New flow observables from BSQ charge fluctuations

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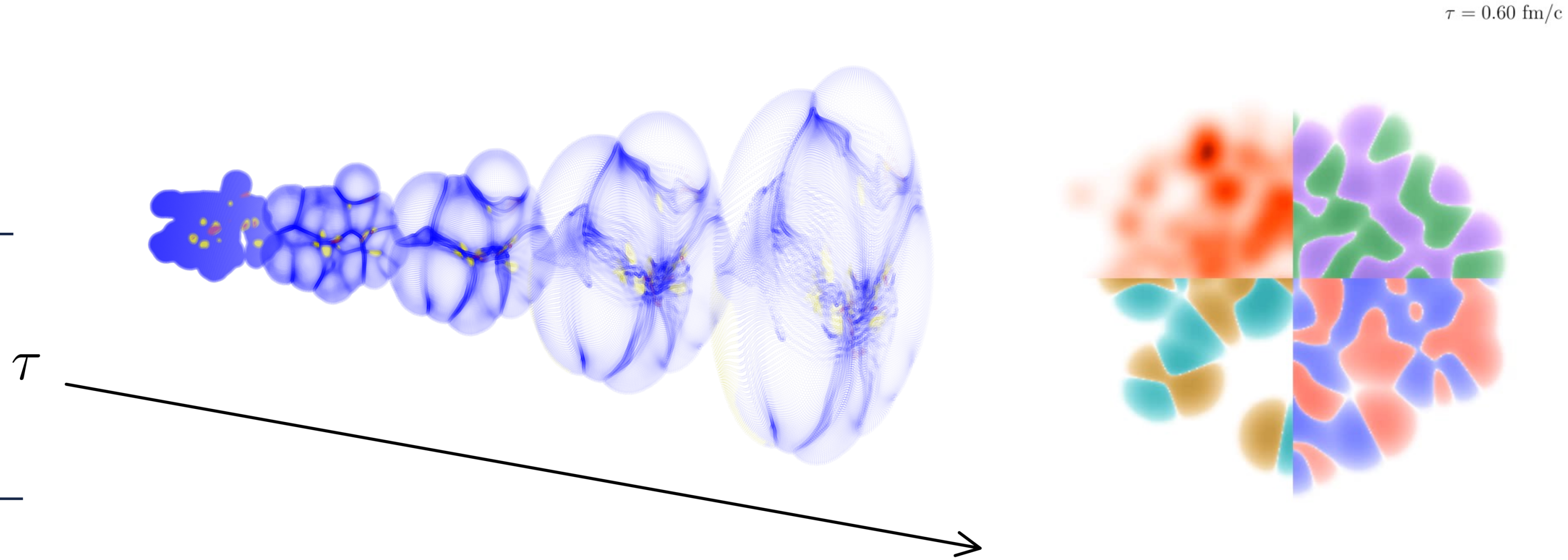
University of Illinois at Urbana-Champaign

In collaboration with *C. Plumberg, D. Almaalol, T. Dore, D. Mroczek, W. M. Serenone, L. Spychalla, P. Carzon, M. Sievert, F. Gardim,* and *J. Noronha-Hostler* – arXiv:2405.09648



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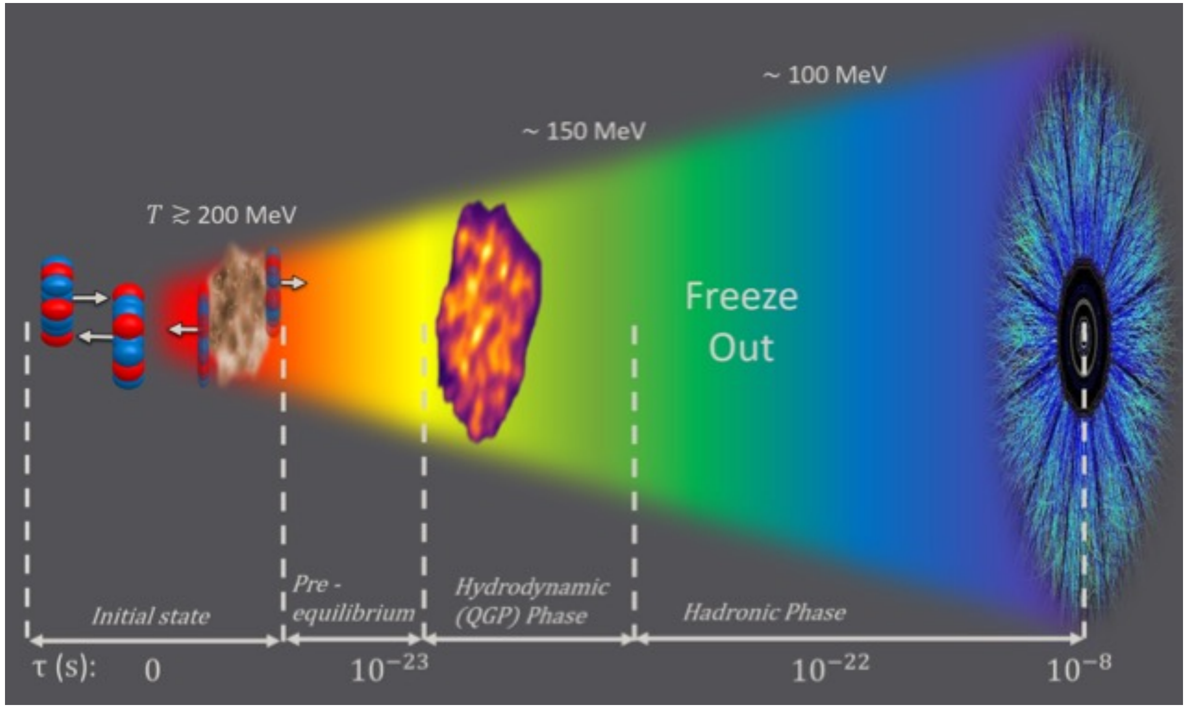
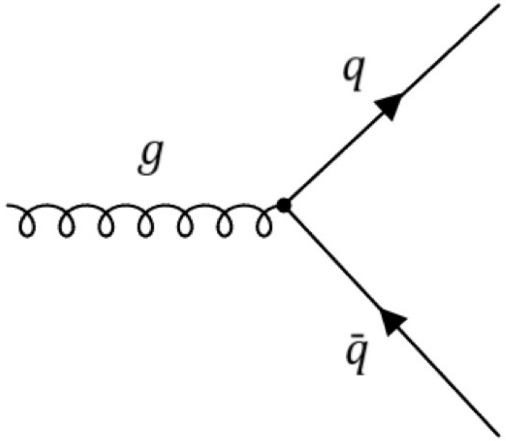
BSQ charge fluctuations in a heavy-ion collision



- Heavy-ion collision is broken in several stages
- Conservation laws dictate the **global conservation** of BSQ charges
- **Local fluctuations** may arise in the initial stage due to gluon splitting at high– or baryon stopping at lower energies

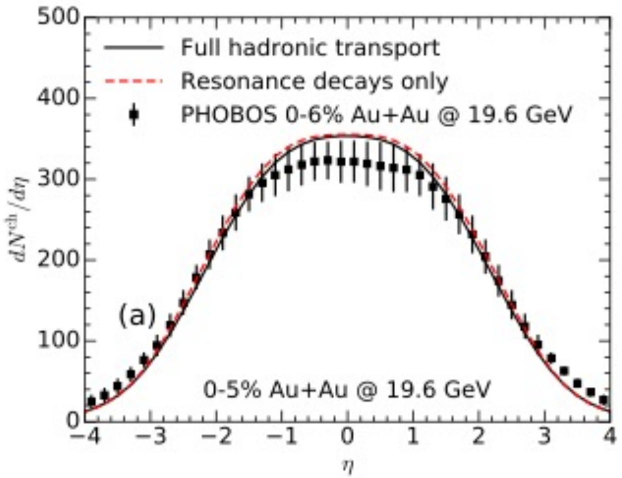
P. Carzon, PRC 105 (2022) 034908, 1911.12454

O. García Montero, PRC 109 (2024) 044916, 2308.11713

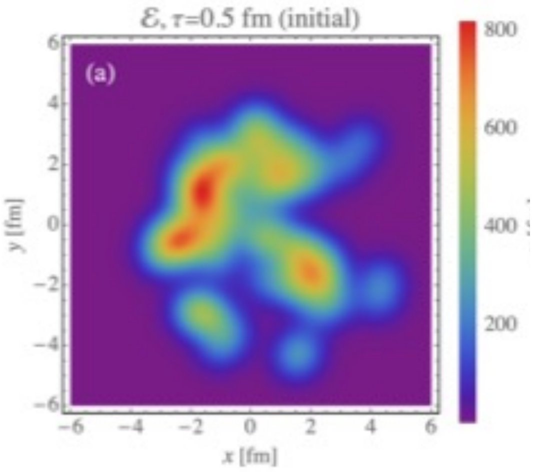


- BSQ fluctuations of chemical potentials are then evolved with hydrodynamics
- After fluid reaches energy density threshold, freezes-out and particlizes

BSQ charge fluctuations in a heavy-ion collision

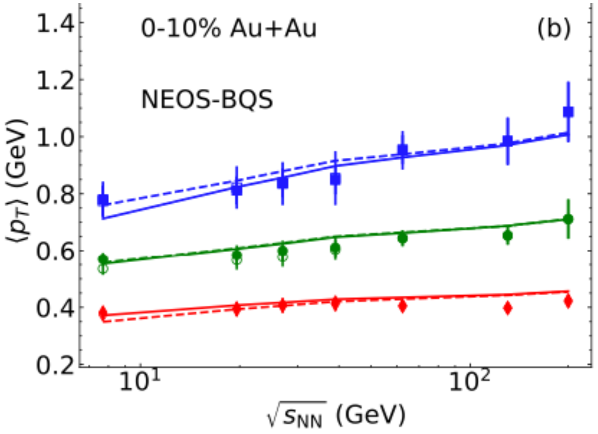


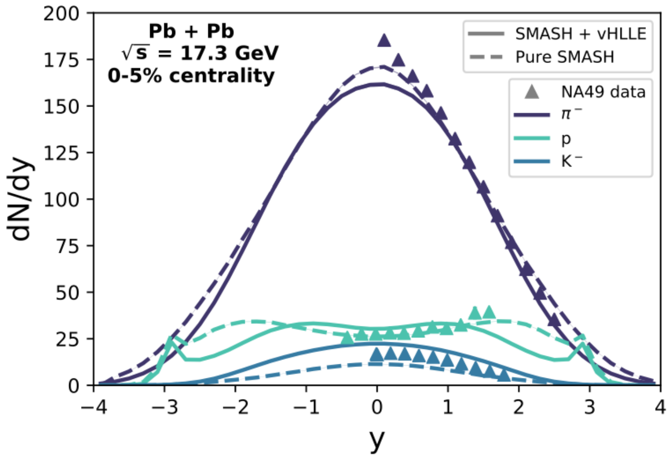
G. Denicol et al., PRC 98 (2018) 034916, 1804.10557



L. Du and U. Heinz, CPC 251 (2020) 107090, 1906.11181

L. Du, (2023) 2401.00596





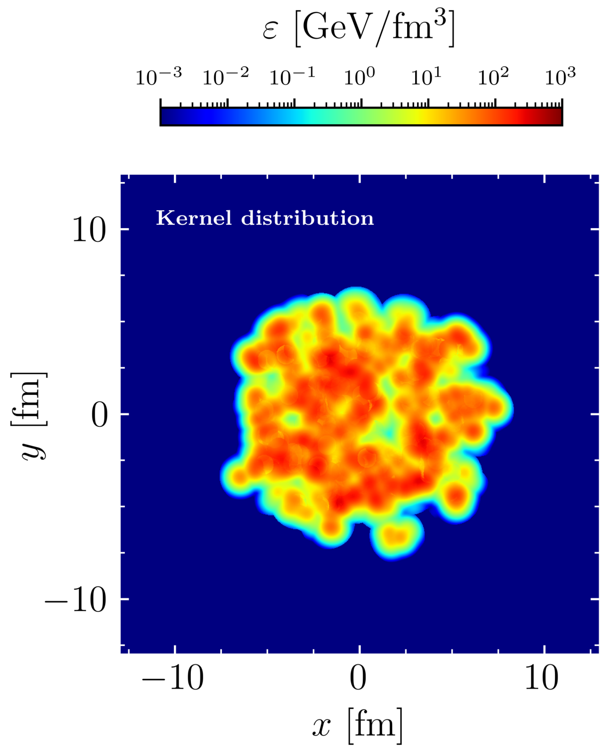
A. Schäfer et al., EPJA 58 (2022) 230, 2112.08724

Previous works including one or more conserved charges have pointed at their importance

Complete evolution of conserved charges needs:

1. A full 4D EoS
2. Solution of BSQ equations with diffusion matrix
3. Initialization of new transport coefficients

BSQ charge fluctuations in the initial state

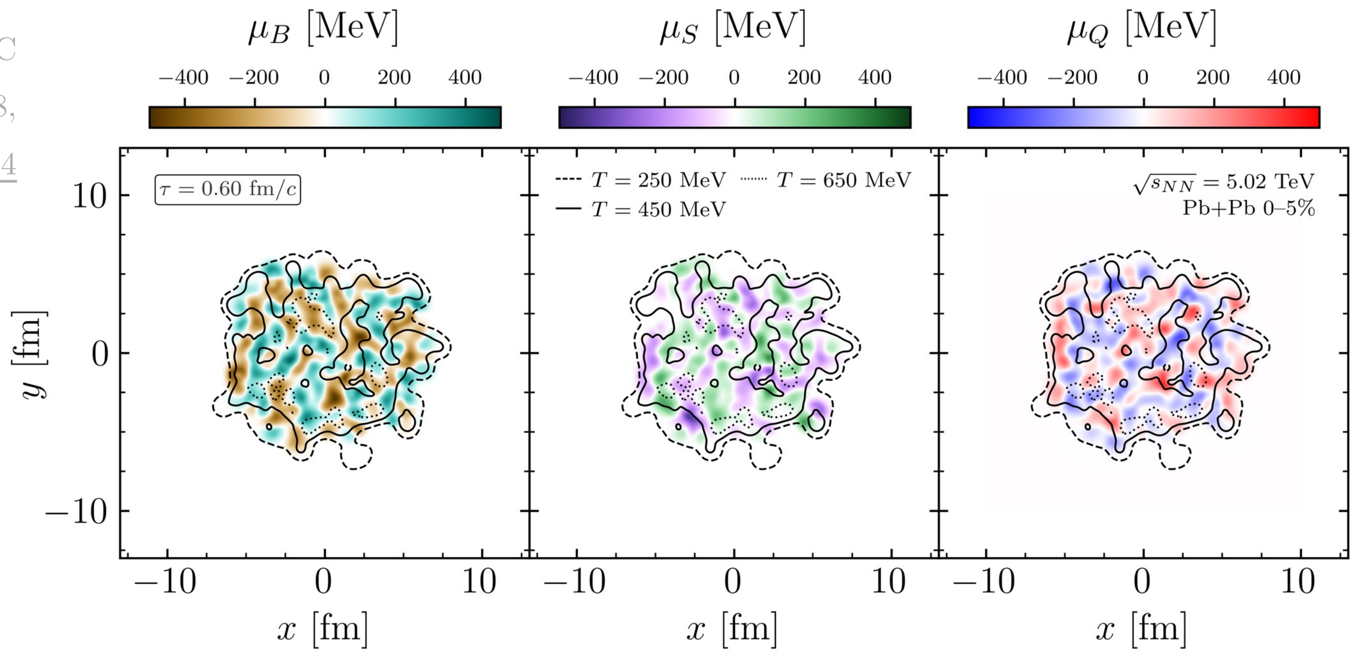


C. Plumberg, JSSM et al. (2024) 2405.09648

P. Carzon et al, PRC 105 (2022) 034908, 1911.12454

ICCING sampling

4D BSQ LQCD EoS inversion



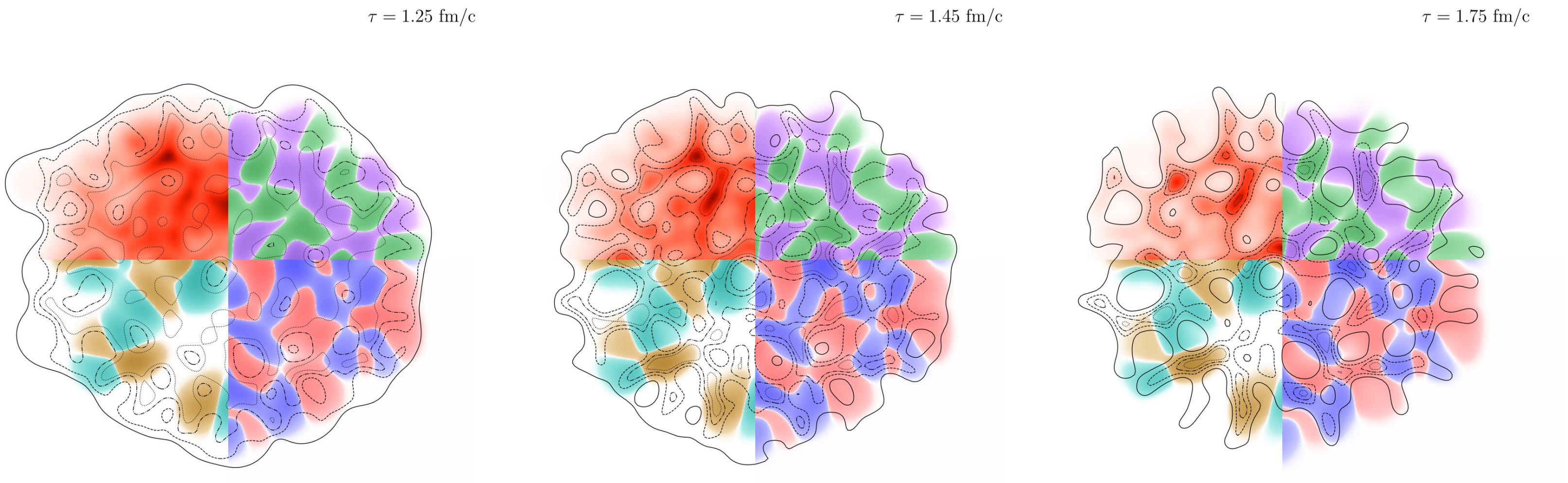
ICCING provides BSQ fluctuations at the initial stage by splitting gluons within CGC framework

- ICCING (Initial Conserved Charges in Nuclear Geometry) samples an energy density profile to **initialize BSQ densities**
- To be useful, densities need to be **converted** to BSQ chemical potentials and temperature using a 4D EoS

Propagating BSQ fluctuations w hydrodynamics

- We use a **lattice based 4D EoS**
- Inversion of table EoS requires **high computational cost** and loss of some solutions
- We use CCAKE – an SPH hydrodynamical approach to solve the equations of motion
- SPH has the natural benefit of knowing all densities for all SPH particles

Smoothed Particle Hydrodynamics (SPH) is used to evolve initial BSQ densities in time



CCAKE := **C**onserved **C**h**A**rges with hydrodynami**K** **E**volution

We use Israel-Stewart equations of motion with shear viscosity and, in principle, non-zero bulk viscosity

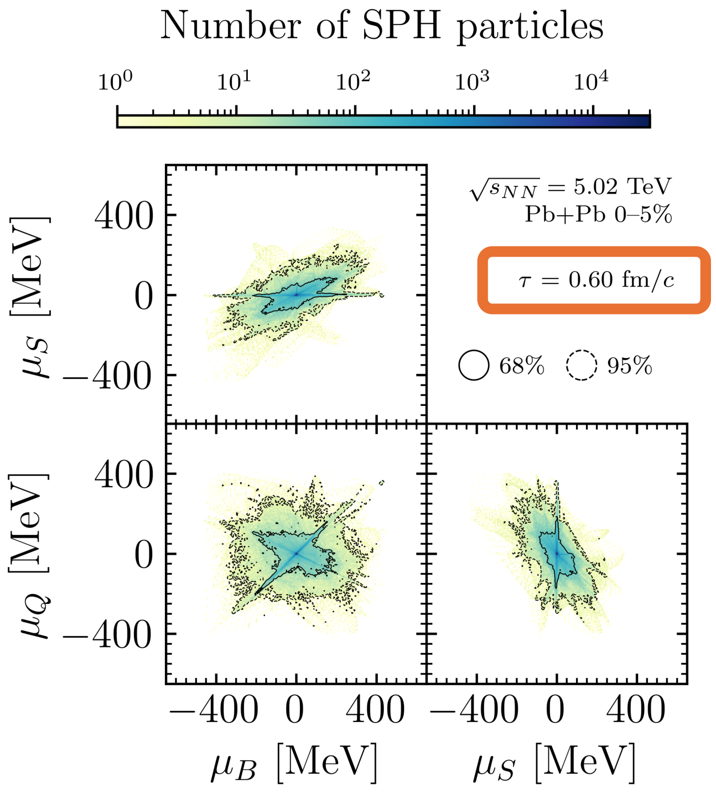
$$D_\mu T^{\mu\nu} = 0,$$

$$D_\mu N^\mu_X = 0, \qquad X \in \{B, S, Q\}$$

$$N^\mu_X = \rho_X u^\mu + n^\mu_X = 0,$$

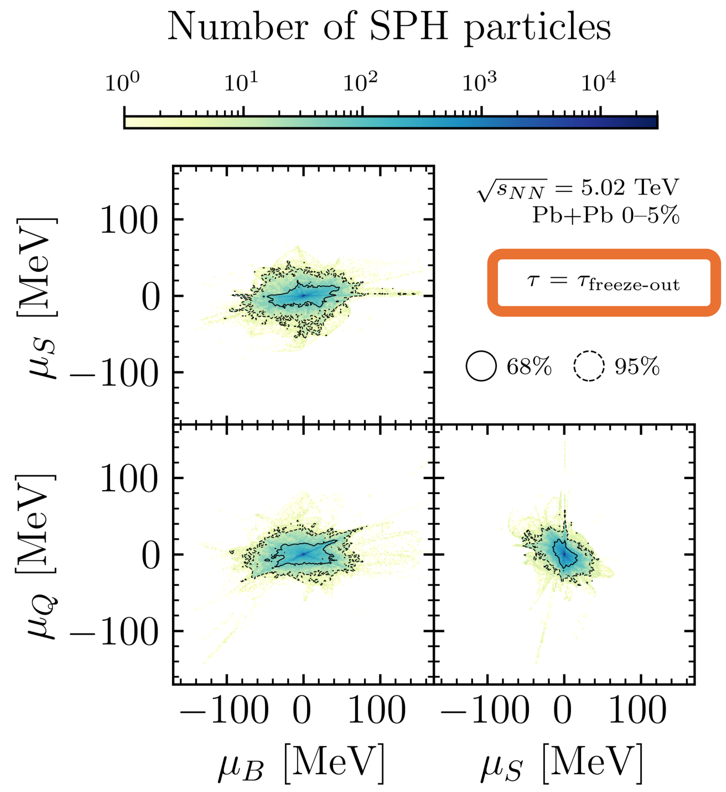
Fluctuations of BSQ charges at freeze-out

C. Plumberg, JSSM et al. (2024) 2405.09648



Chemical potentials at initial time

CCAKE hydro evolution



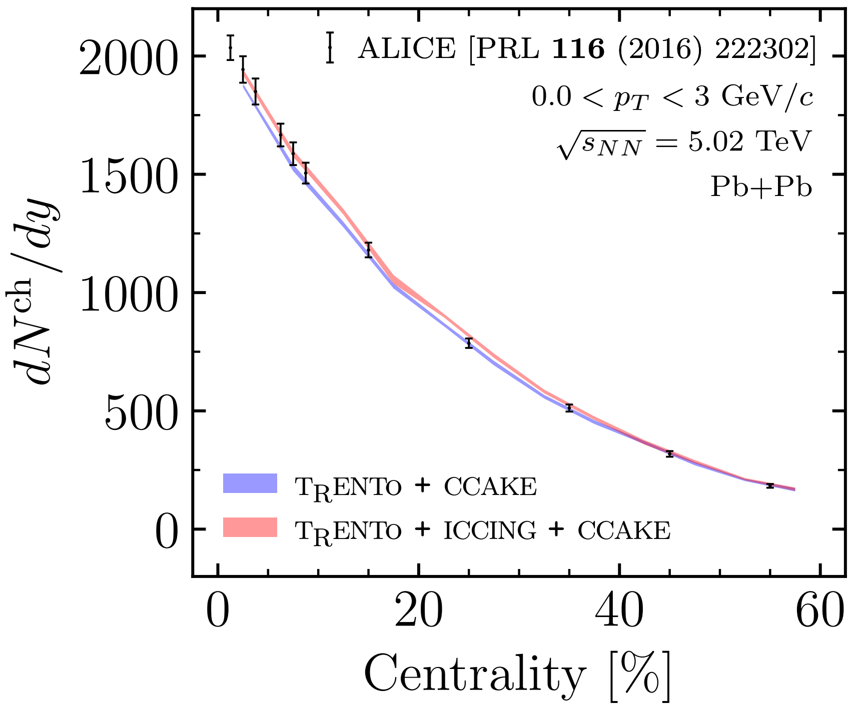
Chemical potentials freeze-out

- Initial chemical potentials are as **large as 400 MeV**
- Average chemical potentials are still **consistent with zero** (LHC) at all times
- Most SPH particles (68%) have $\mu_B \lesssim 50$ MeV at freeze-out

Initial charge chemical potential fluctuations survive until freeze-out!

Standard observables: charged particle spectra

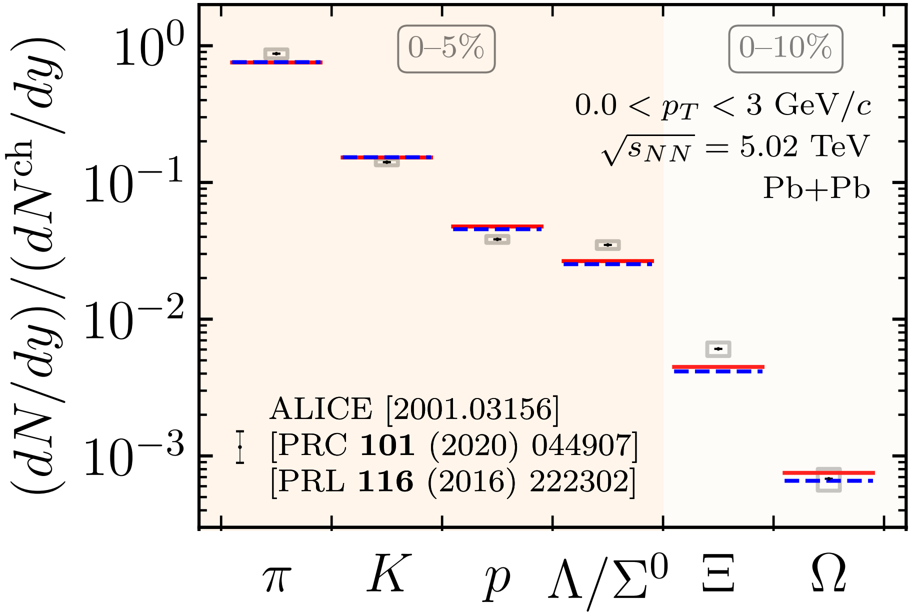
C. Plumberg, JSSM et al. (2024) 2405.09648



Q. What is the influence of charges on the charged particle spectra?

- Previous framework (w.o. charge evolution) already described data
- Multiplicity is **reproduced well** with and without initial state fluctuations
- Identified particle yields are also consistent

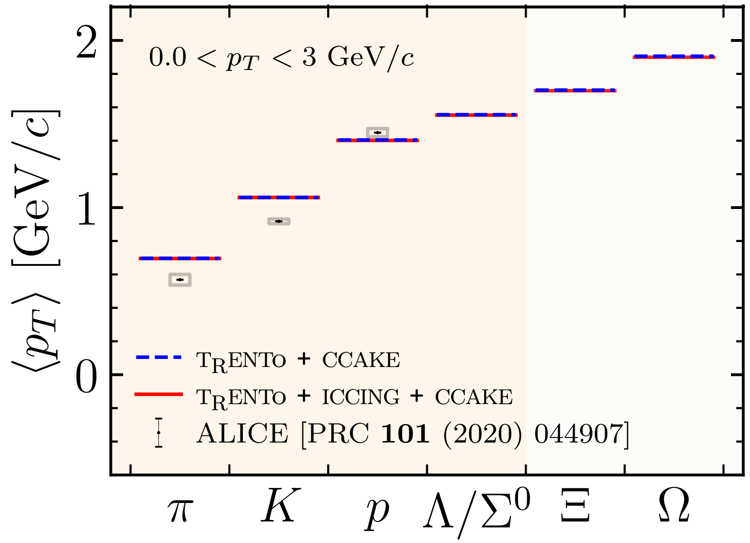
C. Plumberg, JSSM et al. (2024) 2405.09648

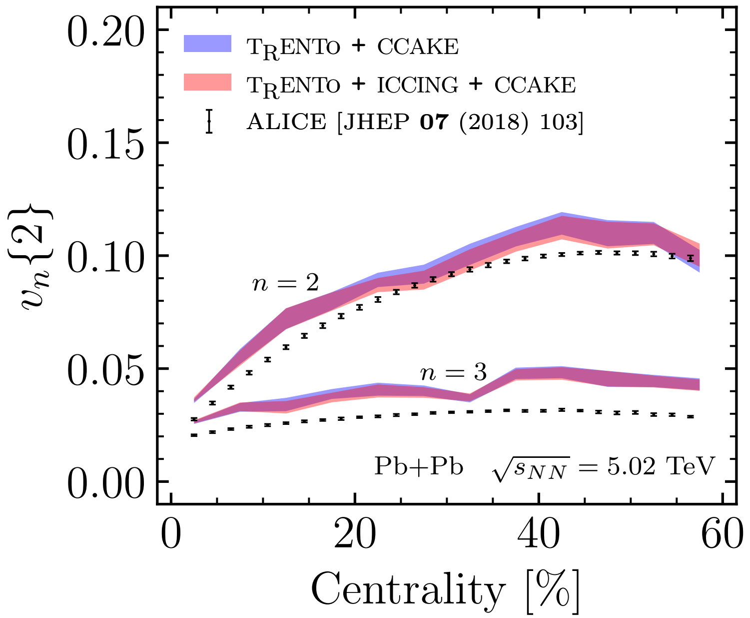


All charged particles' and identified particles' multiplicities are consistent with previous results

Standard observables: <pT> and flow

C. Plumberg, JSSM et al. (2024) 2405.09648





Q. What is the influence of charges on <pT>?

- Proton <pT> fits very well but mesons overshoot
- If we add bulk viscosity, this will improve!
- Tuning other simulation parameters will bring this to a better agreement
- Using the PDG2021+ hadron list also has an influence on the yields

JSSM et al. (2023) 2309.01737

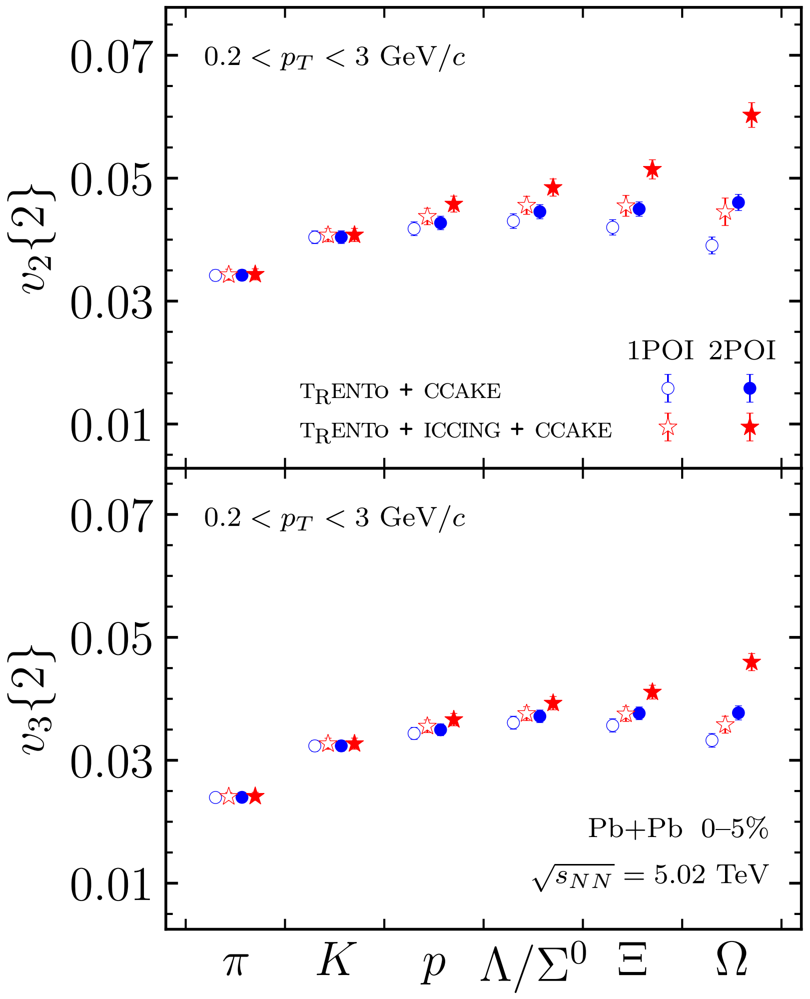
Q. What is the influence of charges on flow?

- Flow coefficients are approximated quite well
- Improved statistics and a slightly larger shear viscosity can bring results to a better agreement with experimental measurements
- Including charge fluctuations makes essentially no difference here (makes sense!)

Since energy density distribution is unchanged after ICCING, total flow is unchanged

Signals from BSQ fluctuations in flow

C. Plumberg, JSSM et al. (2024) 2405.09648



Q. What other influence do BSQ fluctuations have on flow?

- 1POI and 2POI method is used for identified particle flow coefficients

$$v_n^{1\mathrm{POI}}\{2\} = \frac{\langle v_n v_n' \cos n(\Psi_n - \Psi_n')\rangle}{v_n\{2\}}$$

A. Holtermann et al. (2023, 2024) 2307.16796, 2402.03512

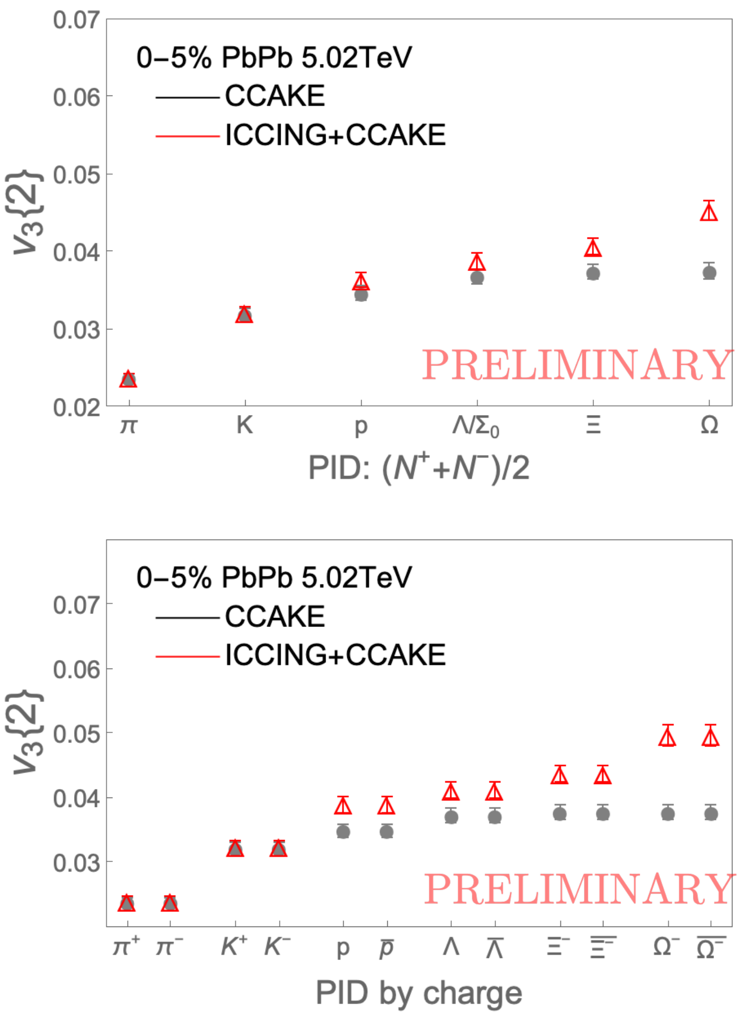
- If the event plane angles are not aligned, 1POI gets suppressed

$$v_n^{2\mathrm{POI}}\{2\} = \sqrt{\langle (v_n'')^2 \rangle}$$

- 2POI is not suppressed, even if event plane angles are fully misaligned

- BSQ charge fluctuations lead to an enhancement of 2POI flow for (multi-)strange baryons
- LHC updates will bring the statistics necessary to contrast with experiment

Signals from BSQ fluctuations in flow

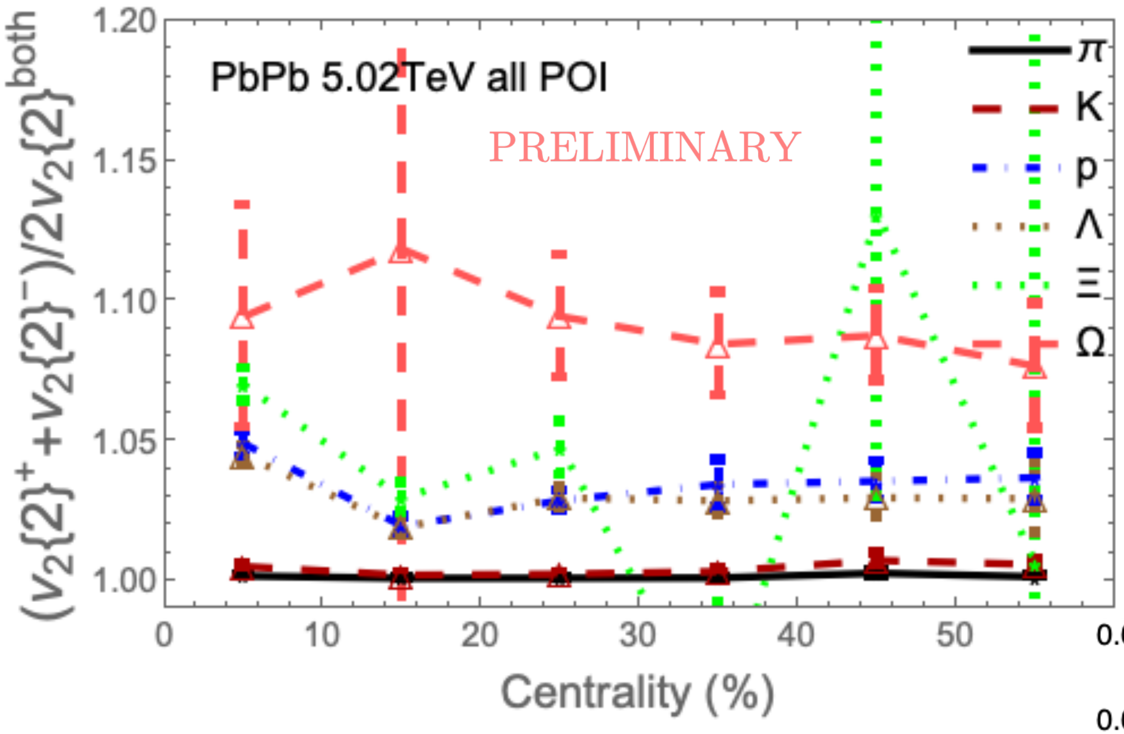


Q. What if we compute flow coefficients for particles and anti-particles separately?

- When computing flow of particles and anti-particles together, any potential difference gets smeared out – even if it's statistically significant!
- This effect seems to be amplified by mass and charge content (e.g., Omega baryons all BSQ charges)

Measuring the individual flow coefficients for particles and anti-particles can be a signal of BSQ fluctuations

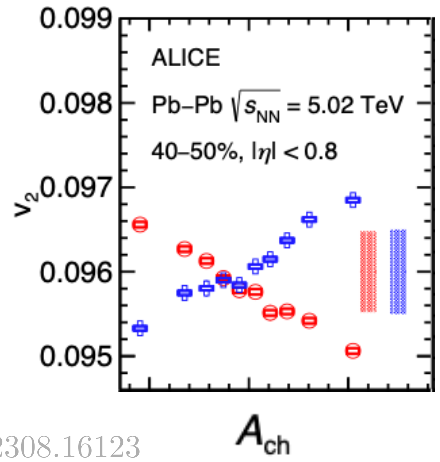
New observables



$$C_n(\text{hadron}) = \frac{v_n^h\{2\} + v_n^{\bar{h}}\{2\}}{2v_n^{h+\bar{h}}\{2\}}$$

- Generalizable to n-th order
- Ready to be measured
- Will require more statistics from theory (currently very large error bars)

Other potential observables:



$$D_n(\text{hadron}) = \frac{v_n^h\{2\} - v_n^{\bar{h}}\{2\}}{2v_n^{h+\bar{h}}\{2\}}$$

$$A_{\text{ch}}(\text{hadron}) \propto \frac{D_n(\text{hadron})}{C_n(\text{hadron})}$$

Preliminary results show a measurable effect in protons ($\sim 5\%$)

S. Acharya et al (ALICE), JHEP 2023 (2023) 67, 2308.16123

Conclusions

- Baryon, strangeness, and electric charge fluctuations produced from **gluon splitting on the initial state** are relevant – **even at the LHC**
- Chemical potentials can reach large values and then get damped to **non-negligible values** until freeze-out
- Good description of **multiplicities** (all charged and *averaged* identified) and **mean transverse momentum**
- 1POI and **2POI** flow observables sensitive to charge fluctuations on the initial state from gluon splitting
- ***Individual* identified particle flow coefficients** also sensitive to BSQ fluctuations

Flow observables can be sensitive to BSQ charge fluctuations in the initial state from gluon splitting!

Outlook

- Study new flow observables with improved statistics

$$C_n(\text{hadron}) = \frac{v_n^h\{2\} + v_n^{\bar{h}}\{2\}}{2v_n^{h+\bar{h}}\{2\}} \qquad D_n(\text{hadron}) = \frac{v_n^h\{2\} - v_n^{\bar{h}}\{2\}}{2v_n^{h+\bar{h}}\{2\}} \qquad A_{\text{ch}}(\text{hadron}) \propto \frac{D_n(\text{hadron})}{C_n(\text{hadron})}$$

& more! (In progress)

- Second-order transport coefficients and full BSQ diffusion matrix in CCAKE
- Out-of-equilibrium contributions to ICCING (See work from KØMPØST group)
- Use an improved 4D LQCD EoS (See work from C. Ratti's group)

Thank you!

Back-up

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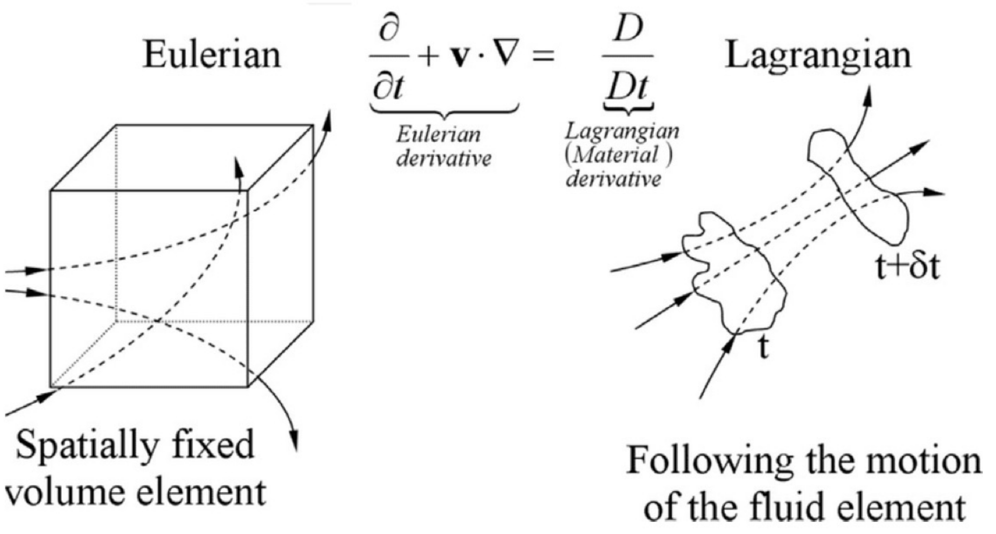
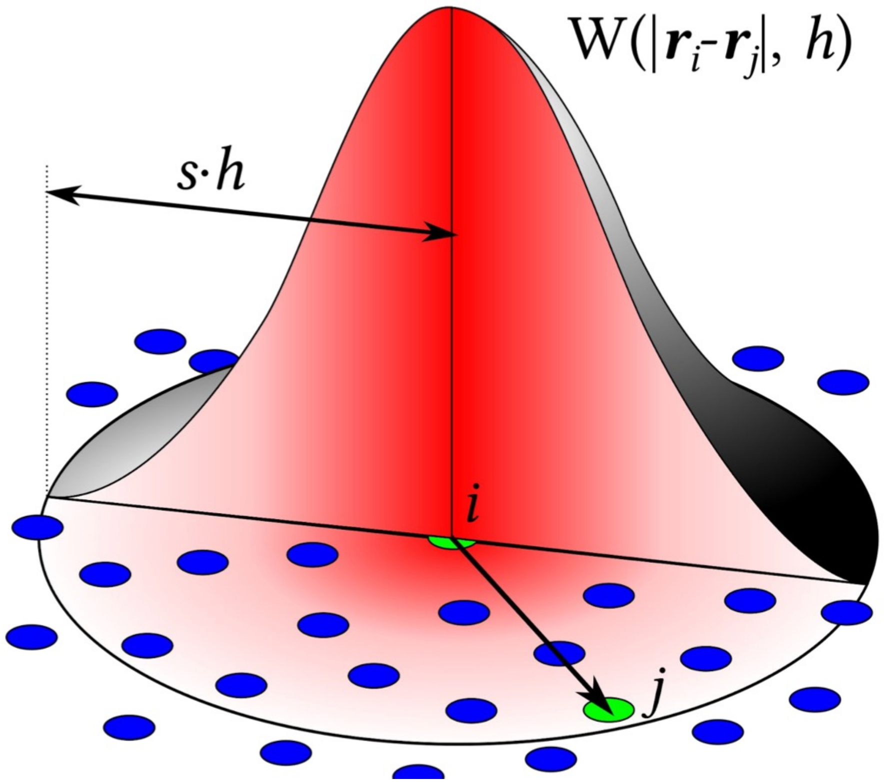


Grid-based hydrodynamics

Smoothed particle hydrodynamics

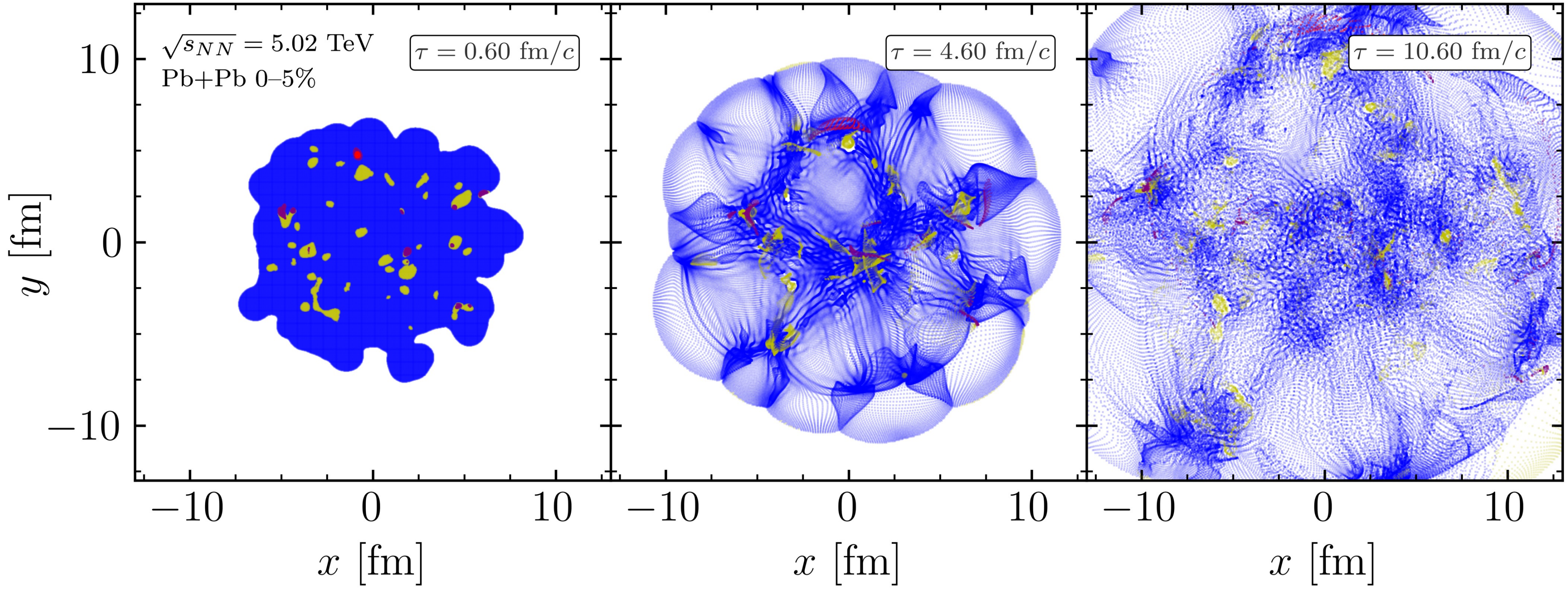
Conservation laws built-in by construction

Kernel function W imposes coarse-graining onto set of fictitious 'SPH particles'

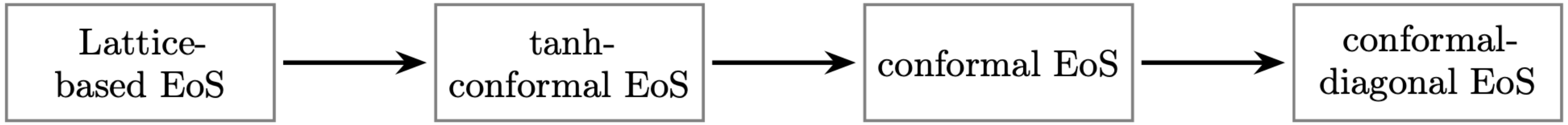


Slide credit: C. Plumberg, CPOD 2024

Back-up



Blue := LQCD EoS Yellow := tanh-conformal EoS Purple := Conformal EoS Red := Conformal Diag EoS



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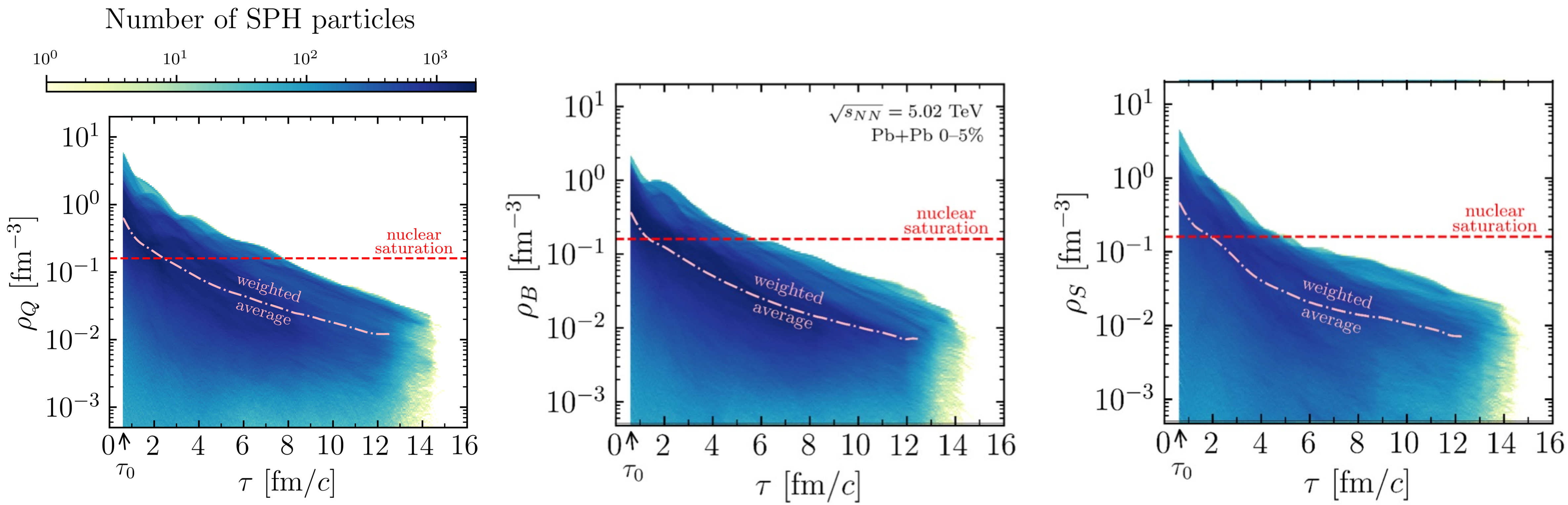
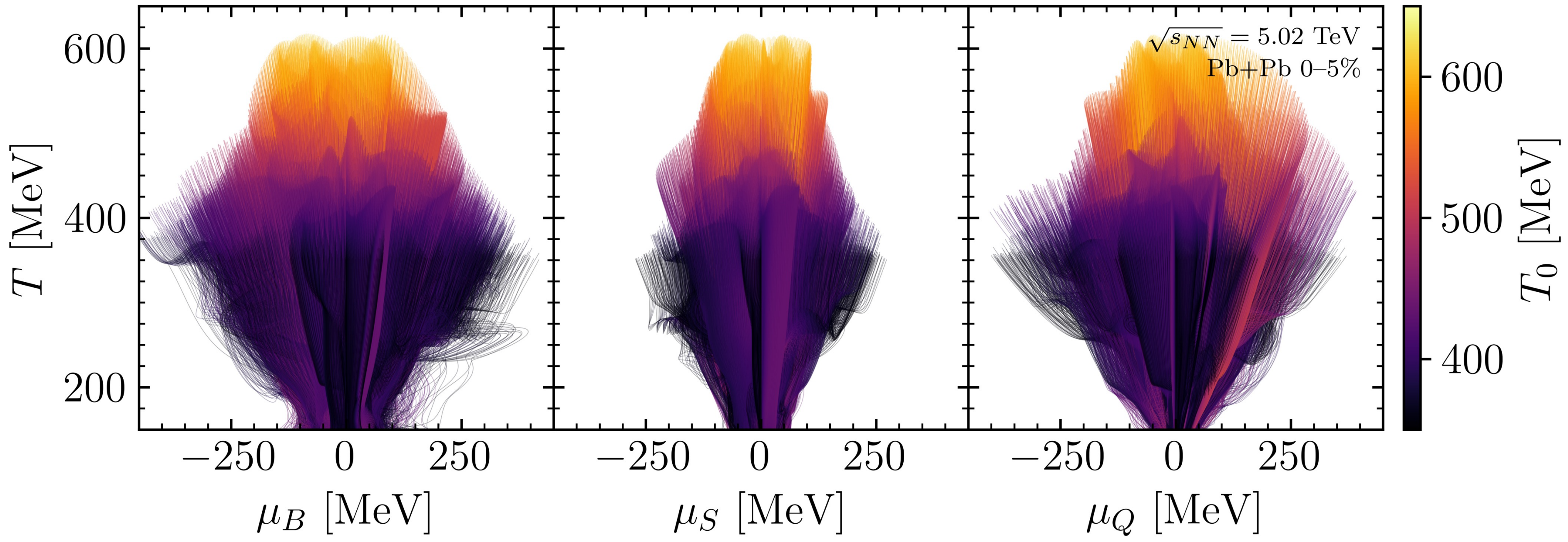


- Initial fluctuations set density scale
- Most of SPH particles fall beneath nuclear saturation density after a few fm/c

Back-up



- Fluid spans a wide range in chemical potentials during evolution
- Average values are consistent with zero
- Freeze-out values are below 50–100 MeV