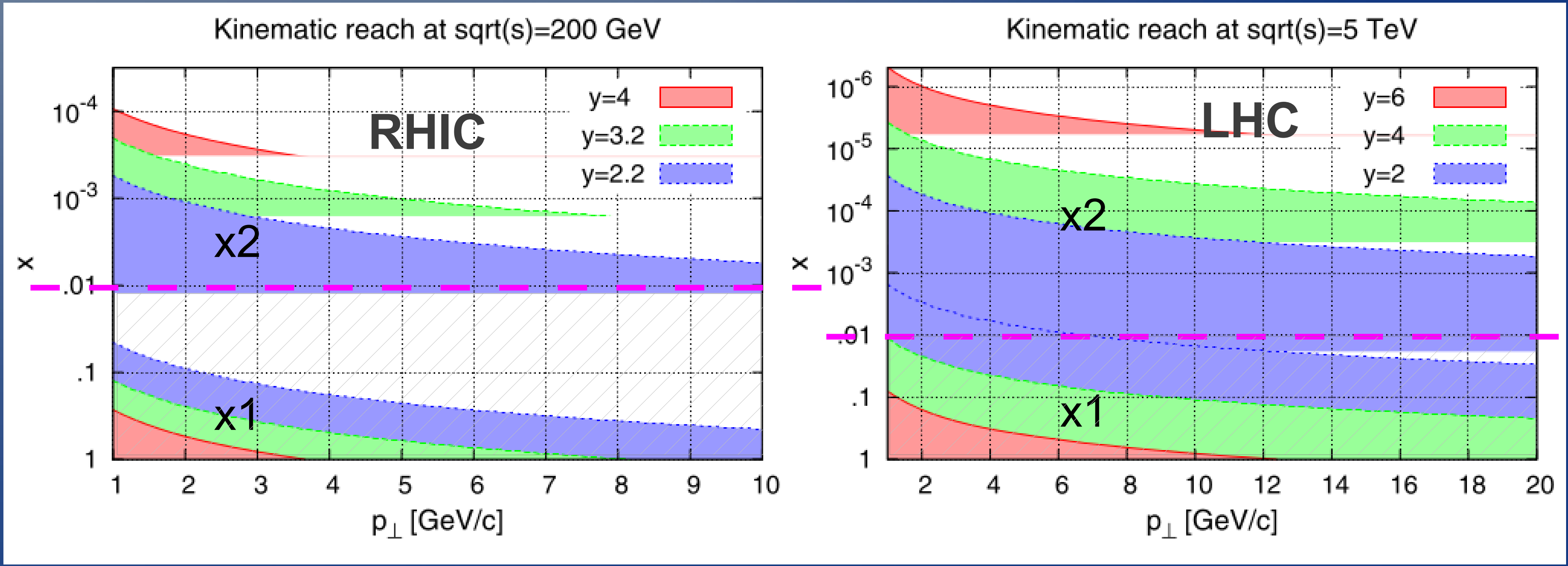
Fig by Kovchegov-Levin

# Kinetic coverage at colliders

- $x_{1,2} \sim$ pT/sqrt(s) exp(+-y)
  - High energy, forward rapidity
- "small" $x < x_0 = 0.01$ for nuclei

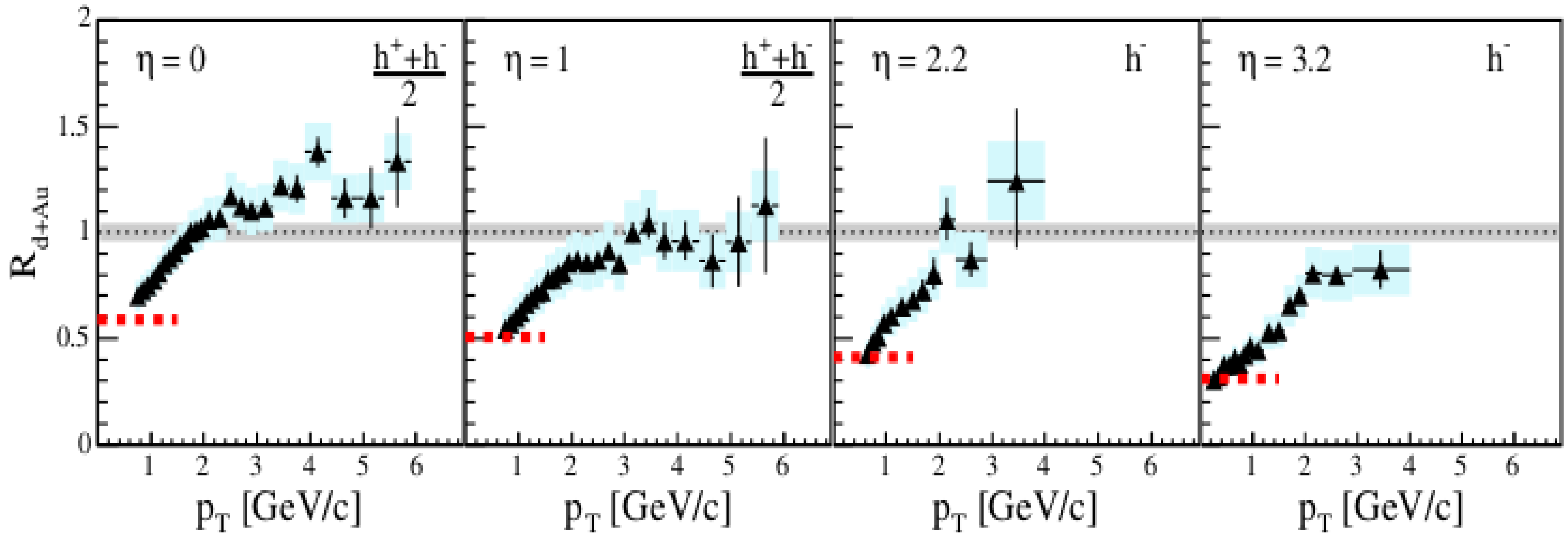


# Evidence in dA collisions

Forward suppression in d+Au at RHIC

Nuclear modification factor: $R_{dA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{dA}/d^2p_\perp d\eta}{dN_{pp}/d^2p_\perp d\eta}$




- BRAHMS [arXiv: nucl-ex/0403005] shows
  $\eta = 0$ : Cronin peak, $\eta \sim 3$ : Suppression
- Qualitatively consistent with the CGC

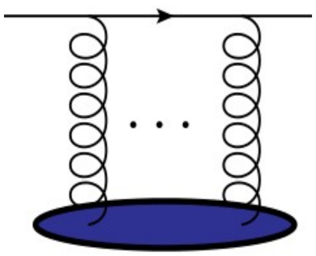
# rcBK phenomenology

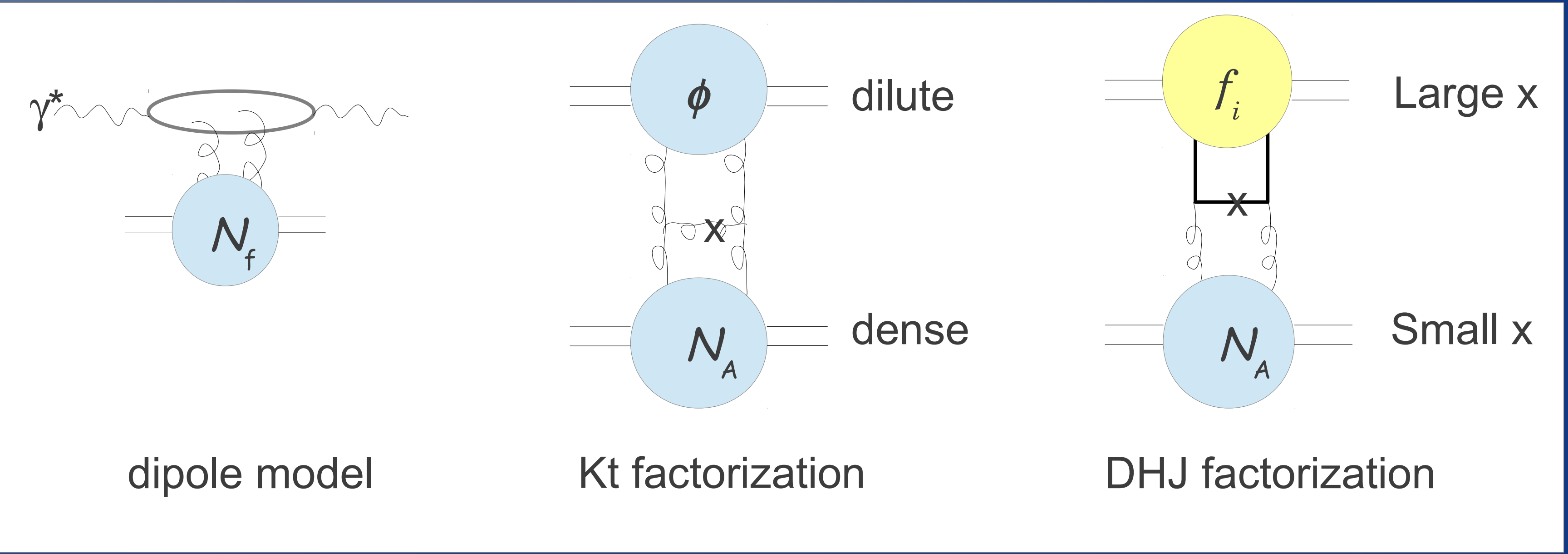
# rcBK phenomenology

- Energetic parton coherently interact with target (eikonal multiple scatterings)

$$U(z_\perp) = \mathcal{P}\exp\left[ig\int dz^+ A^-(z^+, z)\right]$$

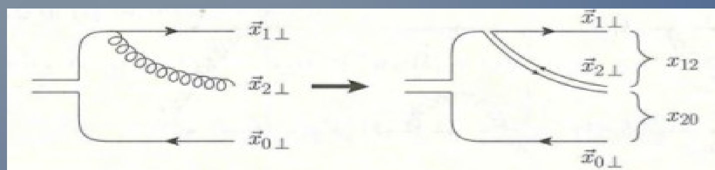
$$\mathcal{N}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \int [D\rho] W_Y[\rho]\left[1 - \frac{1}{N_c}\mathrm{tr}(U(\boldsymbol{x}_\perp)U^\dagger(\boldsymbol{y}_\perp))\right]$$





# rcBK phenomenology

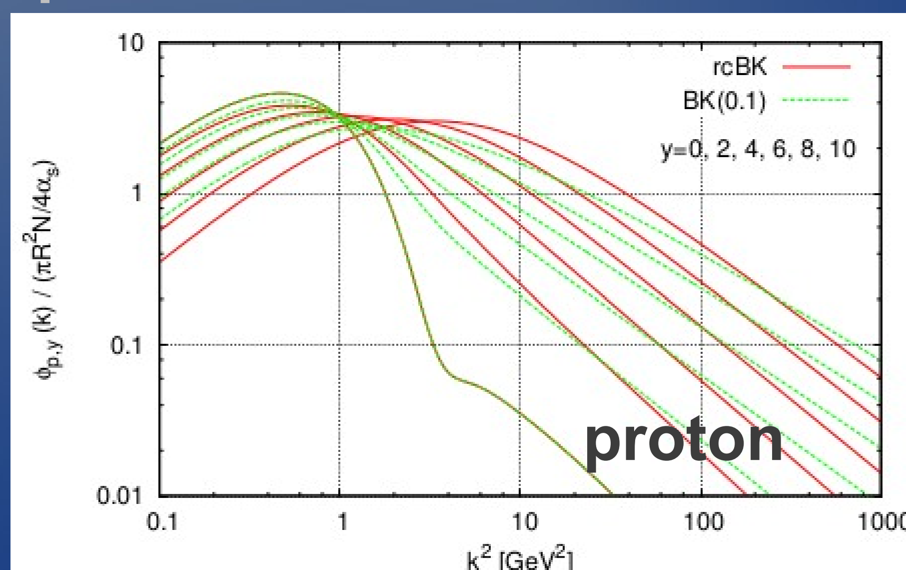
- Energy (x) dependence described by BK eqn with running coupling correction (in large $N_c$ )




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

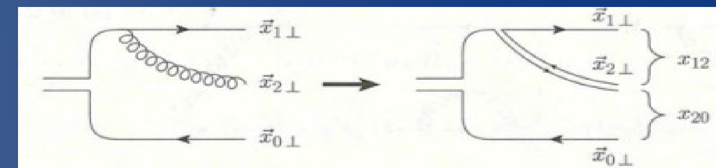
Kovchegov-Weigert, Balitsky-Chirilli

**Example of evolution**



# rcBK phenomenology

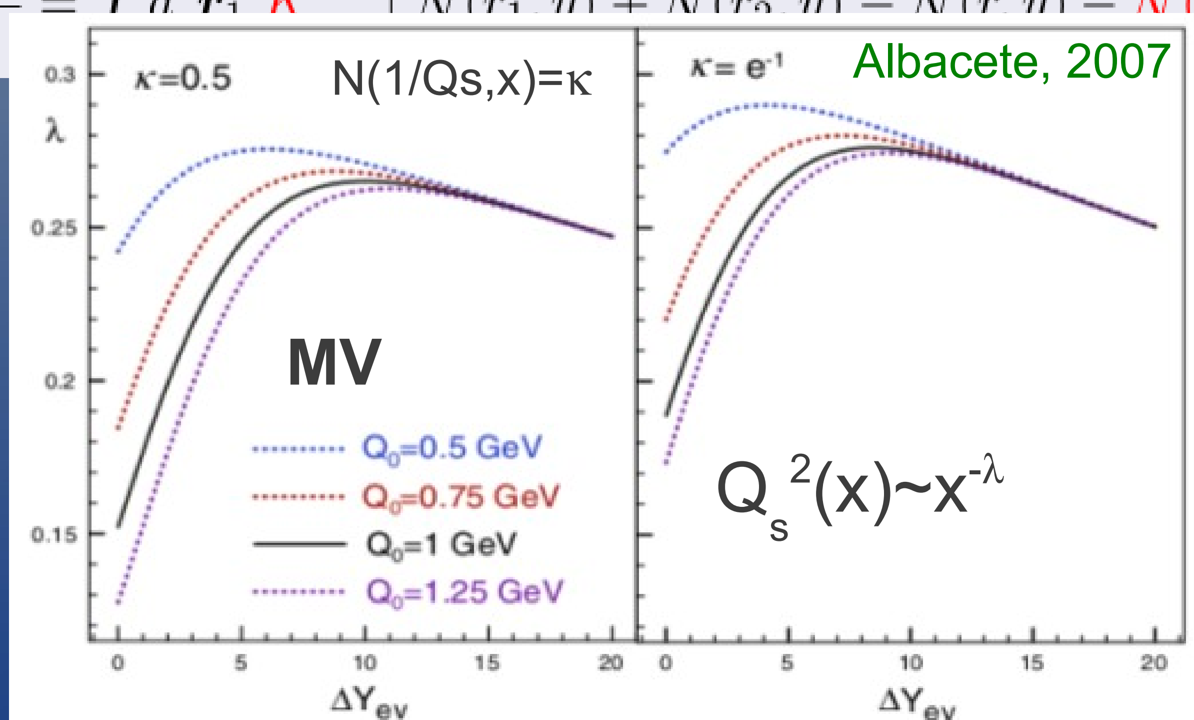
- In large $N_c$ limit, evolution of dipole is closed




- Balitsky-Kovchegov eqn with running coupling

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

igert, Balitsky-Chirilli



# Constraining $N$ with DIS data

## Initial condition and evolution

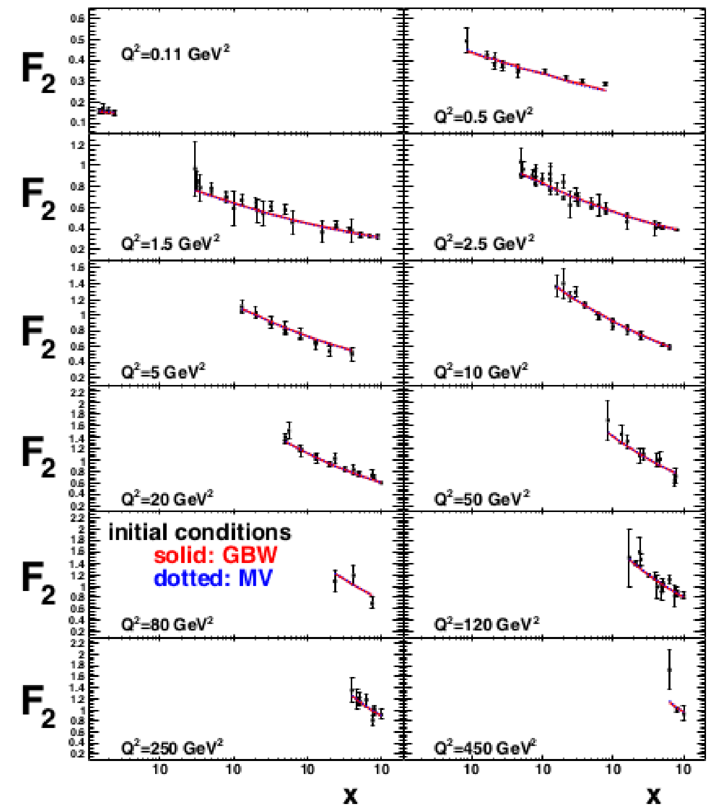
$$\mathcal{N}_F(r, x=x_0) = 1 - \exp\left[-\frac{\left(r^2 Q^2_{s0,\mathrm{proton}}\right)^\gamma}{4} \ln\left(\frac{1}{\Lambda r} + e\right)\right]$$

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

Albacete et al. PRD80

## Fit to HERA-DIS data

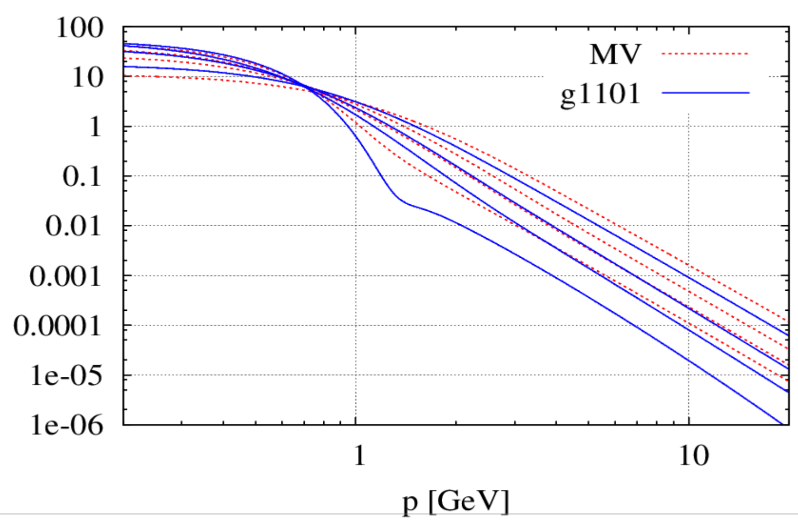
$$\sigma_{T,L}(x, Q^2) = \sigma_0 \int_0^1 dz \int d\mathbf{r} |\Psi_{T,L}(z, Q^2, \mathbf{r})|^2 \mathcal{N}(r, Y)$$




## Parameter set

| UGD Set | $Q^2_{s0,\mathrm{proton}}$ (GeV$^2$) | $\gamma$ | $\alpha_{fr}$ | $C$ |
|---|---|---|---|---|
| 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 |

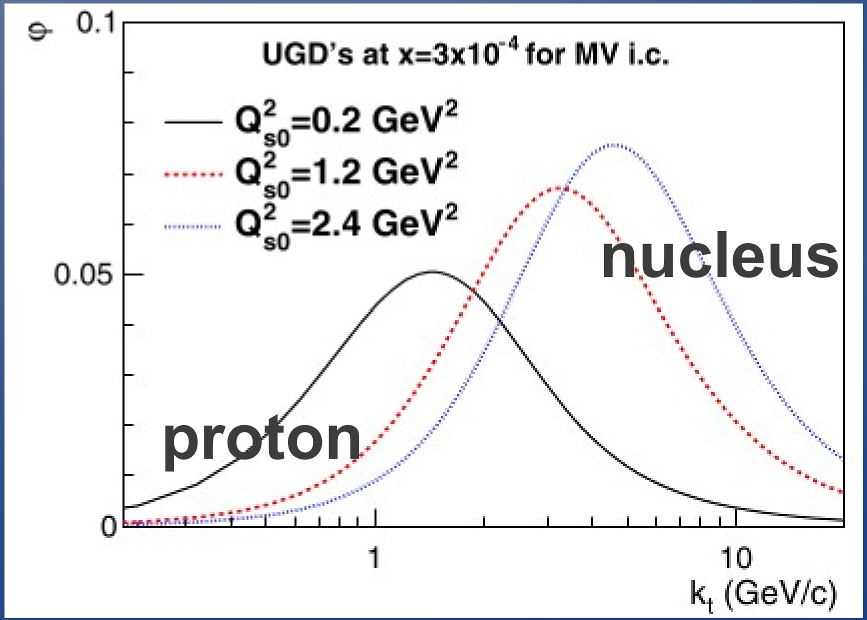
N(k,y), y=0, 1.5, 3, 6

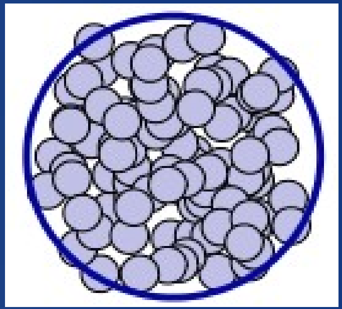


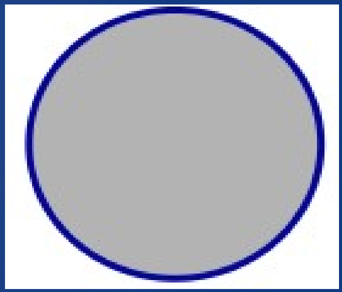
# Modeling of nuclear target

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

- Effectve Qs2 w/o impact param dependence – simplest
- MC modeling with local $Qs^2(b)$
- 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 for small x1,2 (y ~ 0)

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

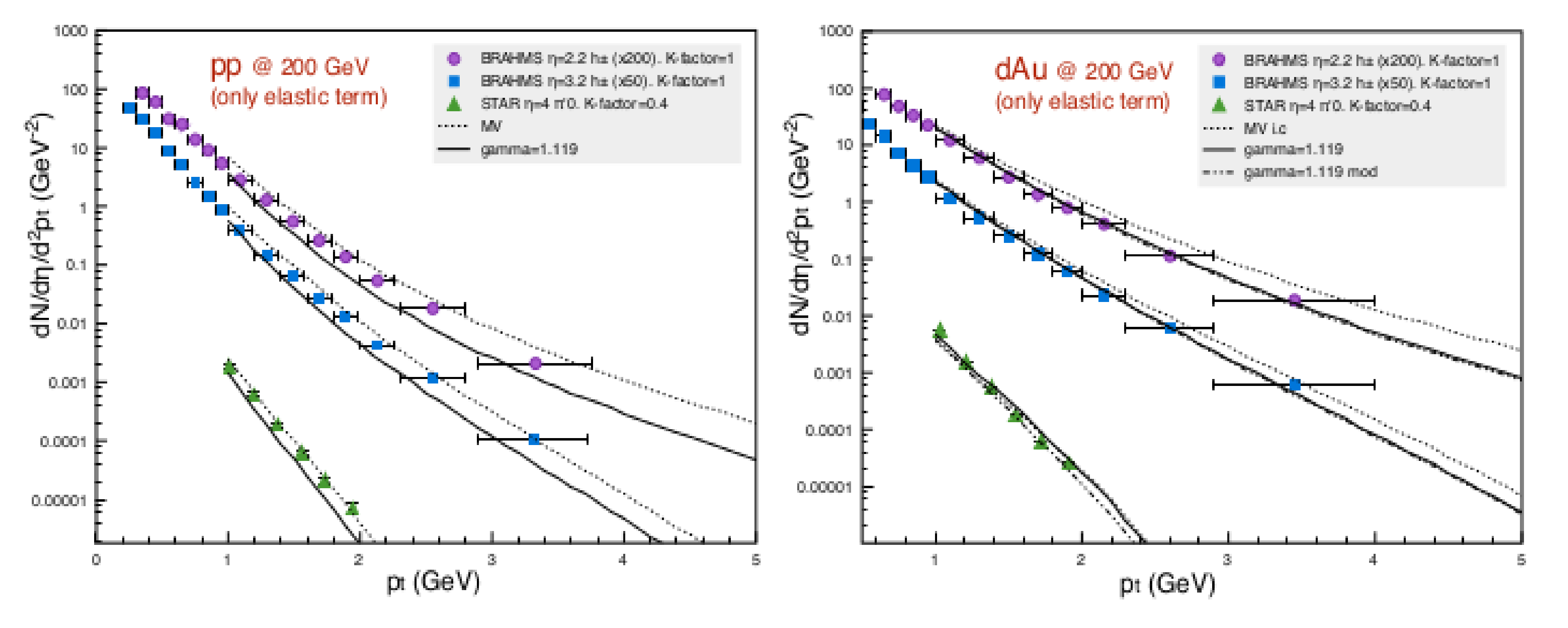
- DHJ *hybrid* formula for small x2 for y > 0

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

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

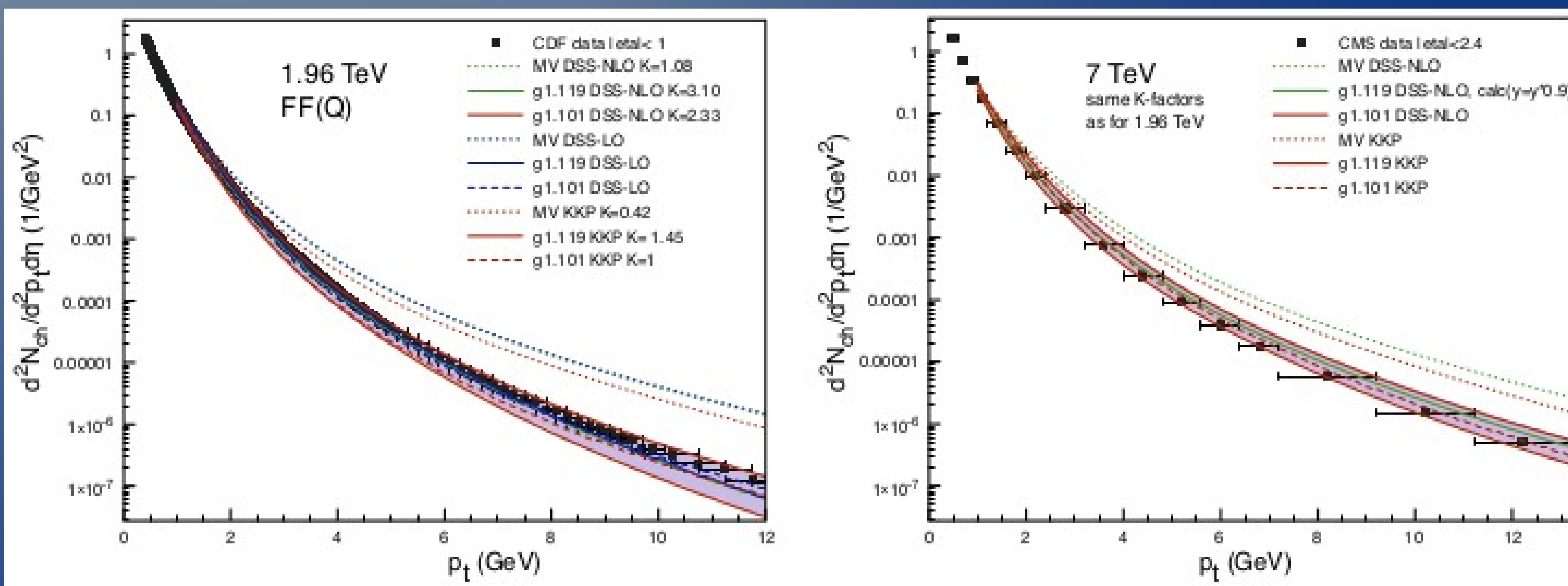
# Hadron spectrum in pp, dA at RHIC

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

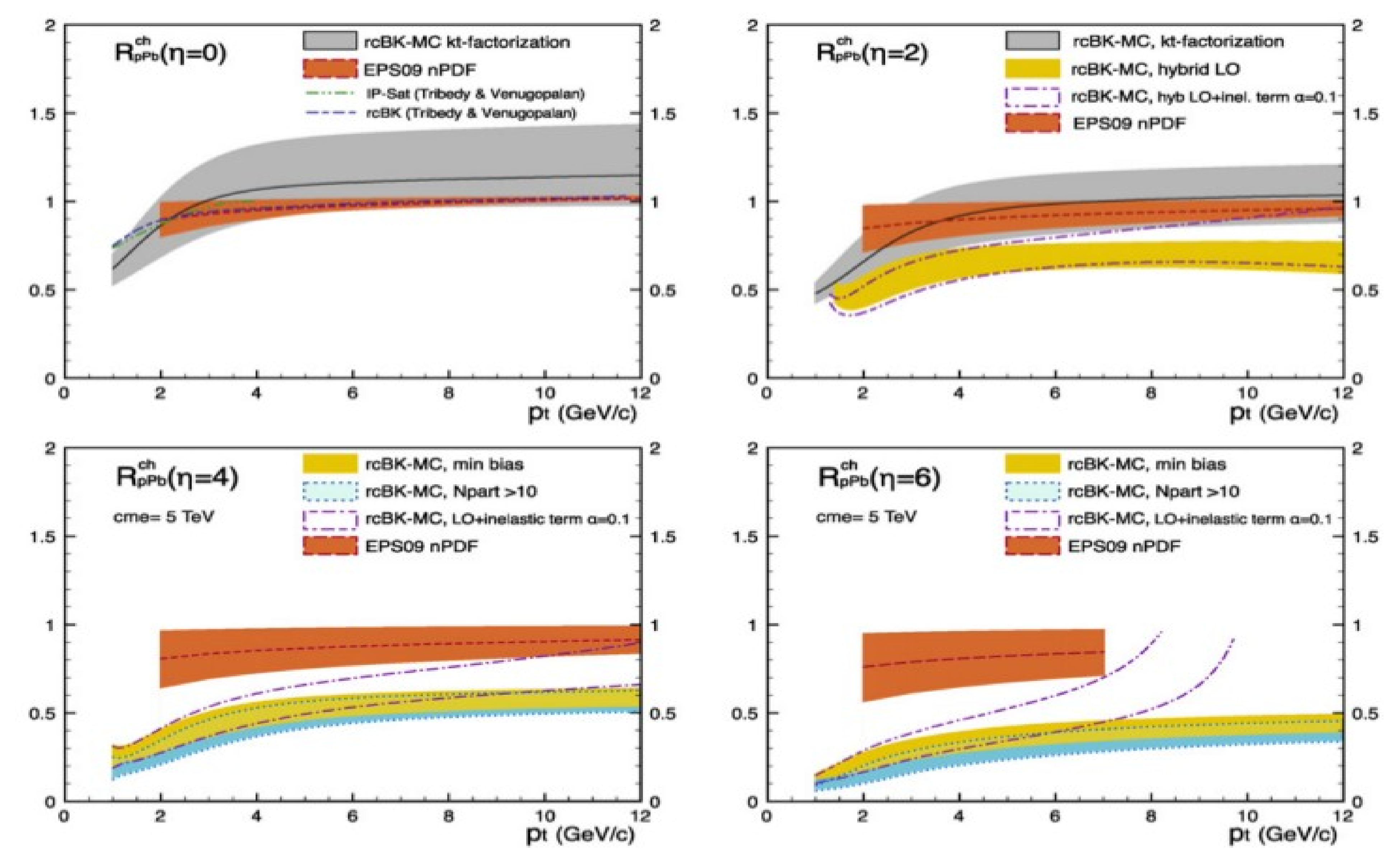


# Hadron spectrum at pp colliders

- kT-factorized formula
  - Normalized at pT=1 GeV for sqrt(s)=1.96 TeV
  - uGD set (γ ~ 1.1) describes energy and pt depndences



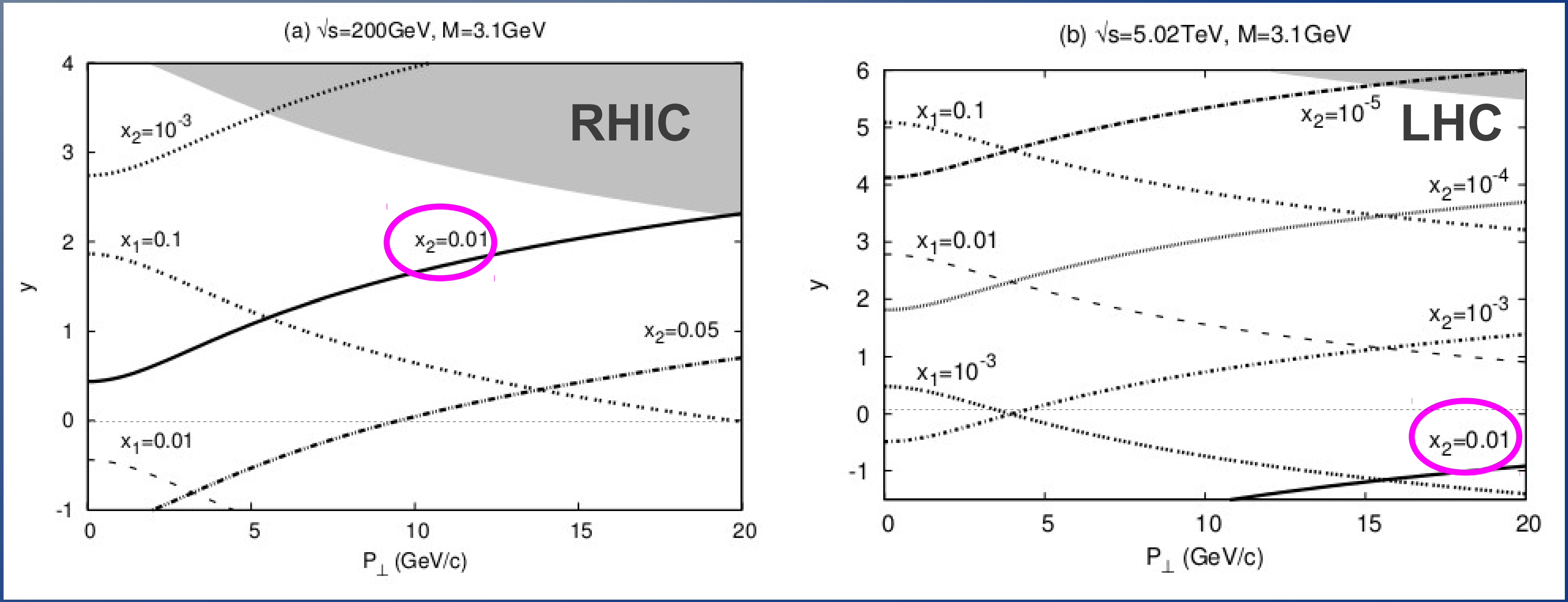
# y-dependence of RpA at the LHC



# Heavy quarks are sensitive?

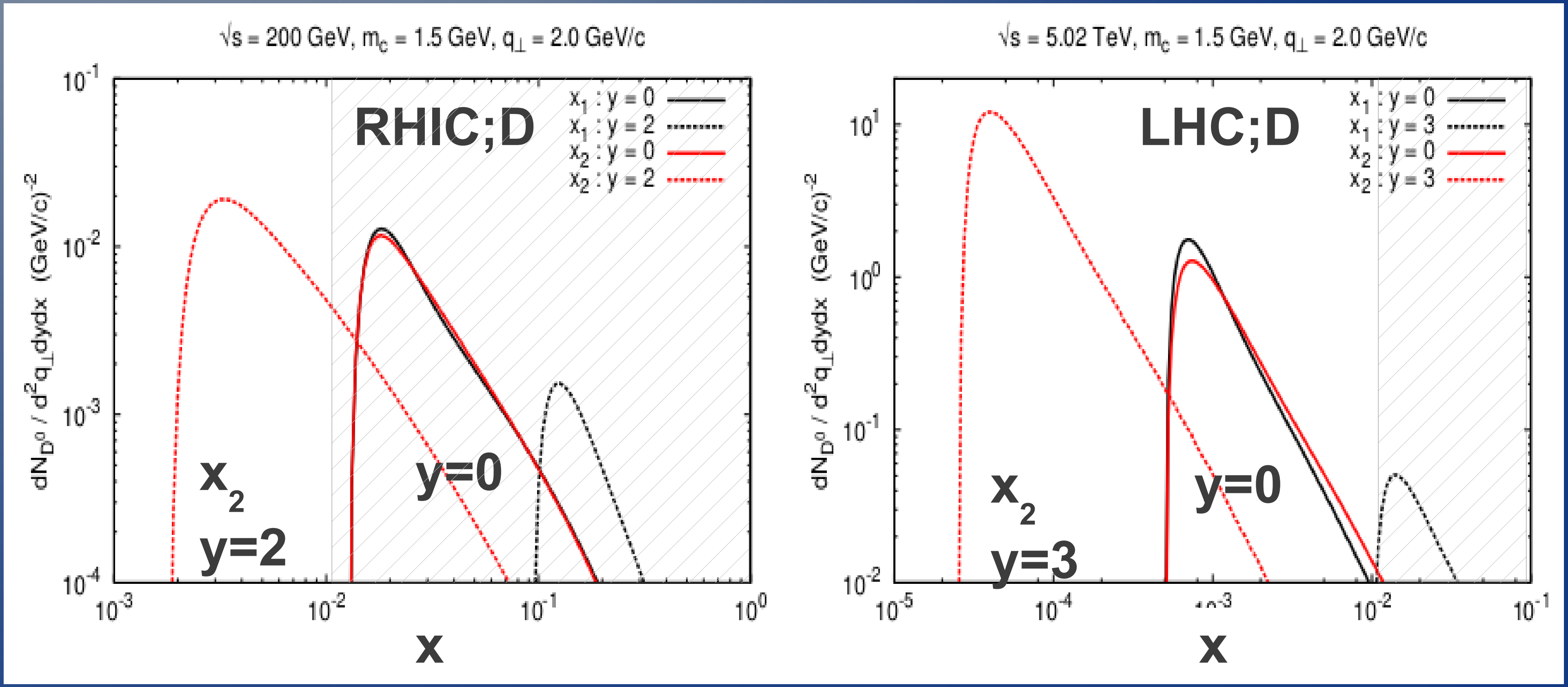
# Heavy quarks are sensitive?

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



# How about open heavy flavors ?

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



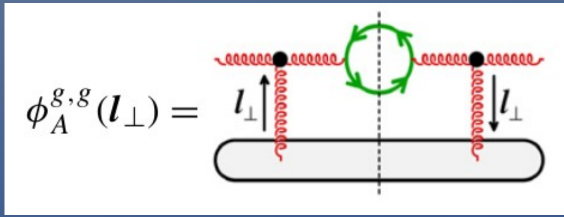
# Quark pair production in pA

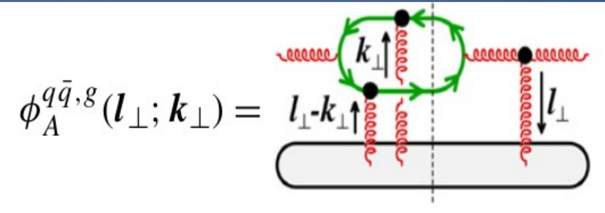
- Formula at $O(\rho_p\, \rho_A^{\infty})$ in large Nc limit

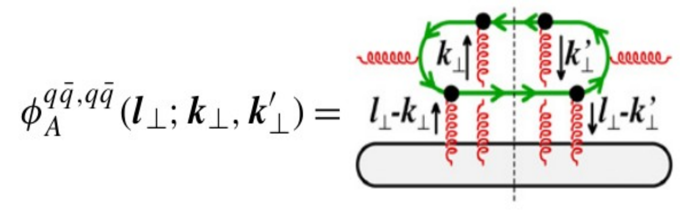
$$\frac{dN_{q\bar{q}}}{d^2\boldsymbol{p}_\perp d^2\boldsymbol{q}_\perp dy_p dy_q} = \frac{1}{\pi R_A^2}\frac{\alpha_s^2 N}{8\pi^4 d_A}\frac{1}{(2\pi)^2}\int_{\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp} \frac{\Xi(\boldsymbol{k}_{1\perp},\boldsymbol{k}_{2\perp},\boldsymbol{k}_\perp)}{\boldsymbol{k}_{1\perp}^2\,\boldsymbol{k}_{2\perp}^2}\;\phi_{A,y_2}^{q\bar{q},g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

Gelis-Blaizot-Venugopalan
HF-Gelis-Venugopalan

- Pair production --> multi-parton correlators



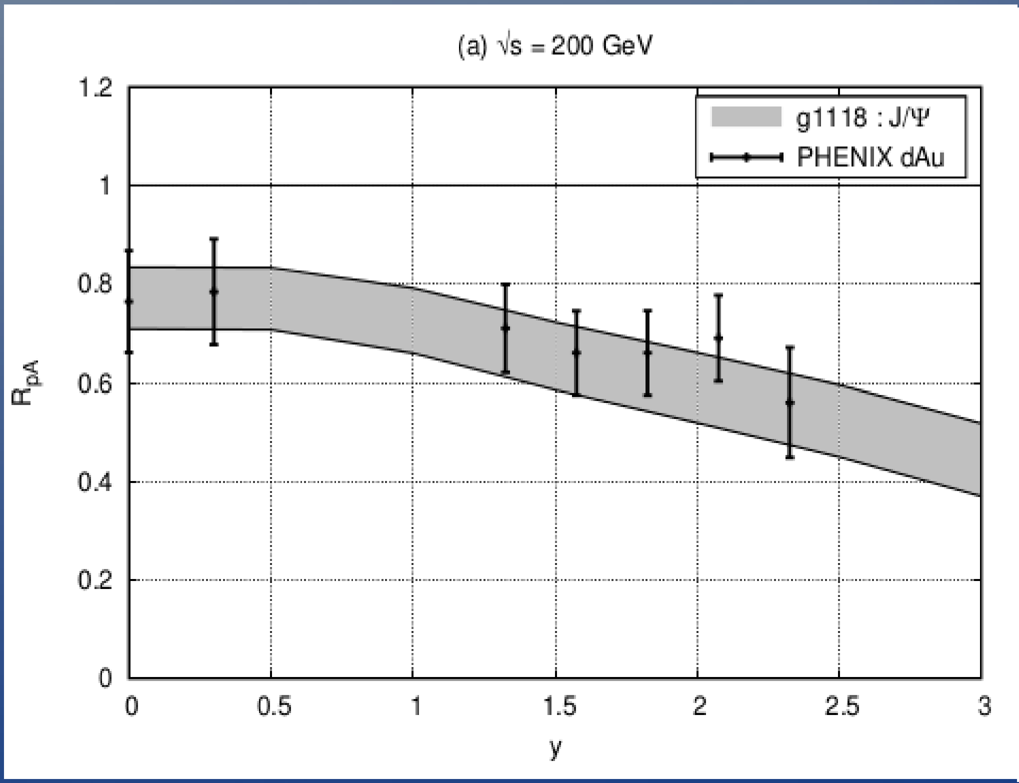



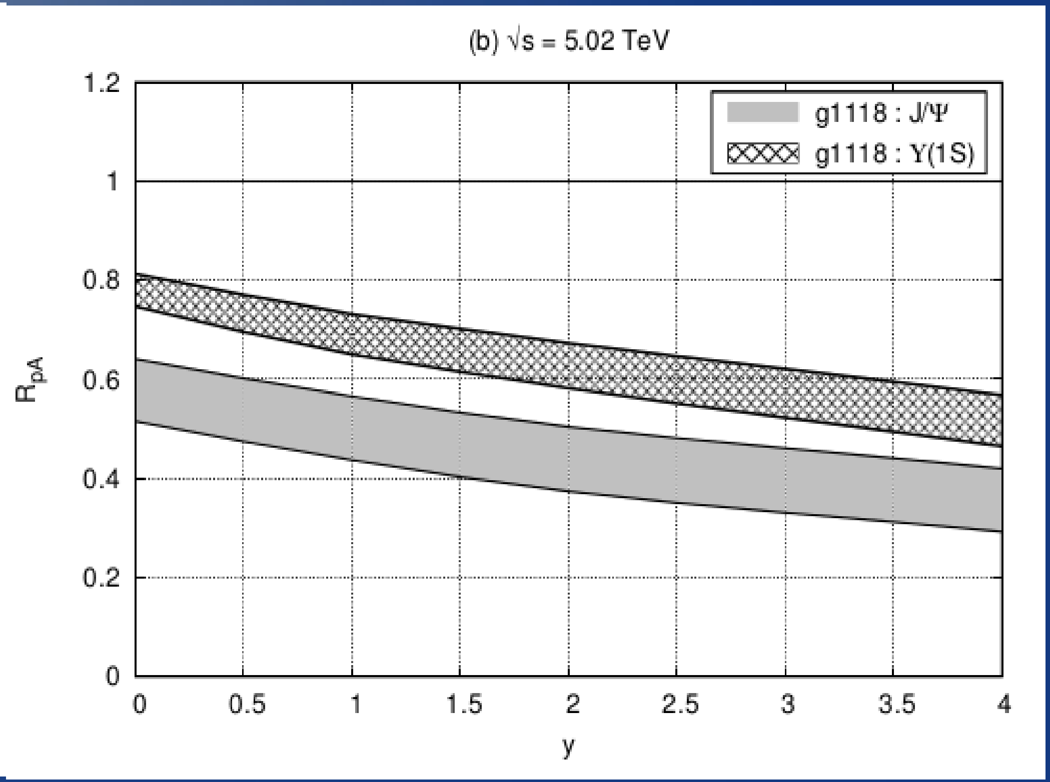




- 4-pt & 3-pt functions simplify to a product of fundamental 2-pt funs in large Nc limit

# RpA(y) for J/psi at the LHC

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

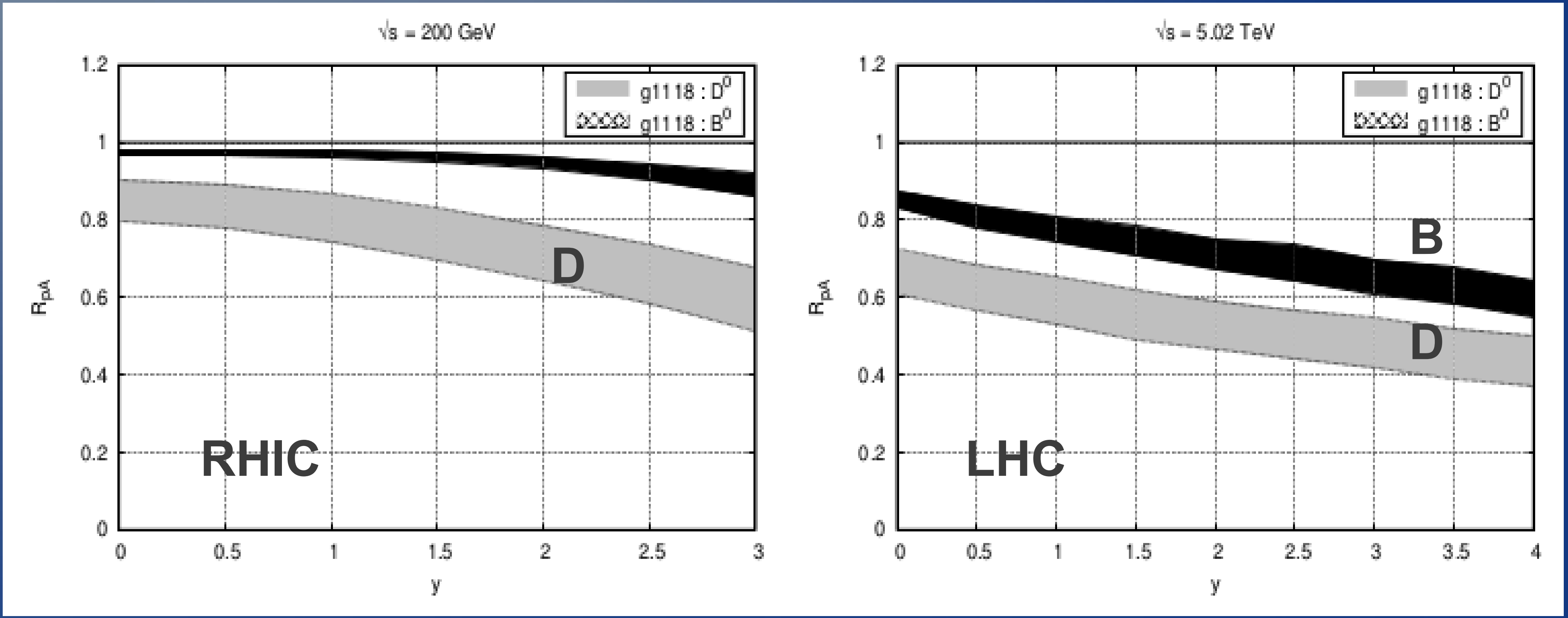



HF, Watanabe, NPA915,1, 2013

# RpA(y) for D,B (prelim)

- Suppression due to saturation is seen






HF, Watanabe

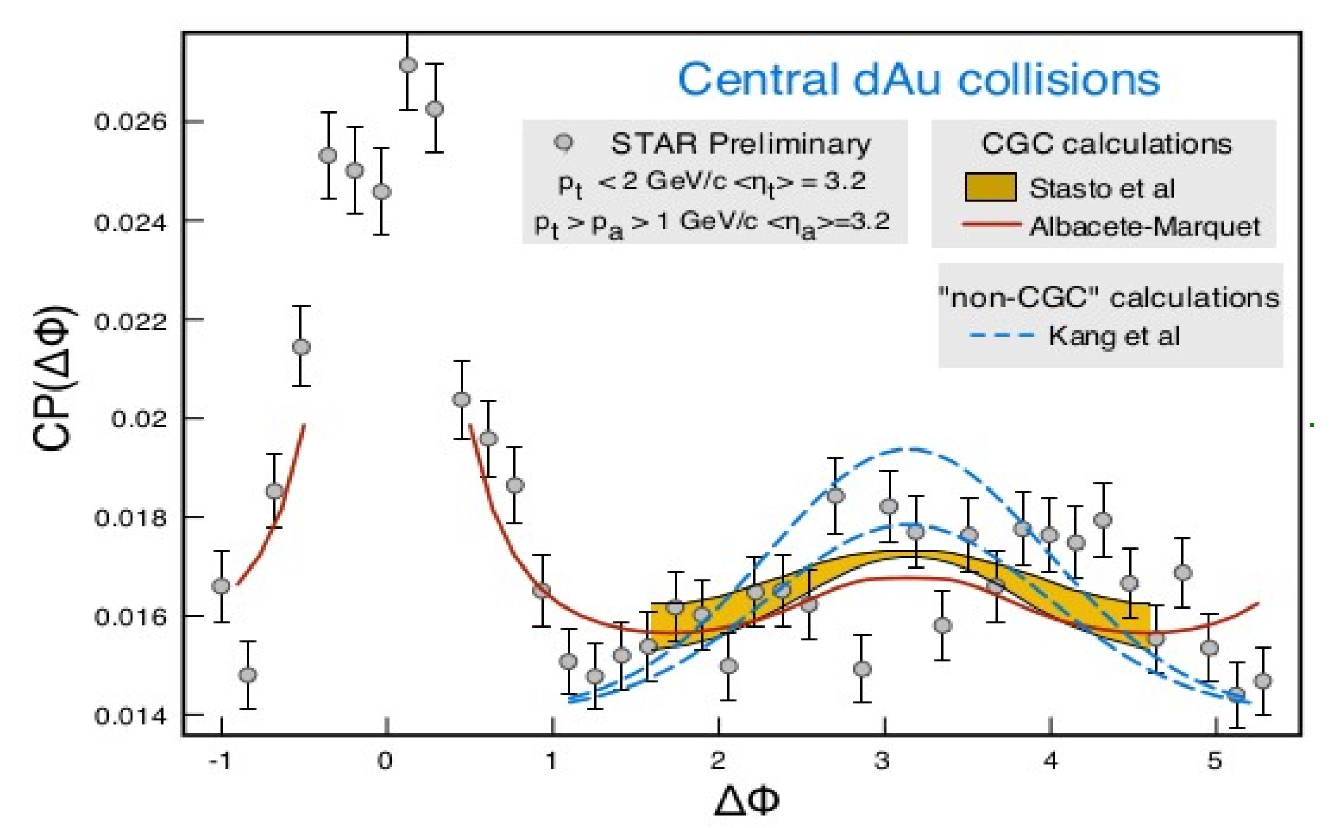
# Challenges

- Multi parton correlators from JIMWLK
- Towards NLO calculations in CGC

# di-hadron correlations at RHIC

- Extend hybrid formula to 2 particle production

$$N_{pair}(\Delta\phi) = \int_{y_i, |p_{i\perp}|} \frac{dN^{pA\to h_1 h_2 X}}{d^3p_1 d^3p_2}, \quad N_{trig} = \int_{y,\ p_\perp} \frac{dN^{pA\to hX}}{d^3p}$$

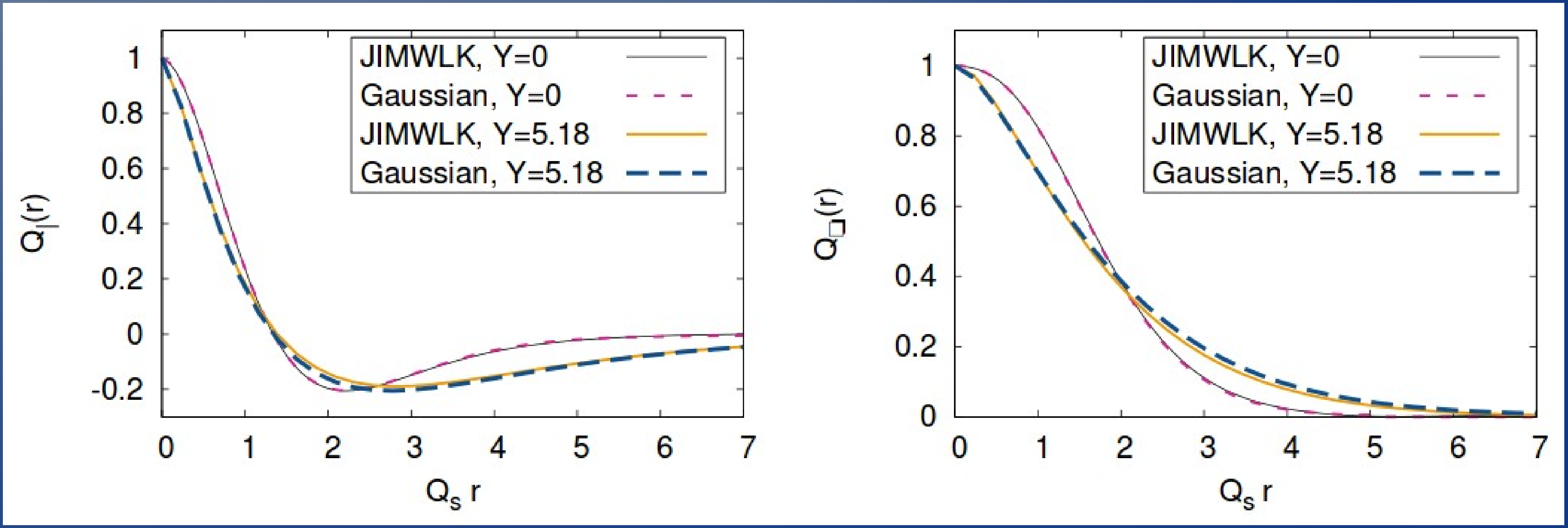



Albacete-Marquet, PRL 105, (2010)
Stasto et al. arXiv:1109.1817 [hep-ph]
Z.-B. Kang, et al. PRD85, (2012)

# di-hadron correlations at RHIC

- Extend hybrid formula to 2 particle production
- involves 4-pt correlator, which needs JIMWLK

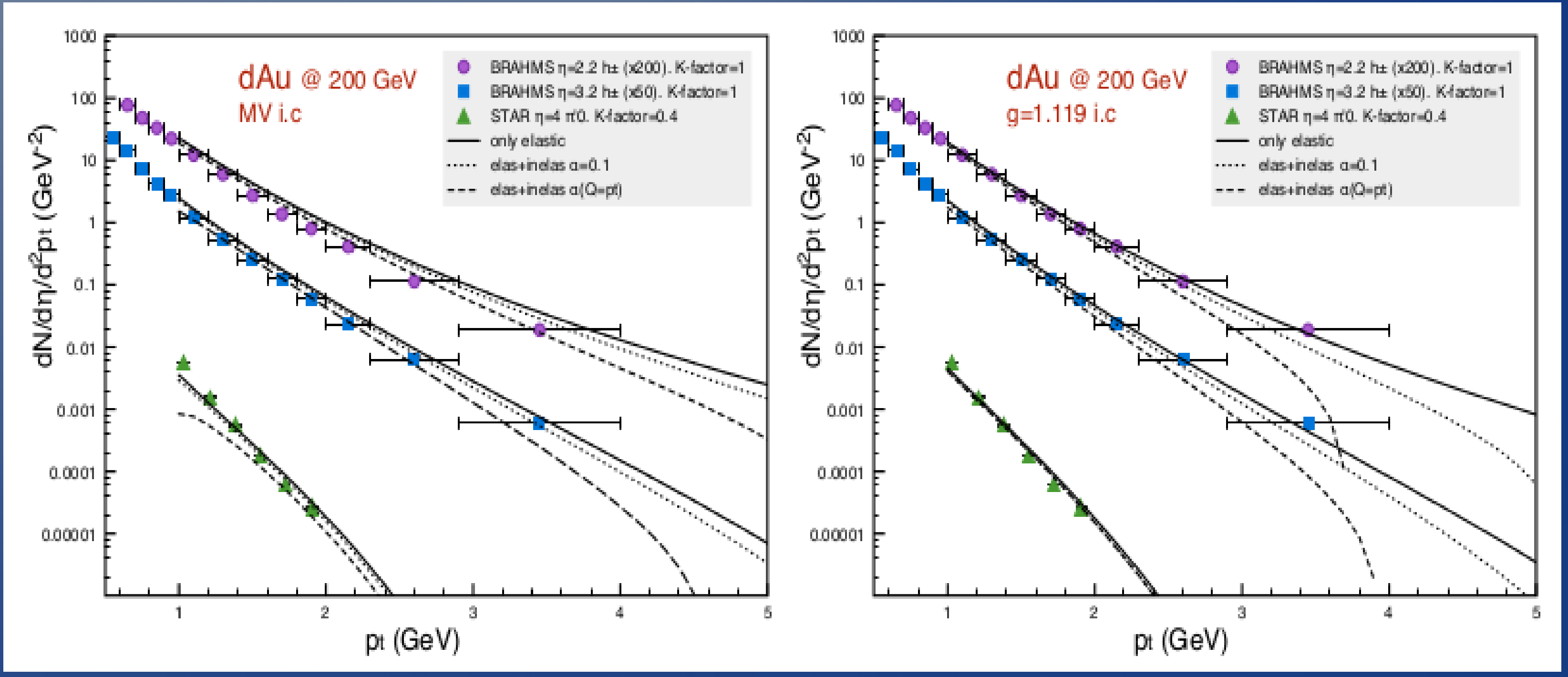
$$\hat{Q}(\mathbf{x}_T, \mathbf{y}_T, \mathbf{u}_T, \mathbf{v}_T) = \frac{1}{N_c} \mathrm{Tr}\, U(\mathbf{x}_T) U^\dagger(\mathbf{y}_T) U(\mathbf{u}_T) U^\dagger(\mathbf{v}_T).$$




Dumitru et al., Phys.Lett.B706, 219 (2011)

# Towards NLO calculation

- Part of  NLO contributionsis known to be large
- Full NLO calculation is desired



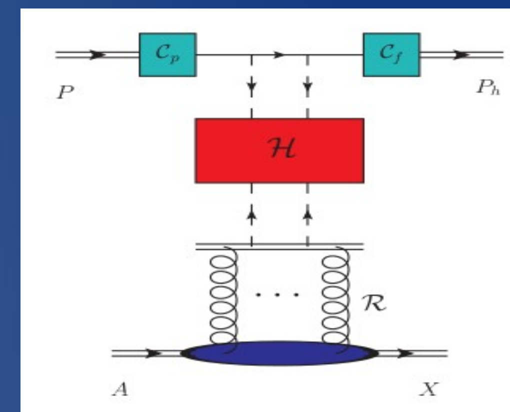

Albacete, Dumitru, HF, Nara, NPA897,1 2012

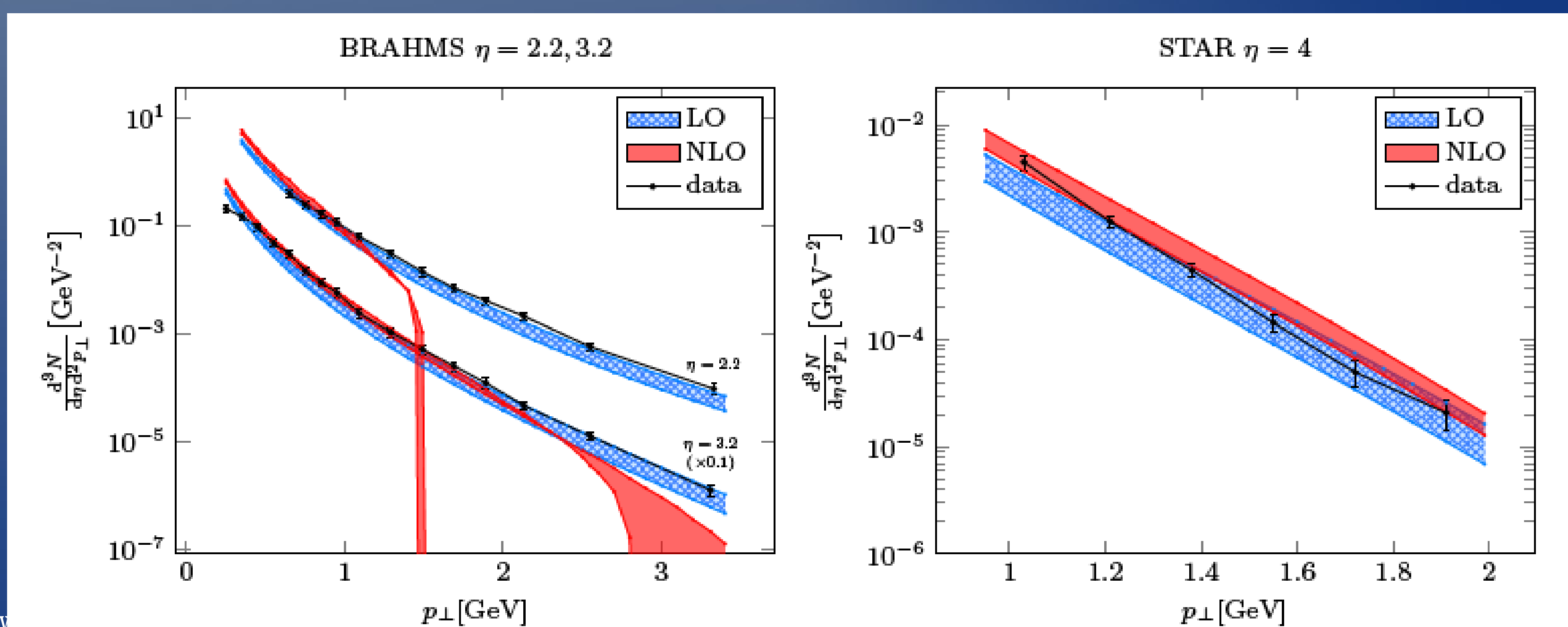
# Towards NLO calculation

Chirilli, Xiao, Yuan (2012)
Stasto, Xiao, Zaslavsky, arXiv:1307.4057

- Rapidity, collinear divergences identified and absorbed in uGD, pdf&FF, resp.

$$d\sigma = \int x f_a(x) \otimes D_a(z) \otimes \mathcal{F}_a^{x_g}(k_\perp) \otimes \mathcal{H}^{(0)} + \frac{\alpha_s}{2\pi} \int x f_a(x) \otimes D_b(z) \otimes \mathcal{F}_{(N)ab}^{x_g} \otimes \mathcal{H}_{ab}^{(1)},$$




MSTW NLO
DSS NLO
rcBK

sPHENIX w

# Summary

- rcBK phenomenology fairly works for inclusive obs in pA from RHIC to LHC
- For more robust results,
  - multi-point correlations for more exclusive obs.
  - NLO extension from LO
- Important for providing the correct I.C. for AA

# dN/dy in p-Pb collisions

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

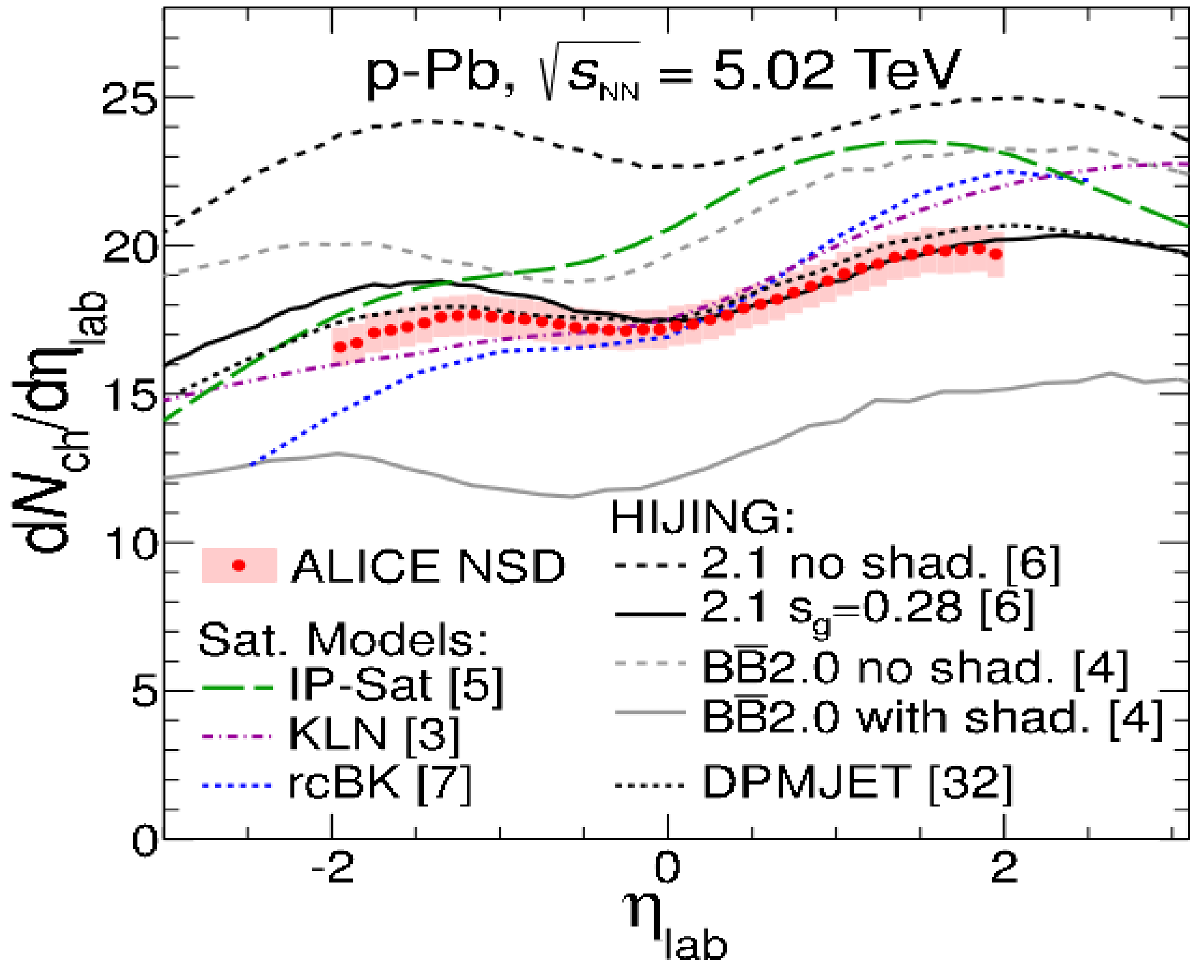



**Fig. 1:** Pseudorapidity density of charged particles measured in NSD p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared to theoretical predictions [3–7]. The calculations [4, 5] have been shifted to the laboratory system.