The Initial State of Heavy Ion Collisions*

[*Comments on pPb data**]

(** on just a couple of subjects)

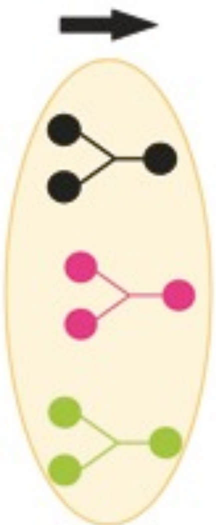
Javier L Albacete

Universidad de Granada & CAFPE

Large Hadron Collider Physics 2013. 13-18 May, Barcelona.

High-density and coherence effects in HIC

High gluon densities in the projectile/target



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

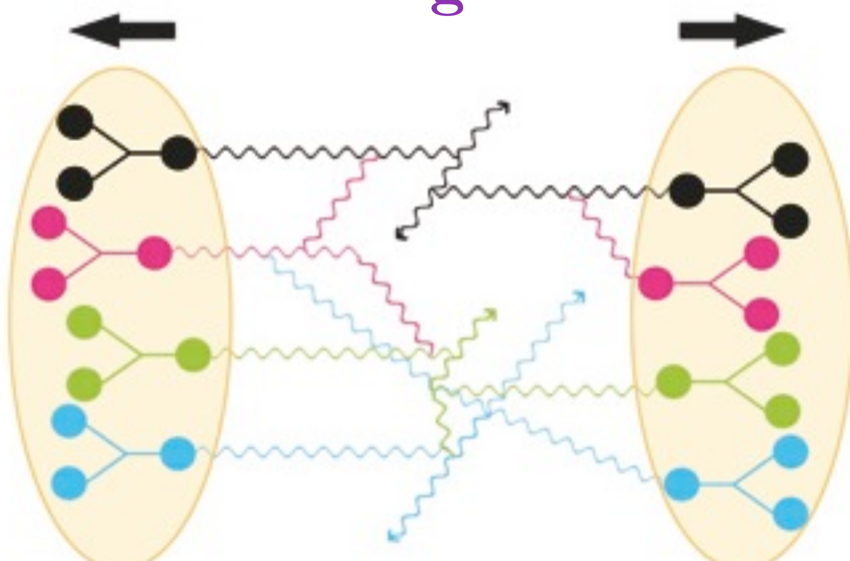
$$\frac{\partial \phi(\mathbf{x},\mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x},\mathbf{k_t}) - \phi(\mathbf{x},\mathbf{k_t})^2$$

radiation recombination

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

Breakdown of independent particle production

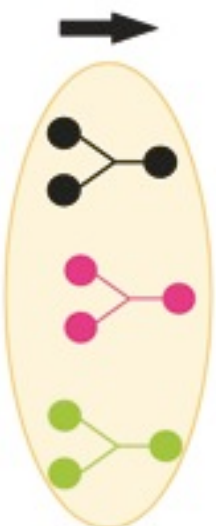
$$\mathcal{A}(\mathbf{k} \lesssim \mathbf{Q_s}) \sim \frac{\mathbf{1}}{\mathbf{g}} \qquad \mathbf{g}\mathcal{A} \sim \mathcal{O}(\mathbf{1})$$



M. Floris, this morning

What the CGC is about : coherence effects

High gluon densities in the projectile/target



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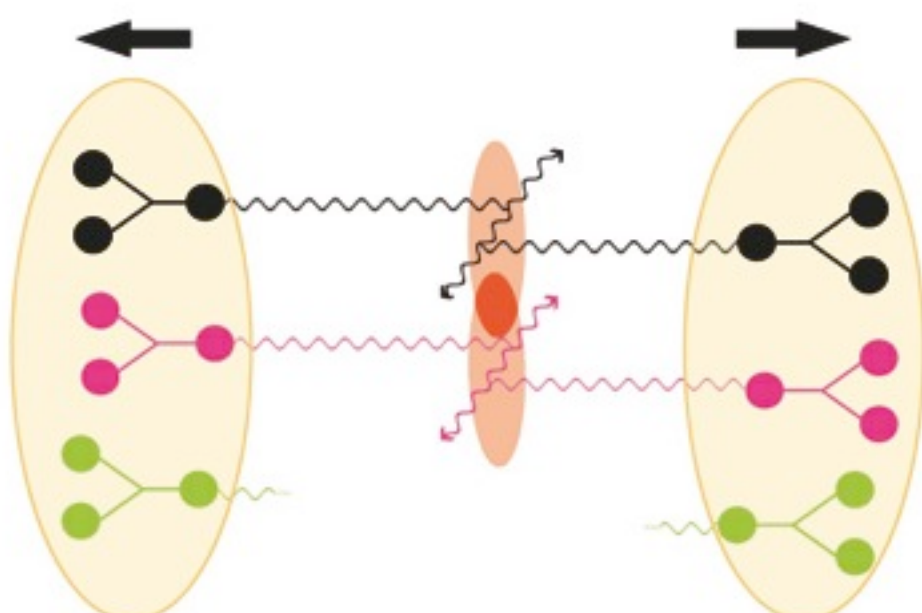
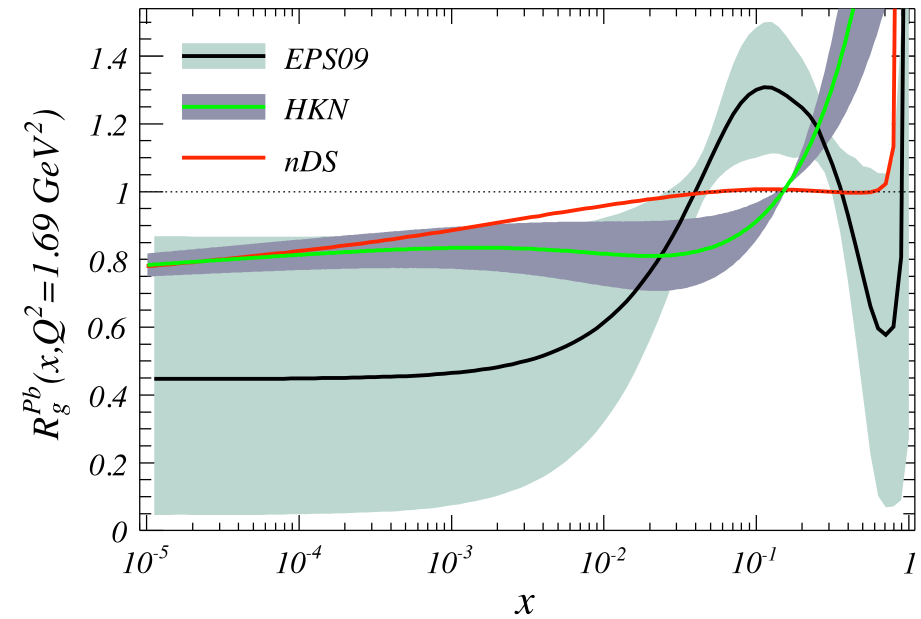
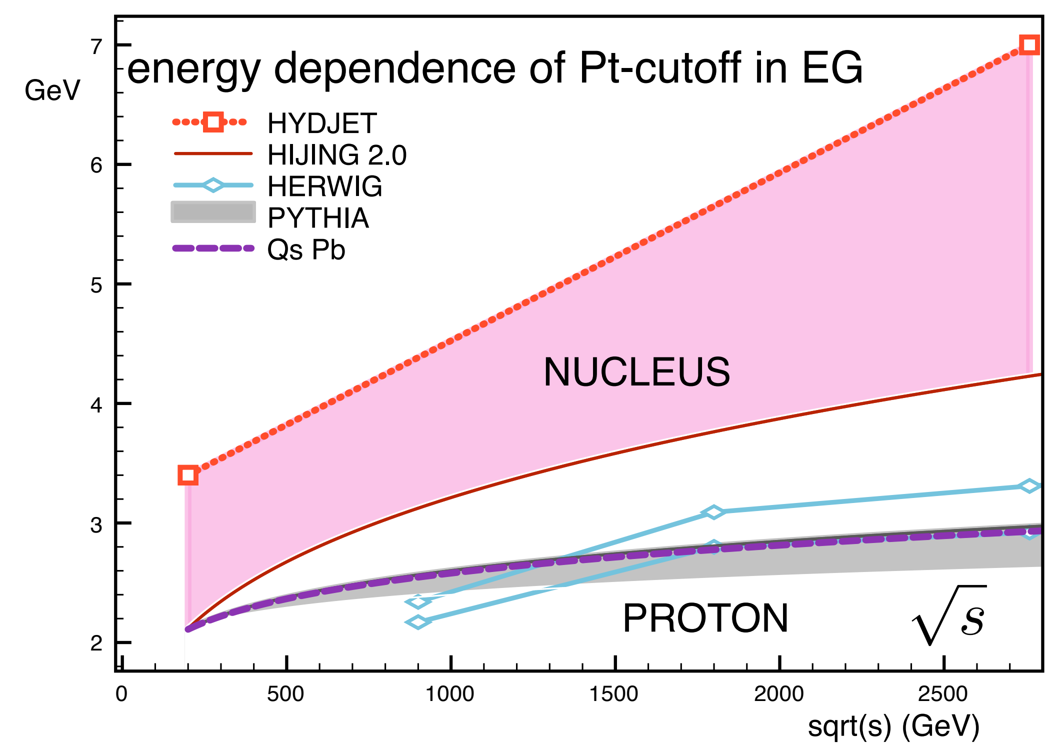


HIC phenomenology

- Nuclear shadowing, String fusion, percolation

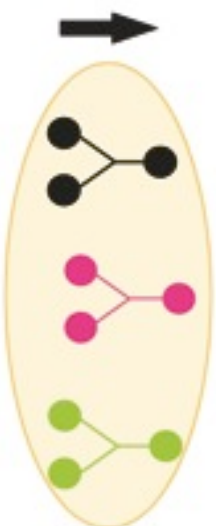


- Resummation of multiple scatterings
- kt-broadening
- Energy dependent cutoff in event generators



What the **CGC** is about : coherence effects

High gluon densities in the projectile/target



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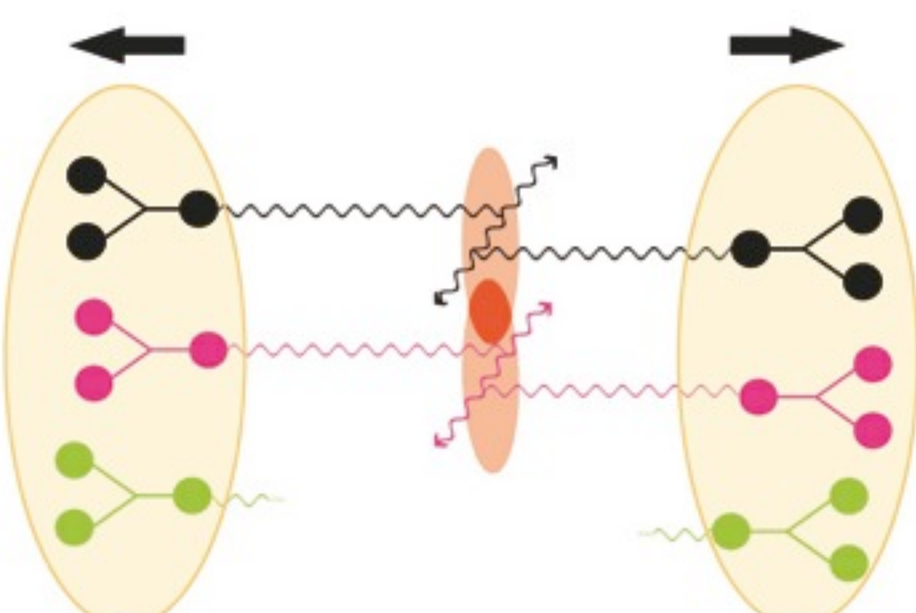

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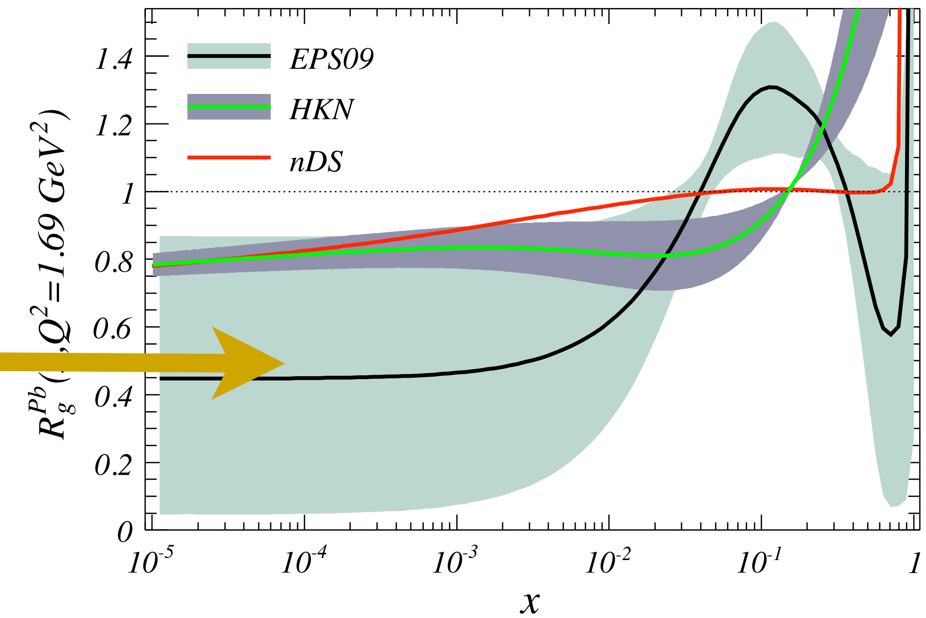

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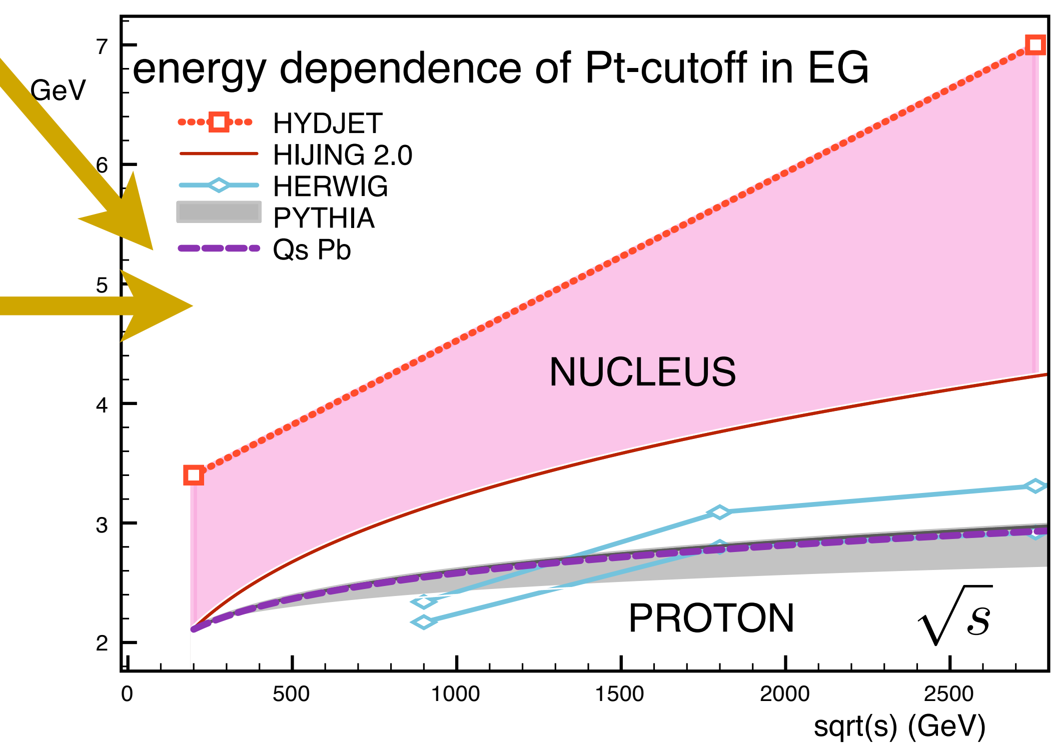
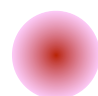


Baseline of small-x studies: electron-proton collisions at HERA

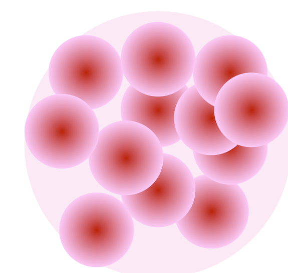
:) **proton**

- Abundant high quality data at small-x
- Simple system well understood theoretically



:(**nucleus**

- Few data at small-x
- LHC Pb+Pb data and RHIC dAu forward.

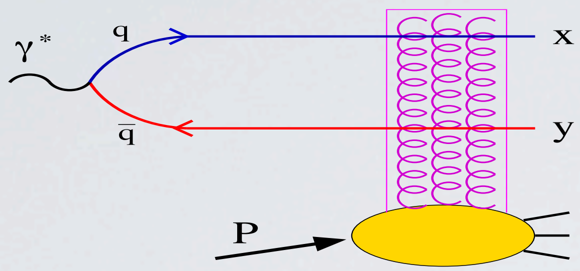


modeling impact parameter dependence!

- pPb is the quintessential baseline experiment for initial state studies

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

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



CGC approaches

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

Kowalski-Teany; Venugopalan et al

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

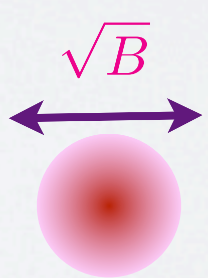
• rcBK $\frac{\partial \mathcal{N}(x,r,b)}{\partial \ln(1/x)} = \theta(b-b_0) \int dr_1\, \mathcal{K}^{r.c}\, [\mathcal{N}(x,r_1)+\mathcal{N}(x,r_2)-\mathcal{N}(x,r)-\mathcal{N}(x,r_1)\mathcal{N}(x,r_2)]$

- Running coupling non-linear BK equation

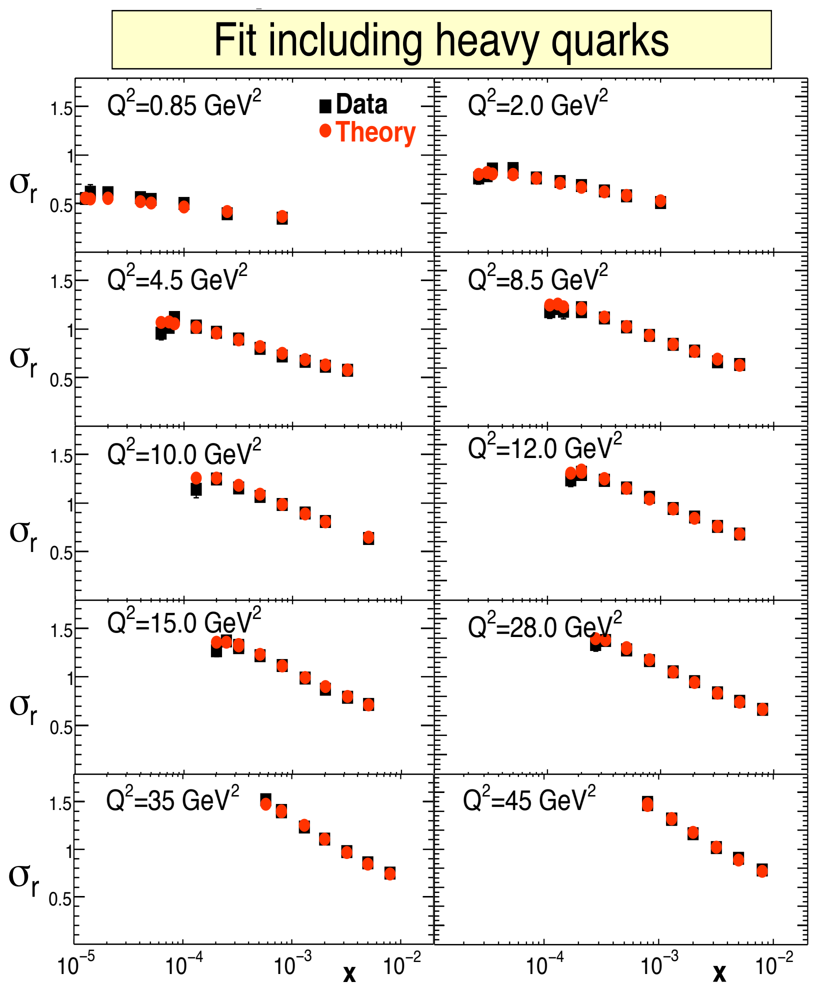
JLA, Armesto, Milhano, Quiroga, Salgado

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

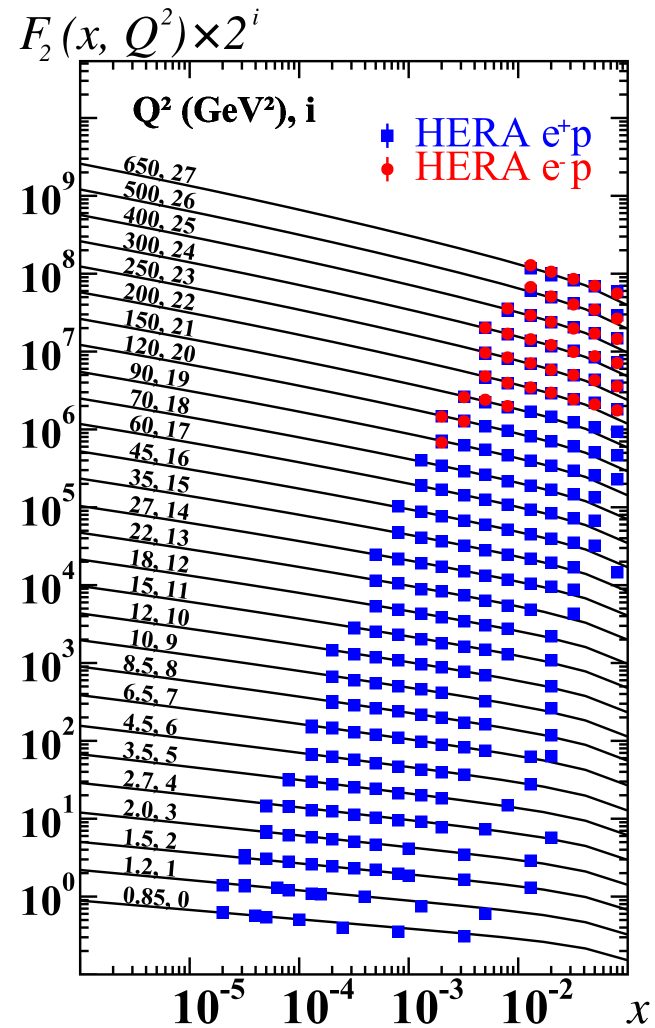
$$T_G(b) \sim \exp\left[-\frac{b^2}{2B_g}\right]; \quad B \sim 4 \div 6\,\mathrm{GeV}^{-2}$$



• **rcBK fit**



• **IP-Sat fit**



- 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:

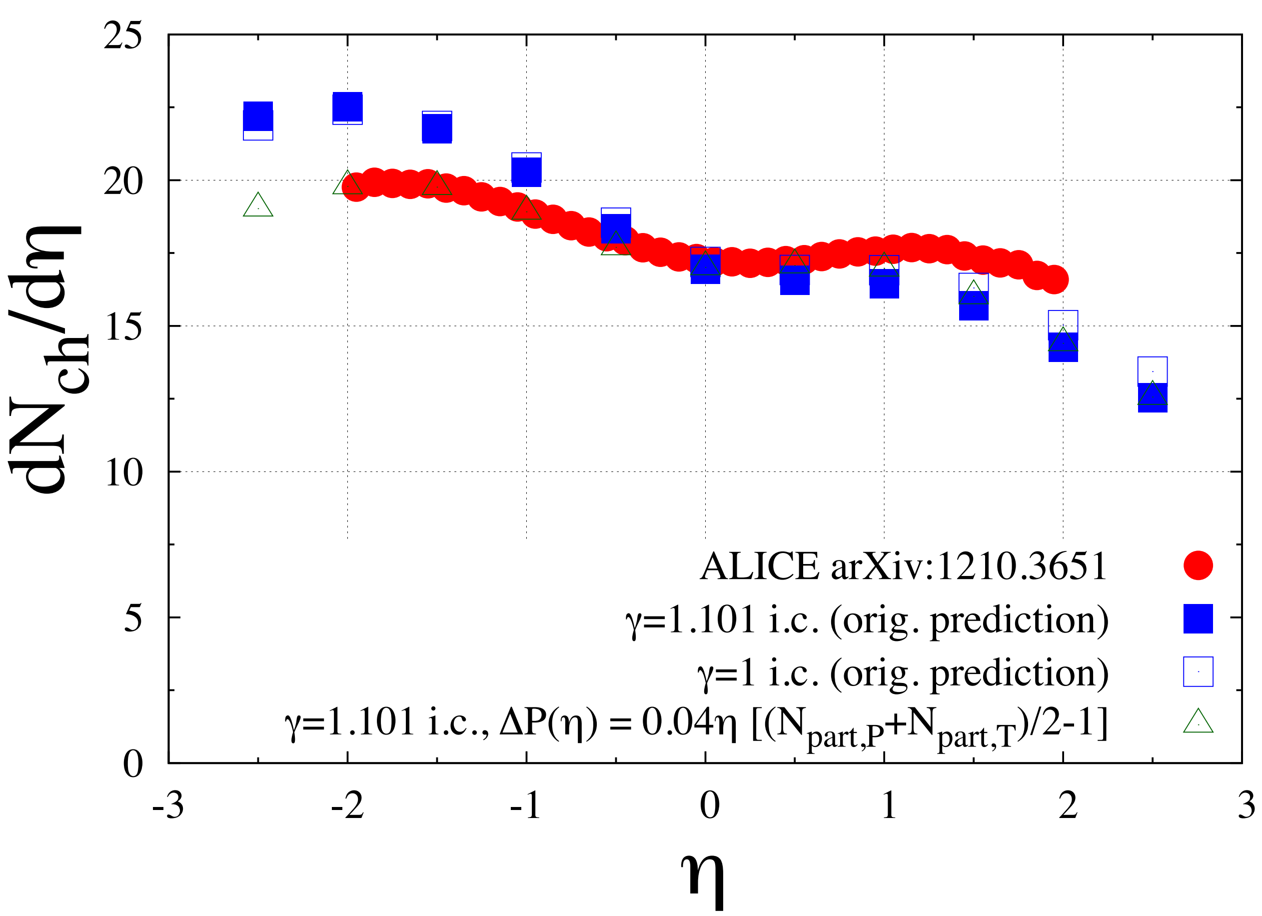
Theory (CGC)

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

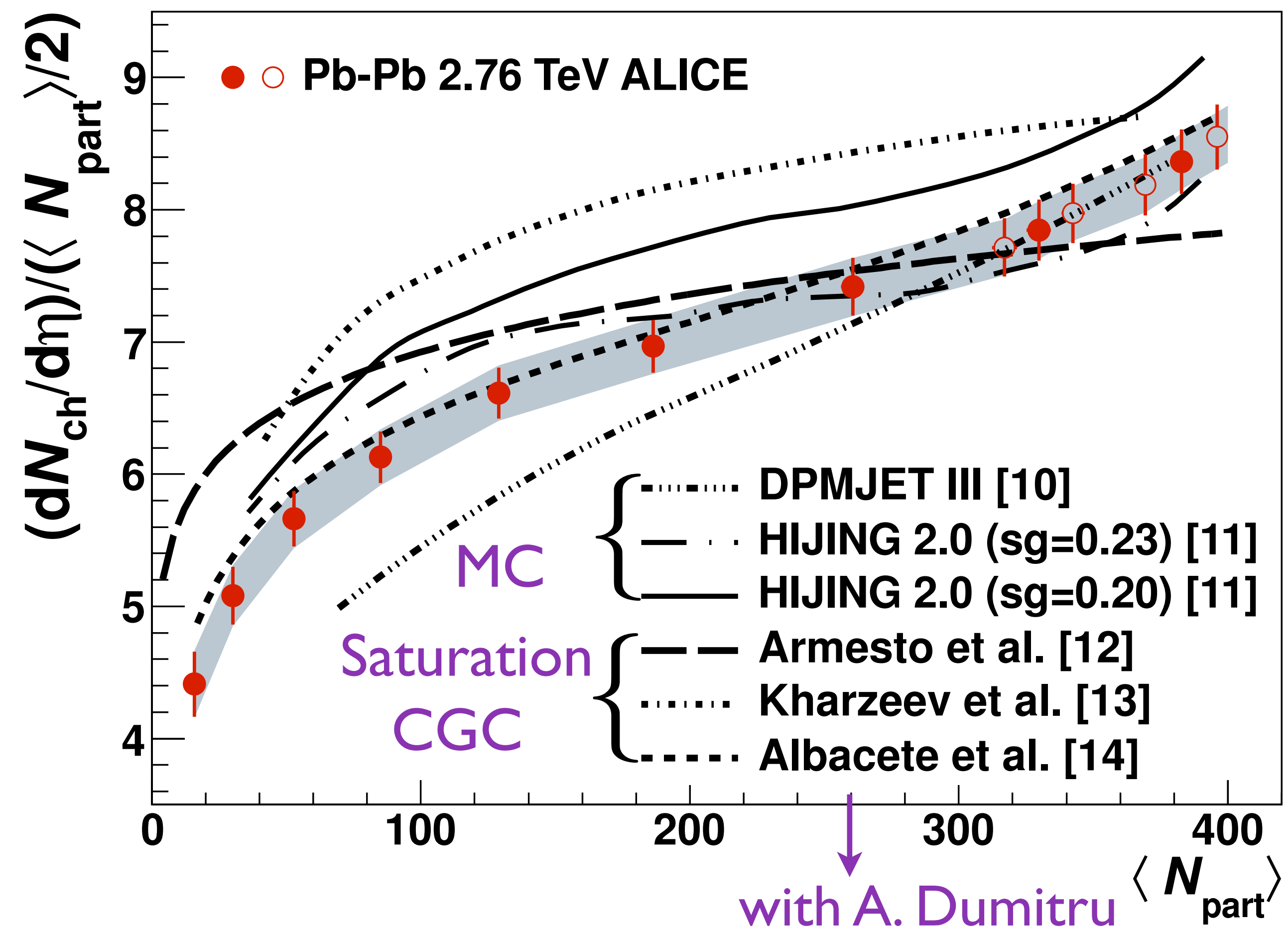
Data

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

Rapidity dependence pPb



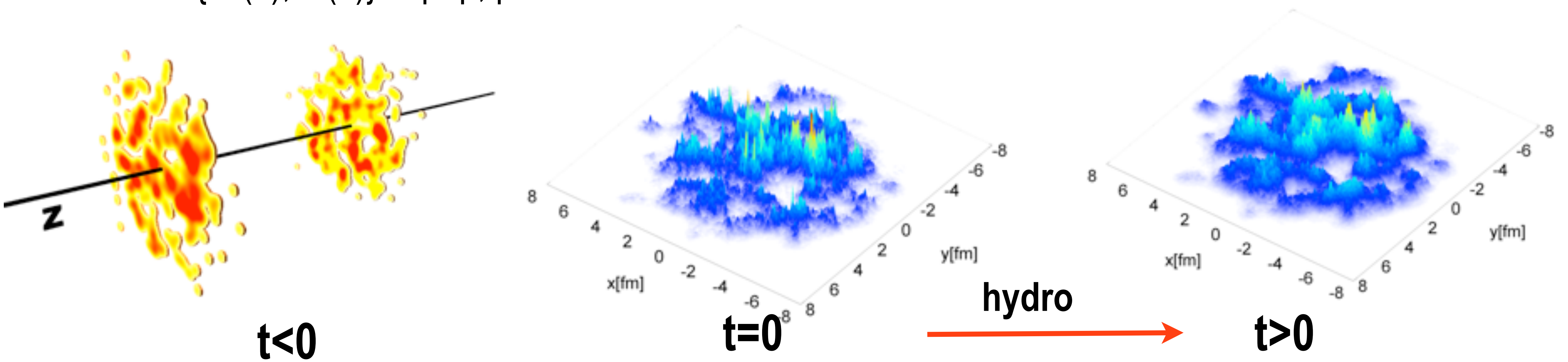
Centrality dependence PbPb



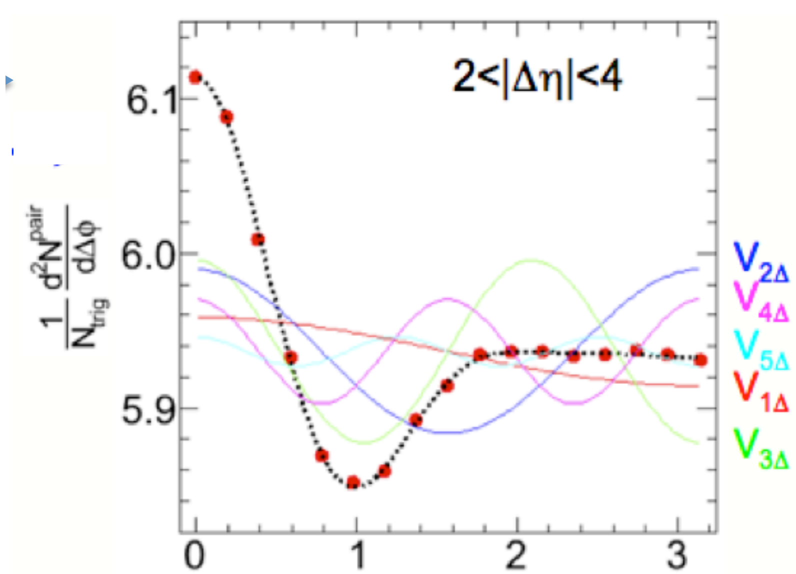
- p+p and d+Au multiplicities and single inclusive spectra are also well described by these models

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



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

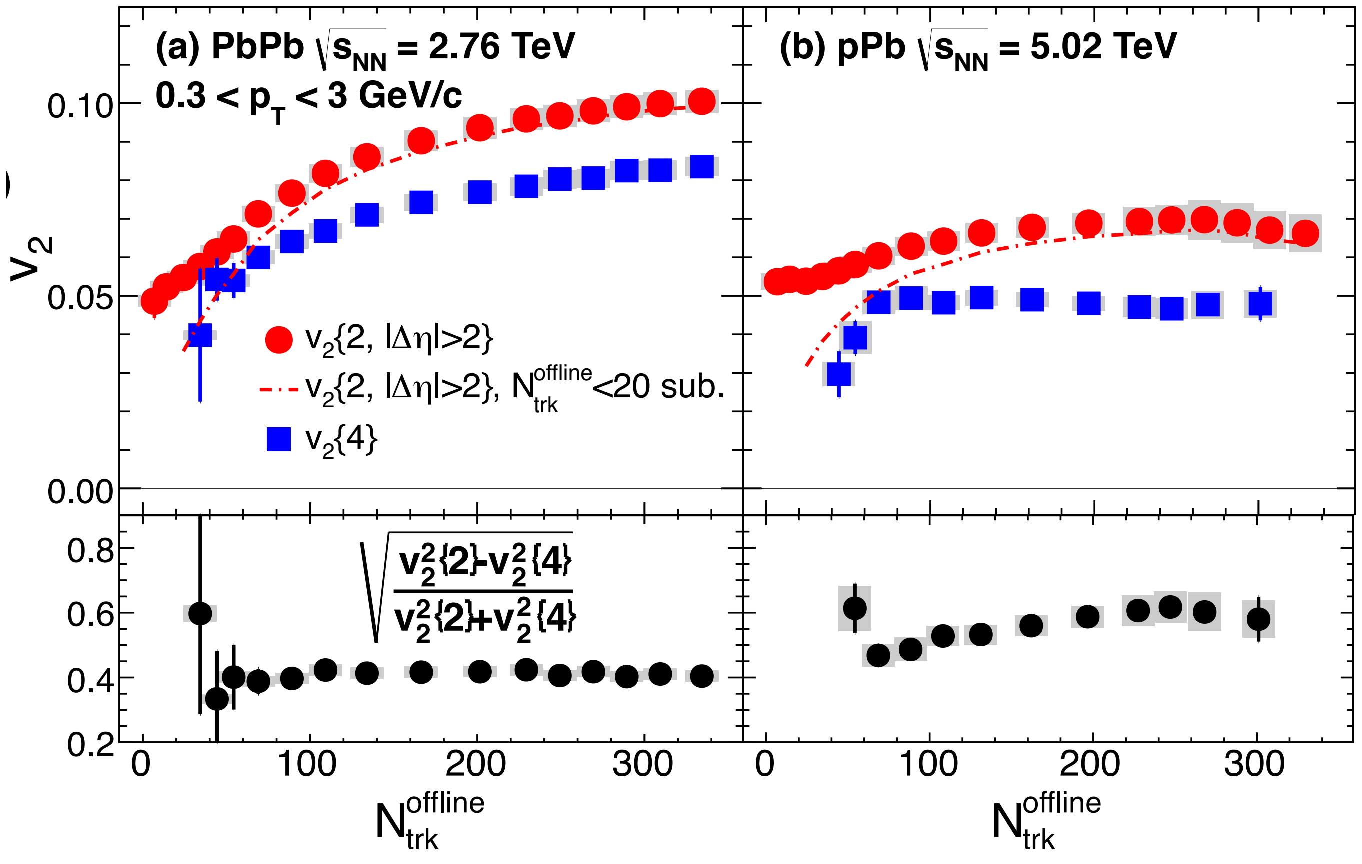
This is crucial input for the hydro evolution and to extract QGP transport properties (viscosity).

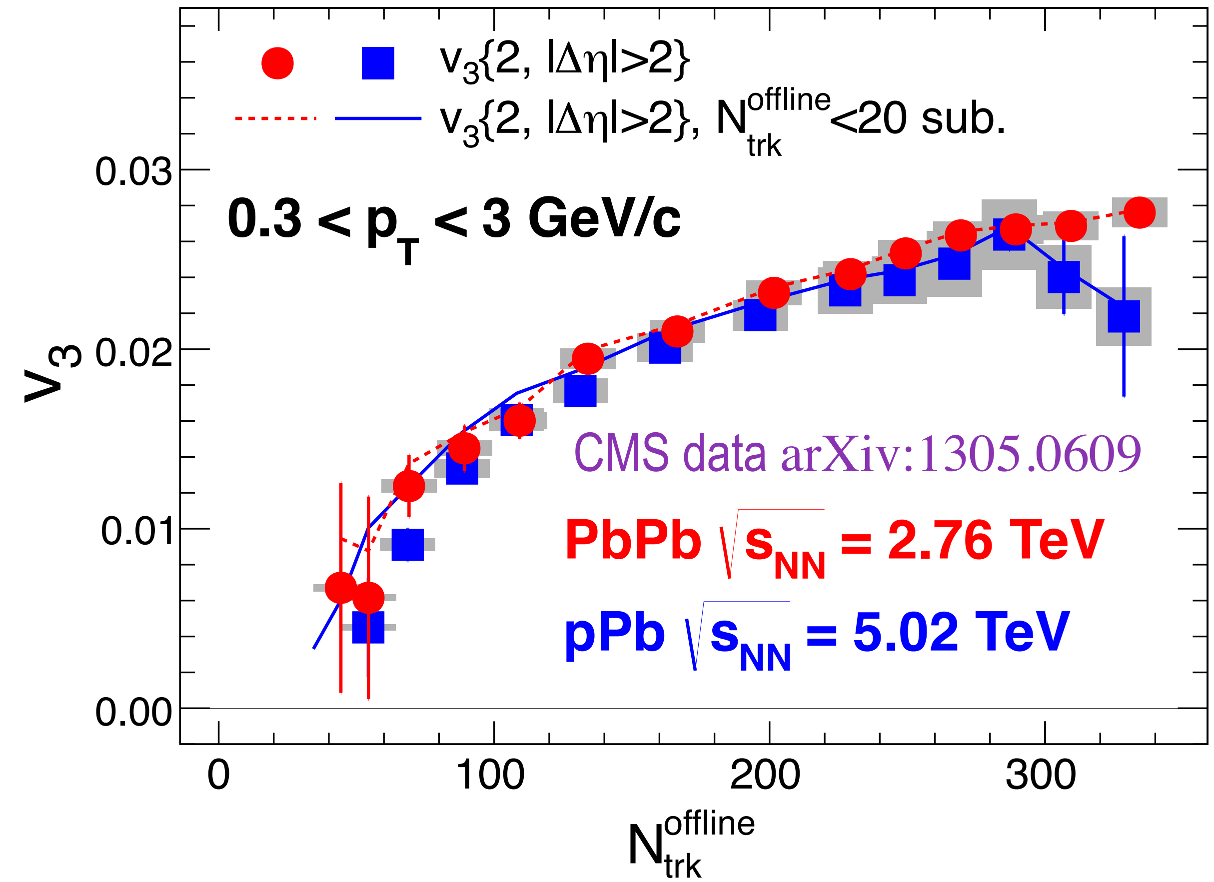
Matt Luzum, QM2012 talk, in the conclusions:

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

Multiplicities and energy density fluctuations and flow in p+Pb

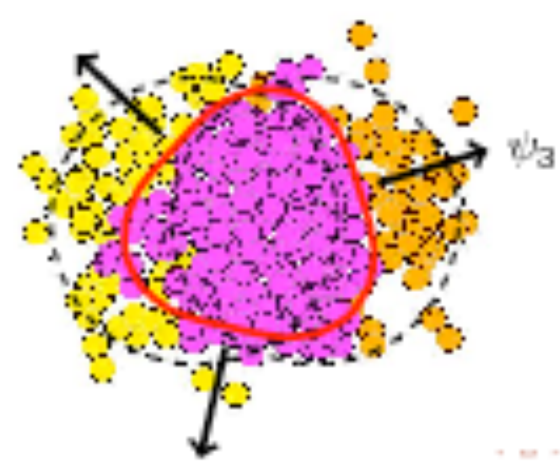
- First p+Pb measurements show strong **v2** and **v3** in p+Pb collisions. Similar observation from PHENIX in d+Au





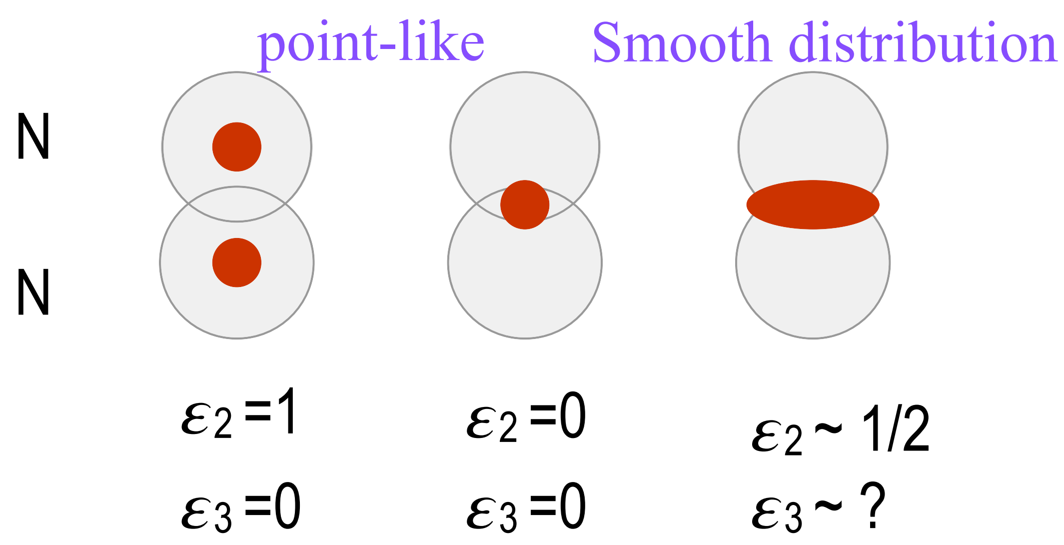
Flow?? (Good qualitative description of data by 3+1 D viscous hydro, e.g. Bozek et al 1304.3044)

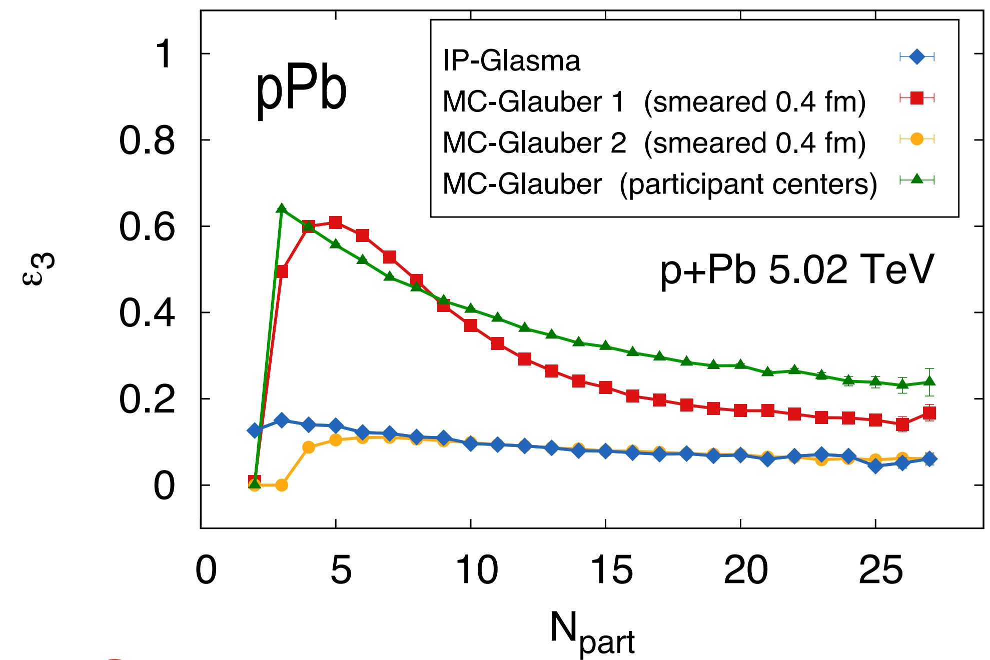
- How to built an analogous geometric picture in proton collision?
- We need to look at the geometrical distribution of fluctuations at the sub-nucleon level
- This problem has a much smaller relevance in nucleus-nucleus collisions



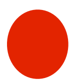
Multiplicities and energy density fluctuations and flow in p+Pb

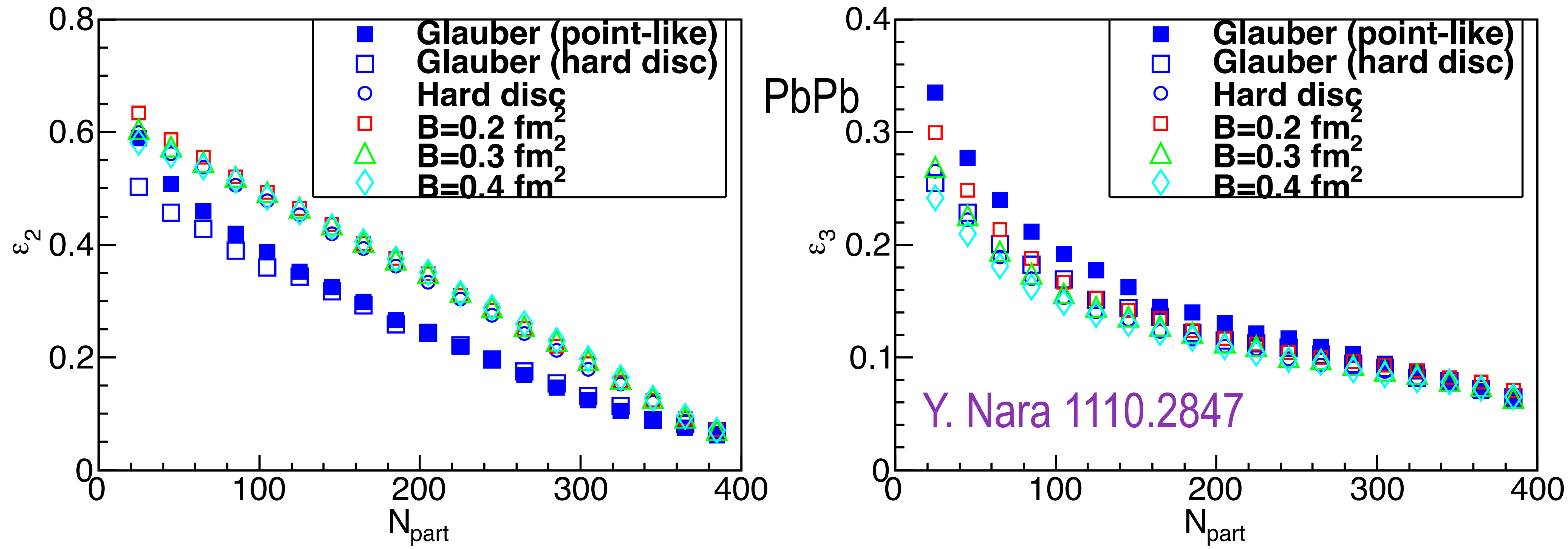
- Energy deposition in elementary N-N collisions in different MC-implementations (Glauber, KLN, rcBK, IP-GLASMA...)





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

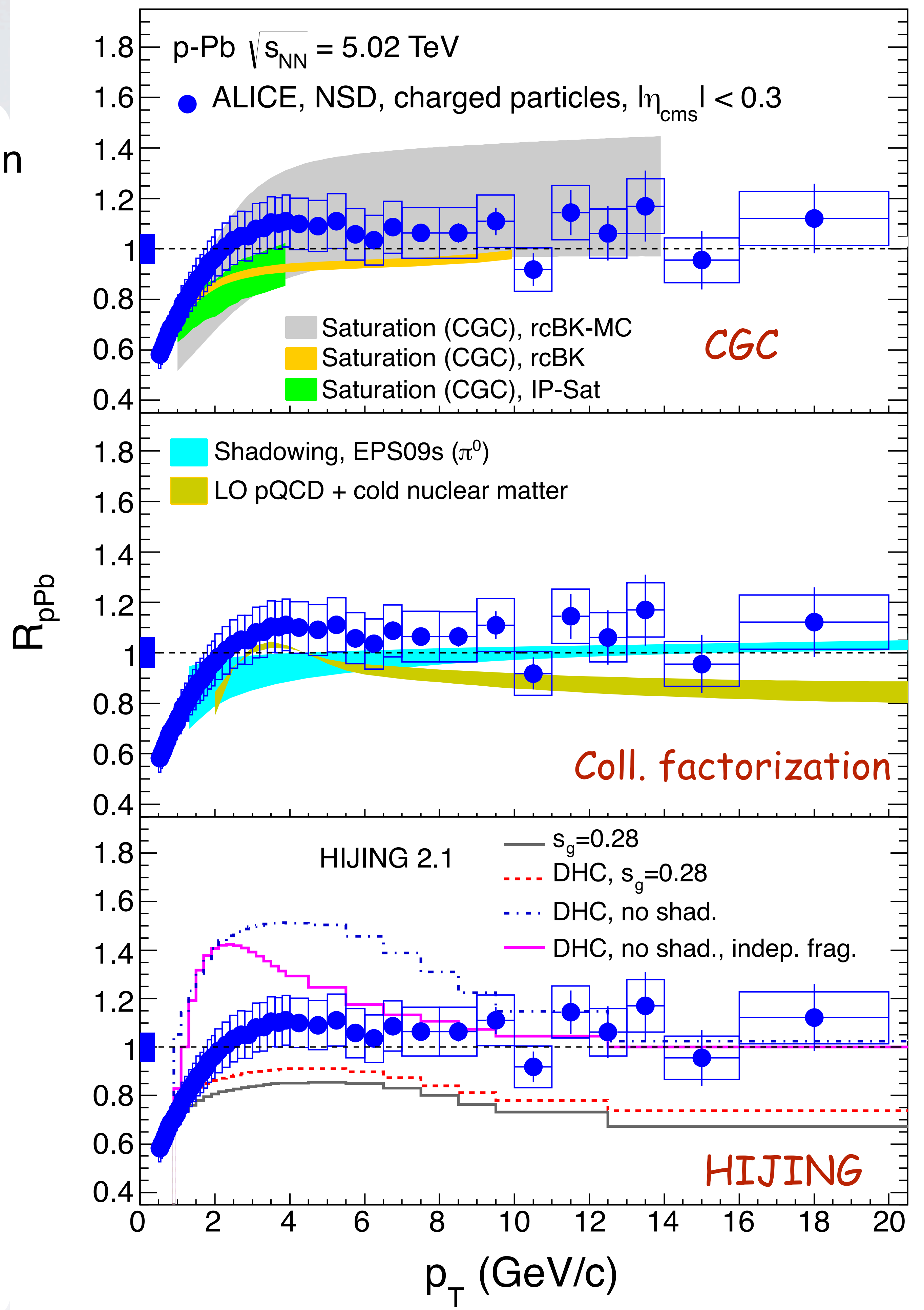
- If the physics governing wave function evolution is non-linear, then the hard and soft sector are interconnected (at least up to the scale of nonlinearities ~ Qs)

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

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

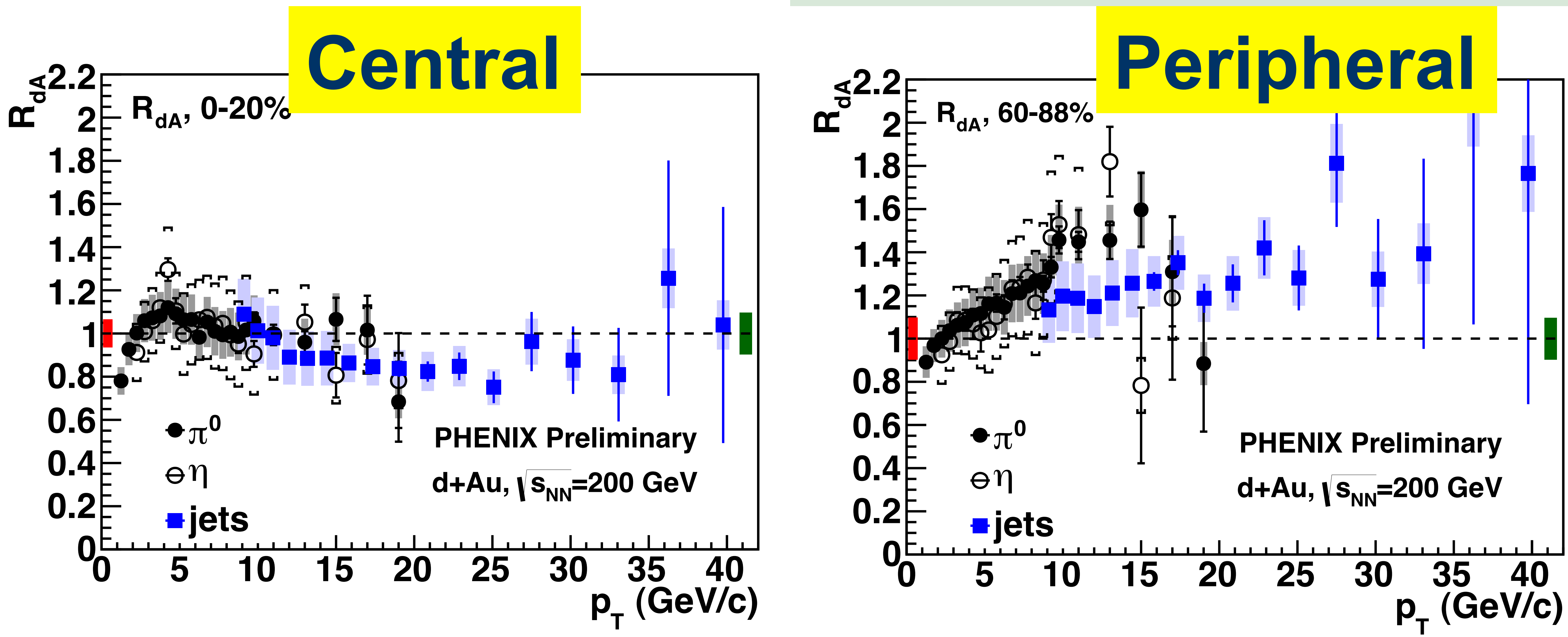
- Moderate suppression for pt < 2 GeV
- No Cronin enhancement
- Data compatible with unity for pt>4-6 GeV

ALICE data from pilot p+Pb run 2012
1210.4520



Nuclear modification factors in dAu. Room for surprises?

Preliminary PHENIX results 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).

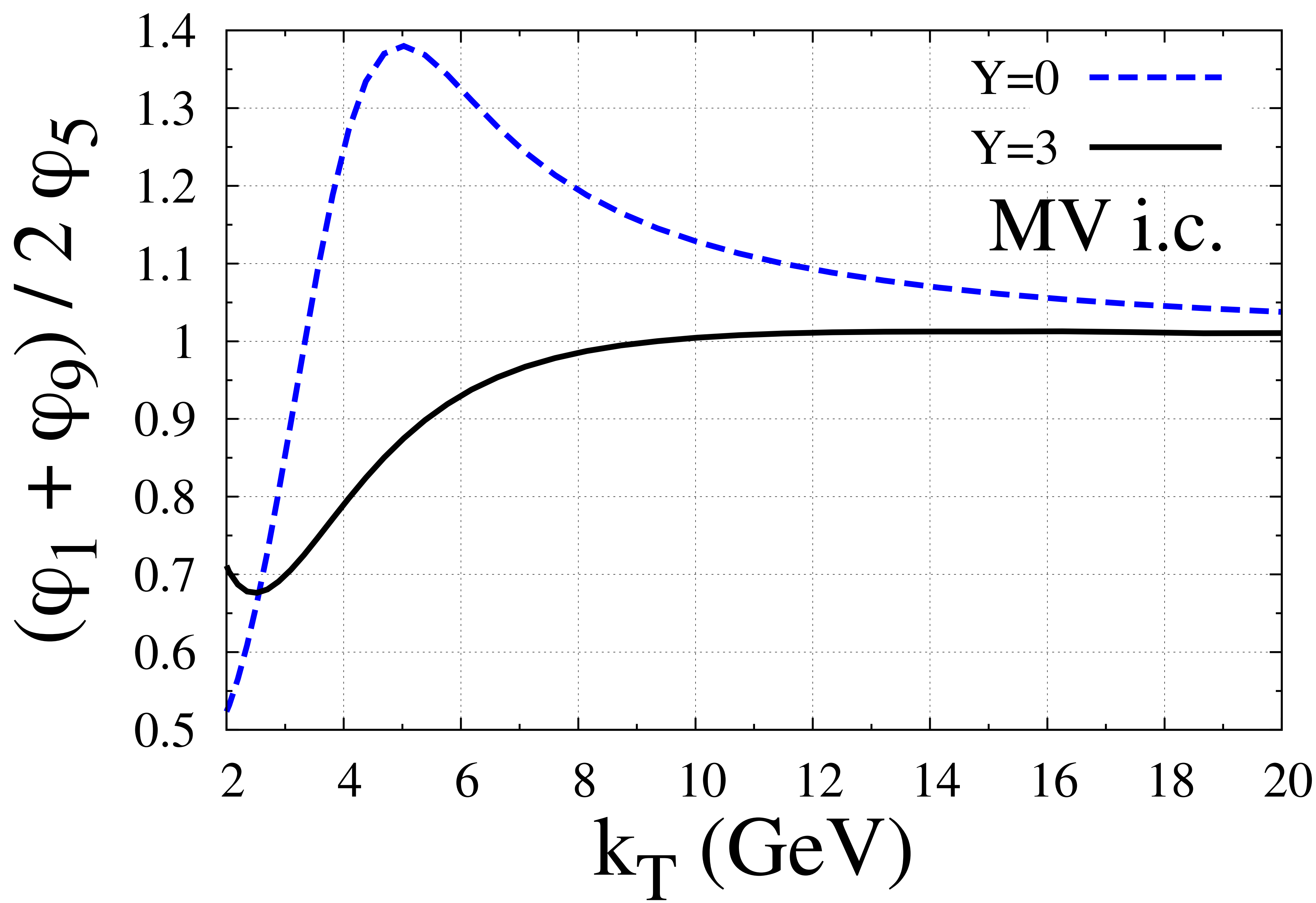


PHENIX’s highlight talk QM2012

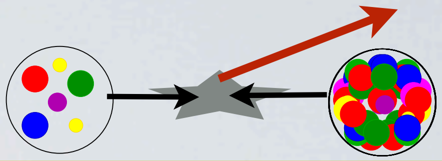
Nuclear modification factors in dAu. Room for surprises?

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

- 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



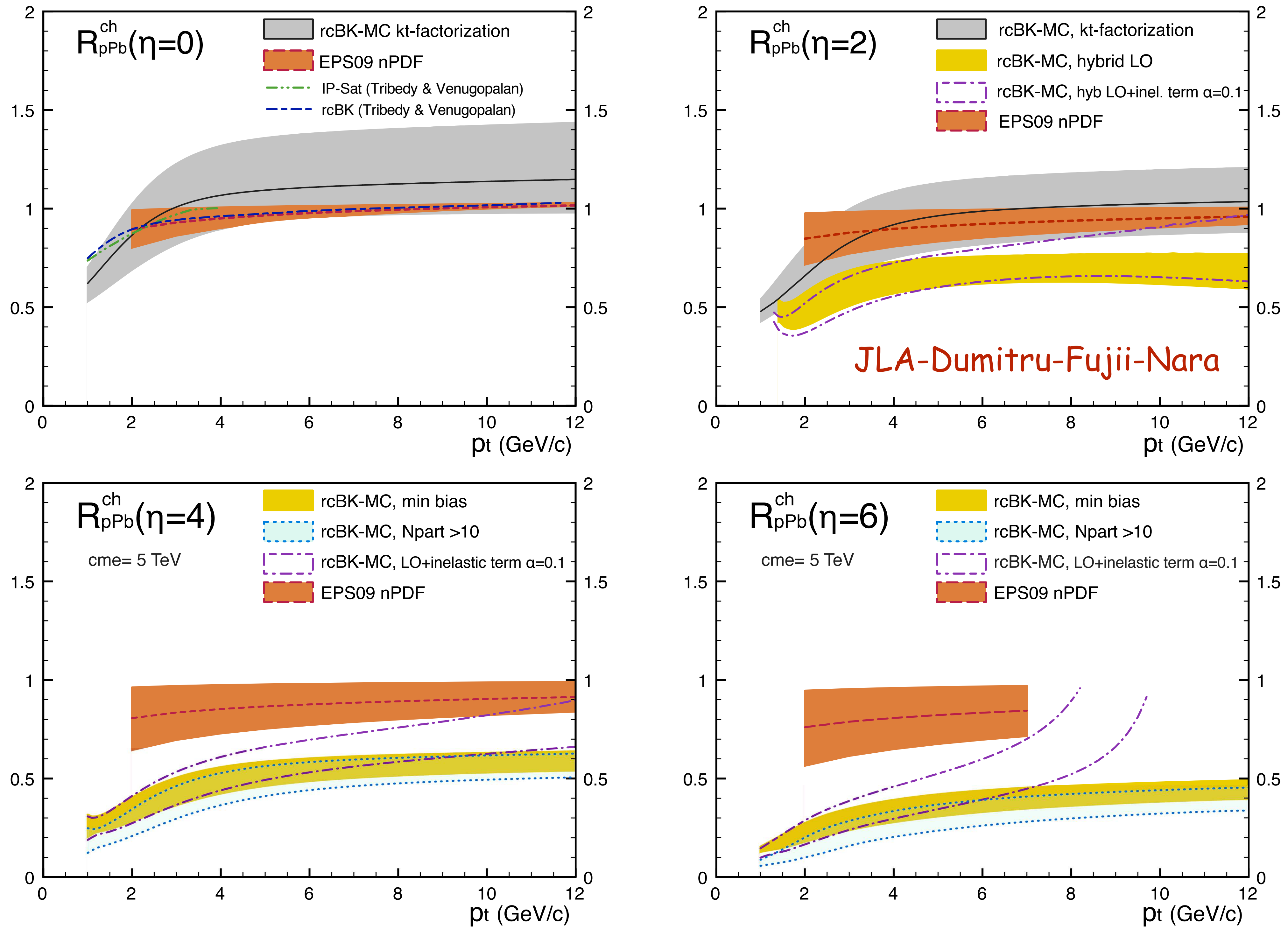
Moving forward: Testing the evolution



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



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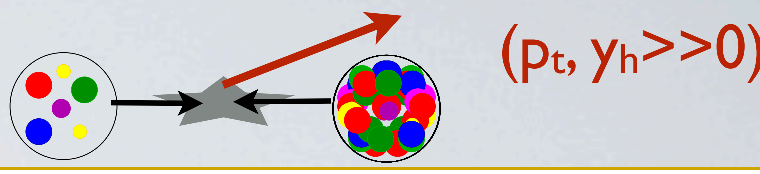
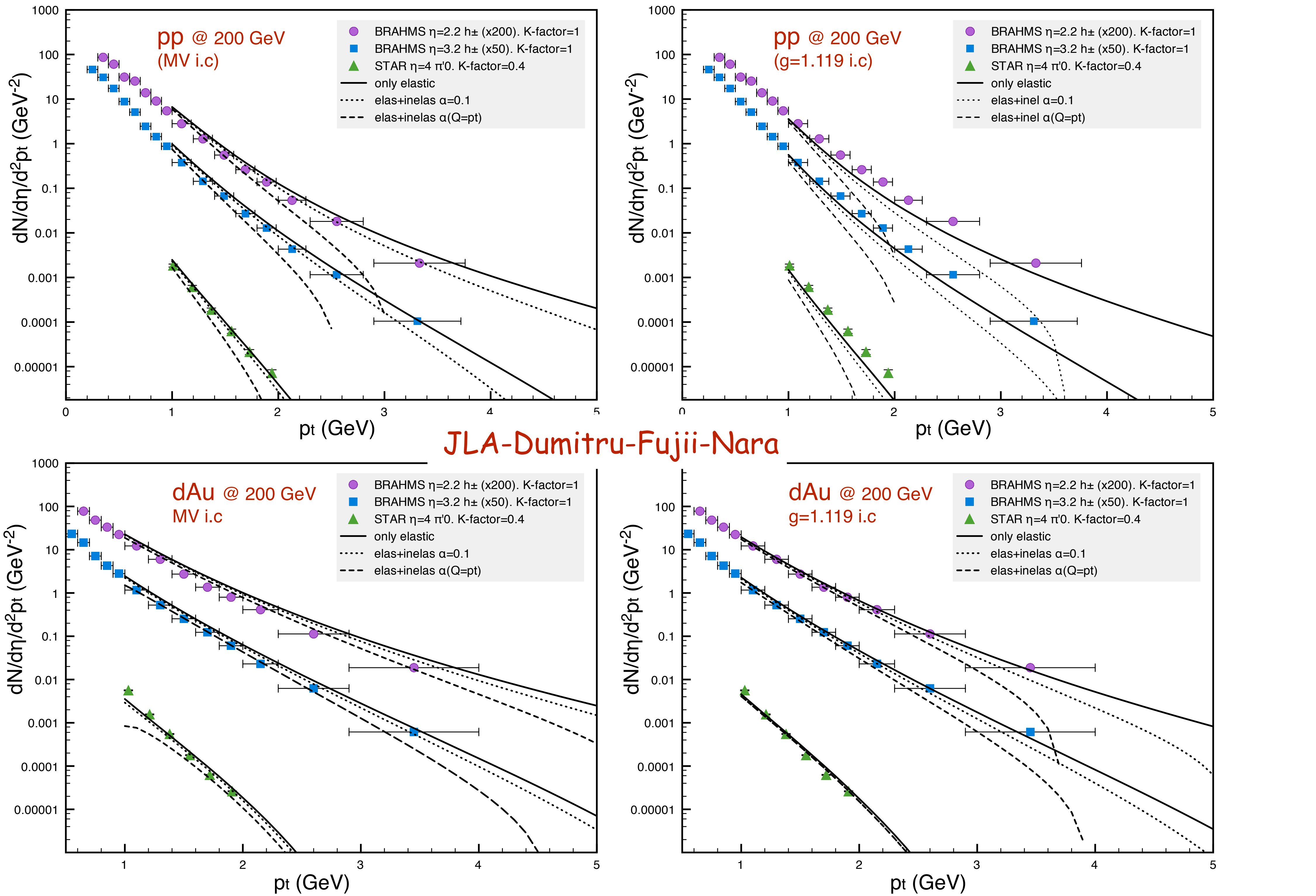


However, partial NLO corrections ("inelastic term", c.f Altinoluk-Kovner) overwhelm the LO contribution at high-pt, making the cross section negative...

Full CGC analysis at NLO needed!



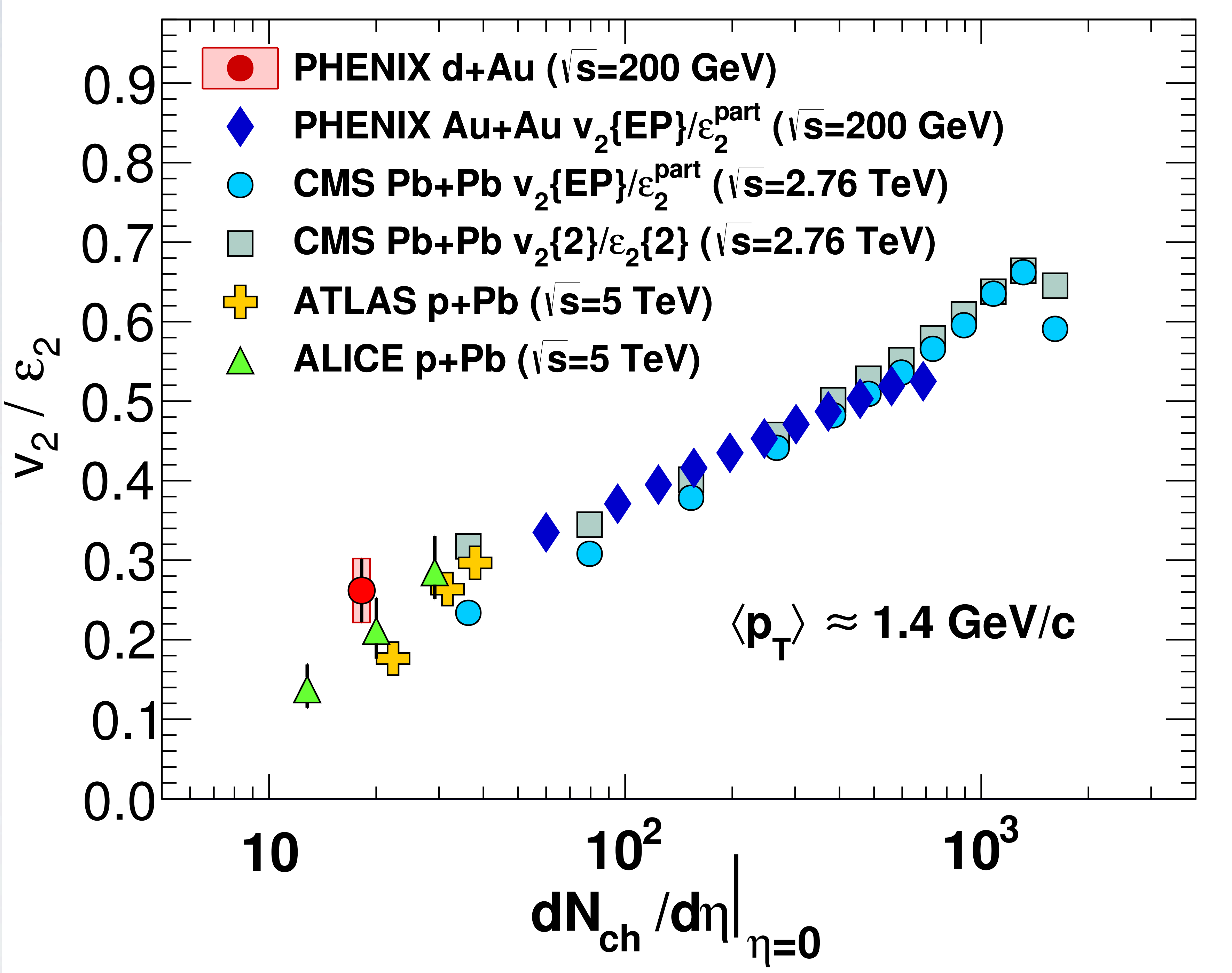
JLA-Dumitru-Fujii-Nara

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

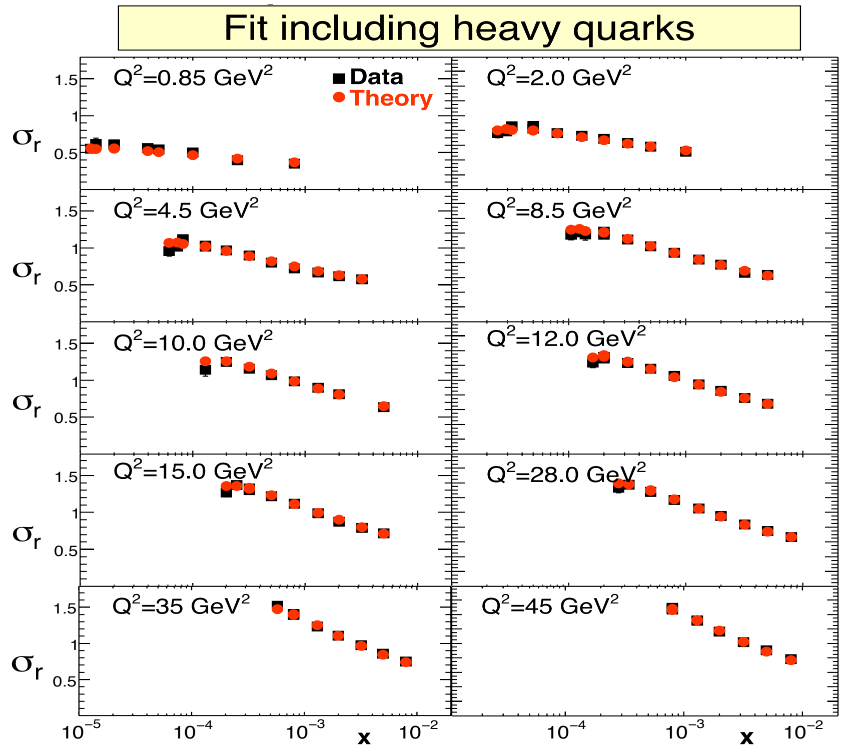


From PHENIX paper 1303.1794

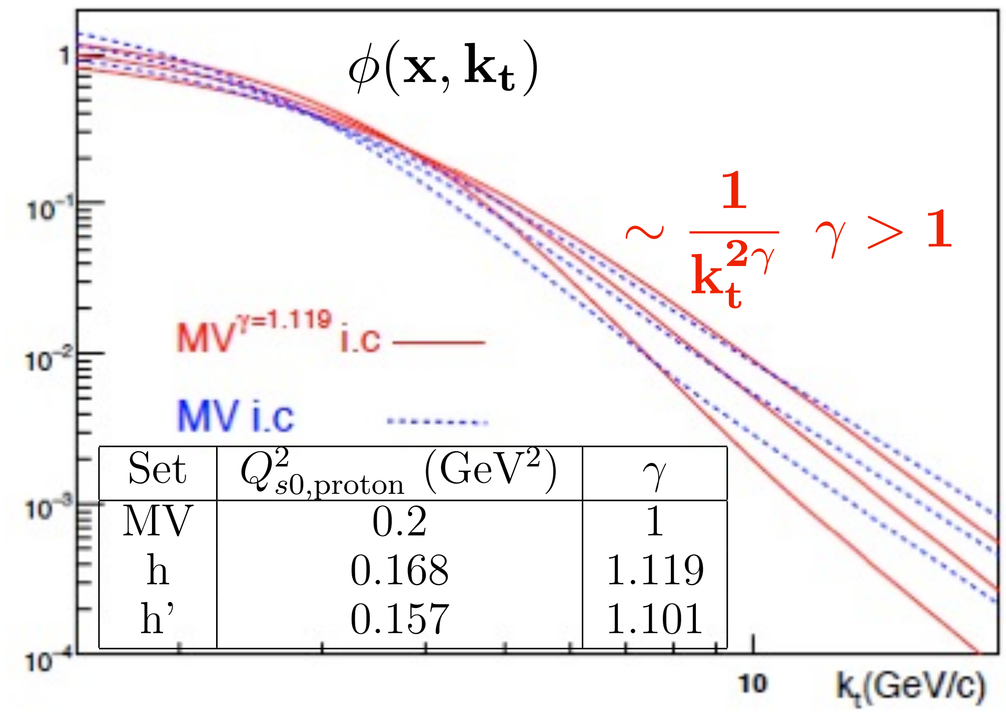
The baseline: e+proton collisions

Talk by P. Quiroga

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

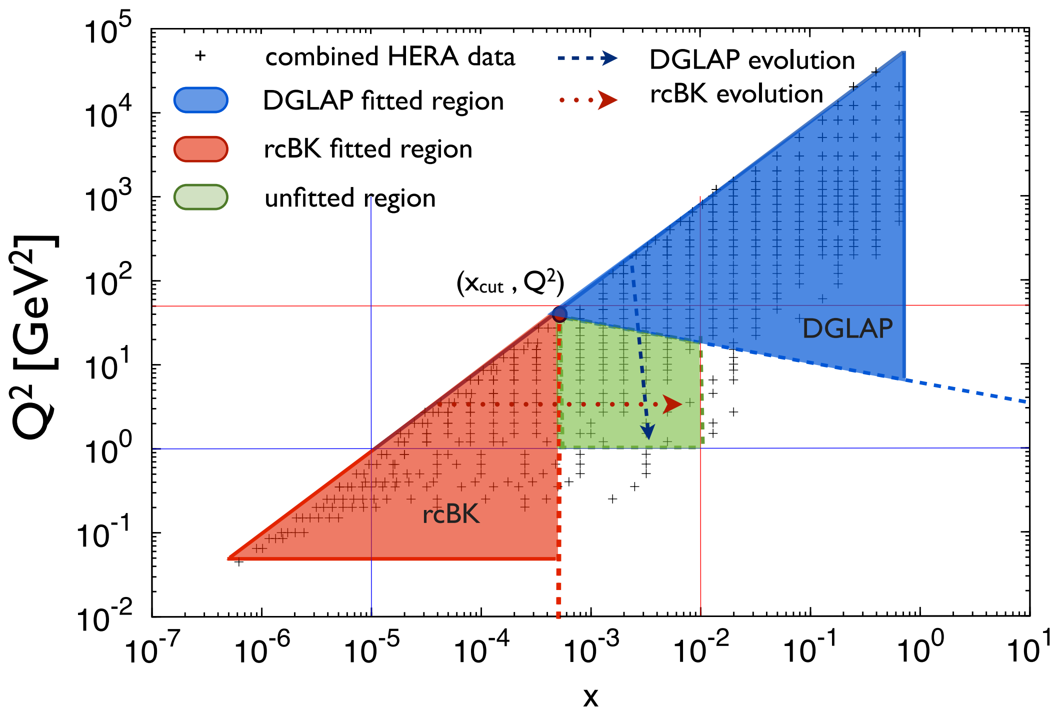


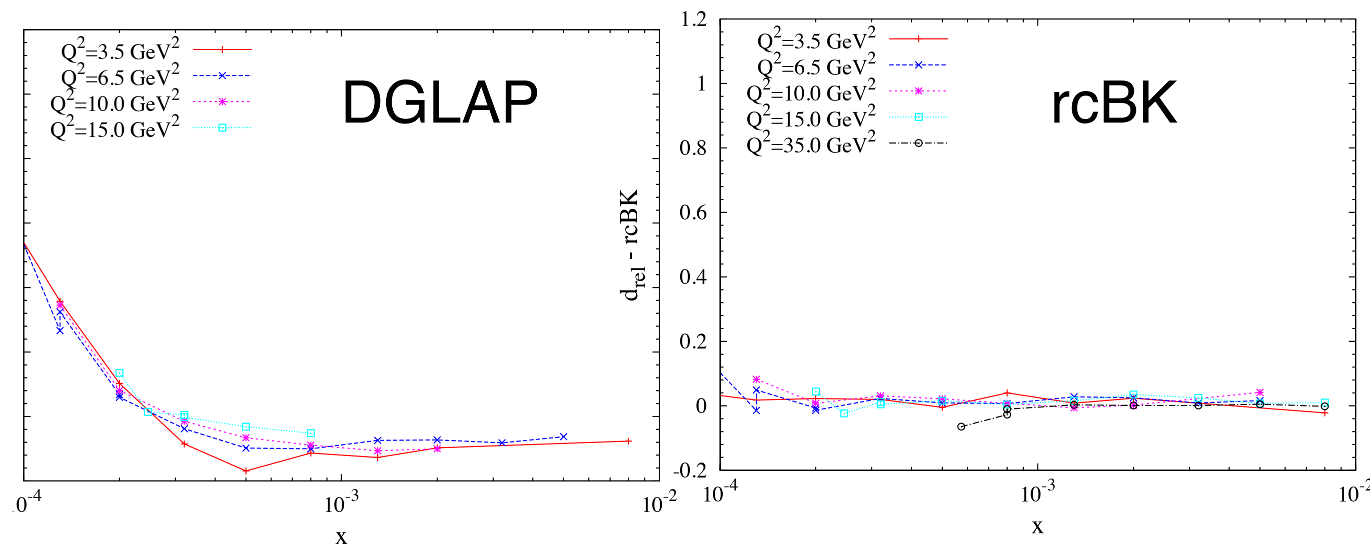
2. Extract NP fit parameters



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

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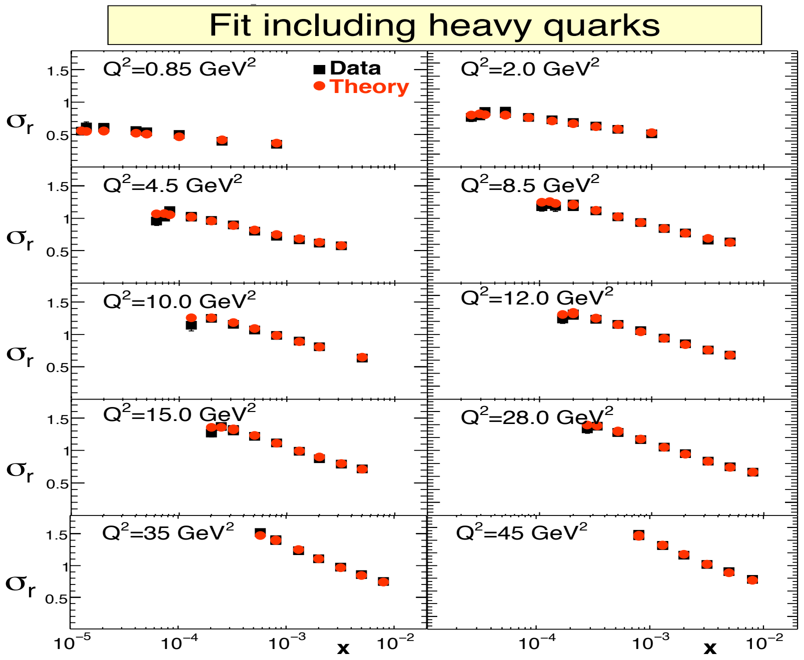

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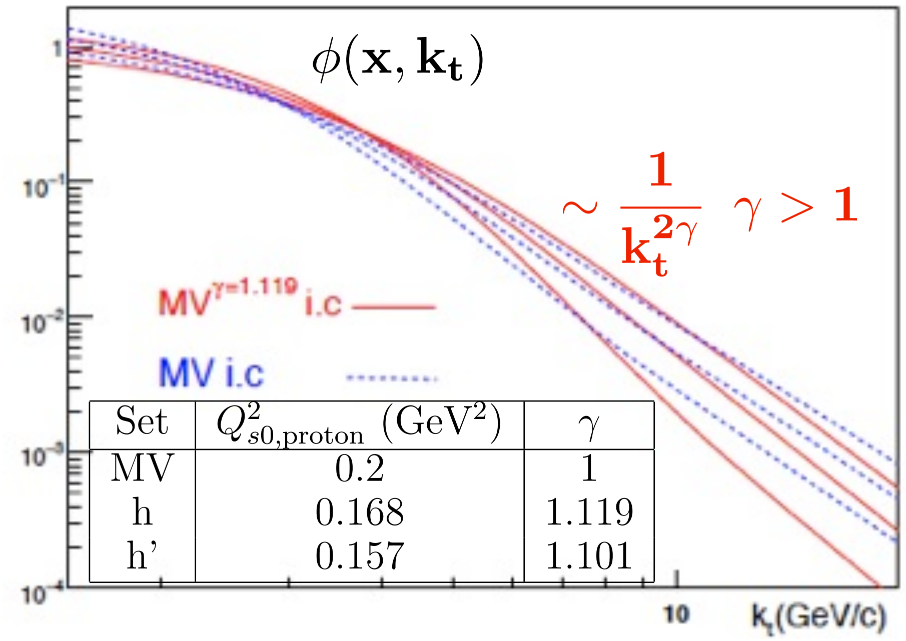
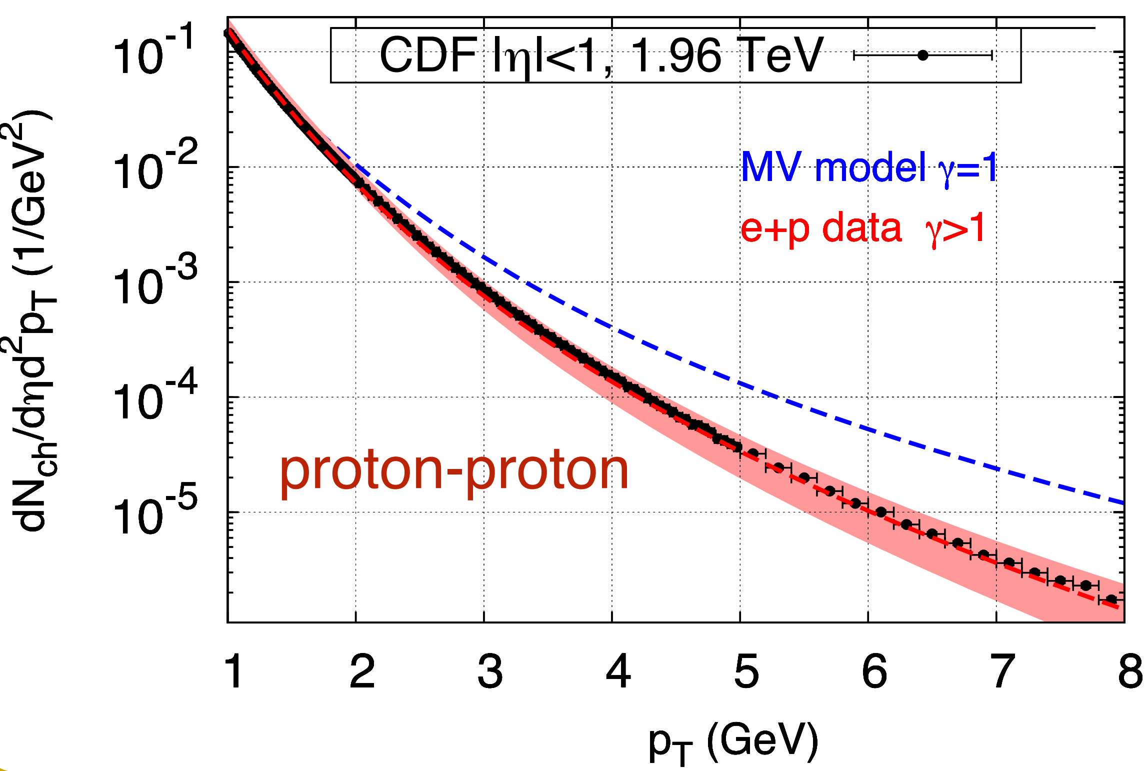
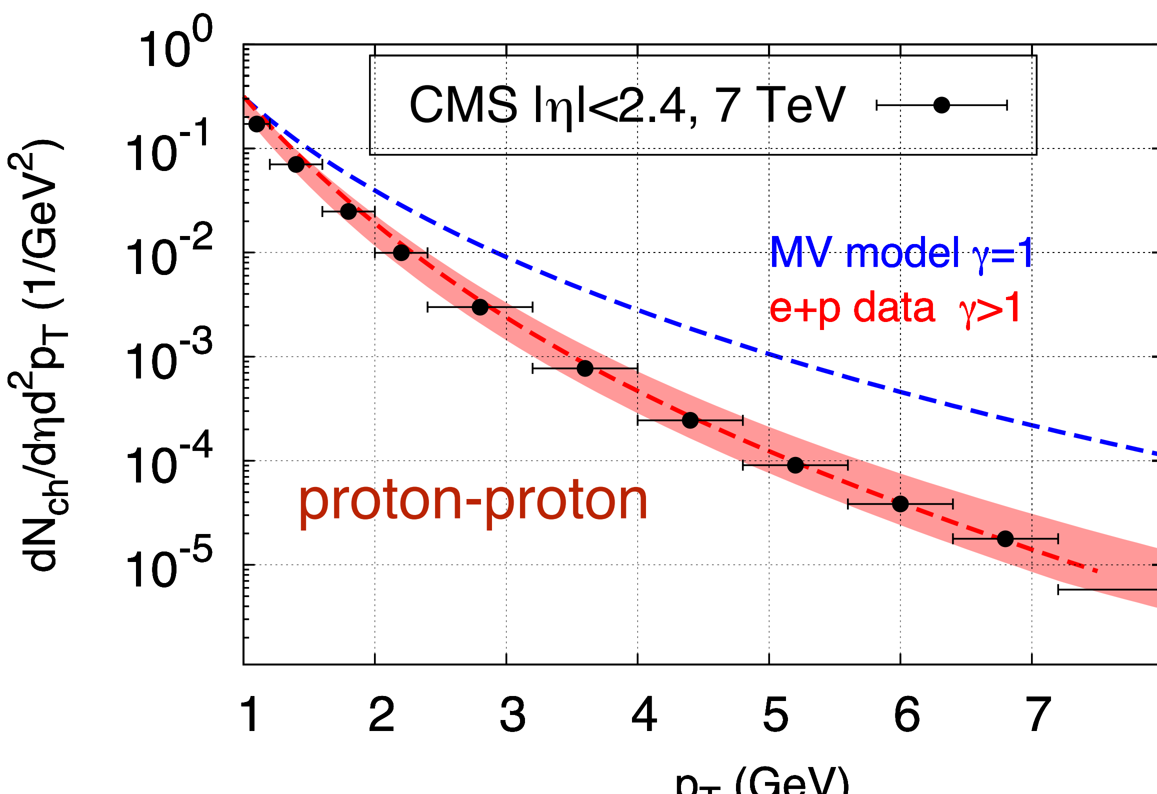


Set	$Q^2_{s0,\mathrm{proton}}$ (GeV^2)	γ
MV	0.2	1
h	0.168	1.119
h'	0.157	1.101

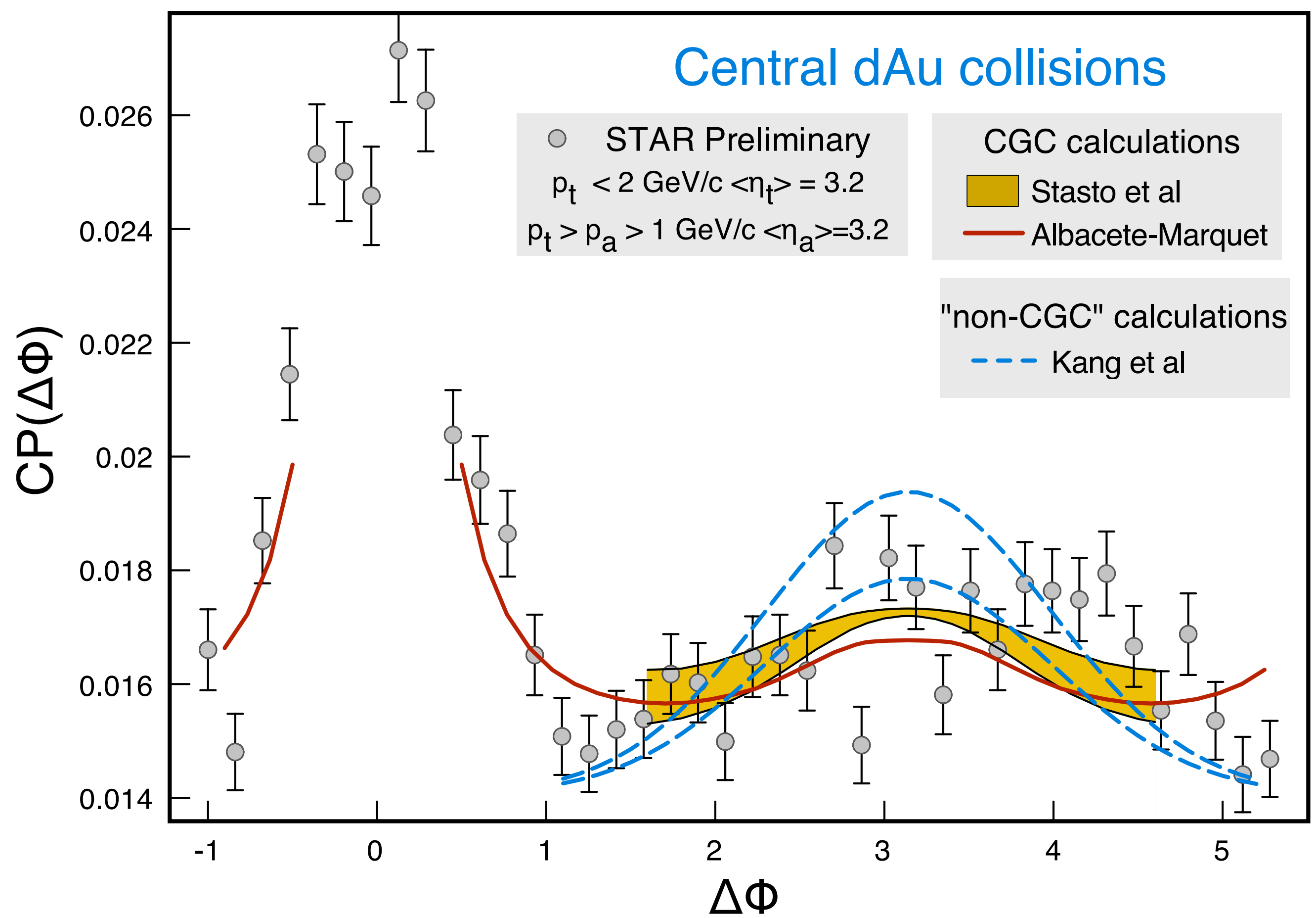
4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

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

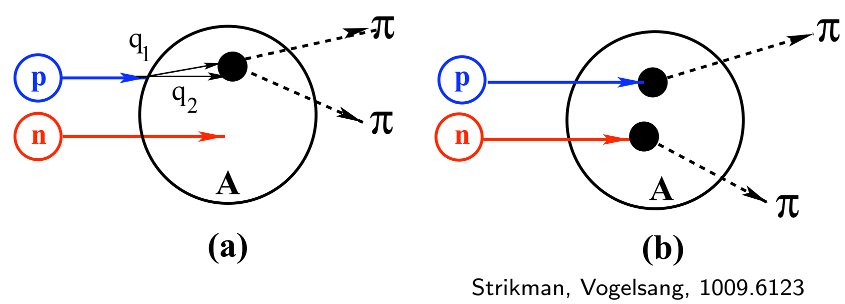


Uncertainties in current CGC phenomenological works:

- 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

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

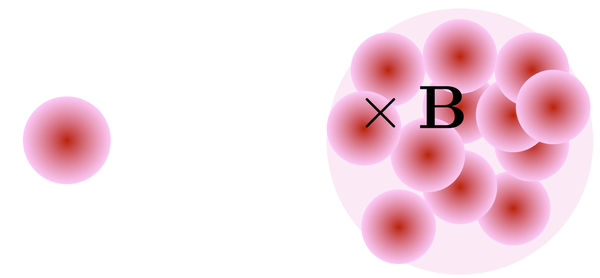
Nuclear ugd's and nuclear modification factors

Setting up the evolution

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

$$\downarrow$$

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



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