Small-x physics with AFTER*

*Biased towards a CGC - Heavy Ion perspective

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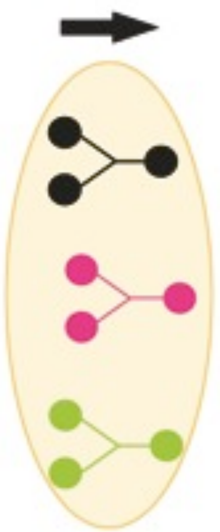
Universidad de Granada & CAFPE

AFTER@Les Houches Jan 2014

Low-x studies and the CGC

Low-x = High gluon densities

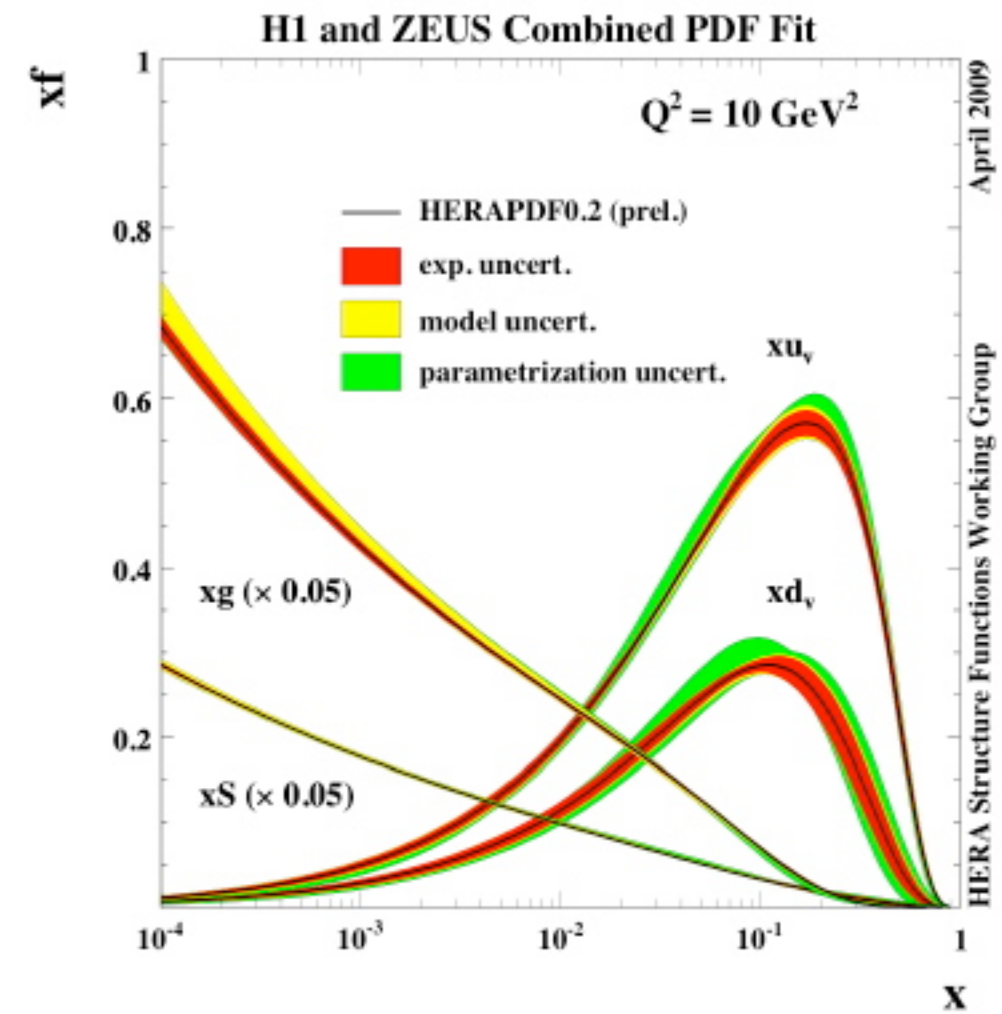


Saturation: gluon self-interactions tame the growth of gluon densities towards small-x

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

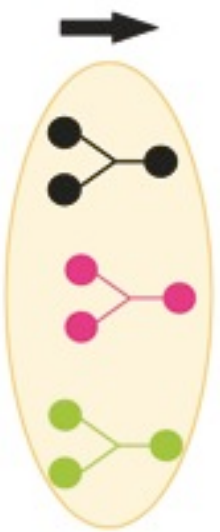
radiation recombination

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



Low-x studies and the CGC

High gluon densities in the projectile/target



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

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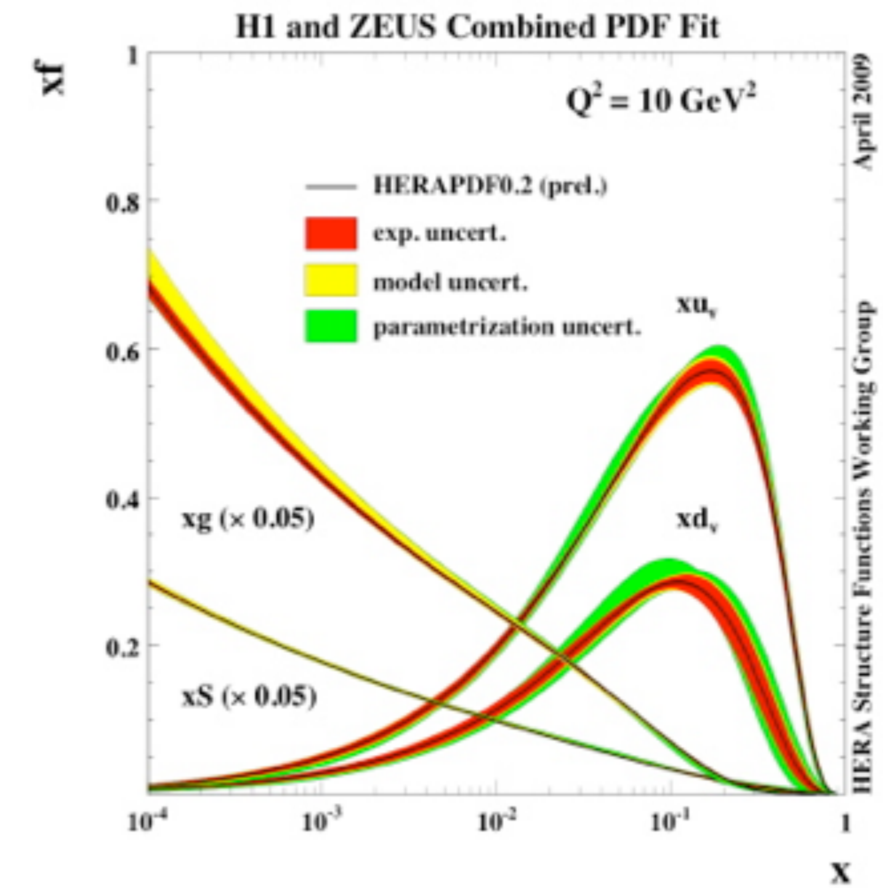
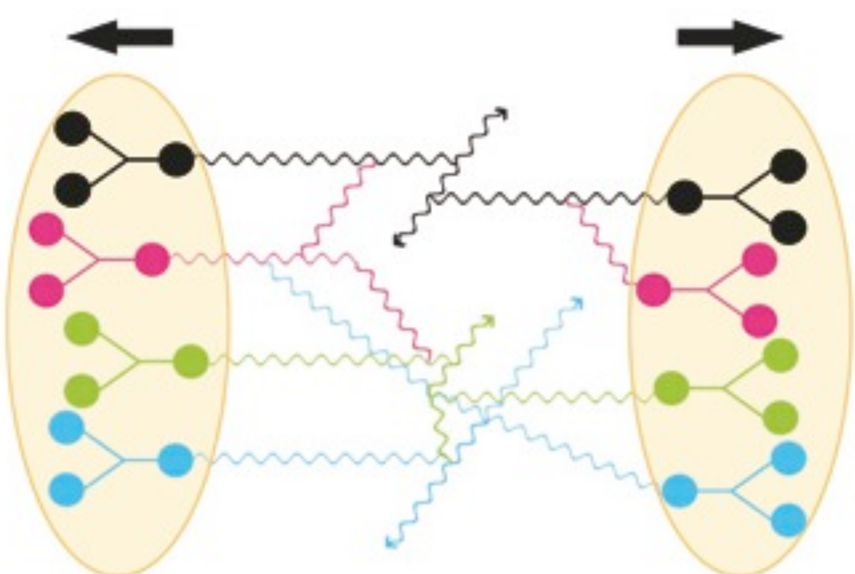


Breakdown of independent particle production



In the high-density regime

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

$$\alpha_s(Q_s) << 1$$

Low-x studies and the CGC

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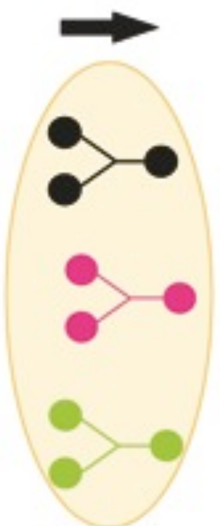

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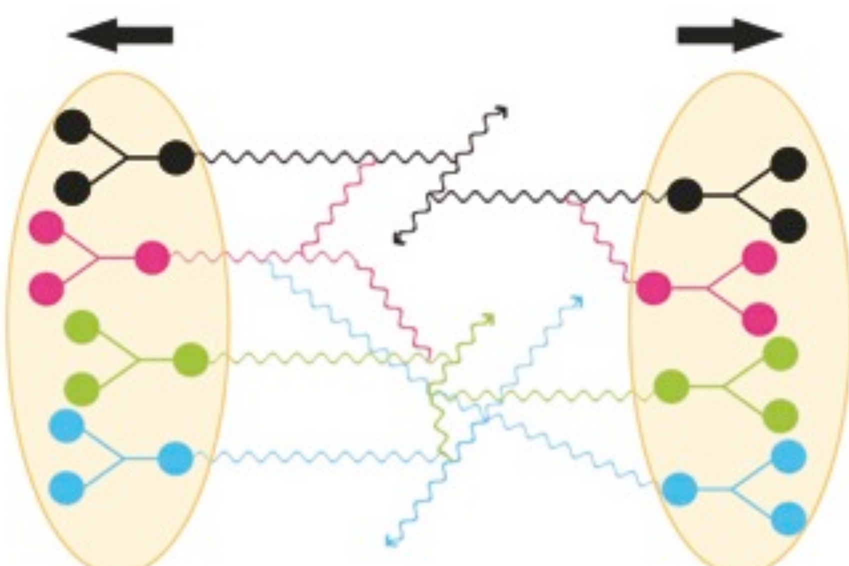
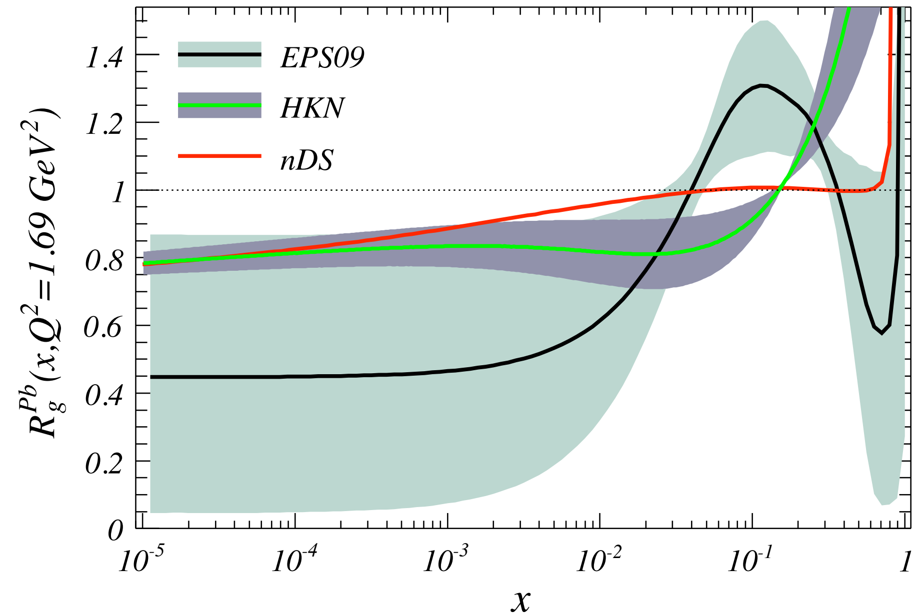
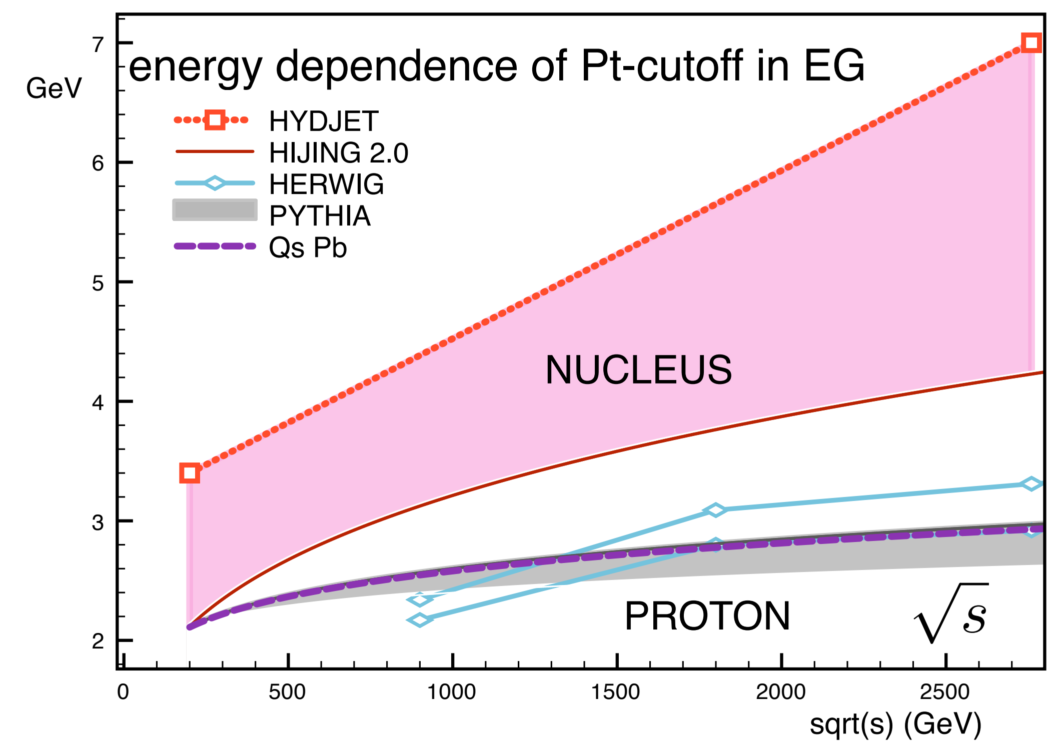


Other approaches (HIC)

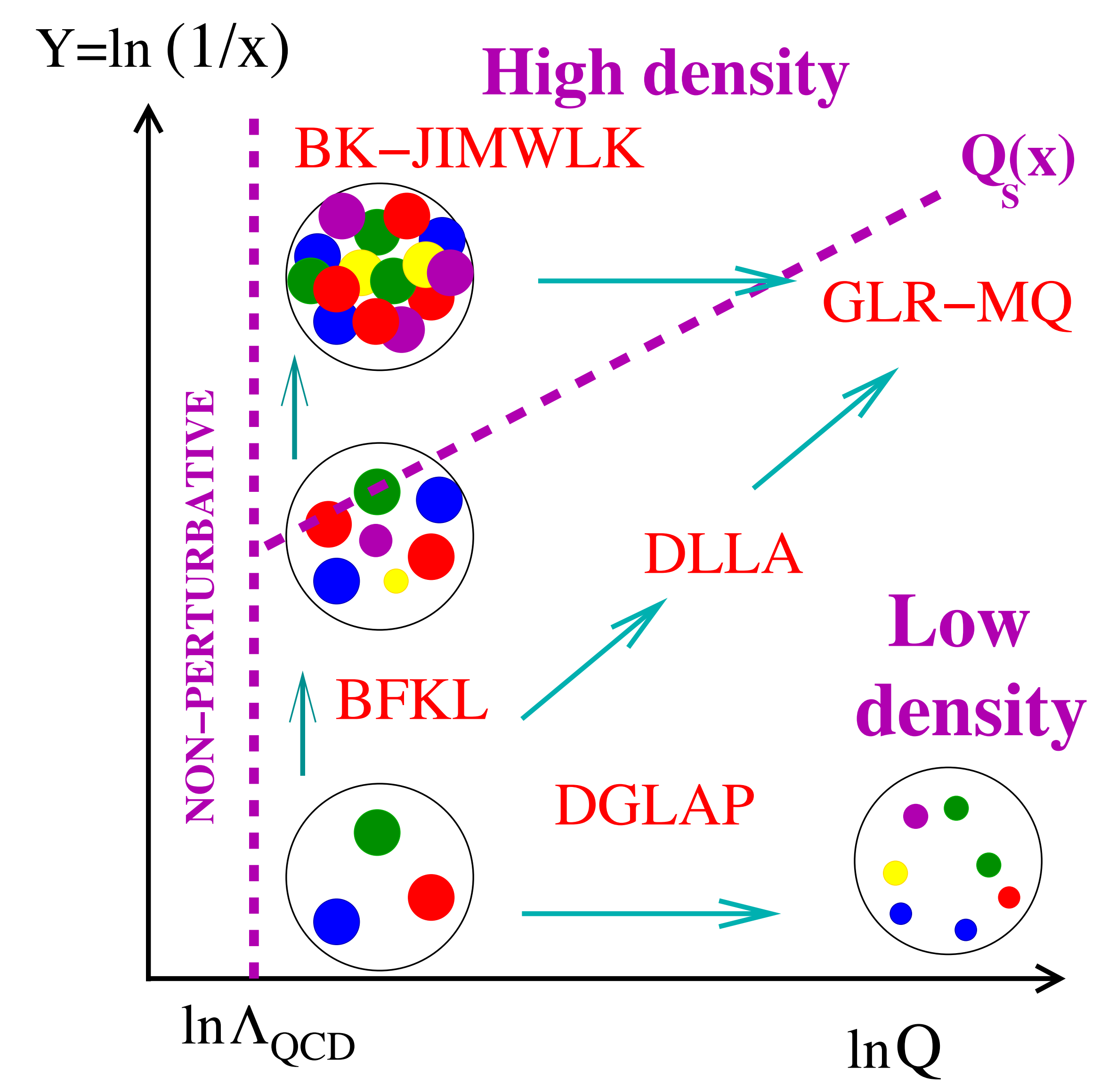
- Nuclear shadowing, String fusion, percolation



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



Main limitation for small-x studies @ AFTER: Kinematic coverage



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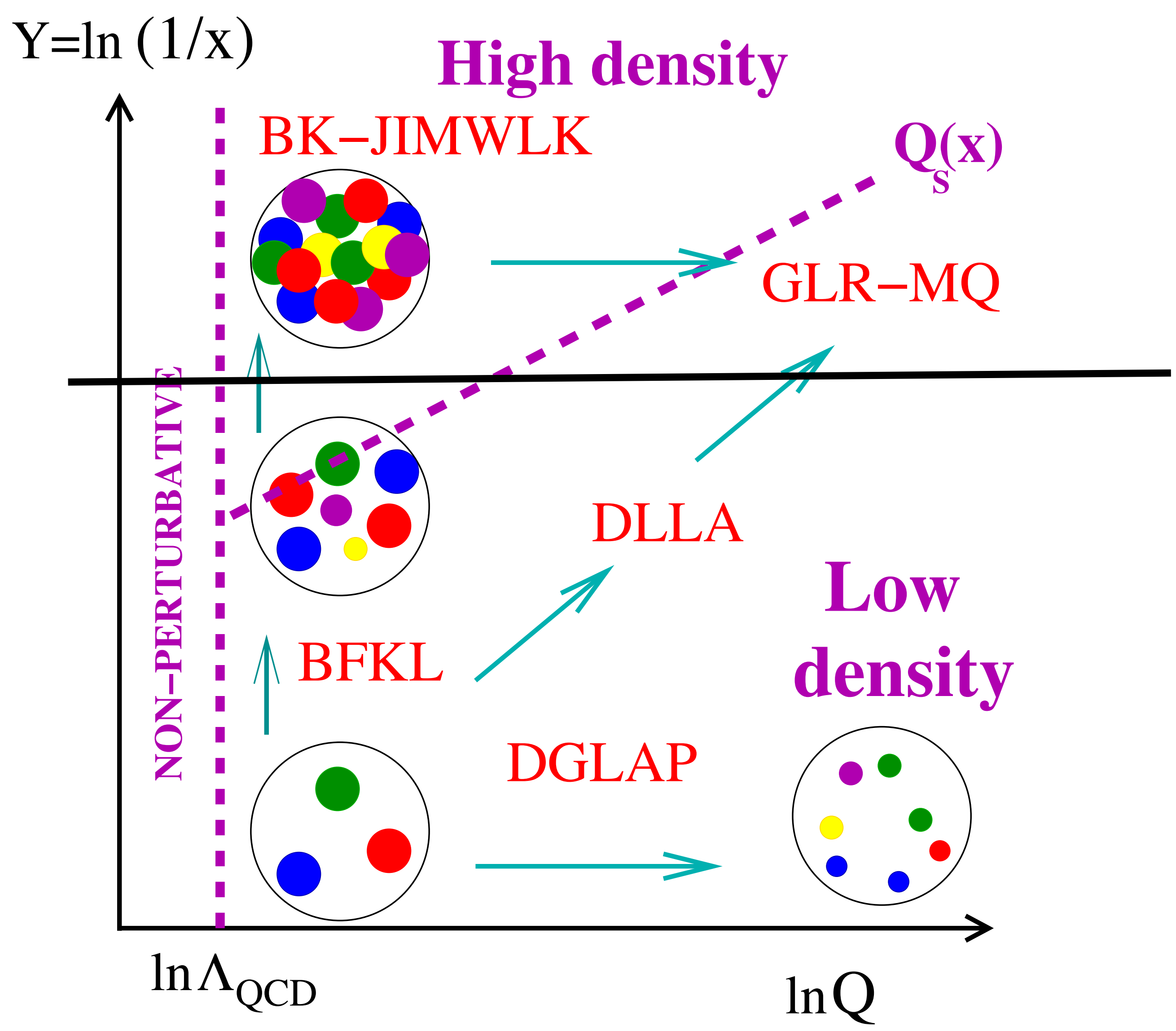
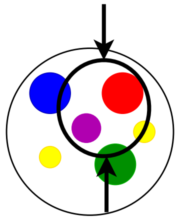


LHC, RHIC
LHeC, EIC

$x \sim 10^{-3}$

AFTER: High-x studies,
(n)PDF’s, intrinsic Q...

Color Glass Condensate quantitative phenomenology

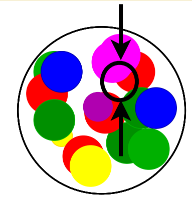


$x=x_0 \sim 10^{-2}$

Initial conditions for the evolution

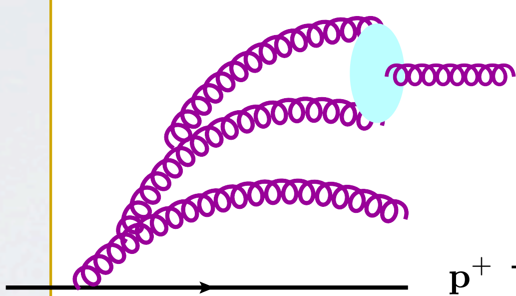
$$\mathbf{W}[\mathbf{A}, \mathbf{x_0}]$$

$$\phi[\mathbf{x_0}, \mathbf{k_t}]$$



$x<x_0 \sim 10^{-2}$

Small-x non-linear evolution



"BK-JIMWLK"

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

radiative + *recombination* processes

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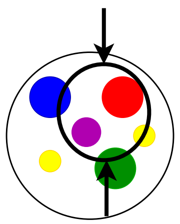

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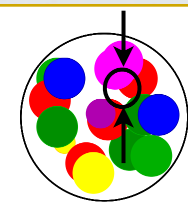

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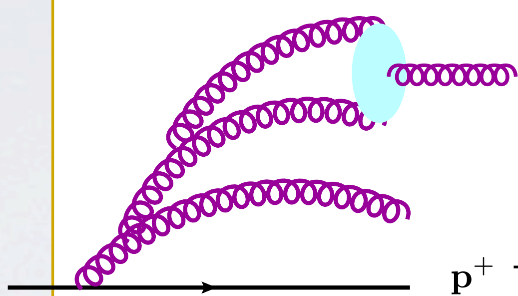


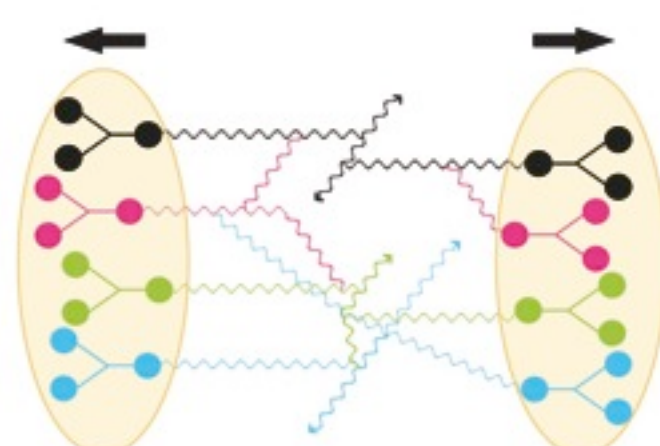
"BK-JIMWLK"

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

radiative + *recombination* processes

Calculate observables (single and double inclusive, multiplicities, Q-production...)

$$\langle \mathbf{O} \rangle_{\mathbf{x}} = \int \mathbf{d}\mathbf{A}\, \mathbf{W}[\mathbf{A}, \mathbf{x}]\mathbf{O}(\mathbf{A})$$



Some problems where AFTER may help:

1. Determination of the initial conditions for the evolution
2. Centrality dependence of the initial conditions for the evolution
3. Identify the onset of non-linear corrections to the standard pQCD calculations
4. Test NLO corrections to the CGC formalism
5. Interplay between large-x and low-x effects

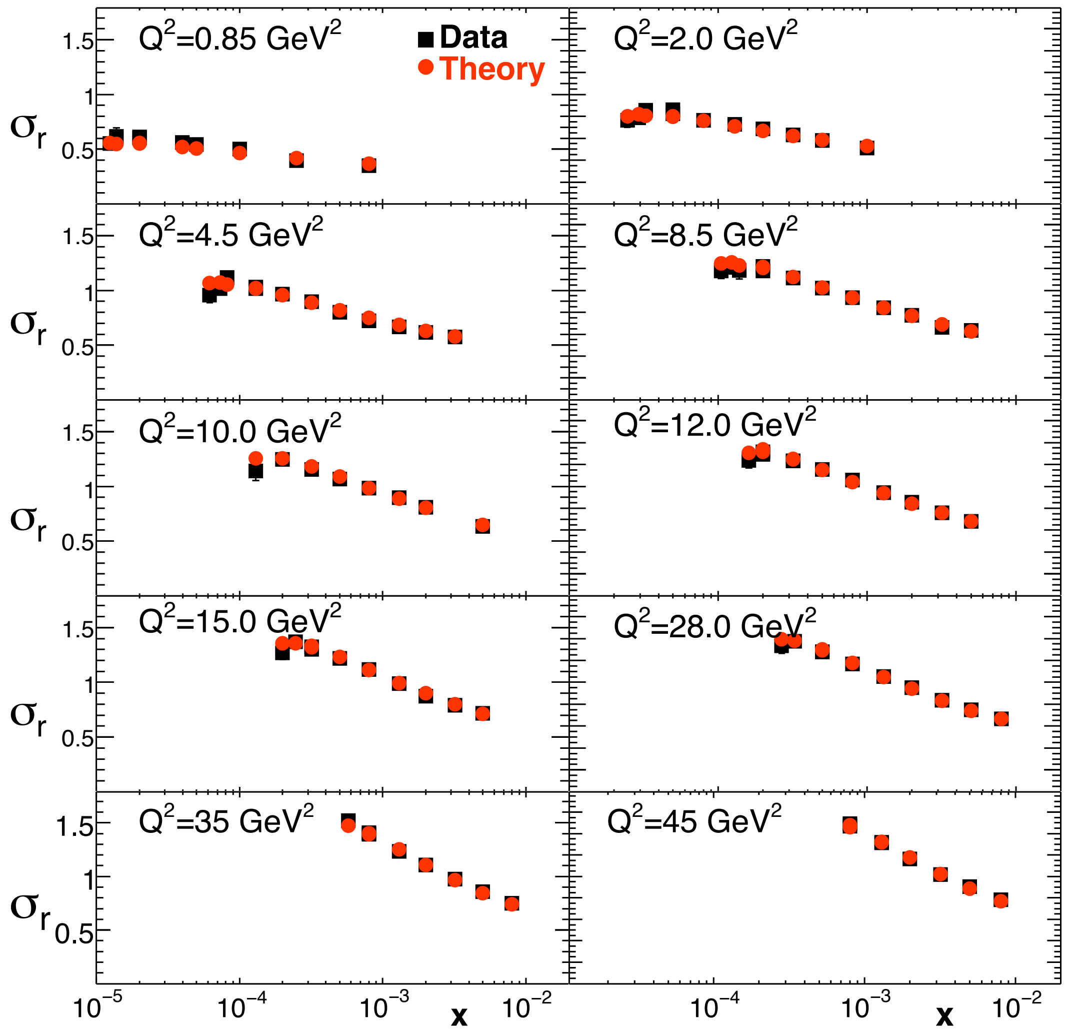
1. Determination of the initial conditions for the evolution

Fits to HERA and RHIC data do not constrain much the IC for proton evolution

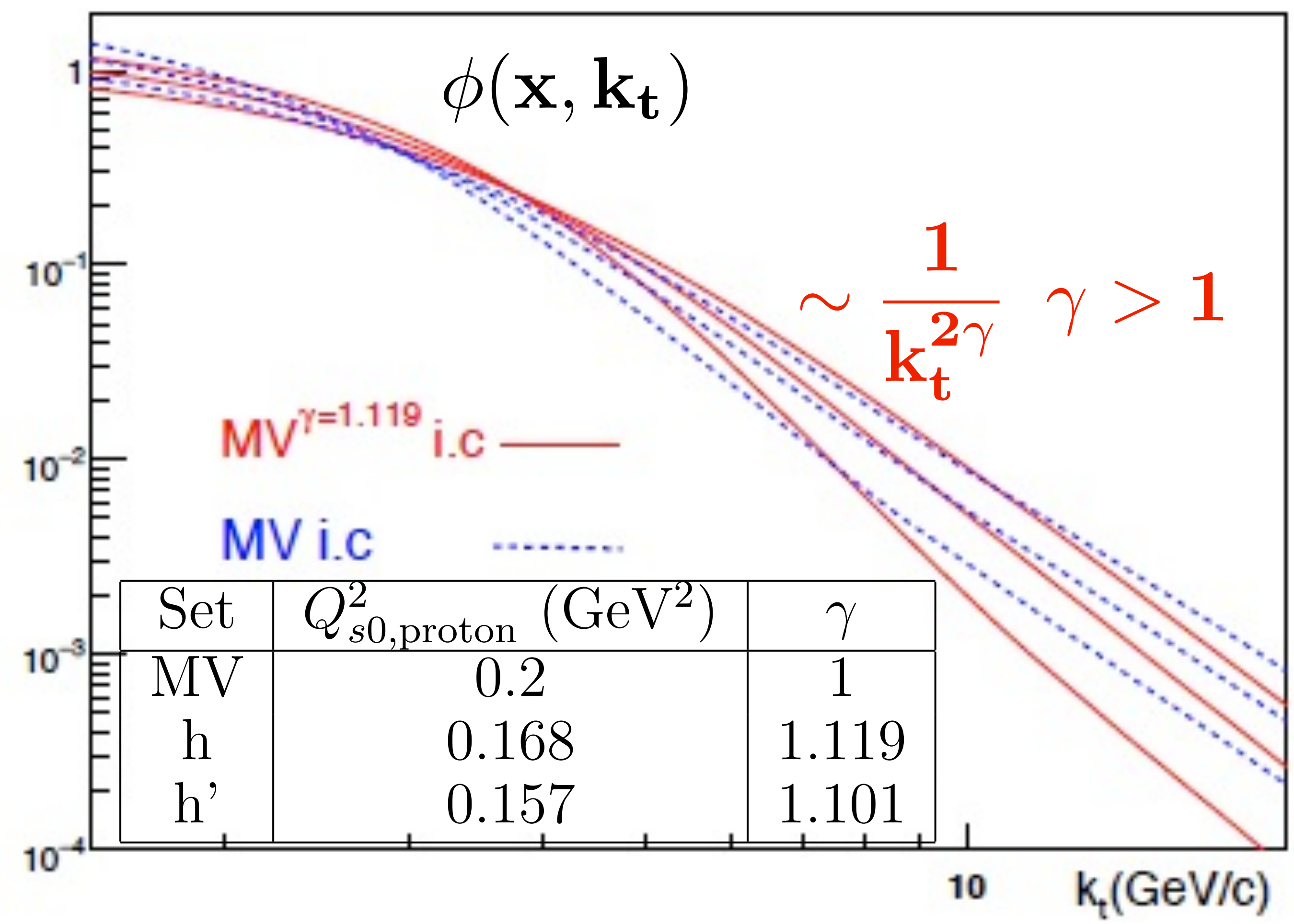
Even worse situation for nuclei: Only p+Pb data can constrain IC for Pb evolution

Uncertainties at the level of the IC account for a large part of uncertainties in CGC predictions

AAMQS fits to e+p data from HERA



Unintegrated gluon distribution



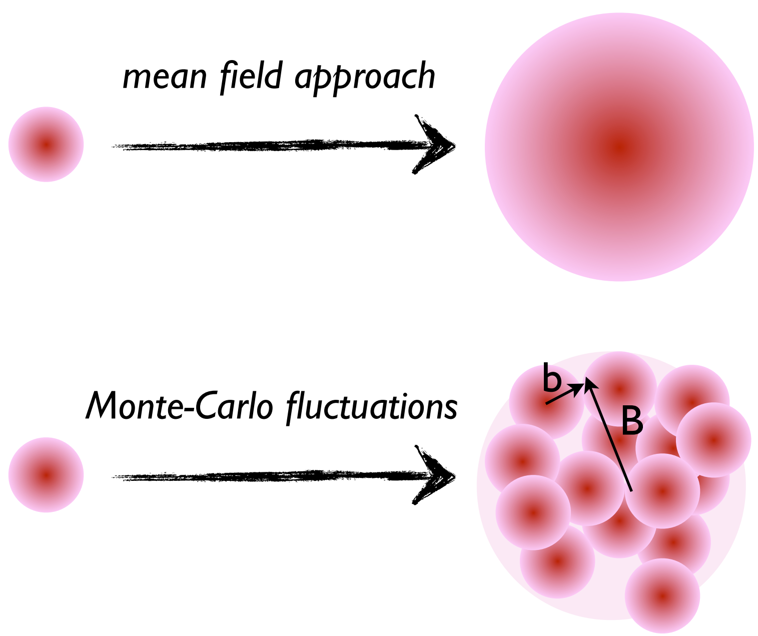
Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h'	0.157	1.101

1. Determination of the initial conditions for the evolution

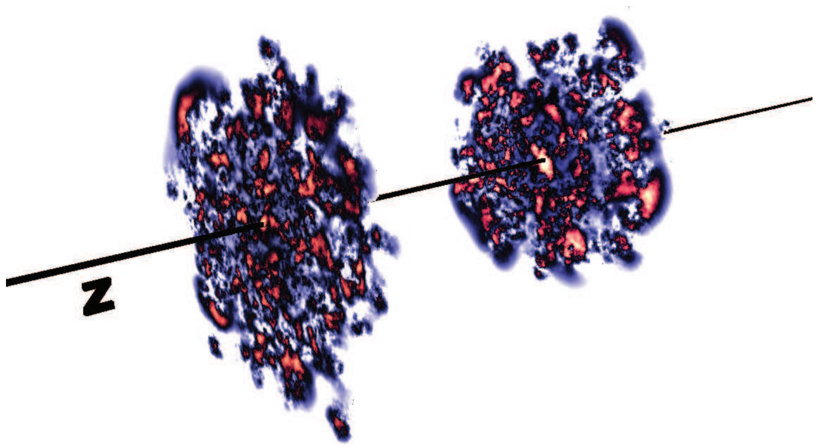
Fits to HERA and RHIC data do not constrain much the IC for proton evolution

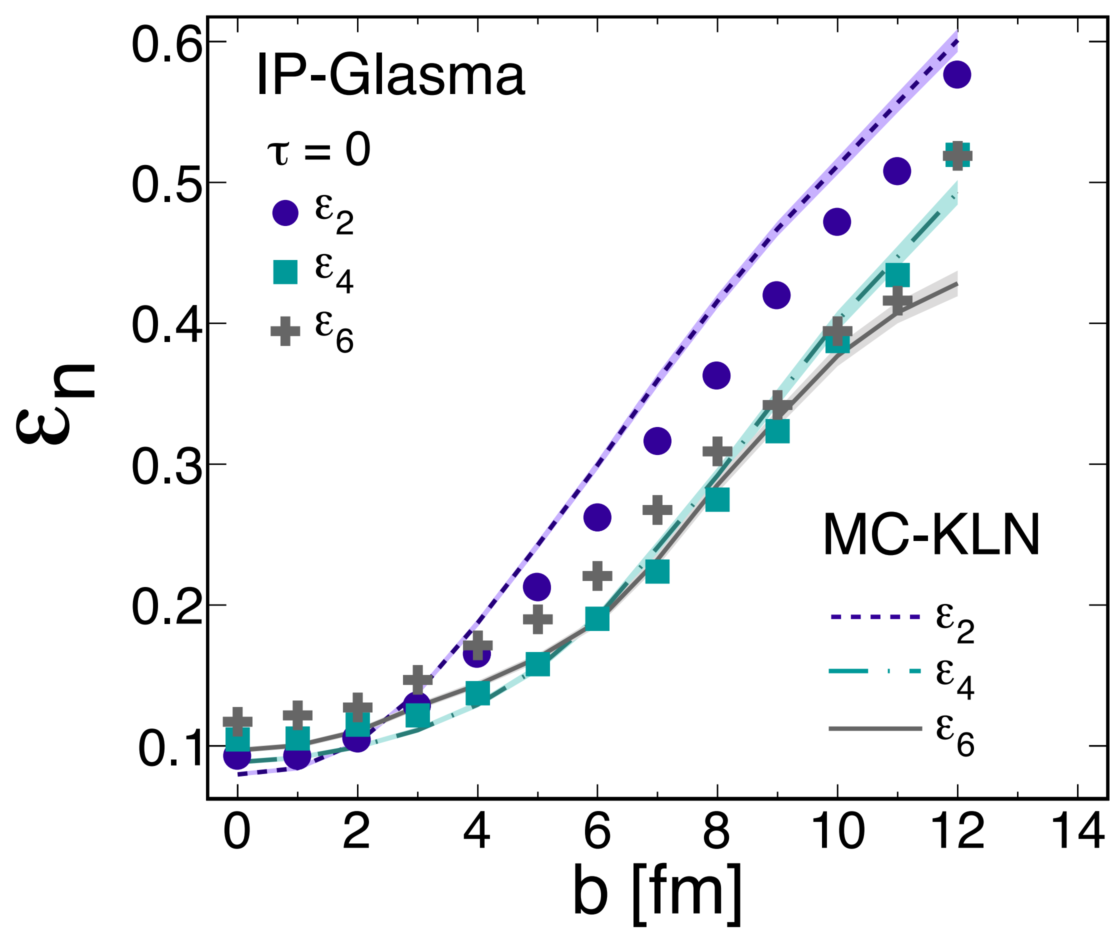
Even worse situation for nuclei: Only p+Pb data can constrain IC for Pb evolution. Centrality determination crucial

p to A modeling



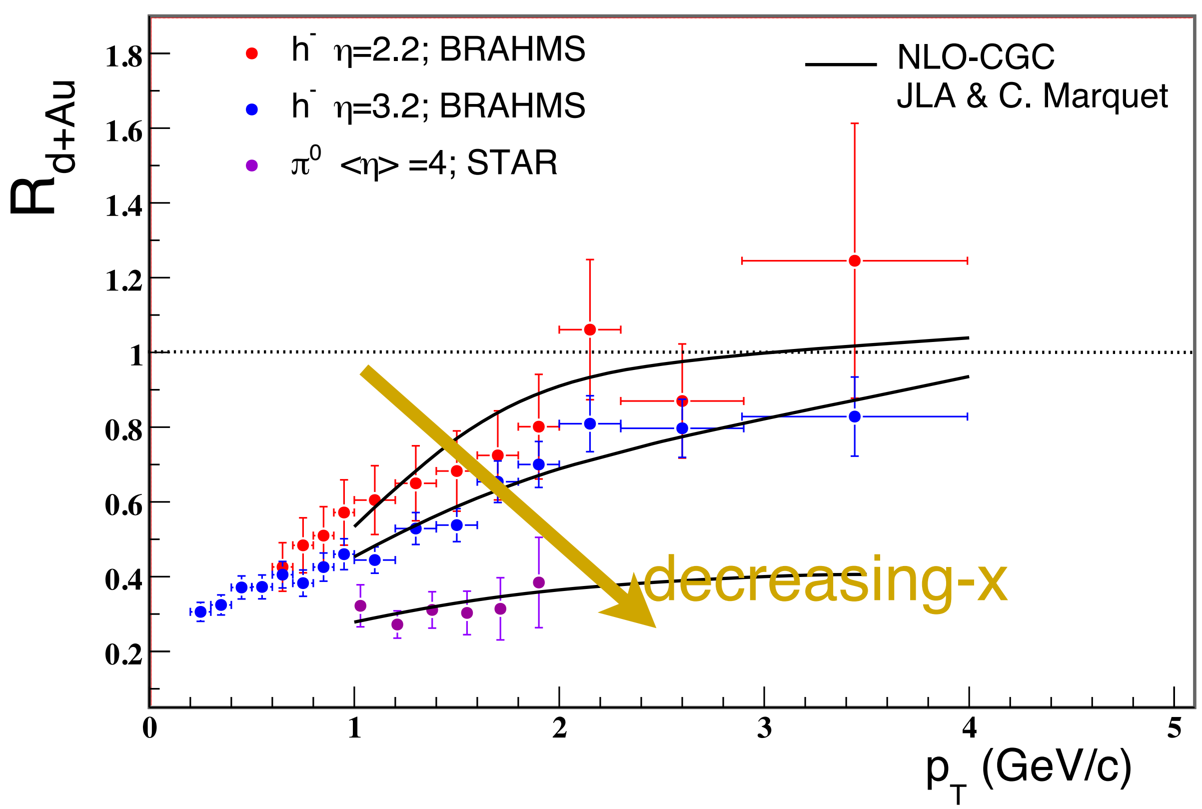
A + A collision

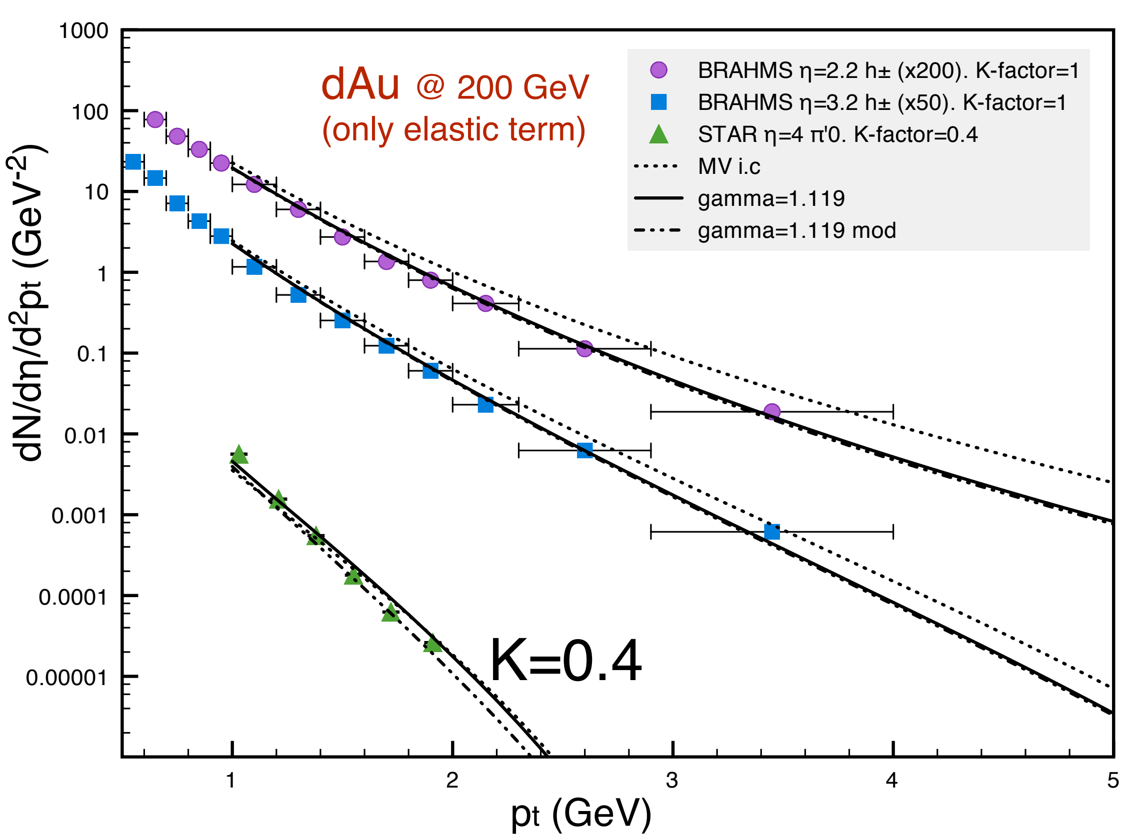


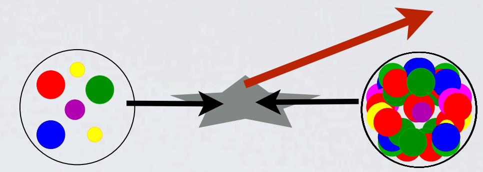


The single largest source of uncertainty in the extraction of medium transport parameters (viscosity) in A+A collisions is still the initial transverse energy density profile

Forward RHIC supression: CGC or large-x_F energy loss?

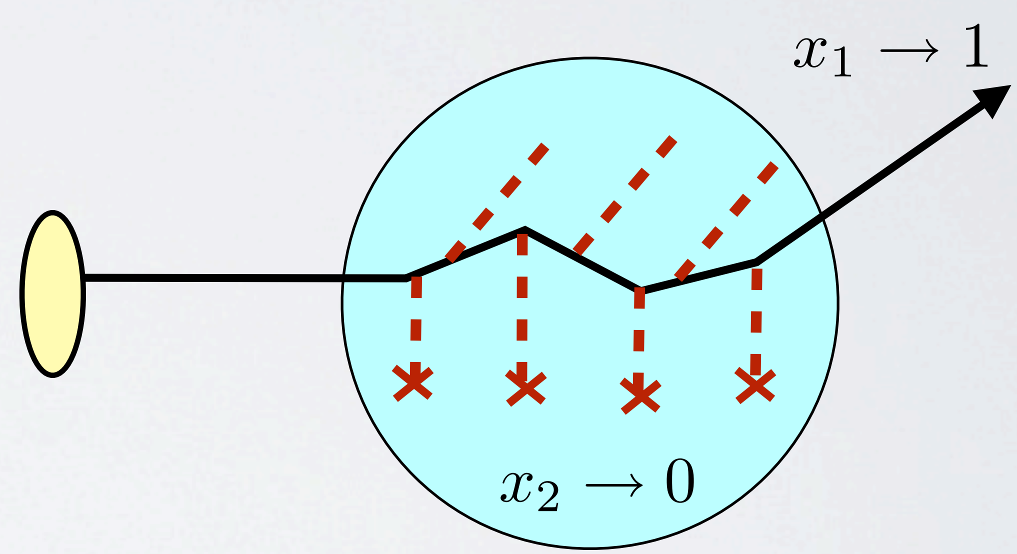






$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm\, y_h)$$

A complete understanding of new large-xF phenomena (energy-loss, breakdown of factorization...) is very important for a proper quantification of low-x, CGC effects

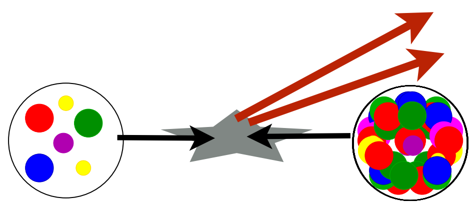


Probability of not losing energy:

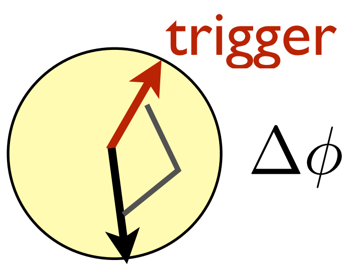
$$P(\Delta y) \approx e^{-n_G(\Delta y)} \approx (1-x_F)^{\#}$$

The species dependence of forward production is not well understood (forward RHIC pions?)

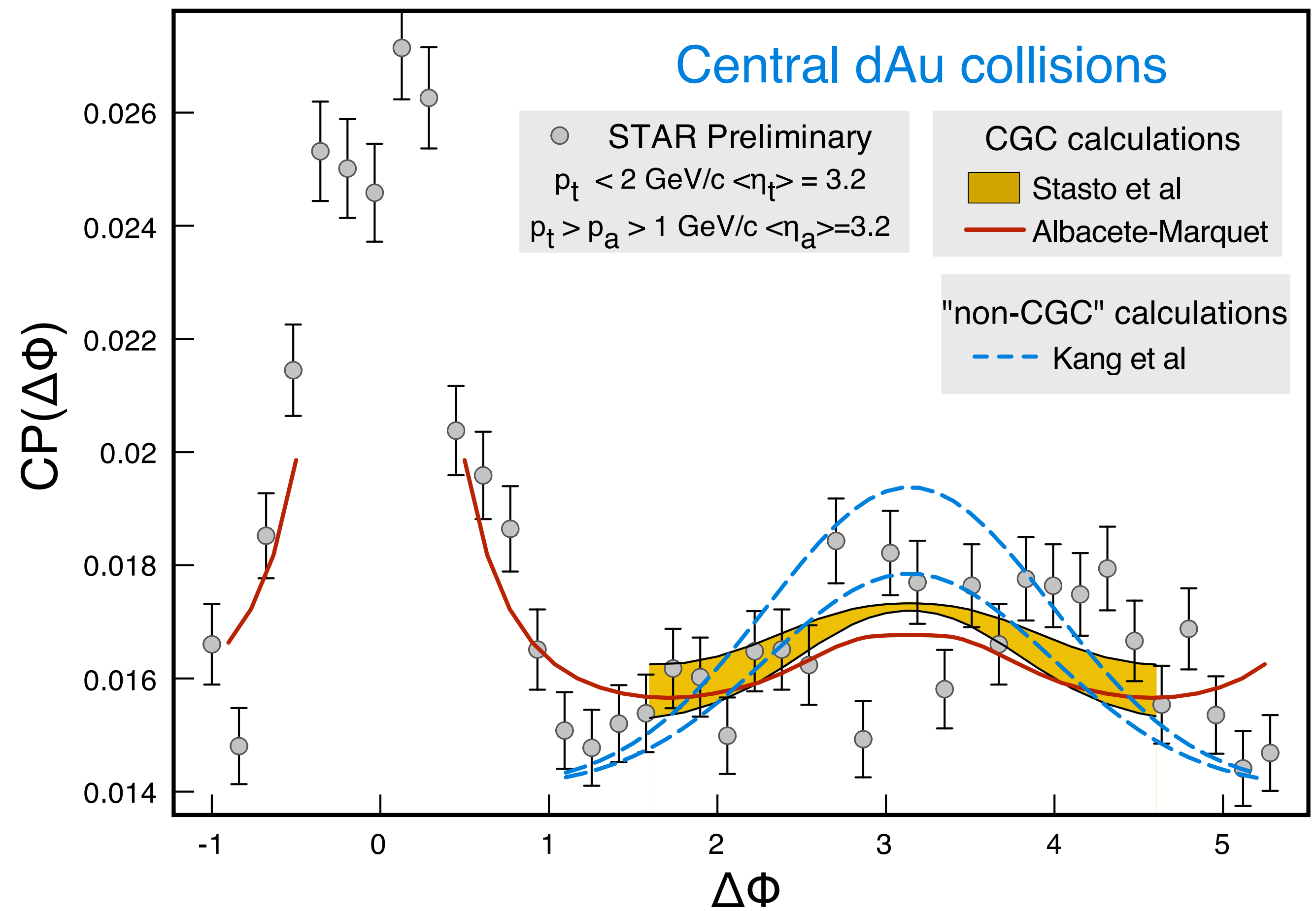
Forward di-hadron angular correlations in RHIC dAu data



➡ Coincidence probability



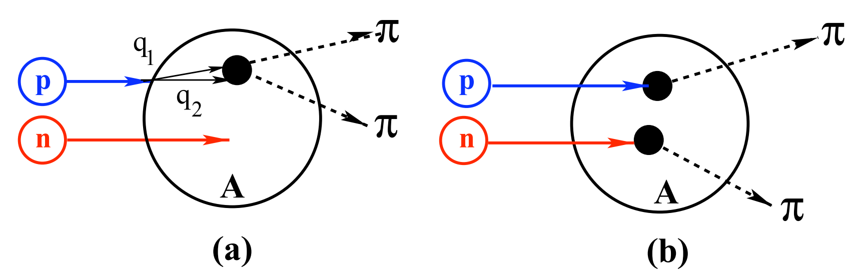
$$CP(\Delta\phi) = \frac{1}{N_{trig}} \frac{dN_{pair}}{d\Delta\phi}$$



One main uncertainty in current phenomenological works is the role of the uncorrelated pedestal

- K-factors in single inclusive production?
  High-x energy loss?
  Role of double parton scattering: Multiparton interaction may be enhanced at large-x

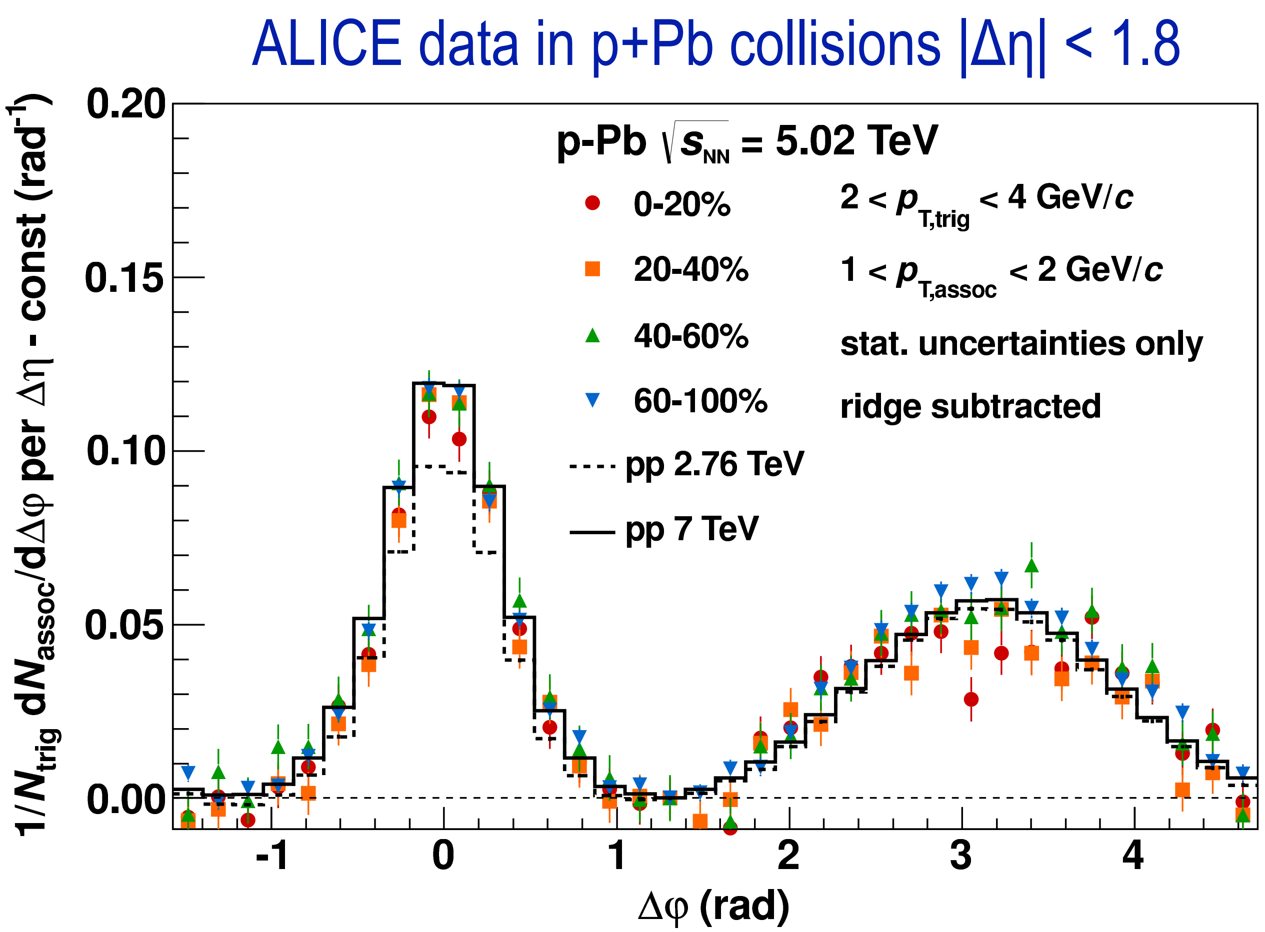
correlated

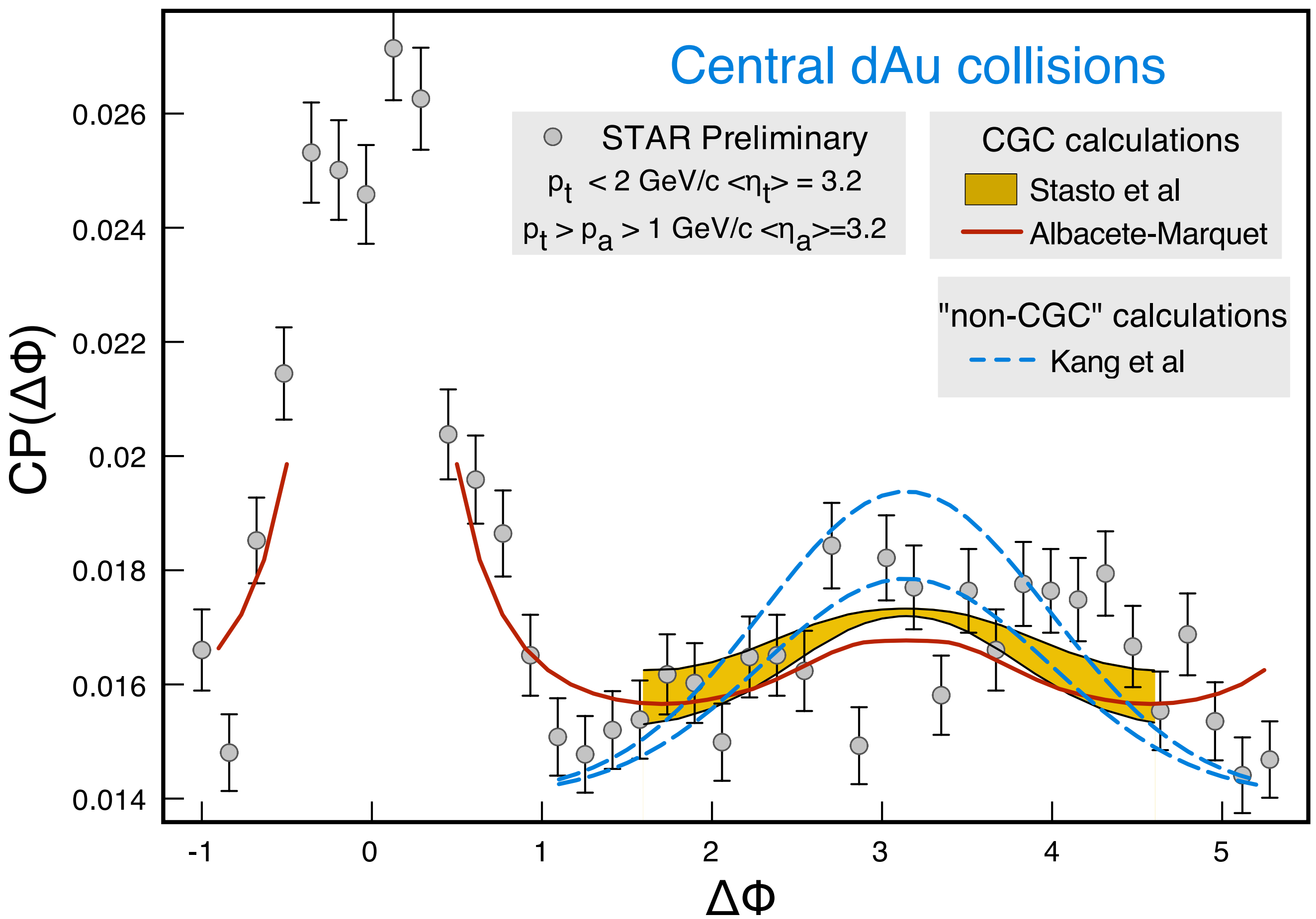


uncorrelated

Strikman, Vogelsang, 1009.6123

Forward di-hadron angular correlations in RHIC dAu data





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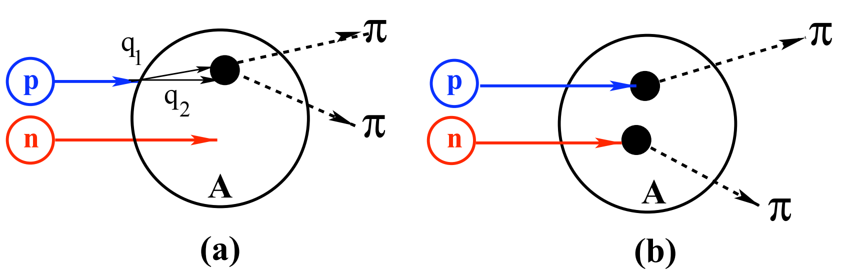

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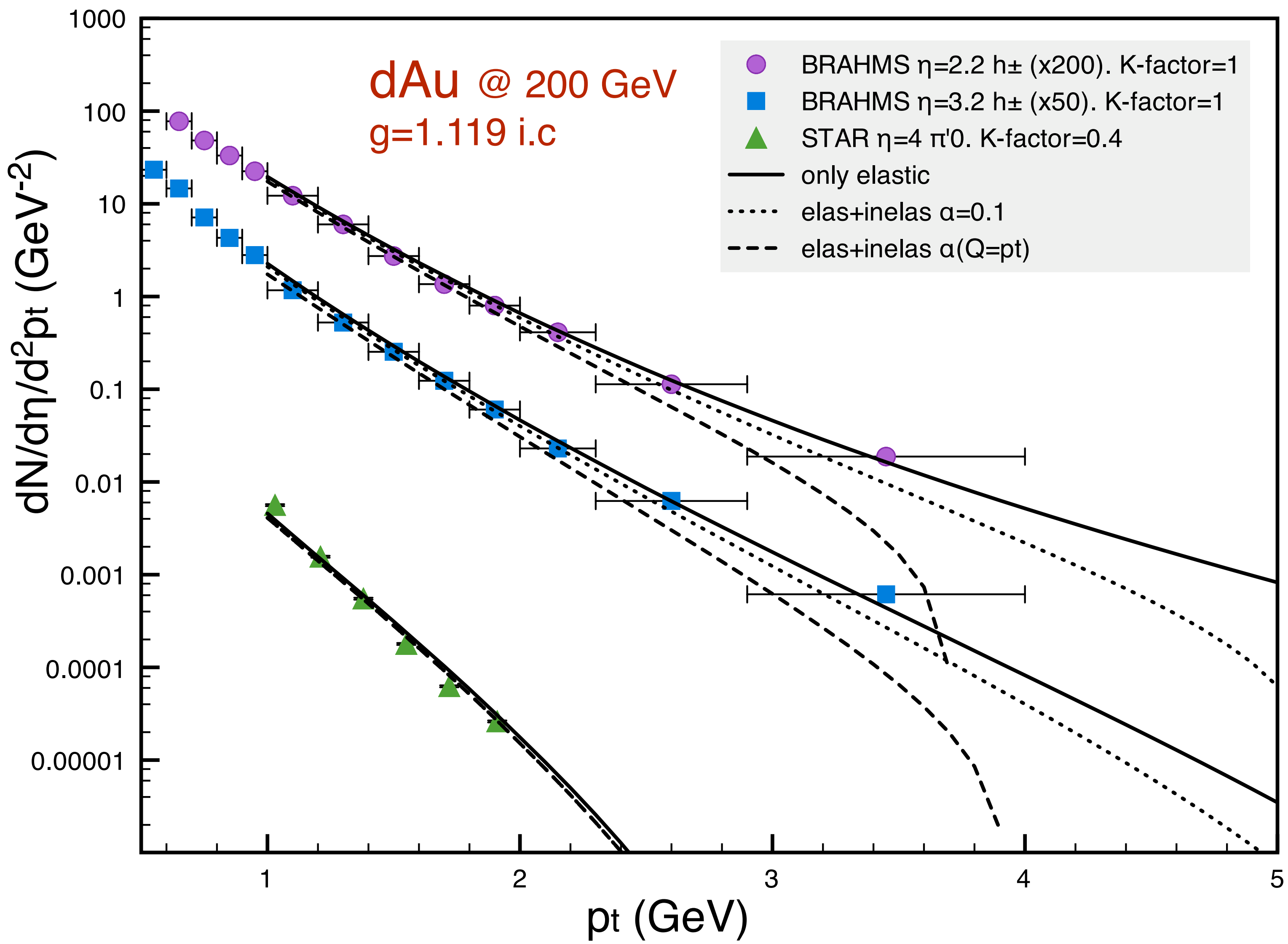
Role of NLO corrections: enhanced at moderate-x

Leading parameter in CGC resummations: $\alpha_s \ln \mathbf{x_0}/\mathbf{x}$

Higher order corrections: running coupling, **kinematic corrections. Expected to dominate at high-x**

$$x_{1(2)} \sim \frac{m_t}{\sqrt{s}} \exp(\pm y_h)$$

Example 1: NLO corrections to single inclusive production overwhelm LO contribution at high-pt



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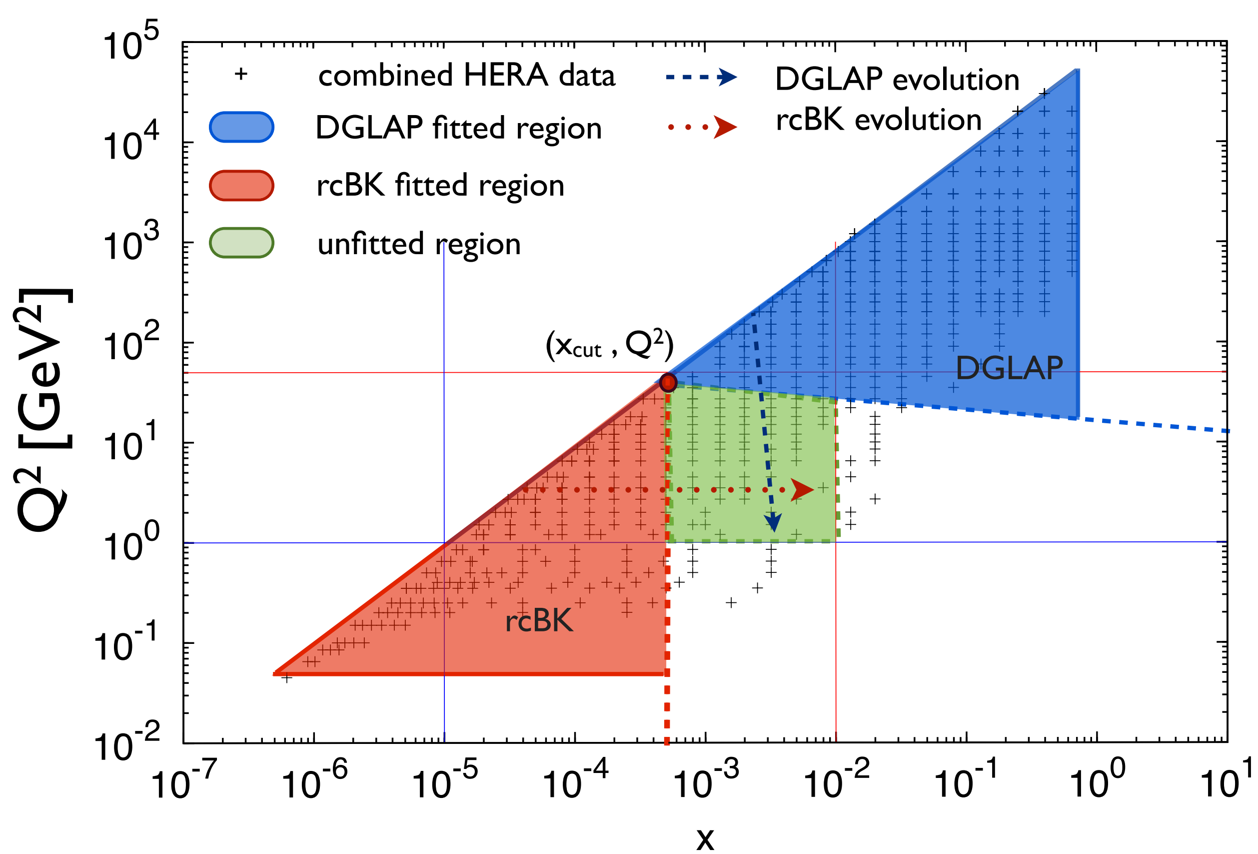
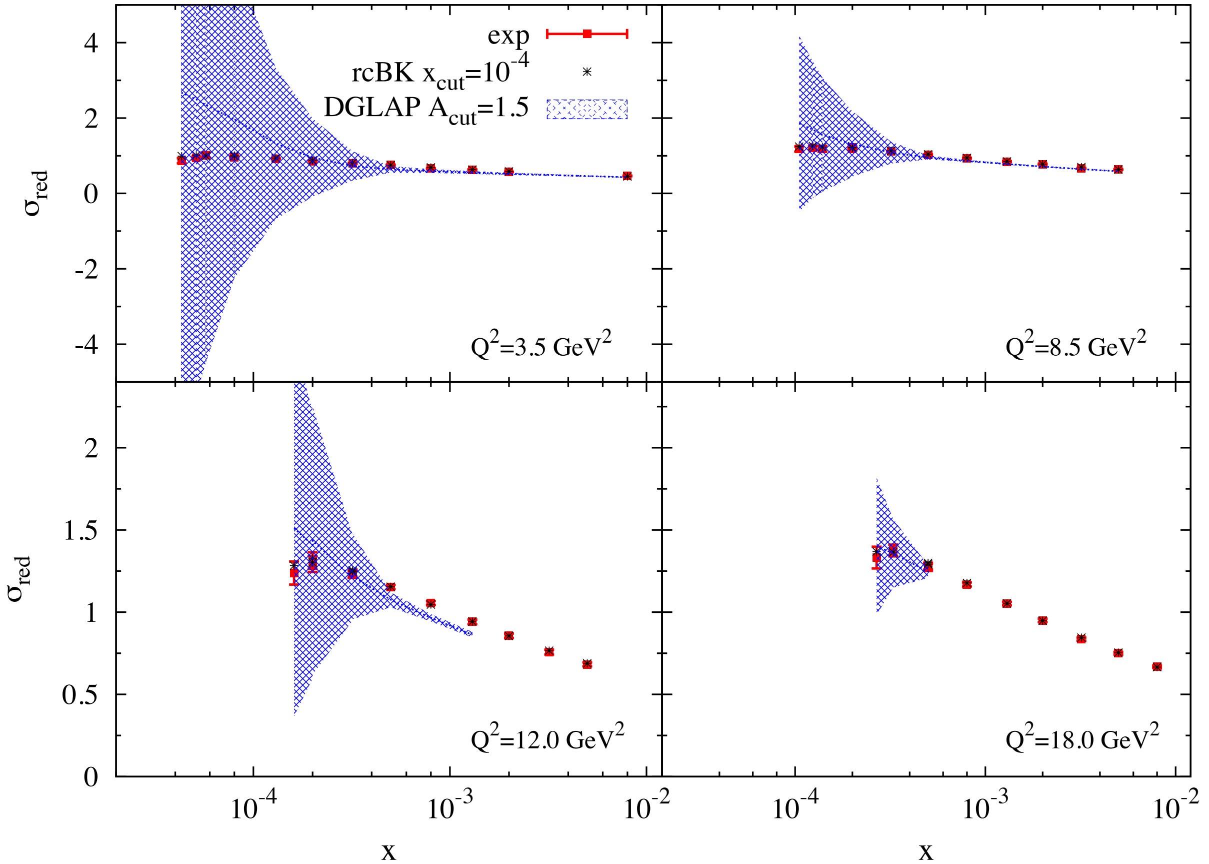
More in general, pinning down the precise scale at which saturation effects kick in and the matching with standard collinear factorization requires data in the intermediate-x region

Preliminary studies of HERA data indicate inconsistency of DGLAP fits at intermediate-x

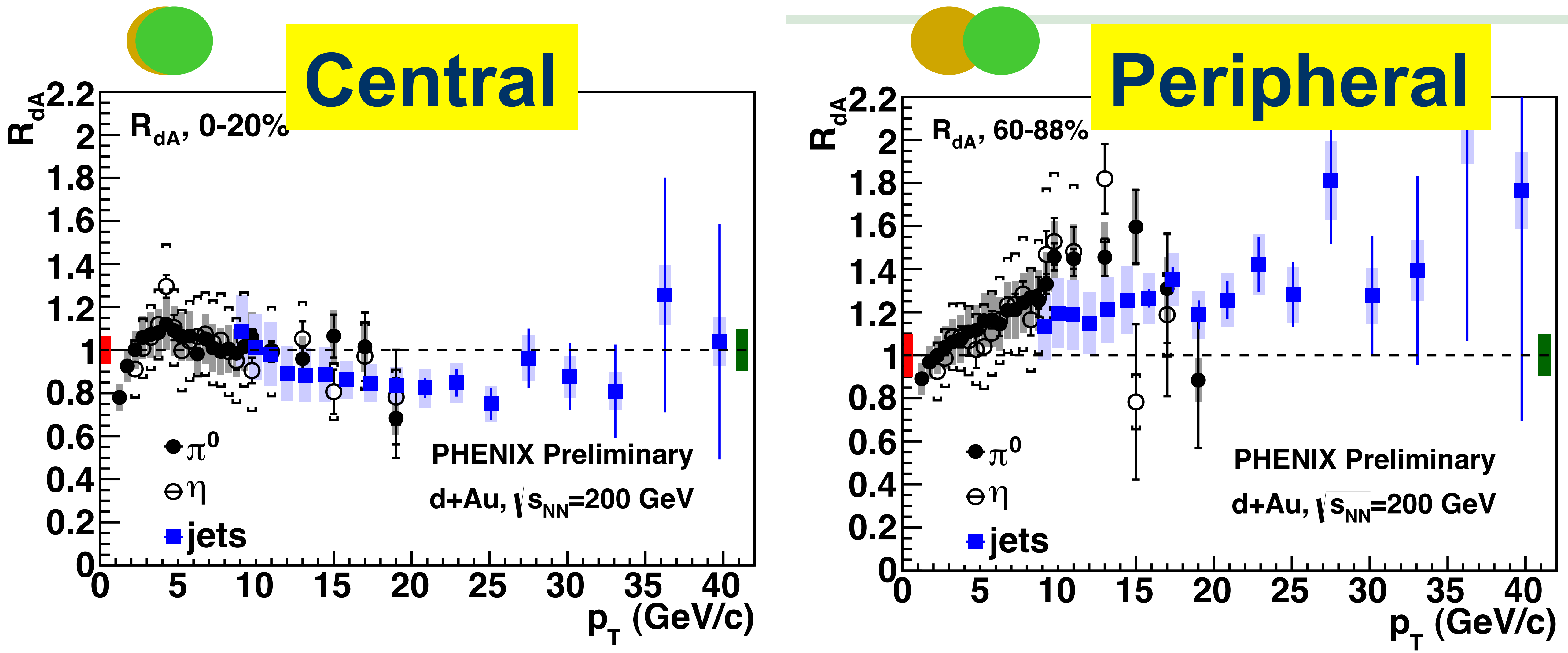




JLA,Milhano, Quiroga, Rojo

Funny data on RpA (intermediate-x):

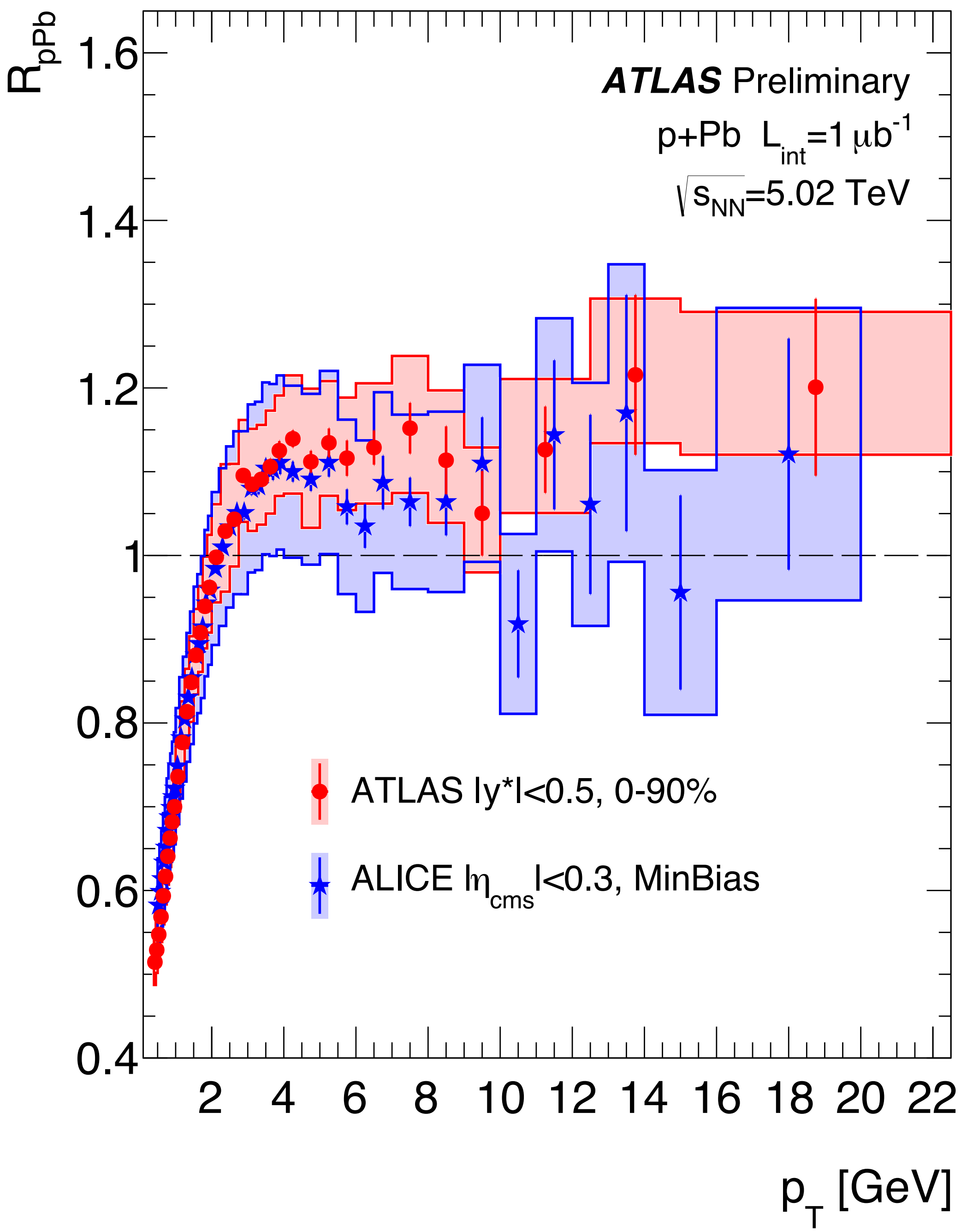
Preliminary PHENIX data on RdAu for pions and jets at η=0 feature a stronger nuclear effect in peripheral vs central collisions.
If confirmed, this challenges most of initial state models (nPDF's etc).

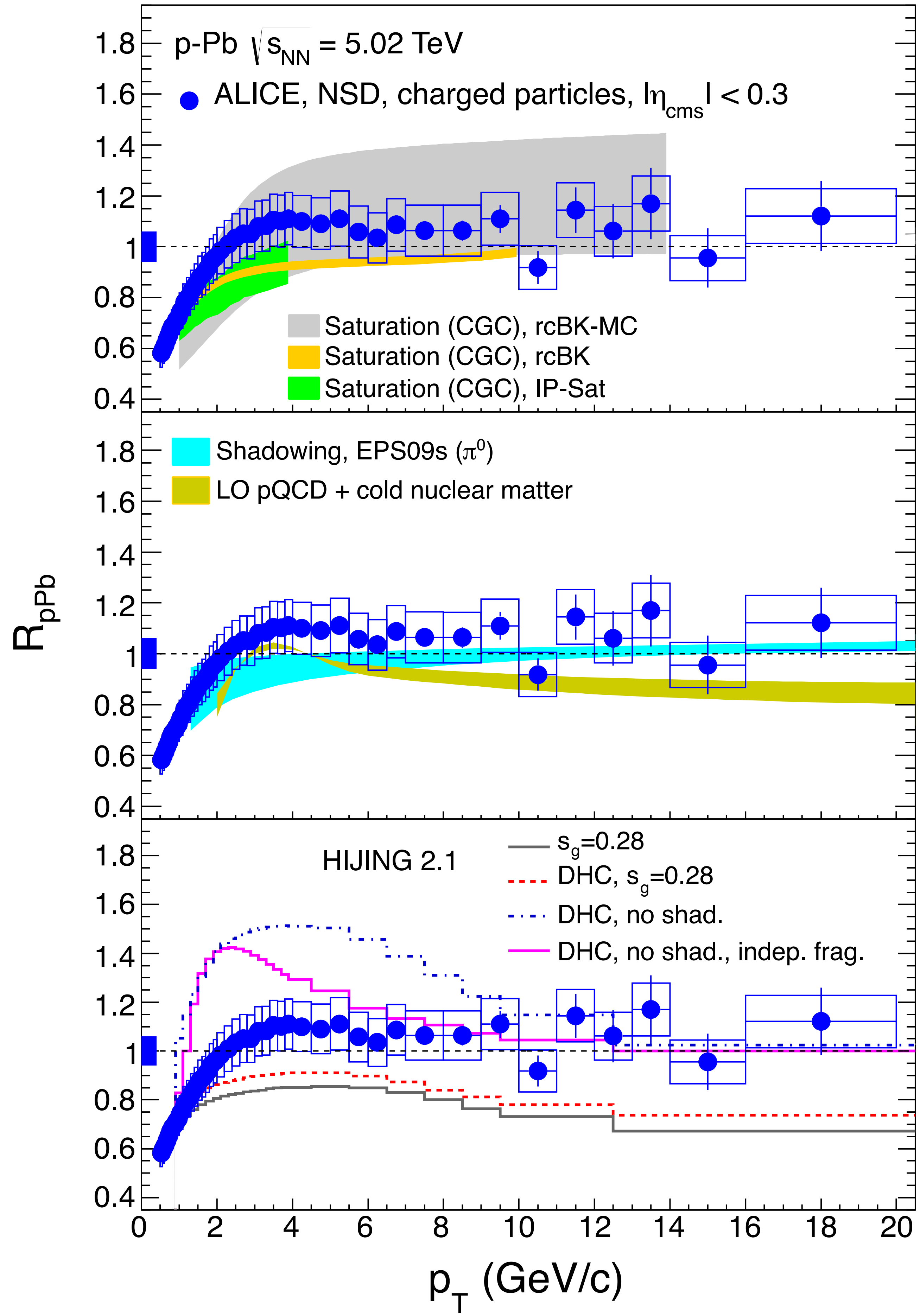


$$R_{pA} = \frac{\frac{dN^h_{pA}}{dy_h d^2k_\perp}}{A^{1/3}\frac{dN^h_{pp}}{dy_h d^2k_\perp}} \sim \frac{\phi_A(x, k^2_\perp)}{A^{1/3}\phi_p(x, k^2_\perp)}$$

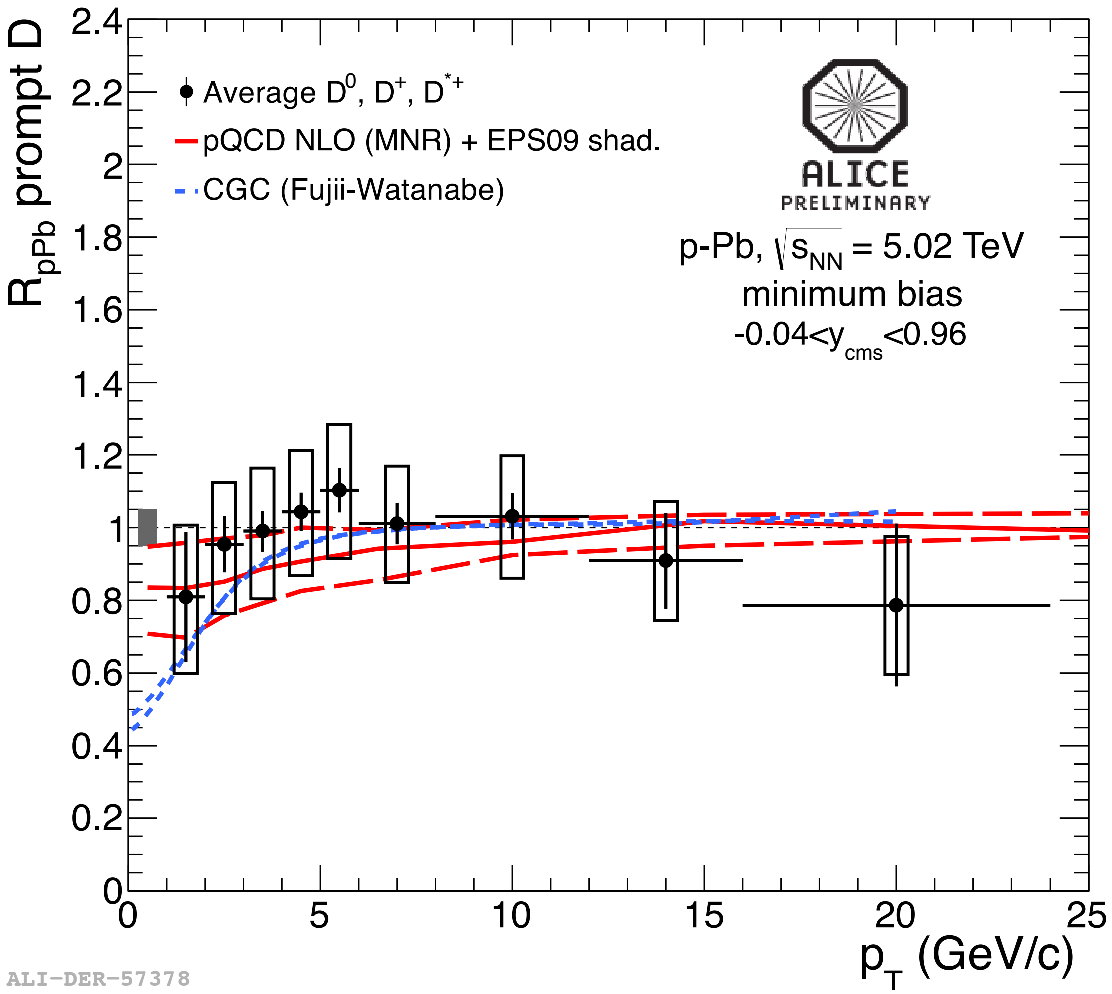
Funny data on RpA (intermediate-x):

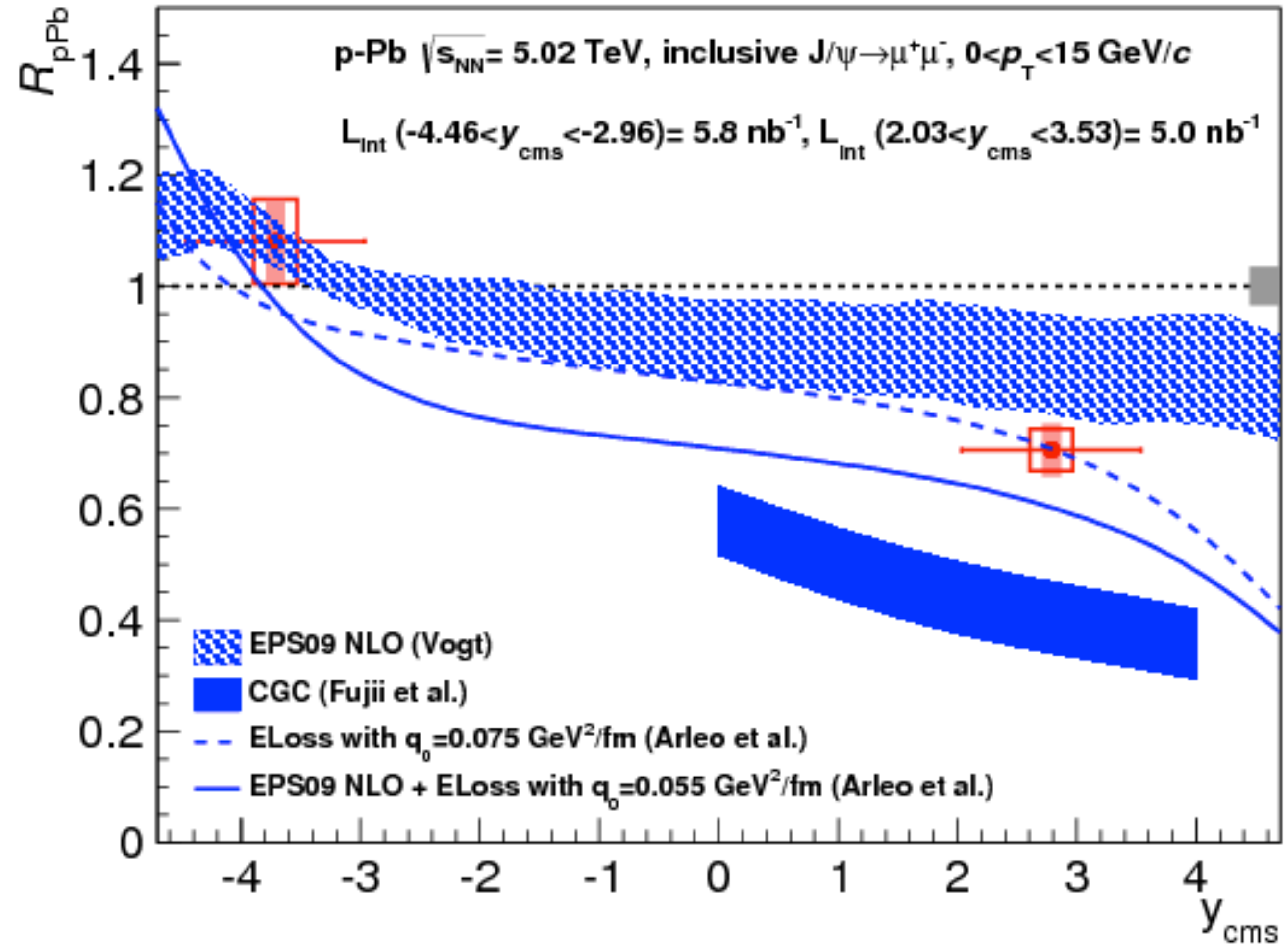
ALICE and ATLAS data on RpPb for charged particles may indicate the presence of "antishadowing" at small-x (?).
This may be naturally explained in the CGC as a consequence of non trivial initial conditions + geometry fluctuations





Heavy Quarks





Interpretation of low-x effects obscured by uncertainties in the production mechanism

pt-dependence of open charm well described by nPDF and CGC calculations

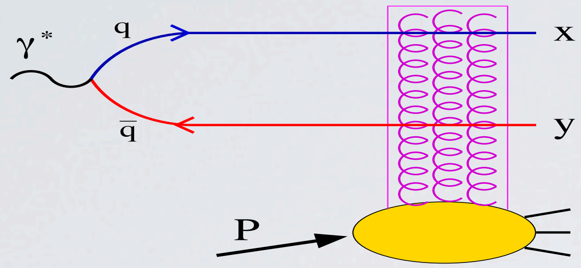
CGC calculation integrated J/Psi pt-yields affected by normalization uncertainties (maybe data too)

Conclusions

- ✔ AFTER would have access only to a limited kinematic range relevant for low-x studies
- ✔ Information at moderate-x potentially very relevant to constrain i.c for small-x evolution. Potential strong impact in heavy ion physics
- ✔ The intermediate-x region is also rich in physical phenomena, as it lies in the border between theoretically well stablished formalisms: Coll. Factorization vs CGC

Baseline of small-x studies: electron-proton collisions at HERA

$\mathcal{N}(x,r,b)$:



CGC approaches

• IP-Sat $\mathcal{N}(x,r,b) = \left(1-\exp\left(-\frac{\pi^2 r^2}{2N_c}\alpha_s\left(\mu^2\right)xg\left(x,\mu^2\right)T_G(b)\right)\right)$

Kowalski-Teany; Venugopalan et al

- Eikonalization of 2-gluon scattering in coll, factorization + Quark-less LO DGLAP evolution

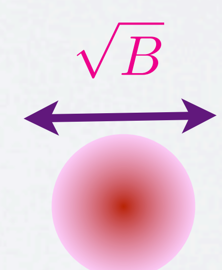
• rcBK $\frac{\partial \mathcal{N}(x,r,b)}{\partial \ln(1/x)} = \theta(b-b_0)\int dr_1\,\mathcal{K}^{r.c}\left[\mathcal{N}(x,r_1)+\mathcal{N}(x,r_2)-\mathcal{N}(x,r)-\mathcal{N}(x,r_1)\mathcal{N}(x,r_2)\right]$

- Running coupling non-linear BK equation

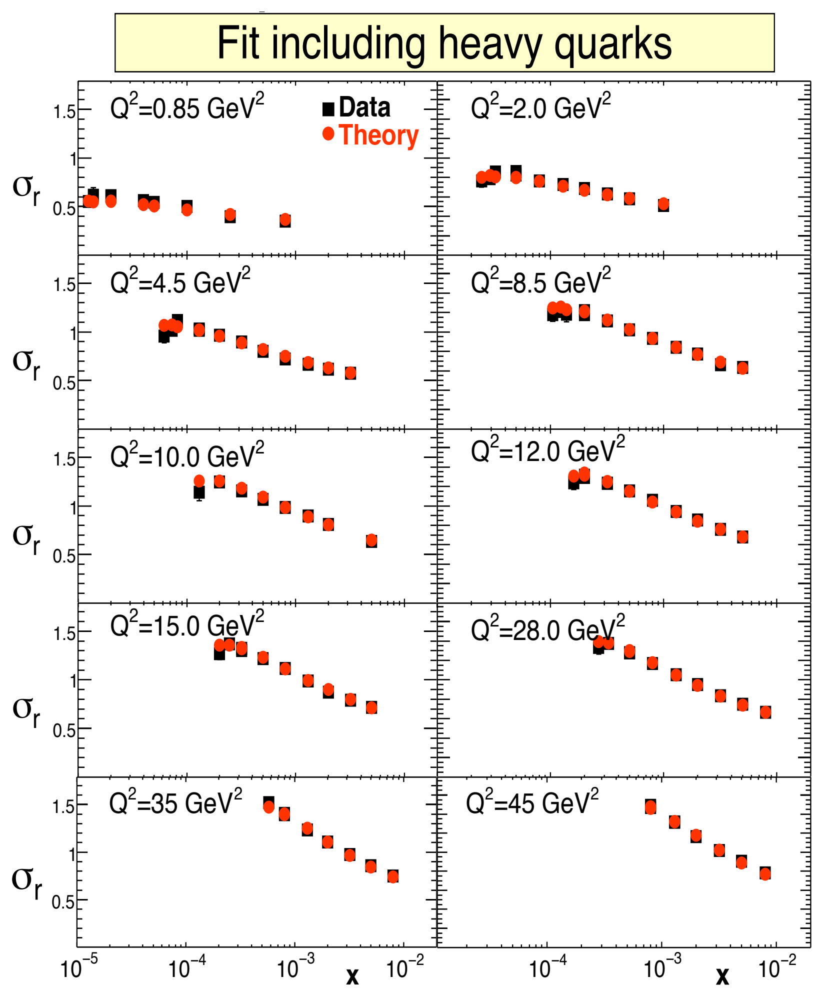
JLA, Armesto, Milhano, Quiroga, Salgado

Information on the “average proton radius” can be obtained from t-dependence of exclusive processes

$$T_G(b)\sim\exp\left[-\frac{b^2}{2B_g}\right]; \quad B\sim 4\div 6\,\mathrm{GeV}^{-2}$$



• **rcBK fit**



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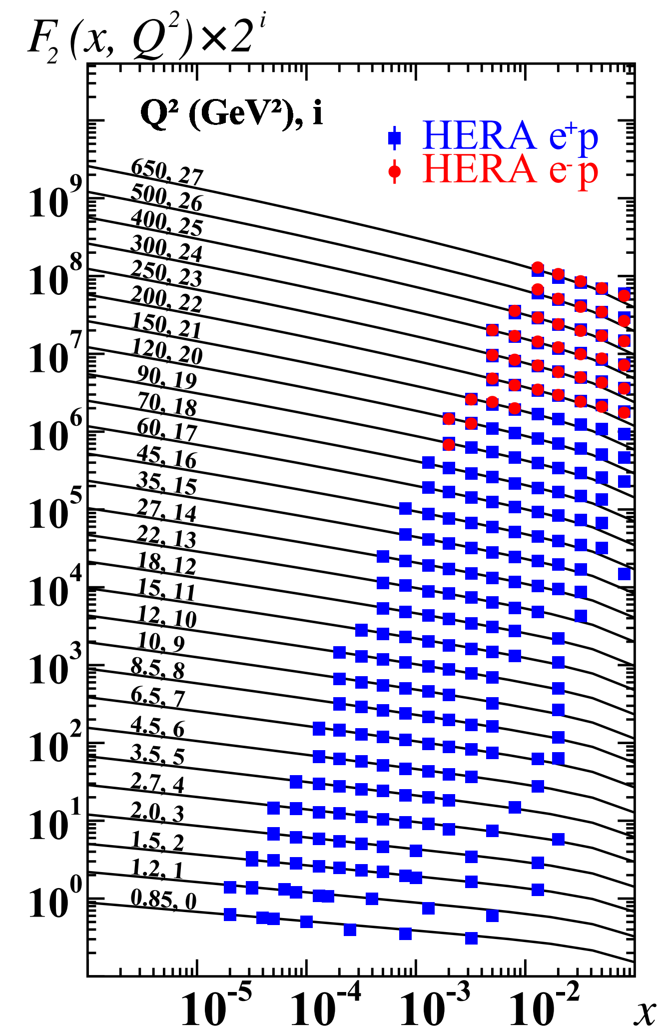


- Both model yields comparably good fits to small-x HERA data
- Precision tests show that rcBK evolution is more stable than DGLAP JLA Milhano Quiroga Rojo;
- Both models are then extrapolated to the nuclear case, **Q_s(A, b):**

rcBK -> rcBK-MC (kt-factorization) ; IP-Sat -> IP-Glasma (CYM)

JLA, Dumitru, Fujii, Nara

Schenke, Tribedy, Venugopalan

- Bulk features of HIC (energy, centrality and rapidity dependence) of total multiplicities well described within the CGC (and others) models:

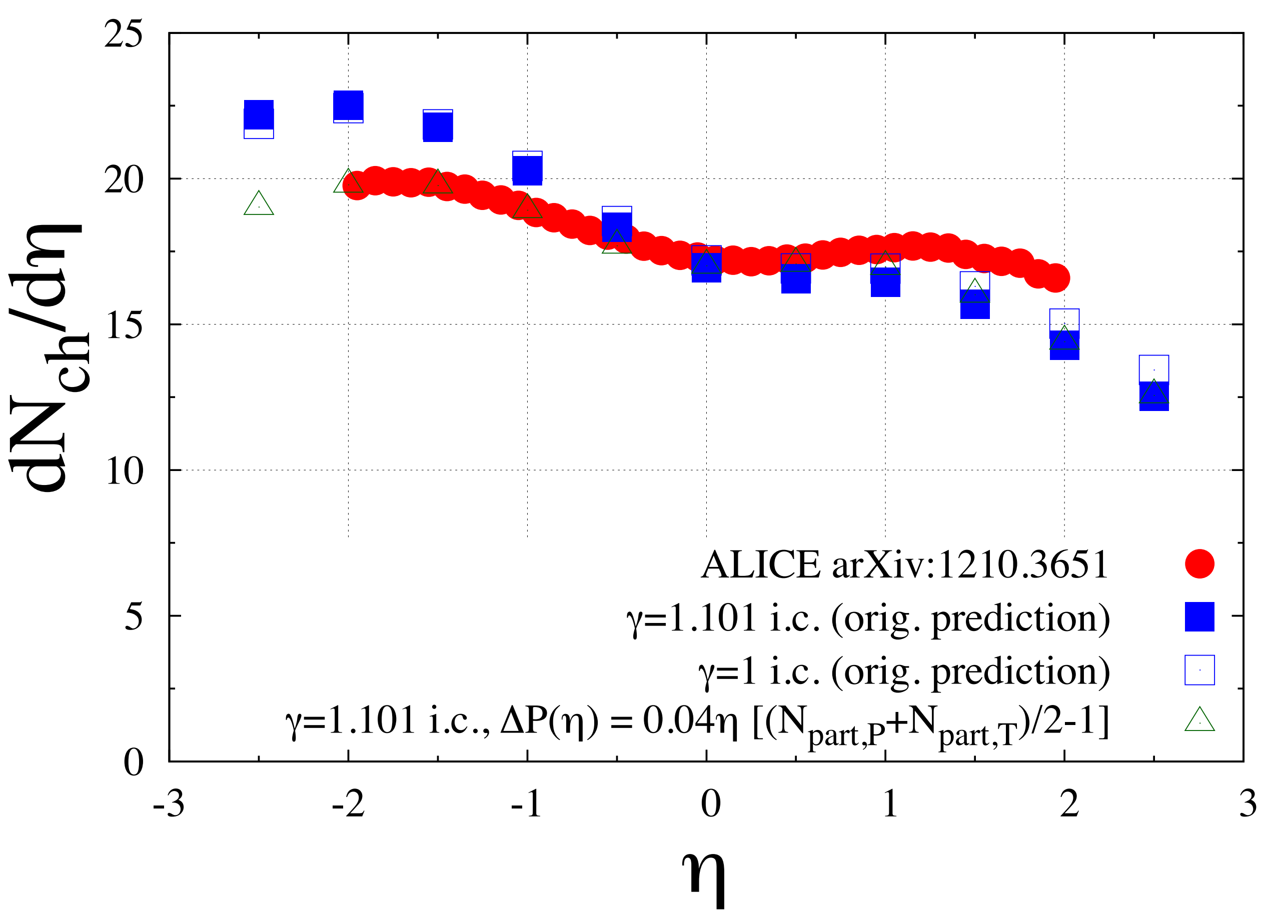
Theory (CGC)

$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} = \frac{2}{3}K\left.\frac{dN^{g}}{d\eta}\right|_{\eta=0} \propto Q_s^2(\sqrt{s},b) \sim \sqrt{s/s_0}^{\lambda} N_{part}$$

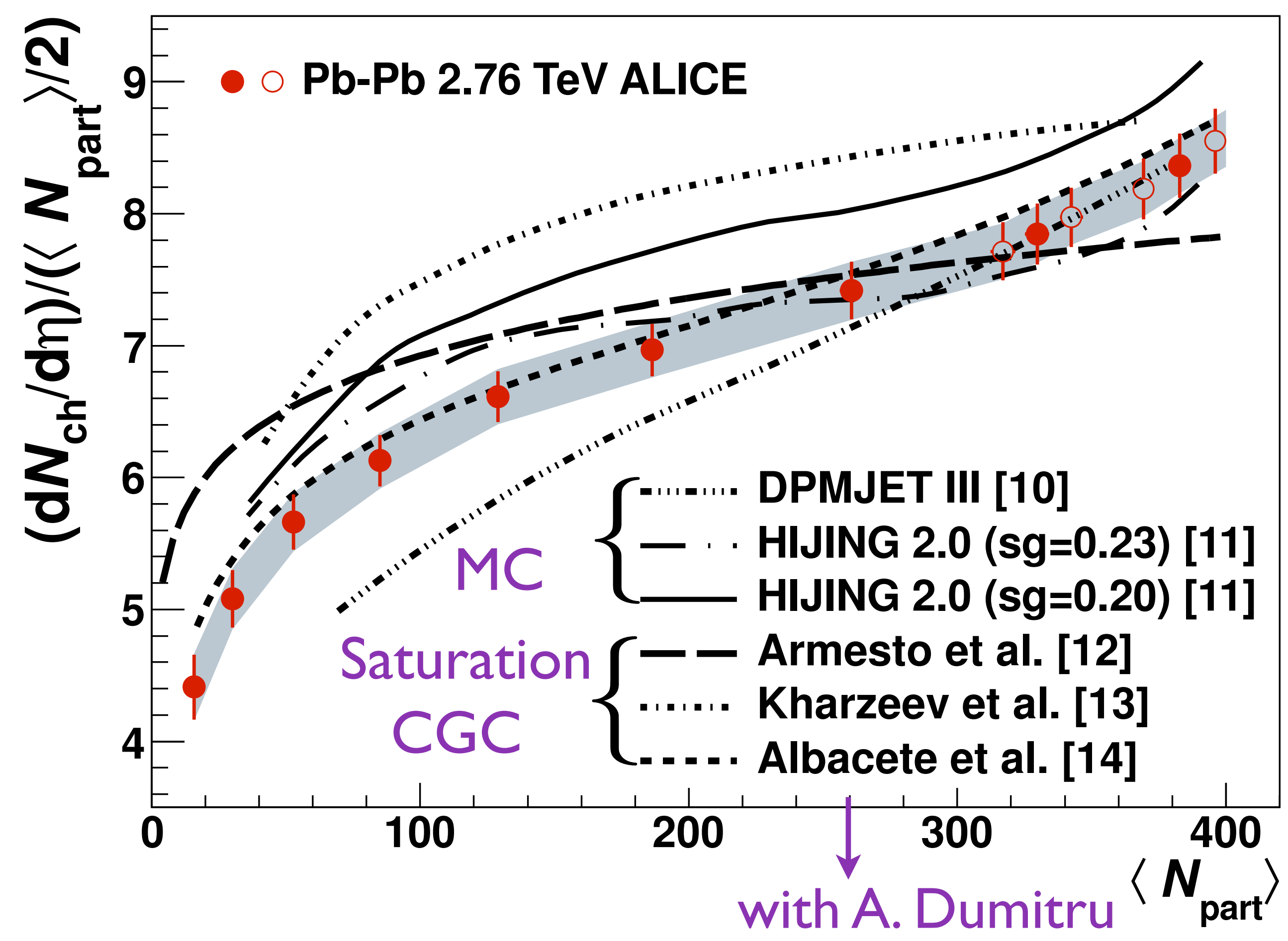
Data

$$\left.\frac{dN^{ch}}{d\eta}\right|_{\eta=0} \approx \sqrt{s}^{0.3} \times f(N_{part})$$

Rapidity dependence pPb



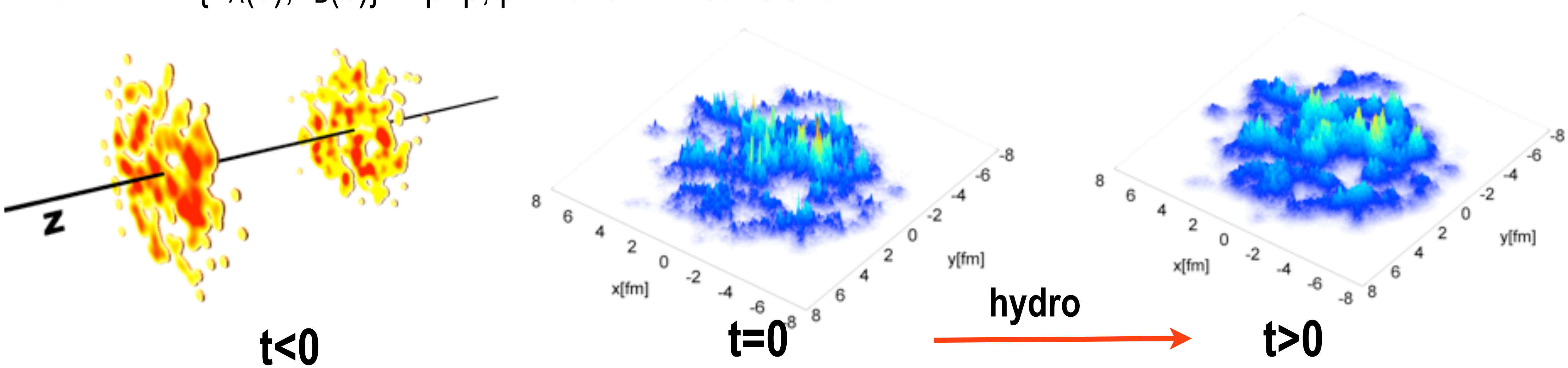
Centrality dependence PbPb



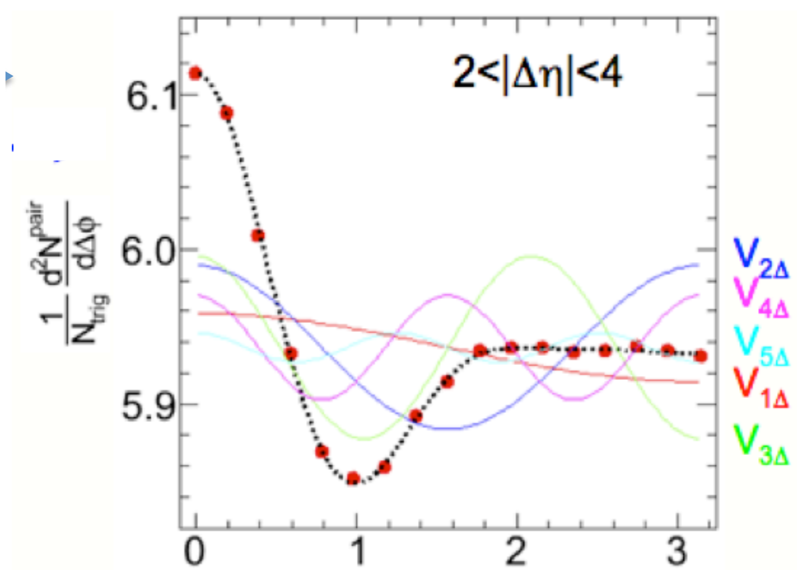
- p+p and d+Au multiplicities and single inclusive spectra are also well described by these models

Fluctuations

- Geometrical: Position of the nucleons fluctuate in the transverse plane
- Sub-nucleon level: Multiplicity distributions well described by a negative binomial distribution with k ~ min{T_A(b),T_B(b)} in p+p, p+A and A+A collisions



Figs from B. Schenke et al 1202.6646



$$v_n = F[\epsilon_n; \eta]$$

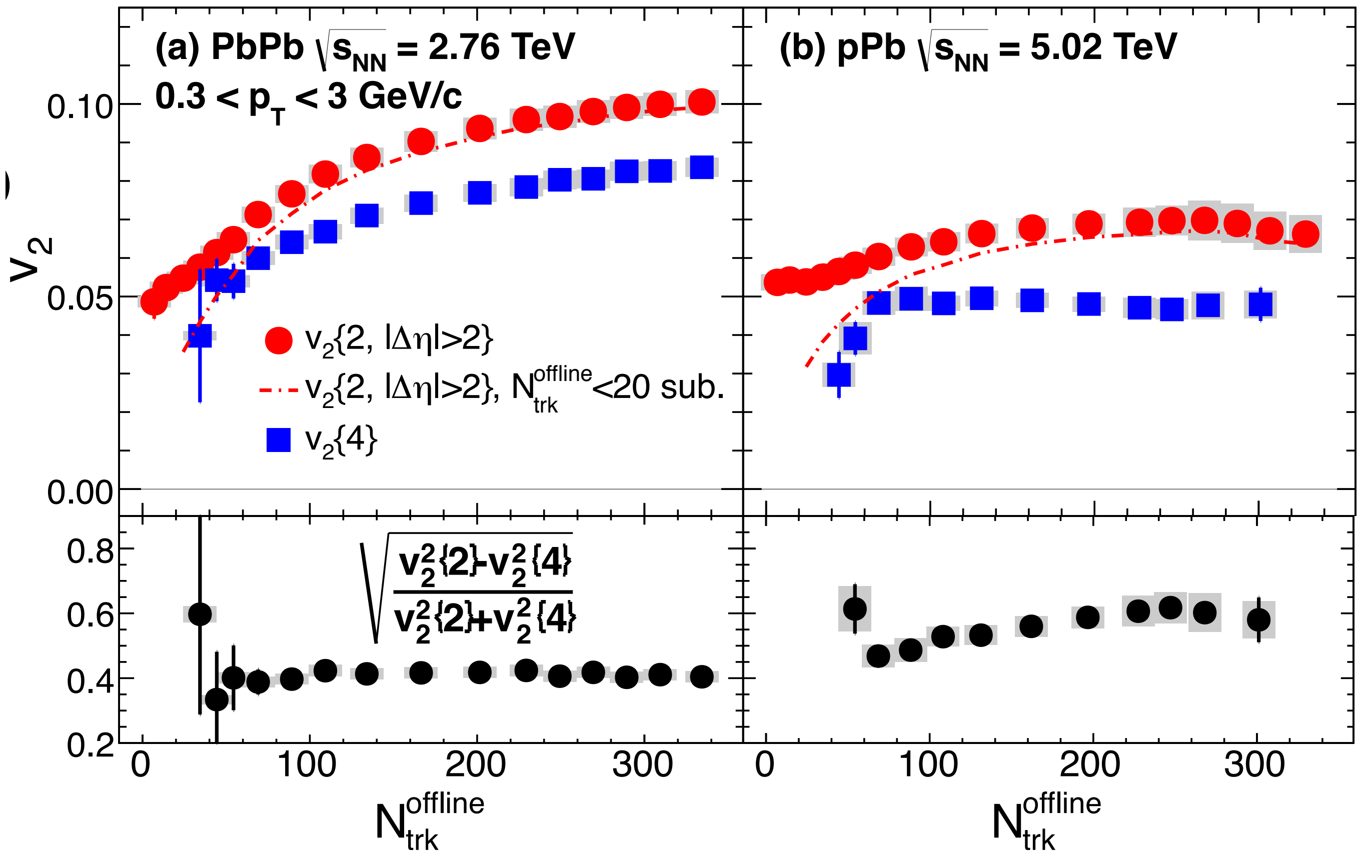
This is crucial input for the hydro evolution and to extract QGP transport properties (viscosity).

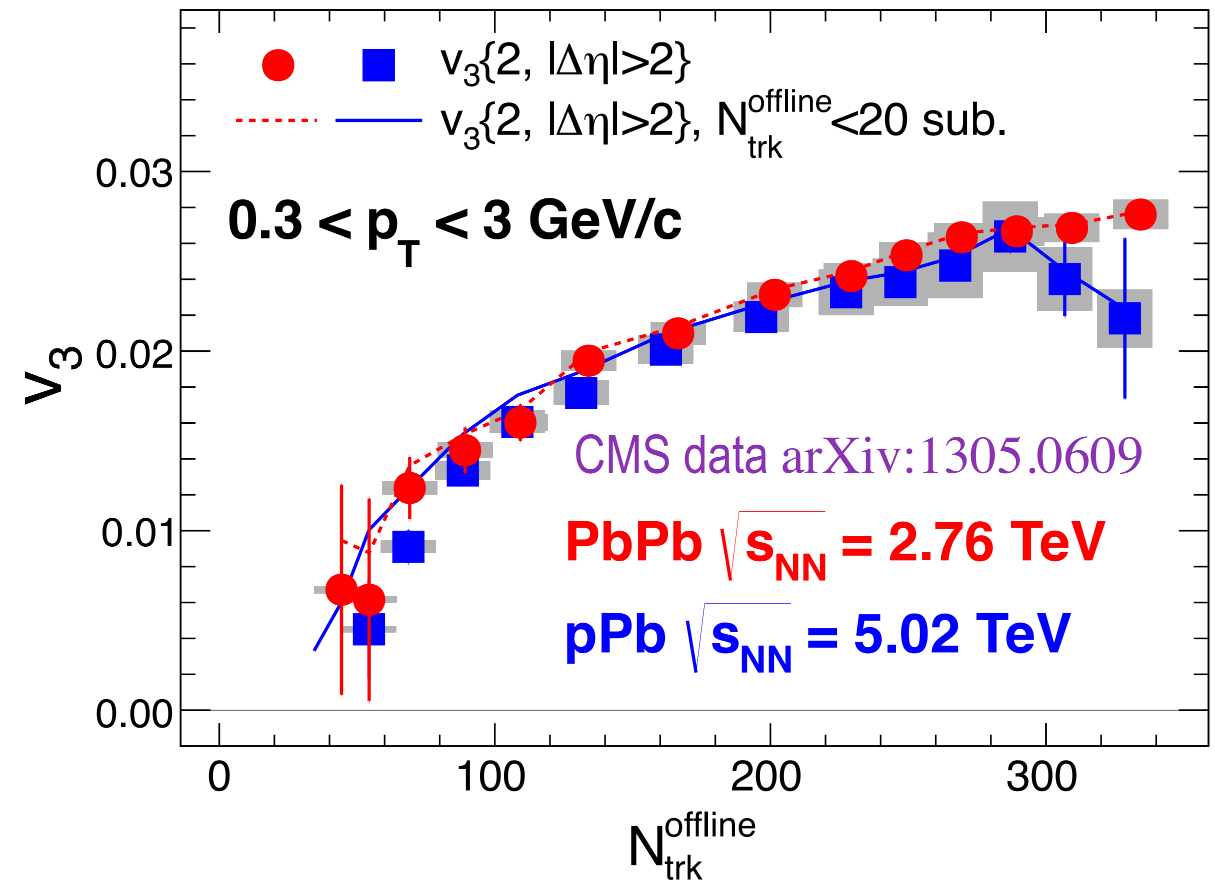
Matt Luzum, QM2012 talk, in the conclusions:

- $0.07 \leq \eta/s \leq 0.43$ (preliminary!!)
- Largest *single* source of uncertainty still initial conditions

Multiplicities and energy density fluctuations and flow in p+Pb

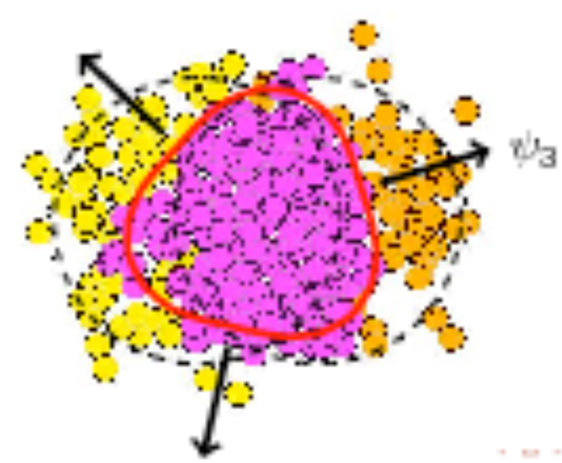
- First p+Pb measurements show strong **v2** and **v3** in p+Pb collisions. Similar observation from PHENIX in d+Au





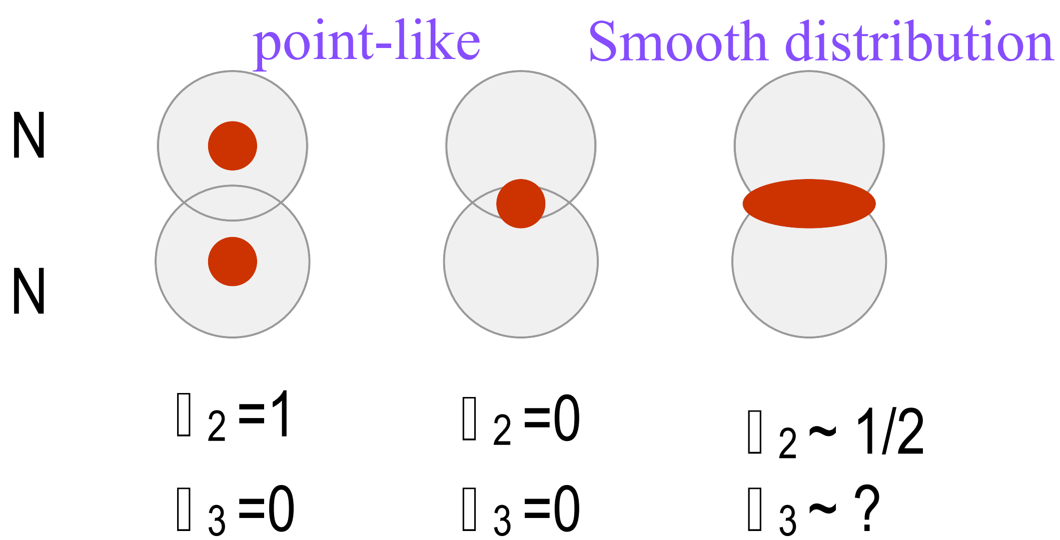
Flow?? (Good qualitative description of data by 3+1 D viscous hydro, e.g. Bozek et al 1304.3044)

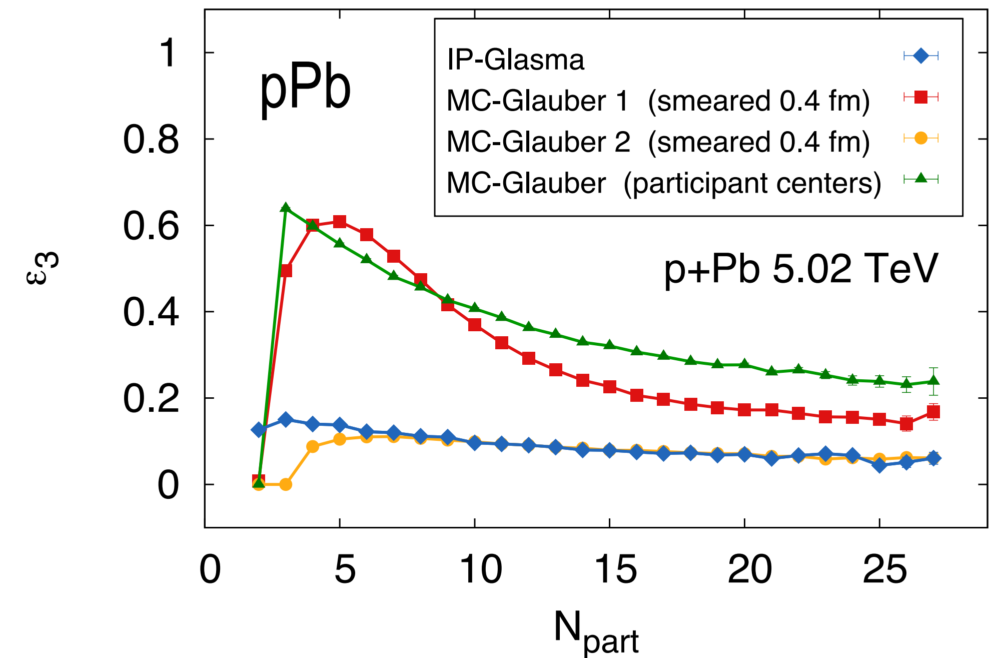
- How to built an analogous geometric picture in proton collision?
- We need to look at the geometrical distribution of fluctuations at the sub-nucleon level
- This problem has a much smaller relevance in nucleus-nucleus collisions



Multiplicities and energy density fluctuations and flow in p+Pb

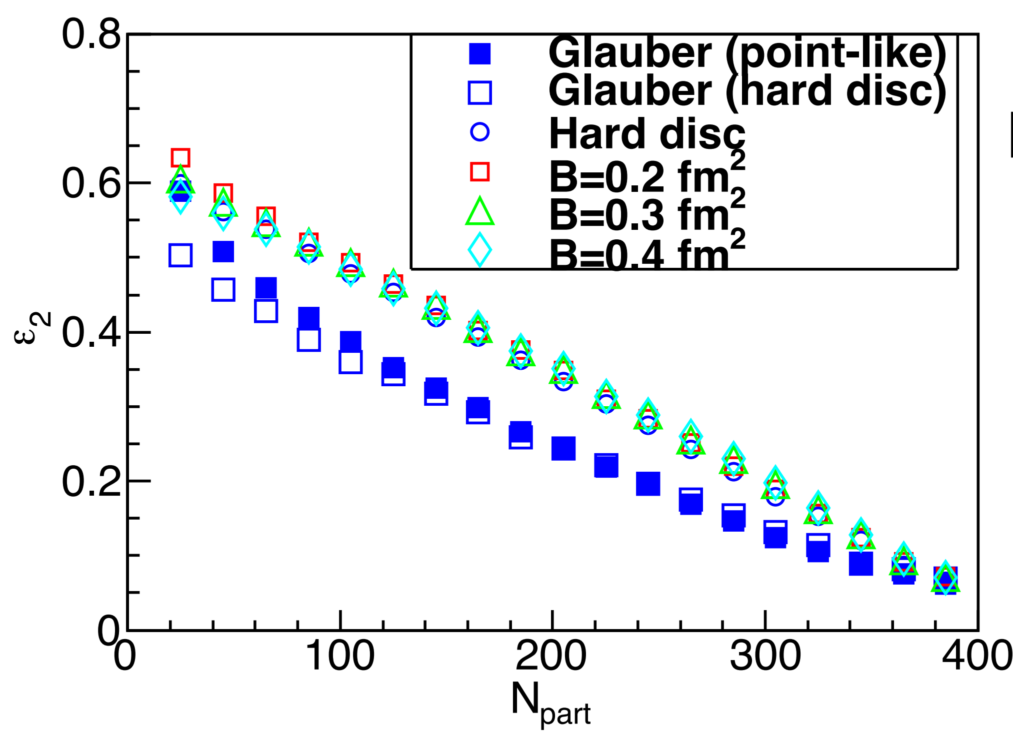
- Energy deposition in elementary N-N collisions in different MC-implementations (Glauber, KLN, rcBK, IP-GLASMA...)

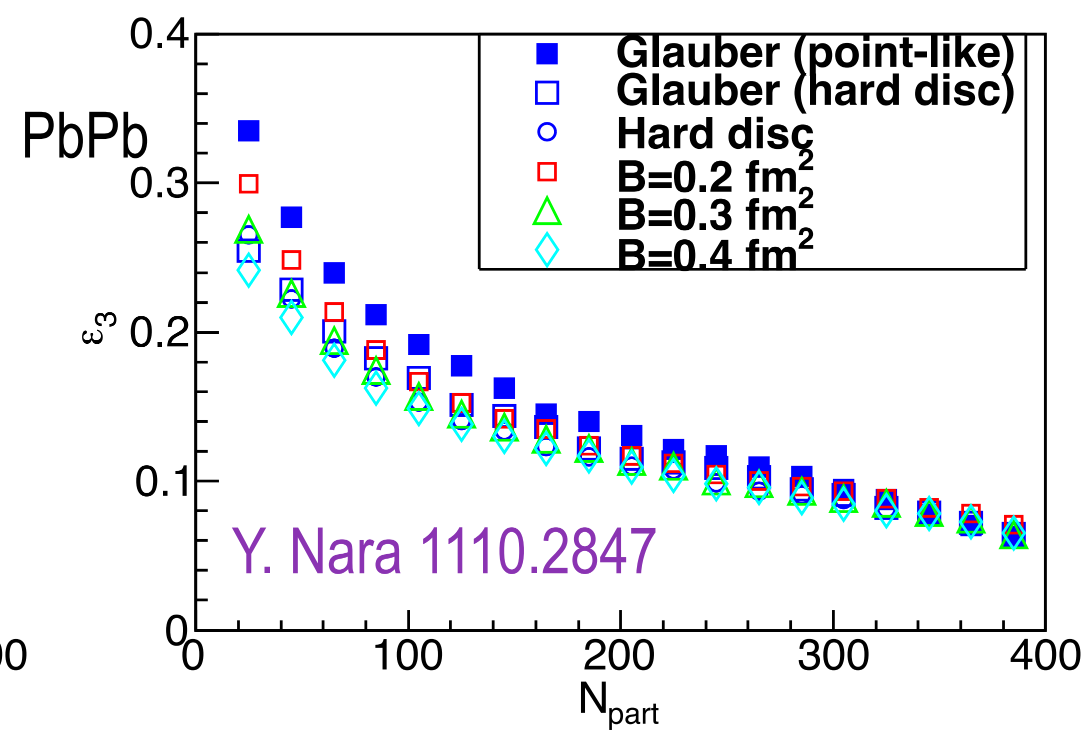




Bzdak et al
1304.3403

- Radius of the gaussian spread of deposited energy:





Different prescriptions lead to very different initial eccentricities $E_{n,}$ up to factors 3~4.

Nuclear modification factors in pPb

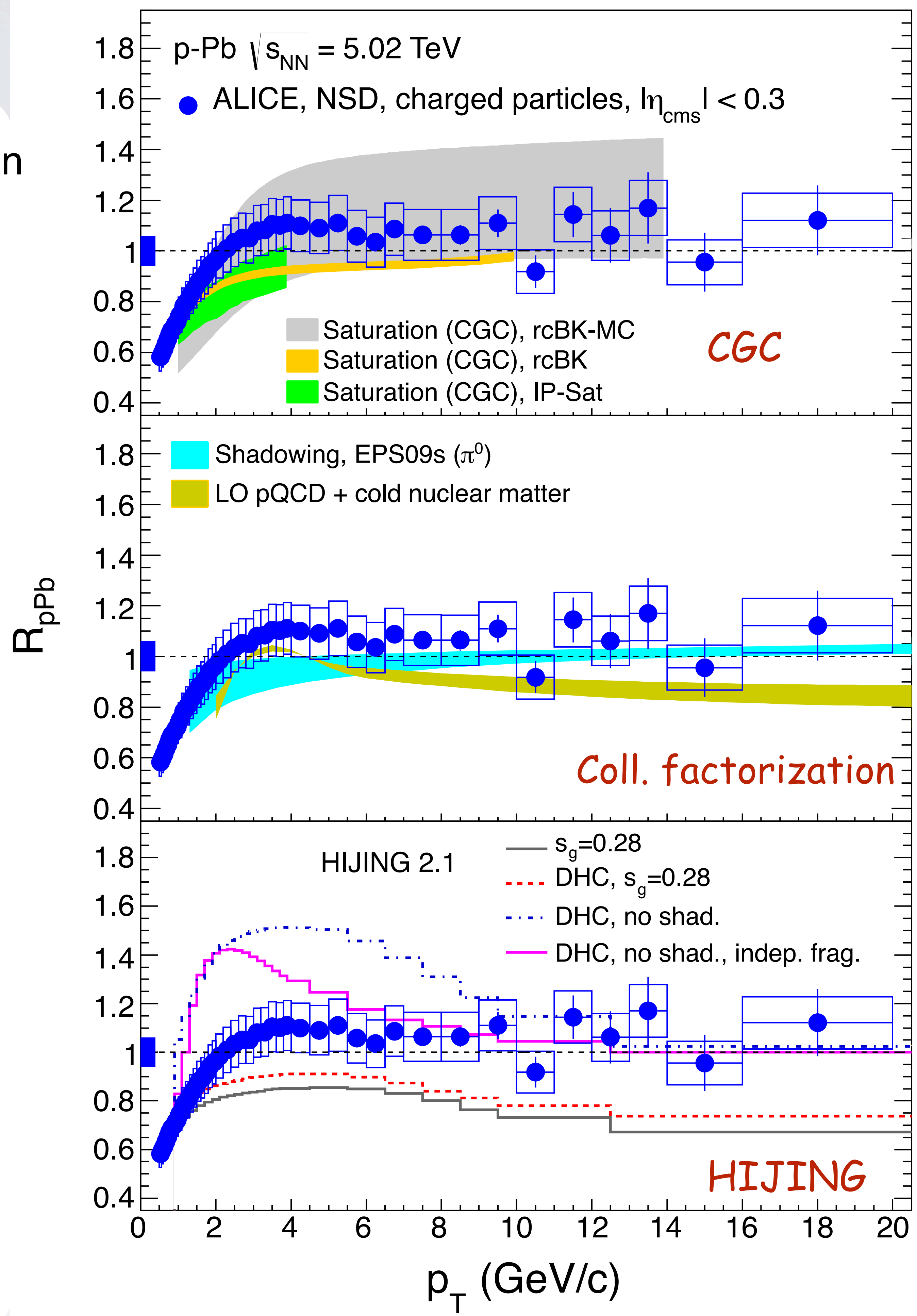
- If the physics governing wave function evolution is non-linear, then the hard and soft sector are interconnected (at least up to the scale of nonlinearities ~ Qs)

$$R_{pA} = \frac{\frac{dN^h_{pA}}{dy_h d^2k_\perp}}{A^{1/3}\frac{dN^h_{pp}}{dy_h d^2k_\perp}}$$

First ALICE results at η=0 compatible with CGC and nPDF approaches, but:

- Moderate suppression for pt < 2 GeV
- No Cronin enhancement
- Data compatible with unity for pt>4-6 GeV

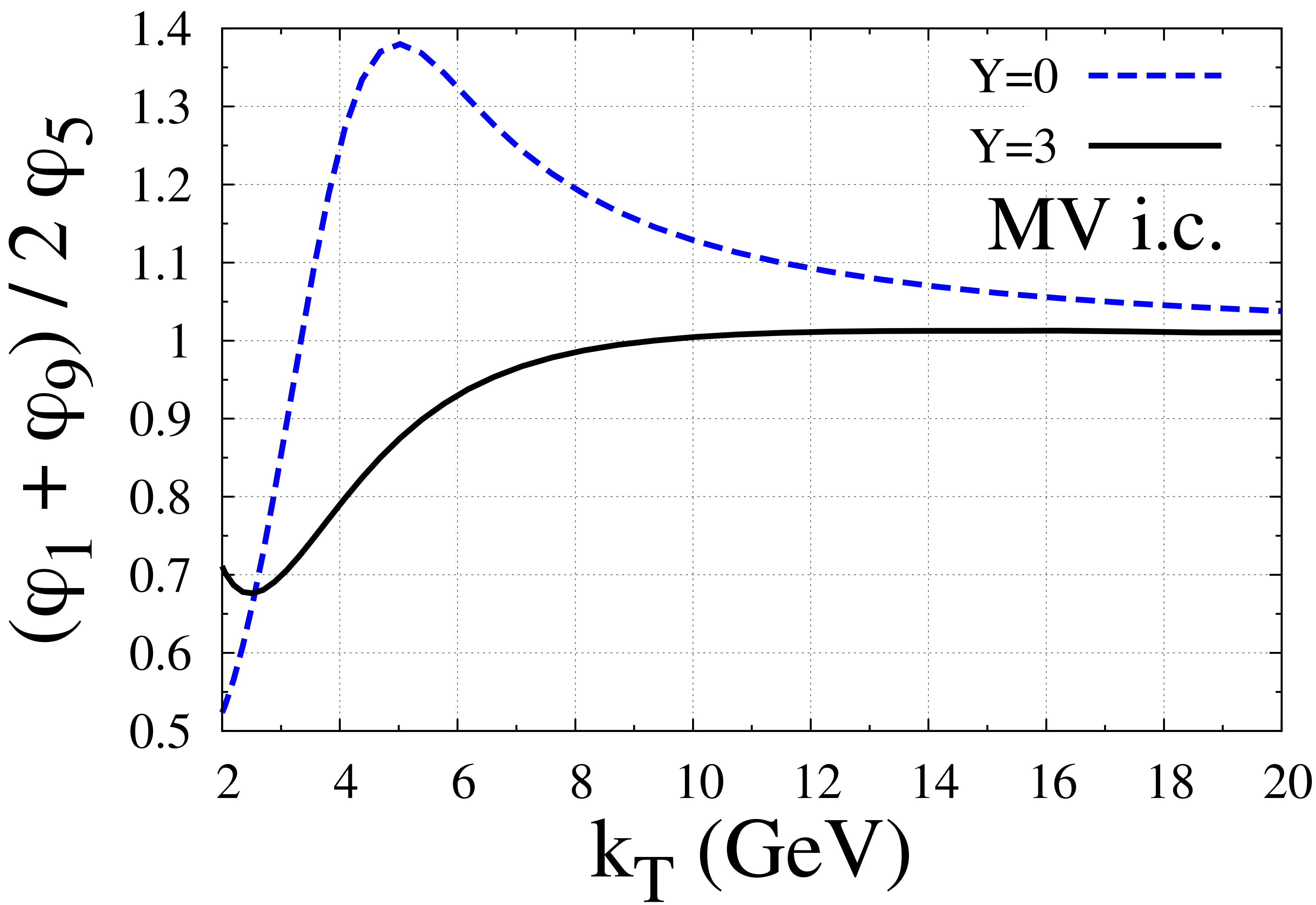
ALICE data from pilot p+Pb run 2012
1210.4520



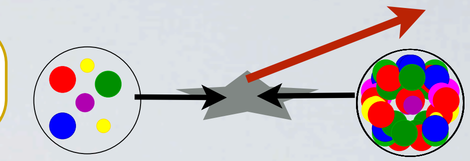
Nuclear modification factors in dAu. Room for surprises?

$\varphi[9]+\varphi[1] \neq 2\varphi[5]$

- Unintegrated gluon distributions are a strongly non-linear function of the # of nucleons.
- Fluctuations (mostly geometrical) can strongly distort the RpPb wrt to a mean field approach
- High-kt behavior of ugd



Moving forward: Testing the evolution

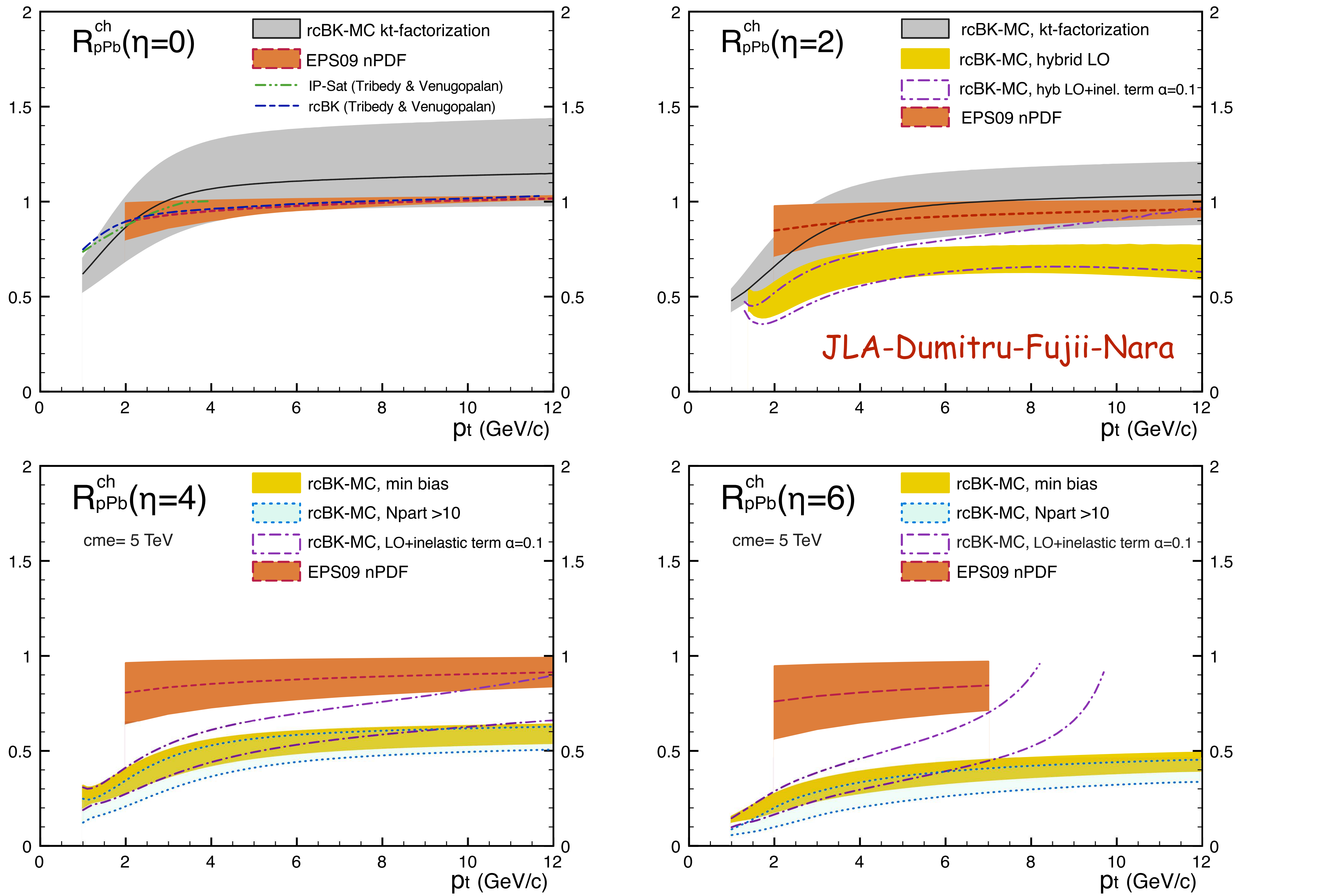


(p_t, y_h>>0)

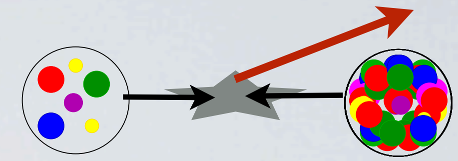
Forward measurements (LHCb, LHCf) could disentangle between different approaches

Non-linear QCD evolution predicts a stronger suppression that nPDF approaches

Fluctuations also affect the expectations for RpPb compared to mean field approaches



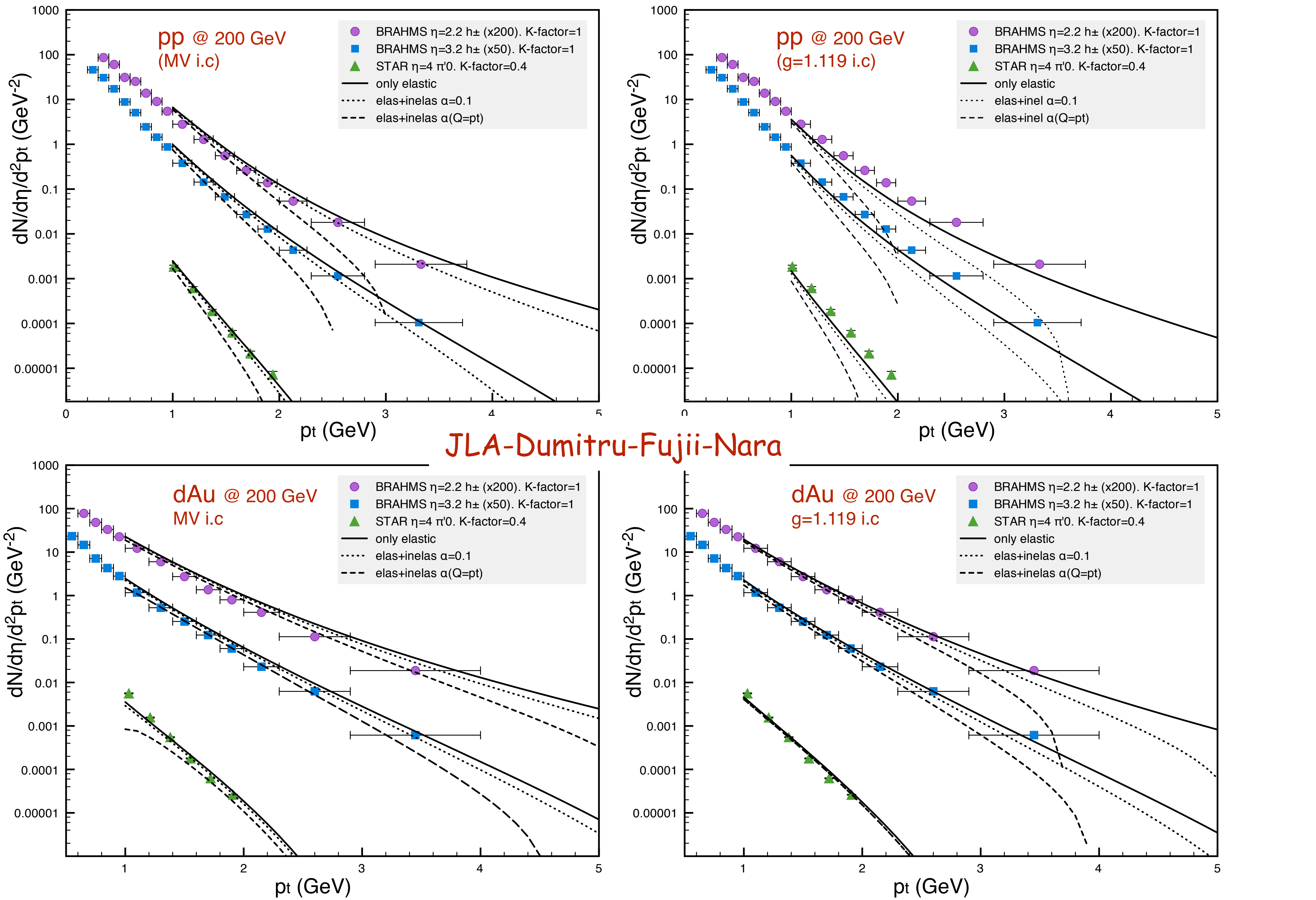
Moving forward: Testing the evolution



(p$_t$, y$_h$>>0)

However, partial NLO corrections (“inelastic term”, c.f Altinoluk-Kovner) overwhelm the LO contribution at high-pt, making the cross section negative...

Full CGC analysis at NLO needed!



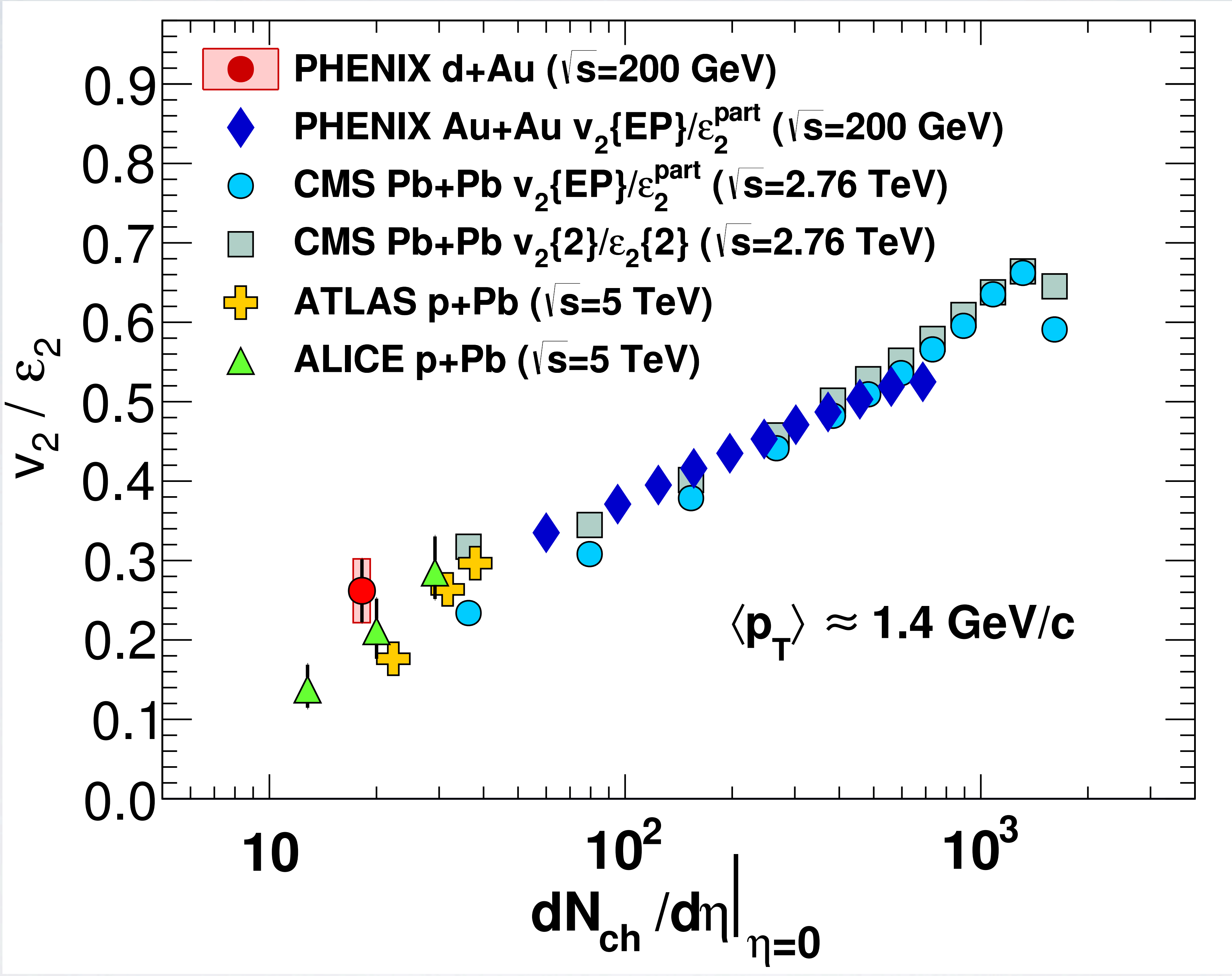
JLA-Dumitru-Fujii-Nara

Conclusions

- ✔ p+Pb data pose strong constraints to A+A models both in the soft and hard sector
- ✔ Surprising (?) indications of flow in p+Pb collisions offer additional opportunity to improve technical details concerning geometry dependence of fluctuations of AA event generators (provided the flow part o the story is properly understood)
- ✔ First data on RpPb at moderate momentum do not allow a clear distinction between “orthogonal approaches” (collinear factorization vs CGC) to describe particle production
- ✔ Exploring more forward rapidities will allow to discriminate different approaches to small-x evolution. NLO analyses on the CGC side needed!
- ✔ A detailed study of many other observables (ridge, di-hadron correlations, photon production, quarkonia etc) will most likely elucidate which is the most appropriate framework to describe initial state effects in HIC, both in the hard and soft sector.

Thanks!!

v2 in different collision systems

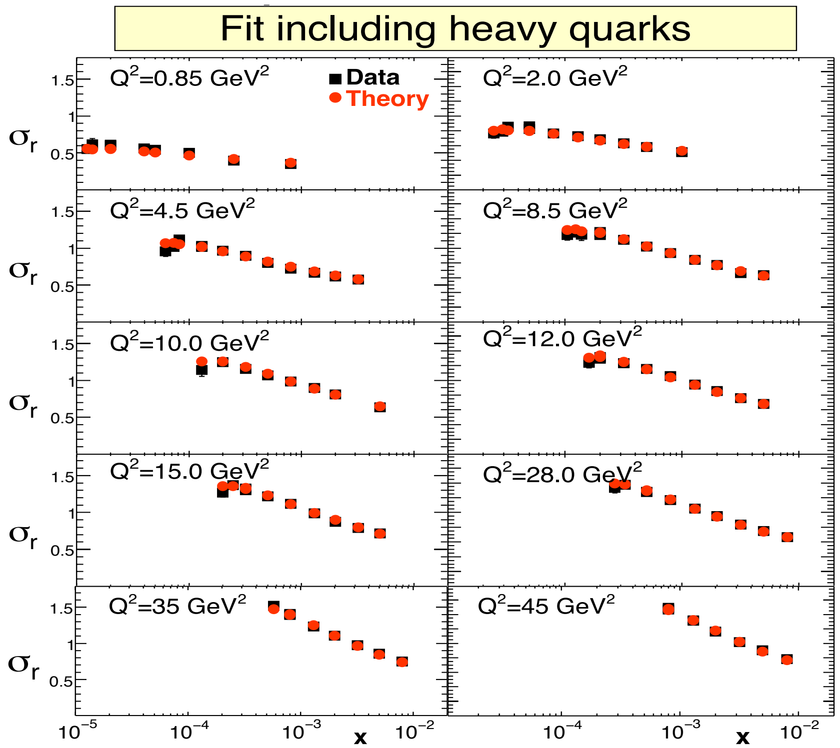


From PHENIX paper 1303.1794

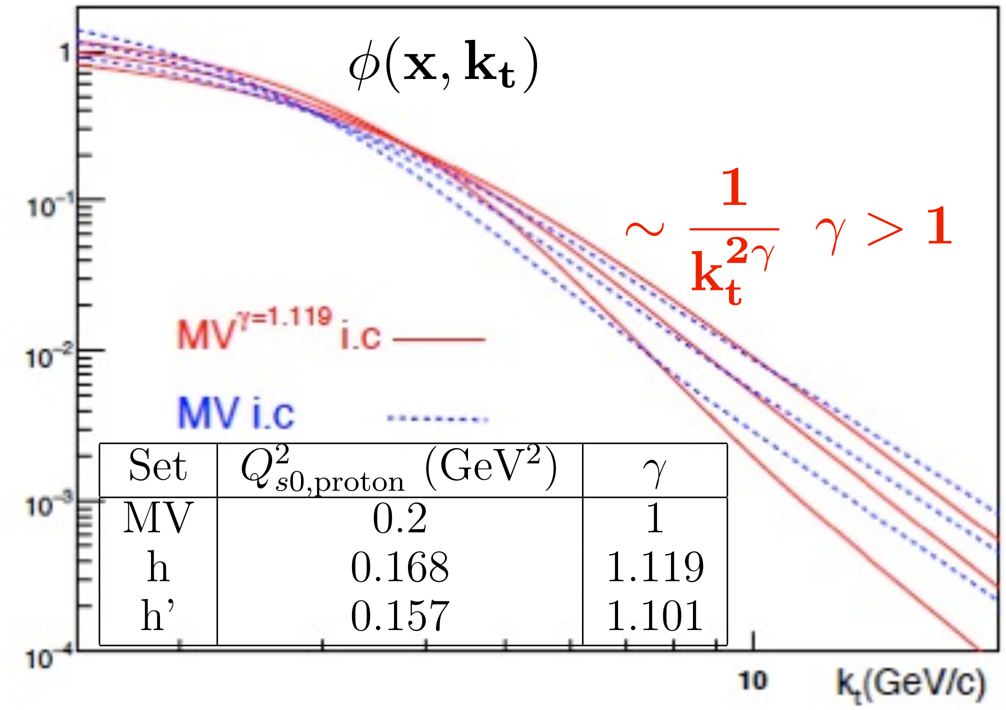
The baseline: e+proton collisions

Talk by P. Quiroga

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

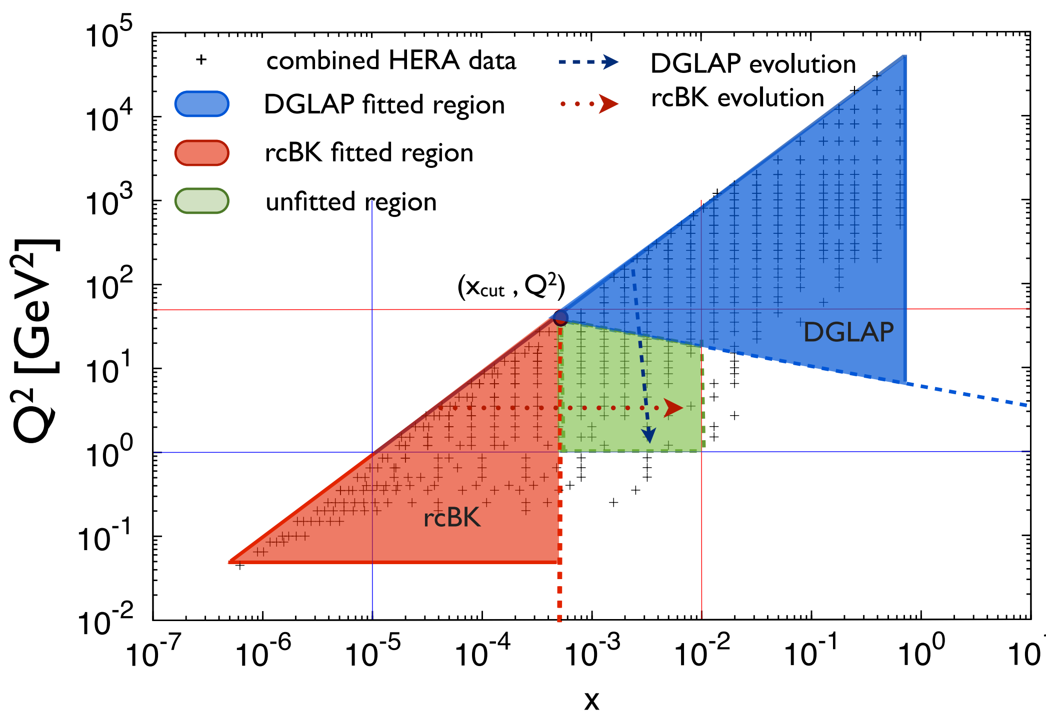


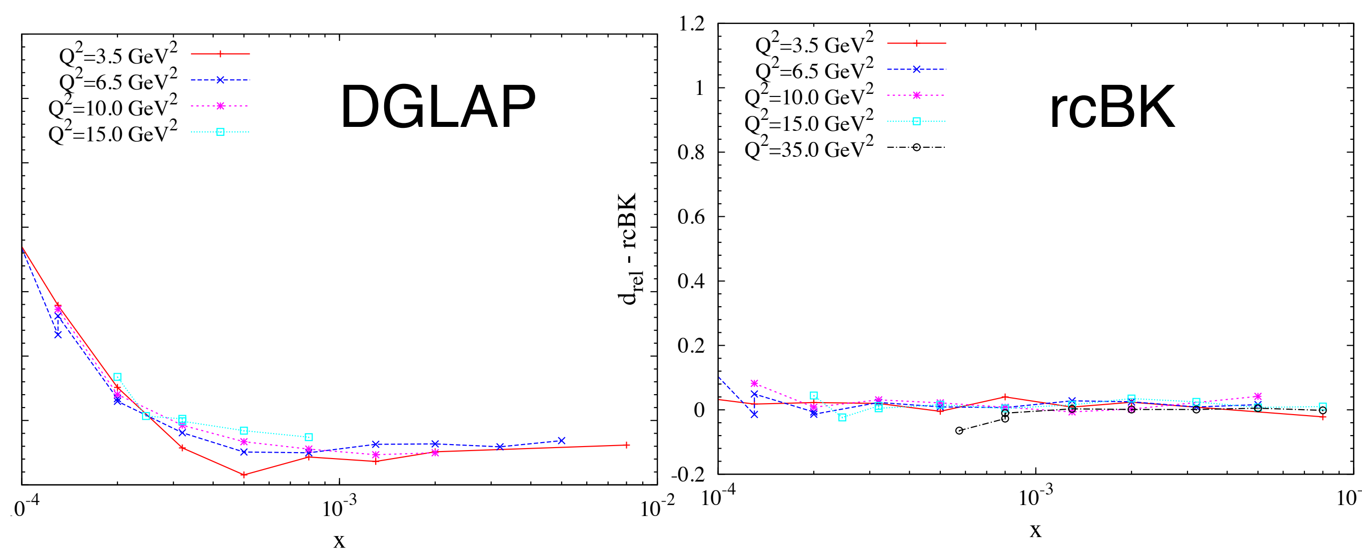
2. Extract NP fit parameters



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



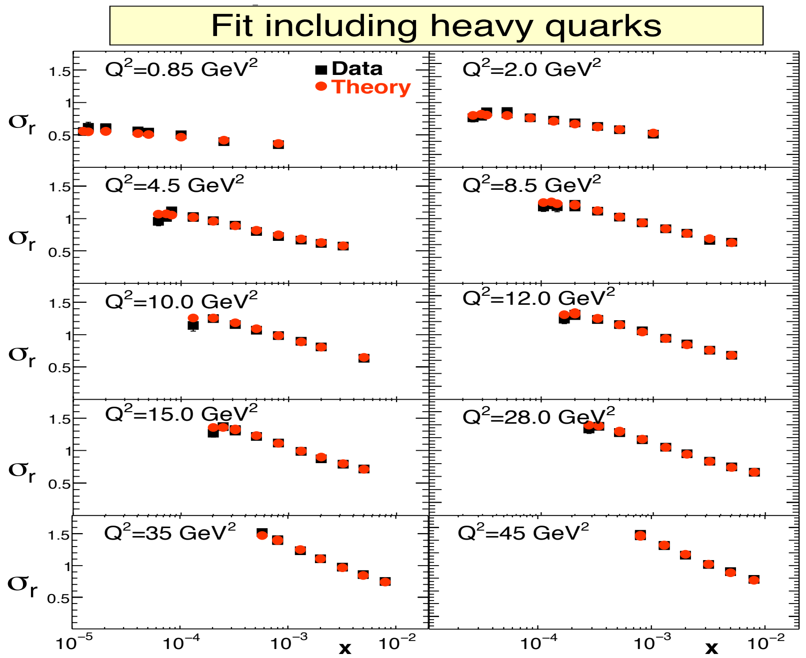


rcBK fits more stable than DGLAP fits at small-x

The baseline: proton collisions

Talk by P. Quiroga

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



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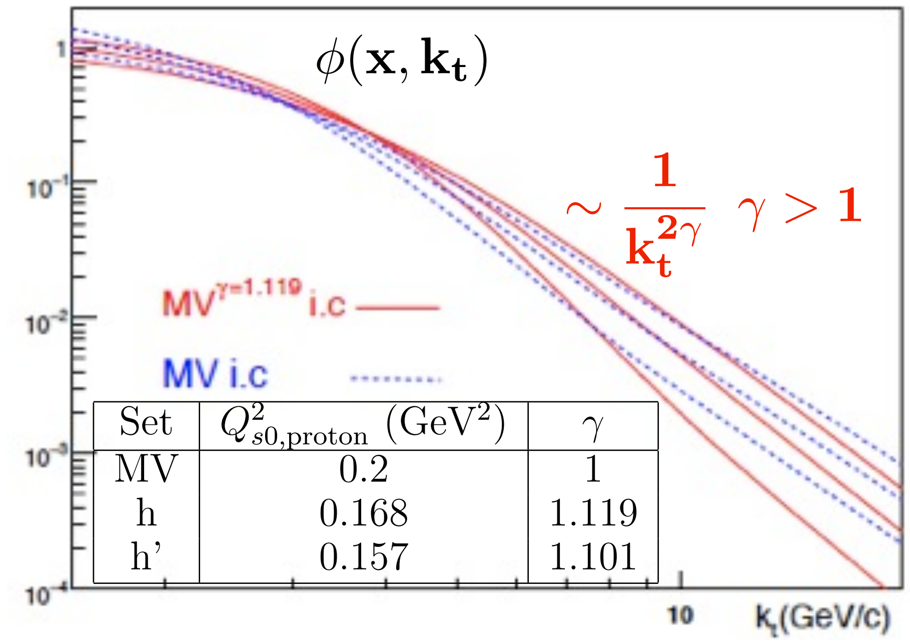
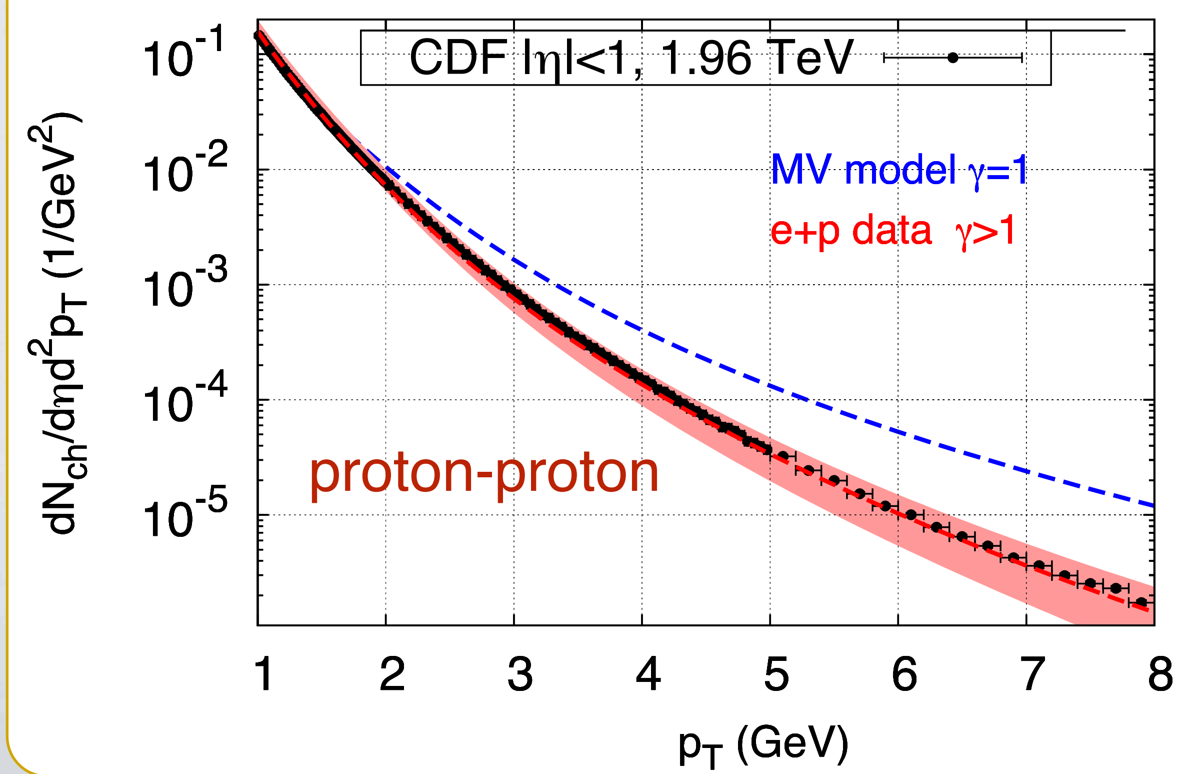
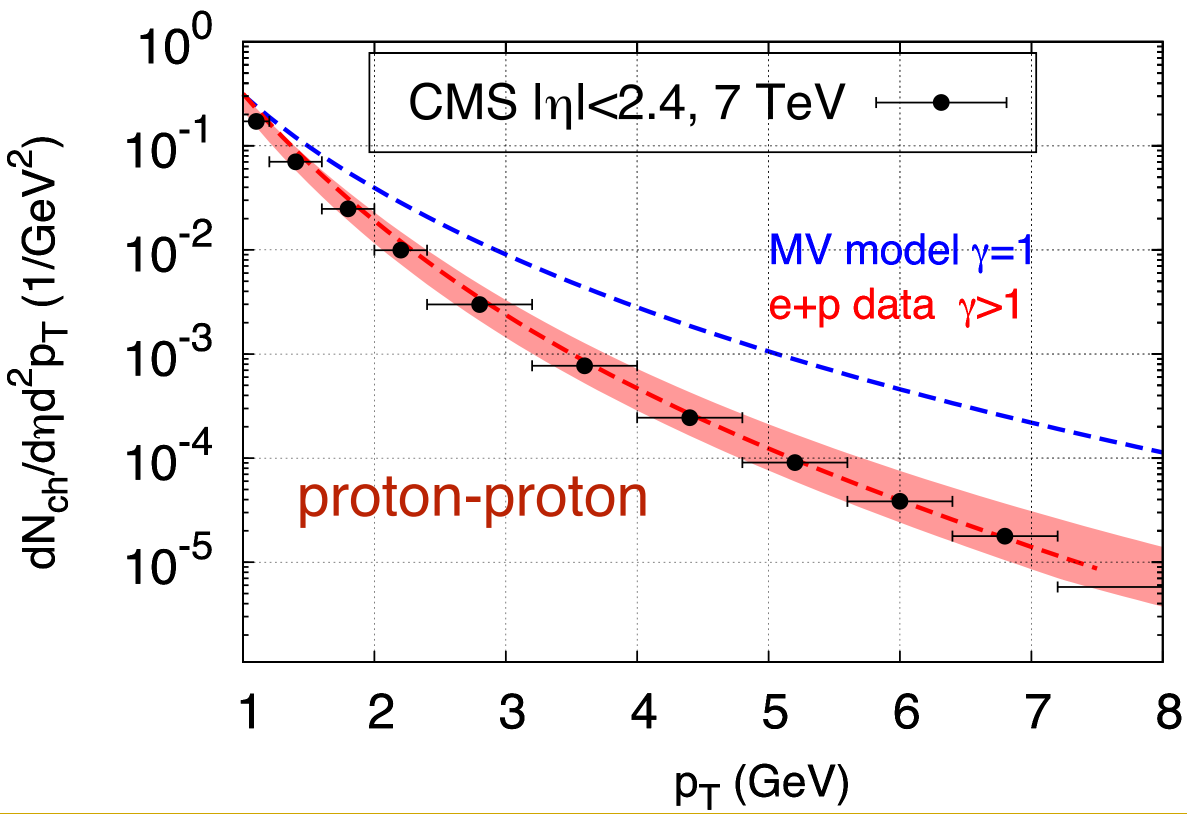


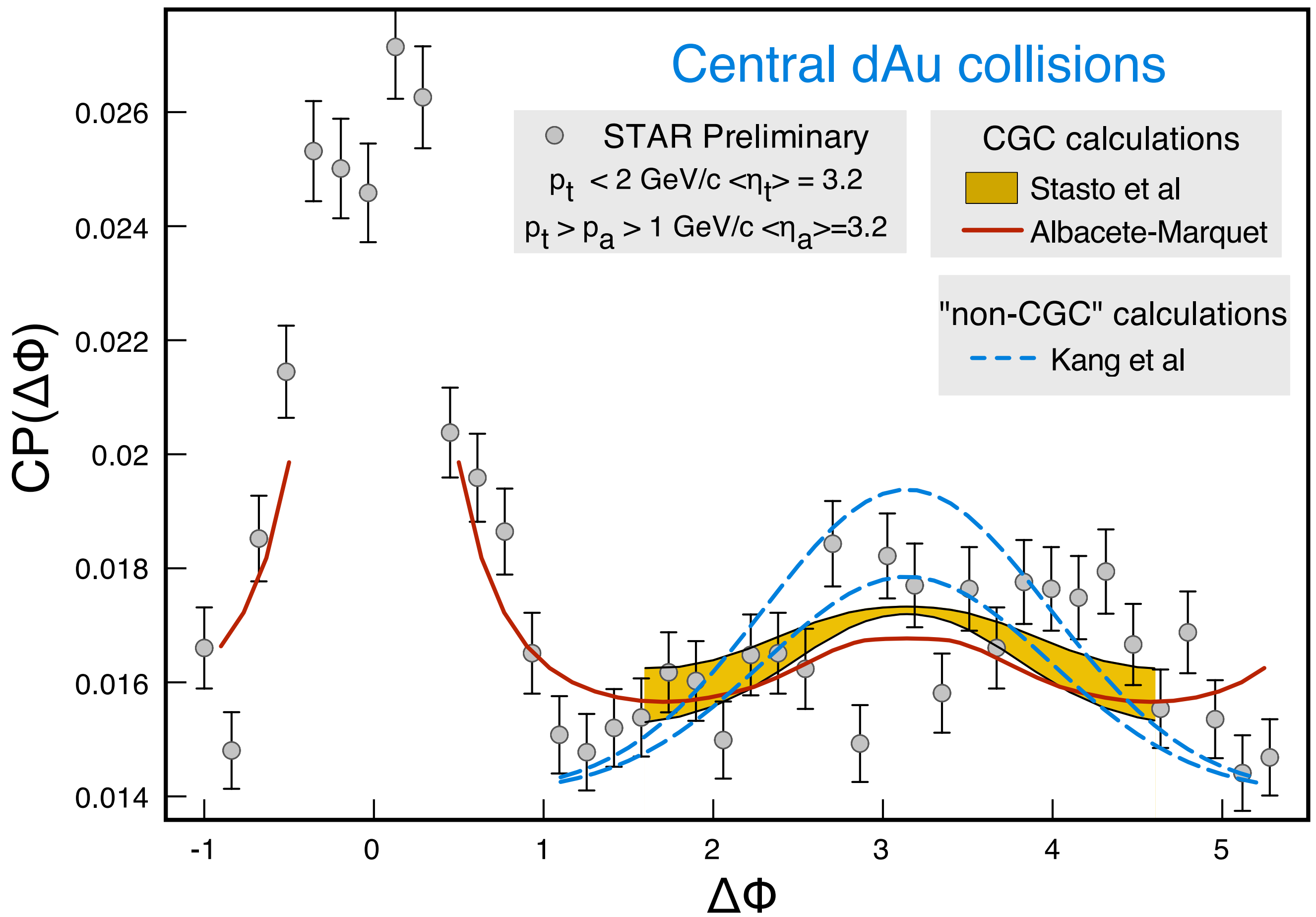
4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

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





Forward di-hadron angular correlations in RHIC dAu data

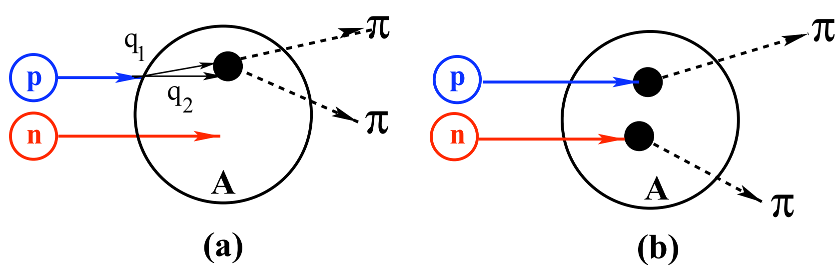


Uncertainties in current CGC phenomenological works:

- Need for a better description of n-point functions: [D. Triantafyllopoulos's and T. Lappi's talk]
- Better determination of the pedestal: K-factors in single inclusive production? Role of double parton scattering?

[Heikki Mäntysaari's talk]

correlated



uncorrelated

Strikman, Vogelsang, 1009.6123

- Alternative descriptions including resummation of multiple scatterings, nuclear shadowing and cold nuclear matter energy loss seem possible...

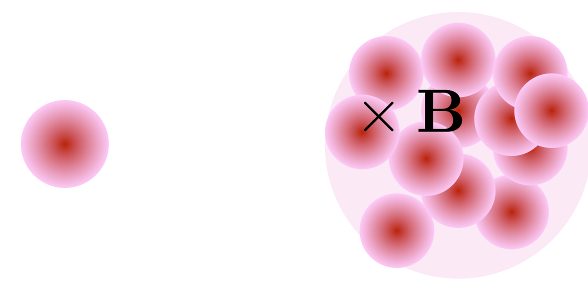
Nuclear ugd's and nuclear modification factors

Setting up the evolution

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

$$\downarrow$$

$$\phi^{Pb}(x, k_t, B) = \mathrm{rcBK}[\phi^{Pb}(x_0, k_t, B)]$$



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

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 $\gamma^{Pb} = 1(MV) + \frac{\#}{A^2/3}$