Off Equilibrium Effects on Kurtosis Along Strangeness-Neutral Trajectories

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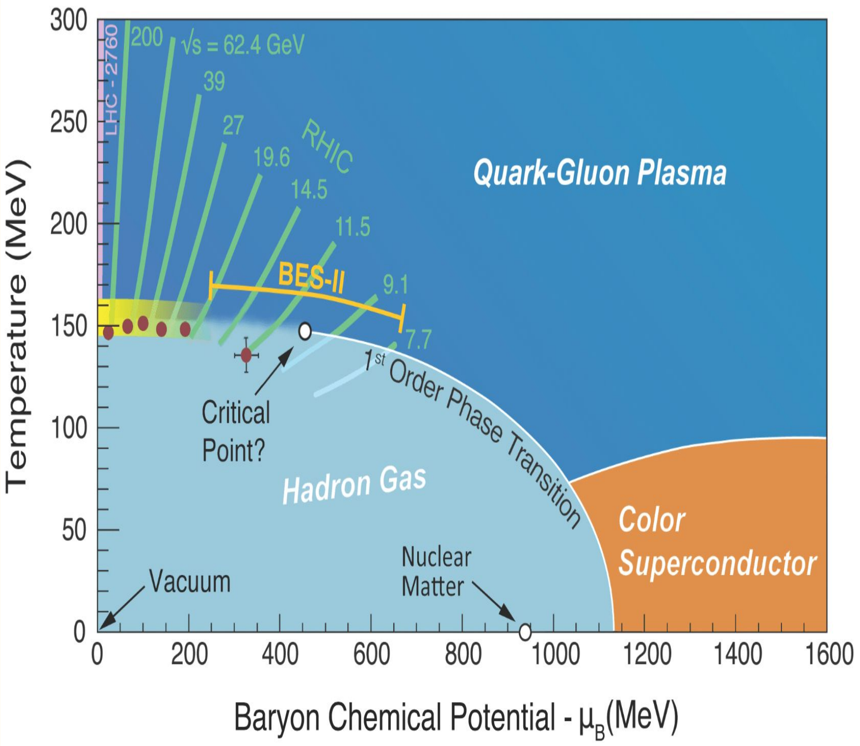
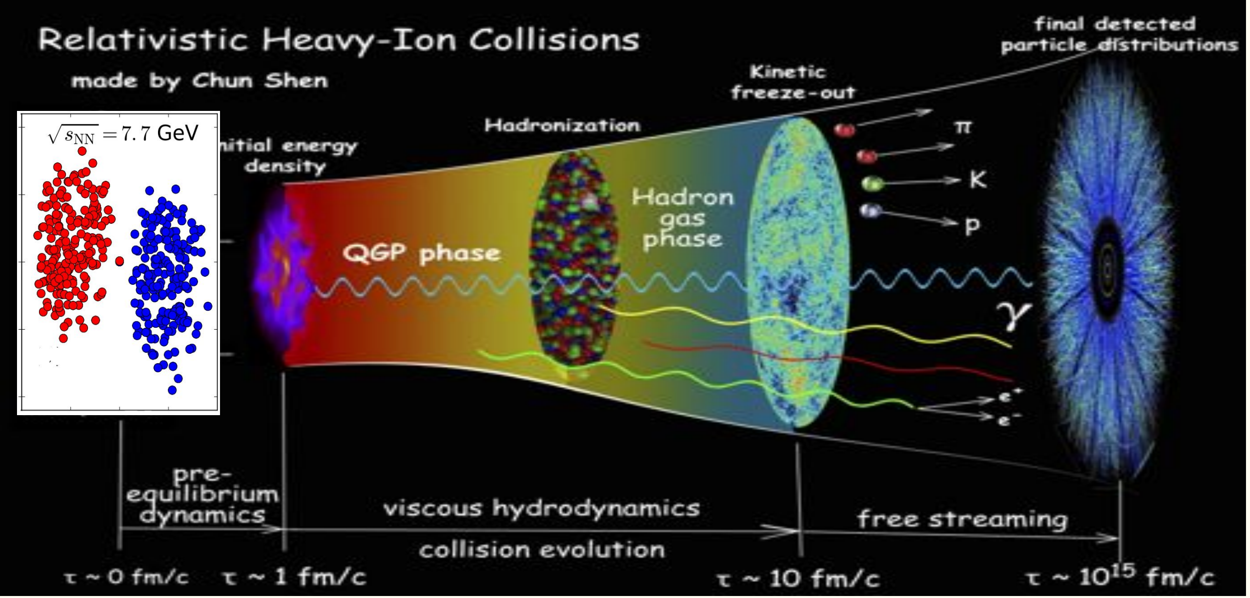
The Beam Energy Scan (BES)



- ➢ <u>Main Objective</u>:
  Probe thermal behavior of QCD in Baryon rich regime

- ➢ Onset of criticality?

- ➢ Complicated by lower energies, finite lifetime, out of equilibrium effects



Initial State

- ➢ Baryon Stopping (some work has been done)
  C. Shen, B. Schenke *Phys.Rev.* C. **97**
- ➢ Initializing full $T^{\mu\nu}$
  - ○ Also problem at $\mu_B = 0$

Equation of State

- ➢ QCD EoS and Fermi Sign Problem

Freeze-out

- ➢ Need to conserve locally, not just on average D. Oliinychenko, et al., *Phys. Rev.C* 102 (2020) 3
- ➢ Out of equilibrium corrections
  - ○ Also problem at $\mu_B = 0$

Hydro Implementation

- ➢ (3+1)D with finite BSQ
- ➢ Transport Coefficients?
- ➢ Critical Fluctuations
- ➢ Correct Formulation?

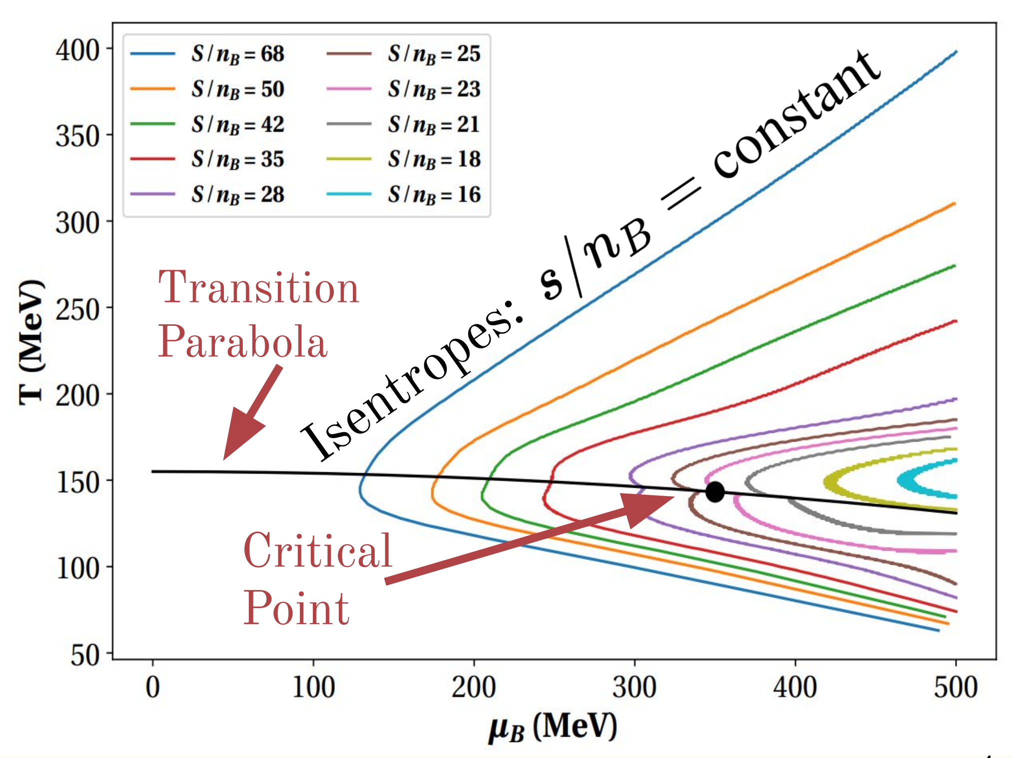
This talk touches on these different areas of needed research

J. Stafford et al.
arXiv:2103.08146v1

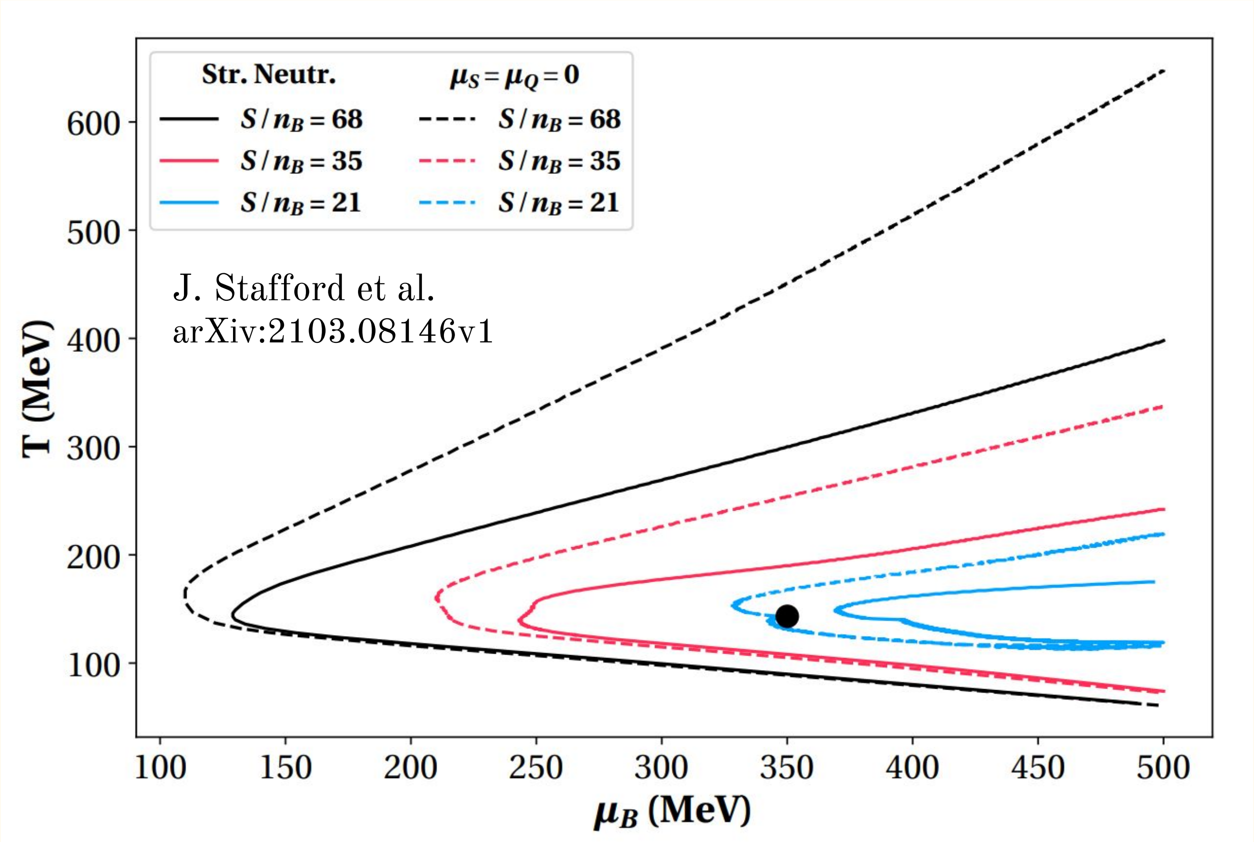
Phenomenological Tool:

Lattice QCD EoS with Parameterized CP (3D Ising University Class)

- Ideal hydrodynamics evolves along isentropic trajectories
- How do out of equilibrium effects influence trajectories?
- Interplay of EoS, Hydro and observables?



Enforcement Of Strangess Neutrality:

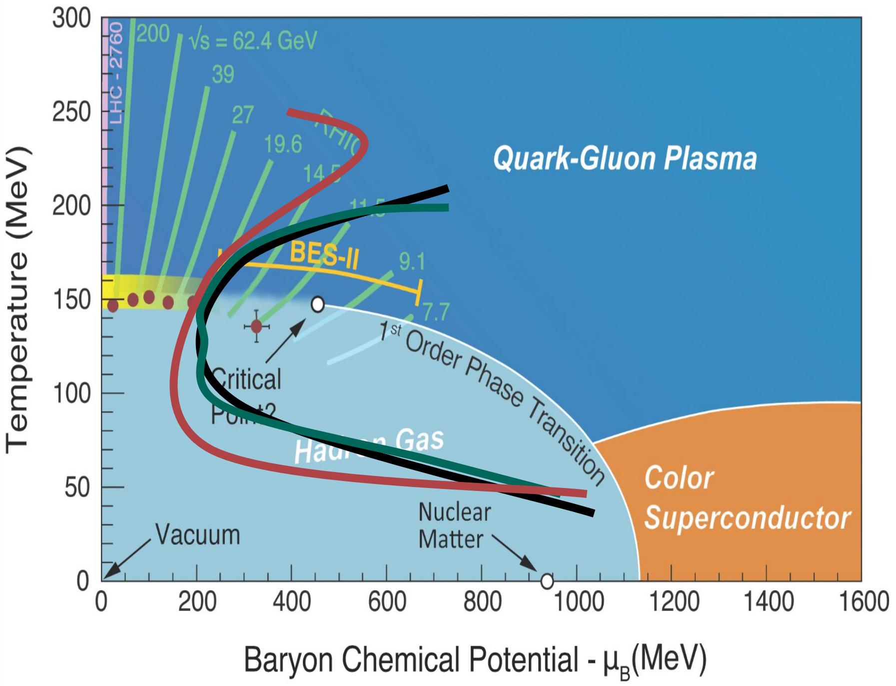


Enforcing the condition (solid) $n_S = 0, n_Q = .4$

Leads to very different behavior compared to (dashed)

$\mu_S = 0, \mu_Q = 0$

An Evolving Hydrodynamic Picture



- ➢ Without viscous effects there is no entropy production. System evolves isentropically
- ➢ Close to equilibrium scenario may not alter trajectories dramatically
- ➢ Far from equilibrium effects may significantly affect trajectories.

Main Question:

For a given beam energy, how might the probed kurtosis change with an off equilibrium initial state?

This Work:

Qualitative study on kurtosis using a simplified hydrodynamic scenario

DNMR Equations of Motion

- ★ Independent and dynamic viscous currents that *relax* to Navier-Stokes values before equilibrium
  Independent of initial energy distribution and flow!!
- ★ Energy conservation *requires* knowledge of EoS

Relaxation equations with boost invariance and polar symmetry:

$$\tau_\pi \dot{\pi}^\eta_\eta + \pi^\eta_\eta = \frac{1}{\tau}\left[\frac{4\eta}{3} - \pi^\eta_\eta\left(\delta_{\pi\pi} + \tau_{\pi\pi}\right) + \lambda_{\pi\Pi}\Pi\right]$$

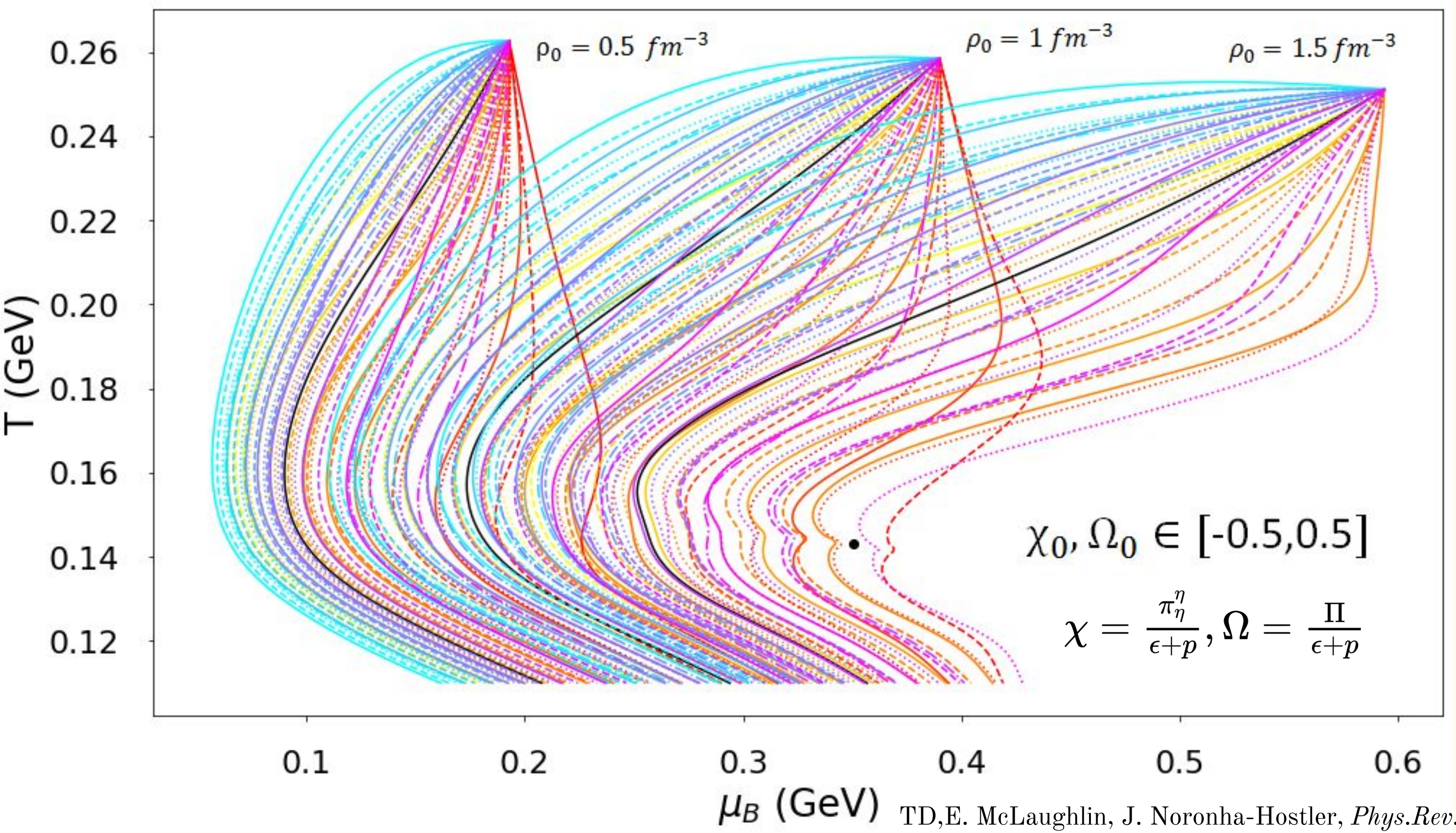
$$\tau_\Pi \dot{\Pi} + \Pi = -\frac{1}{\tau}\left(\zeta + \delta_{\Pi\Pi}\Pi + \frac{2}{3}\lambda_{\Pi\pi}\pi^\eta_\eta\right)$$

G. Denicol, et al, *Eur.Phys.* J.A 48 (2012)

$$\dot{\epsilon} = -\frac{\epsilon + p + \Pi - \pi^\eta_\eta}{\tau}$$

Where p is the thermodynamic pressure

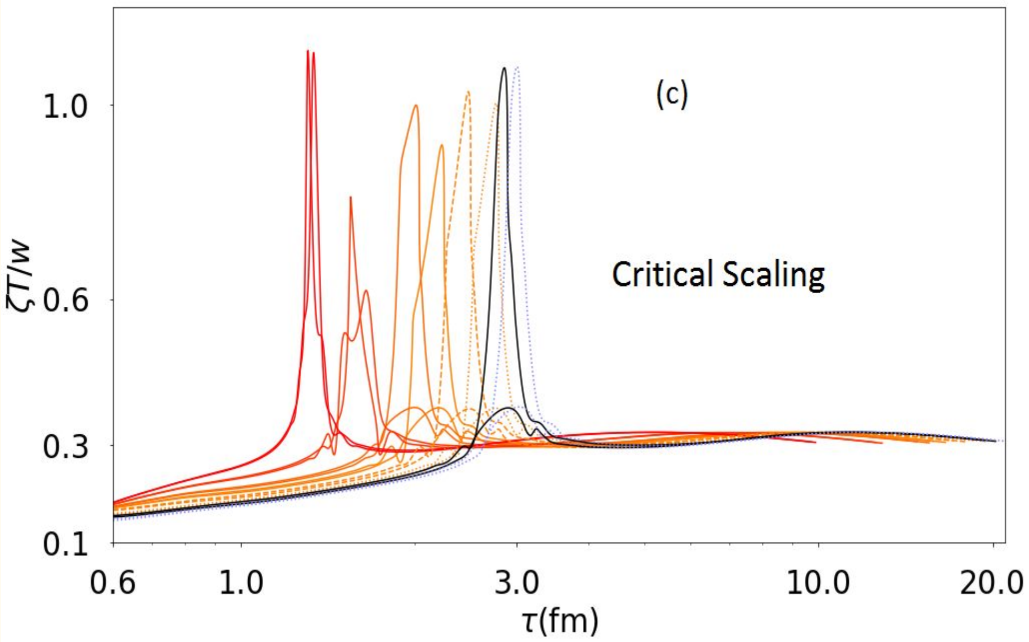
Out Of Equilibrium Effects Are Important



TD,E. McLaughlin, J. Noronha-Hostler, *Phys.Rev.*D 102 (2020) 7

Influence of Criticality on Bulk Viscosity

TD,E. McLaughlin, J. Noronha-Hostler, *Phys.Rev.*D 102 (2020) 7



Monnai, Akihiko et al, Nucl. Phys. ,A967,2017

Critically Scaled Bulk:

$$\left(\frac{\zeta T}{w}\right)_{CS} = \frac{\zeta T}{w}\left[1 + \left(\frac{\xi}{\xi_0}\right)^3\right]$$

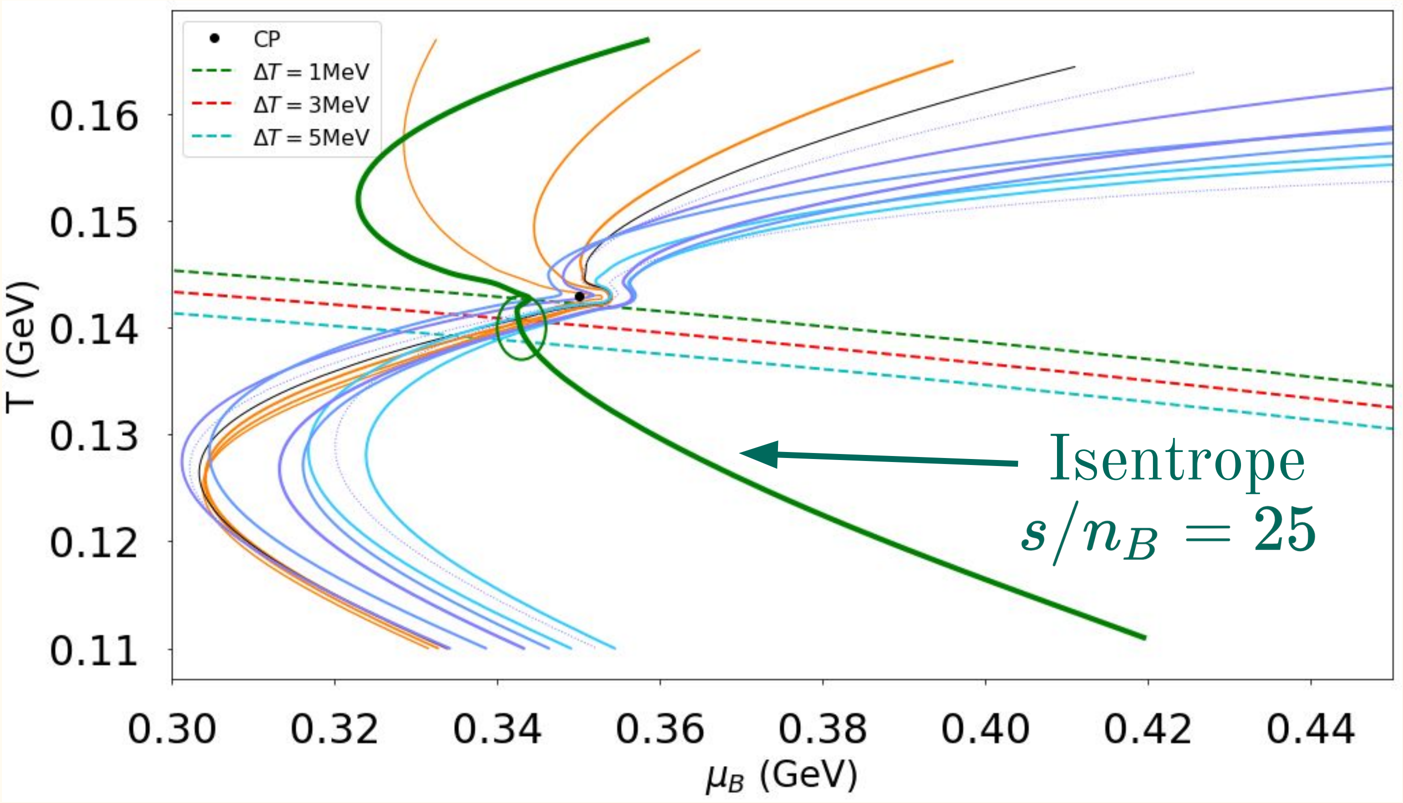
Correlation length ξ *diverges* at the critical point

Correlation length calculated in linear parametrization model

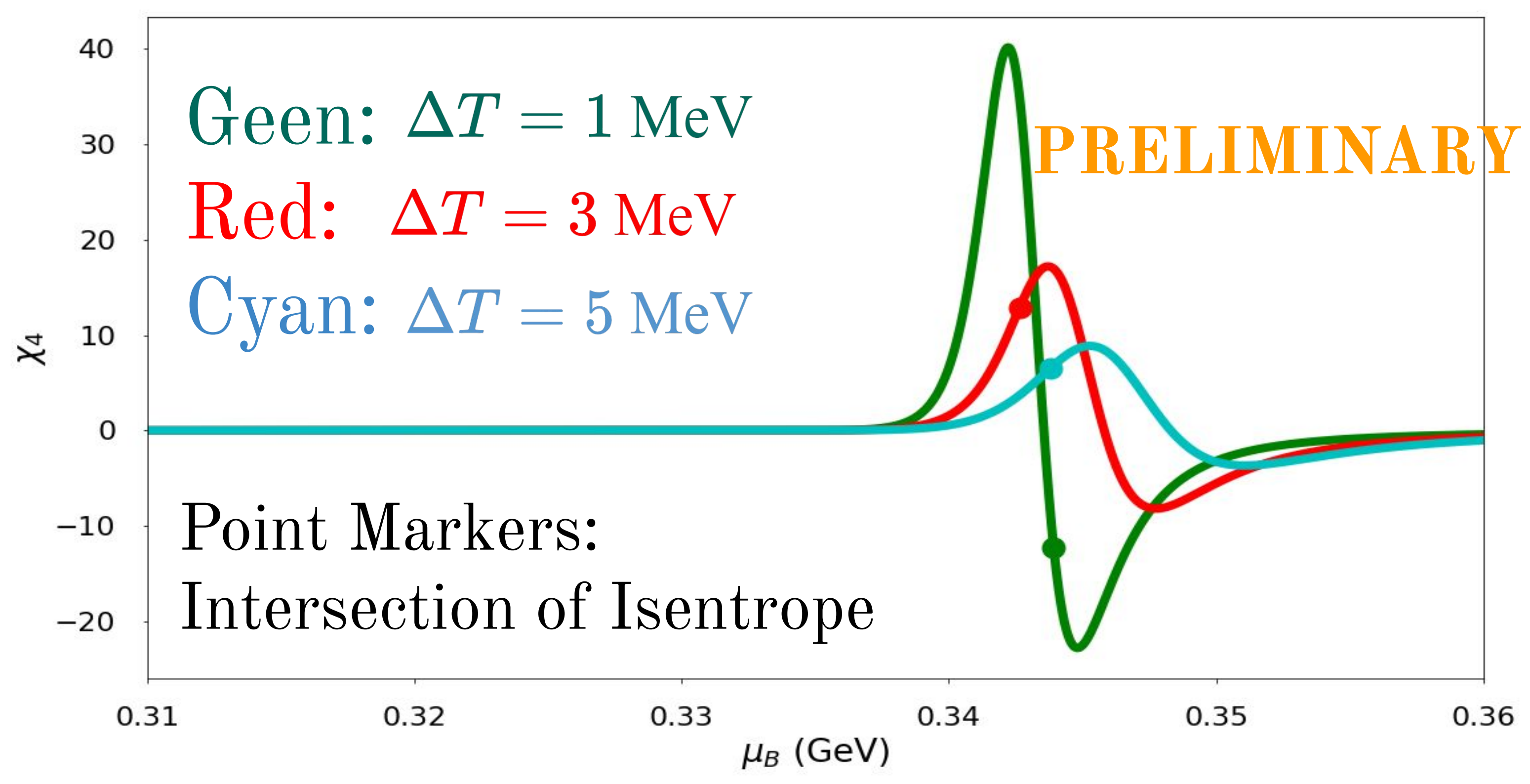
For more on transport coefficients see talk: E. Mclaughlin, Bulk Correlations

Trajectories For Same Initial Energy

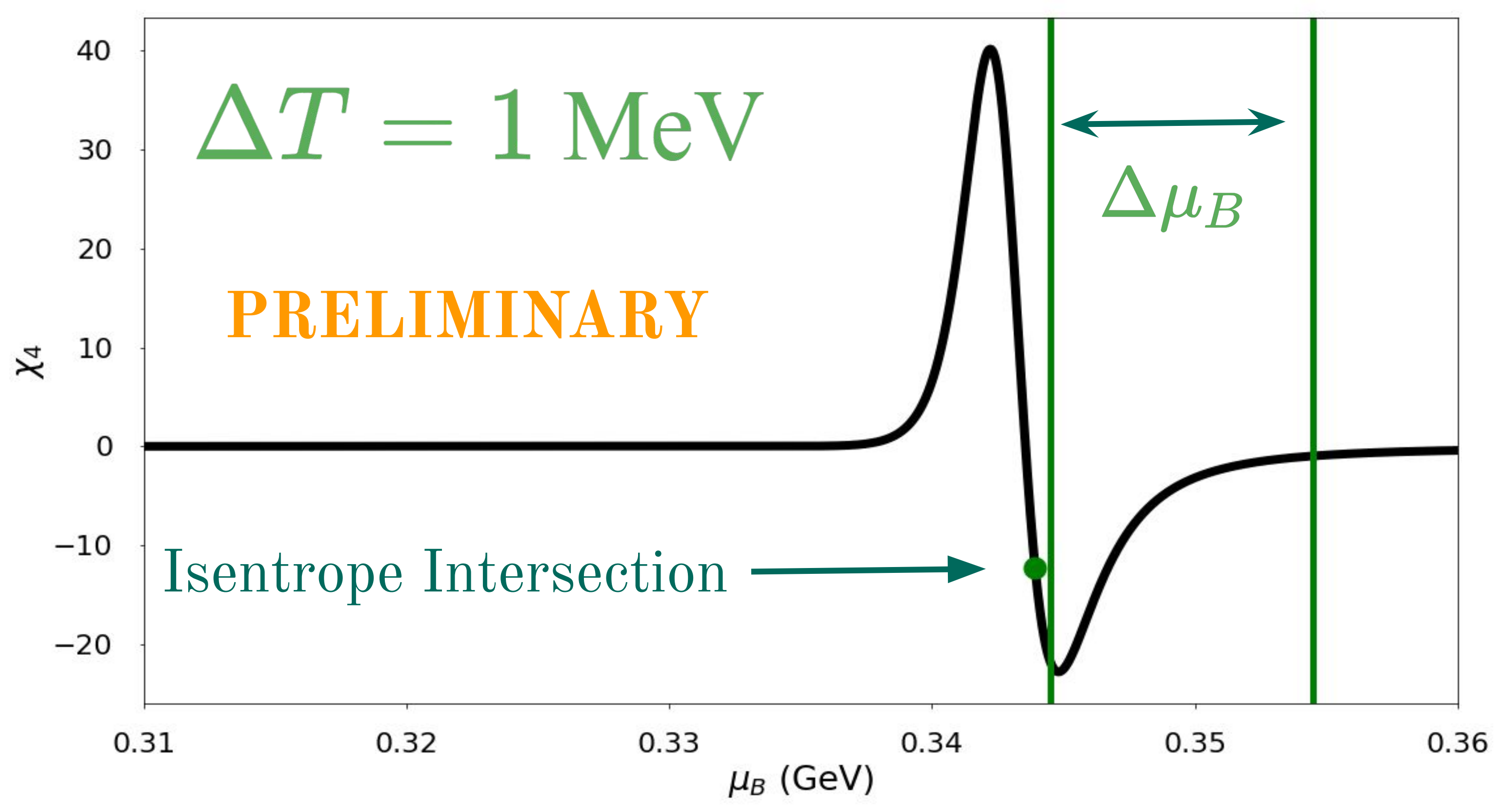
Shifted Chiral Transition Lines (by 1, 3, and 5 MeV) Are Plotted As Dashed Lines



χ_4 Along Transition Parabola



Range of χ_4 Given Off Equilibrium Initial State



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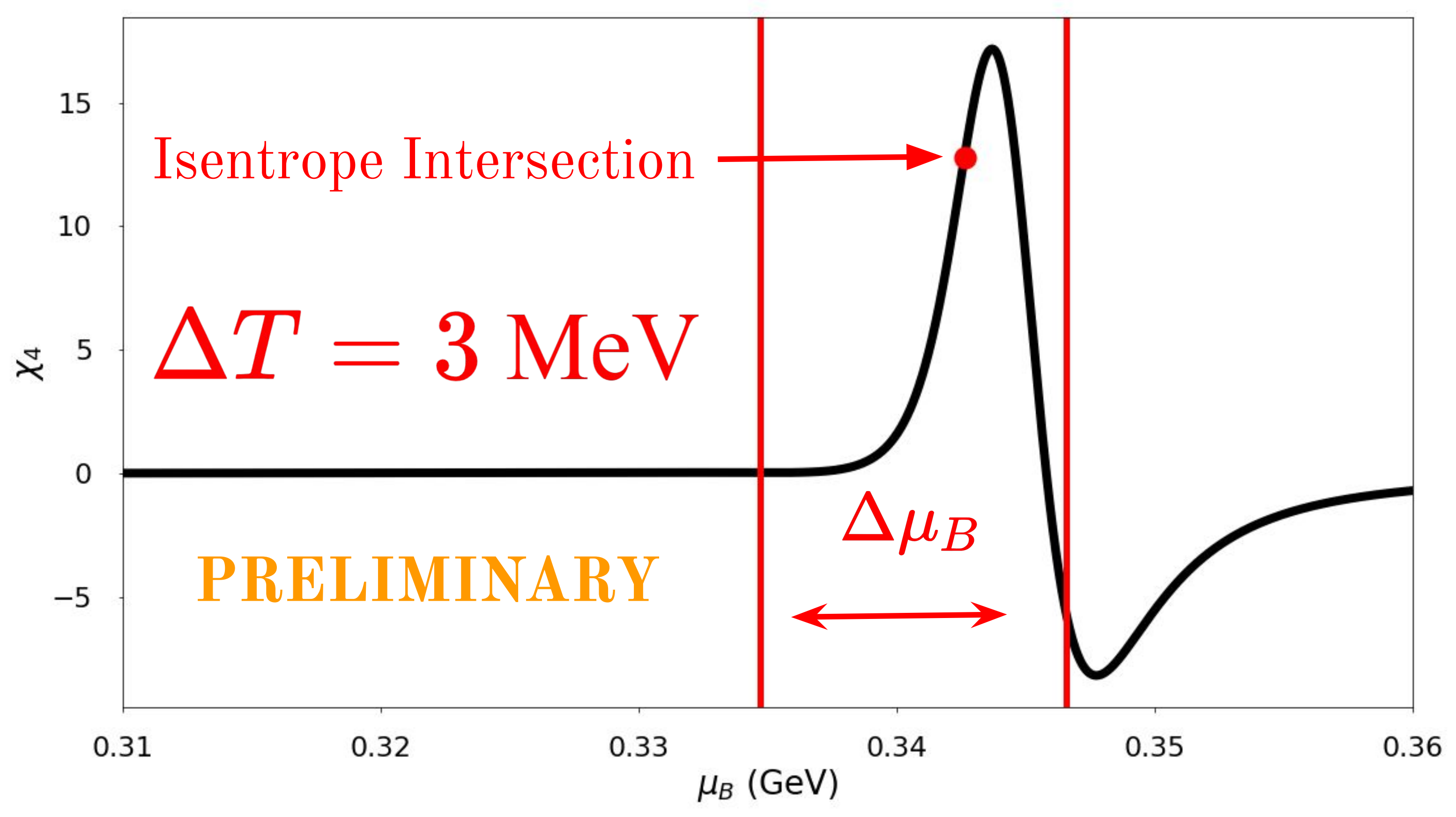
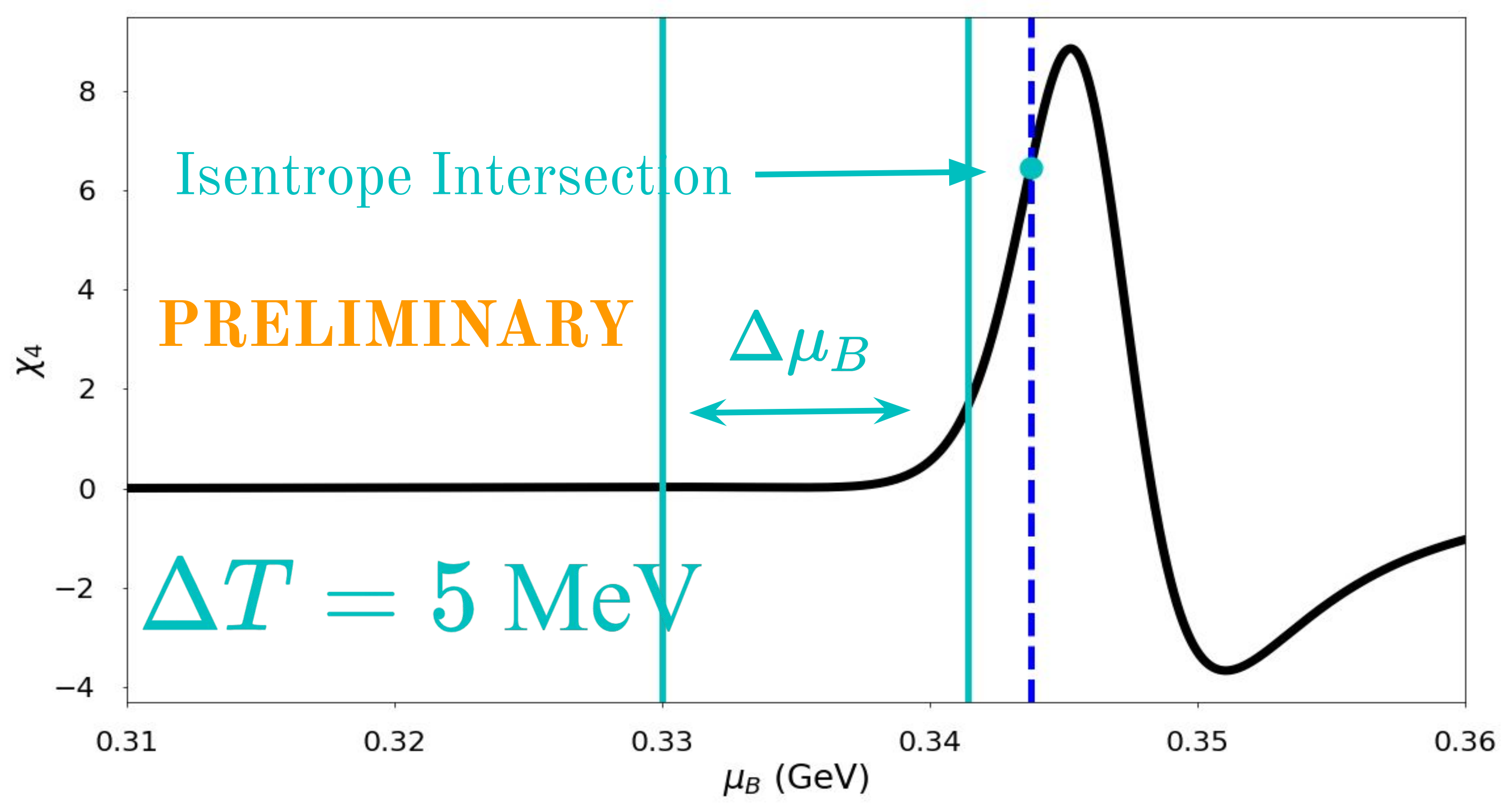
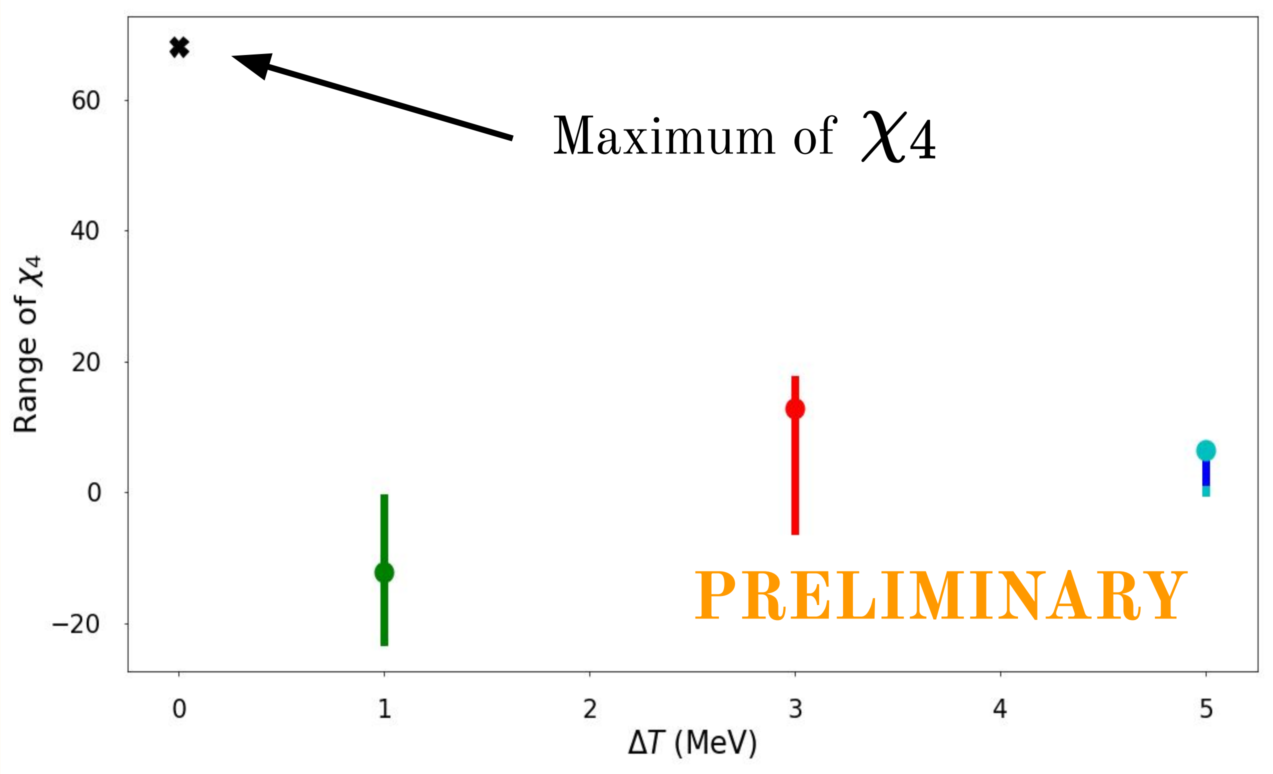


Range of χ_4 Given Off Equilibrium Initial State



Max and Min of Probed Off Equilibrium χ_4

Takeaway:
Out of equilibrium effects lead to spread in χ_4 probed on event-by-event basis



Conclusions

- Initial state effects have important consequences on hydro evolution, and thus probed observables
- Out of equilibrium effects leads to EbE spread at freeze out
- Much more dynamic modeling needs to be done
  - See talk V. Vovchenko (earlier this session)

Backup Slides

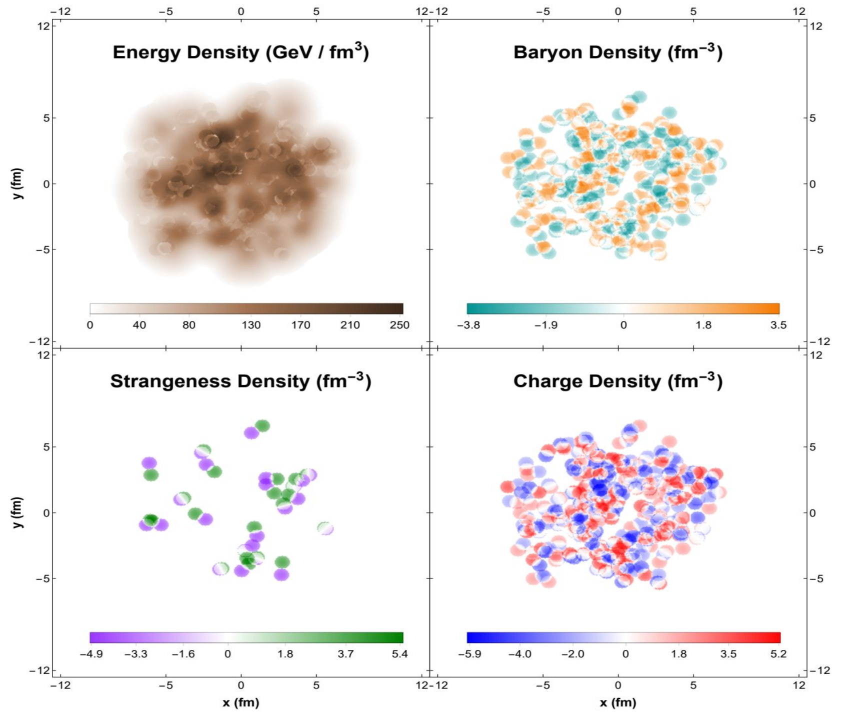
Next Steps towards BES Hydrodynamics

Start with what we know: LHC energies and ICCING

Initializing
Conserved
Charges
in Nuclear
Geometries

M. Martinez, et al., arXiv:1911.12454

M. Martinez, et al., arXiv:1911.10272



Initializing charges at 0 ***net*** density allows study of diffusion in a better controlled environment

Requirements:

- (2+1) dimensional Hydro
  - V-USPhydro
- 4D EoS Noronha-Hostler, et al. *Phys.Rev.C 100 (2019)*
  - $\{\epsilon, \rho_B, \rho_Q, \rho_S\} \rightarrow \{T, \mu_B, \mu_Q, \mu_S\}$

For more on ICCING, see poster: Carzon (session O)

$$\tau_\pi \dot{\pi}^\eta_\eta + \pi^\eta_\eta = \frac{4\eta}{3\tau} - \frac{\eta T \pi^\eta_\eta}{2}\left(\frac{\beta_\pi}{\tau} + \dot{\beta}_\pi\right)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\frac{\zeta}{\tau} - \frac{\zeta T \Pi}{2}\left(\frac{\beta_\Pi}{\tau} + \dot{\beta}_\Pi\right)$$

$$\tau_\pi = \frac{5\ \eta}{\epsilon + p}$$

$$\tau_\Pi = \frac{\zeta}{15(\epsilon + p)\left(\frac{1}{3} - c_s^2\right)^2}$$

$$\lambda_{\pi\Pi} = \frac{6}{5}\tau_\pi$$

$$\delta_{\pi\pi} = \frac{4}{3}\tau_\pi$$

$$\tau_{\pi\pi} = \frac{10}{7}\tau_\pi$$

$$\lambda_{\Pi\pi} = \tau_\Pi \frac{8}{5}\left(\frac{1}{3} - c_s^2\right)\tau_\Pi$$

$$\delta_{\Pi\Pi} = \frac{2}{3}\tau_\Pi$$

$$\beta_\pi = \frac{\tau_\pi}{2\eta T}$$

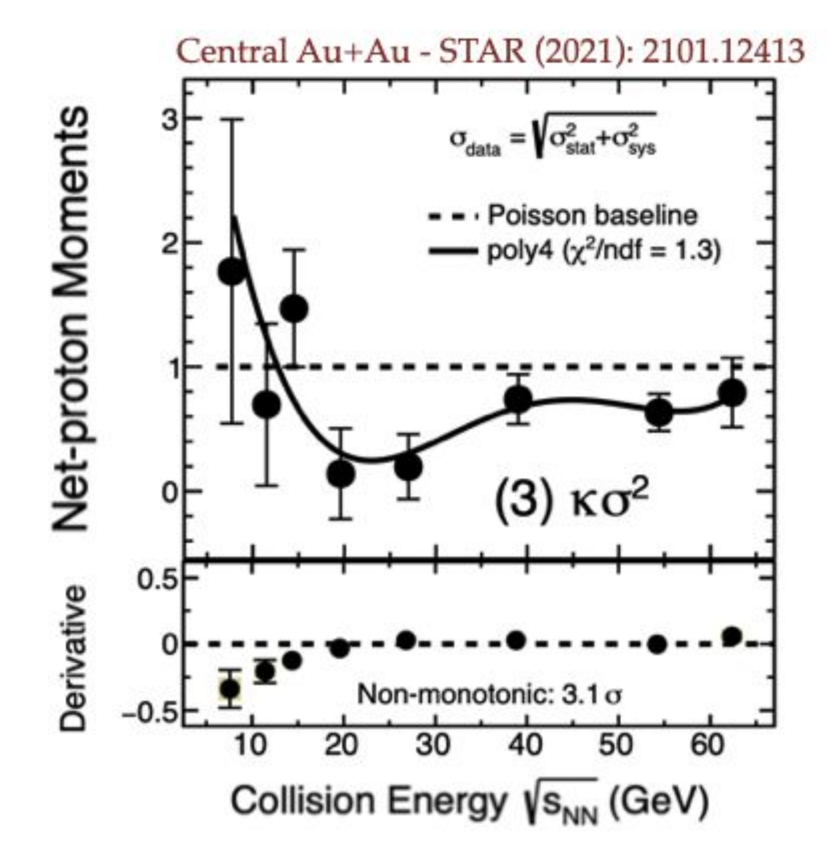
$$\beta_\Pi = \frac{\tau_\Pi}{\zeta T}.$$

$$\dot{\epsilon} = -\frac{1}{\tau}\left[\epsilon + p + \Pi - \pi^\eta_\eta\right]$$

$$\tau_\pi \dot{\pi}^\eta_\eta + \pi^\eta_\eta = \frac{1}{\tau}\left[\frac{4\eta}{3} - \pi^\eta_\eta\left(\delta_{\pi\pi} + \tau_{\pi\pi}\right) + \lambda_{\pi\Pi}\Pi\right]$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\frac{1}{\tau}\left(\zeta + \delta_{\Pi\Pi}\Pi + \frac{2}{3}\lambda_{\Pi\pi}\pi^\eta_\eta\right)$$

$$\dot{\rho} = -\frac{\rho}{\tau}$$



Central Au+Au - STAR (2021): 2101.12413
$\sigma_{data} = \sqrt{\sigma^2_{stat}+\sigma^2_{sys}}$
Poisson baseline
poly4 (χ^2/ndf = 1.3)
(3) $\kappa\sigma^2$
Net-proton Moments
Derivative
Non-monotonic: 3.1 σ
Collision Energy $\sqrt{s_{NN}}$ (GeV)

Keeping Track of Reference Density: Example

$$\Pi + \tau_\Pi \frac{d}{d\tau}\Pi + = -\zeta\theta \quad \Longrightarrow \quad \frac{\Pi}{\sigma} + \tau_\Pi \frac{d}{d\tau}\left(\frac{\Pi}{\sigma}\right) = -\frac{\zeta}{\sigma}\theta$$

$$\frac{\Pi}{\sigma} + \tau_\Pi \frac{1}{\sigma}\frac{d}{d\tau}\Pi + \tau_\Pi \Pi \frac{d}{d\tau}\frac{1}{\sigma} = -\frac{\zeta}{\sigma}\theta$$

$$\Pi + \tau_\Pi \frac{d}{d\tau}\Pi + \tau_\Pi \Pi \sigma \frac{d}{d\tau}\frac{1}{\sigma} = -\zeta\theta$$

Use relation

$$\sigma \frac{d}{d\tau}\frac{1}{\sigma} = \theta$$

$$\Pi + \tau_\Pi \frac{d}{d\tau}\Pi + = -(\zeta + \tau_\Pi \Pi)\theta$$

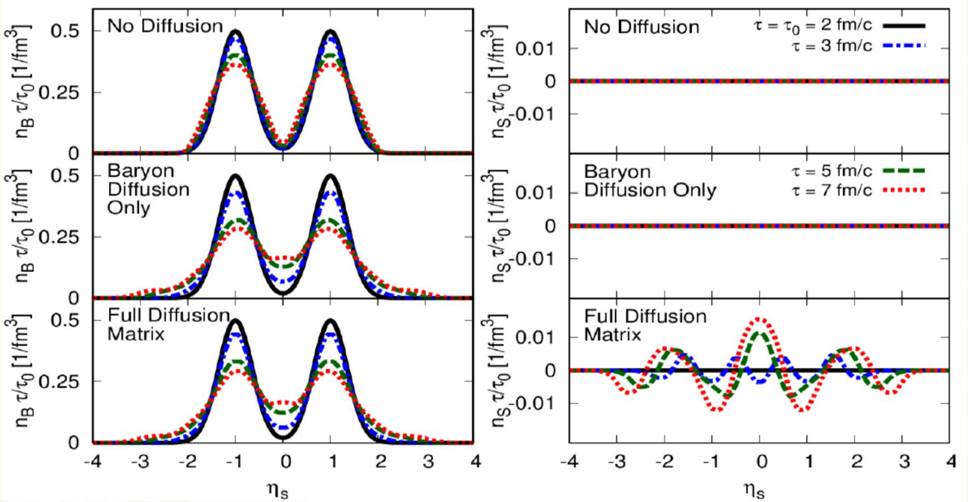
Extra term unique to SPH

Relativistic Coupled Diffusion

Generalization: $for\ q, l \in \{B, S, Q\}$

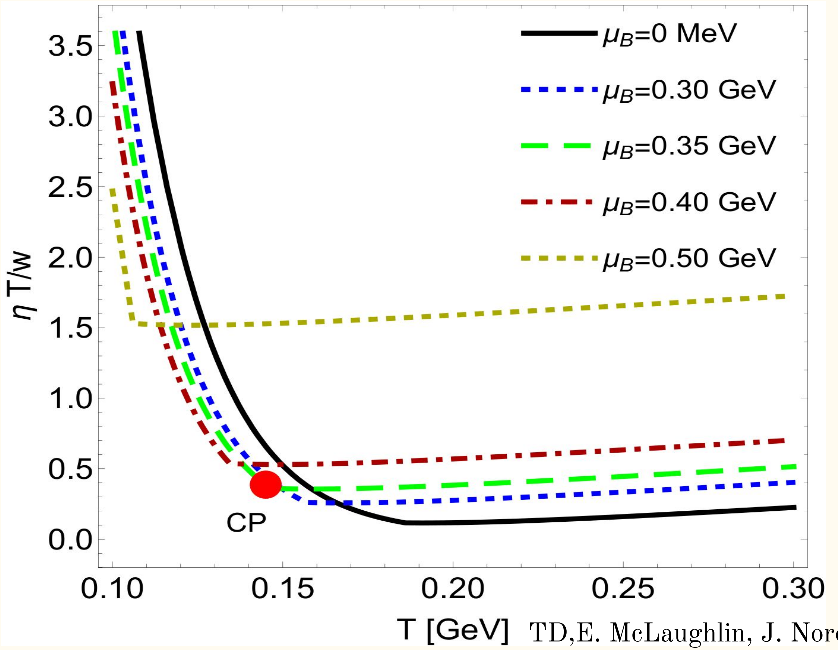
Greif, Fotakis et al., PRL 120, 242301 (2018)
Fotakis, Greif et al., PRD 101, 076007 (2020)

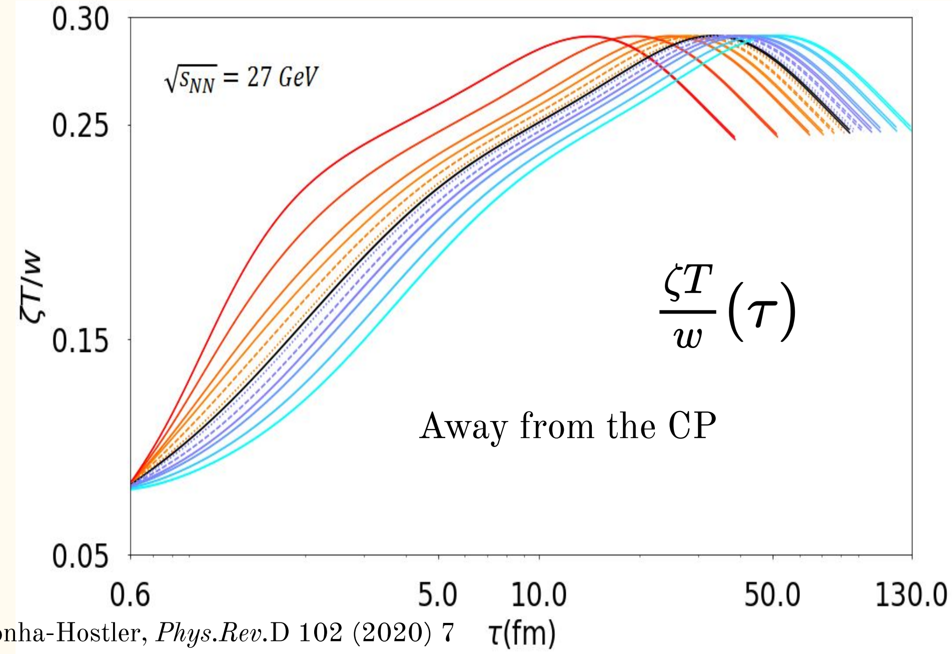
$$\tau_q \dot{n}_q^\mu + n_q^\mu = \kappa_q \nabla^\mu \alpha_q \Rightarrow \sum_l \tau_{ql} \dot{n}_l^\mu + n_q^\mu = \sum_l \kappa_{ql} \nabla^\mu \alpha_l$$



(2+1) SPH equations for Israel-Stewart currently being derived and implemented into existing v-USPhydro code

Transport Coefficient Behavior





TD,E. McLaughlin, J. Noronha-Hostler, *Phys.Rev.*D 102 (2020) 7

Shear viscosity not sensitive to criticality explicitly

Bulk viscosity away from CP shows similar behavior