Shadowing, saturation, CGC and other initial state effects on heavy quark production

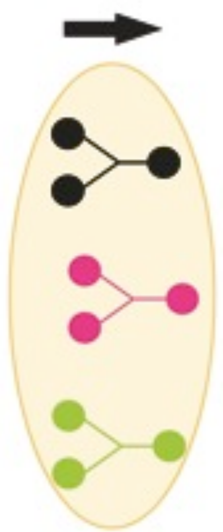
Javier L Albacete

1st Sapore Gravis Meeting, Orsay 23 Nov 2012

Saturation vs shadowing

Both relate to the same concept: # of gluons in the wave function of a nucleus at small-x is reduced wrt the simple addition of the gluon field of constituent nucleons

Saturation: Dynamical description via gluon self-interactions that tame the growth of gluon densities towards small-x

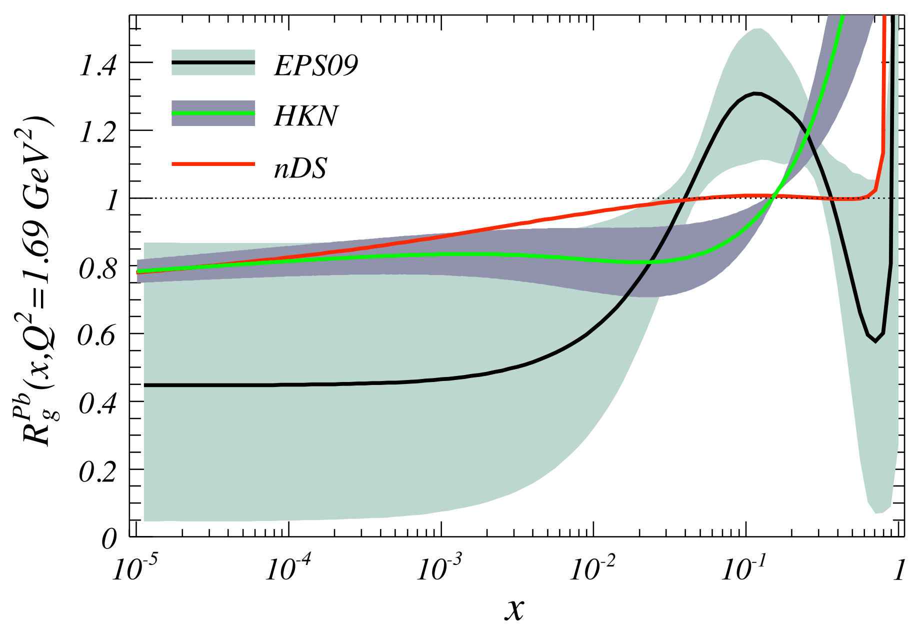


"BK-JIMWLK":

$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^{\mathbf{2}}$$

radiation recombination

• Nuclear shadowing: Empiric parametrization fitted to data. Q2-depencende assumed to be described by DGLAP evolution.

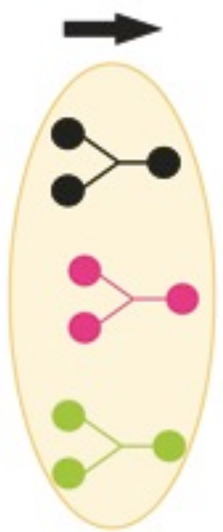


• Also models 'a la' Gribov-Glauber

Saturation vs shadowing

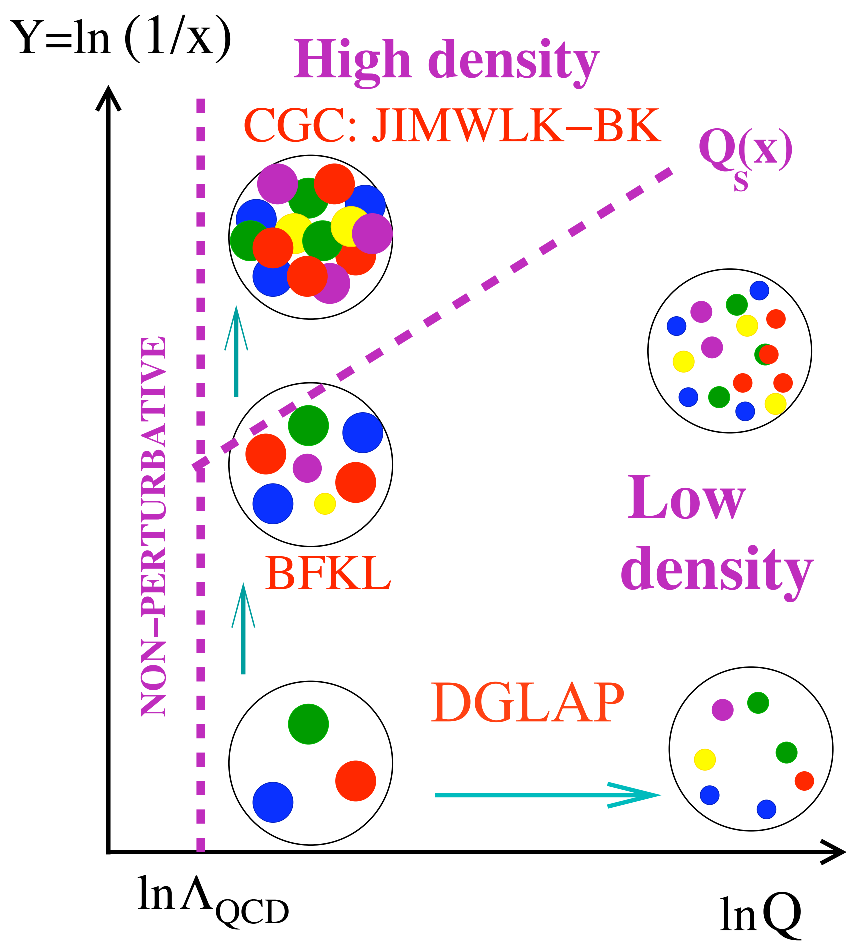
Both relate to the same concept: # of gluons in the wave function of a nucleus at small-x is reduced wrt the simple addition of the gluon field of constituent nucleons

Saturation: Dynamical description via gluon self-interactions that tame the growth of gluon densities towards small-x

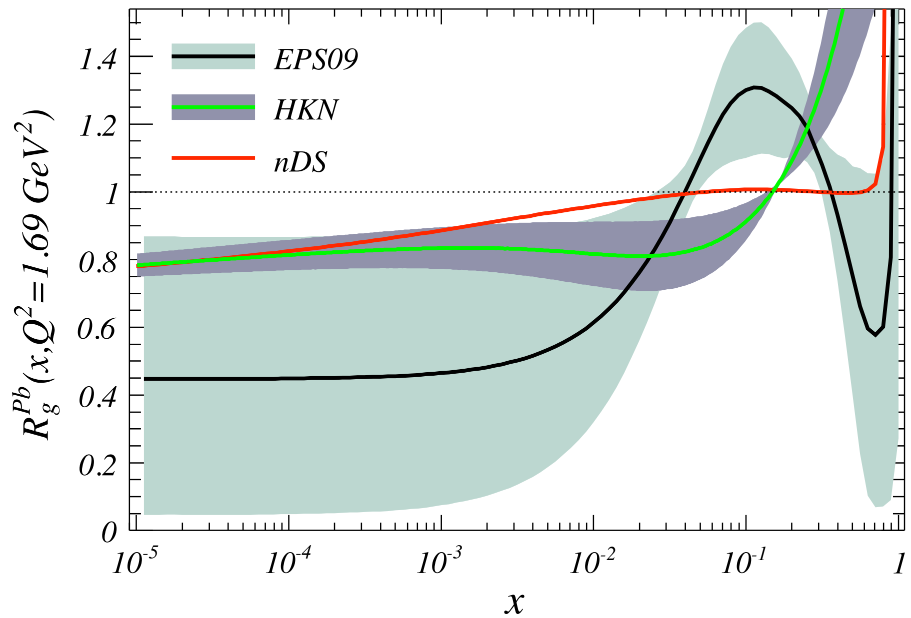


"BK-JIMWLK":

$$\frac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \underbrace{\mathcal{K}\otimes\phi(\mathbf{x},\mathbf{k_t})}_{\text{radiation}} - \underbrace{\phi(\mathbf{x},\mathbf{k_t})^{\mathbf{2}}}_{\text{recombination}}$$



• Nuclear shadowing: Empiric parametrization fitted to data. Q2-depencende assumed to be described by DGLAP evolution.

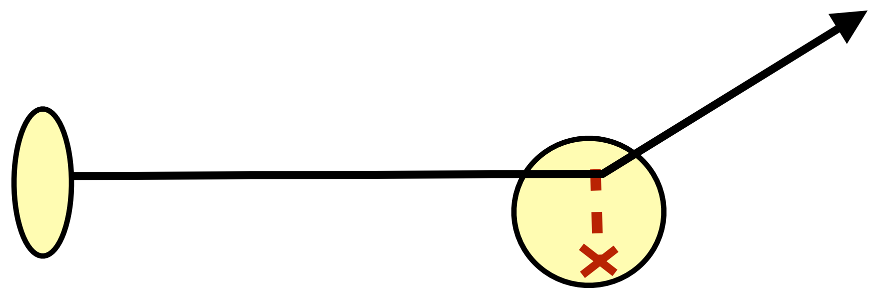


• Also models 'a la' Gribov-Glauber

Formalisms to describe particle production

- COLLINEAR FACTORIZATION: $\mathbf{d\sigma \sim xf_1(x_1, Q^2) \otimes xf_2(x_2, Q^2) \otimes d\sigma^{ab\to cd} + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)}$

  - Q^2-dependence: DGLAP evolution
    - x-dependence: fitted to data



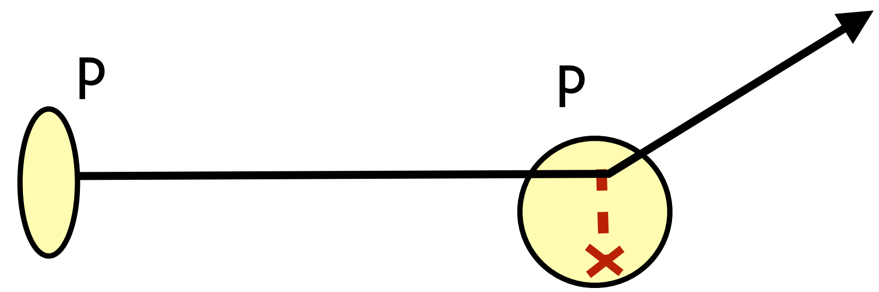
- Multiple scatterings (higher twists) neglected
- All nuclear effects absorbed in nPDF's

$$f_{a/Au}(x, Q^2) = f_{a/p}(x, Q^2)\, R_{a/Au}(x, Q^2)$$

Formalisms to describe particle production

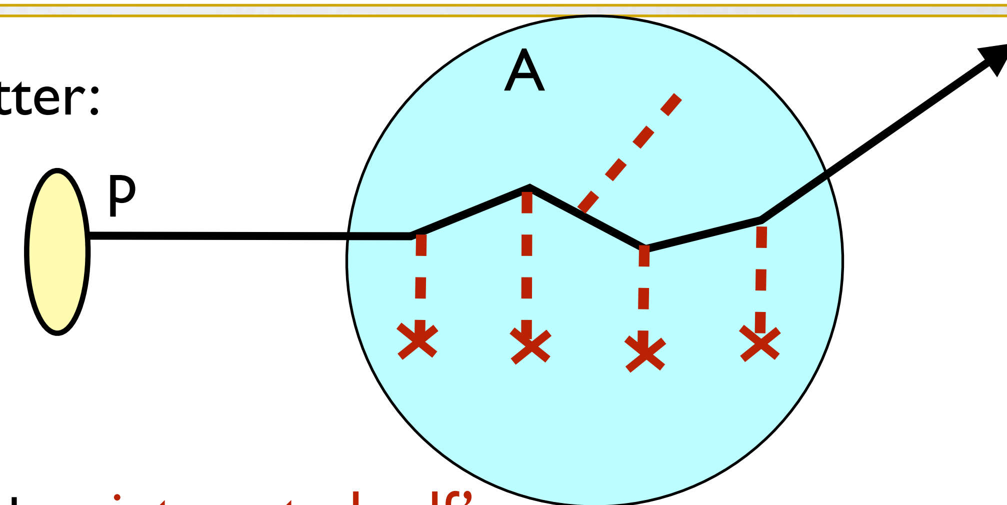
- COLLINEAR FACTORIZATION: $d\sigma \sim xf_1(x_1, Q^2) \otimes xf_2(x_2, Q^2) \otimes d\sigma^{ab\to cd} + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$

  - Q^2-dependence: DGLAP evolution
    - x-dependence: fitted to data
- Multiple scatterings (higher twists) neglected
- All nuclear effects absorbed in nPDF's



$$f_{a/Au}(x, Q^2) = f_{a/p}(x, Q^2)\, R_{a/Au}(x, Q^2)$$

- At small-Q multiple (elastic and inelastic) scatterings matter:
  - Momentum broadening
  - Energy loss, absorption (Ask experts in the room)



$\Rightarrow$ Glauber-Eikonal multiple independent scatterings + unintegrated pdf's:

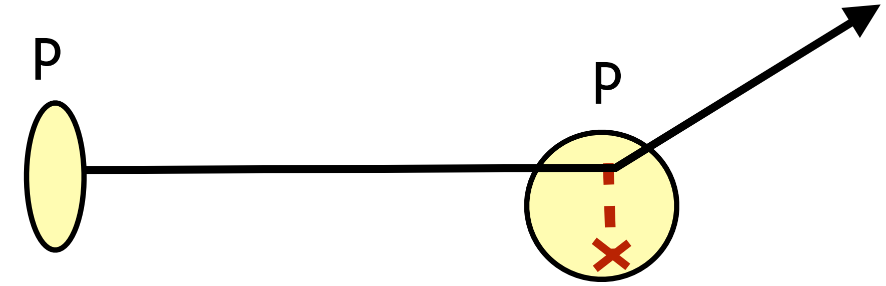
$$f_{a/A}(x, Q^2) \rightarrow F_{a/A}(x, Q^2, <k_T^2>) \rightarrow F_{a/A}(x, Q^2, <k_T^2> + \Delta k_T^2(\sqrt{s}, b, p_t))$$

intrinsic kt　　　　momentum broadening

$\Rightarrow$ Coherent High Twist calculation (up to twist-4)

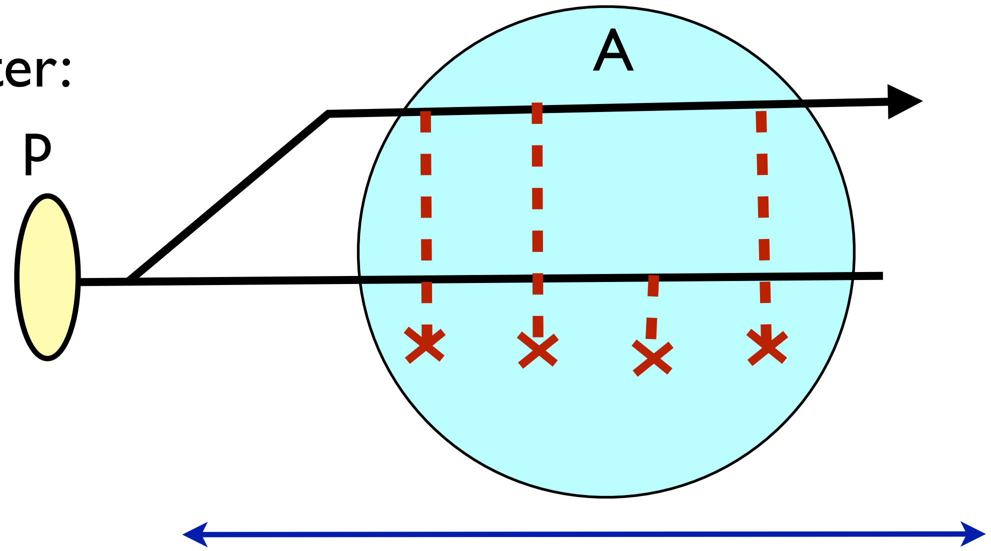
Formalisms to describe particle production

- COLLINEAR FACTORIZATION: $\mathbf{d}\sigma \sim \mathbf{xf_1(x_1, Q^2)} \otimes \mathbf{xf_2(x_2, Q^2)} \otimes \mathbf{d}\sigma^{\mathbf{ab\to cd}} + \mathcal{O}\left(\frac{\mathbf{\Lambda^2}}{\mathbf{Q^2}}\right)$
  - Q^2-dependence: DGLAP evolution
    - x-dependence: fitted to data
- Multiple scatterings (higher twists) neglected
- All nuclear effects absorbed in nPDF's



$$f_{a/Au}(x, Q^2) = f_{a/p}(x, Q^2)\, R_{a/Au}(x, Q^2)$$

- At small-Q multiple (elastic and inelastic) scatterings matter:
  - Momentum broadening
  - Energy loss (Ask experts in the room)



$$L_{coh} \sim \frac{1}{2m_N x_2} \gtrsim R_A$$

⇒ CGC

- At small-x, the multiple scatterings are coherent
- High density enhances HT ~ $O(Q_s^2/Q^2)$
- CGC= All order coherent resummation of multiple scatterings

+ small-x non-linear evolution (in the eikonal, recoil-less approximation

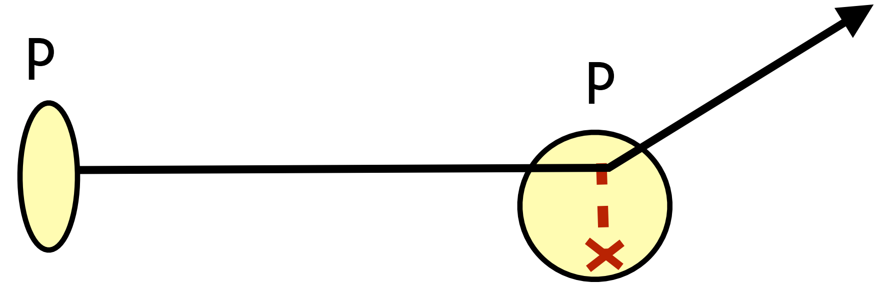
- In simple cases (inclusive gluon production) factorizable results:

$$\mathbf{d}\sigma \sim \varphi_{\mathbf{1}}(\mathbf{x_1}, \mathbf{k_t}) \otimes \varphi_{\mathbf{1}}(\mathbf{x_2}, \mathbf{k_t}) \otimes \sigma^{\mathbf{off-shell}}$$

Formalisms to describe particle production

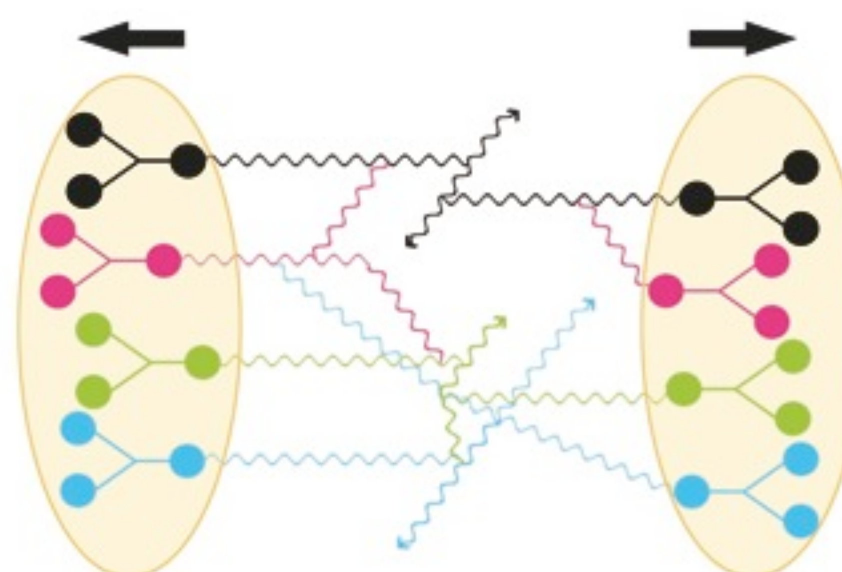
- COLLINEAR FACTORIZATION: $d\sigma \sim xf_1(x_1, Q^2) \otimes xf_2(x_2, Q^2) \otimes d\sigma^{ab\to cd} + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$

  - Q^2-dependence: DGLAP evolution
    - x-dependence: fitted to data
- Multiple scatterings (higher twists) neglected
- All nuclear effects absorbed in nPDF's



$$f_{a/Au}(x, Q^2) = f_{a/p}(x, Q^2)\, R_{a/Au}(x, Q^2)$$

- At small-Q multiple (elastic and inelastic) scatterings matter:
  - Momentum broadening
  - Energy loss (Ask experts in the room)



$\Rightarrow$ CGC

- At small-x, the multiple scatterings are coherent
- High density enhances HT ~ $O(Q^2_s/Q^2)$
- CGC= All order coherent resummation of multiple scatterings

+ small-x non-linear evolution (in the eikonal, recoil-less approximation

$$\mathcal{A}(k \lesssim Q_s) \sim \frac{1}{g}$$

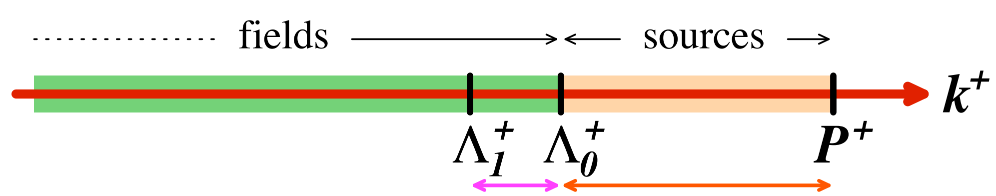
$$g\mathcal{A} \sim \mathcal{O}(1)$$

- **Coherence effects are essential for the description of data in HIC collisions (RHIC, LHC)**

- **Is the CGC effective theory (at its present degree of accuracy) the best suited framework to quantify those coherence phenomena in LHC HI collisions?**

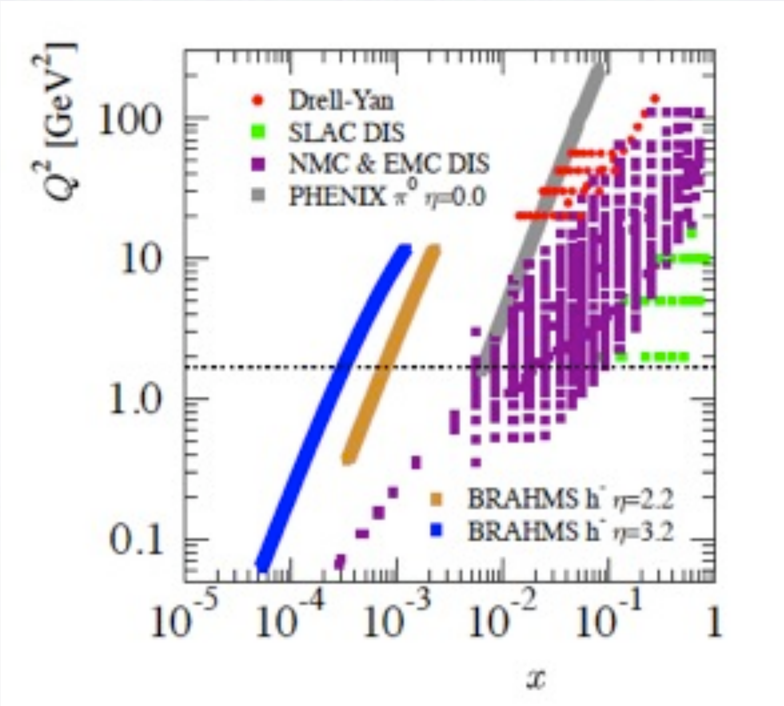
- **Pros and Cons:**
  - Derived from QCD within a controlled approximation -> Theory driven predictive power
  - Systematic unified description of different observables/collision systems
  - Limited degree of applicability: High-(x,Q2) effects not accounted for

small-x d.o.f (dynamical) **valence d.o.f (static)**



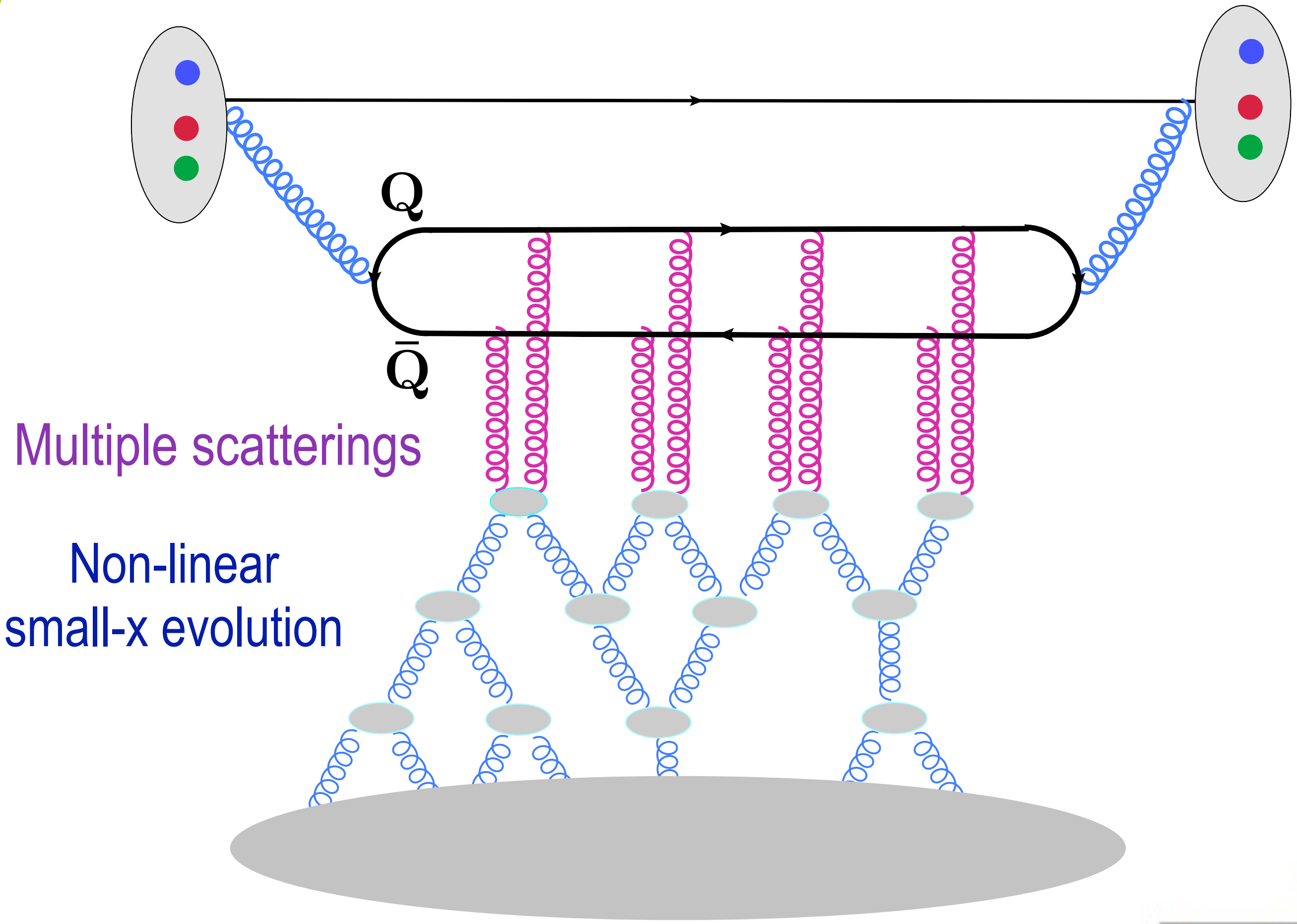
LHC **RHIC** **SPS**

- **Common problem:** - Severe paucity of small-x data on nuclei to constrain NP parameters of the theory

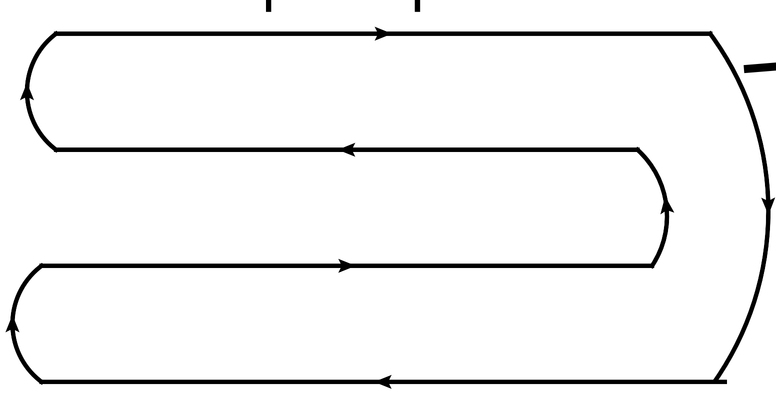


Heavy Quark Production in the CGC in pA collisions

Gelis, Blaizot, Venugopalan
Fujii, Gelis, Venugopalan
Kovchegov, Tuchin



- Full result violates kt-factorization
- Involves 3 diferent "objects to describe the nucleus objects (e.g. quadrupole)
- Multiple scatterings: redistribution in pt-space
- Small-x evolution: Suppression of total yields

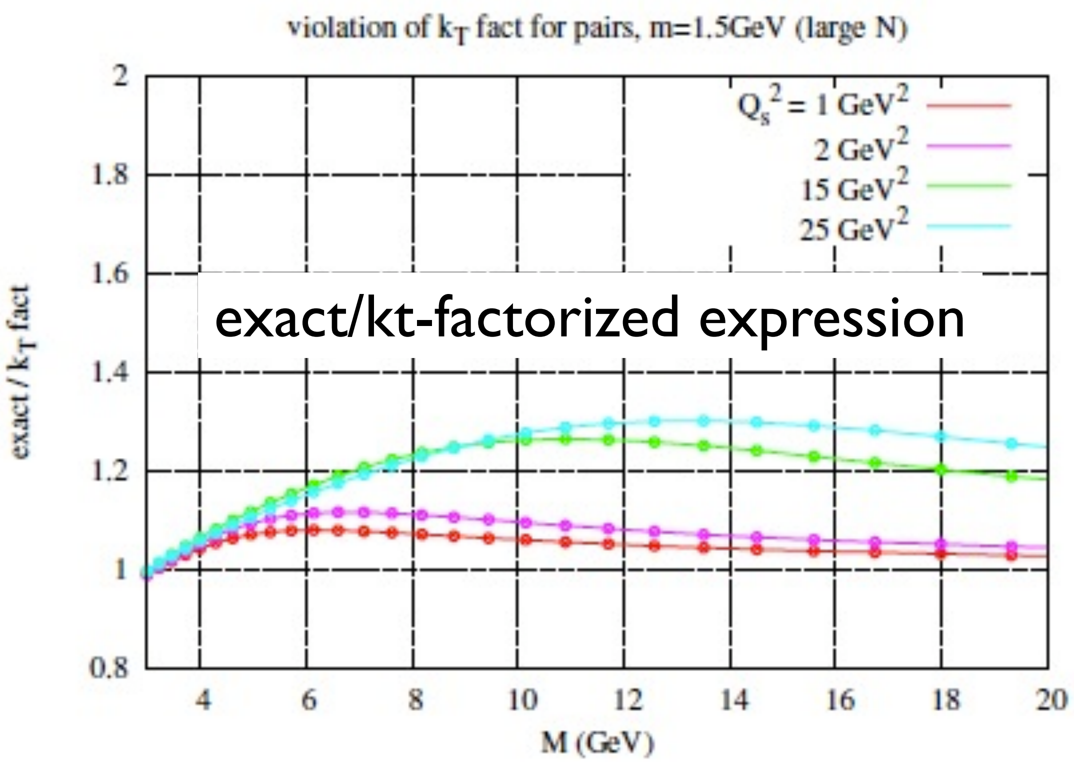


$$
\begin{aligned}
\frac{d\sigma}{d^2p_\perp d^2q_\perp dy_p dy_q} = \frac{\alpha_s^2 N}{8\pi^4 d_A} \int_{k_{1\perp},k_{2\perp}} & \frac{\delta(p_\perp + q_\perp - k_{1\perp} - k_{2\perp})}{k_{1\perp}^2 k_{2\perp}^2} \\
\times \Big\{ & \int_{k_\perp,k'_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T'^{\dagger}_{q\bar{q}}\gamma^0\Big] \varphi_A^{q\bar{q},q\bar{q}}(k_\perp, k_{2\perp}-k_\perp; k'_\perp, k_{2\perp}-k'_\perp) \\
& + \int_{k_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{q\bar{q}}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0\Big] \varphi_A^{q\bar{q},g}(k_\perp, k_{2\perp}-k_\perp; k_{2\perp}) \\
& + \int_{k_\perp} \mathrm{tr_d}\Big[(\not{q}+m)T_{g}(\not{p}-m)\gamma^0 T^{\dagger}_{q\bar{q}}\gamma^0\Big] \varphi_A^{q\bar{q},g}(k_\perp, k_{2\perp}-k_\perp; k_{2\perp}) \\
& + \mathrm{tr_d}\Big[(\not{q}+m)T_{g}(\not{p}-m)\gamma^0 T^{\dagger}_{g}\gamma^0\Big] \varphi_A^{g,g}(k_{2\perp}) \Big\} \varphi_p(k_{1\perp}) \, . \qquad (48)
\end{aligned}
$$

Gelis, Blaizot, Venugopalan
Fujii, Gelis, Venugopalan
Kovchegov, Tuchin

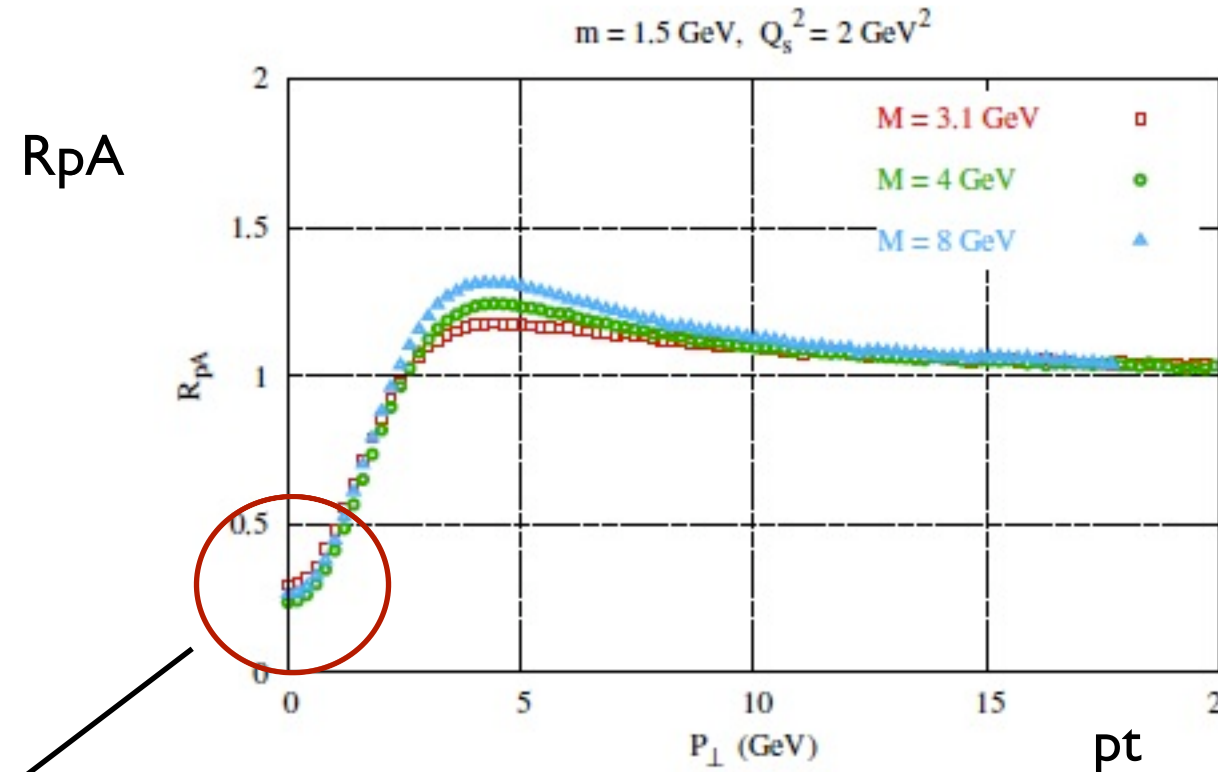
Heavy Quark Production in the CGC: Generic Features

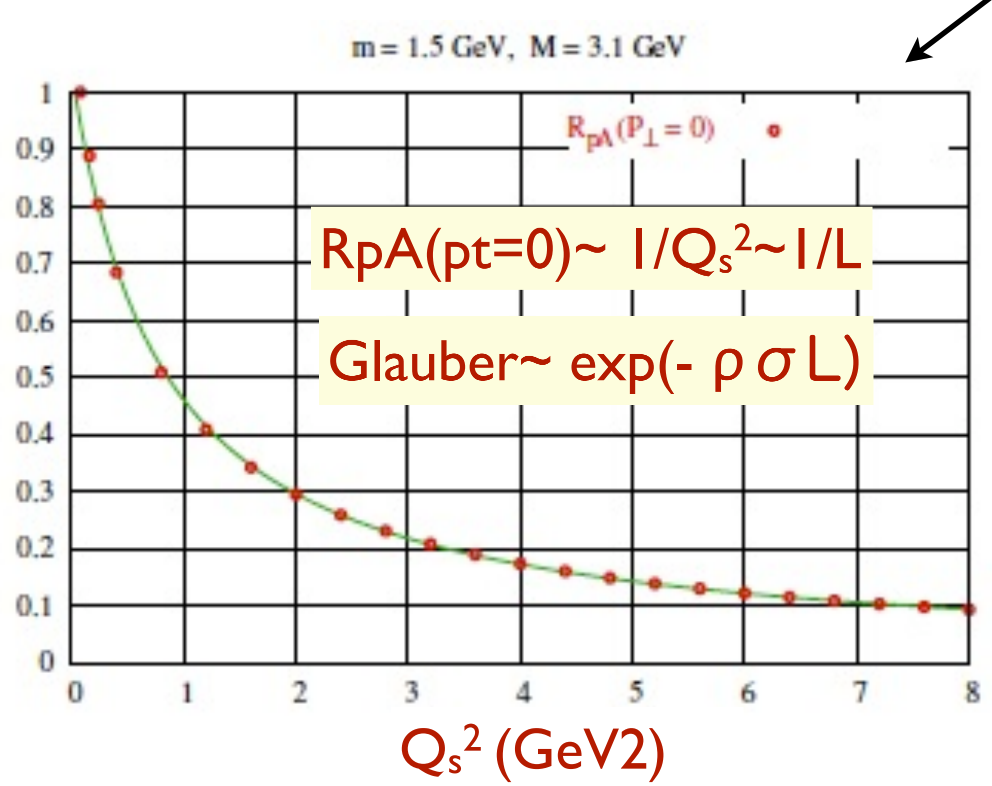
- Full result violates kt-factorization



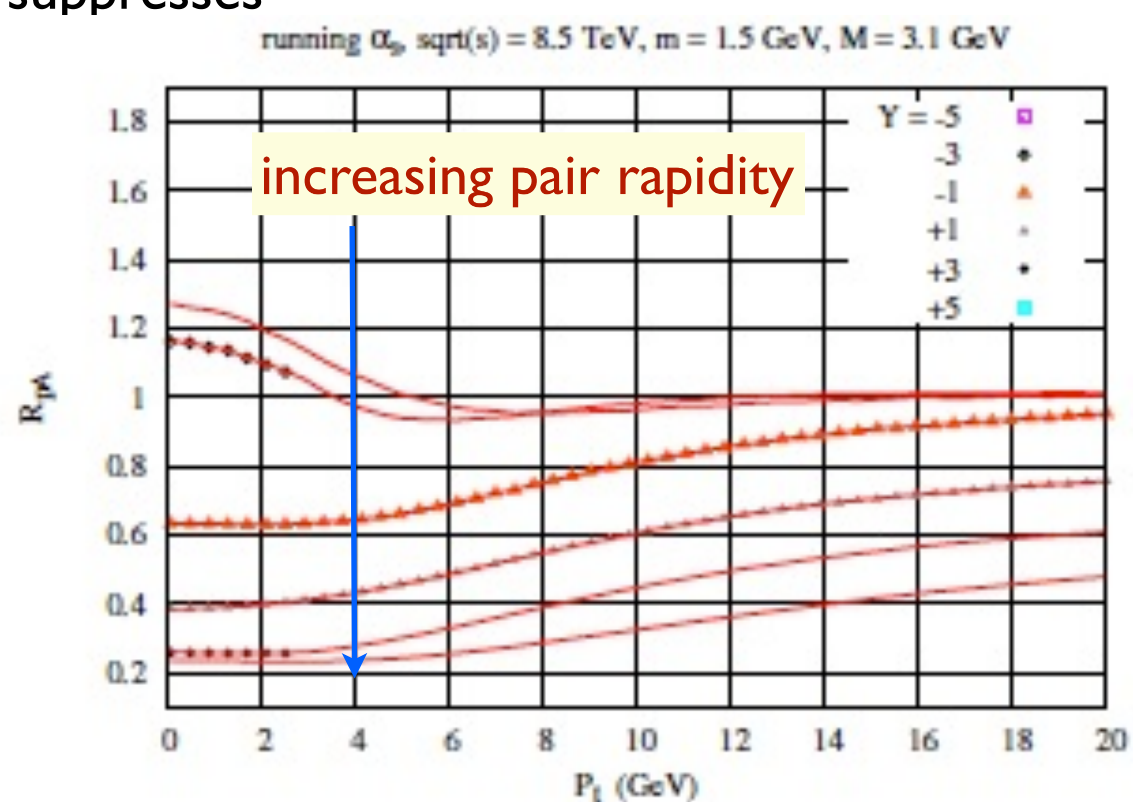
Fujii, Gelis, Venugopalan

- Multiple scatterings: redistribution in pt-space





Non-linear small-x evolution: further suppression suppresses



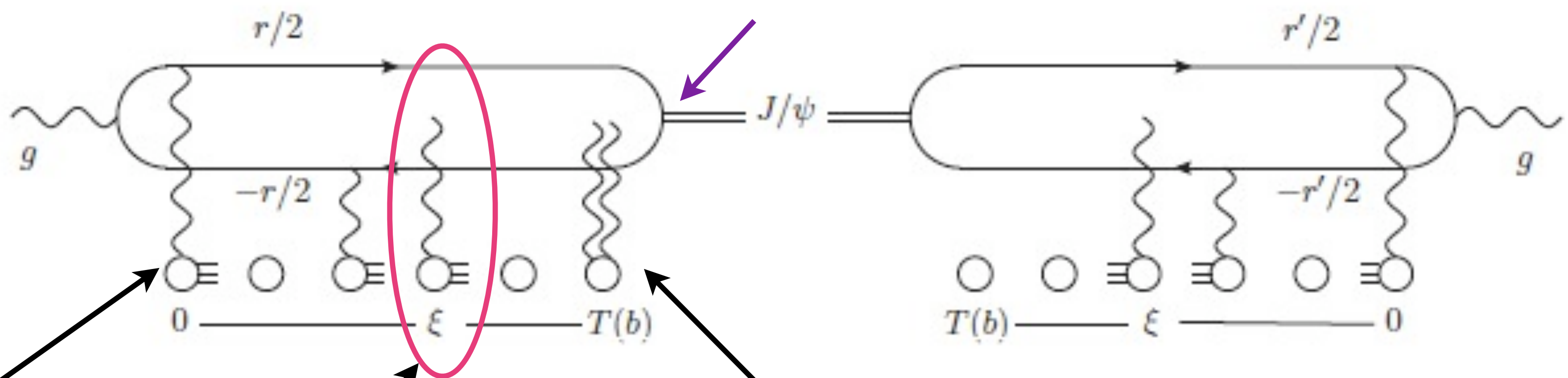
J/Psi production in the CGC in pA collisions

Dominguez, Kharzeev, Levin, Mueller Tuchin

- Color singlet model for J/Psi production assumed
- J/Psi quantum numbers (1^{--}) impose constraints to the resummation of multiple scatterings

Proyection of cc into J/Psi

gluon pdf



Inelastic & elastic rescatterings

Inelastic scattering putting the dipole in color singlet

Only elastic (not-color changing) rescatterings

$$\frac{d\sigma_{pA\to J/\psi X}}{dy d^2b} = x_1 G(x_1, m_c^2) \int_0^1 dz \int \frac{d^2 r}{4\pi} \Phi(r, z) \int_0^1 dz' \int \frac{d^2 r'}{4\pi} \Phi^*(r', z') \times \frac{4 r \cdot r'}{(r + r')^2} \left(e^{-\frac{Q_s^2}{16}(r - r')^2} - e^{-\frac{Q_s^2}{8}(r^2 + r'^2)} \right).$$

AA collisions (ad-hoc extension and symmetrization of the pA result):

$$\frac{d\sigma_{A_1A_2\to J/\psi X}}{dy\, d^2b\, d^2B} = \int_0^1 dz \int \frac{d^2\underline{r}}{4\pi} \int_0^1 dz' \int \frac{d^2\underline{r}'}{4\pi} \Phi(\underline{r}, z)\, \Phi^*_{\lambda\lambda'}(\underline{r}', z')\, 2T_{A_1A_2\to JX}(\underline{r}, \underline{r}')$$

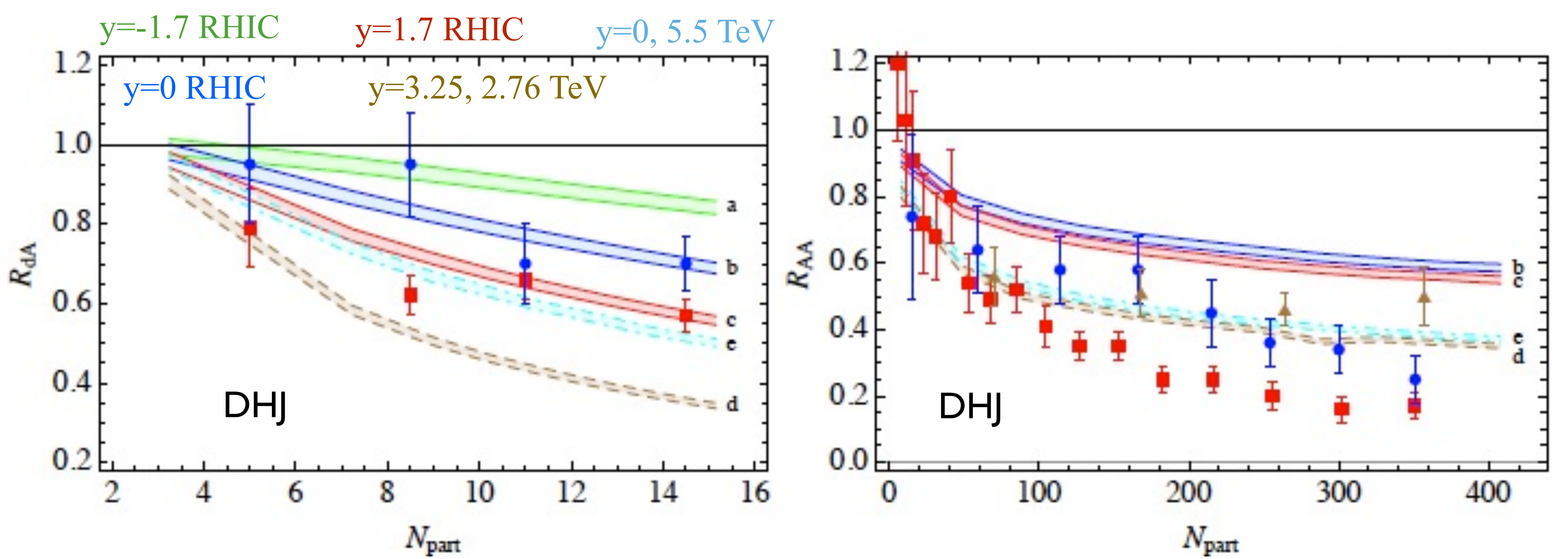
$$T_{A_1A_2\to JX}(\underline{r}, \underline{r}') = \frac{C_F}{2\alpha_s \pi^2} \frac{Q_{s1}^2 Q_{s2}^2}{Q_{s1}^2 + Q_{s2}^2} \frac{4\underline{r}\cdot\underline{r}'}{(\underline{r}+\underline{r}')^2} \left(e^{-\frac{1}{16}(Q_{s1}^2+Q_{s2}^2)(\underline{r}-\underline{r}')^2} - e^{-\frac{1}{8}(Q_{s1}^2+Q_{s2}^2)(r^2+r'^2)} \right)$$

Phenomenology

Dominguez, Kharzeev, Levin, Mueller Tuchin, Sep 2011

- pp baseline calculated using the limit A->1 in the pA calculation
- x-dependence: Non-linear evolution replaced by DHJ or bCGC models

pt-integrated yields:

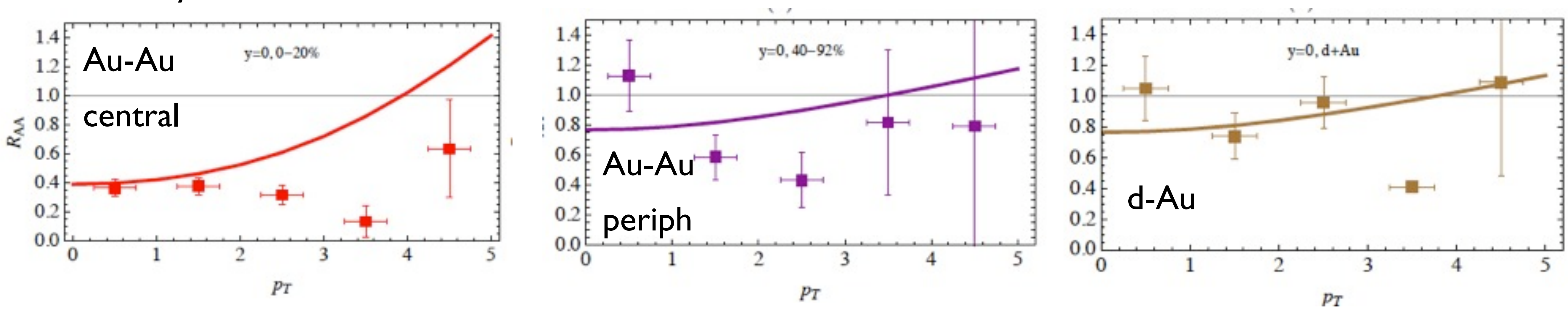


Phenomenology: pt-distributions

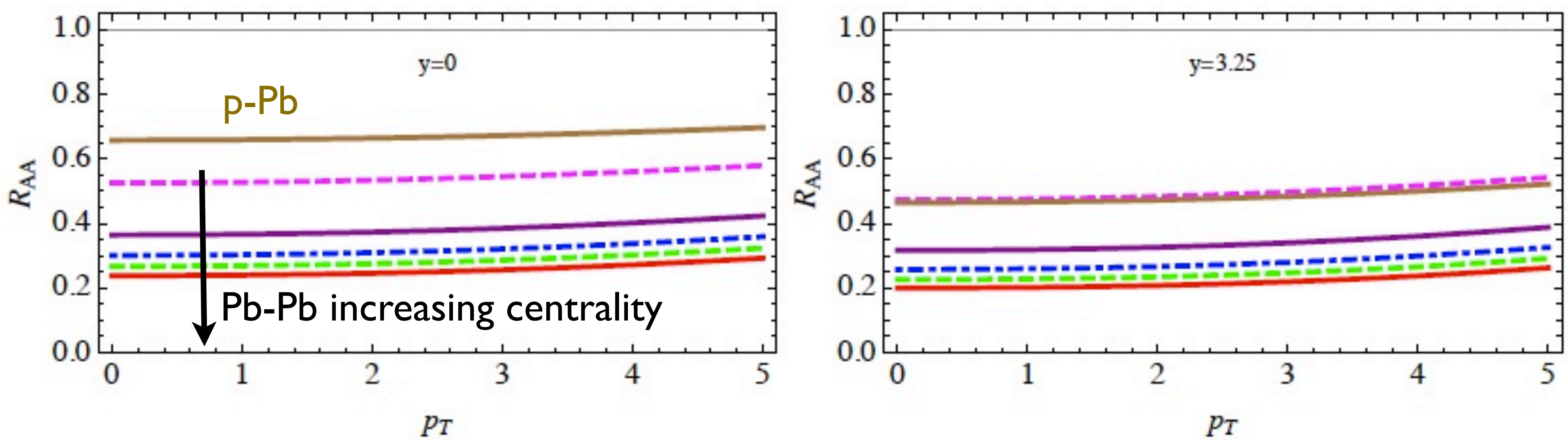
Kharzeev, Levin, Tuchin, May 2012

- x-dependence: Non-linear evolution replaced by DHJ model with $Q_s^2 = \Lambda^2 A^{1/3} e^{\lambda y} = 0.13\,\mathrm{GeV}^2 e^{\lambda y} N_{\mathrm{coll}}$
- pp distribution fitted to ALICE data: $\dfrac{d\sigma_{pp\to J/\psi X}}{\sigma_{pp}\, d^2p_\perp} = \mathcal{N}\left(1+\dfrac{p_\perp^2}{p_0^2}\right)^{-6}$

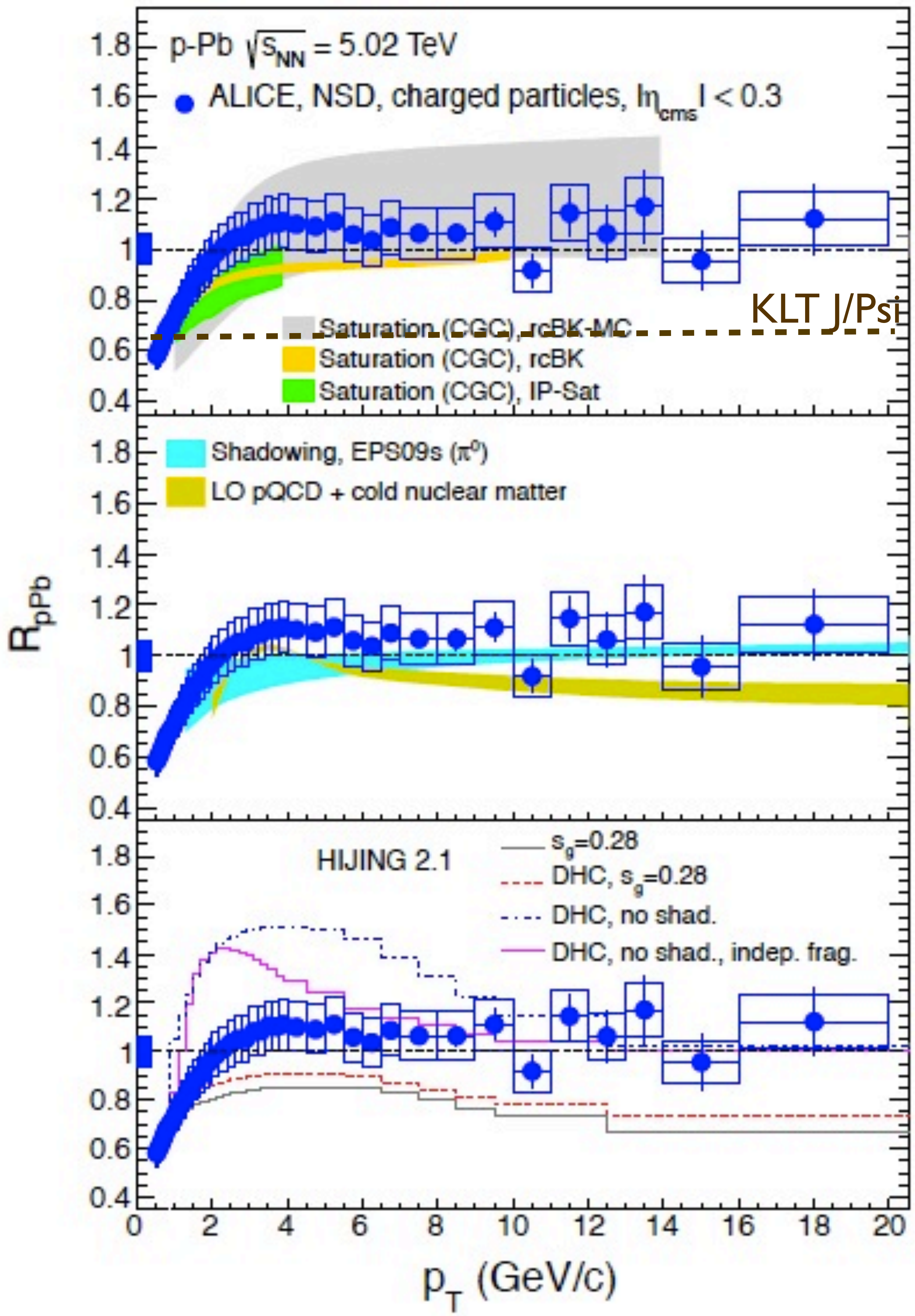
RHIC, y=0



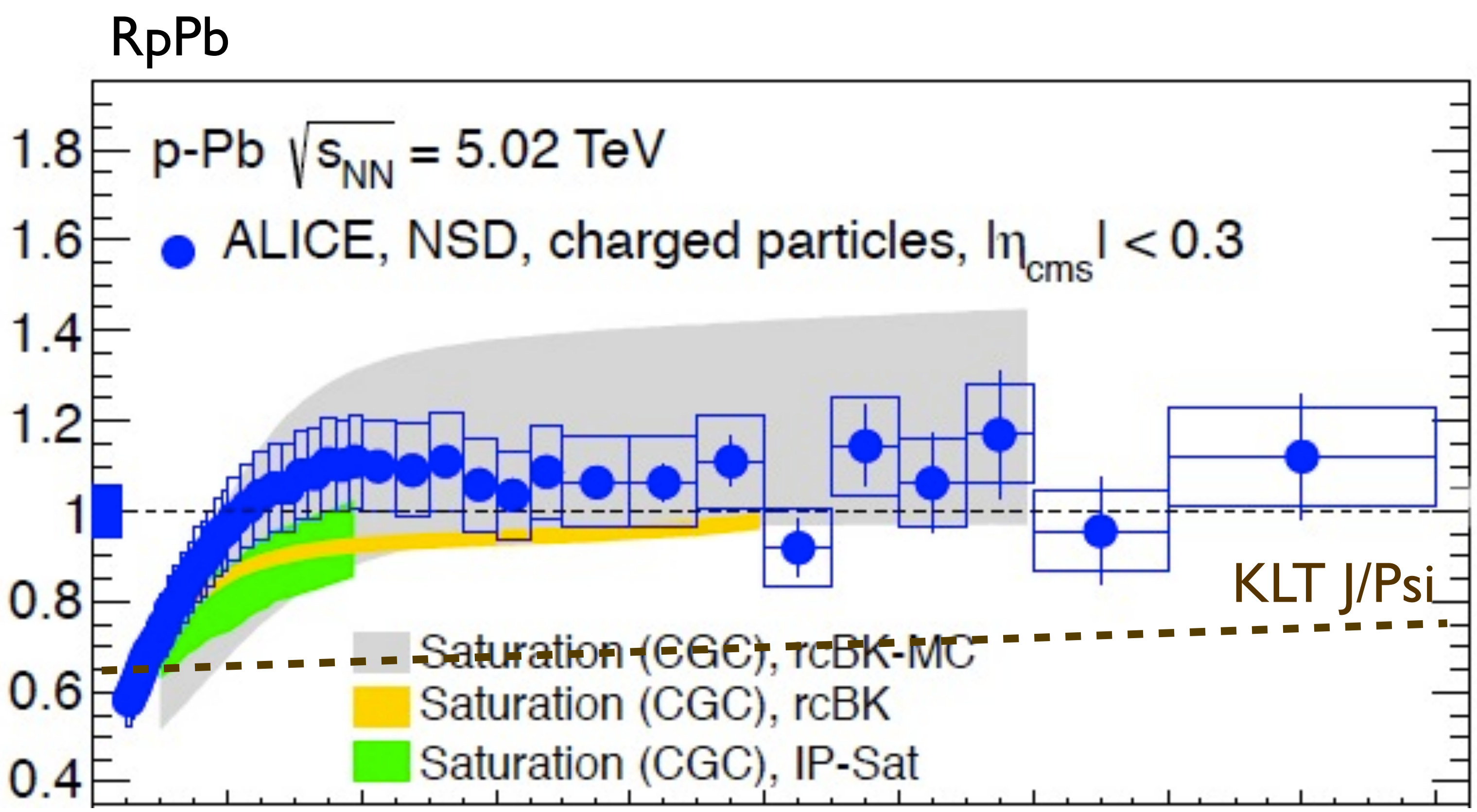
LHC @ 7TeV



Comments on recent p-Pb ALICE data



Comments on recent p-Pb data

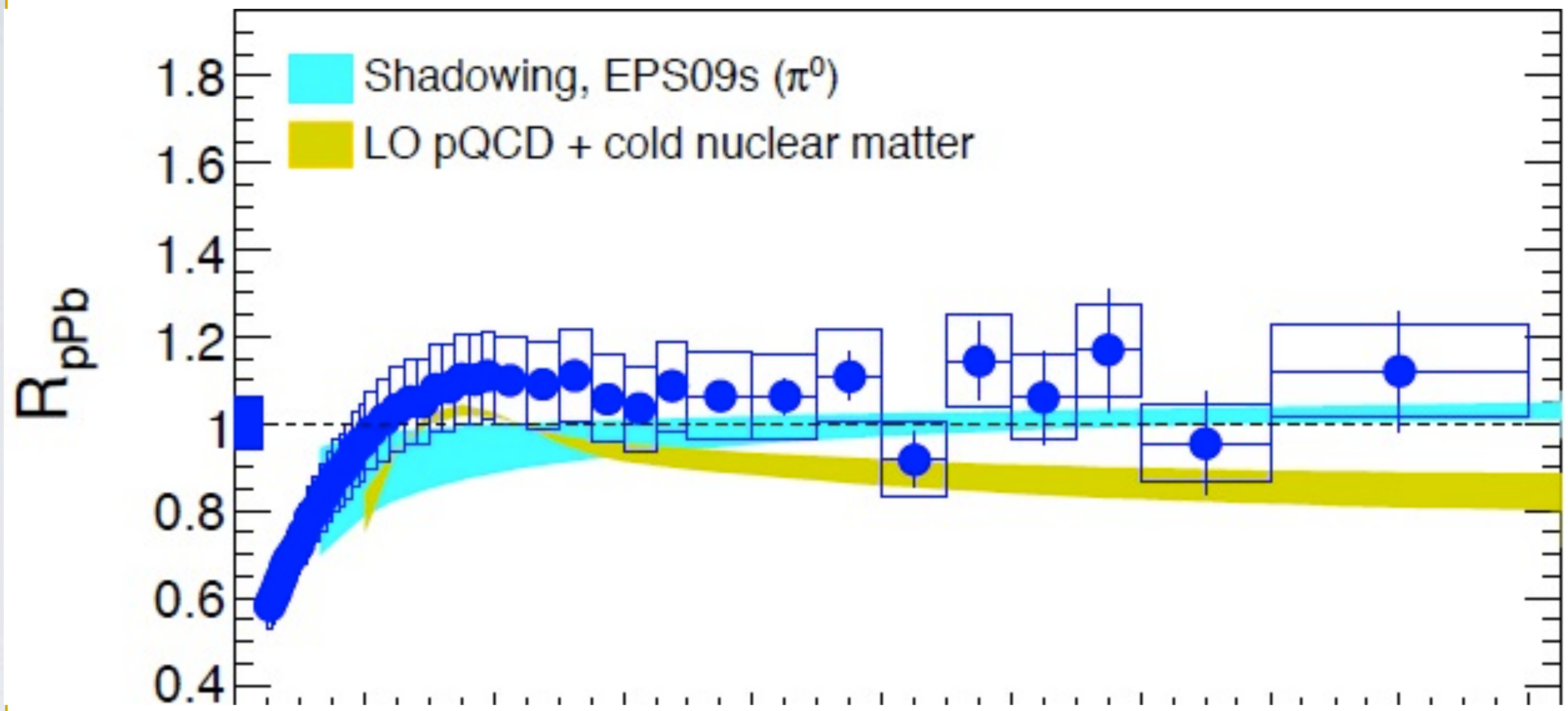


- rcBK-MC CGC prediction for charged hadrons (including running coupling BK evolution, MC treatment of geometry, NLO corrections and precision tested against e+p, p+p and d+Au data) shows good agreement with data and larger RpA than KLT prediction for J/Psi (??)

- Strength of CGC effects should increase with $\frac{Q_s^2}{M_t^2}$

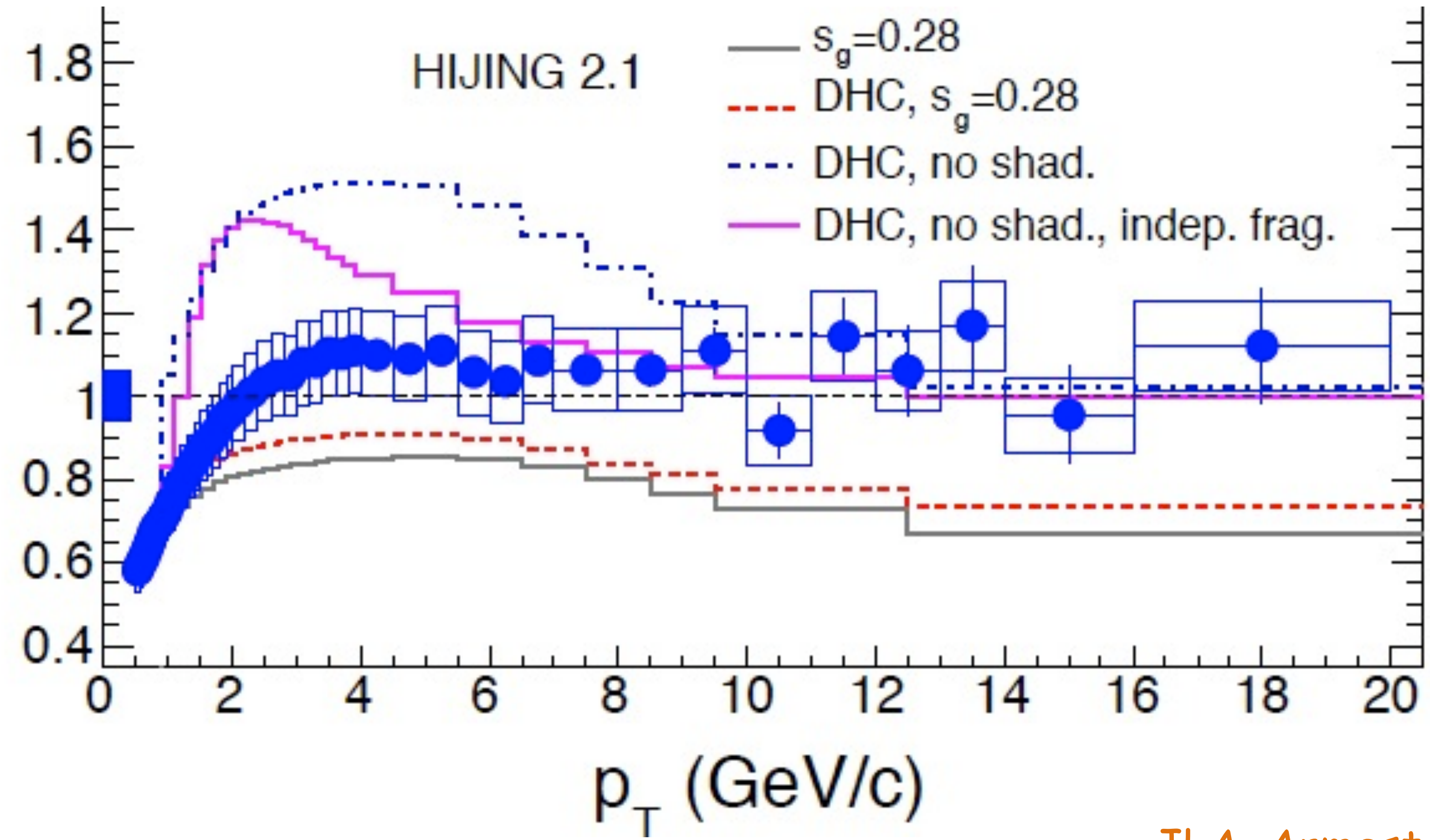
- Details matter!!

Comments on recent p-Pb data



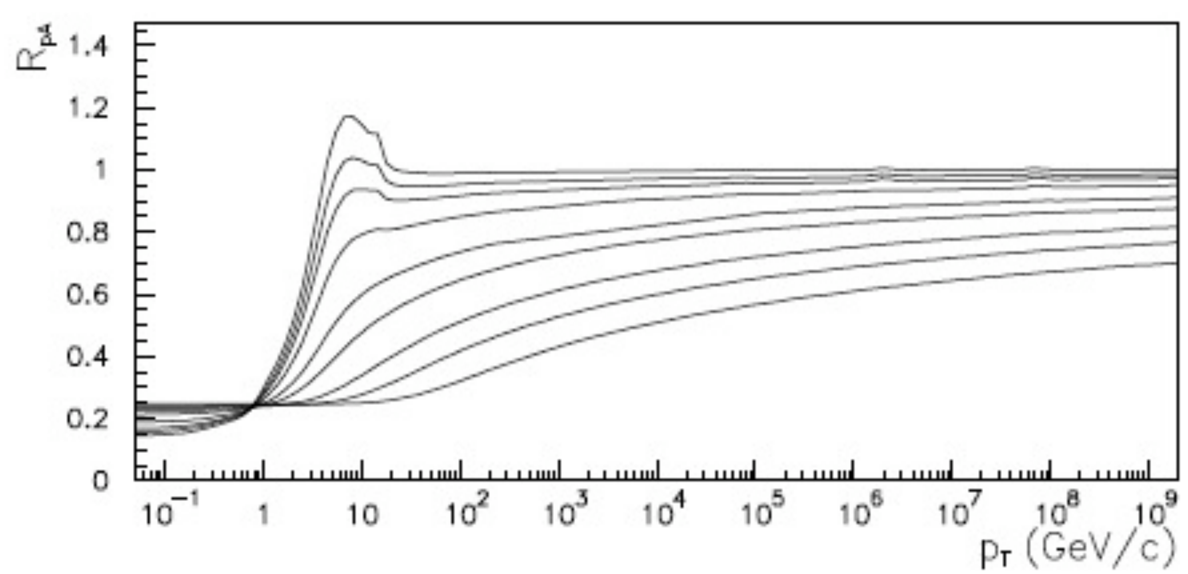
- NLO-EPS09 predictions also compatible with data.
- It would be very difficult for nPDF approaches to cope with an enhancement of RpPb at moderate pt (small-x)
- Higher Twist + shadowing +Cold nuclear matter energy loss seems to have the wrong trend (?)

Comments on recent p-Pb data



No Cronin peak!!! Important test for non-linear small-x evolution

JLA, Armesto Kovner, Salgado, Wiedemann 2003

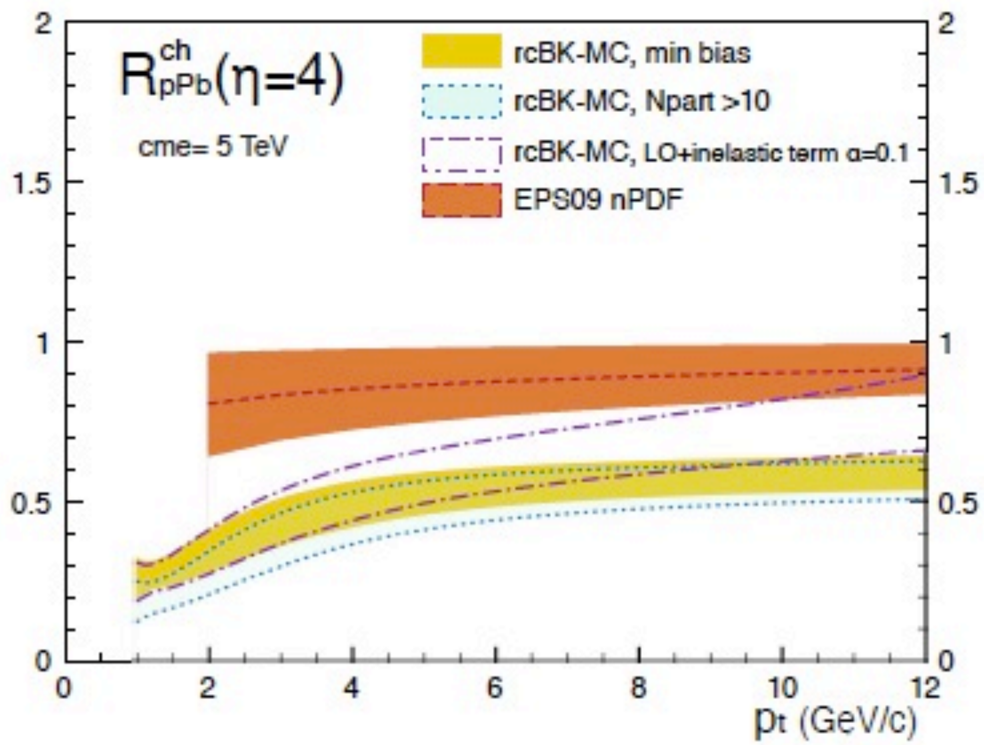


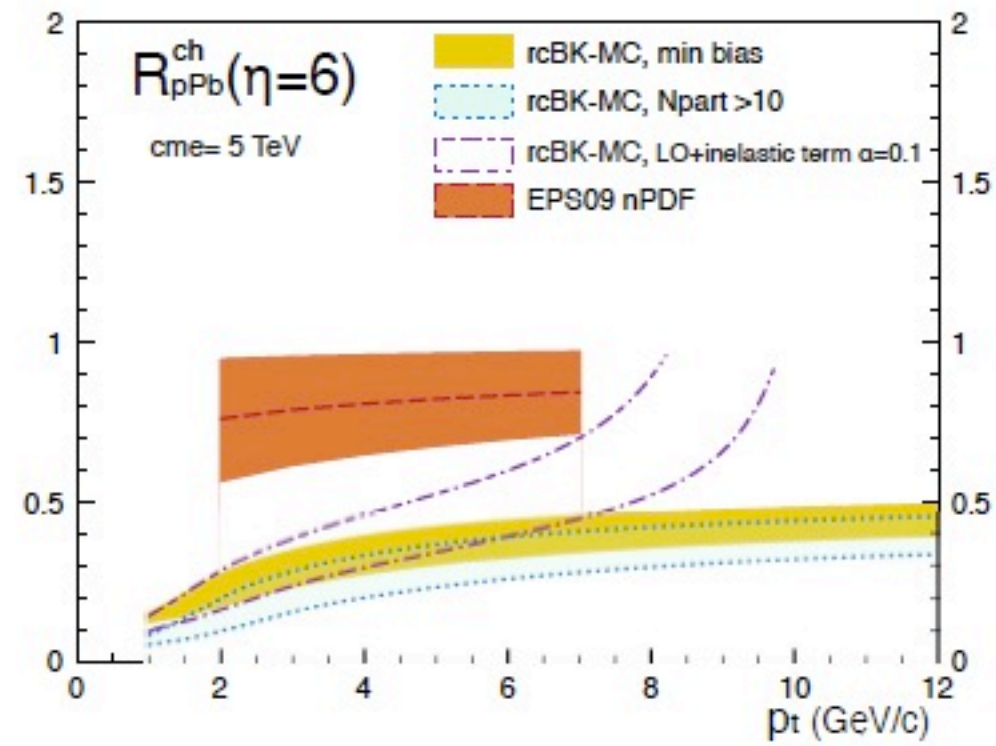
Independent multiple scatterings lead to Cronin, with a displacement of <k_t>

$$\rightarrow F_{a/A}(x, Q^2, < k_T^2 > + \Delta k_T^2(\sqrt{s}, b, p_t))$$

Looking forward / Outlook

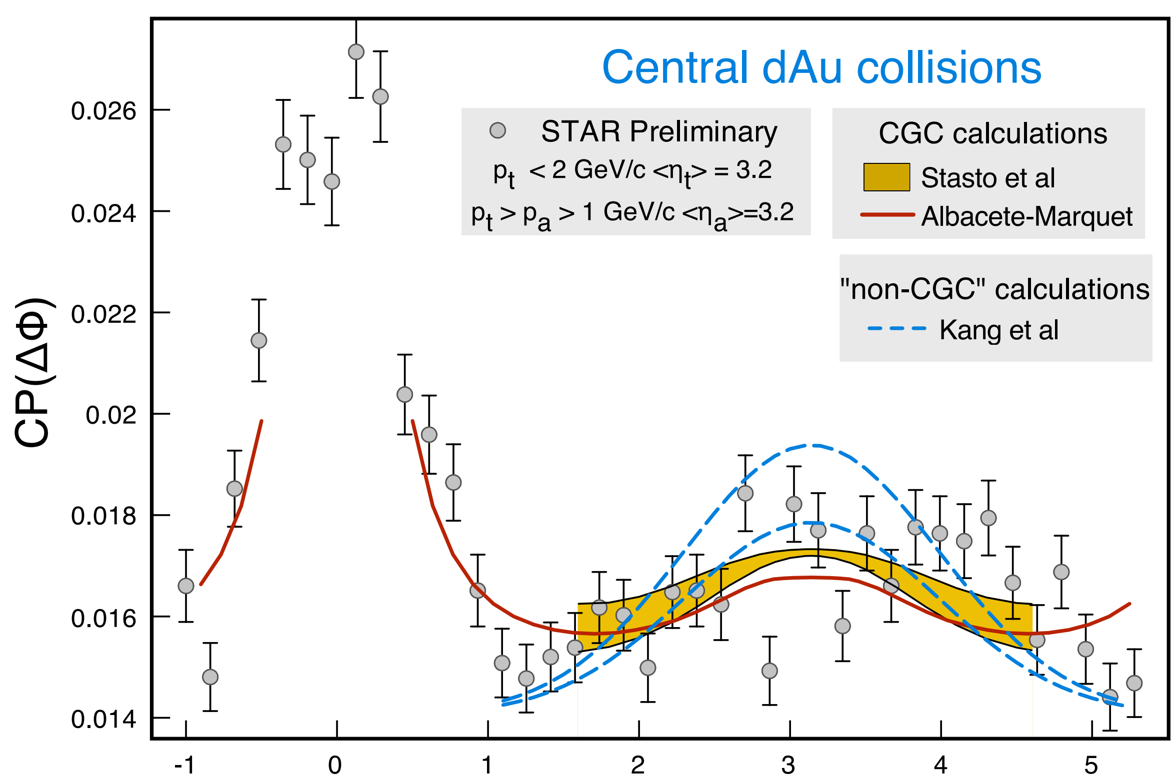
- Differences between nPDF's and CGC calculation should become visible at more forward rapidities:



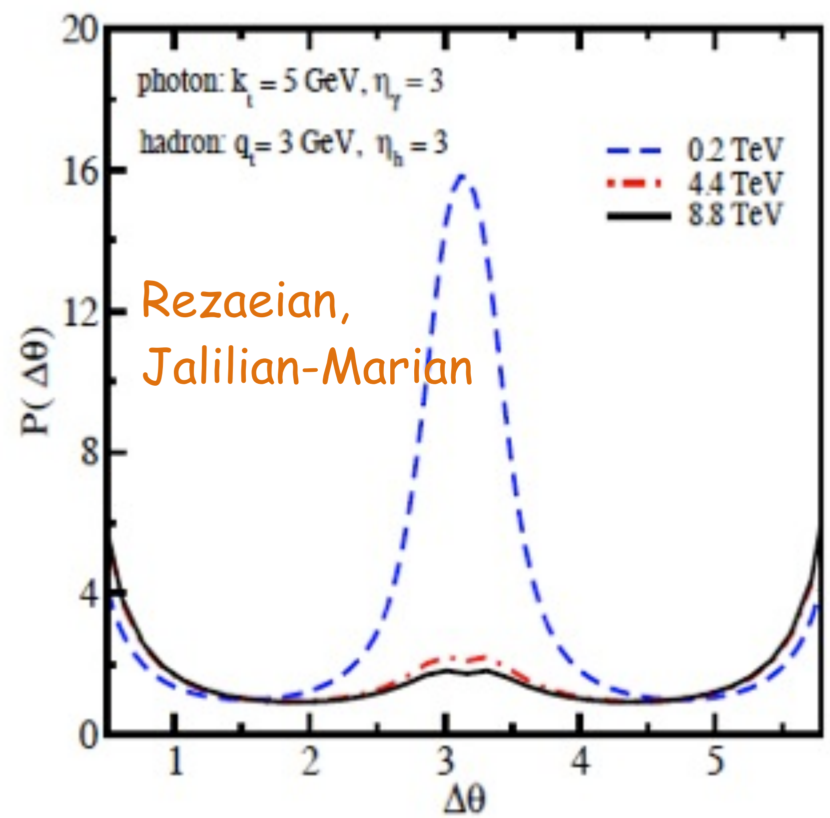


- Or in more differential observables: (hadron-hadron, photon*-hadron correlations)

pion-pion azimuthal decorrelation @ RHIC



photon-hadron correlation at the LHC



Final comments

✔ Important steps have been taken in promoting GCG to an useful quantitative tool
- Continuos progress on the theoretical side
- Phenomenological effort to systematically describe data from different systems (e+p, e+A, p+p, d+Au, Aa+Au and Pb+Pb) in an unified framework

✔ p+Pb can (and will!!) provide constraints to discriminate models for CNM effects:

✔ Rapidity/centrality scan and info on differential observables needed

✔ Systematic self-consistent phenomenology also needed

✔ rcBK-MC code is public and easy to use

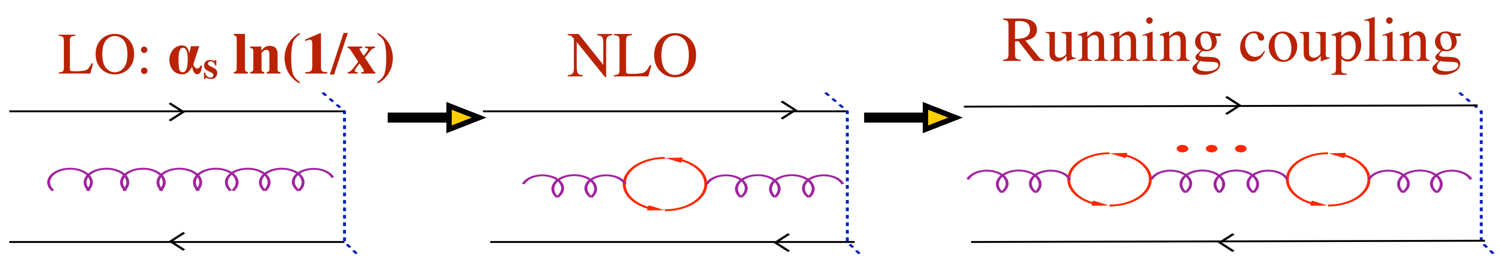
http://faculty.baruch.cuny.edu/naturalscience/physics/dumitru/CGC_IC.html

(brief and incomplete) CGC Theory Status: Entering the NLO era

G. Beuf's Talk

Evolution Equations: $$\frac{\partial\,\phi(x,k)}{\partial\,\ln(1/x)} = \mathcal{K}\otimes\phi(x,k) - \phi^2(x,k) \qquad \frac{\partial\,W[\rho]}{\partial\,Y} = \ldots$$

- ✓ - Running coupling kernel in BK evolution for the 2-point function Kovchegov Weigert Gardi Balitsky
- ✗ - Full NLO kernel for BK-JIMWLK [Balitsky Chirilli]
- ✓ - Analytic [Iancu & Triantafyllopoulos's] and numerical [Dumitru et al] solutions of full B-JIMWLK hierarchy for n-point functions
- - ...



Production processes $$\frac{dN^{AB\to X}}{d^3p_1\ldots}[\phi(x,k);W_Y[\rho]]$$

- ✗ - Running coupling and full NLO corrections to kt-factorization [Kovchegov, Horowitz, Balitsky, Chirilli]
- ✓ - Inelastic terms in the hybrid formalism [Altinoluk and Kovner]
- ✓ - Hadron-hadron, hadron-photon* correlations [Heikki's talk, Jalilian Marian's talk]
- ✗ - Factorization of multiparticle production processes at NLO [Gelis et al]
- ✗ - DIS NLO photon impact factors [Chirilli]
- - ...

Used in phenomenological works? ✓ Yes ✗ No ✓A bit :)

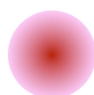
(brief and incomplete) CGC Phenomenology Status

Empiric information needed to constrain:

- Non-perturbative parameters: initial conditions for BK-JIMWLK evolution, impact parameter dependence
- K-factors to account for higher order corrections (effectively also for missing high-(x,Q2) contributions, energy-conservation corrections etc)

proton

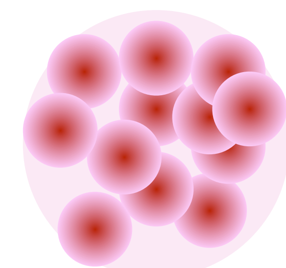
- Abundant high quality data at small-x
- Good simultaneous description of e+p and p+p data
- Global rcBK fits to constrain gluon distribution

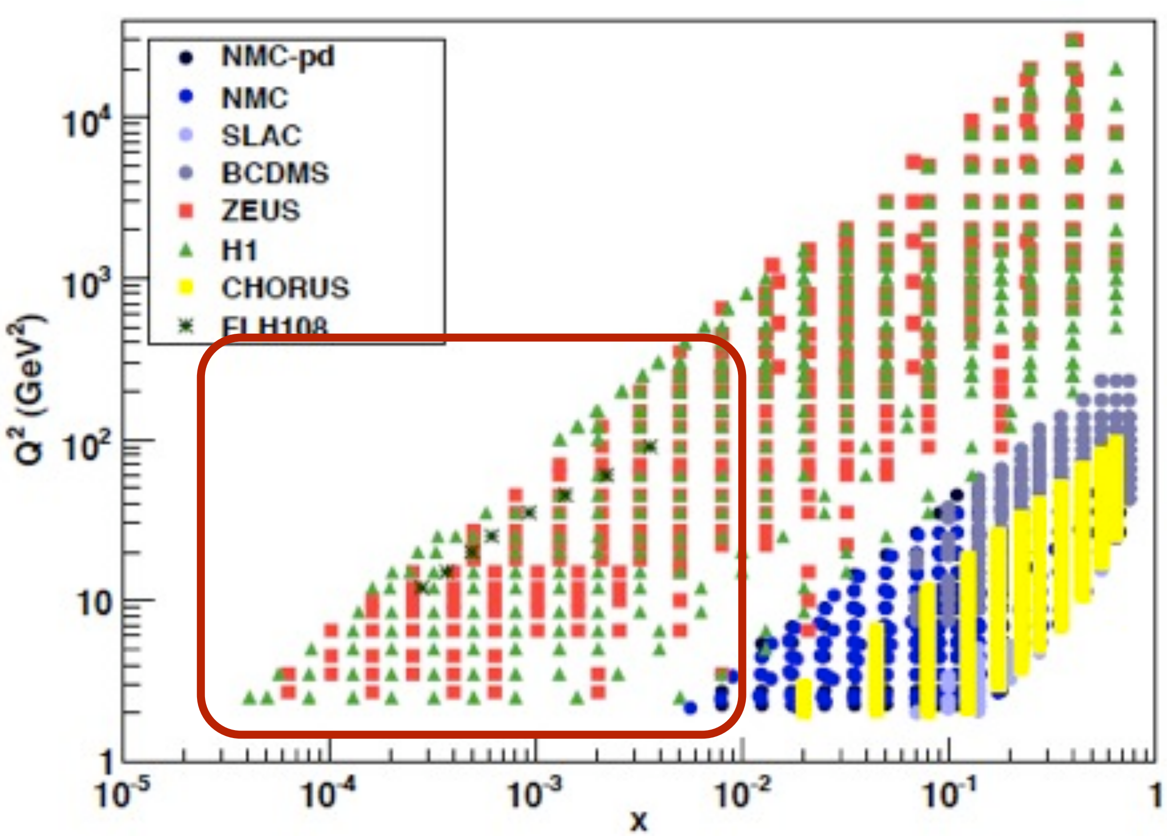


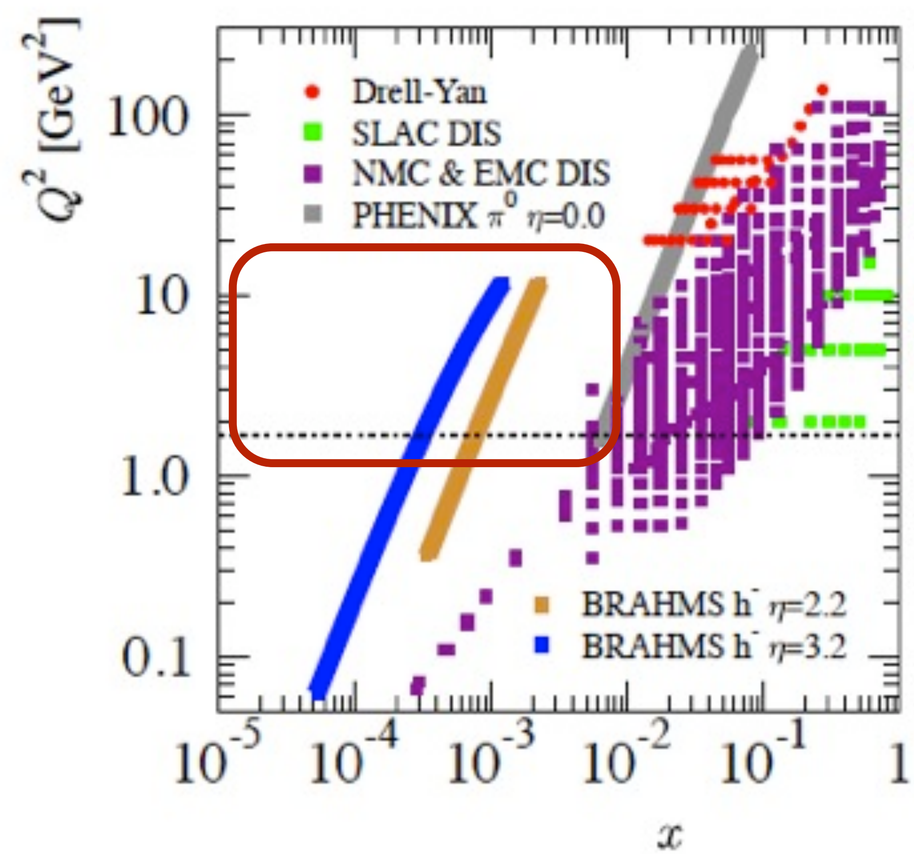
modelling!

nuclei

- Few data at small-x
- LHC Pb+Pb data and RHIC dAu forward data troublesome (more later)

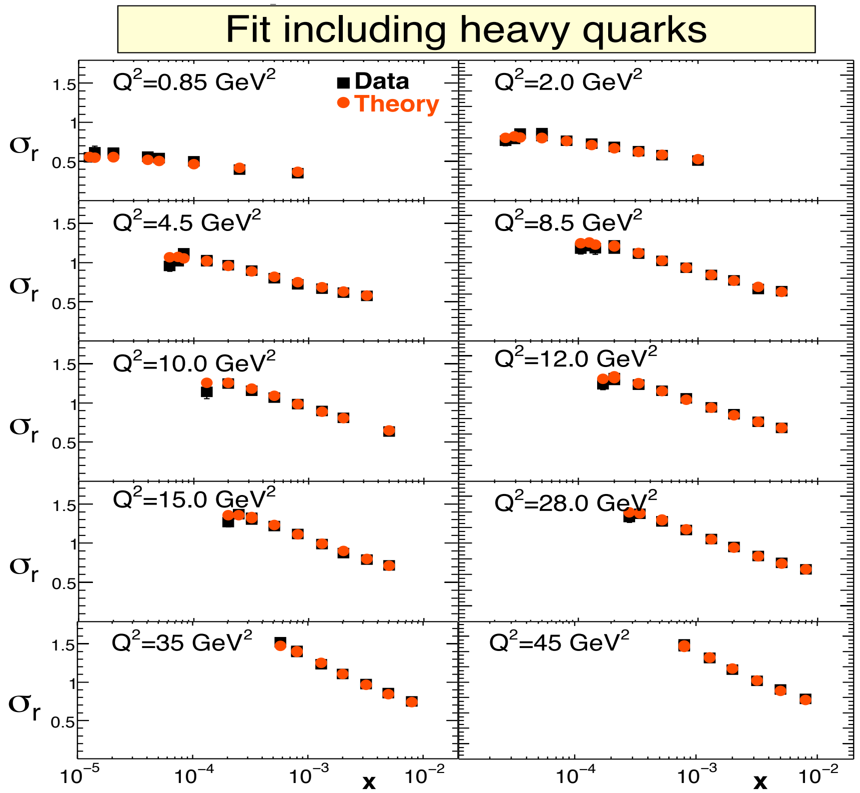






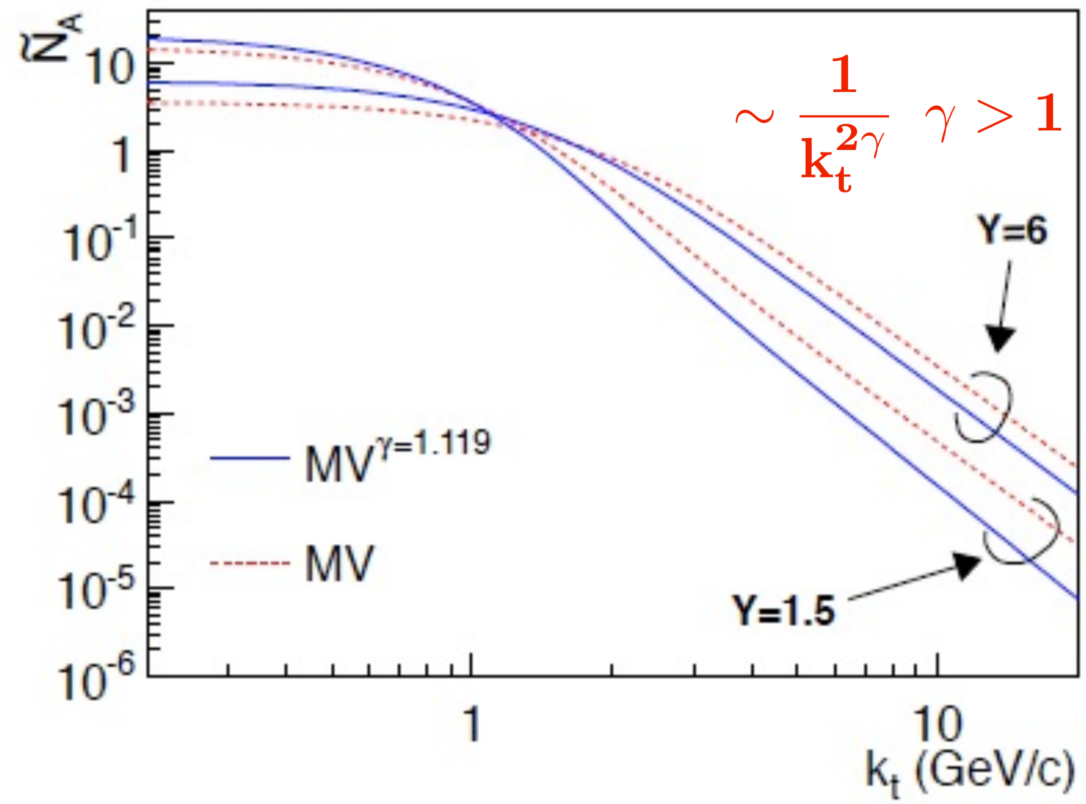
The baseline: proton collisions

1. Global fits to e+p data at small-x



JLA, Armesto, Milhano, Quiroga, Salgado

2. Extract NP fit parameters
(initial conditions for evolution)



$$\phi\left[\mathbf{k_t}, \mathbf{x_0} = \mathbf{10^{-2}}, \mathbf{Q^2_{s0}}, \gamma, ...\right] \qquad \frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2 \qquad \sigma^{\gamma^* \mathbf{P}}[\phi(\mathbf{k_t}, \mathbf{x})]$$

initial conditions

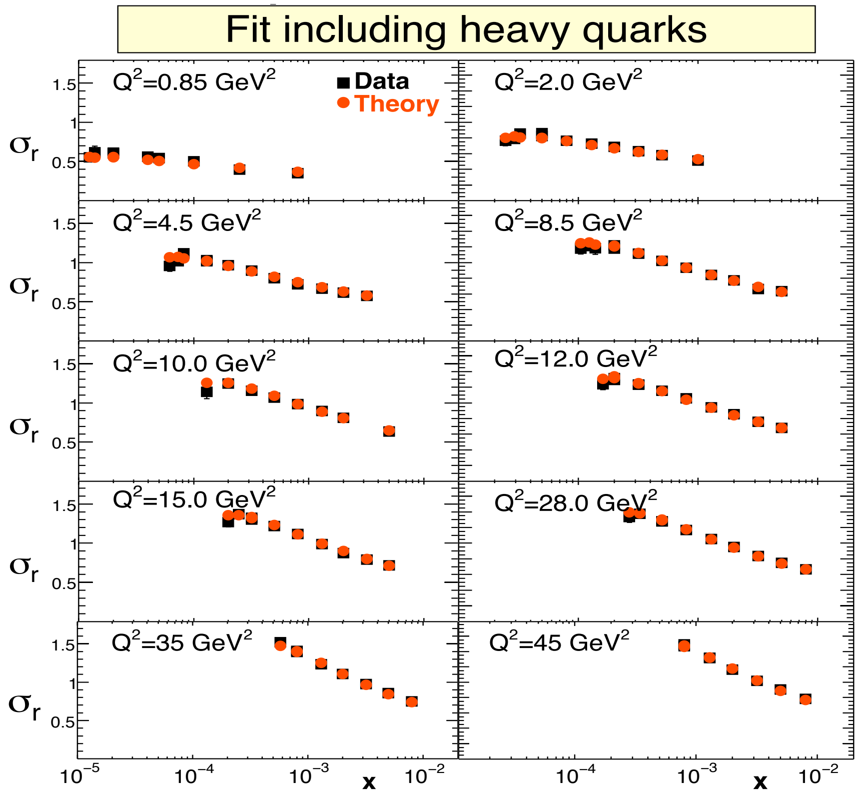
rcBK evolution

e+p x-section

Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h’	0.157	1.101

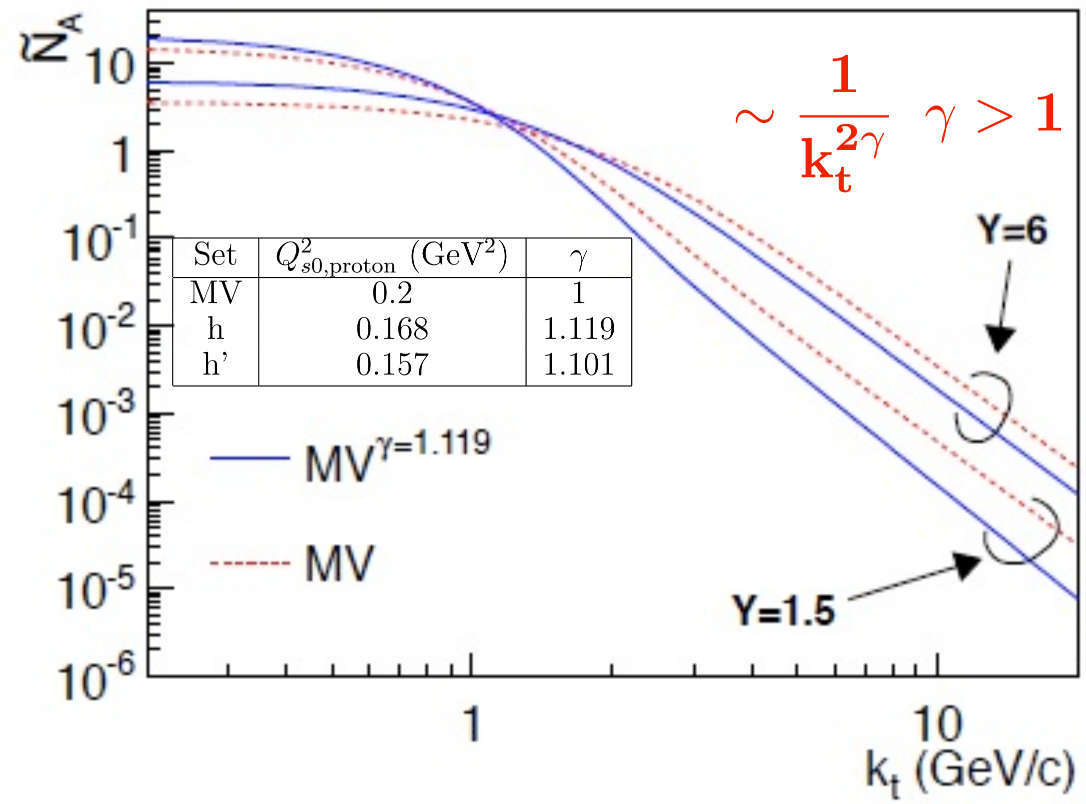
The baseline: proton collisions

1. Global fits to e+p data at small-x

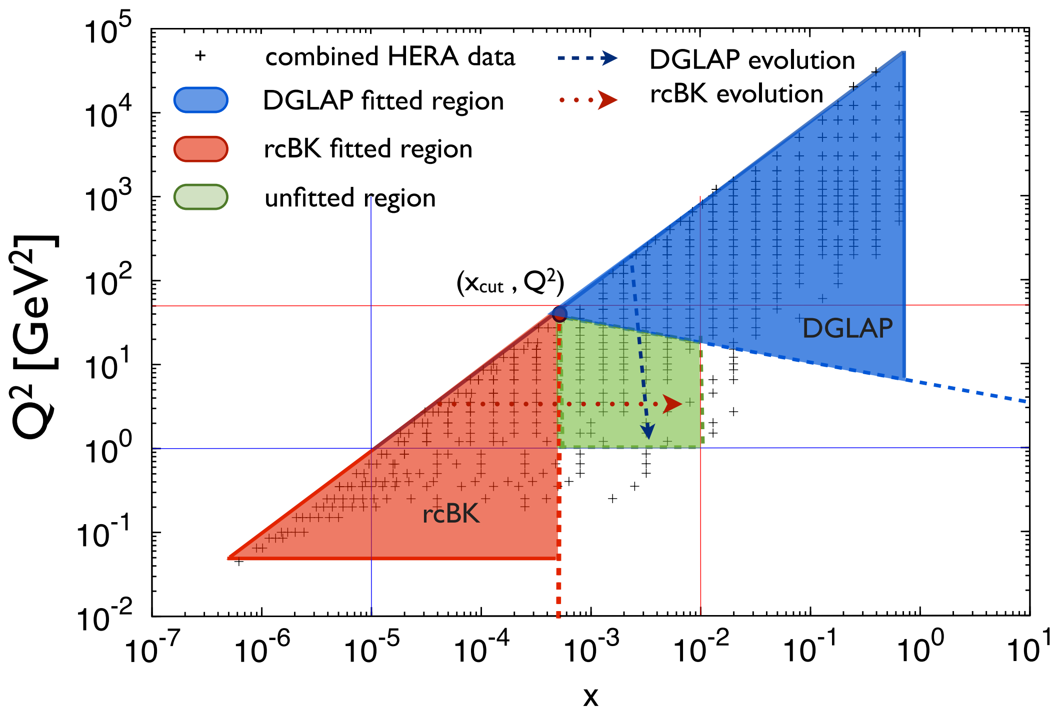


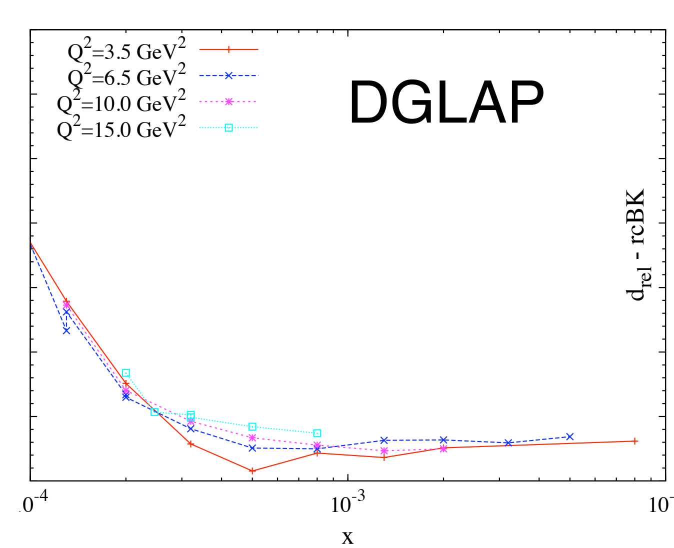
JLA, Armesto, Milhano, Quiroga, Salgado

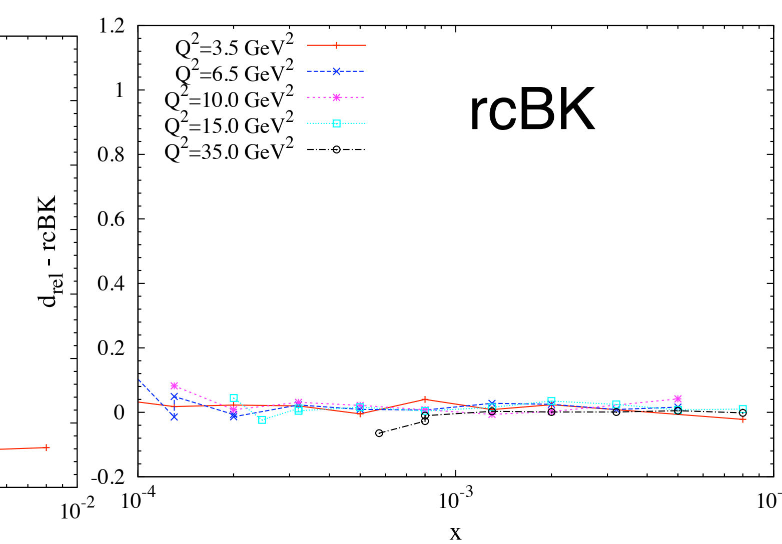
2. Extract NP fit parameters
(initial conditions for evolution)



3. Run consistency and stability checks





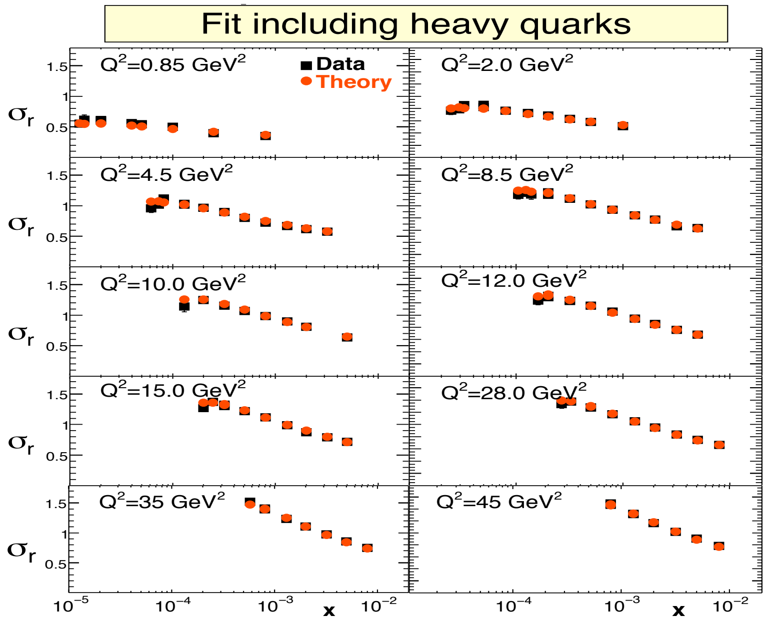


rcBK fits more stable than DGLAP fits at small-x

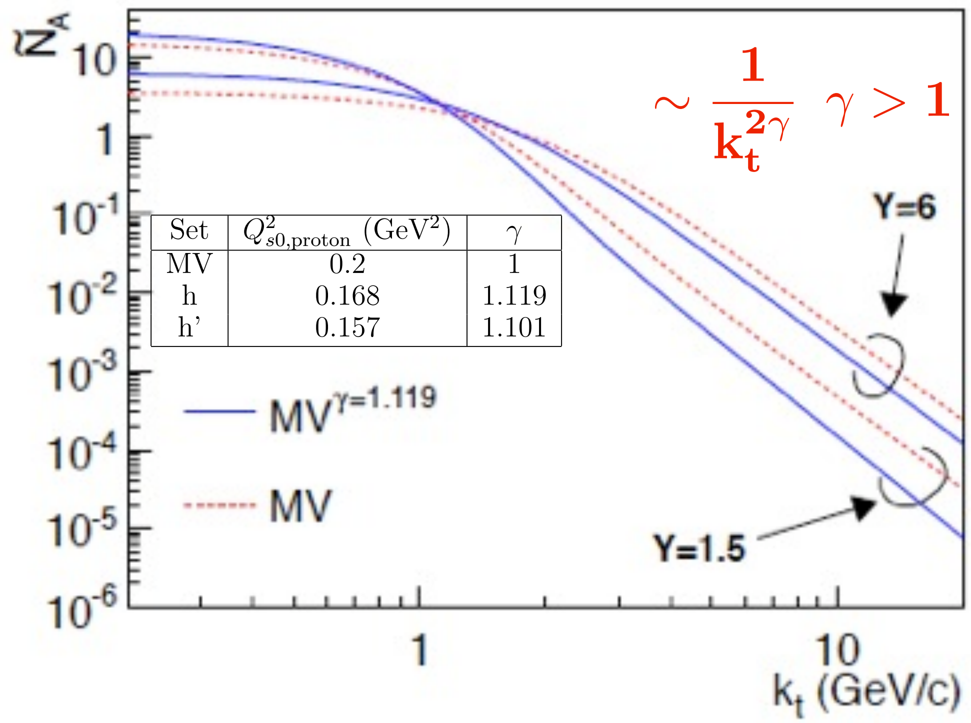
JLA, Milhano, Quiroga, Rojo

The baseline: proton collisions

1. Global fits to e+p data at small-x



2. Extract NP fit parameters
(initial conditions for evolution)



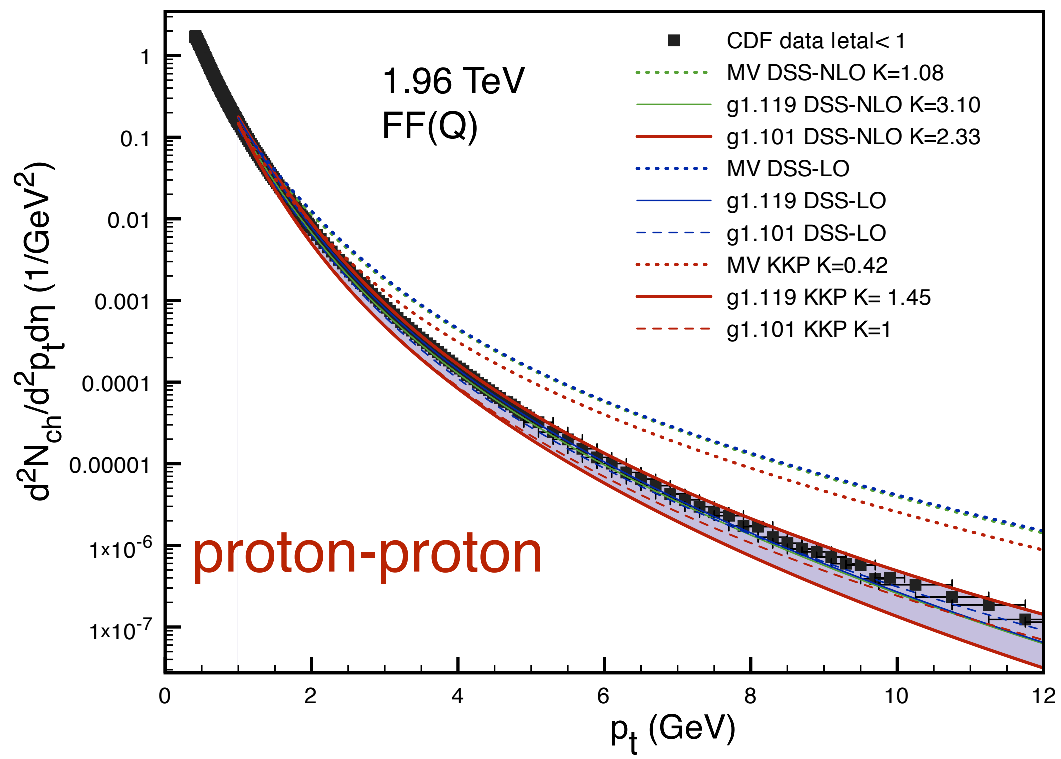
Set	$Q^2_{s0,proton}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h'	0.157	1.101

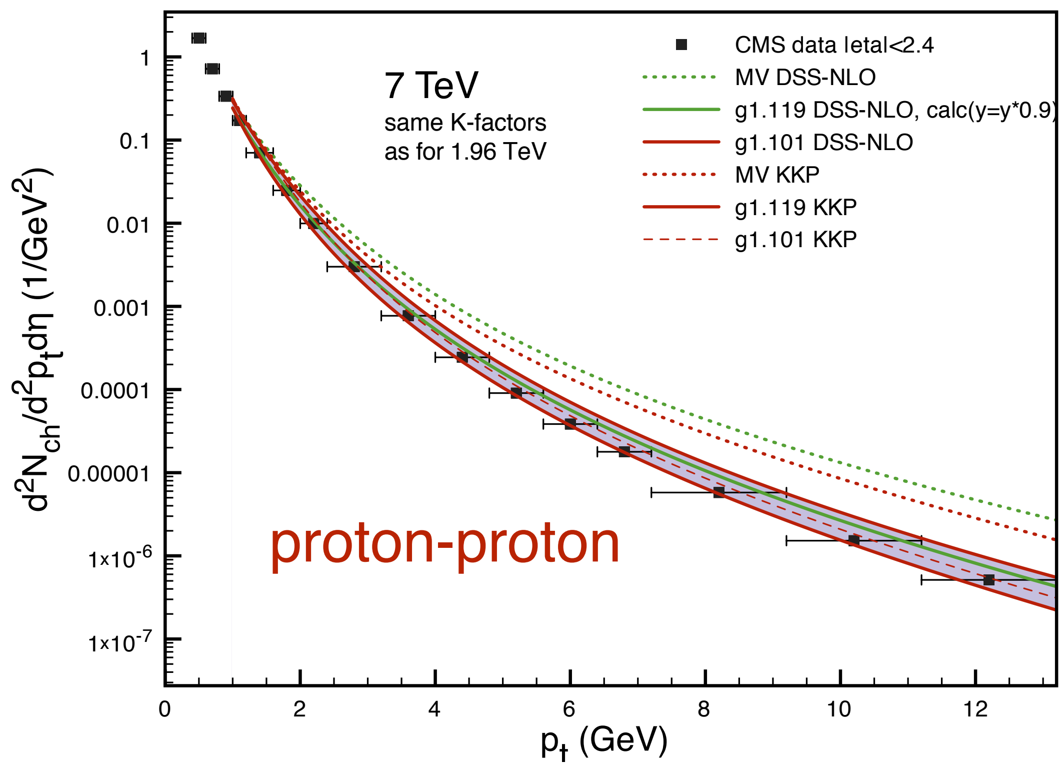
4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

JLA, Dumitru, Fujii, Nara

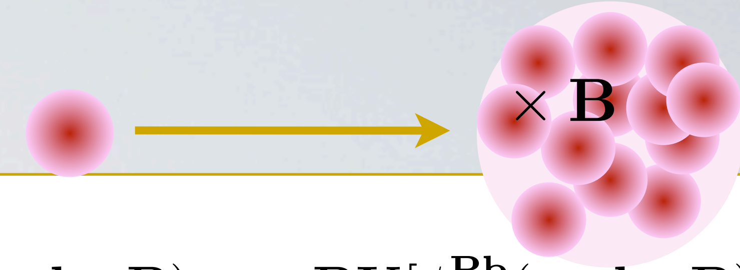
LO kt-factorization:

$$\frac{dN^g}{d\eta d^2p_t} \sim K\,\alpha_s(Q_r^2)\,\phi(x_1,k_t)\otimes\phi(x_2,k_t-pt)\otimes FF(Q_f^2)$$





Modeling the impact parameter dependence



$$\phi^{Pb}(x_0, k_t, B) = \phi^{p}(x_0, k_t; \{Q^2_{s0,p} \to Q^2_{s0,Pb}(B)); \gamma\} \quad \longrightarrow \quad \phi^{Pb}(x, k_t, B) = \mathrm{rcBK}[\phi^{Pb}(x_0, k_t, B)]$$

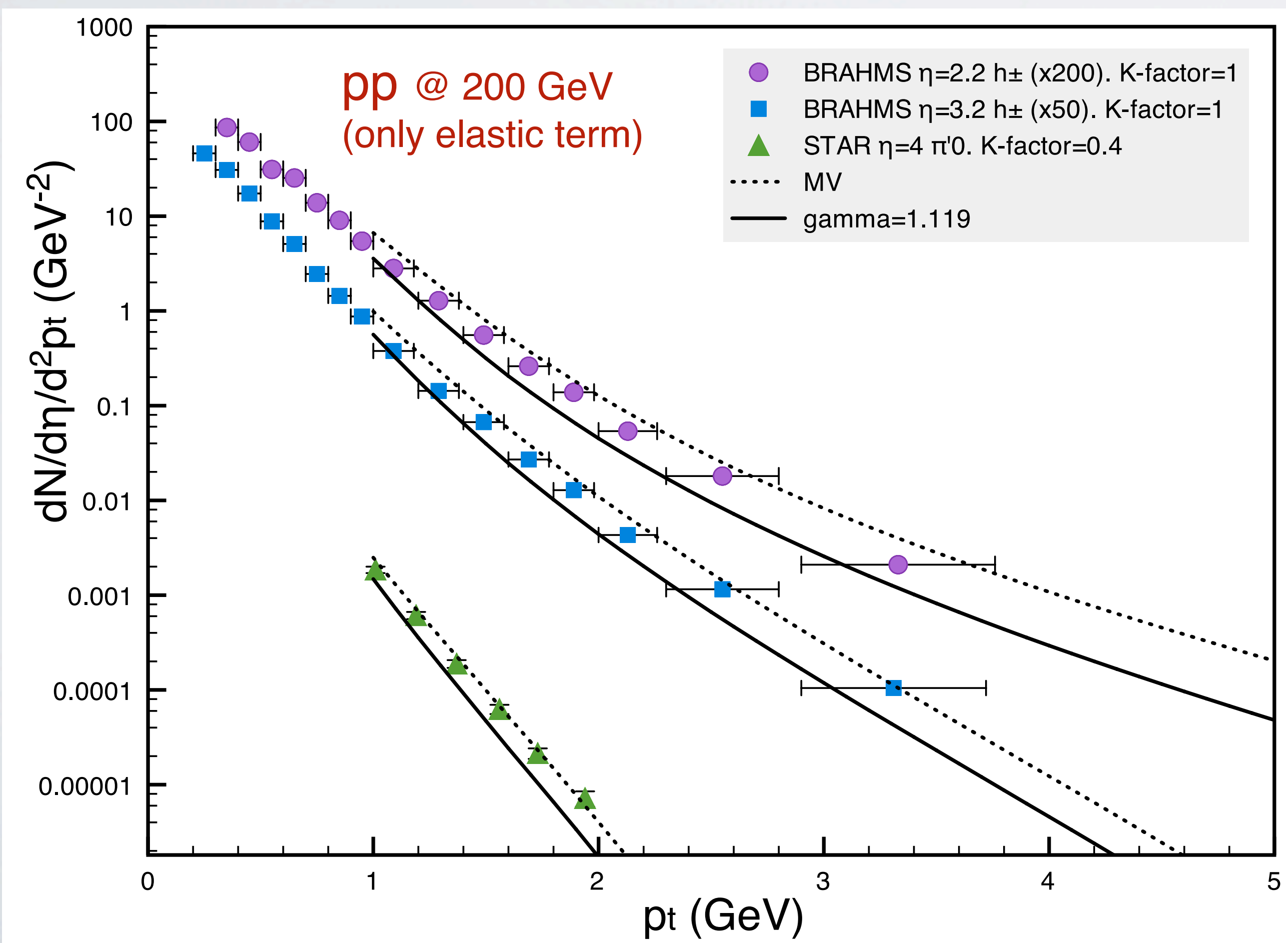
A) Most "natural" option: $Q^2_{s0,Pb}(B) = T_A(B)\, Q^2_{s0,p} \qquad \gamma^{Pb} = \gamma^{p} (> 1)$

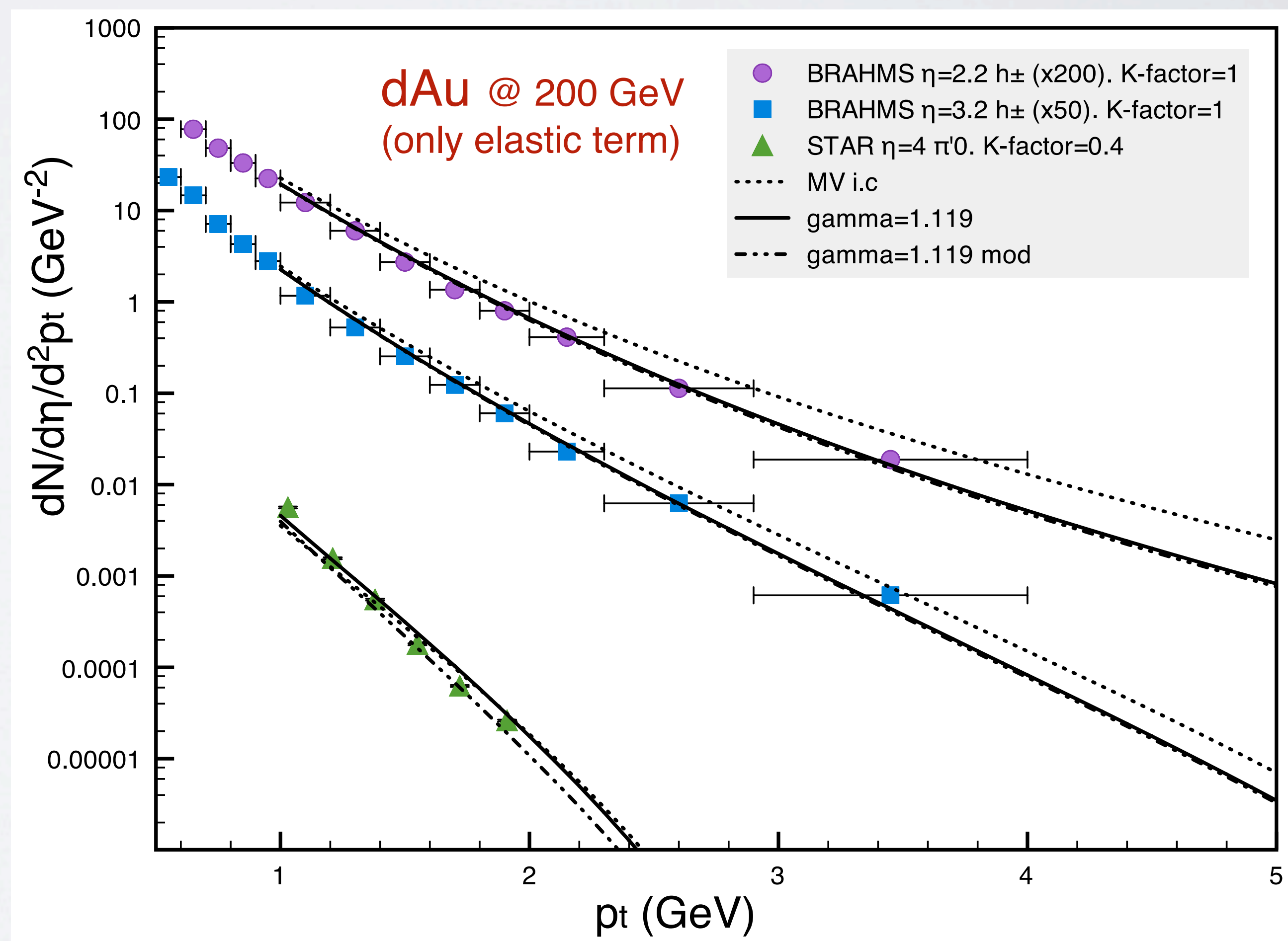
PROBLEM: yields $R_{pPB} > 1$ at high transverse momentum

B) Possible solution $Q^2_{s0,Pb}(B) = T_A(B)^{1/\gamma}\, Q^2_{s0,p}$ and/or $\gamma^{Pb} = 1(MV) + \frac{\#}{A^2/3}$

hybrid formalism: $$\frac{dN^g}{dy_h d^2k_t} \approx xq(x_1, k_\perp) \otimes \phi_A(x_2, k_t)$$

RHIC data does not constrain much the i.c. for BK evolution. K-factor needed at most forward rapidity





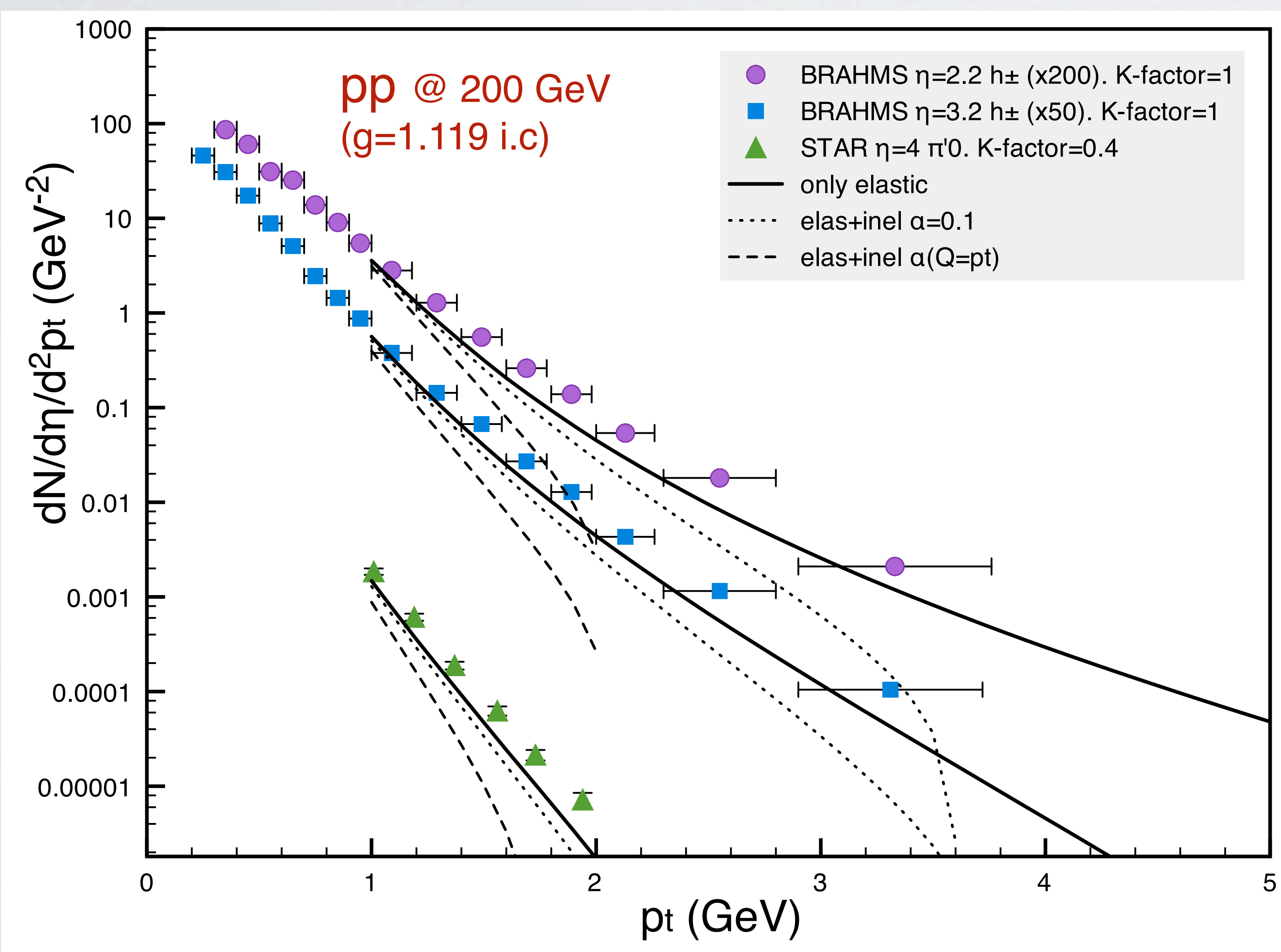
Effect of NLO corrections

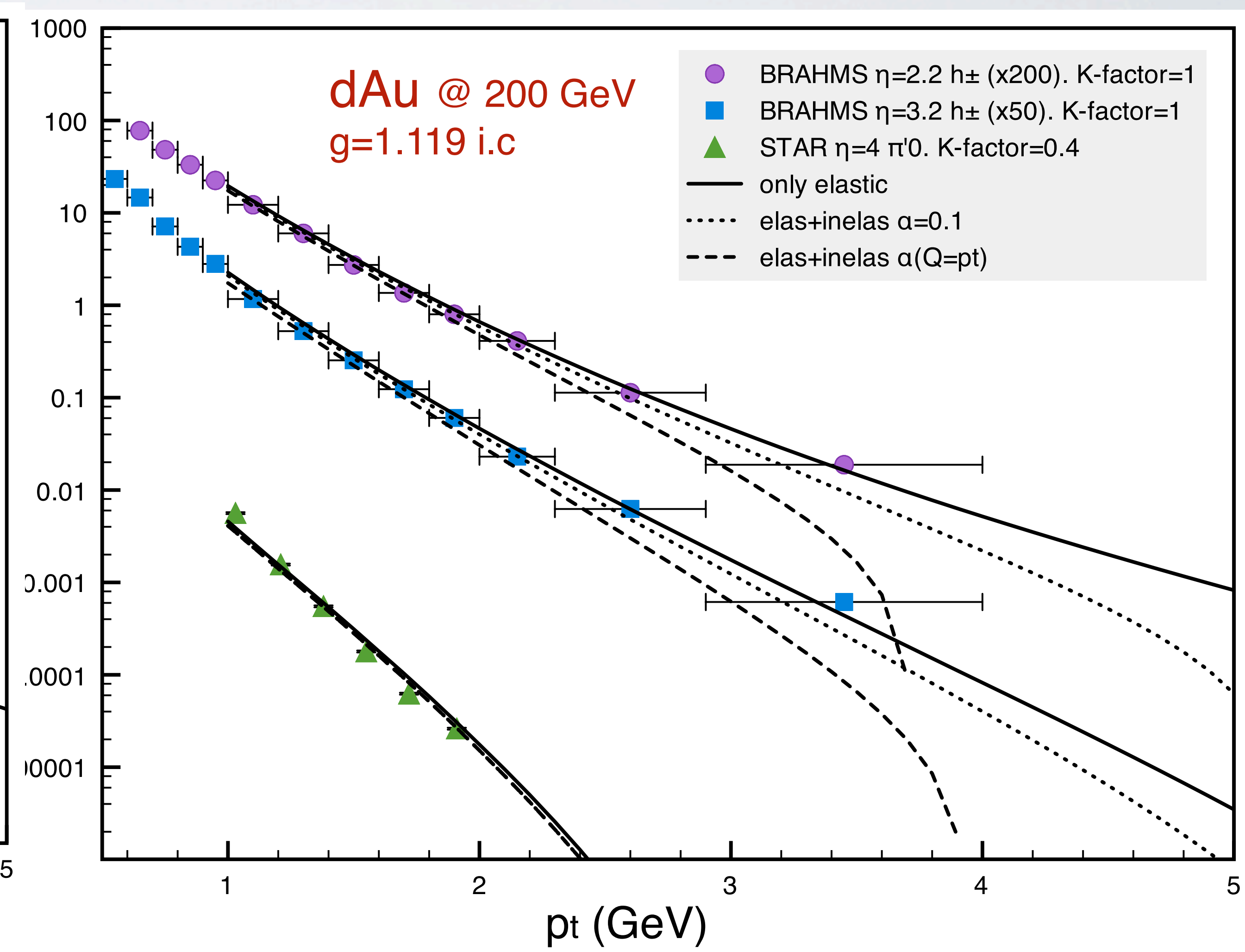
The effect of NLO corrections to the hybrid formalism can be very large!!!. Full NLO analyses needed

$$\frac{dN^{pA\to hX}}{d\eta\, d^2k} = K^h \left(\left[\frac{dN_h}{d\eta\, d^2k}\right]_{\rm el} + \left[\frac{dN_h}{d\eta\, d^2k}\right]_{\rm inel} \right)$$

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

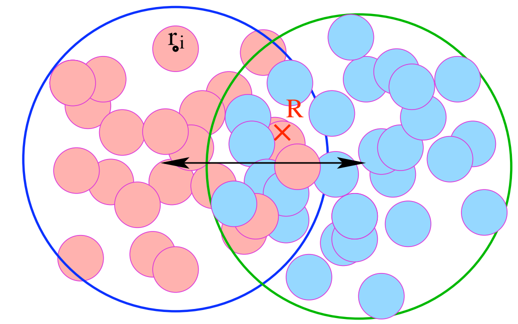
$$\left[\frac{dN_h}{d\eta\, d^2k}\right]_{\rm inel} = \frac{\alpha_s(Q)}{2\pi^2} \int_{x_F}^{1} \frac{dz}{z^2}\frac{z^4}{k^4} \int^{Q} \frac{d^2q}{(2\pi)^2} q^2 \tilde{N}_F(x_2,q) x_1 \int_{x_1}^{1} \frac{d\xi}{\xi} \sum_{i,j=q,q,g} w_{i/j}(\xi) P_{i/j}(\xi) f_j\left(\frac{x_1}{\xi},Q^2\right) D_{h/j}(z,Q^2)$$





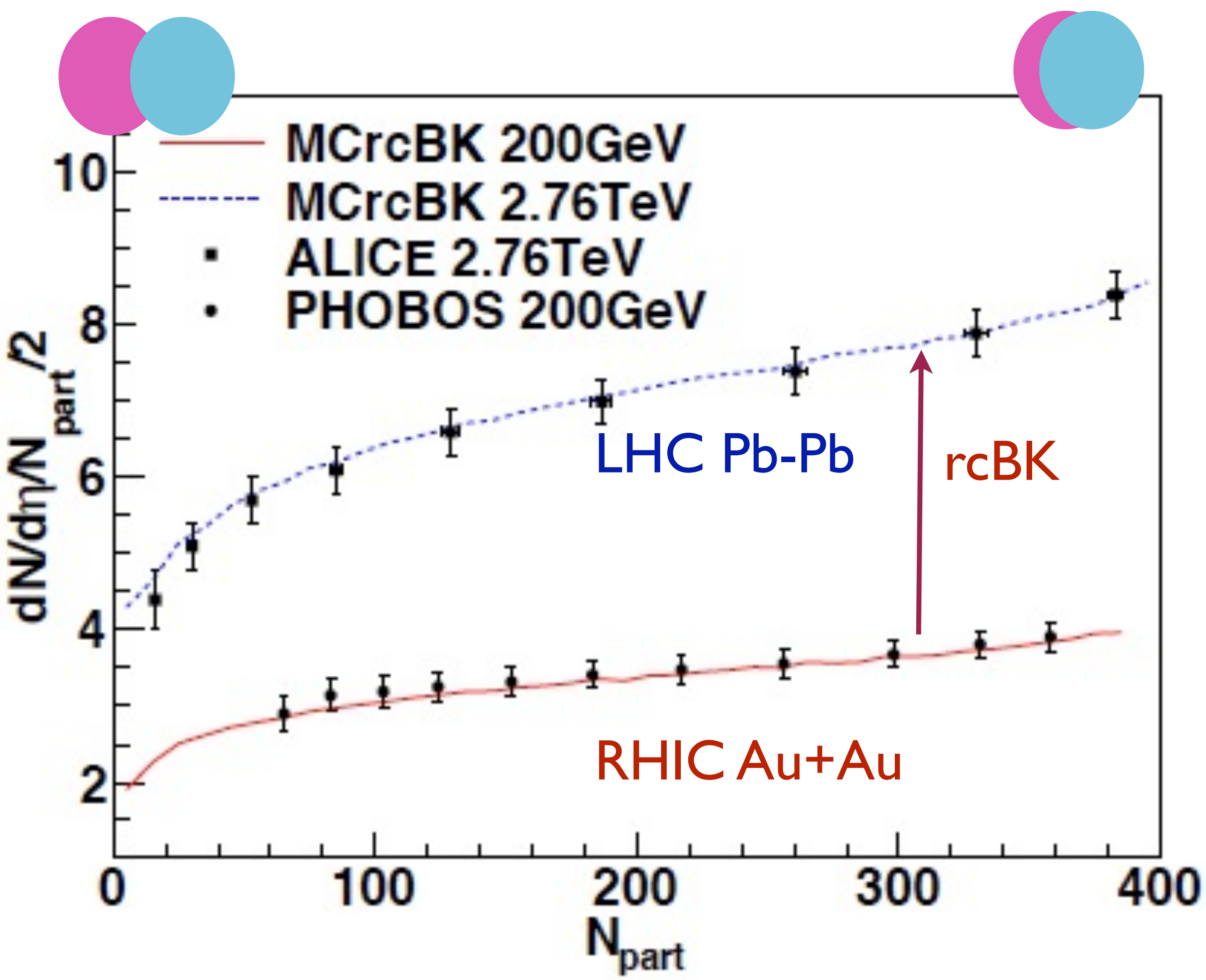
Multiplicities

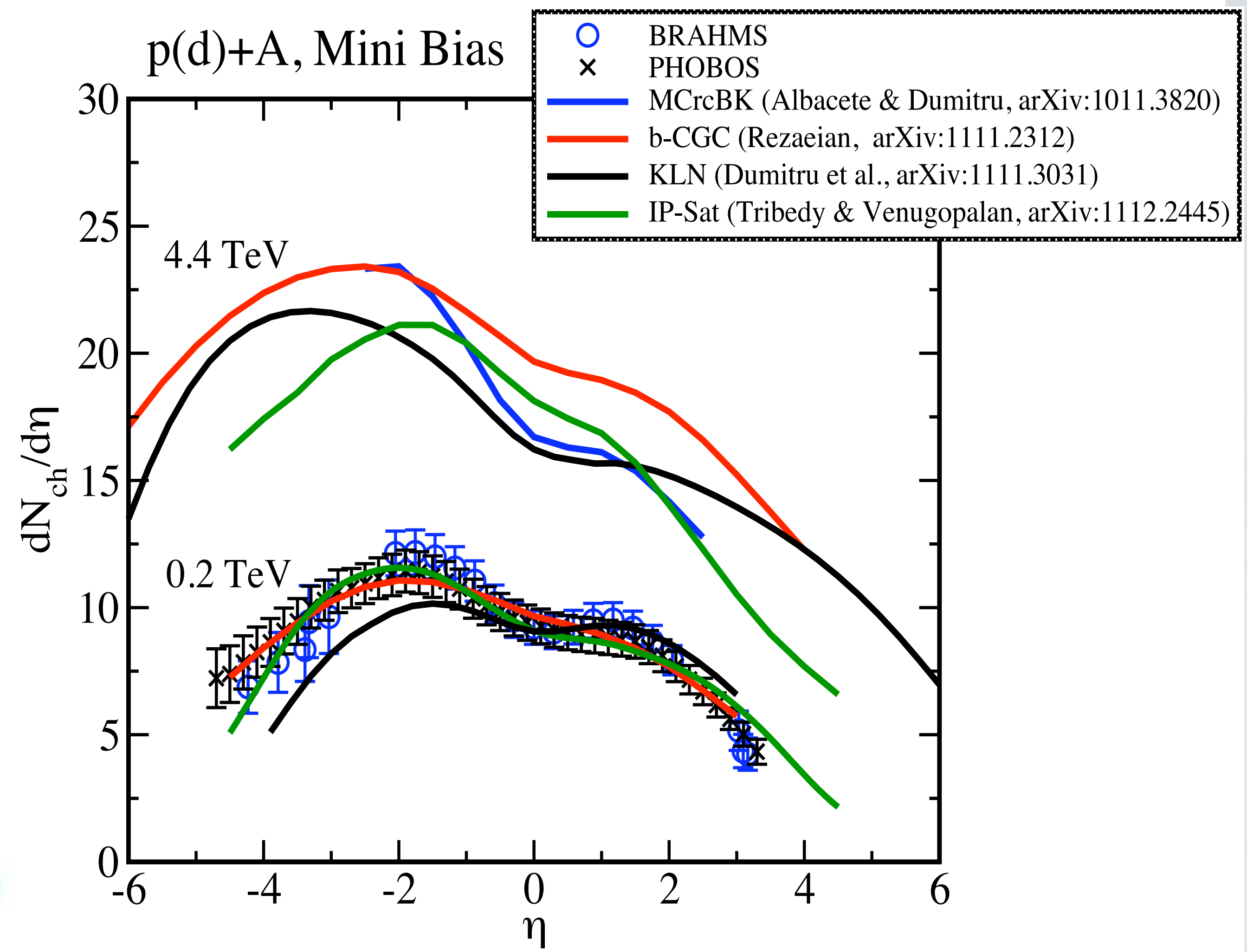
Kt-factorization: $$\frac{dN^g}{dy_h d^2k_t} \approx \frac{\alpha_s C_F}{k_t^2}\,\phi_p(x_1,k_t)\otimes\phi_A(x_2,k_t) \qquad x_{1(2)} = \frac{k_t}{\sqrt{s}}\,e^{\pm y_h}$$



- In the CGC, multiplicities rise proportional to the (local) saturation scale

$$\left.\frac{dN^{gluons}}{d\eta\, d^2b}\right|_{\eta=0} \propto Q_s^2(\sqrt{s},b) \sim \sqrt{s}^{0.3}\, N_{part}$$





Overall, different CGC works predict $\left.\frac{dN^{ch}_{pPb}}{d\eta}\right|_{\eta=0} (5\,\mathrm{TeV}) \sim 17 \pm 2$

we'll know the answer very soon!!

Nuclear ugd's and nuclear modification factors

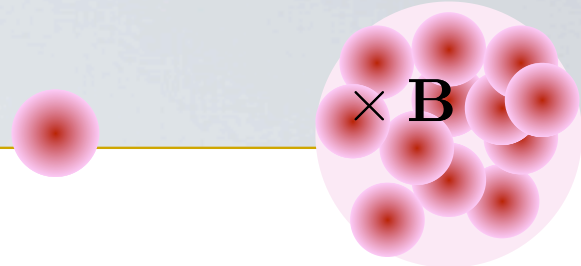
Setting up the evolution

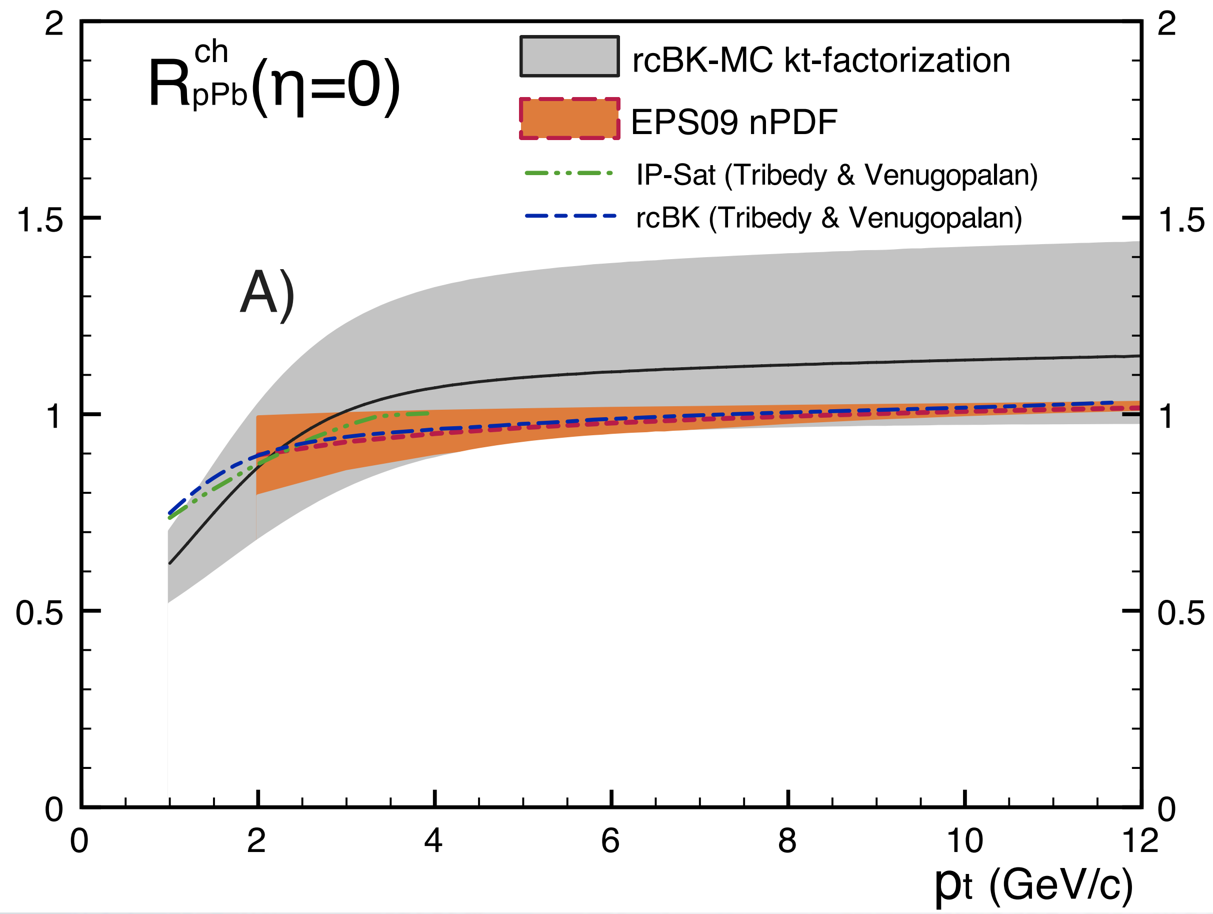
$$\phi^{Pb}(x_0, k_t, B) = \phi^{p}(x_0, k_t; \{Q^2_{s0,p} \to Q^2_{s0,Pb}(B)); \gamma\} \longrightarrow \phi^{Pb}(x, k_t, B) = rcBK[\phi^{Pb}(x_0, k_t, B)]$$

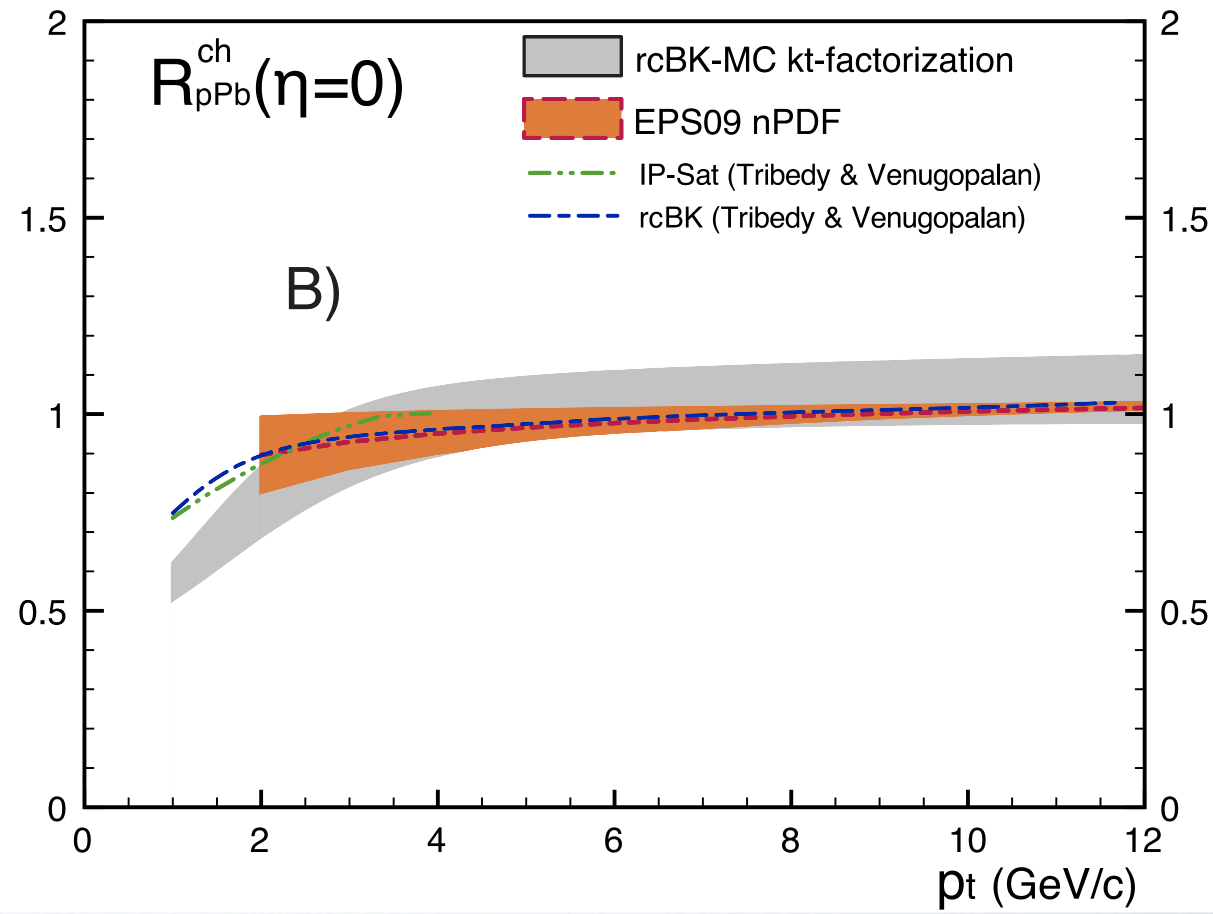
A) Most "natural" option: $Q^2_{s0,Pb}(B) = T_A(B)\, Q^2_{s0,p}$ $\quad \gamma^{Pb} = \gamma^{p}(> 1)$

PROBLEM: yields $R_{pPB} > 1$ at high transverse momentum

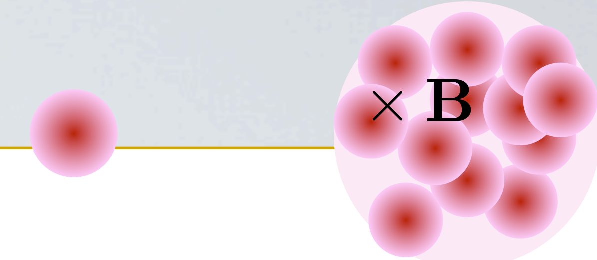
B) Possible solution $Q^2_{s0,Pb}(B) = T_A(B)^{1/\gamma}\, Q^2_{s0,p}$ and/or $\gamma^{Pb} = 1(MV) + \frac{\#}{A^2/3}$







Nuclear ugd's and nuclear modification factors



Setting up the evolution

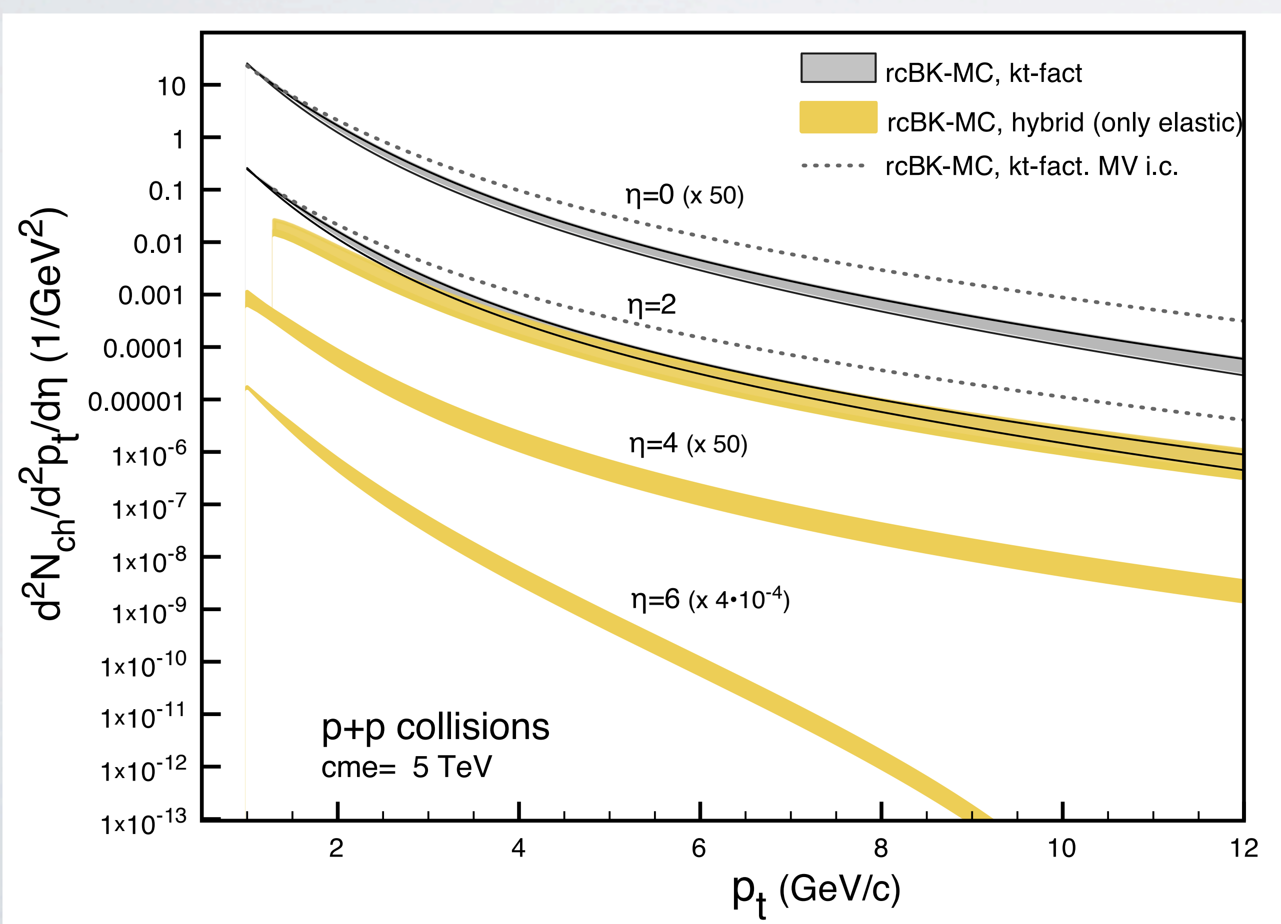
$$\phi^{\mathbf{Pb}}(\mathbf{x_0}, \mathbf{k_t}, \mathbf{B}) = \phi^{\mathbf{p}}(\mathbf{x_0}, \mathbf{k_t}; \{\mathbf{Q^2_{s0,p}} \to \mathbf{Q^2_{s0,Pb}}(\mathbf{B})); \gamma\} \longrightarrow \phi^{\mathbf{Pb}}(\mathbf{x}, \mathbf{k_t}, \mathbf{B}) = \mathbf{rcBK}[\phi^{\mathbf{Pb}}(\mathbf{x_0}, \mathbf{k_t}, \mathbf{B})]$$

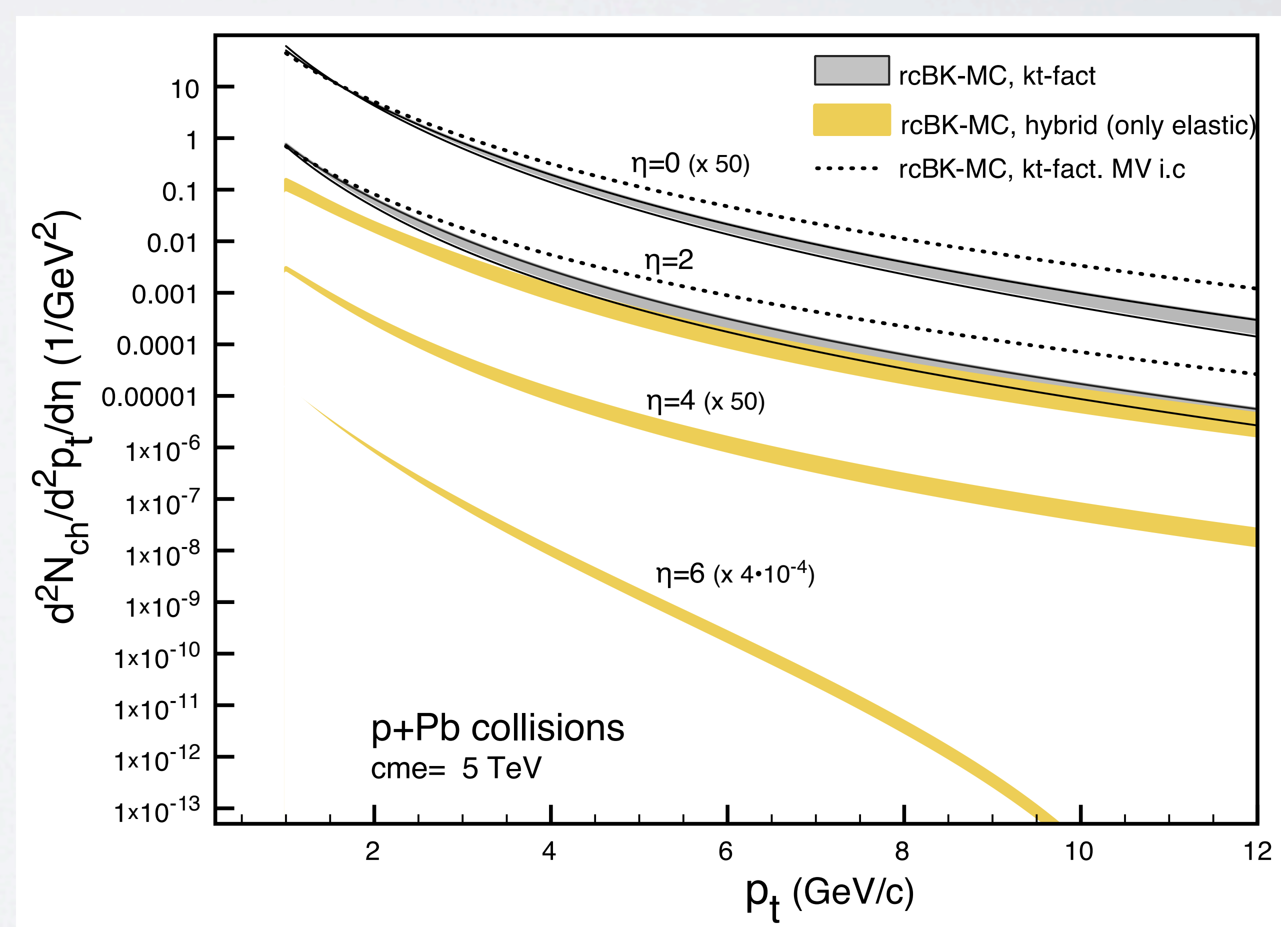
A) Most "natural" option: $\mathbf{Q^2_{s0,Pb}}(\mathbf{B}) = \mathbf{T_A}(\mathbf{B})\,\mathbf{Q^2_{s0,p}}$ $\quad \gamma^{\mathbf{Pb}} = \gamma^{\mathbf{p}}(> \mathbf{1})$

PROBLEM: yields $R_{pPB} > 1$ at high transverse momentum

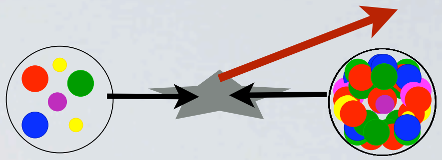
B) Possible solution $\mathbf{Q^2_{s0,Pb}}(\mathbf{B}) = \mathbf{T_A}(\mathbf{B})^{1/\gamma}\,\mathbf{Q^2_{s0,p}}$ and/or $\gamma^{\mathbf{Pb}} = \mathbf{1}(\mathbf{MV}) + \frac{\#}{\mathbf{A^2/3}}$

The yields themselves carry very valuable information!





Moving forward



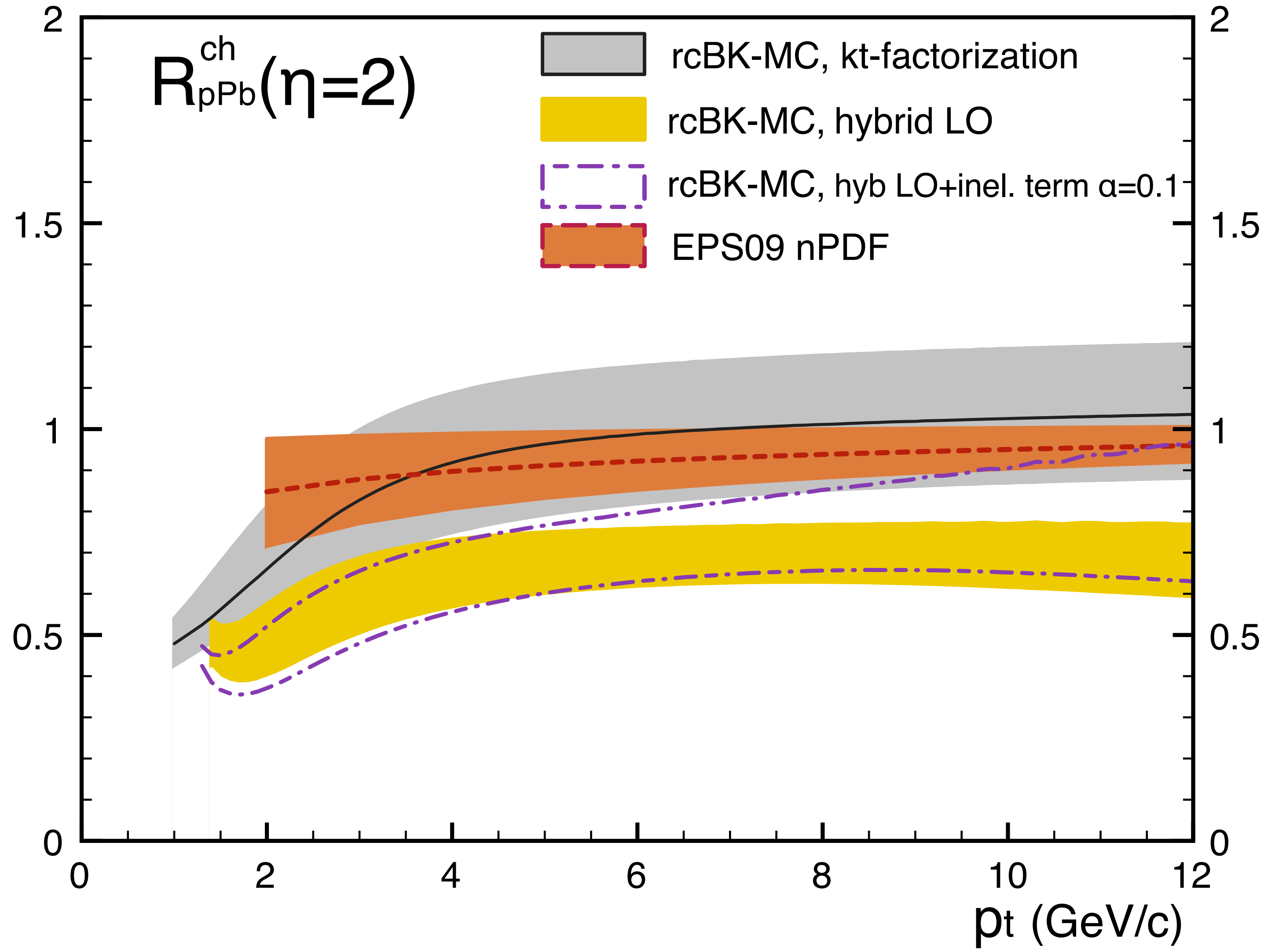
Yet another issue: Where to switch from kt-factorization to hybrid formalism? $x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$

Midrapidity: kt-factorization:

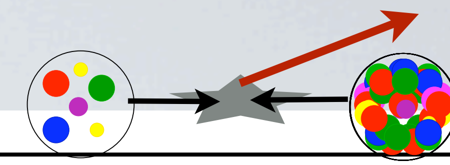
$$\frac{\mathbf{dN^g}}{\mathbf{d\eta d^2p_t}} \sim \phi^{\mathbf{p}}(\mathbf{x_1}) \otimes \phi^{\mathbf{Pb}}(\mathbf{x_2})$$

Forward rapidity: hybrid formalism

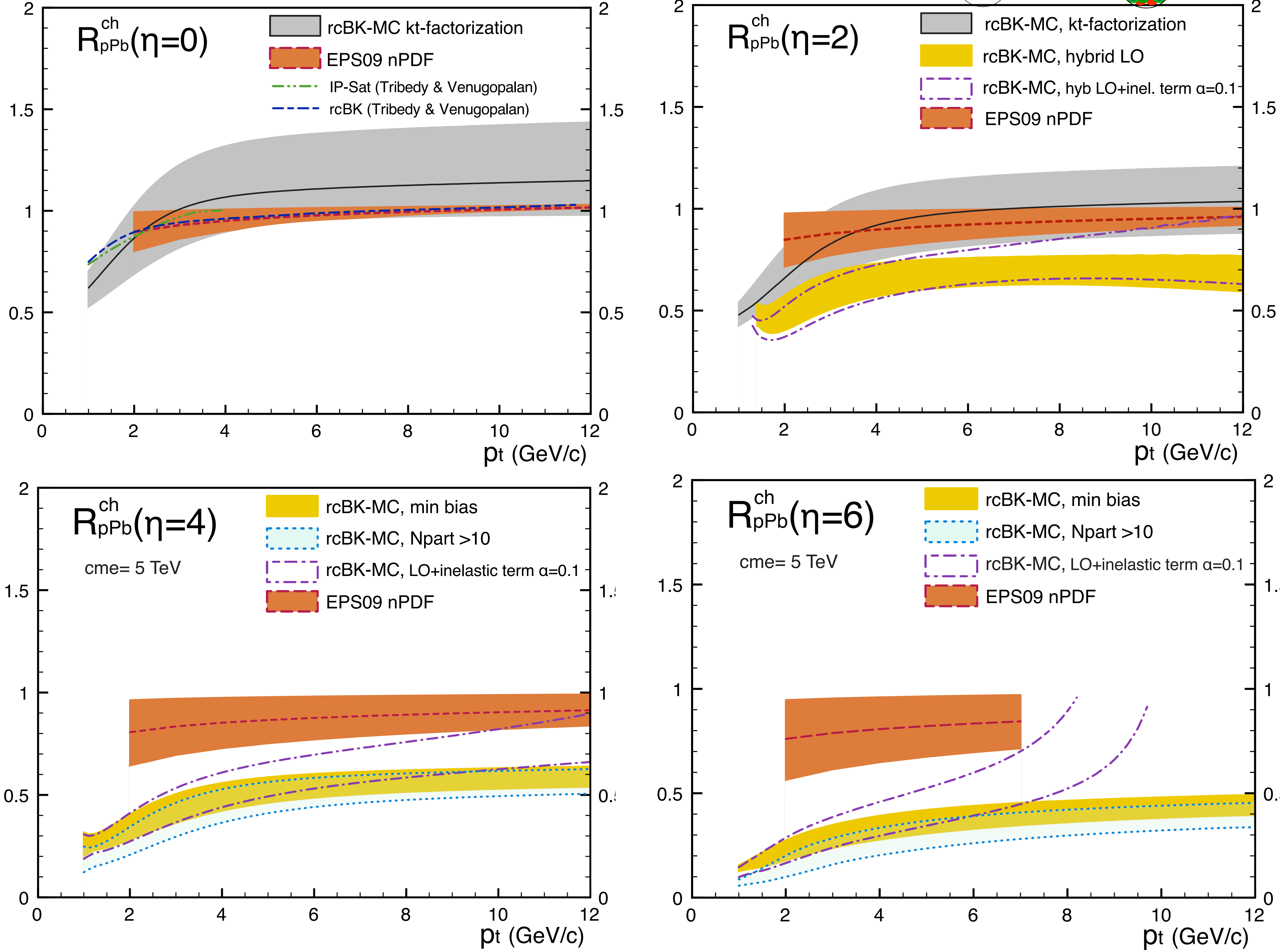
$$\frac{\mathbf{dN}}{\mathbf{d\eta d^2p_t}} \sim \mathrm{pdf}^{\mathbf{p}}(\mathbf{x_1}) \otimes \phi^{\mathbf{Pb}}(\mathbf{x_2})$$



Moving forward: Testing the non-linear evolution

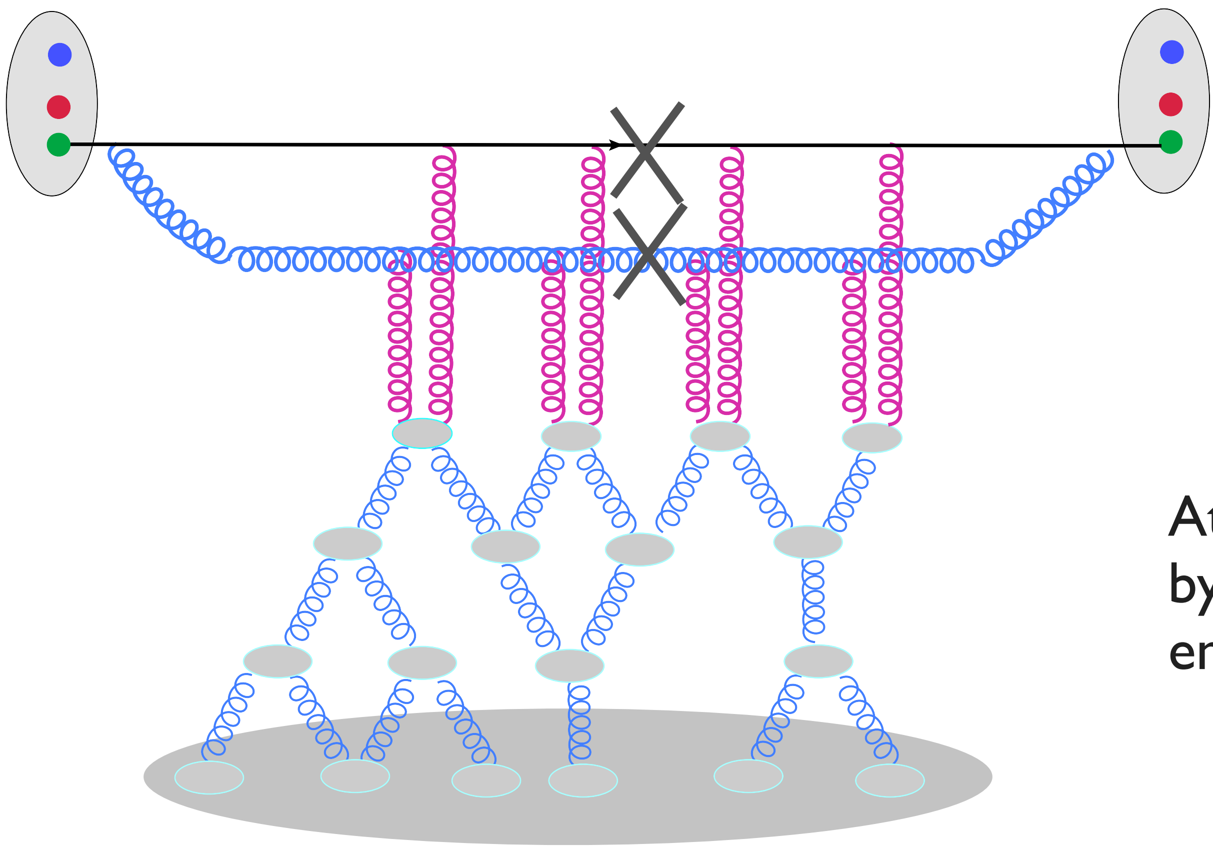


$(p_t, y_h >> 0)$



Forward di-hadron angular correlations

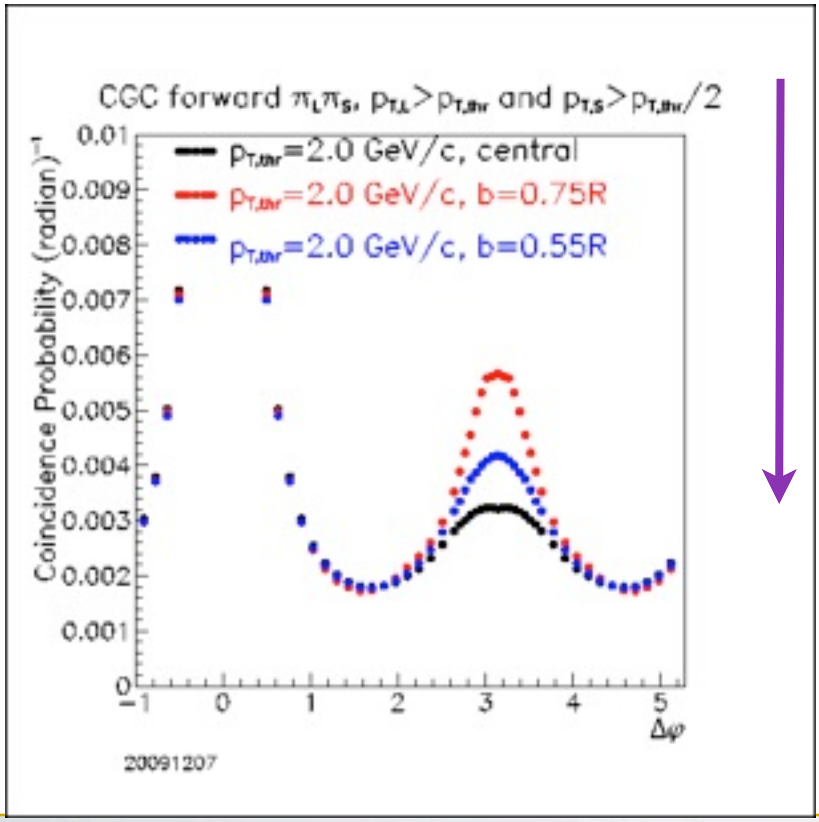
Marquet '07, Dominguez et al



$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

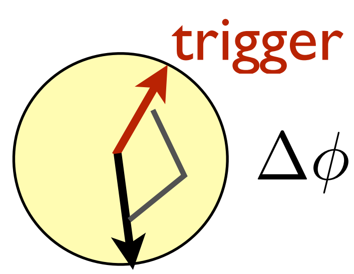
$$x_A = \frac{|k_1|e^{-y_1} + |k_2|e^{-y_2}}{\sqrt{s}}$$

At small-x, the transverse momentum transfer is controlled by the saturation scale. CGC description: A quark (gluon) emits a gluon. The pair scatters independently off the target



Angular decorrelation happens if $\mathbf{Q_s^{Pb}(x_A) \sim (k_1, k_2)}$

➡ Coincidence probability



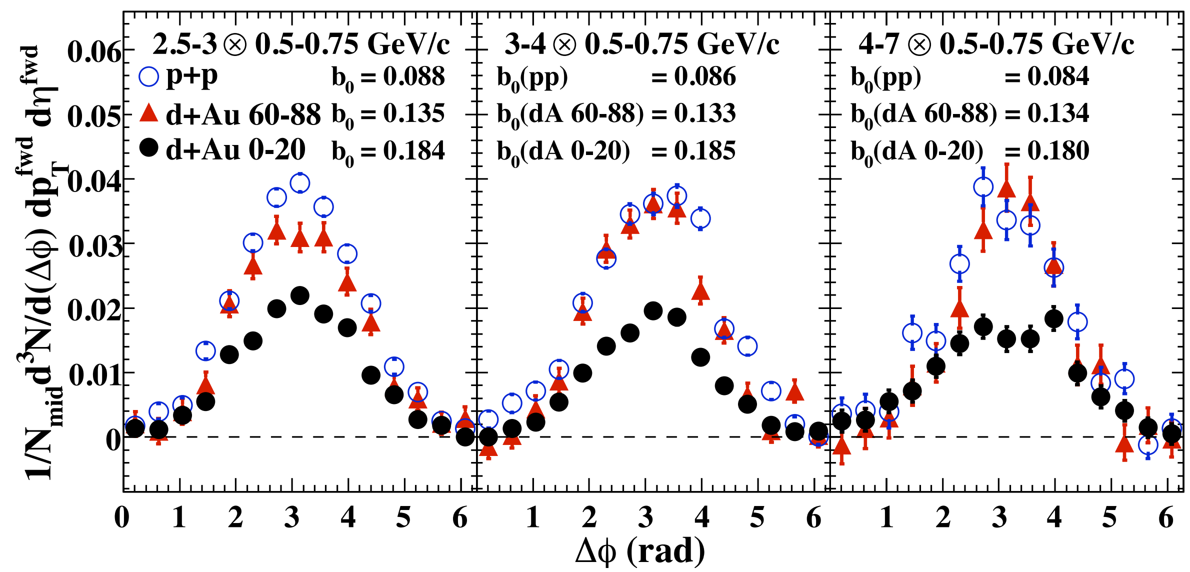
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$

Ergo, decorrelation should be stronger with

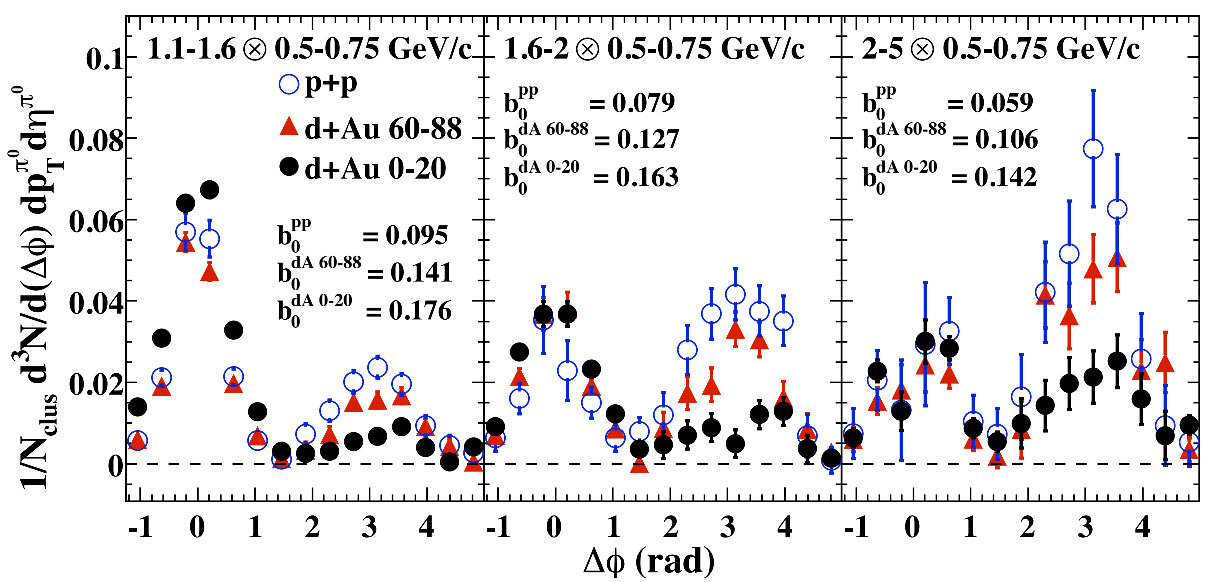
- Increasing rapidity of the pair
- Increasing collision centrality
- Decreasing hadron momentum

Forward di-hadron angular correlations in RHIC dAu data

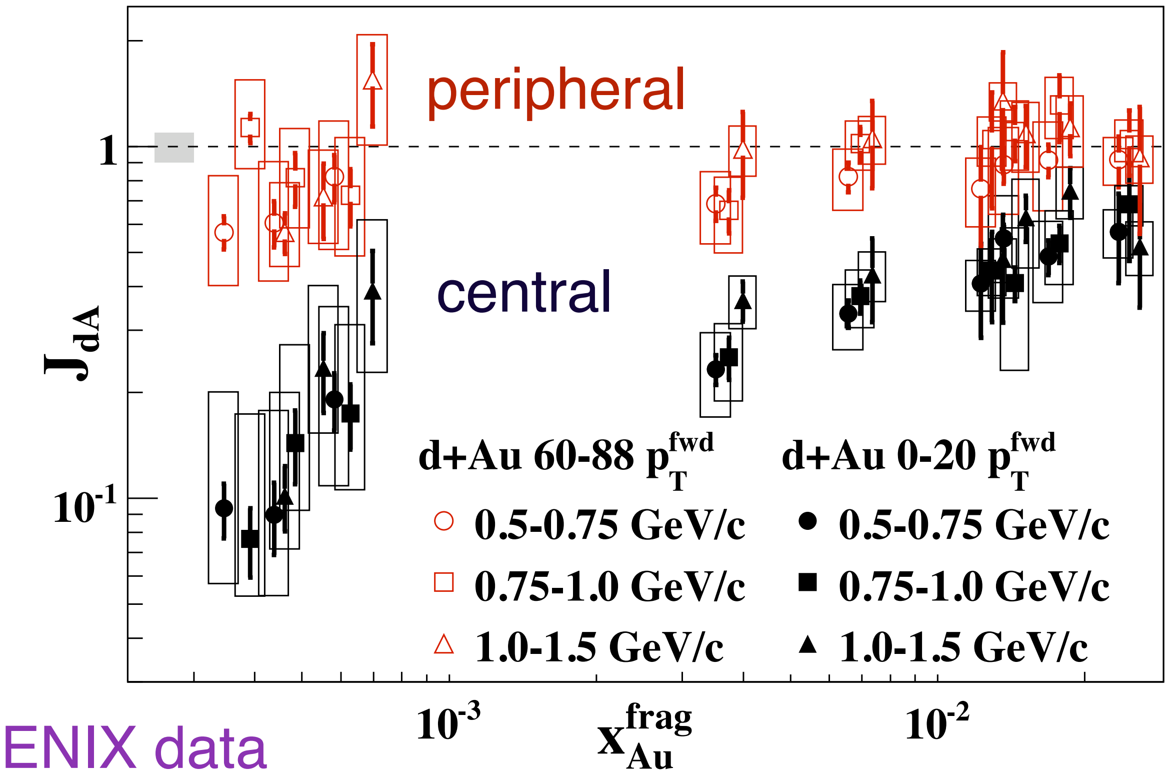
central-forward



forward-forward



$$J_{dA} = I_{dA} \times R^t_{dA} = \frac{1}{\langle N_{\rm coll}\rangle} \frac{\sigma^{\rm pair}_{dA}/\sigma_{dA}}{\sigma^{\rm pair}_{pp}/\sigma_{pp}}$$

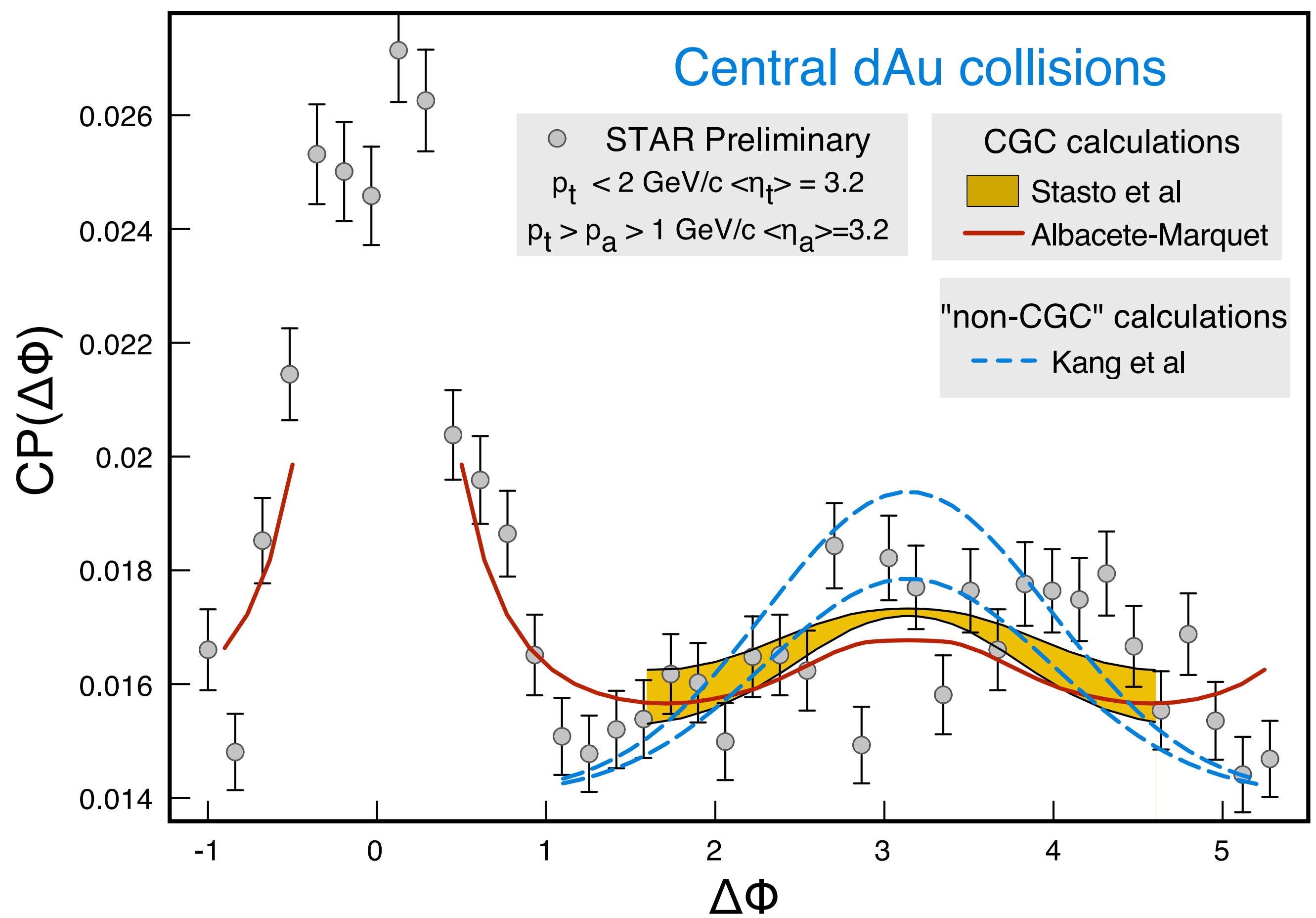


PHENIX data

Observed decorrelation IS stronger with

- Increasing rapidity of the pair
- Increasing collision centrality
- Decreasing hadron momentum

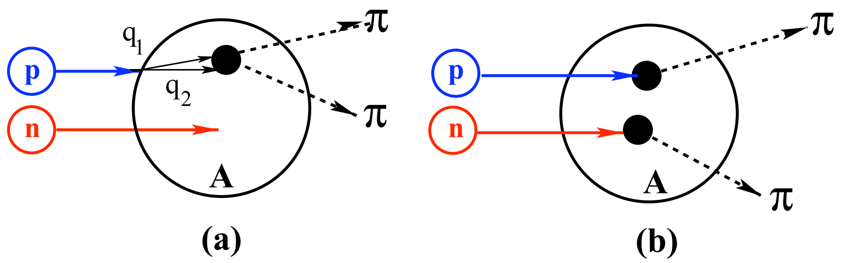
Forward di-hadron angular correlations in RHIC dAu data



Uncertainties in current CGC phenomenological works:

- Need for a better description of n-point functions: [H Mantysaari & T. Lappi]
- Better determination of the pedestal: K-factors in single inclusive production? Role of double parton scattering?

correlated



uncorrelated

Strikman, Vogelsang, 1009.6123

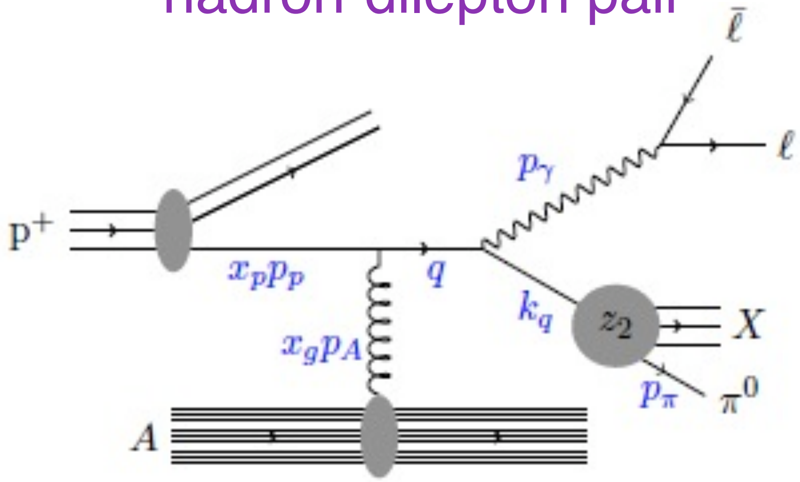
- Alternative descriptions including resummation of multiple scatterings, nuclear shadowing and cold nuclear matter energy loss seem possible... [Kang et al]

di-hadron angular correlations at the LHC

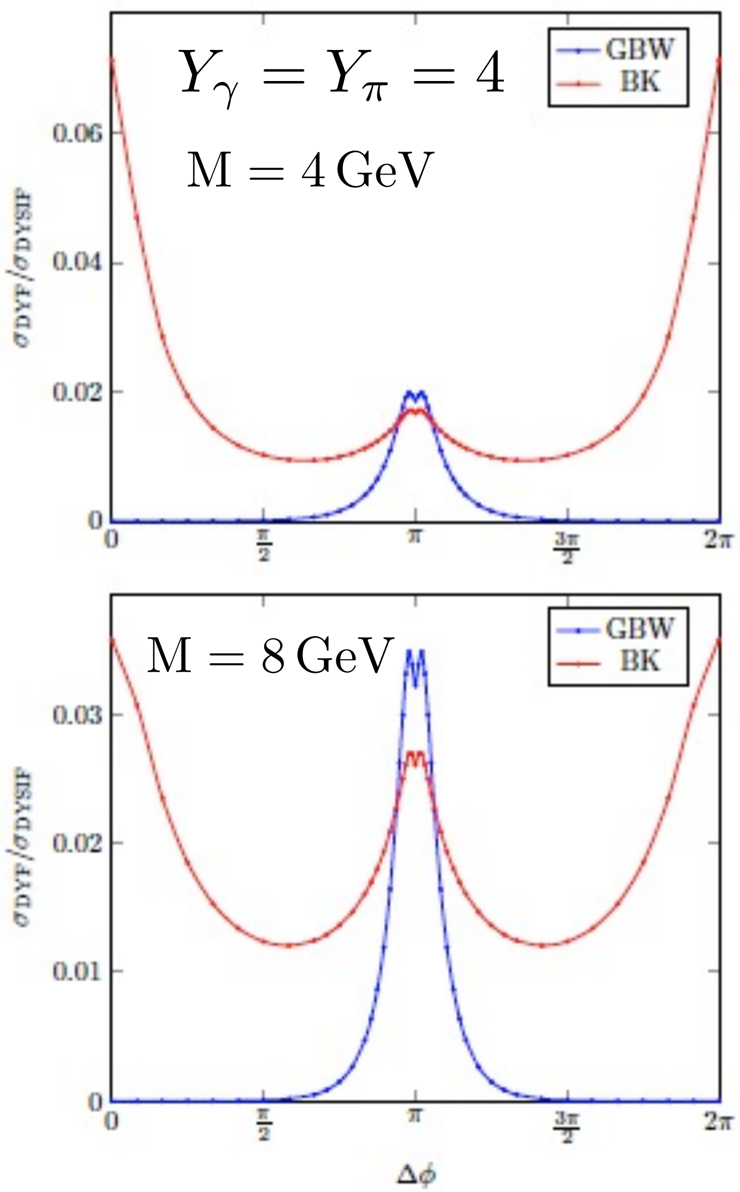
- Analogous decorrelation phenomena should be seen at the LHC
- The increase in collision energy implies that they should be visible at
  * Lower rapidities of the produced pair
  * Higher transverse momentum
- All previously mentioned details are been taken care of. Stay tuned!!!

hadron-photon* correlations in pPb collisions at the LHC

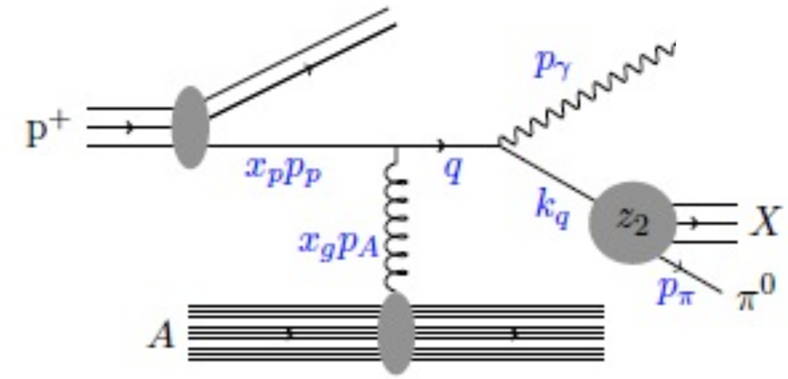
- hadron-dilepton pair



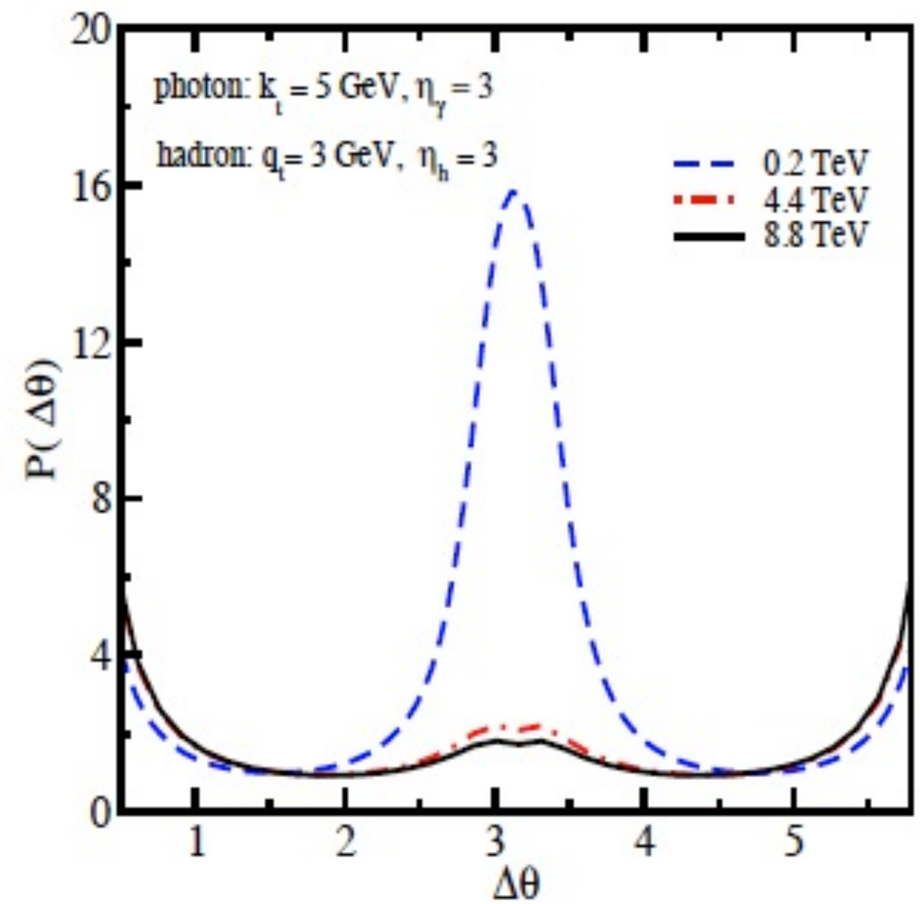
Stasto et al 1204.4861



- hadron-photon



Jalilian-Marian, Rezaeian

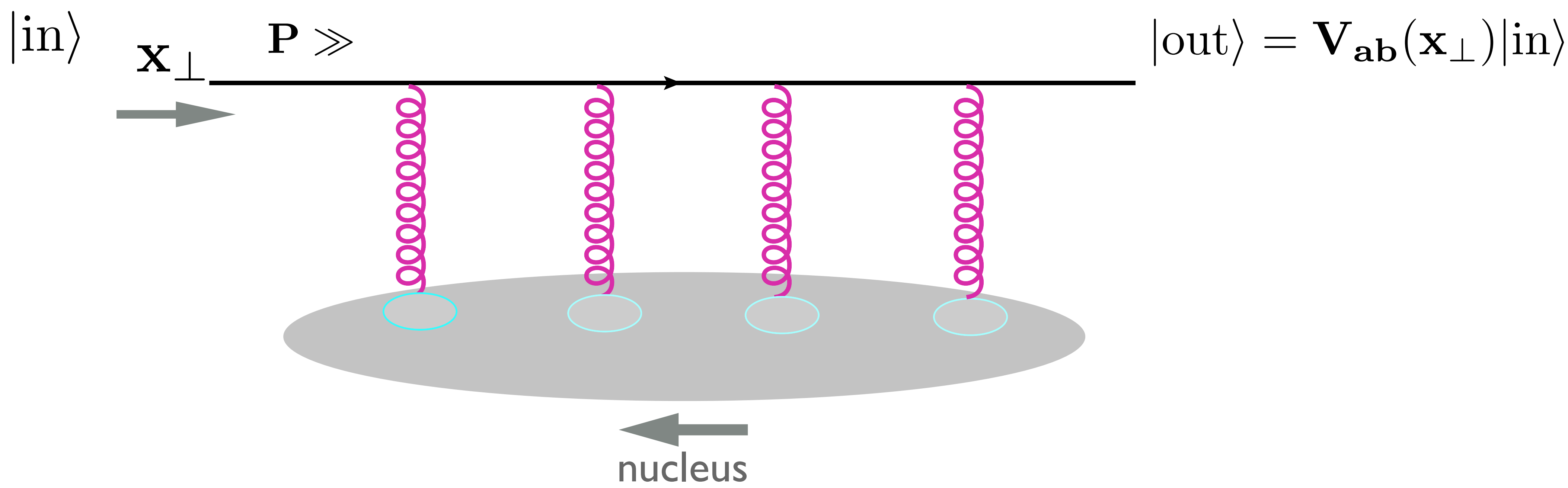


These processes are theoretically cleaner:
Only knowledge of 2-point needed!!

Multiple scatterings, Wilson lines, dipoles etc

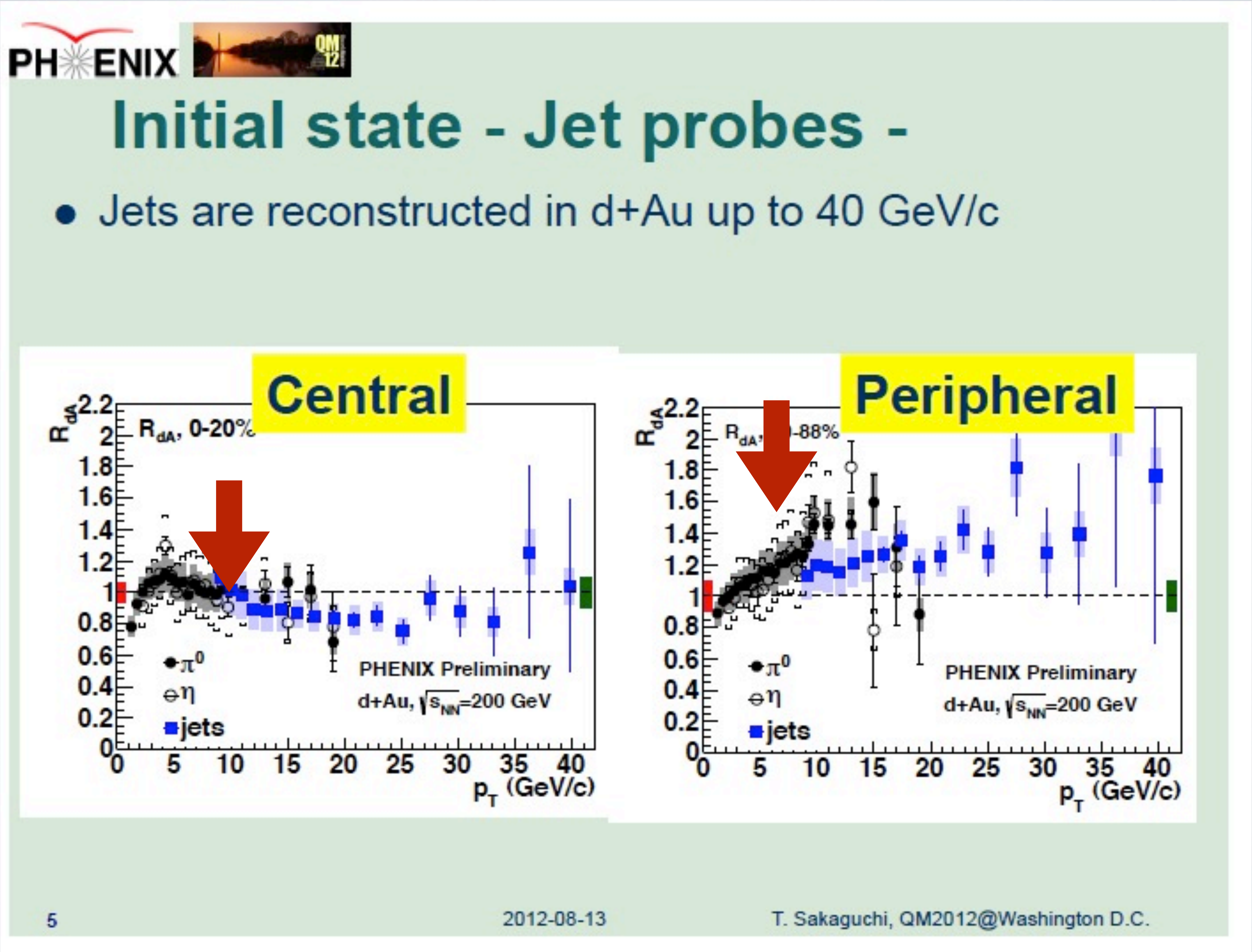
- Wilson lines (and not quarks or gluons) are the relevant degrees of freedom in high energy scattering
- Eikonal propagation: energetic quarks/gluons do not recoil during the propagation through a nucleus, they are just color rotated:

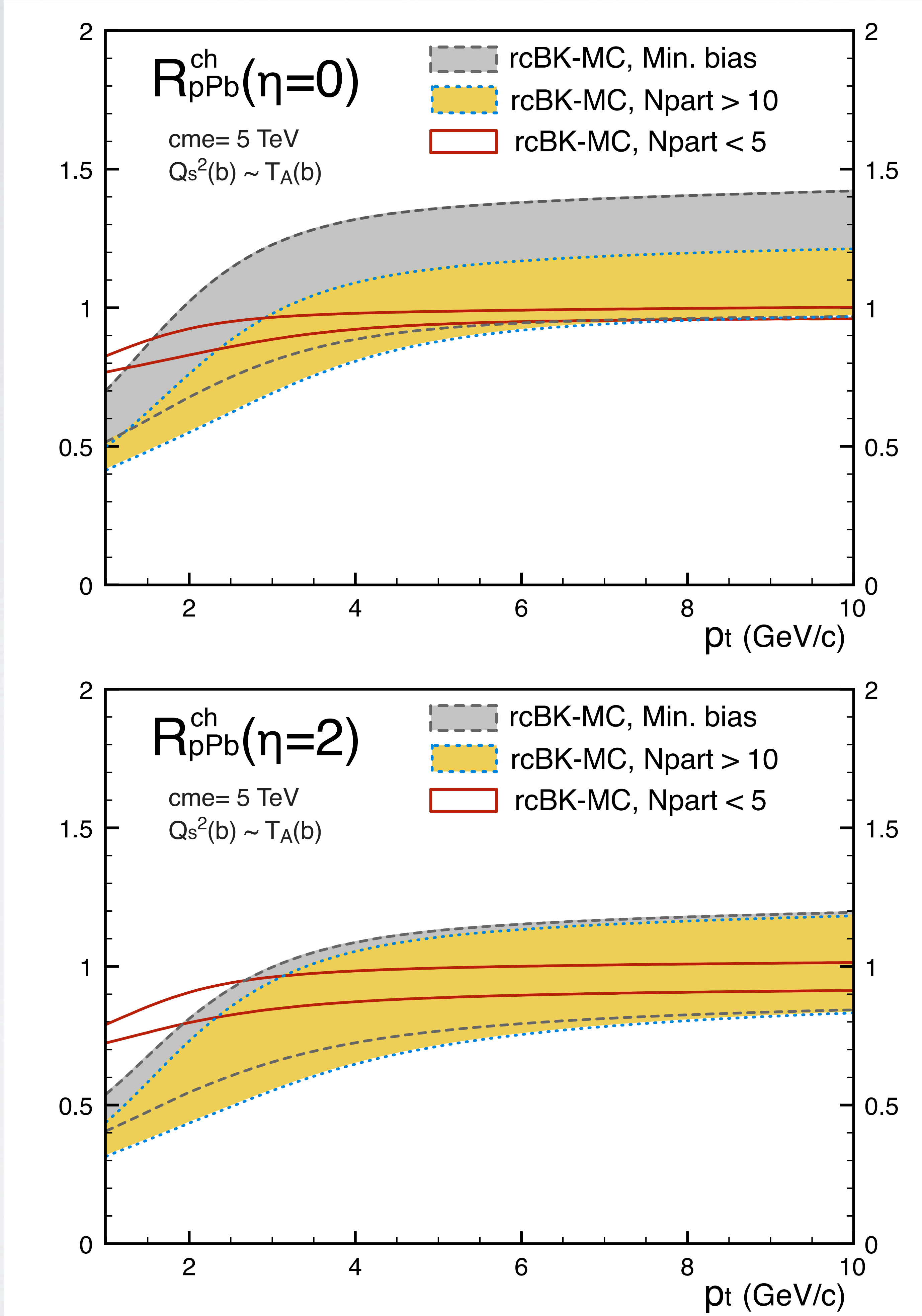
$$\mathbf{V}(\mathbf{x}_\perp) = \mathbf{1} + \mathbf{ig}\mathcal{A}^+ + \frac{(\mathbf{ig})^2}{\mathbf{2}}\mathcal{A}^{+\mathbf{2}} + \cdots = \mathcal{P}\exp\left[\mathbf{ig}\int \mathbf{dx}^- \mathcal{A}^+(\mathbf{x}_\perp, \mathbf{x}^-)\right]$$



Each additional scattering contributes $\mathrm{g}\,\mathcal{A}^+ \sim \mathcal{O}(\mathbf{1})$

If these data are confirmed... ALL initial state models are in trouble!!





$R^{ch}_{pPb}(\eta=0)$
cme= 5 TeV
$Q_s^2(b) \sim T_A(b)$
rcBK-MC, Min. bias
rcBK-MC, Npart > 10
rcBK-MC, Npart < 5
pt (GeV/c)
$R^{ch}_{pPb}(\eta=2)$
cme= 5 TeV
$Q_s^2(b) \sim T_A(b)$
rcBK-MC, Min. bias
rcBK-MC, Npart > 10
rcBK-MC, Npart < 5
pt (GeV/c)