Theory Summary: Strangeness in Quark Matter 2024

Jasmine Brewer

7 June 2024

Apologies for many nice results not able to be shown.

Current status and my biased view of some challenges/ opportunities for the future

Focusing on content of the parallel sessions (mostly) since you are all in the plenary sessions

Outline

Search for the QCD critical point

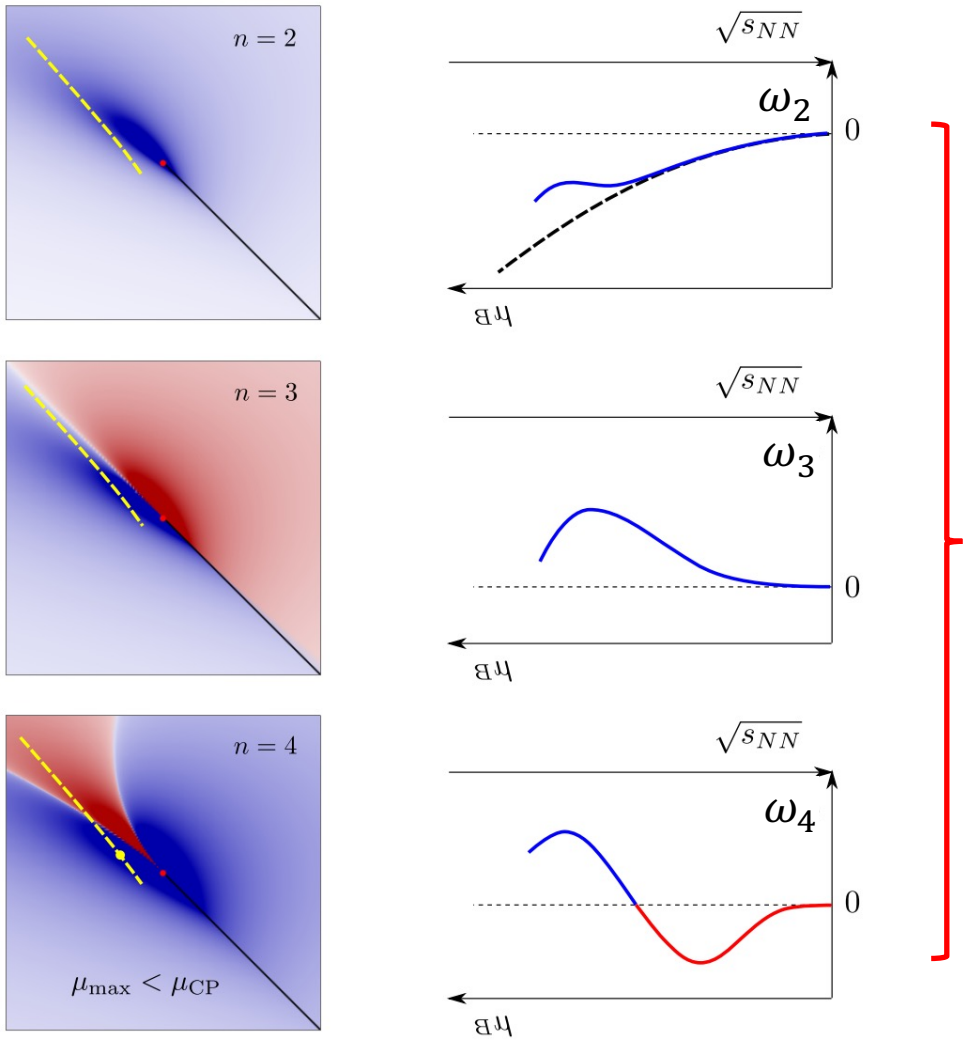
Pushing the boundaries of hydrodynamics
- for the critical point search
- for understanding small systems
- Polarization and spin hydrodynamics

Probes of the pre-equilibrium state

Dynamics of open heavy flavor
- hadronization
- flow
- quenching

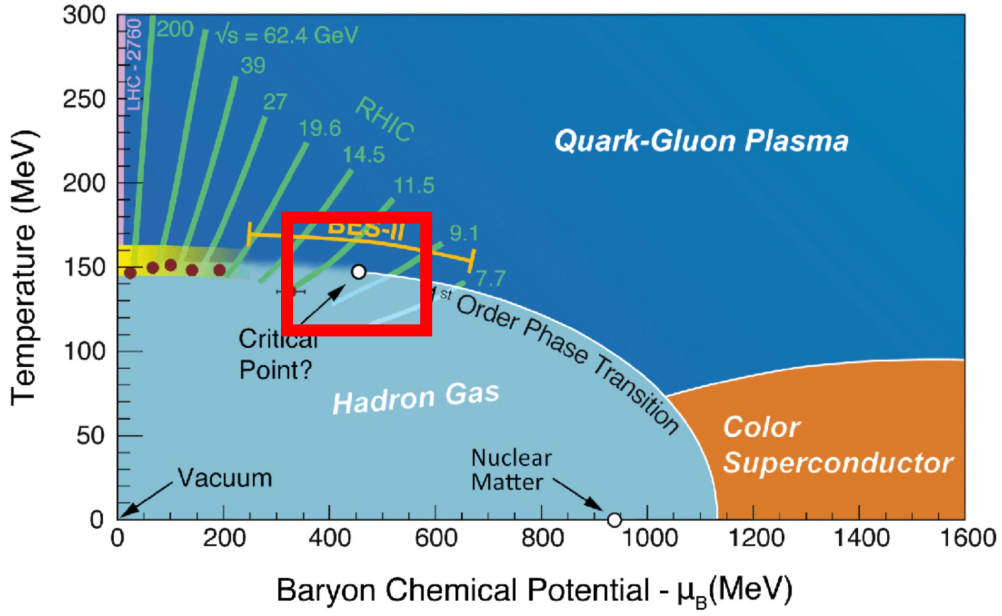
Astrophysics, light(er) hadronization, quarkonia …. (not covered)

Critical point: background and theory status



Stephanov [1104.1627]

[Misha Stephanov talk]



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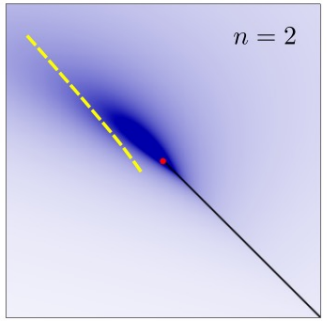
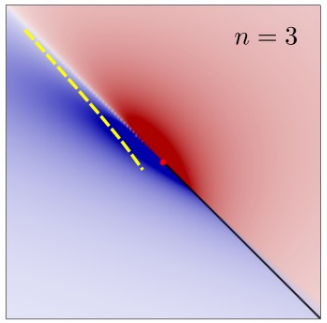
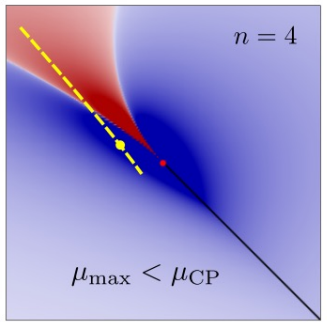
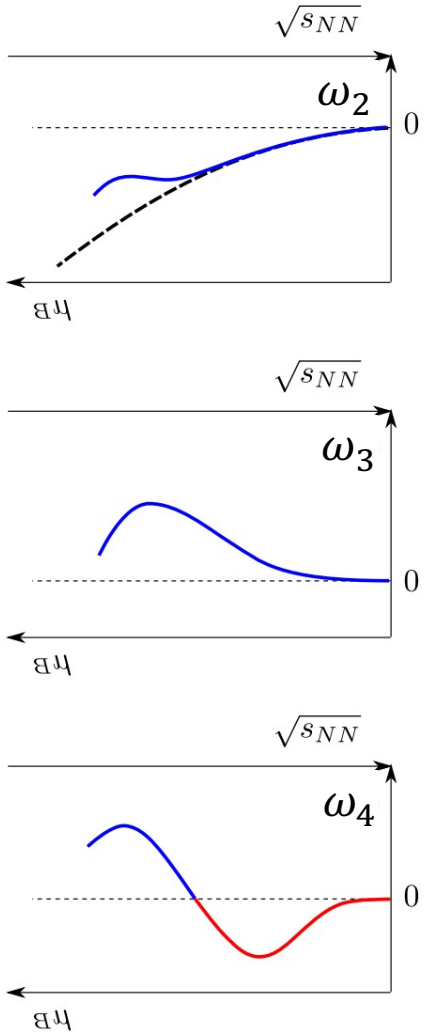
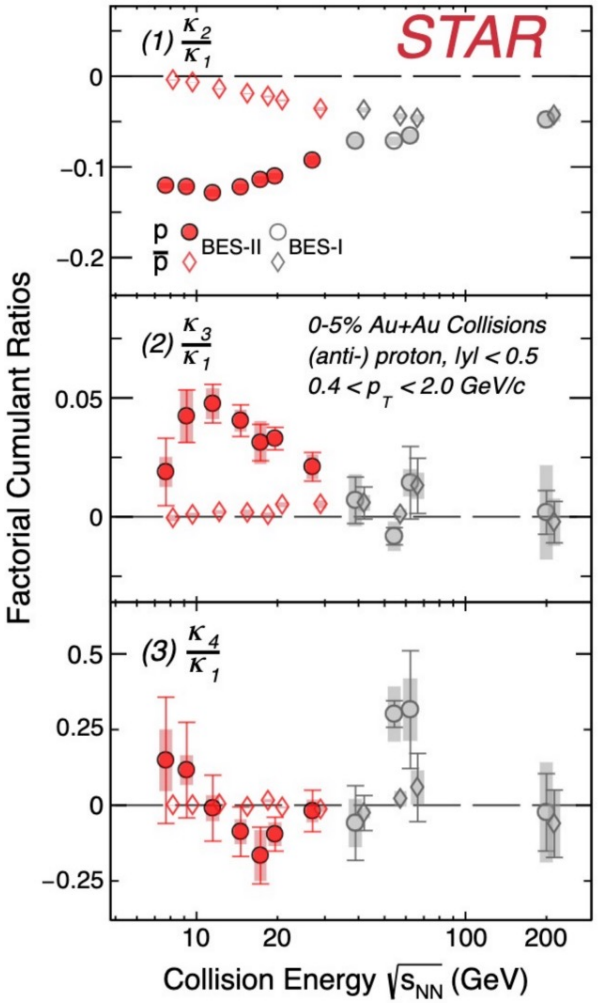










[Misha Stephanov talk]

[Yifei Zhang talk]

[Adam Bzdak talk]

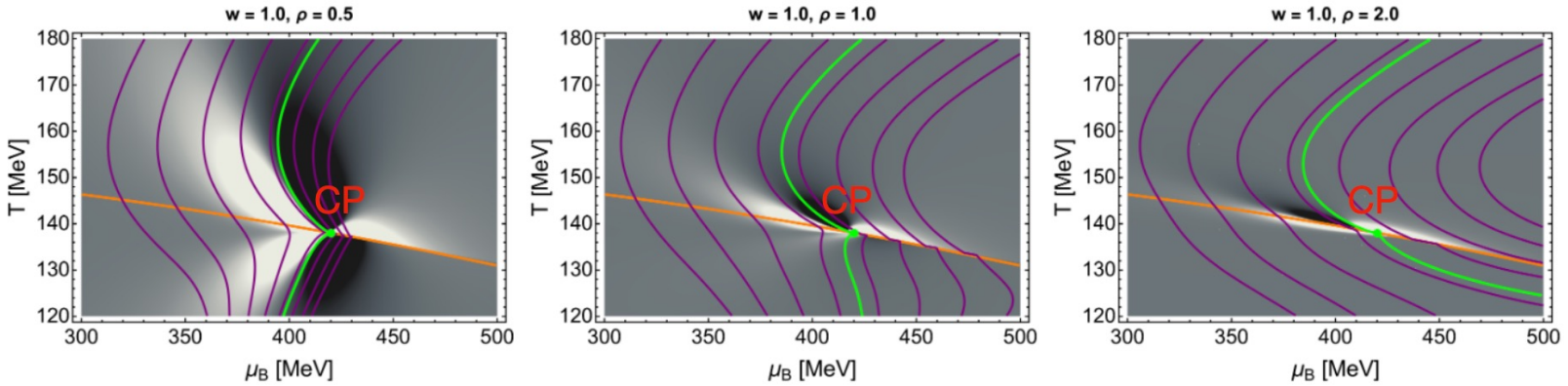
[1104.1627]

At the cartoon level, qualitative signatures one may expect for a critical point $\gtrsim 420$ MeV

However there are many complex effects being explored

Critical point: status and challenges for future work

Size and features of critical signatures depend on unknown mapping between Ising and QCD variables



[Jamie Karthein talk]
[2207.04086]

$$(\mathbf{r},\mathbf{h}) \longleftrightarrow (\mathbf{T},\mu_\mathbf{B}): \quad \frac{T-\mathbf{T_C}}{\mathbf{T_C}} = \mathbf{w}\,(r\rho\,\sin\alpha_1 + h\,\sin\alpha_2)$$
$$\frac{\mu_B-\mu_\mathbf{BC}}{\mathbf{T_C}} = \mathbf{w}\,(-r\rho\,\cos\alpha_1 - h\,\cos\alpha_2)$$

See also [1905.13247]

Non-gaussian fluctuations [Jamie Karthein talk] and [Misha Stephanov talk]

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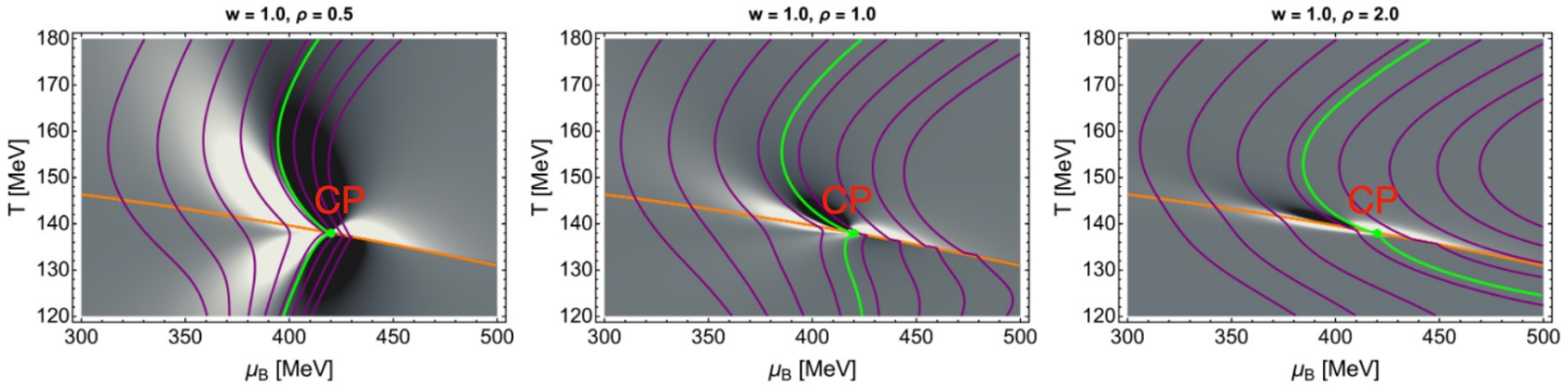

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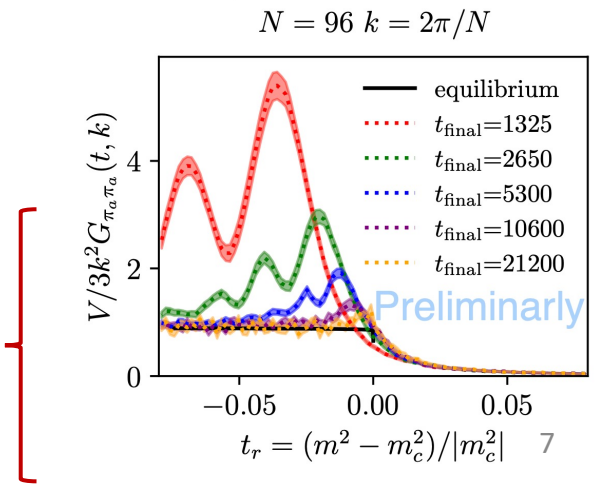
Non-gaussian fluctuations [Jamie Karthein talk] and [Misha Stephanov talk]

Out-of-equilibrium dynamics may have a major impact

New results in models

- Scaling of critical slowing down near Ising critical point
  [Matthis Harhoff poster]
- Enhancement of soft pions from quench over chiral phase transition
  [Eduardo Grossi talk]



New challenges for hydrodynamics: the search for a critical point

Hydrodynamics at low beam energies

- Nuclei can take several fermi to pass through each other

Fireball passes wide swath of the phase diagram

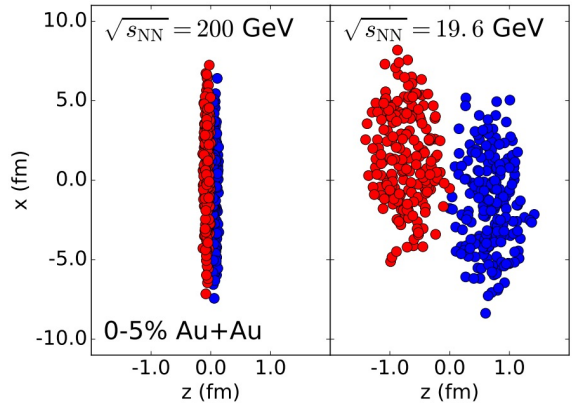
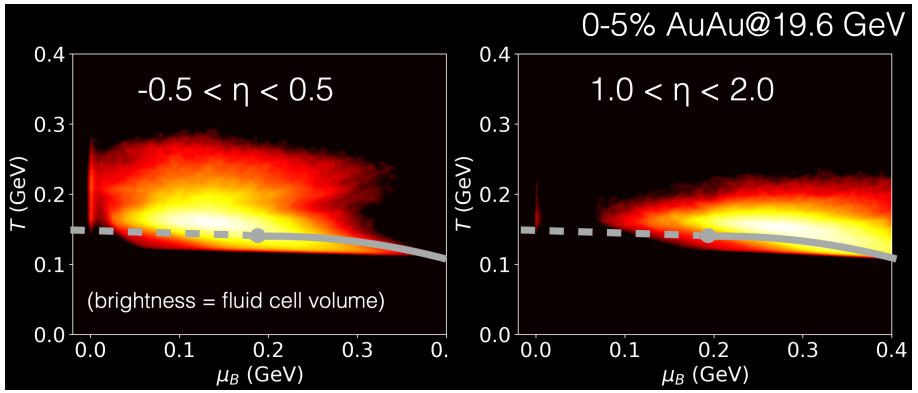


Fig: Schenke Shen [1710.00881]



Chun Shen QM'18

Also in 3-fluid model MUFFIN

[Iurii Karpenko talk]

- New measurements related to charge and baryon stopping
- Necessitates lattice equation of state as a function of (μ_B, μ_S, μ_Q)

[Rongrong Ma talk]

[Johannes Jahan talk]

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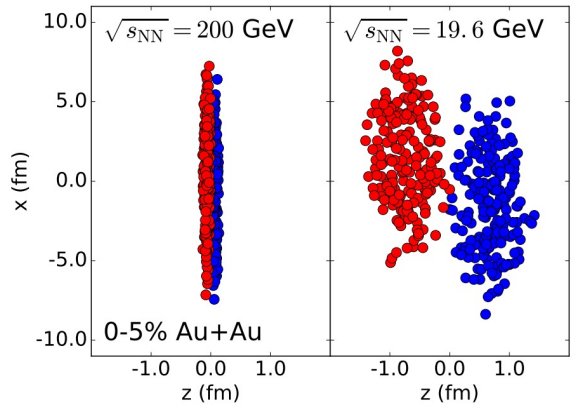

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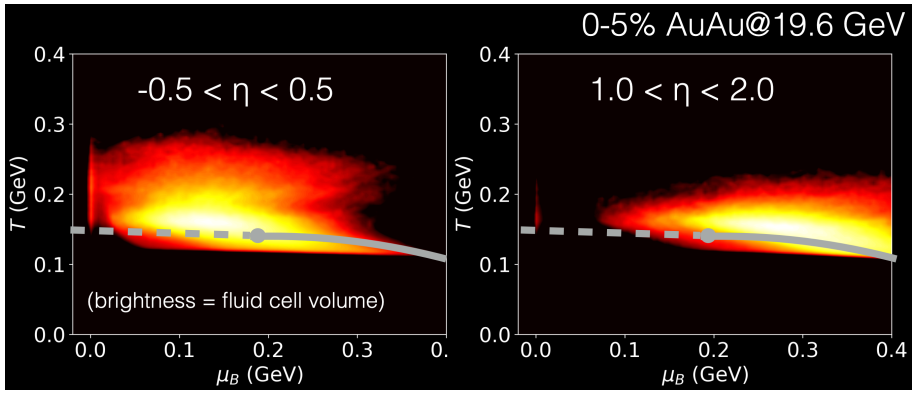

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[Johannes Jahan talk]

Hydrodynamics with slow critical fluctuations

- progress on propagating hydrodynamic correlations into correlations in produced particles with maximum entropy freezeout

[Misha Stephanov talk]

Going beyond hydrodynamics: the pre-equilibrium phase

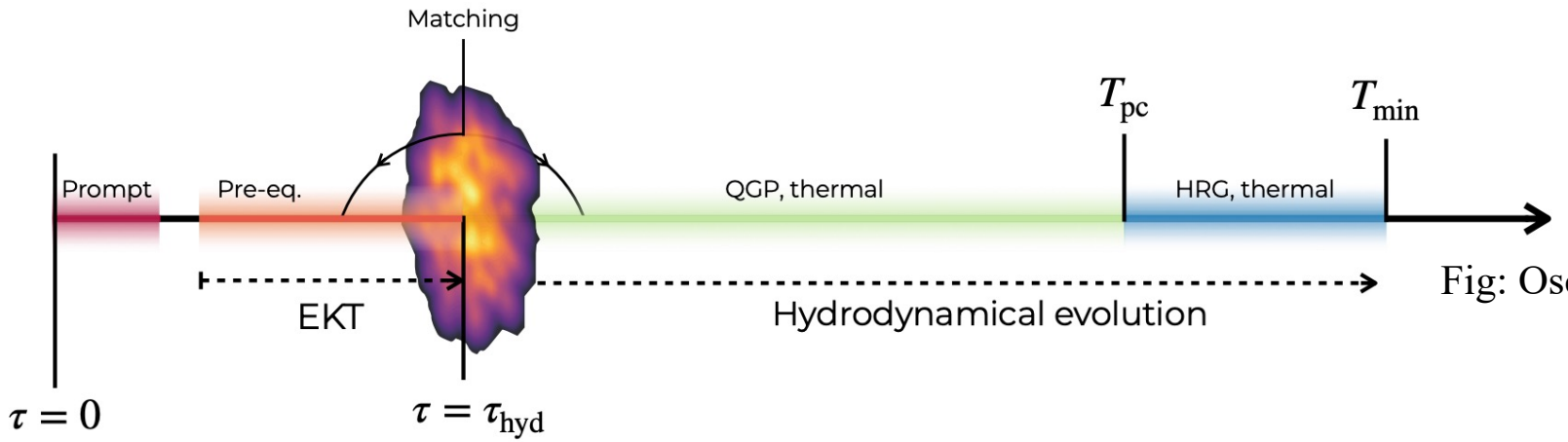
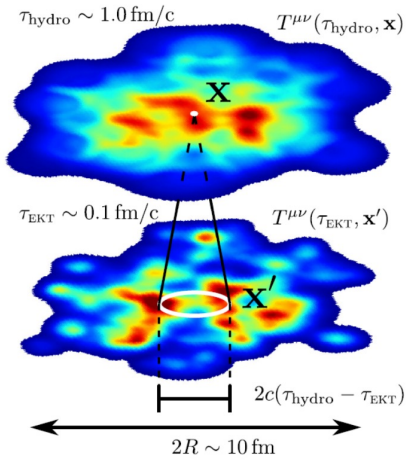
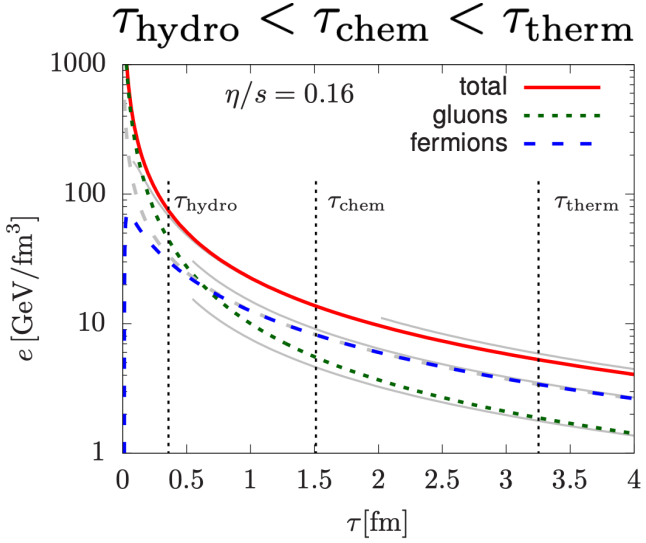


Fig: Oscar Garcia-Montero

Connecting the far-from-equilibrium initial state to hydrodynamics in QCD effective kinetic theory





Kurkela, Mazeliauskas [1811.03040]

- Strangeness propagation in the pre-equilibrium phase [Travis Dore poster]
- Hydrodynamics with conserved charges [Jaki Noronha-Hostler talk] [Stefan Floerchinger talk]

Going beyond hydrodynamics: the pre-equilibrium phase

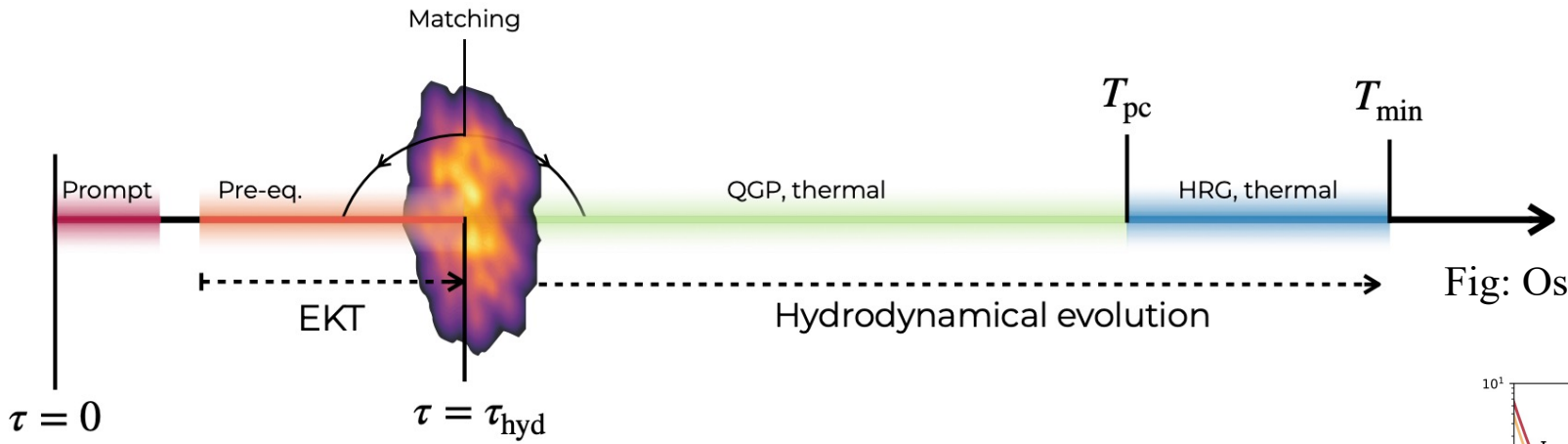


Fig: Oscar Garcia-Montero

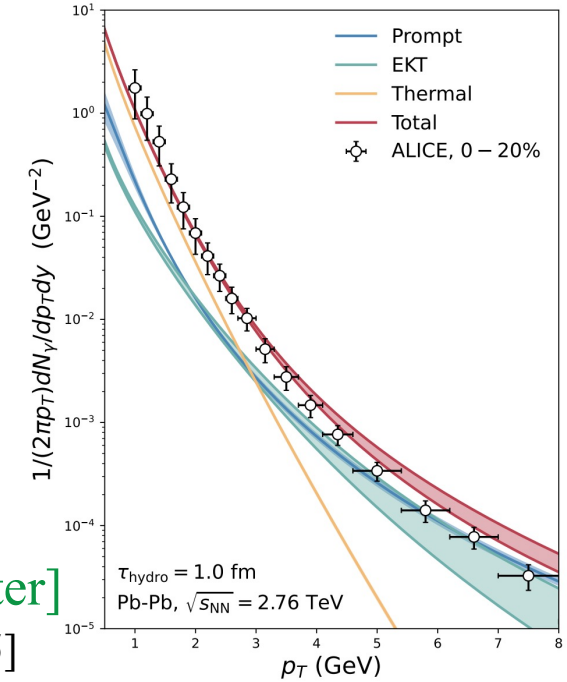
Theory challenges and opportunities

- access non-equilibrium QCD in the pre-thermal phase
- improve initial conditions for hydrodynamics

Pre-thermal photons and dileptons [Oscar Garcia-Montero talk]

Pre-thermal heavy flavor [Manu Kurian talk], [Pooja poster]

[2404.05315]

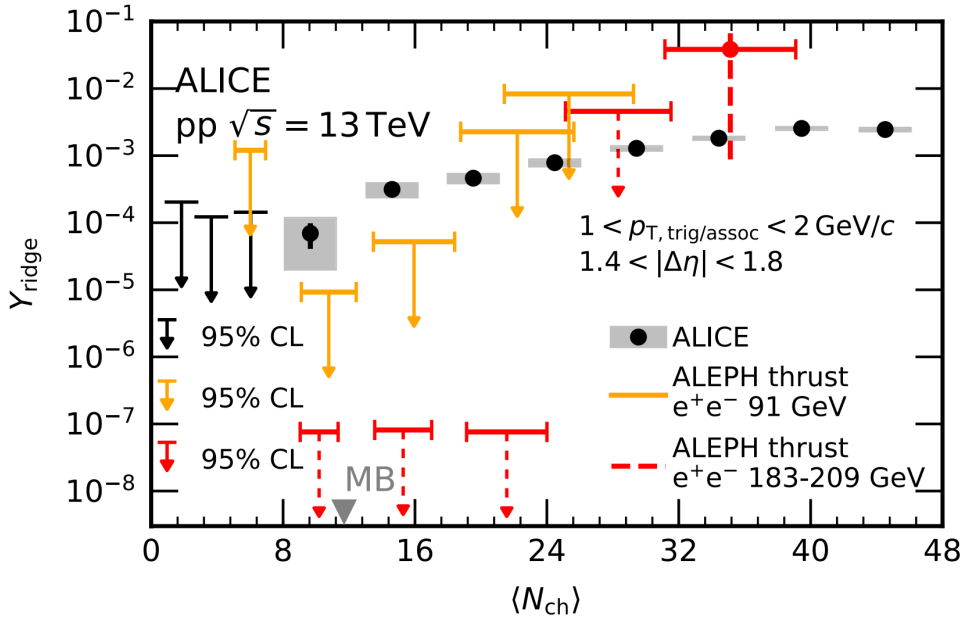


Pushing into smaller collision systems necessitates understanding in detail this pre-thermal phase

Collectivity in the smallest collision systems?

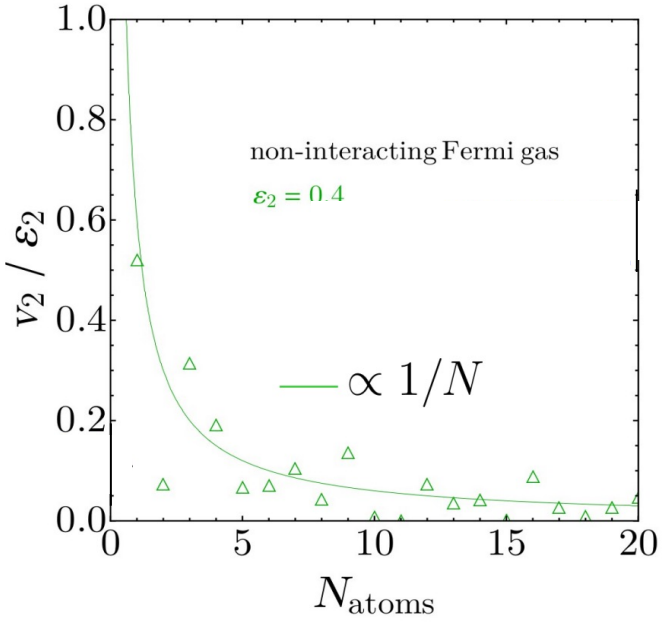
Exciting results on long range correlations in some of the most unlikely places

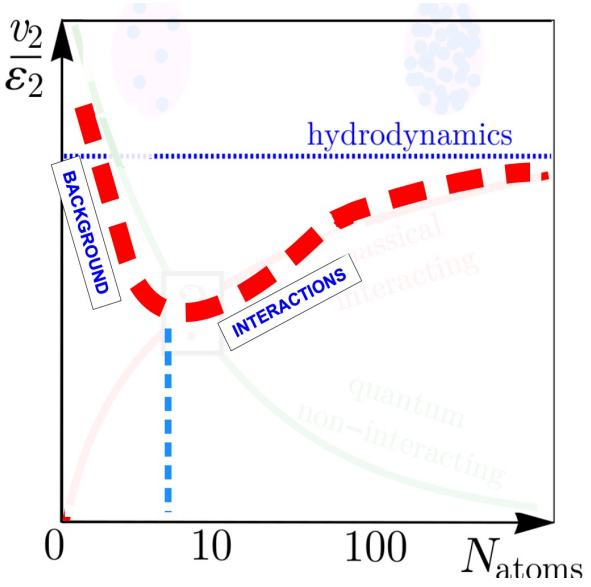
- Low multiplicity pp, e^+e^-, even inside of jets!



[Austin Baty talk], [You Zhou talk]

A word of caution from cold atoms: shape inversion in **non-interacting** Fermi gas!





[Lars Heyen talk]

Difficult challenge for theory: are there other possible sources of these correlations than collectivity?

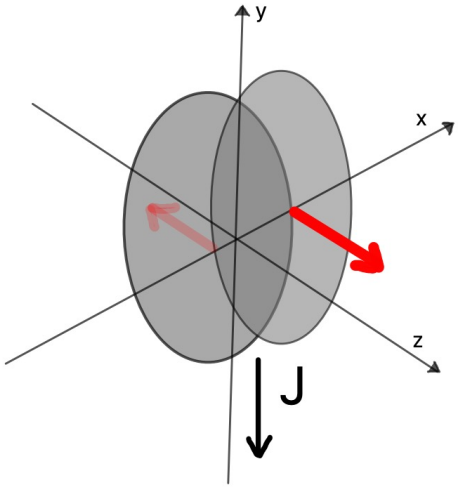
- Maybe high energy physics community can help

Spin hydrodynamics and polarization: current status

Global angular momentum and shear effects couple to the spin of fermions

- macroscopic realization of quantum (spin) effect!

[Xu-Guang Huang talk]



Magnetic moment

$$H_{\text{Zeeman}} = -\gamma \boldsymbol{S} \cdot \boldsymbol{B}$$

magnetic field

Angular momentum

$$H_{\text{Spin-rotation}} = -S \cdot \Omega$$

vortical structure of medium

Spin orbit coupling

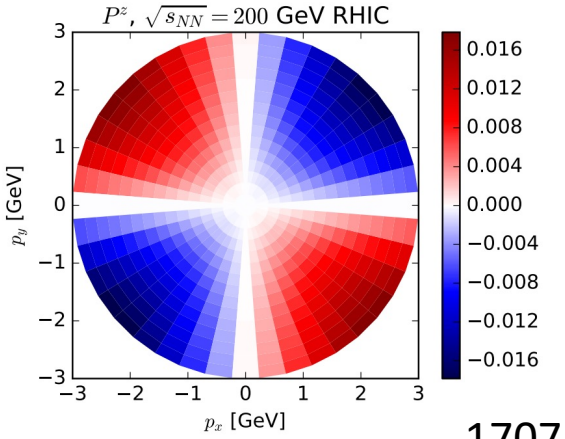
$$H_{\text{SOC-E}} = -\lambda \boldsymbol{S} \cdot (\boldsymbol{p} \times \boldsymbol{E})$$

electric field

Spin orbit coupling

$$H_{\text{SOC-U}} = -\eta \boldsymbol{S} \cdot (\boldsymbol{p} \times \nabla U)$$

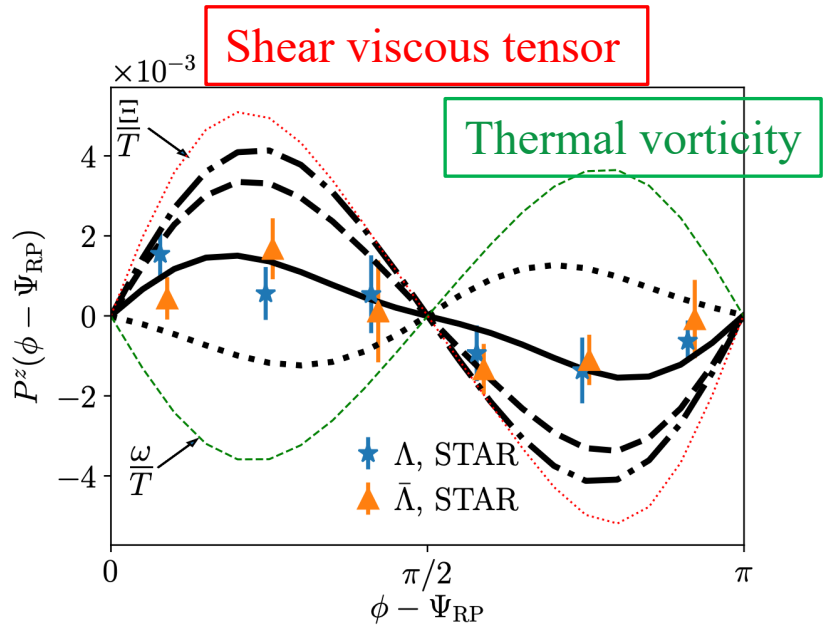
gradients of temperature, density



1707.07984

polarization of Λ

- global: thermal vorticity
- local: large contributions from shear-induced polarization



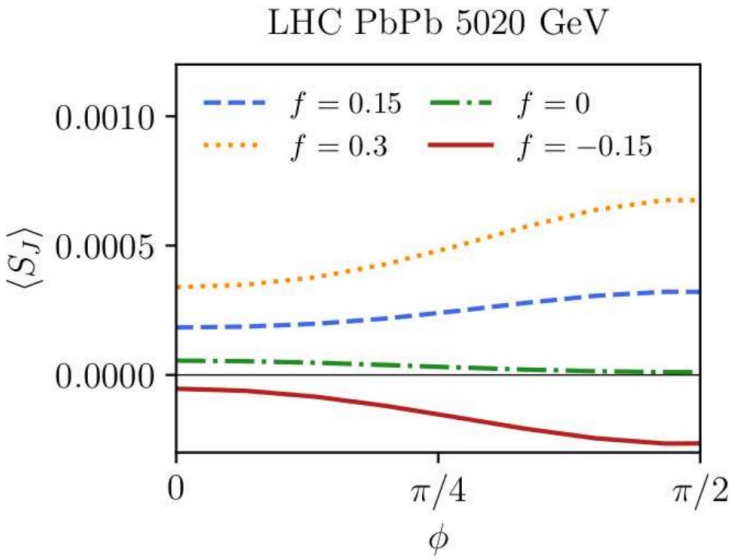
[2103.14621]

Prospects for phenomenology with spin hydrodynamics and polarization

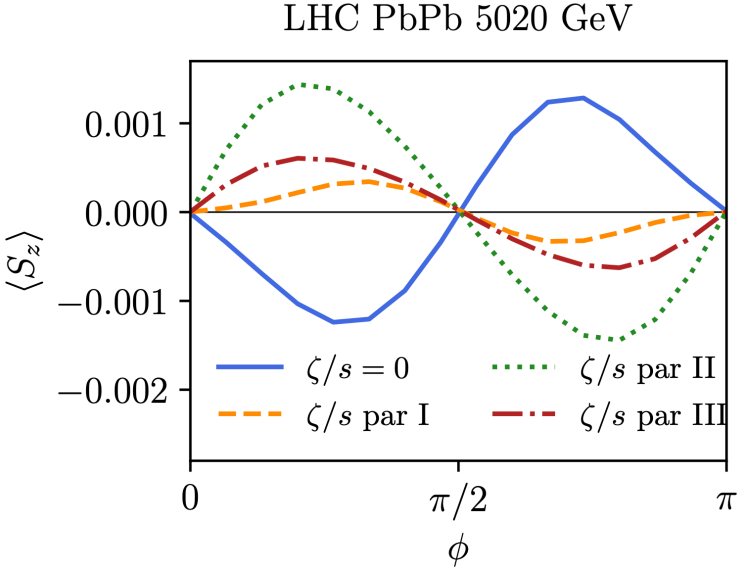
Local polarization appears highly sensitive to features of the flow

[Andrea Palermo talk]

changing longitudinal flow



changing bulk viscosity



Theoretical challenges:

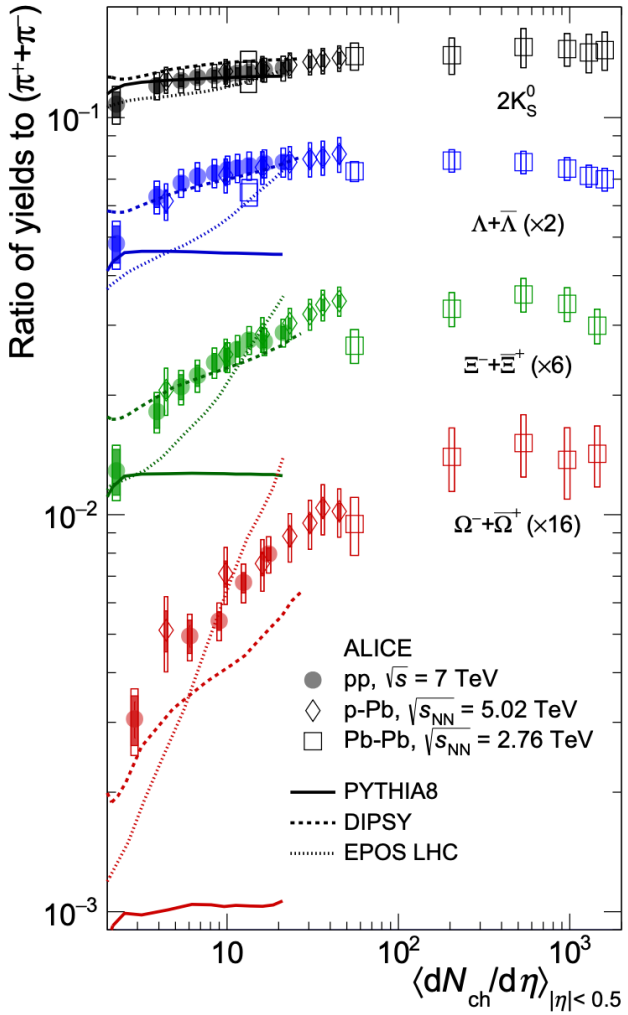
- robustness in more realistic simulations (fluctuations)
- formulating hydrodynamics and kinetic theory with spin, non-equilibrium effects

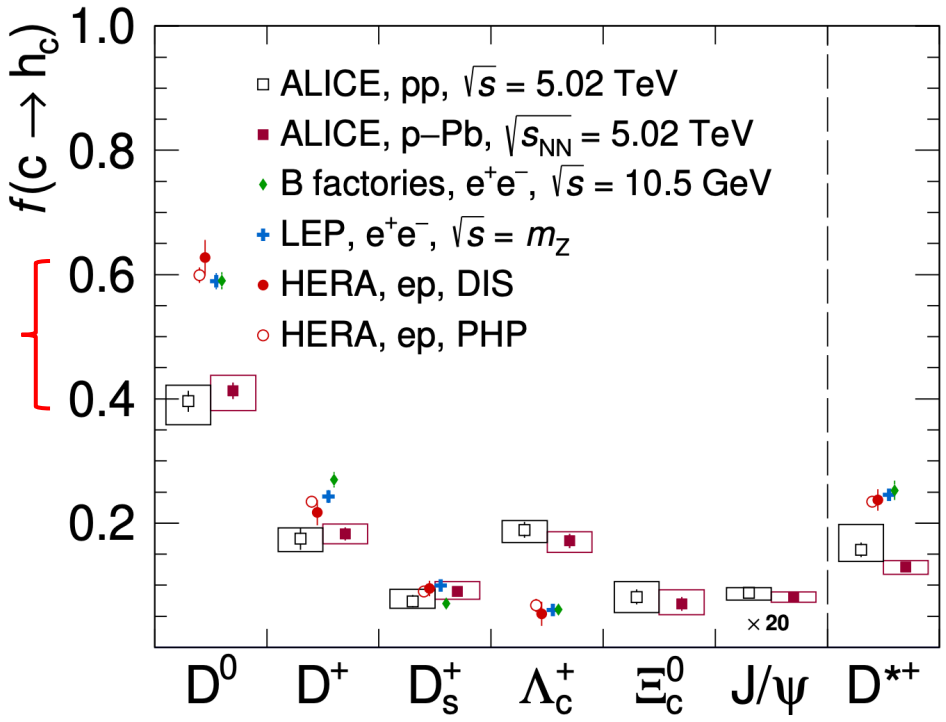
- polarization of vector mesons remains to be understood

[Xu-Guang Huang talk], [Di-Lun Yang talk]

Heavy flavor hadronization: current status

Large enhancements of baryon to meson ratios: non-universality of fragmentation





[2405.14571]

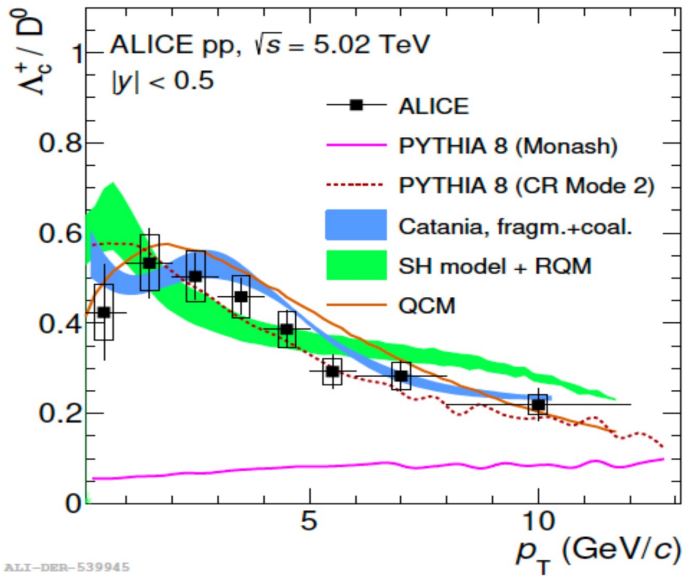
Charm is under better theoretical control since it can't be produced thermally or in hadronization

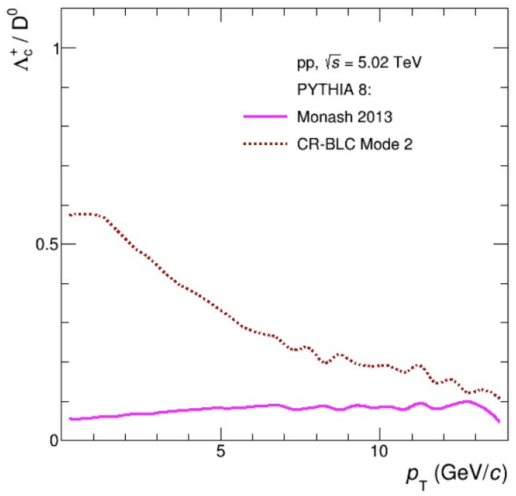
Origin of major differences for charm fragmentation between e^+e^- and pp?

Heavy flavor hadronization: current status

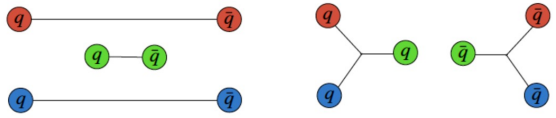
Origin of large baryon/meson enhancement in pp from different effects

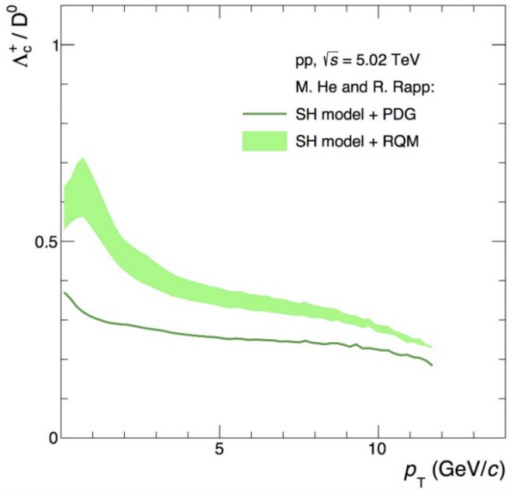
[2405.19137]



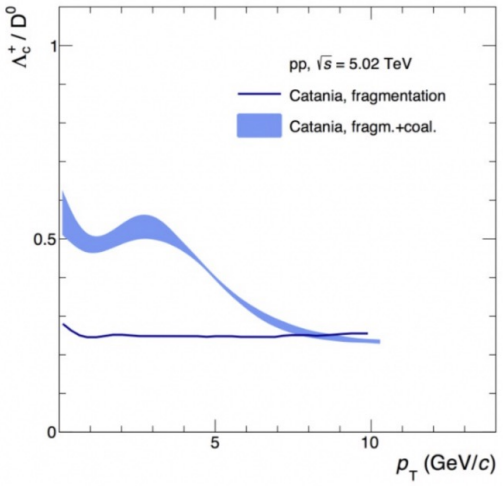


color reconnection

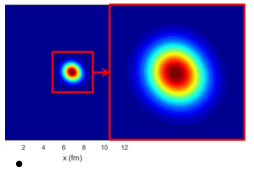




non-PDG resonances



coalescence (collectivity)



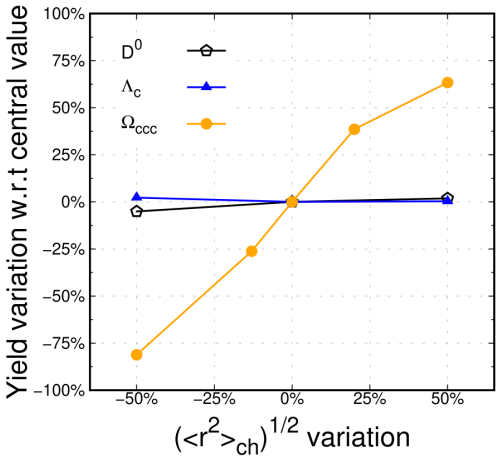
Theoretical challenges: key features and observables to distinguish these scenarios

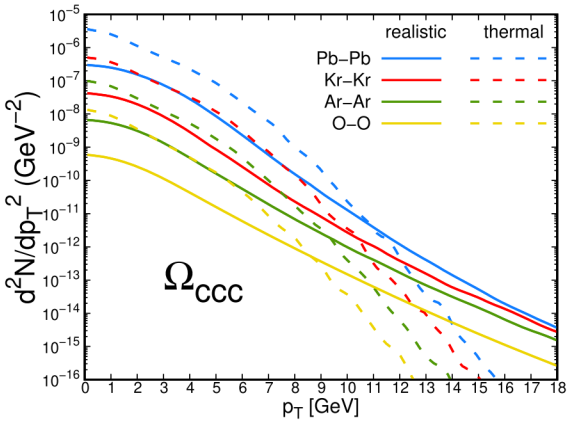
- Yields of other charmed hadrons [Vincenzo Greco talk]
- Fragmentation functions of strange, charm baryons in jets?

Λ_c fragmentation: [2301.13798], strange baryons: [Gijs van Weelden talk]

Observables to distinguish between hadronization mechanisms

Multi-charm hadrons may be more sensitive to hadron wavefunction and to the thermalization of charm





[Salvatore Plumari talk]

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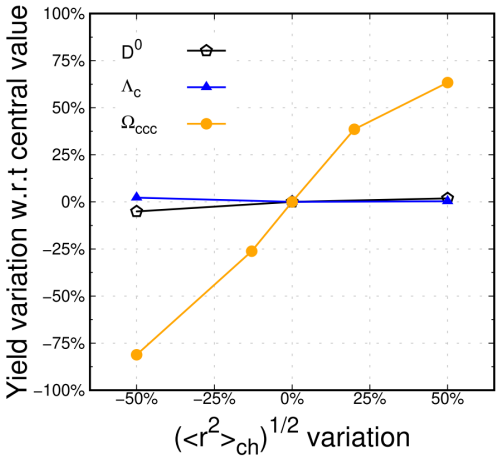
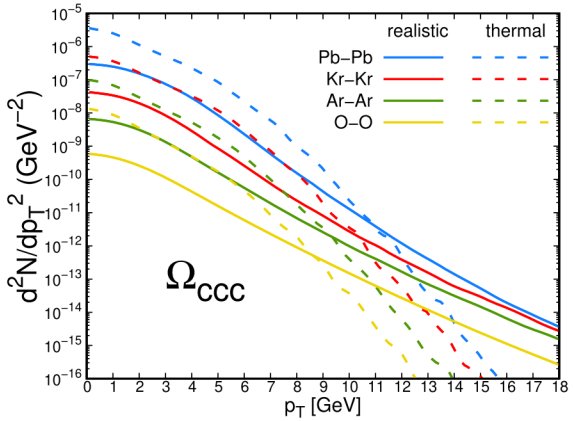




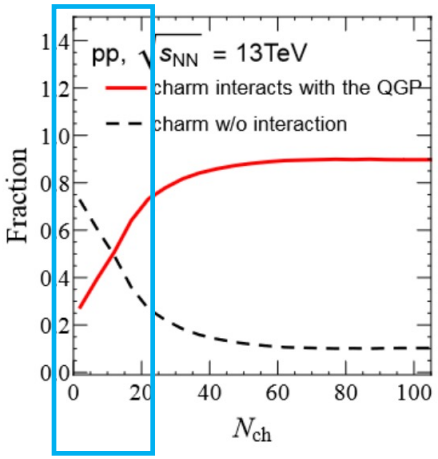
[Salvatore Plumari talk]

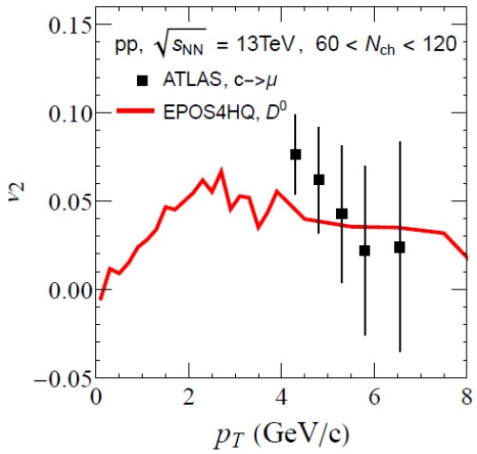
Heavy flavor flow in high-multiplicity pp

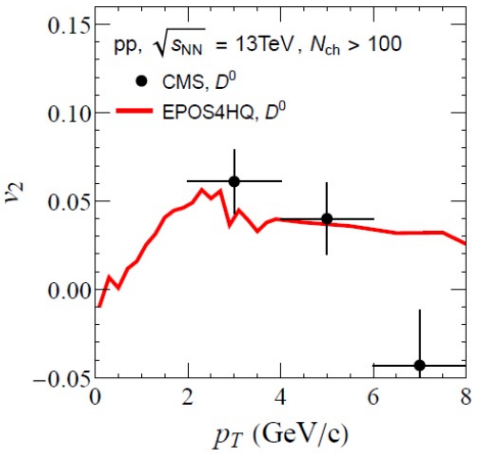
- Is v_2 unique to coalescence and collectivity?

Theory challenge: hydrodynamics in low multiplicity pp collisions built into coalescence scenario for Λ_c/D_0

Fragmentation + coalescence in EPOS4-HQ







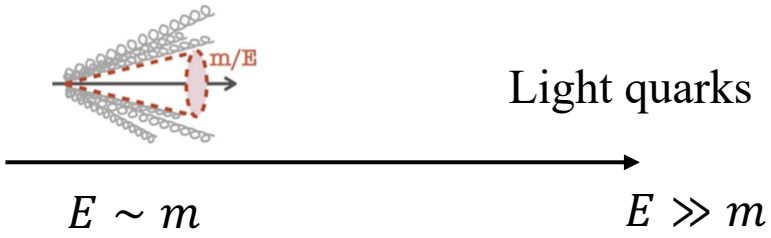
[Pol Gossiaux talk]

Heavy flavor energy loss: current status and opportunities

Heavy quark energy loss is special

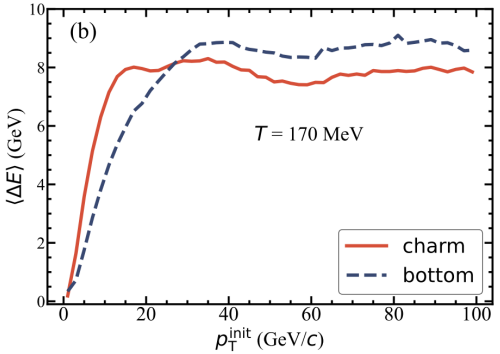
- Conserved: not produced in the medium or during hadronization charm hadron → charm quark in shower
- Complex interplay between vacuum-like, collisional and radiative processes due to the mass

- suppressed vacuum radiation
- less medium-induced radiation



Non-trivial mass-dependence of energy loss?

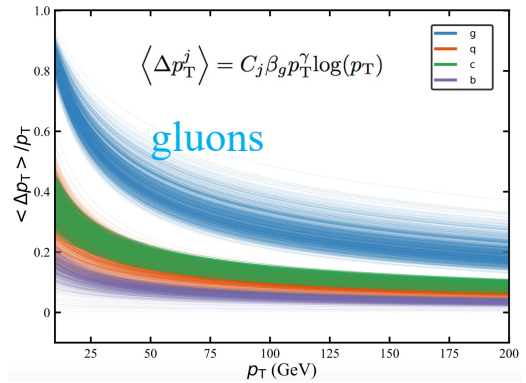
[Yichao Dang talk]



Bayesian analysis of flavor dependence

[Wen-Jing Xing talk]

light
charm
bottom



Heavy flavor: unique opportunity to trace a parton from the highest to lowest scales in heavy ion collisions

Thanks for a fascinating SQM!

Search for the QCD critical point

Pushing the boundaries of hydrodynamics

Dynamics of open heavy flavor

Astrophysics, light(er) hadronization, quarkonia …. (not covered)

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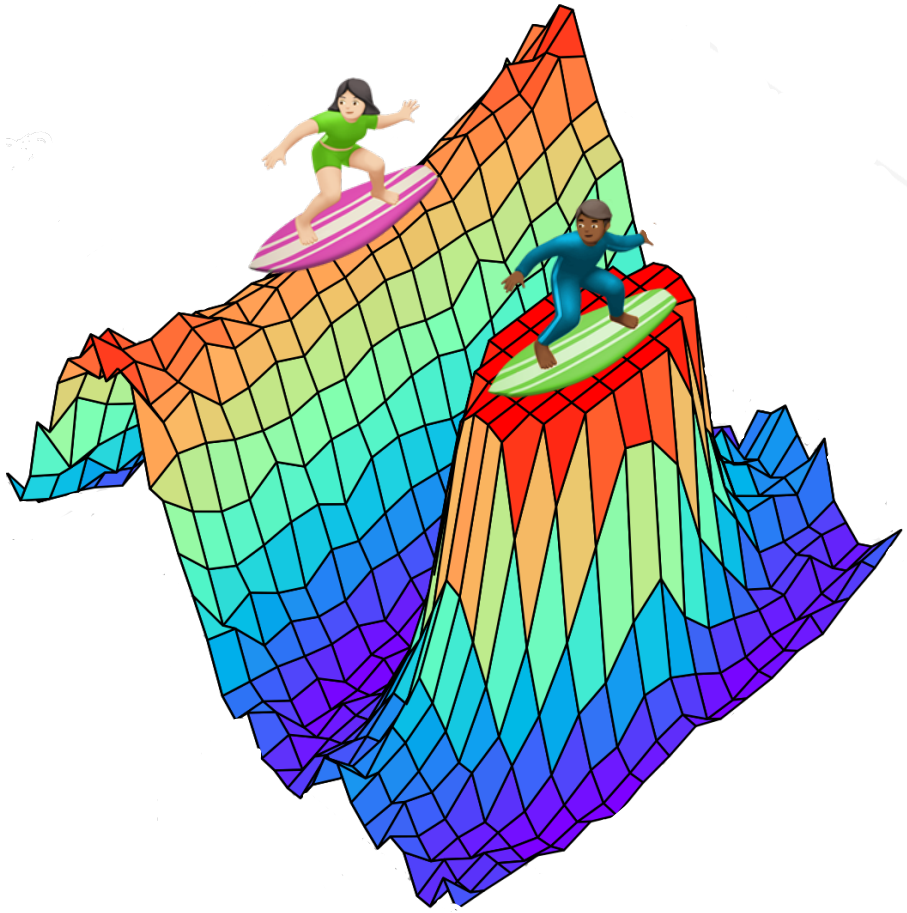

Frontiers of Quark-Gluon Matter

Dates: March 9th – May 7th 2026

Organizers: A. Kurkela, I. Moult, W. v.d.Schee, B. Schenke, A. Soto-Ontoso, JB