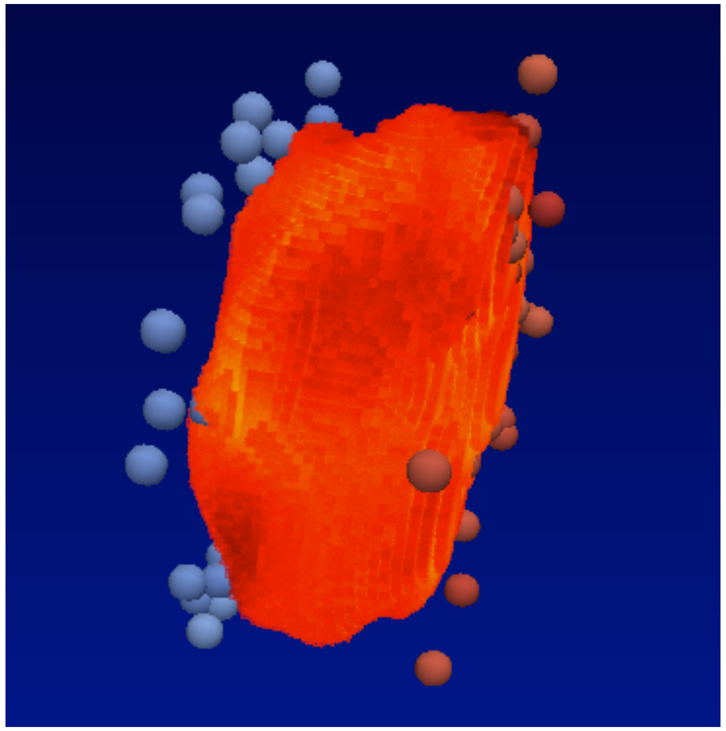
Hydrodynamics: From the highest to the lowest beam energies

Hannah Petersen

19.07.16, ULtra-RelatIvistiCH HEavy IoNZ 2016, CERN, Switzerland

Outline

- Hydrodynamics at LHC:
  - Longitudinal de-correlation of event planes
  - Fluctuating strings
  - v_n as a function of rapidity
- Low beam energies:
  - Viscous hybrid approach
  - SMASH hadron transport
  - Effective N-particle scattering (hydro?)
- Summary and conclusions



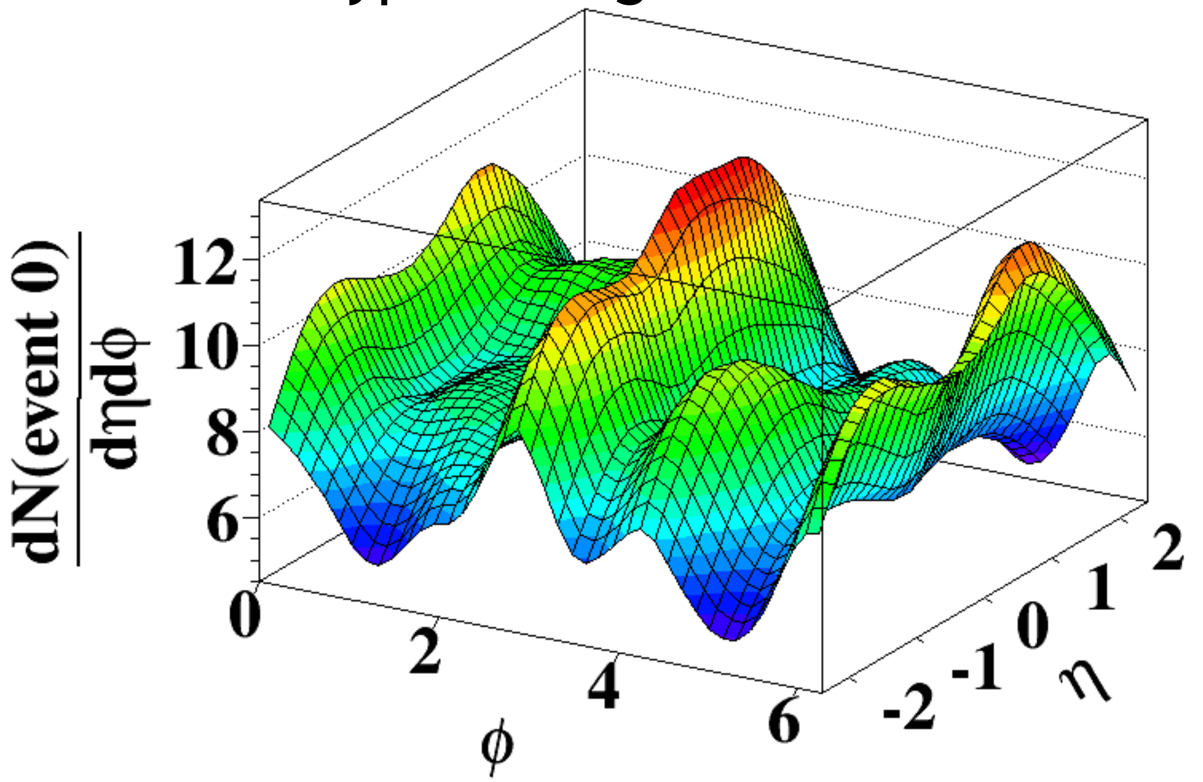
Quark gluon plasma
in a heavy ion reaction

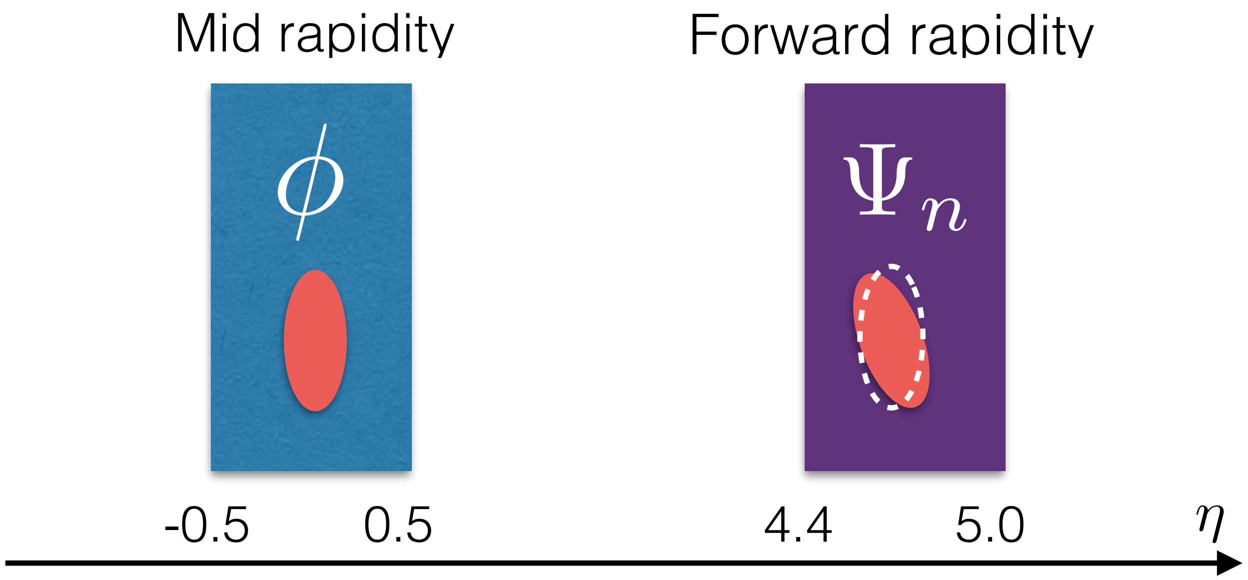
Hydrodynamics at the LHC

in collaboration with L.-G. Pang, Q.-Y. Qin, V. Roy, X.-N. Wang

Motivation

Single particle distribution from AMPT+hydro for a typical single event at RHIC

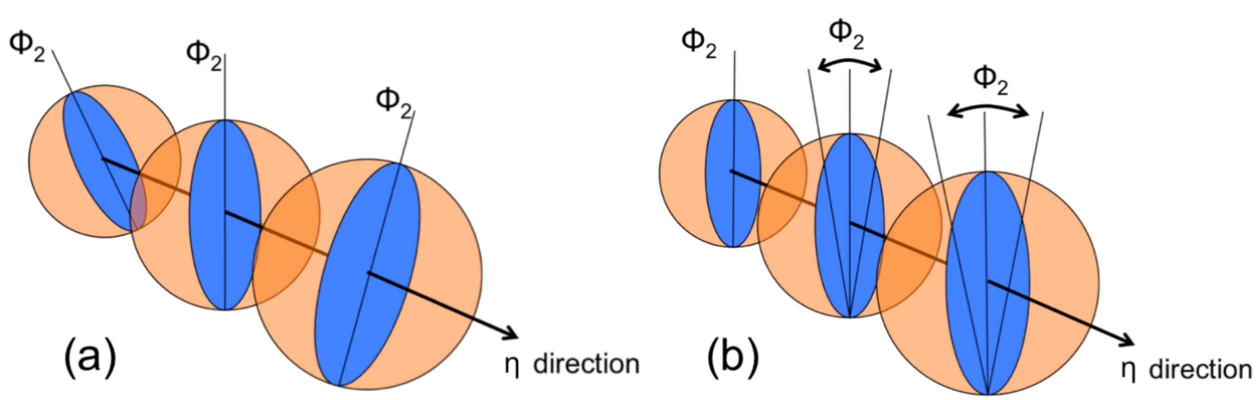




$$v_n = \frac{< \cos(n(\phi - \Psi_n)) >}{R}$$

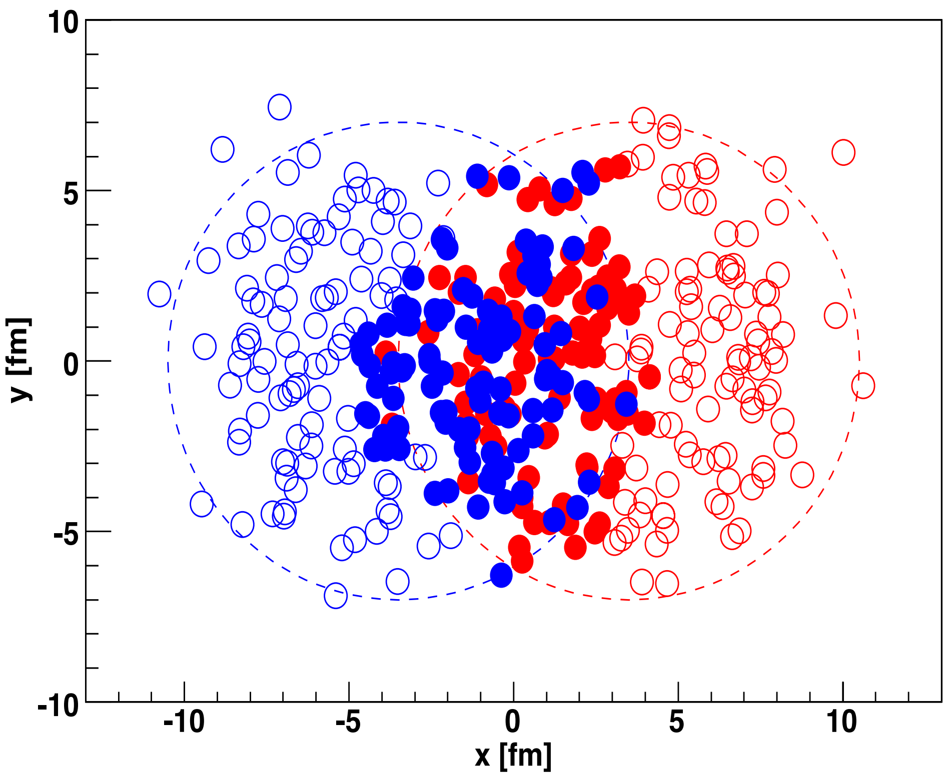
- Flow measurements are questionable when the anisotropic flow (or event plane) de-correlates along the longitudinal direction.

- P.Bozek PRC83, 034911 (2011); arXiv:1506.02817 (2015);
- H. Petersen, V. Bhattacharya, S.A. Bass, and C Greiner PRC 84, 054908 (2011)
- L-G. Pang, X-N. Wang and Q. Wang, PRC 86, 024911 (2012);
- K.Xiao, FQ. Wang, F. Liu PRC 87, 011901 (2013)
- J. Jia and P. Huo, PRC 90, 024910 (2014); PRC 90, 034915 (2014)
- L-G.Pang, G-Y.Qin,V.Roy,X-N.Wang, G-L.Ma, PRC 91, 044904 (2015)



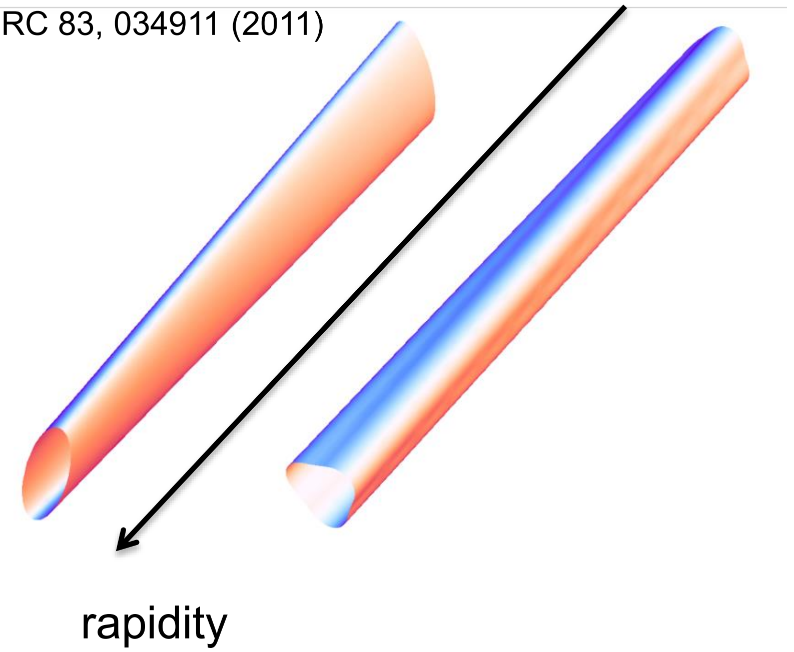
Longitudinal structure of QGP

- Gluon density is twisted because of the asymmetric distribution of forward and backward going participants.

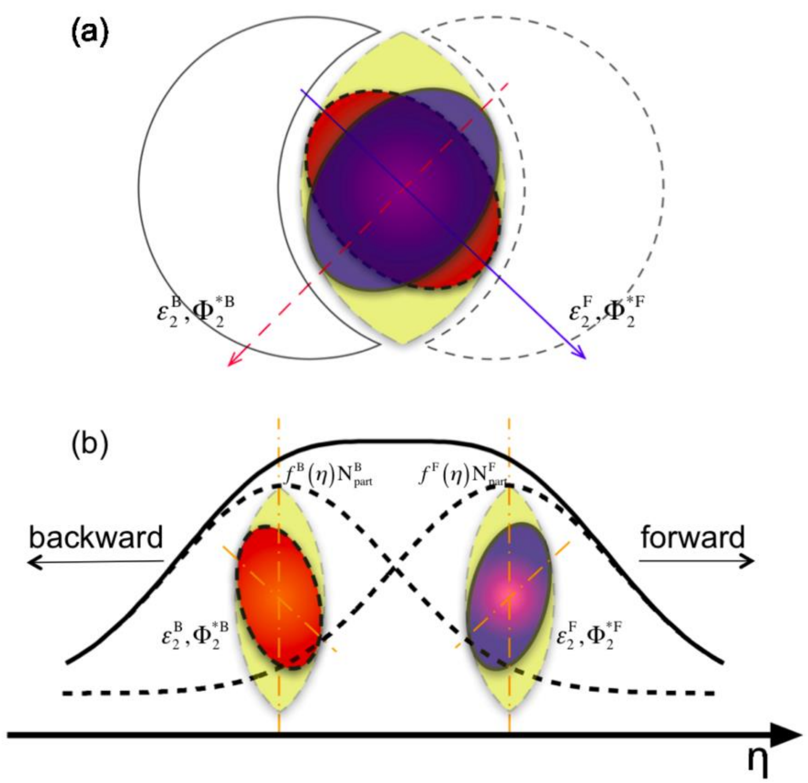


Hydrodynamics , torqued fireball

P Bozek et al,
PRC 83, 034911 (2011)



Transport

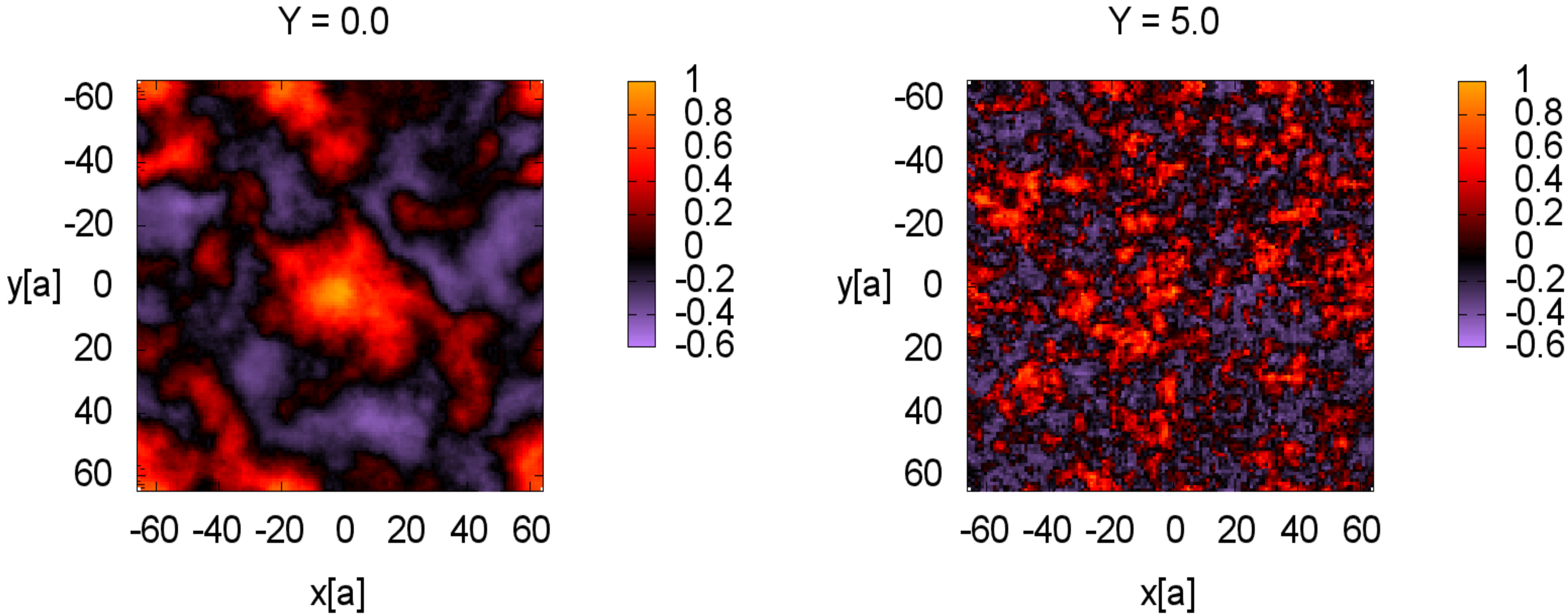


J Jia et al,
PRC 90, 034915 (2014)

- „Twist“ of event planes ->continuous change

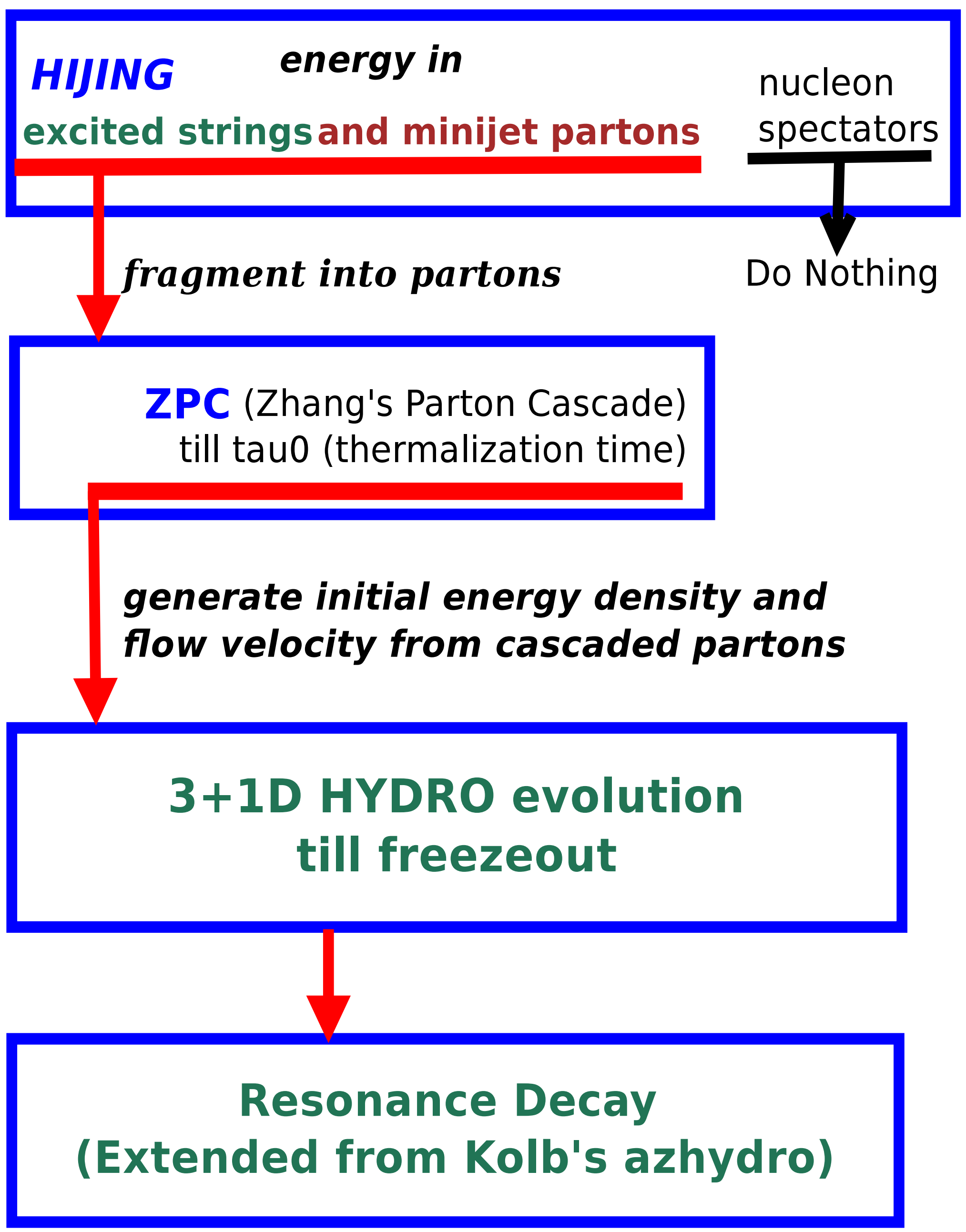
Pure fluctuations in longitudinal direction

A. Dumitru, J. Jalilian-Marian, T. Lappi, B. Schenke and R. Venugopalan PLB 706 (2011) 219-224



- The gluon density fluctuates stronger at large rapidity from CGC
- Random fluctuation of event planes

Model: AMPT + E-B-E (3+1)D hydro



$$T^{\mu\nu}(\tau_0, x, y, \eta_s) = K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} \times$$

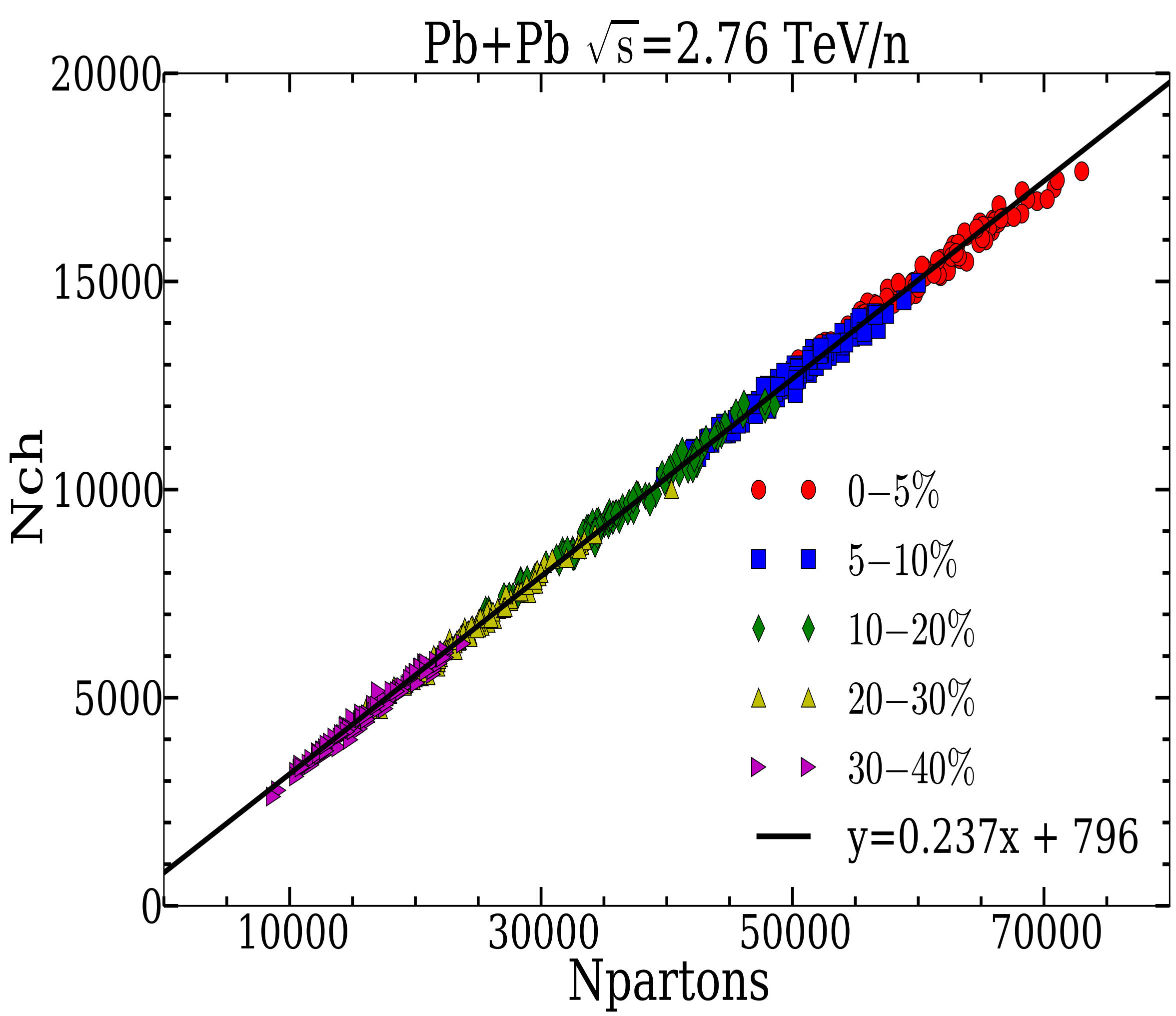
$$\delta(x - x_i, y - y_i, \eta_s - \eta_{si})$$

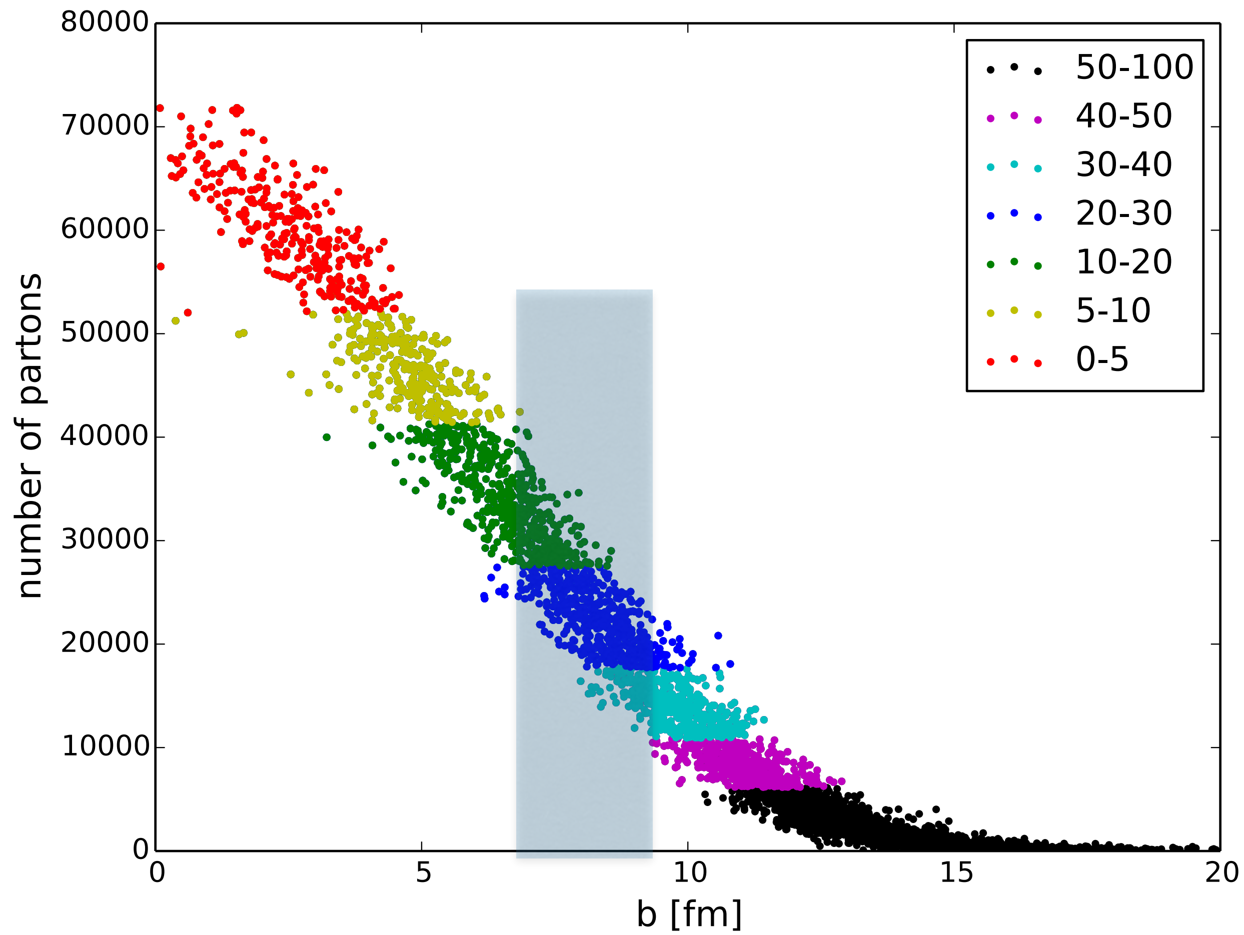
- Newly developed CLVisc: C++/Python, KT algorithm to solve hydrodynamic equations, parallelized on GPU using OpenCL.

L-G Pang, X-N Wang and Q Wang 2012, PRC

L-G Pang, X-N Wang, B-W Xiao, Y. Hatta, 2015 PRD

Centrality bins

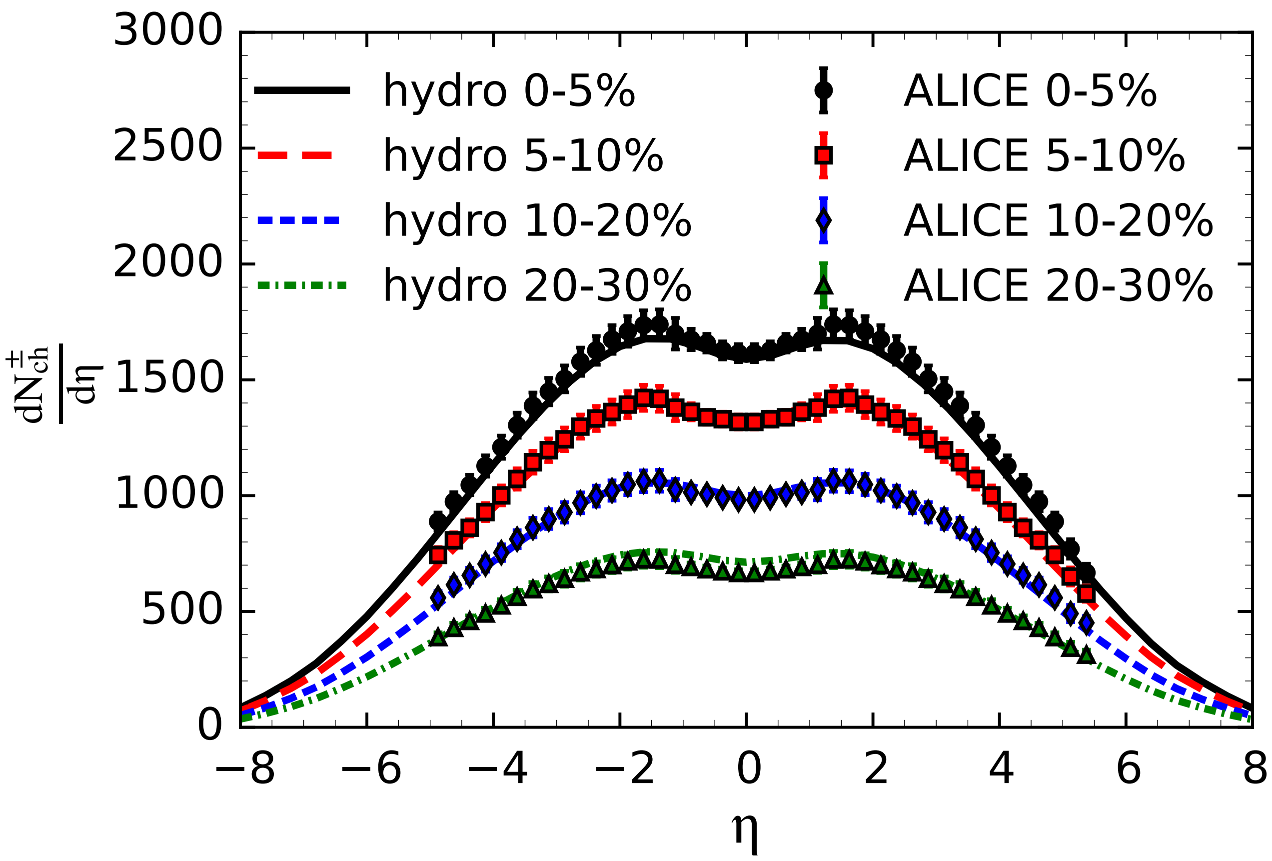


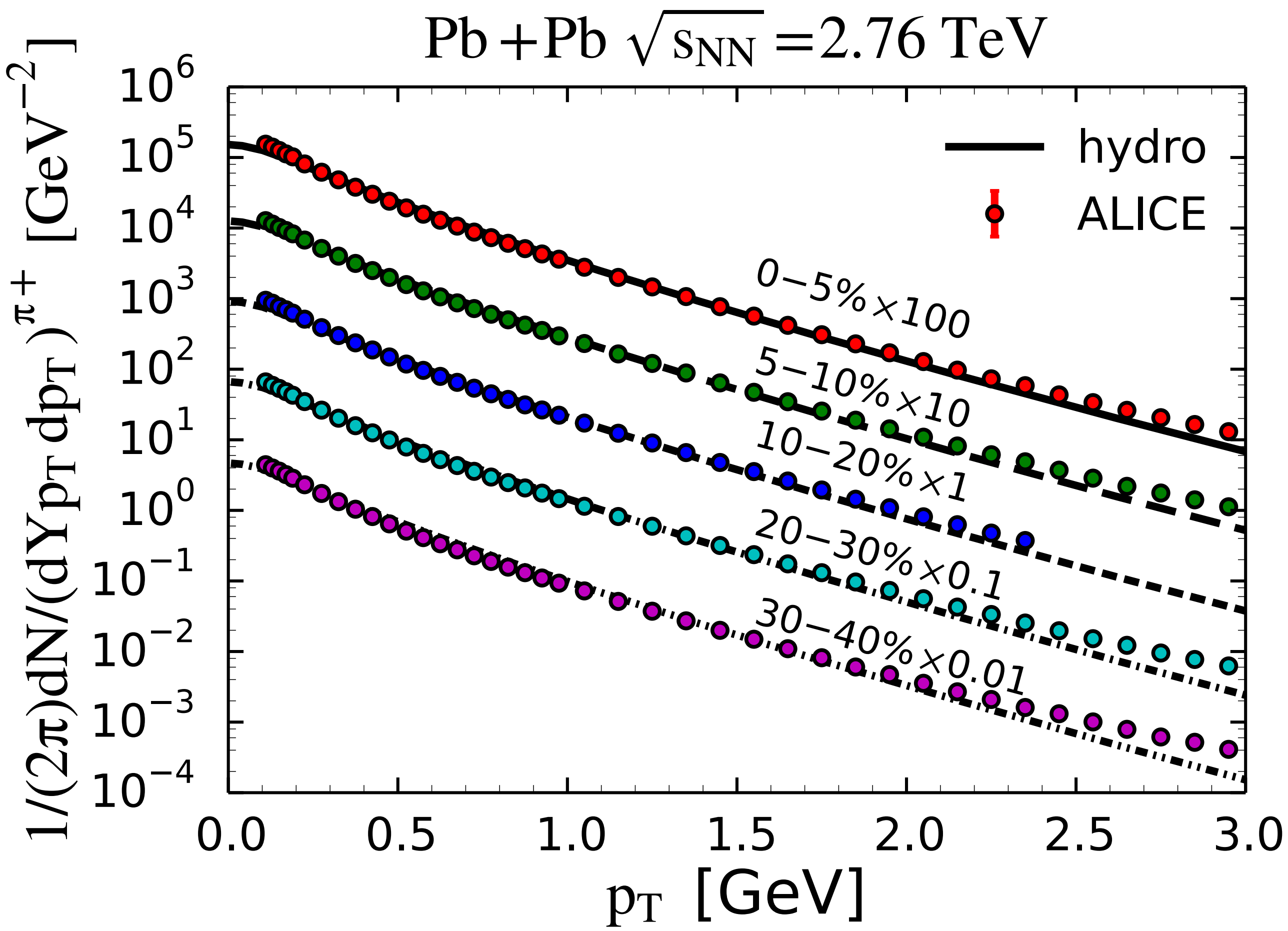


LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

- Linear relationship between the number of partons put in hydro from AMPT and the number of charged hadrons resulting from hydrodynamic evolution
- The number of partons is used to determine centrality bins

Charged multiplicity (LHC)

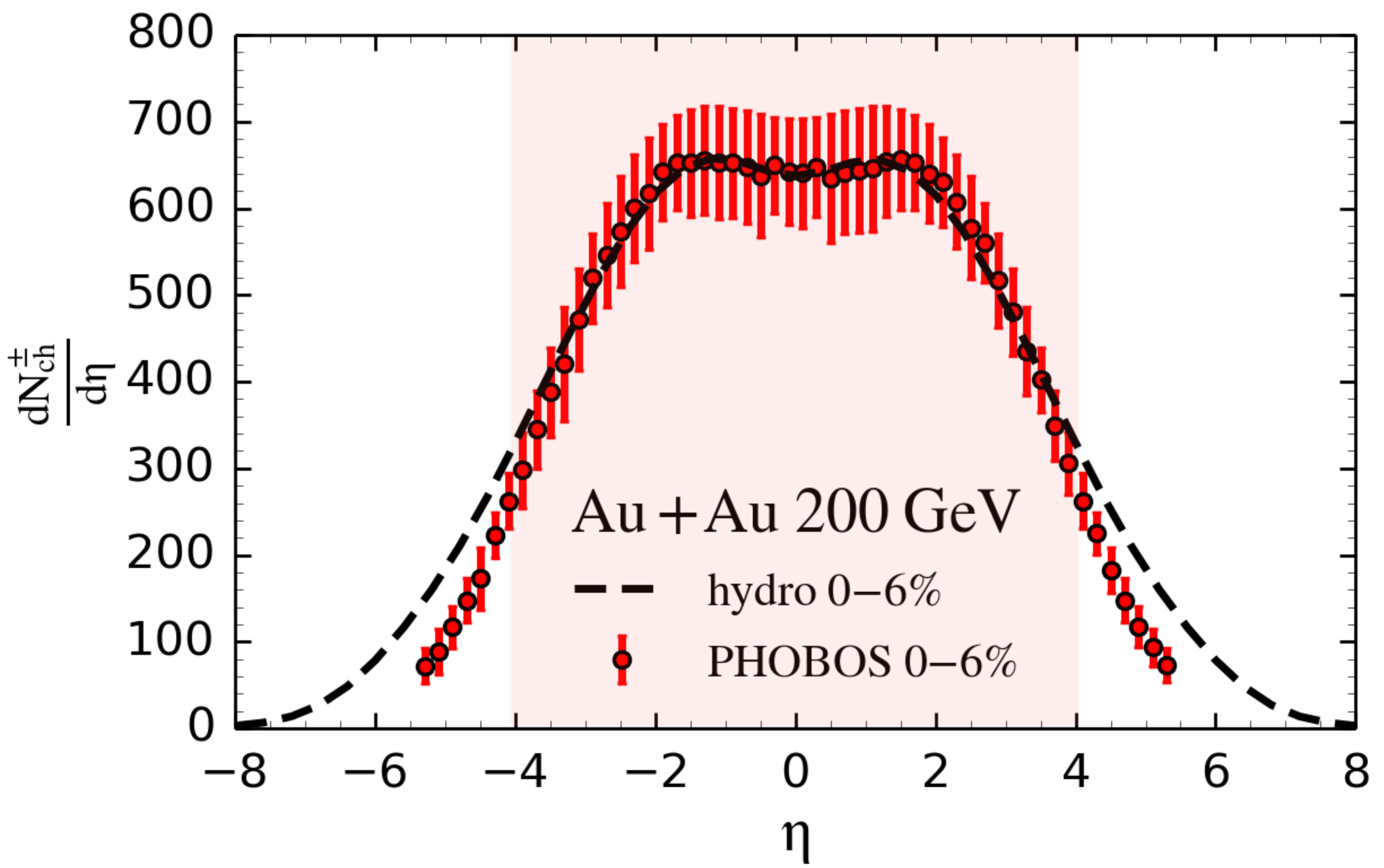




LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

- Rapidity and transverse momentum dependence of charged particle production agrees nicely with experimental data
- Scaling factor for initial energy density K=1.5 and smearing factor $\sigma_r = \sigma_\eta = 0.6$ for CLVisc EOS s95p-PCE-v0.

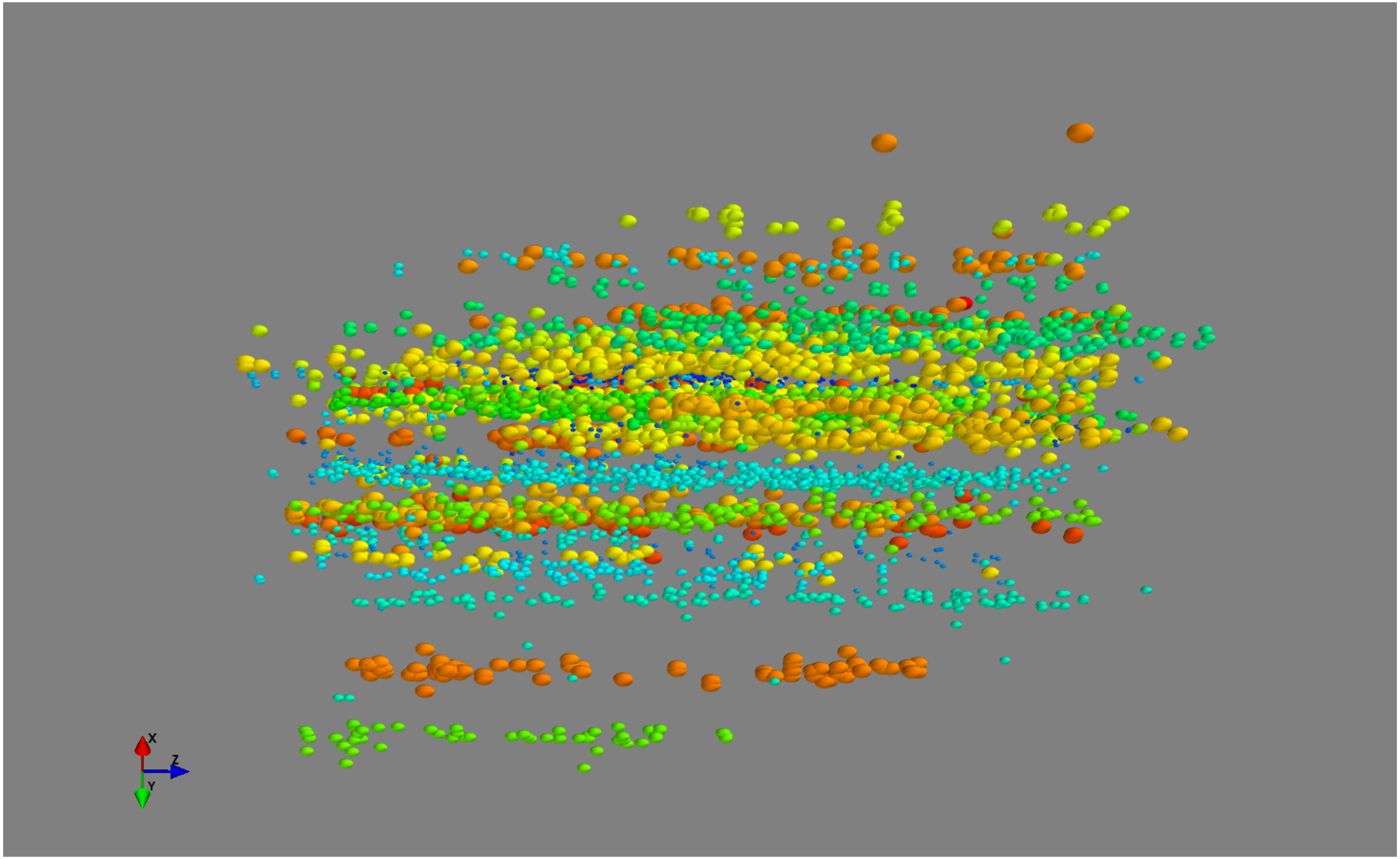
Charged multiplicity (RHIC)



LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

- Pseudorapidity range [-4,4] is used for RHIC in the following
- Net baryon density may be needed for 3+1D hydro (EOS with finite μ_B) at forward and backward rapidities to describe the data.

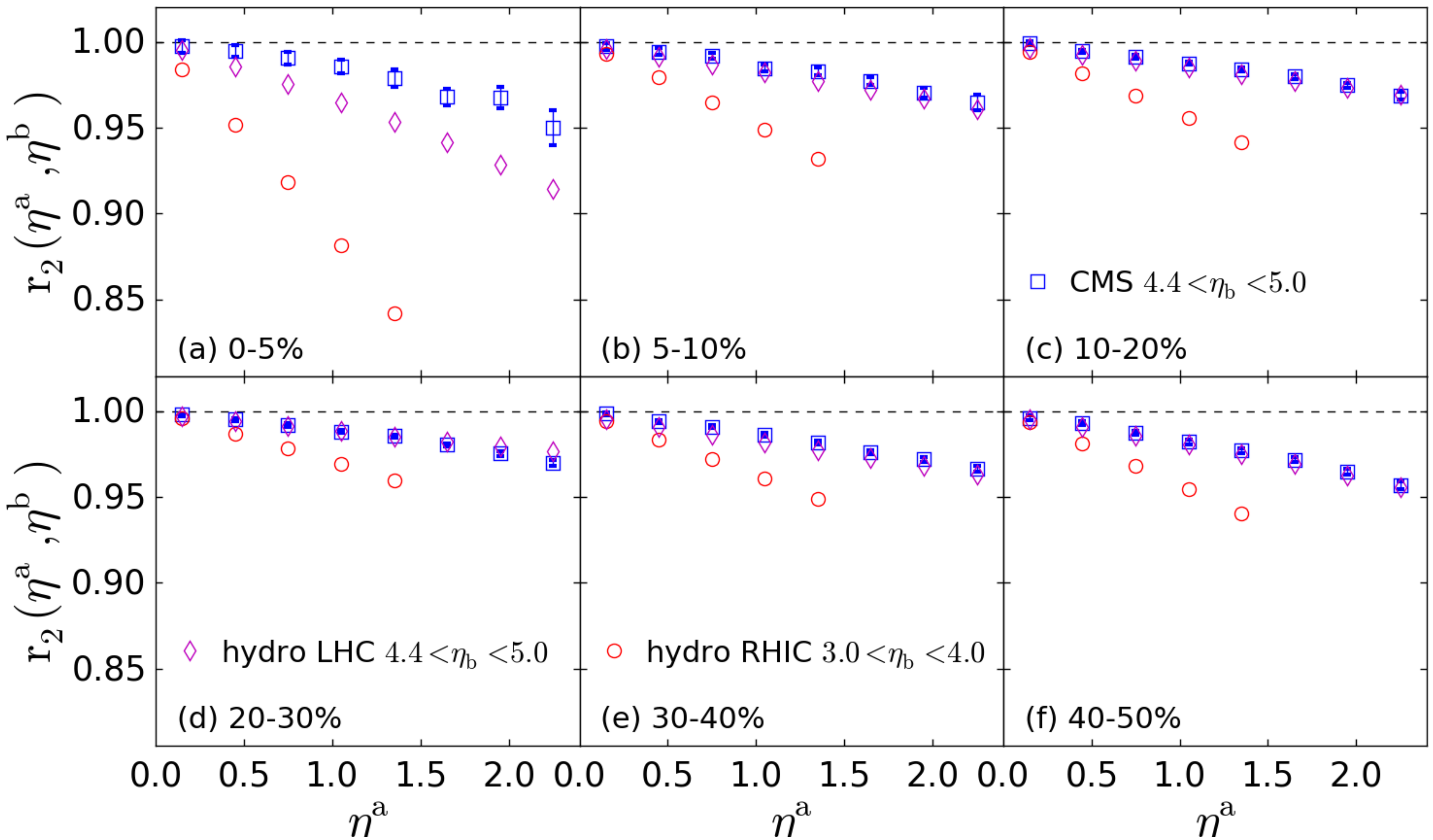
Distribution of initial partons



η_s

Pb+Pb semi central

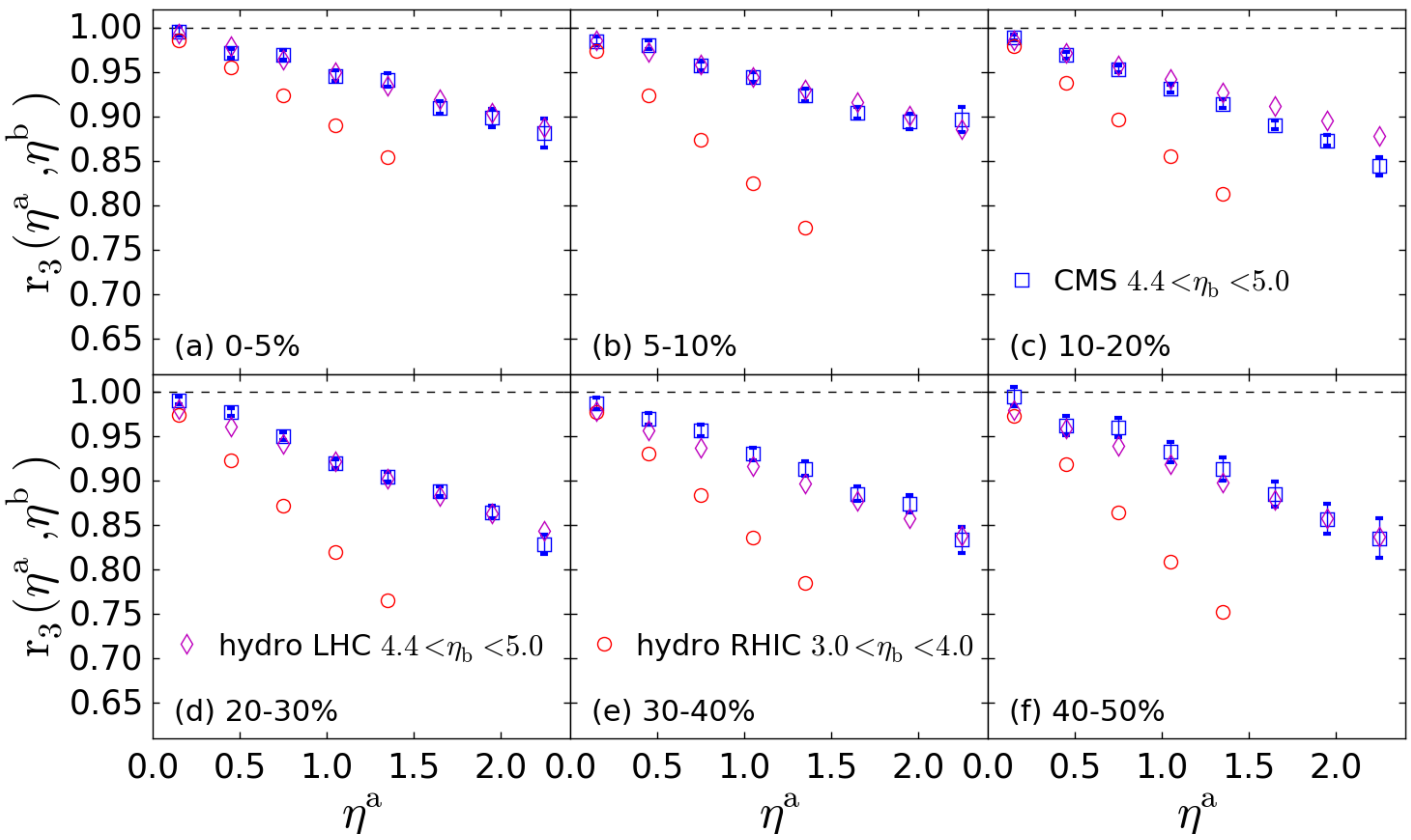
Comparison to CMS, predictions for RHIC



LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

- De-correlation r_2 agrees with CMS perfectly except 0-5% centrality.
- Centrality dependence comes from both FB asymmetry and string length fluctuations.
- RHIC shows much stronger de-correlation which indicates stronger fluctuations at lower collision energies

Compare with CMS, predictions for RHIC

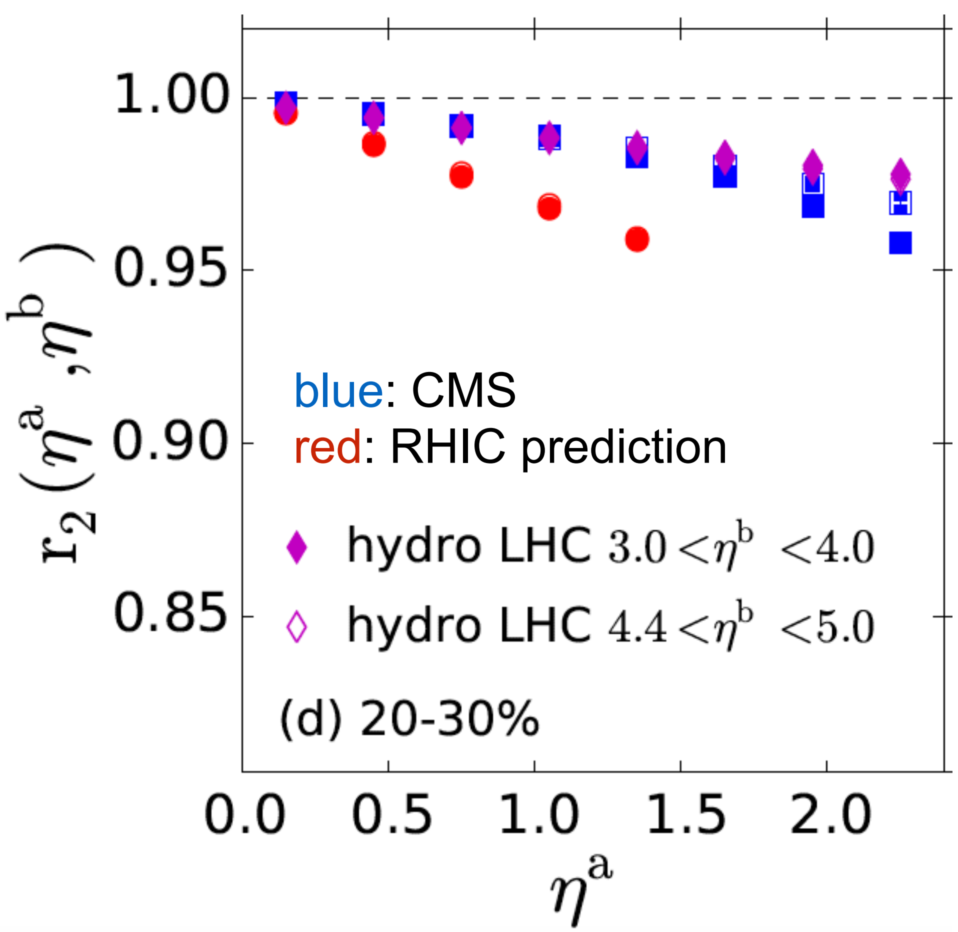


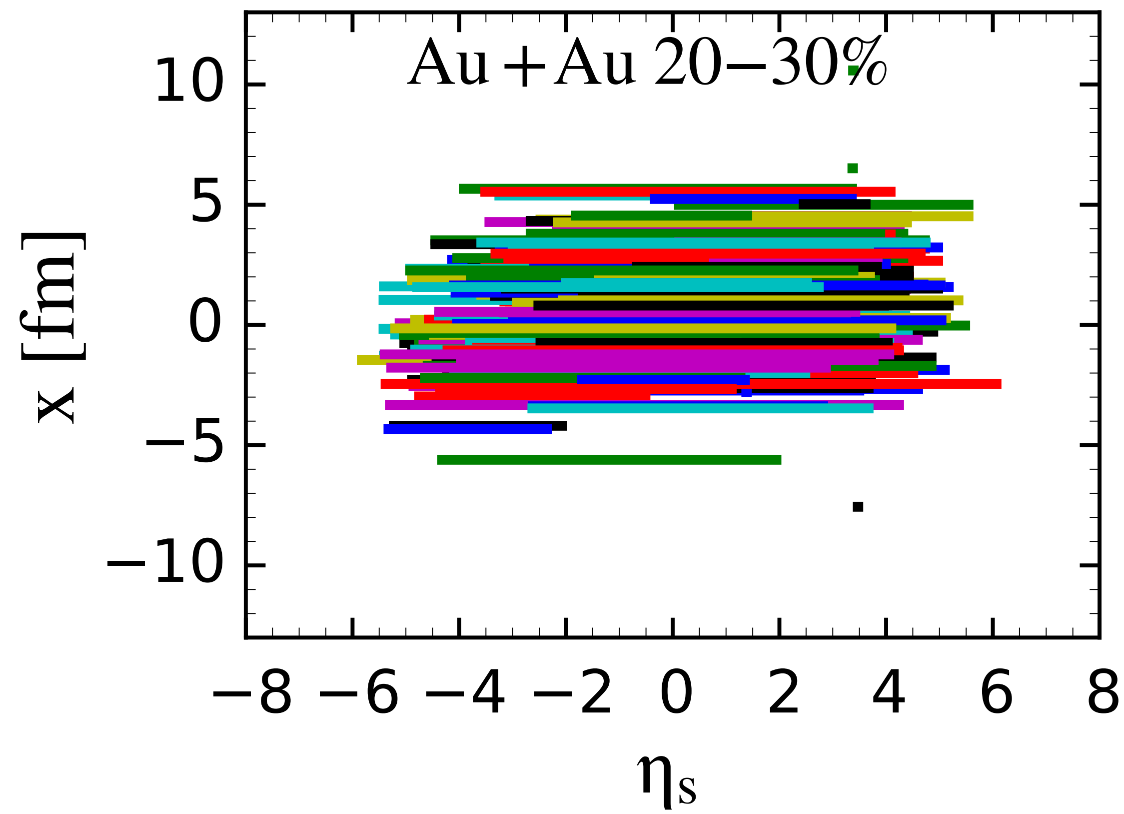
LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

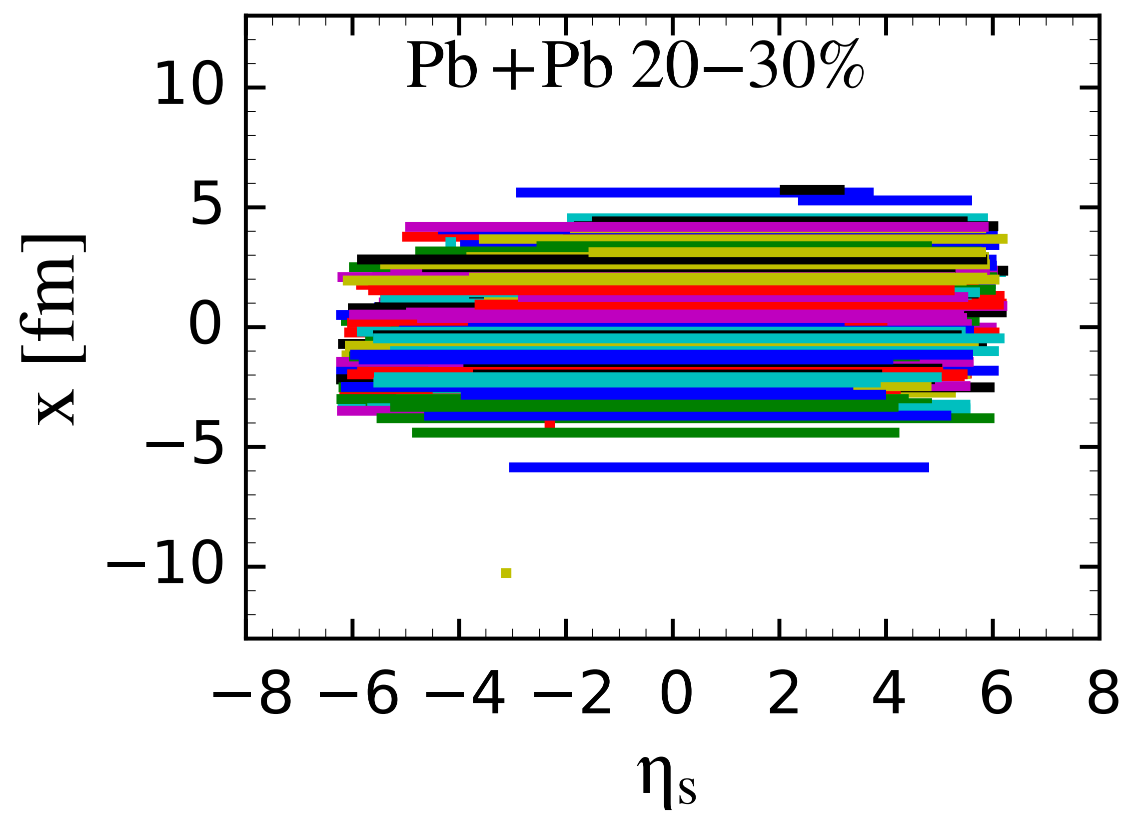
- r_3 has weak centrality dependence
- Nicely reproduced with initial conditions from AMPT

Longitudinal structures AMPT

- String lengths fluctuations increase at RHIC energies
- Insights into particle production mechanism



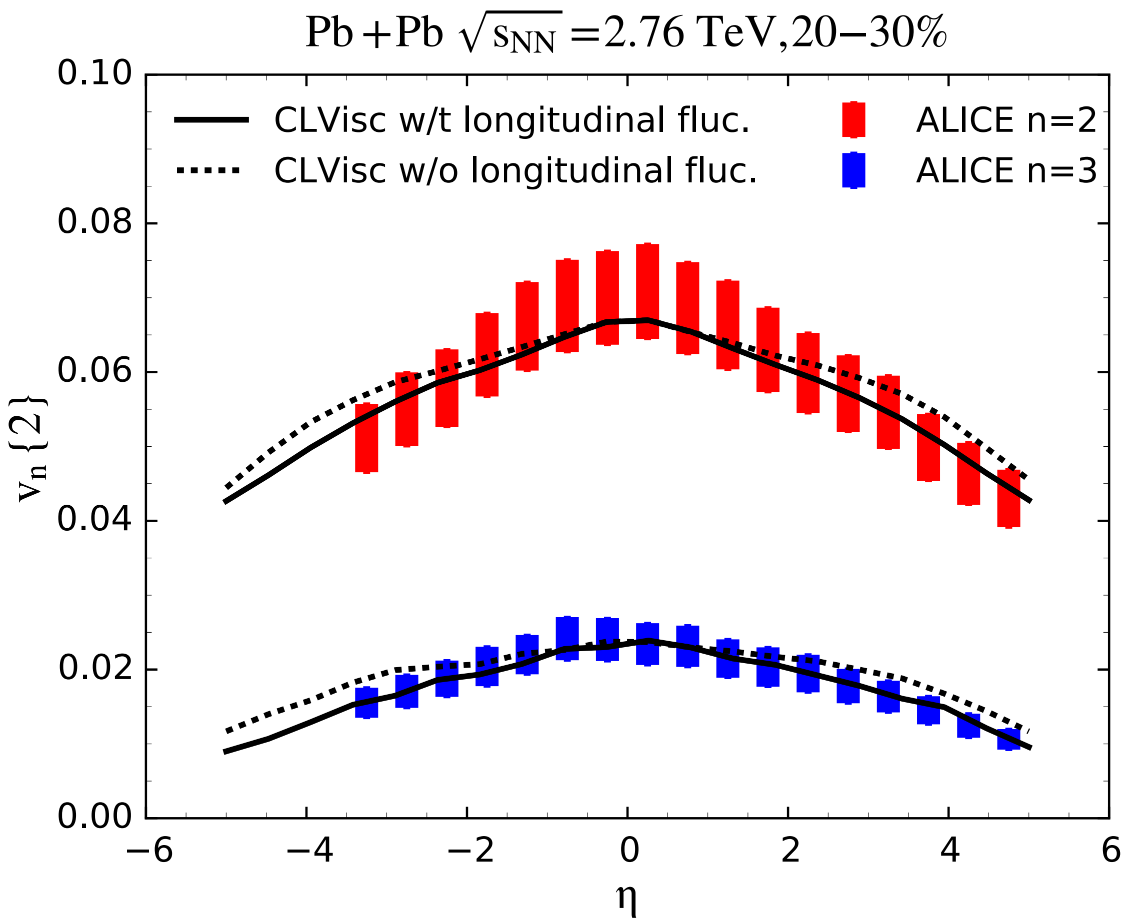




LongGang Pang, HP et al, Eur.Phys.J. A52 (2016) no.4, 97

Rapidity dependence of v_n

- Longitudinal fluctuations lead to a slightly better agreement with experimental data at forward rapidity



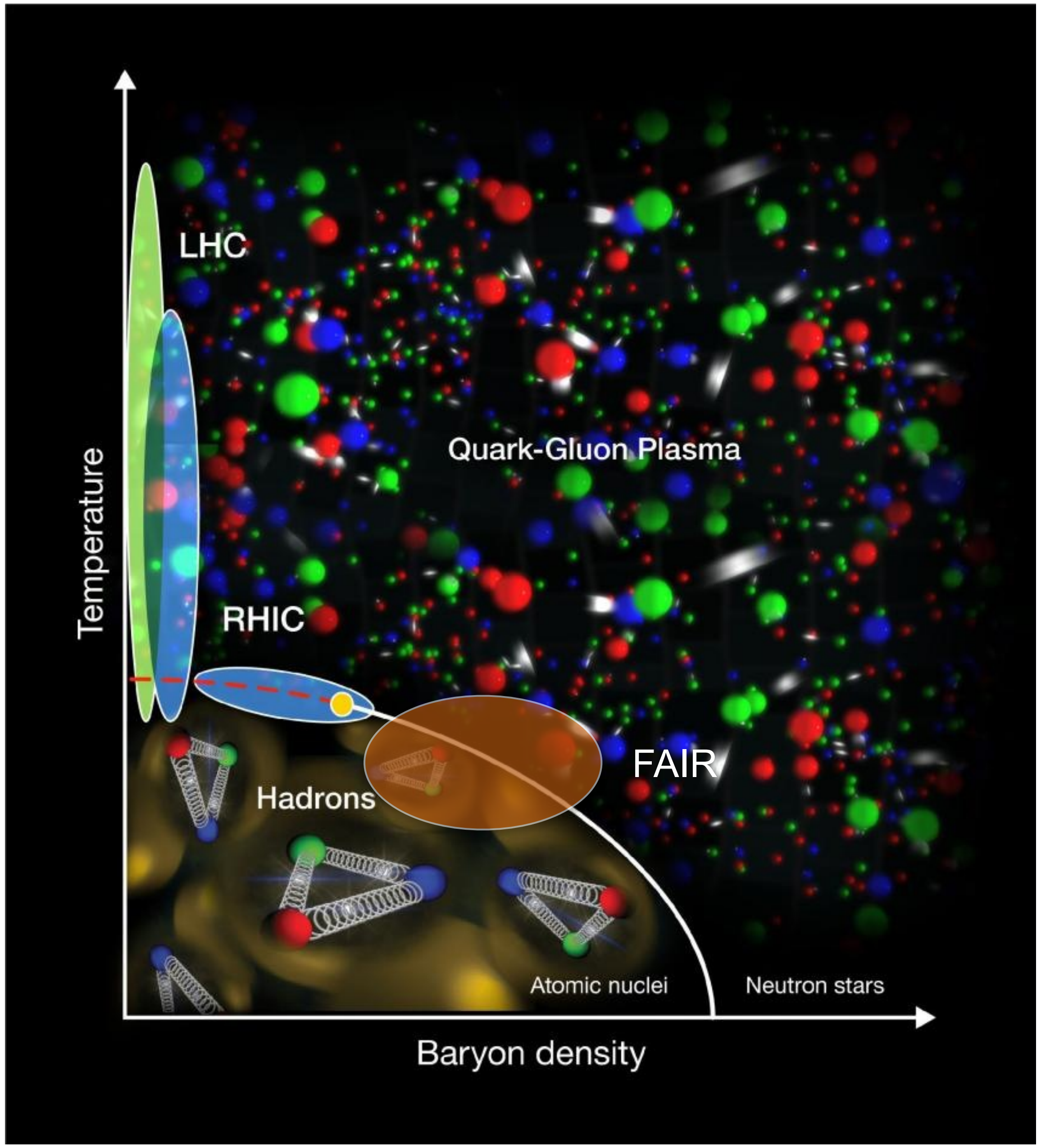
- With smooth initial conditions the p_T spectra are harder at mid rapidity
- Further calculations with viscosity are work in progress…

Low Beam Energies

in collaboration with Y. Karpenko, D. Oliinychenko and the SMASH team

Lower Beam Energies

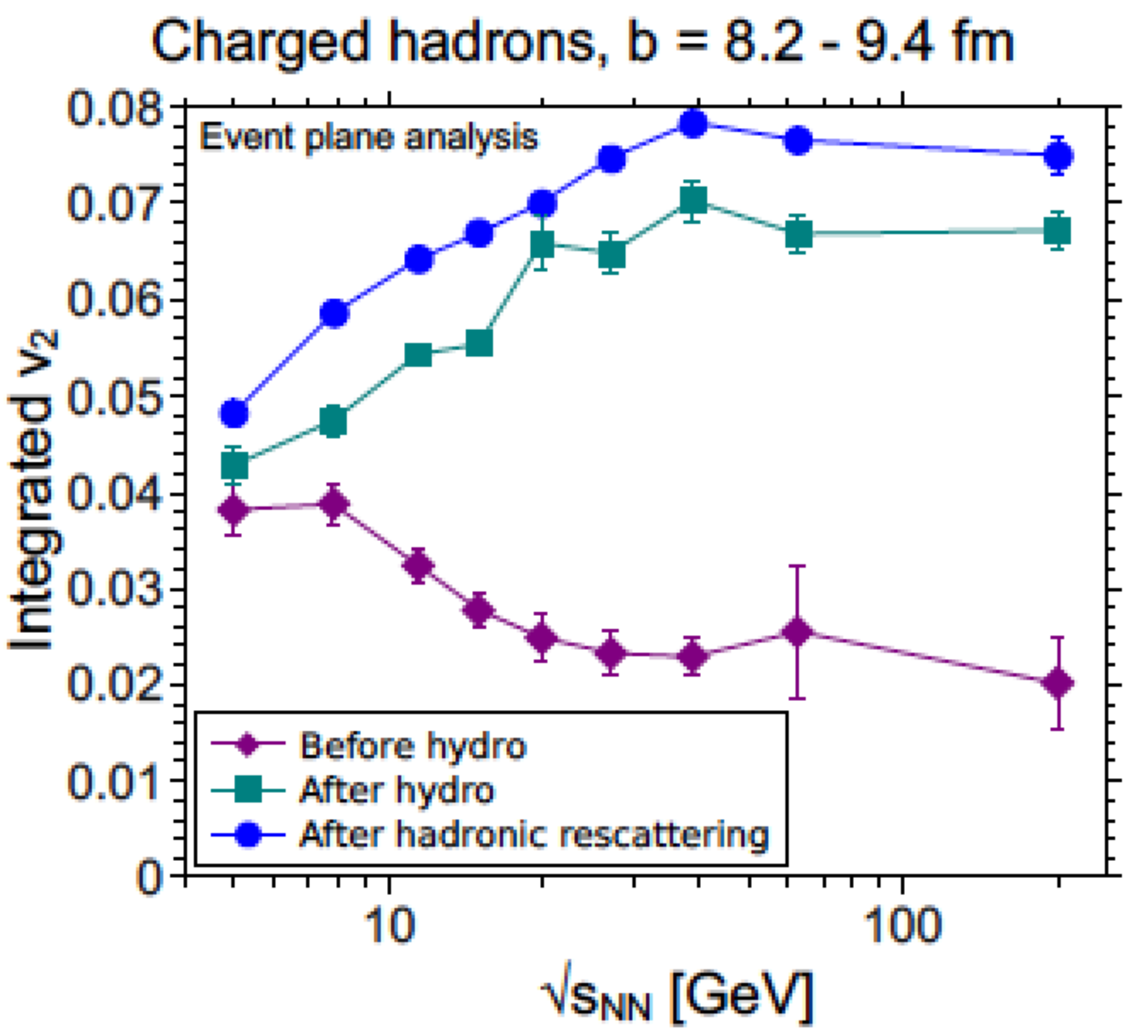
- **Dissipative effects** grow at lower energies (hadronic evolution gains importance)

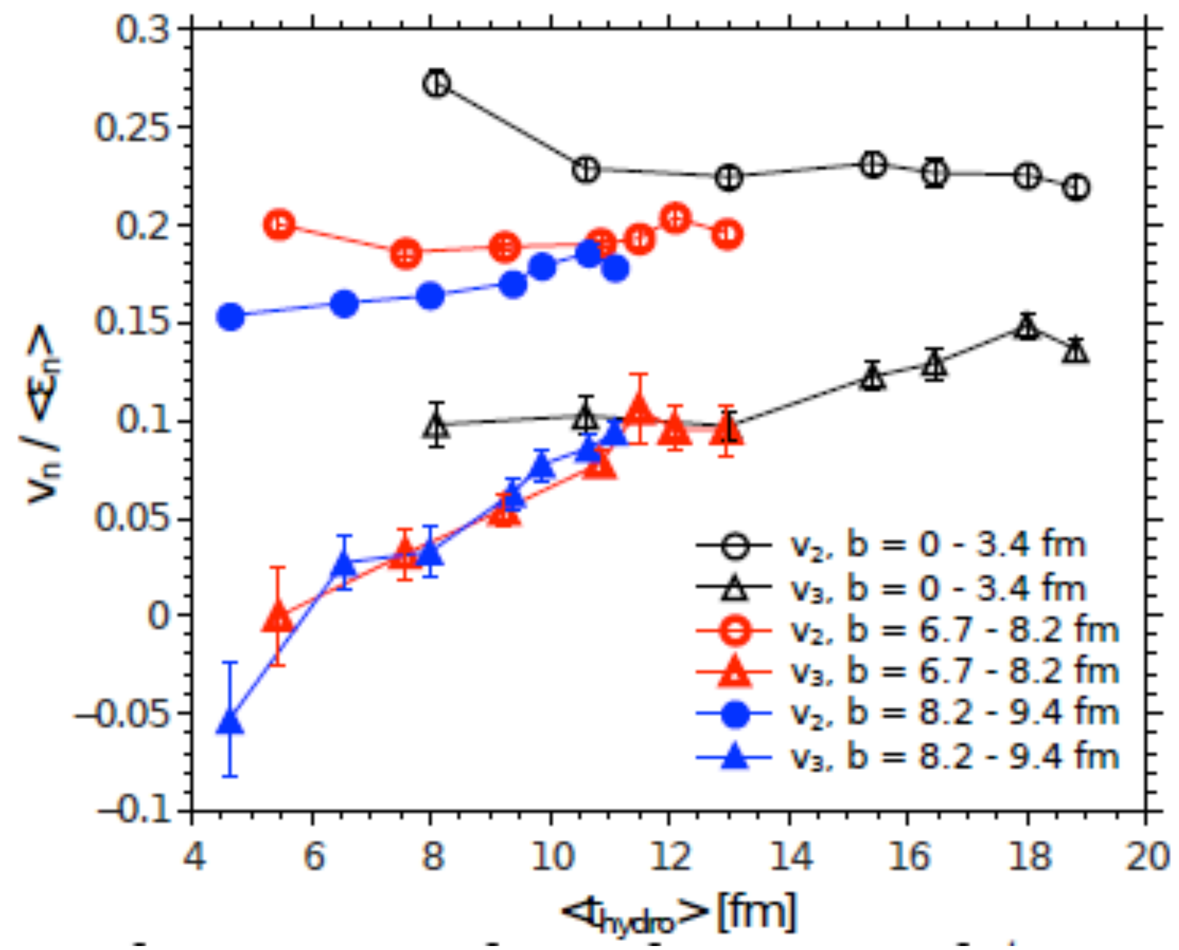


- New results from RHIC beam energy scan expected
- Will be investigated in the future at FAIR
- Two strategies:
  - Adjust existing hybrid approaches to include finite **net-baryochemical potential**
  - Extend vacuum hadronic transport to higher densities and temperatures

- Small systems pose similar challenges

Interplay of Hydro + Transport



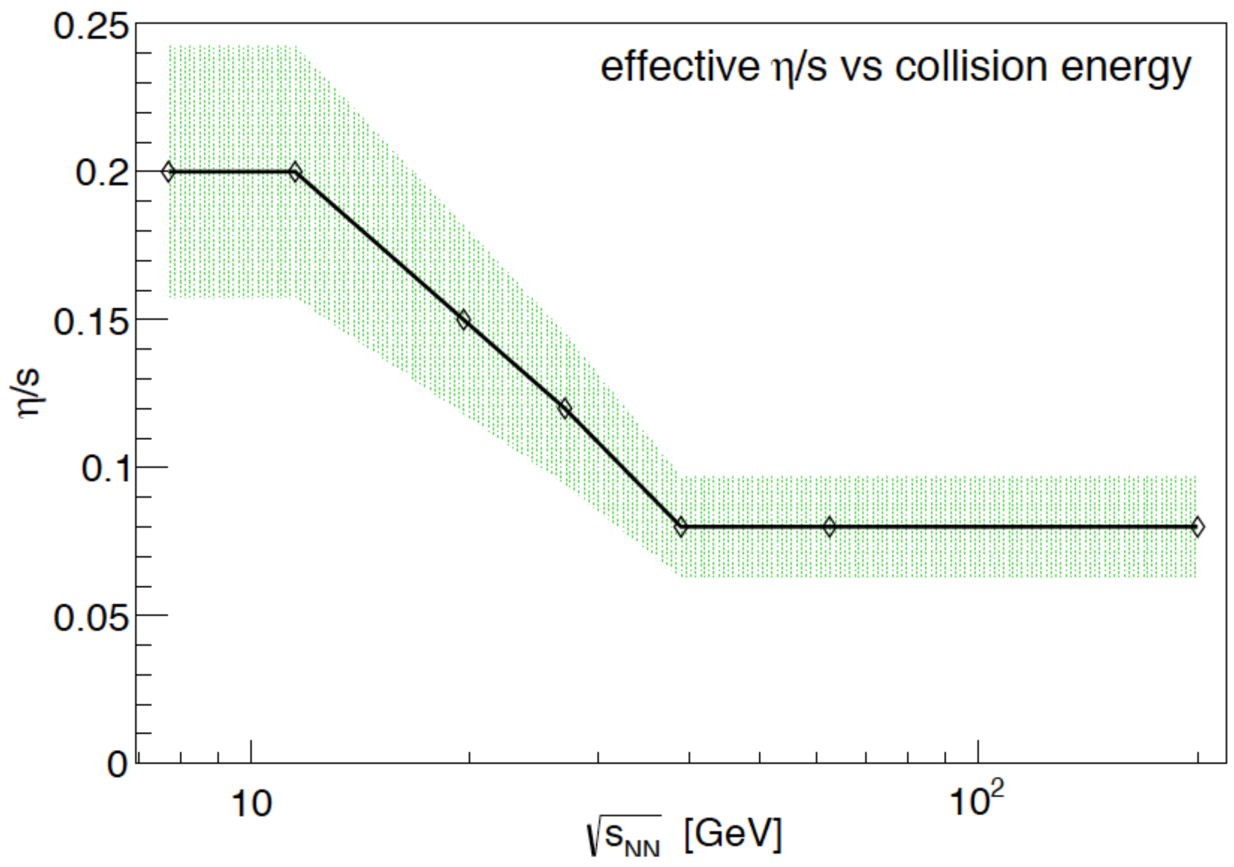


- Contribution of late stage hadronic rescattering ~10%
- v_3/ε_3 shows universal behavior as a function of total duration of hydro phase
- v_2 does not follow scaling because of transport contribution

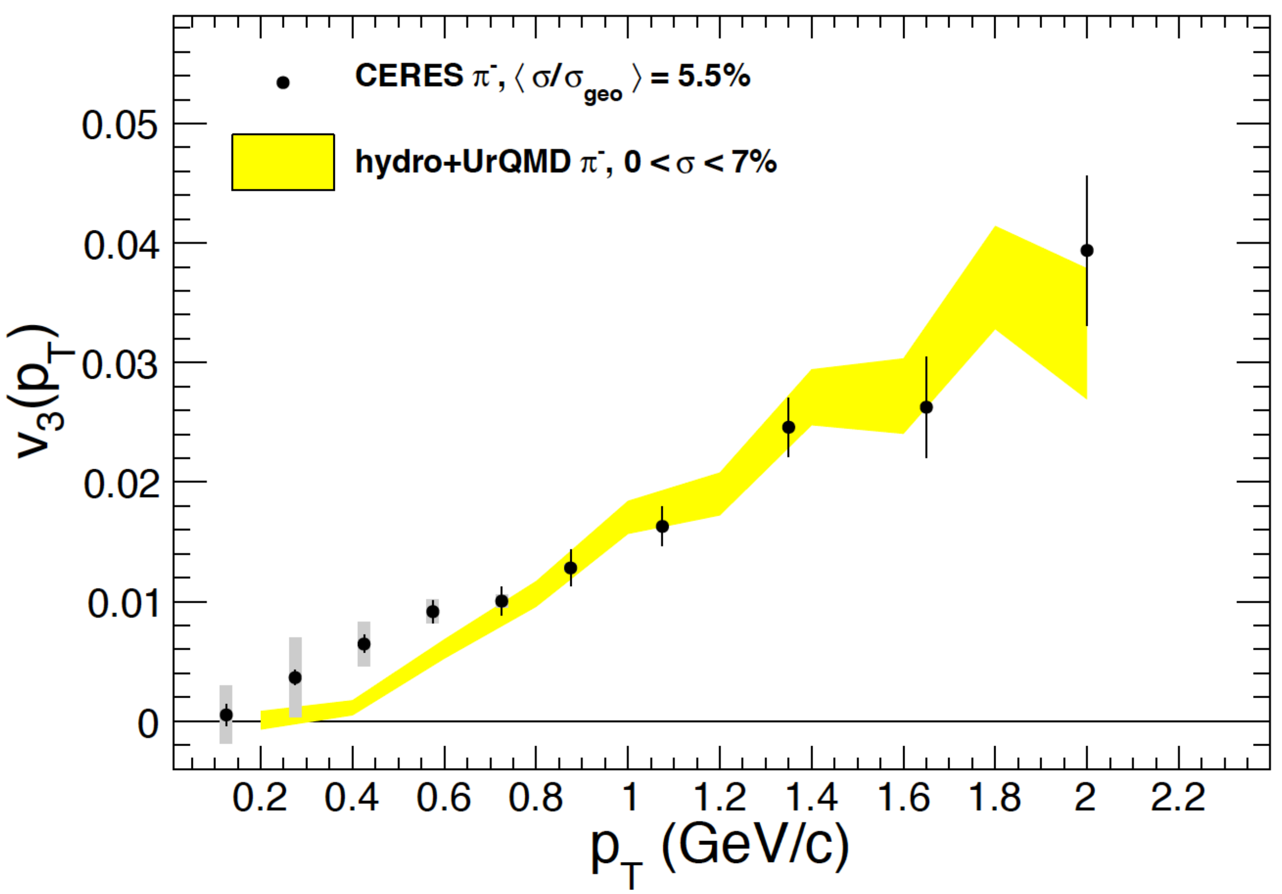
J. Auvinen and HP, Phys.Rev. C88 (2013) 064908

Shear Viscosity and v_3

- Pushing hybrid to lower beam energies:
  - Viscous UrQMD hybrid fitted to beam energy scan and SPS data allows to extract shear viscosity
  - v_3 predictions in line with CERES measurement



Karpenko, P. Huovinen, HP, M. Bleicher, Phys.Rev. C91 (2015) no.6, 064901

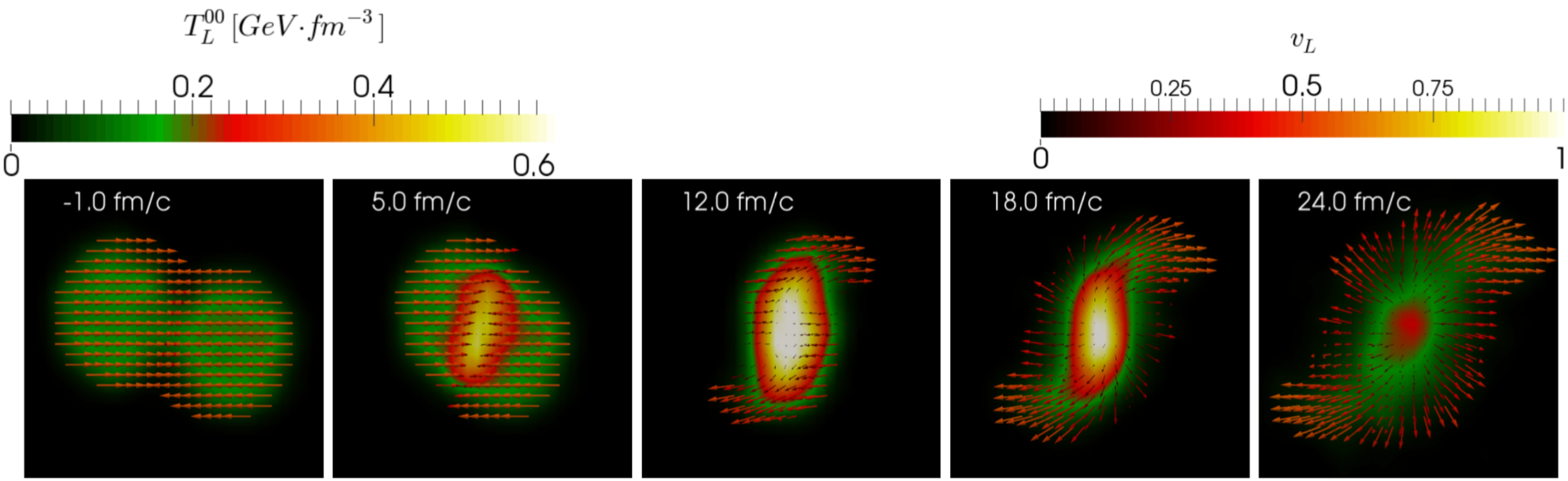


CERES, arXiv:1604.07469

SMASH*

J. Weil et al, arXiv:1606.06642

- New hadronic transport approach:
  - Includes all mesons and baryons up to ~2 GeV
  - Geometric collision criterion
  - Binary interactions: Inelastic collisions through resonance excitation and decay
  - Modern infrastructure: C++, Git, Redmine, Doxygen

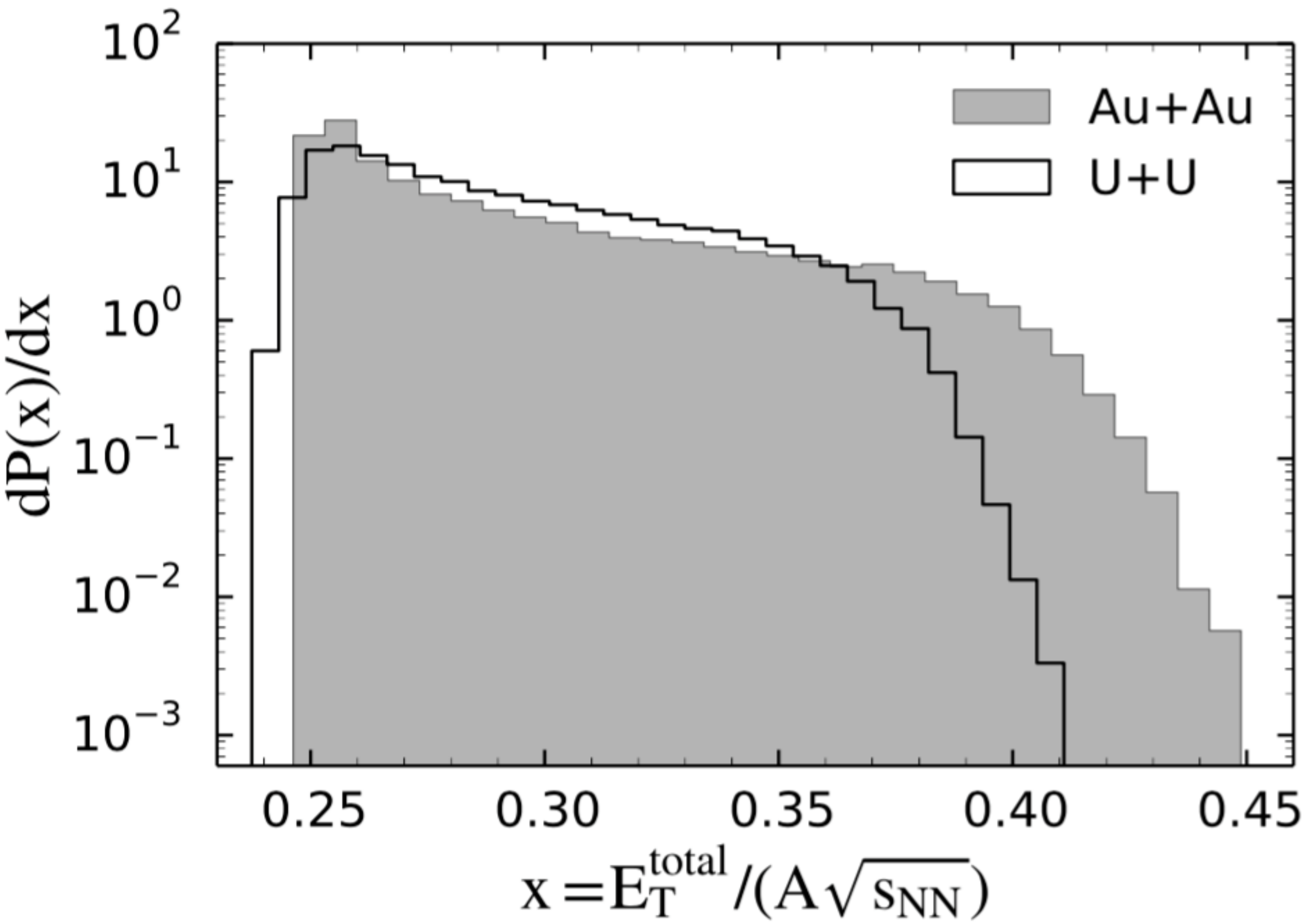


* Simulating Many Accelerated Strongly-Interacting Hadrons

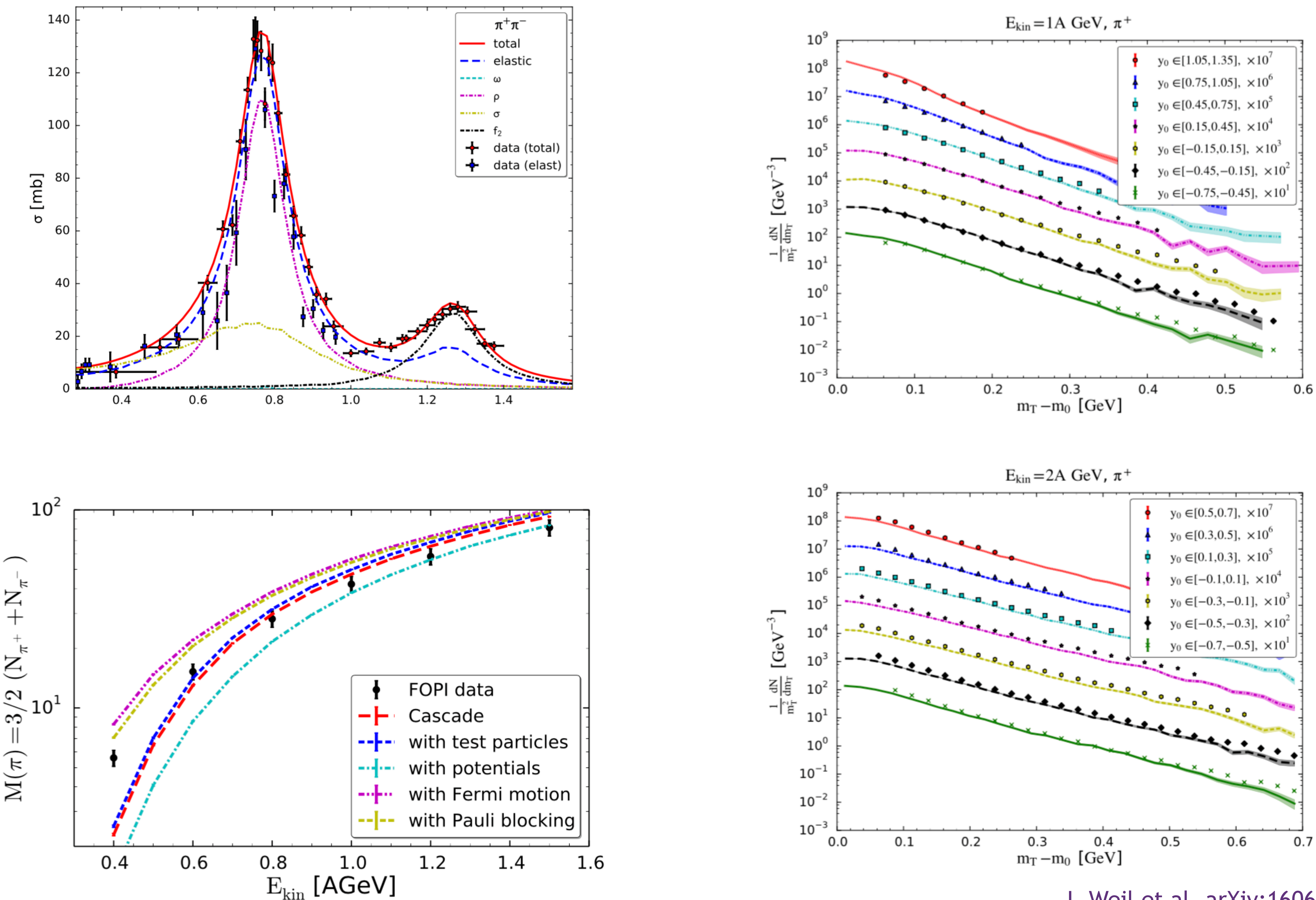
Deformed nuclei

- Summer project of A. Goldschmidt:
  - Framework for treatment of deformed nuclei developed with U. Heinz

J. Weil et al, arXiv:1606.06642



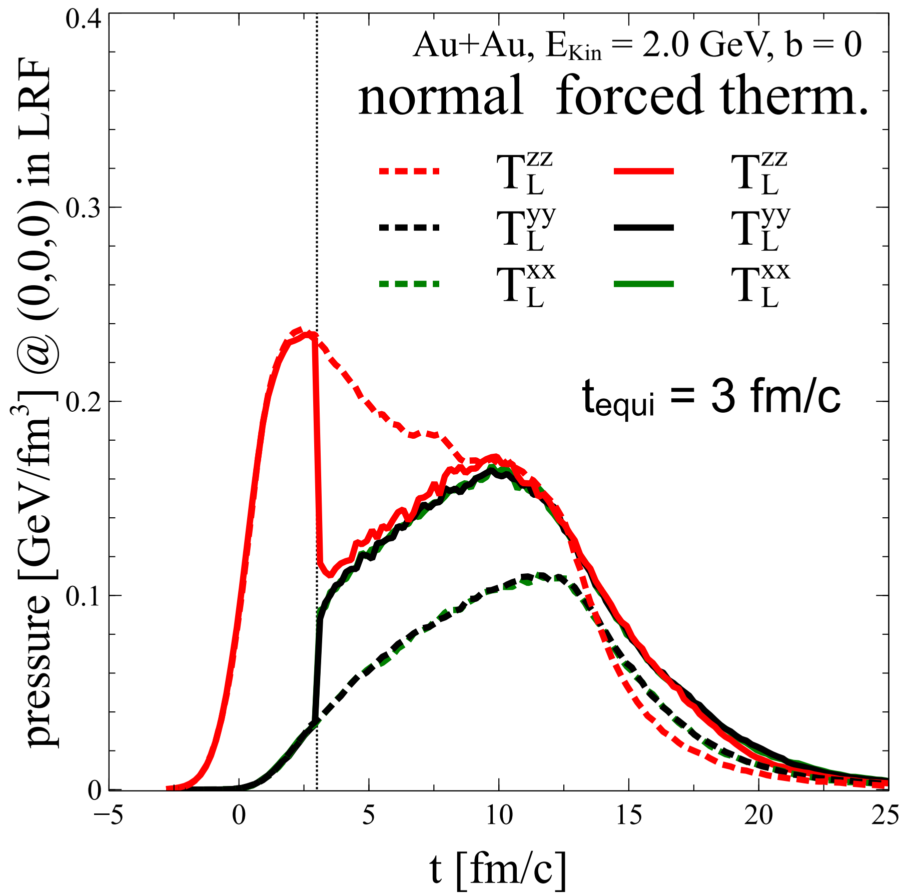
Data comparison

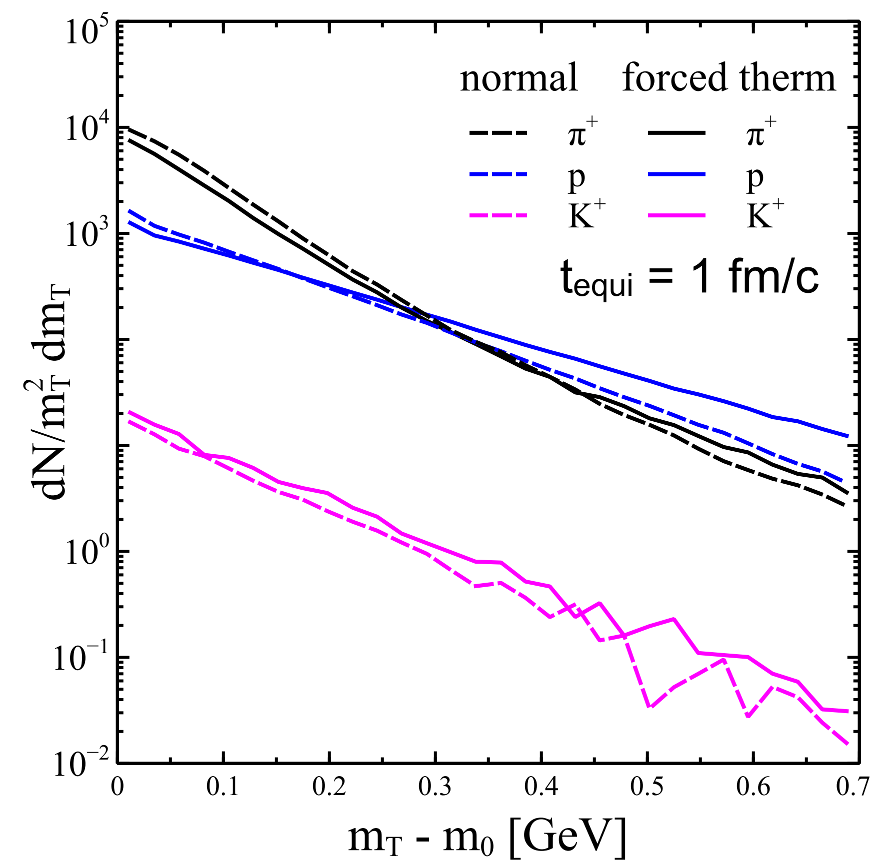


J. Weil et al, arXiv:1606.06642

Effective N-particle scattering

- At higher densities multi-particle scattering becomes important -> here: extreme limit
- Above 0.3 GeV/fm^3 local kinetic equilibrium is enforced by replacing the distribution function with a thermal one



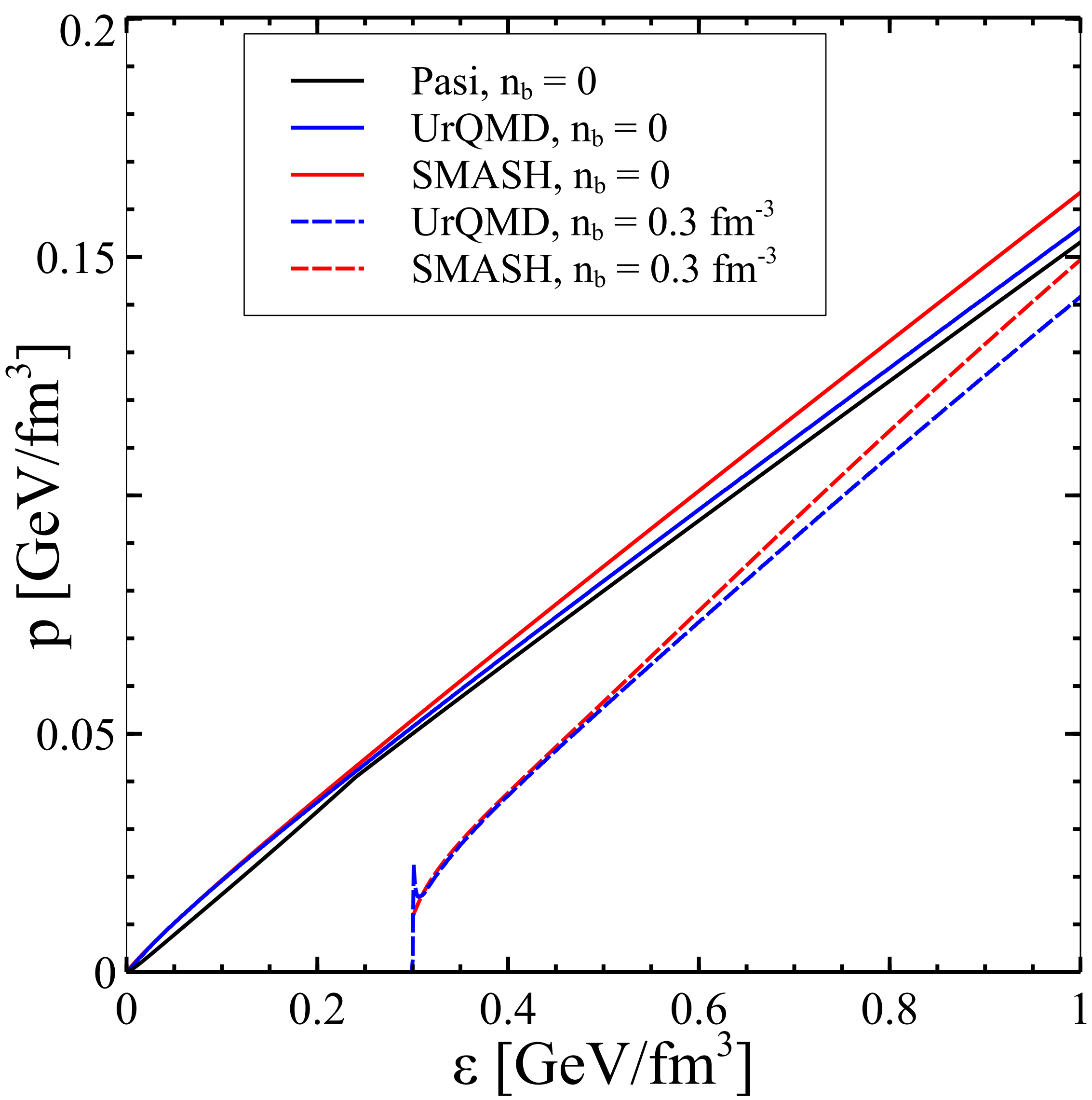


- In the future: Dynamical coupling of transport/hydro-like stage

Dmytro Oliinychenko, HP

Hadron gas EoS

- Sample particles conserving all quantum numbers in small volume

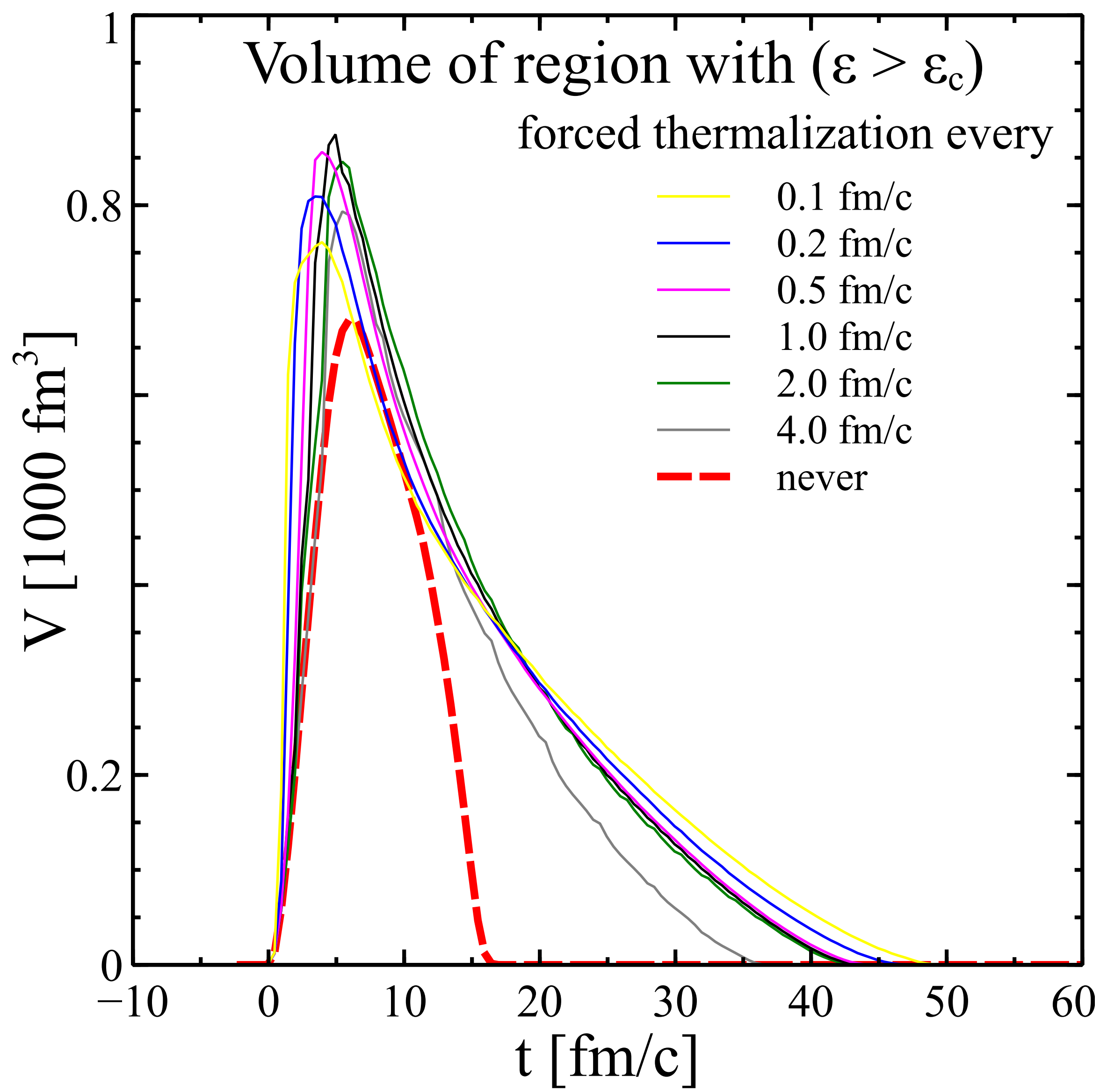


Pasi = Hadron Gas EoS from P. Huovinen, P. Petreczky, Nucl.Phys. A837 (2010) 26-53
UrQMD = Hadron Gas EoS from UrQMD tables by J. Steinheimer

- Consistent equation of state is necessary

Time evolution

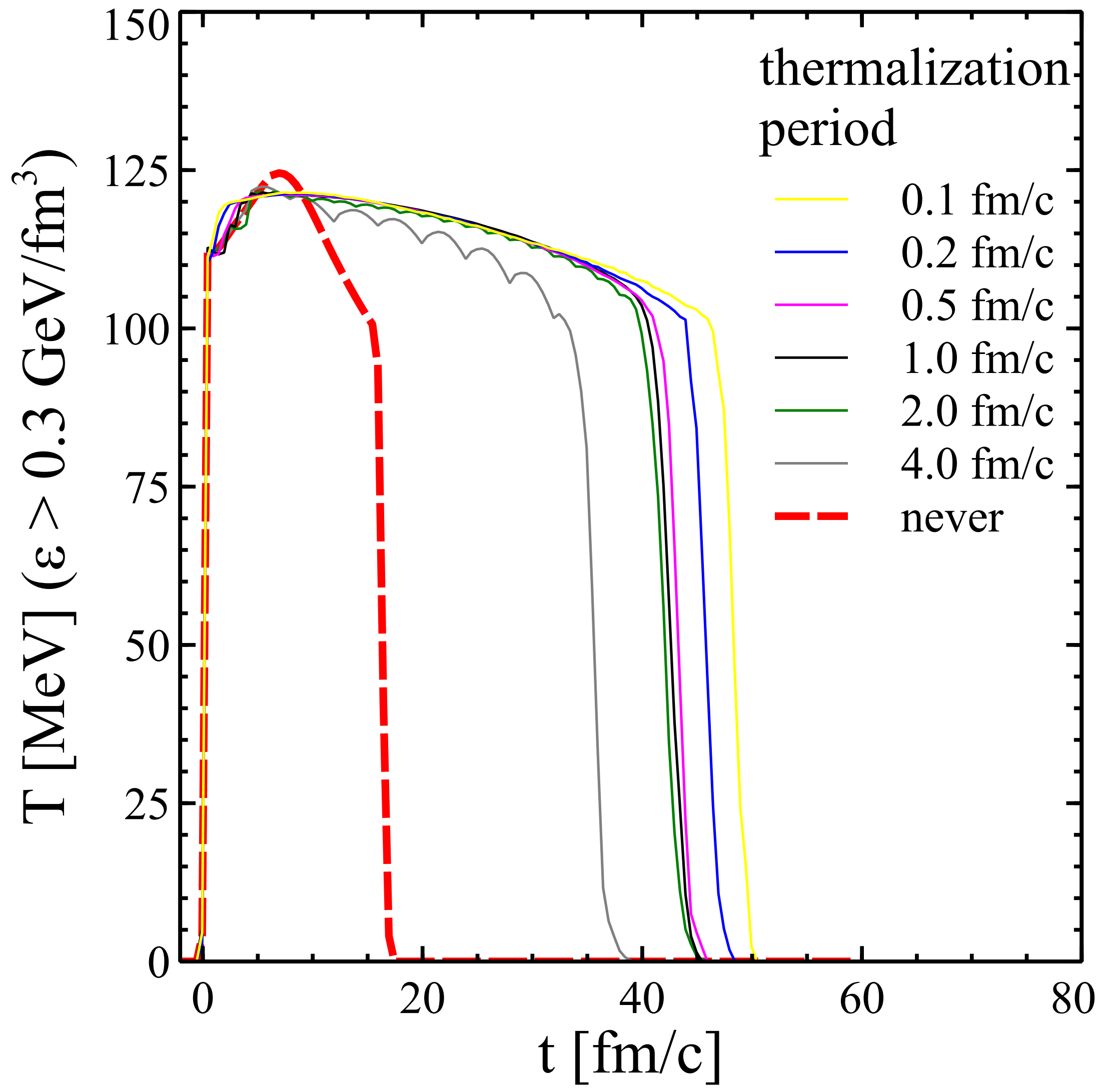
- Au+Au central collision, $\sqrt{s}$ = 3 GeV

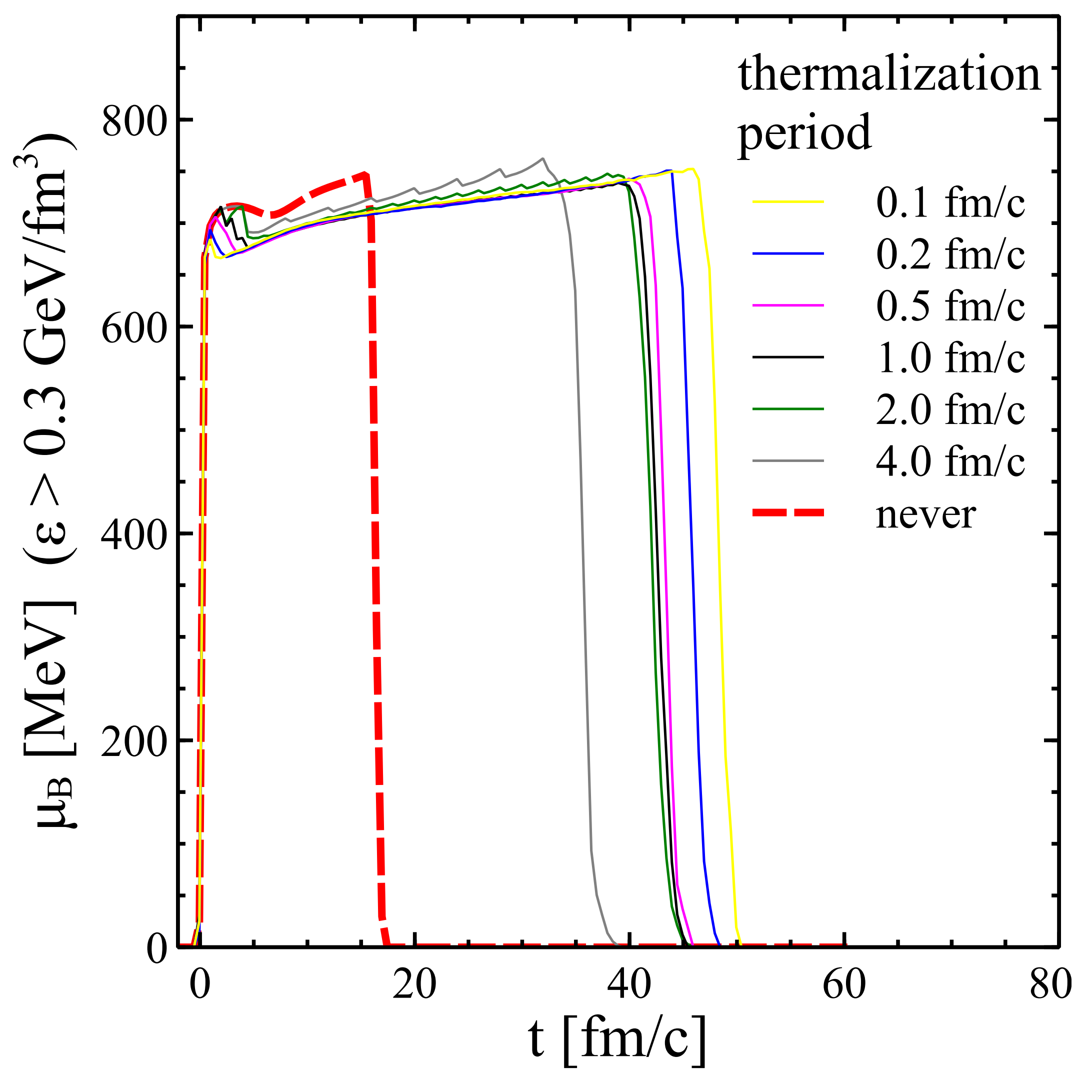


- High density region exists for a longer period

Temperature and chemical potential

- Time evolution of mean of thermodynamic quantities

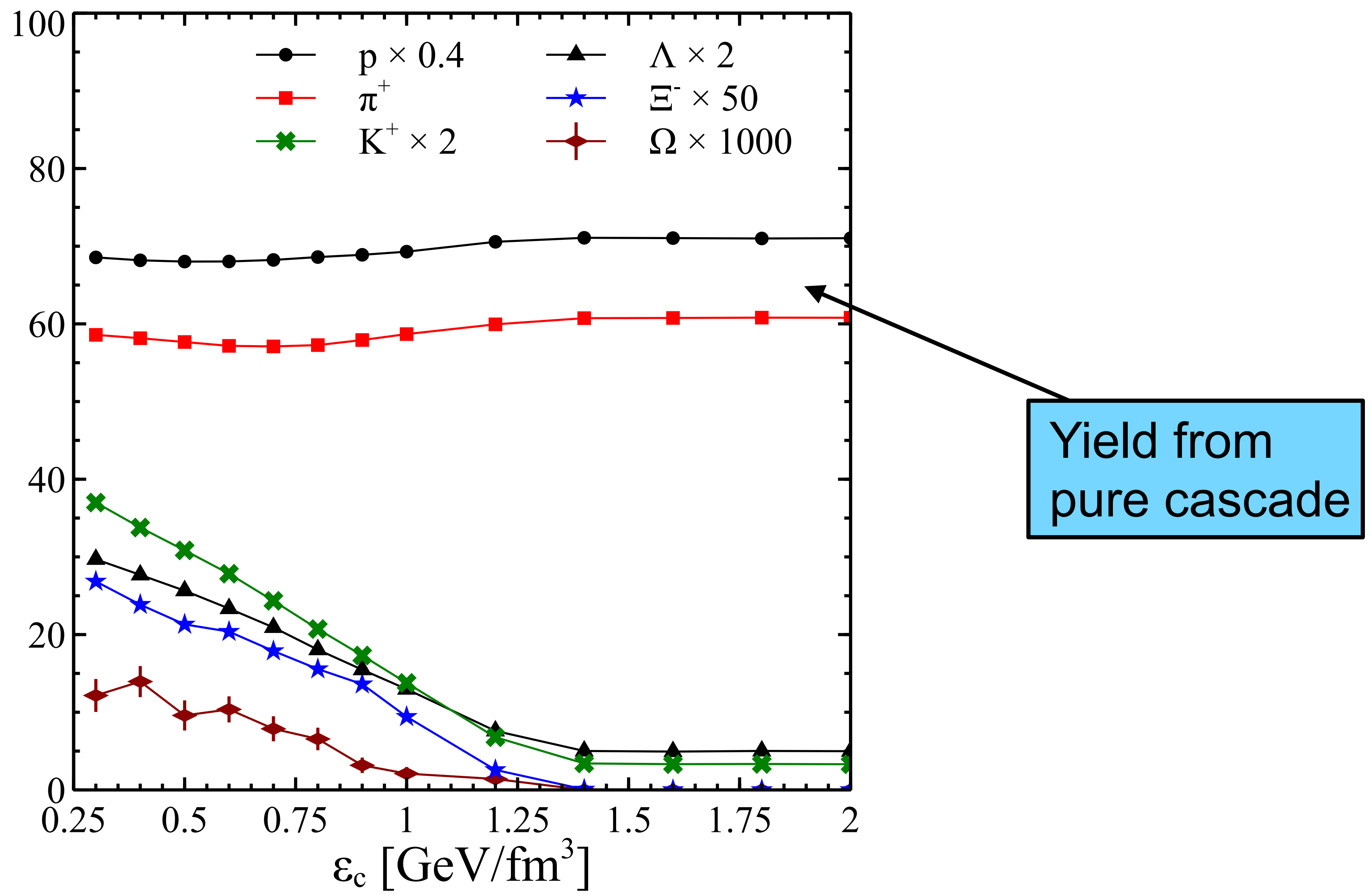




- Equilibration by reactions and forced not identical (wiggles)
  - Some particle species cannot be produced in SMASH
  - Resonances are sampled at pole mass

Effects of N-particle collisions

- System does not reach energy densities above $\varepsilon_C \sim 1.4$ GeV/fm^3



- Strangeness is enhanced as expected

Summary

- Fluctuations in the transverse plane have been thoroughly investigated
- **Longitudinal** structures are interesting as well
  - Interplay of twist effect and pure fluctuations
  - Event-by-event ideal hydrodynamics with **AMPT** initial conditions describes event plane de-correlation as measured by CMS
  - String length fluctuations **increase** at RHIC energies
  - **Viscous** hydrodynamic calculations are in progress
- **Two** strategies at low beam energies:
  - Adapt traditional hybrid approaches
  - Start with vacuum hadron transport (**SMASH**) and include N-particle collisions
  - First basic tests look promising
  - Possibility for **dynamical** coupling of hydrodynamics and transport

Thank you, Uli

- Thanks for pushing me/us to write/organize

IOP PUBLISHING — PHYSICA SCRIPTA

Phys. Scr. **87** (2013) 048001 (5pp) doi:10.1088/0031-8949/87/04/048001

Initial state fluctuations and final state correlations: status and open questions

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Summary of ECT* Workshop 2012

INT Program INT-16-3

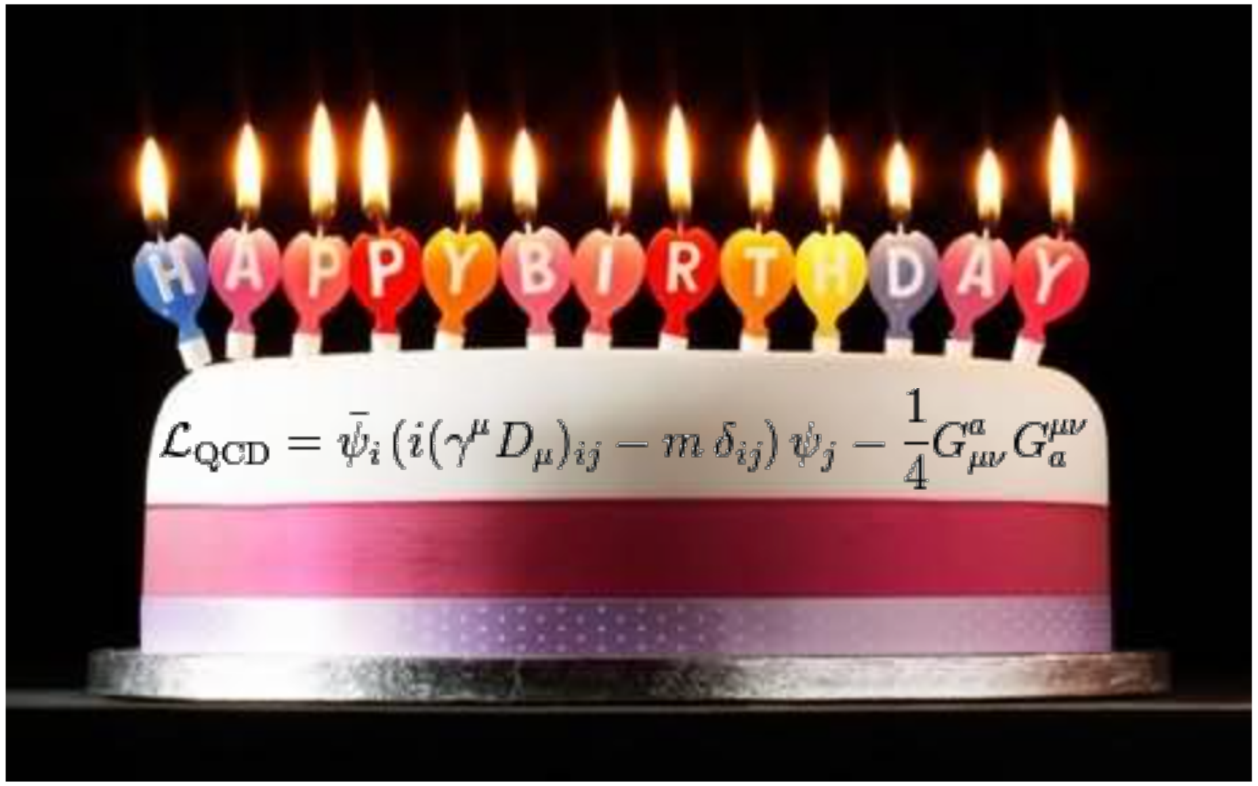
Exploring the QCD Phase Diagram through Energy Scans

September 19-October 14, 2016

Organizers: M. Lisa, H. Petersen, P. Sorensen, V. Koch

- and all your support!

Happy Birthday, Uli!

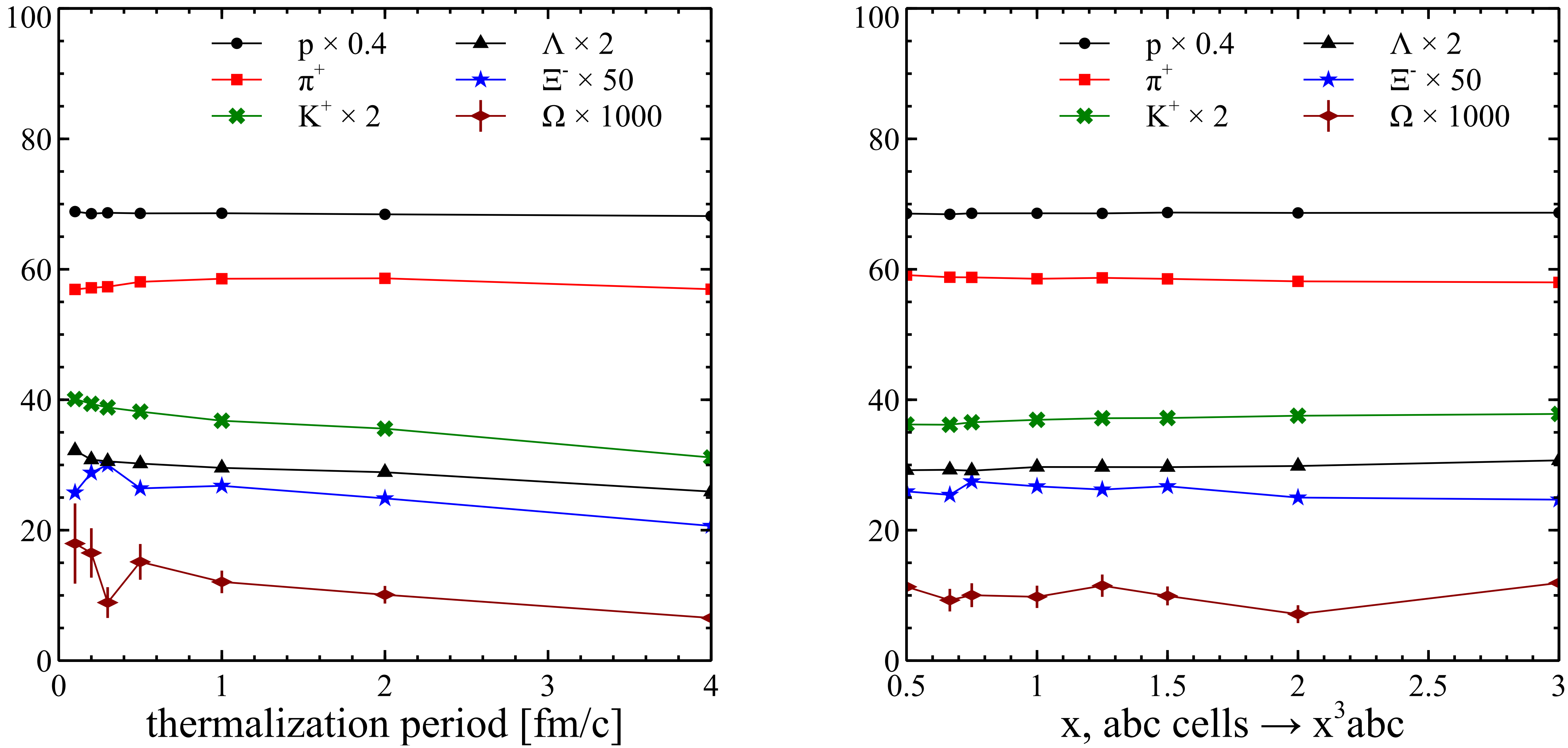


- I wish you many more fun surprise gifts in heavy ion collisions!

Backup

Parameter sensitivities

- Au+Au at $\sqrt{s}$=3 GeV

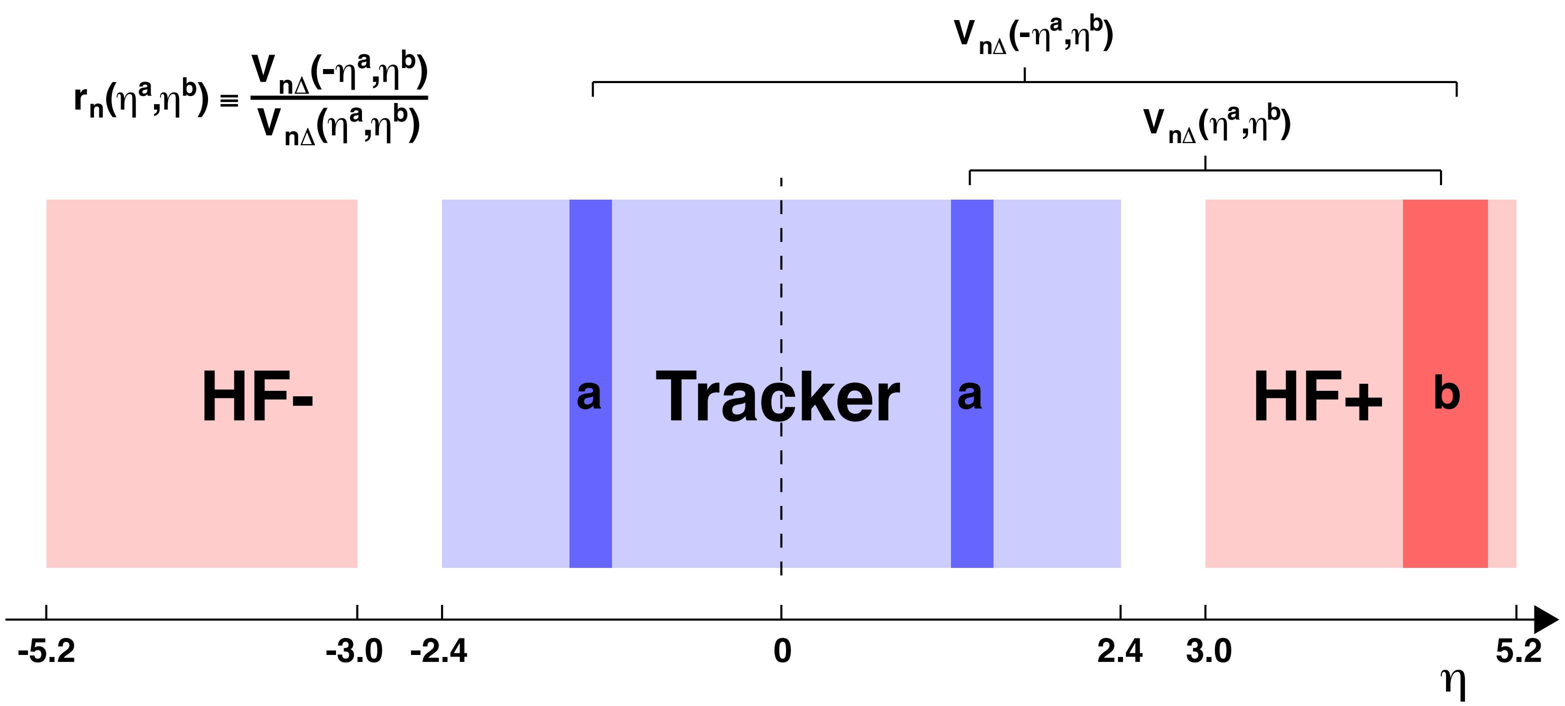


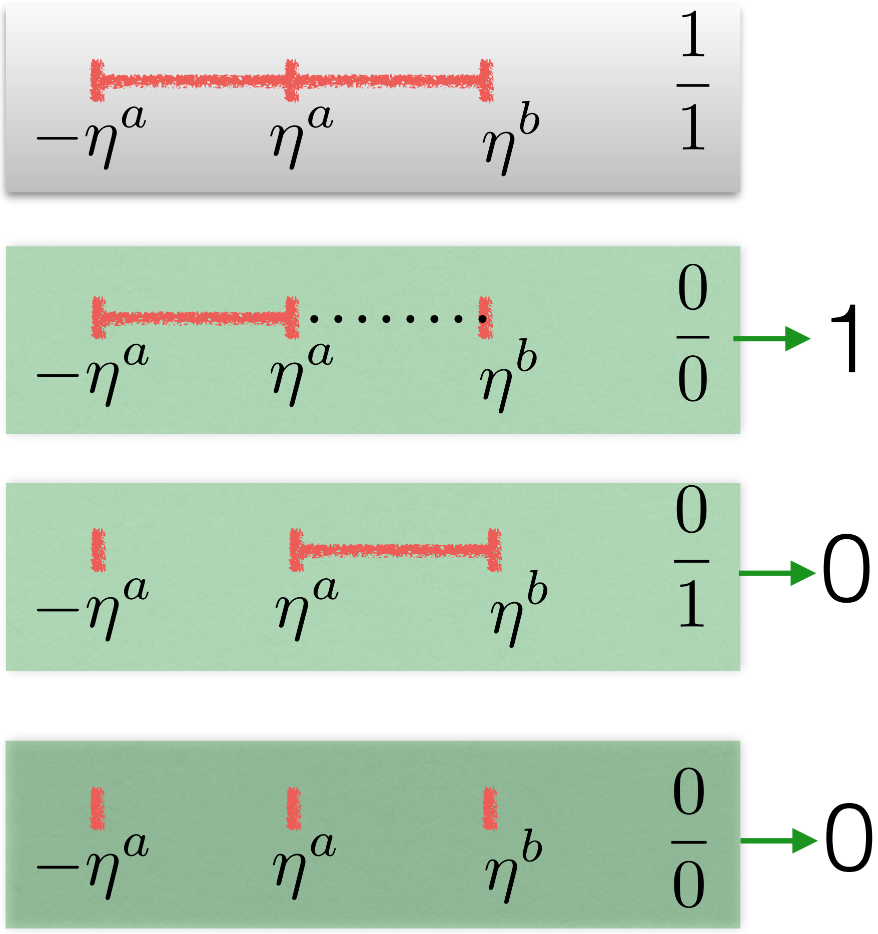
- Thermalization period and lattice spacing do not matter for multiplicities

De-correlation of anisotropic flow by CMS

(CMS 2015 ARXIV:1503.01692)

$$r_n(\Delta\eta = 2\eta^a) = \frac{< \mathbf{Q}_n(-\eta^a)\mathbf{Q}_n^*(\eta^b) >}{< \mathbf{Q}_n(\eta^a)\mathbf{Q}_n^*(\eta^b) >}$$





- The short range correlations (jet, resonance decay, Bose-Einstein correlation …) are removed if the rapidity gap between a and b is bigger than 2.