Mode-by-mode hydrodynamics for the quark-gluon plasma:

Moving towards precision in heavy-ion phenomenology

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Overview

- Current state of heavy-ion collisions
- Mode-by-mode hydrodynamics – FluiduM
- Application: Isobar collisions
- Conclusion

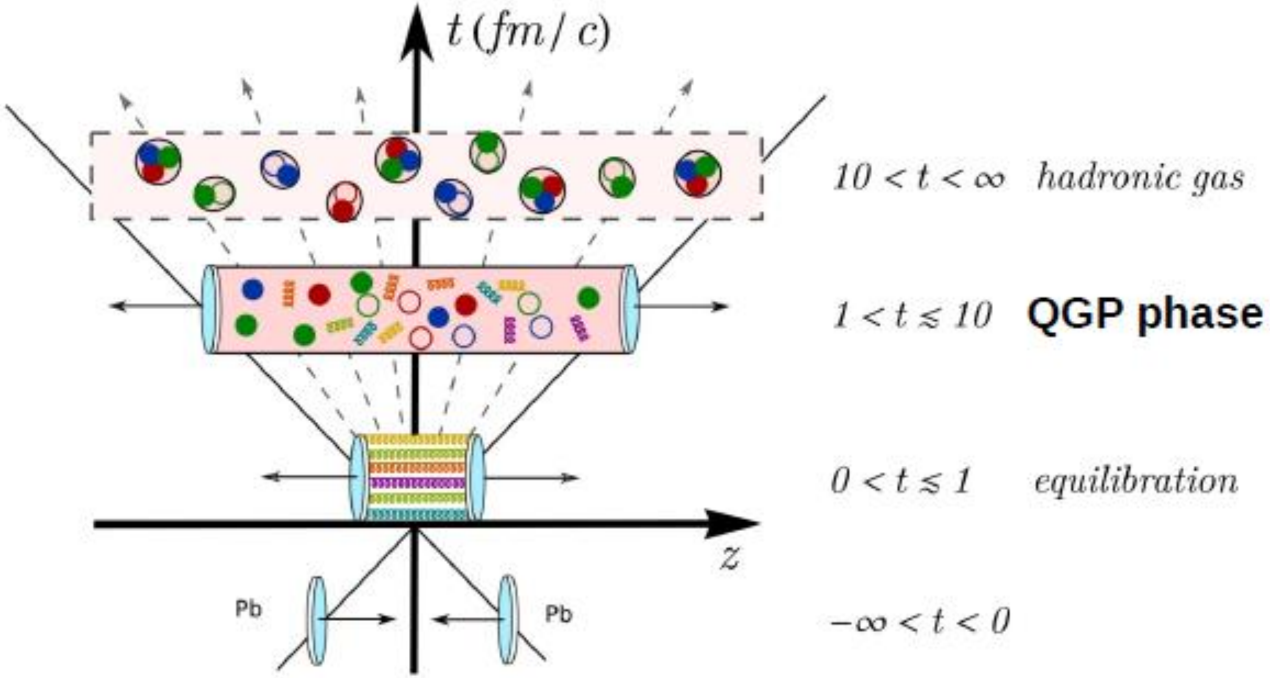
Current state of heavy ions

- Effective description of HIC: relativistic fluid

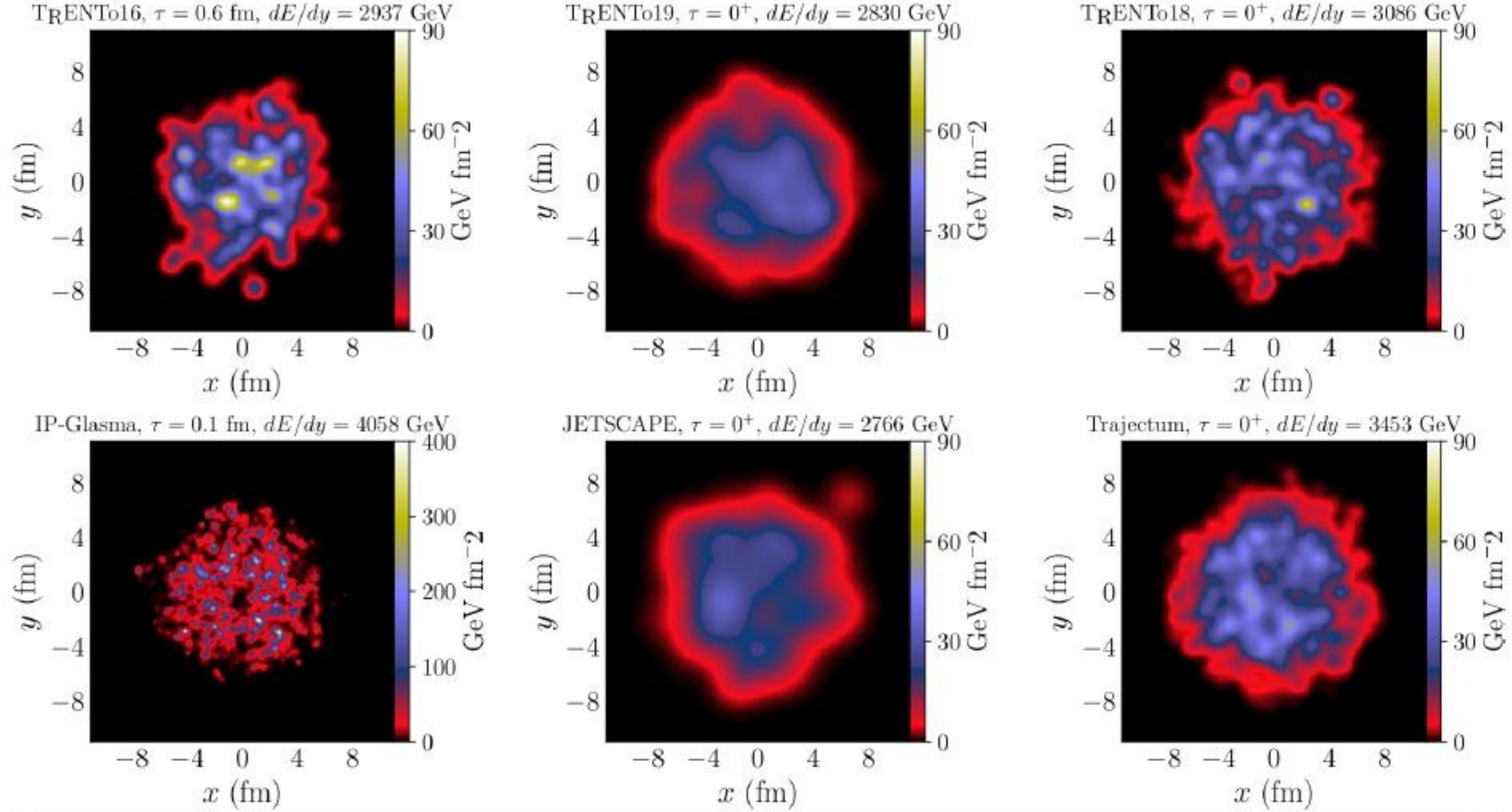
$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - Pg^{\mu\nu}$ + viscous corrections (η/s, ζ/s, ...) **+** $\partial_\mu T^{\mu\nu} = 0$

- Main goals: understanding the initial conditions and transport properties

BUT
Only thing available are particle spectra
-> Reconstruct information from observables

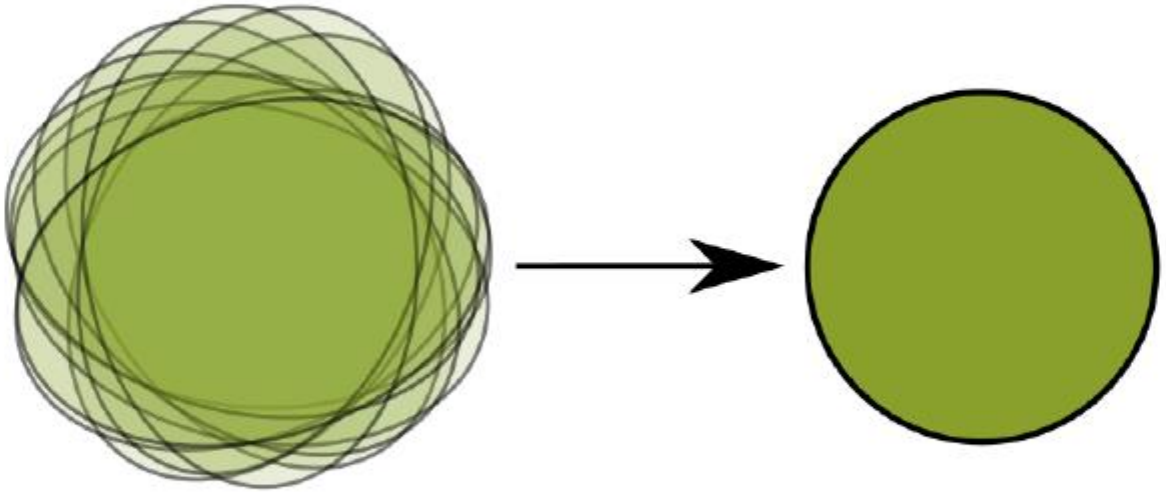


Current state: initial conditions



-> Test different models by comparing with data -> Framework for comparison needed

Mode-by-mode hydrodynamics



- Idea: Describe event ensemble instead of single event

-> Statistical symmetry

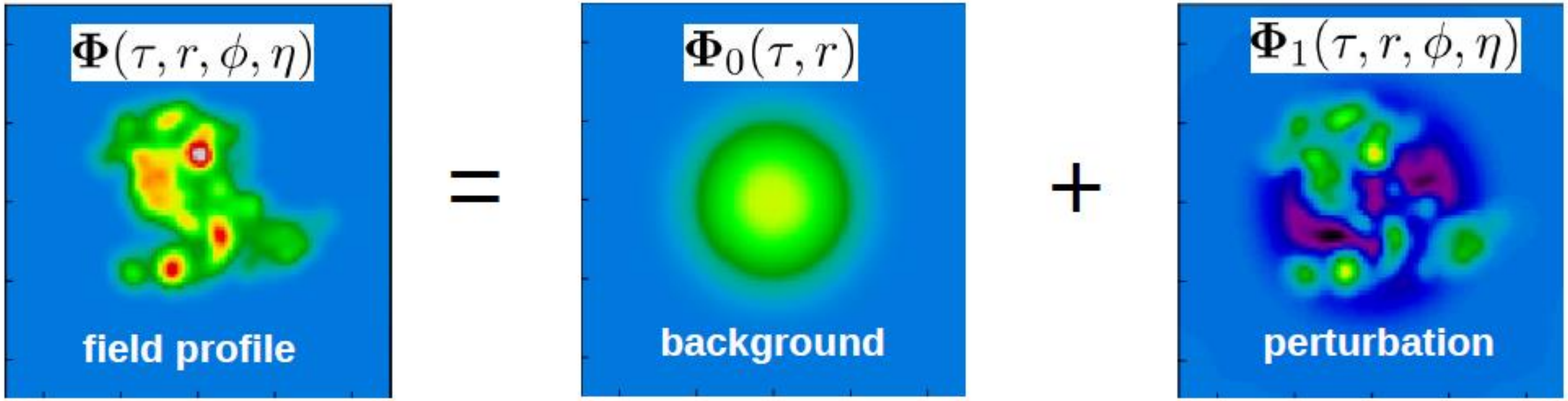
-> BG-fluctuation splitting

$$\Phi(\tau, r, \varphi, \eta) = \Phi_0(\tau, r) + \epsilon\Phi_1(\tau, r, \varphi, \eta)$$

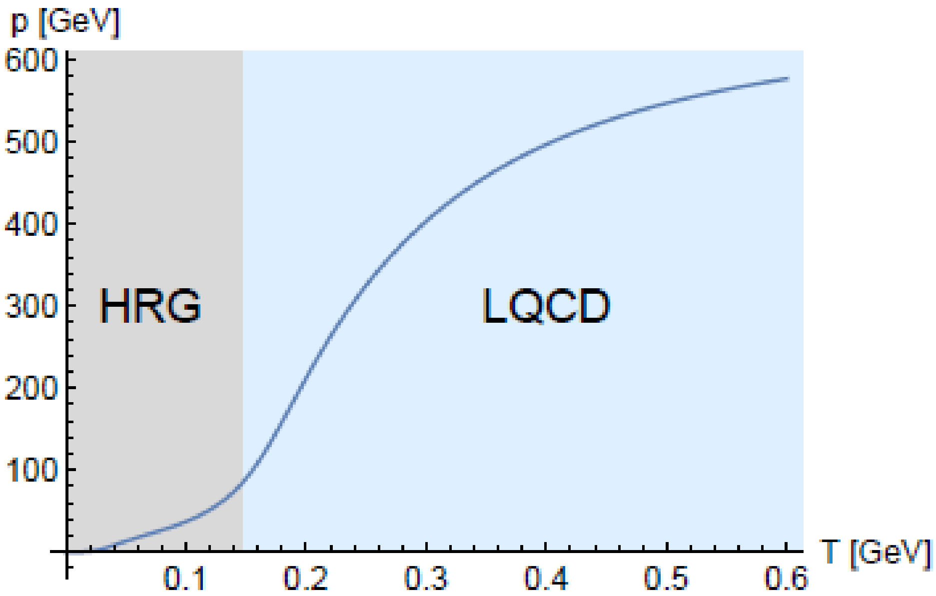
- BG has Bjorken boost invariance + statistical symmetry -> 1+1D EoM
- 1+1D linearised EoM for perturbations coupled with BG
- BG gives averaged quantities (yields, <pT>), while fluctuations encoded in perturbations

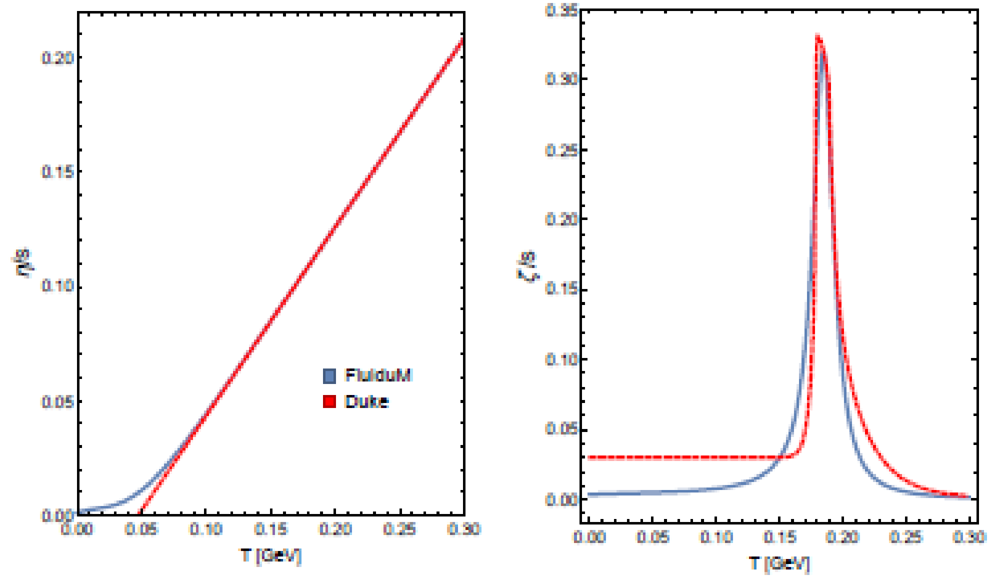
Implementation: FLuiduM

- FluiduM is Mathematica code package to solve 1+1D hydro equations
- EoM: Energy-momentum conservation + 2nd order Israel-Stewart
- Evolution does not violate causality
- Validated against Gubser-Flow
- Particlization+Resonance decays: Cooper-Frye+FastReso



Validation: Setup



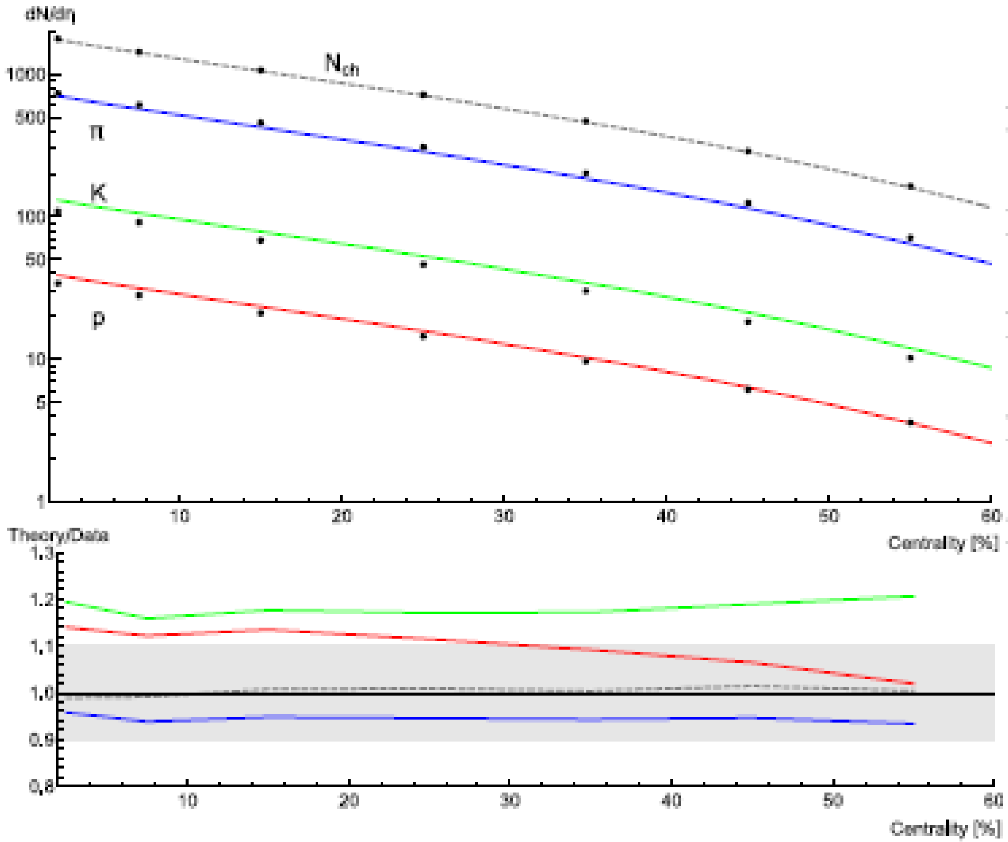


- EoS: HRG ($T < T_c = 154\,\text{MeV}$) and LQCD ($T > T_c$)
- Viscosities $\frac{\eta}{s}(T)$ and $\frac{\zeta}{s}(T)$
- $T_{fo} = 148\,\text{MeV}$

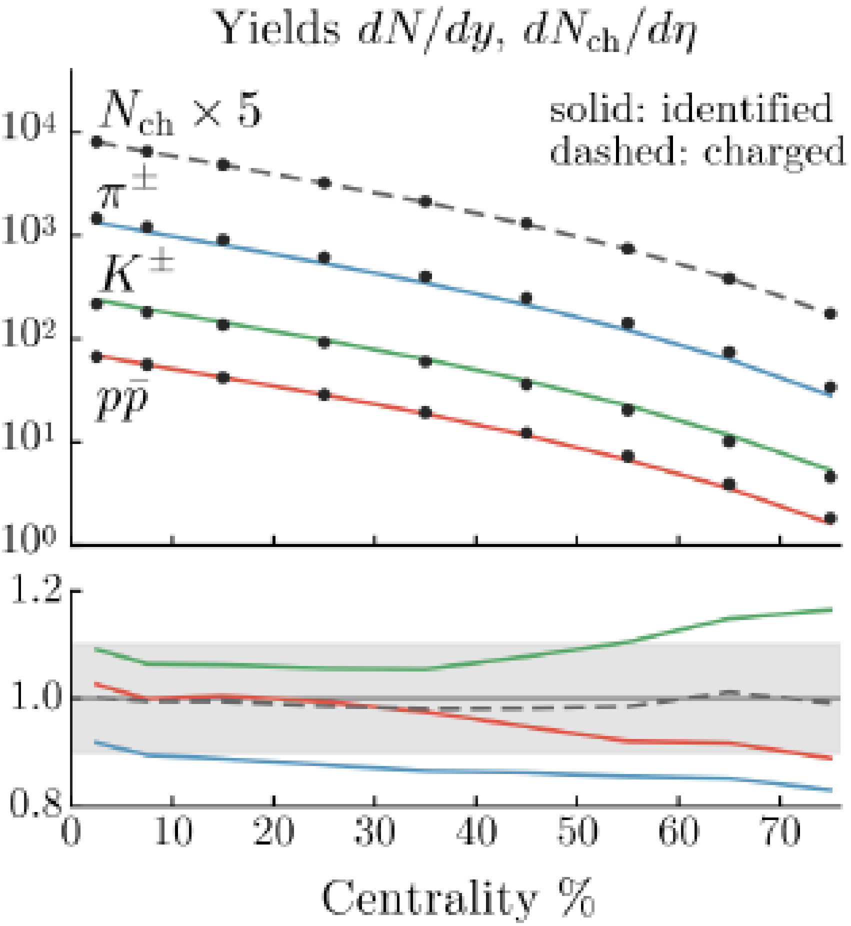
- δf_{shear}, but no δf_{bulk}
- Setup nearly identical to model of first bayesian analysis of Duke group (arxiv:1605.03954)

Validation: Results

FluiduM

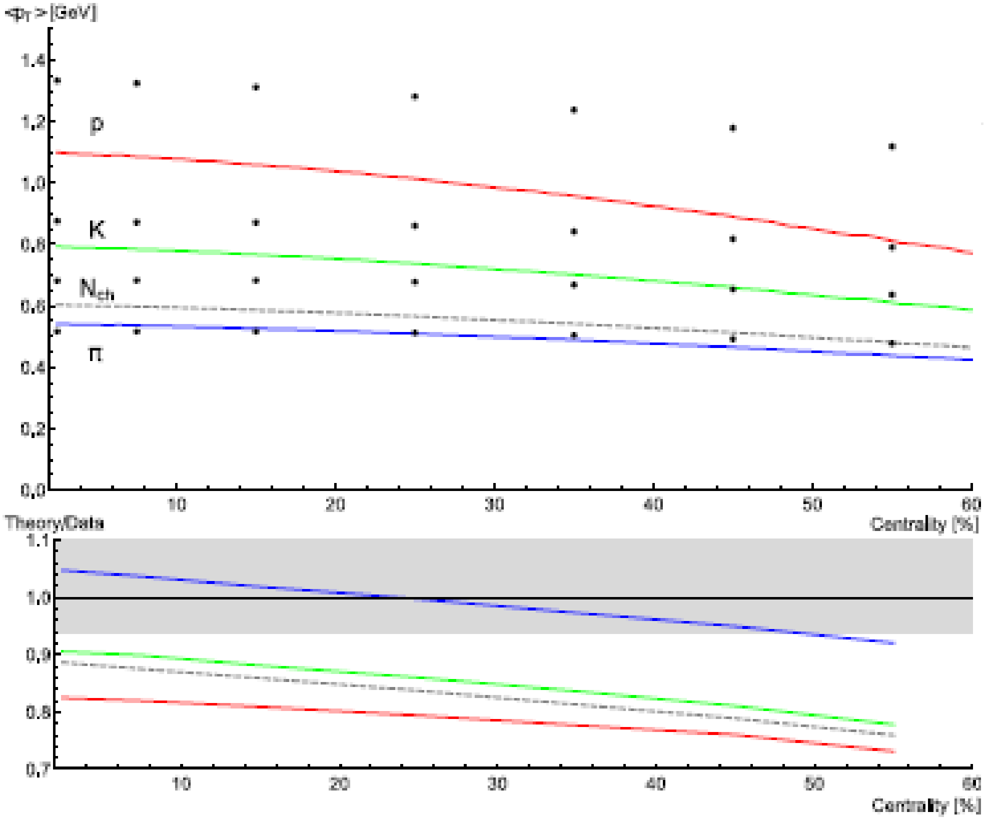


Duke

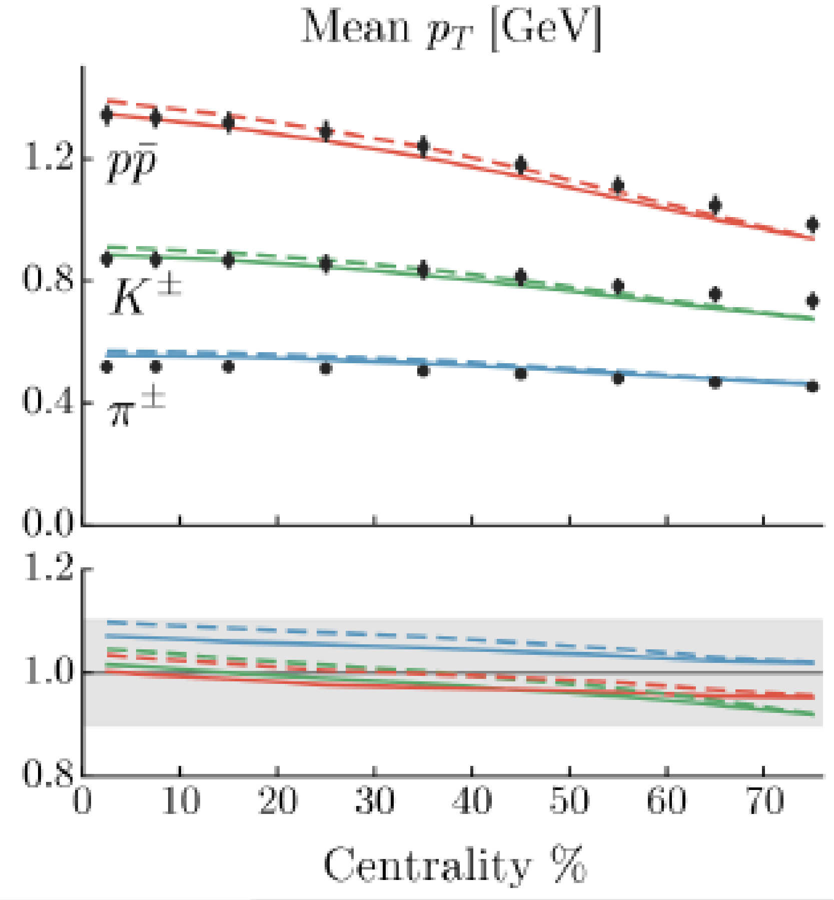


Validation: Results

FluiduM

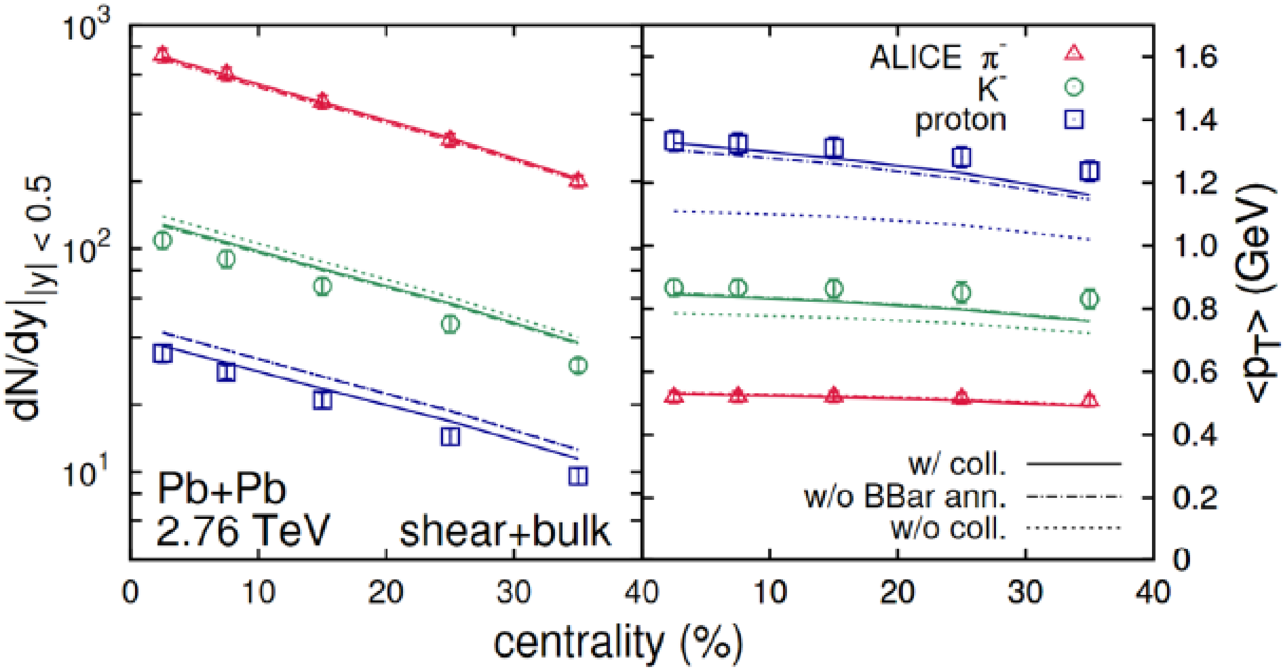


Duke



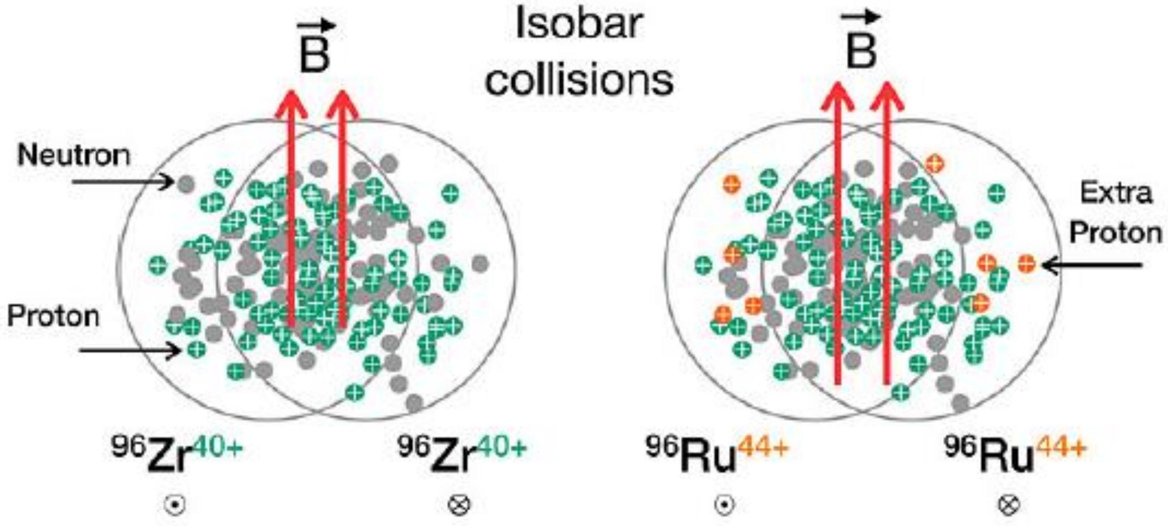
Validation: Interpretation

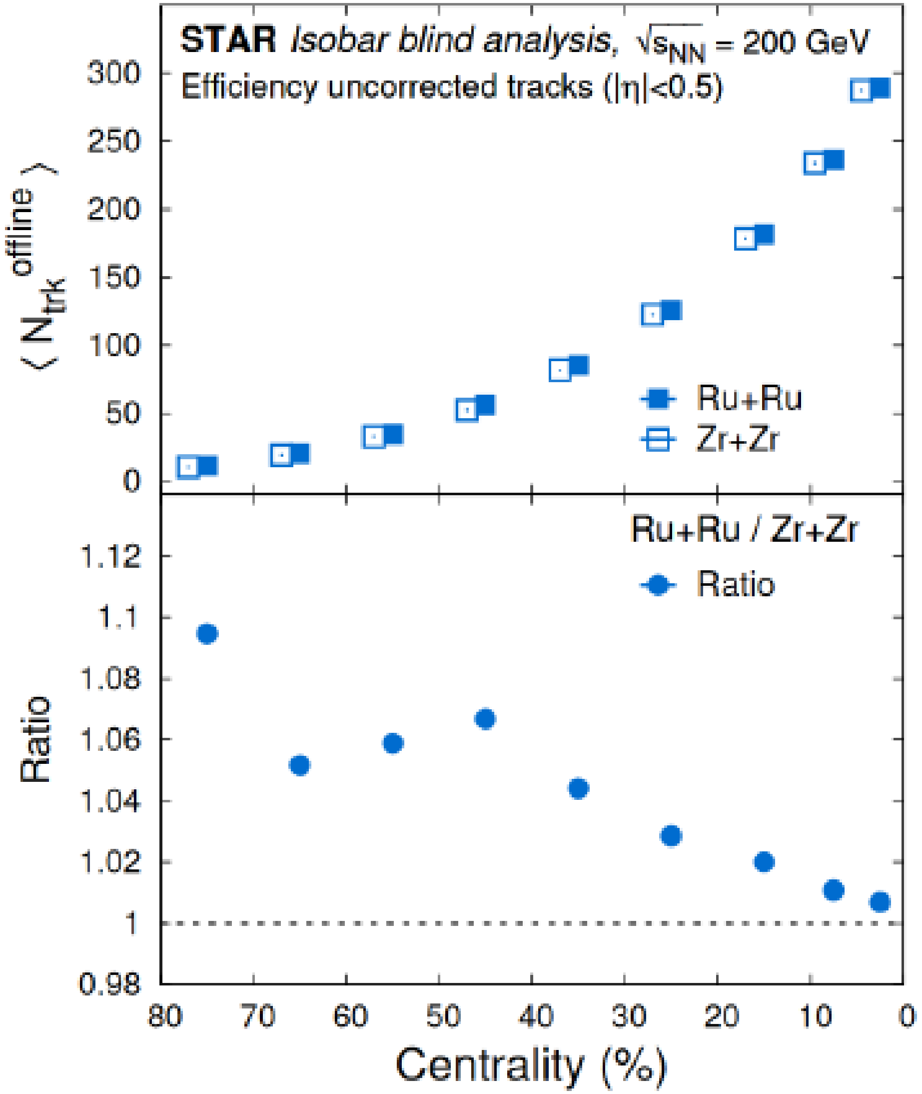
- Same tendencies for spectra as results from Duke group, but to many kaons and protons
- <pT> to small for heavier particles (kaons, protons)
- Both discrepancies ascribable to the UrQMD afterburner implemented in the Duke analysis (absent in FluiduM)



Arxiv: 1704.04216

Isoboar collision@RHIC





Isobar Zr+Zr and Ru+Ru collisions @200GeV

→ Original goal: find signatures of electromagnetic field (e.g Chiral magnetic effect)

→ High precision data (4B collisions for each system)

→ Signatures of EM-field investigated in ratios of observables (departures from unity)

Expectation: same multiplicity

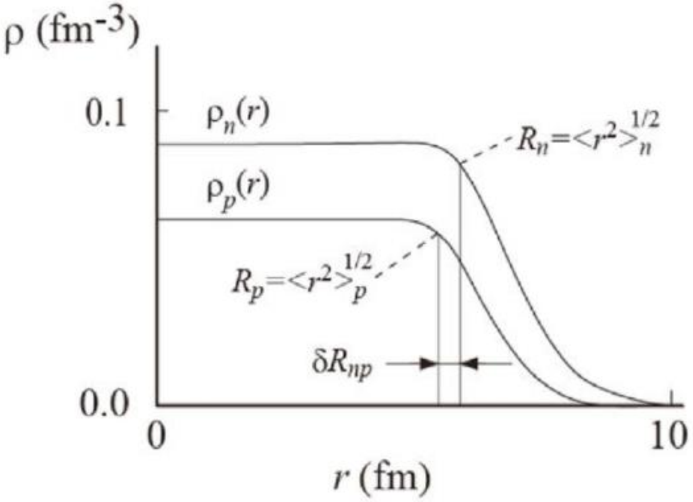
Origin of differences: nuclear structure

Main diff.: number of protons/neutrons
→ bigger neutron skin in Zr
→ different nuclear geometry
Woods-Saxon parametrization:

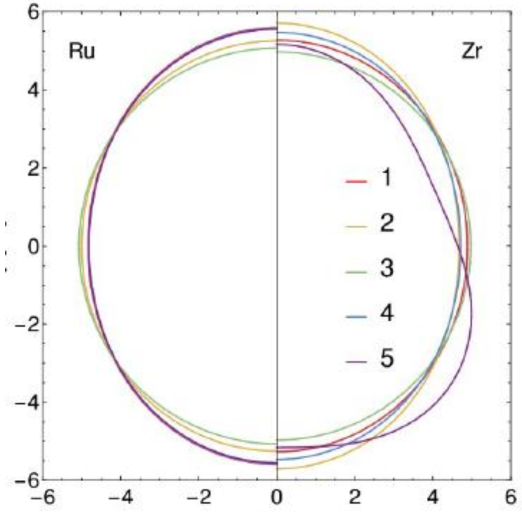
$$\rho(r,\theta,\phi) \propto \frac{1}{1+e^{[r-R_0(1+\underline{\beta_2 Y_2^0(\theta,\phi)+\beta_3 Y_3^0(\theta,\phi)})]/a_0}}$$

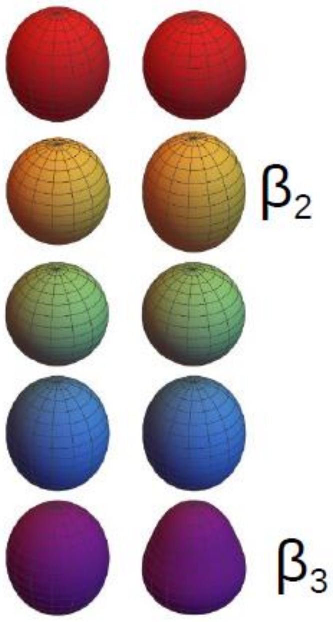
Half-width radius Nuclear deformations Diffusitvity

Diffusivity related to neutron skin thickness



(2112.13771)



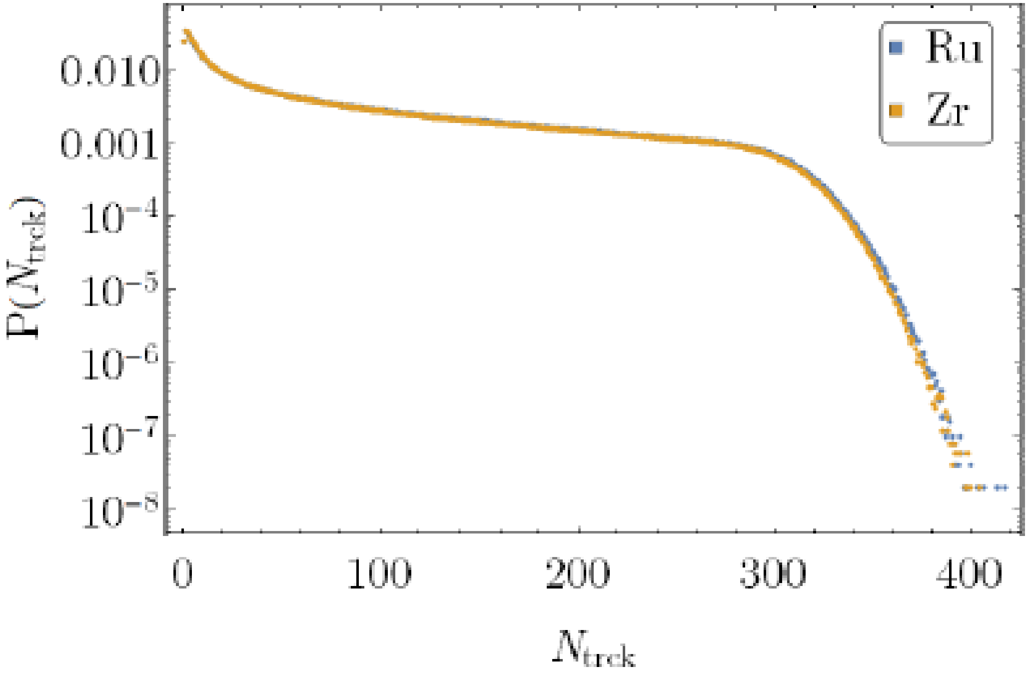


→ Multiplicity ratio dominated by neutron skin (2111.14812, 2111.15559, 2112.13771, 1808.06711, 2103.05595)

But only transport/initial state/limited hydro calculations
→ **FluiduM**

Application: Setup

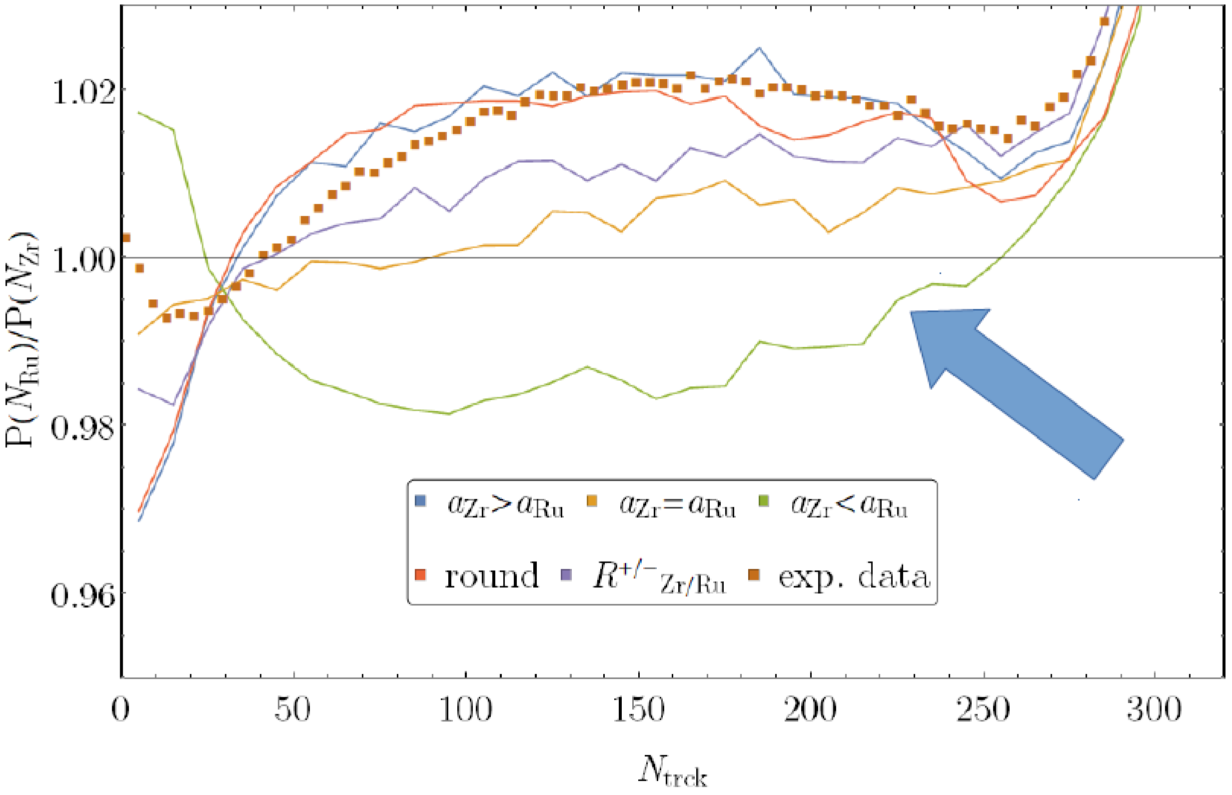
- Run TrenTo for initial state
- Define 0.5% centrality bins using 50M minimum bias events
- Run 400k events in select bins (→ effectively 80M events)
- Scan large range of nuclear (R, a, β_2, β_3), collision (k → multiplicity fluctuation, p → energy depostition, w → nucleon size, d → nucleon repulsive core, m → number of partons, v → parton size) and QGP (η/s, ζ/s, T_{fo}, τ_0) parameters

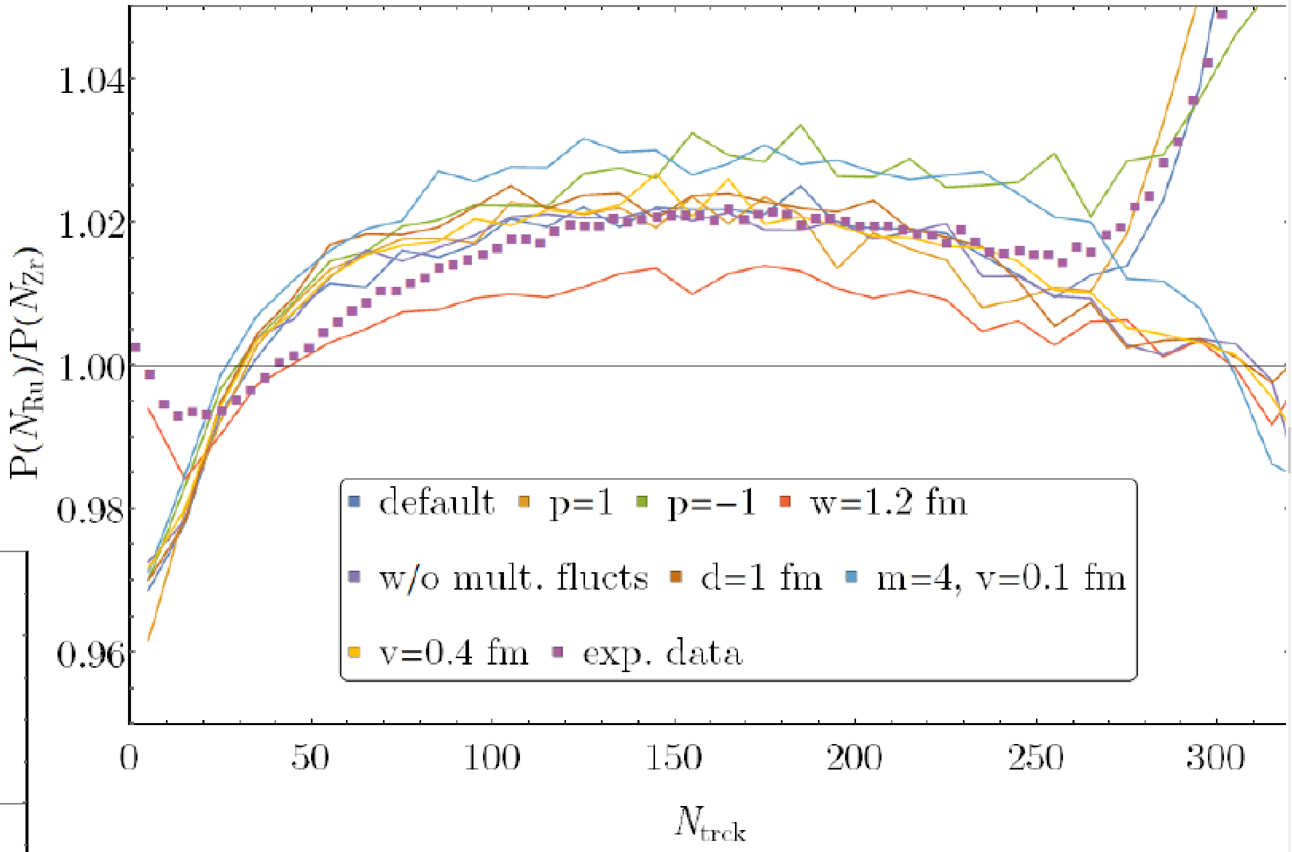


Histogram multiplicity through linear rescaling of TrenTo entropy

Initial state results

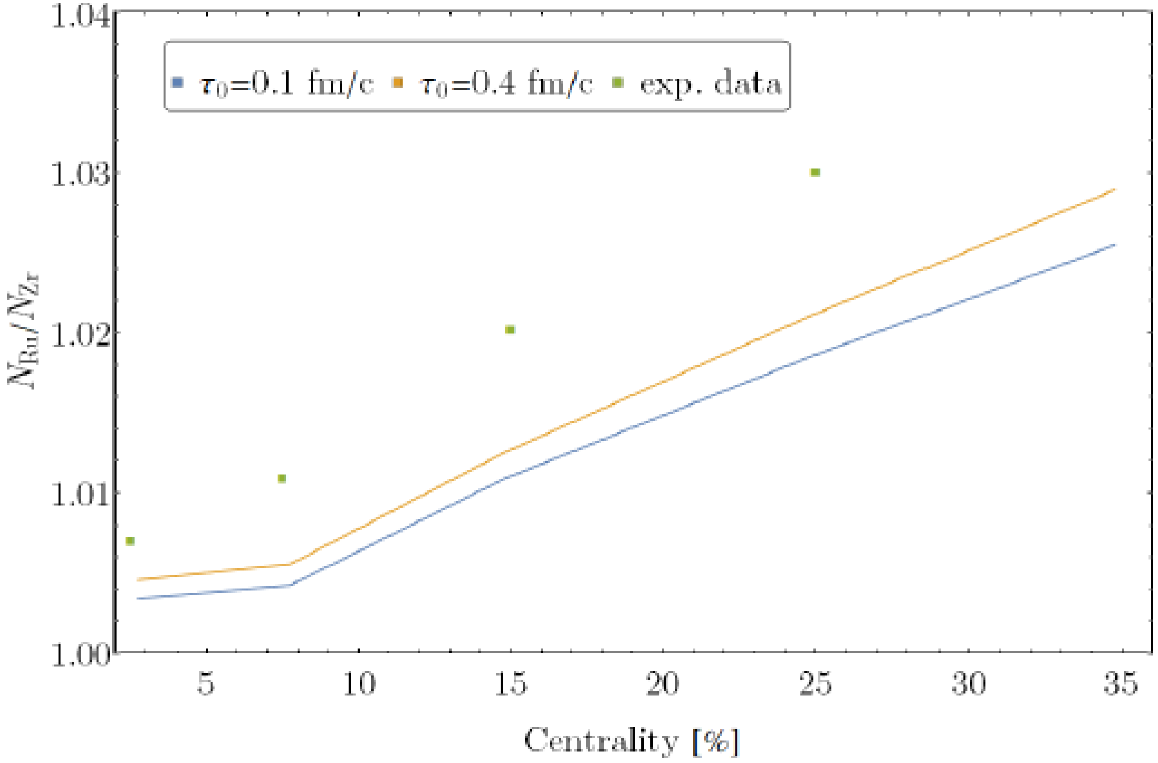
Histogram multiplicity ratio dominated by diffusivity

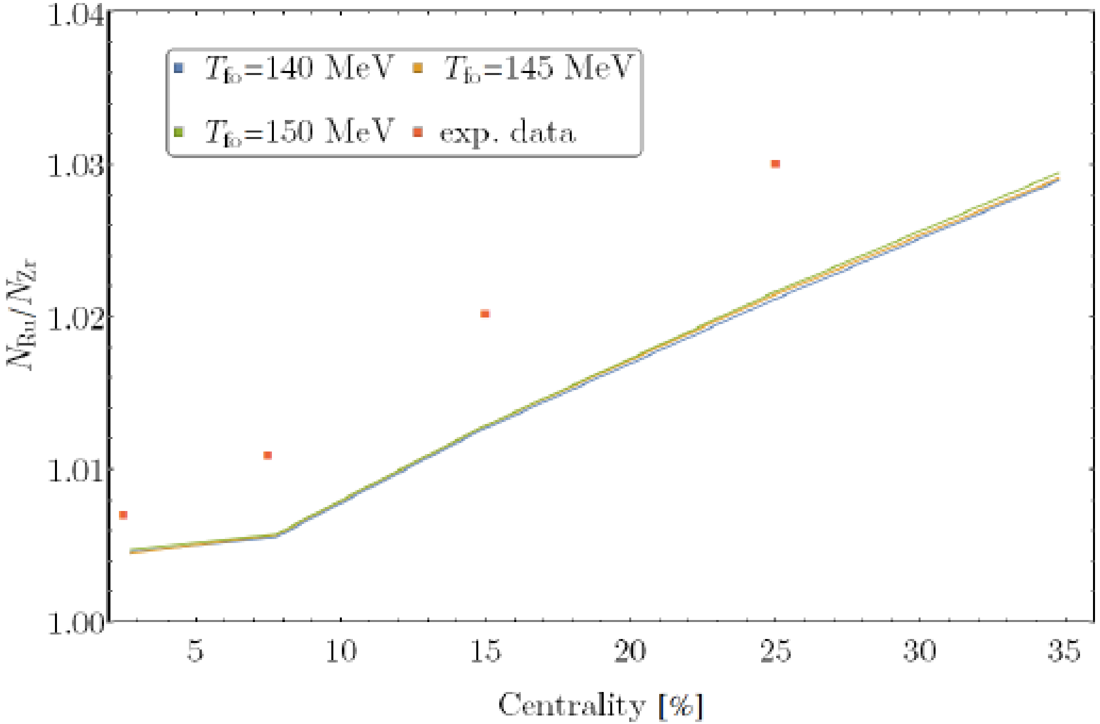




Default: p=0, w=0.5 fm, k=1

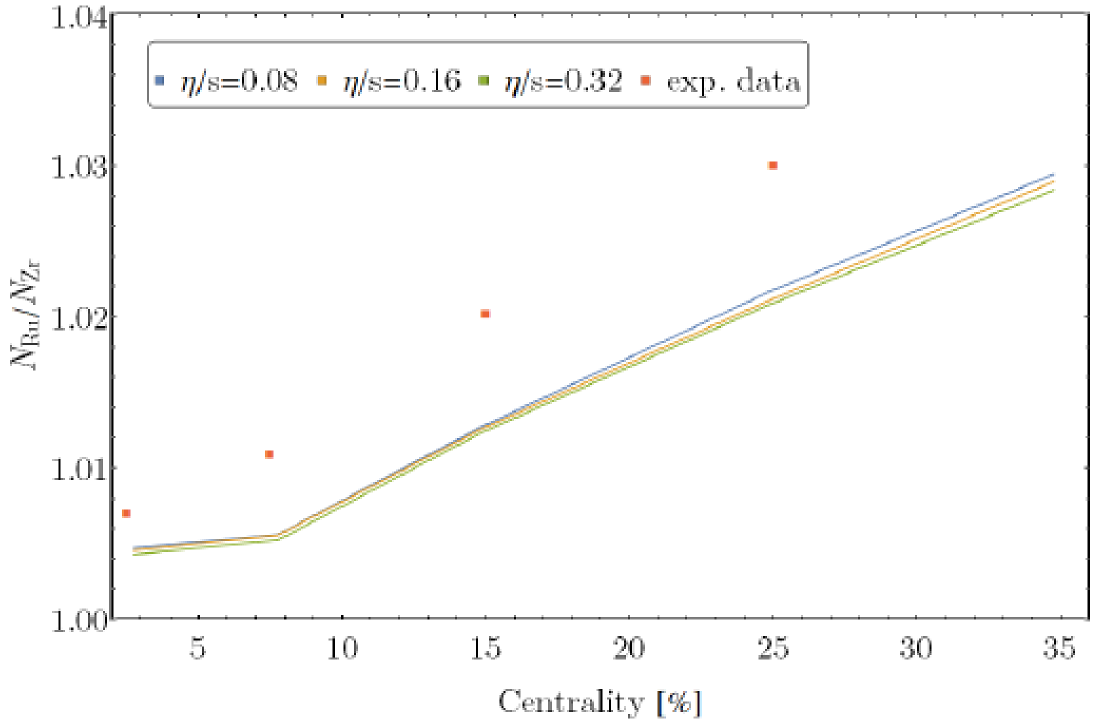
QGP parameters

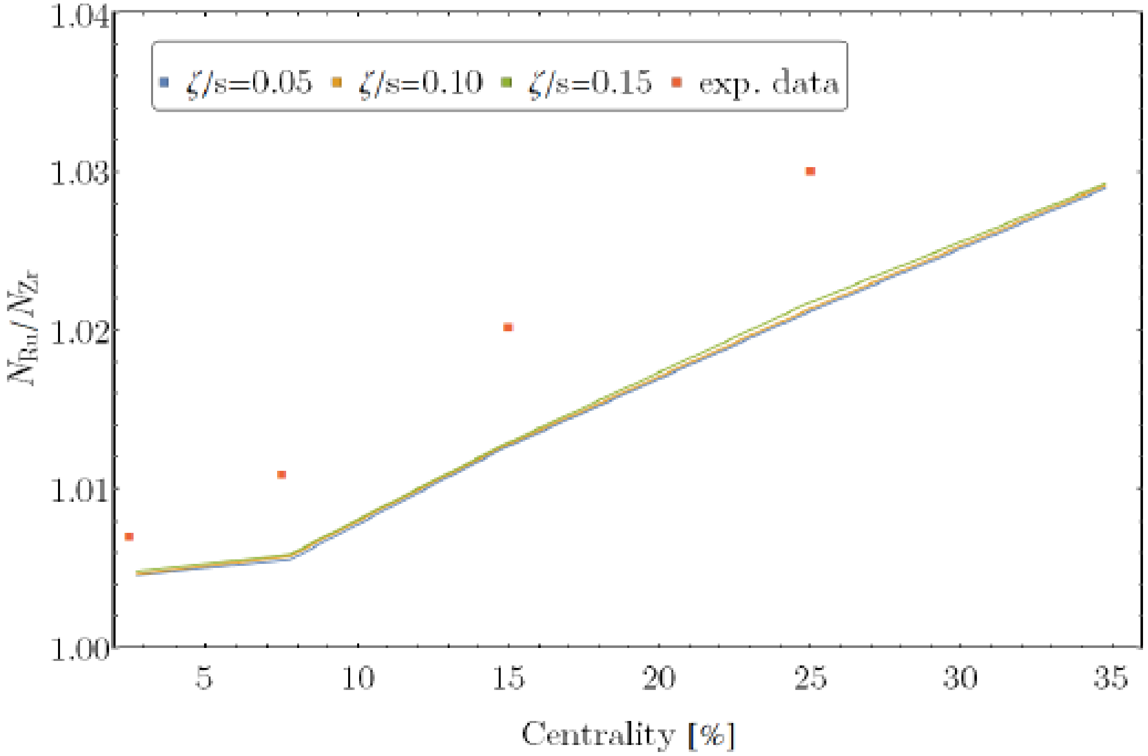




Multiplicity ratio not dependent on initialization time and freeze-out temperature

QGP parameters

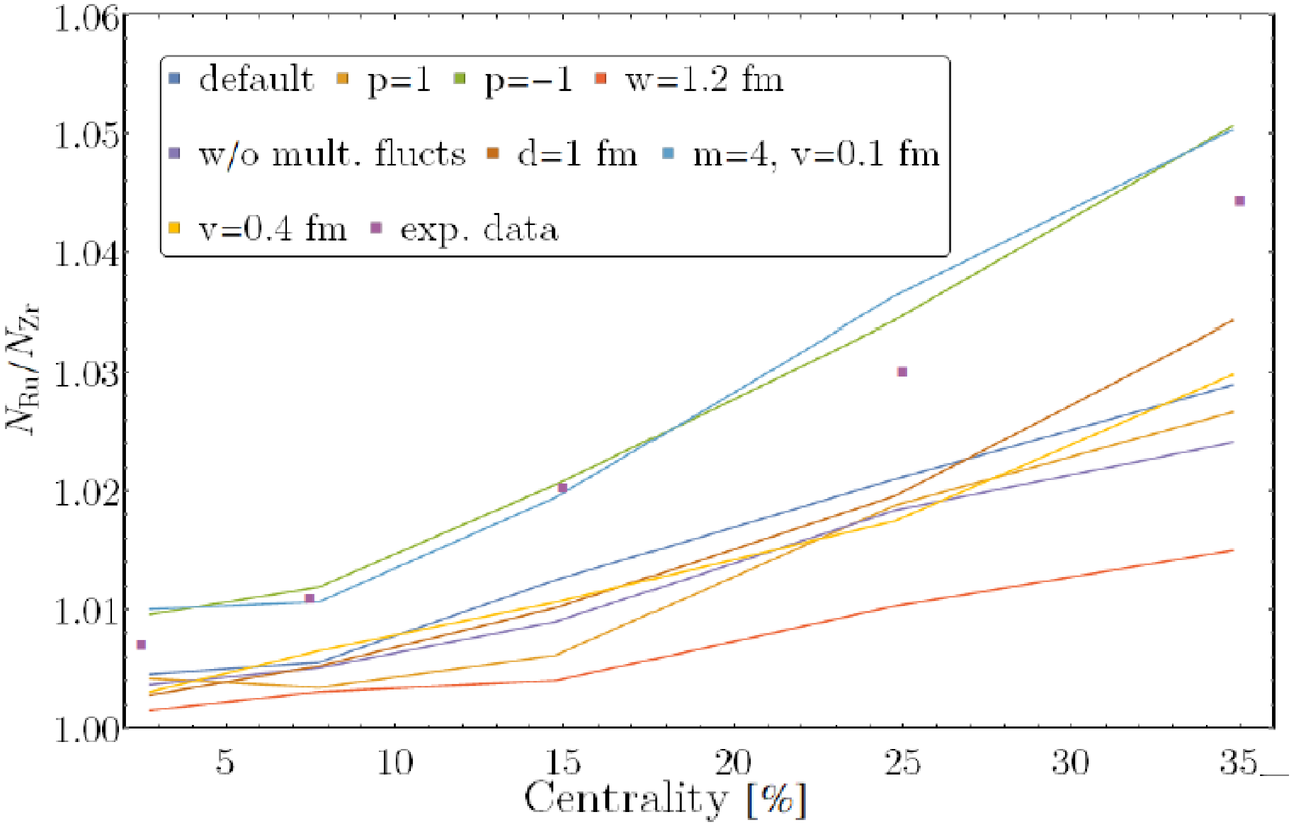


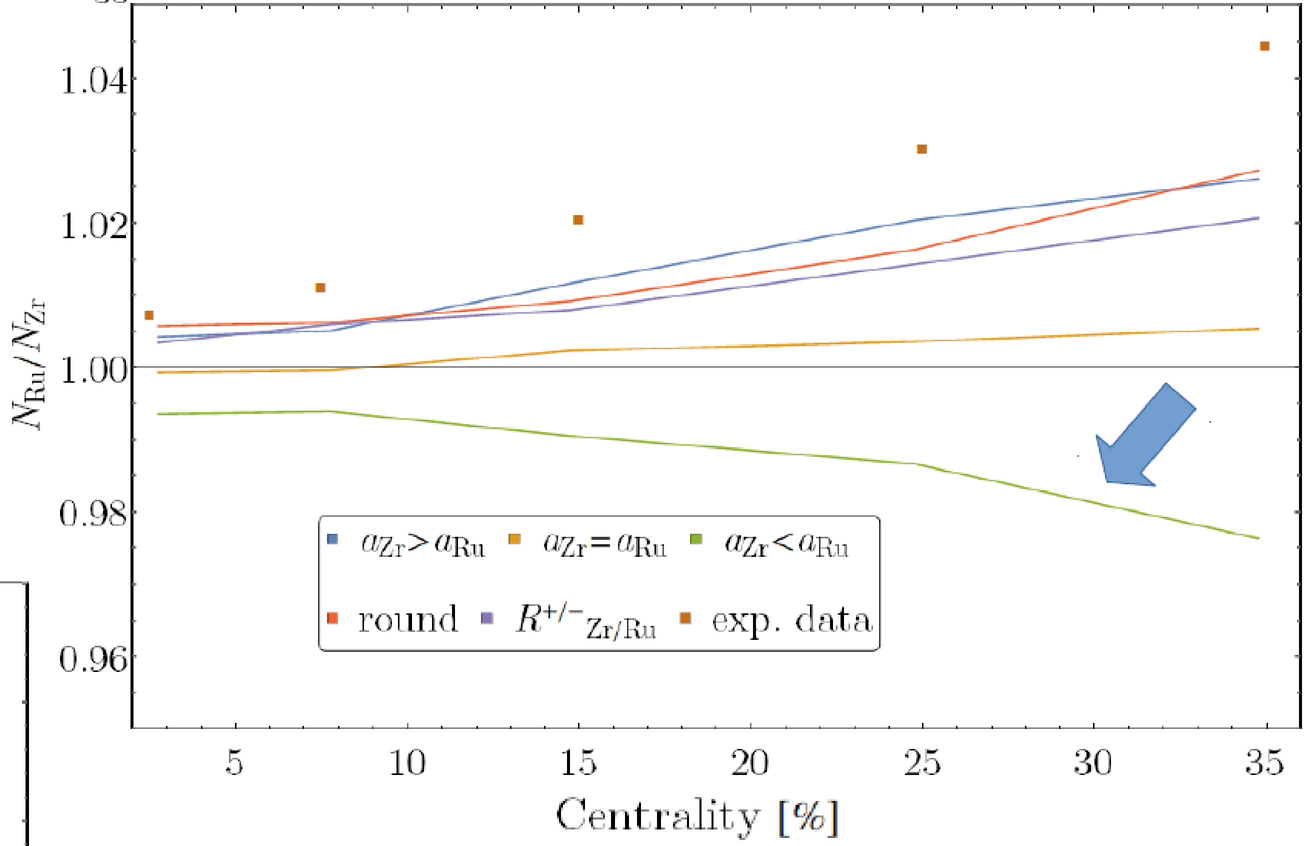


Multiplicity ratio not sensitve to medium viscosities

Final state results

Multiplicity ratio dependent on
``degree of sharpness´´ of GQP





Multiplicity ratio dominated by diffusivity

Default: p=0, w=0.5 fm, k=1

Outlook and summary

- We have presented a new hydro framework FluiduM based on mode-by-mode hydro
- Our results are fully consistent with other state of the art hydro codes
- The advantage? We obtain hydro results for 10 centrality classes in a couple of minutes

-> We are able to do a scan over many parameters to analyse the recent high precision isobar RHIC data

-> Initial AND final state dominated by nuclear structure

=> New gateway for nuclear structure studies?

Outlook: Improve framework (``loop corrections´´) and include more observables in analysis (flow coefficients)