Bulk quantities in nuclear collisions from CGC and hybrid hydrodynamic simulations

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in collaboration with
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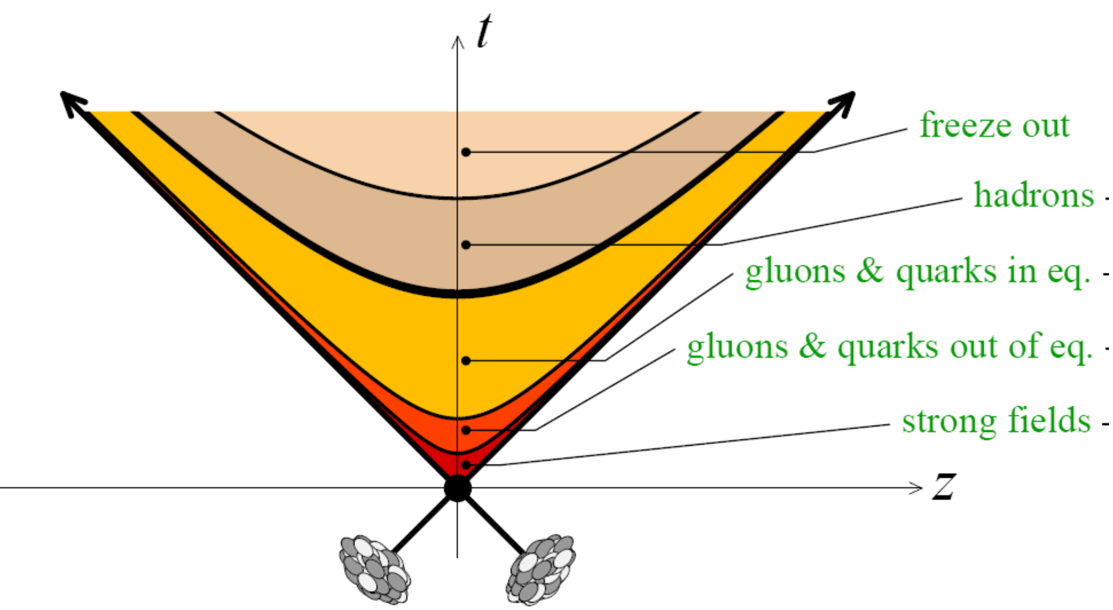
Heavy-ion collisions



Hybrid dynamical models:

Initial conditions +

Pre-equilibrium +

Fluid expansion +

Hadronic dynamics...

observables of interest

Complicated, several inputs, highly non-trivial...

Still: there exists comparisons of initial-state models to exp. data on bulk quantities

Centrality, energy and system size dependence of ch. particle multiplicity...

Outline:

In what extent initial state models can be compared to data?
How different compared to more complete simulation?

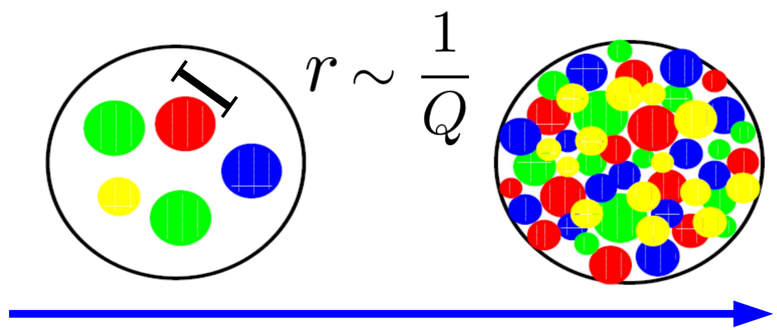
Saturation/CGC

Bulk quantities from kt-fact. in nuclear collisions

Bulk quantities from hybrid simulation + comparison with initial-state approach (kt-fact.)

Here: centrality dependence + avg. pt of ch. hadron multiplicity

Saturation physics (QCD matter at high gluon densities)



gluon density grows due to radiation processes

Increasing the collision energy, $\sqrt{s}$

If the gluon density is too high...

$$x \sim k_T/\sqrt{s} \to 0$$

gluons start to overlap → recombination processes / multiple interactions

QCD evolution equations become non-linear due to coherence effects

Q_s **: momentum scale where non-linear effects can not be neglected anymore**

↳ **Tipical momentum scale on the hadronic wave function,** $k_T \sim Q_s$

Color Glass Condensate: EFT for perturbative QCD at small-x

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

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

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

convolution of the projectile's & target's 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.: $\alpha_s = \mathrm{const.}$

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

The running coupling k_T – fact. formula

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

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

Horowitz and Kovchegov, NPA 849, 72 (2011)

α_s**-factors explicitly in the expression**

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, Weigert, NPA 807, 158 (2008)

Moderate effect: ~ 10%

Dumitru, AVG, Luzum, Nara, PLB784 (2018) 417

The running coupling k_T – fact. formula

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

Horowitz and Kovchegov, NPA 849, 72 (2011)

Q^2 **given by:**

$$\ln \frac{Q^2}{\mu_{\overline{\text{MS}}}^2} = \frac{1}{2} \ln \frac{\boldsymbol{q}^2\, (\boldsymbol{k}-\boldsymbol{q})^2}{\mu_{\overline{\text{MS}}}^4} - \frac{1}{4\, \boldsymbol{q}^2\, (\boldsymbol{k}-\boldsymbol{q})^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right]^6} \Bigg\{ \boldsymbol{k}^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right]^3$$

$$\times \left\{ \left[\left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2 - \left(\boldsymbol{q}^2\right)^2\right] \left[\left(\boldsymbol{k}^2\right)^2 + \left((\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right)^2\right] + 2\, \boldsymbol{k}^2 \left[\left(\boldsymbol{q}^2\right)^3 - \left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^3\right]\right.$$

$$\left. - \boldsymbol{q}^2\, (\boldsymbol{k}-\boldsymbol{q})^2 \left[2\, \left(\boldsymbol{k}^2\right)^2 + 3\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right]^2 - 3\, \boldsymbol{k}^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 + \boldsymbol{q}^2\right]\right] \ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right) \right\}$$

$$+ i\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right]^3 \left\{ \boldsymbol{k}^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right] \left[\boldsymbol{k}^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 + \boldsymbol{q}^2\right] - \left(\boldsymbol{q}^2\right)^2 - \left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2\right]\right.$$

$$\left. + \boldsymbol{q}^2\, (\boldsymbol{k}-\boldsymbol{q})^2 \left(\boldsymbol{k}^2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 + \boldsymbol{q}^2\right] - 2\, \left(\boldsymbol{k}^2\right)^2 - 2\, \left[(\boldsymbol{k}-\boldsymbol{q})^2 - \boldsymbol{q}^2\right]^2\right) \ln\left(\frac{(\boldsymbol{k}-\boldsymbol{q})^2}{\boldsymbol{q}^2}\right) \right\}$$

$$\times \sqrt{2\, \boldsymbol{q}^2\, (\boldsymbol{k}-\boldsymbol{q})^2 + 2\, \boldsymbol{k}^2\, (\boldsymbol{k}-\boldsymbol{q})^2 + 2\, \boldsymbol{q}^2\, \boldsymbol{k}^2 - \left(\boldsymbol{k}^2\right)^2 - \left(\boldsymbol{q}^2\right)^2 - \left[(\boldsymbol{k}-\boldsymbol{q})^2\right]^2}\; \Bigg\},$$

Caveats:

CGC: early time dynamics determines all bulk quantities!

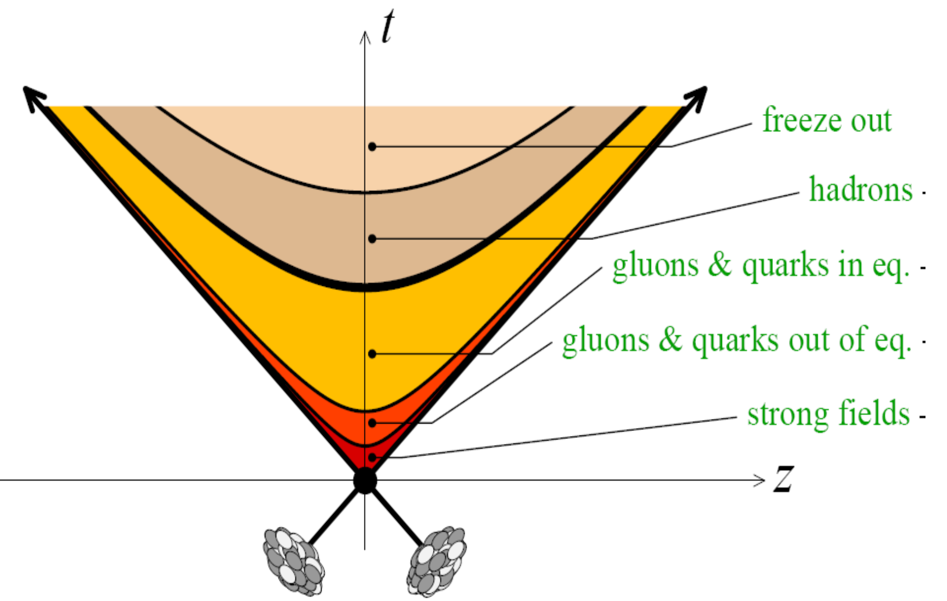
CGC vs data: comparison at partonic level!

No actual hadrons in the calculation, no medium effects...

Consider other stages of nuclear collisions via hybrid (hydro+transport) simulations!

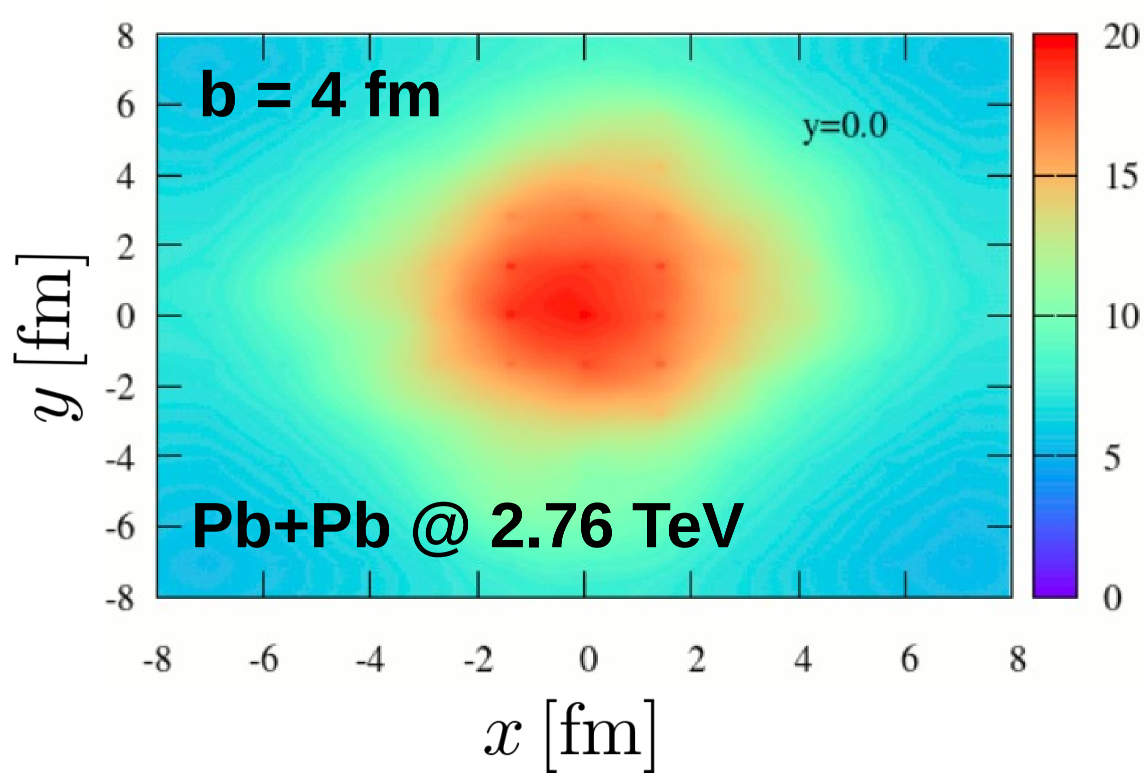
CGC as initial condition for a hybrid hydrodynamic simulations

Sketch of our calculation

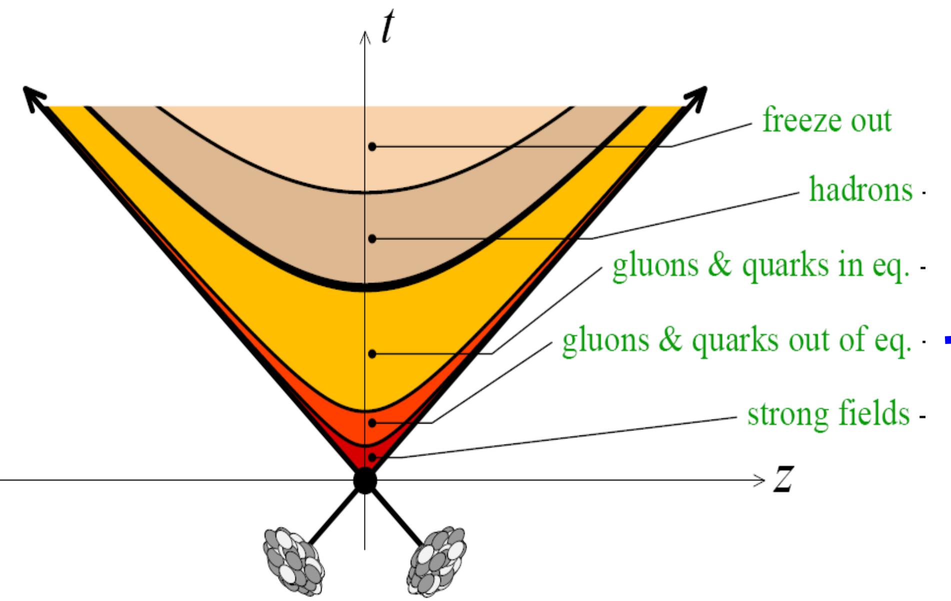


gluon density from kt-fact. + rcBK

$$\frac{dN_g}{d^2x_\perp dy}$$



Sketch of our calculation



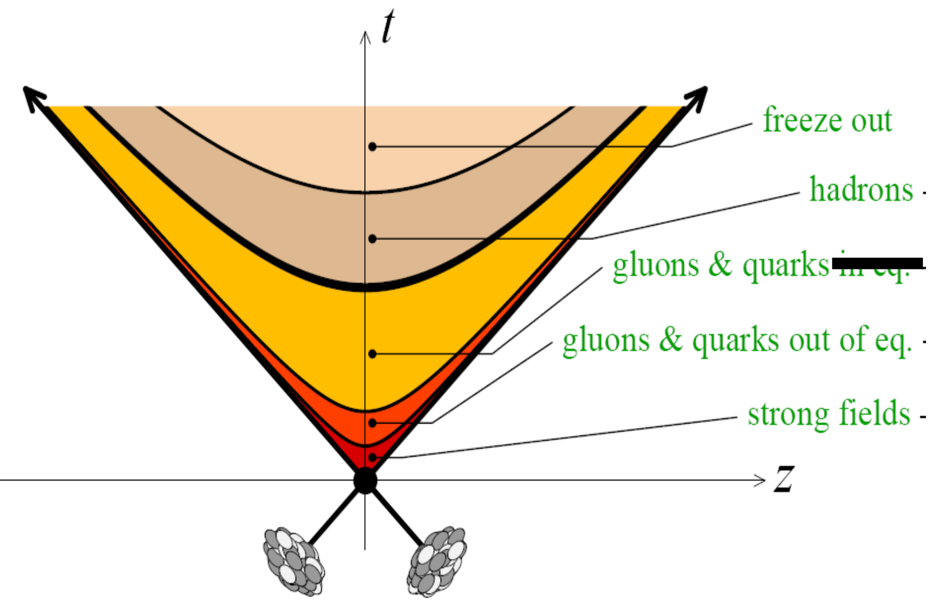
NO "pre-equilibrium" dynamics at the moment

Zero initial shear tensor and bulk pressure

+

No initial transverse fuid velocity

Sketch of our calculation



near equilibrium

relativistic hydrodynamic expansion

at $\tau = 0.2\ fm$

MUSIC: 3+1 D viscous & ideal hydrodynamics simulation code;

MUSIC manual: https://webhome.phy.duke.edu/~jp401/music_manual/music_manual_20180809.pdf

Solves 2nd order viscous hydrodynamics eqs.

Same parameters as in J. E. Bernhard, arXiv:1804.06469, but different normalization

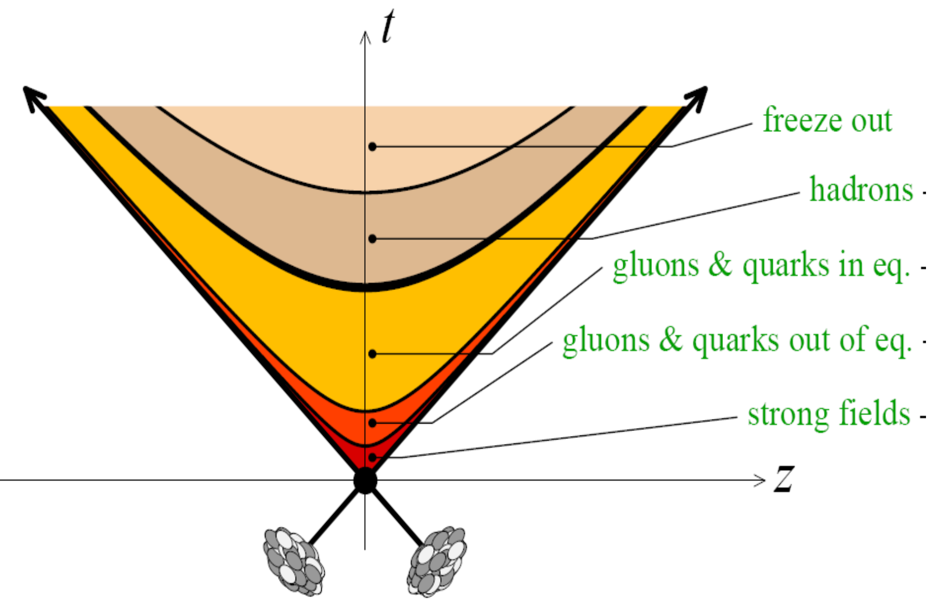
$$S\Big|_{\tau=\tau_0} \propto \frac{1}{\tau_0}\frac{dN_g}{d^2x_\perp dy}$$

then $S\Big|_{\tau_0} \rightarrow \varepsilon_0$ **via thermodynamics**

Equation of state: s95p-v1.2

Huovinen, Petreczky, Nucl. Phys. A 837, 26 (2010)

Sketch of our calculation



$T < T_{\rm sw}$: "particlization"

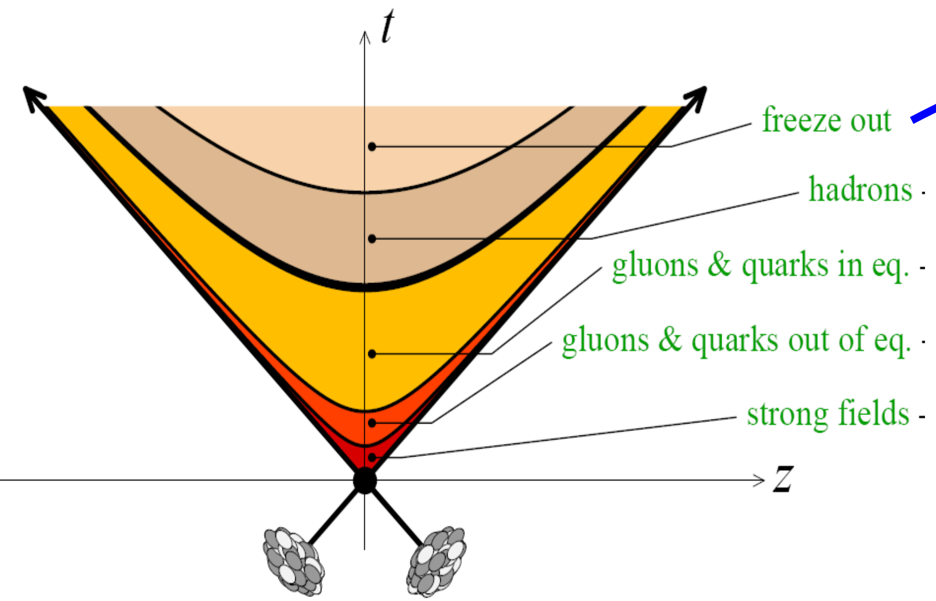
conversion from fluid to particles

Fluid description matched to a kinetic one by sampling discrete particles along the hypersurface

UrQMD: hadronic transport kinetic theory (Boltzmann eq.)

Consider "ch. particles" (pions, protons and kaons)

Sketch of our calculation



Non-interacting system

↓

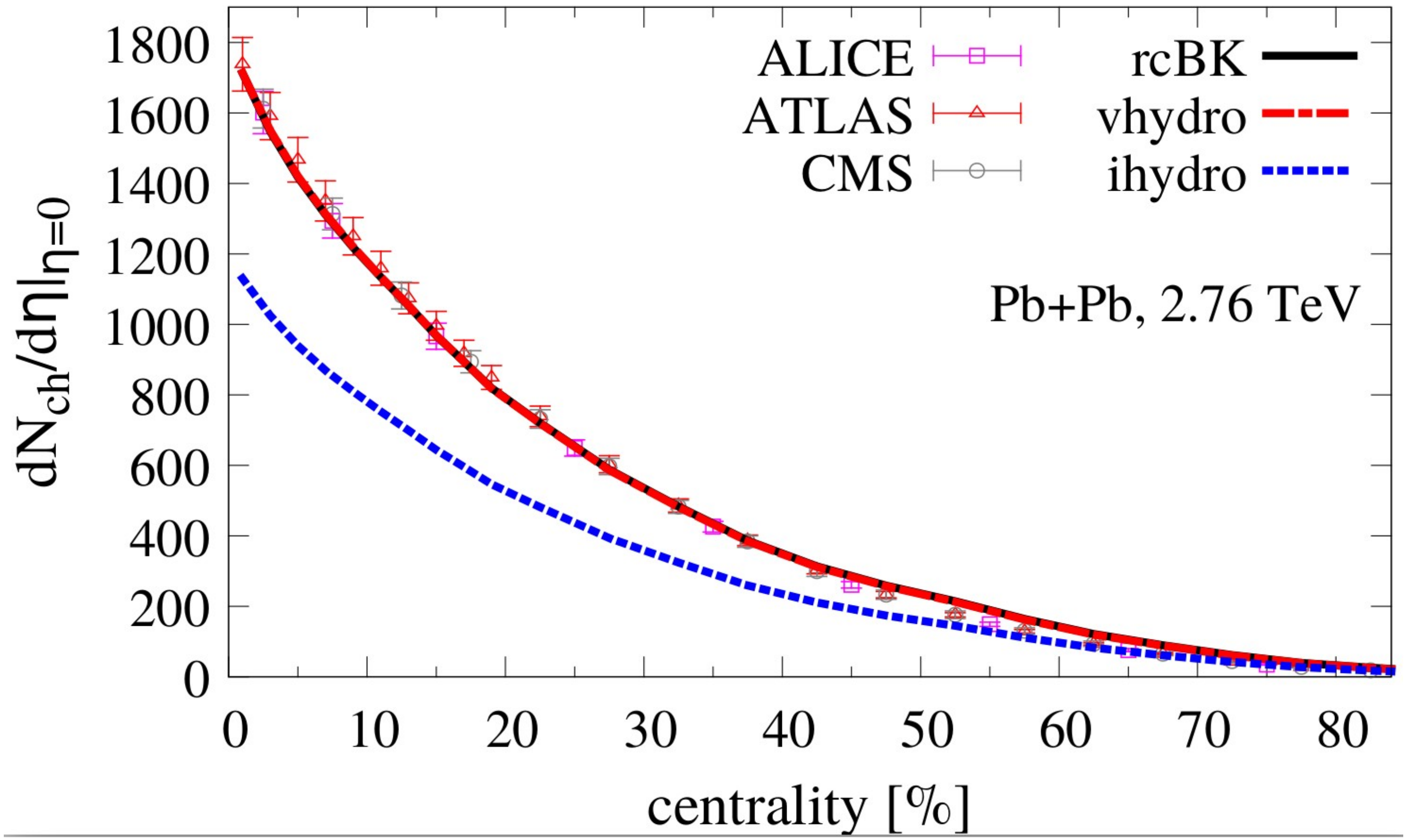
observables

Results from 2D hydro simulations with
rcBK initial conditions + MUSIC + UrQMD

+

comparison with pure initial state model

Multiplicity vs centrality: Pb+Pb @ 2.76 TeV



rcBK (CGC)

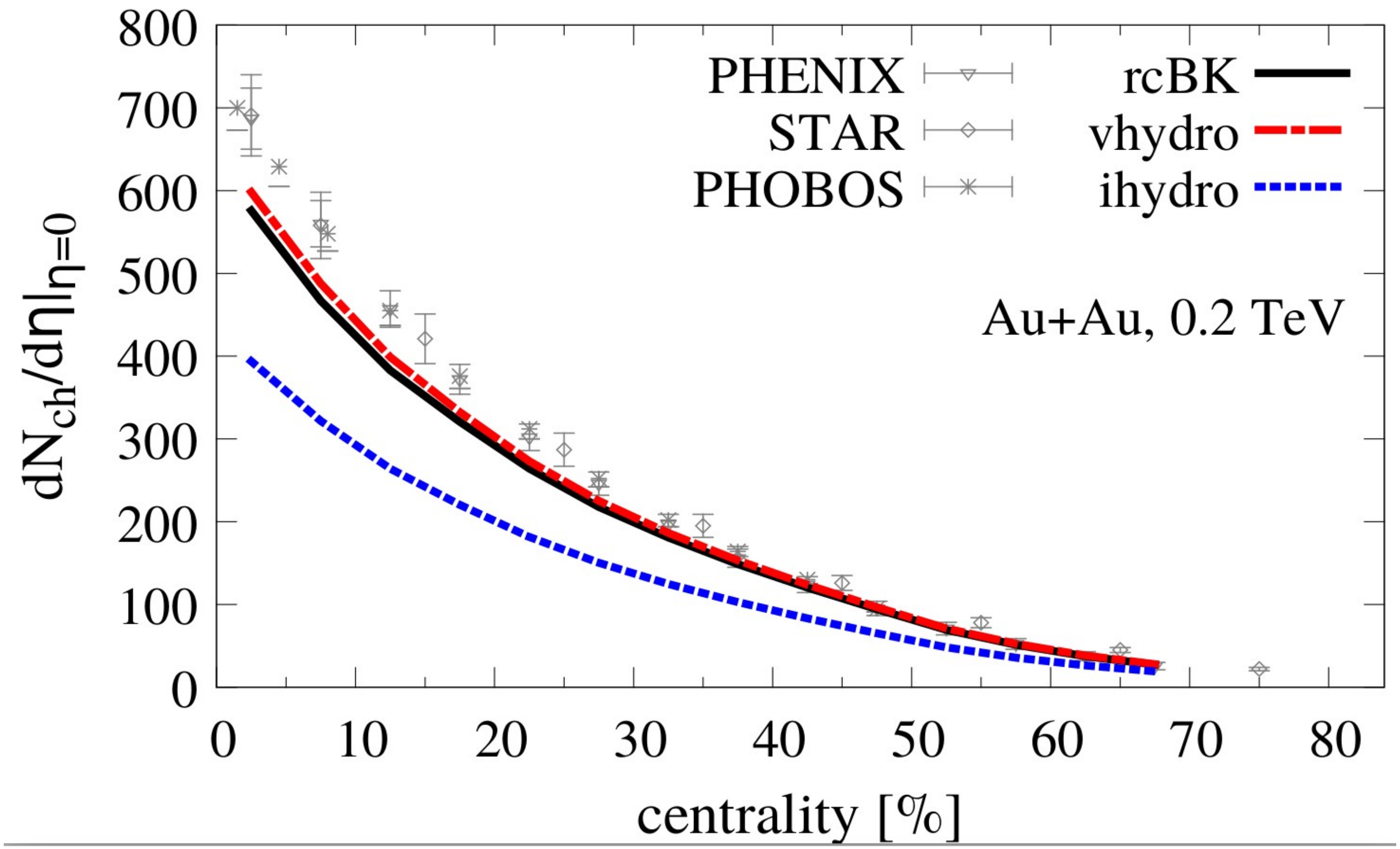
rcBK I.C. + viscous hydro + UrQMD

rcBK I.C. + ideal hydro + UrQMD

Fix normalization for rcBK and viscous hydro calculations

Do not change it for other systems and collision energies

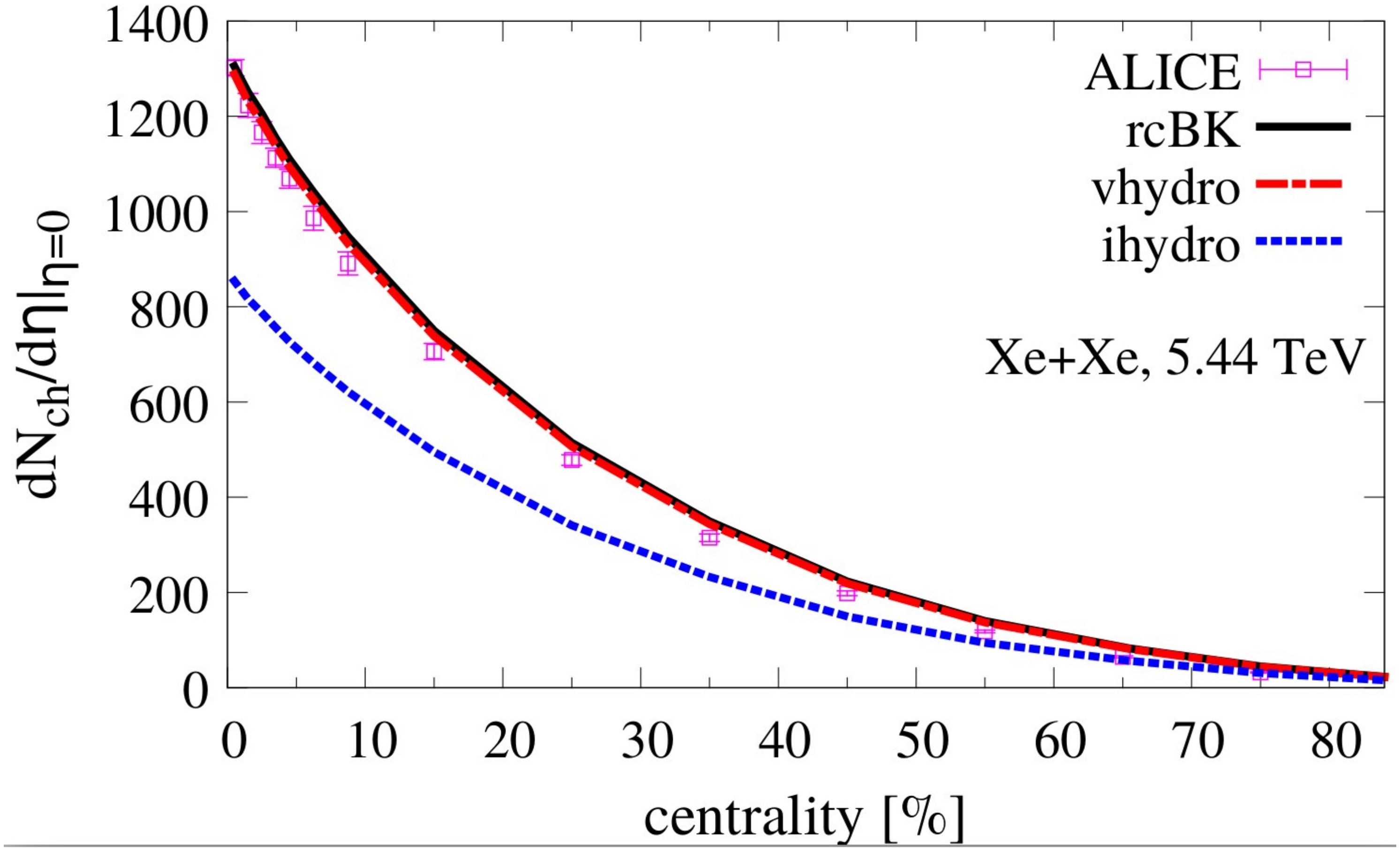
Multiplicity vs centrality: Au+Au @ 0.2 TeV



Down to RHIC: similar situation as in TeV regime!

Biggest energy difference; worst comparison w/ data

Multiplicity vs centrality: Xe+Xe @ 5.44 TeV

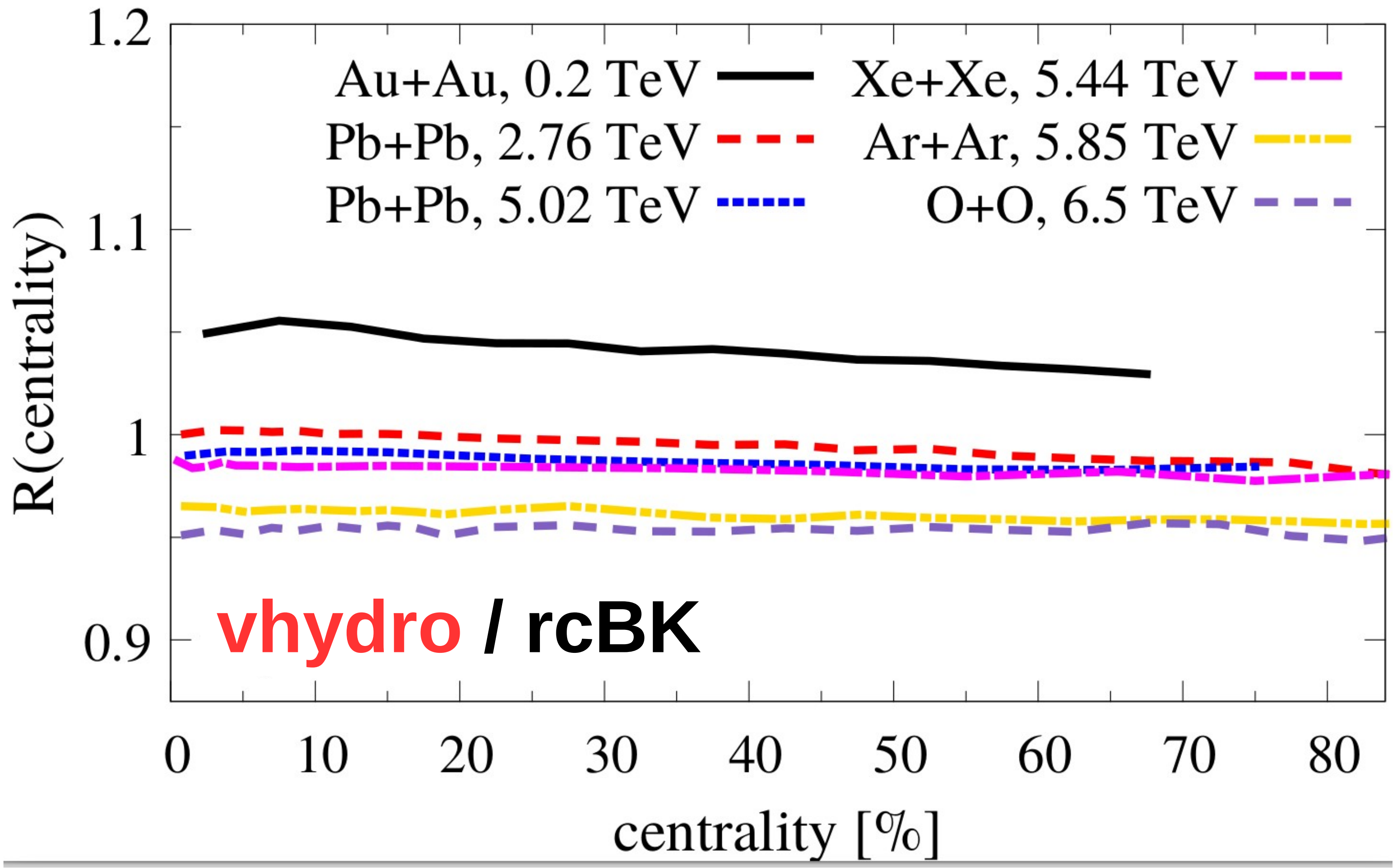


Back to TeV regime but different collision system

Hydro expansion + hadronic dynamics do not lead to strong change in centrality dependence compared to initial stage

Multiplicity vs centrality: ratio vhydro / rcBK

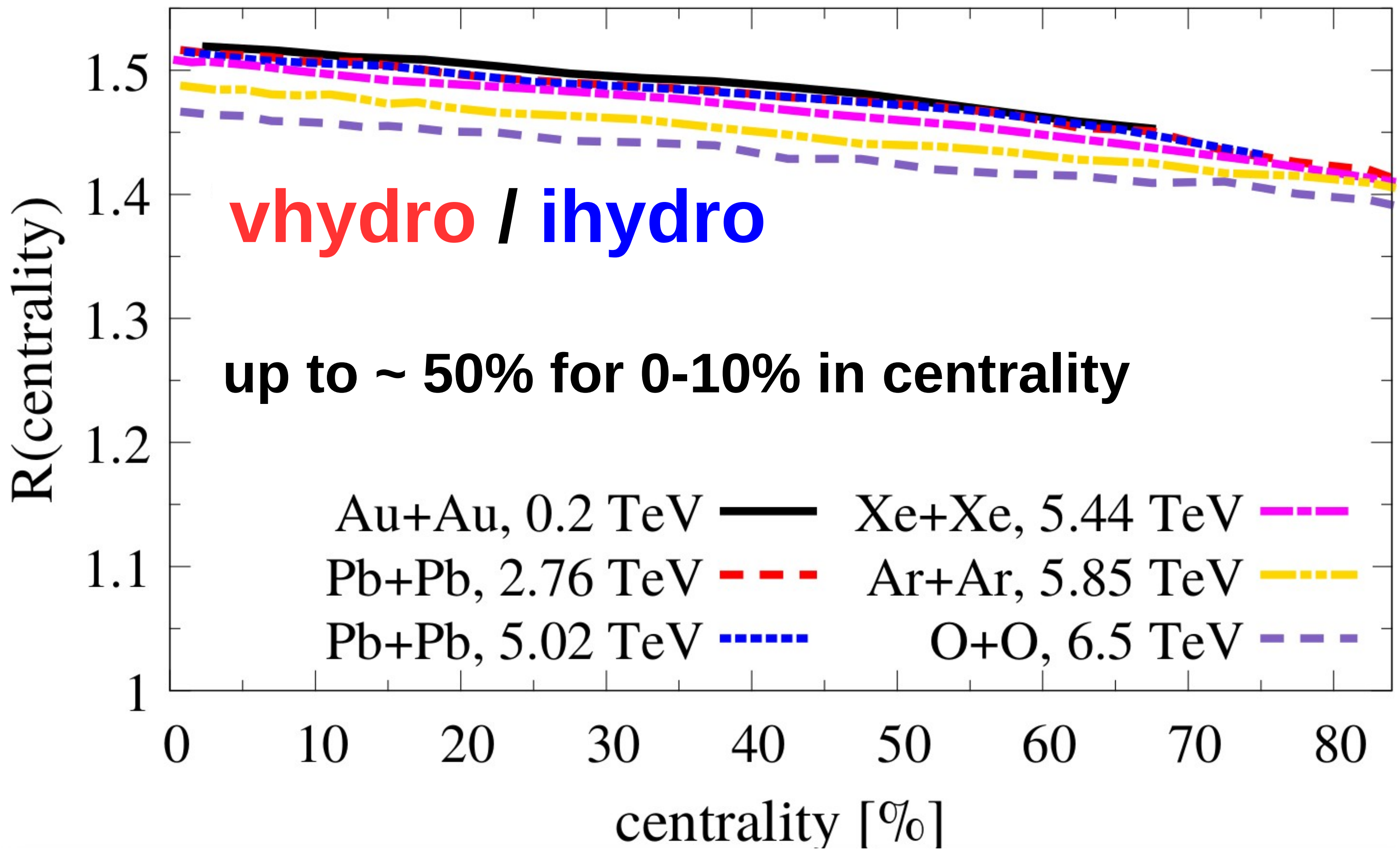
Difference of ~5% depending on the collision system and collision energy



Backup slide: this ratio vs collision energy

Entropy production in heavy-ion collisions

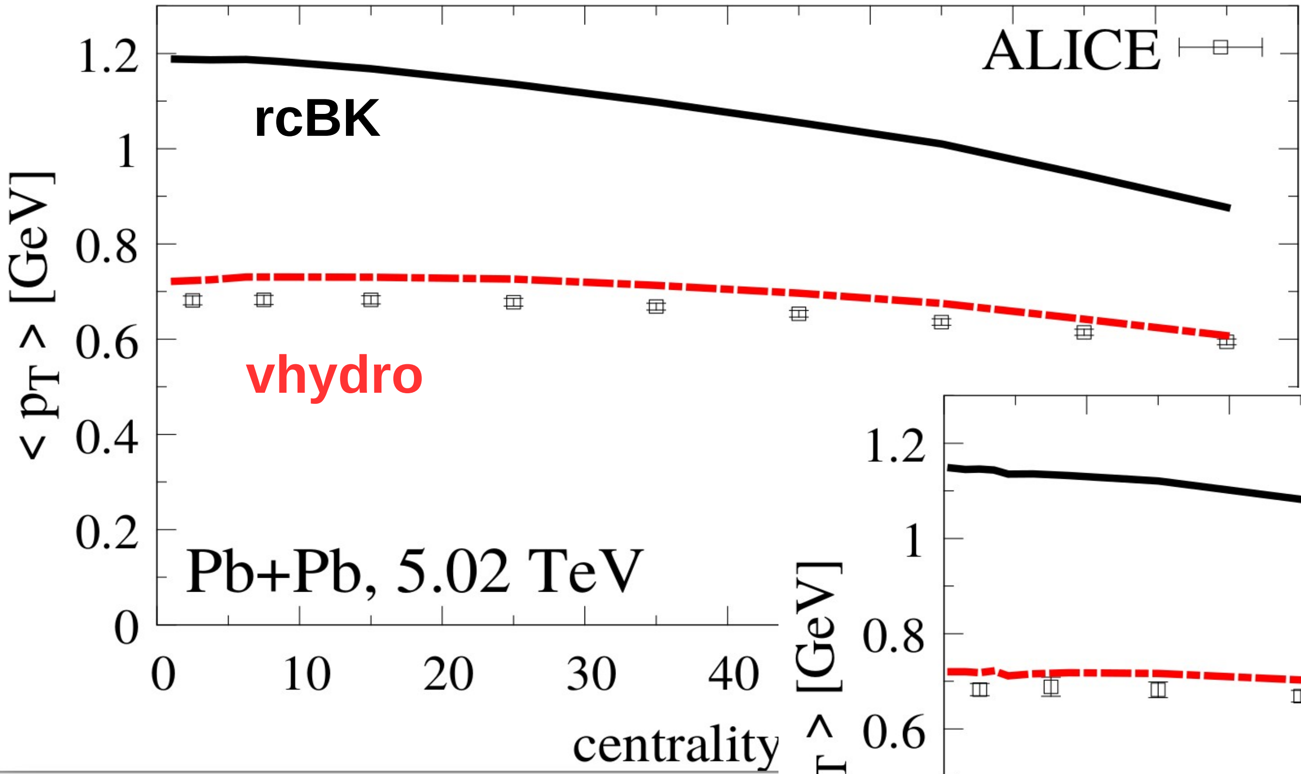
R(cent.) = $\frac{\text{rcBK i.c. + viscous hydro + UrQMD}}{\text{rcBK i.c. + ideal hydro + UrQMD}}$



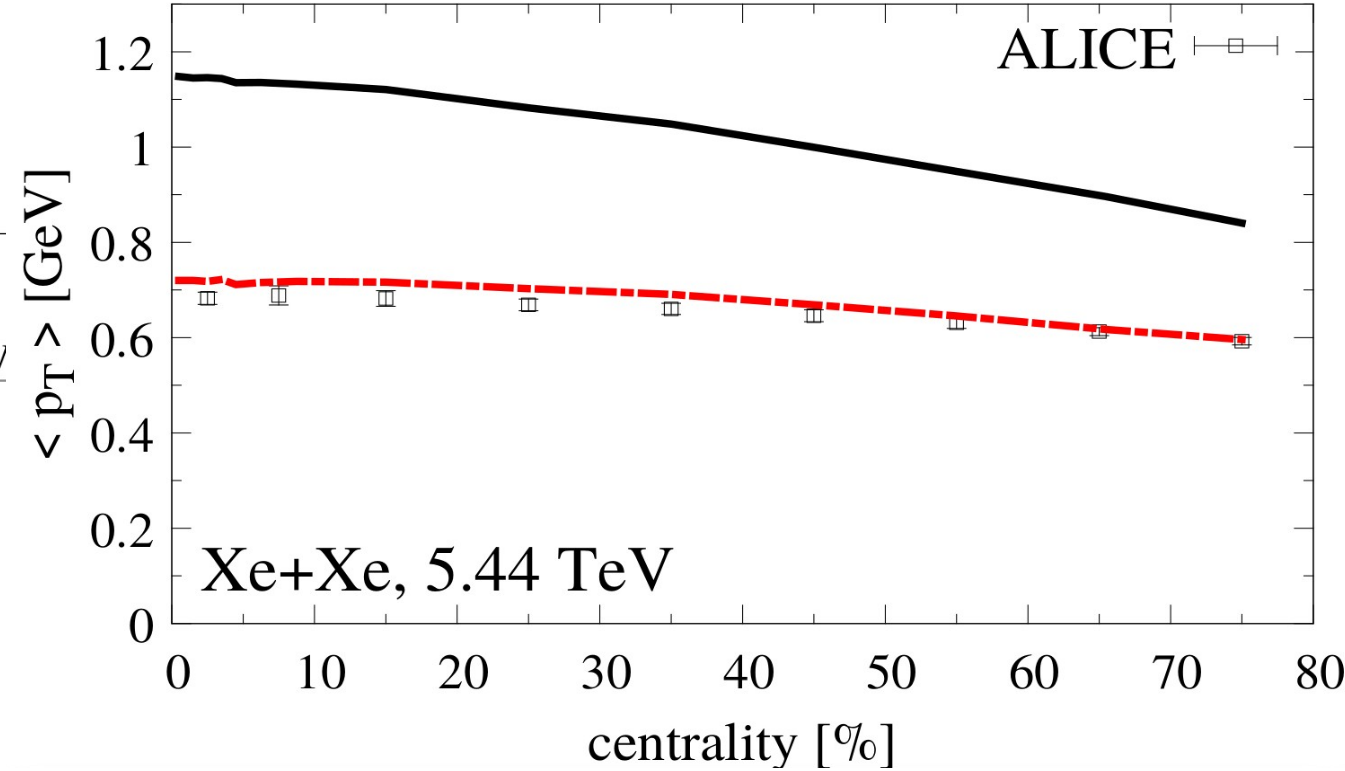
"**Upper-limit**" as $\tau_0 = 0.2\mathrm{fm}$

Less particle production if hydro starts later!

< pT > in nuclear collisions



rcBK: final avg. pt ~ initial avg. pt ~ Qs



Backup slides:
Au+Au @ 0.2 TeV
p+Pb @ 5.02 TeV

vhydro: space-time evolution + final state dynamics (hydro+UrQDM) redistribute momentum → closer to data!

Ratio of < pT > in nuclear collisions

Giacalone, Noronha-Hostler, Luzum, Ollitrault, arXiv:1711.08499

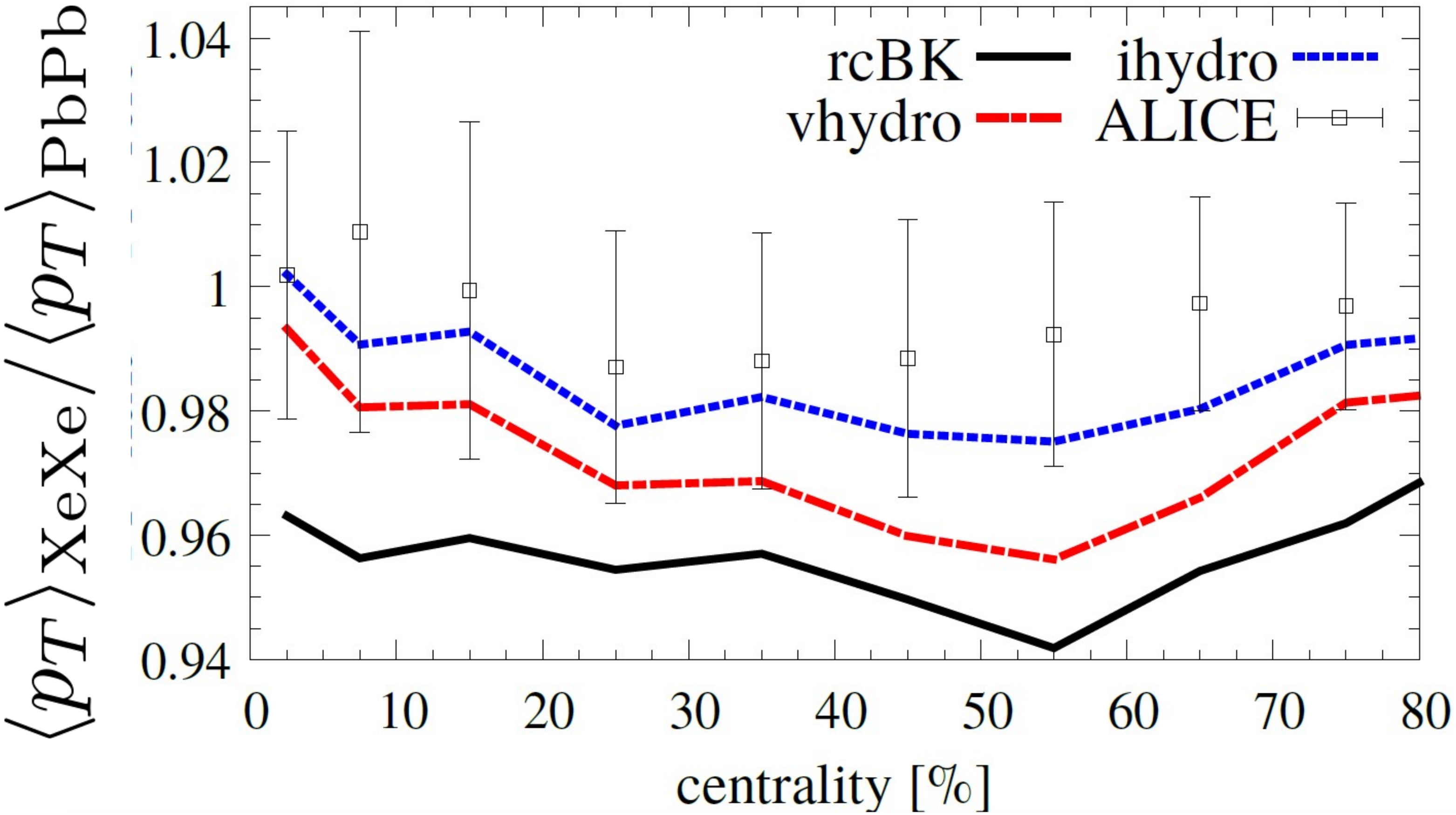
Ratio of <pT> in different systems but same energy: robust test of hydrodynamic behaviour

Should depend little on details of hydrodynamic system & can be different for system with different dynamics

$$\langle p_T \rangle_{\rm XeXe} / \langle p_T \rangle_{\rm PbPb}$$

Several uncertainties cancel when taking a ratio. Still...

Ratio $\langle p_T \rangle_{\mathrm{XeXe}} / \langle p_T \rangle_{\mathrm{PbPb}}$



rcBK always below data!

hybrid simulation does a better job

vhydro result 1% below to Giacalone et all.

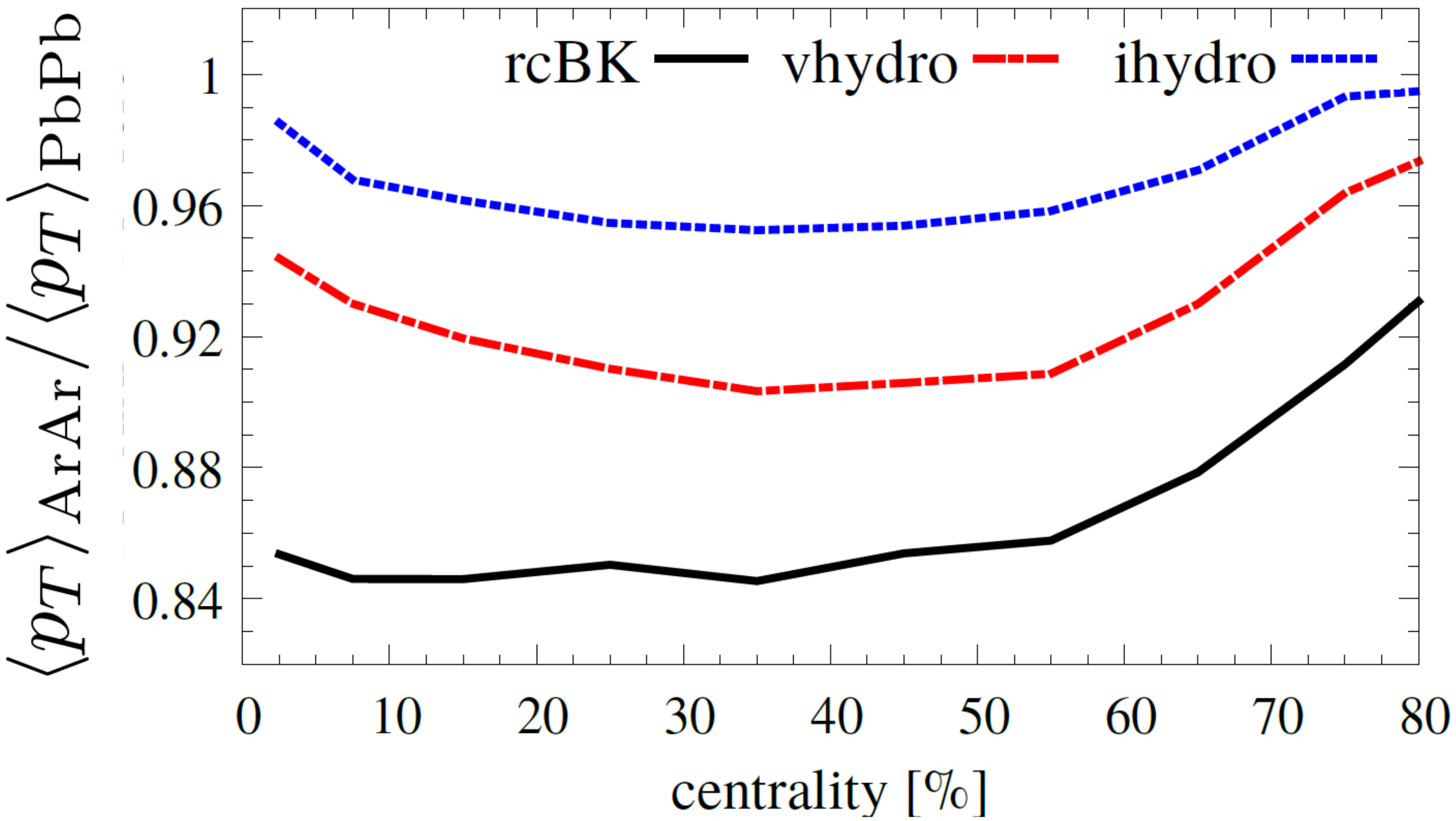
Perhaps potential probe for viscous effects in different systems?

Final remarks

- Calculated bulk observables considering i) only initial state physics (CGC) and ii) initial+final state physics (CGC+hydro+UrQMD)
- Matched them to same exp. data;
- Both approaches present same centrality dependence;
- Up to ~ 50% of ch. particle multiplicity produced due to dissipative effects; expect lower percentage for bigger τ_0
- Final state interactions allow for redistribution of momentum changing centrality dependence of avg. pt $\rightarrow$ closer to data
- Ratio of <pT>: favor hybrid simulation over pure initial state; potential probe of viscous effects in different systems?

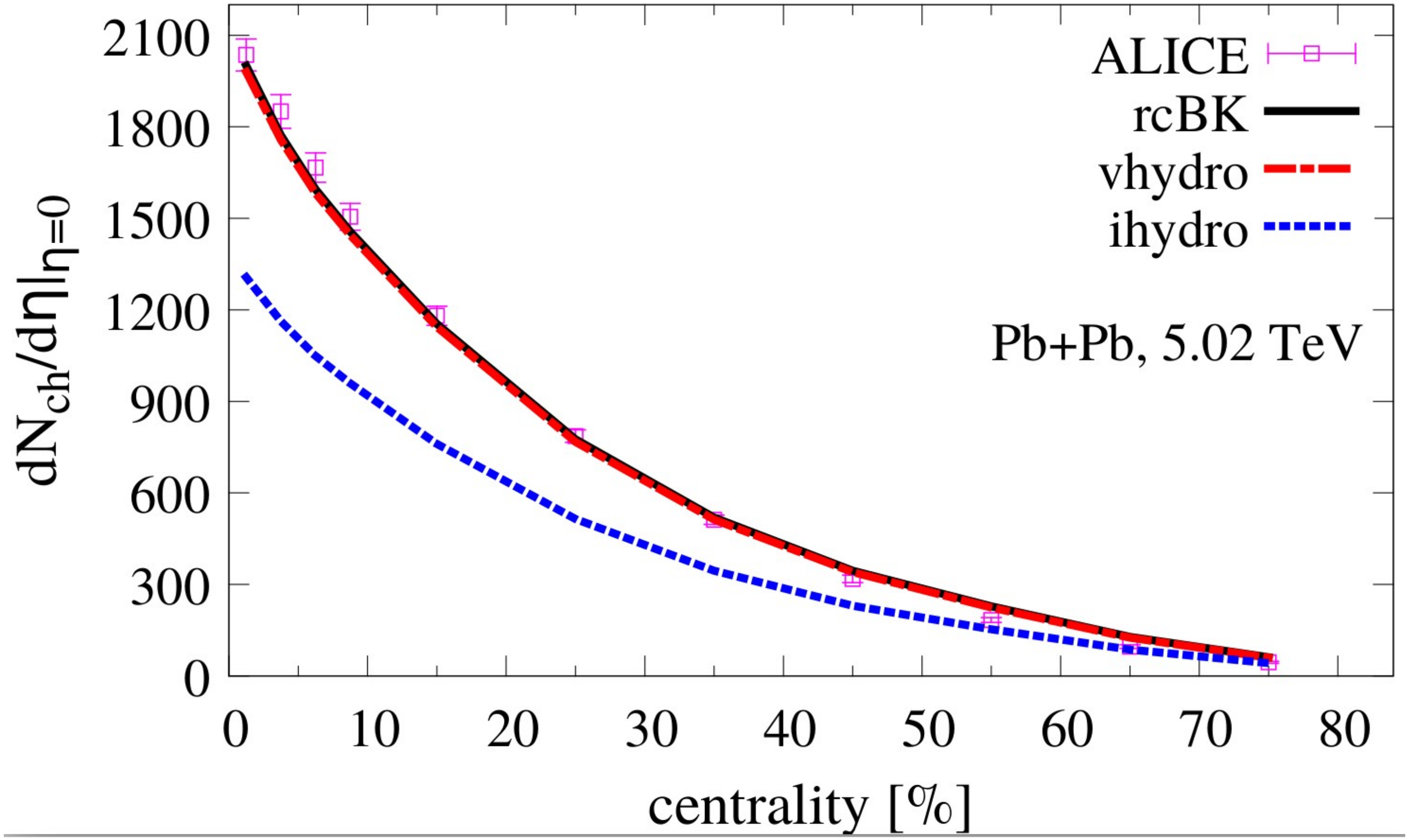
Backup slides

Ratio $\langle p_T \rangle_{\mathrm{ArAr}} / \langle p_T \rangle_{\mathrm{PbPb}}$



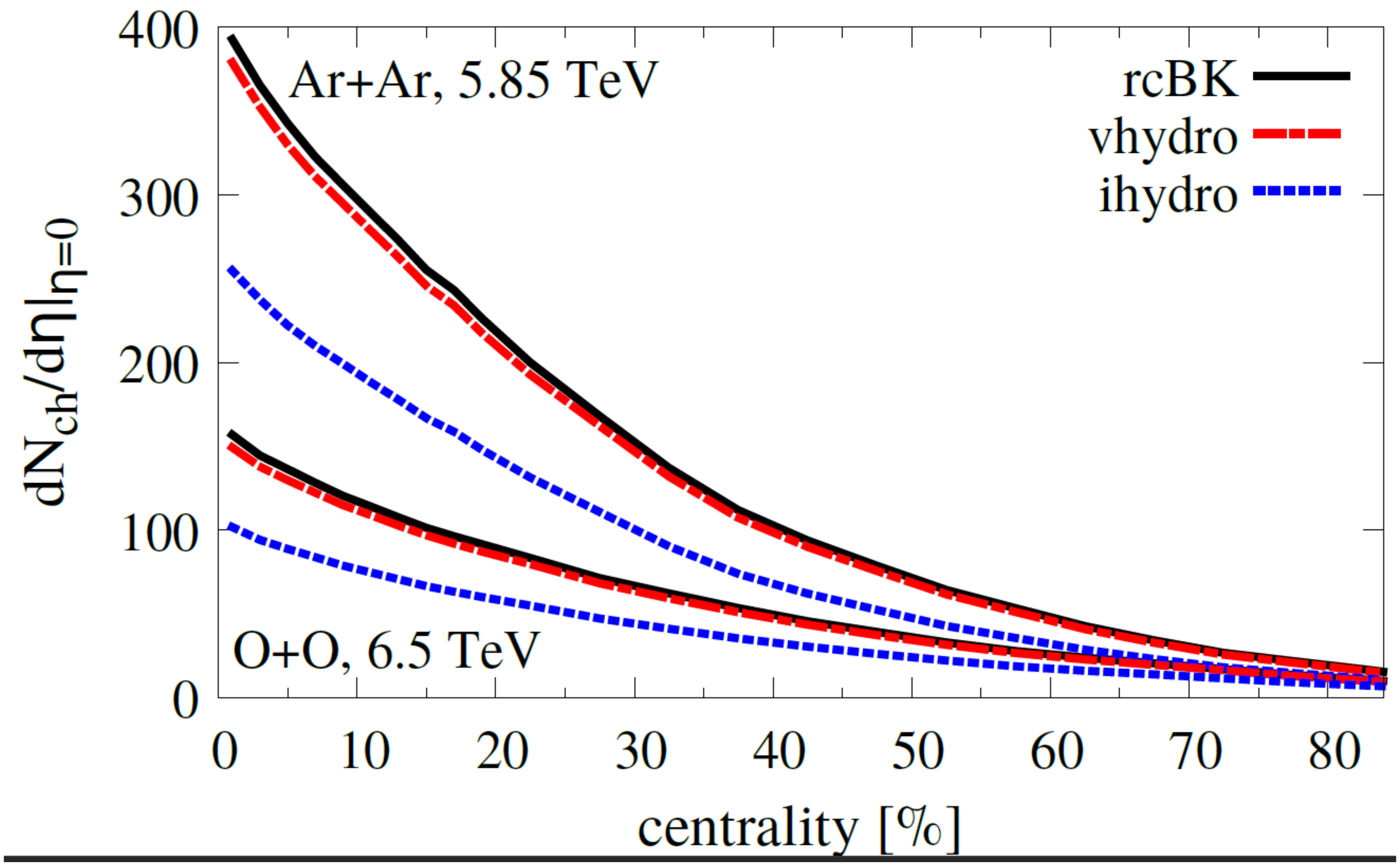
Increasing system size difference → larger splitting from different simulations

Multiplicity vs centrality: Pb+Pb @ 5.02 TeV



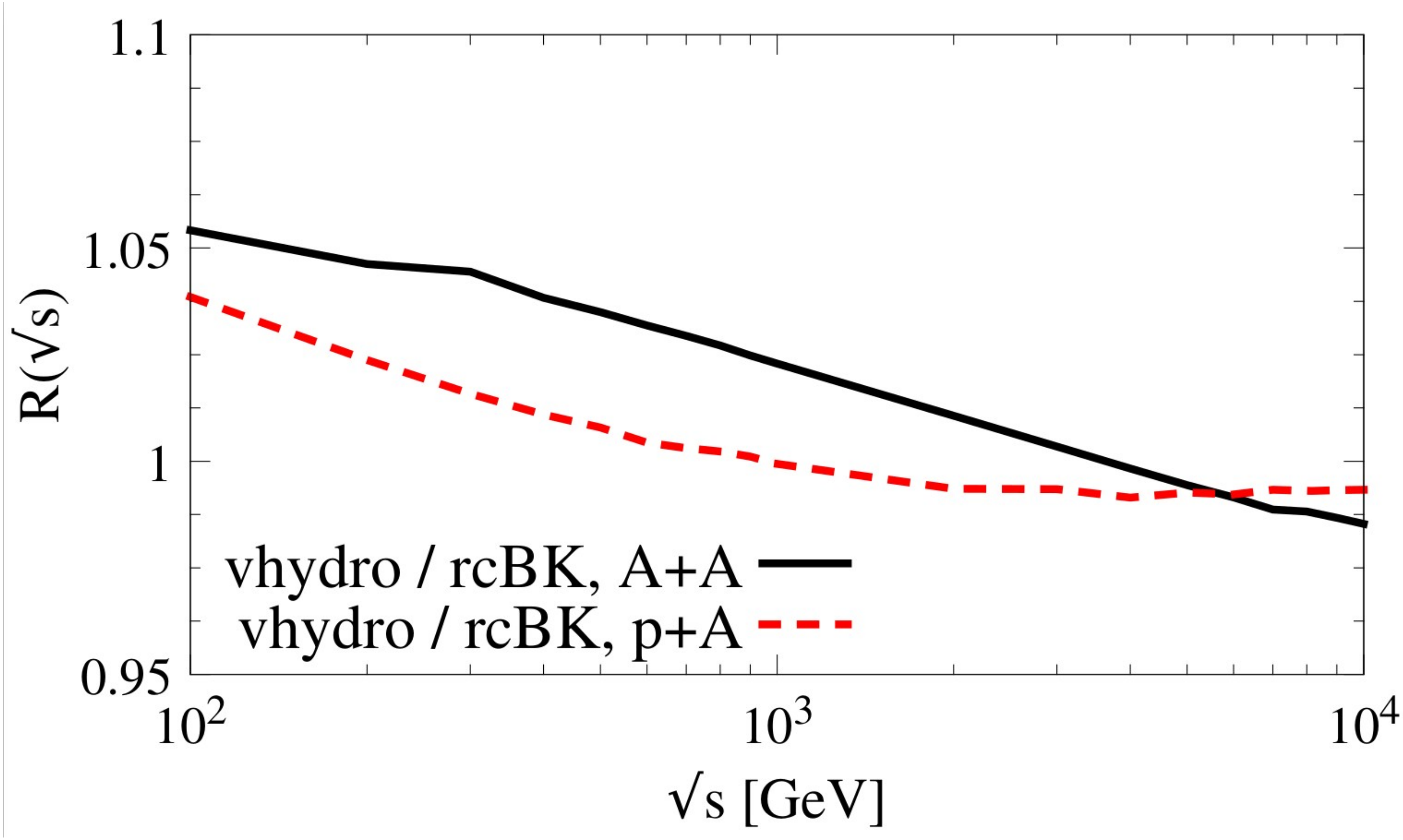
Viscous hydrodynamics + hadronic dynamics do not lead to strong change in centrality dependence

Multiplicity vs centrality: Ar+Ar & O+O



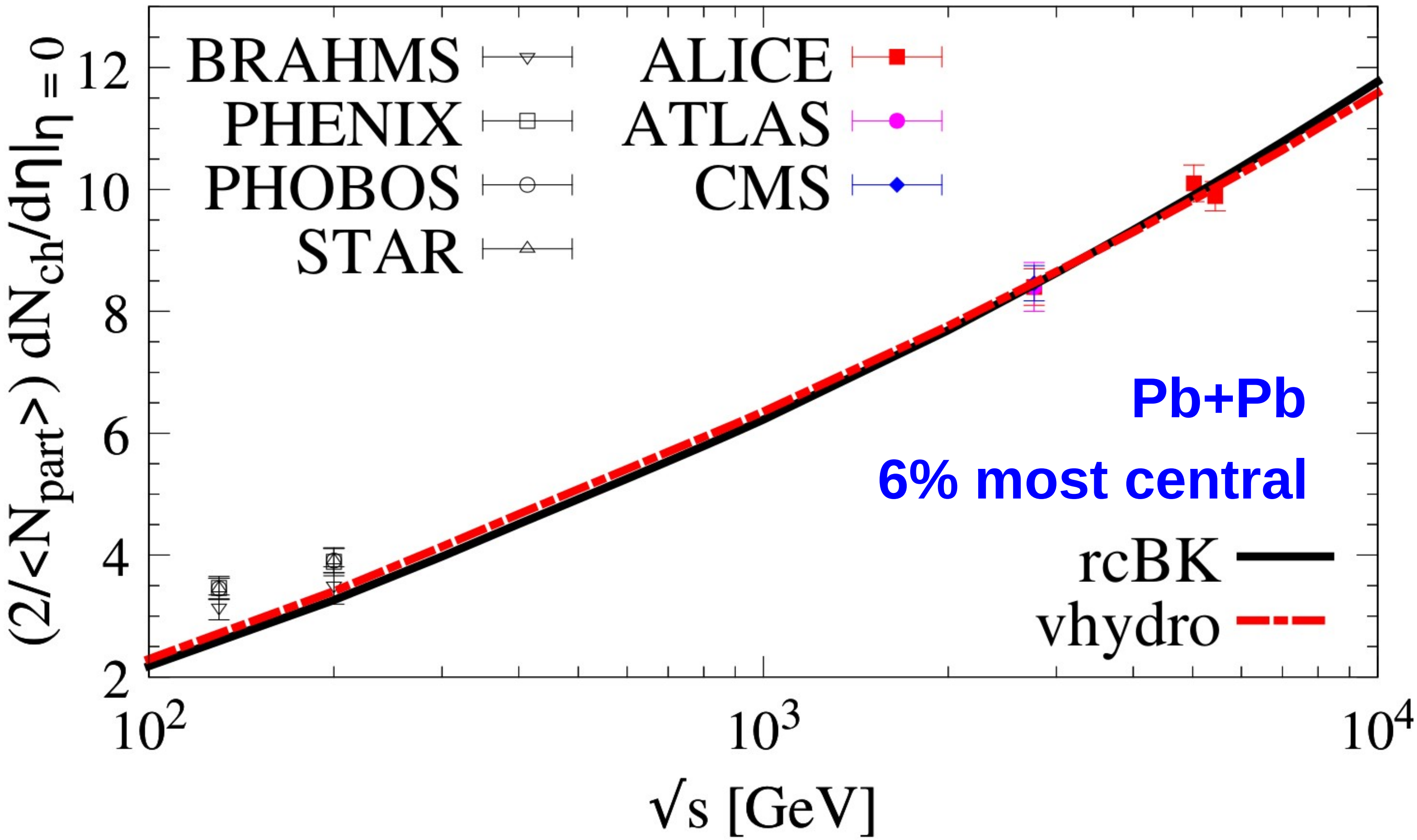
Viscous hydrodynamics + hadronic dynamics do not lead to strong change in centrality dependence

Energy evolution: ratio vhydro / CGC



No difference at high energies; ~5% at RHIC energies

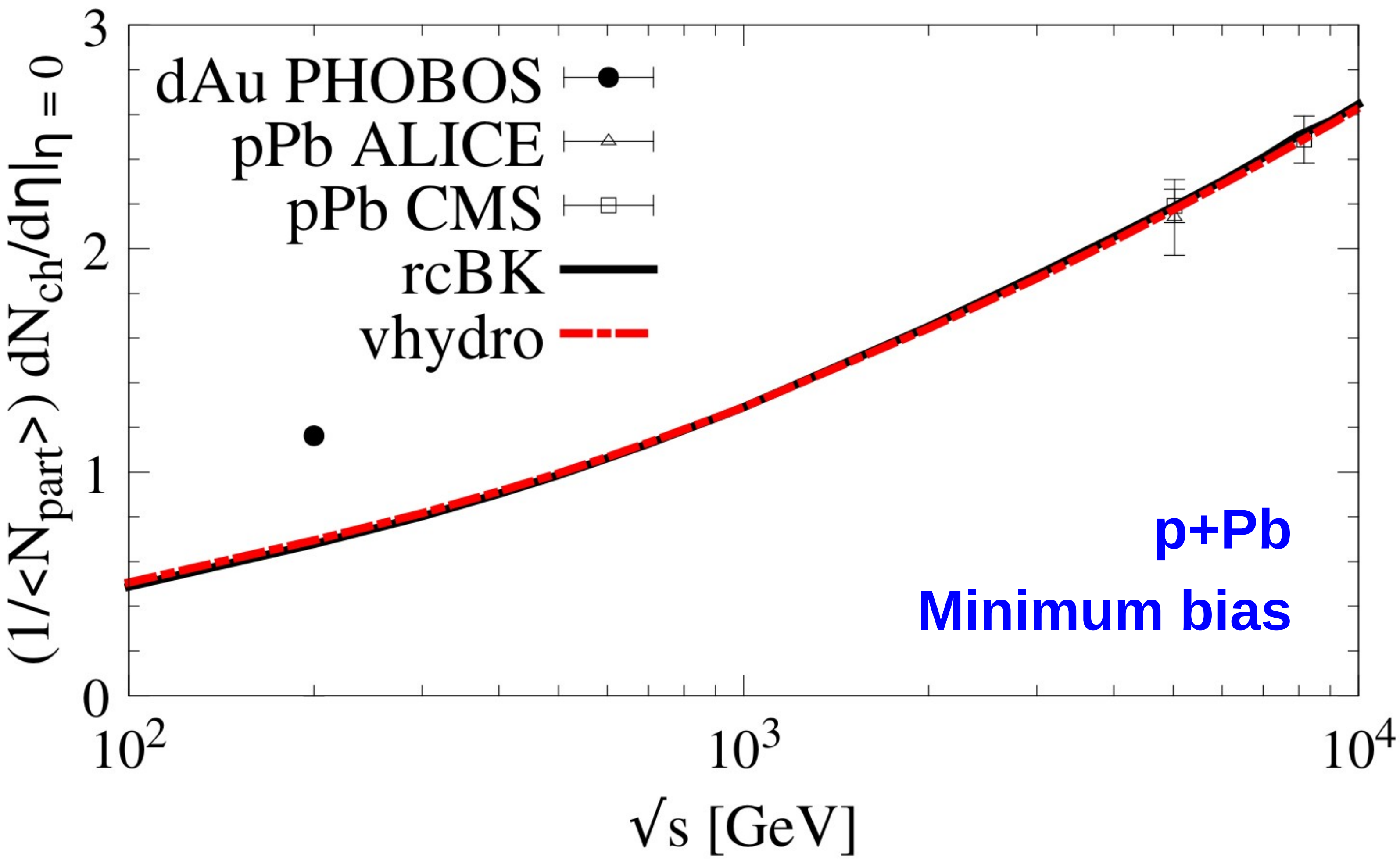
Energy evolution: CGC & vhydro, Pb+Pb



Same trend seen in centrality dependence plots as expected

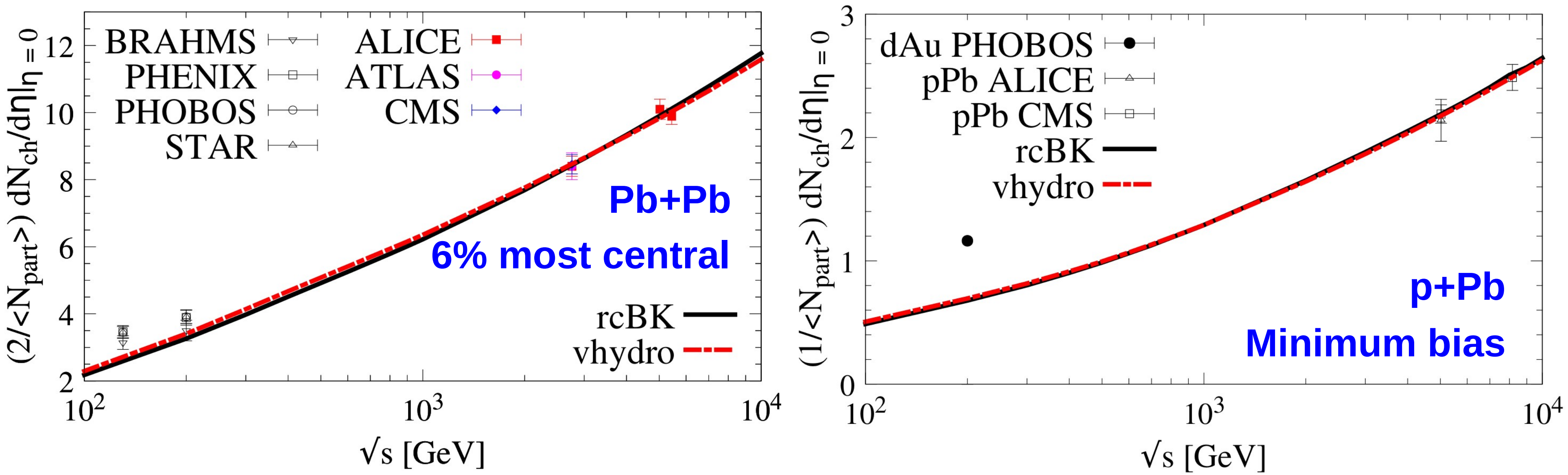
Nice agreement with exp. data

Energy evolution: CGC & vhydro, p+Pb



Hydro+UrQMD dynamics do not change energy evolution in smaller systems as well

Energy evolution: CGC & vhydro, Pb+Pb, p+Pb



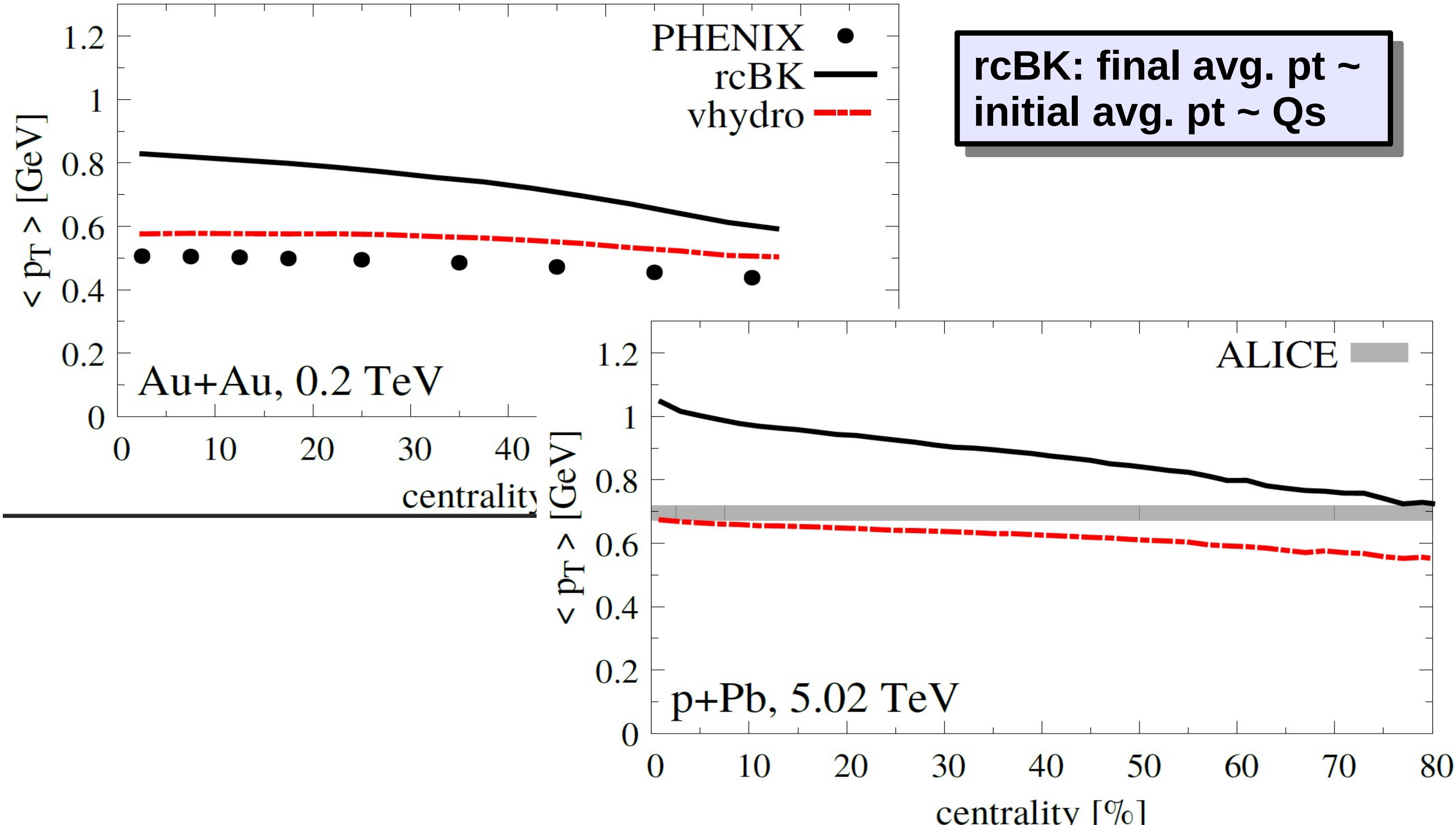
Simultaneous description of A+A & p+A data for:

Presence of hydrodynamic phase in both in A+A and p+A

Only initial-state dynamics (w/ no hydro!) in A+A and p+A

Assuming hydro in A+A but not in p+A: impossible to describe both cases simultaneously (using this framework!)

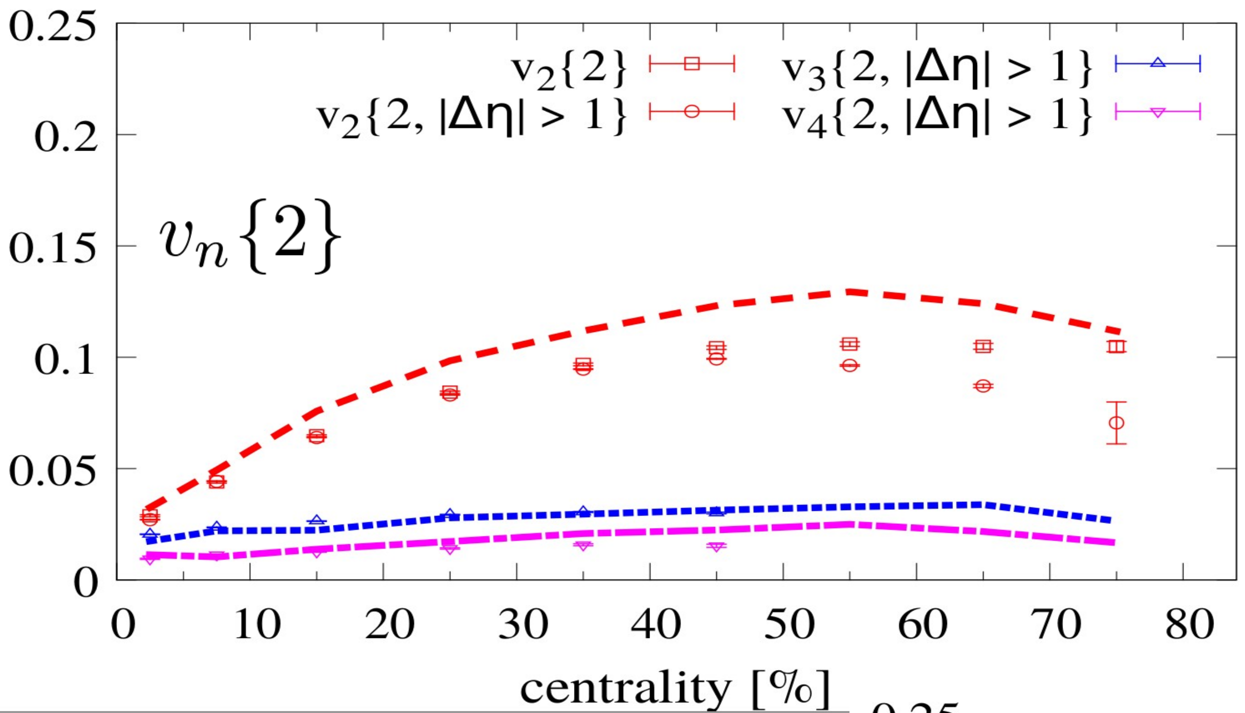
< pT > in nuclear collisions



rcBK: final avg. pt ~ initial avg. pt ~ Qs

vhydro: space-time evolution + final state dynamics (hydro+UrQDM) redistribute momentum → closer to data!

vn{2} and vn{4} from vhydro

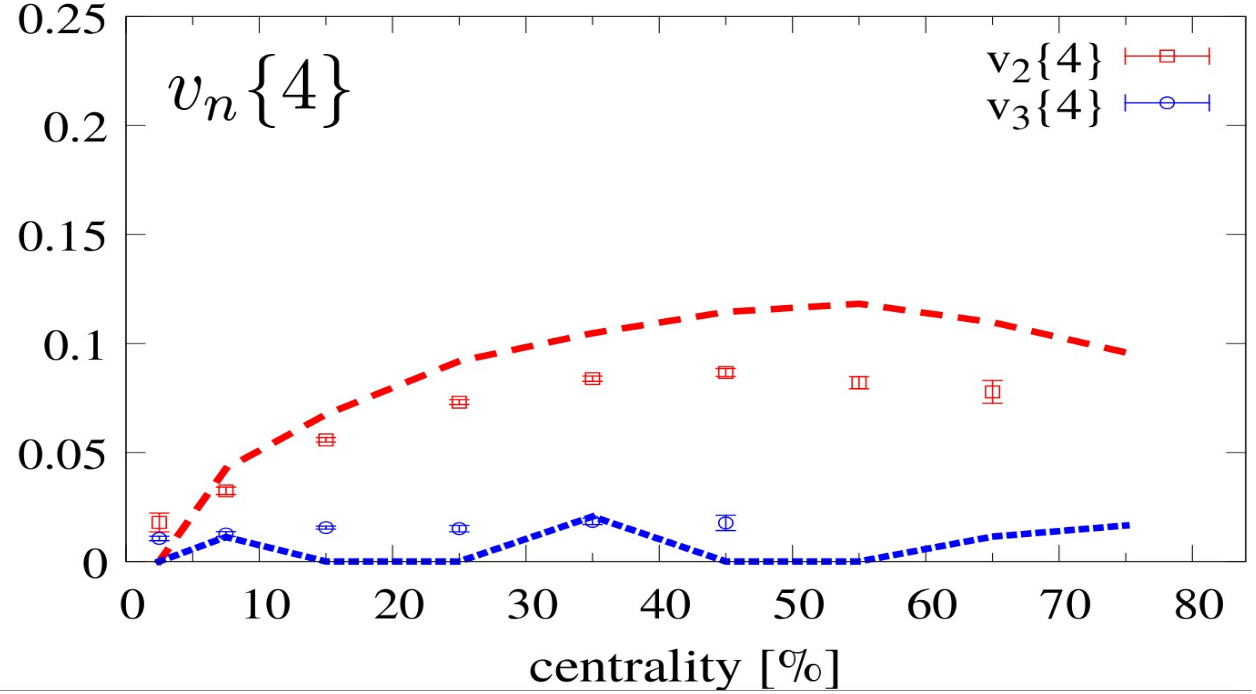


overshoot v2{2} while being ok with v3{2}

Translates to eps2 / eps3 too large

No agreement with all vn{2} for any value of viscosity!

Retinskaya, Luzum, Ollitrault, PRC 89, no. 1, 014902 (2014)



Similar results as old MC-KLN model

AAMQS I.C. :

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

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

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

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

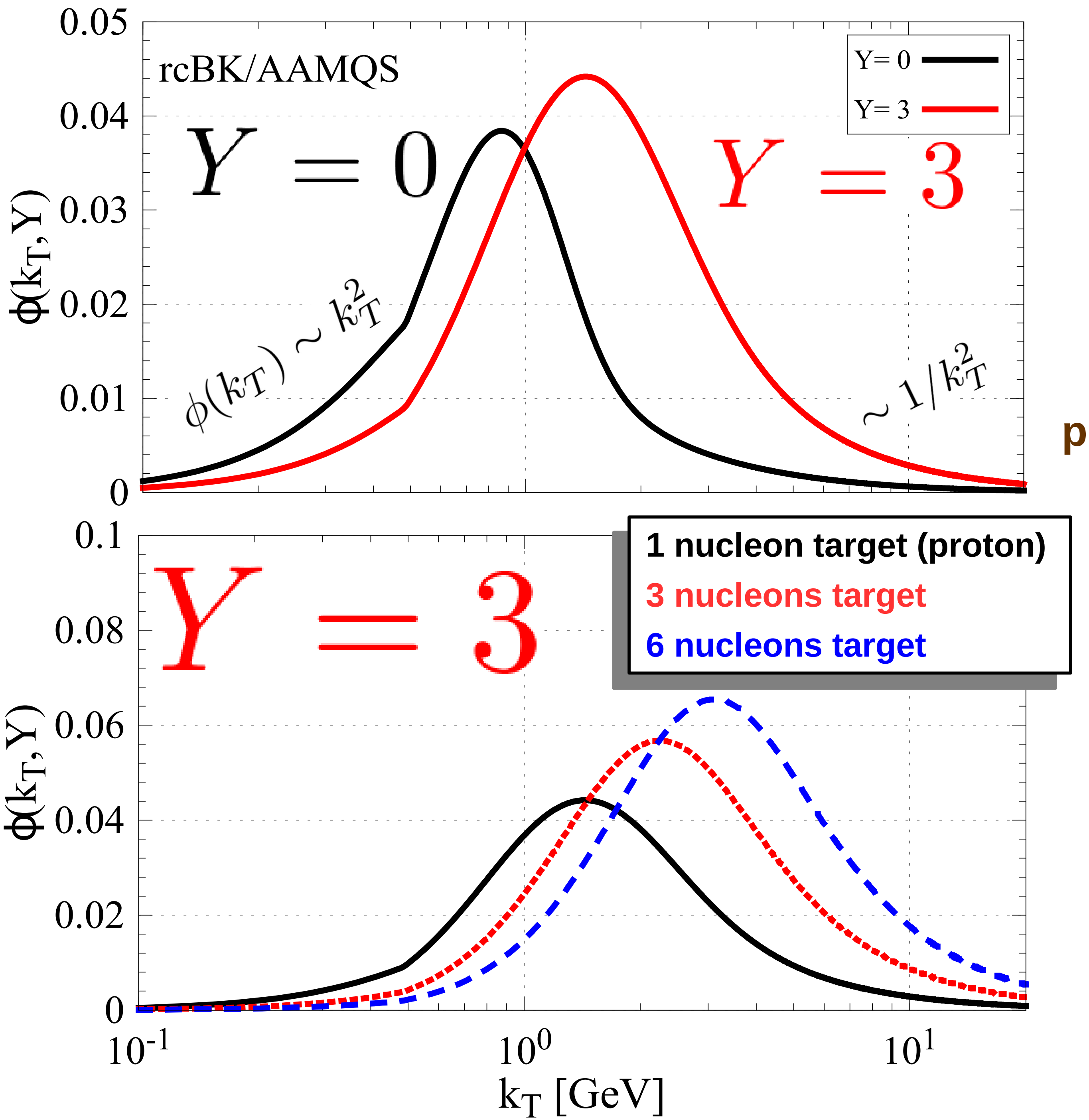
Albacete, Armesto, Milhano and Salgado, PRD 80, 034031 (2009); Albacete, Armesto, Milhano, Quiroga-Arias and Salgado, Eur. Phys. J. C 71, 1705 (2011)

$Q^2_{s0,\mathrm{proton}}$ **= 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 HERA data!**

Examples of nuclear UGDs:



$$Y = ln(x_0/x)$$

$$x_0 = 0.01$$

onset of small-x evolution

proton UGD

Nuclear targets:

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

perturbative regime

2^{nd}-ordrer viscous hydrodynamics

$$T^{\mu\nu} = T^{\mu\nu}_{\text{ideal}} + \pi^{\mu\nu} - (g^{\mu\nu} - u^\mu u^\nu)\Pi \quad + \quad \partial_\mu T^{\mu\nu}(X) = 0 \quad +$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \varphi_1 \Pi^2 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \varphi_3 \pi^{\mu\nu}\pi_{\mu\nu} \quad +$$

$$\begin{aligned}\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} &= 2\eta\sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} \\ &\quad - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_6 \Pi\pi^{\mu\nu}\end{aligned}$$

Denicol, Jeon and Gale, PRC90, no. 2, 024912 (2014)

Total of 14 coupled eqs. with 13 transport coefficients

[Transport coeff.: quantify the deviation from equilibrium] $\eta(T),\ \zeta(T),\ \tau_\pi(T),\ \ldots$

Equation of state closes the system of eqs: s95p-v1.2

derived from Lattice QCD calculations

Huovinen, Petreczky, Nucl. Phys. A 837, 26 (2010)