Update on BEST collaboration and status of lattice QCD

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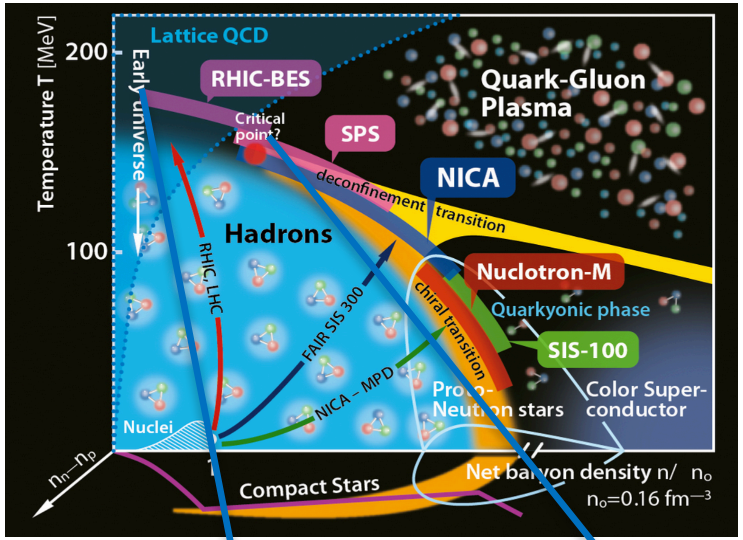
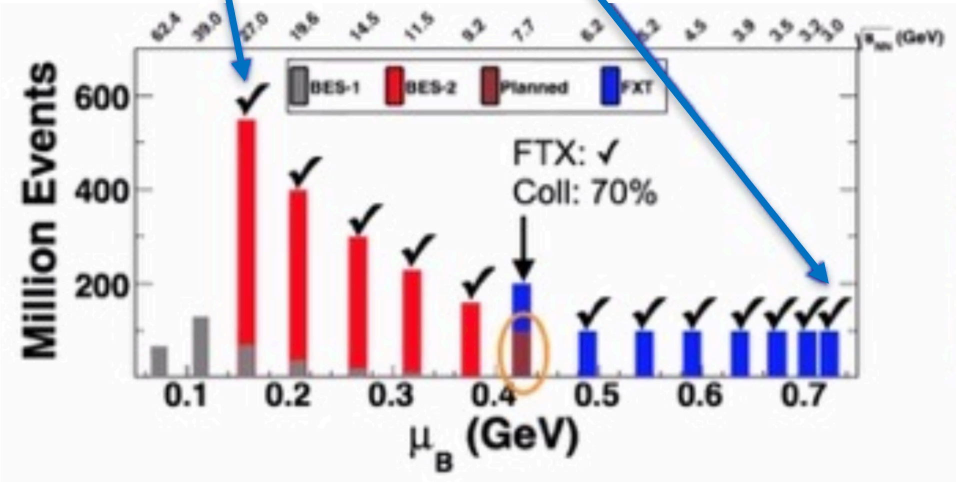
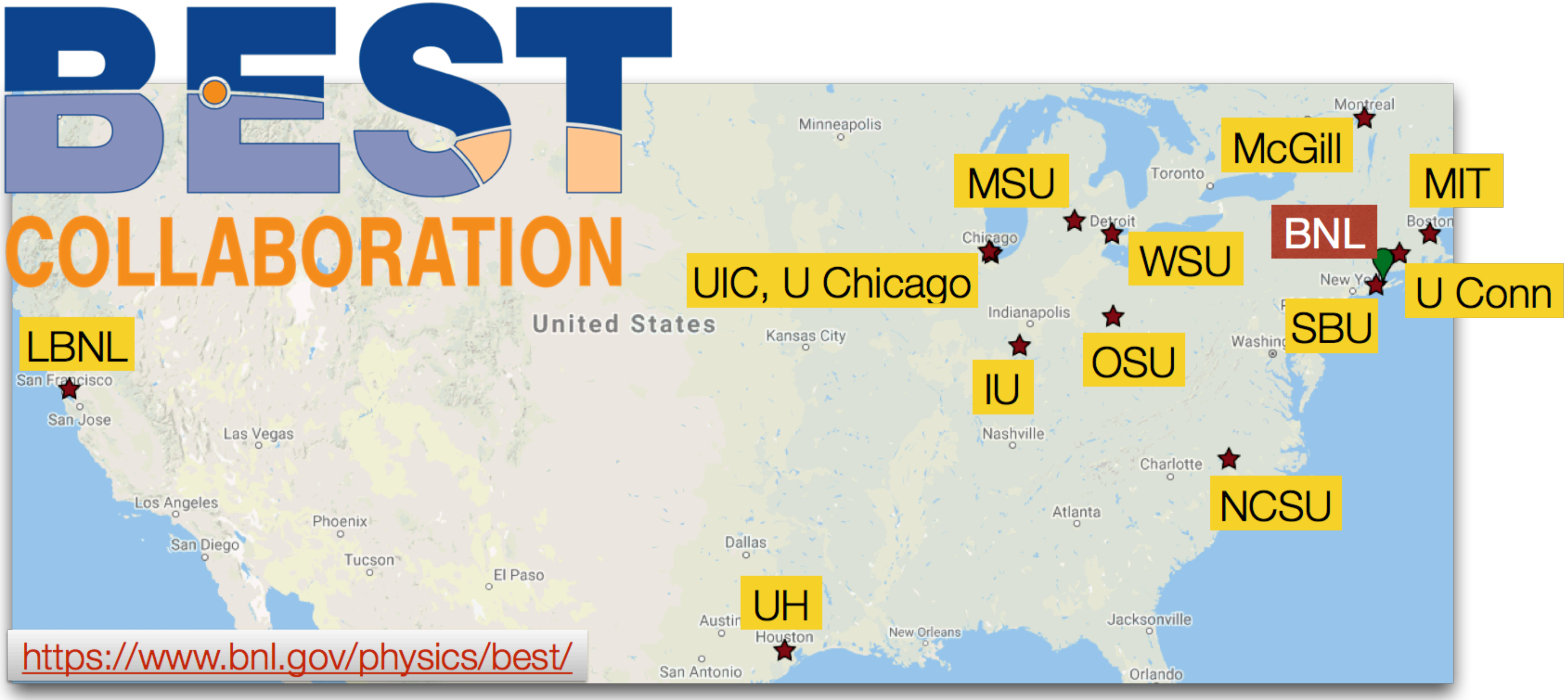
Open Questions

- Is there a critical point in the QCD phase diagram?
- What are the degrees of freedom in the vicinity of the phase transition?
- Where is the transition line at high density?
- What are the phases of QCD at high density?
- Are we creating a thermal medium in experiments?





- Run 2019:
  - Collider: $\sqrt{s_{NN}}$=14.6, 19.6, 200 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.2 GeV
- Run 2020:
  - Collider: $\sqrt{s_{NN}}$=9.2, 11.5 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7 GeV
- Run 2021:
  - Collider: $\sqrt{s_{NN}}$=7.7 GeV

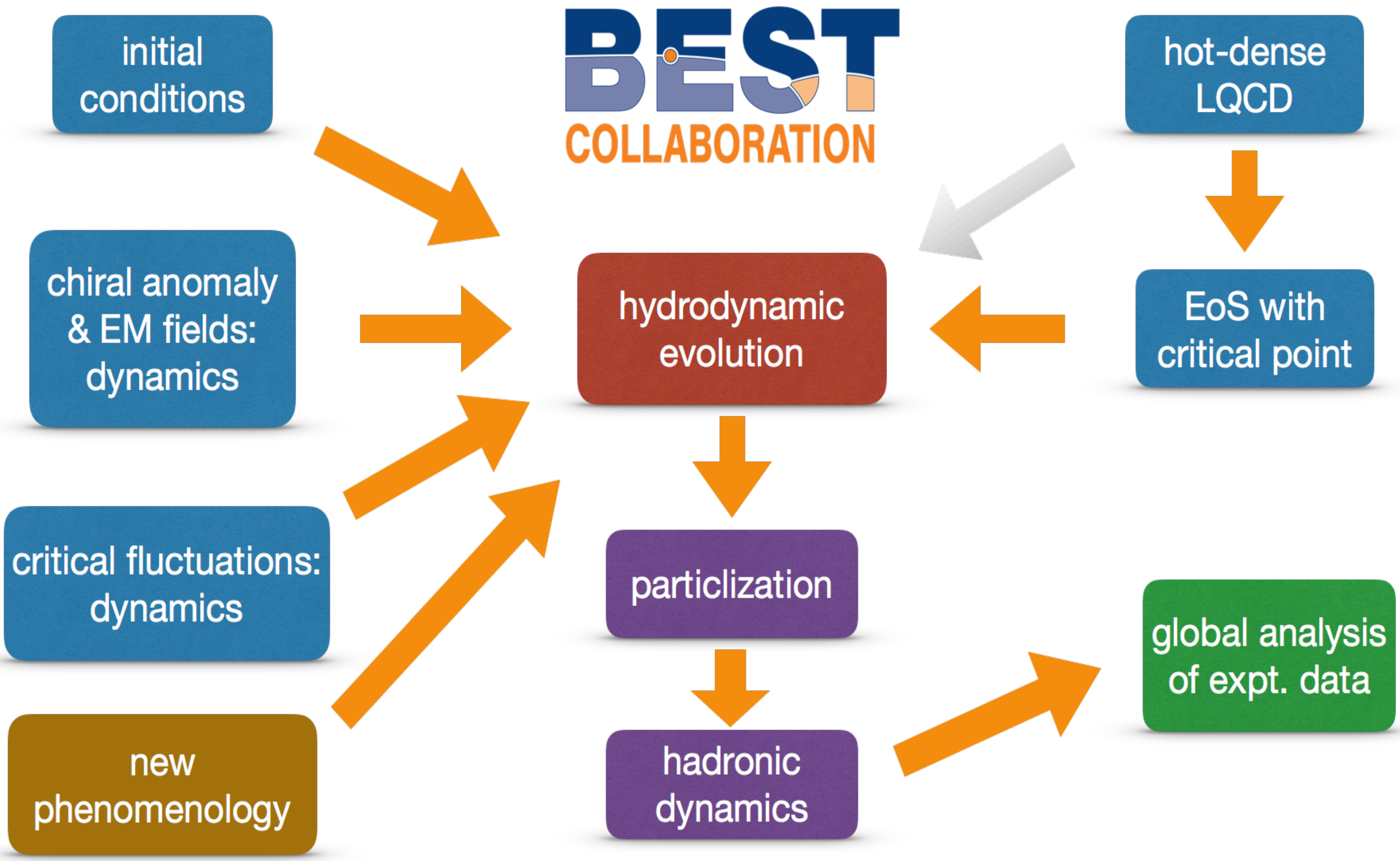


objectives:

- constraints on the existence of a critical point in the QCD phase diagram
- properties of baryon-rich QGP
- probe chiral symmetry restoration through chiral anomaly induced phenomena

path:

- construct a theoretical framework for interpreting the results from the BES @ RHIC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Hot and dense lattice QCD

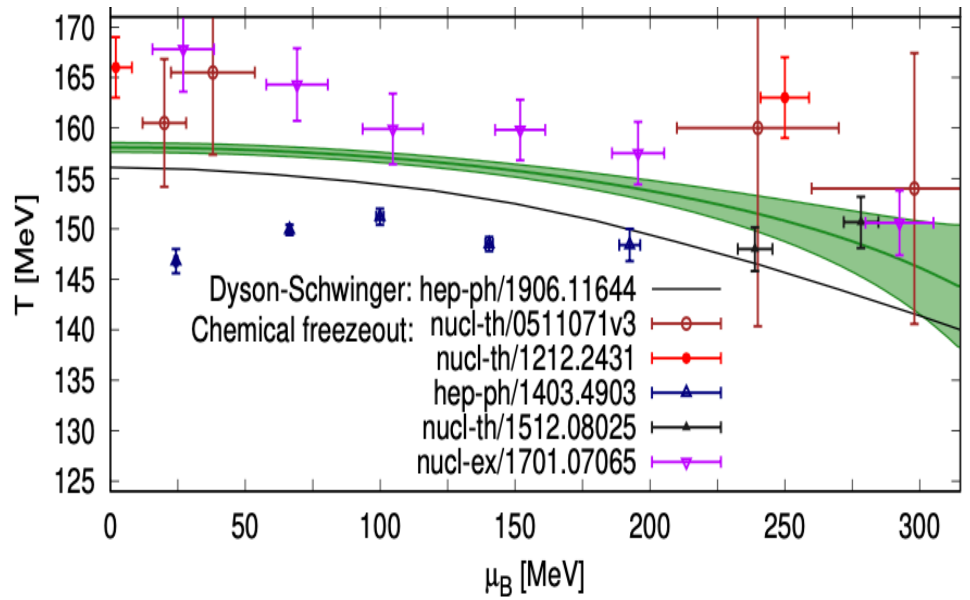
BNL, UH

Major goals:

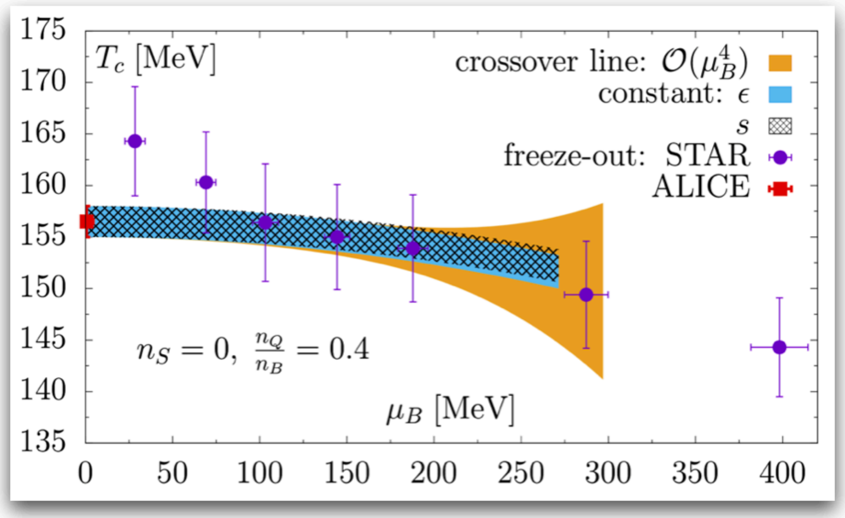
- QCD crossover temperature $T_c(\mu_B)$
  - switching temperature/energy density for fluid-dynamical modeling
- QCD equation of state (EoS) for $\mu_B>0$
  - input for fluid-dynamical modeling & EoS with critical point
- skewness and kurtosis of conserved charge fluctuations for $\mu_B>0$
  - equilibrium QCD baseline for the experimentally measured higher order cumulants of net proton, electric charge and kaon fluctuation

QCD crossover temperature

WB:PRL (2020)



HotQCD: PLB (2019)



$$\frac{T_c(\mu_B)}{T_0} = 1 - \kappa_2 \left(\frac{\mu_B}{T_0}\right)^2 - \kappa_4 \left(\frac{\mu_B}{T_0}\right)^4 + \mathcal{O}(\mu_B^6)$$

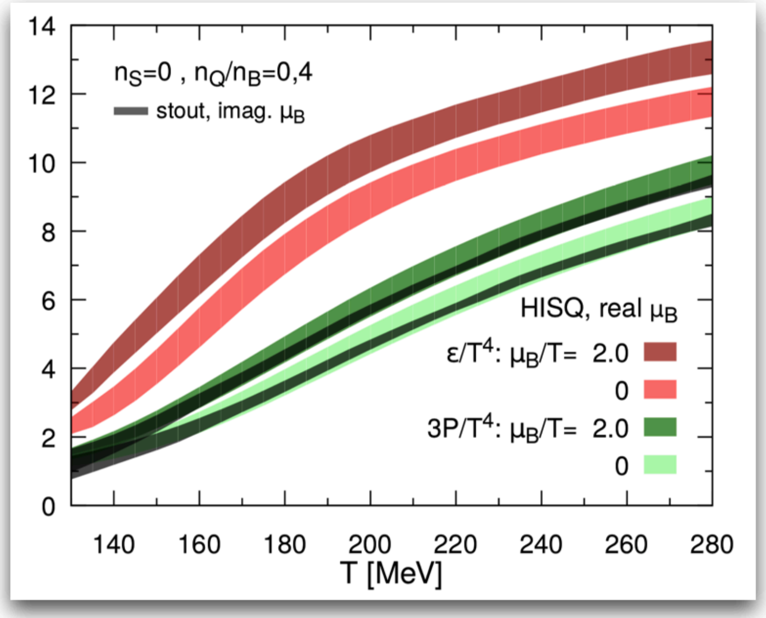
T_0=158.0±0.6 MeV
κ_2=0.0153±0.0018
κ_4=0.00032±0.00067

QCD Equation of state for $\mu_B>0$

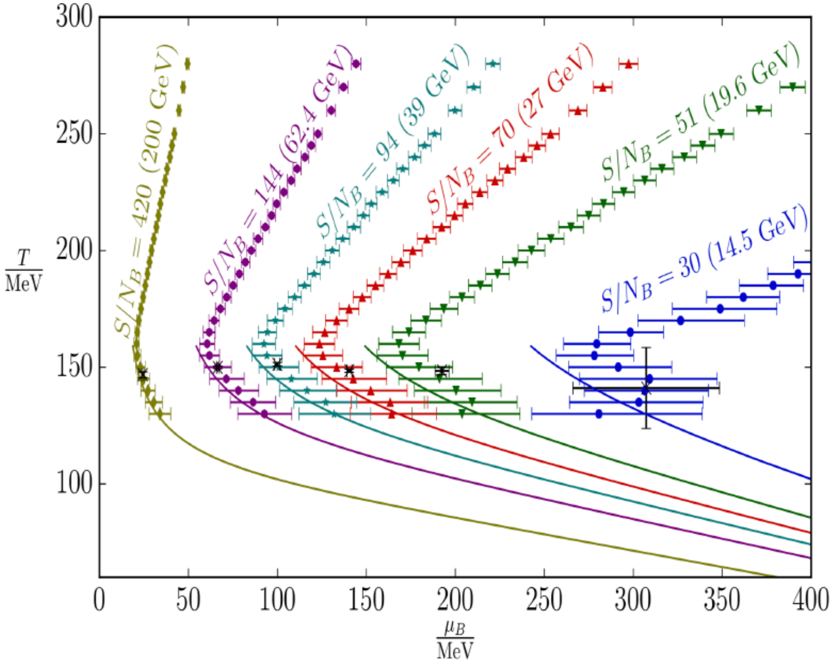
- Taylor expansion of the pressure:

$$\frac{p(T,\mu_B)}{T^4} = \frac{p(T,0)}{T^4} + \sum_{n=1}^{\infty} \frac{1}{(2n)!} \frac{\mathrm{d}^{2n}(p/T^4)}{d(\frac{\mu_B}{T})^{2n}}\Bigg|_{\mu_B=0} \left(\frac{\mu_B}{T}\right)^{2n} = \sum_{n=0}^{\infty} c_{2n}(T) \left(\frac{\mu_B}{T}\right)^{2n}$$

HotQCD: PRD (2017)



WB: NPA (2017)

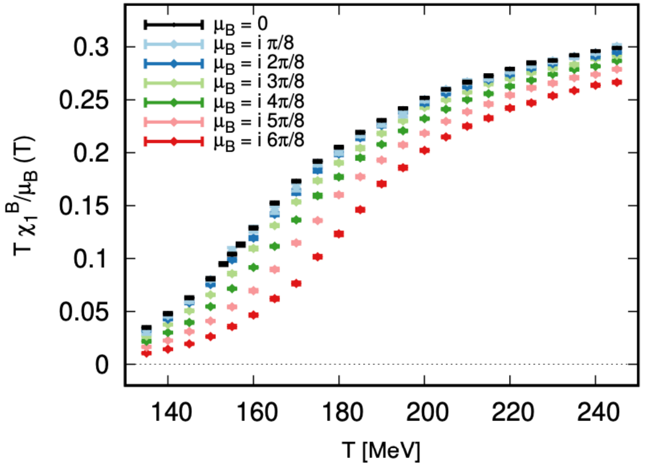


Novel expansion scheme

Exploiting the T and μ_B dependence of the density

we can write $$\frac{\chi_1^B(T,\hat{\mu}_B)}{\hat{\mu}_B} = \chi_2^B(T',0)$$

with $$T'(T,\hat{\mu}_B) = T\left(1+\kappa_2^{BB}(T)\hat{\mu}_B^2+\kappa_4^{BB}(T)\hat{\mu}_B^4+\mathcal{O}(\hat{\mu}_B^6)\right)$$



P. Parotto, C. R. et al., 2102.06660

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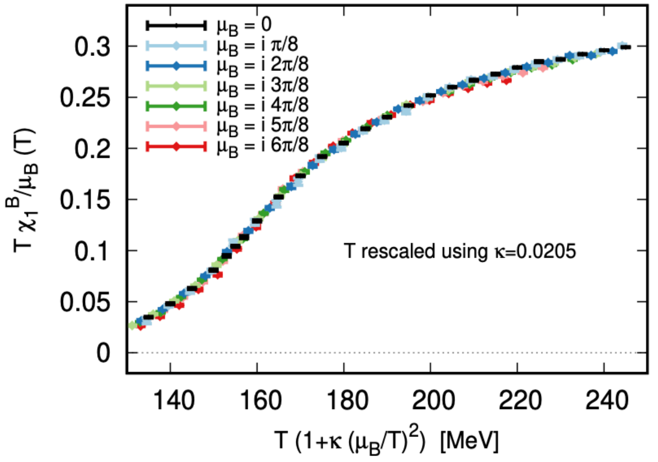
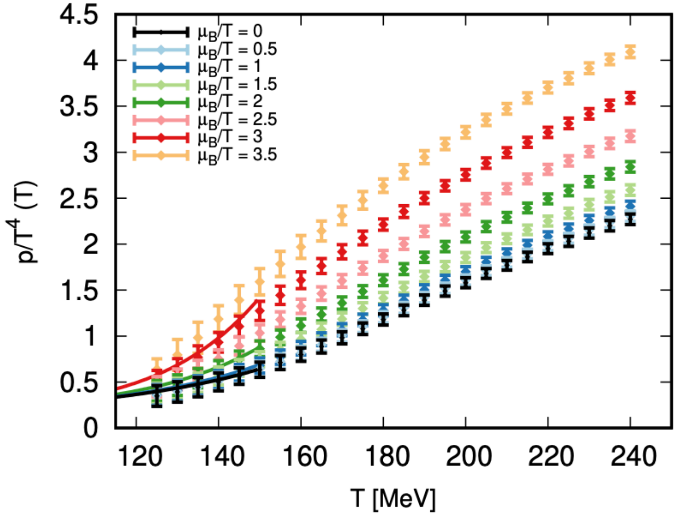
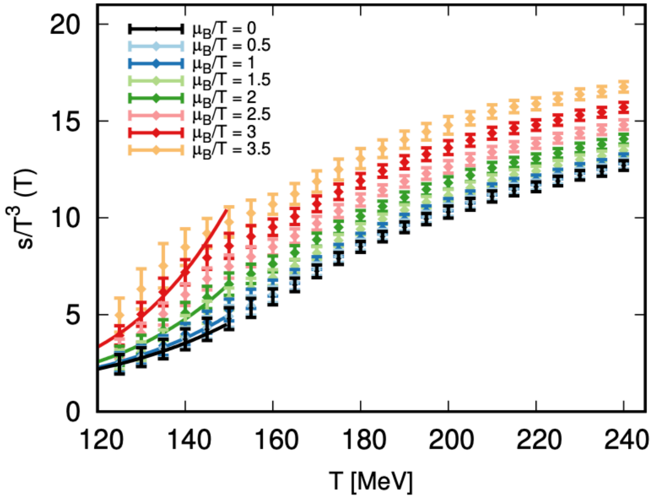
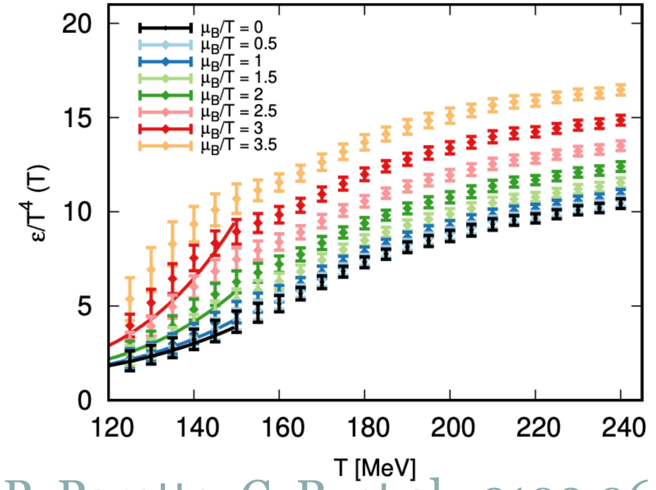


We get all other thermodynamic quantities from the density







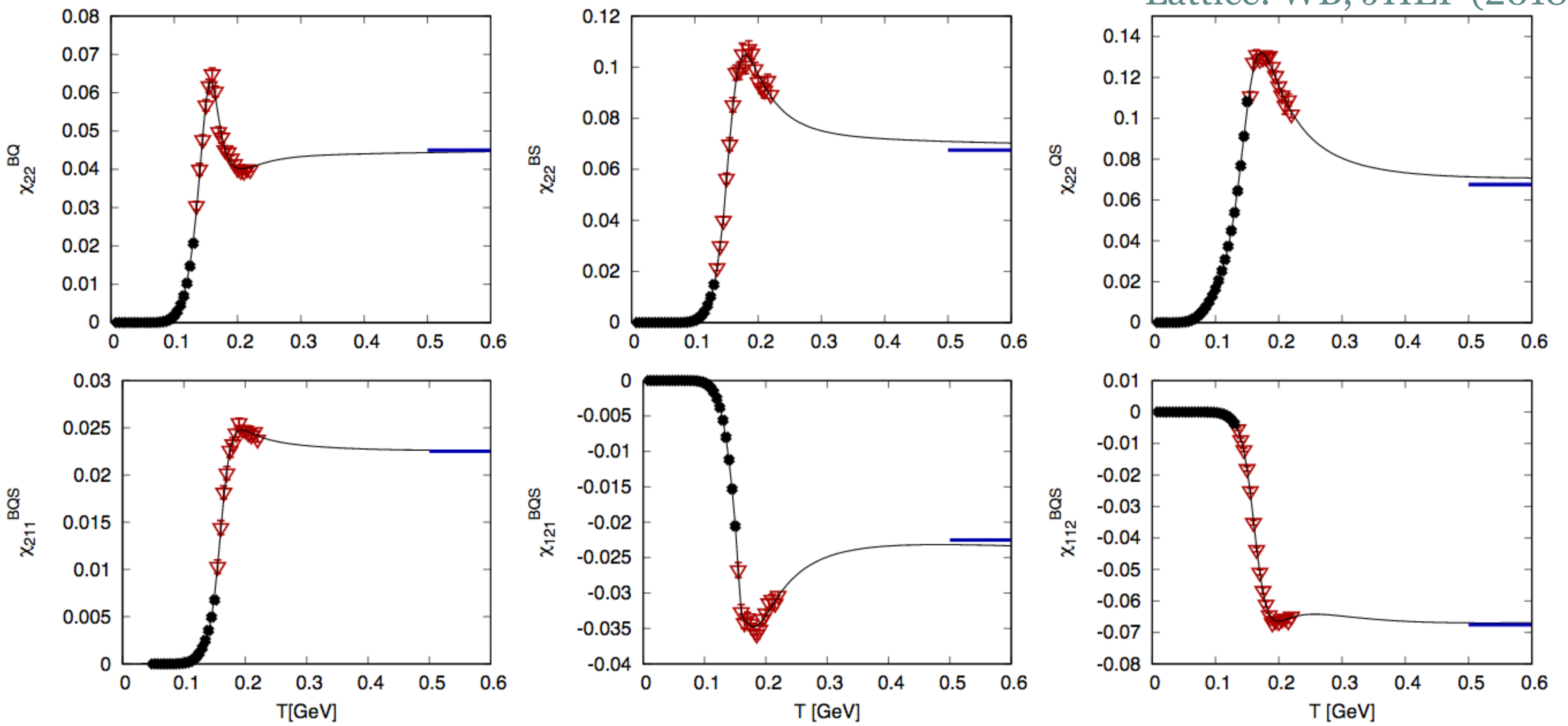
P. Parotto, C. R. et al., 2102.06660

QCD Equation of state for $\mu_B, \mu_S, \mu_Q > 0$

J. Noronha-Hostler, C.R. et al., PRC (2019)

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

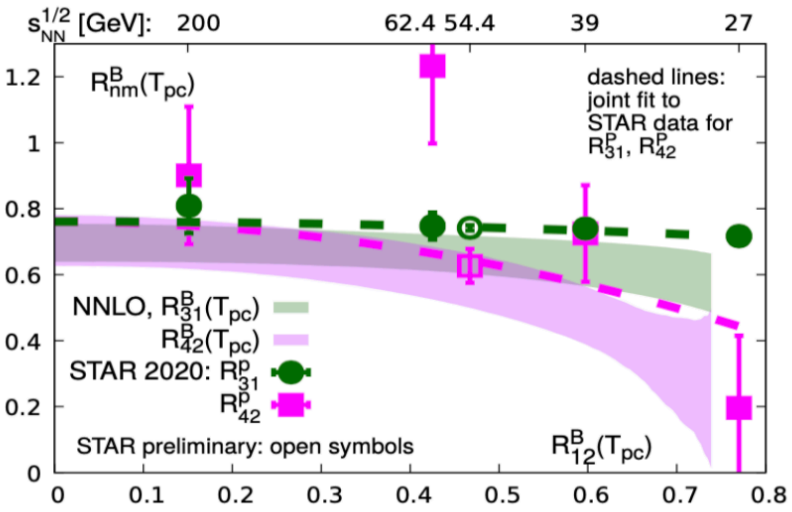
Lattice: WB, JHEP (2018)

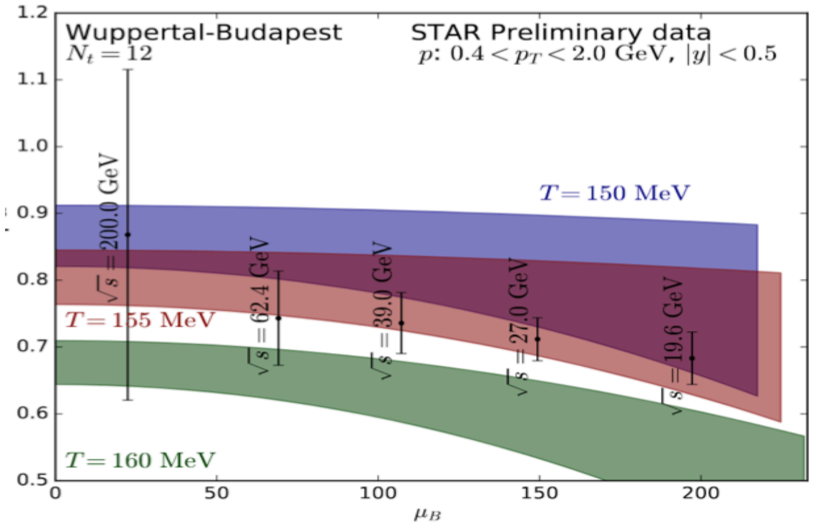


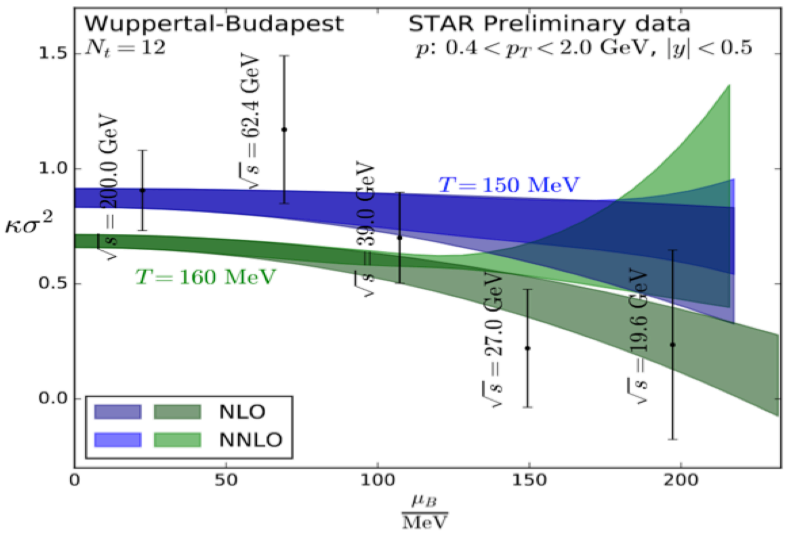
Higher order fluctuations

HotQCD, PRD (2020)

WB, JHEP (2018)







$$\frac{S_B\sigma_B^3}{M_B} = \frac{\chi_3^B(T,\mu_B)}{\chi_1^B(T,\mu_B)} = \frac{\chi_4^B + s_1\chi_{31}^{BS} + q_1\chi_{31}^{BQ}}{\chi_2^B + s_1\chi_{11}^{BS} + q_1\chi_{11}^{BQ}} + \mathcal{O}(\mu_B^2) \equiv r_{31}^{B,0} + r_{31}^{B,2}\hat{\mu}_B^2 + \mathcal{O}(\mu_B^4)$$

$$\kappa_B\sigma_B^2 = \frac{\chi_4^B(T,\mu_B)}{\chi_2^B(T,\mu_B)} = \frac{\chi_4^B}{\chi_2^B} + \mathcal{O}(\mu_B^2) \equiv r_{42}^{B,0} + r_{42}^{B,2}\hat{\mu}_B^2 + \mathcal{O}(\mu_B^4)\ ,$$

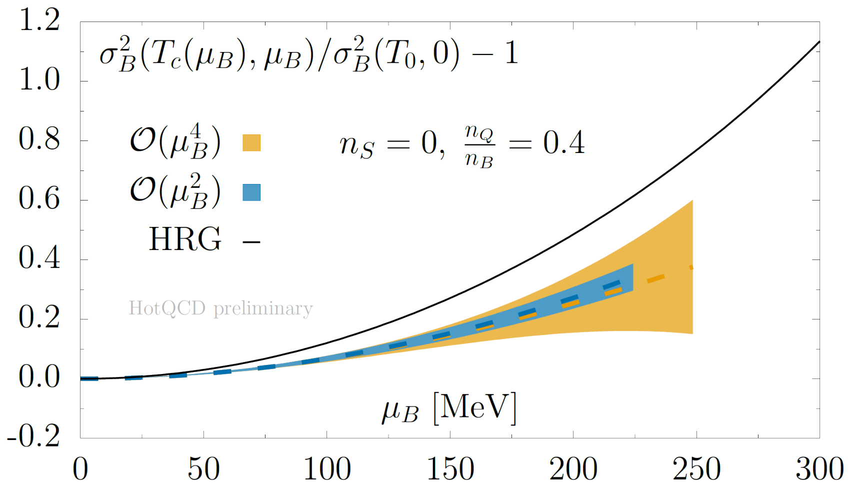
Alternative explanation: canonical suppression

P. Braun Munzinger et al., NPA (2017)

Other lattice QCD results

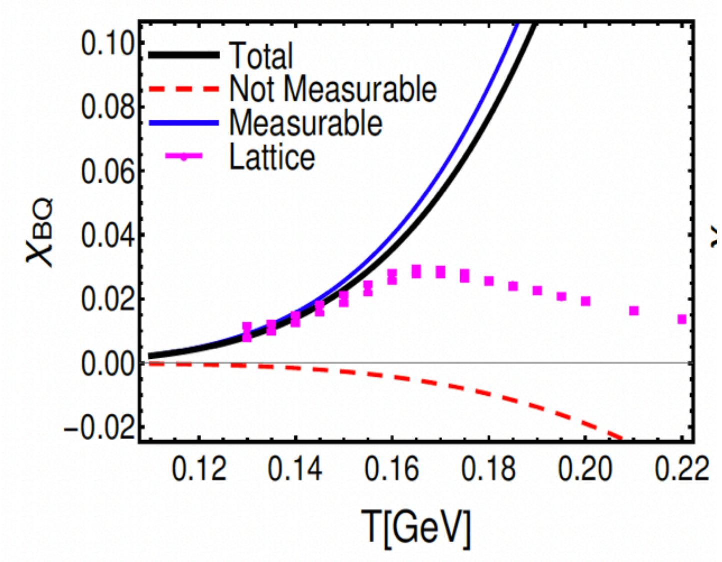
- Fluctuations along the QCD crossover

HotQCD, 1807.05607



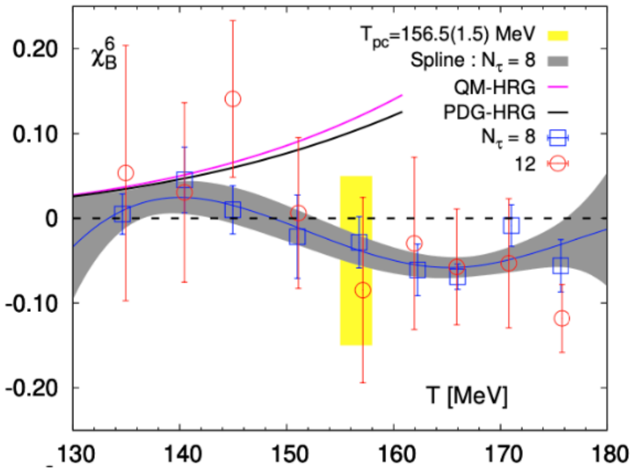
- Off-diagonal correlators

WB, PRD (2020)

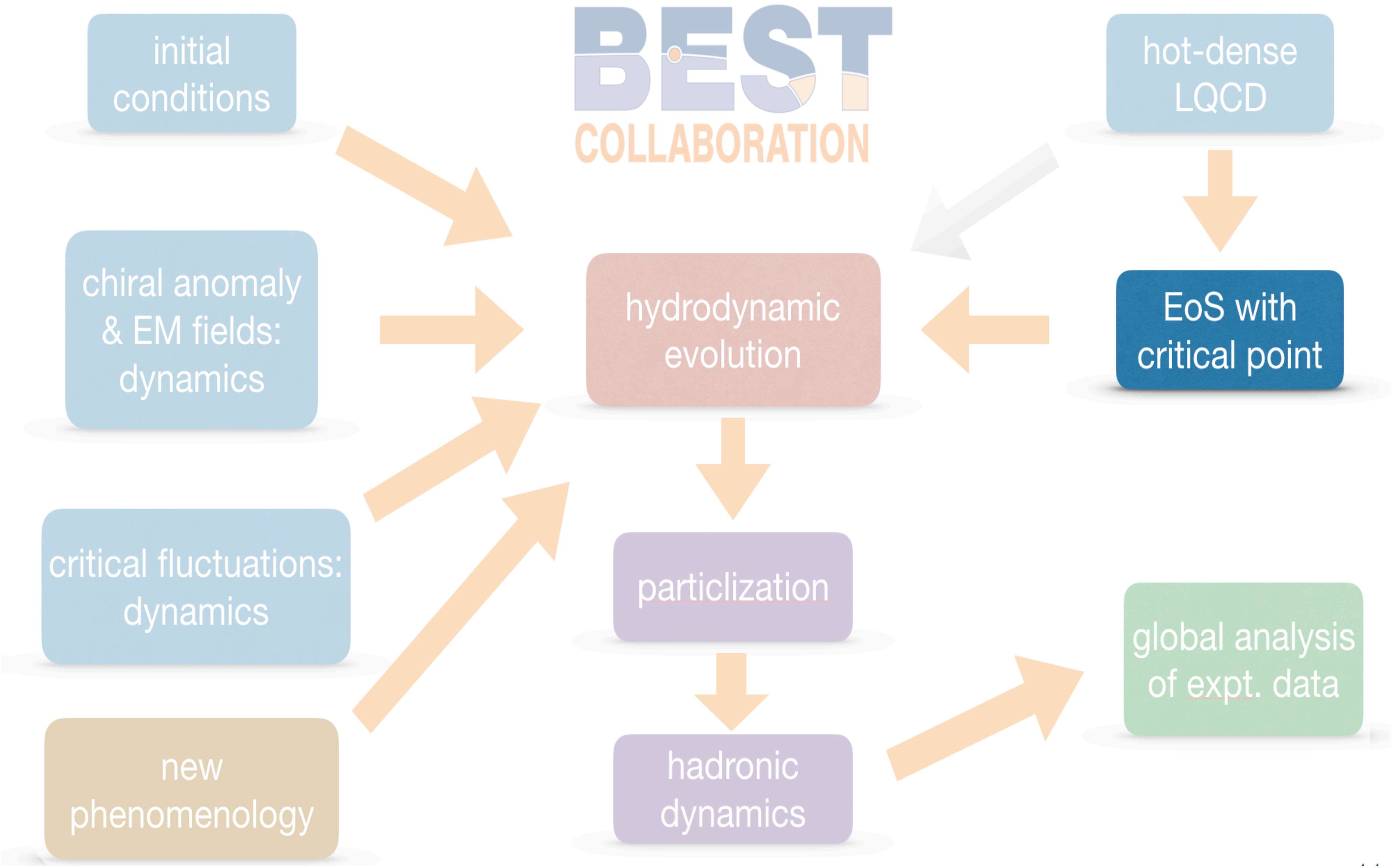


- Higher order fluctuations

HotQCD, PRD (2020)



... and many more!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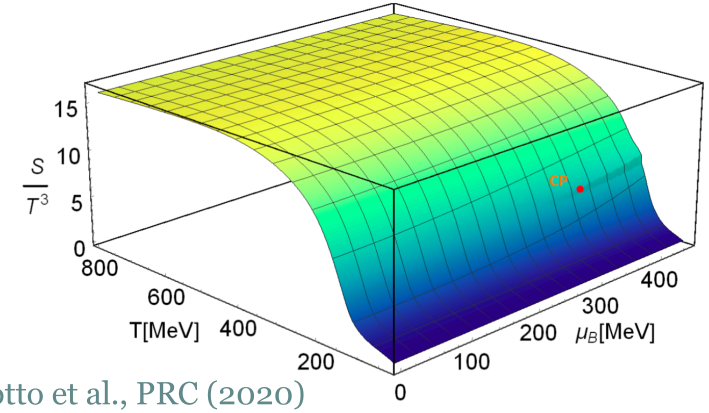
Strategy

✓ We built an equation of state which:
  - ✓ Reproduces the one from lattice QCD up to $O(\mu_B{}^4)$
  - ✓ Contains a critical point in the 3D Ising model universality class

○ Future hydro simulations and comparison with BESII data will help to constrain the position of the critical point

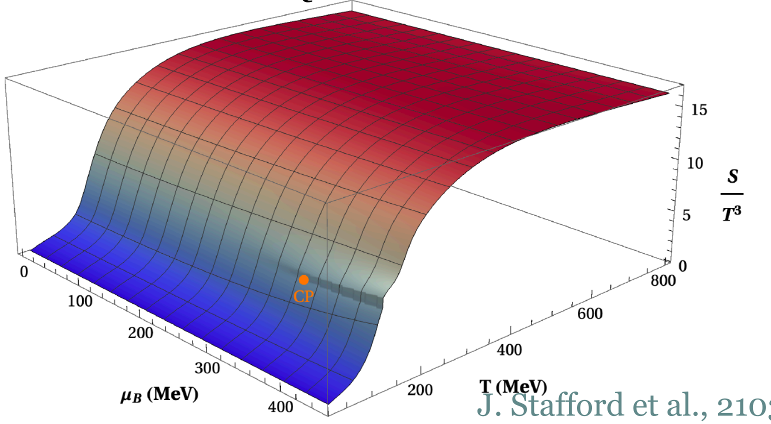
✓ Code available for download from https://www.bnl.gov/physics/best/resources.php

- Finite T and μ_B, but $\mu_S = \mu_Q = 0$

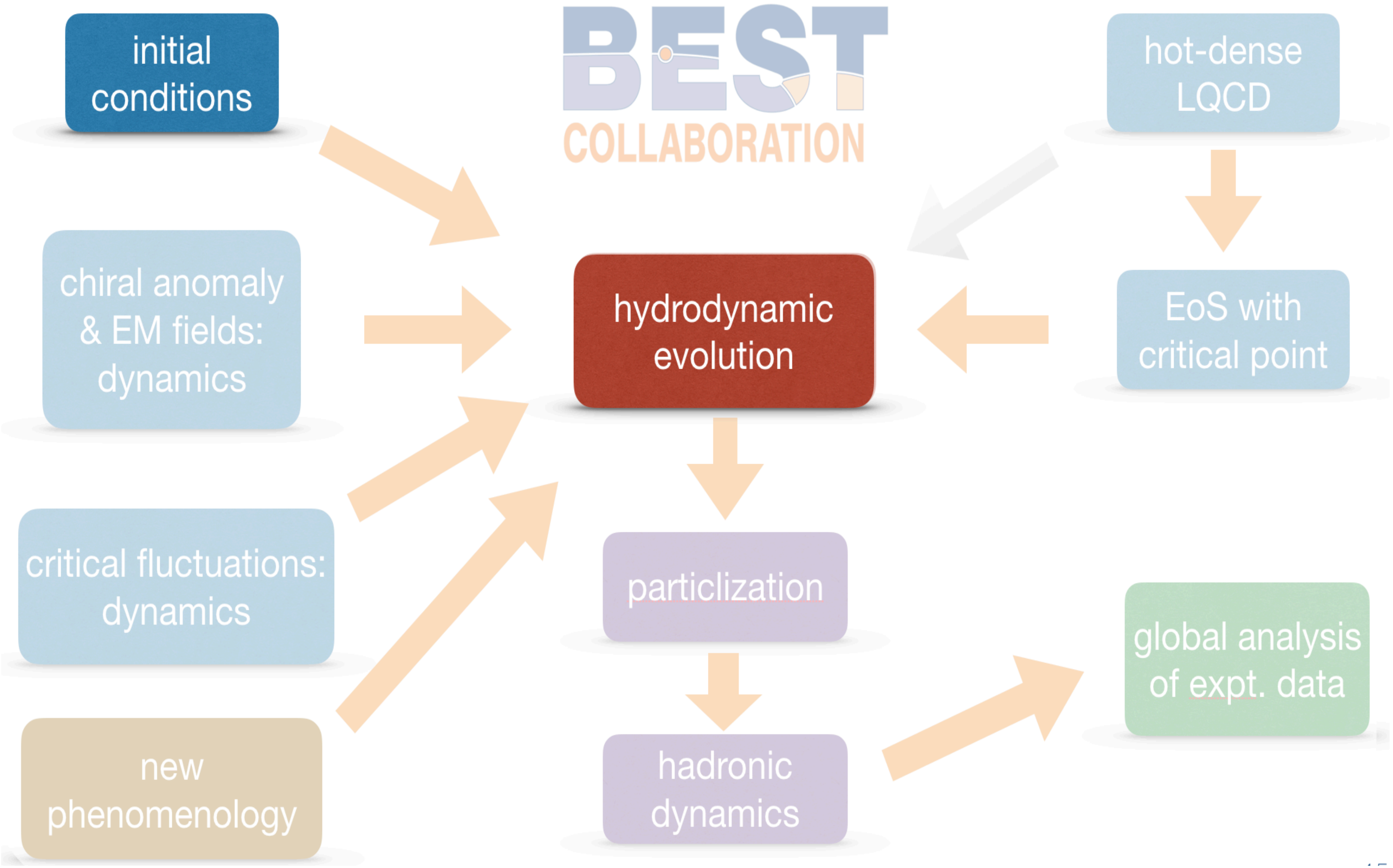


P. Parotto et al., PRC (2020)

- Finite T, μ_B, μ_S and μ_Q such that $n_S=0$ and $n_Q=0.4n_B$



J. Stafford et al., 2103.08146 (2020)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Scientific goals

- Model the *fluctuating initial conditions* for the baryon-asymmetric matter for baryon, electric charge, and strangeness

C. Shen, B. Schenke, PRC (2018)
C. Shen, B. Schenke, NPA (2019)

- Develop **(3+1)D** viscous hydrodynamic code which includes all conserved currents and connect it to model for initial conditions

G. Denicol et al., PRC (2018)
L. Du et al., NPA (2019)

- Extract *transport properties* of nuclear matter at finite baryon density

M. Li, C. Shen, PRC (2018)
C. Gale et al., NPA (2019)

Hydrodynamics evolution

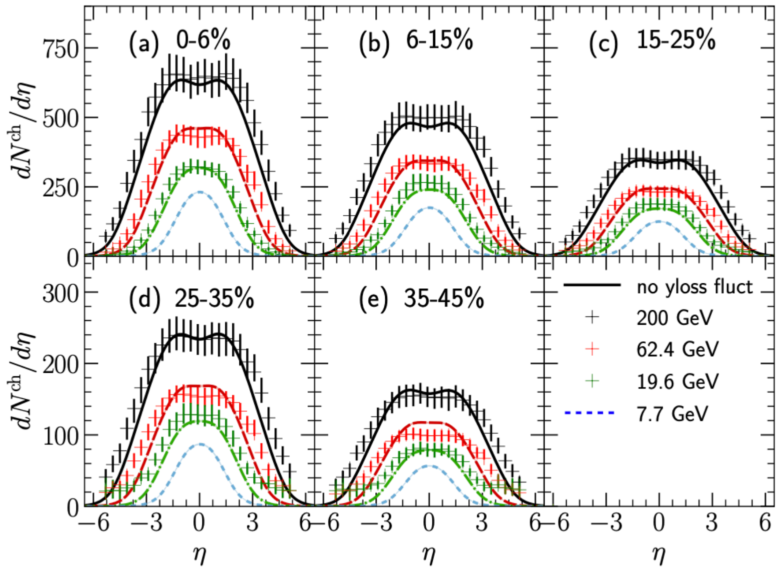
- The sequential collisions between nucleons contribute as energy-momentum and net-baryon density sources to the hydrodynamic fields

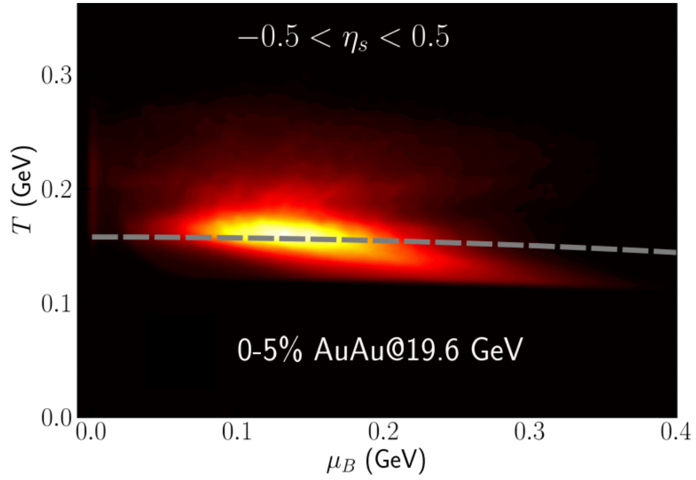
C. Shen, B. Schenke, PRC (2018)
L. Du et al., NPA (2019)

- For recent developments and an alternative method based on a minimal extension of the Glauber model see
  C. Shen, S. Alzhrani, PRC (2020)

- Relativistic viscous hydrodynamic simulations extended to include the propagation of net baryon current including its dissipative diffusion

C. Shen, B. Schenke, NPA (2018)





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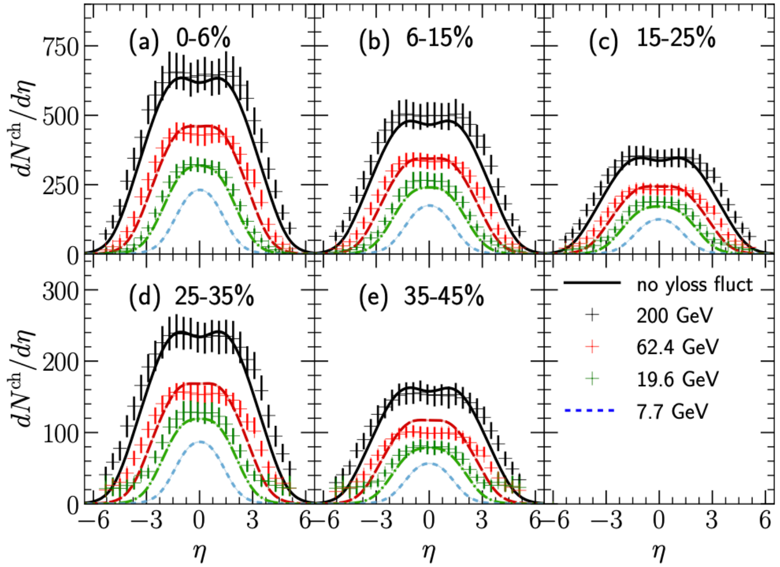

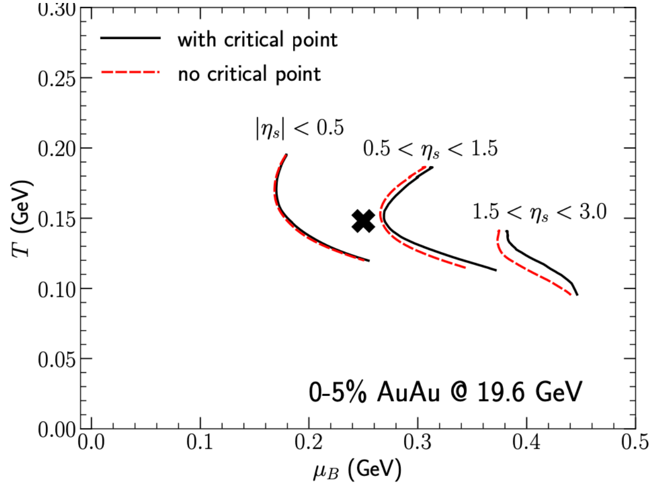

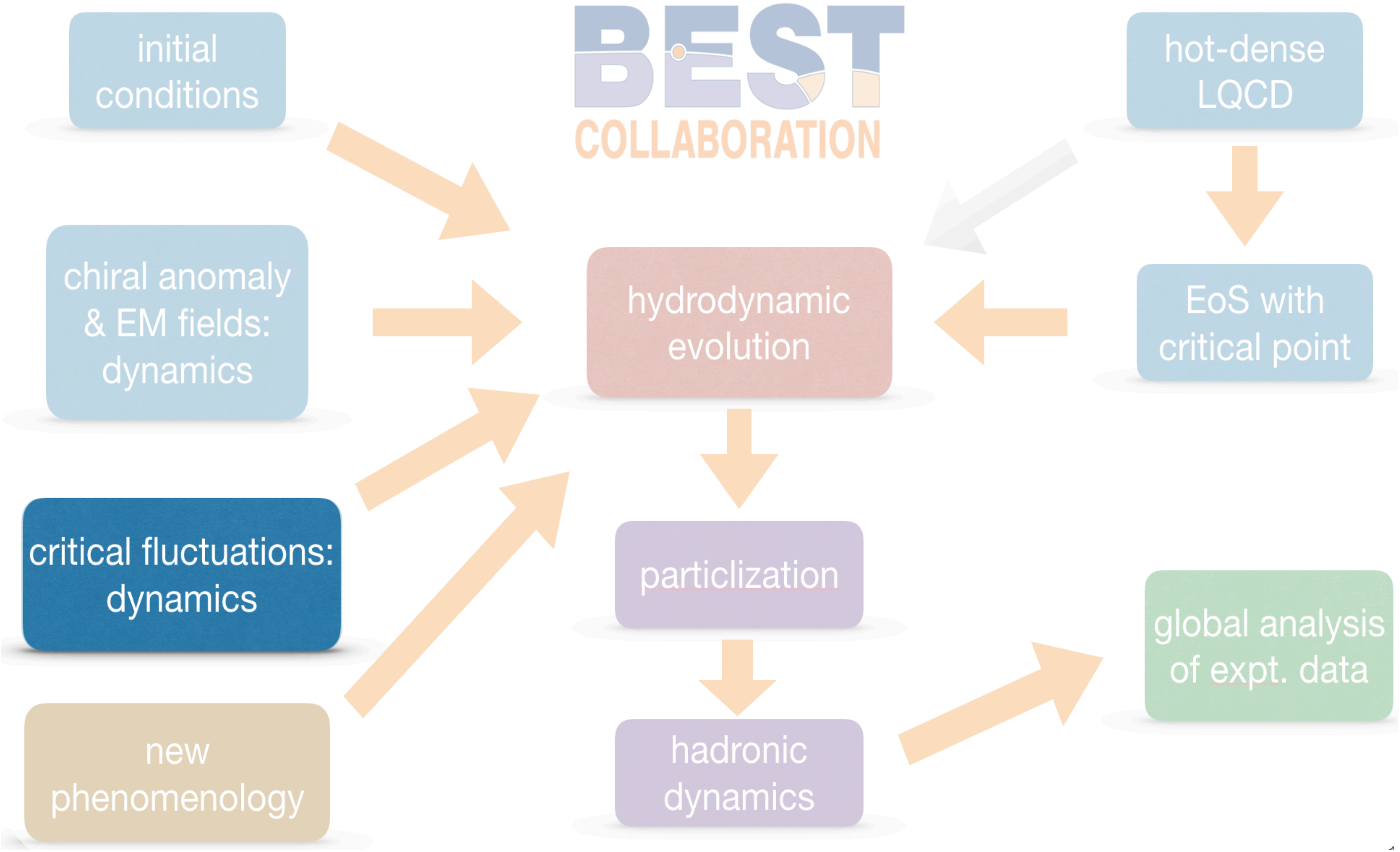
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Approaches

One of the central goals of the BEST collaboration is to develop quantitative understanding of fluctuations near the CP

- Stochastic approach with noise

M. Nahrgang et al., PRD (2019)

- Deterministic approach in which correlation functions are treated as additional variables with the hydrodynamics ones (Hydro+)

M. Stephanov and Yi Ying, PRD (2018)

  - So far only applicable to crossover side of phase boundary

  - So far limited to two-point functions

See also Y. Akamatsu et al, PRC (2017 and 2018); M. Martinez and T. Schaefer, PRC (2019); X. An et al., PRC (2020)
S. Pratt and C. Plumberg, PRC (2019 and 2020)

Implementation

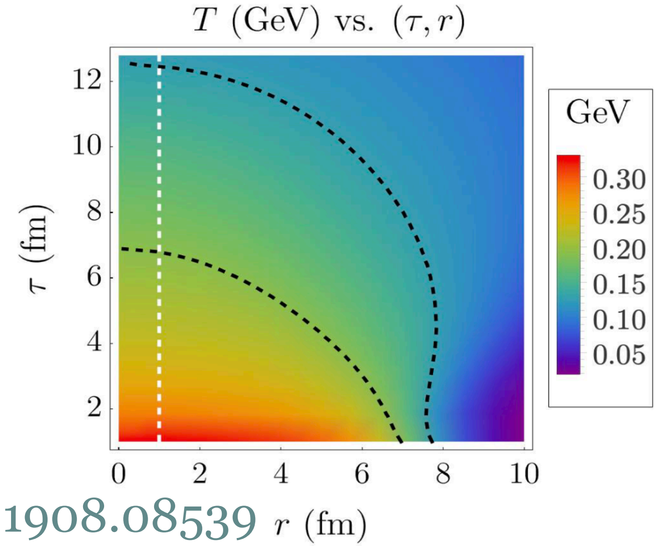
- Solution of stochastic hydro equations using a momentum filter by which fluctuating modes above a cutoff given by a microscopic scale are removed

M. Singh et al., QM2018 proceedings

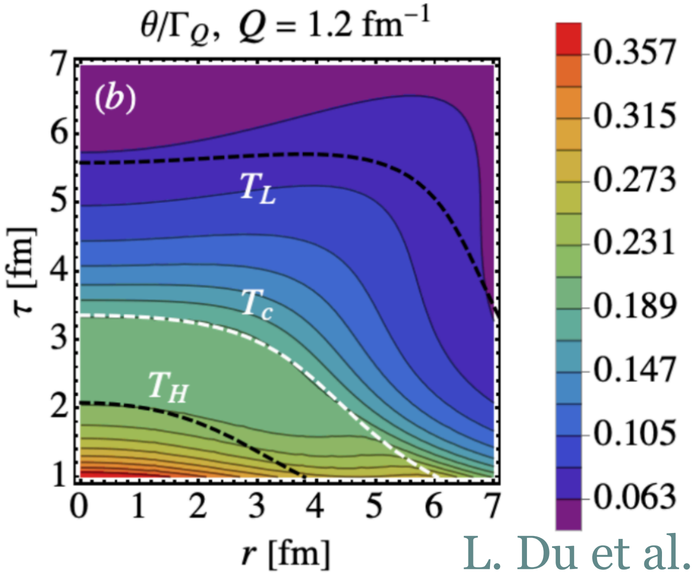
- Solution of full stochastic diffusive equation in a finite-size system with Gaussian white noise: critical slowing down is observed

M. Nahrgang et al., 1804.05728

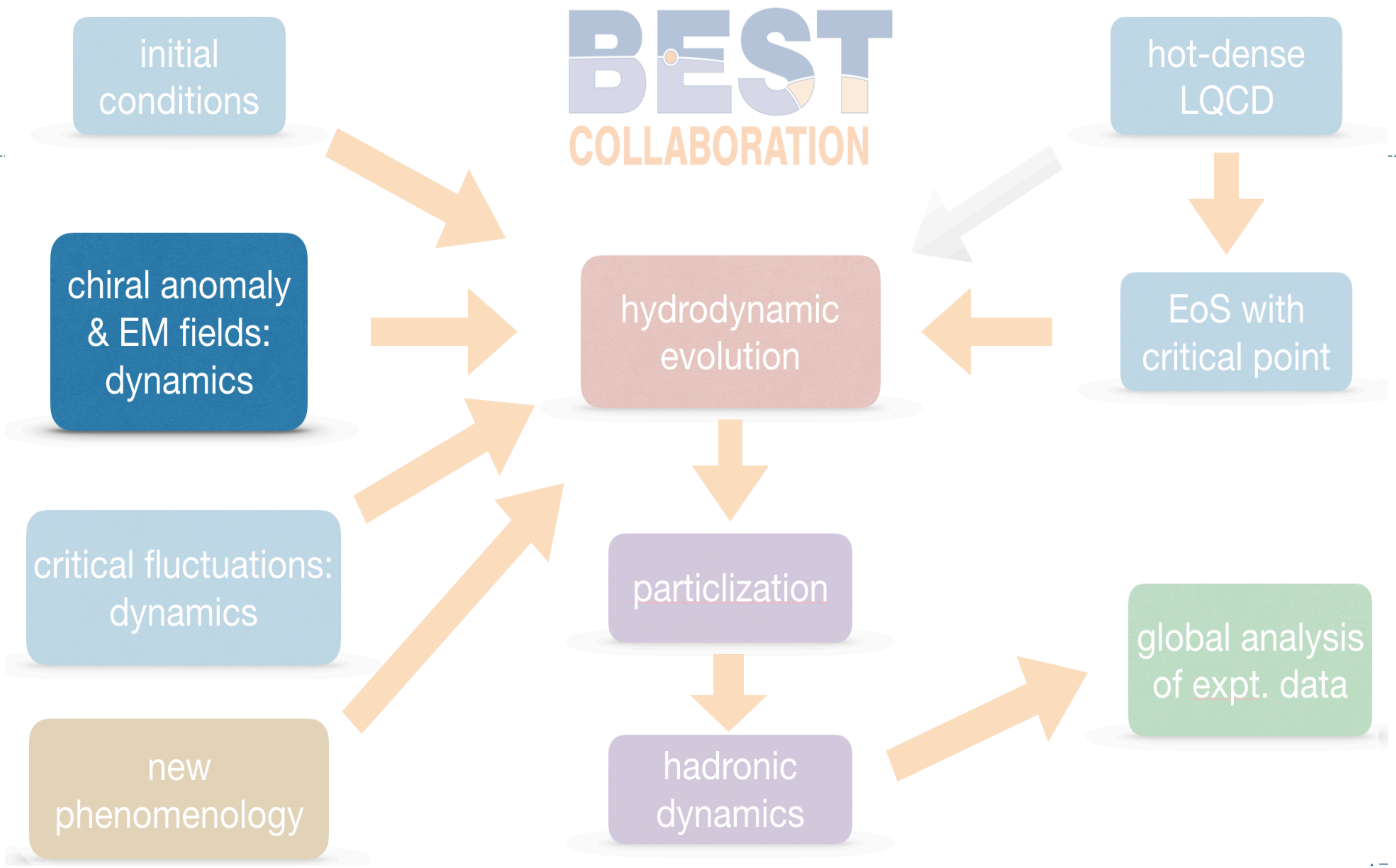
- Hydro+ implemented in two main simulations



K. Rajagopal et al., 1908.08539



L. Du et al., 2004.02719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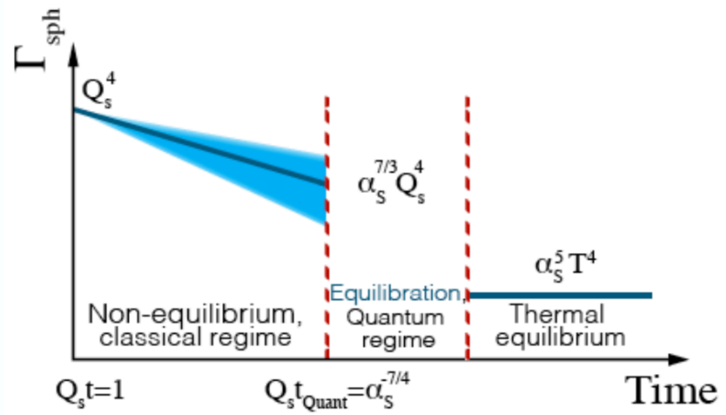
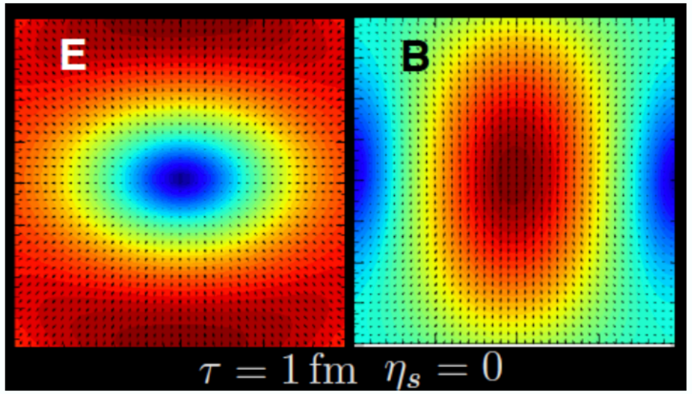
Scientific goals and achievements

- Model fluctuating initial conditions for axial charges

  Mace et al., PRD (2016)
  Shi et al., PRL (2020)



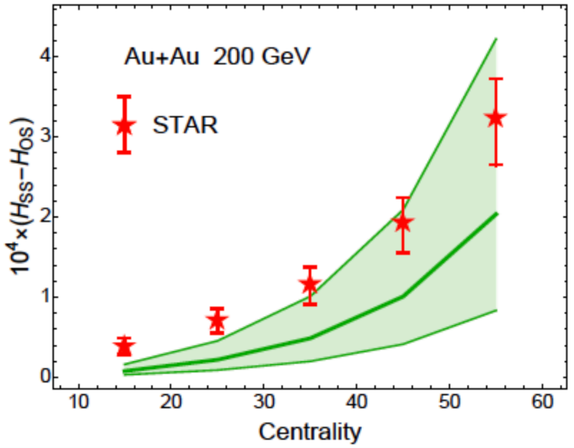


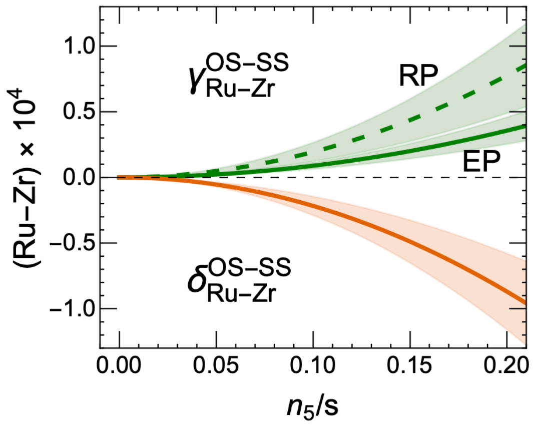
- Develop magneto-hydro code and incorporate anomalous hydro terms, studying the co-evolution of the dynamical magnetic field with the medium

  U. Gursoy et al., PRC (2018)

- Quantitatively characterize the experimental signals of CME

  Shi et al., Annals of Physics (2018)



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Particlization

- Develop the interface between the hydrodynamic evolution and hadronic transport, such that it preserves fluctuations

  - micro-canonical Metropolis sampling algorithm: conserves all the charges as well as energy and momentum as given by hydrodynamics

    D. Oliinychenko, V. Koch, PRL (2019)

  - Particlization of hydro+: projects fluctuations from hydro+ onto the represented hadrons

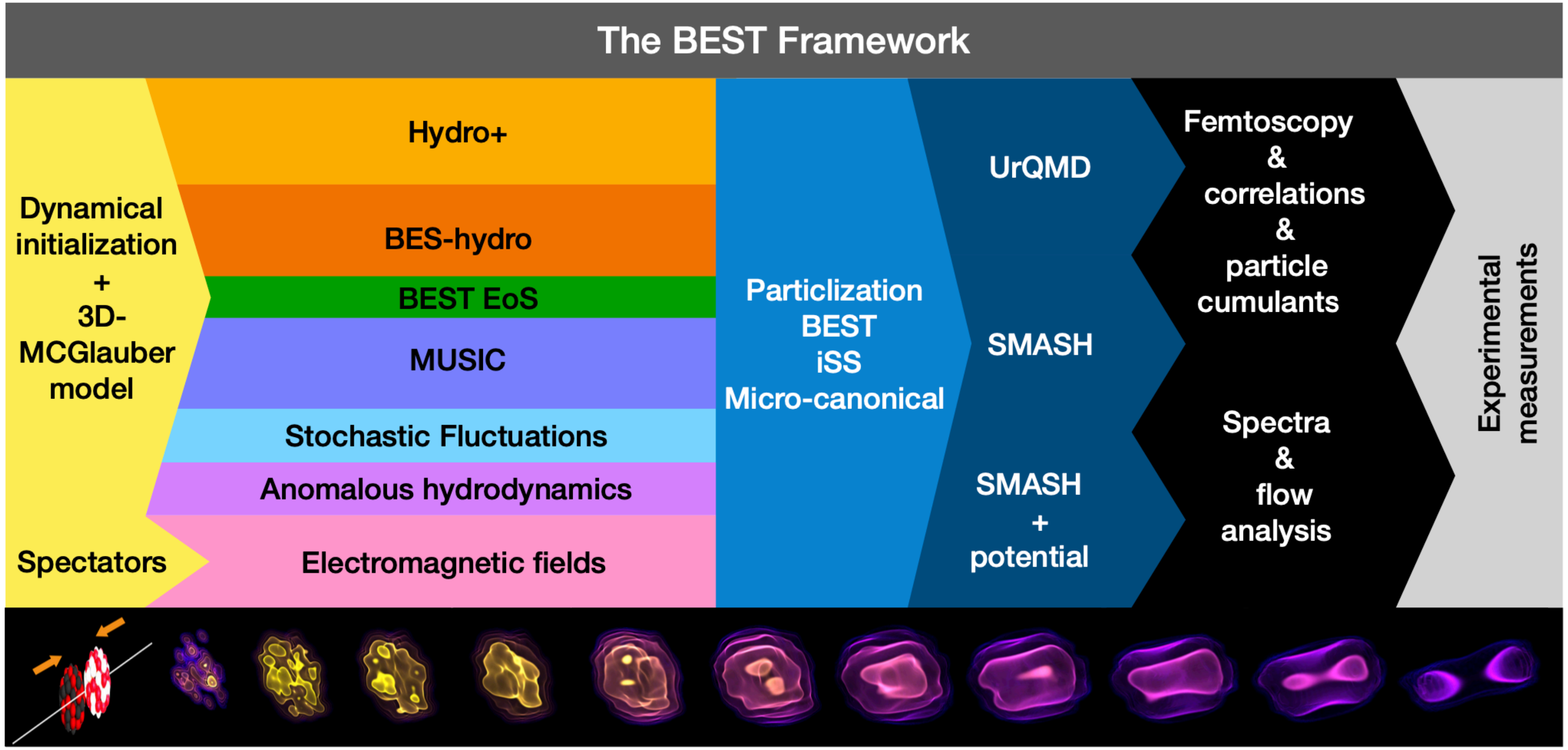
    Pradeep, Rajagopal, Stephanov, Weller and Yin, in progress

  - Hadronic transport with tunable potentials

    A. Sorensen, V. Koch, 2011.06635

Conclusions

- The BEST collaboration has made tremendous strides towards developing a dynamical framework for a quantitative description of low-energy heavy-ion collisions
- The BEST framework is modular: all components are being thoroughly tested
- The design will accommodate a global Bayesian analysis of BESII data, when they become available

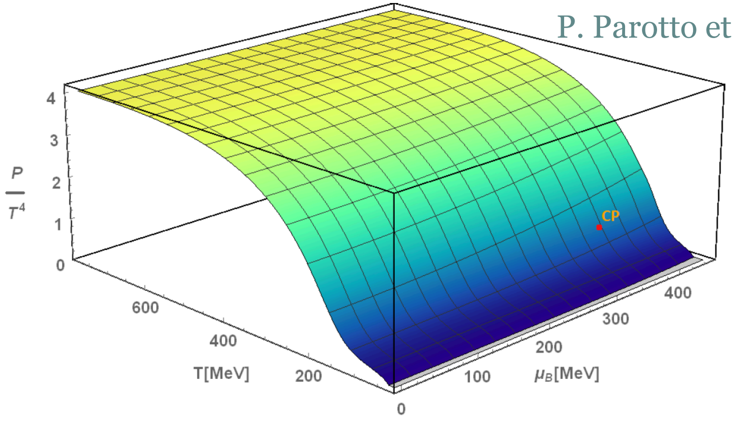


Backup Slides

Two versions of the EoS

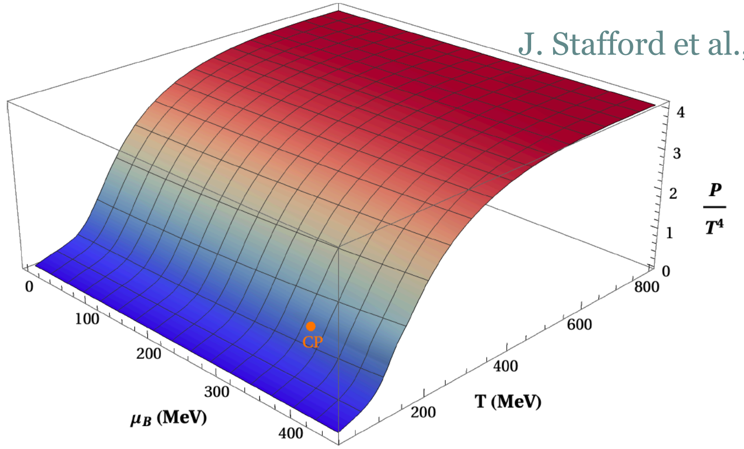
- Finite T and μ_B, but $\mu_S = \mu_Q = 0$

P. Parotto et al., PRC (2020)

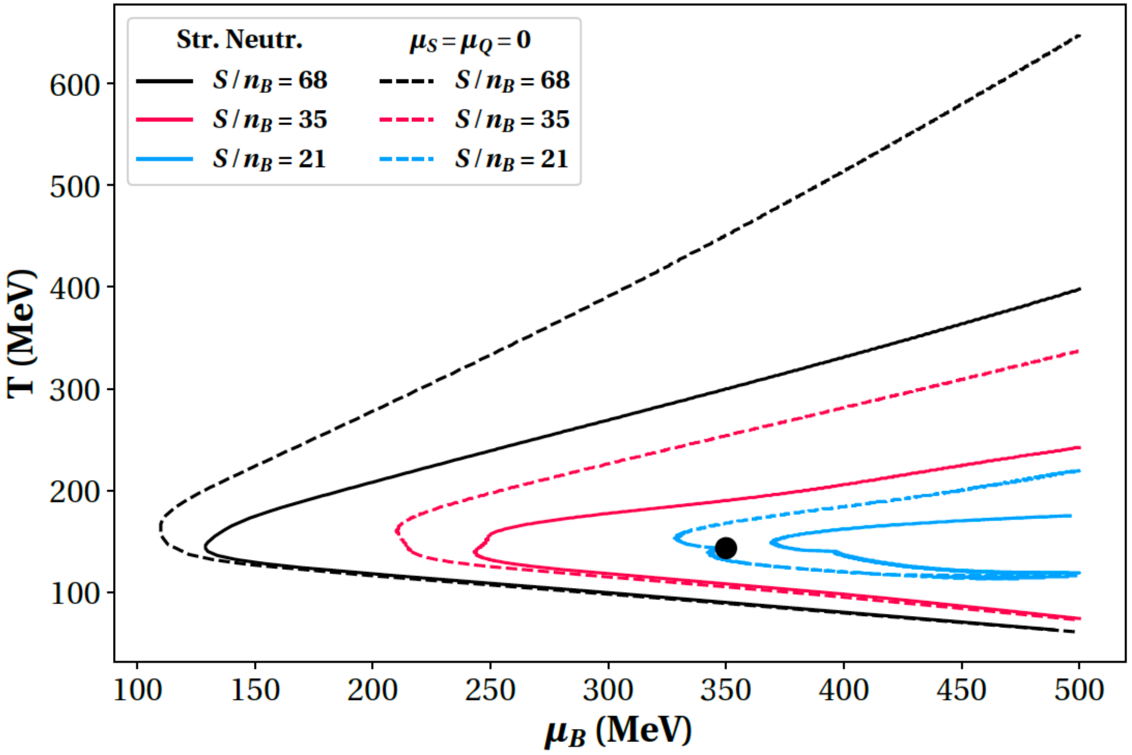


- Finite T, μ_B, μ_S and μ_Q such that $n_S=0$ and $n_Q=0.4n_B$

J. Stafford et al., 2103.08146 (2020)



- Comparing isentropes...



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J. Noronha-Hostler, C.R. et al., PRC (2019)

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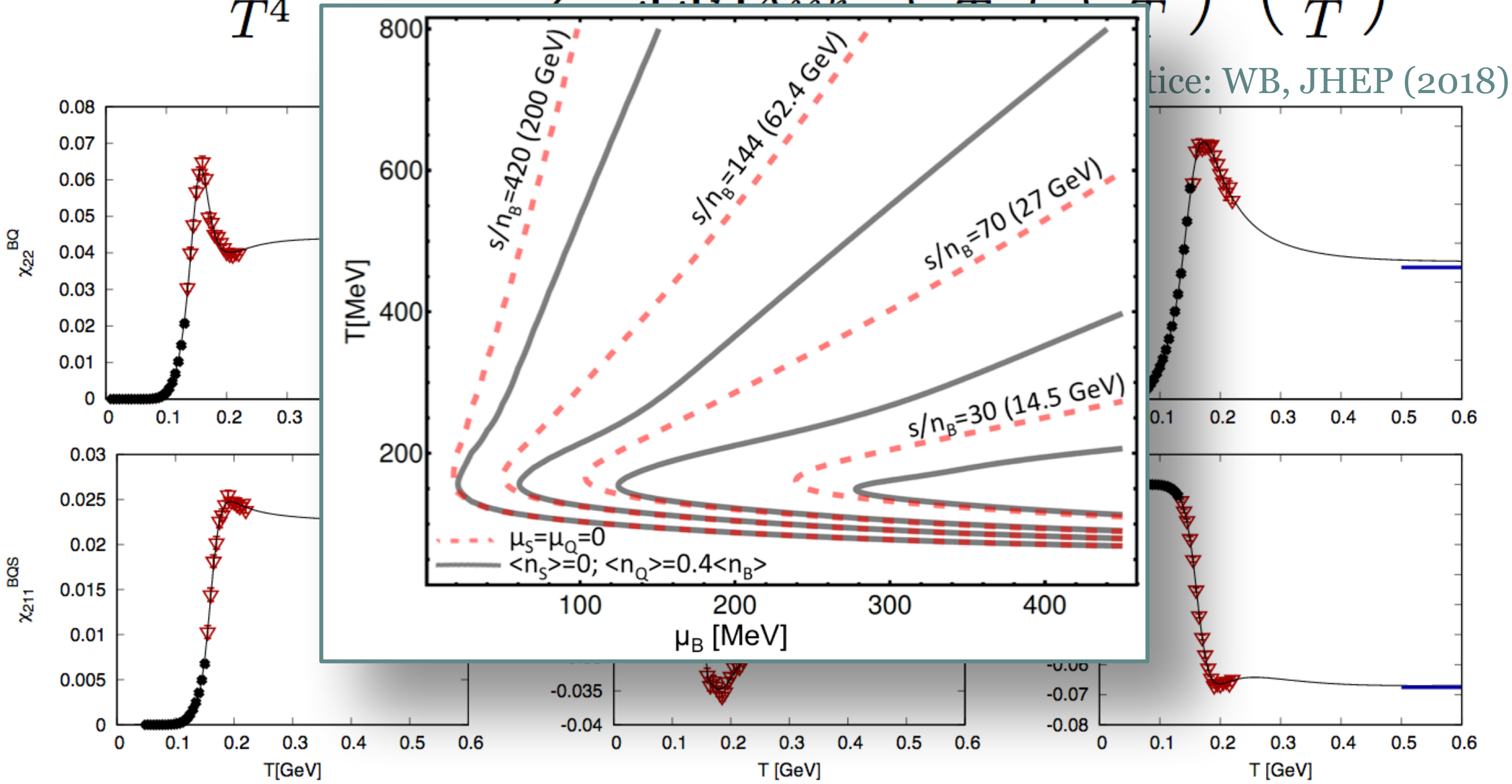
tice: WB, JHEP (2018)



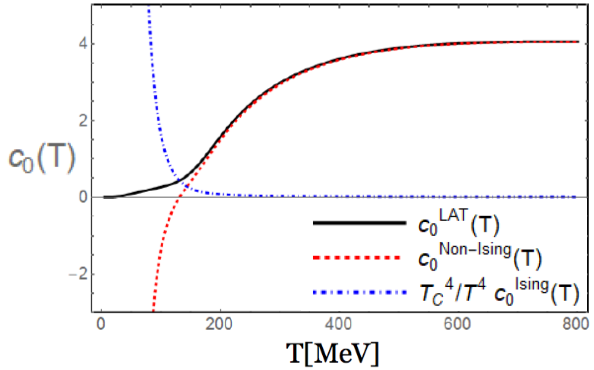
See also A. Monnai et al., 1902.05095PRC (2019)

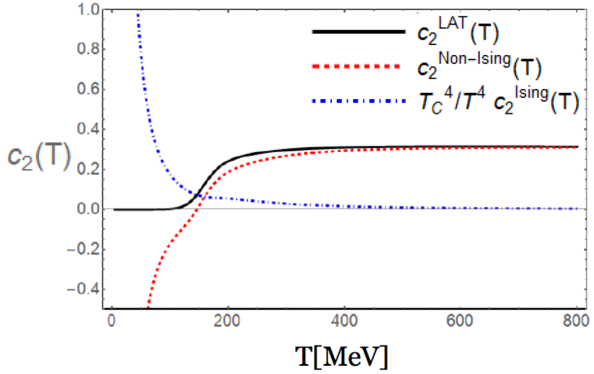
Expansion coefficients and EoS

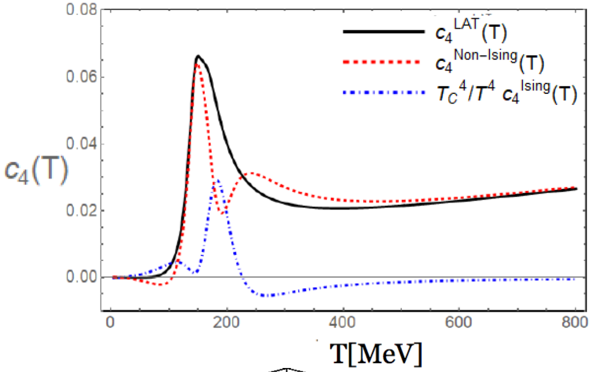
P. Parotto et al.,: PRC (2020)

Extract the “regular” contribution as the difference between the lattice and Ising ones

$$T^4 c_n^{\mathrm{LAT}}(T) = T^4 c_n^{\text{Non-Ising}}(T) + T_C^4 c_n^{\mathrm{Ising}}(T)$$

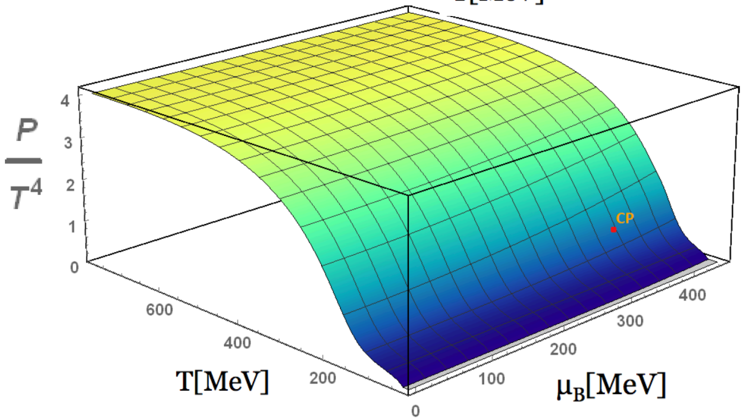






Total pressure becomes:

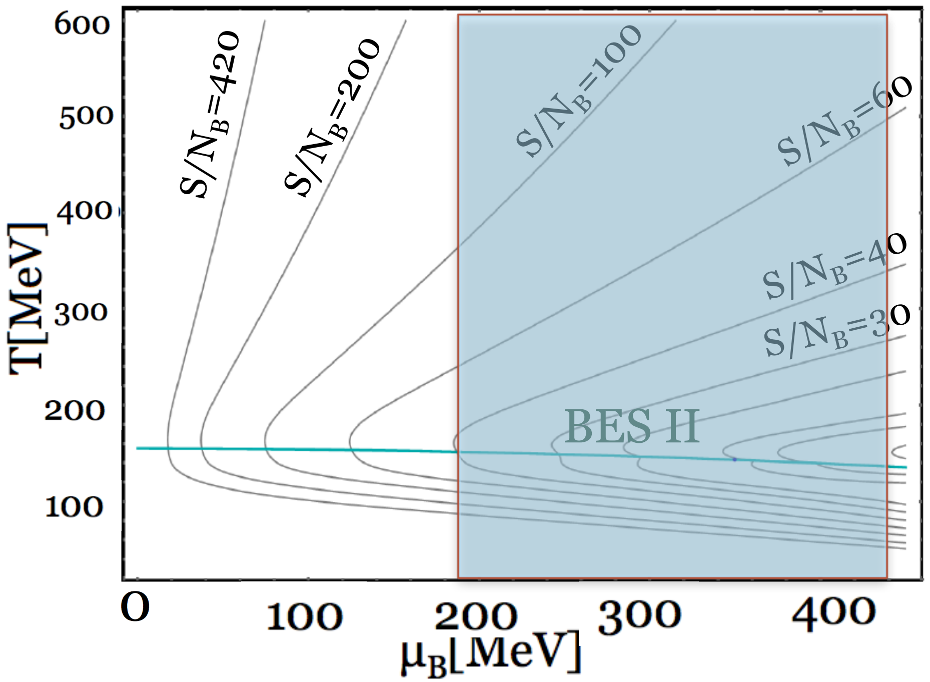
$$P(T, \mu_B) = T^4 \sum_n c_{\text{Non-Ising}}^n(T) \left(\frac{\mu_B}{T}\right)^n + T_C^4 P_{\mathrm{Ising}}(T, \mu_B)$$

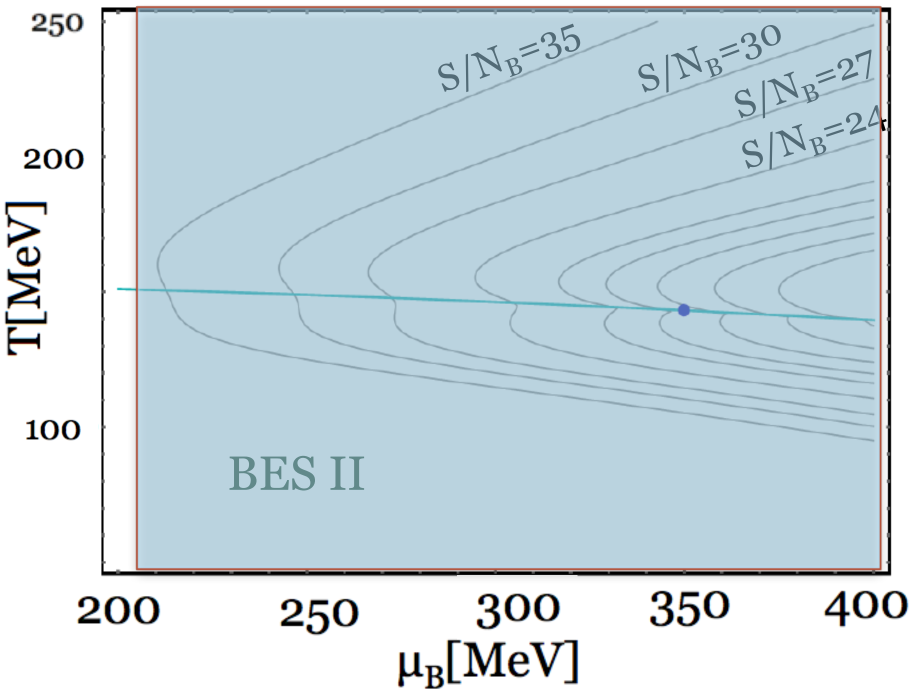


Final EoS: Isentropic trajectories

P. Parotto et al.,: hep-ph/1805.05249

- Relevant for hydrodynamic evolution are the lines of $s/n_B = \text{const}$:
  - Low-μ_B: match behavior from Lattice QCD
  - Close to the CP: some structure appears



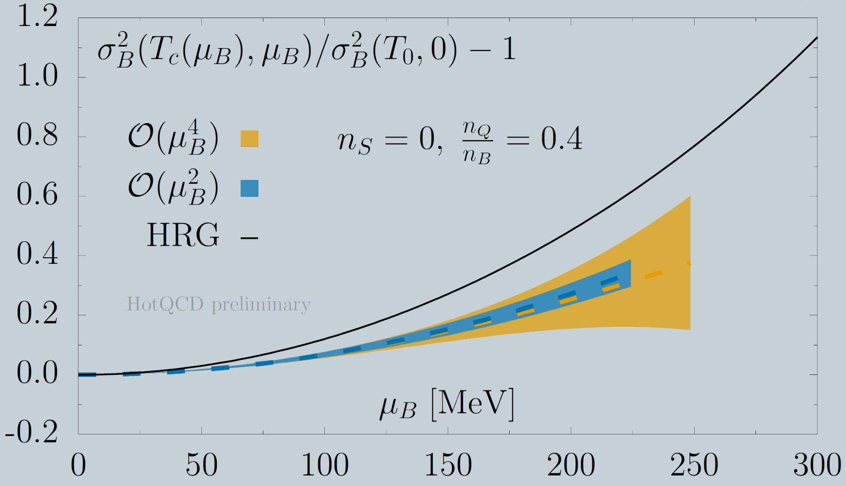


Fluctuations along the QCD crossover

P. Steinbrecher for HotQCD, 1807.05607

Net-baryon variance

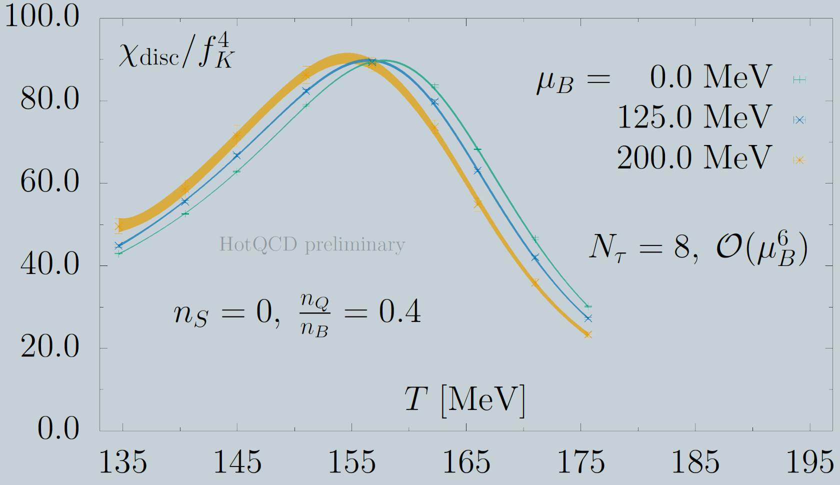
$$\frac{\sigma_B^2(T_c(\mu_B),\mu_B)-\sigma_B^2(T_0,0)}{\sigma_B^2(T_0,0)} = \lambda_2\left(\frac{\mu_B}{T_0}\right)^2 + \lambda_4\left(\frac{\mu_B}{T_0}\right)^4 + \mathcal{O}(\mu_B^6)$$



- Expected to be larger than HRG model result near the CP
- No sign of criticality

Disconnected chiral susceptibility

$$\chi_{\text{sub}} \equiv \frac{T}{V} m_s\left(\frac{\partial}{\partial m_u}+\frac{\partial}{\partial m_d}\right)\left[m_s(\Sigma_u+\Sigma_d)-(m_u+m_d)\Sigma_s\right]$$

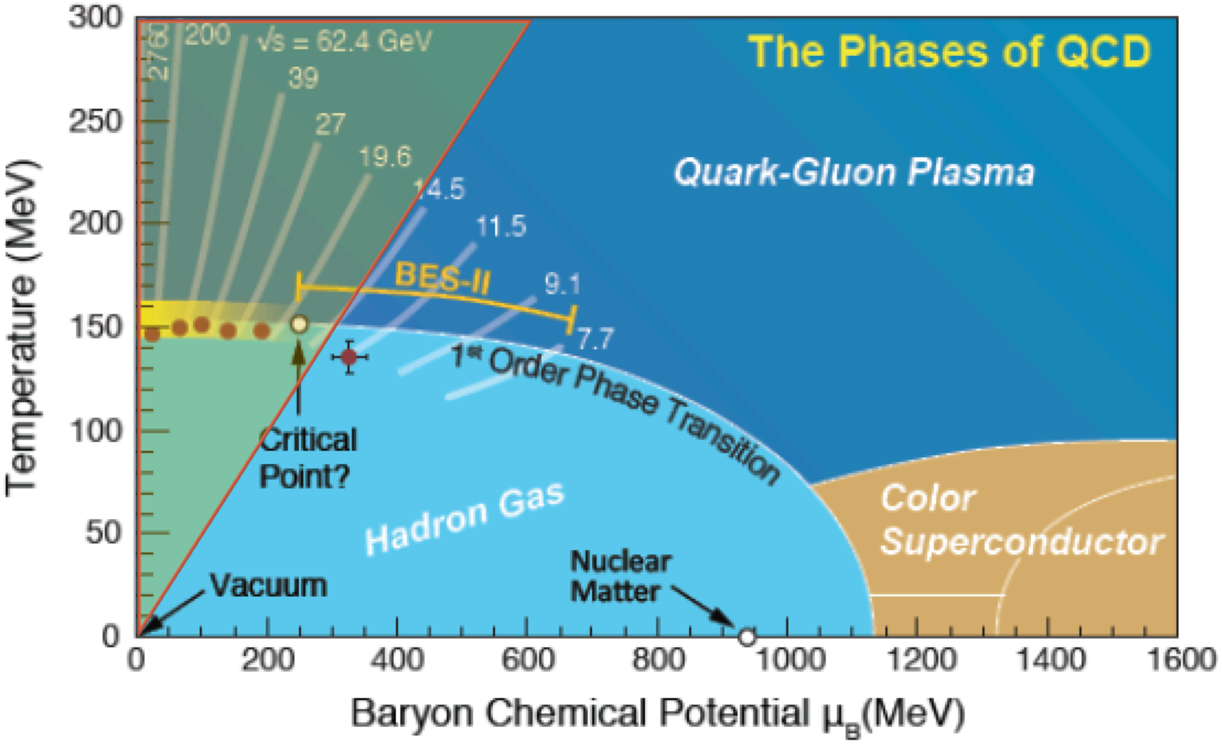


- Peak height expected to increase near the CP
- No sign of criticality

QCD Equation of state for $\mu_B>0$

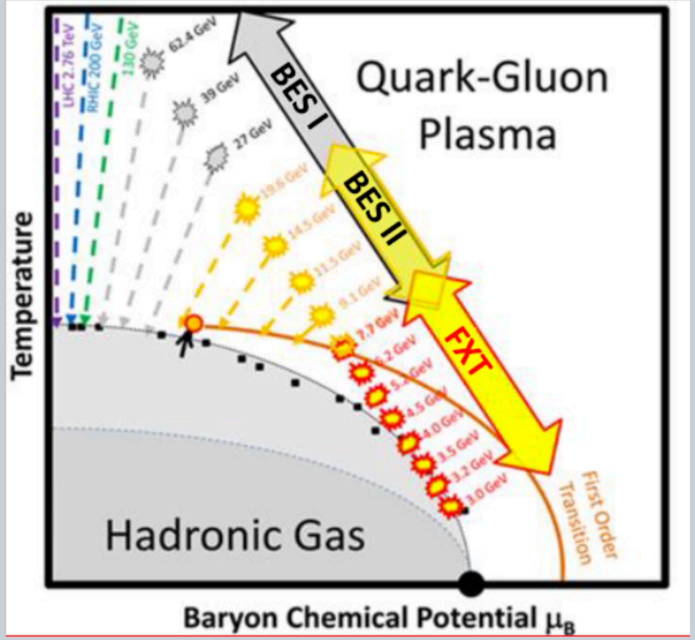
- We now have the equation of state for $\mu_B/T\leq 2$ or in terms of the RHIC energy scan:

$$\sqrt{s}=200,\ 62.4,\ 39,\ 27,\ 19.6,\ 14.5\mathrm{GeV}$$



Second Beam Energy Scan (BESII) at RHIC

- Planned for 2019-2020
- 24 weeks of runs each year
- Beam Energies have been chosen to keep the μ_B step ~50 MeV
- Chemical potentials of interest: μ_B/T~1.5…4



√s (GeV)	19.6	14.5	11.5	9.1	7.7	6.2	5.2	4.5
μ_B (MeV)	205	260	315	370	420	487	541	589
# Events	400M	300M	230M	160M	100M	100M	100M	100M

Collider | Fixed Target

Comparison of the facilities

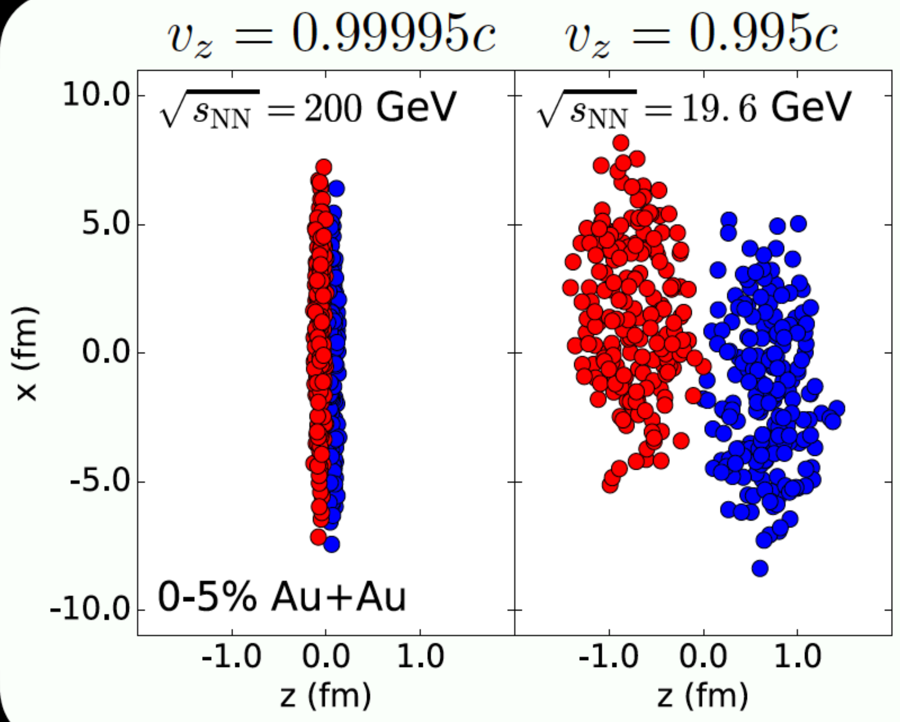
Compilation by D. Cebra

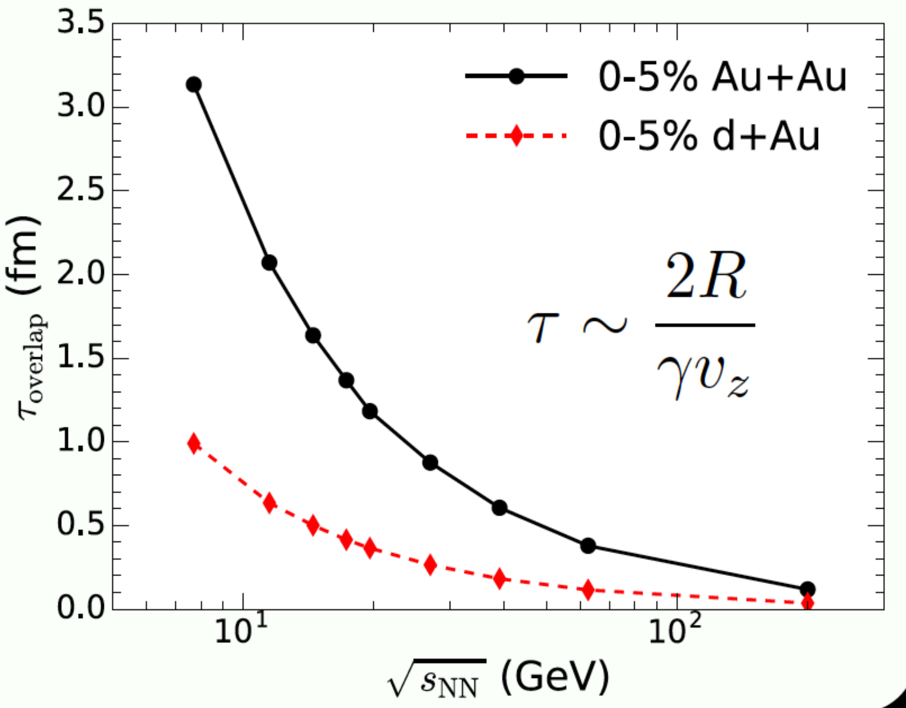
Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed target	Fixed target Lighter ion collisions	Collider Fixed target	Fixed target	Fixed target

CP=Critical Point OD= Onset of Deconfinement DHM=Dense Hadronic Matter

Heavy-ion collisions at RHIC BES

I. A. Karpenko, P. Huovinen, H. Petersen and M. Bleicher, Phys. Rev. C91 (2015) 064901
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



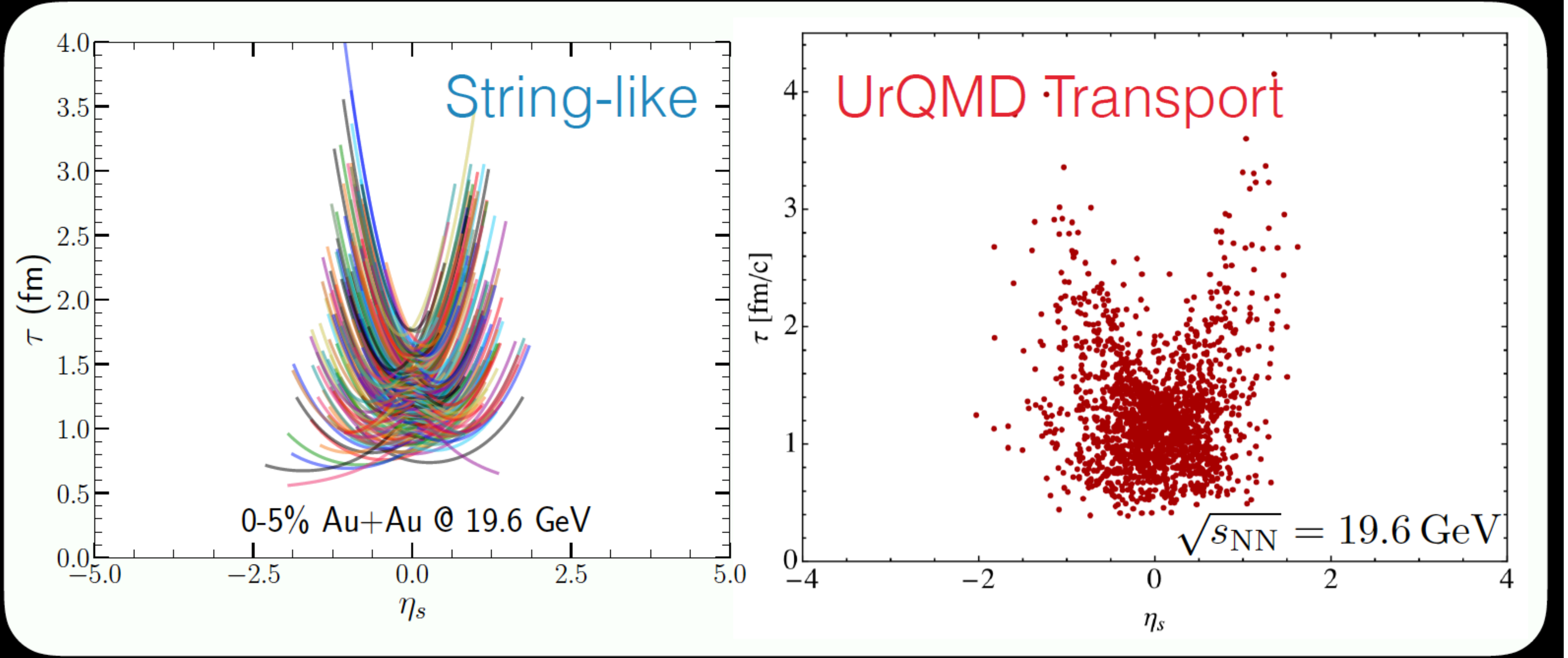


- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

note: total evolution time ~ 10 fm

Energy-momentum space-time distribution

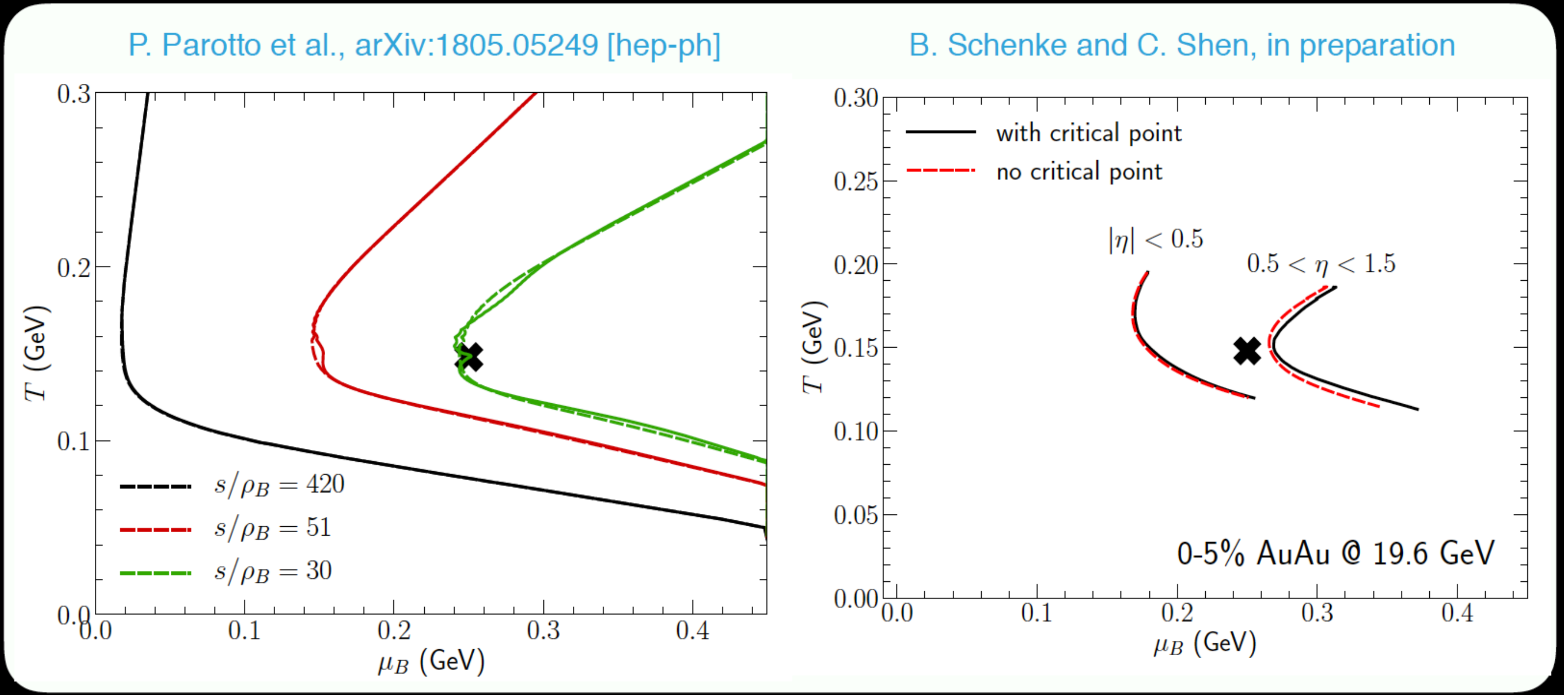
C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907
L. Du, U. Heinz and G. Vujanovic, Nucl. Phys. A982 (2019) 407-410



- An extended interaction zone for the energy-momentum sources from the 3D collision geometry

Dynamically interweaves with hydrodynamics

BEST EOS with a critical point



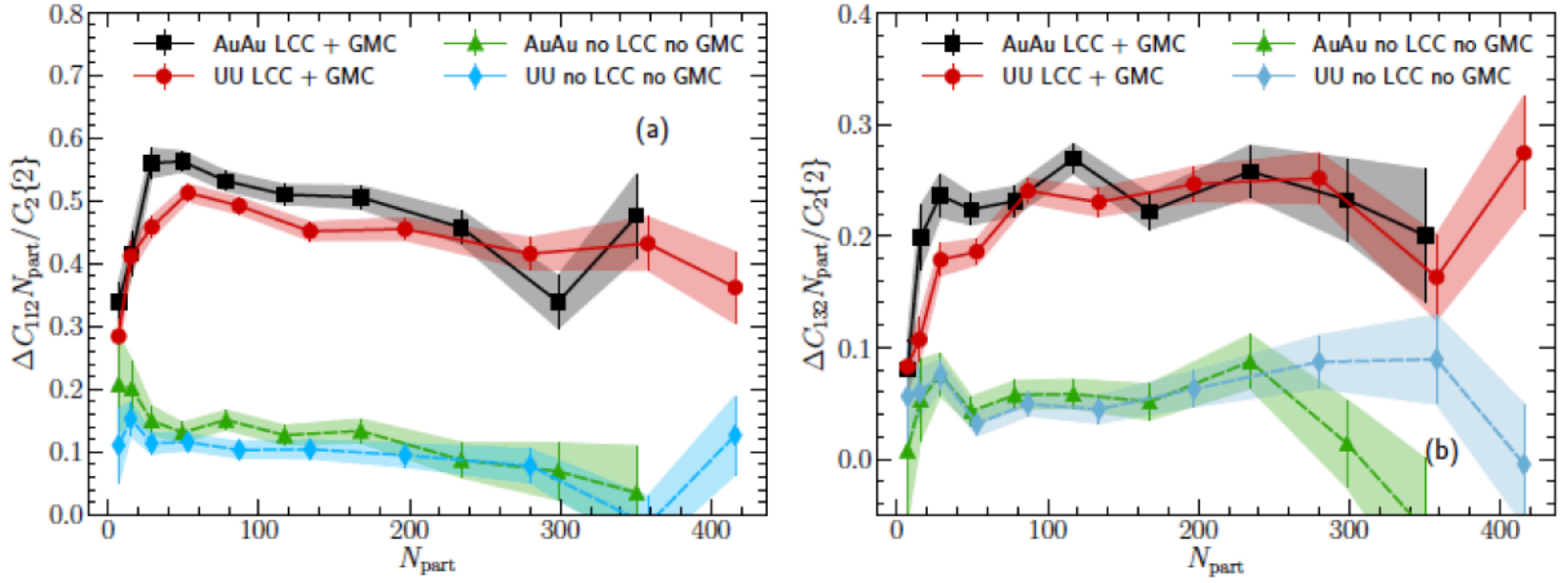
- The BEST EOS is implemented in the state-of-the-art 3D hydrodynamic code (MUSIC)

Visible difference in the fireball trajectories with a critical point

CME Working Group Achievements

Specific Goals #2 & #4:

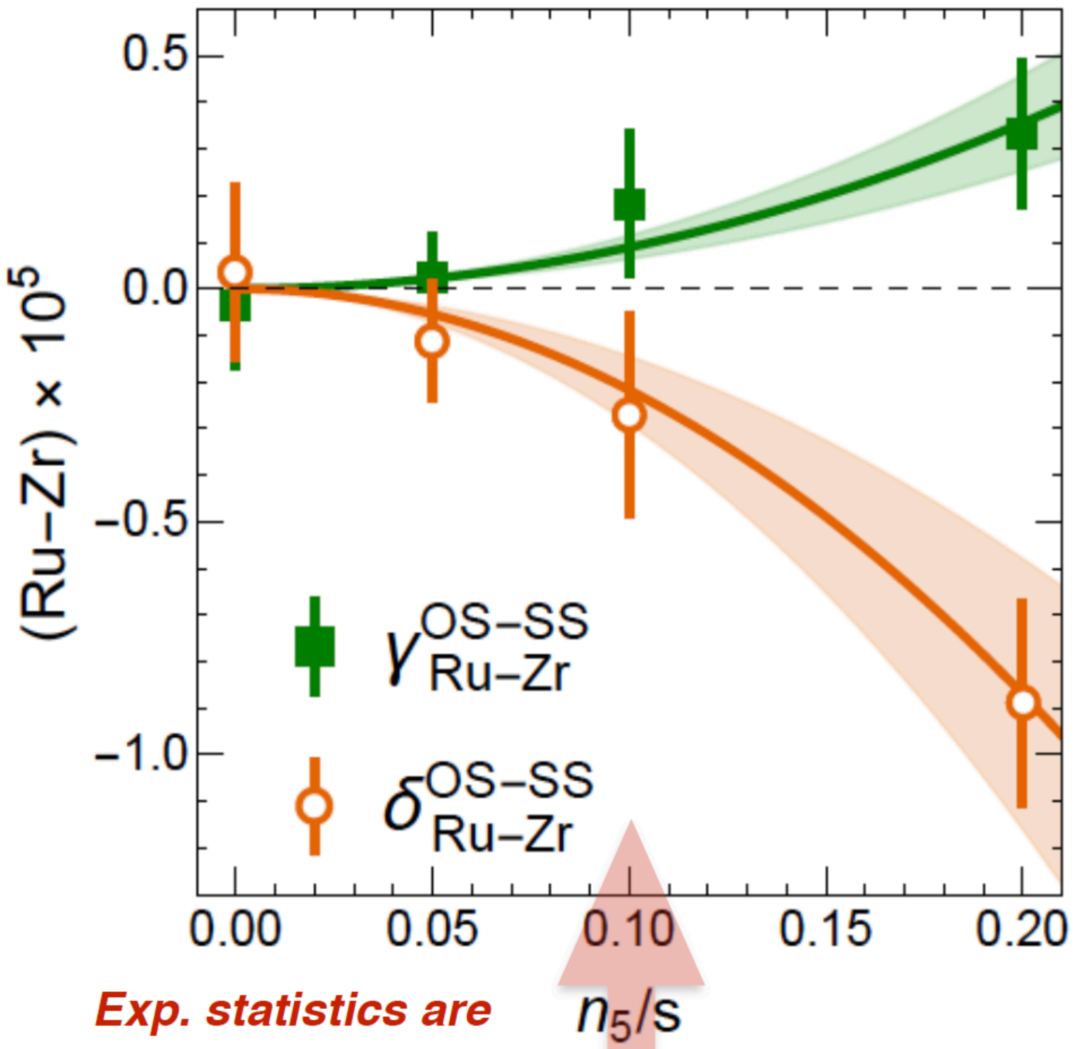
– "…backgrounds"



A detailed quantification of various background correlations in the data-validated state-of-art hydrodynamic framework

[Schenke, Shen, Tribedy, 2019]

New Opportunity: Isobaric Collisions



AVFD predictions for CME signals in isobars

EBE-AVFD: Include EBE fluctuations

- Initial Conditions
- Statistic @ Freeze-out
- Hadron Cascade

[Shi, JL, …, QM2018]
[BEST: IU-McGill]

Exp. statistics are expected to shrink error bar by a factor of ~10

Projected axial charge level based on comparison AuAu data

Data analysis

GOAL: Bayesian Comparison of BEST models to BES data

- Collect and distill data (once BES data are available)
  — state uncertainties

- Parameterize BEST beginning-to-end model
  — a few dozen parameters; once model is available

- Construct and tune model emulator
  — Gaussian process or machine learning
  — Requires significant computational resources

- Determine (including uncertainty) likelihood of parameters
  — Markov Chain Monte Carlo
  — Parameters describe:
  EoS, Viscosity, Diffusion constants….
  and ultimately critical point and anomalous transport

Progress

John Bower
grad stud, MSU

- Emulators constructed:
  — Gaussian process
  — Machine-learning
  — Comparison underway
  — Strategies for expressing uncertainties are being developed

- Sample problem
  — Imaging charge correlations
  — Should also be applicable to BES data

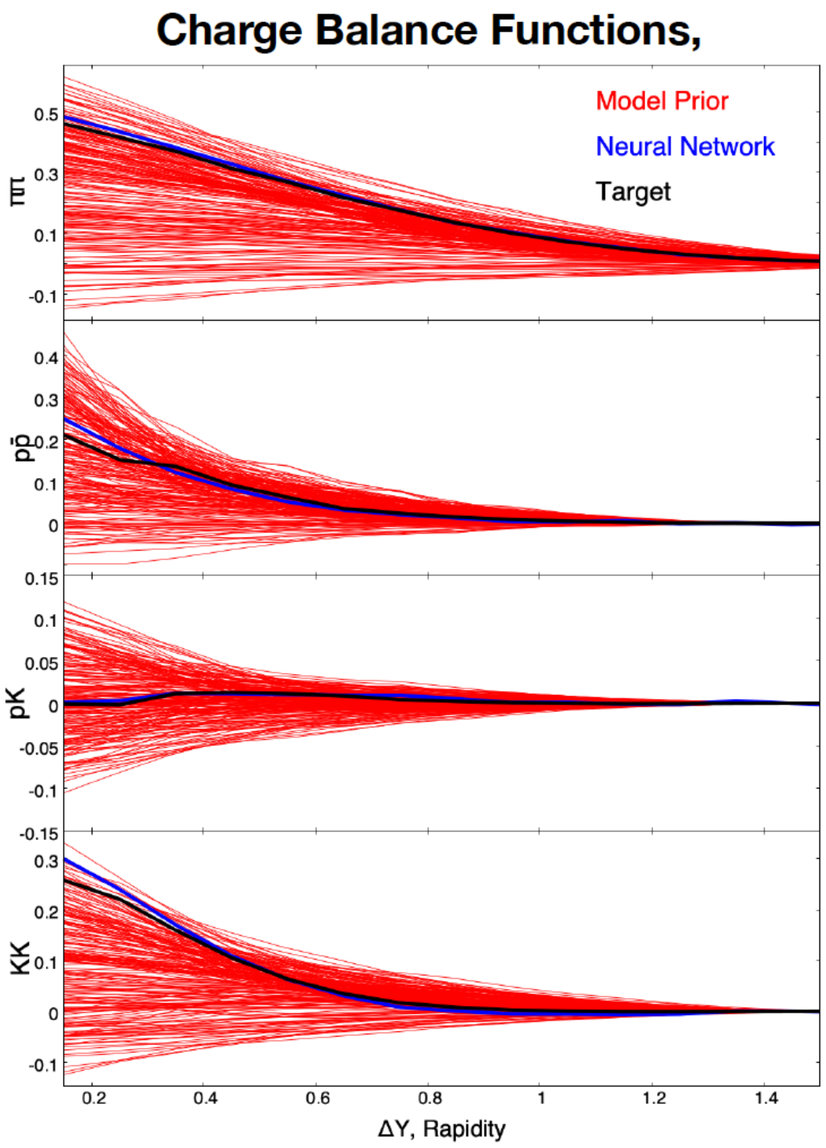
$$B_{\pi,\pi}(\Delta y), B_{K,K}(\Delta y), B_{p,p}(\Delta y), B_{p,K}(\Delta y)$$

Measured by STAR

$$\rightarrow C_{uu}(\Delta\eta), C_{ud}(\Delta\eta), C_{ss}(\Delta\eta), C_{us}(\Delta\eta)$$

Correlations in coordinate space

Progress



Two emulators constructed:

1. Gaussian Process
2. Neural network

Currently being compared

<u>Test of Neural Network Emulator</u>

Balance functions used for training

Balance function from trained Neural Network

True BF using full model

Next steps

- Transport
  - Particlization for deterministic hydro (hydro+)
  - Connect particlization algorithm + SMASH to hydro; test
  - Implement mean field into SMASH transport; test
  - Run full code and calculate global observables such as flow
  - Connect to stochastic hydro; test
  - Match mean field to EOS
  - Ready to calculate fluctuations
- Data analysis
  - Finish warm-up projects
    - — imaging
    - — Machine learning vs Gaussian emulator comparison
  - Connect statistics codes with full BEST time evolution code
  - Collect statistics from experiments
  - Develop strategy for running, and allocate resources