Particle multiplicities in the central region of high-energy collisions from running coupling k_T – factorization

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in collaboration with

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Motivation

CGC effective theory entered the next-to-leading order era → several processes calculated @ NLO (and their numerical implementation are underway)

- **Regarding the Balitsky-Kovchegov (BK) evolution eq.:**

Running coupling corrections to the kernel of BK eq. with the solution being able to describe several observables @ HERA, RHIC, LHC

Balitsky, PRD 75, 014001 (2007); Balitsky and Chirilli, PRD 77, 014019 (2008); Kovchegov and Weigert, NPA 784, 188 (2007), NPA 789, 260 (2007); Kovchegov, Kuokkanen, Rummukainen and Weigert, NPA 823, 47 (2009).

Large single and double transverse logarithms resummed to all orders in NLO BK eq. → resulting evolution eq. is stable & generates a physically meaningful evolution of the dipole amplitude

Iancu, Madrigal, Mueller, Soyez and Triantafyllopoulos, PLB 750, 643 (2015); Lappi and Mäntysaari, PRD 91, no. 7, 074016 (2015), PRD 93, no. 9, 094004 (2016).

- **Also, JIMWLK evolution eq. @ NLO;**

Kovner, Lublinsky and Mulian, PRD 89, no. 6, 061704 (2014), JHEP 1408, 114 (2014); Lublinsky and Mulian, arXiv:1610.03453.

Motivation

- **Regarding the "hybrid formalism":**

NLO corrections calculated and implemented numerically → better agreement with experimental data @ RHIC/LHC energies for forward hadron production;

Chirilli, Xiao and Yuan, PRL 108, 122301 (2012); Stasto, Xiao and Zaslavsky, PRL 112, no. 1, 012302 (2014); Altinoluk, Armesto, Beuf, Kovner and Lublinsky, PRD 91, no. 9, 094016 (2015); Watanabe, Xiao, Yuan and Zaslavsky, PRD 92, no. 3, 034026 (2015).

- **Regarding the k_T – factorization:**

k_T – factorization formula for inclusive gluon production @ small-x beyond LO with running coupling corrections conjectured

Horowitz and Kovchegov, Nucl. Phys. A 849, 72 (2011)

So far, only a qualitative study done in

Durães, A.V.G., Gonçalves and Navarra, **PRD 94, 054023 (2016)**

KLN UGD + Local Parton-Hadron Duality + minimum bias collisions

Motivates a more robust calculation

k_T -factorization: multiplicity in A+B→g+X @ low-x

fixed by data; includes “K-factors” due to high order corrections + Frag. Functions

$$\frac{d^3\sigma}{d^2k_T\,dy} = \frac{N}{C_F}\,\frac{2}{\mathbf{k}^2}\int d^2b\,d^2b'\,d^2q\,\alpha_s\,\phi_{h_1}(\mathbf{q},\mathbf{b},x_1)\,\phi_{h_2}(\mathbf{k}-\mathbf{q},\mathbf{b}-\mathbf{b}',x_2)$$

convolution of the projectile’s & target’s unintegrated gluon distribution (UGD)

$$\phi(\mathbf{k},\mathbf{b},y) = \frac{C_F}{\alpha_s\,(2\pi)^3}\int d^2r\,e^{-i\mathbf{k}\cdot\mathbf{r}}\,\nabla_r^2\,\mathcal{N}_{\mathcal{A}}(\mathbf{r},\mathbf{b},y) \qquad \mathbf{k}=(k_x,k_y)$$

UGD

2-D Fourier Transform of the gluon dipole scattering amplitude

$$x_{1,2} = k_T/\sqrt{s}\,\exp(\pm y)$$

momentum fraction of the proj./targ. gluon

Originally derived in the fixed coupling (FC) approx.: $\alpha_s = \text{const.}$

(the impact parameter dependence will be omitted for sake of simplicity)

k_T -factorization: multiplicity in A+B→g+X @ low-x

$$\frac{d^3\sigma}{d^2k_T\,dy} = \frac{N}{C_F}\,\frac{2}{\mathbf{k}^2}\int d^2b\,d^2b'\,d^2q\,\alpha_s\,\phi_{h_1}(\mathbf{q},\mathbf{b},x_1)\,\phi_{h_2}(\mathbf{k}-\mathbf{q},\mathbf{b}-\mathbf{b}',x_2)$$

Originally derived in the fixed coupling (FC) approx.: $\alpha_s = \mathrm{const.}$

Later, $\alpha_s \to \alpha_s(Q^2)$ **in FC formula: better agreement of theory & data;**

Q^2 **fixed by hand! Distinct choices for** Q^2 $\to$ **similar results**

Levin & Rezaeian, PRD 82, 014022 (2010), PRD 82, 054003 (2010), PRD 83, 114001 (2011); Albacete and Dumitru, arXiv:1011.5161; Albacete, Dumitru, Fujii & Nara, NPA 897, 1 (2013); Dumitru, Kharzeev, Levin & Nara, PRC 85, 044920 (2012); Tribedy & Venugopalan, NPA 850, 136 (2011), NPA 859, 185 (2011), PLB 710, 125 (2012) Schenke, Tribedy & Venugopalan, PRC 89, no. 2, 024901 (2014)

The running coupling k_T – fact. formula

$$\frac{d^3\sigma}{d^2 k_T\, dy} = \frac{2\,C_F}{\pi^2}\,\frac{1}{\mathbf{k}^2}\int d^2q\;\overline{\phi}_{h_1}(\mathbf{q}, x_1)\,\overline{\phi}_{h_2}(\mathbf{k}-\mathbf{q}, x_2)\,\frac{\alpha_s\left(\Lambda^2_{\text{coll}}\,e^{-5/3}\right)}{\alpha_s\left(Q^2\,e^{-5/3}\right)\,\alpha_s\left(Q^{*\,2}\,e^{-5/3}\right)}$$

Result of resummation of relevant 1-loop corrections into the running coupling

Horowitz and Kovchegov, NPA 849, 72 (2011)

Q^2 from a formal calculation!

$$\bar{\phi}(\mathbf{k}, \mathbf{b}, y) = \alpha_s \phi(\mathbf{k}, \mathbf{b}, y)$$

$$\Lambda_{coll} \sim k_T$$

Kovchegov and Weigert, NPA 807, 158 (2008)

α_s-factors appear explicitly in the expression

The running coupling k_T – fact. formula

$$\frac{d^3\sigma}{d^2k_T\,dy} = \frac{2\,C_F}{\pi^2}\,\frac{1}{\mathbf{k}^2}\int d^2q\;\overline{\phi}_{h_1}(\mathbf{q},x_1)\,\overline{\phi}_{h_2}(\mathbf{k}-\mathbf{q},x_2)\,\frac{\alpha_s\left(\Lambda_{\text{coll}}^2\,e^{-5/3}\right)}{\alpha_s\left(Q^2\,e^{-5/3}\right)\,\alpha_s\left(Q^{*\,2}\,e^{-5/3}\right)}$$

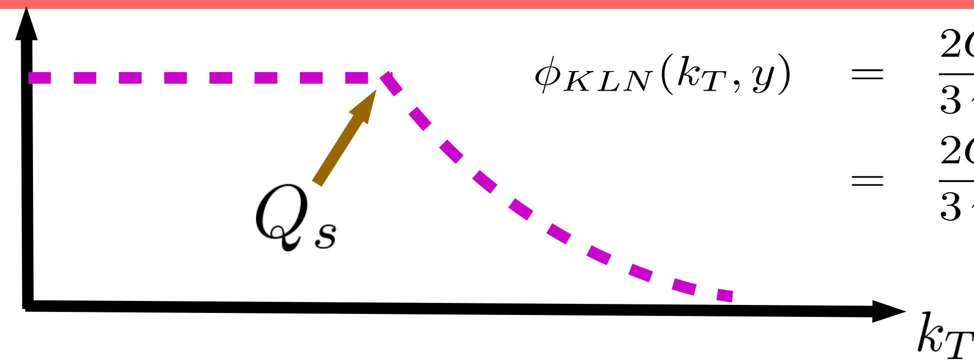
Horowitz and Kovchegov, NPA 849, 72 (2011)

Q^2 **given by:**

$$\begin{aligned}
\ln\frac{Q^2}{\mu_{\overline{\text{MS}}}^2} = {} & \frac{1}{2}\ln\frac{\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2}{\mu_{\overline{\text{MS}}}^4} - \frac{1}{4\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^6}\Bigg\{\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3 \\
& \times\Bigg\{\left[\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2-\left(\boldsymbol{q}^2\right)^2\right]\left[\left(\boldsymbol{k}^2\right)^2+\left((\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right)^2\right]+2\,\boldsymbol{k}^2\left[\left(\boldsymbol{q}^2\right)^3-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^3\right] \\
& -\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\left[2\,\left(\boldsymbol{k}^2\right)^2+3\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2-3\,\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]\right]\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\Bigg\} \\
& +i\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^3\,\Bigg\{\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]\left[\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2\right] \\
& +\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2\,\left(\boldsymbol{k}^2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2+\boldsymbol{q}^2\right]-2\,\left(\boldsymbol{k}^2\right)^2-2\,\left[(\boldsymbol{k}-\boldsymbol{q})^2-\boldsymbol{q}^2\right]^2\right)\ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right)\Bigg\} \\
& \times\sqrt{2\,\boldsymbol{q}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{k}^2\,(\boldsymbol{k}-\boldsymbol{q})^2+2\,\boldsymbol{q}^2\,\boldsymbol{k}^2-\left(\boldsymbol{k}^2\right)^2-\left(\boldsymbol{q}^2\right)^2-\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2}\Bigg\}\,,
\end{aligned}$$

Going quantitative:

Instead of ϕ_{KLN}



$$\phi_{KLN}(k_T, y) = \frac{2C_F}{3\pi^2}, \quad k_T \le Q_s$$
$$= \frac{2C_F}{3\pi^2}\frac{Q_s^2}{k_T^2}, \quad k_T > Q_s$$

... get UGD from rcBK evolution eq.:

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

$$\mathcal{N}_F(r,Y) \equiv \mathcal{N}(r,Y) \;;\; \mathcal{N}_A = 2\mathcal{N}_F - \mathcal{N}_F^2 \;;\; Y = ln(x_0/x) \;;\; x_0 = 0.01$$

rcBK provides small-x evolution given an initial condition (I.C.)!

AAMQS I.C.:

$$\mathcal{N}_F(r,x_0) = 1 - exp\left[-\frac{(r^2\, Q^2_{s0,\mathrm{proton}})^\gamma}{4}\, ln\left(\frac{1}{\Lambda r} + e\right)\right]$$

Albacete, Armesto, Milhano and Salgado, PRD 80, 034031 (2009); Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, Eur. Phys. J. C 71, 1705 (2011)

AAMQS I.C. :

Albacete, Armesto, Milhano and Salgado, PRD 80, 034031 (2009); Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, Eur. Phys. J. C 71, 1705 (2011)

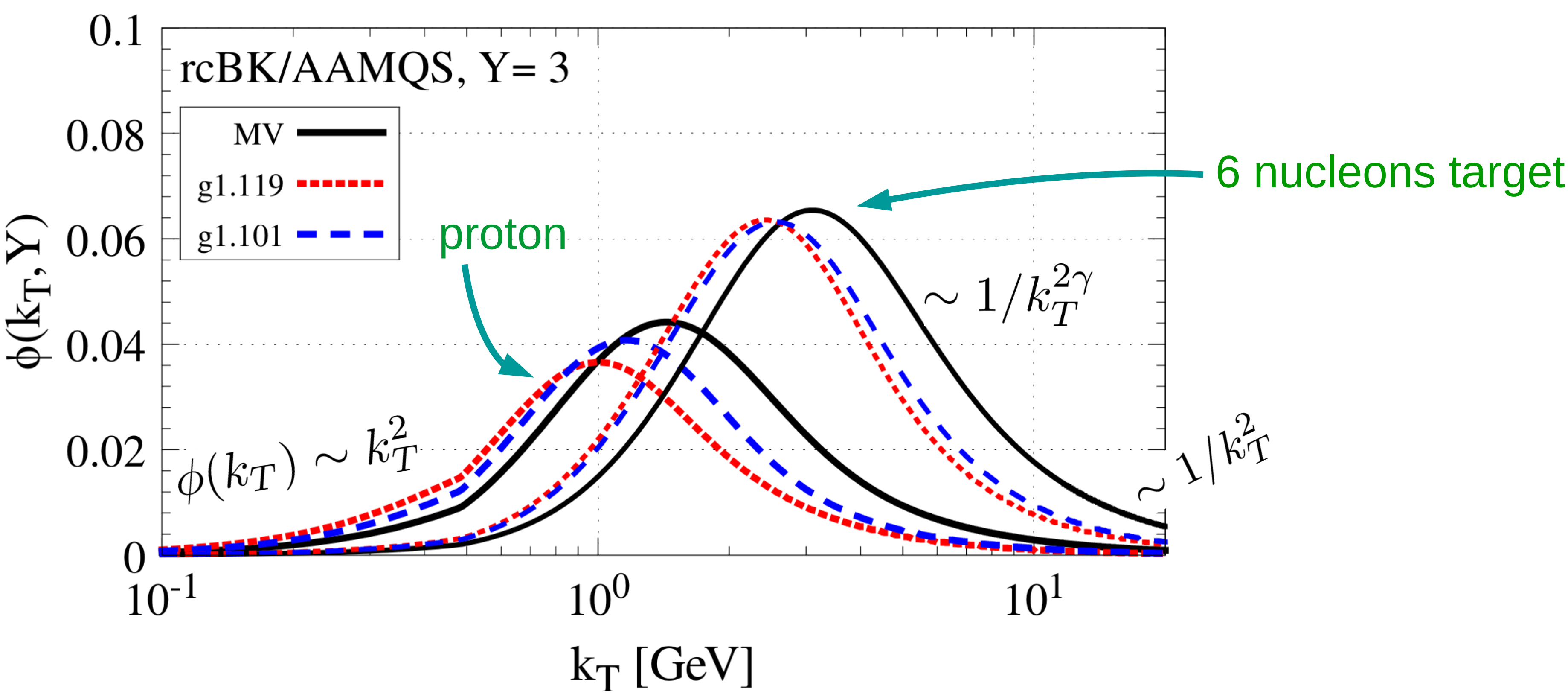
$Q^2_{s0,\mathrm{proton}}$ = **proton's sat. scale at the initial scale** x_0

γ = **controls steepness of the UGD tail for** $k_T > Q^2_{s0,\mathrm{proton}}$

} **fitted to data!**

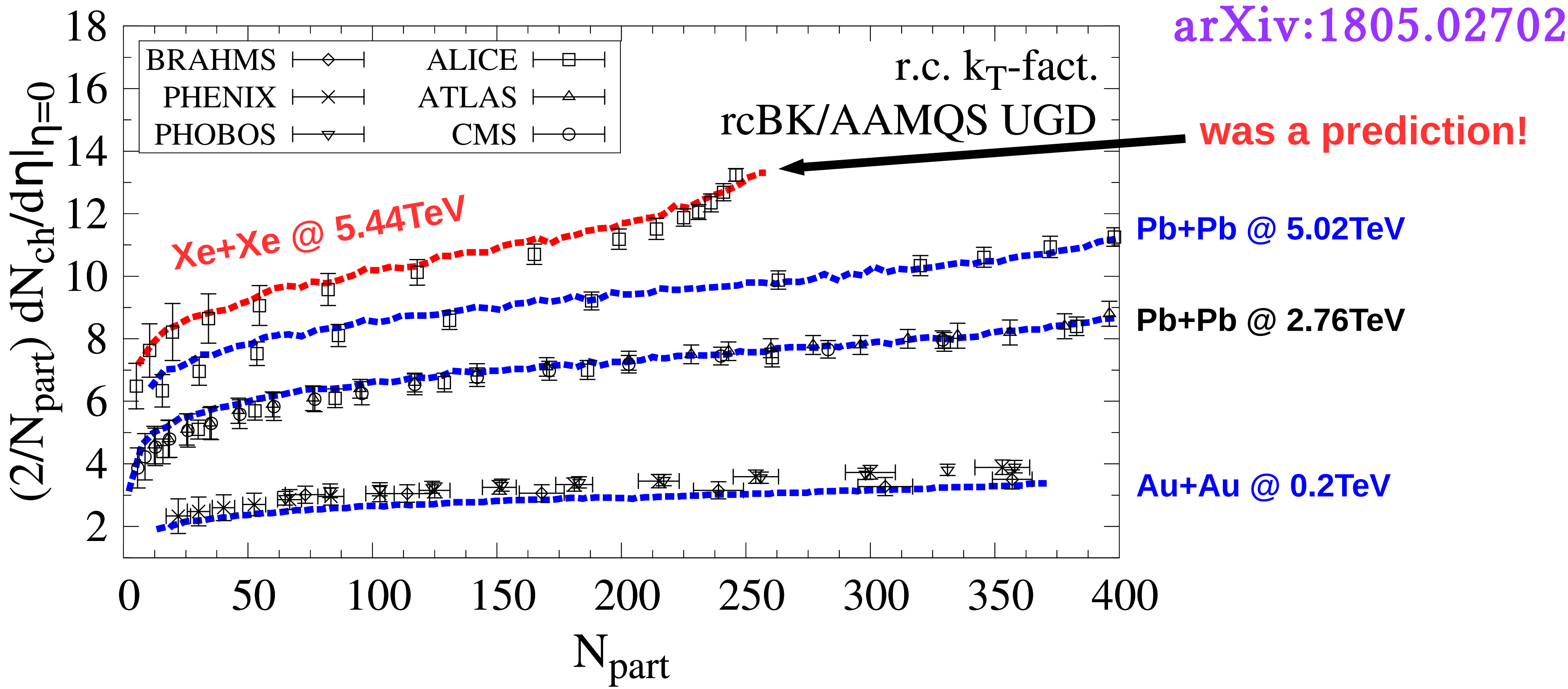
$\gamma = 1$ **McLerran-Venugopalan (MV) model as I.C.**

For proton: I.C. with $\gamma > 1$ **lead to best fit of HERA e+p data**



Multiplicity vs N_{part} : A + A, MV I.C.

arXiv:1805.02702

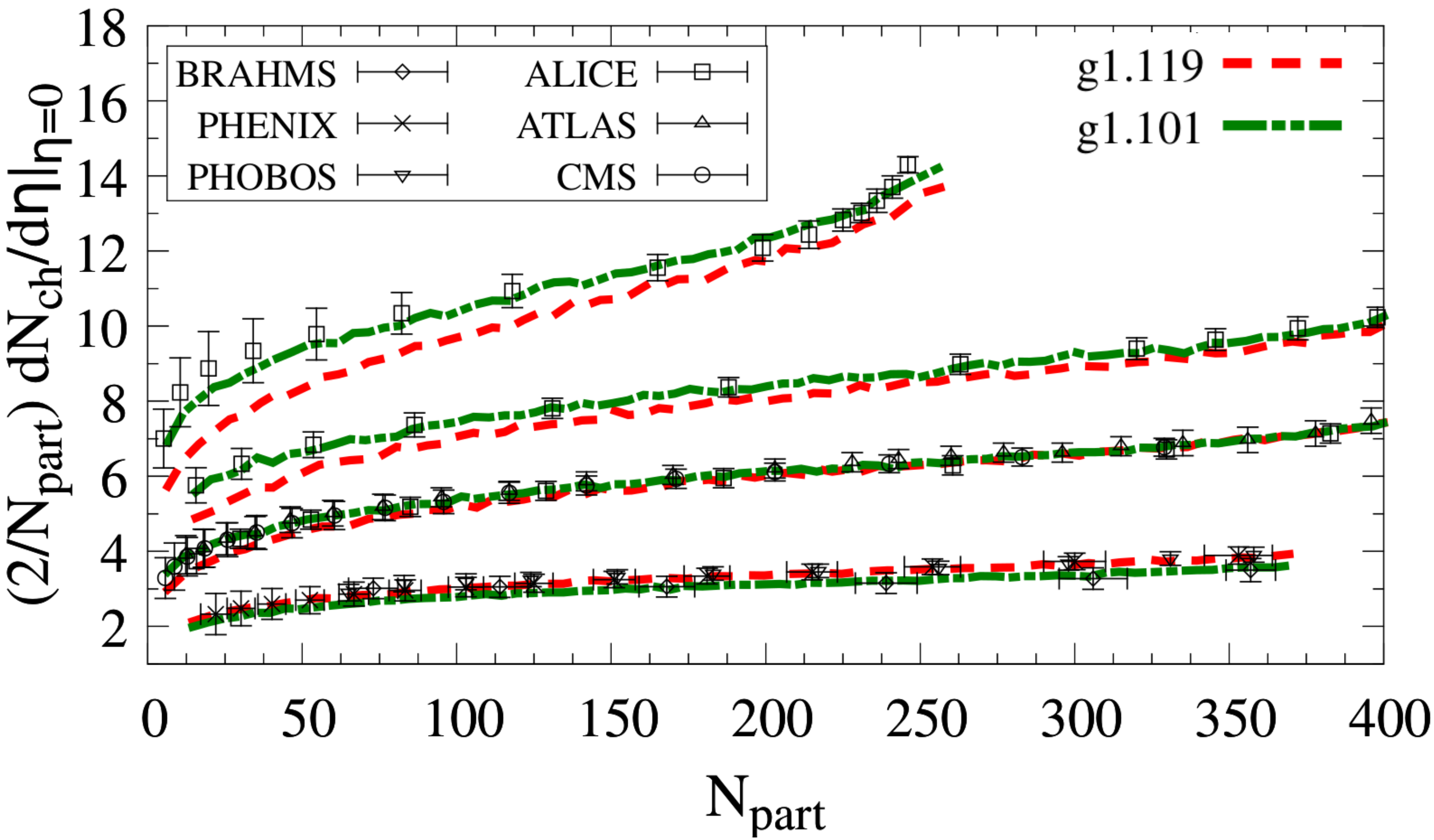


Normalization fixed by Pb+Pb data @ 2.76 TeV; not changed later!

Nice agreement with exp. data from 0.2 TeV to 5.02 TeV & also with new Xe+Xe data @ 5.44 TeV !

Also, good agreement regarding energy evolution! (Backup slides)

Multiplicity vs N_{part} : A + A, $\gamma > 1$ I.C.

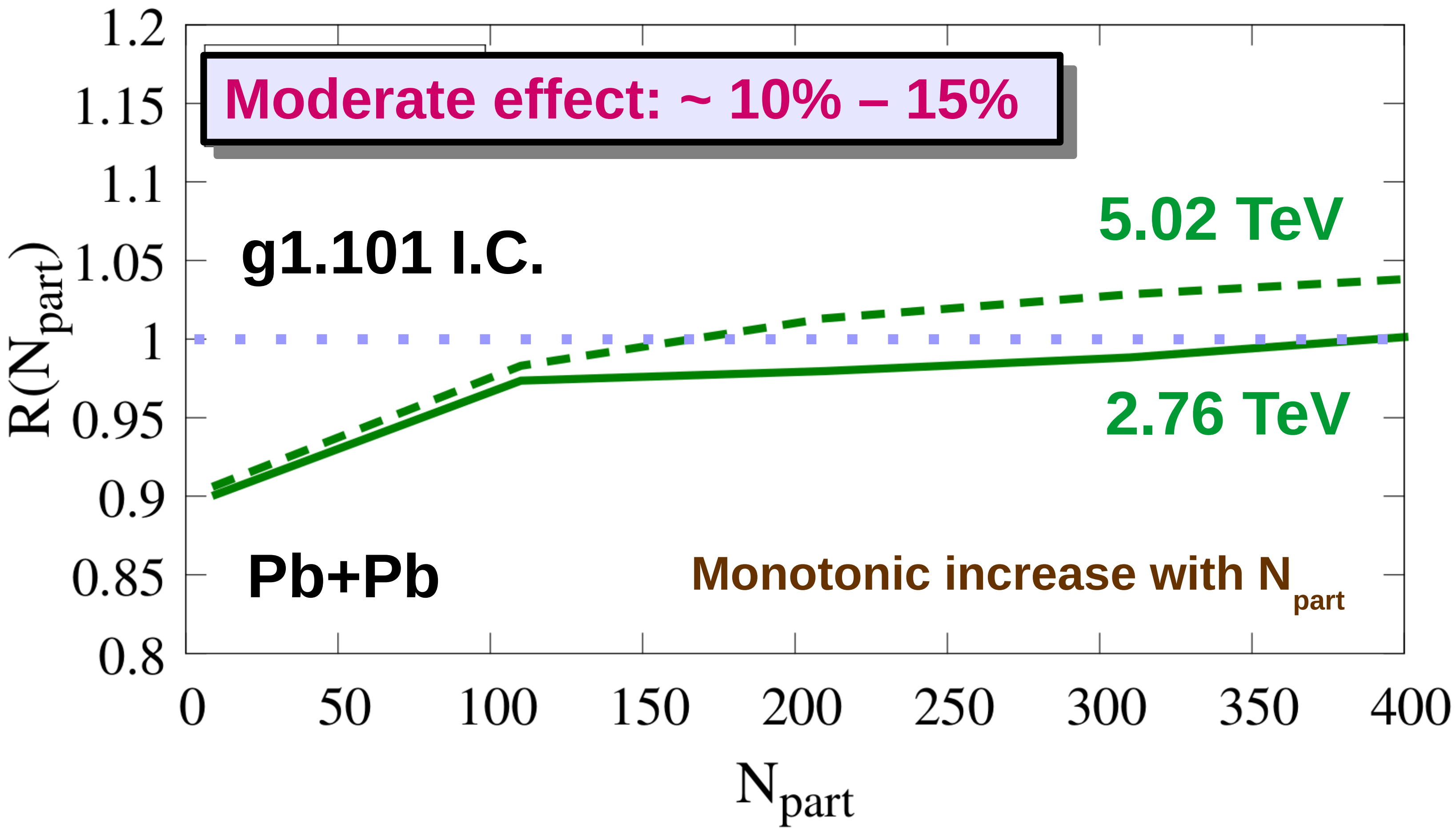


γ = 1.119 I.C. : poor agreement with data @ highest energies

γ = 1.101 I.C. : similar results as MV I.C.

Quantifying the running coupling effects

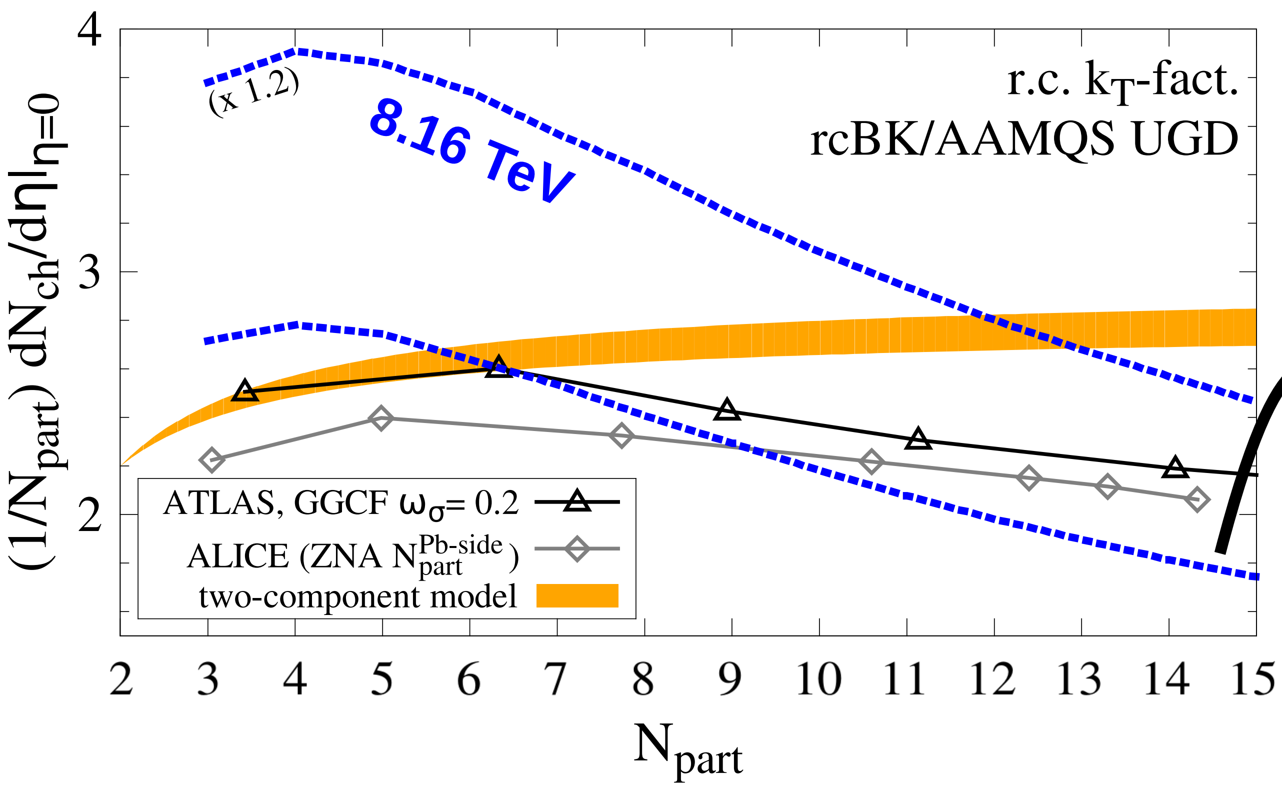
$$R(N_{part}) = \frac{\text{Fixed coupling expression + running coupling effects by hand}}{\text{Running coupling expression}}$$



Similar results for all I.C. & p+Pb @ 5.02, 8.16 TeV

Multiplicity vs Npart : p + A, MV I.C.

arXiv:1805.02702



$$\sim \frac{ln^{1.25}(N_{part})}{N_{part}}$$

p+Pb @ 5.02TeV, MV I.C.

The convolution of two UGDs grows slower than Npart!

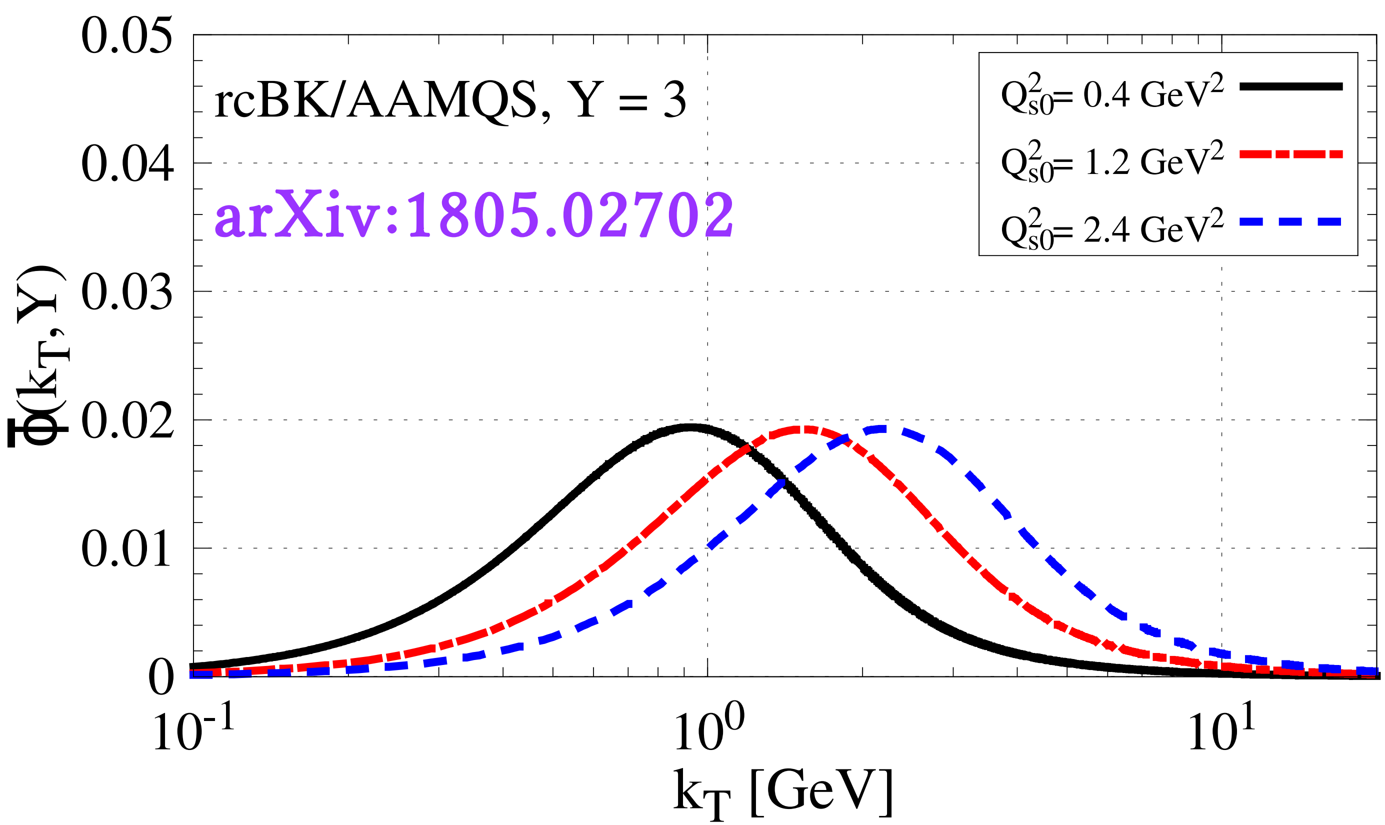
Qualitative agreement with ATLAS & ALICE data @ 5.02 TeV !

$[dE_T/d\eta]/[dN_{ch}/d\eta]$ increases with Npart! Backup slide

Multiplicity vs Npart : p + A, MV I.C.

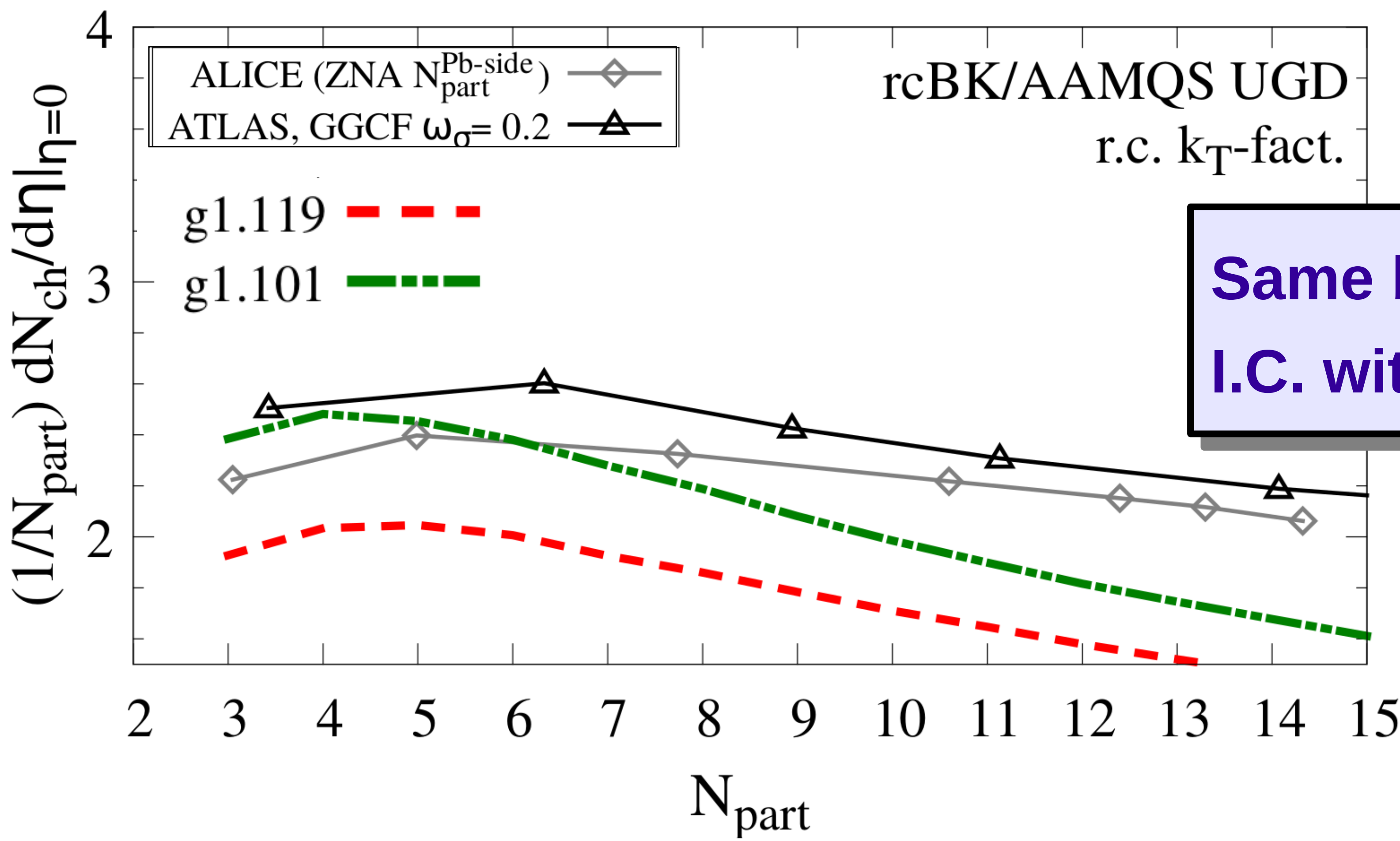
A+A collisions become more symmetric as Npart increases
(proj. and targ. have kt near Qs)

while p+A collisions become more asymmetric!
(proton's UGD stay put but target's UGD moves to higher kt)



1 nucleon target (proton)
3 nucleons target
6 nucleons target

Multiplicity vs N_{part} : p + A, $\gamma > 1$ I.C.



Same behavior for I.C. with $\gamma > 1$

However: exp. data is flatter than our result!

Lack of realistic b-dependence on proton's UGD?

Bias introduced by experimental centrality selection?

Multiplicity vs N_{part} : two-component model, A + A

Two energy dependent shares controlled by f

$$\frac{dN_{AB}}{d\eta} = \left[\frac{1-f}{2} N_{\rm part} + f N_{\rm coll}\right] \frac{dN_{pp}}{d\eta}$$

[“Soft” + “Hard”] component

from ALICE: arXiv:1412.6828

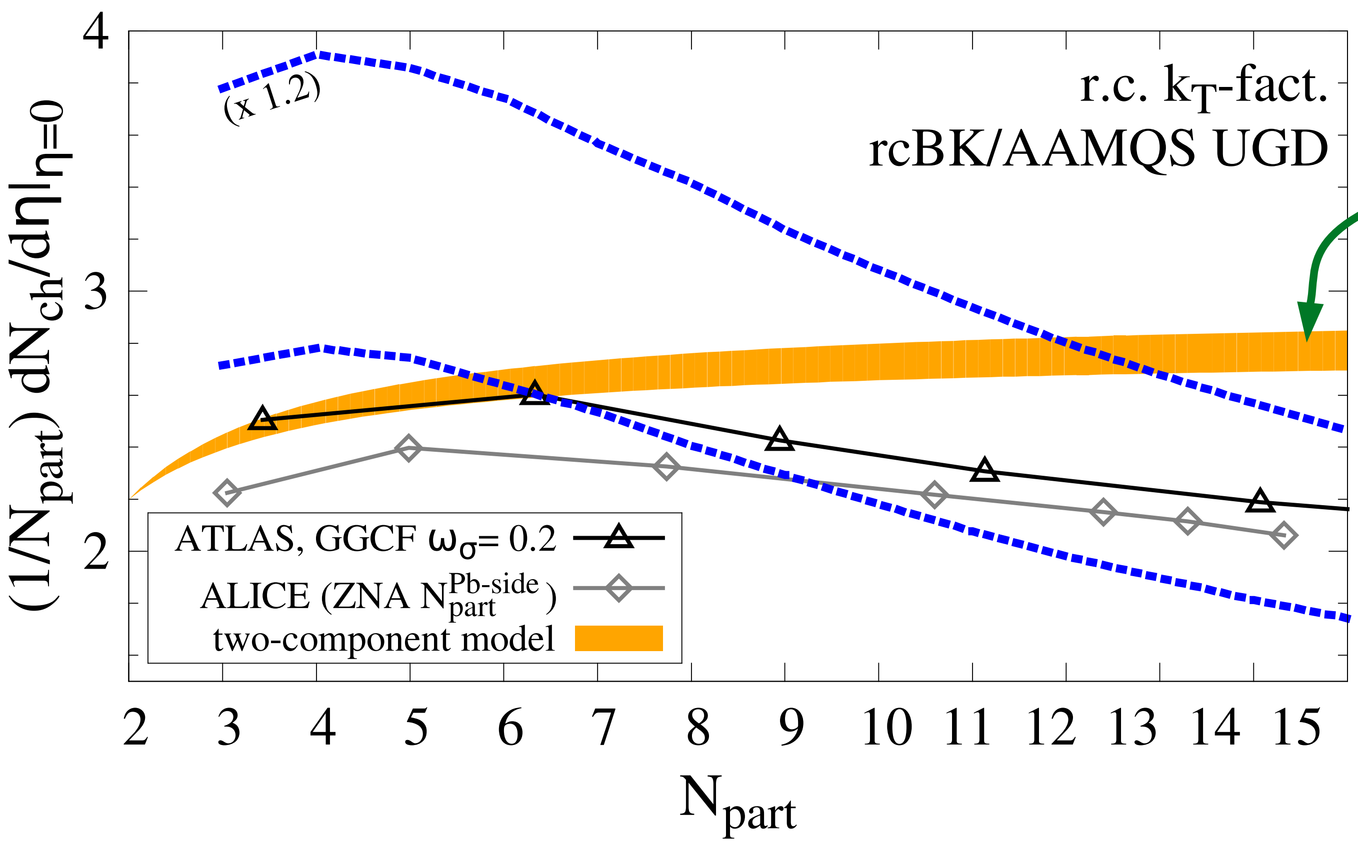
From fit of peripheral region [N_{part} < 34] of Pb+Pb & Xe+Xe data:

$$f = 0.26 - 0.34$$

Going back to p+Pb...

Multiplicity vs N_{part} : p + A, two-component model

arXiv:1805.02702



$f = 0.26 - 0.34$

always increasing with Npart!

For p+A: $N_{coll} = N_{part} - 1$

from ALICE: arXiv:1412.6828

$$\frac{1}{N_{part}}\frac{dN_{pA}}{d\eta} = \left[\frac{1+f}{2} - \frac{f}{N_{part}}\right]\frac{dN_{pp}}{d\eta}$$

Conclusions

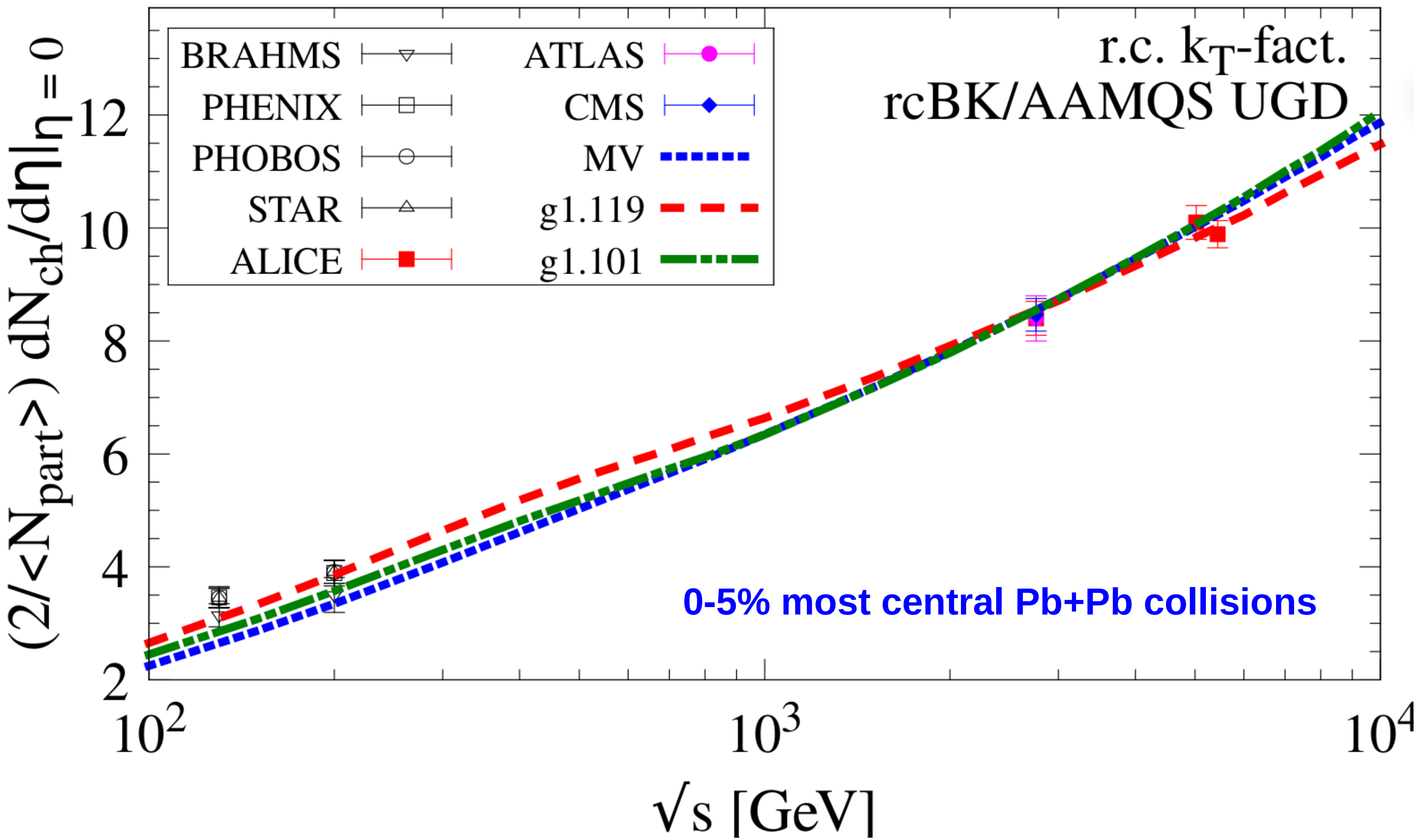
- 1st quantitative comparison of the r.c. kt-fact. with the centrality and energy dependence of particle multiplicities at midrapidity in high-energy p+A and A+A collisions;
- Overall agreement with these observables by adjusting only one parameter!
- The CGC framework is in qualitative agreement with the decreasing of the multiplicity per participant with Npart in p+Pb collisions;
- However, exp. data is flatter than our result… Need to know proton UGD better;
- This data is far different from a simple “2-component model” (for $N_{part} \gtrsim 6$)
- For p+A: coherent effects from CGC make the multiplicity per participant decrease while the transverse energy per charged particle increases with Npart.

Thank you for the attention!

[and the organizers for the opportunity to be here]

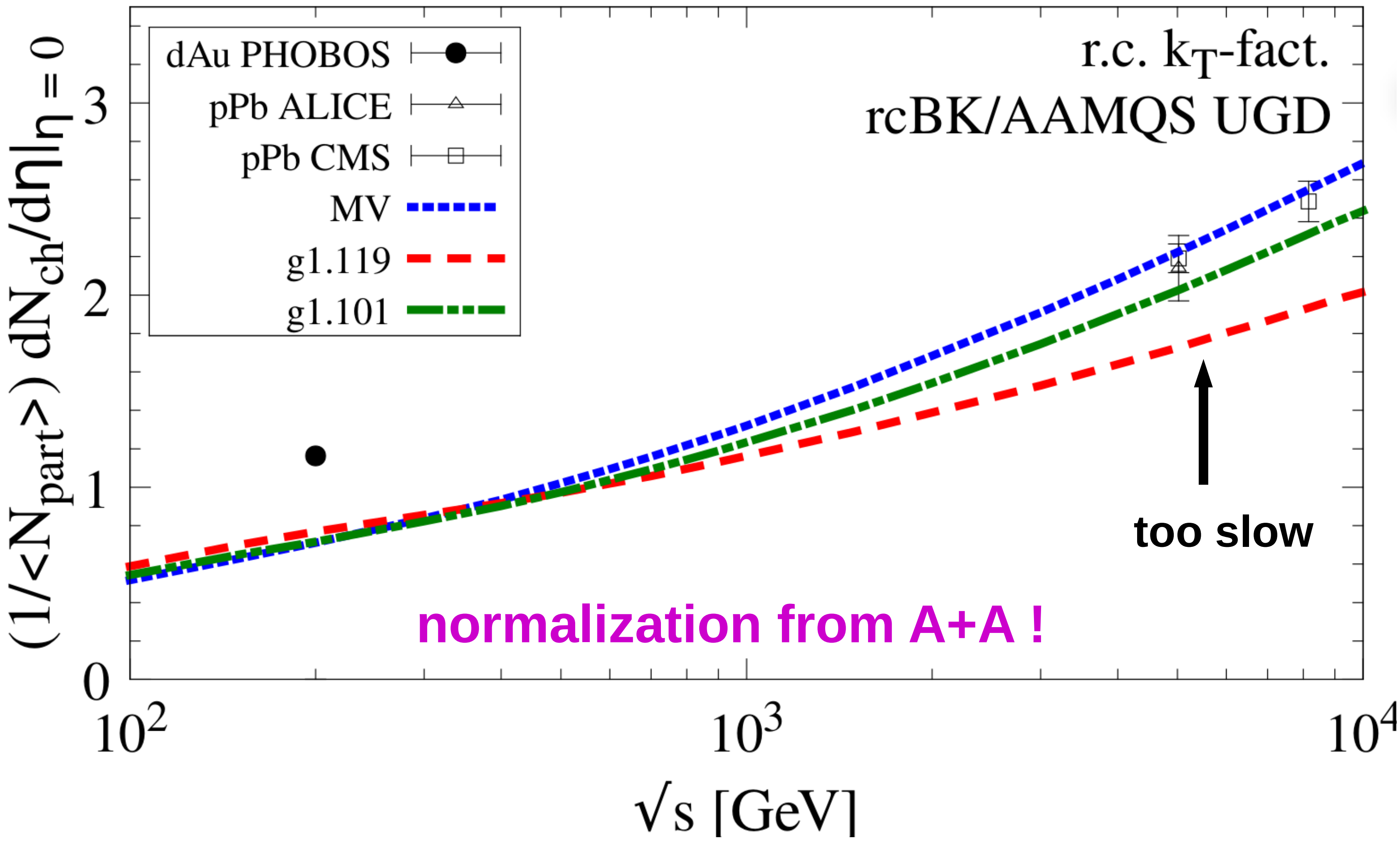
Backup slides

Multiplicity vs energy: A+A



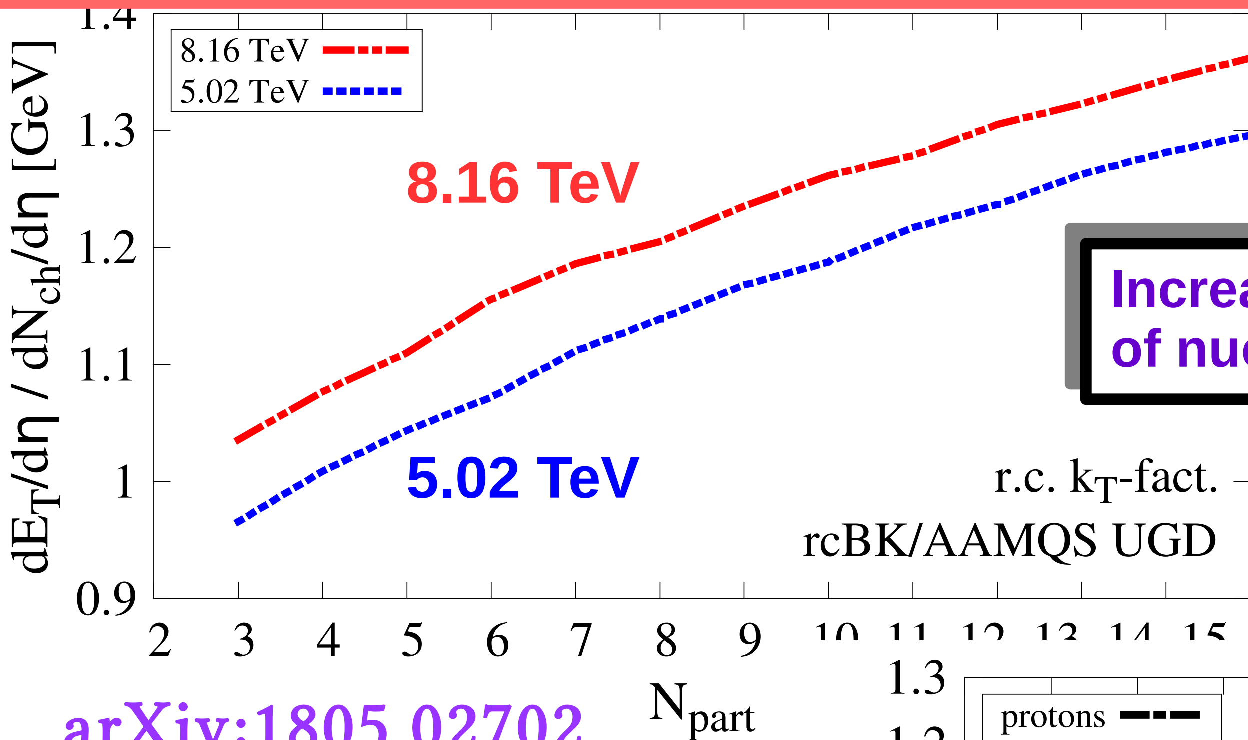
Good description of the energy dependence for all I.C.

Multiplicity vs energy: p+A



At 200 GeV: x ~ 0.01 and the calculation is most sensitive to the rcBK initial condition rather than the small-x evolution!

$[dE_T/d\eta]/[dN_{ch}/d\eta]$ vs Npart: p+A

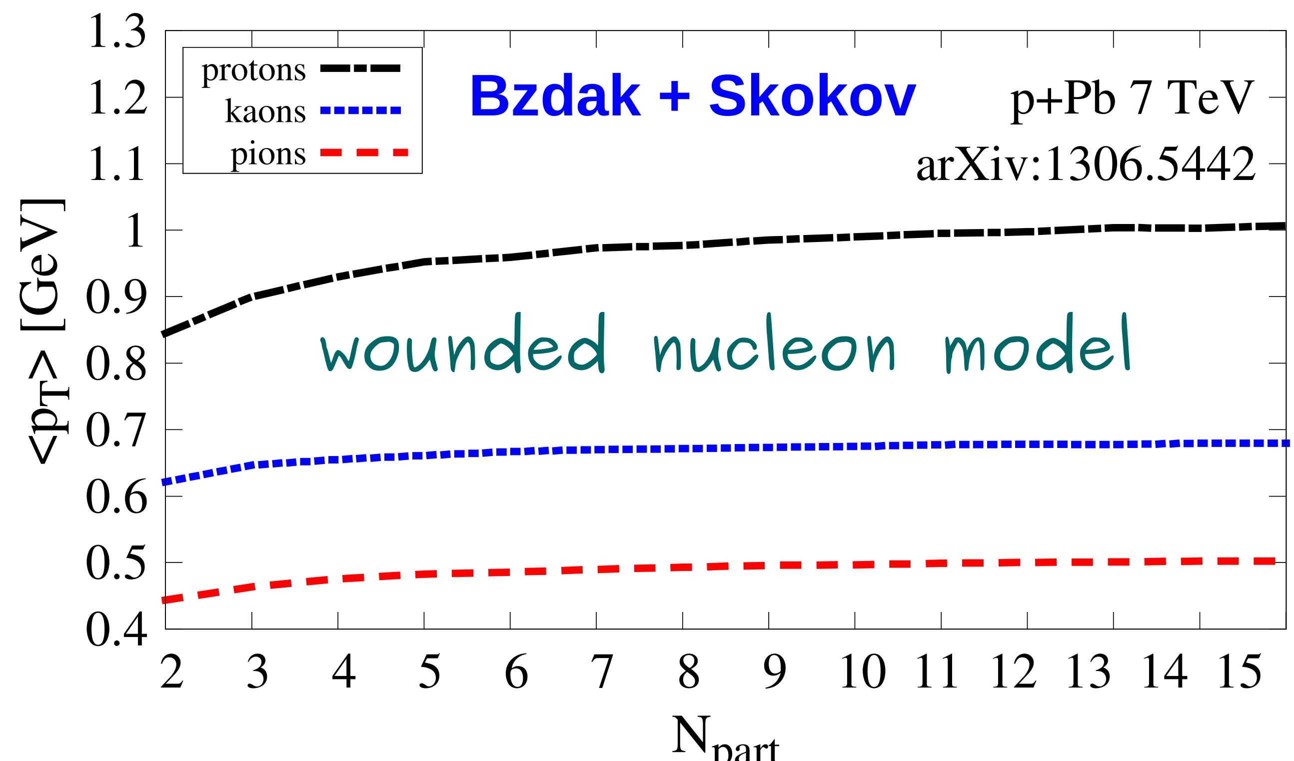


Increase is expected due to increase of nucleus's saturation scale

arXiv:1805.02702

Incoherent model

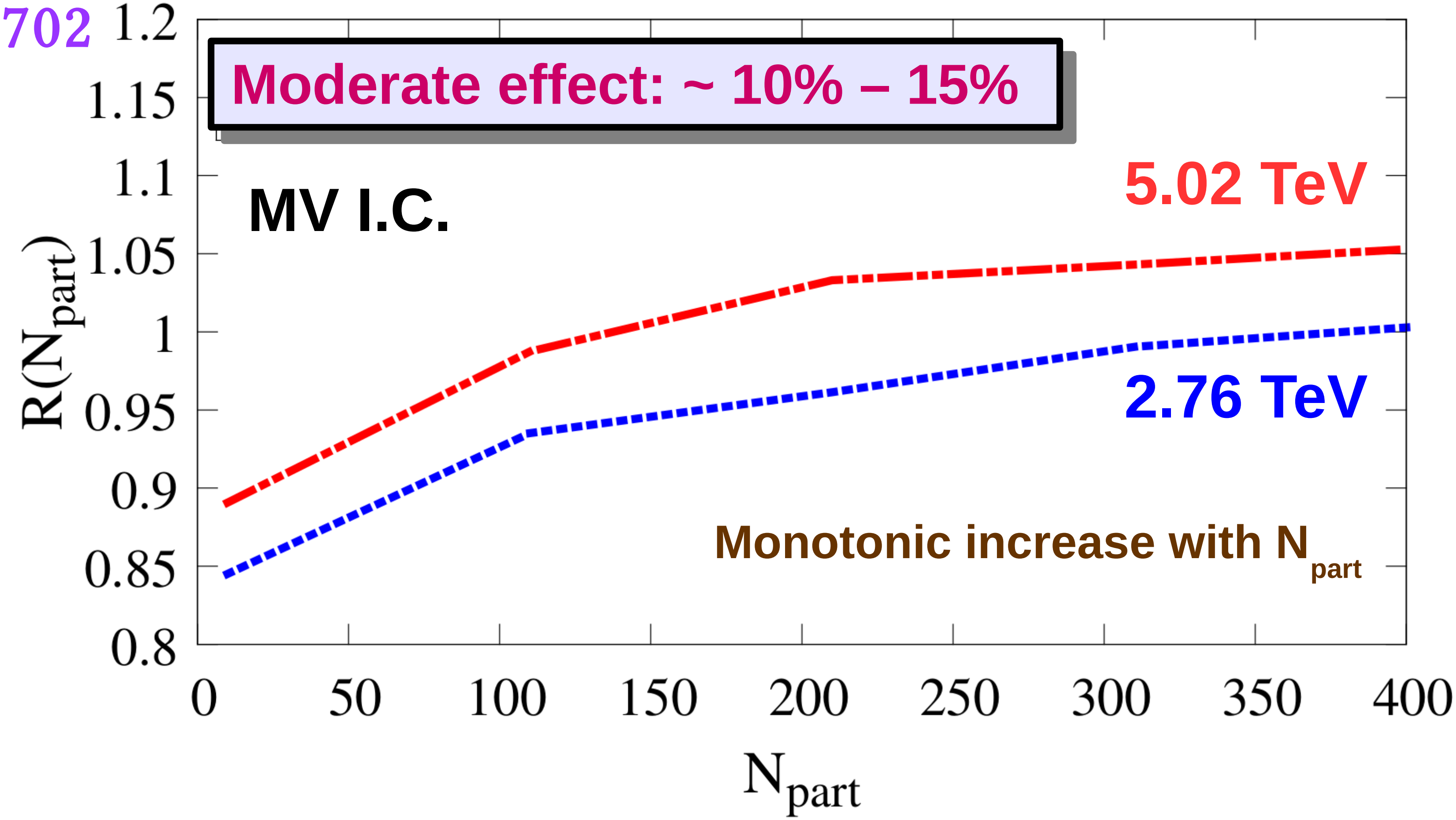
pA = Npart x pp



Quantifying the running coupling effects

$$R(N_{part}) = \frac{\text{Fixed coupling expression + running coupling effects by hand}}{\text{Running coupling expression}}$$

arXiv:1805.02702



Similar results for all I.C. & p+Pb @ 5.02, 8.16 TeV