CGC predictions for R_{pA}, multiplicities and KNO scaling in pA@LHC

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pA @ LHC, June 4-8, 2012

Energy and centrality dependence of multiplicities

i) KLN model

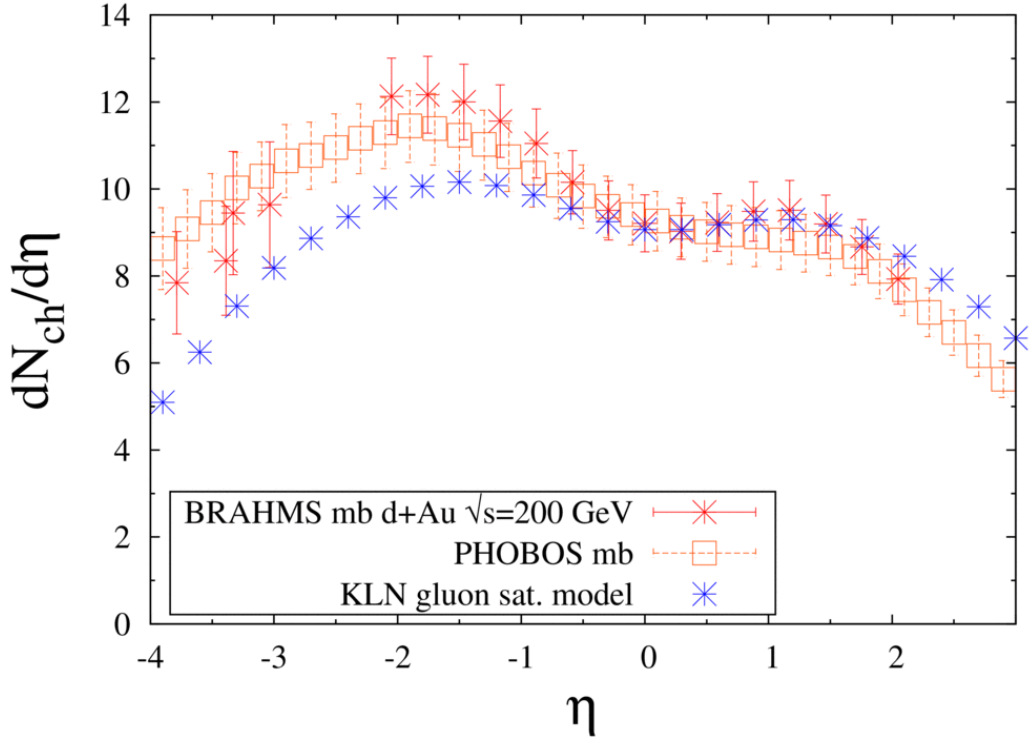
(updated predictions from arXiv:1111.3031)

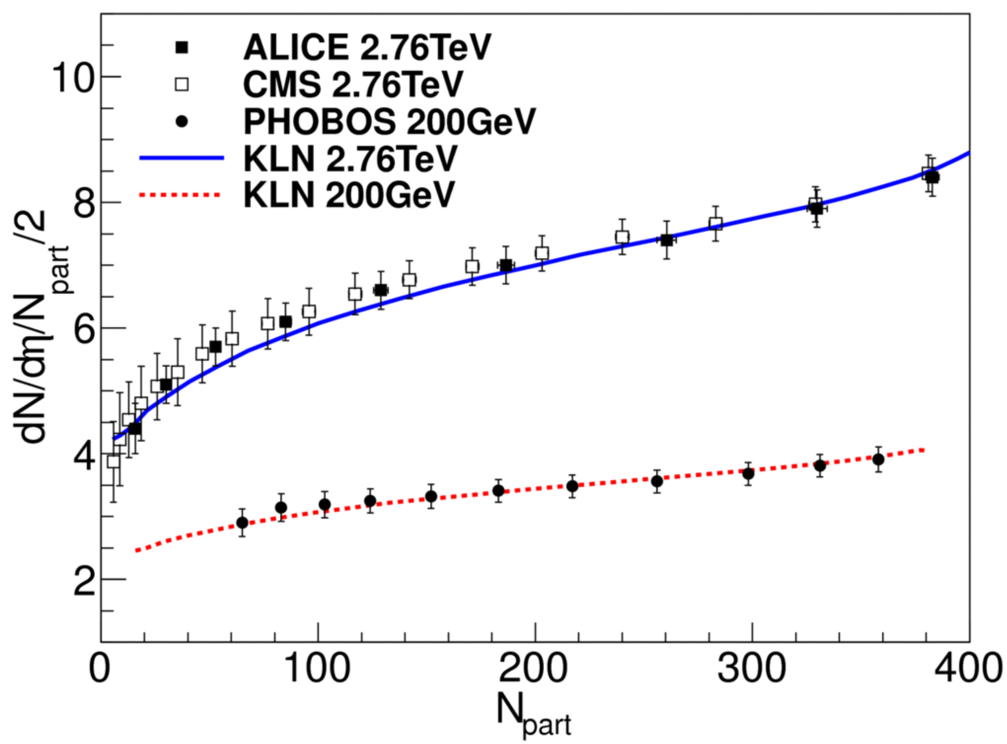
$$\frac{dN}{dy} = K \, \frac{4\pi N_c}{N_c^2 - 1} \int d^2 r_t \int_0^\infty \frac{d\,p_t^2}{p_t^4} \; \alpha_s \; x_2 G_{A_2}(x_2, p_t^2) \; x_1 G_{A_1}(x_1, p_t^2)$$

with

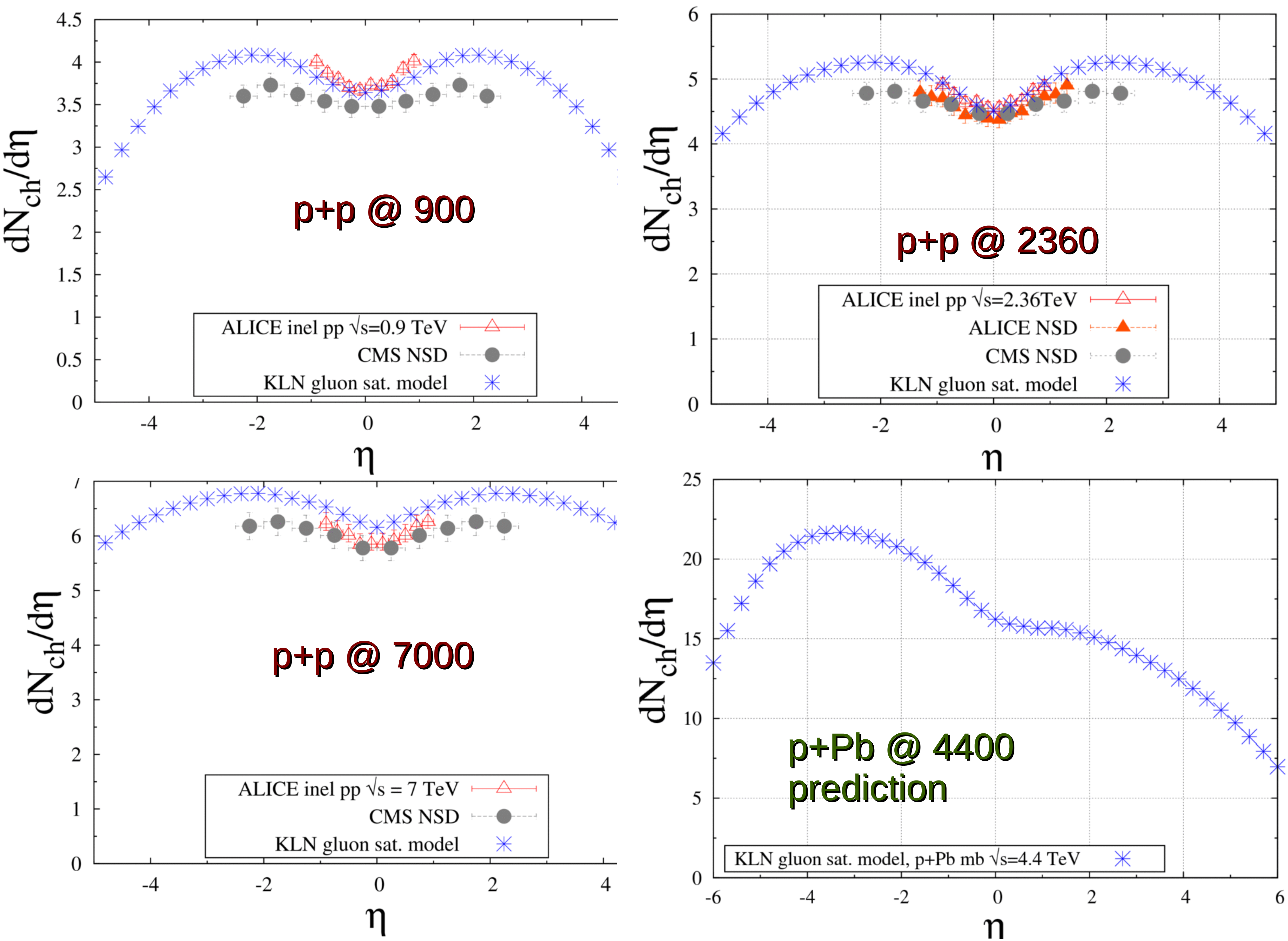
$$xG(x, p_t^2) = \begin{cases} \frac{1}{\alpha_s(Q_s)} \, p_t^2 \;\; (1-x)^4 & , \quad p_t < Q_s(x) \\ \frac{1}{\alpha_s(Q_s)} \, Q_s^2 \;\; (1-x)^4 & , \quad p_t > Q_s(x) \end{cases}$$

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





- probe $A^{1/3}$ and $\sqrt{s}$ dependence of Q_s


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

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

(generalized) unintegrated gluon distribution:

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

$k_\perp$-factorization, multiplicity in A+B --> g+X

(generalized) unintegrated gluon distribution:

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

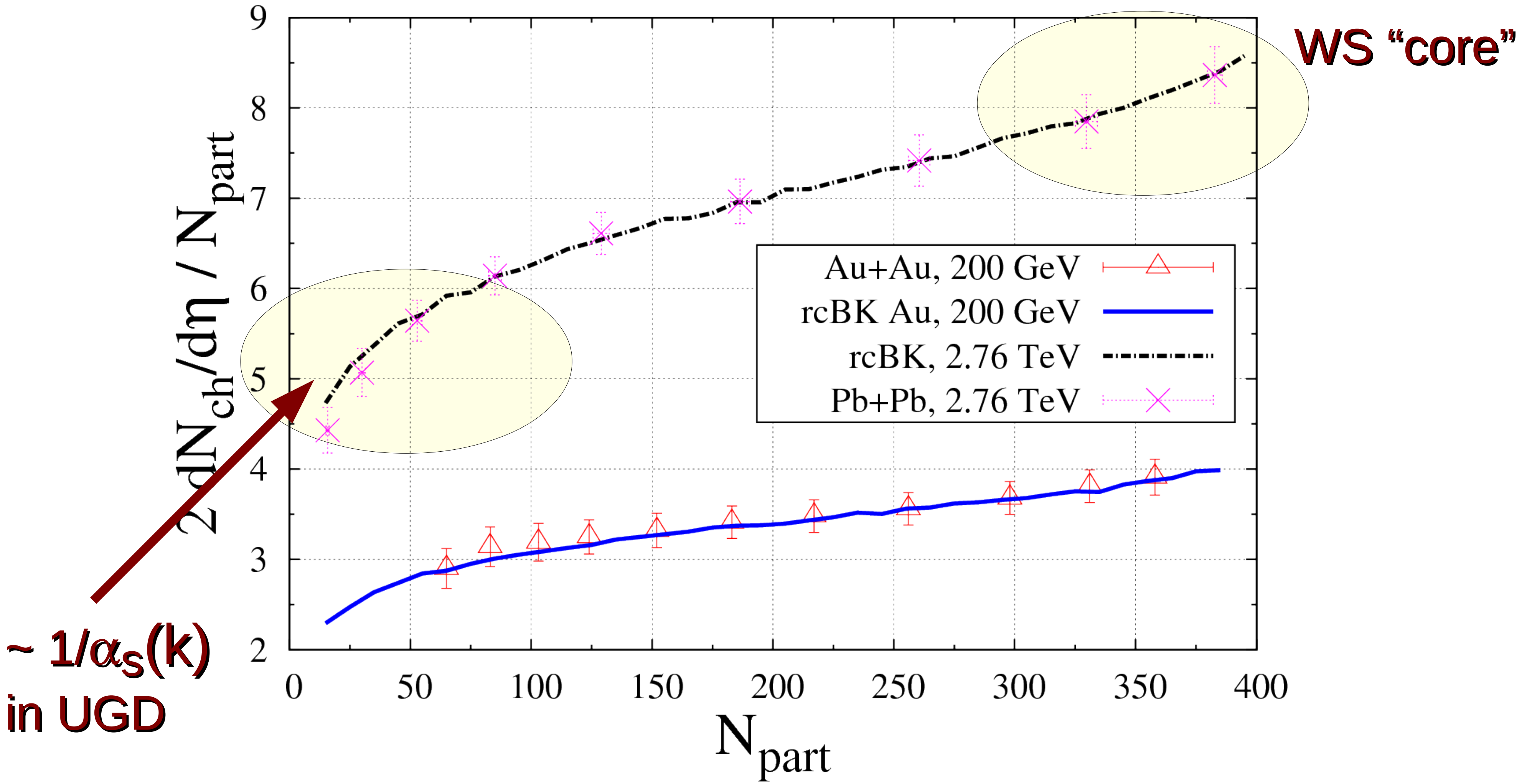
multiplicity: (Kharzeev, Levin, Nardi ansatz)

$$\frac{dN^{A+B\to g}}{dy\, d^2b} = K\, \frac{1}{2C_F} \int \frac{d^2p_t}{p_t^2} \int^{p_t} d^2k_t \; \alpha_s(Q)\, \varphi\left(\frac{|p_t+k_t|}{2}, x_1\right) \varphi\left(\frac{|p_t-k_t|}{2}, x_2\right)$$

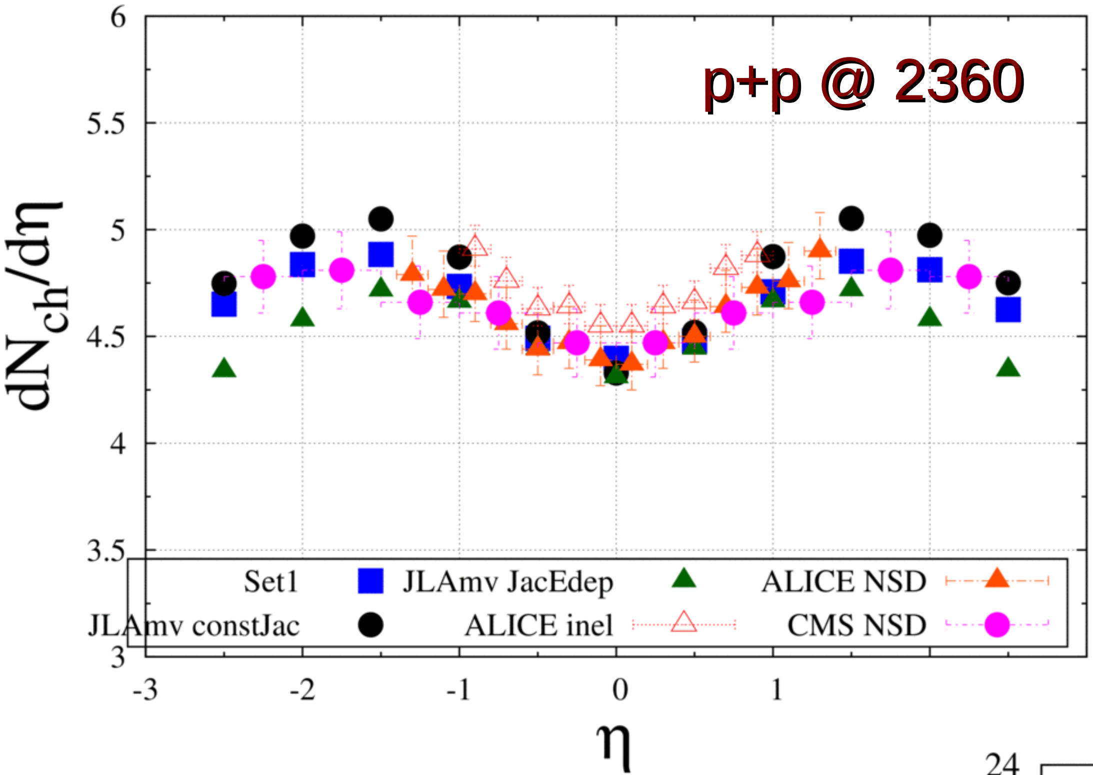
- finite at $p_t \to 0$ if UGD does not blow up
- $x_{1,2} = (p_t/\sqrt{s})\exp(\pm y)$; $Y_{1,2} = \log(x_0/x_{1,2})$ where $x_0=0.01$ is assumed onset of rcBK evol.

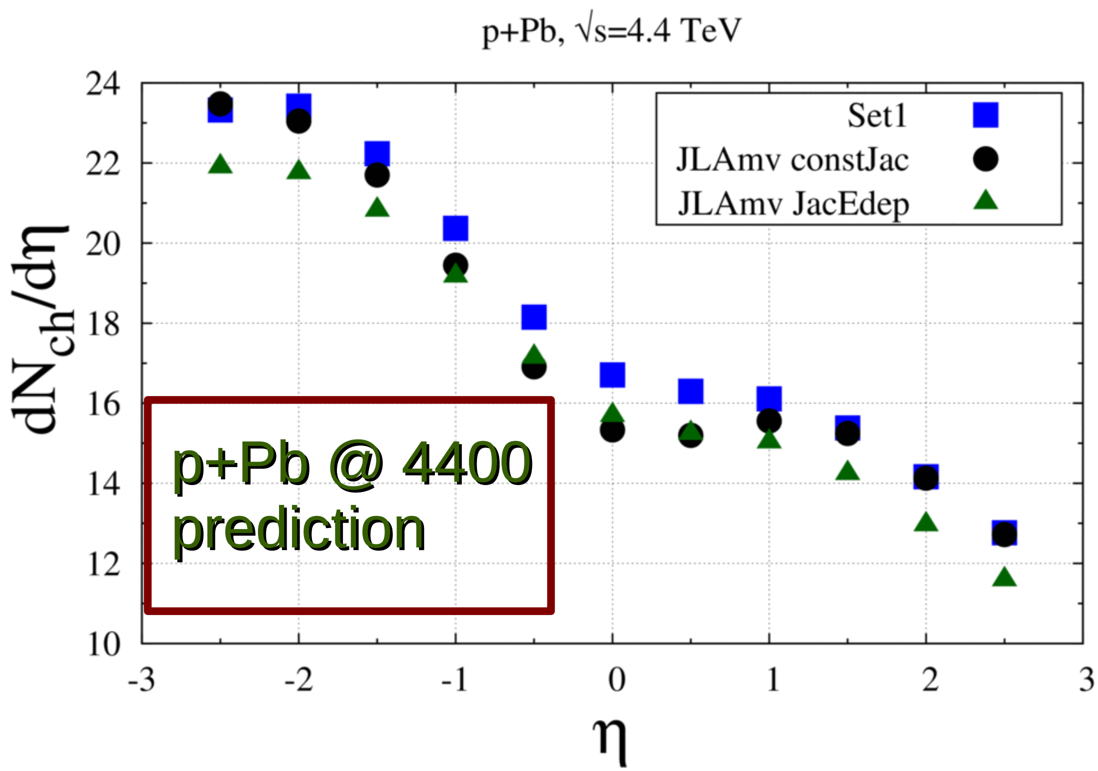
AA : centrality and energy dependence of multiplicities

Albacete & Dumitru: arXiv:1011.5161



- assumes N_{hadr} ~ N_{glue}

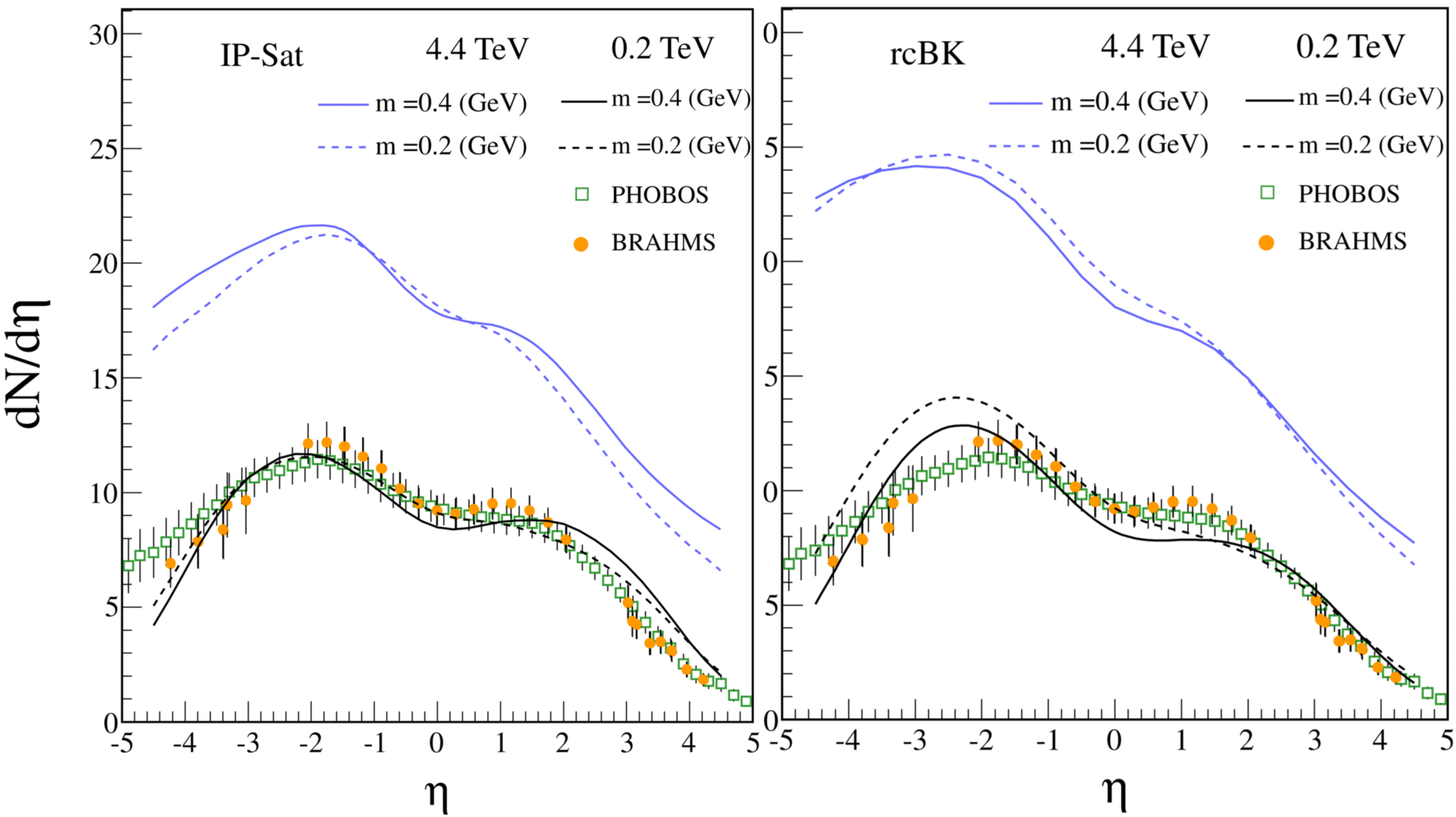


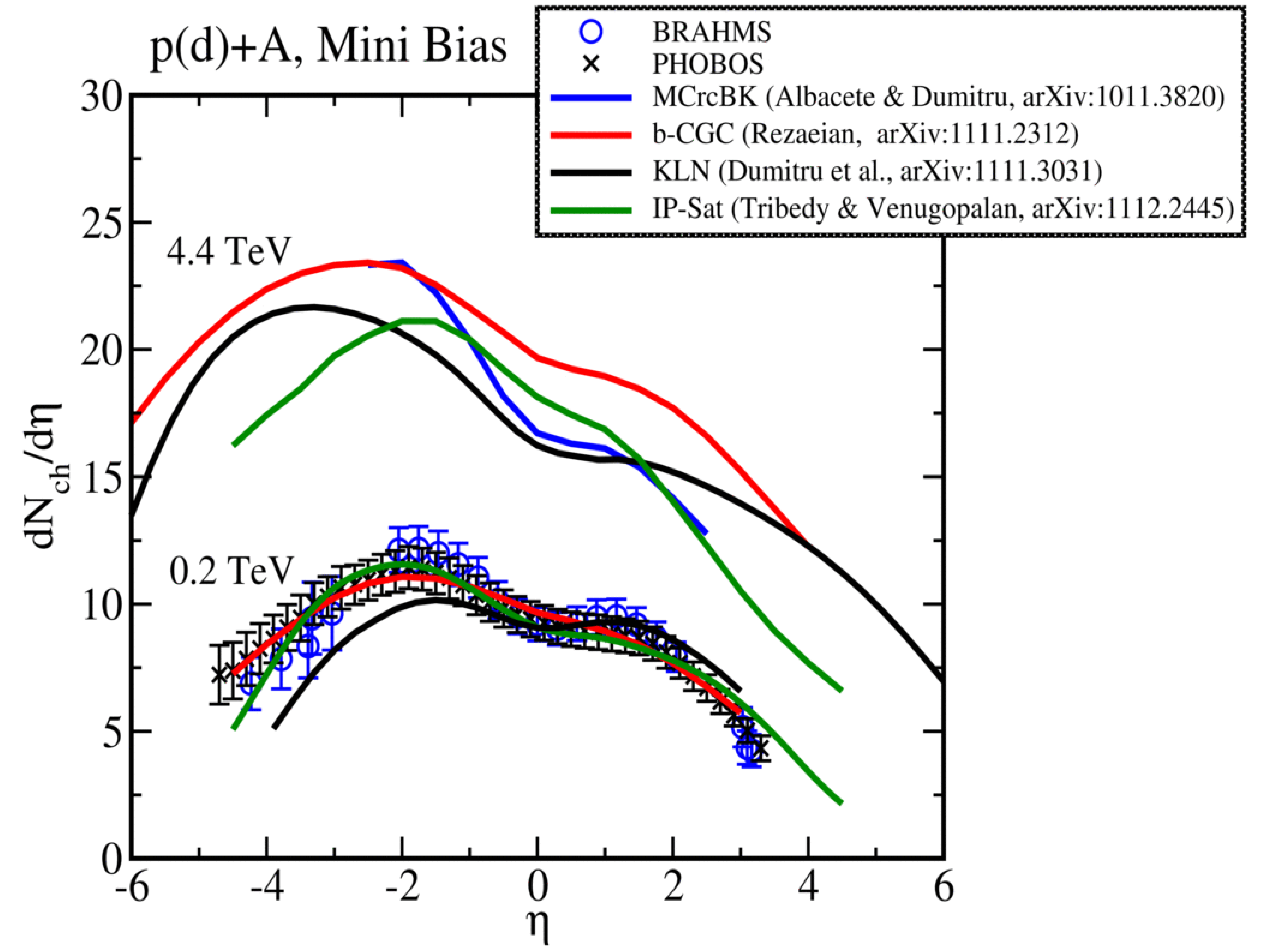


if dN/dη works out, we have a very economical description of multiplicities in terms of <u>single</u> scale $Q_s(A,\sqrt{s})$

IP-Sat model and an independent rcBK study:

Tribedy & Venugopalan: arXiv:1112.2445





p(d)+A, Mini Bias
BRAHMS
PHOBOS
MCrcBK (Albacete & Dumitru, arXiv:1011.3820)
b-CGC (Rezaeian, arXiv:1111.2312)
KLN (Dumitru et al., arXiv:1111.3031)
IP-Sat (Tribedy & Venugopalan, arXiv:1112.2445)
4.4 TeV
0.2 TeV
dN_ch/dη
η
30
25
20
15
10
5
0
-6
-4
-2
0
2
4
6

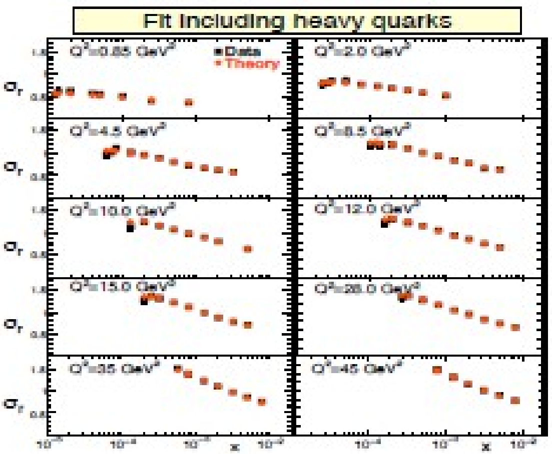
- CGC based approaches (constrained by RHIC, LHC-pp & reasonable model for A) predict similar dN/dη around η~0 for upcoming p+Pb at LHC !

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

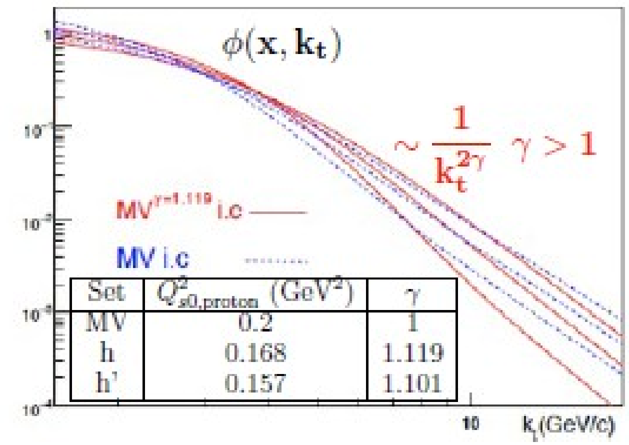
(η~0, min bias)

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

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

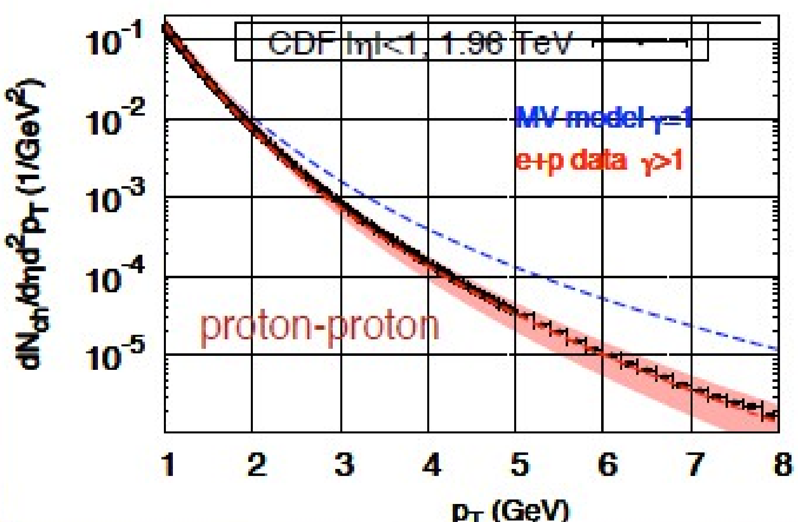


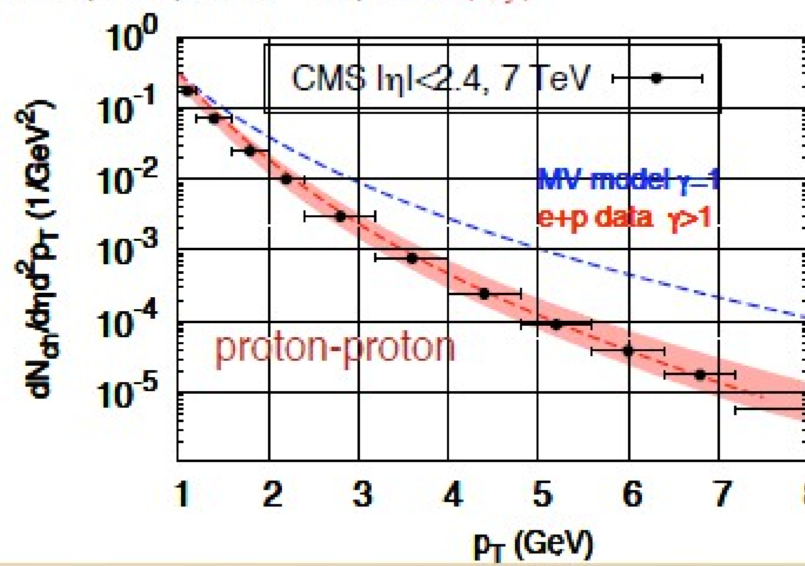
2. Extract NP fit parameters



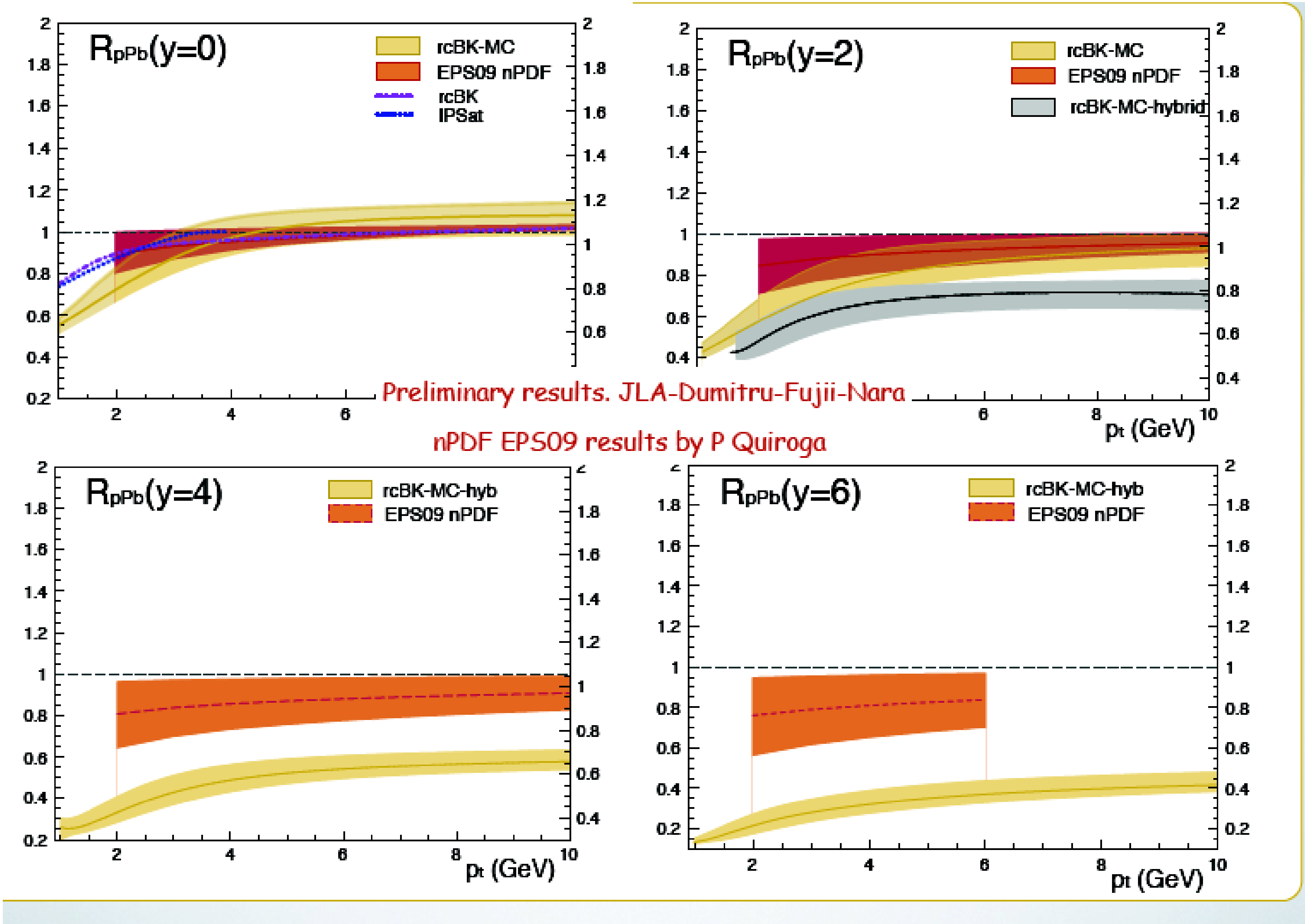
4. Apply gained knowledge in the study of other systems (theory driven extrapolation)

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

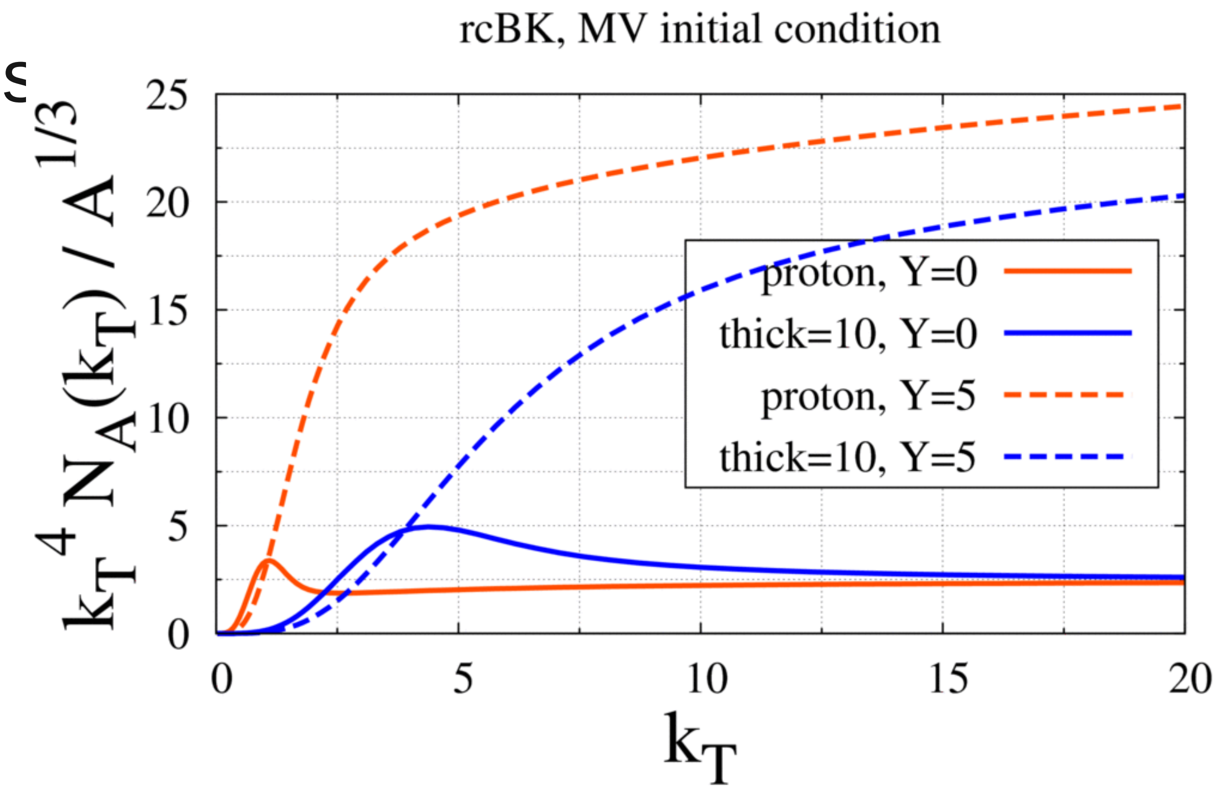




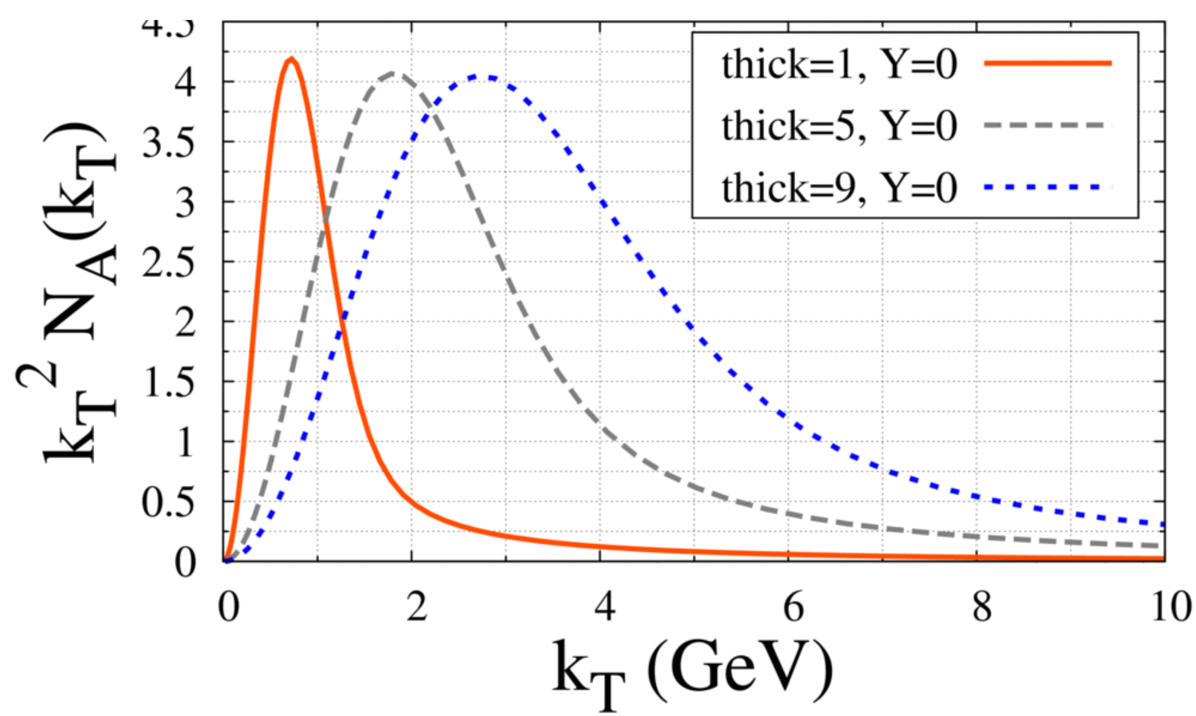
Minimum Bias p+Pb @ 4400 GeV

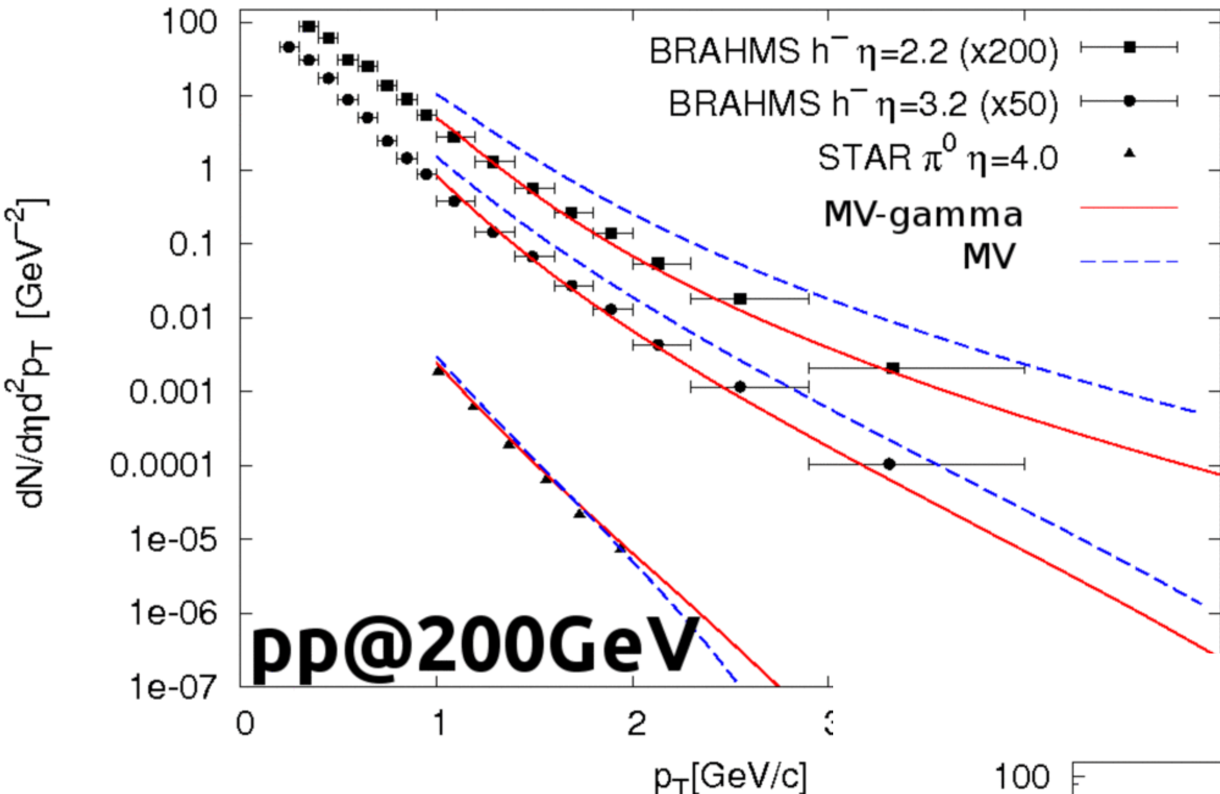


● “Shadowing” depends on k_T



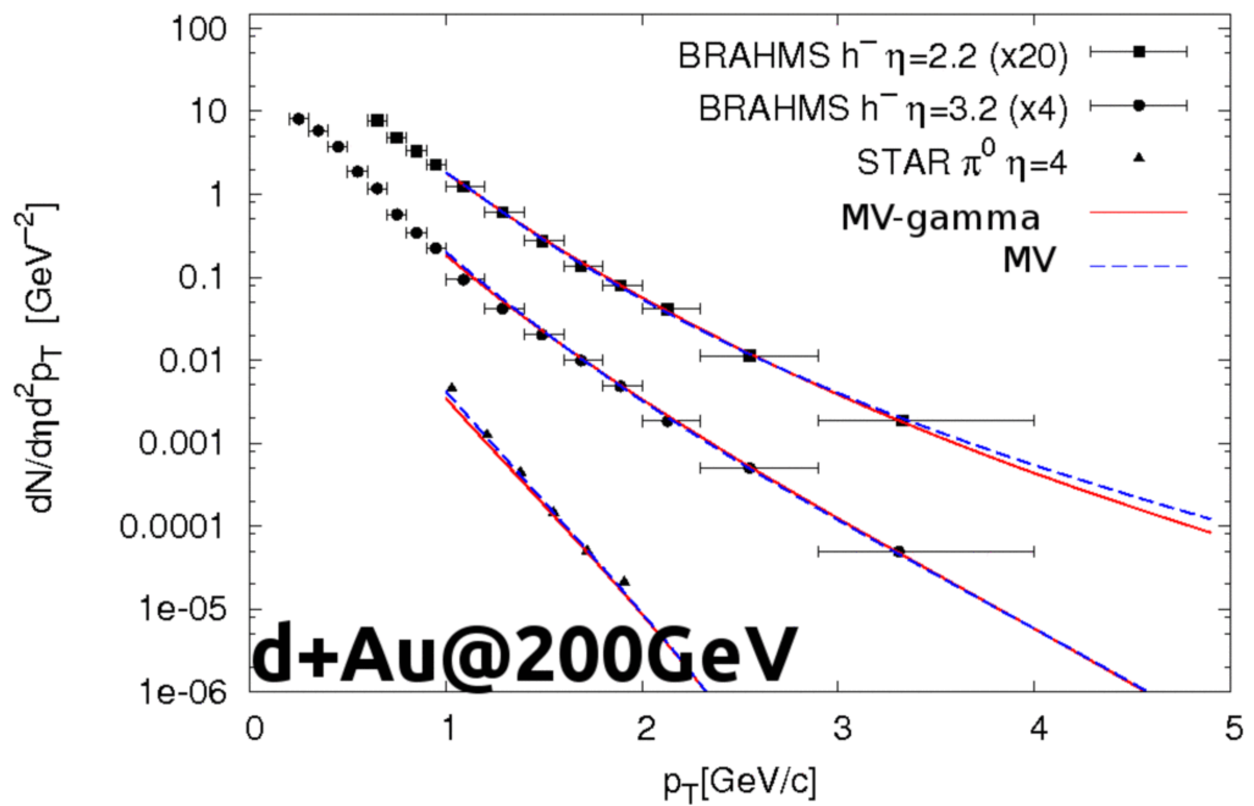
● Target nucleon fluct. can either cause suppr. or enhancement, depending on k_T



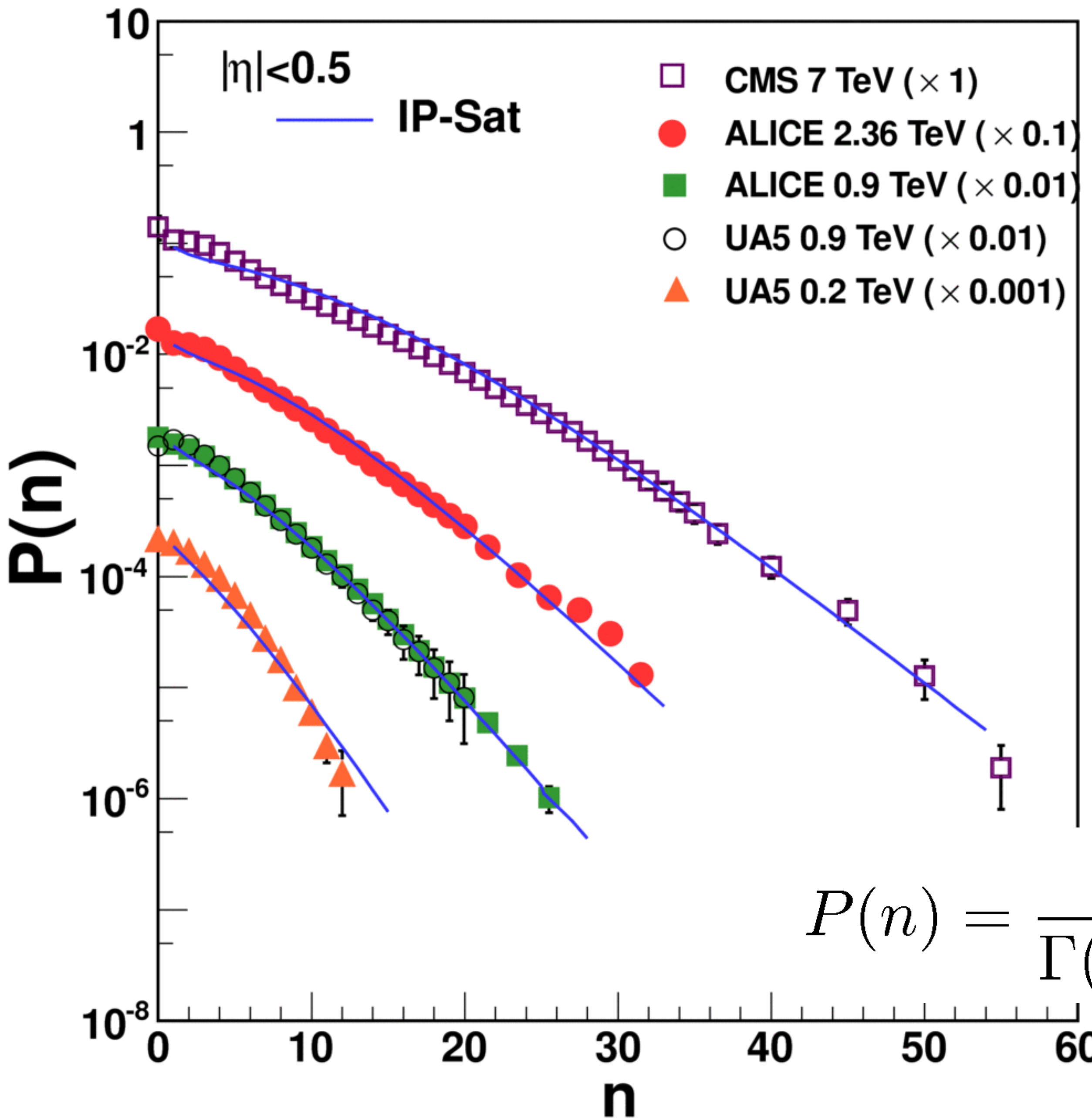


H. Fujii et al, ISMD 2011, Hiroshima, Japan

LO only;
Altinoluk-Kovner term in the works



Multiplicity distributions in *pp* collisions

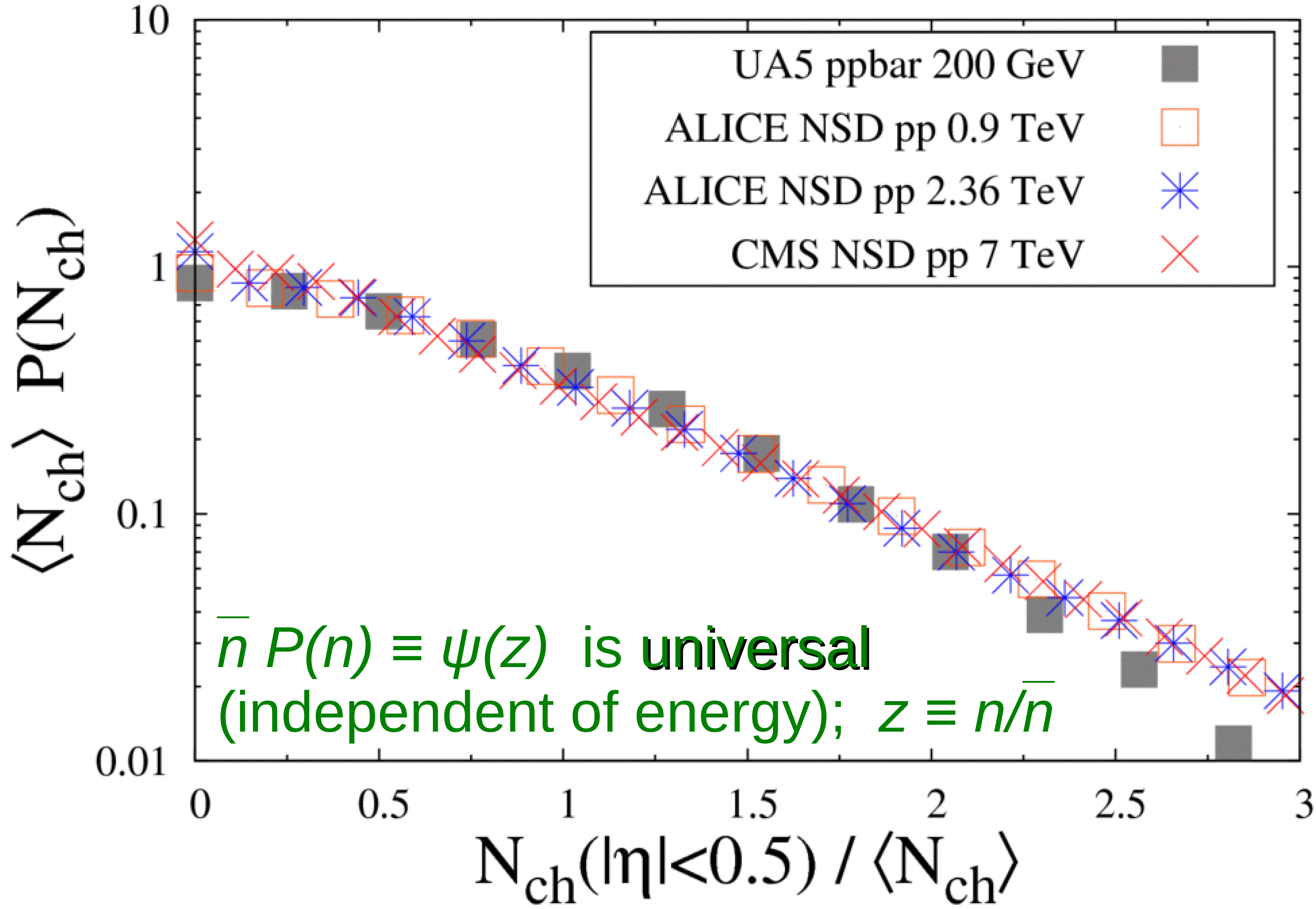


P(n): negative binomial distribution

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

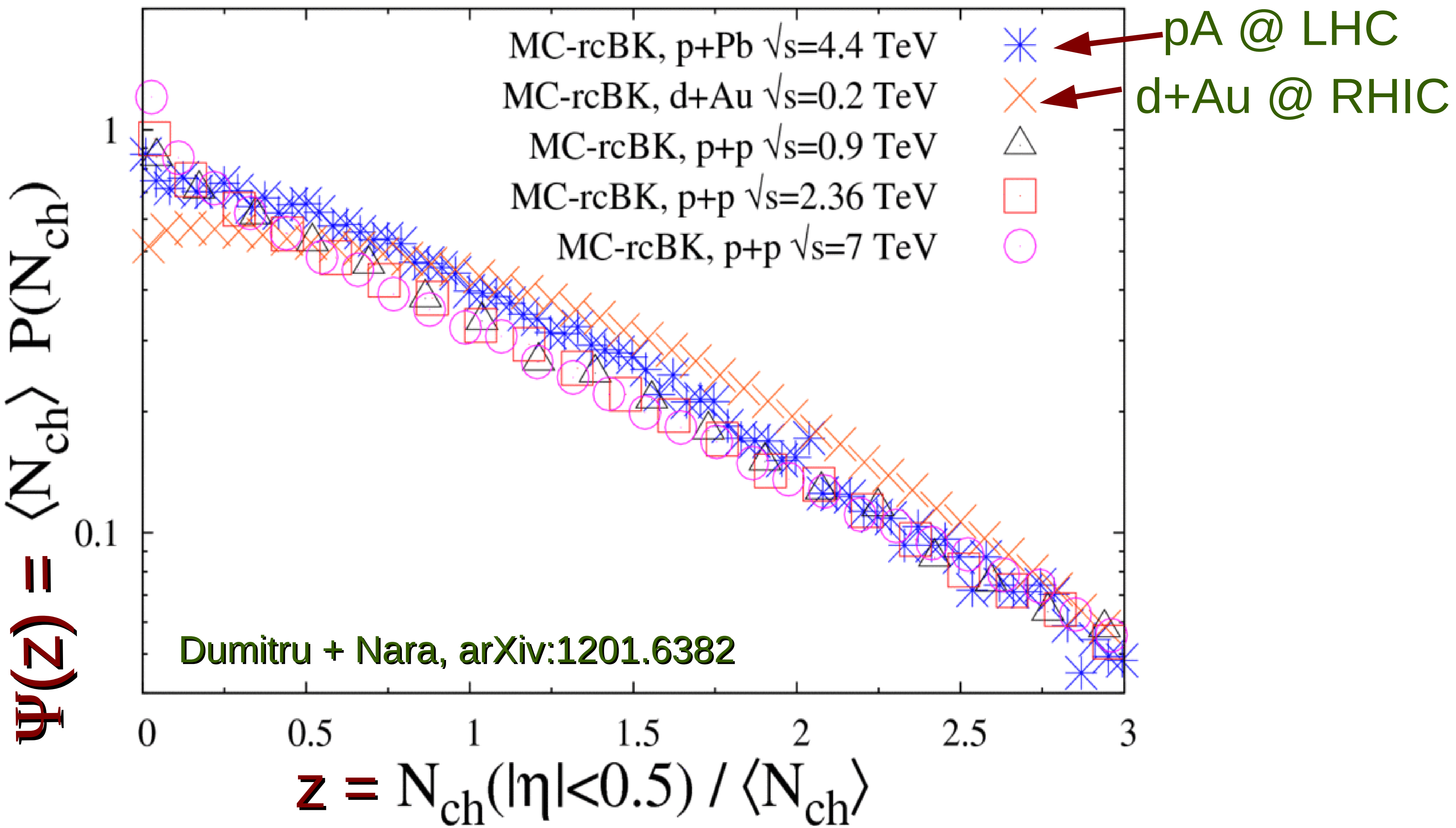
Tribedy & Venugopalan: arXiv:1112.2445

KNO scaling in high-energy pp data

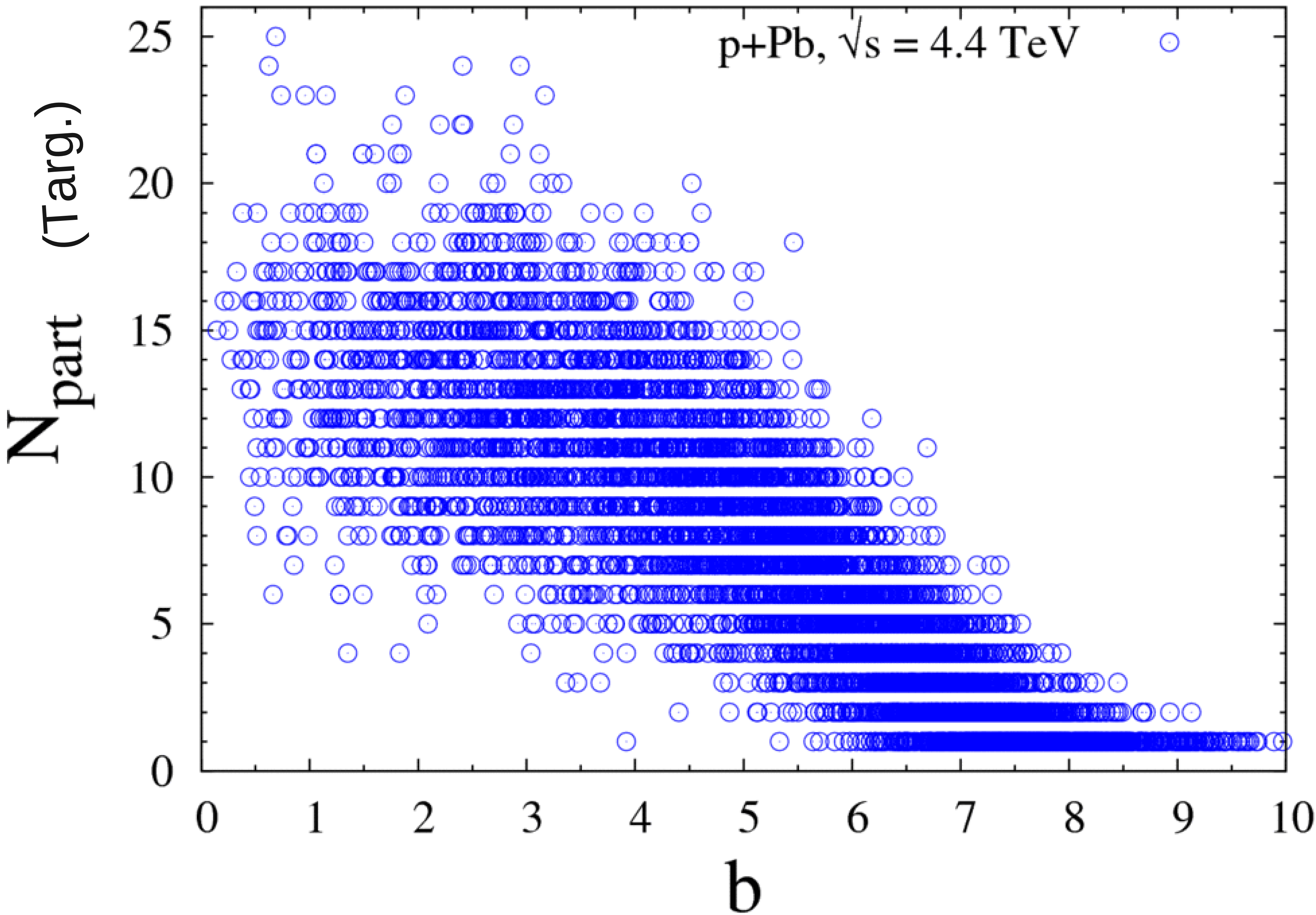


KNO scaling (even p+Pb approx.; prediction)

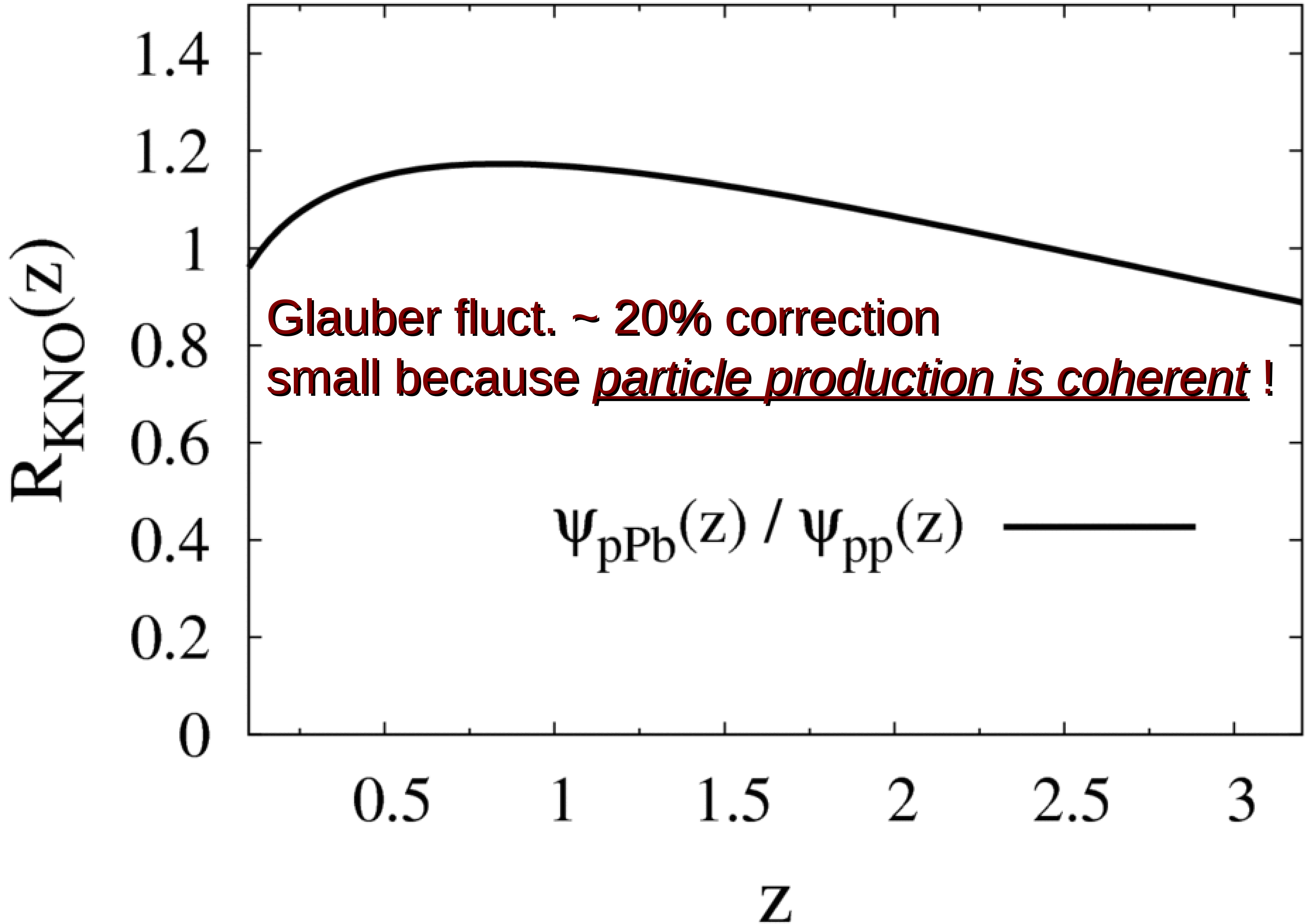
for A+B : $k_{AB} \sim k_{pp} \min(T_A, T_B)$



N_{part} fluctuations in p+Pb:

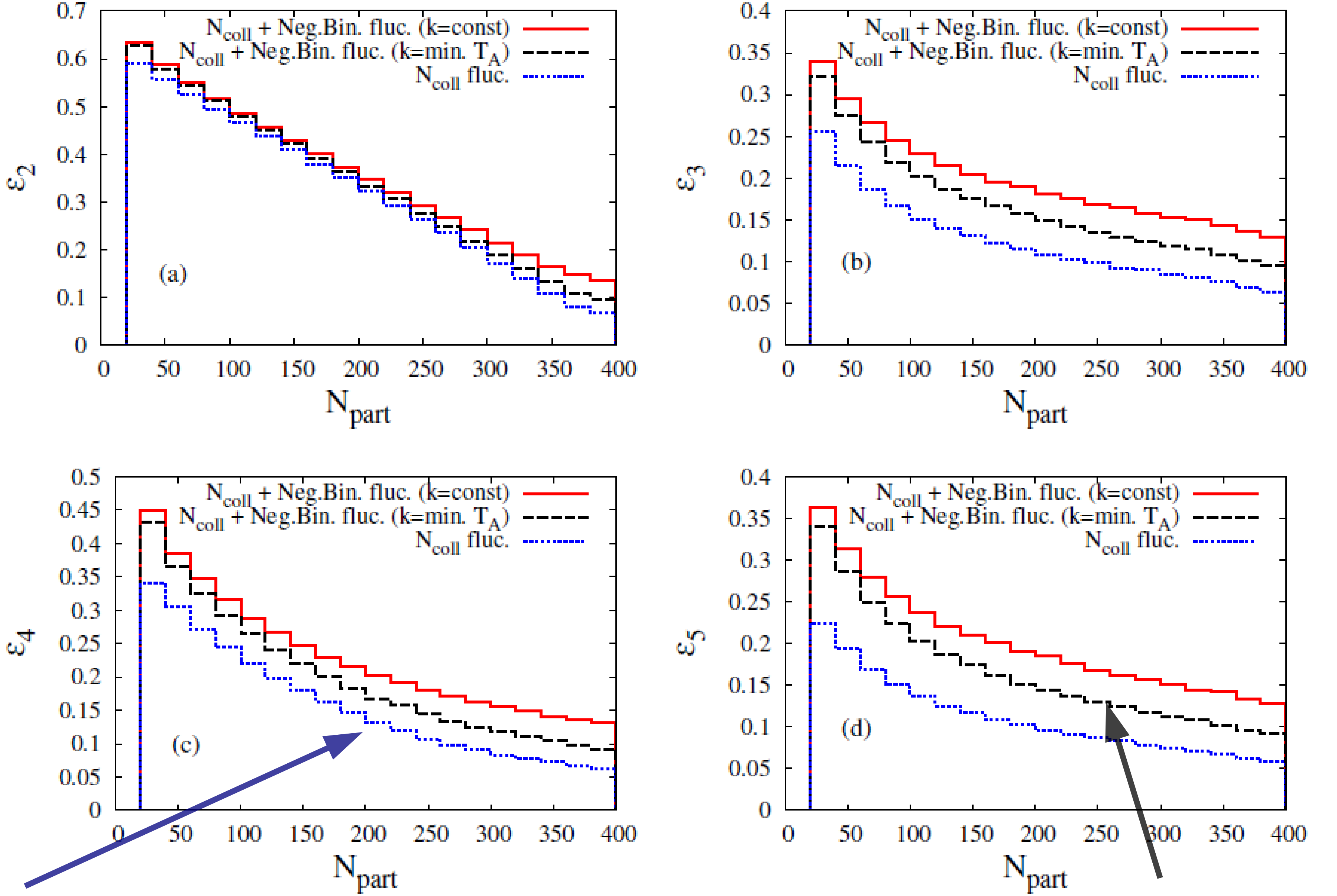


KNO scaling in p+Pb @ 4.4TeV on linear scale



Eccentricities ε_n in Au+Au

Dumitru + Nara, arXiv:1201.6382



Glauber fluc only

Glauber + NBD
$k \sim \min(T_A,T_B)$

KNO scaling:

Koba, Nielsen, Olesen, NPB 40 (1972) 317

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

Note that if $k \ll \bar{n}$, NBD can be written as

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

So, if k≈const, this leads to KNO scaling !

fit to pp @ LHC: $k / \bar{n} \sim 0.16$ at 2360 GeV

but why is

i) P(n) a NBD ?

ii) $k \ll \bar{n}$?

NBD from MV model

Gelis, Lappi, McLerran:
arXiv:0905.3234

for large nucleus, $A^{1/3} \to \infty$

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

+ soft YM fields +
coupling of soft $\leftrightarrow$ hard

$$\left\langle \frac{dN}{dy_1 \cdots dy_n} \right\rangle_{\rm conn.} = \beta_n \left\langle \frac{dN}{dy_1} \right\rangle \cdots \left\langle \frac{dN}{dy_n} \right\rangle$$

$$\beta_n = (n-1)! \;\; k^{1-n} \longrightarrow \text{NBD}$$

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

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

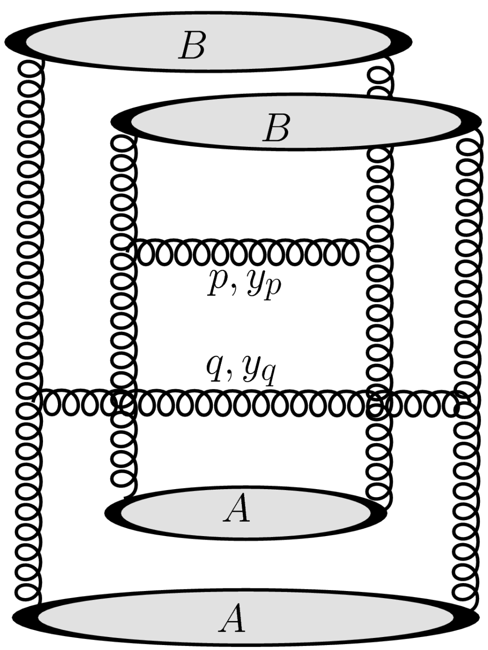
So, why KNO then ?

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

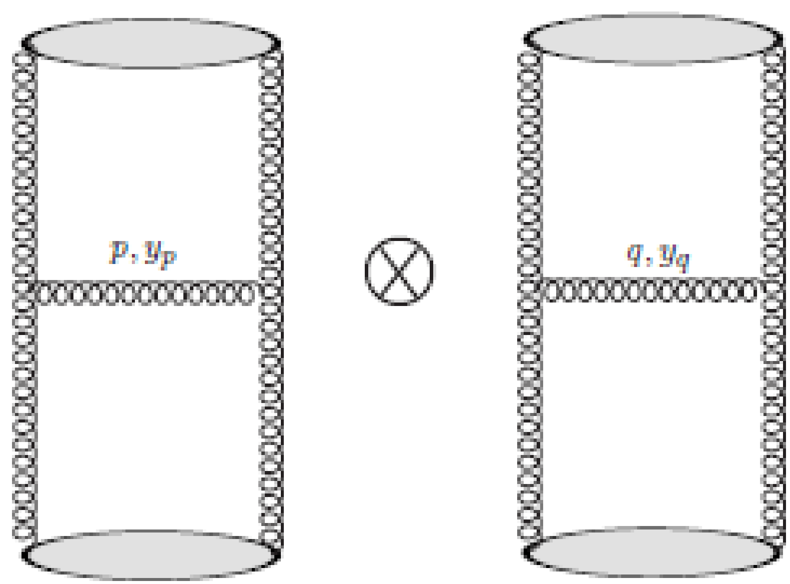
$$k = \# \frac{N_c^2-1}{2\pi} Q_s^2 \, \pi R^2$$

$$\boxed{\frac{\bar{n}}{k} \sim \frac{N_c}{\alpha_s} \gg 1}$$

Why is k = O($\alpha_s^{\,0}$) ?



same order in α_s



New interpretation for KNO at high energy:

KNO scaling emerges if

i) Gaussian action

ii) high occupation number

How about

i) quantum evolution

ii) corrections to Gaussian action ?

Beyond MV action...

Elena Petreska et al: PRD 2011

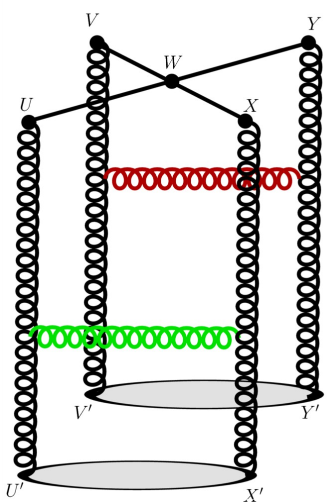
$$S = \int d^2x_\perp \left\{ \frac{1}{2\mu^2}\rho^a\rho^a + \frac{1}{\kappa_4}\left(\delta^{ab}\delta^{cd} + \delta^{ac}\delta^{bd} + \delta^{ad}\delta^{bc}\right)\rho^a\rho^b\rho^c\rho^d \right\}$$

+ soft YM fields + coupling of soft $\leftrightarrow$ hard

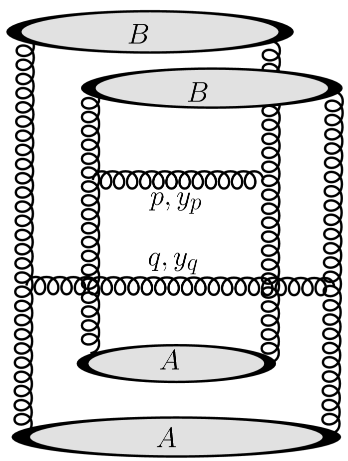
- $\mu^2 \sim g^2 A^{1/3}$; $\kappa_4 \sim g^4 A$

Recalculate width k^{-1} of mult. distribution

$$\left\langle \frac{dN_2}{dy_1 dy_2} \right\rangle_{\text{conn.}} = \frac{1}{k} \left\langle \frac{dN}{dy_1} \right\rangle \left\langle \frac{dN}{dy_2} \right\rangle$$

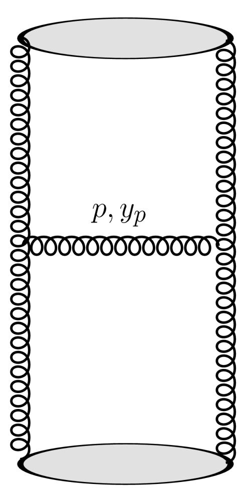


+

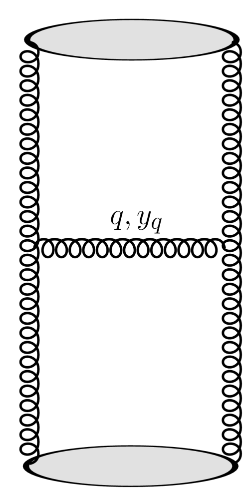


+ ... =

k^{-1} x



$\otimes$



compute k^{-1} from 2-particle connected diagrams:

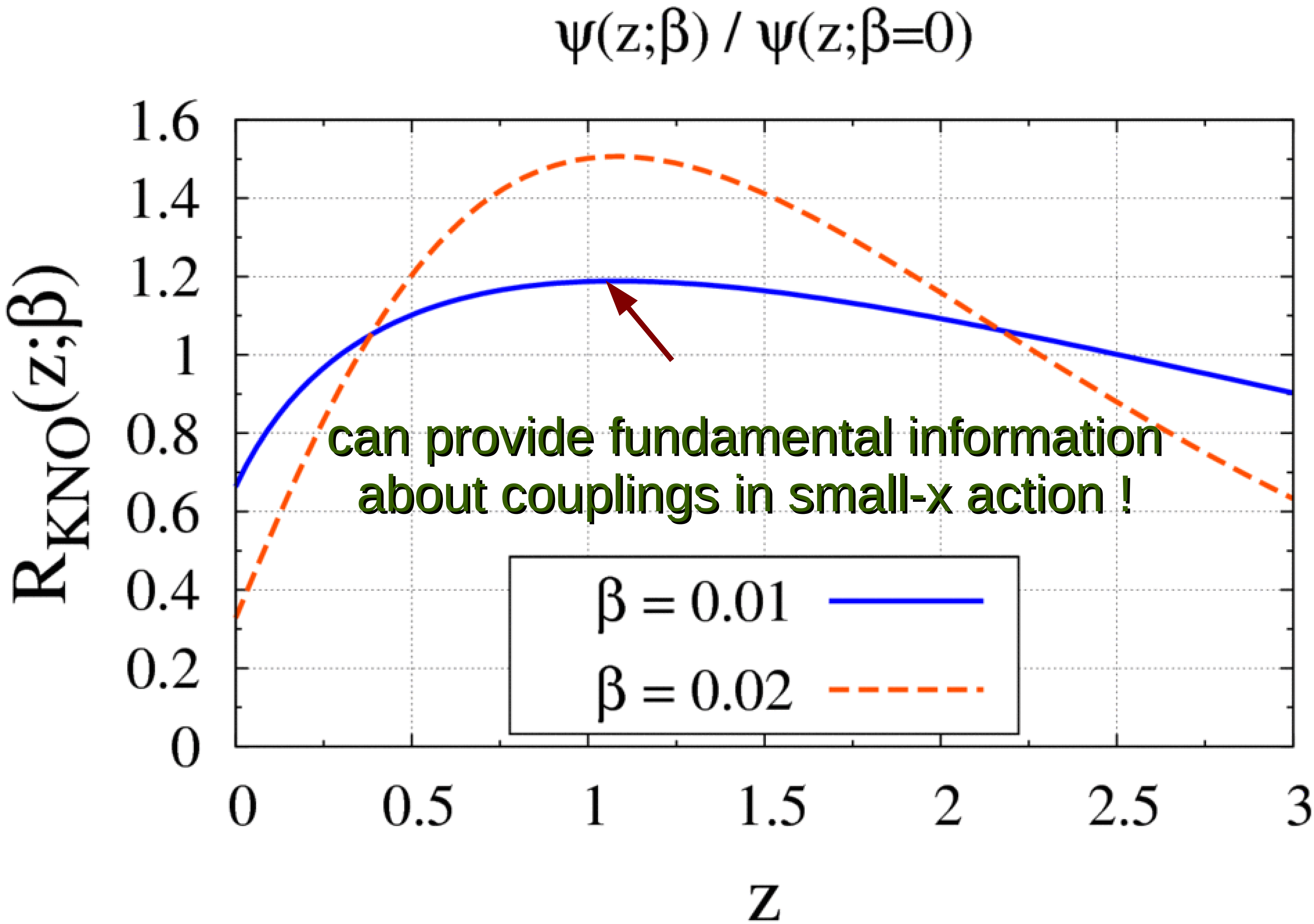
$$\frac{Q_s^2\, S_\perp}{2\pi}\;\frac{1}{k} \simeq \frac{1}{N_c^2-1} - 3\,\frac{N_c^2+1}{N_c^2-1}\,\beta + \cdots$$

MV ρ^4

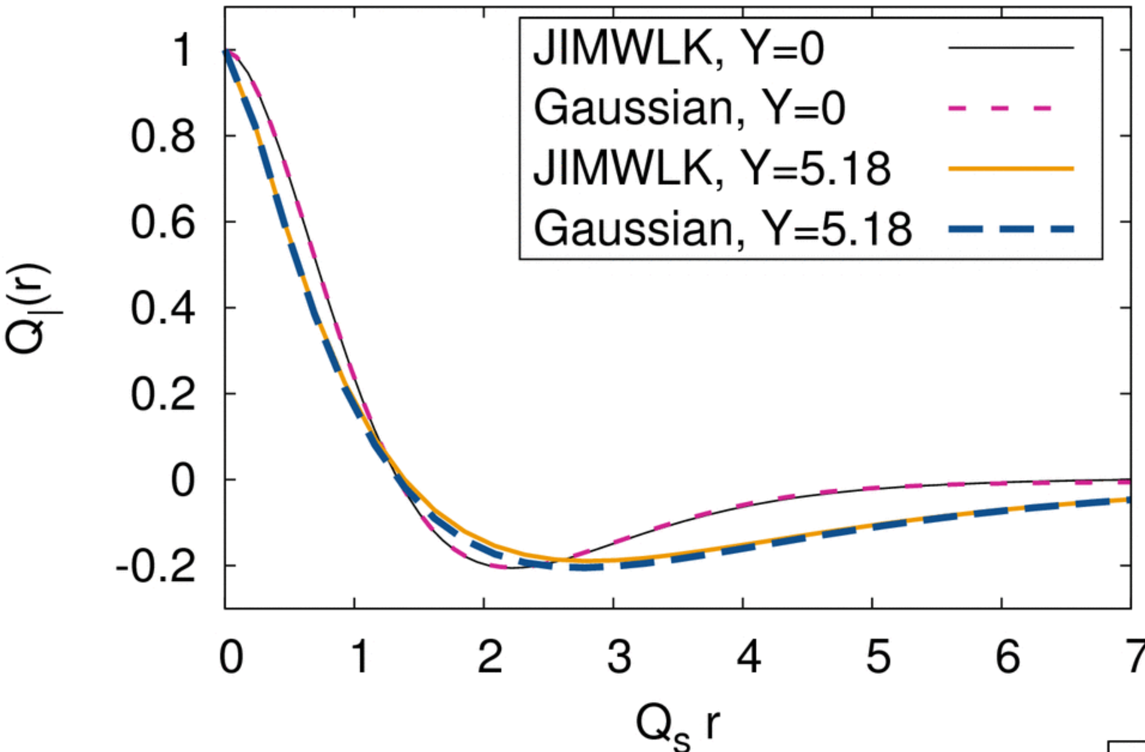
$\beta>0$ makes k bigger,
should be sufficiently small so as not to ruin KNO !

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

$\approx 0.01\ A^{-2/3}$



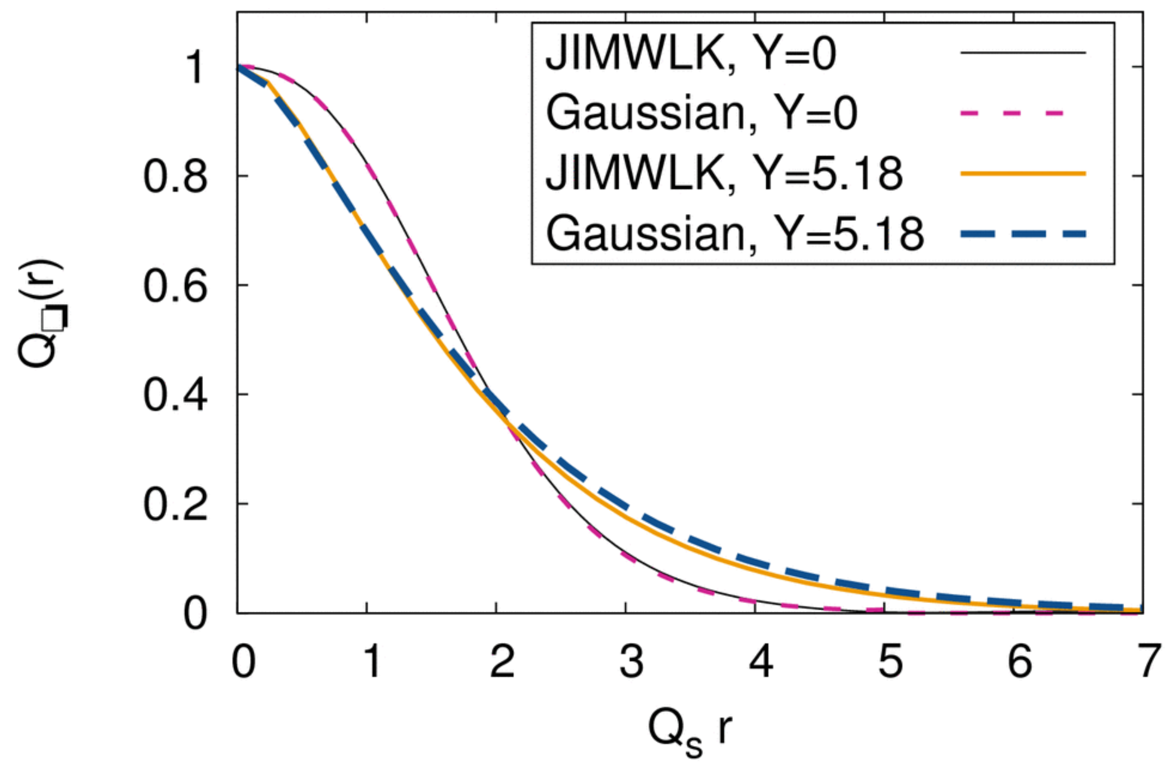
ψ(z;β) / ψ(z;β=0)
R_KNO(z;β)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
z
can provide fundamental information
about couplings in small-x action !
β = 0.01
β = 0.02



JIMWLK evolution appears to preserve Gaussianity of initial MV action !
(more to come)

Quadrupole evolution

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



A.D., Jalilian-Marian, Lappi, Schenke, Venugopalan: arXiv:1108.4764

Iancu & Triantafyllopoulos: arXiv:1112.1104

JIMWLK Hamiltonian :

$$H = -\frac{1}{16\pi^3} \int_{uvz} \mathcal{M}_{uvz} \left(1 + V_u^\dagger V_v - V_u^\dagger V_z - V_z^\dagger V_v\right)^{ab} \frac{\delta}{\delta \alpha_u^a} \frac{\delta}{\delta \alpha_v^b}$$

$$\mathcal{M}_{uvz} = \frac{(u-v)^2}{(u-z)^2\,(v-z)^2}$$

Gaussian evolution described by eff. Hamiltonian with only virt. parts:

$$H = -\frac{1}{8\pi^2} \int_{uv} \log\,(u-v)^2 Q_s^2(Y)\ \left(1 + V_u^\dagger V_v\right)^{ab} \frac{\delta}{\delta \alpha_u^a} \frac{\delta}{\delta \alpha_v^b}$$

Summary I

Kinematics at y~0 @ LHC and y~3-4 @ RHIC is NOT the same

(elementary kinematics)

much higher gluon-pT are probed at LHC,
even if x is roughly similar,
due to very different <z> in fragmentation !

Ex.: $p_{T,hadr.}$~4 GeV at y=3.2 RHIC probes regime ~$Q_{s,adj}$ or just above
same $p_{T,hadr.}$ at y=0 LHC is also sensitive to $p_{T,glue} \gg Q_{s,adj}$

Summary II

min bias pA is sensitive to large b,
and Glauber fluctuations (push up R_{pA})

cut on more central collisions ?

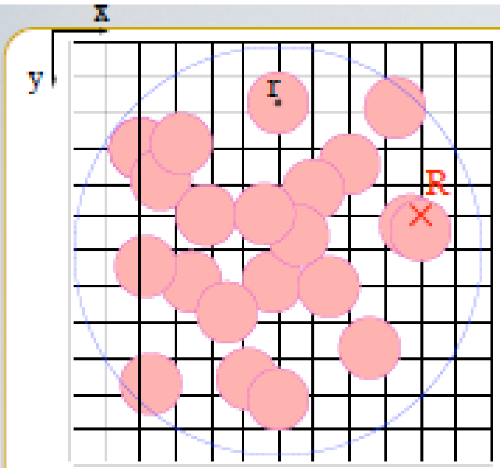
Summary

- predicted $\langle dN_{ch}/d\eta \rangle = 17 \pm 2$
- multiplicity distributions in pp @ LHC exhibit KNO scaling ($\eta=0$, $n/\bar{n}$ <~ 3)
- can be described by NBD with $k \ll \bar{n}$
- approx. KNO scaling predicted for p+Pb @ LHC
  (slight distortion of KNO due to Glauber flucs)
- higher-order eccentricities ε_3 etc. in HIC increase

- theoretical studies of fluctuations:
  - constrain magnitude of higher ρ^n operators
  - evolution with energy to test validity of Gaussian approximation from JIMWLK

Backup Slides

fluctuations of valence partons in ⊥ plane



1. Initial conditions for the evolution (x=0.01)

$$N(\mathbf{R}) = \sum_{i=1}^{A} \Theta\left(\sqrt{\frac{\sigma_0}{\pi}} - |\mathbf{R} - \mathbf{r_i}|\right) \longrightarrow Q_{s0}^2(\mathbf{R}) = N(\mathbf{R})\, Q_{s0,\,\mathrm{nucl}}^2$$

$$\downarrow$$

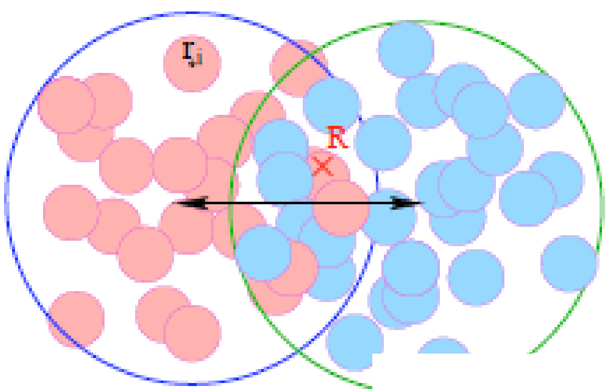
$$\varphi(x_0 = 0.01, k_t, R)$$

2. Solve local running coupling BK evolution at each transverse point

rcBK equation or KLN model

$$\downarrow$$

$$\varphi(x, k_t, R)$$



3 Calculate gluon production at each transverse point according to kt-factorization

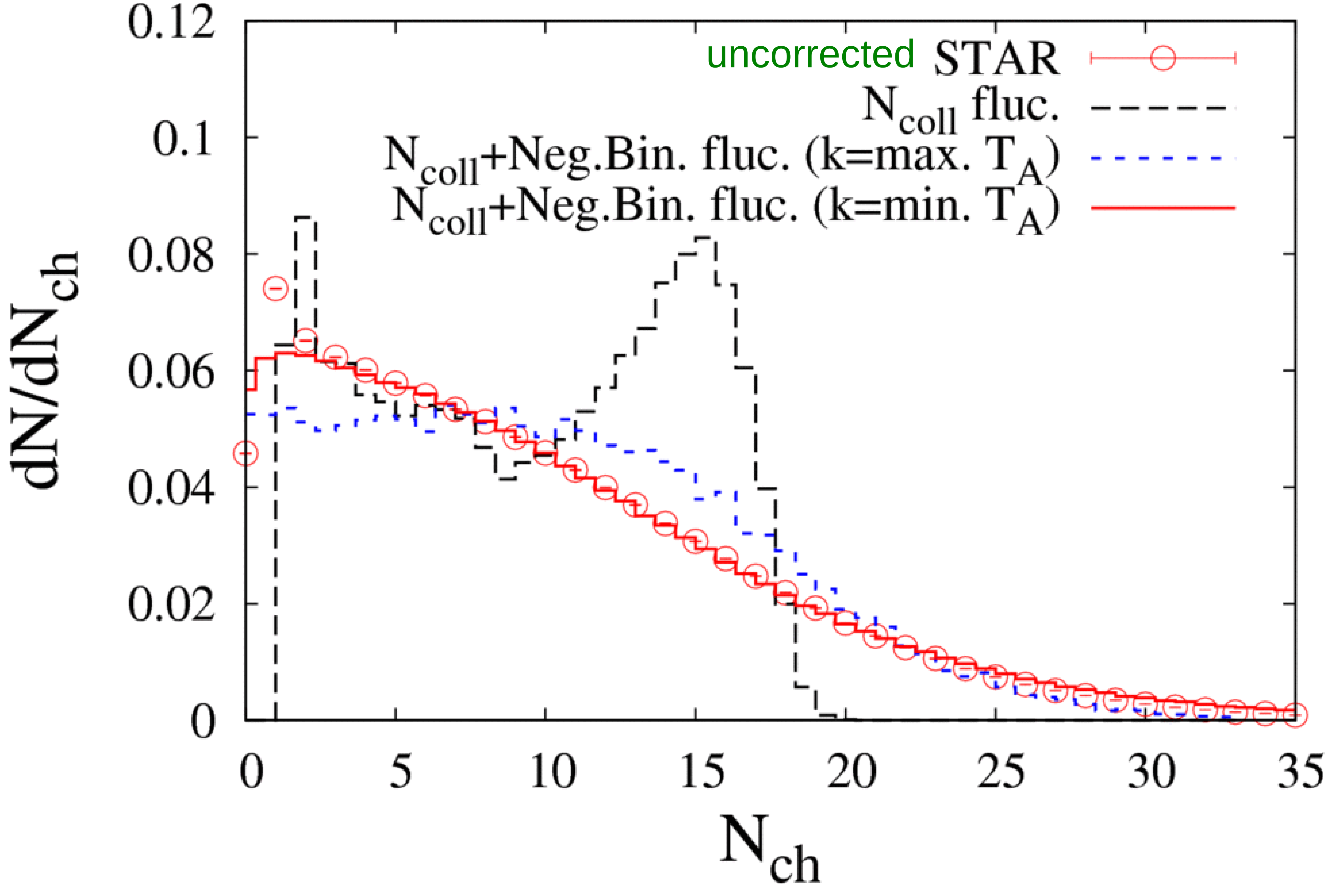
INPUT: $\varphi(\mathbf{x} = \mathbf{0.01}, \mathbf{k_t})$ FOR A SINGLE NUCLEON:

$$N_{\mathrm{part,A}}(\vec{b}) = \sum_{i=1\cdots A} \Theta\left(P(\vec{b} - \vec{r}_i) - \nu_i\right) \; .$$

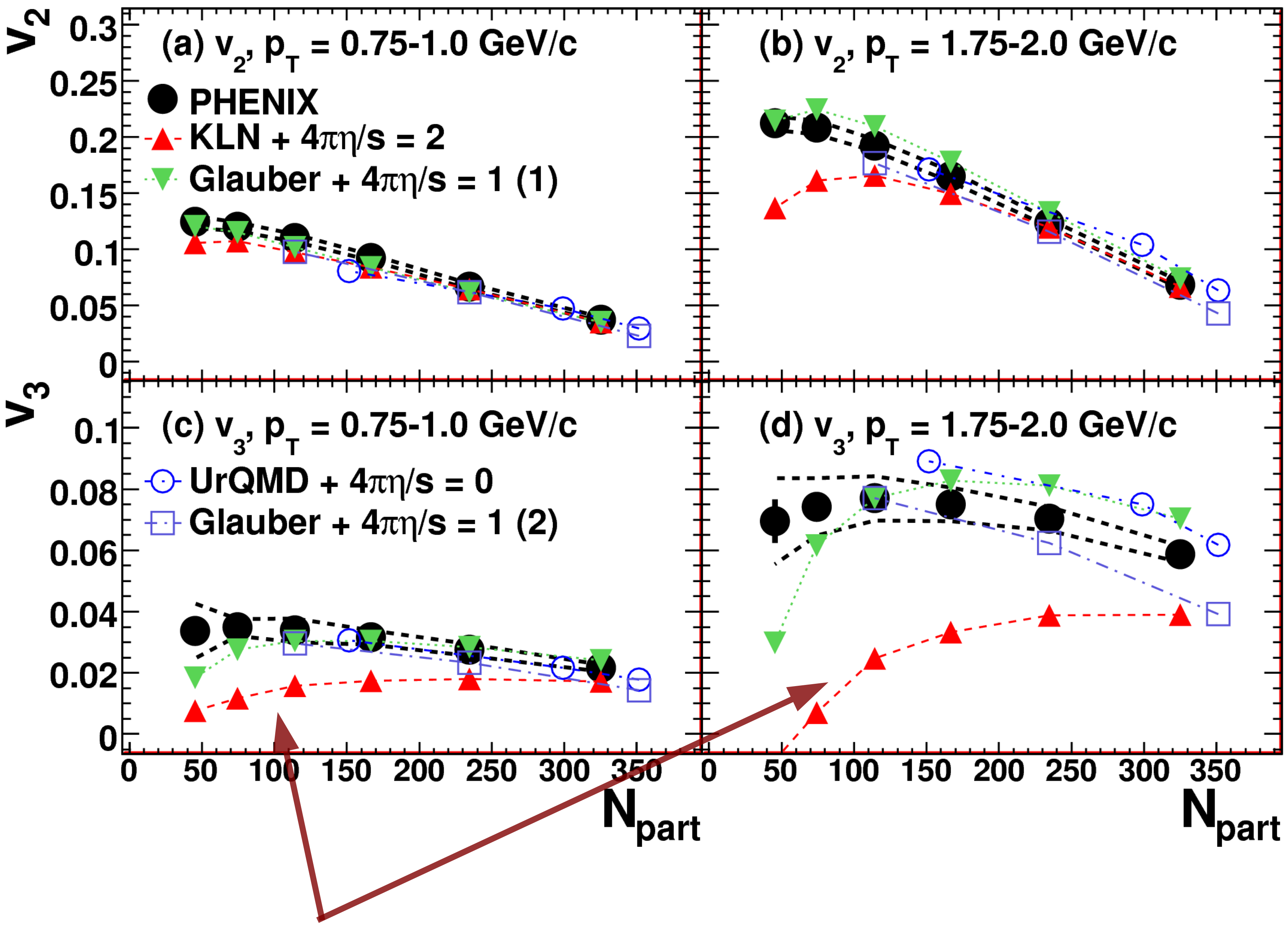
$$P(b) = 1 - \exp[-\sigma_g T_{pp}(b)], \qquad T_{pp}(b) = \int d^2s\, T_p(s)\, T_p(s-b)$$

$$T_p(r) = \frac{1}{2\pi B} \exp[-r^2/(2B)] \qquad \sigma_{NN}(\sqrt{s}) = \int d^2b\, (1 - \exp[-\sigma_g T_{pp}(b)])$$

need KNO flucs also for d+Au@RHIC

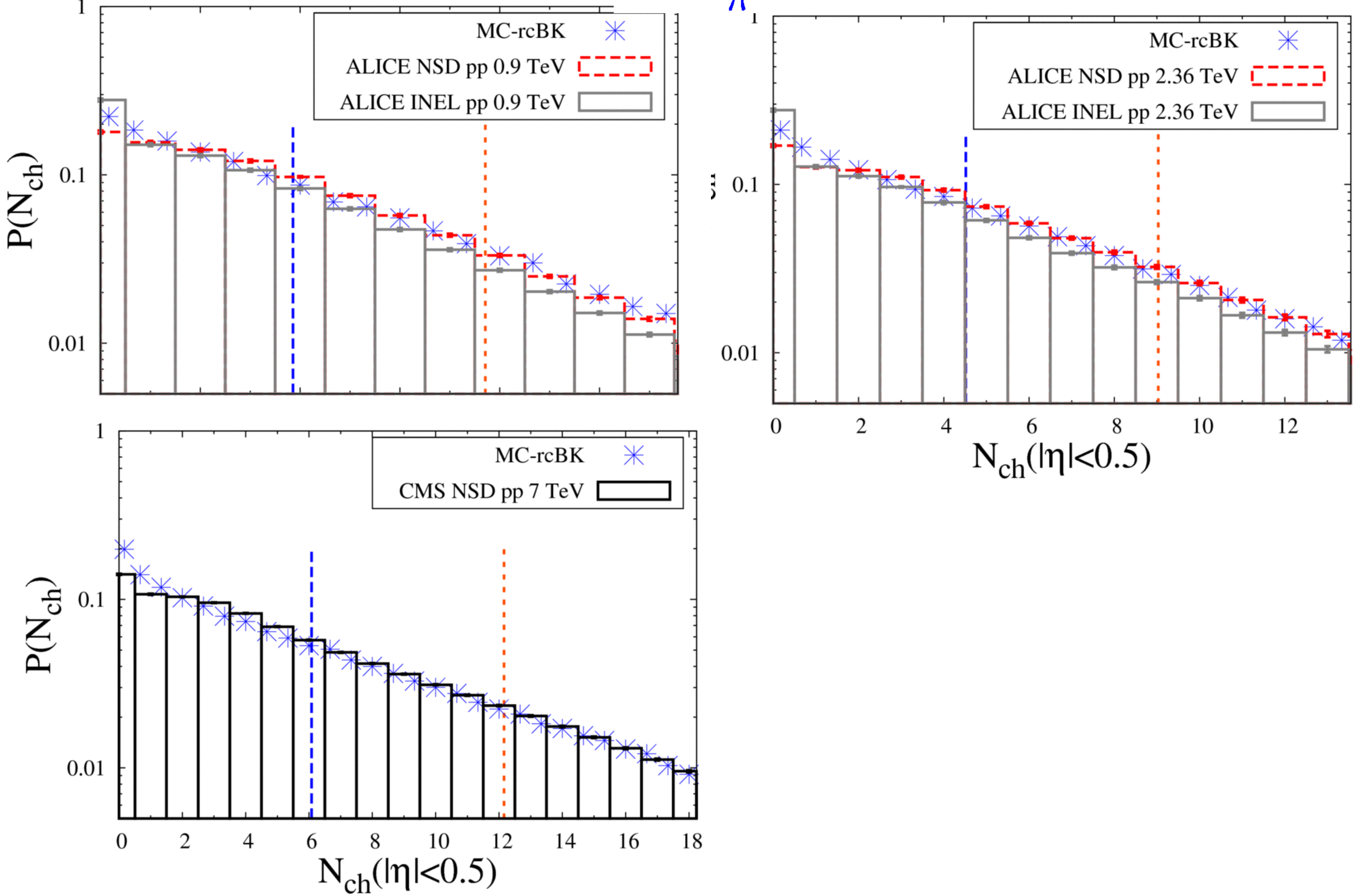


Phenix Collab., arXiv:1105.3928

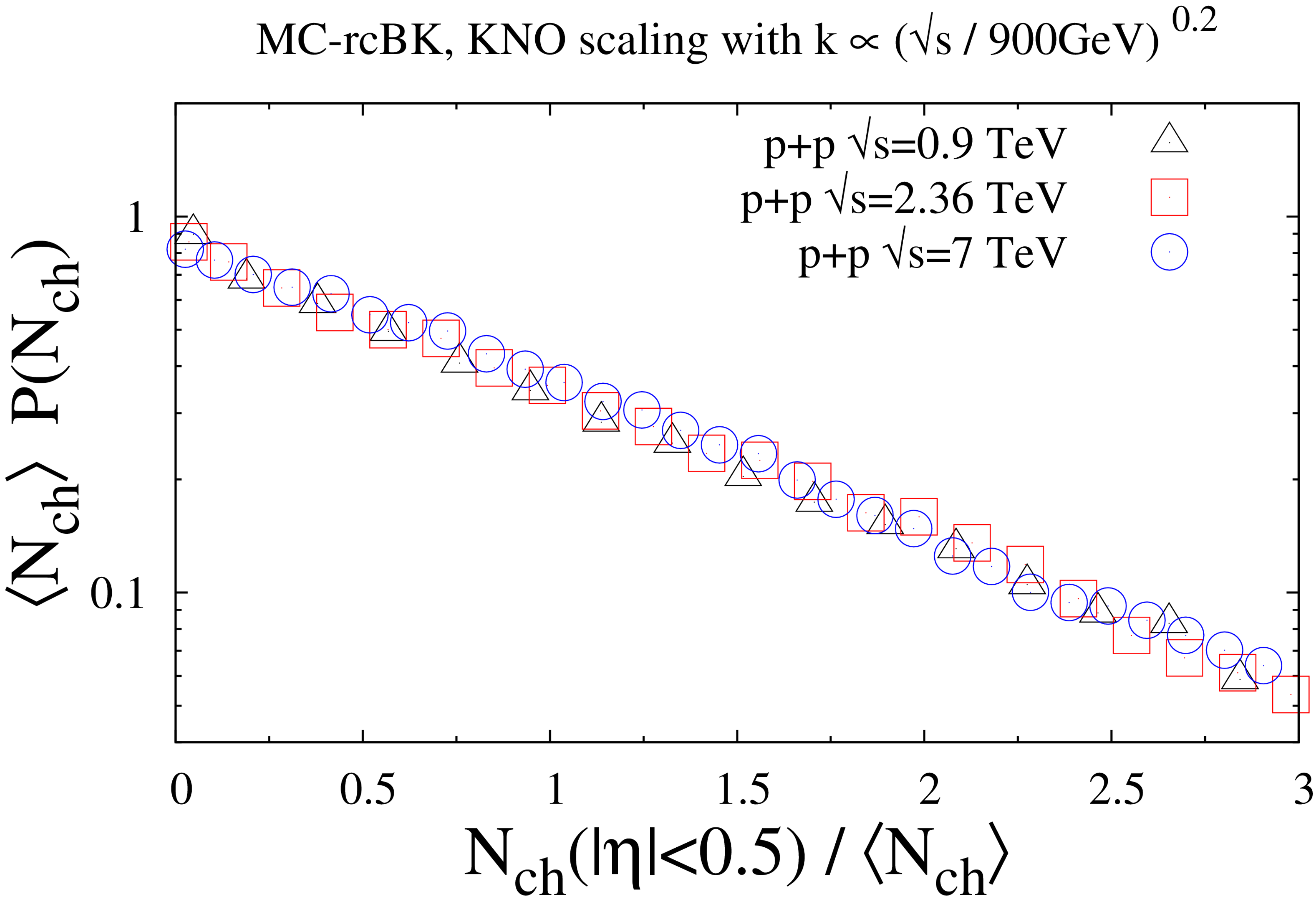


- MC-KLN initial condition (k_T factorization with Glauber fluct. only) leads to underestimate of v_3 !

result for constant $k = \frac{1}{\pi} \Delta x_\perp^2 \Delta\eta \, \Lambda_{\mathrm{QCD}}^2$



energy dependent k ~ $E_{CM}^{0.2}$



Non-Gaussian initial conditions for high-energy evolution

- Odderon operator $-d^{abc}\rho^a\rho^b\rho^c/\kappa_3$

S. Jeon and R. Venugopalan,

Phys. Rev. D70, 105012 (2004); 71, 125003 (2005)

- Effective action for a system of $k \sim N_c A^{1/3} \gg 1$ valence quarks in SU(3);
- Random walk of SU(3) color charges in the space of representations (m,n);

- Probability $P(m,n) = e^{-S(m,n)}$

$$S(m,n;k) \simeq \frac{N_c}{k}C_2(m,n) - \frac{1}{3}\left(\frac{N_c}{k}\right)^2 C_3(m,n) + \frac{1}{6}\left(\frac{N_c}{k}\right)^3 C_4(m,n)$$

$C_2,\ C_3,\ C_4$ - Casimir operators for the representation (m,n)

- Define color charge per unit area $\rho^a \equiv g\,Q^a/\Delta^2 x$

where $|Q| = \sqrt{Q^a Q^a} \equiv \sqrt{C_2}$