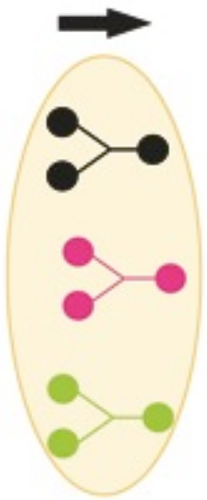
Testing the CGC in p+Pb collisions at the LHC

Javier L Albacete

Rencontres QGP France-12. Étretat, 25-28 Sep 2012

What the CGC is about : coherence effects in high energy QCD (small-x)

High gluon densities in the projectile/target



Saturation: gluon self-interactions tame the growth of gluon densities towards small-x

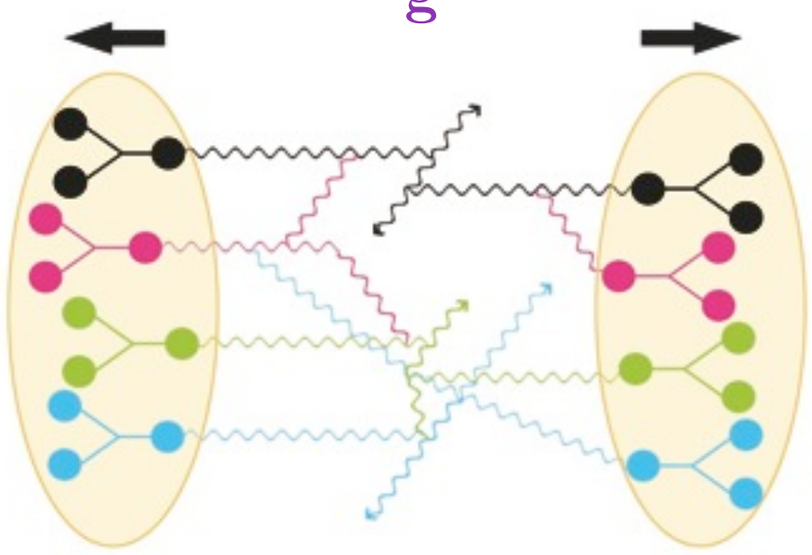
$$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^{\mathbf{2}}$$

radiation recombination

$$\mathbf{k_t} \lesssim \mathbf{Q_s}(\mathbf{x})$$

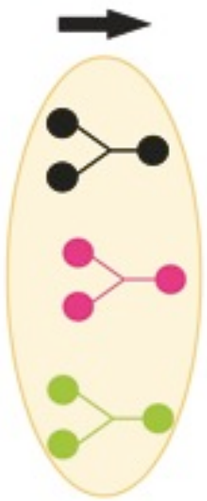
Breakdown of independent particle production

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



What the CGC is about : coherence effects

High gluon densities in the projectile/target



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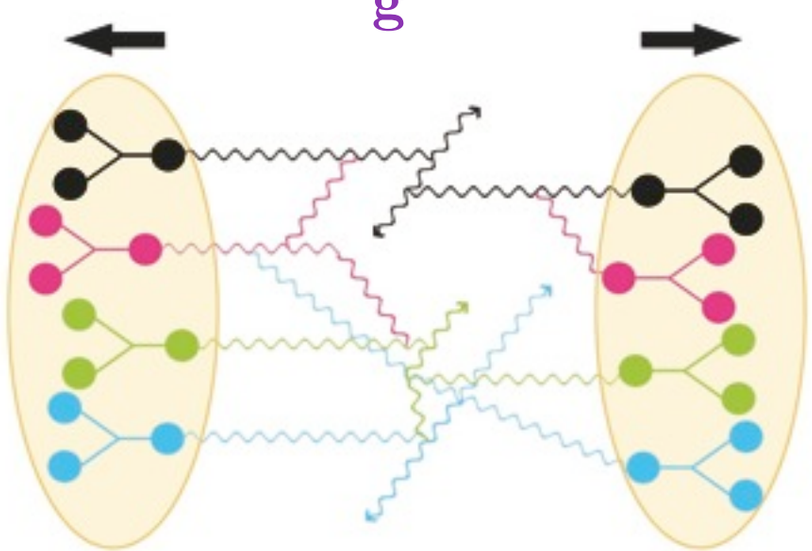
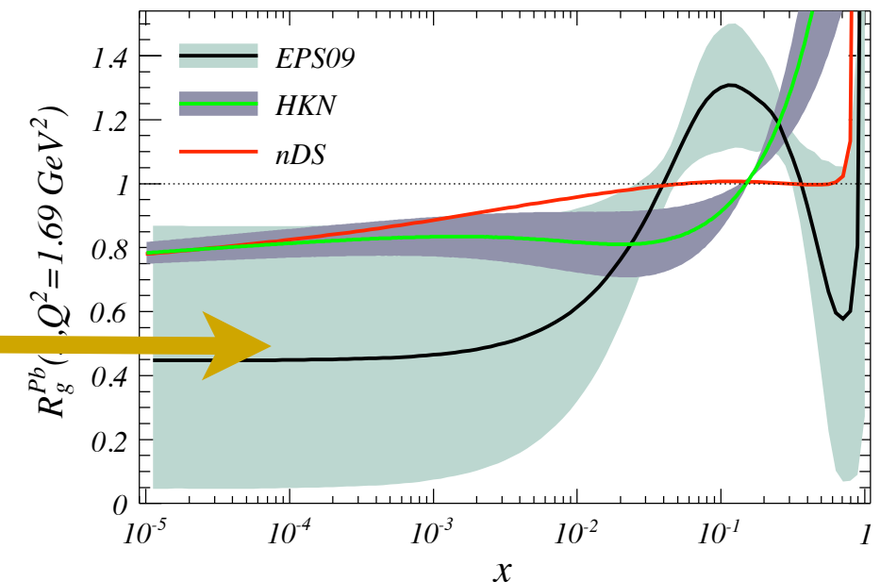
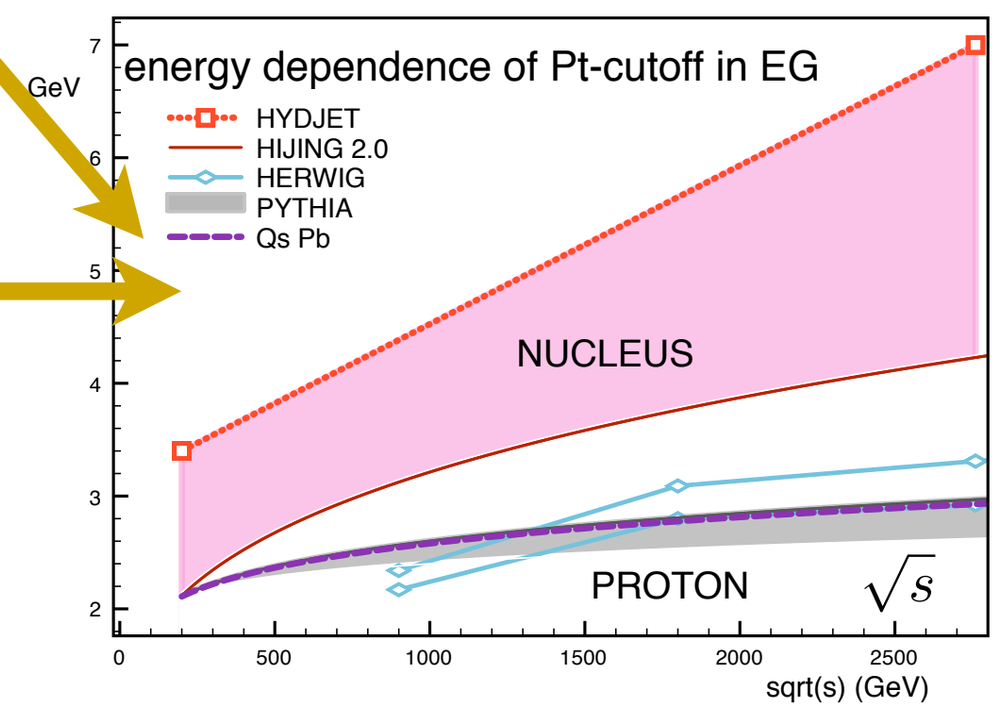


HIC phenomenology

- Nuclear shadowing, String fusion, percolation



- Resummation of multiple scatterings
- kt-broadening
- Energy dependent cutoff in event generators



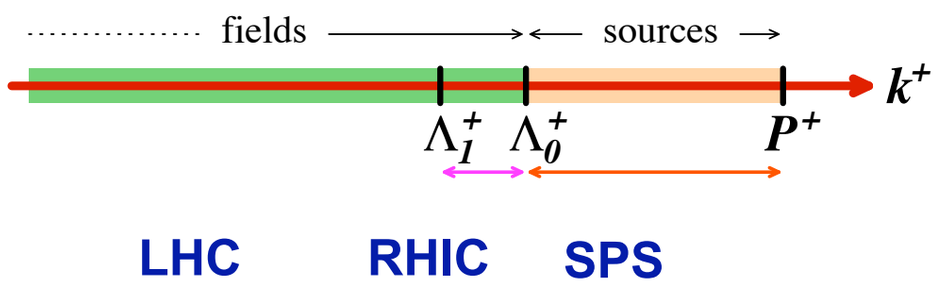
OUTLINE

- **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)**

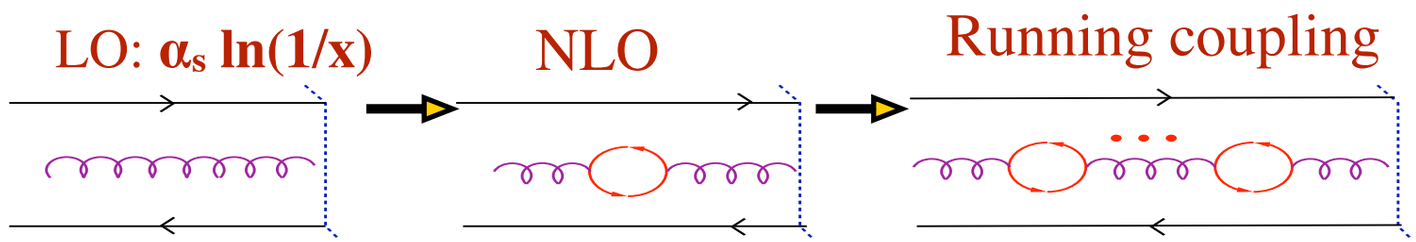


(brief and incomplete) CGC Theory Status: Entering the NLO era

G. Beuf's Talk

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

- ✓ - 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)

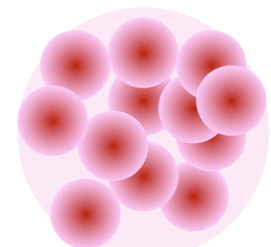
proton

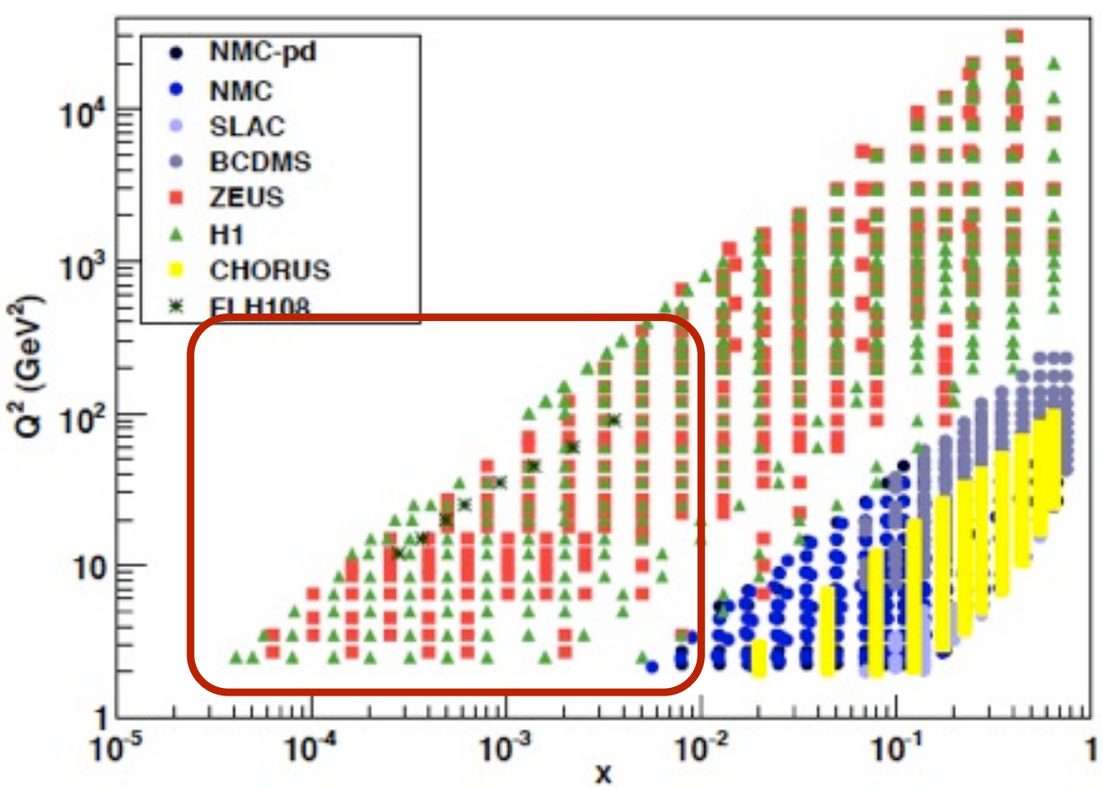
- Abundant high quality data at small-x
- Good simultaneous description of e+p and p+p data
- Global rcBK fits to constrain gluon distribution

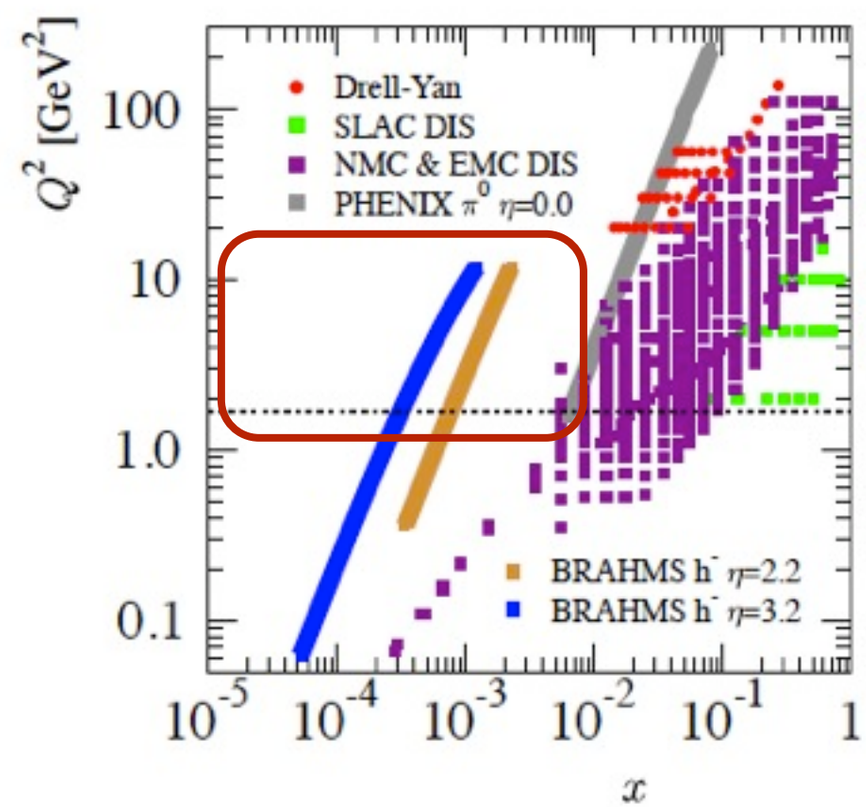
nuclei

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

modelling!

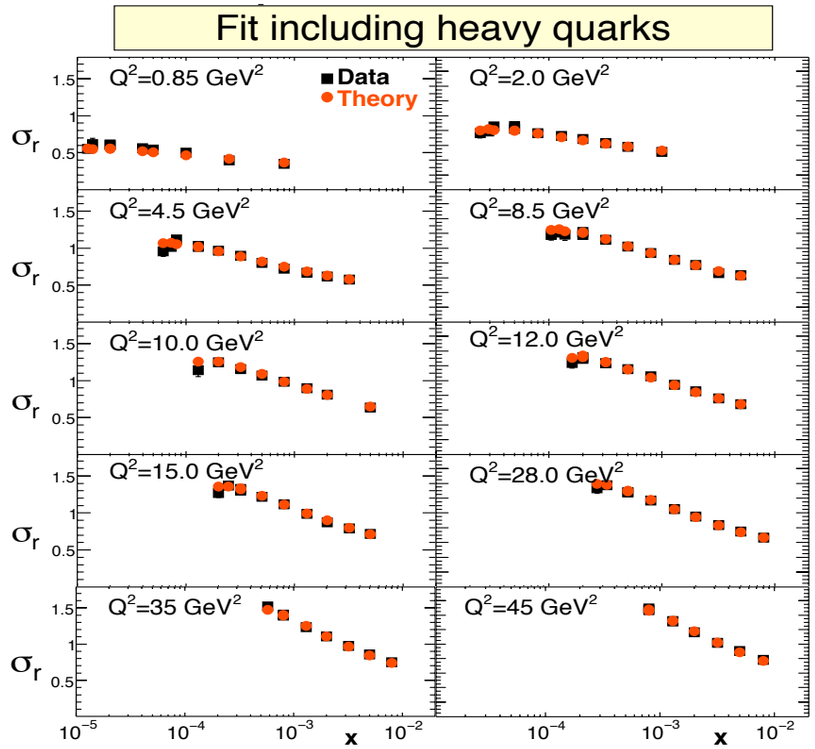






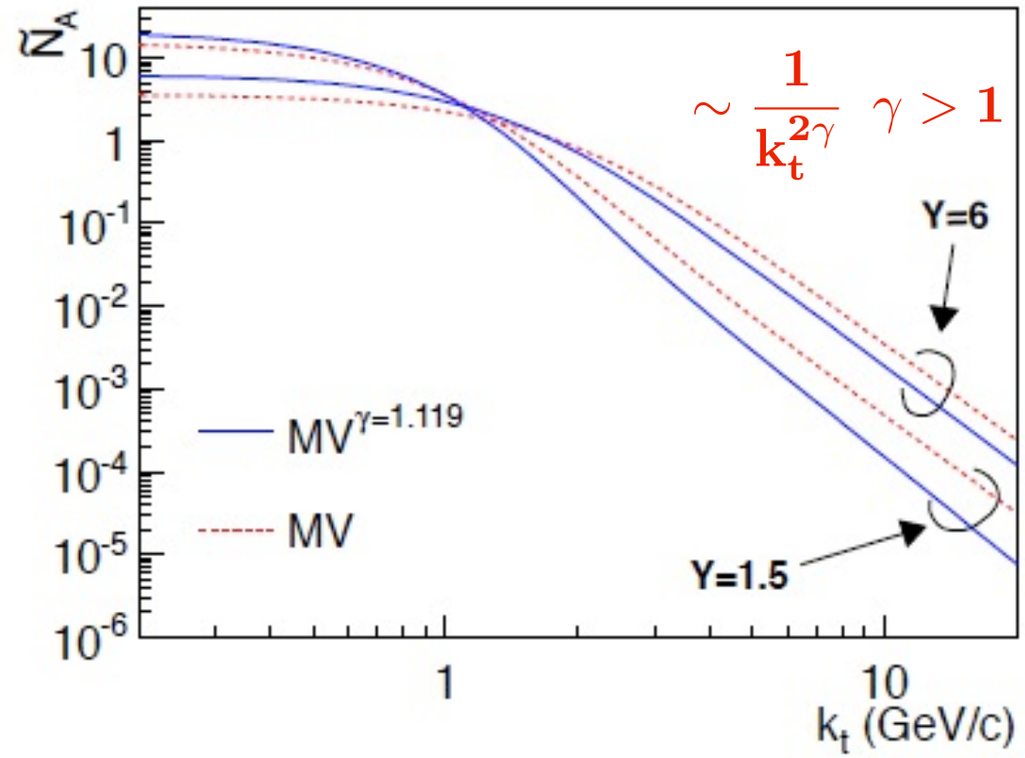
The baseline: proton collisions

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



JLA, Armesto, Milhano, Quiroga, Salgado

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



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

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

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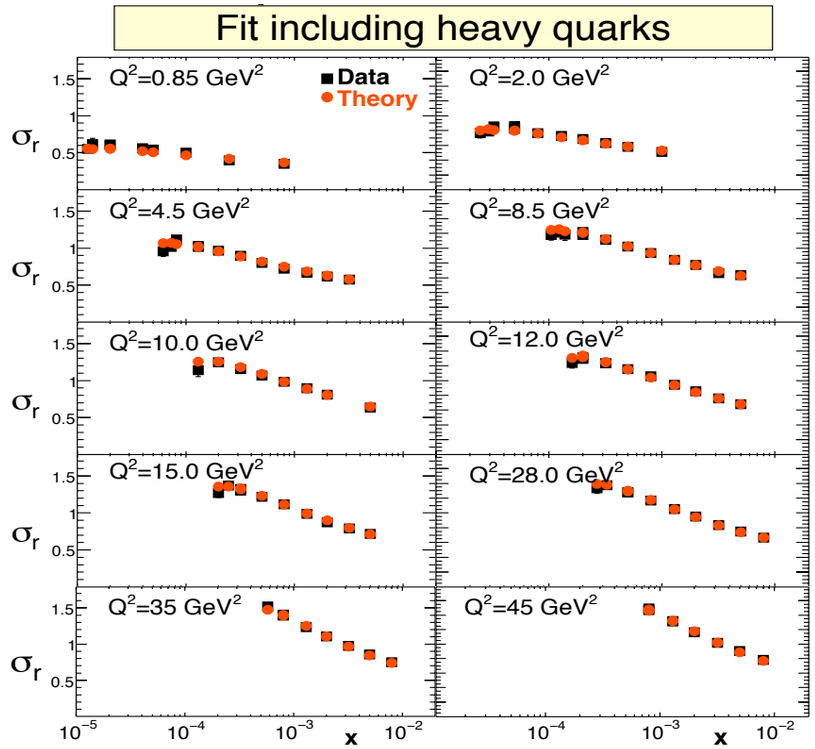

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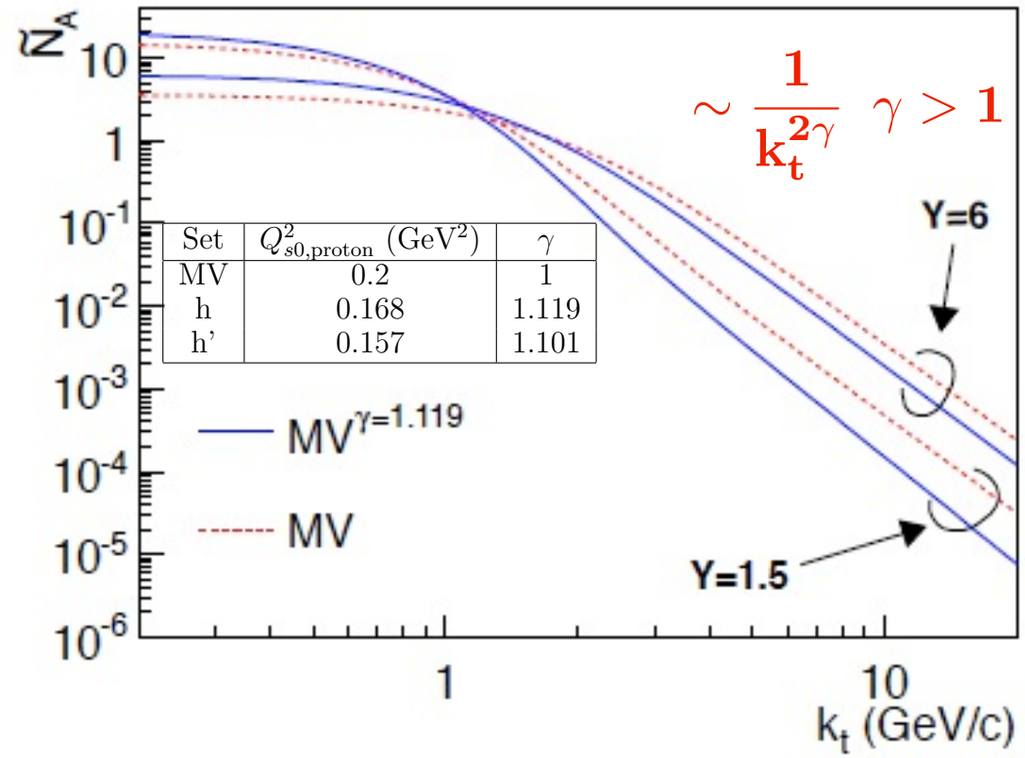
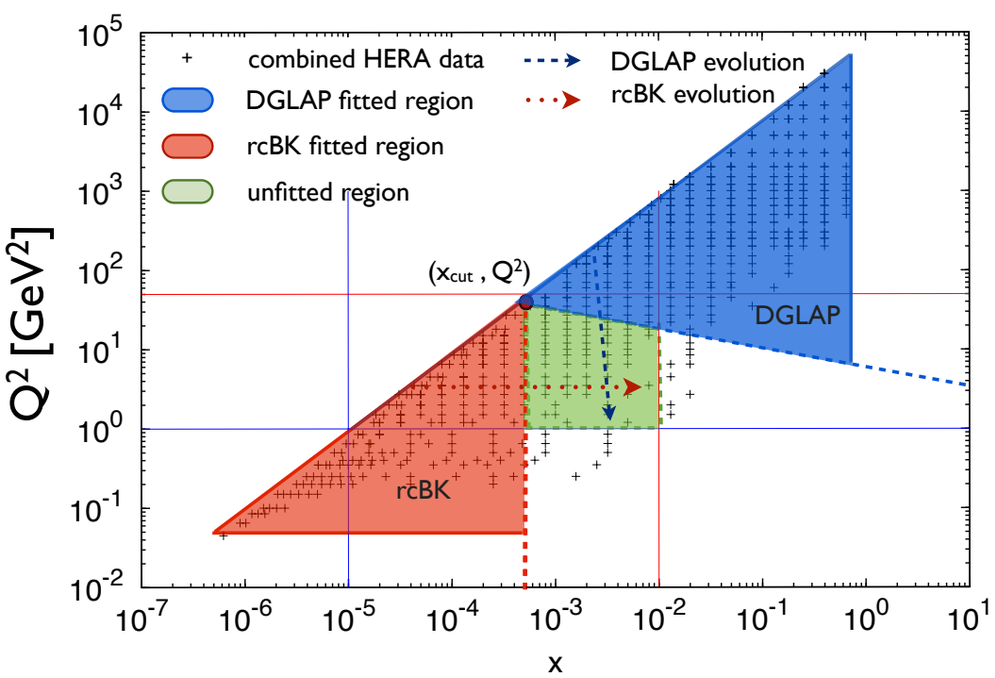
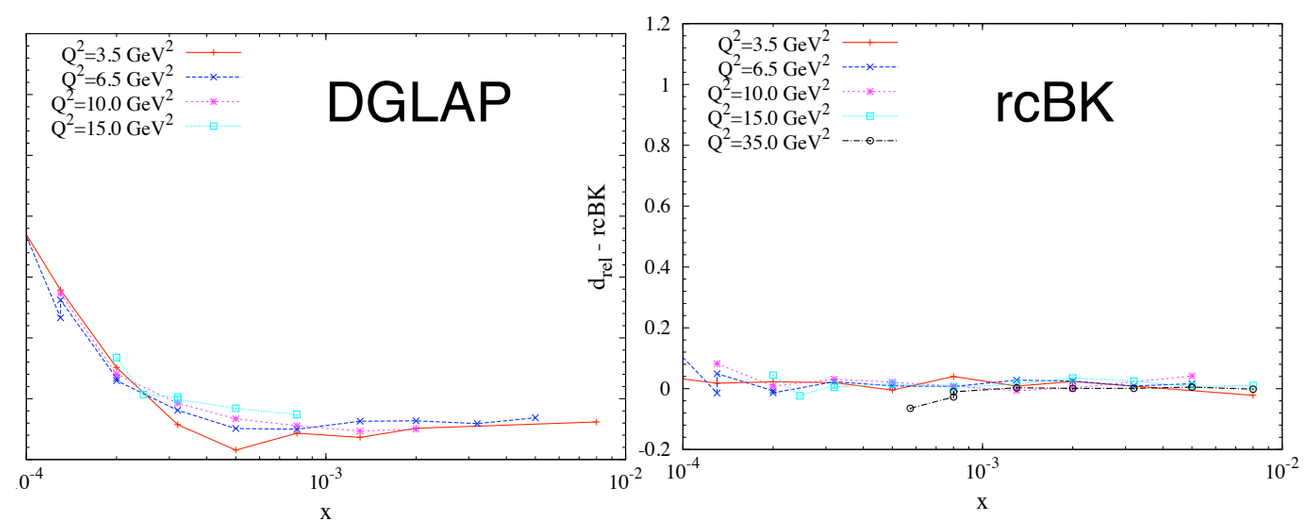


Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h'	0.157	1.101

3. Run consistency and stability checks



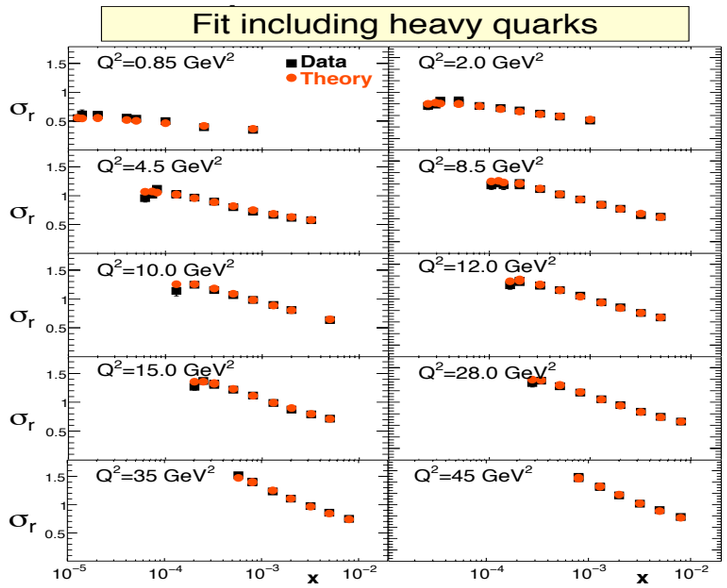


rcBK fits more stable than DGLAP fits at small-x

JLA, Milhano, Quiroga, Rojo

The baseline: proton collisions

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



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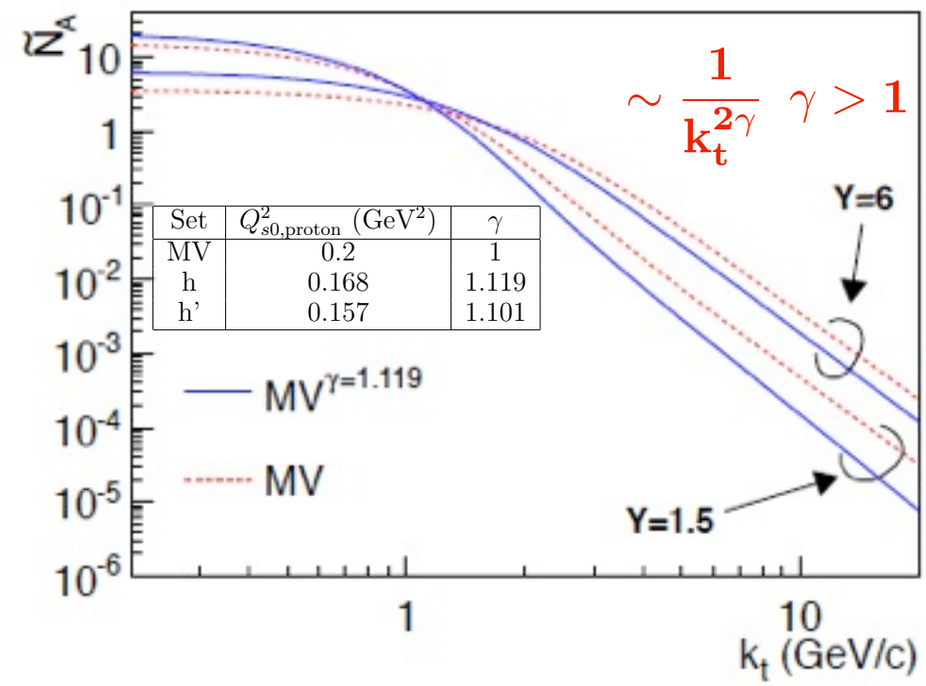
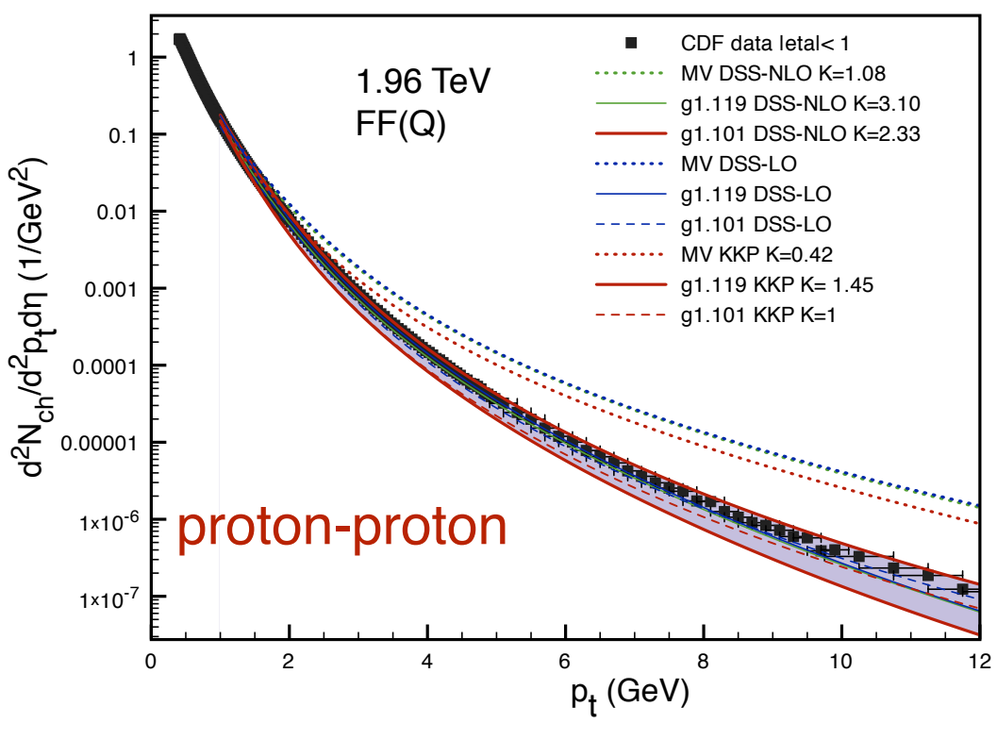


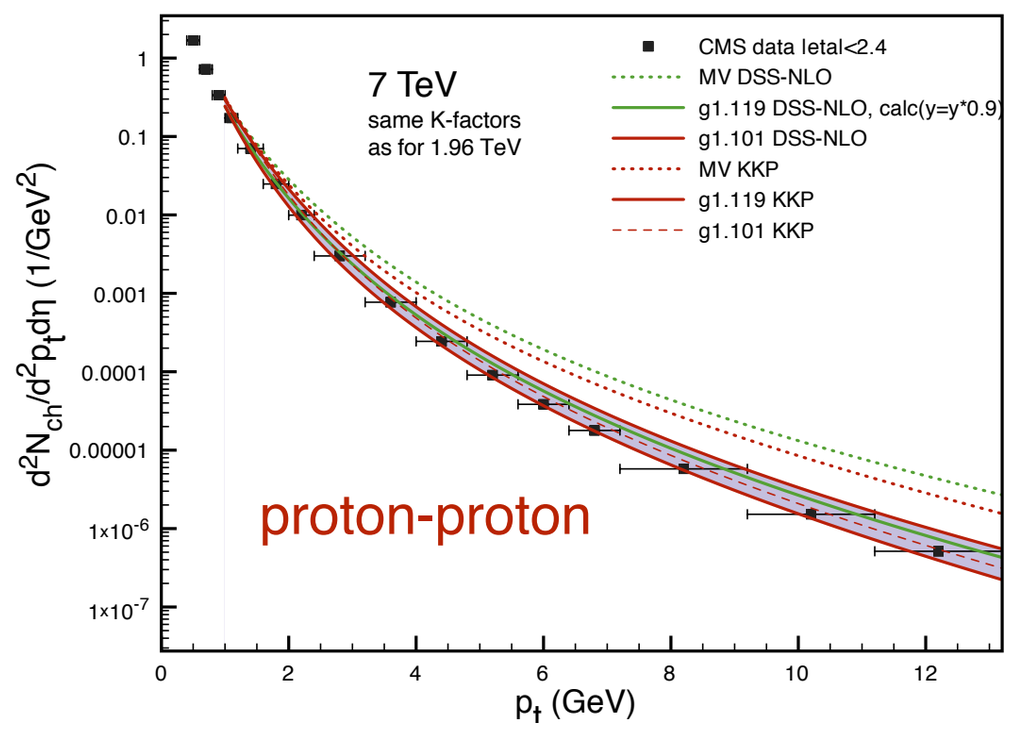
Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h'	0.157	1.101

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

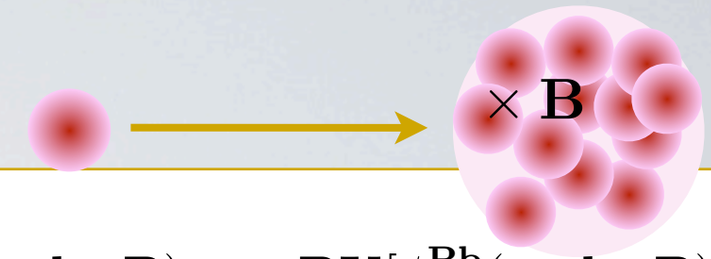
JLA, Dumitru, Fujii, Nara

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



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

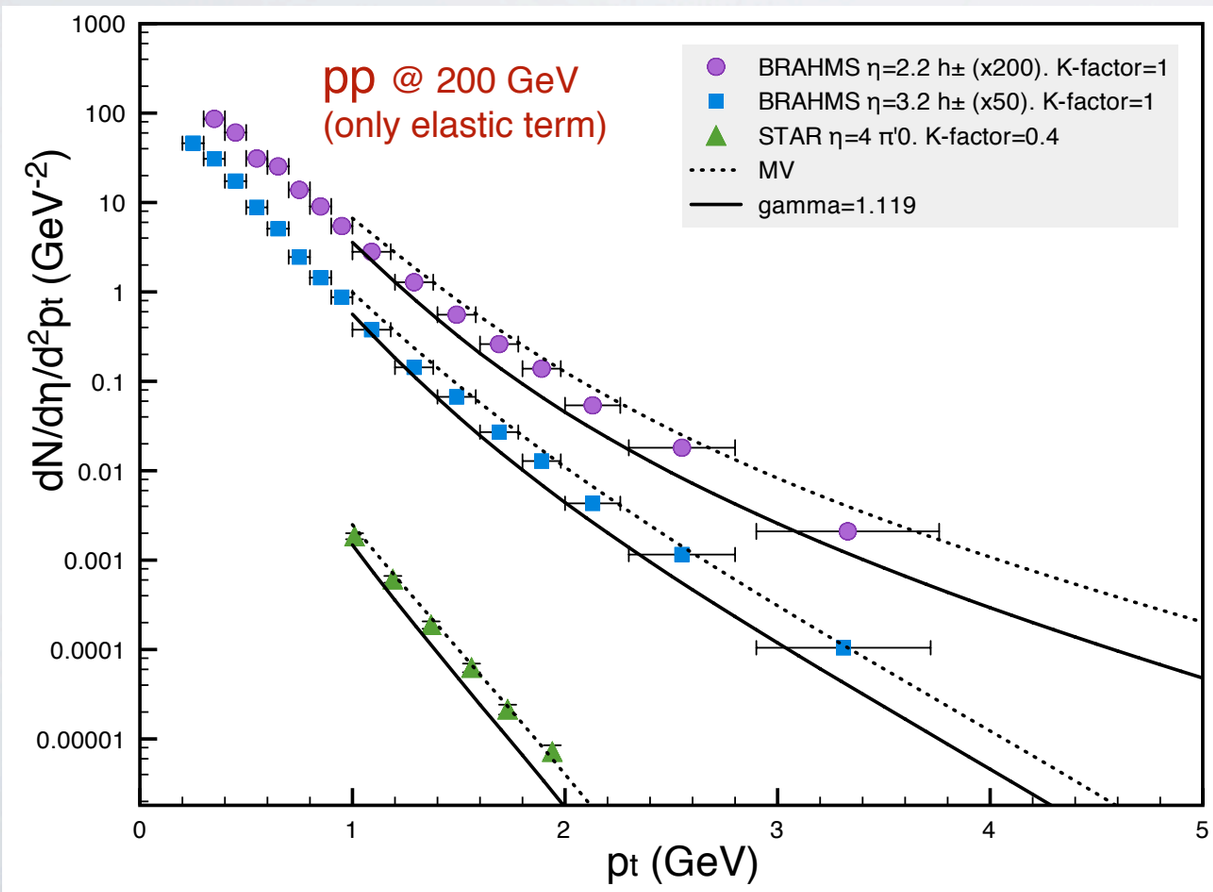
A) Most "natural" option: $Q^2_{s0,Pb}(B) = T_A(B)\, Q^2_{s0,p}$ $\quad \gamma^{Pb} = \gamma^{p}(> 1)$

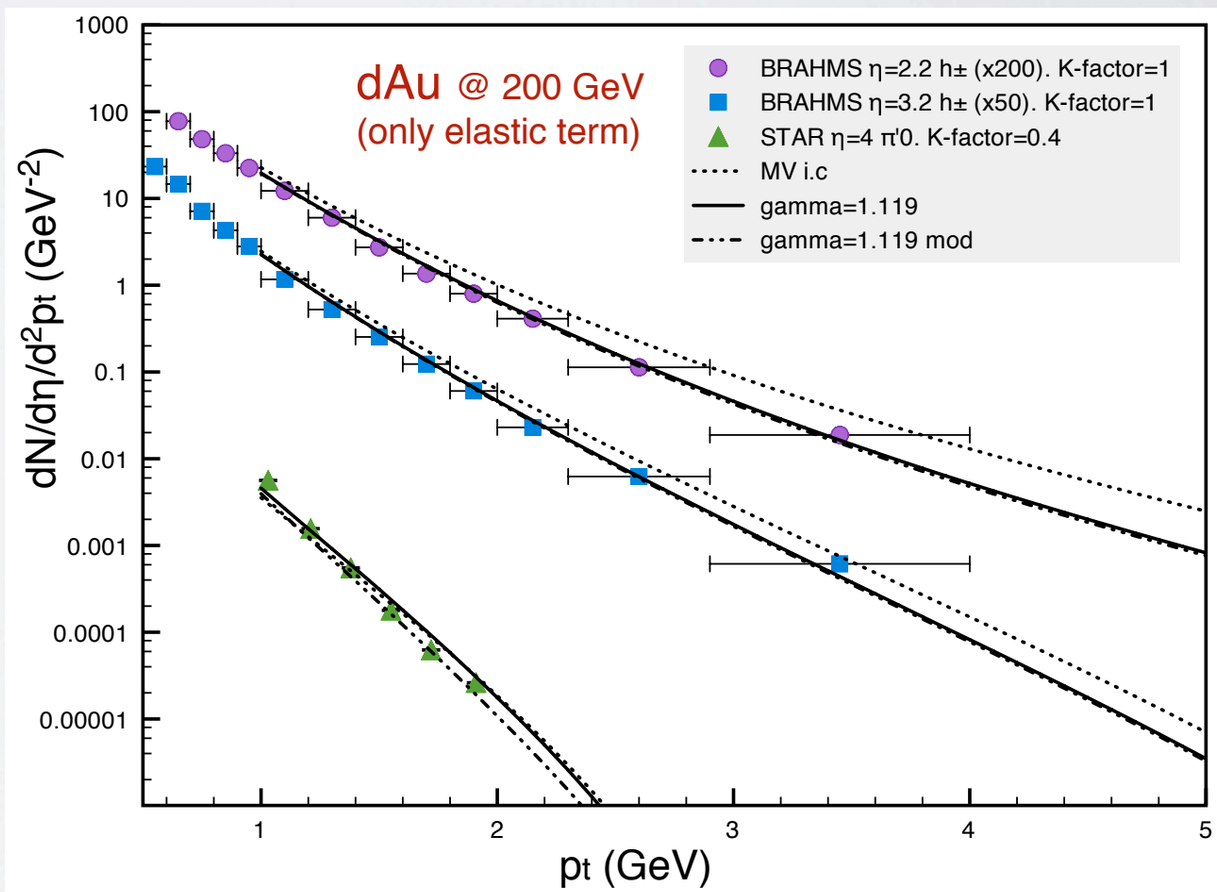
PROBLEM: yields $R_{pPB} > 1$ at high transverse momentum

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

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





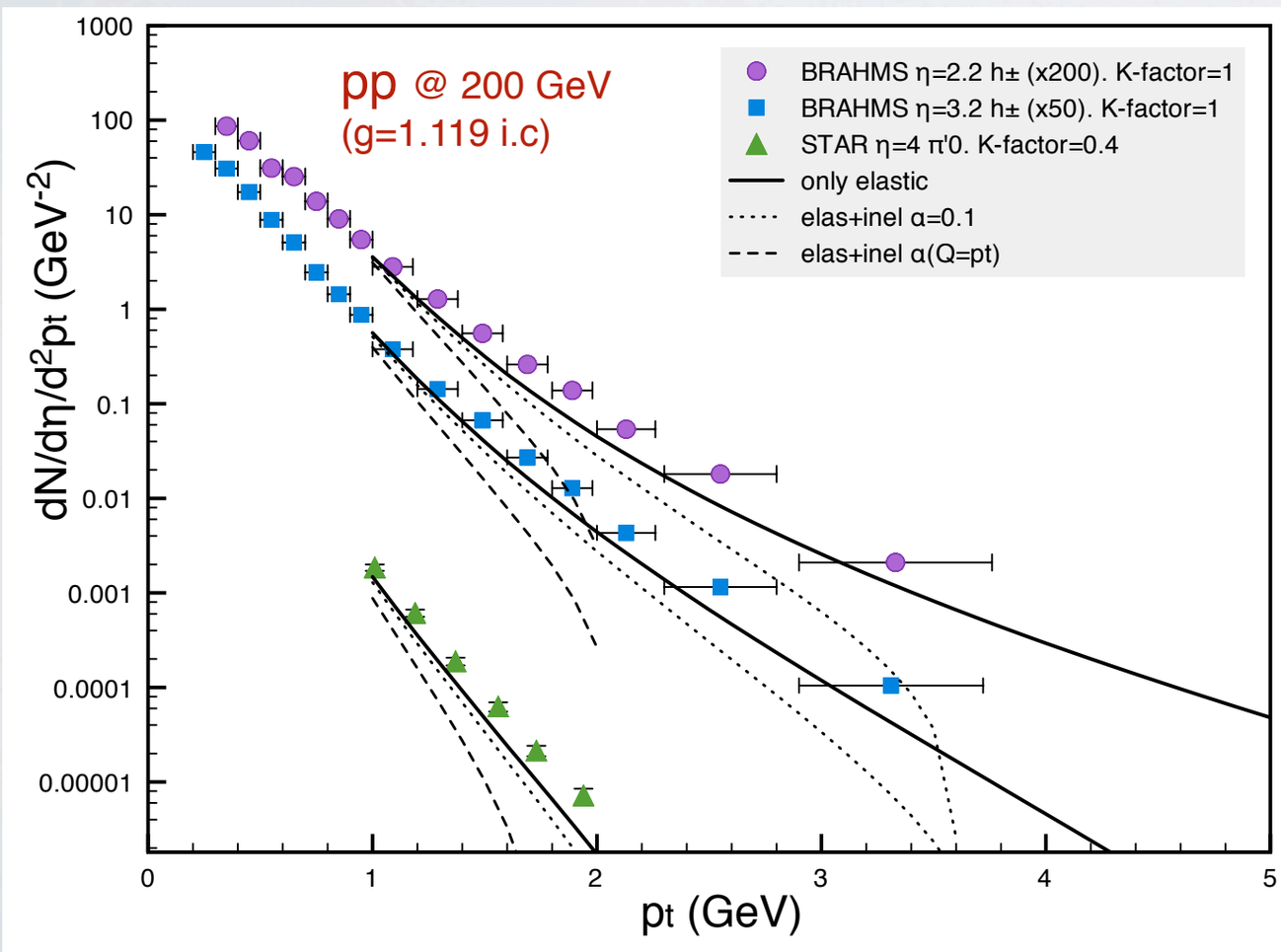
Effect of NLO corrections

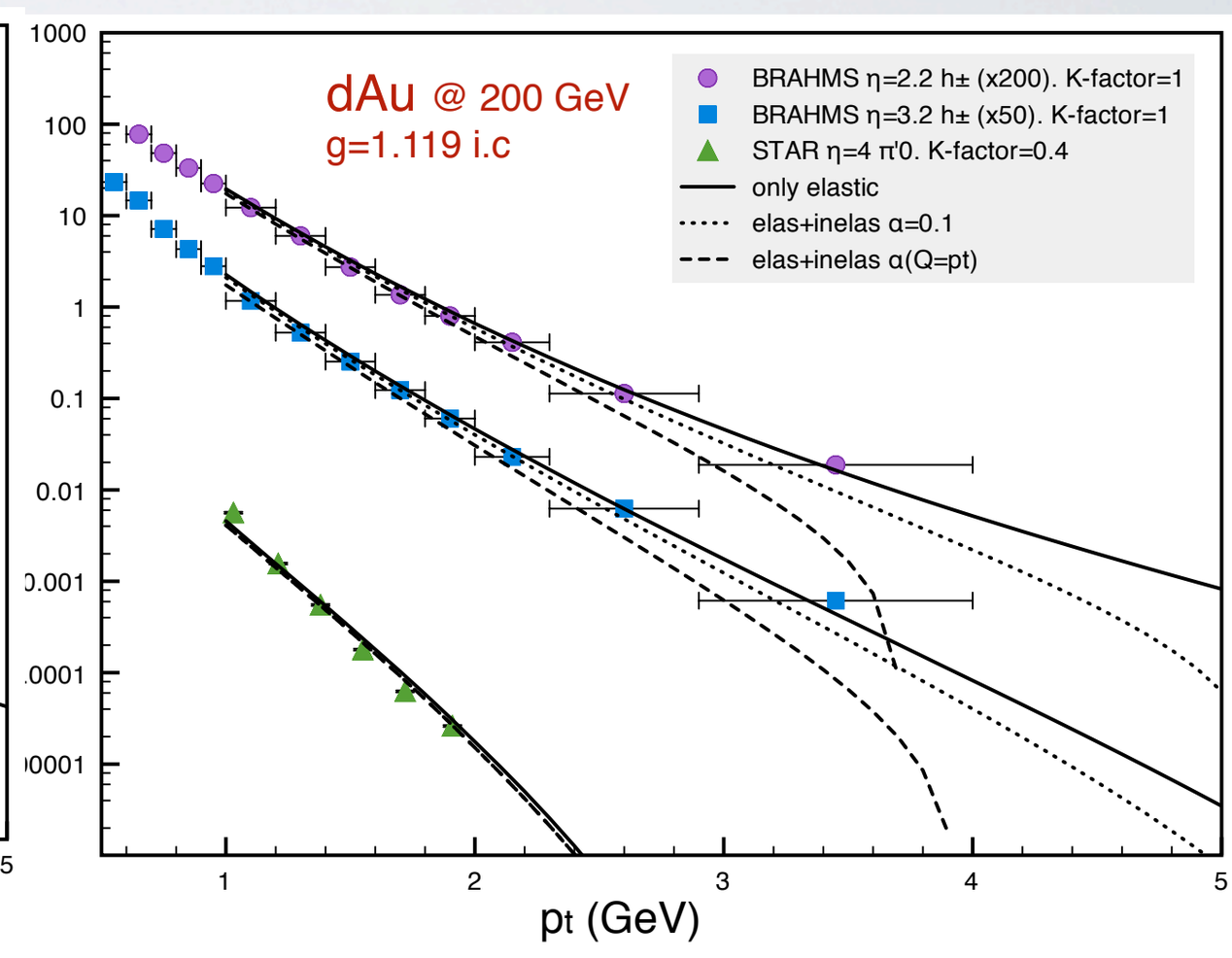
The effect of NLO corrections to the hybrid formalism can be very large!!!. Full NLO analyses needed

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

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

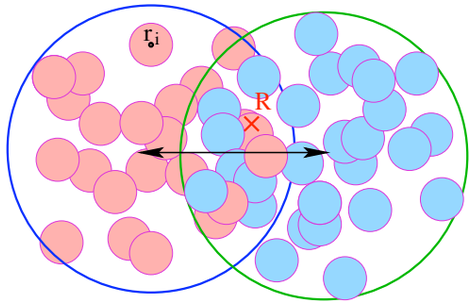
$$\left[\frac{dN_h}{d\eta\, d^2k}\right]_{\rm inel} = \frac{\alpha_s(Q)}{2\pi^2}\int_{x_F}^{1} \frac{dz}{z^2}\frac{z^4}{k^4}\int^{Q}\frac{d^2q}{(2\pi)^2} q^2 \tilde{N}_F(x_2,q)\, x_1 \int_{x_1}^{1}\frac{d\xi}{\xi}\sum_{i,j=q,\bar{q},g} w_{i/j}(\xi) P_{i/j}(\xi) f_j\left(\frac{x_1}{\xi},Q^2\right) D_{h/j}(z,Q^2)$$





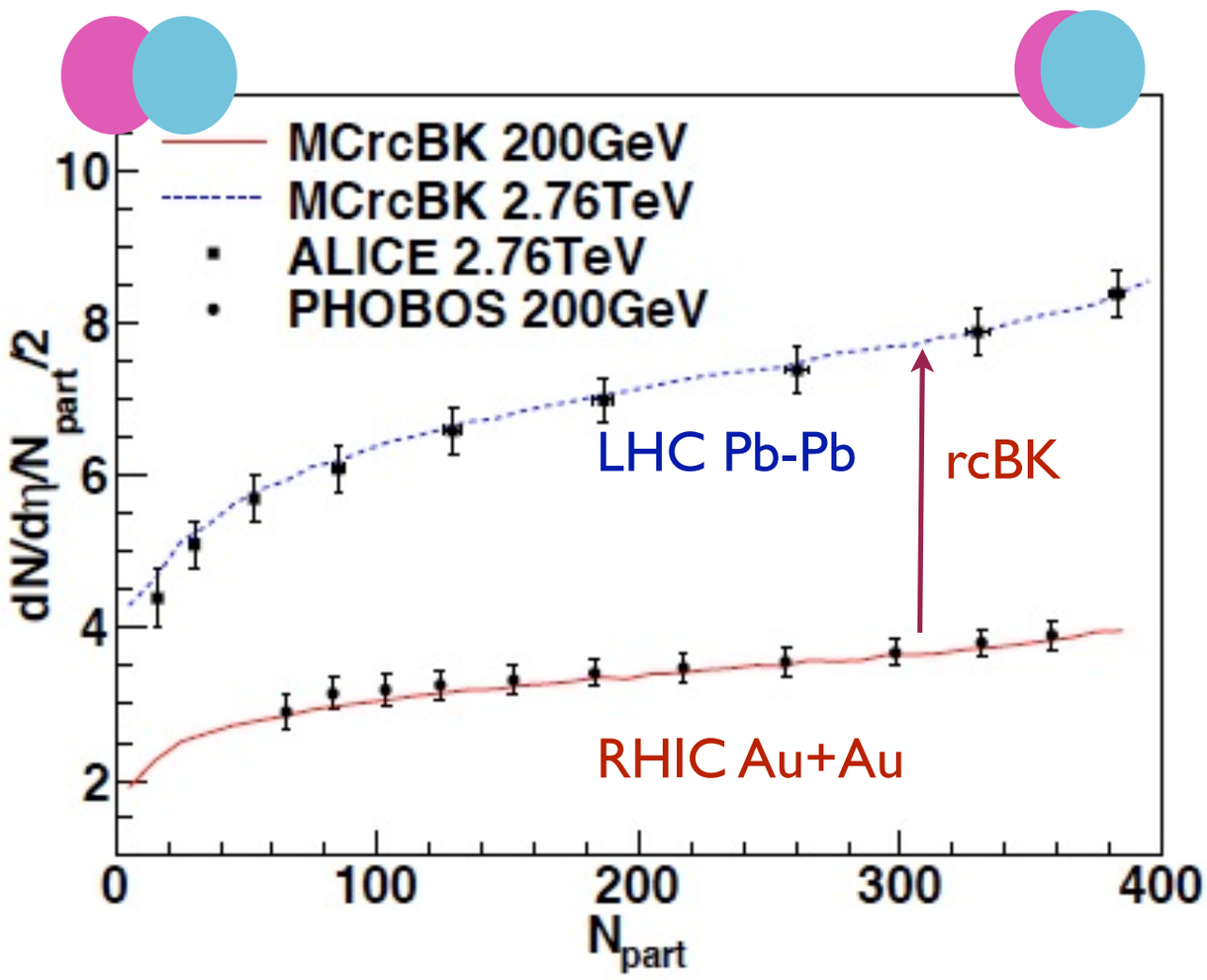
Multiplicities

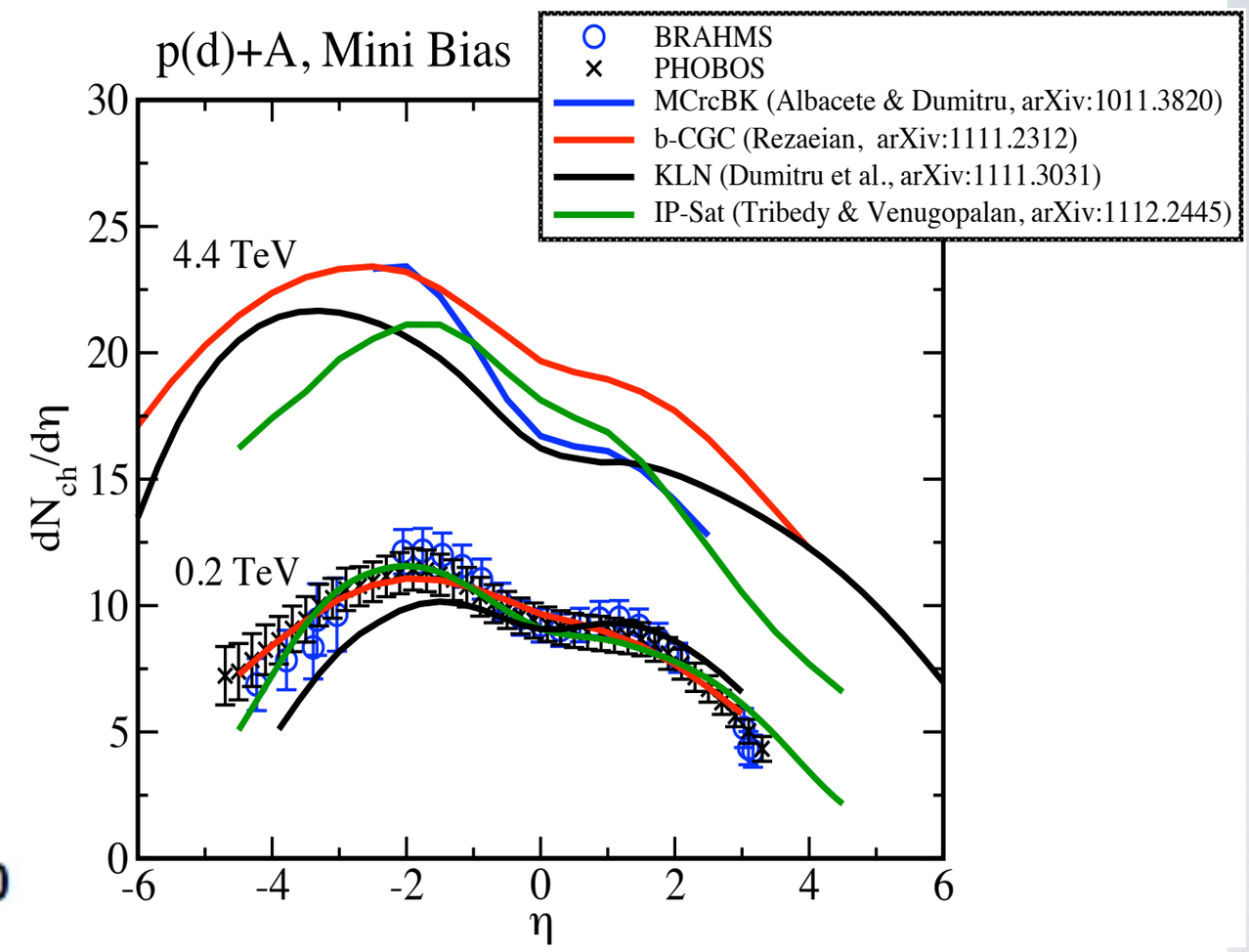
Kt-factorization: $$\frac{dN^g}{dy_h d^2k_t} \approx \frac{\alpha_s C_F}{k_t^2}\,\phi_p(x_1,k_t)\otimes\phi_A(x_2,k_t) \qquad x_{1(2)} = \frac{k_t}{\sqrt{s}}\,e^{\pm y_h}$$



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

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



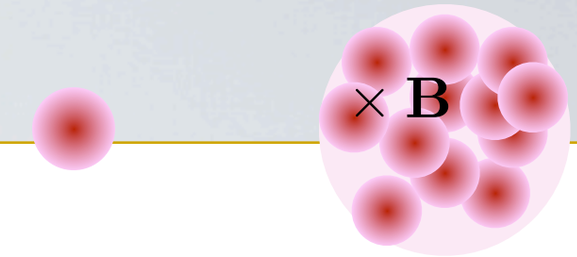


Overall, different CGC works predict

we'll know the answer very soon!!

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

Nuclear ugd's and nuclear modification factors



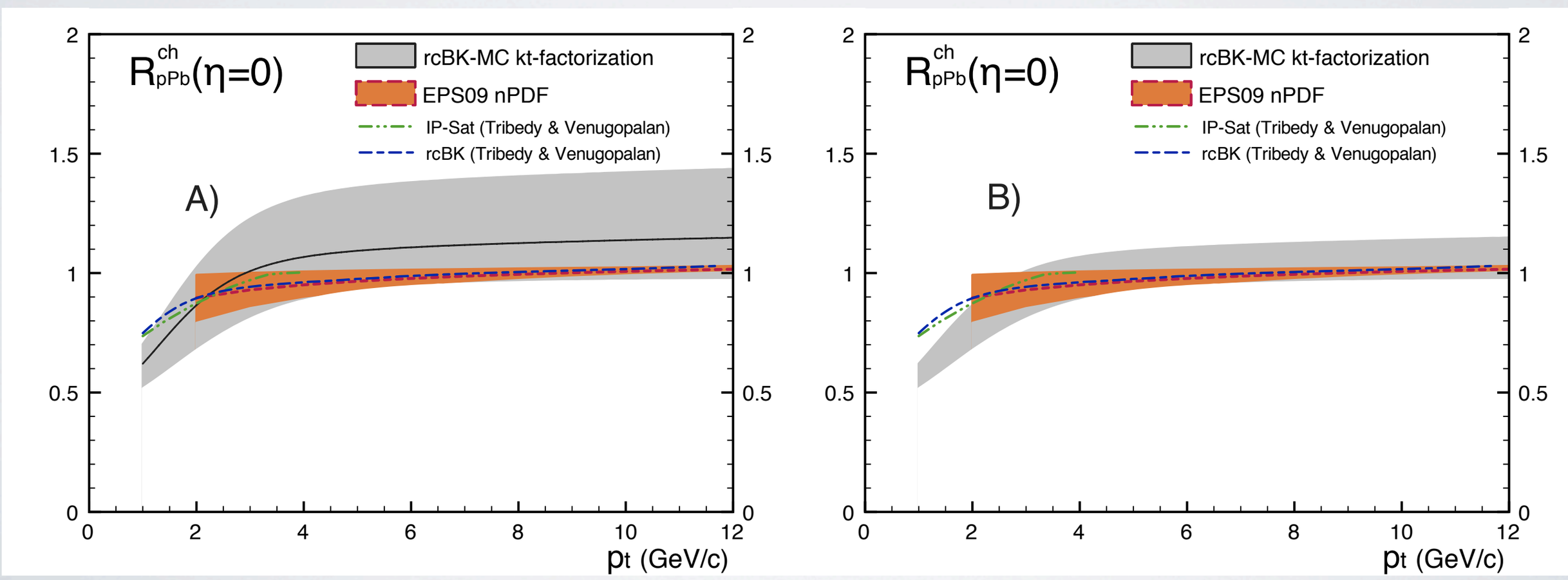
Setting up the evolution

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

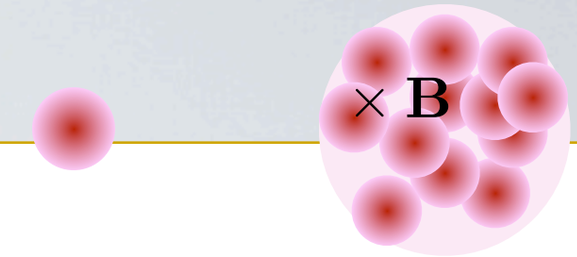
A) Most "natural" option: $\mathbf{Q^2_{s0,Pb}(B)} = \mathbf{T_A(B)}\, \mathbf{Q^2_{s0,p}}$ $\quad \gamma^{\mathbf{Pb}} = \gamma^{\mathbf{p}}(> \mathbf{1})$

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

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



Nuclear ugd's and nuclear modification factors



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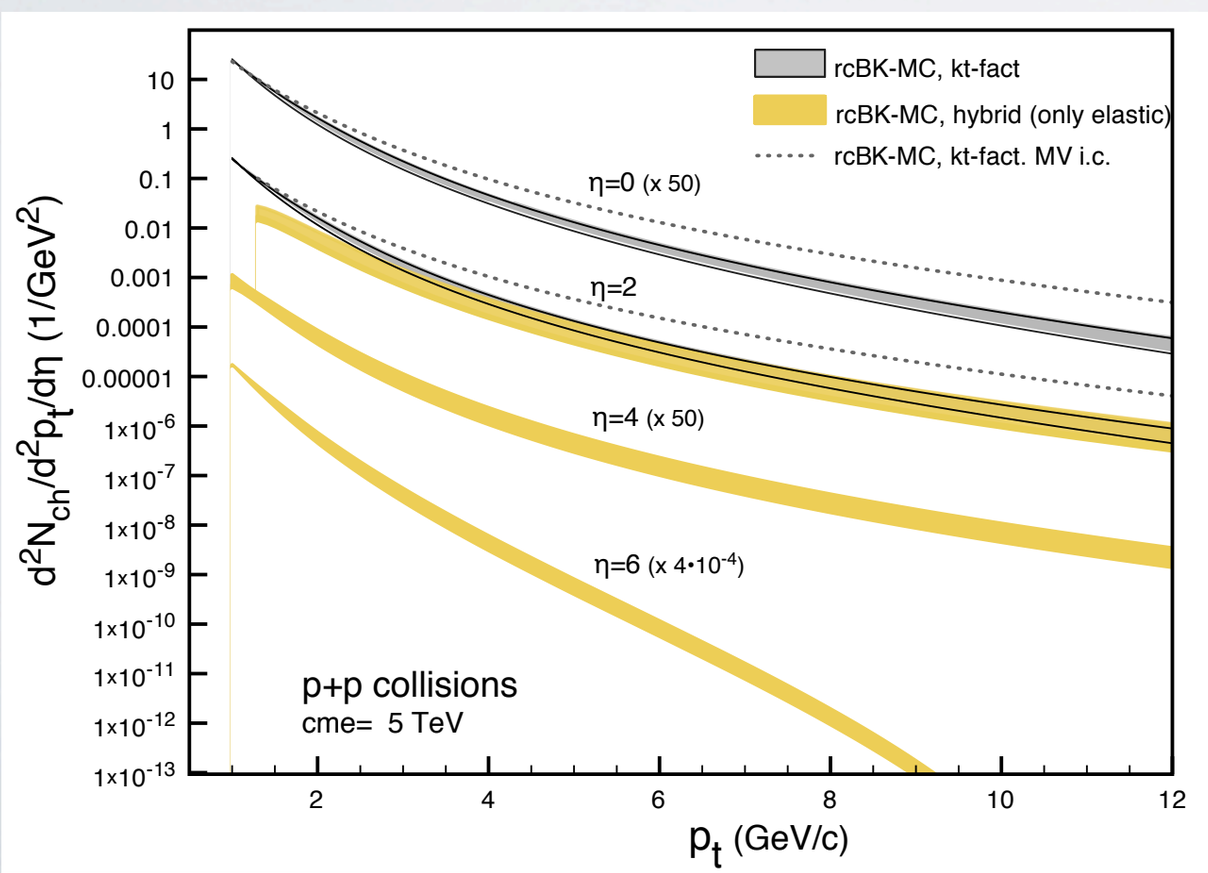
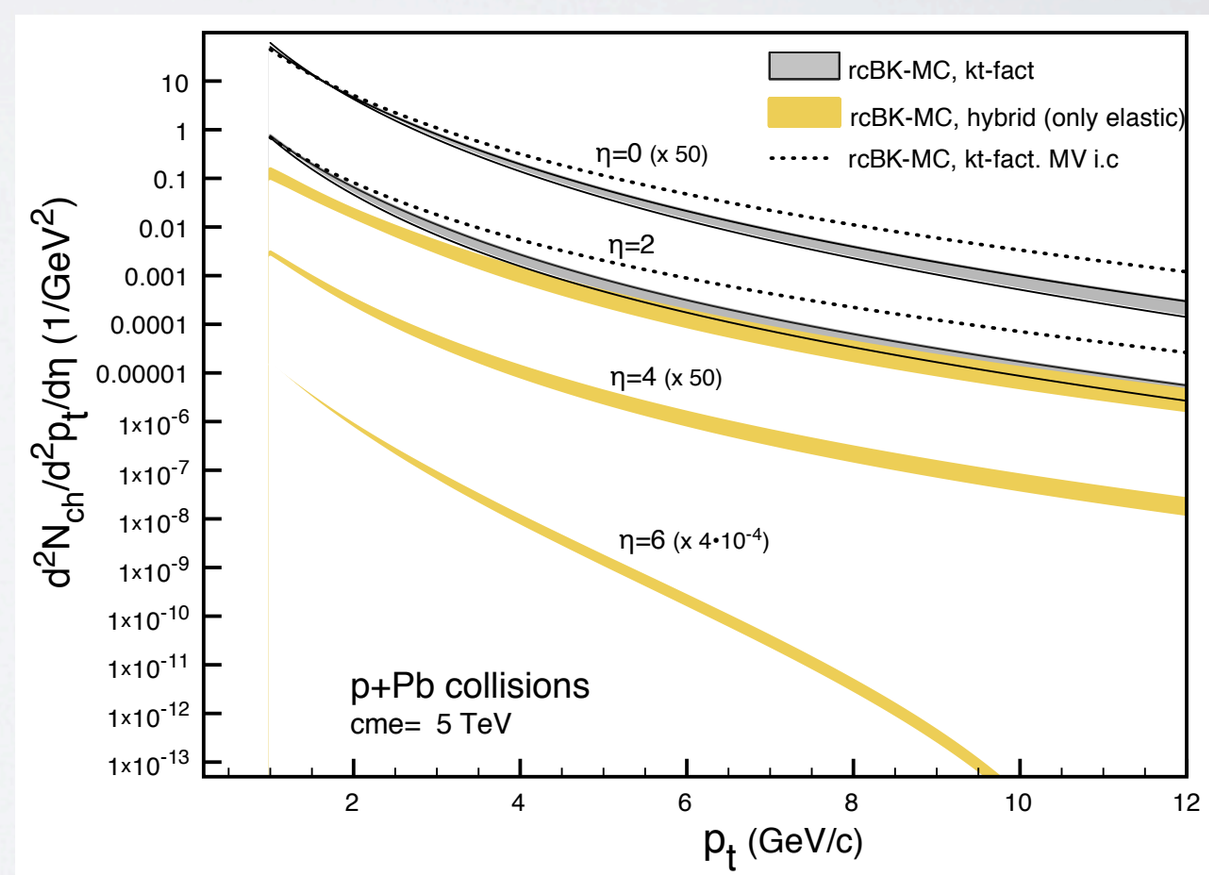
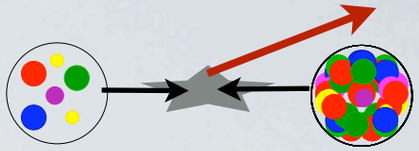
The yields themselves carry very valuable information!





Moving forward



(p_t, y_h>>0)

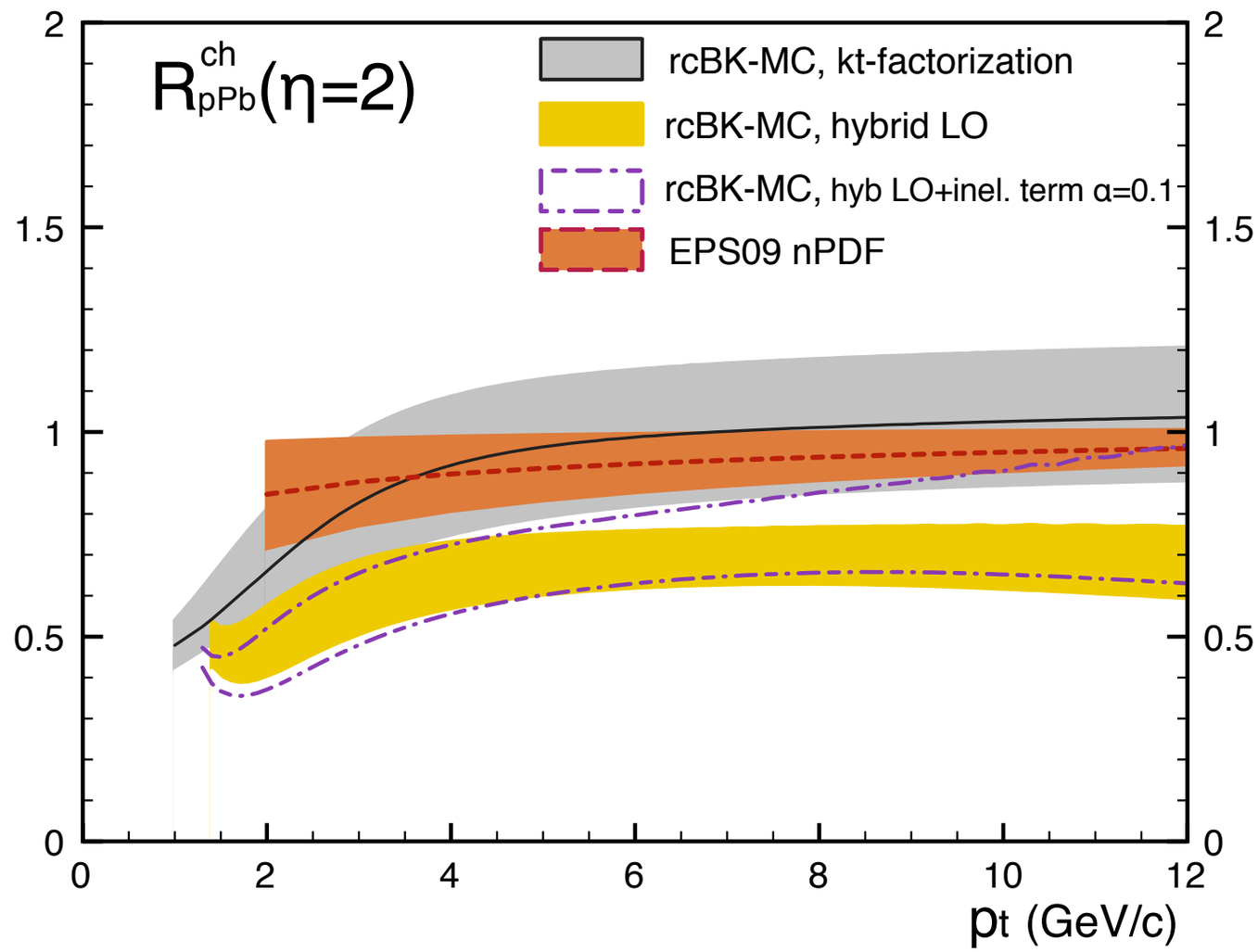
Yet another issue: Where to switch from kt-factorization to hybrid formalism? $x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$

Midrapidity: kt-factorization:

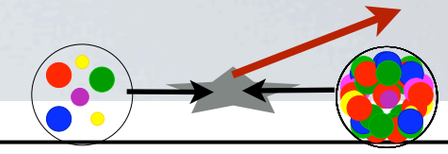
$$\frac{dN^g}{d\eta d^2 p_t} \sim \phi^p(x_1) \otimes \phi^{Pb}(x_2)$$

Forward rapidity: hybrid formalism

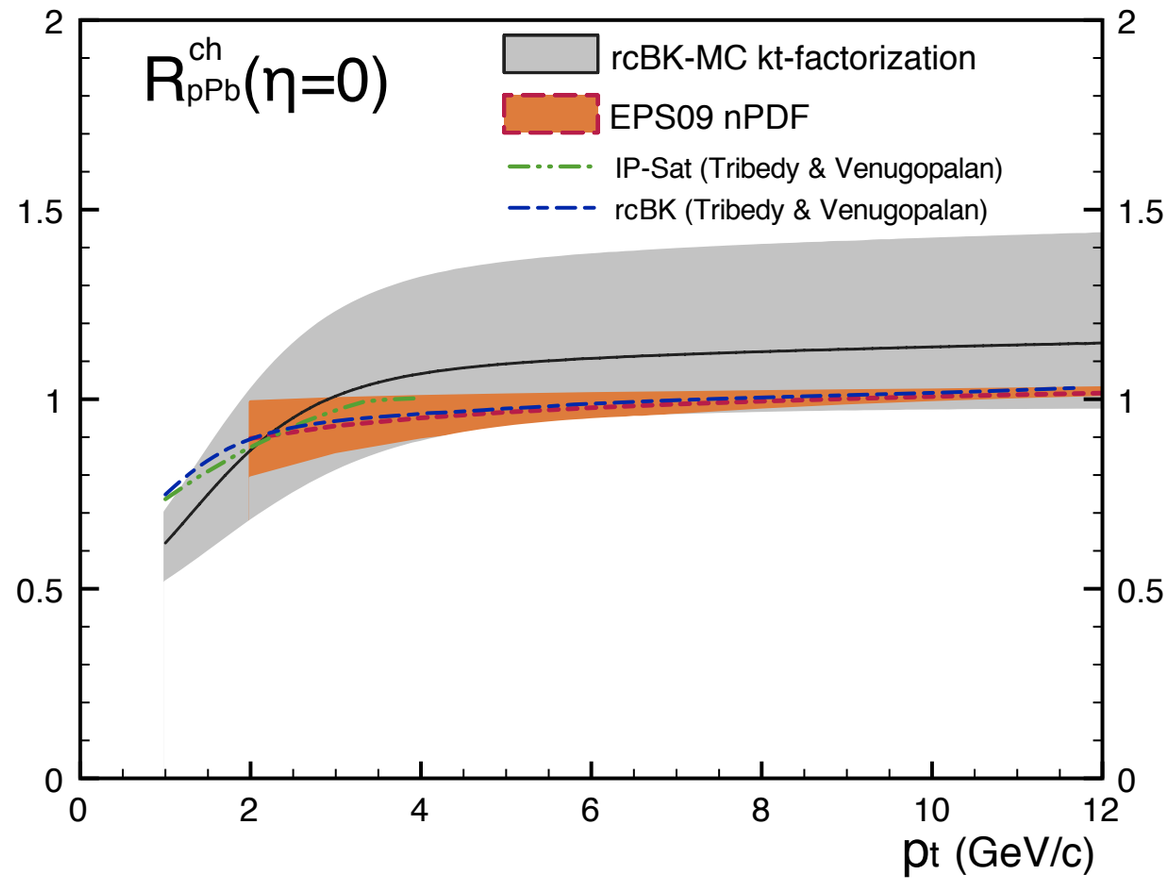
$$\frac{dN}{d\eta d^2 p_t} \sim \mathrm{pdf}^p(x_1) \otimes \phi^{Pb}(x_2)$$

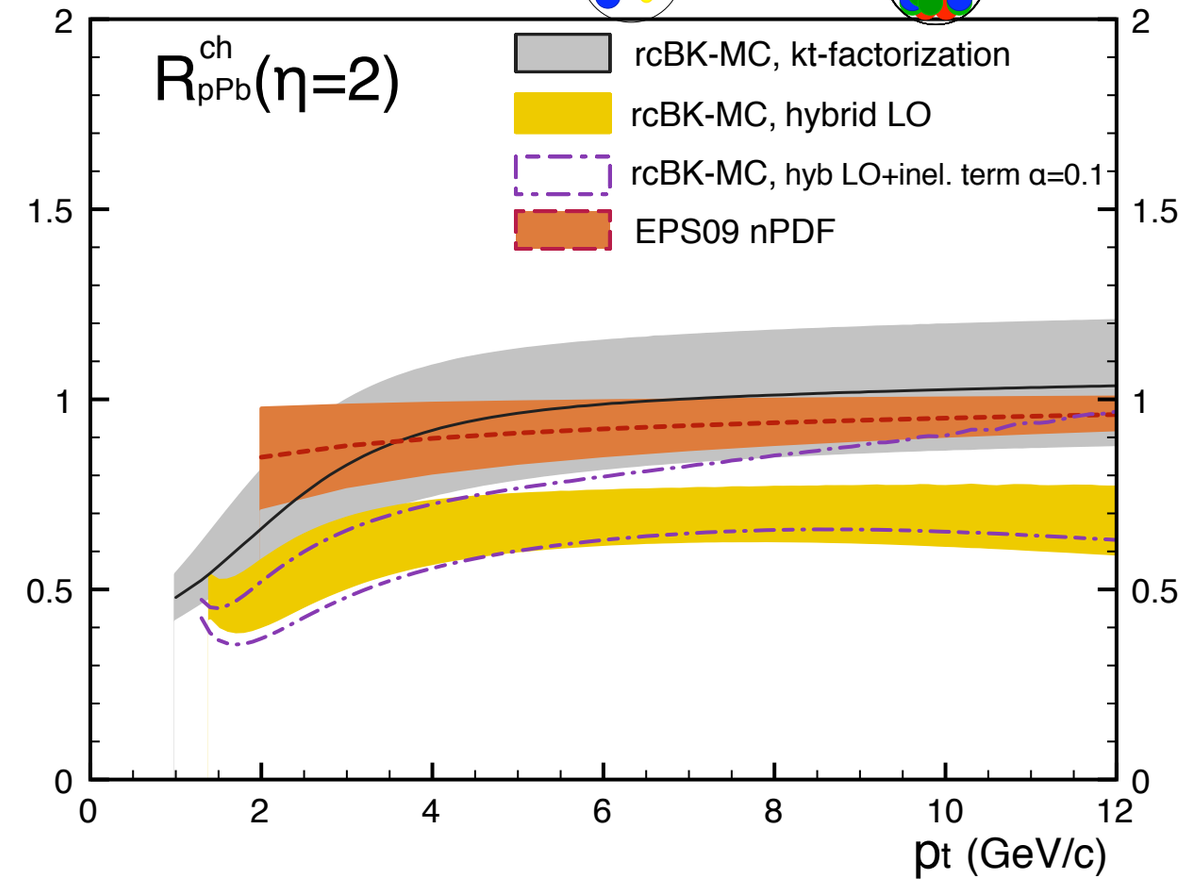


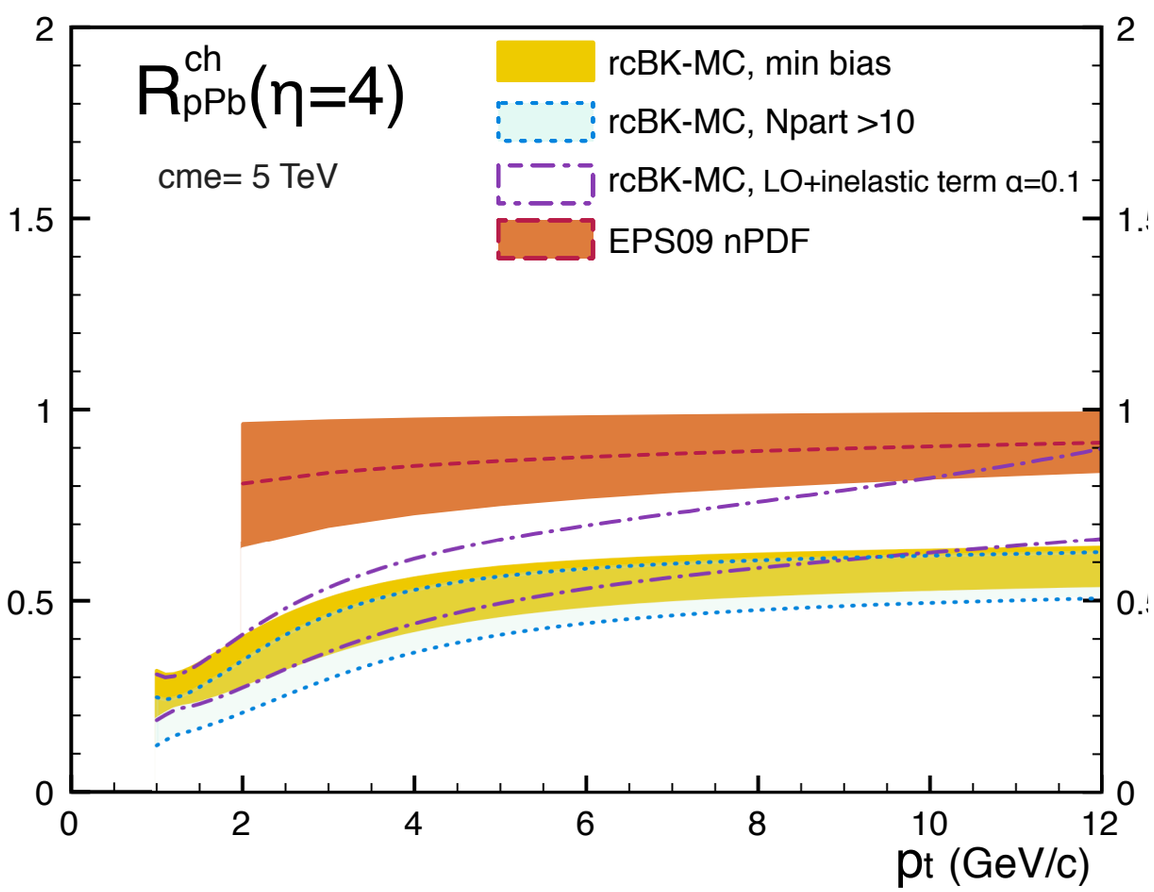
Moving forward: Testing the non-linear evolution

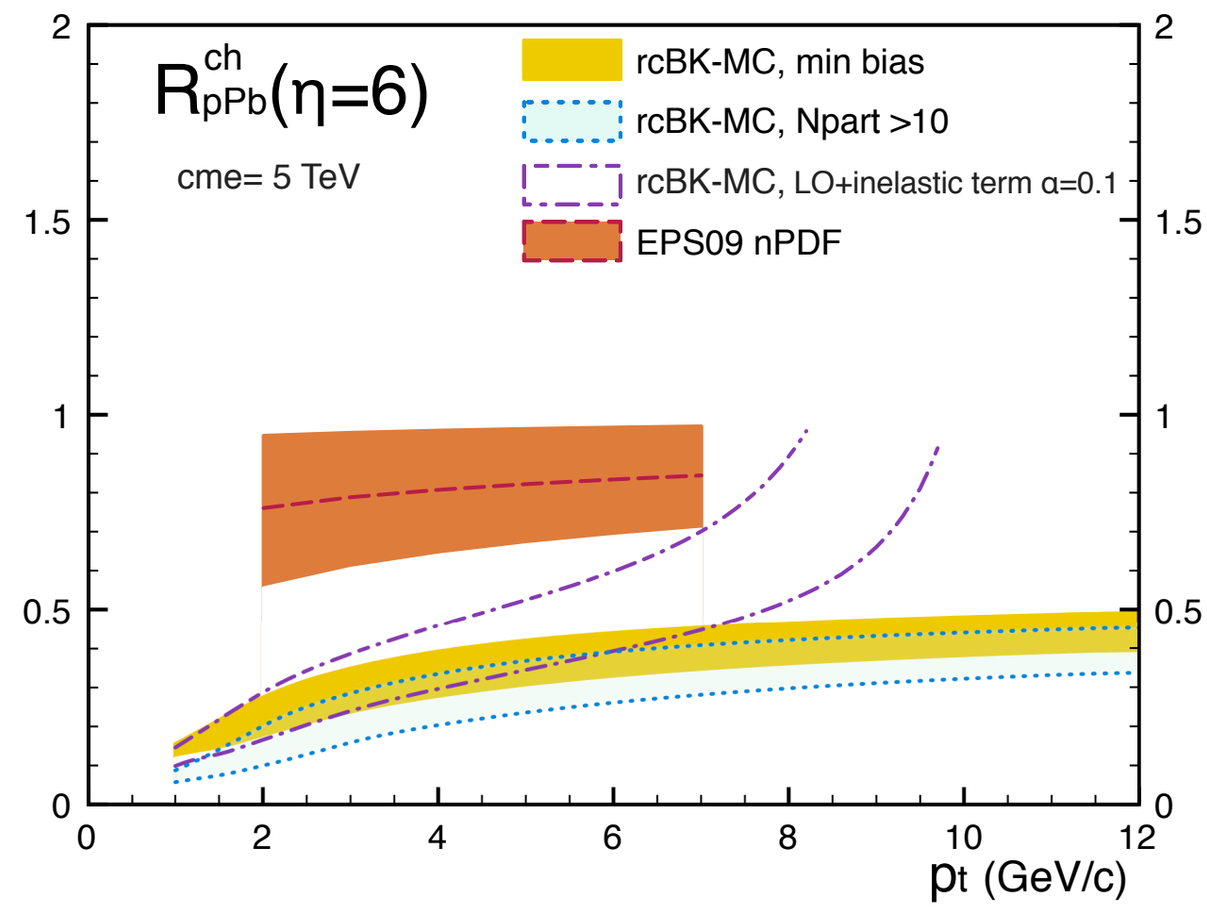


(p_t, y_h>>0)



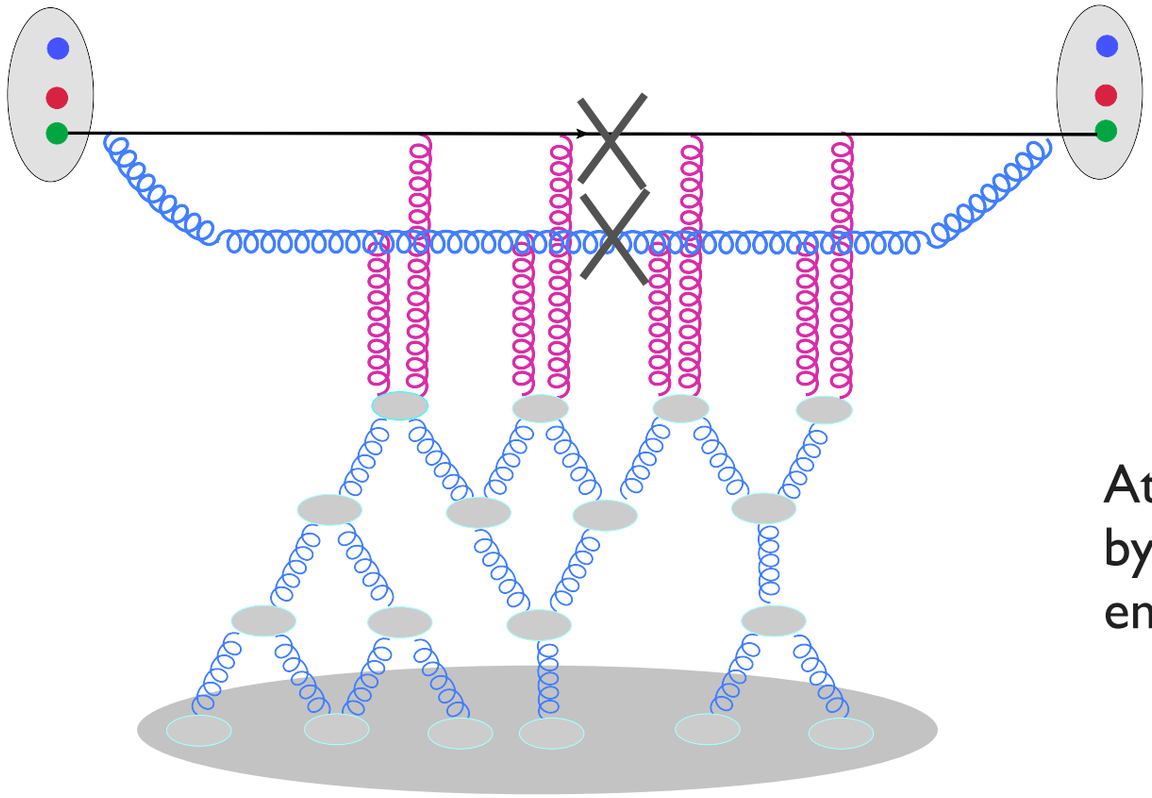






Forward di-hadron angular correlations

Marquet '07, Dominguez et al

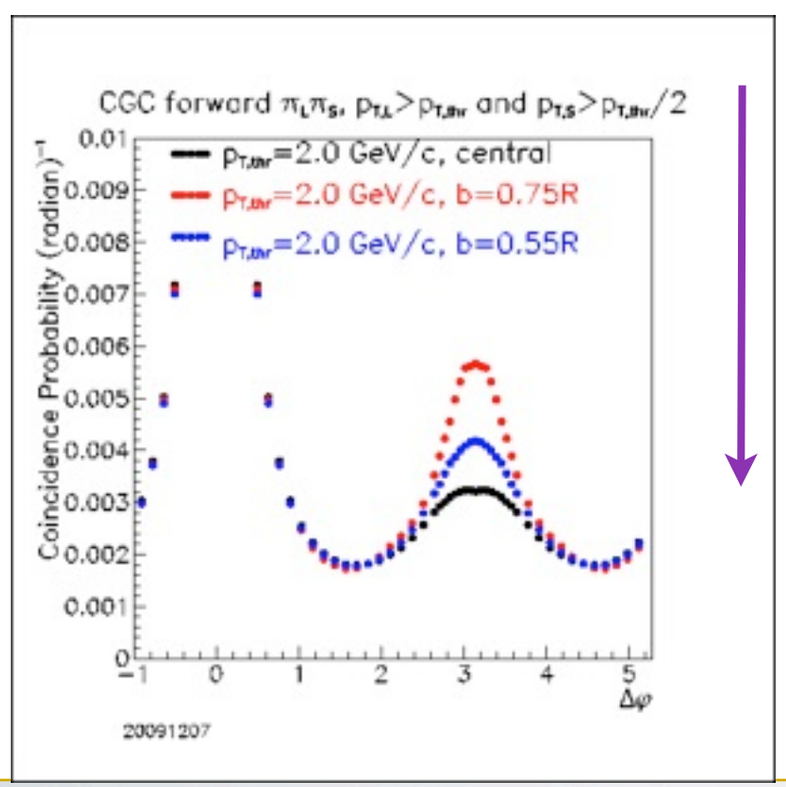


$$x_p = \frac{|k_1|e^{y_1} + |k_2|e^{y_2}}{\sqrt{s}}$$

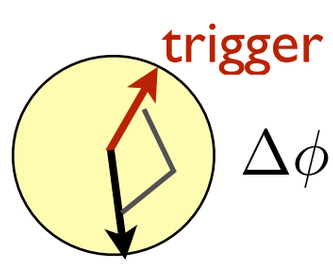
$$x_A = \frac{|k_1|e^{-y_1} + |k_2|e^{-y_2}}{\sqrt{s}}$$

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



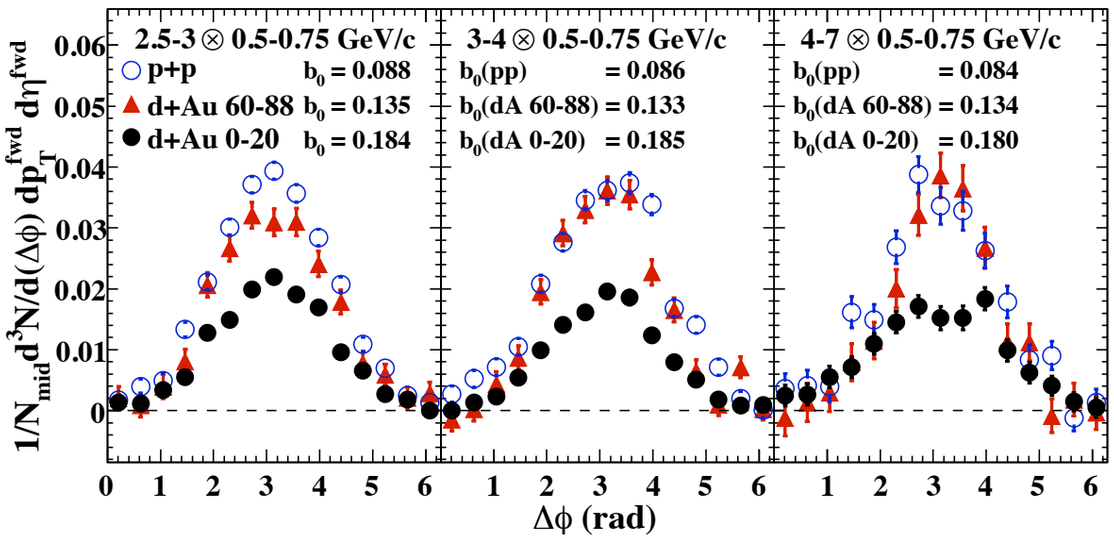
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$

Ergo, decorrelation should be stronger with

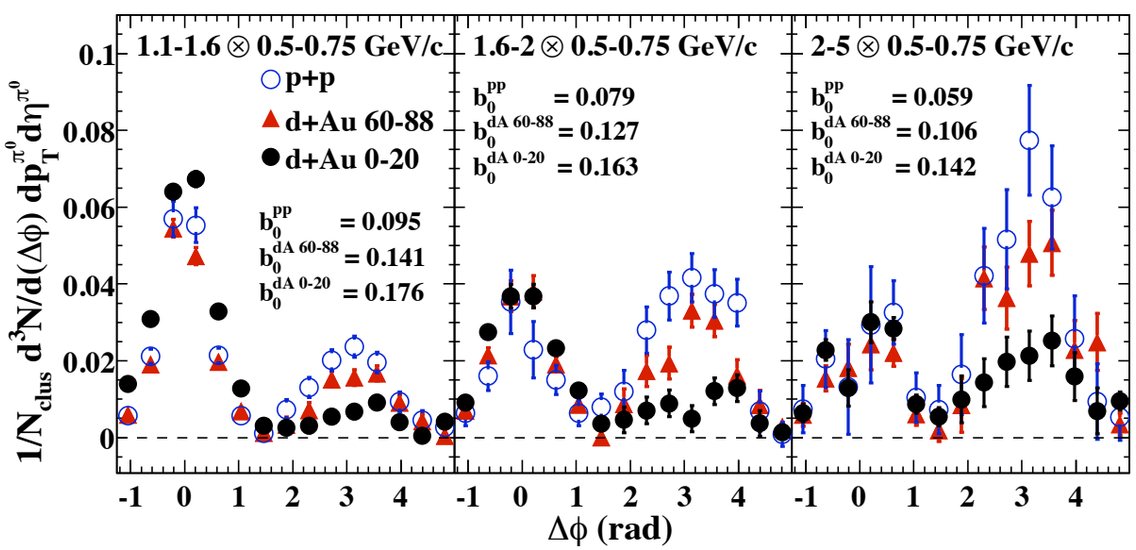
- Increasing rapidity of the pair
- Increasing collision centrality
- Decreasing hadron momentum

Forward di-hadron angular correlations in RHIC dAu data

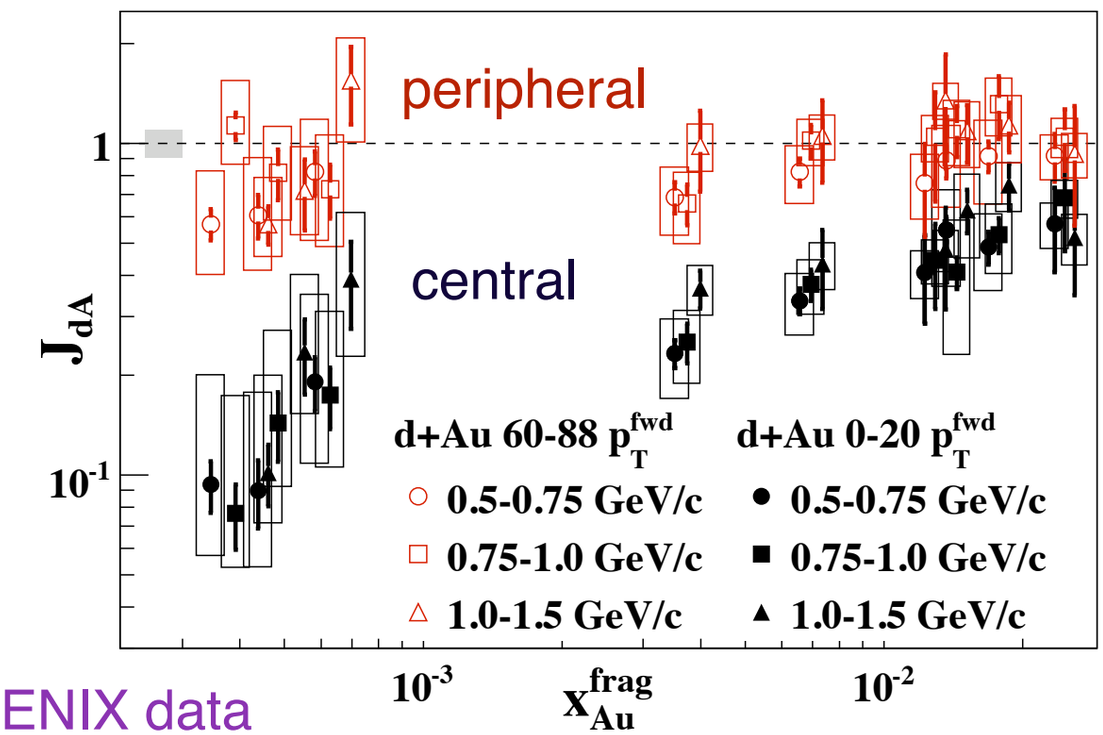
central-forward



forward-forward



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

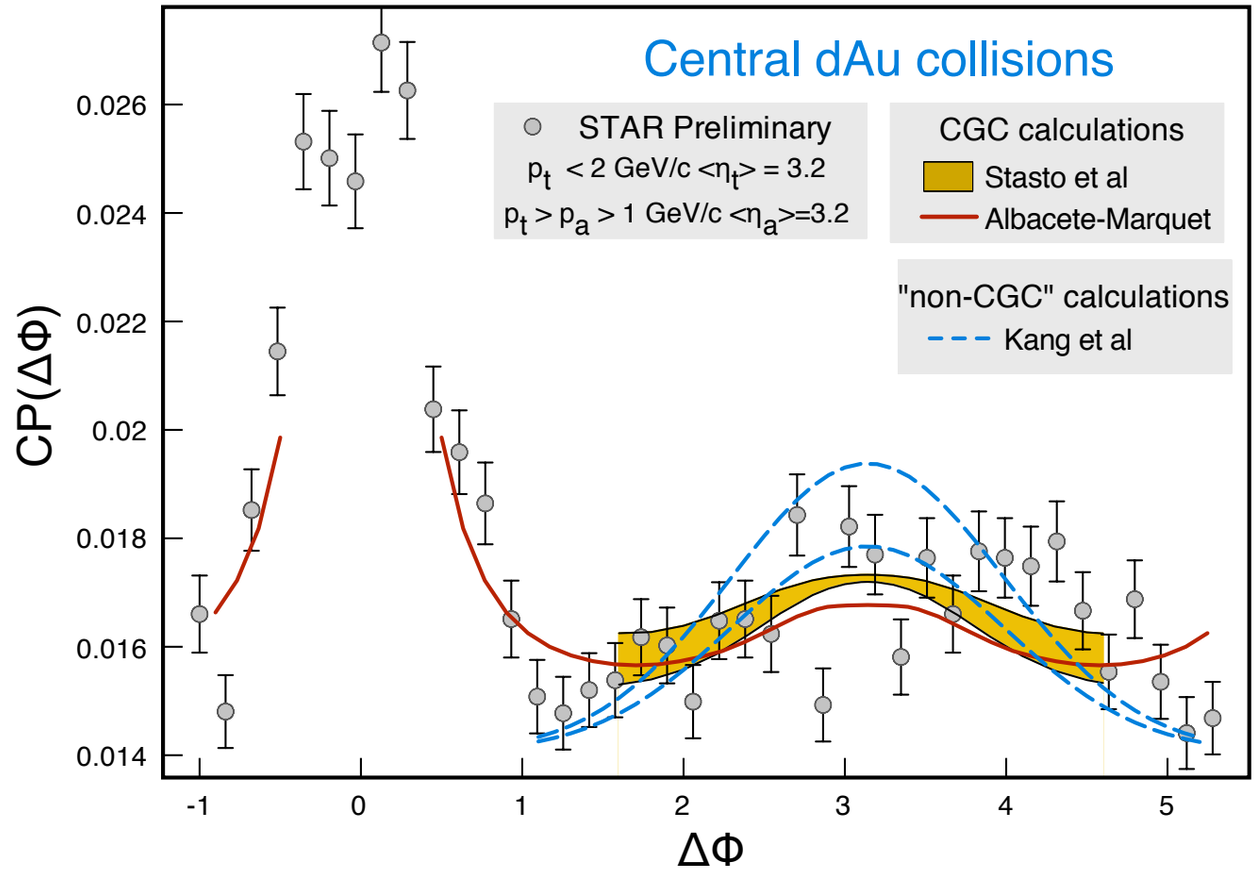


PHENIX data

Observed decorrelation IS stronger with

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

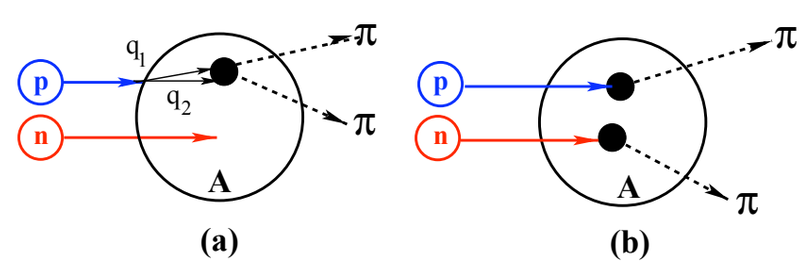
Forward di-hadron angular correlations in RHIC dAu data



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



Strikman, Vogelsang, 1009.6123

uncorrelated

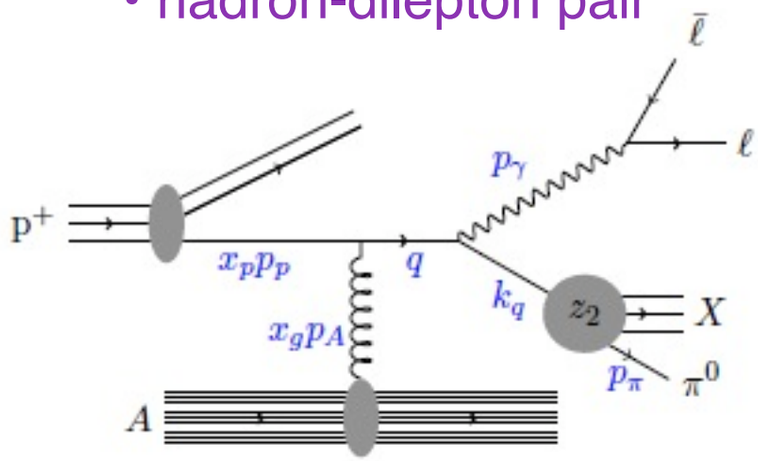
- Alternative descriptions including resummation of multiple scatterings, nuclear shadowing and cold nuclear matter energy loss seem possible... [Kang et al]

di-hadron angular correlations at the LHC

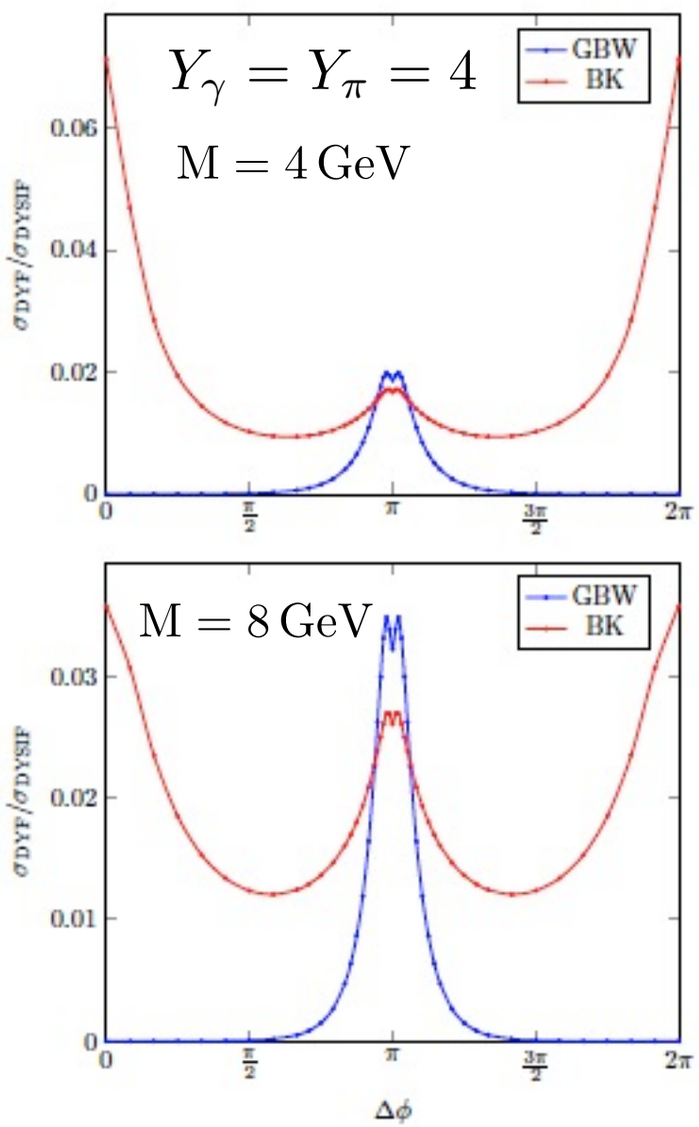
- Analogous decorrelation phenomena should be seen at the LHC
- The increase in collision energy implies that they should be visible at
  * Lower rapidities of the produced pair
  * Higher transverse momentum
- All previously mentioned details are been taken care of. Stay tuned!!!

hadron-photon* correlations in pPb collisions at the LHC

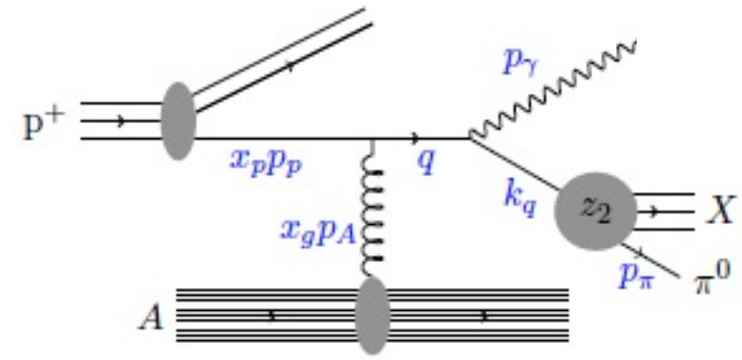
- hadron-dilepton pair



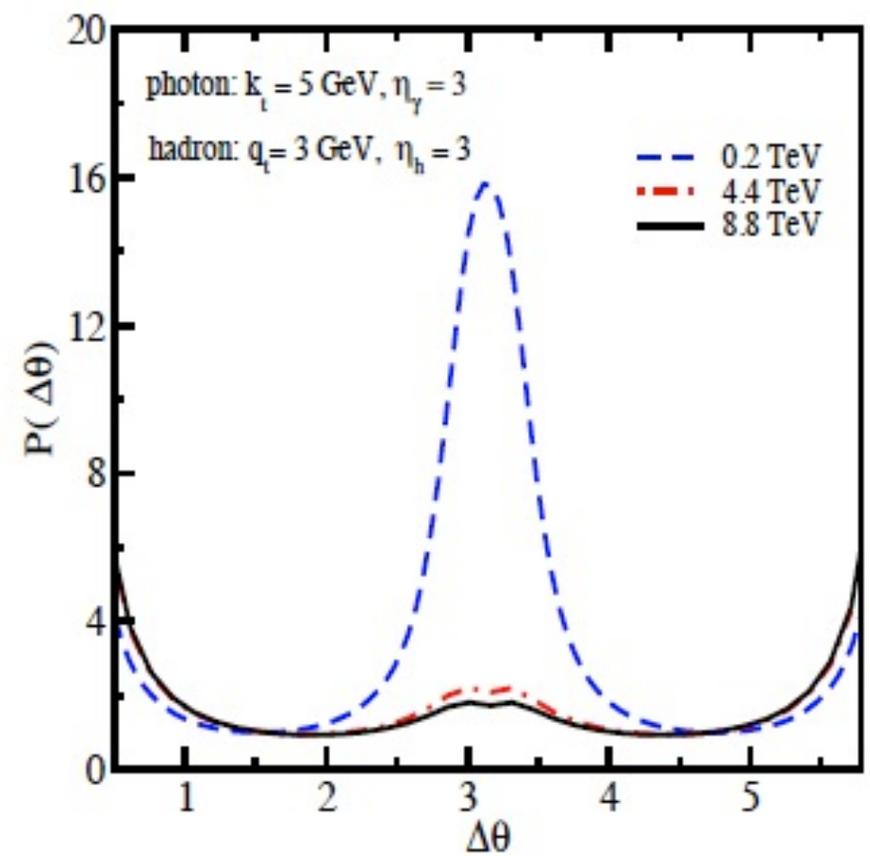
Stasto et al 1204.4861



- hadron-photon



Jalilian-Marian, Rezaeian



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

Outlook

✔ 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

✔ Most solid CGC predictions for the upcoming p+Pb run:
- Suppression of nuclear modification factors at moderate pt already at mid-rapidity
- Stronger suppression at more forward rapidities (evolution)
- Suppression of di-hadron and photon-hadron angular correlations

✔ Current predictions carry some uncertainty due to lack of data to constrain NP aspects of nuclear UGD. This problem can be largely fixed through the measurement of simple observables (i.e. single inclusive spectra) in p+Pb collisions

✔ Phenomenological implementation of recent theoretical progress needed

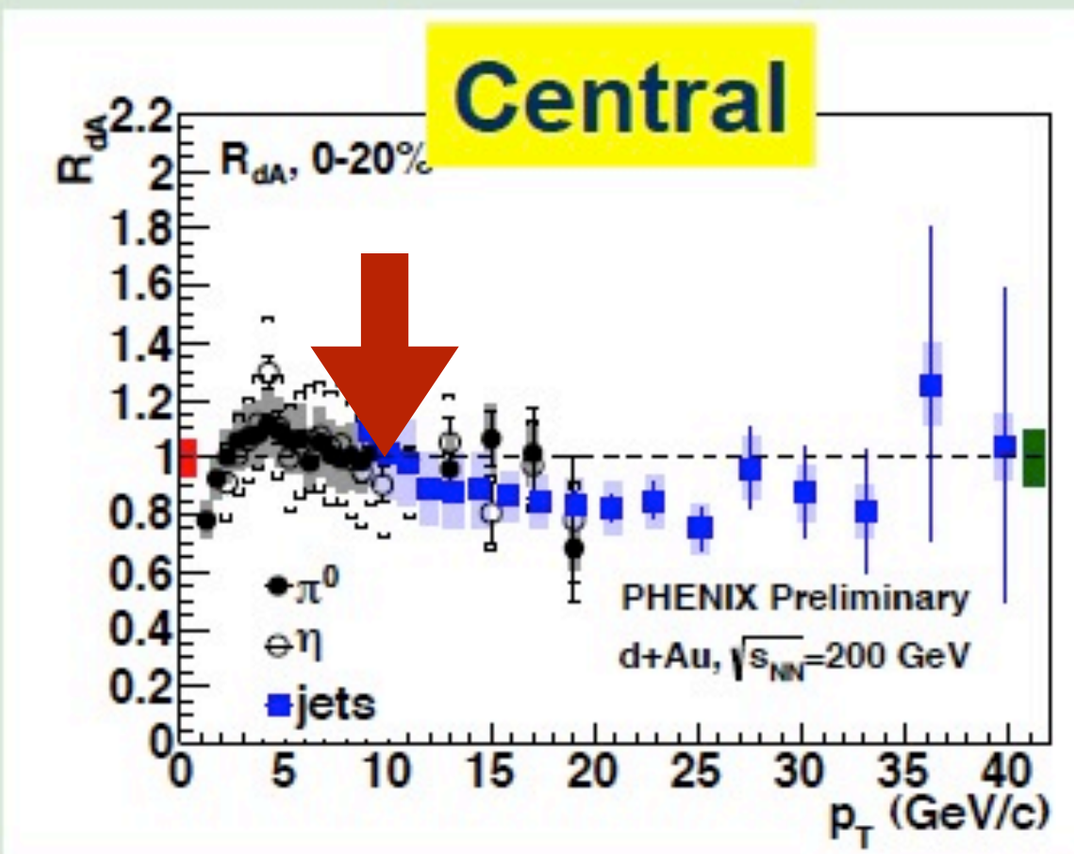
Merci!!

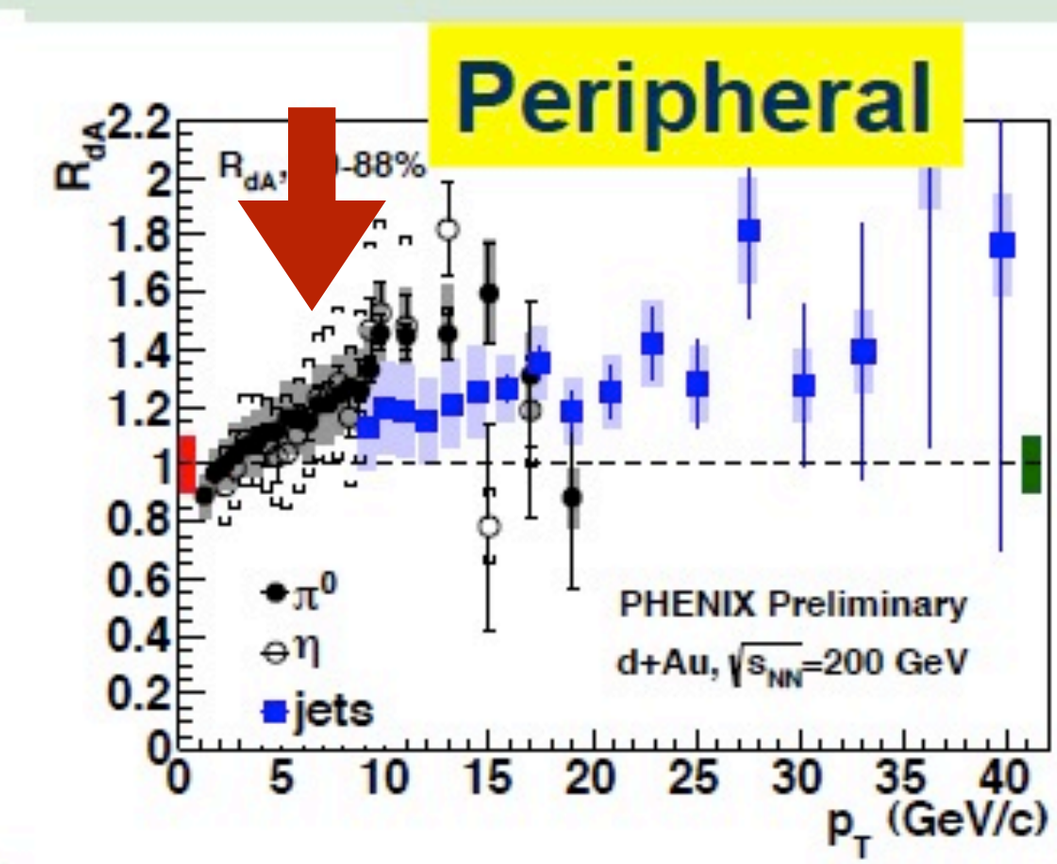
If these data are confirmed... ALL initial state models are in trouble!!

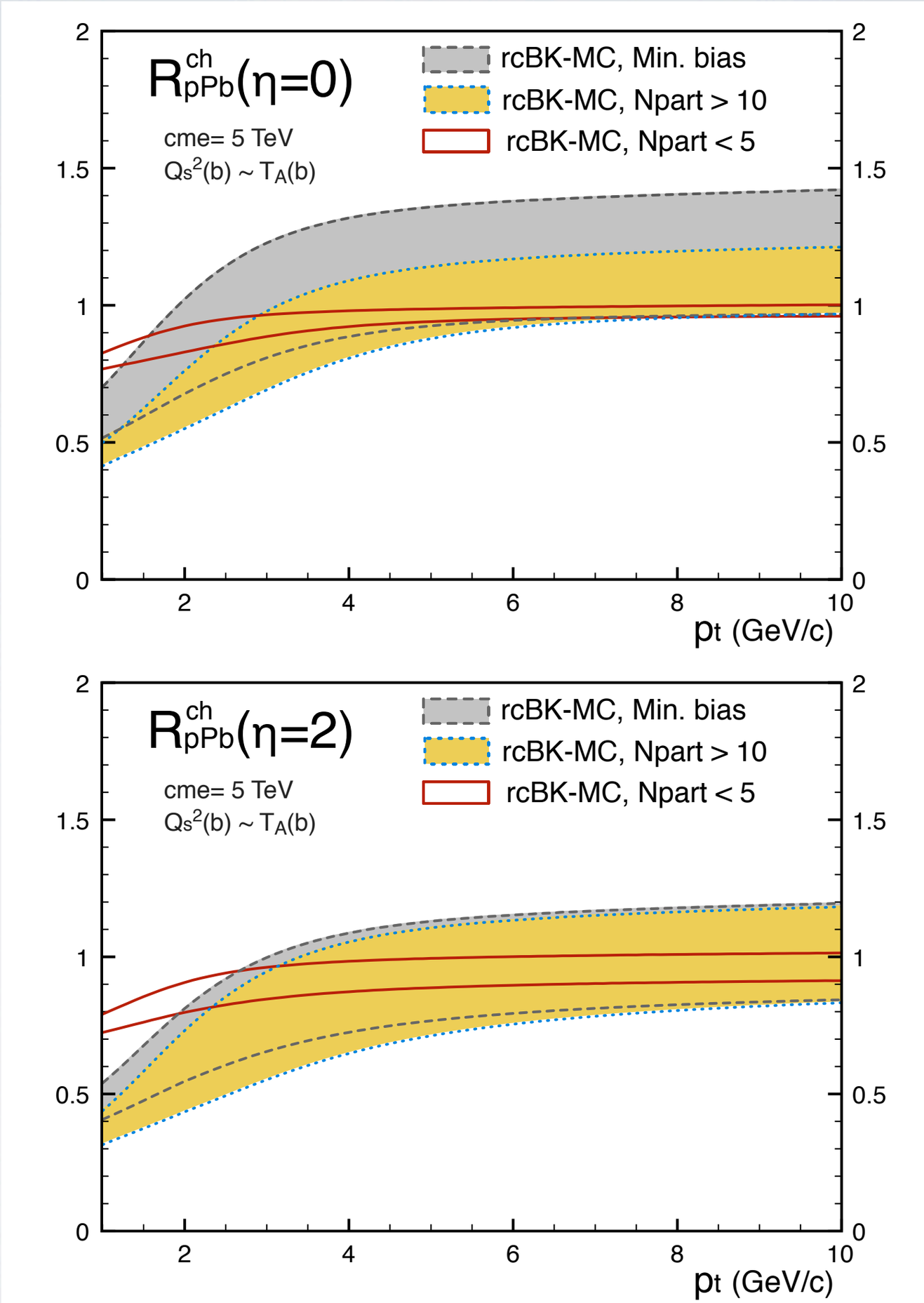
PHENIX

Initial state - Jet probes -

- Jets are reconstructed in d+Au up to 40 GeV/c






$R^{ch}_{pPb}(\eta=0)$
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)