Hot Topics in Heavy Ion Collisions Theory

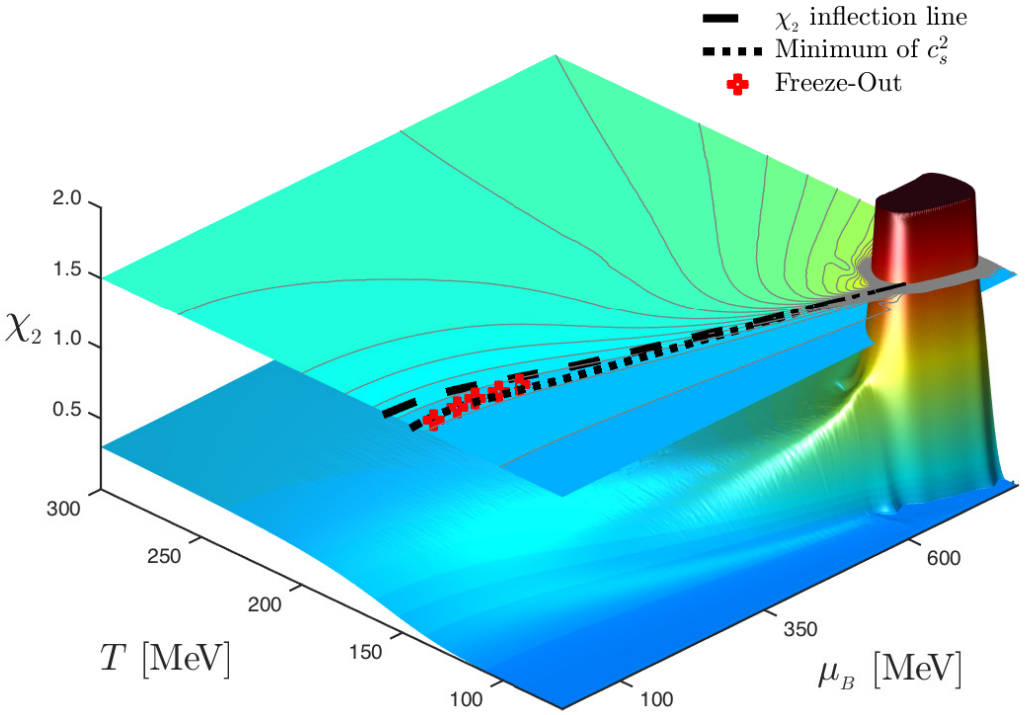
Jacquelyn Noronha-Hostler
University of Houston

RHIC & AGS User's Meeting 2017
June 22th 2017

Sadly I won't be able to cover

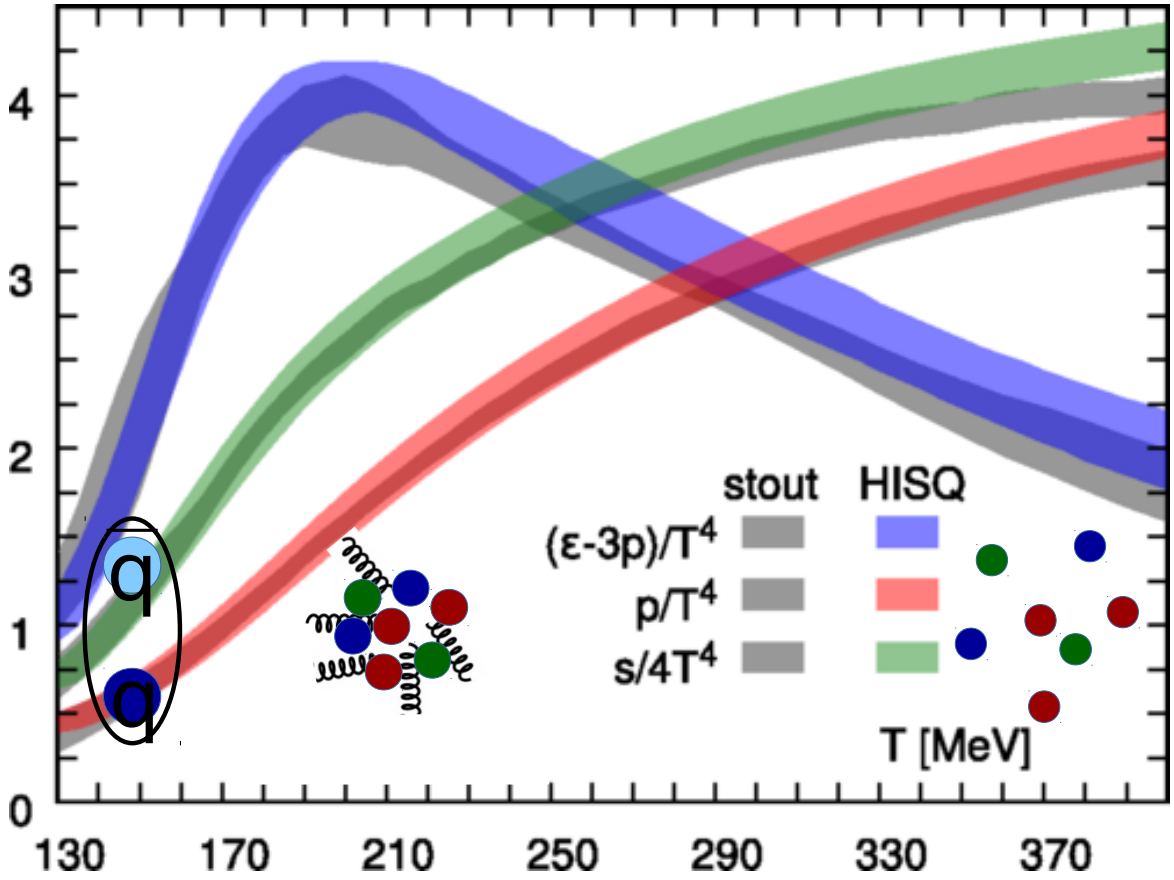
- Electron Ion Collider/Spin
  (Matt Sievert, Ferdinand Willeke, Salvatore Fazio, Bernd Surrow)
- sPHENIX
  (Rosi Reed, Anne Sickles, Sanghwa Park)
- Small Systems
  (Mark Mace, Shenglu Huang, Heikki Mantysaari)
- Heavy Flavor
  (Miguel Escobedo, Zhenyu Ye)

Equation of State



Equation of State- Lattice QCD

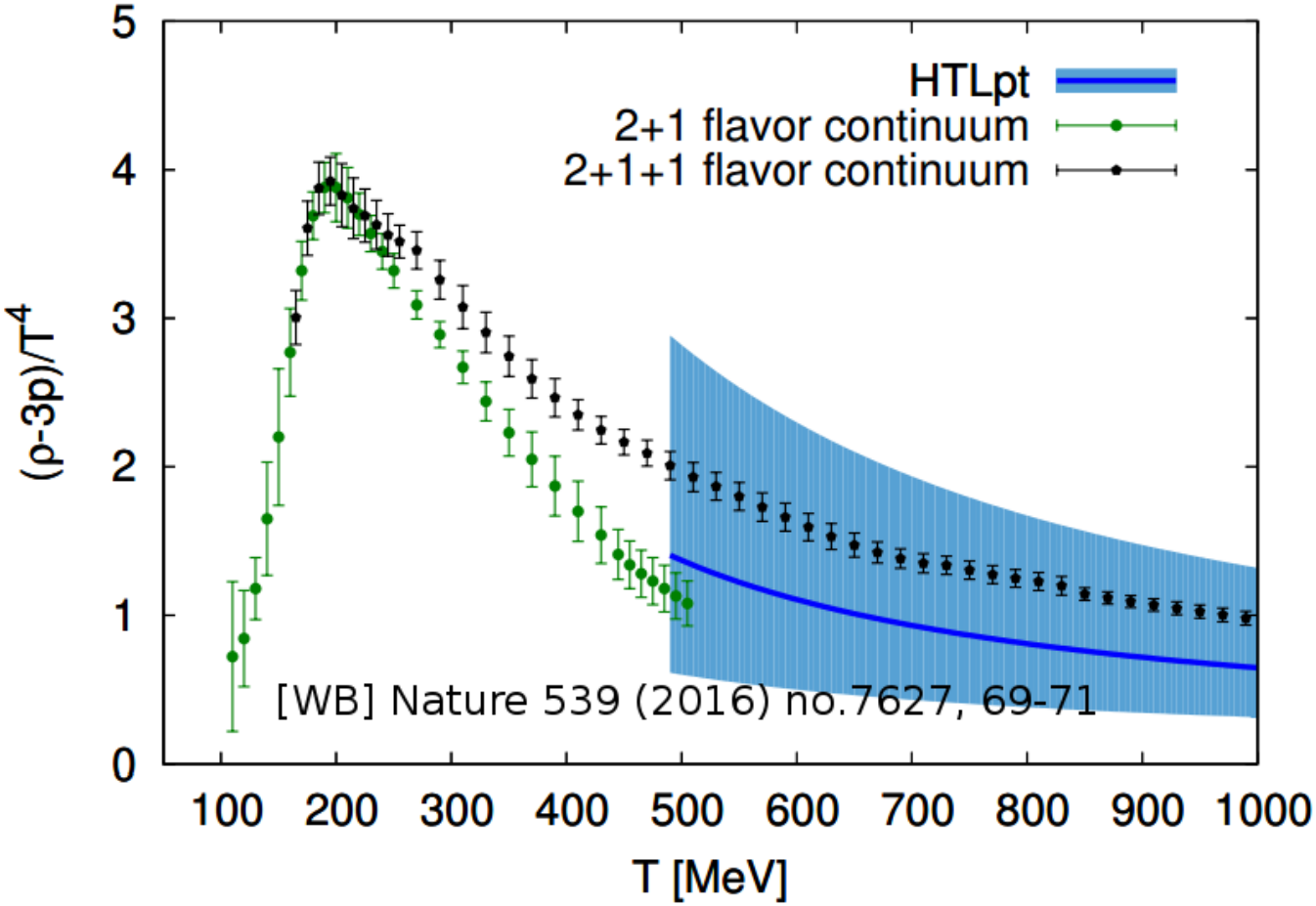
Equation of State agrees for stout (WB) and HISQ (HotQCD) actions



WB Phys.Lett. B730 (2014) 99-104
HotQCD Phys.Rev. D90 (2014) 094503

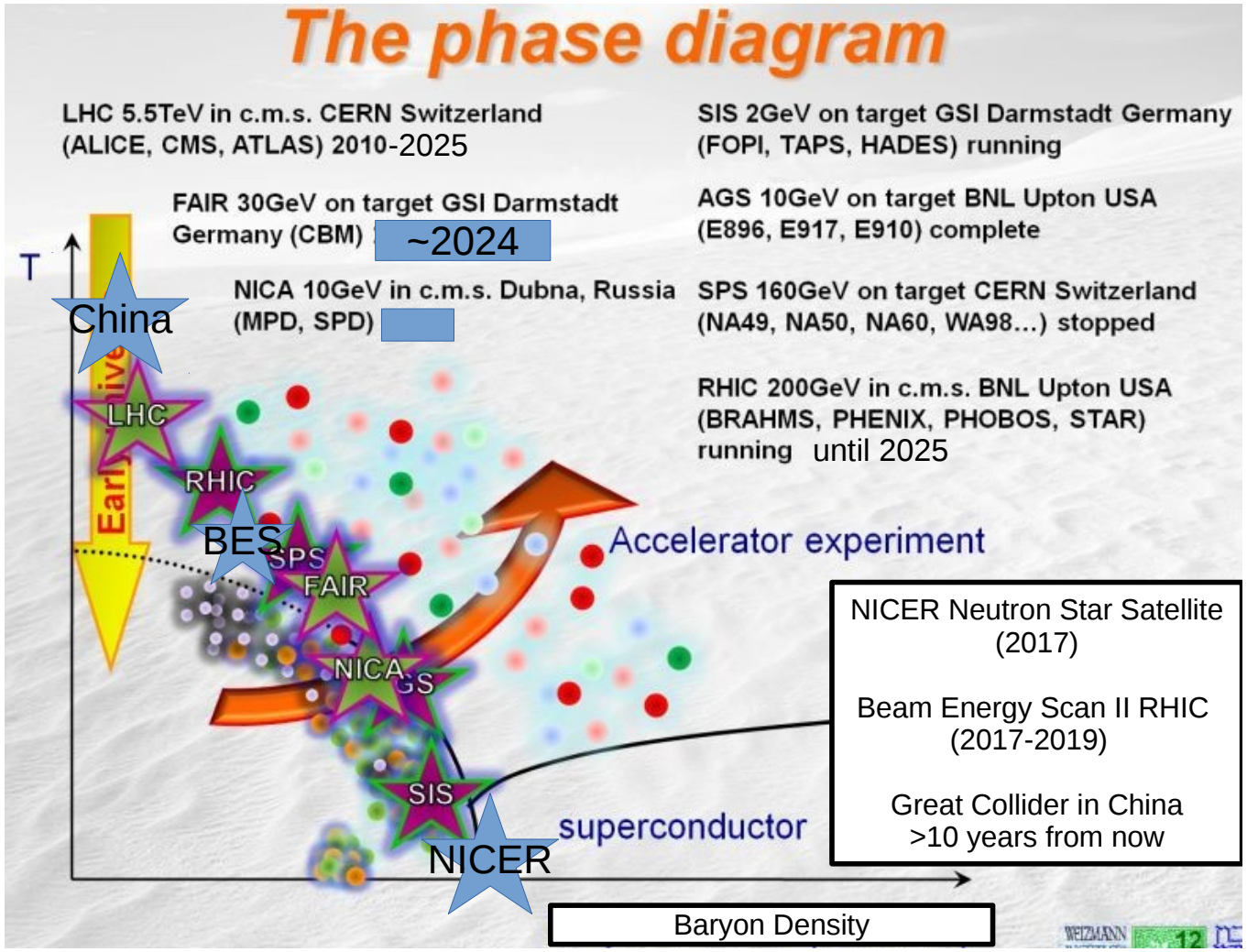
Thermalized charm quarks?

Still questions at $\mu_B = 0$. Sensitive Observables?



WB Collaboration Nature 539 (2016) no.7627, 69-71

Large baryon densities

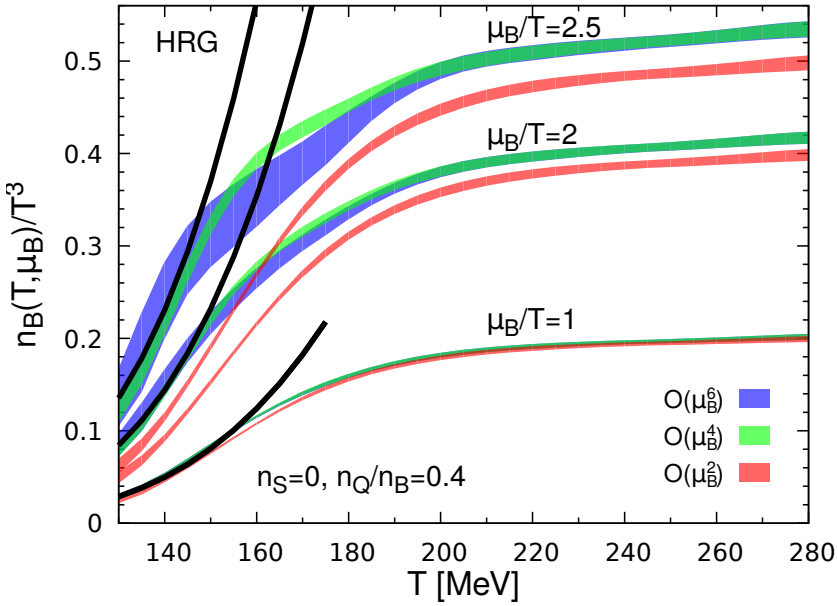


Reconstructing EOS at finite μ_B from Lattice QCD

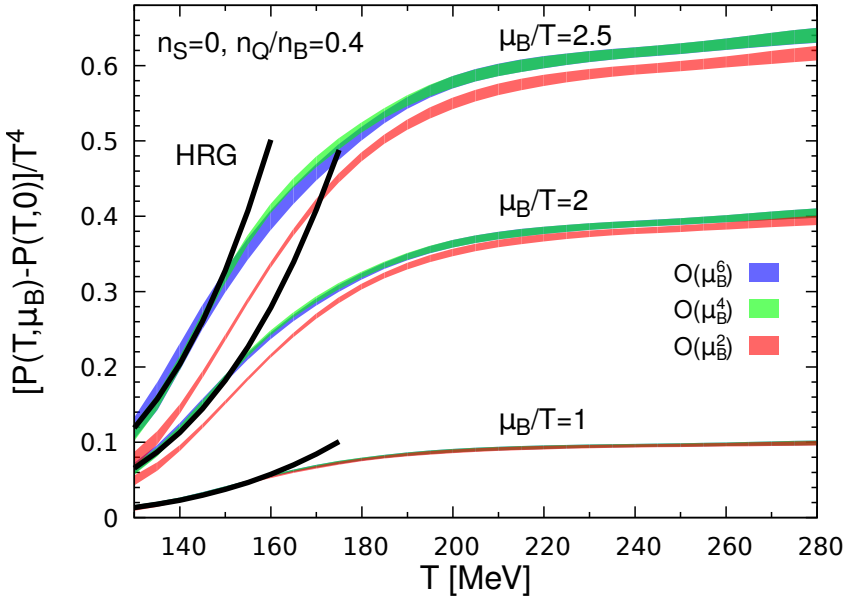
BEST COLLABORATION

Lattice QCD Equation of State+ variable CP

See also J. Noronha Tues and S. Sharma Weds



HotQCD Phys.Rev. D95 (2017) no.5, 054504



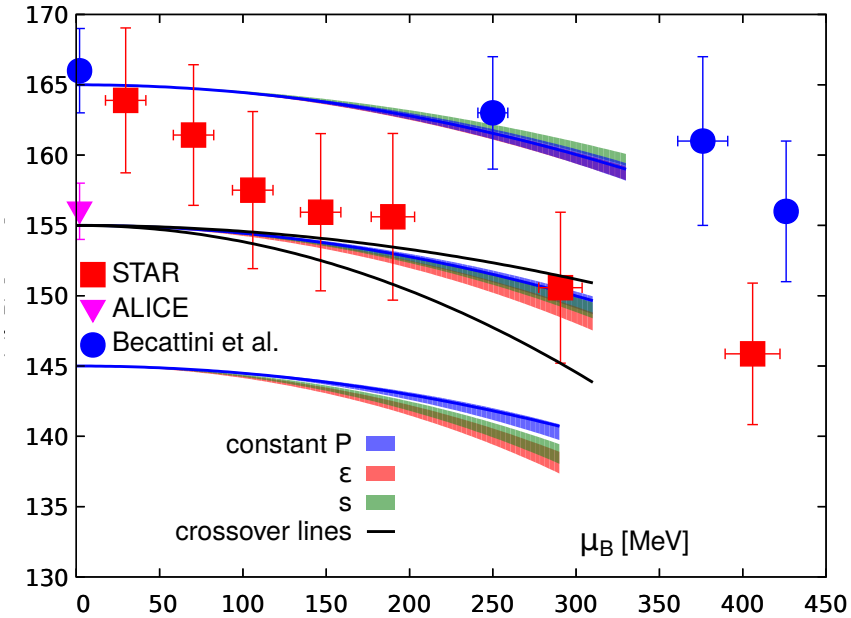
HotQCD Phys.Rev. D95 (2017) no.5, 054504

Critical Point

No sign of criticality up to $\mu_B/T \leq 2$ and $T \geq 0.9T_c$ for $\mathcal{O}(\mu_B^6)$

Mapping the phase diagram- part 1

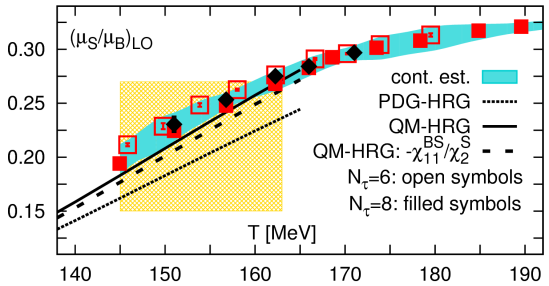
$$T_f(\mu_B) = T_0 \left(1 - \kappa_2^f \left(\frac{\mu_B}{T_0}\right)^2\right)$$



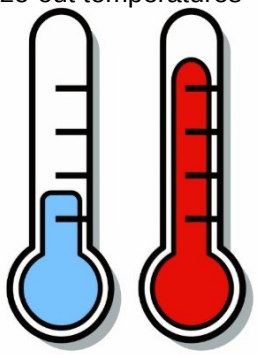
See S. Sharma

- Lattice QCD: relatively flat curvature across μ_B
- Thermal fits consistently above the pseudo-critical T

Missing strange baryons?



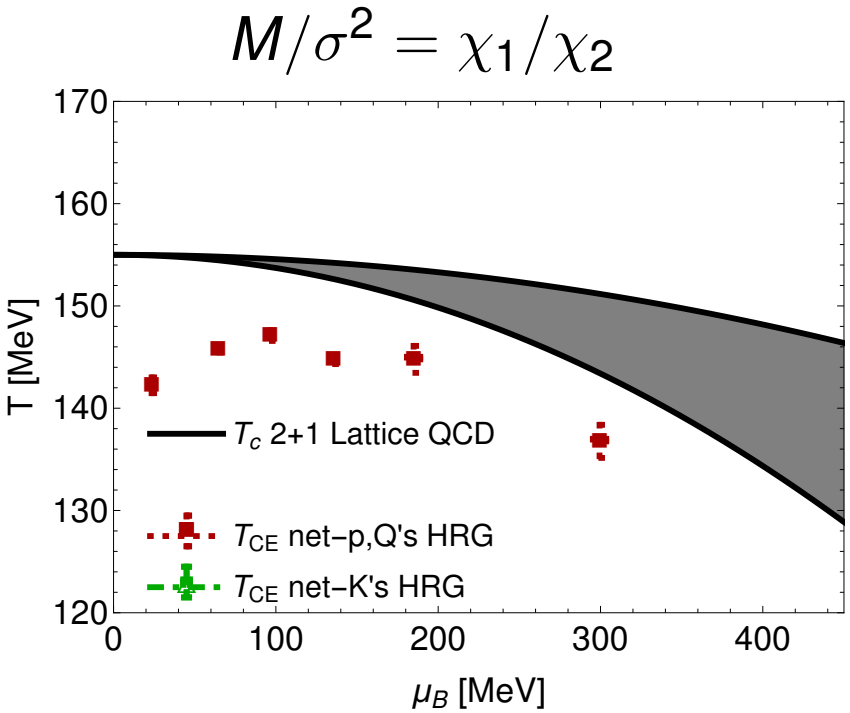
Separate lights vs. strange freeze-out temperatures



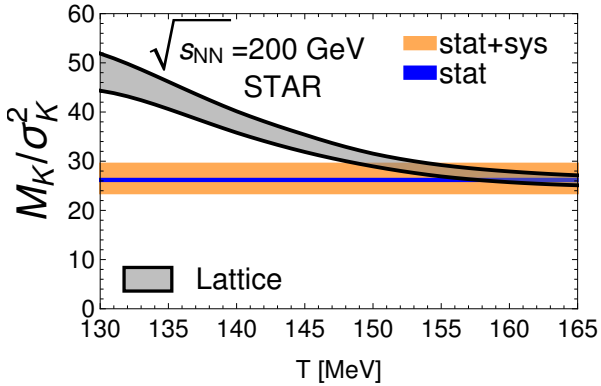
References

Lattice QCD [HotQCD] PRD95 (2017) no.5, 054504, PRD 83, 014504 (2011); [WB] PLB 751, 559 (2015), JHEP 1104, 001 (2011); [INFN] PRD 92, no. 5, 054503 , **Thermal Fits** [STAR] arXiv:1701.07065; [ALICE] J.Phys.Conf.Ser. 779 (2017) no.1, 012012; **Missing Hadrons**: PRL113 (2014) no.7, 072001; NPA931 (2014) 1108-1113 ; arXiv:1702.01113 **2 Temperatures**: PRL111 (2013) 202302

Mapping the phase diagram- part 2



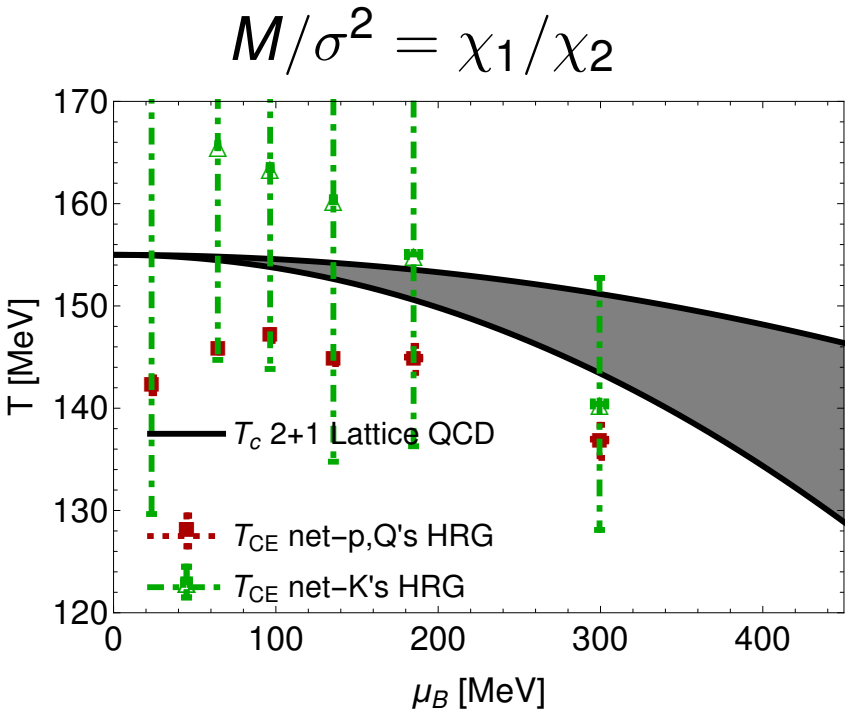
- net-K results including most up-to-date strange resonances $\rightarrow T_{str} > T_{light}$
- net-K comparisons to Lattice QCD (partial pressures) $T_{str} \geq 148$ MeV



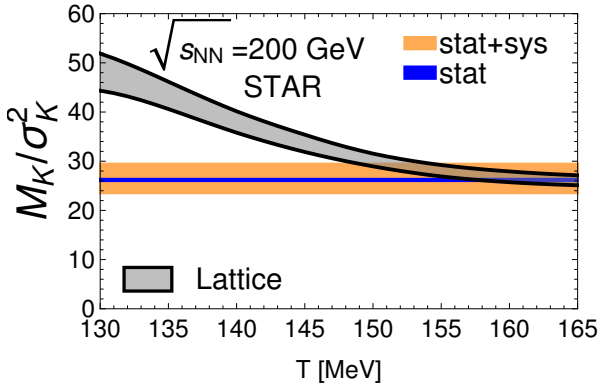
References

Lattice QCD [HotQCD] Phys.Rev. D95 (2017) no.5, 054504, Phys. Rev. D 83, 014504 (2011); [WB] Phys. Lett. B 751, 559 (2015), JHEP 1104, 001 (2011); [INFN] Phys. Rev. D 92, no. 5, 054503 , **net-p,Q HRG** Phys.Lett. B738 (2014) 305-310 **net-K HRG** HRG from [WB] arXiv:1702.01113; **Partial Pressures** arXiv:1607.02527

Mapping the phase diagram- part 3



- net-K results including most up-to-date strange resonances $\rightarrow T_{str} > T_{light}$
- net-K comparisons to Lattice QCD (partial pressures) $T_{str} \geq 148$ MeV

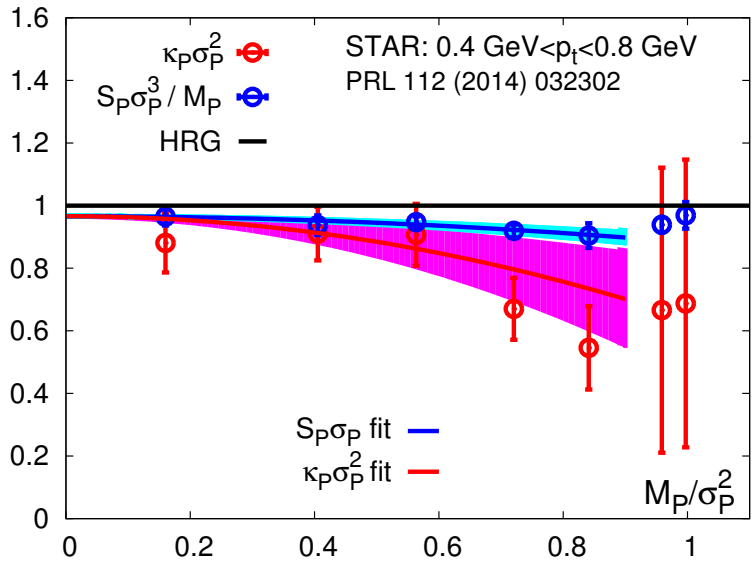


References

Lattice QCD [HotQCD] Phys.Rev. D95 (2017) no.5, 054504, Phys. Rev. D 83, 014504 (2011); [WB] Phys. Lett. B 751, 559 (2015), JHEP 1104, 001 (2011); [INFN] Phys. Rev. D 92, no. 5, 054503 , **net-p,Q HRG** Phys.Lett. B738 (2014) 305-310 **net-K HRG** HRG from [WB] arXiv:1702.01113; **Partial Pressures** arXiv:1607.02527

net-p Skewness vs. kurtosis

$$\kappa\sigma^2(\sqrt{s_{NN}}) = \frac{\chi_4}{\chi_2}(T,\mu_B)_{CE} = \underbrace{r_{42}^{B,0}}_{r_{31}^{B,0}} + \underbrace{r_{42}^{B,2}}_{3r_{31}^{B,2}}(\mu_B/T) + \mathcal{O}(\mu_B^4)$$



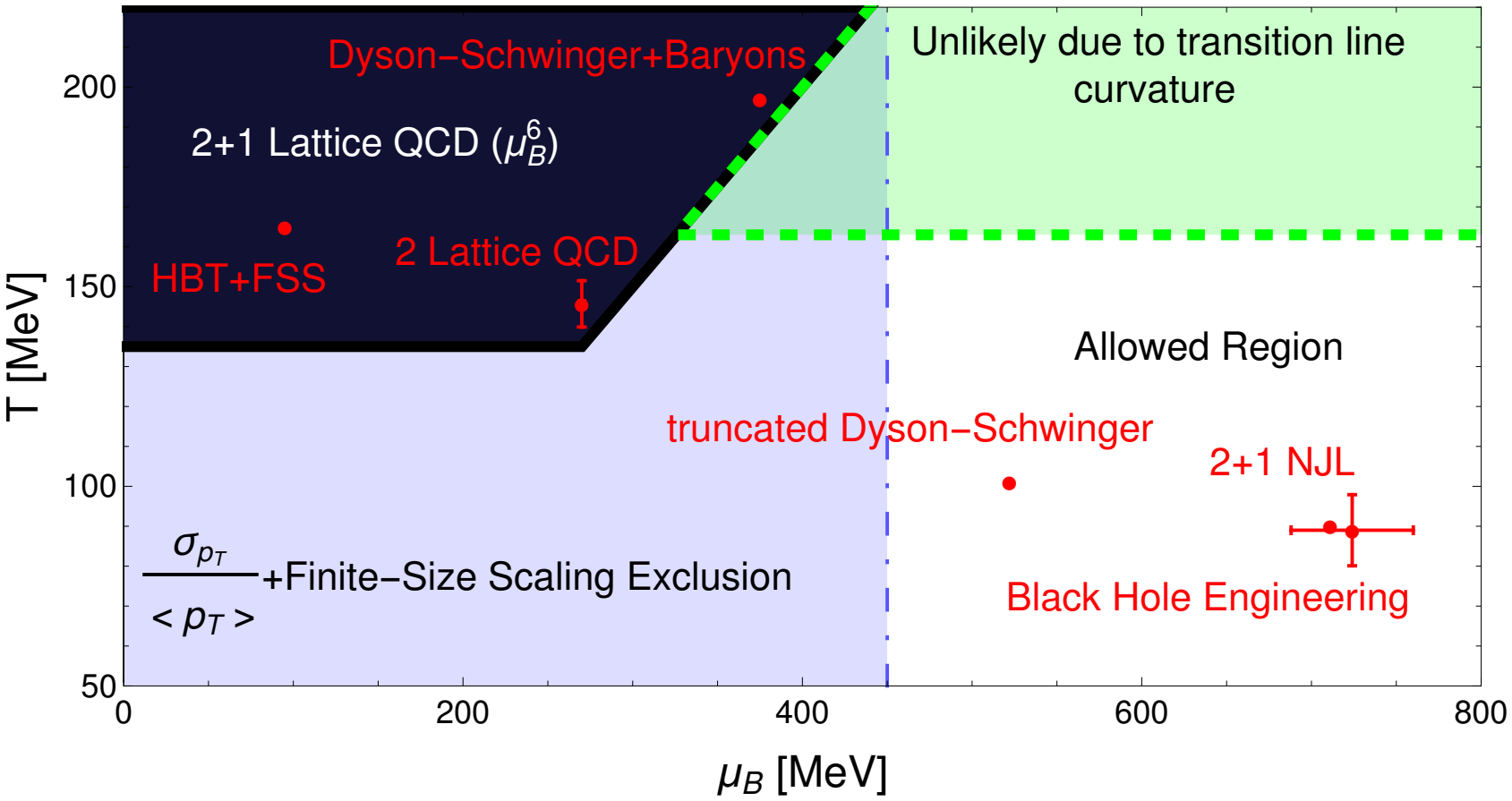
Many caveats:

- Volume variation vs. centrality binning V. Skokov et al., PRC (2013)
- Efficiencies A.Bzdak,V.Koch, PRC (2012)
- Spallation protons
- Kinematic/acceptance cuts V. Koch, S. Jeon, PRL (2000)
- Protons vs. baryon fluctuations M. Asakawa and M. Kitazawa, PRC(2012), M. Nahrgang et al., EPJ(2015)
- Hadronic interactions J.Steinheimer et al., PRL (2013)

References

Lattice QCD J.Phys.Conf.Ser. 779 (2017) no.1, 012015;

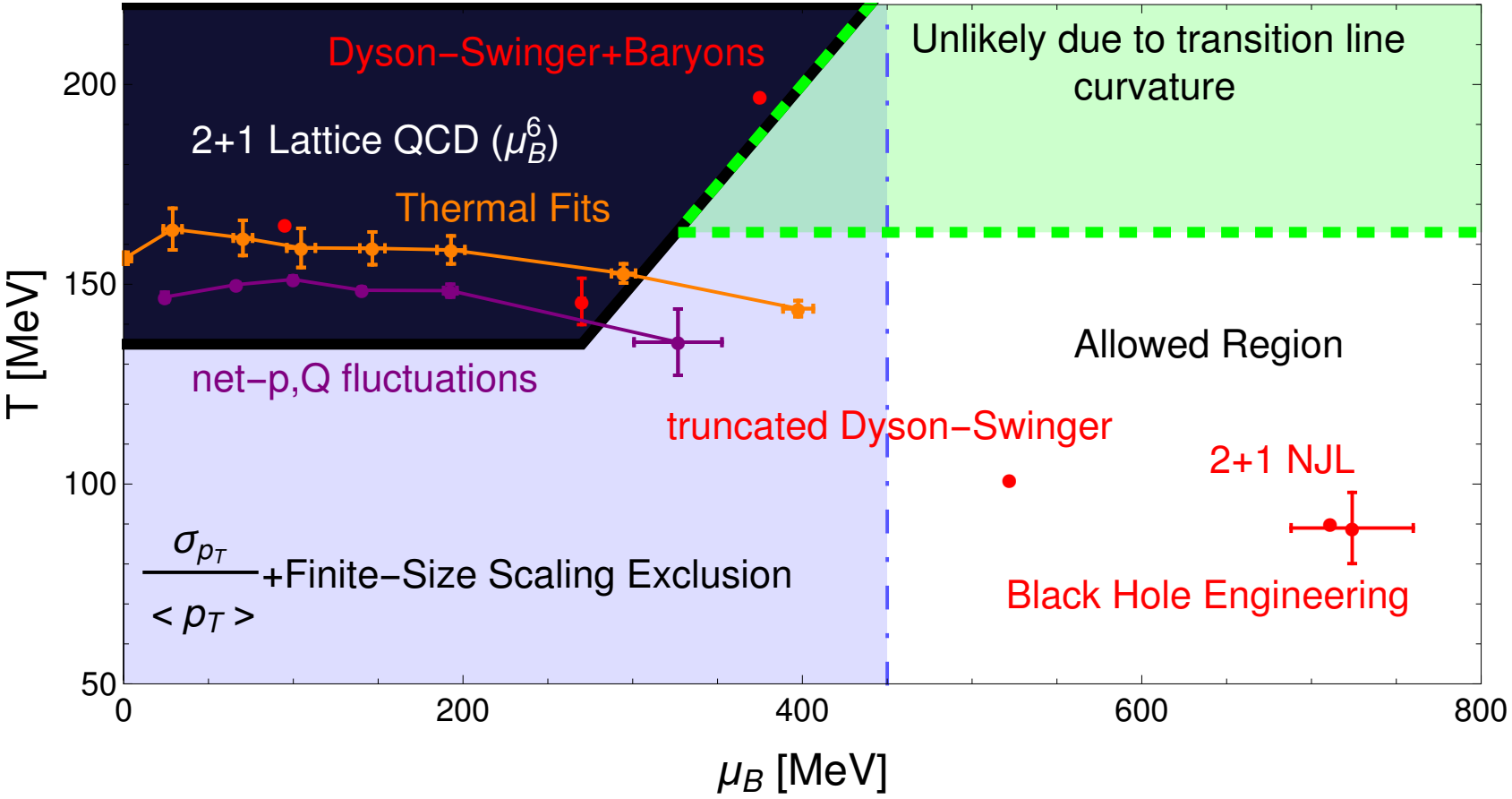
Modern Critical Point Predictions



References

Lattice QCD [HotQCD]PRD95(17)no.5,054504; **Finite-Size Scaling**PRC84,011903(11); **R. Lacey** PRL114(15)no.14,142301; **Black Hole Engineering** arXiv:1706.00455; **2+1 Polyakov Loop**PLB732(14)273; **Dyson-Swinger**PRD93(16)no.3,034013 ; **DGG**PRD95(17)no.5,054512; **2+1 NJL**IJMPA32(17)no.11,1750061; Older summary: Stephanov PoS LAT2006:024,2006

Modern Critical Point Predictions

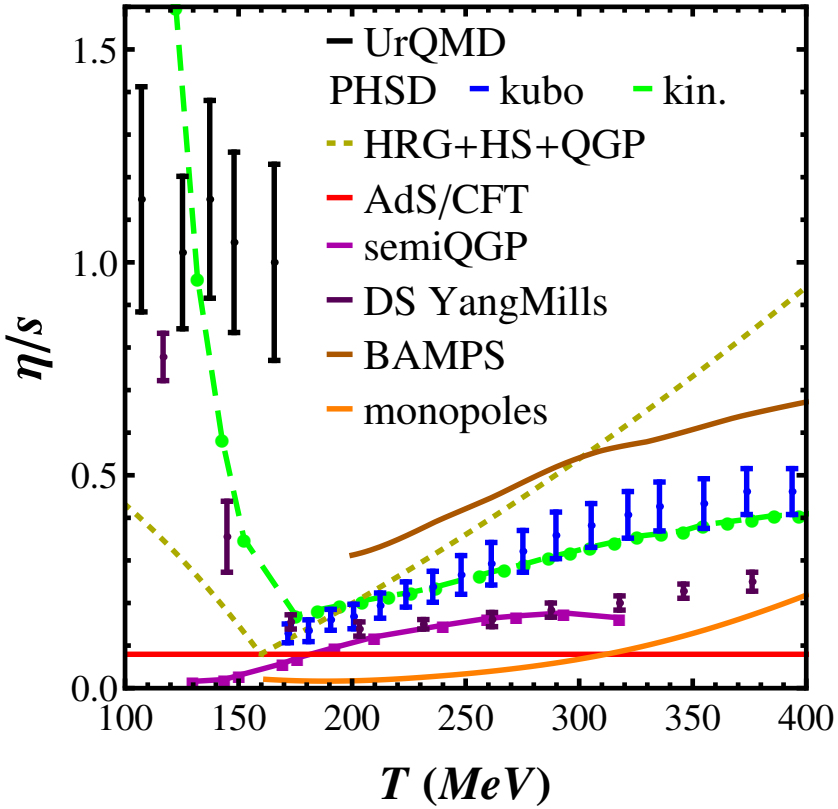


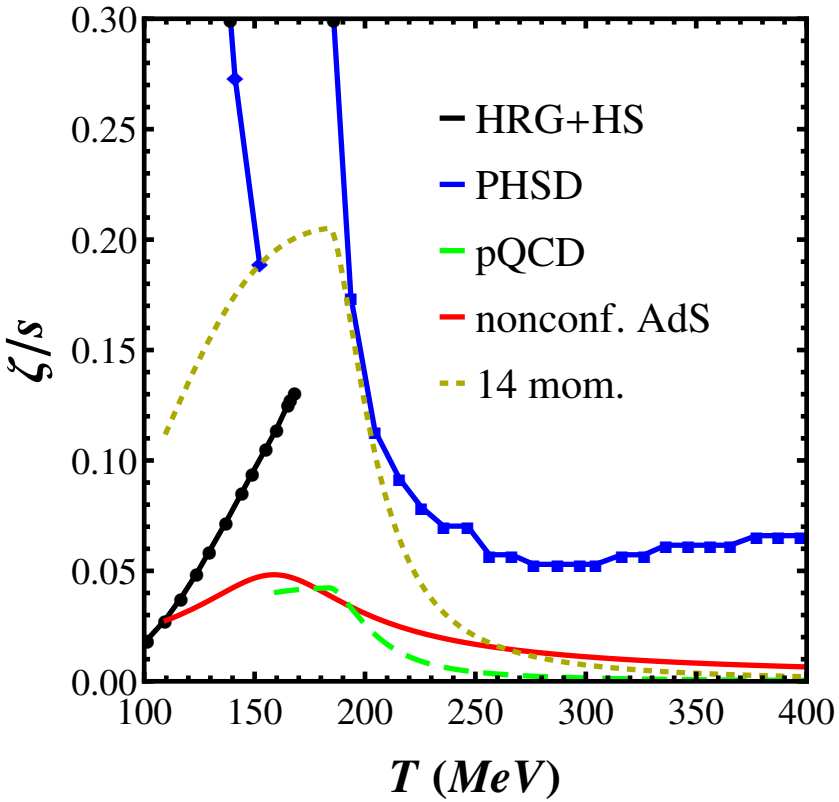
References

Lattice QCD [HotQCD]PRD95(17)no.5,054504; **Finite-Size Scaling**PRC84,011903(11); **R. Lacey** PRL114(15)no.14,142301; **Black Hole Engineering** arXiv:1706.00455; **2+1 Polyakov Loop**PLB732(14)273; **Dyson-Swinger**PRD93(16)no.3,034013 ; **DGG**PRD95(17)no.5,054512; **2+1 NJL**IJMPA32(17)no.11,1750061; Older summary: Stephanov PoS LAT2006:024,2006

Transport Coefficients ($\eta/s(T,\mu_B)$, $\zeta/s(T,\mu_B)$, $D_B(T,\mu_B)$ ...)

Theoretical calculations of viscosity at $\mu_B = 0$



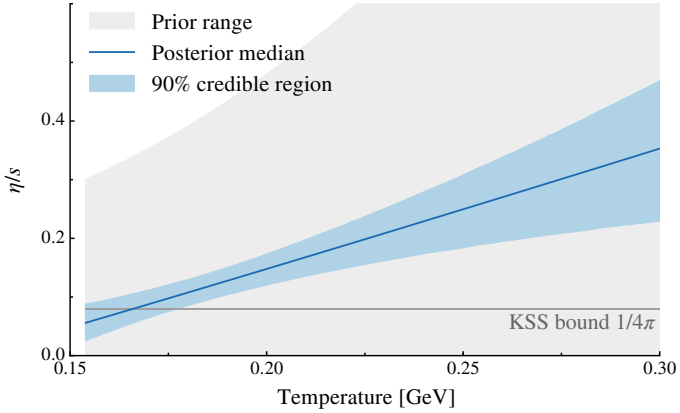


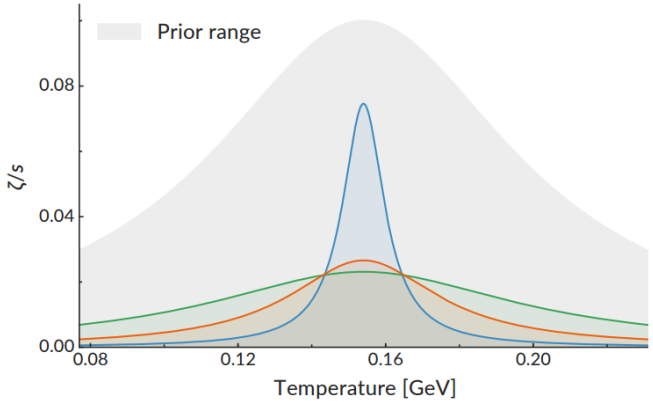
References

See references in JNH arXiv:1512.06315

Bayesian Analysis

$$T_{min\eta/s} = T_{peak\zeta/s} = T_{SW}$$



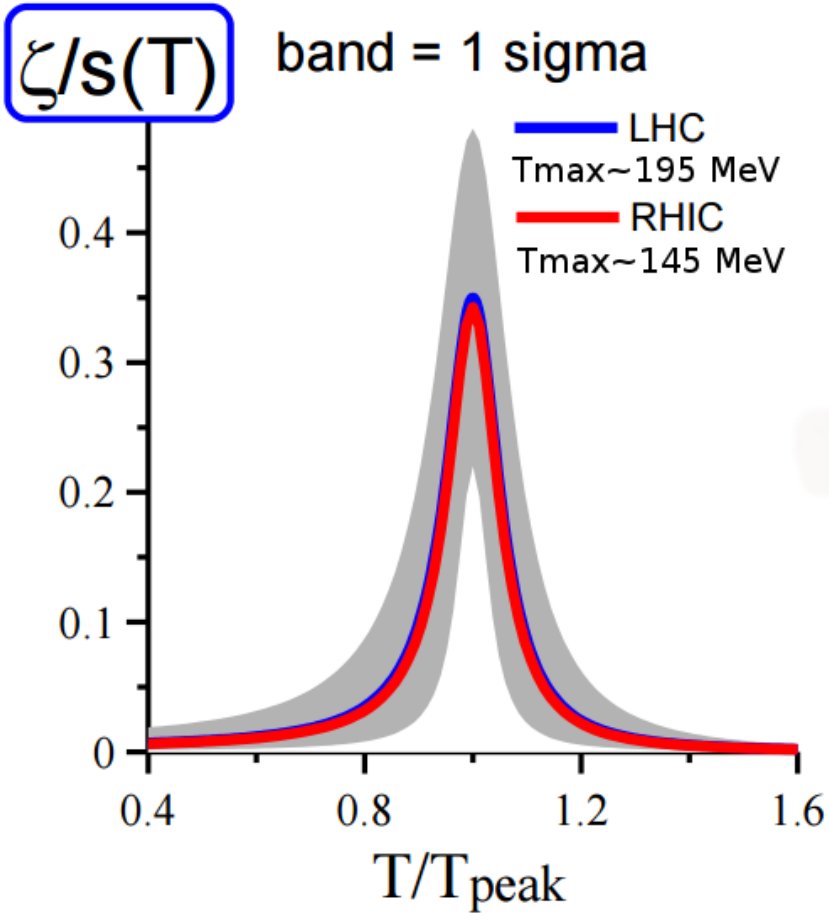


[*DUKE*] arXiv:1704.04462

Small systems?

Talks by R. Belmont, M. Mace, S. Huang

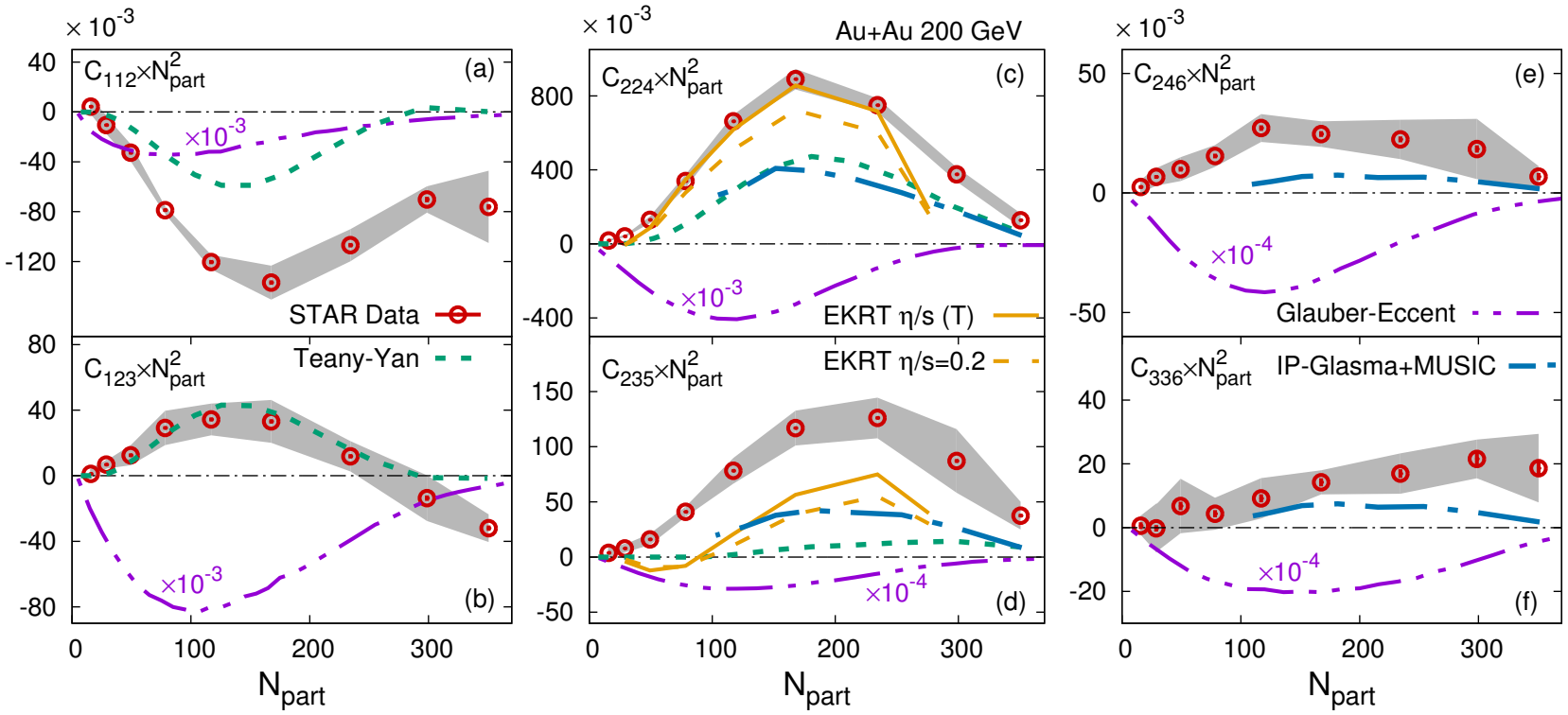
$$(\eta/s)_{RHIC} \sim 0.12$$
$$(\eta/s)_{RHIC} \sim 0.06$$



[*McGill*] Gabriel Denicol Quark Matter 2017

Mixed Harmonic Correlations- a solution?

$$C_{m,n,m+n} = \langle \cos(m\phi_1 + n\phi_2 - (m+n)\phi_3) \rangle$$



[*STAR*] arXiv:1701.06497

Need to understand $v_1, v_5, v_6 \rightarrow \varepsilon_n$'s or $\eta/s(T)$, $\zeta/s(T)$?

BES: Viscosity vs. Dynamic Universality Class

No Critical Point

- $\Uparrow \mu_B$, $\Downarrow$ viscosity
- From HRG, Transport: Kadam, Mishra Nucl.Phys. A934 (2014) 133-147
  See also Denicol, Jeon, Gale, Noronha Phys.Rev. C88 (2013) no.6, 064901

Critical Point Universality Class H

- Divergence $\Uparrow$ in viscosity at CP
- 3D Ising Model-Mixing between chiral condensate and baryon density

  PRD70 (2004) 056001

Critical Point Universality Class B

- Finite viscosity at CP
  PRL115(2015)no.20,202301
- AdS/CFT:
  PRD78 (2008) 106007
  AdS/non-CFT:
  PRD83(2011)086005

Dynamical CP phenomena Review

Rev. Mod. Phys. 49, 435

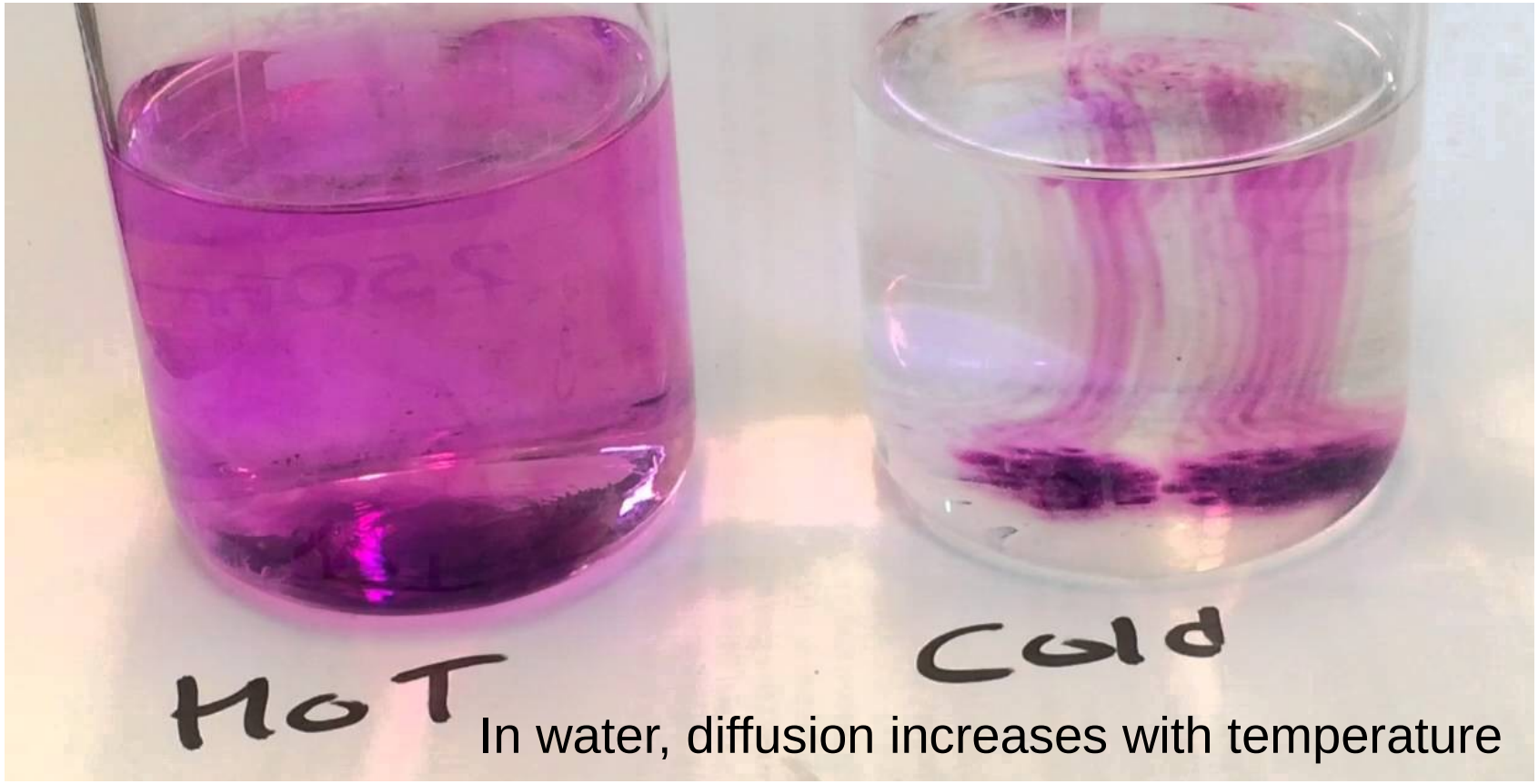
Hydrodynamic upgrades needed at the BES

Make hydrodynamic code MUSIC ready for the BES by

- including finite net-baryon density
  - equation of state (EoS) at finite net-baryon density
  - baryon diffusion
  - test EoS with critical point
- coupling it to a **dynamical** fluctuating initial state appropriate for long medium formation times
- including a proper treatment of strangeness and isospin (not yet in this talk)

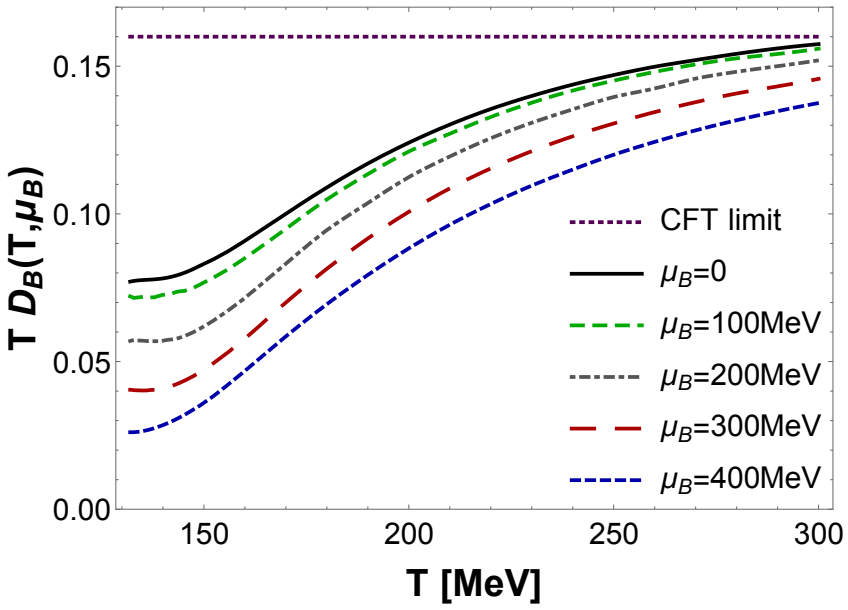
from B. Schenke Tues.

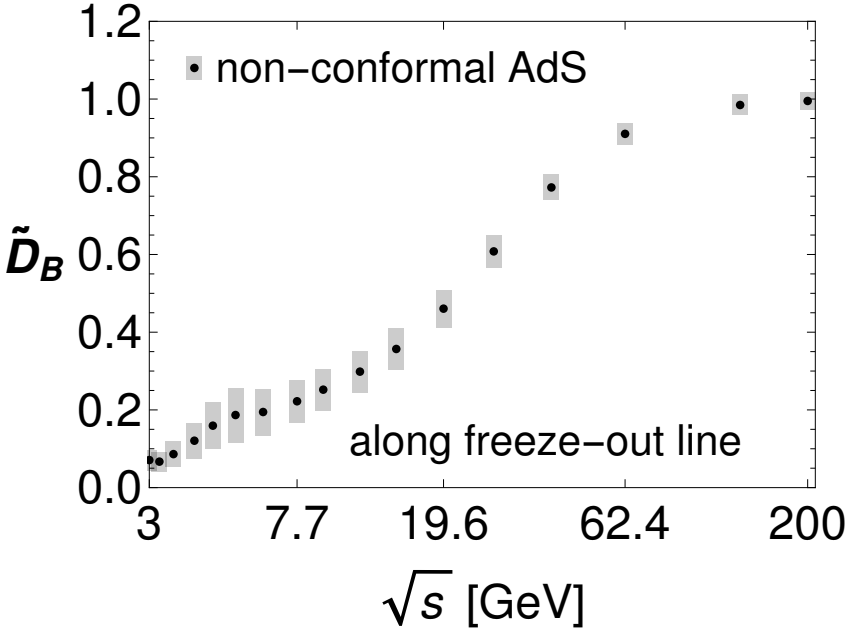
Diffusion



In water, diffusion increases with temperature

Diffusion of Baryons

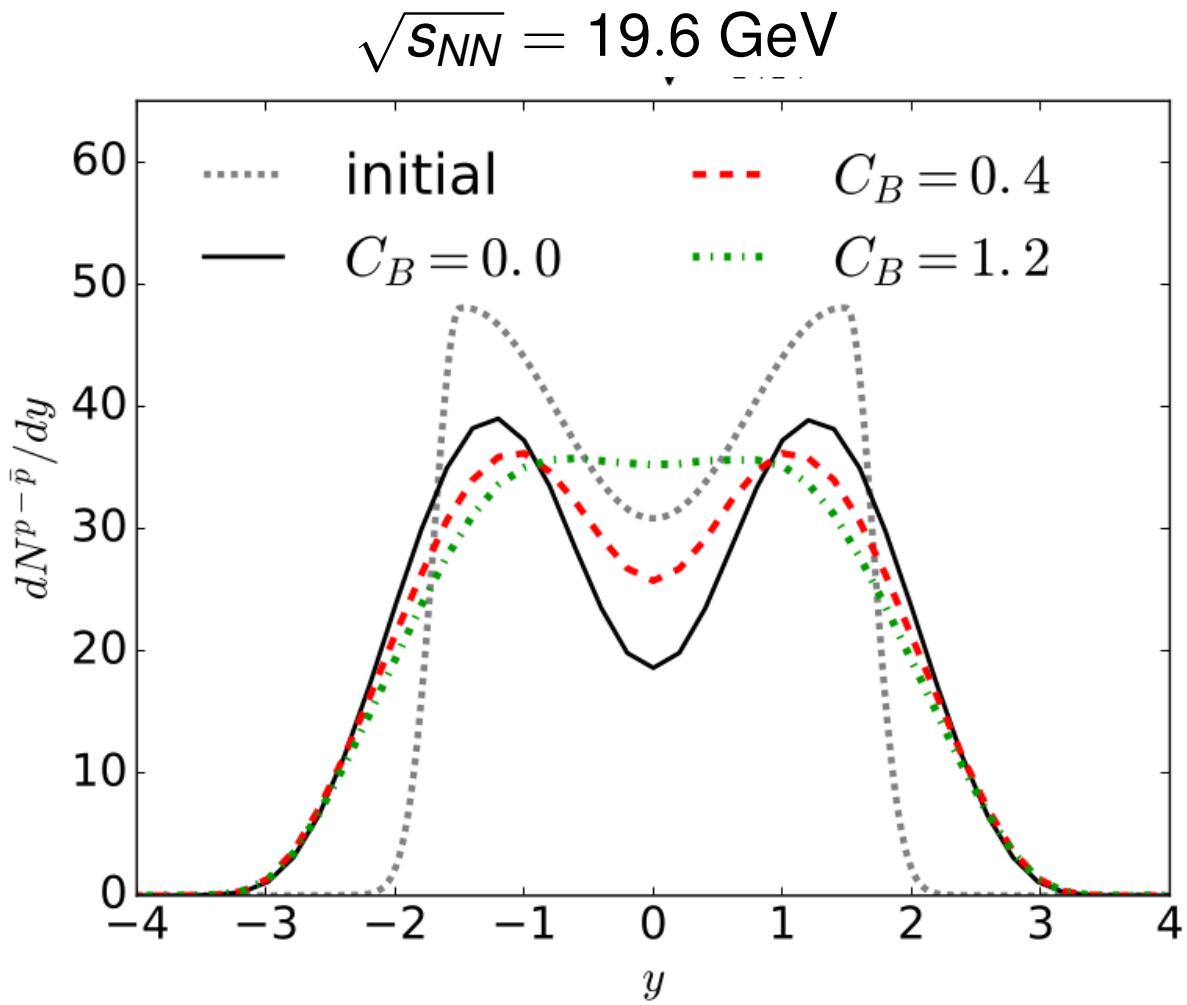




Baryons get “stuck" at the critical point- implementation into hydro+new observables needed for BESII

Phys.Rev.Lett. 115 (2015) no.20, 202301 ; arXiv:1704.05558

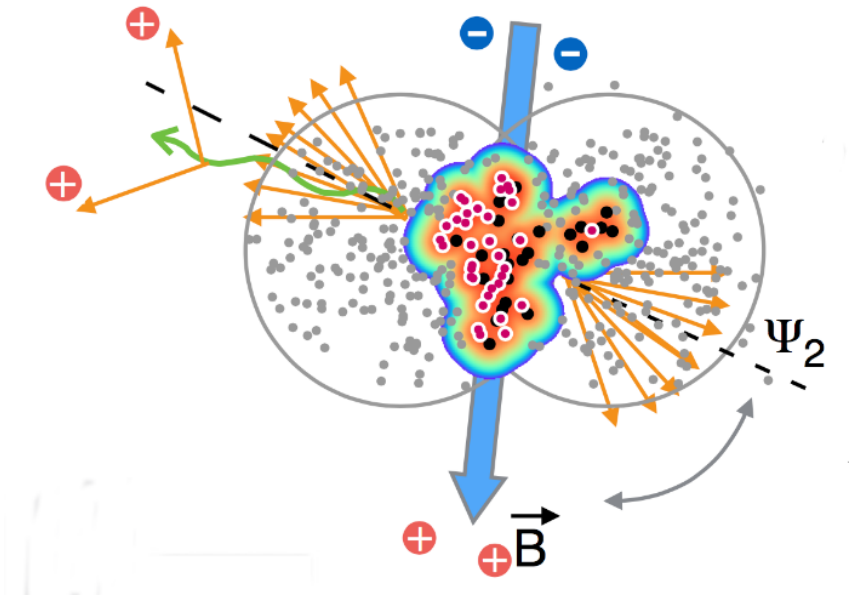
Sensitivity to baryon diffusion in hydro



C. Shen, G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke, arXiv:1704.04109

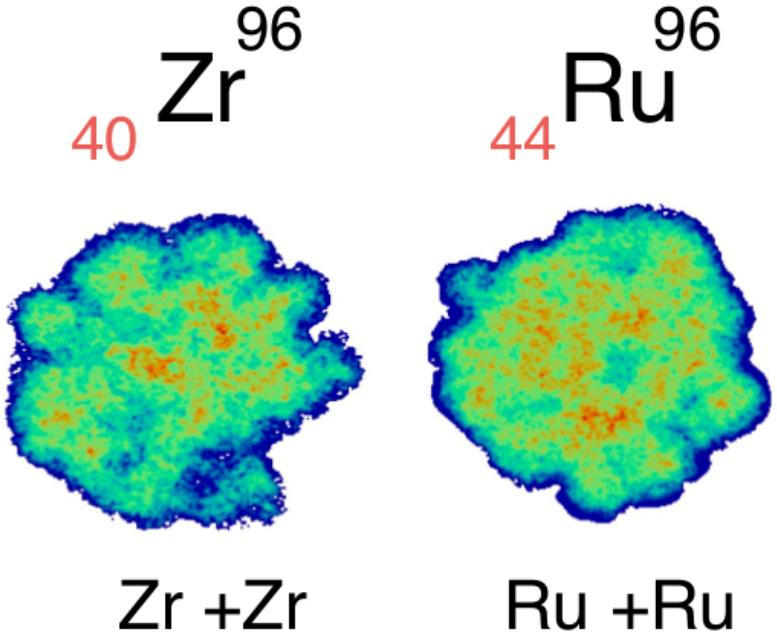
Finding the Chiral Magnetic Effect

Chiral Magnetic Effect (CME) should follow B field



Isobar Run 18

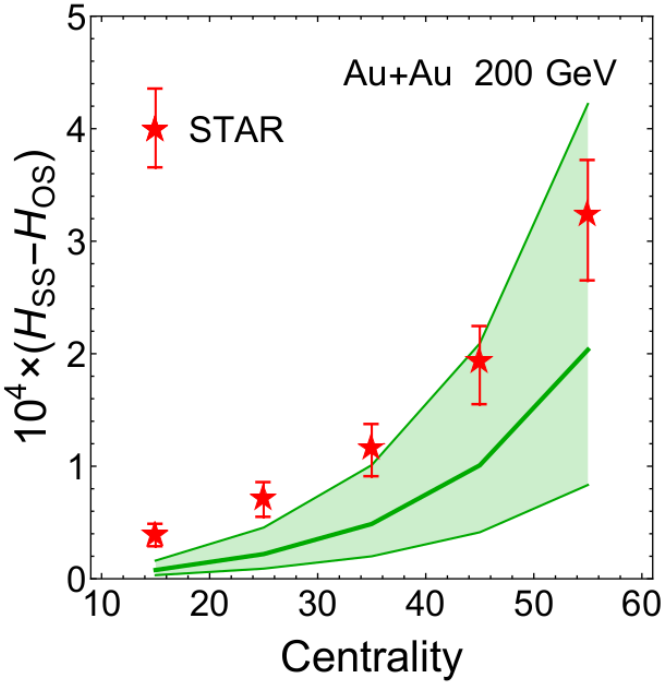
Hold v_2 (background) constant, vary B field



Deng et al PRC94,041901 (2016)

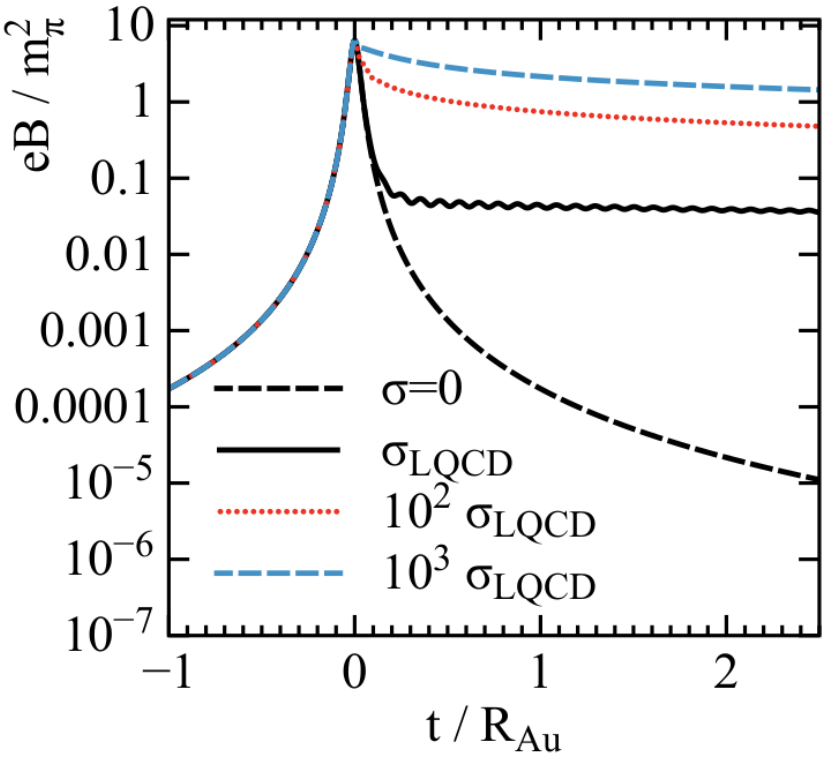
Magnetohydrodynamics

Best estimates of B field/initial charge density



See Talk by S. Shi Tues.

Lifetime of the B Field

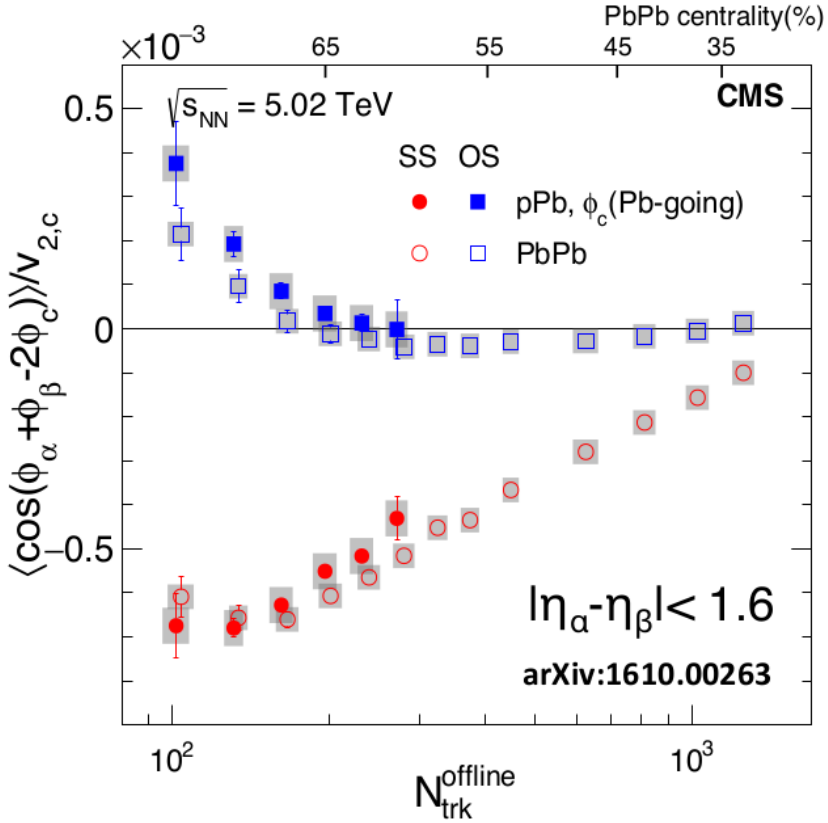


See Talk by V. Skokov Tues.

Questions still remain about initial charge density, lifetime of B field, axial charge non-conservation. See S. Schlichting Weds

Question 1: Small Systems

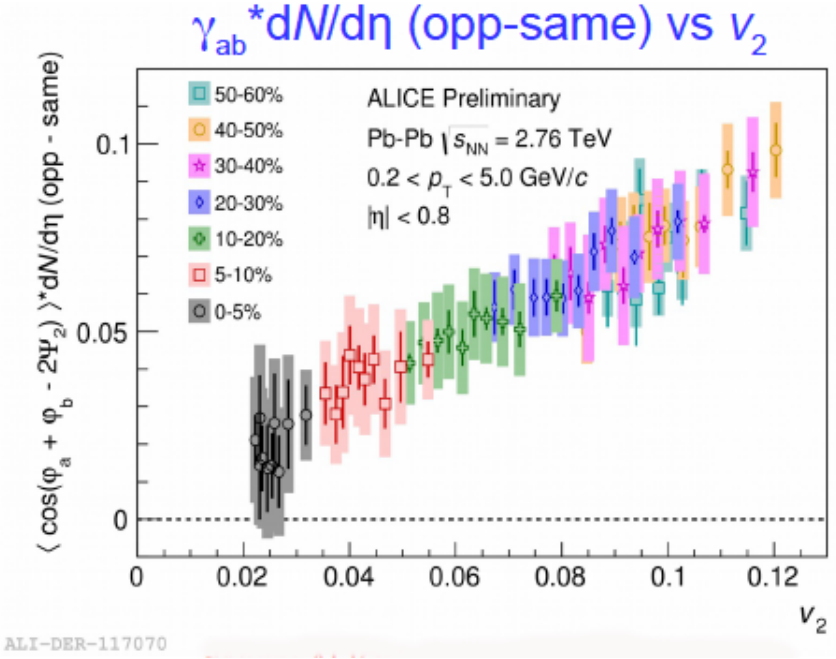
B field no longer aligned with ψ_2 (arXiv:1610.07964), but signal still seen



- Could the proton size grow in high multiplicity events? $R_p^2(s;N) = R_p^2(s)\frac{N}{\bar{N}}$
  D. Kharzeev QCD Chirality 2017
- Could it be a background effect?
  Schlichting and Pratt PRC83,014913 (2011)
- What new observables could distinguish these scenarios?

Question 2: Flow Background

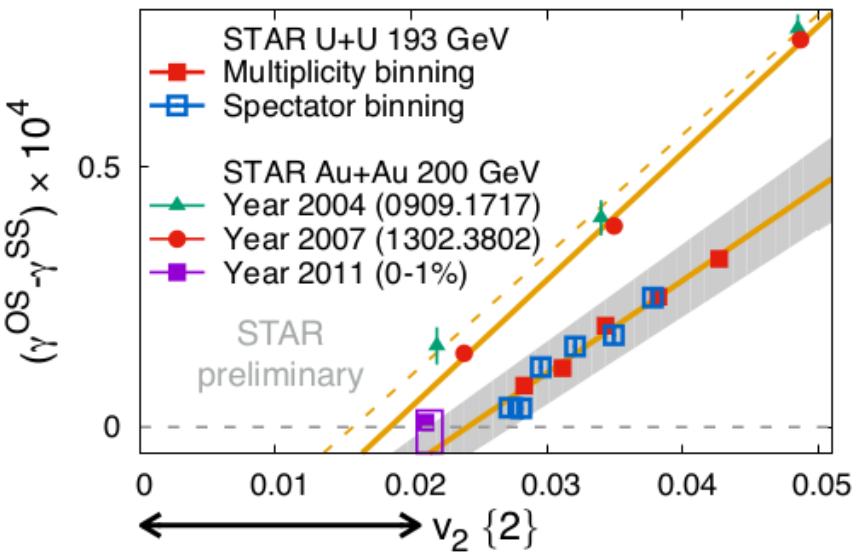
Event-shape engineering

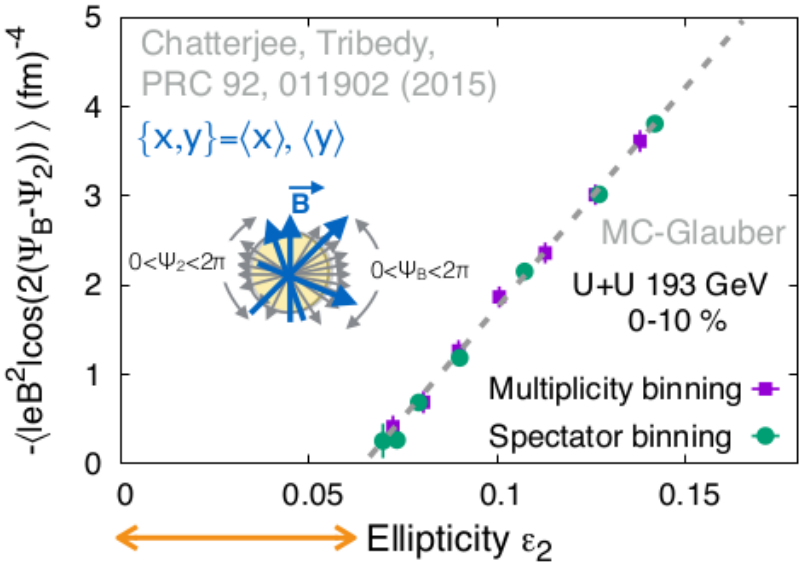


[ALICE] QM2017

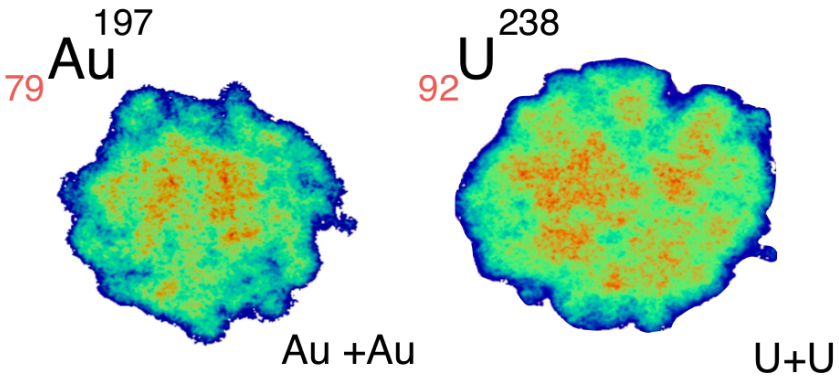
- How does it scale with other v_n's?
- What about RHIC/small systems?
- Need theoretical models to explain all observables

Question 3: Central Collisions

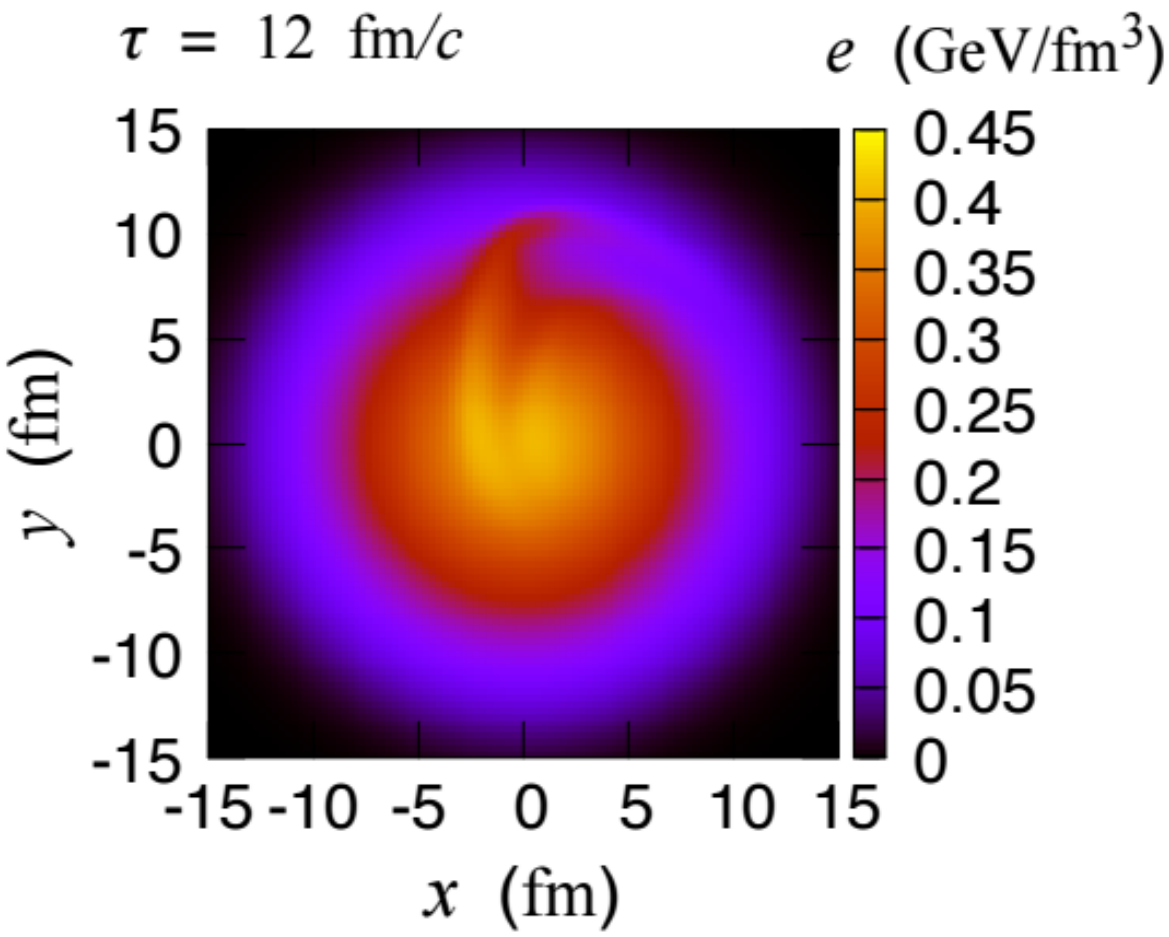




- ψ_2 and ψ_B no longer aligned for central collisions
- B-field consistent with data
- Would Event shape engineering be flat for central RHIC collisions?



Jets fully coupled to a realistic medium

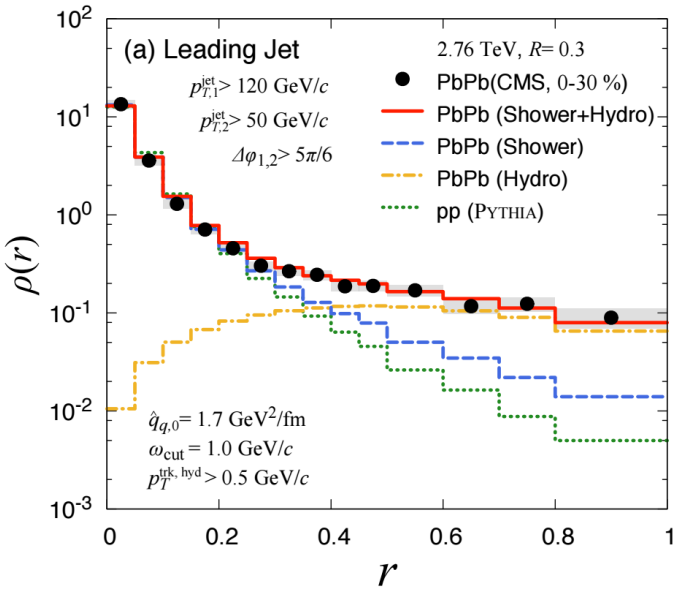


Coupling jets+relativistic viscous hydrodynamics

$$\partial_\mu T^{\mu\nu}_{\rm QGP}(x) = J^\nu(x)$$

Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jet



- Realistic event-by-event fluctuating hydro backgrounds
  PRL 116(2016) no.25,252301; PRC 95(2017)no. 4,044901
- Coupled to advances from pQCD
  Z. Kang and T. Chien Tues.
- Bayesian analysis
  [JETSCAPE] S. Cao Tues.
- Exploration of jet substructure, jet grooming etc

"We call for an agreement between theorists and experimentalists on the appropriate treatment of the background, Monte Carlo generators that enable experimental algorithms to be applied to theoretical calculations, and a clear understanding of which observables are most sensitive to the properties of the medium, even in the presence of background. " Connors, Nattrass, Reed, and Salur arxiv:1705.01974

References

Shown Tachibana et al, PRC95(2017)no.4,044909; **Others** Pang et al, PRC86(2012)024911; HYDJET++ (many papers); LBT (many papers); Andrade et al, PRC90(2014)no.2,024914; Schule and Tomasik PRC90(2014)no.6,064910

Outlook

- **Beam energy scan:**
  - Equation of State at finite μ_B. Almost there for BES
  - Critical Point? Still need hydro updates, work in progress
- **Transport coefficients:**
  - Numerous effective models. Bayesian analysis helpful
  - Baryon Diffusion promising for CP searches.
- **Chiral Magnetic Effect:**
  - Significant progress made on Magnetohydrodynamics
  - Isobar run 18 to shed light on signal vs. background
- **Jets:** Efforts underway for combining realistic event-by-event hydrodynamics+reconstructed jets and Bayesian analysis.