Color Glass Condensate and parton saturation: overview of recent developments

Adrian Dumitru
RIKEN BNL and Baruch College, CUNY

Quark Matter 2012, August 13 – 18,
Washington D.C.

Outline

- Introduction & Motivation
- Multiplicity fluctuations and KNO scaling
- *From Protons* to non-linear color fields in nuclei: testing quantum evolution and initial conditions dN/dy, dN/dp_T, R_{pA} in p+Pb at LHC
- From dipoles to quadrupoles: h-h angular correlations
- γ-h angular correlations
- Summary & Outlook

(p)QCD very successful for short-distance phenomena involving few particles / quanta

- $Q\overline{Q}$ quarkonium spectrum, $M_Q / \Lambda_{QCD} \gg 1$
- High-E_T jets in hadronic collisions and $e^+ e^- \longrightarrow q \, \overline{q} \, g$
  $E_T / \Lambda_{QCD} \gg 1$
- DIS with highly virtual photon $\sqrt{Q^2} / \Lambda_{QCD} \gg 1$
- ...

Because:

- $\alpha_s(Q^2) \ll 1$
- Expand about free quanta,
  add in interactions one by one

$$\phi_H(t,\vec{x}) \;=\; \int \frac{d^4p}{(2\pi)^4}\left(a_{\vec{p}}\, e^{-ip\cdot x} + a^\dagger_{\vec{p}}\, e^{ip\cdot x}\right)\,(2\pi)\delta(p^2-m^2)$$

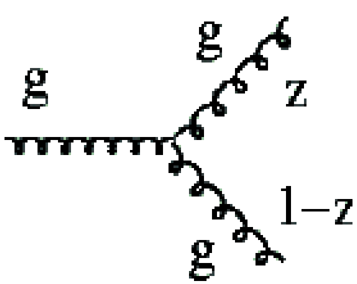
$$\left[a_{\vec{p}}, a^\dagger_{\vec{p}\,'}\right] \;=\; (2\pi)^3\,\delta(\vec{p}-\vec{p}\,')$$

But fails for:

- Distances ~ 1 fm;
  ok, let's leave confinement for another day...

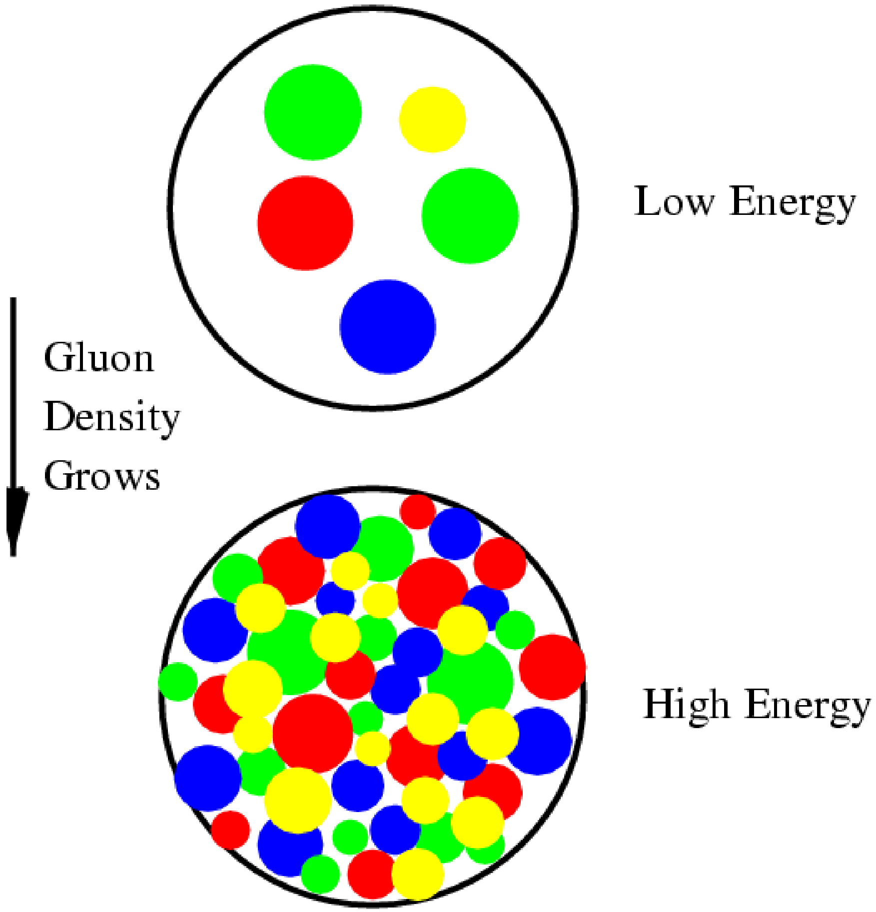
- Hot QCD, even when $T / \Lambda_{QCD} \gg 1$
  (Pisarski: necessary to expand about Debye screened E field !)

- High-energy processes at fixed virtuality:
  effective charge² $\alpha_s(Q^2) \ll 1$ but there are many $O(1/\alpha_s)$
  partners to interact with: gluons interact a lot!
  $\longrightarrow$ (semi-hard) QCD becomes non-linear



$$P_{gg}(z) = 2N_c \times \left(\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right)$$

McLerran & Venugopalan (1994+):



Gluon density per unit transverse area at small x:

$$Q_s^2 \sim \frac{1}{\pi R^2} \frac{dN}{dy}$$

intrinsic semi-hard scale !

$$\alpha_s(Q_s^2) \ll 1$$

large phase-space density, occupation number $O(1/\alpha_s)$

Non-linear fields are a great intellectual challenge in modern physics:

- Gravity: formation of black holes, ...
- QED pair creation in extreme laser fields
- QCD: non-linear color fields in hadrons / nuclei boosted to rapidity $y \gg 1$

- MV: try climbing the camel from back !
- If occupation number is high, expand about classical solution rather than about "nothing"

$$A^{\mu} = A^{\mu}_{\mathrm{cl}} + A^{\mu}_{\mathrm{qu}}$$

- A^{μ}_{cl} : classical field behind "pancake" of valence charges
- A^{μ}_{qu} : quantum fluctuations (small-x evolution)

e&m fields of boosted charge (v → 1):

J.D. Jackson:
classical E&M

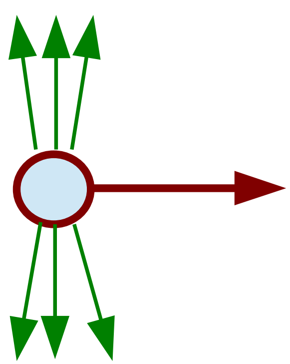
$$A^\mu_{\rm cl} = \delta^{\mu +}\delta(x^-)\,\Lambda(x_\perp)$$

$$= \delta^{\mu +}\delta(x^-)\,\frac{1}{\nabla^2_\perp}\rho(x_\perp)$$

2d Coulomb potential

valence charge density

"shock wave"



$$E_i = \frac{e}{2\pi}\frac{x_i}{x^2_\perp}\delta(t-z) \quad , \quad B_i = \epsilon_{ij}E_j$$

In a hadron / nucleus the local valence color charge density is random

$$S = \int d^2x_\perp \left\{ \frac{1}{2\mu^2}\rho^a\rho^a - \frac{1}{\kappa_3} d^{abc}\rho^a\rho^b\rho^c + \frac{1}{\kappa_4}\rho^a\rho^a\rho^b\rho^b + \cdots \right\}$$

+ soft YM fields +

coupling of soft $\leftrightarrow$ hard

$\mu^2 \sim g^2 A^{1/3}$; $\kappa_3 \sim g^3 A^{2/3}$; $\kappa_4 \sim g^4 A$

Averages: $$\langle O \rangle \equiv \frac{\int \mathcal{D}\rho \; O[\rho] \;\exp\left(-S[\rho]\right)}{\int \mathcal{D}\rho \;\exp\left(-S[\rho]\right)}$$

Multiplicity distribution: Negative Binomial from MV model

Gelis, Lappi, McLerran: NPA (2009)
Schenke, Tribedy, Venugopalan: 2012

$$S_{\rm MV} = \int d^2x_\perp \frac{1}{2\mu^2}\rho^a\rho^a \longrightarrow \text{NBD}$$

$$P(n) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\bar{n}^n k^k}{(\bar{n}+k)^{n+k}}$$

$$\bar{n} = \# \frac{N_c(N_c^2-1)}{\alpha_s} Q_s^2\, \pi R^2$$

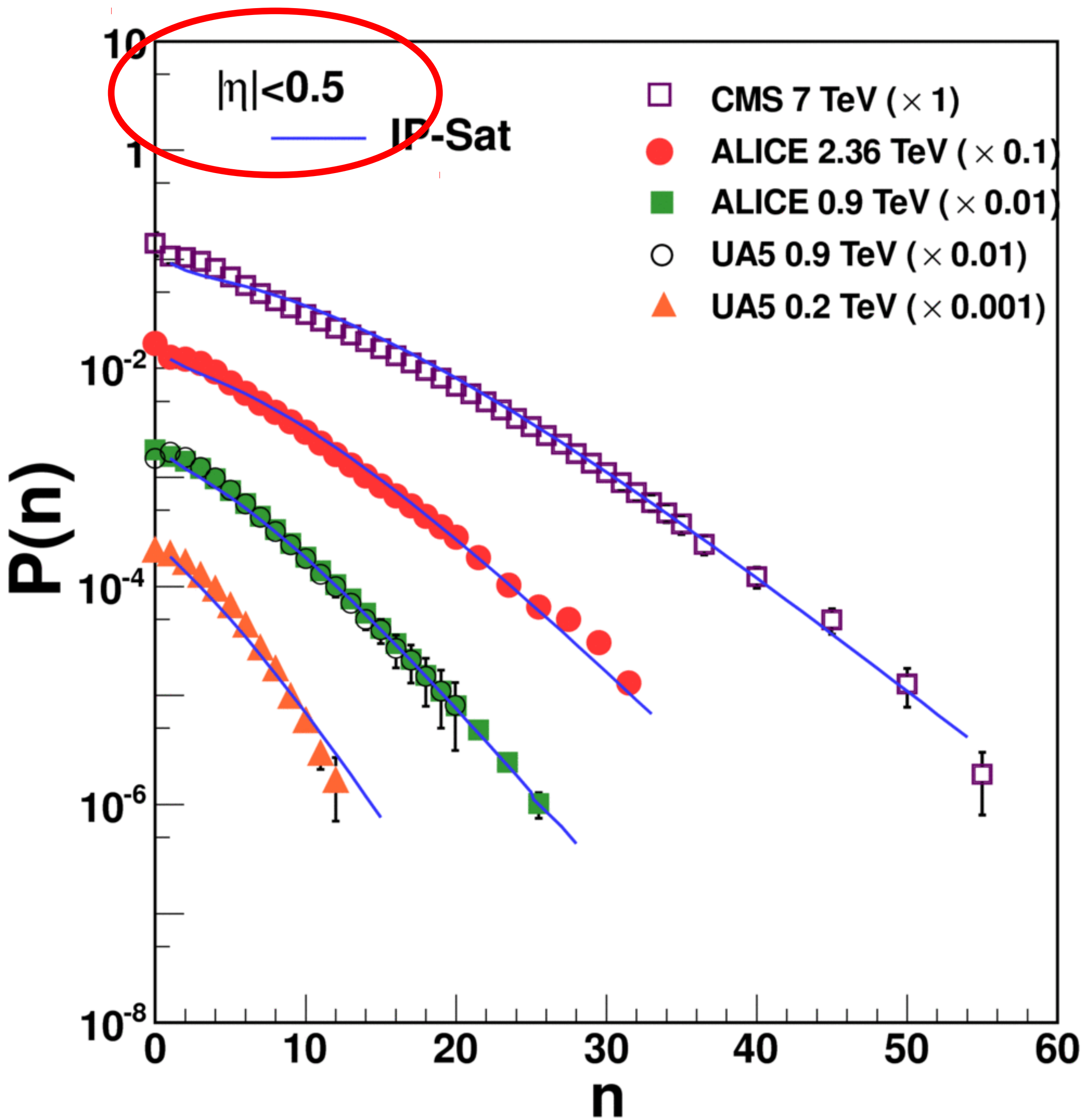
$$k = \# \frac{N_c^2-1}{2\pi} Q_s^2\, \pi R^2$$

two parameter distribution :

mean $\bar{n}$,

width $\bar{n}\sqrt{\frac{1}{k}+\frac{1}{\bar{n}}} \sim \frac{\bar{n}}{\sqrt{k}}$

Multiplicity distributions in *pp* collisions

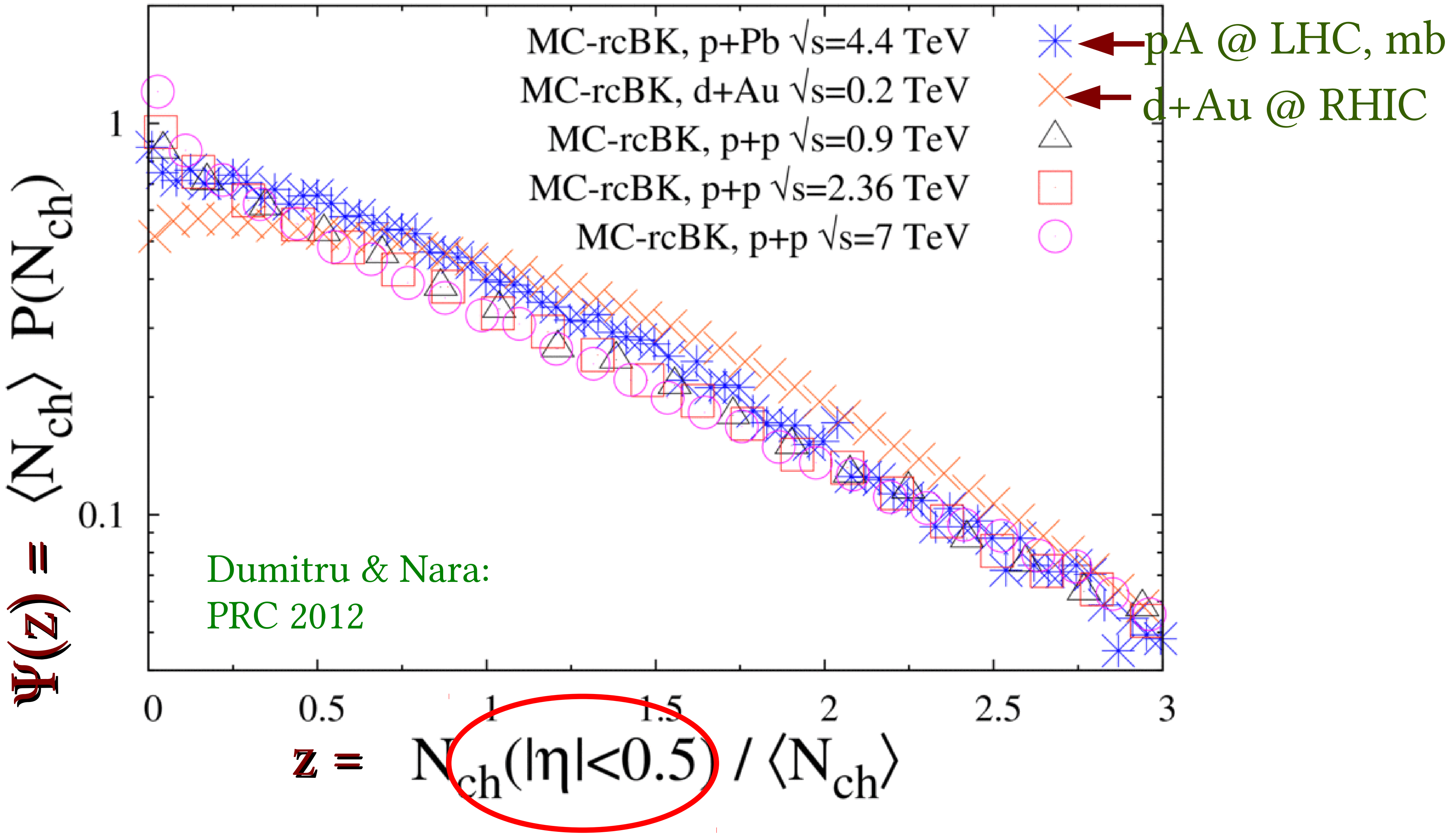


Tribedy & Venugopalan: PLB 2012

P(n): negative binomial distribution

KNO scaling (even p+Pb approx.)

for A+B : $k_{AB} \sim k_{pp} \min(T_A, T_B)$



KNO from Neg. Binomial Distribution ?

$\bar{n}\, P(n) \equiv \psi(z)$ is **universal** (independent of energy)

Koba, Nielsen, Olesen, NPB (1972)

In the limit **$1 \ll \bar{n} / k$**, NBD can be written as

$$\bar{n}\, P(n)\, dz \sim z^{k-1}\, e^{-kz}\, dz \qquad , \quad z \equiv n/\bar{n}$$

which is independent of $\bar{n}$!

For action with ~ρ^4 operator:

Poster by Elena Petreska !

$$\frac{\bar{n}}{k} \sim \# \frac{N_c}{\alpha_s} \left\{ 1 - 3(N_c^2+1)\beta \right\} + \cdots \quad \gg 1$$

Gauss/MV (→ 1)

ρ^4 (→ $3(N_c^2+1)\beta$)

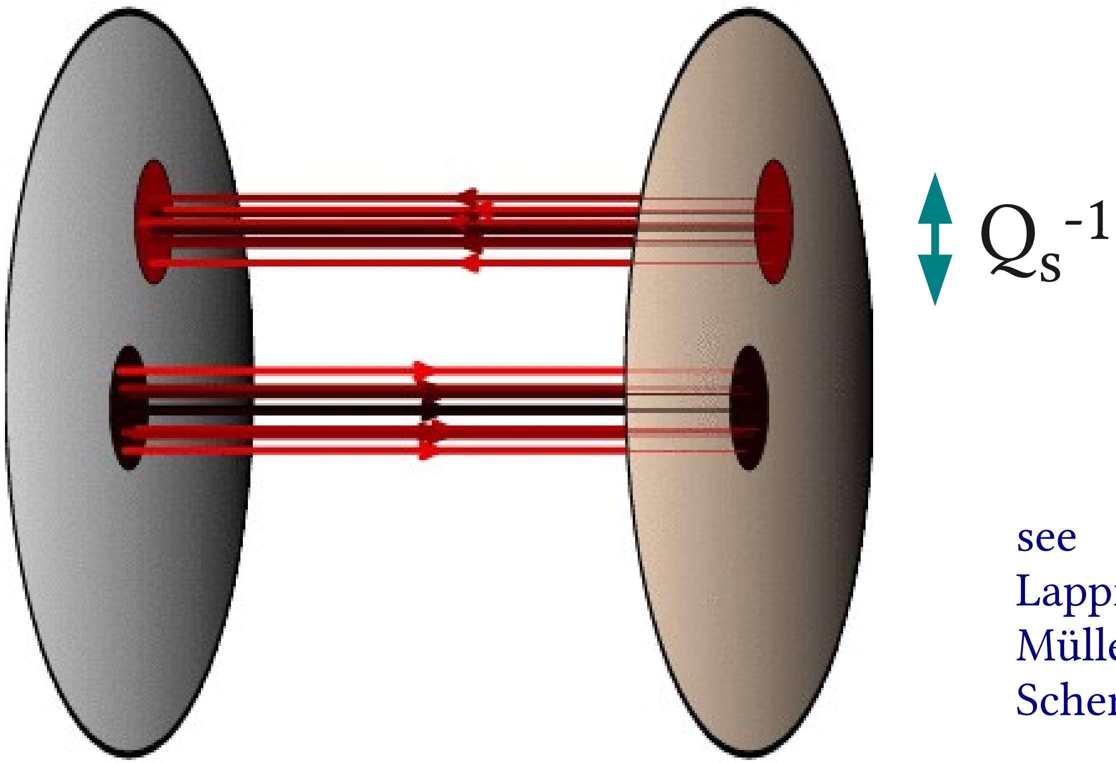
$$\beta \equiv \frac{C_F^2}{6\pi^3} \frac{g^8}{Q_s^2\,\kappa_4} \left[\int_{-\infty}^{\infty} dz^- \mu^4(z^-) \right]^2$$

KNO in terms of small-x gluons (p_T~Q_s):

i) approx. Gaussian action

ii) high occupation number

Sub nucleon scale for KNO fluctuations ?



see
Lappi & McLerran,
Müller & Schäfer,
Schenke, Tribedy, Venugopalan, ...

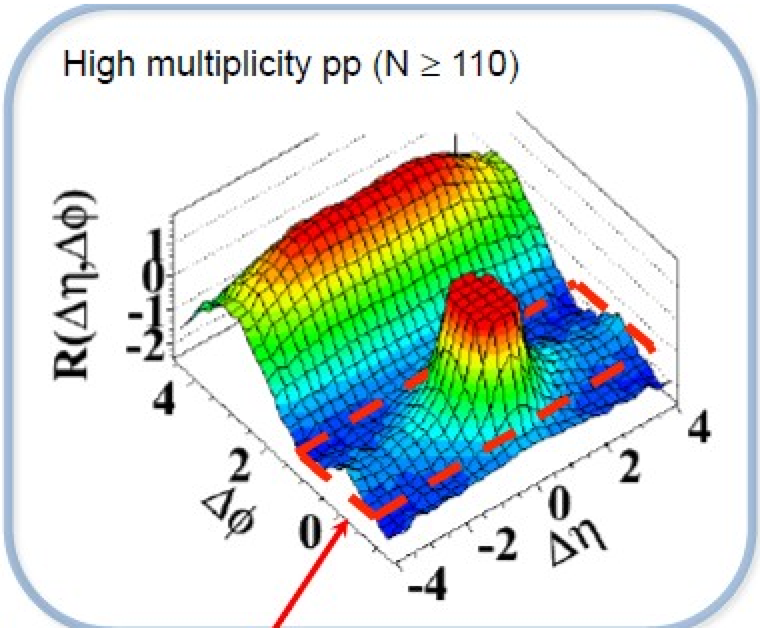
- → "spikier" initial density distribution for hydro ?

(see work by Gavin & Moschelli, H. Petersen, T. Kodama et al, ...)

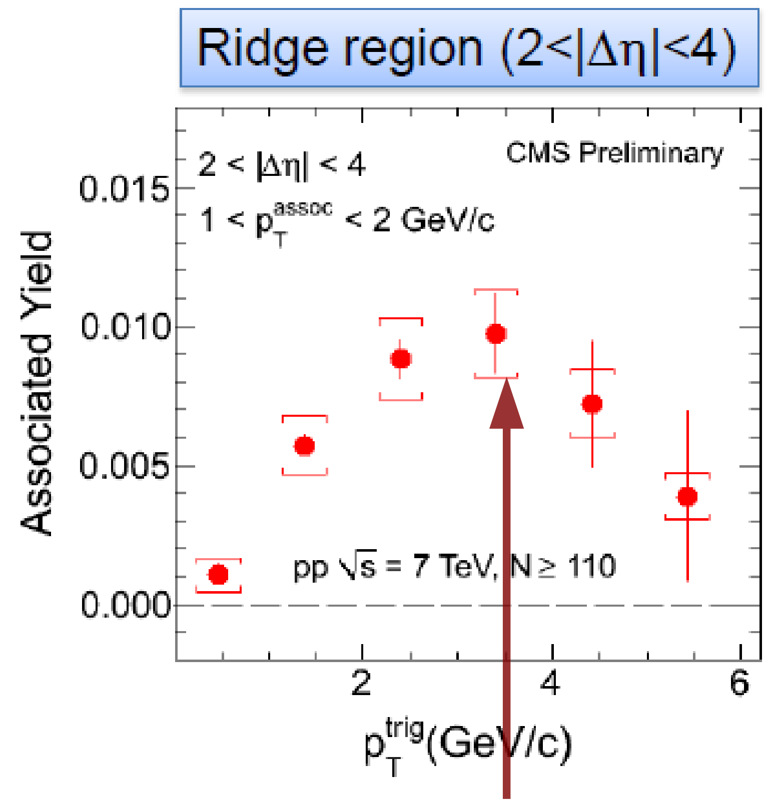
Talk by S. Moreland at QM12 !

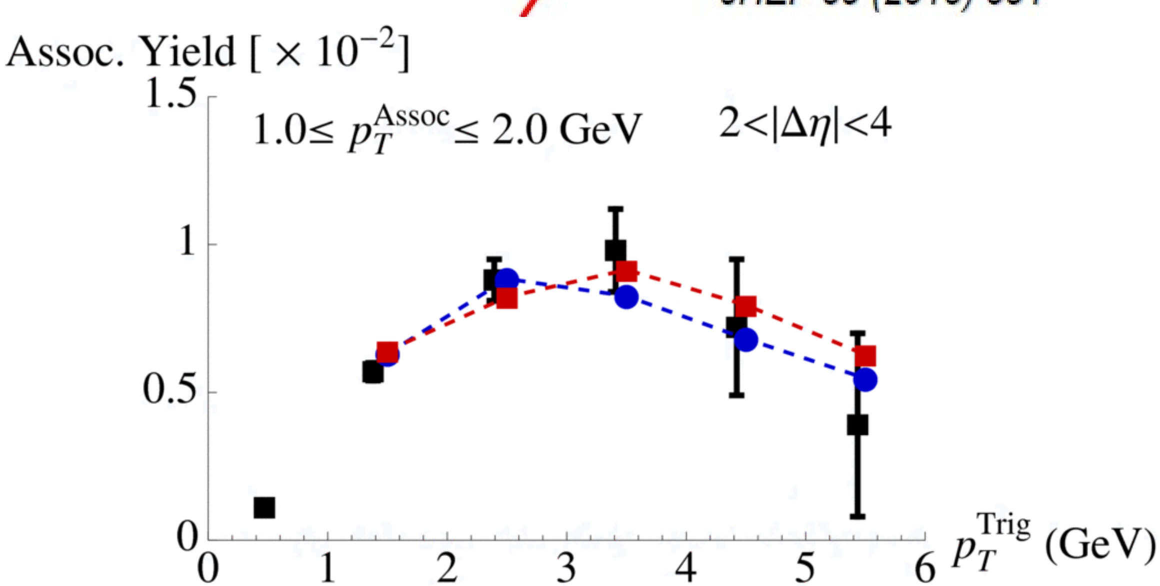
Ridge in very high-multiplicity pp @ 7 TeV

(Wei Li for CMS, Quark Matter 2011, Annecy)



JHEP 09 (2010) 091



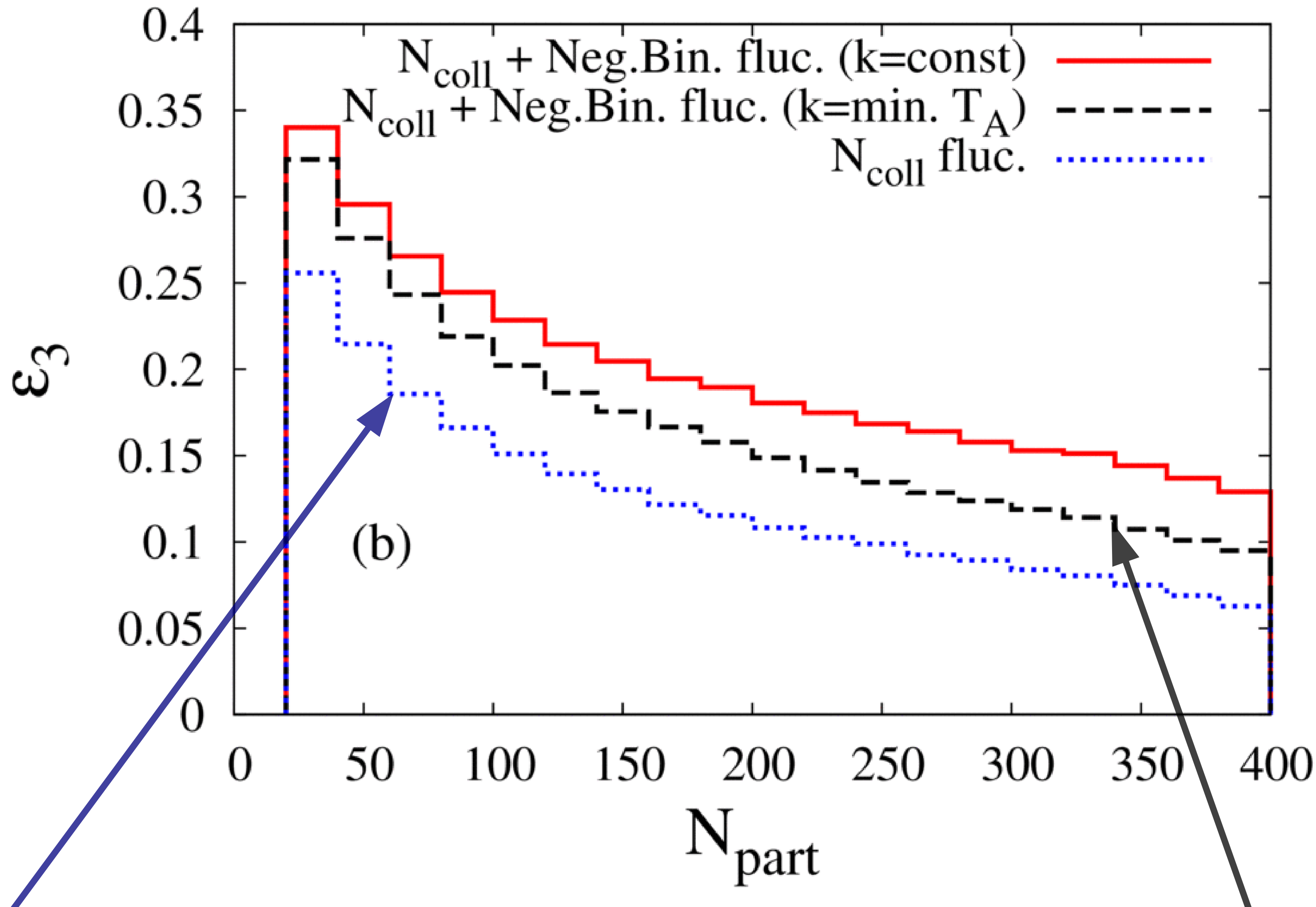


peaks at ~ 3.5 GeV !

Dusling & Venugopalan: arXiv:1201.2658

Eccentricity ε_3 in Au+Au

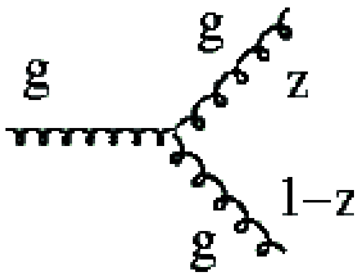
Dumitru & Nara:
PRC 2012



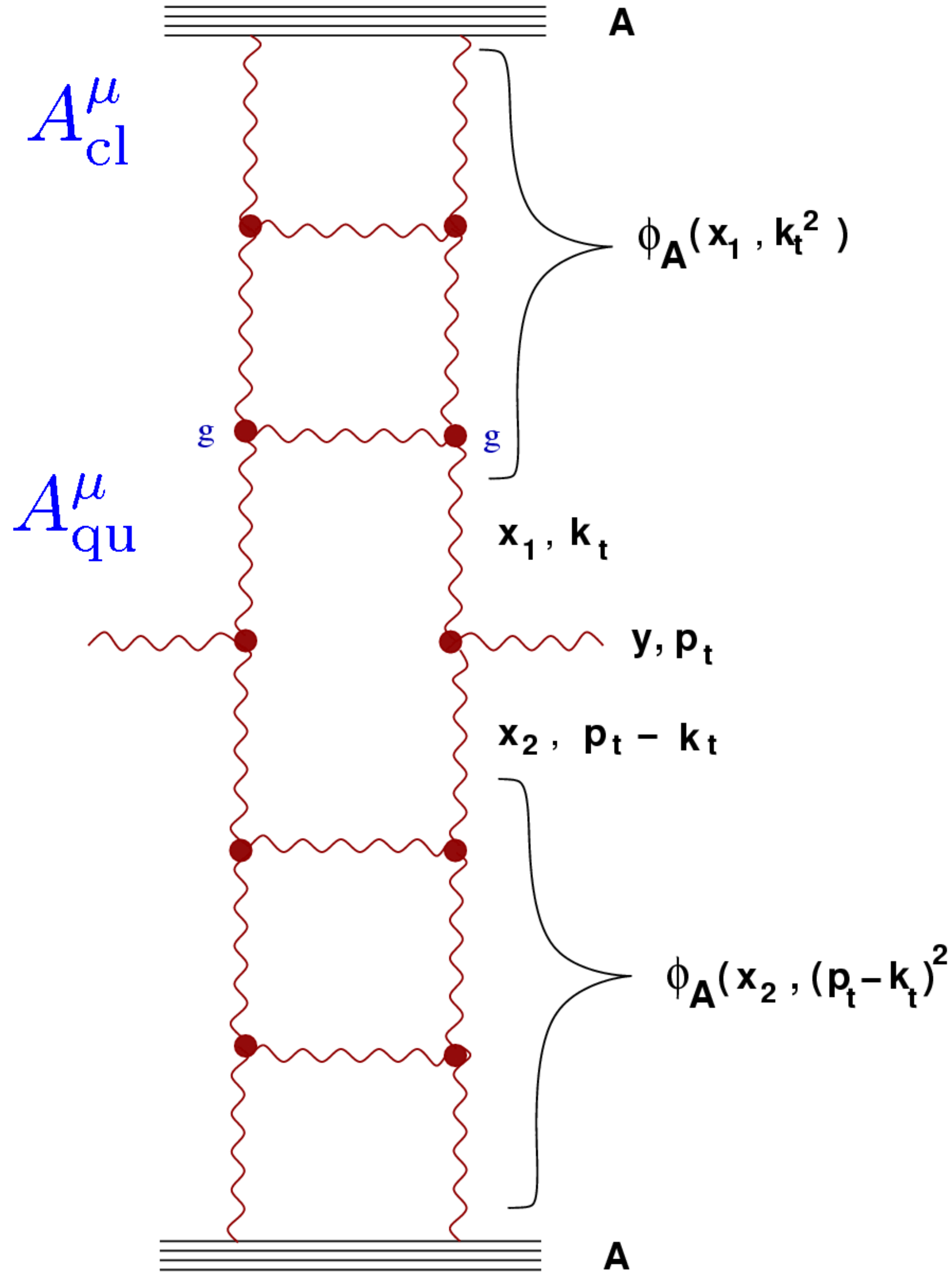
Glauber fluc only

Glauber + NBD
k ~ min(T_A,T_B)

Evolution with energy: quantum fluctuations

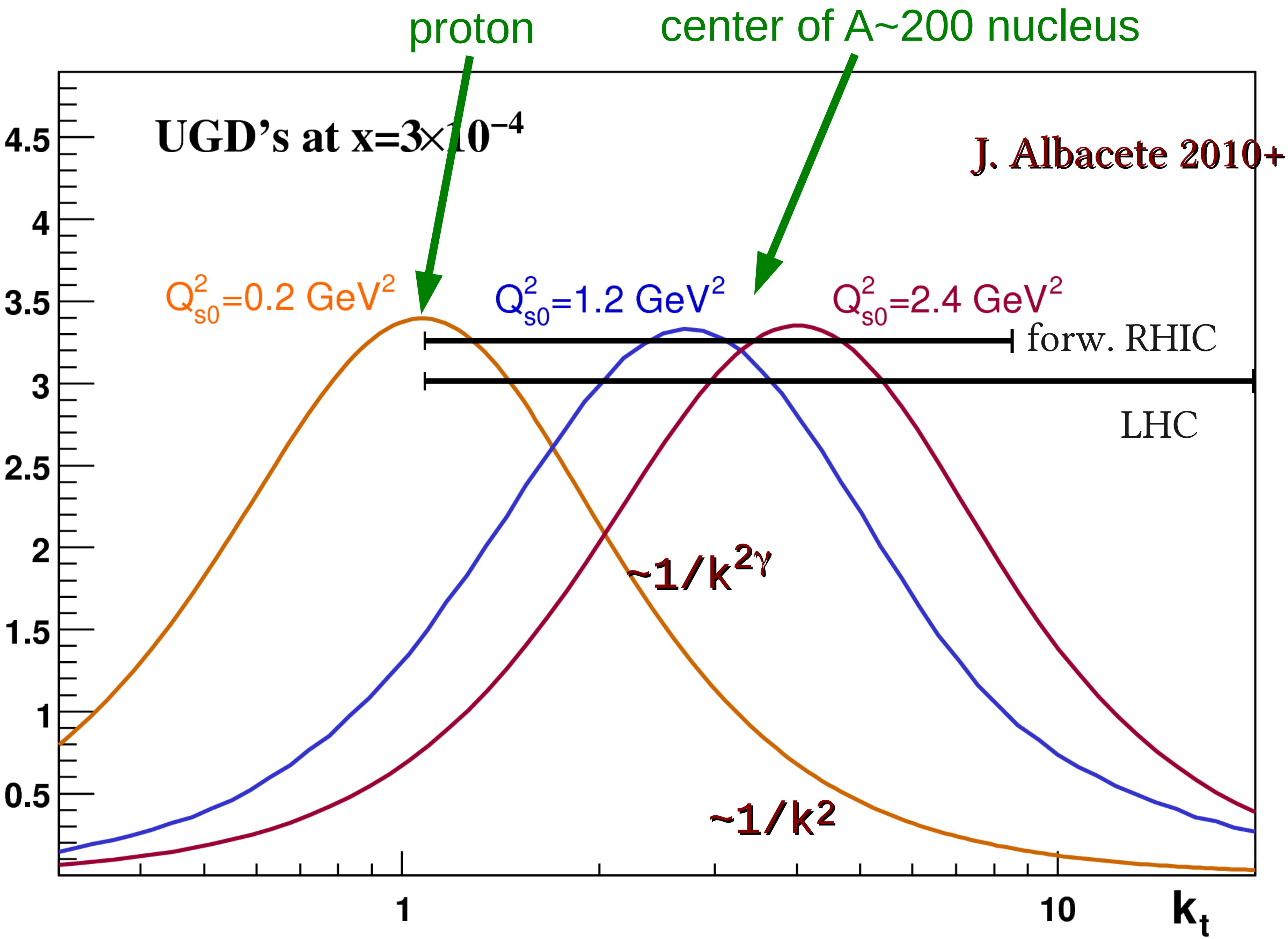


$$P_{gg}(z) = 2N_c \times \left(\frac{1-z}{z} + \frac{z}{1-z} + z(1-z)\right)$$



- At rapidity far from valence charges, resummation to all orders in $(\alpha_s Y)^n$ required

rcBK (generalized) unintegr. gluon density



Energy and centrality dependence of multiplicities

i) Kharzeev, Levin, Nardi model

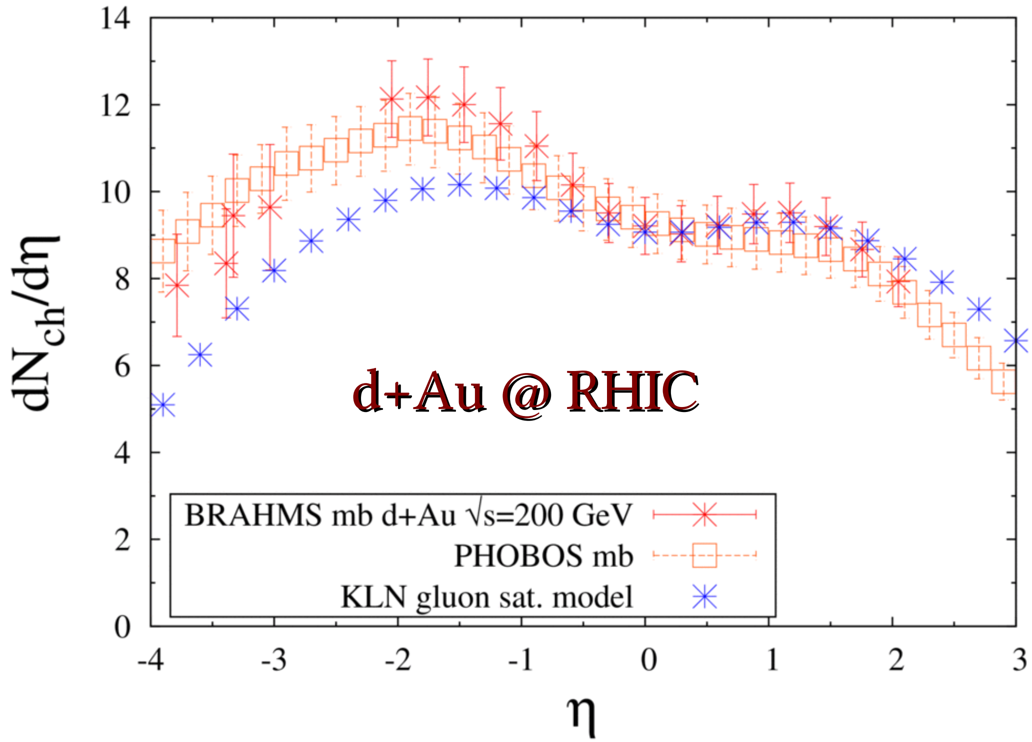
(updated predictions from arXiv:1111.3031)

$$\frac{dN}{dy} = K \, \frac{4\pi N_c}{N_c^2 - 1} \int d^2 r_t \int_0^\infty \frac{d\,p_t^2}{p_t^4} \, \alpha_s \; x_2 G_{A_2}(x_2, p_t^2) \; x_1 G_{A_1}(x_1, p_t^2)$$

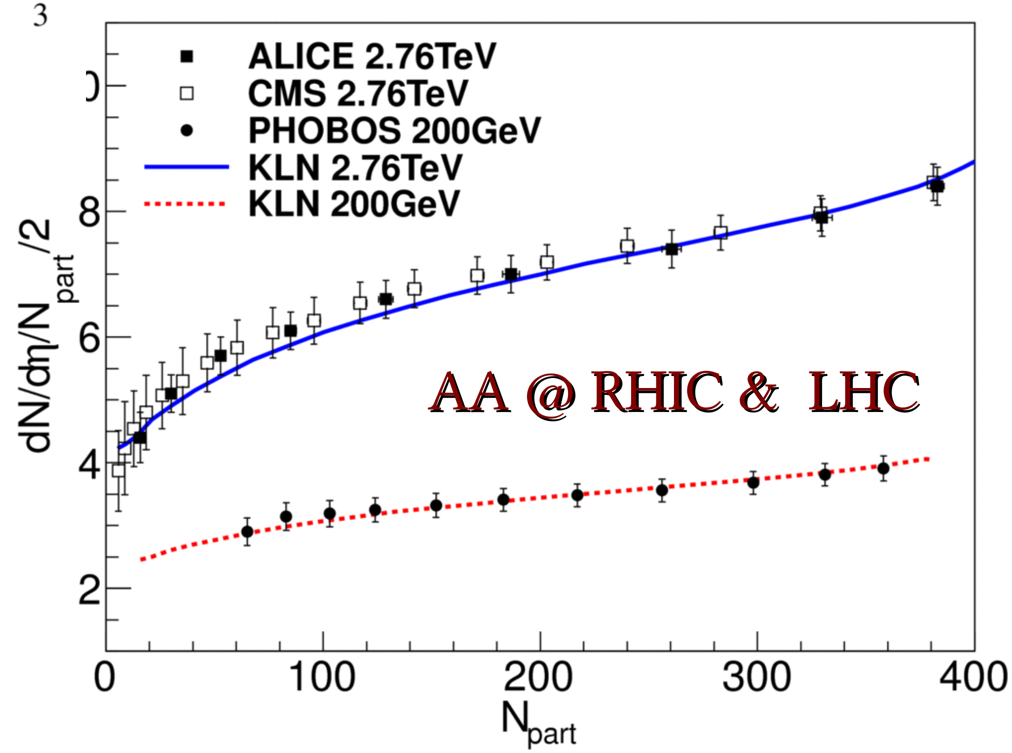
with

$$xG(x, p_t^2) = \begin{cases} \frac{1}{\alpha_s(Q_s)} \, p_t^2 \; (1-x)^4 & , \quad p_t < Q_s(x) \\ \frac{1}{\alpha_s(Q_s)} \, Q_s^2 \; (1-x)^4 & , \quad p_t > Q_s(x) \end{cases}$$

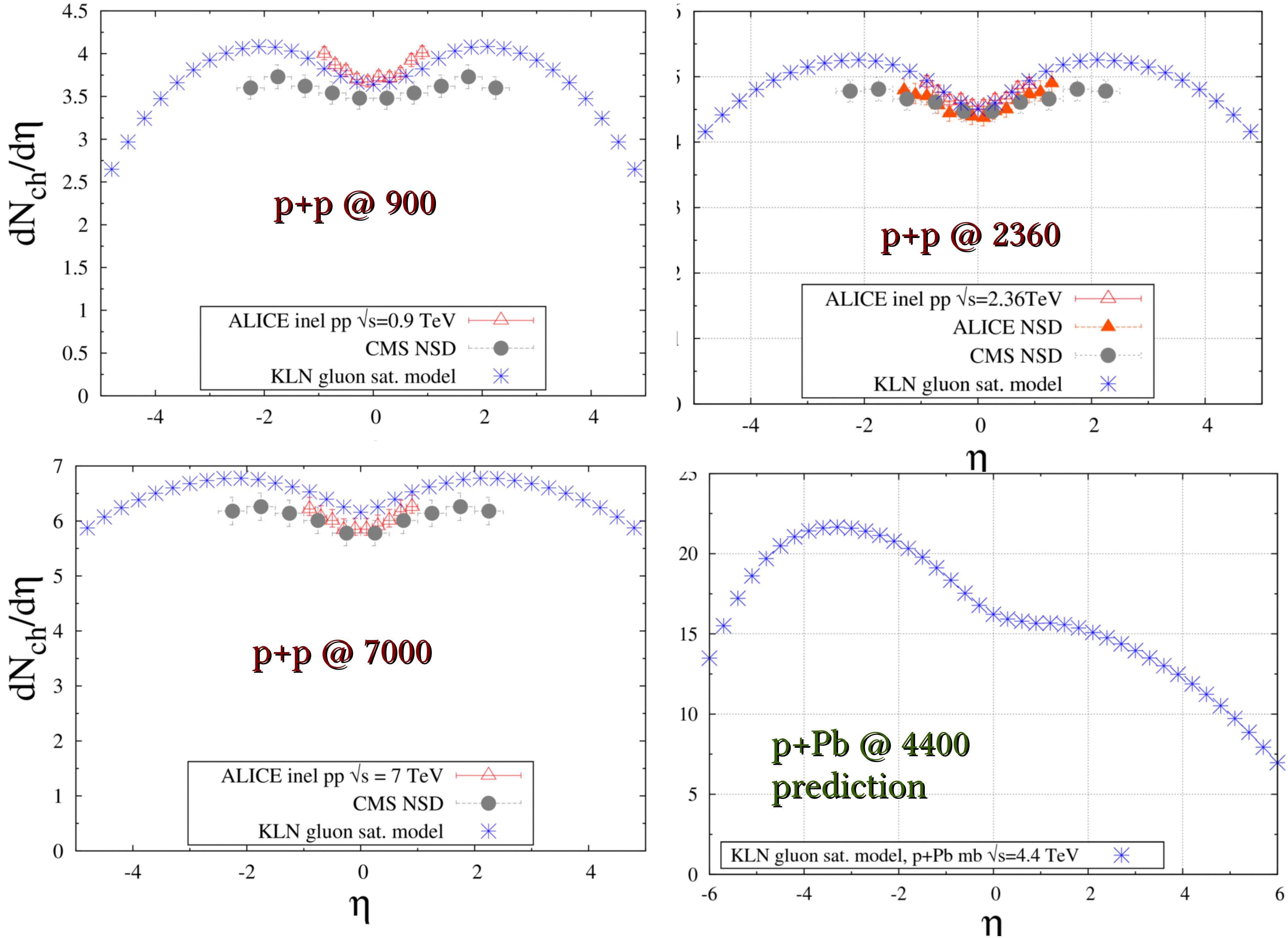
$$Q_s^2(y) = Q_0^2 \; N_{\rm part} \; \left(x_0 \frac{\sqrt{s}}{Q_0} e^{\mp y} \right)^{\bar{\lambda}}$$



d+Au @ RHIC
BRAHMS mb d+Au √s=200 GeV
PHOBOS mb
KLN gluon sat. model
dNch/dη
η



ALICE 2.76TeV
CMS 2.76TeV
PHOBOS 200GeV
KLN 2.76TeV
KLN 200GeV
AA @ RHIC & LHC
dN/dη/Npart/2
Npart


p+p @ 900
ALICE inel pp √s=0.9 TeV
CMS NSD
KLN gluon sat. model
dNch/dη
p+p @ 2360
ALICE inel pp √s=2.36TeV
ALICE NSD
CMS NSD
KLN gluon sat. model
η
p+p @ 7000
ALICE inel pp √s = 7 TeV
CMS NSD
KLN gluon sat. model
dNch/dη
η
p+Pb @ 4400
prediction
KLN gluon sat. model, p+Pb mb √s=4.4 TeV
η

ii) $k_\perp$ factorization with rcBK UGDs

BK equation (incl. non-linear terms → saturation of scattering amplitude!)

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

running-coupling kernel (Balitsky prescription)

$$K(\mathbf{r},\mathbf{r_1},\mathbf{r_2}) = \frac{N_c\,\alpha_s(r^2)}{2\pi^2}\left[\frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)}-1\right)+\frac{r^2}{r_1^2\,r_2^2}+\frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)}-1\right)\right]$$

dipole scattering amplitude in adj. rep.

$$\mathcal{N}_A = 2\,\mathcal{N}_F - \mathcal{N}_F^2$$

(dipole) unintegrated gluon distribution:

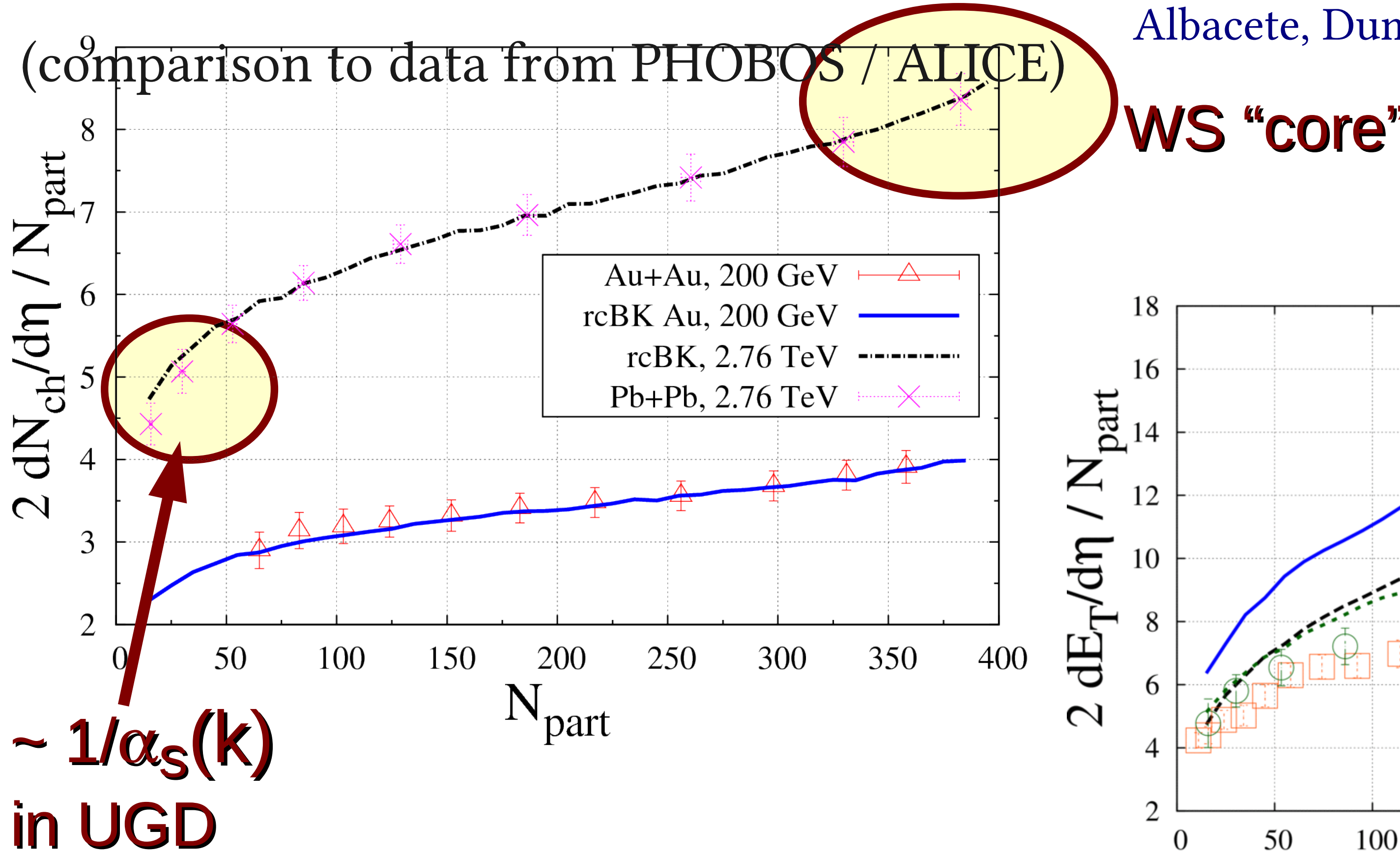
$$\varphi(k,Y;b,A) = \frac{C_F\,k^2}{\alpha_s(k)}\int \frac{d^2\mathbf{r}}{(2\pi)^3}\,e^{-i\mathbf{k}\cdot\mathbf{r}}\mathcal{N}_A(r,Y;b,A)$$

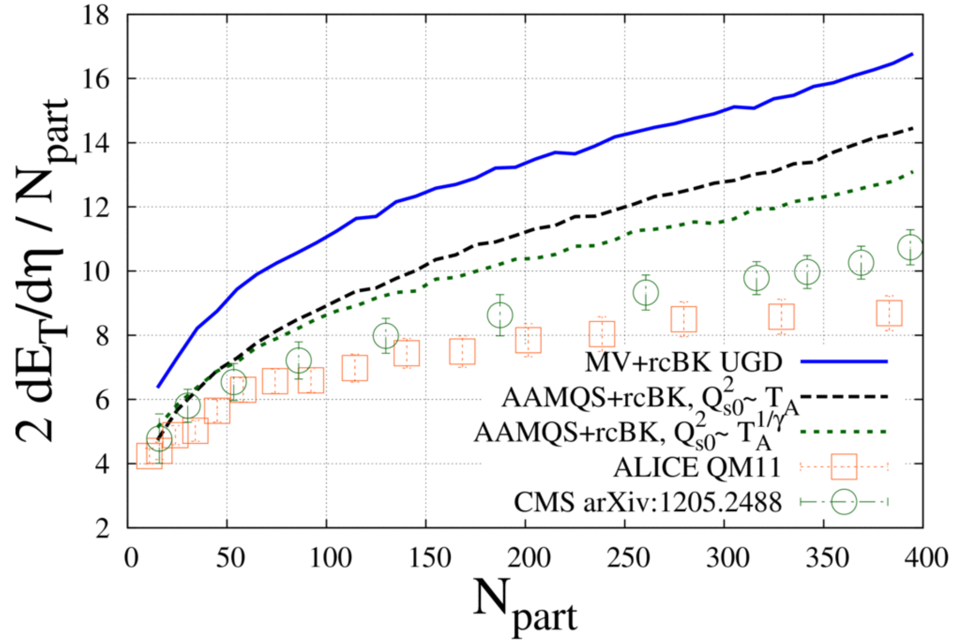
Centrality and energy dependence of multiplicities from rcBK:

Albacete & Dumitru: arXiv:1011.5161

Albacete, Dumitru, Fujii, Nara: in preparation

(comparison to data from PHOBOS / ALICE)

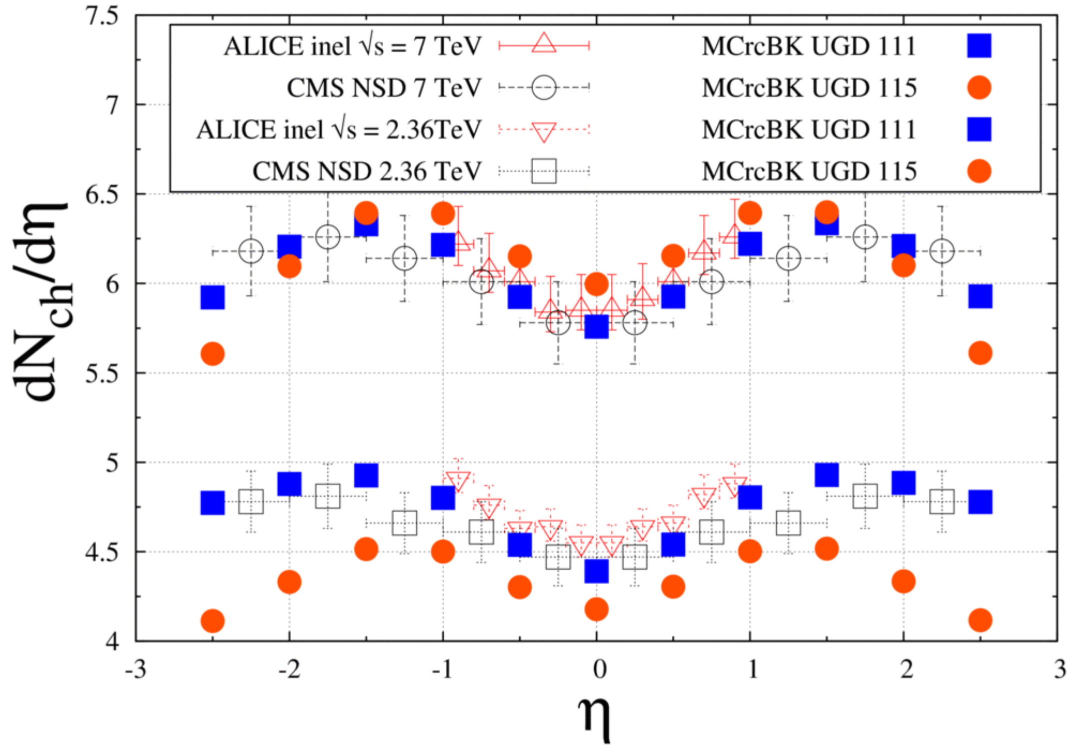


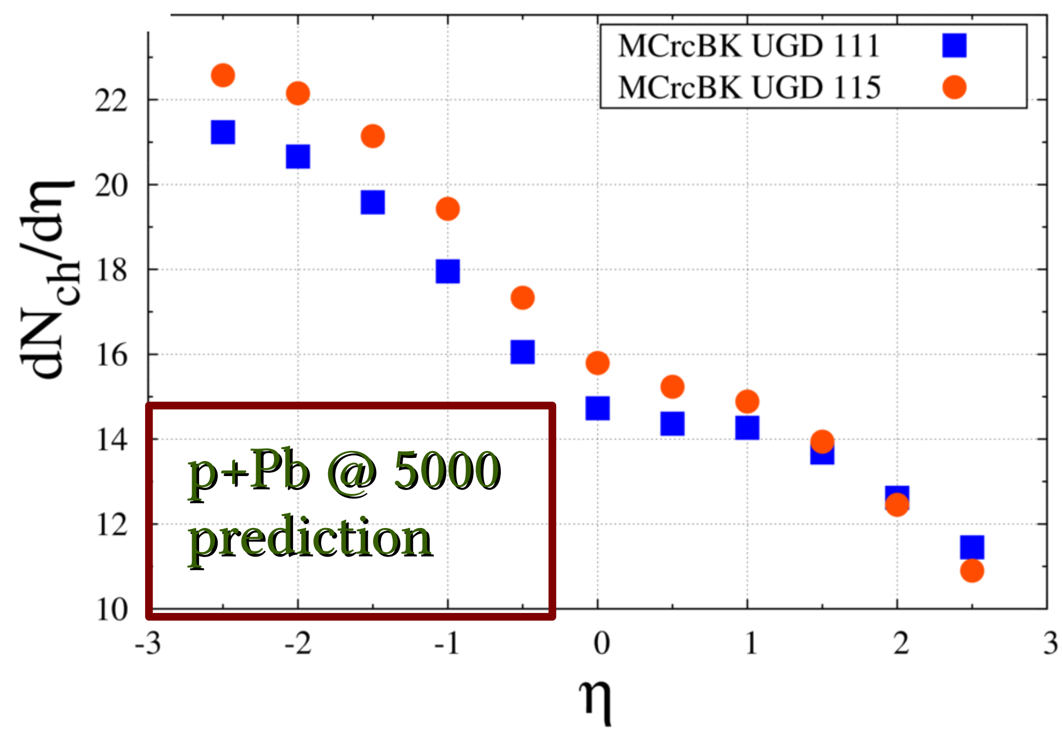


- assumes $N_{hadr} \sim N_{glue}$

- Different UGDs give different E_T !
- Which works best with (viscous) hydro ?

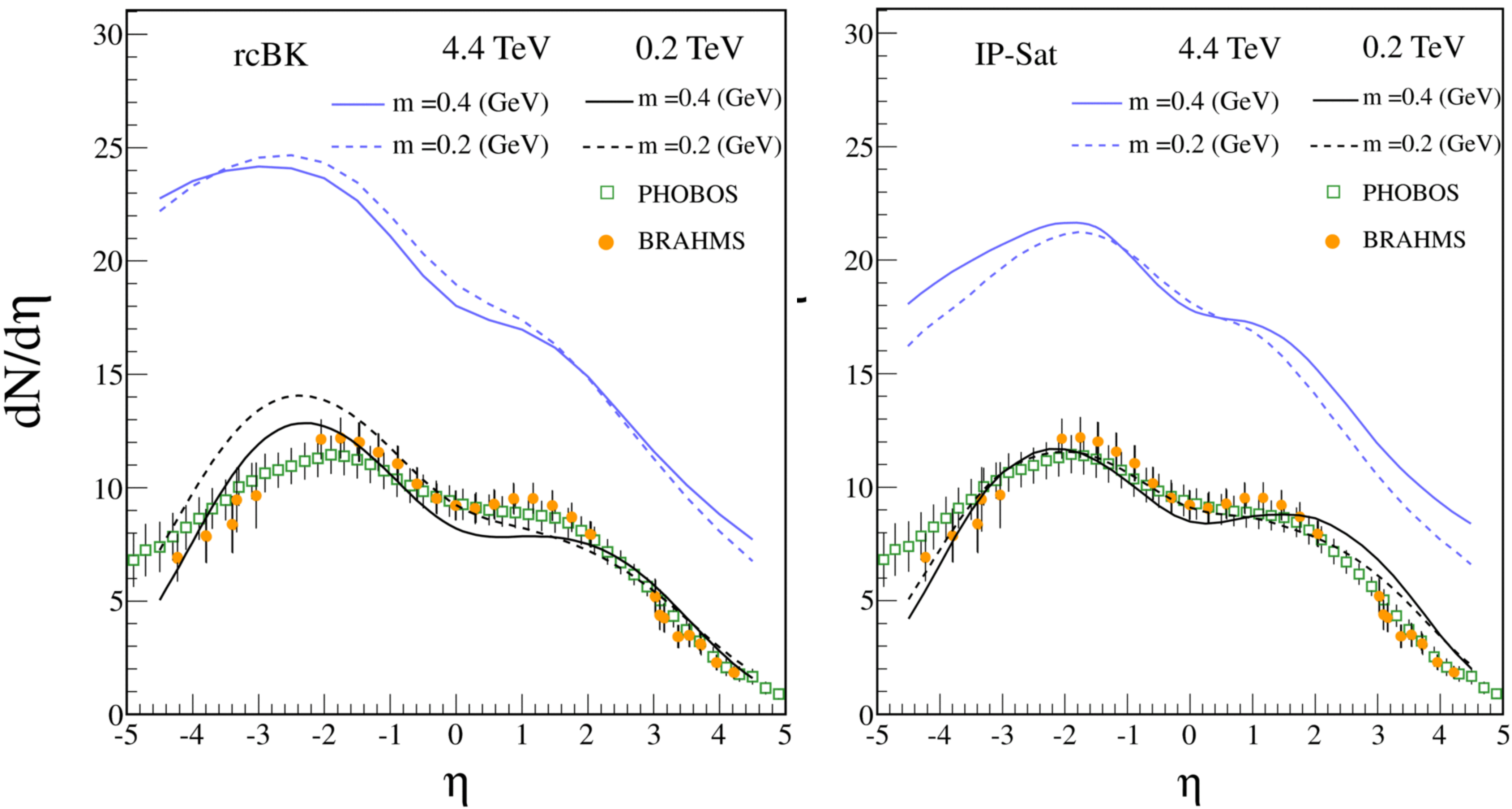
p+p @ 2360, 7000 GeV





IP-Sat model and an independent rcBK study:

Tribedy & Venugopalan: PLB 2012



- CGC based approaches
(constrained by RHIC, LHC-pp & reasonable model for A)
predict similar dN/dη around η~0 for upcoming p+Pb at LHC !

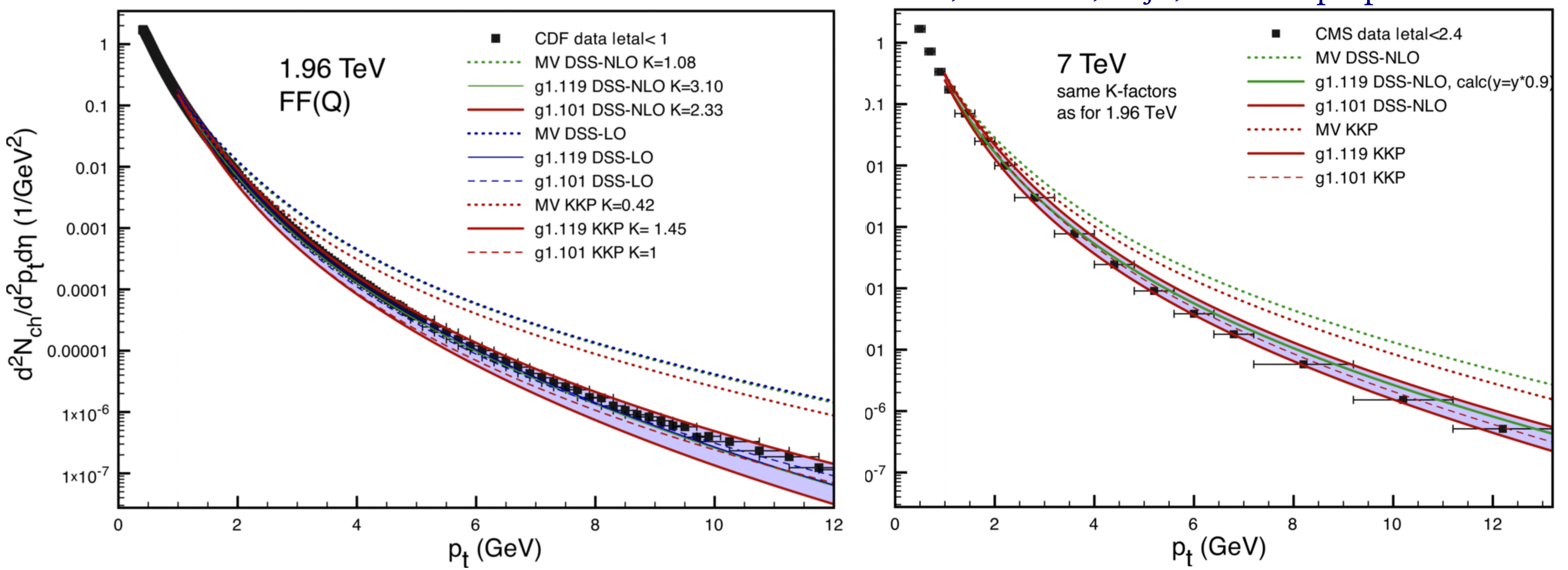
$$\frac{dN_{\rm ch}}{d\eta} \simeq 17 \pm 2$$

(η~0, min bias)

- if ok, we have a very economical description of multiplicities in terms of <u>single</u> scale $Q_s(A,\sqrt{s})$!

Baseline: p_T spectra in pp at high energies

Albacete, Dumitru, Fujii, Nara: in preparation

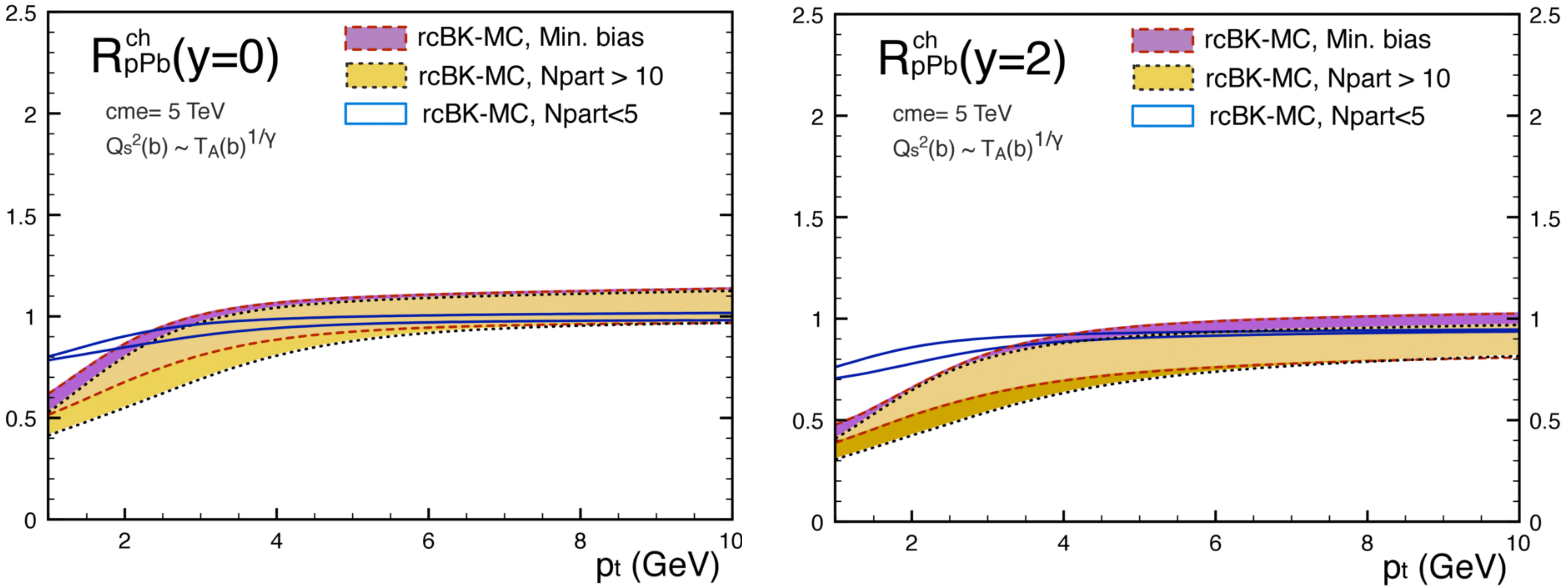


Using AAMQS (Albacete et al.) unintegrated gluon distribution fitted to HERA-DIS !

Initial condition for rcBK evol (γ=1.1 !):

$$\mathcal{N}_F(r, Y=0; b) = 1 - \exp\left[-\frac{\left[r^2\, Q_{s0}^2(b)\right]^{\gamma}}{4} \ln\left(\frac{1}{\Lambda\, r} + e\right)\right]$$

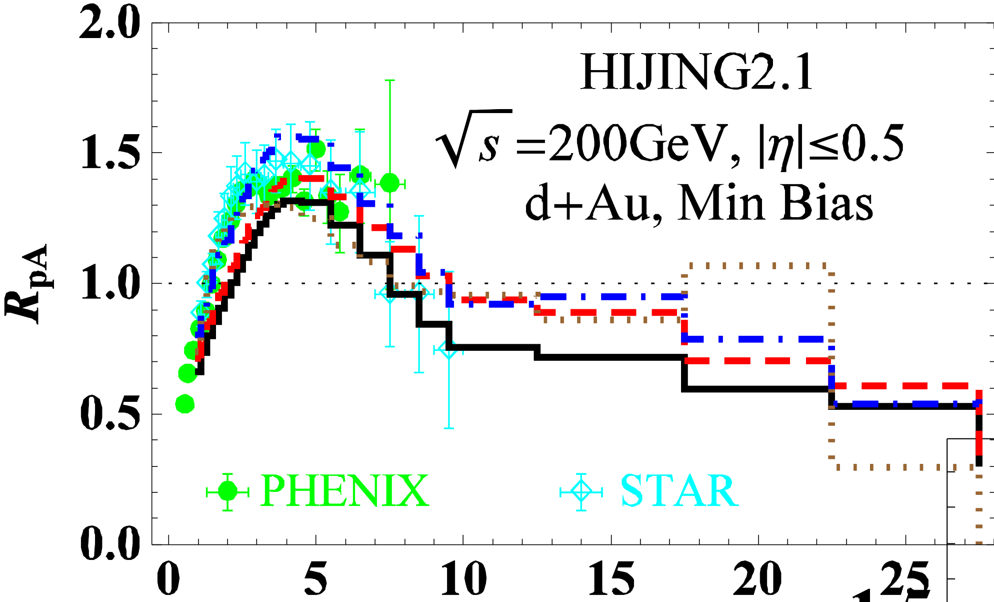
R_{pA} for p+Pb at 5 TeV :



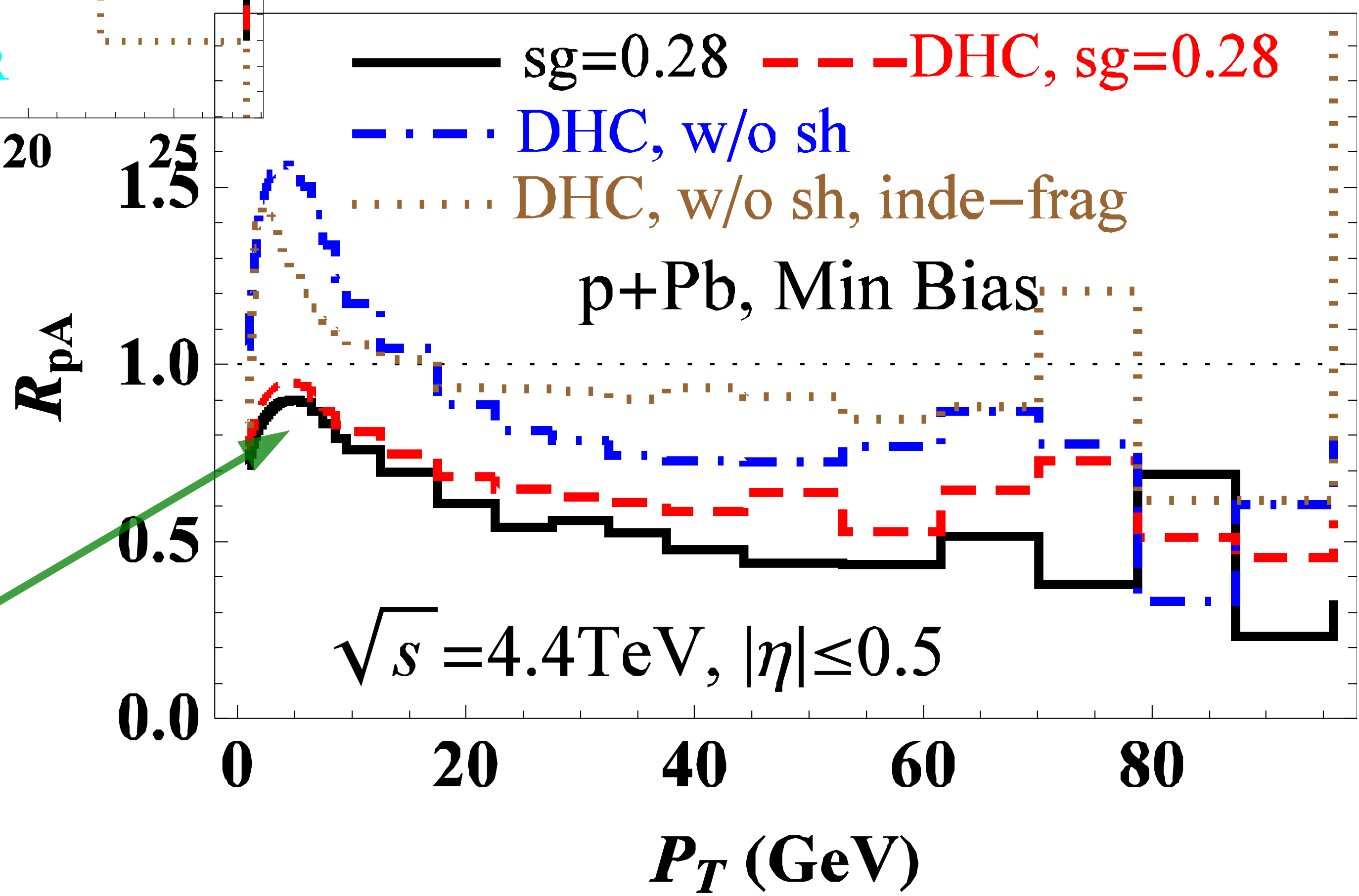
Albacete, Dumitru, Fujii, Nara: in preparation

- $R_{pA} < 1$ at $p_{T(hadron)} \sim$ 1-2 GeV
- R_{pA} decreases (slightly) with rapidity
- generically R_{pA}(central) < R_{pA}(mb)
- Cronin peak washed out by evolution

Hadron spectra modification in pA

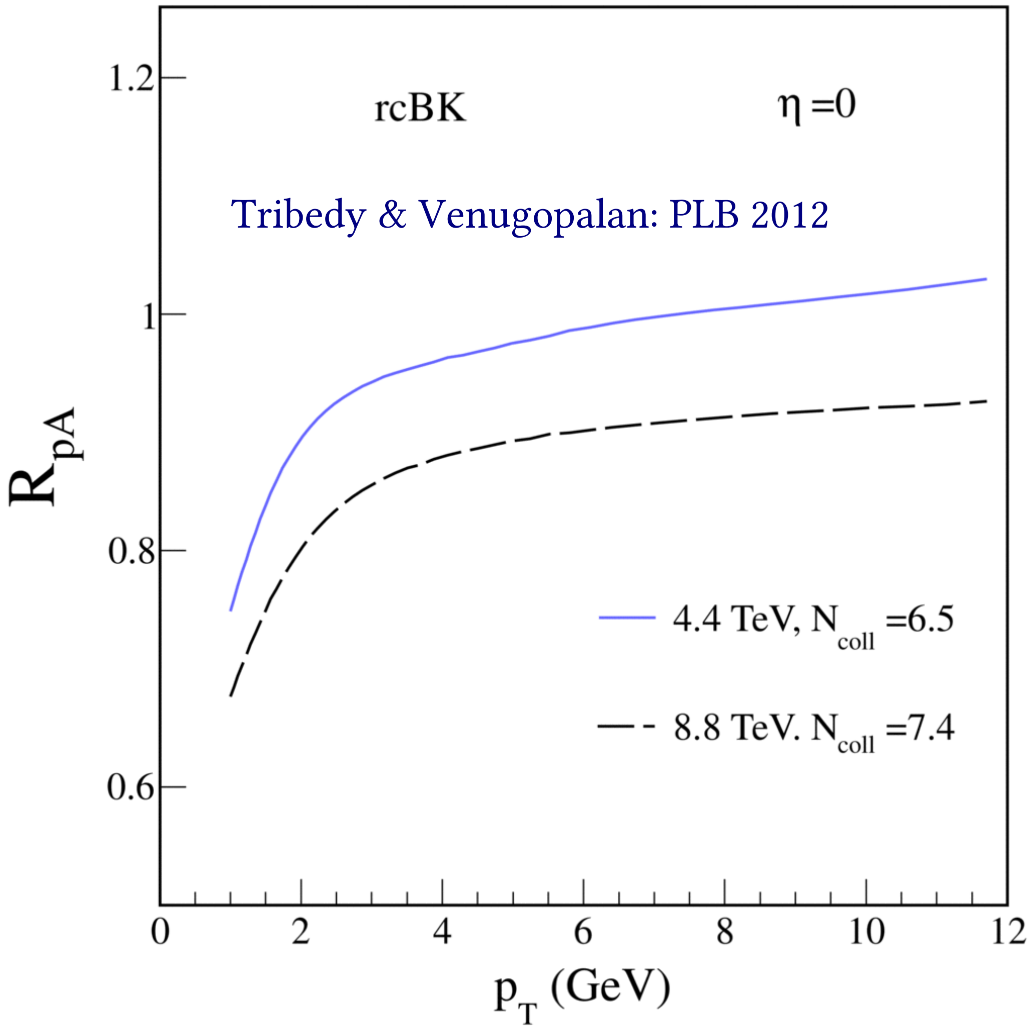


X.-N. Wang: pA @ LHC wkshp, CERN, june 4 – 8, 2012

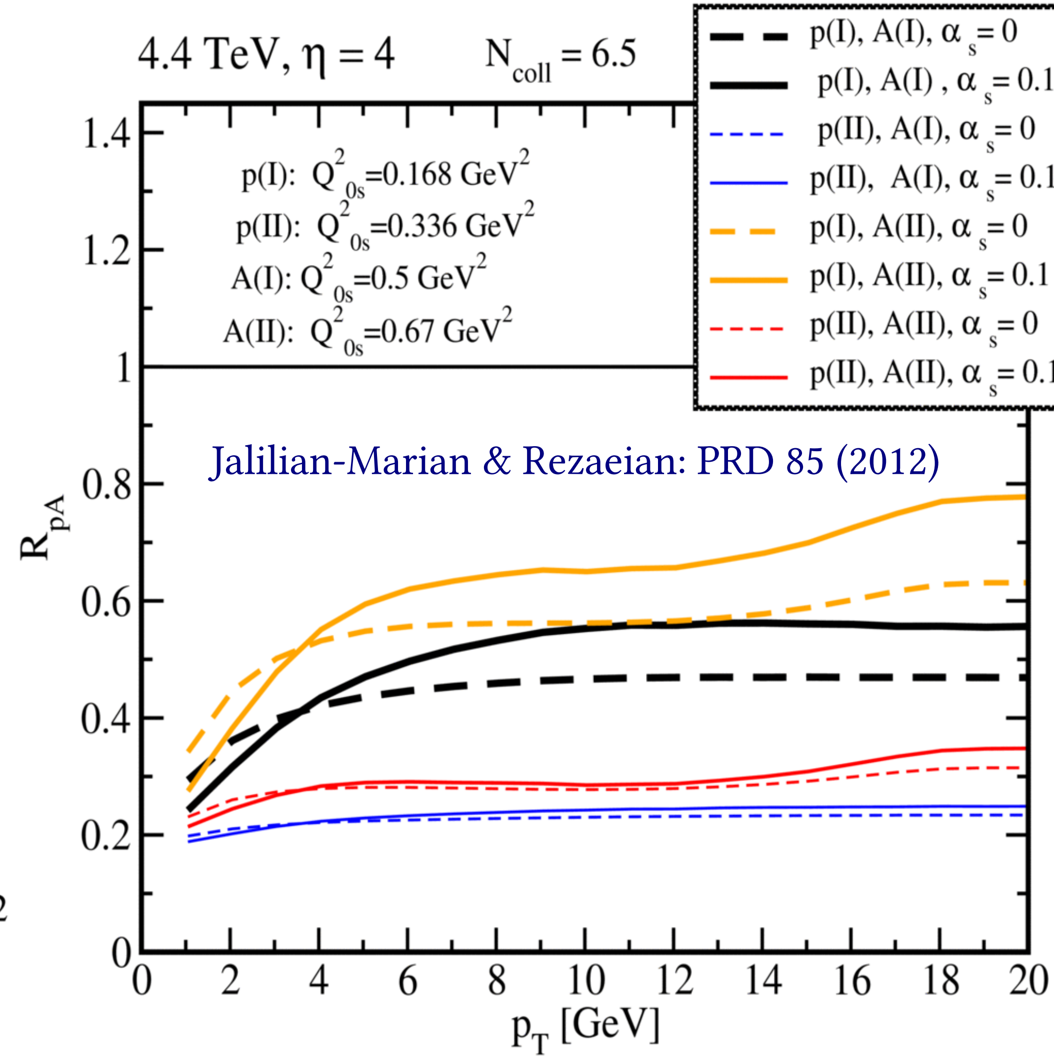


surviving Cronin peak ?

other CGC based predictions for R_{pA} @ LHC, min bias



(with explicit WS geometry)



NLO corrections increase R_{pA} slightly

(note: *implicit* average over WS
assumed N_{coll}=6.5; $(Q_{sA}/Q_{sp})^2$=2-4)

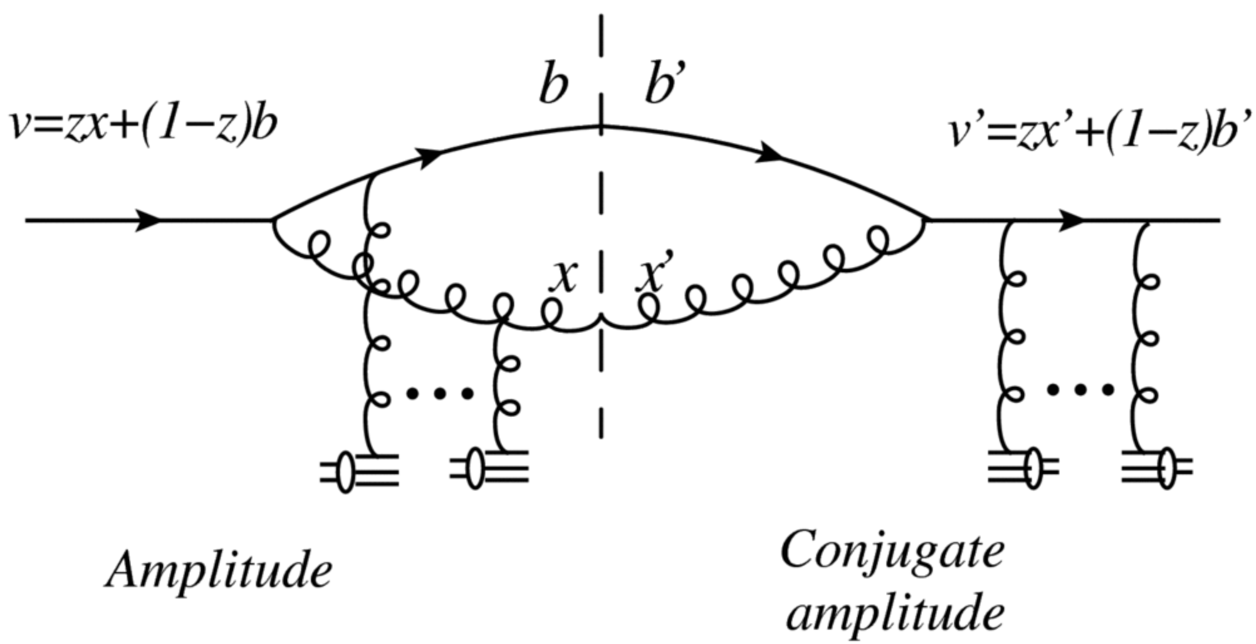
Dihadron angular correlations in pA

involves new objects (higher n-point functions) such as quadrupole:

$$Q \equiv \frac{1}{N_c} \langle \mathrm{tr}\, V_x V_y^\dagger V_u V_w^\dagger \rangle$$

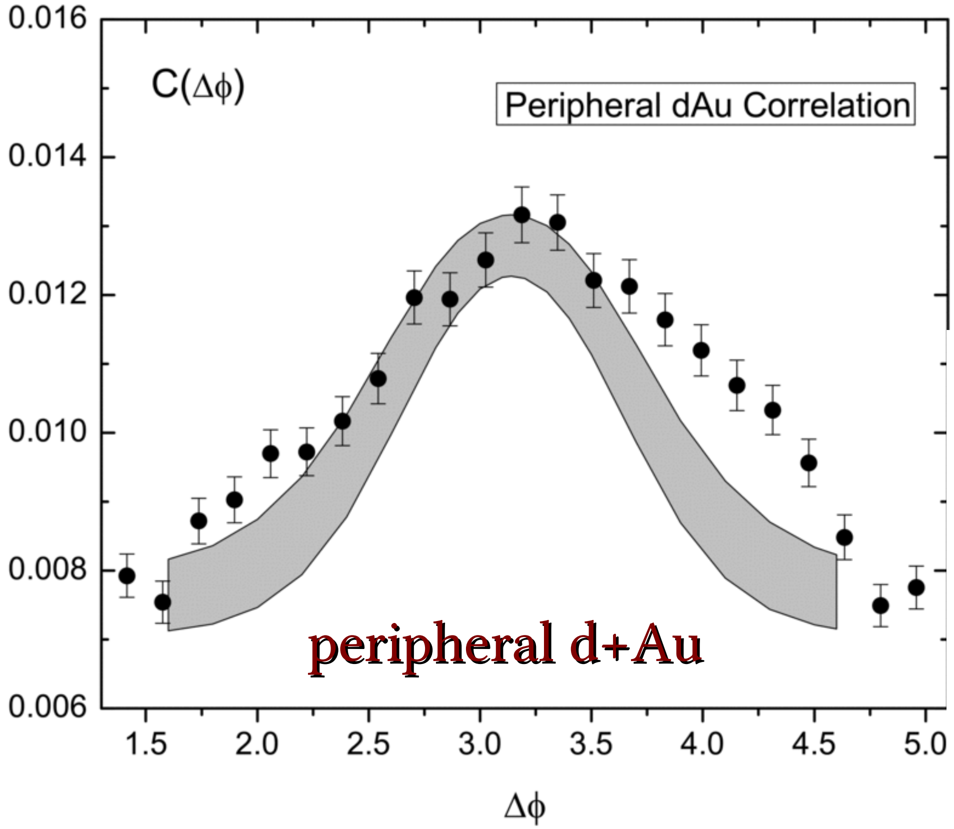
Jalilian-Marian & Kovchegov: PRD (2004)
F. Dominguez et al.: PRD (2011)

Talk by T. Lappi at QM12 !

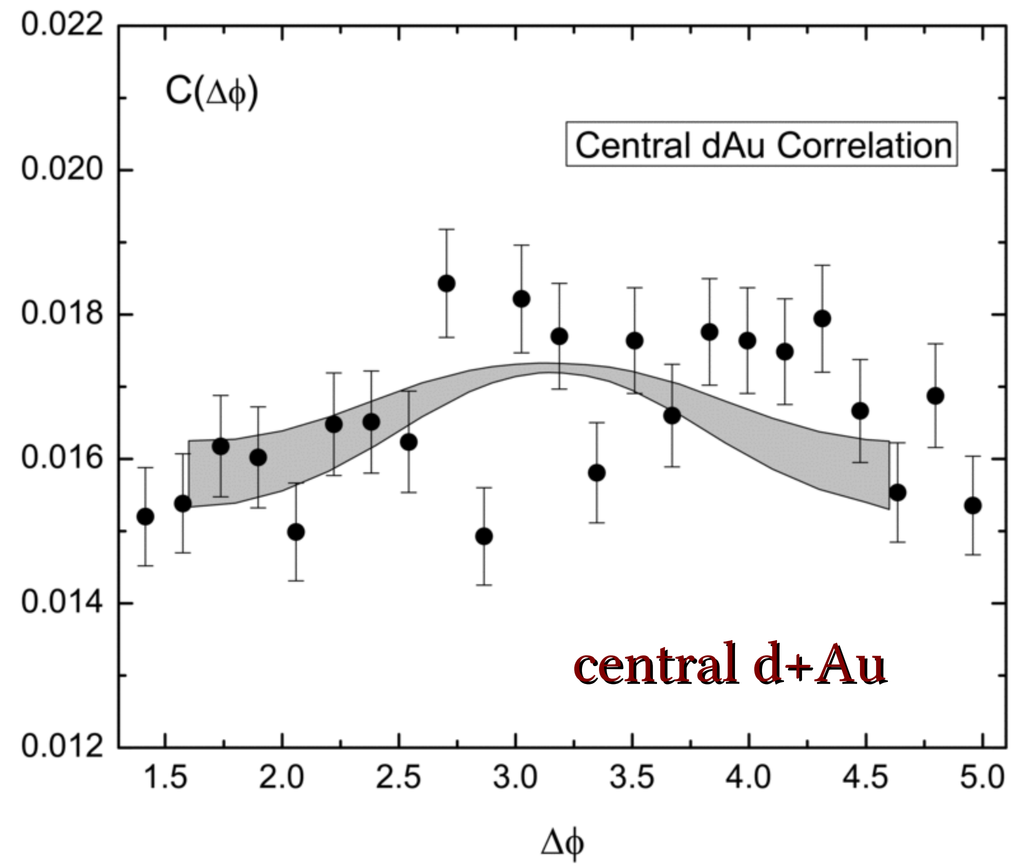


Angular decorrelation for dense target

Stasto, Xiao, Yuan: arXiv:1109.1817



Talk by B. Xiao at QM12 !



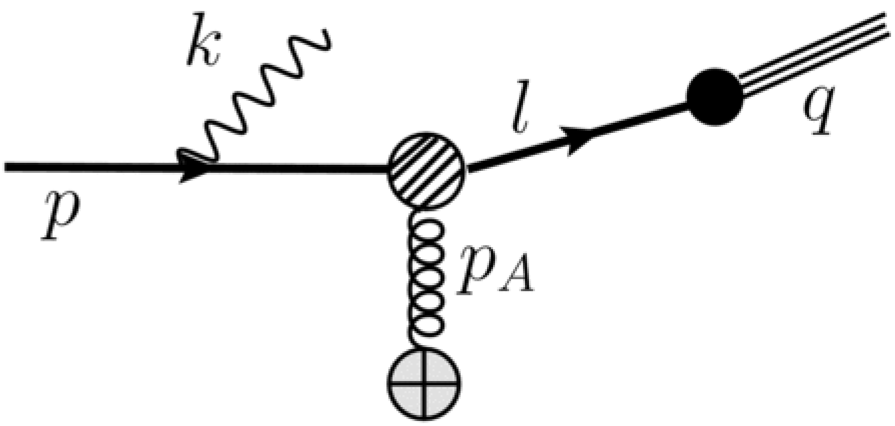
$y_1 \sim y_2 \sim 3.2$

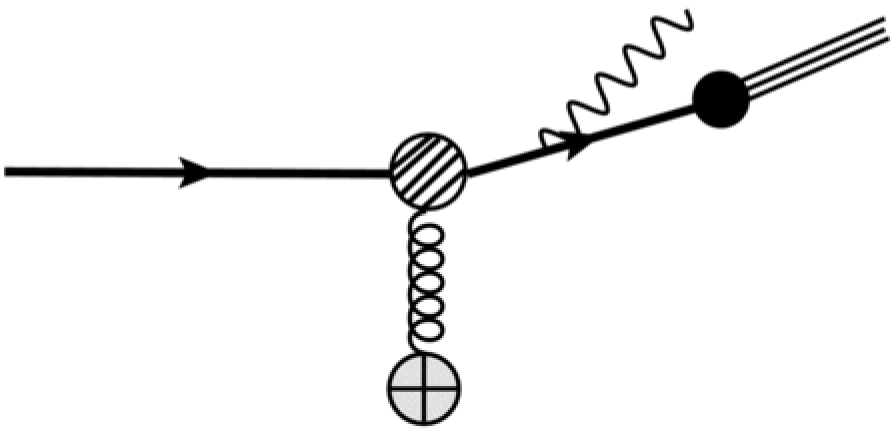
γ-hadron angular correlations in pA

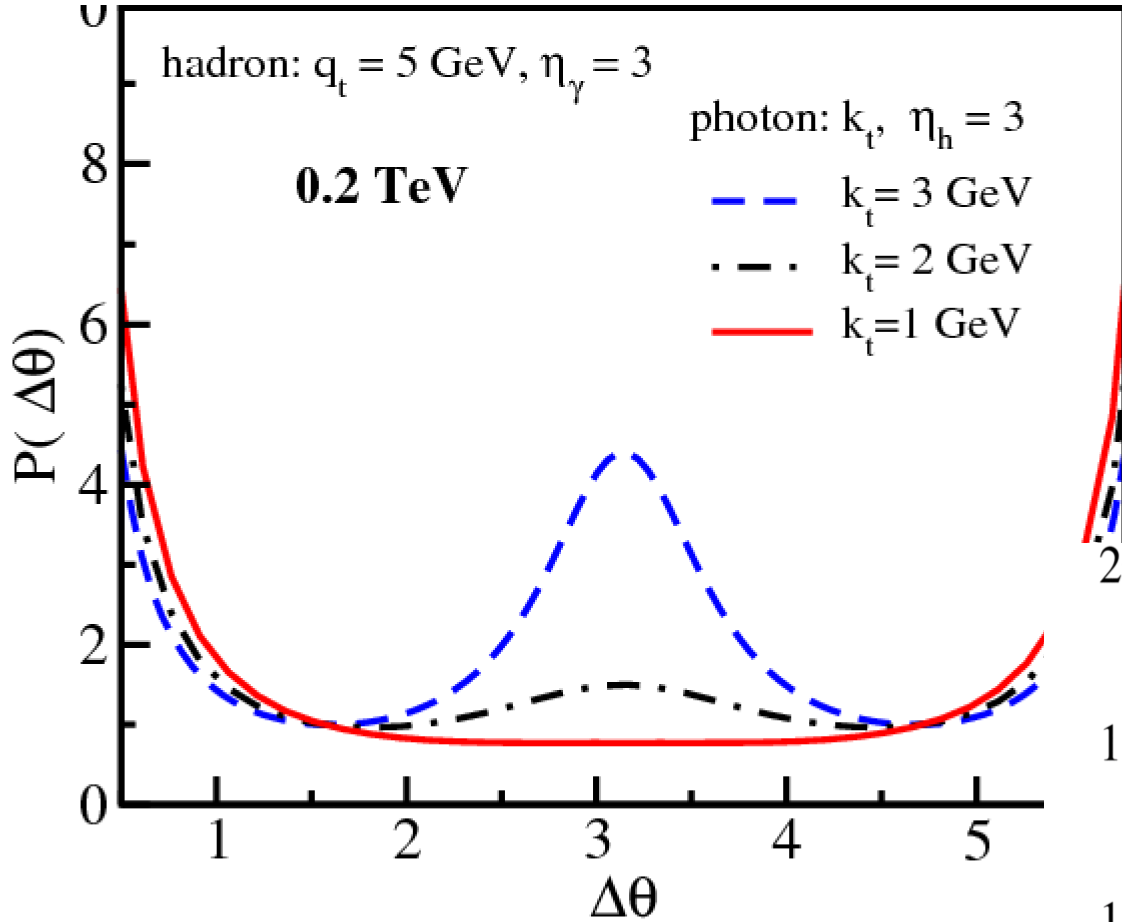
Jalilian-Marian and Rezaeian: arXiv:1204.1319

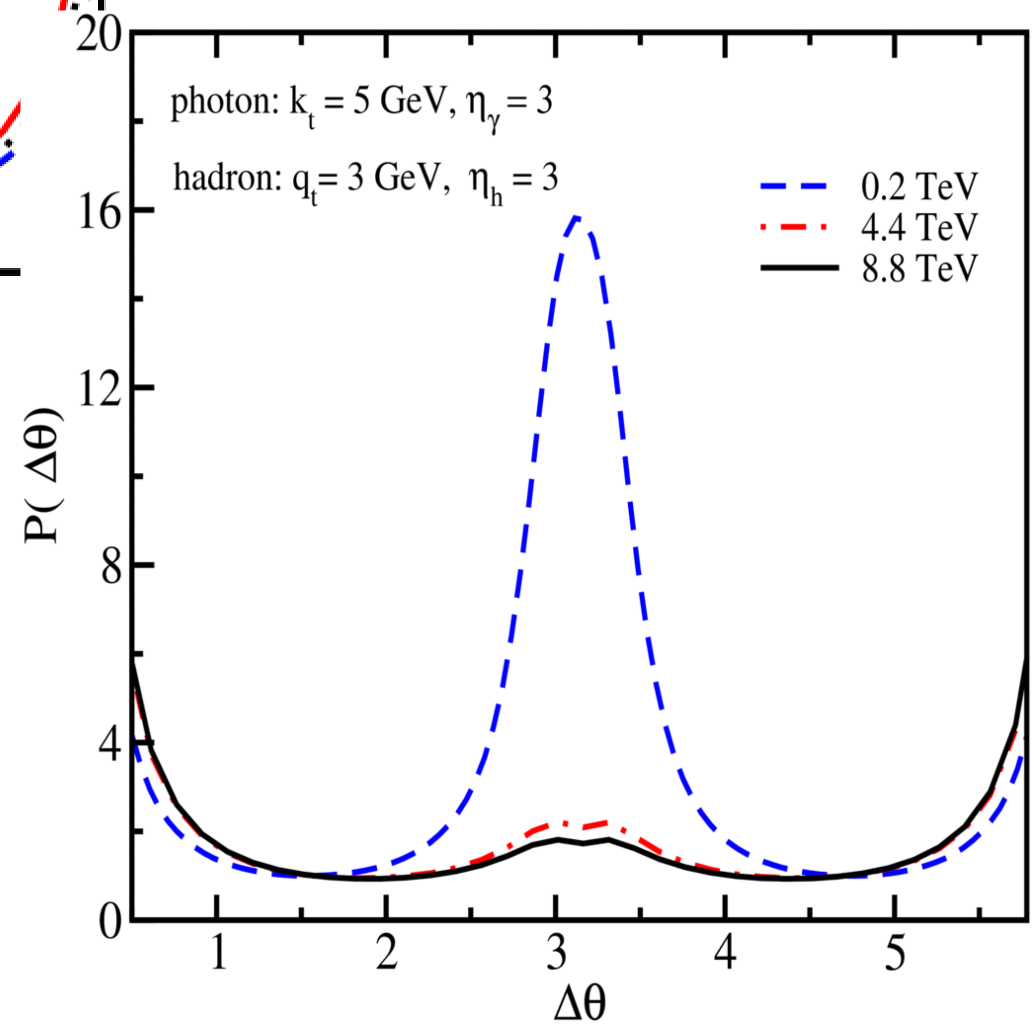
Talk by J. Jalilian-Marian at QM12 !

involves only uGD / 2-point function (rcBK):





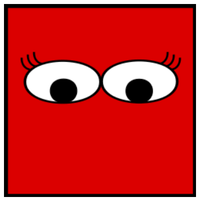




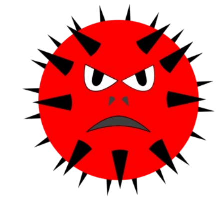
back-to-back peak disappears with

- lower k_T
- higher energy

Summary / Outlook



Currently, all CGC eyes are on p+Pb @ LHC!



Physics:

- RHIC ⟶ LHC: open up phase space for virtual gluon fluctuations !
- LHC can probe k_T tails at small $x \leq 10^{-2}$
- effective MV-type action for hard "valence" charges $S = \int d^2r\, dy\, (\rho^2+\rho^4)$
- rcBK resummation of average (dipole) density; full NLO needed ?
- fluctuations: KNO & hydro initial condition
- higher n-point correlation functions (Quadrupole)

Observables:

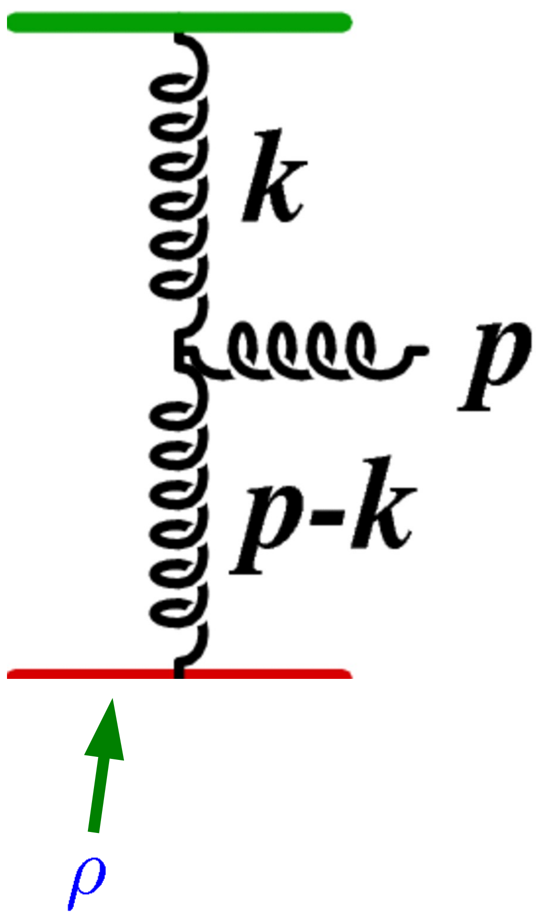
- multiplicity $dN_{ch}/d\eta$
- multiplicity distribution P(n)
- nuclear modification factor $R_{pPb}(p_T,y)$
- h-h and γ-h angular correlations

More on eA, pA and future of CGC: Talk by C. Marquet at QM12 !

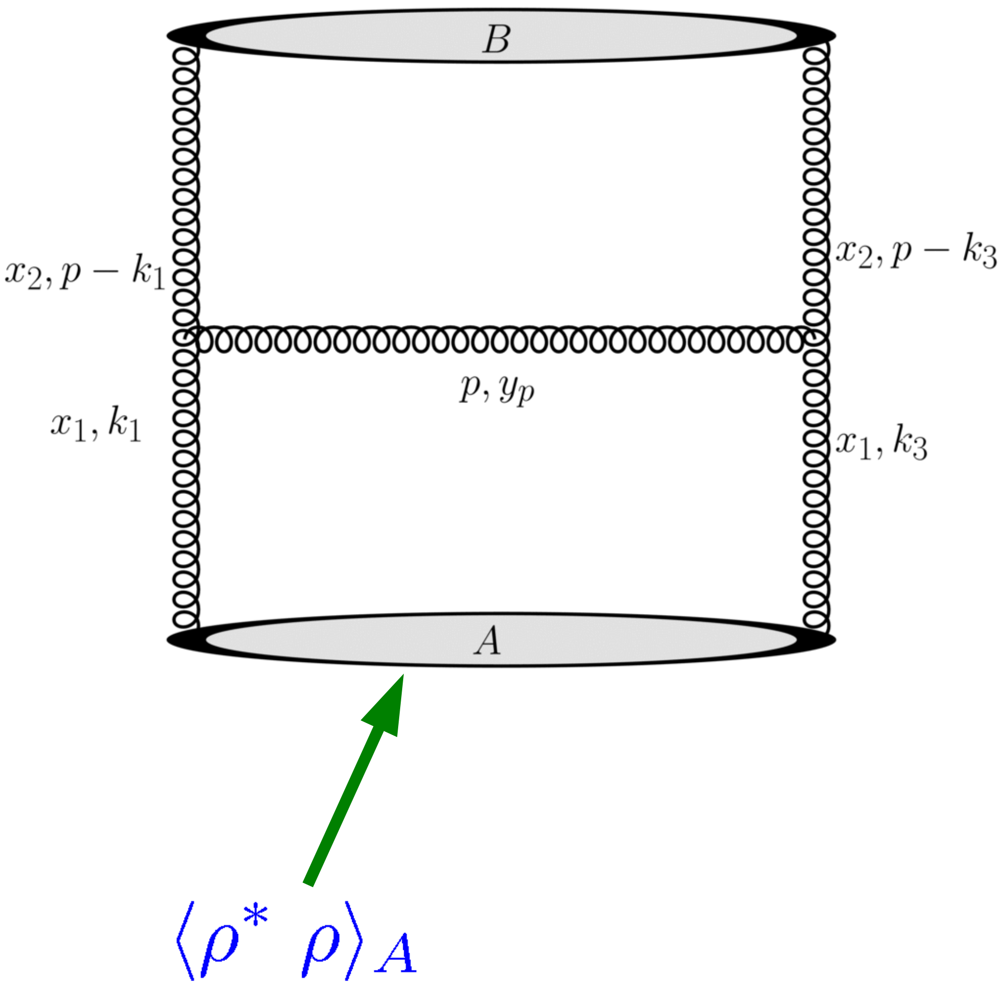
Backup Slides

Single-inclusive production (at LO in ρ):

amplitude



|amplitude|^2

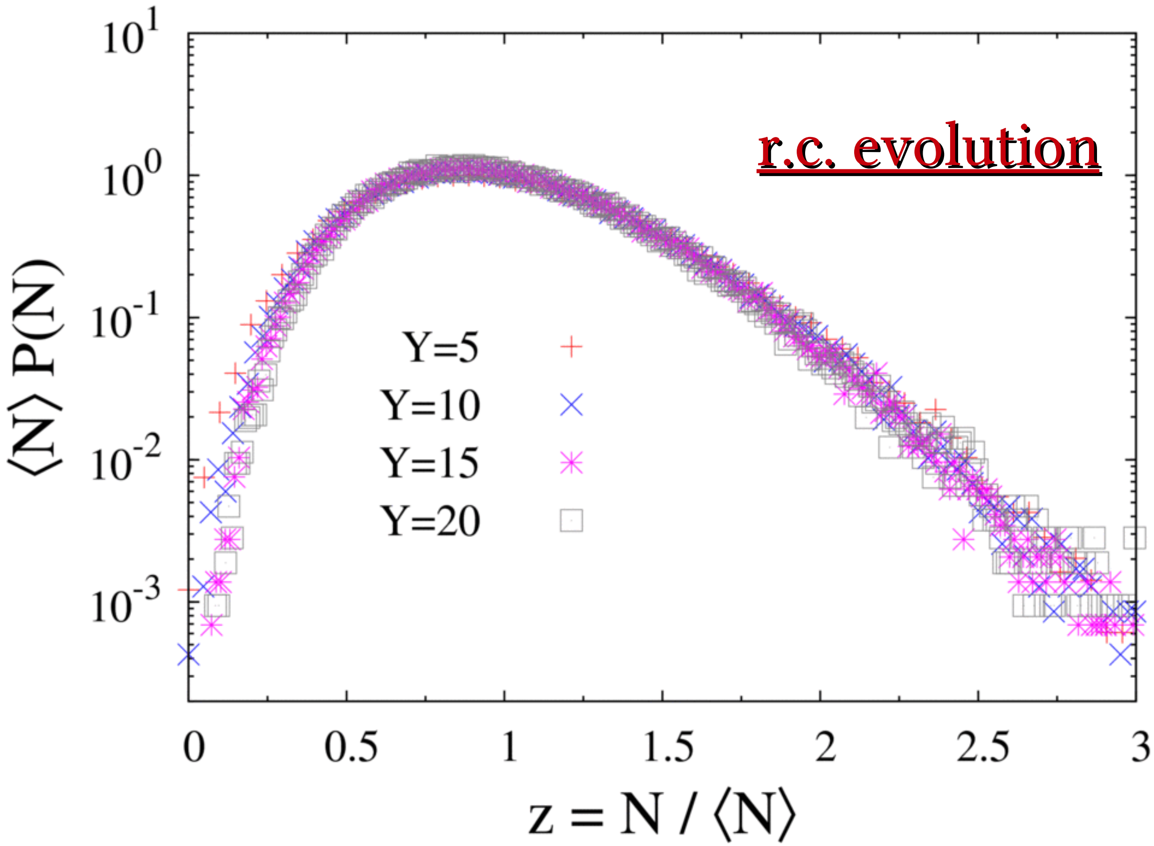


Dipole evolution with fluctuations & saturation

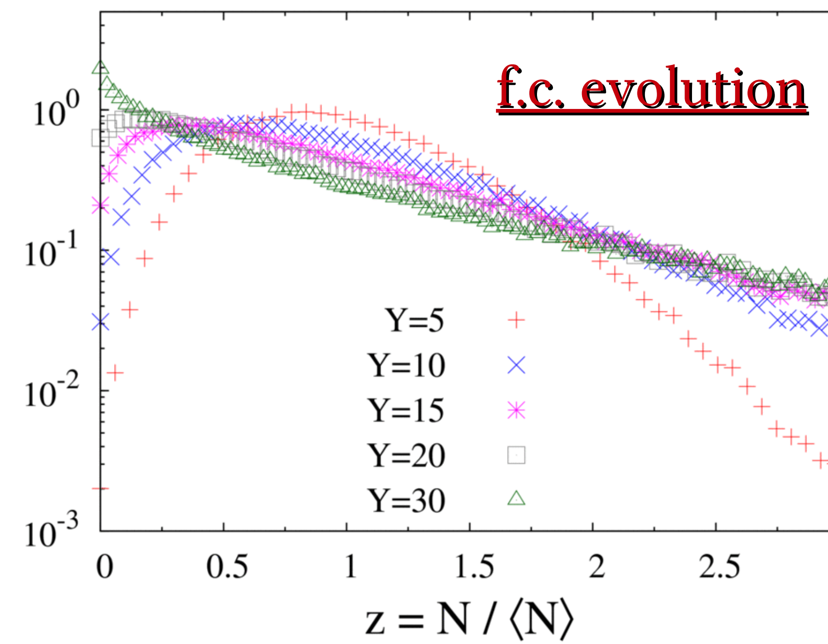
(Iancu, Kovner, Lublinsky, Mueller, Munier, Shoshi, Triantafyllopoulos, ...)

running coupling version: A. Dumitru et al., JHEP (2007)

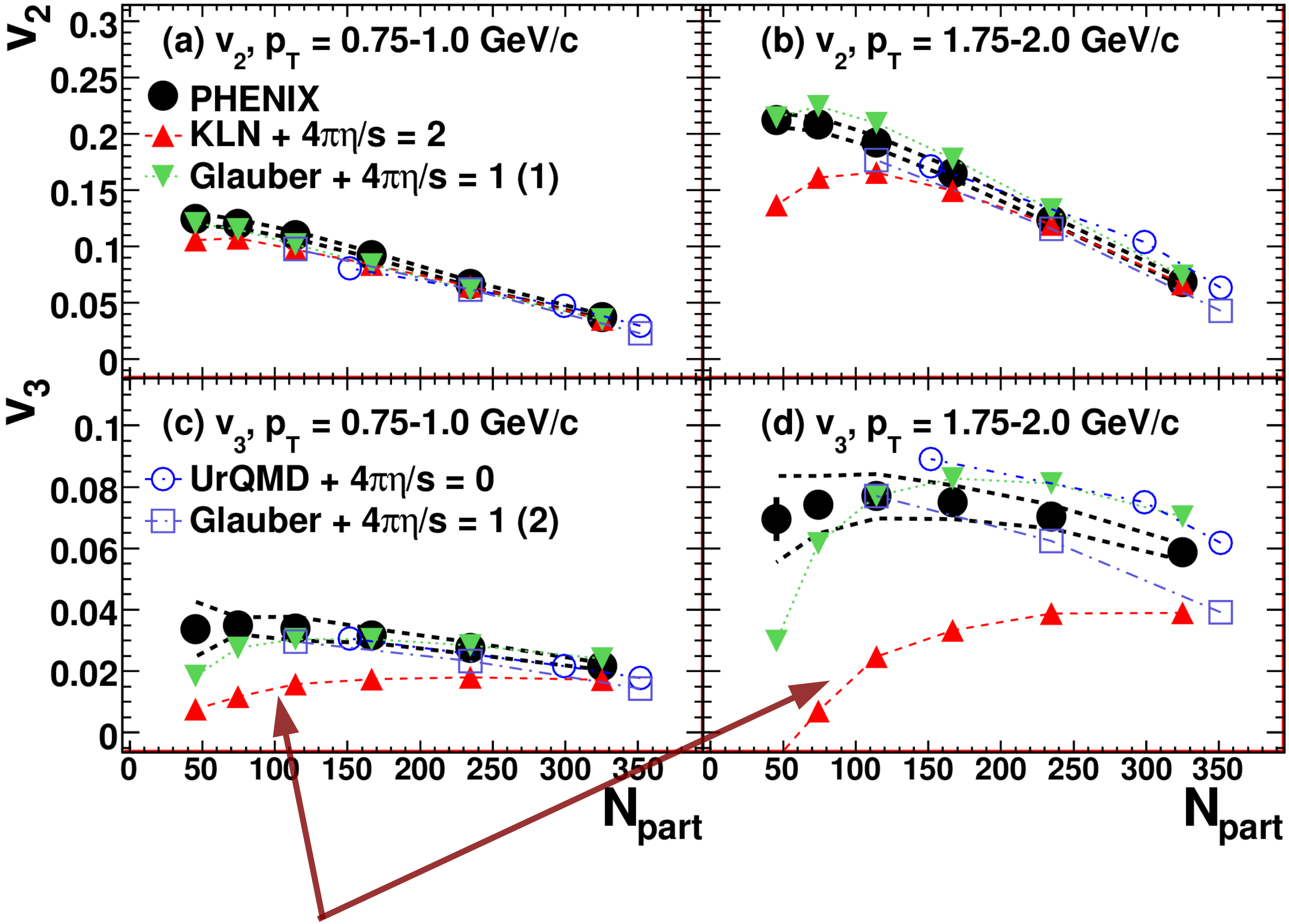
distribution of dipole number in target, $r \le 1/Q_s$



- r.c. evolution satisfies KNO !
- f.c. evolution too strong diffusion



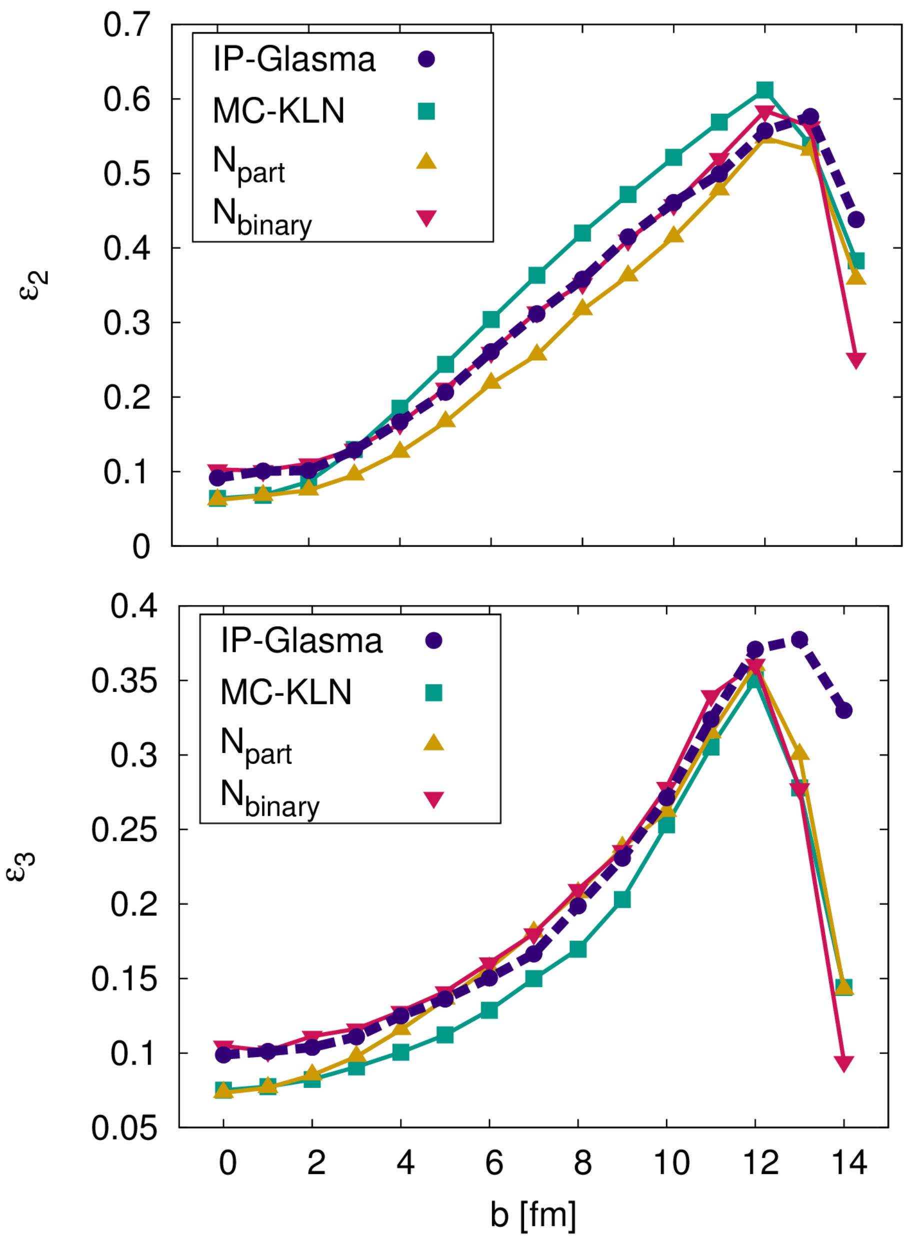
Phenix Collab., PRL 2011



- MC-KLN initial condition (k_T factorization with **Glauber fluct. only**) underestimates v_3 !

Classical YM solutions w/ fluctuating initial conditions (incl. NBD !)

Schenke, Tribedy, Venugopalan, arXiv:1202.6646

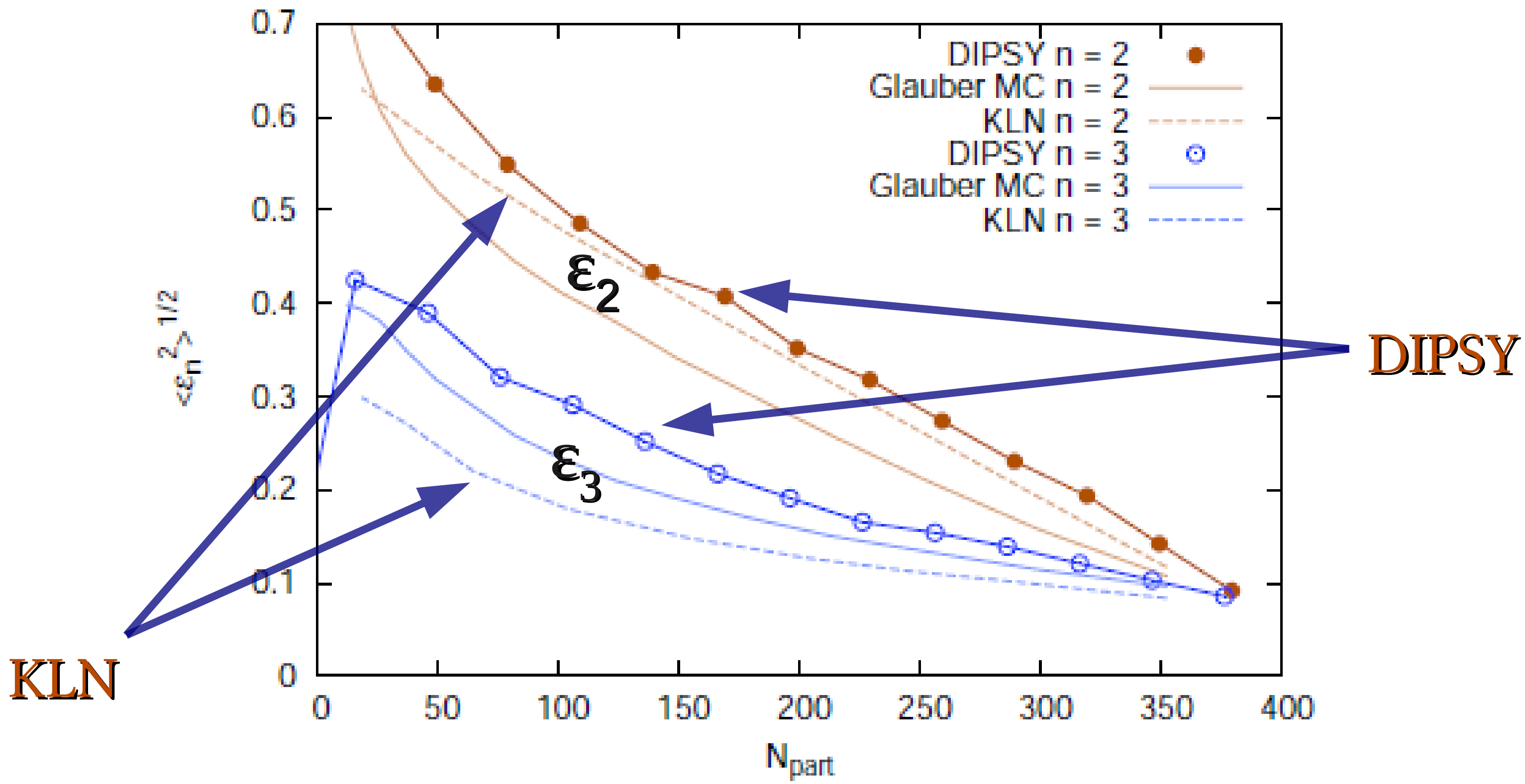


- lower ε_2 than MC-KLN
- higher ε_3

DIPSY MC (Lund) w. fluctuations in BFKL ladders

Results: $\varepsilon_2, \varepsilon_3$

C. Flensburg: ISMD 2011, Hiroshima



compare DIPSY <-----> MC-KLN:
ε_2 similar, ε_3 larger

- does DIPSY reproduce KNO in pp, pA ?