Overview of the BEST collaboration and status of lattice QCD

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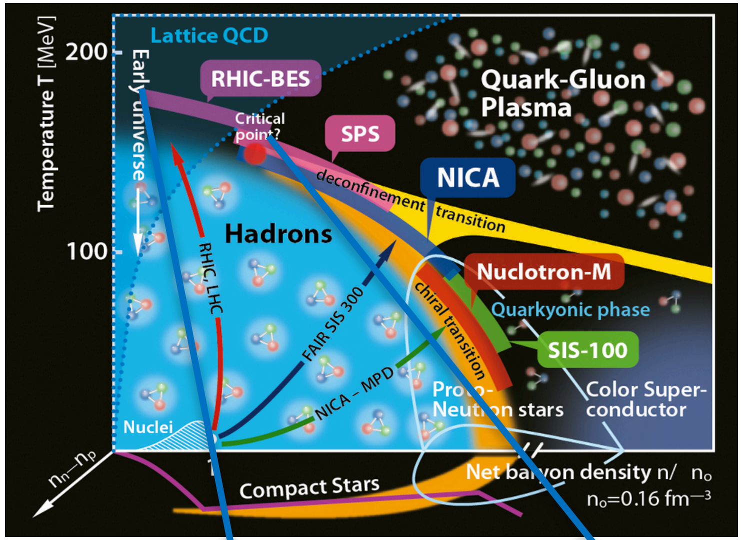
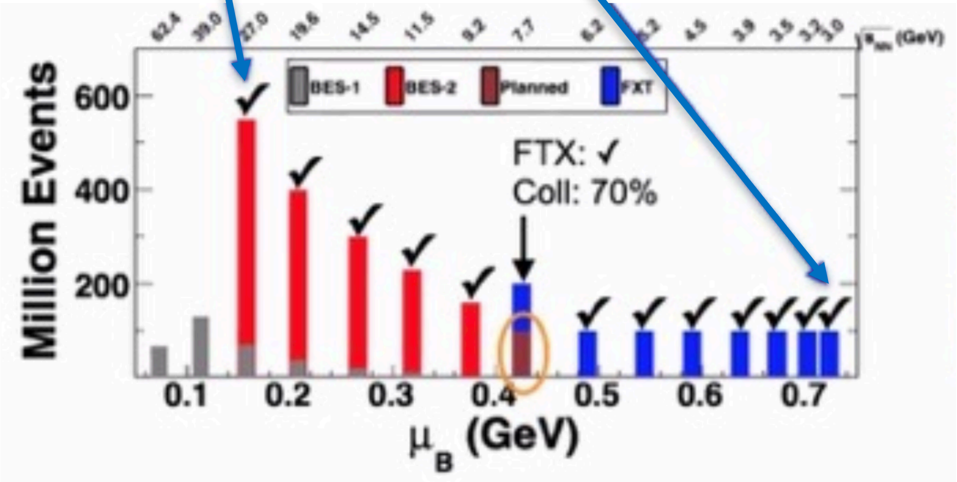
X. An et al, "The BEST framework for the search for the QCD critical point and the chiral magnetic effect", NPA (2022)

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?





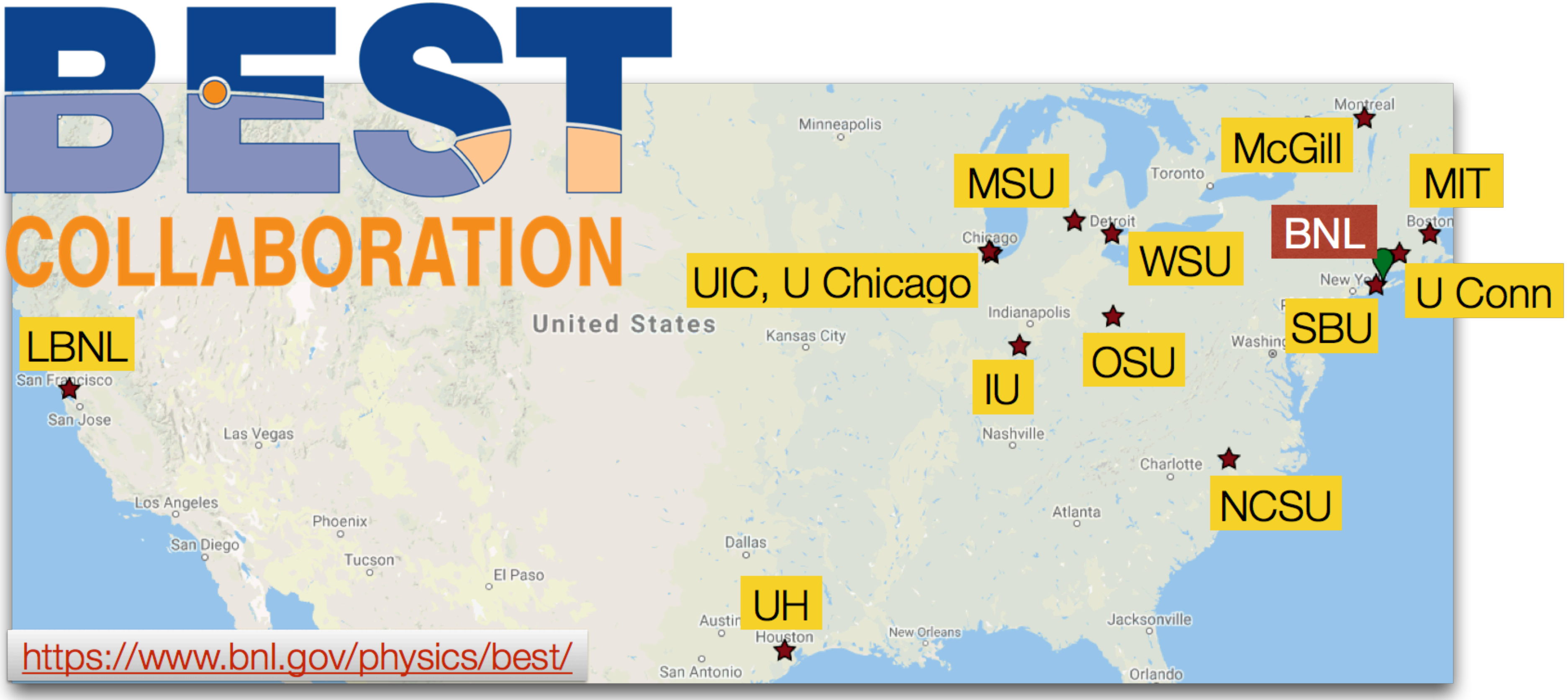
- Run 2019:
  - Collider: $\sqrt{s_{NN}}$=14.6, 19.6, 200 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.2 GeV
- Run 2020:
  - Collider: $\sqrt{s_{NN}}$=9.2, 11.5 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7 GeV
- Run 2021:
  - Collider: $\sqrt{s_{NN}}$=7.7 GeV

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:	2019-2021	2009	2022	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

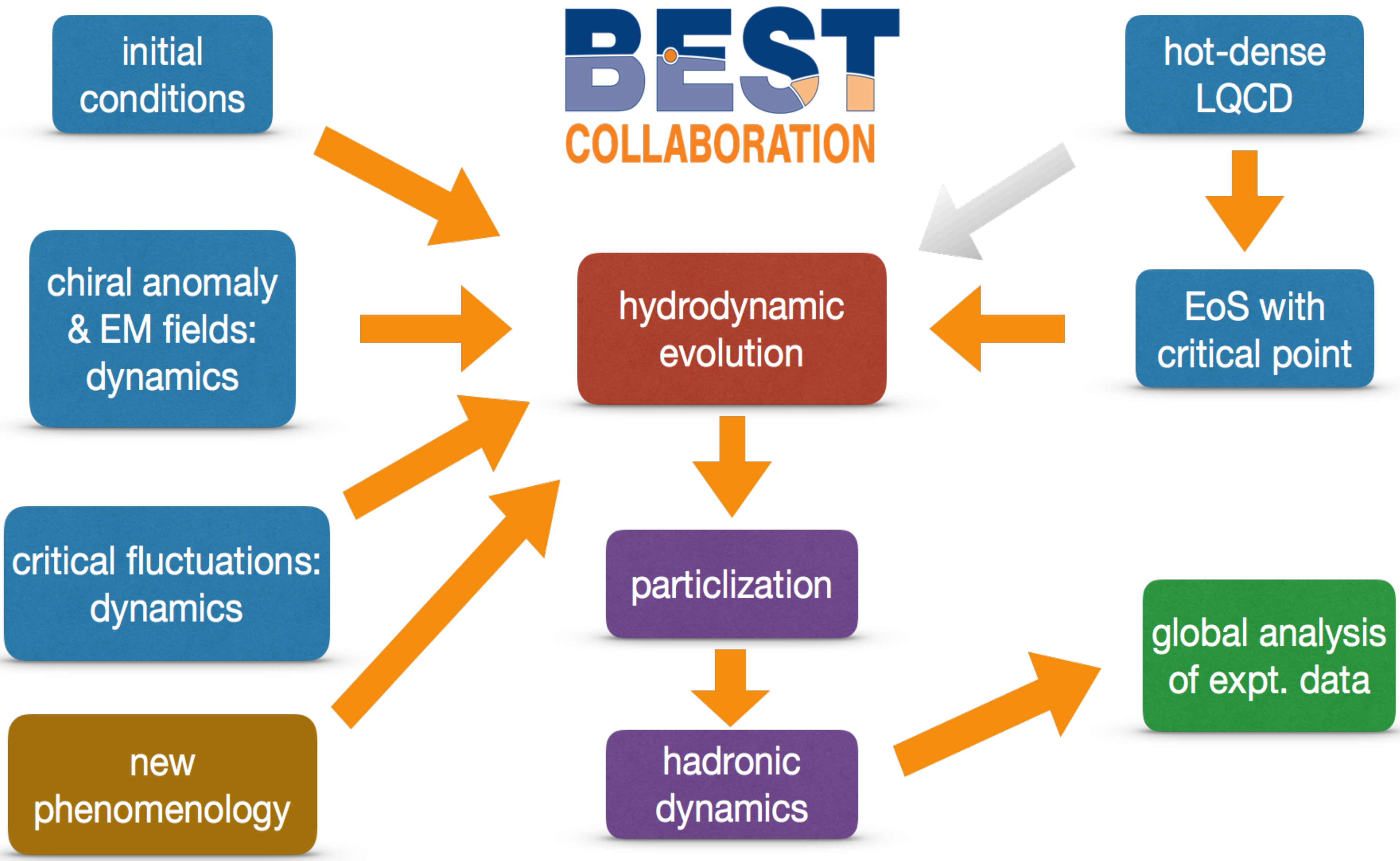


objectives:

- 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


BEST
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chiral anomaly & EM fields: dynamics
critical fluctuations: dynamics
new phenomenology
hydrodynamic evolution
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Hot and dense lattice QCD

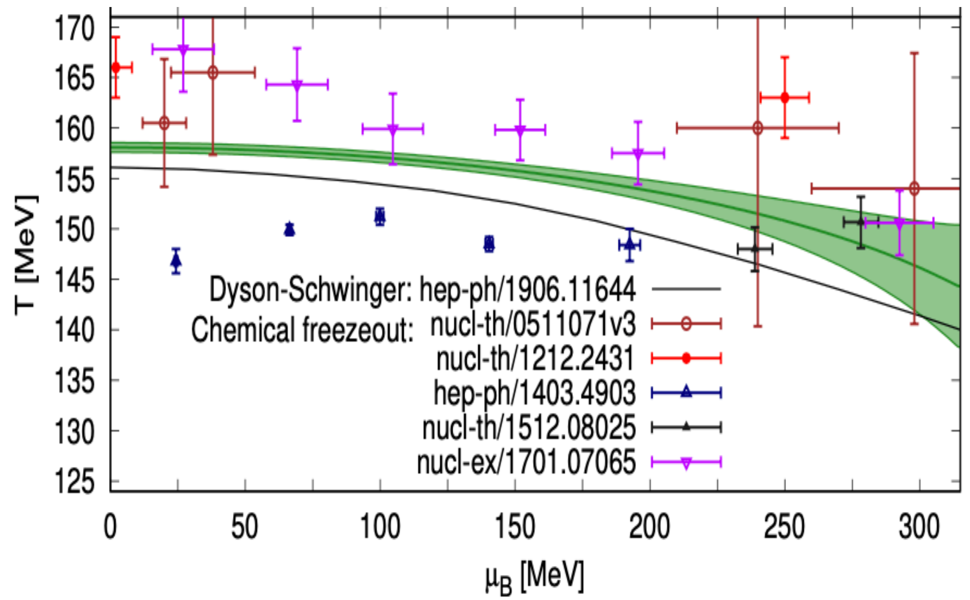
BNL, UH

Major goals:

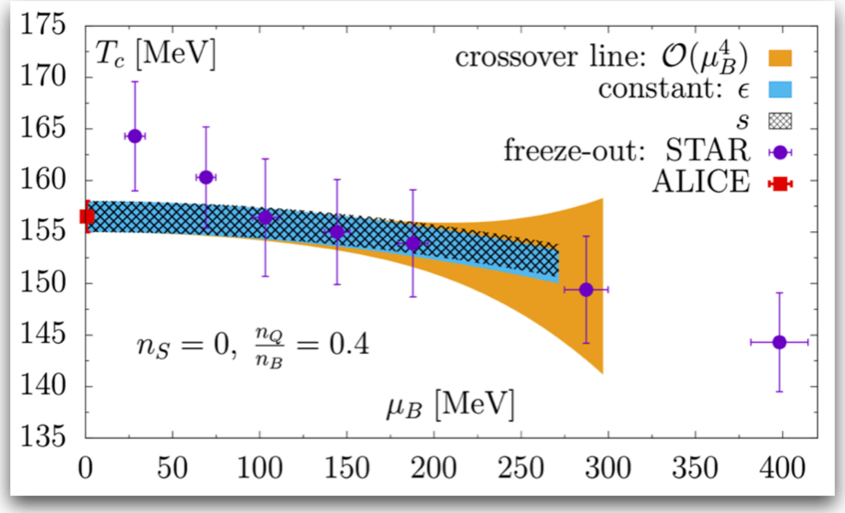
- QCD crossover temperature $T_c(\mu_B)$
  - switching temperature/energy density for fluid-dynamical modeling
- QCD equation of state (EoS) for $\mu_B>0$
  - input for fluid-dynamical modeling & EoS with critical point
- skewness and kurtosis of conserved charge fluctuations for $\mu_B>0$
  - equilibrium 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)



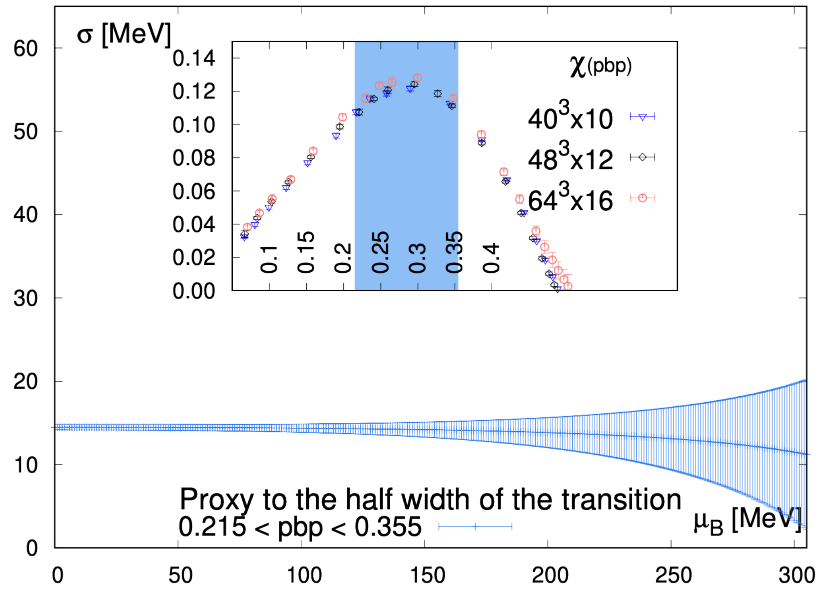
$$\frac{T_c(\mu_B)}{T_0} = 1 - \kappa_2\left(\frac{\mu_B}{T_0}\right)^2 - \kappa_4\left(\frac{\mu_B}{T_0}\right)^4 + \mathcal{O}(\mu_B^6)$$

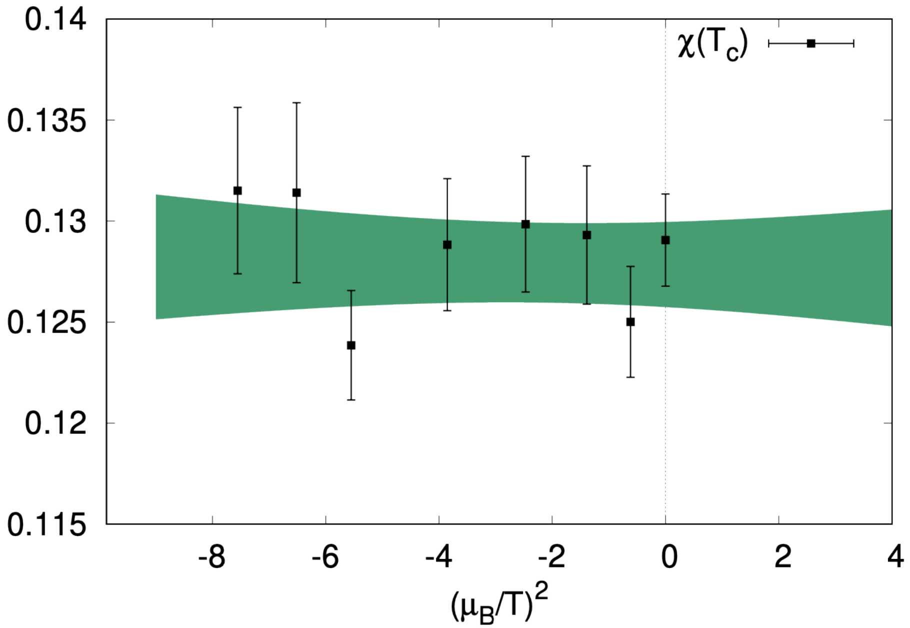
T_0=158.0±0.6 MeV
κ_2=0.0153±0.0018
κ_4=0.00032±0.00067

T_0=156.5±1.5 MeV
κ_2=0.012±0.004
κ_4=0.000±0.004

Width and strength of the transition

WB:PRL (2020)





- The width of the transition is constant up to μ_B~300 MeV
- Height of the peak of the chiral susceptibility at the crossover temperature: proxy for the strength of the crossover: roughly constant

QCD Equation of state for $\mu_B>0$

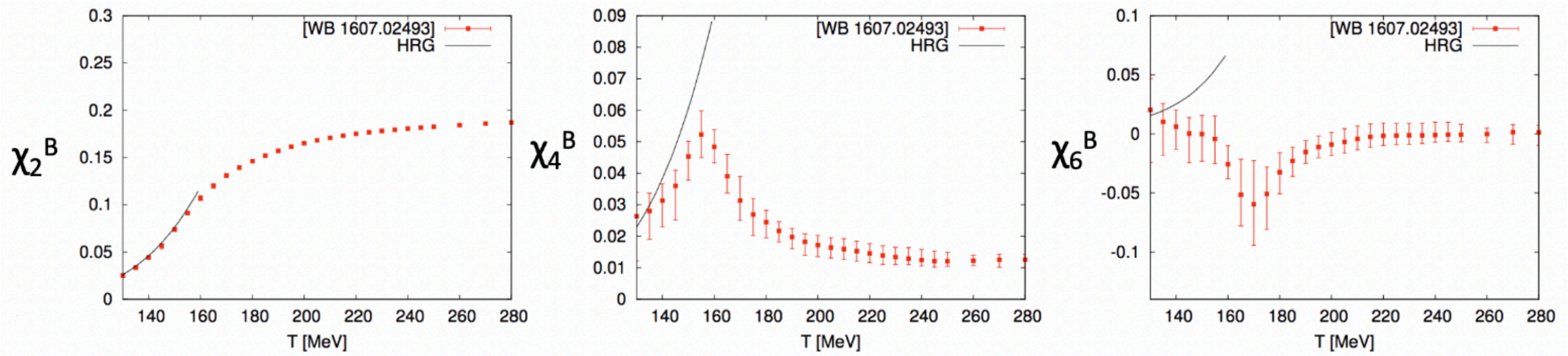
- Taylor expansion of the pressure:

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

- Two choices: - $\mu_B \neq 0$, $\mu_S=\mu_Q=0$
  - μ_S and μ_Q are functions of T and μ_B to match the experimental constraints:

$\langle n_S\rangle=0$ $\langle n_Q\rangle=0.4\langle n_B\rangle$

WB: NPA (2017)



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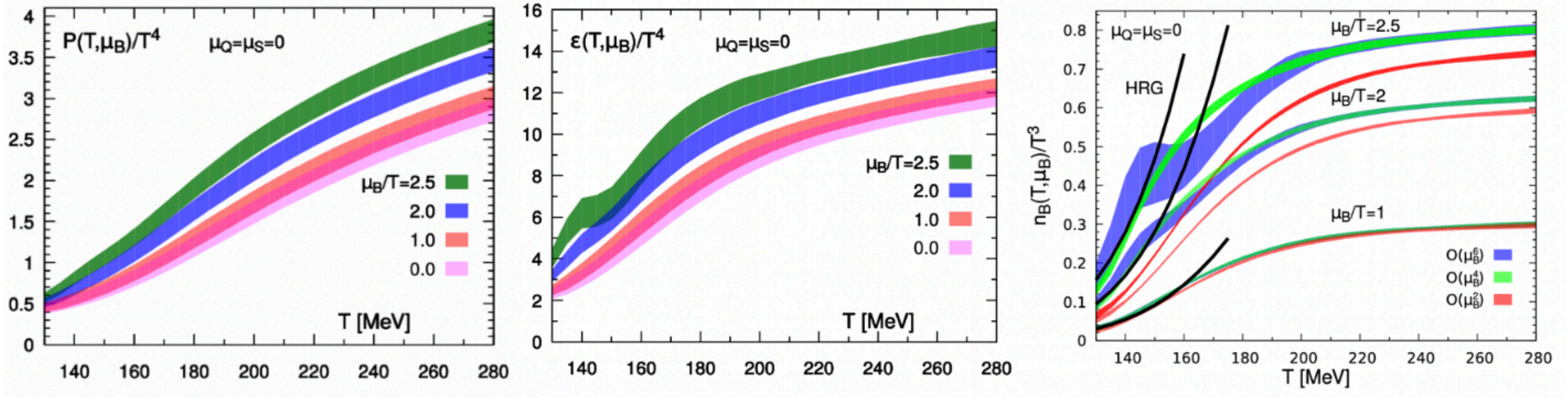
HotQCD: PRD (2017)

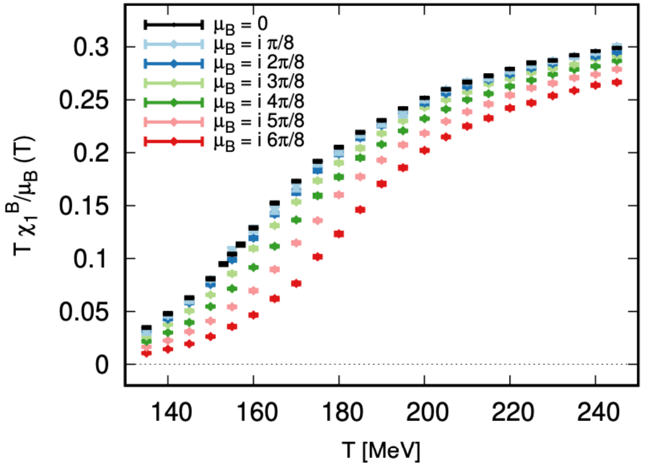


Novel expansion scheme

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



S. Borsanyi, C. R. et al., PRL (2021)

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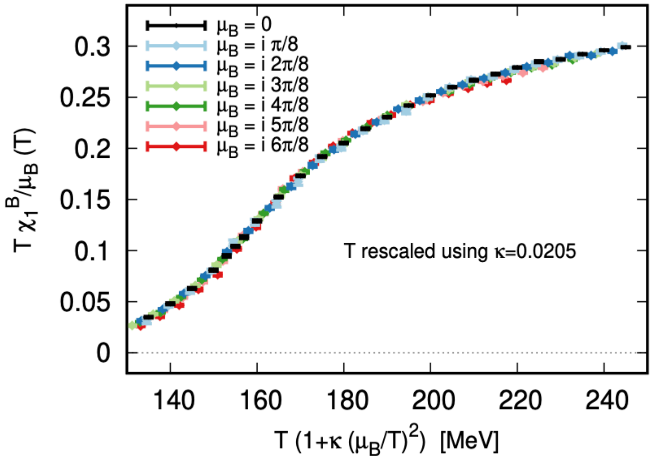
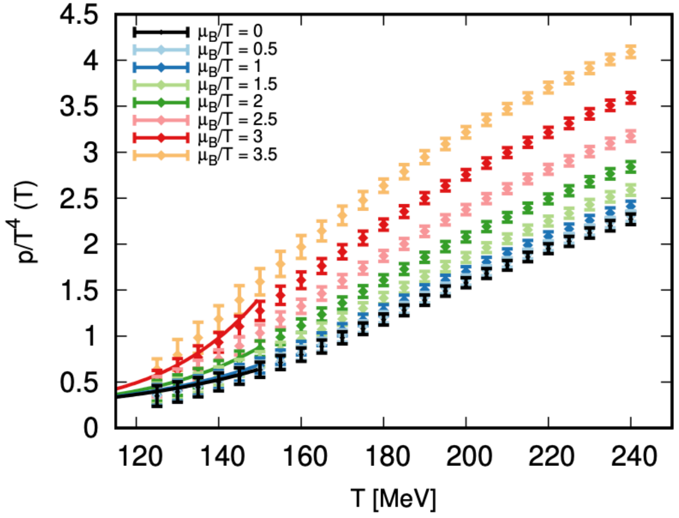
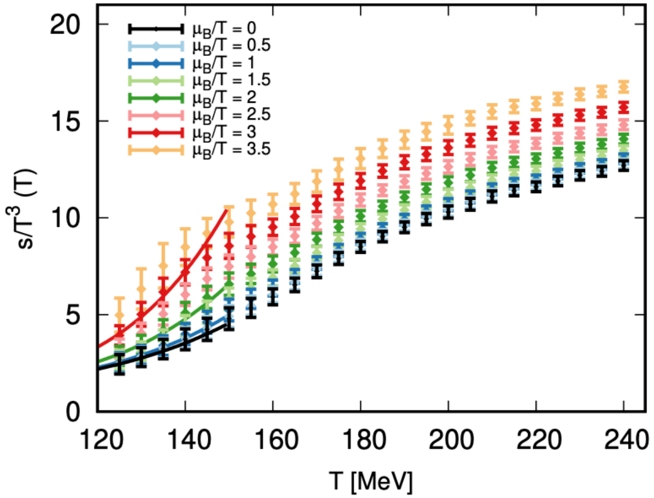
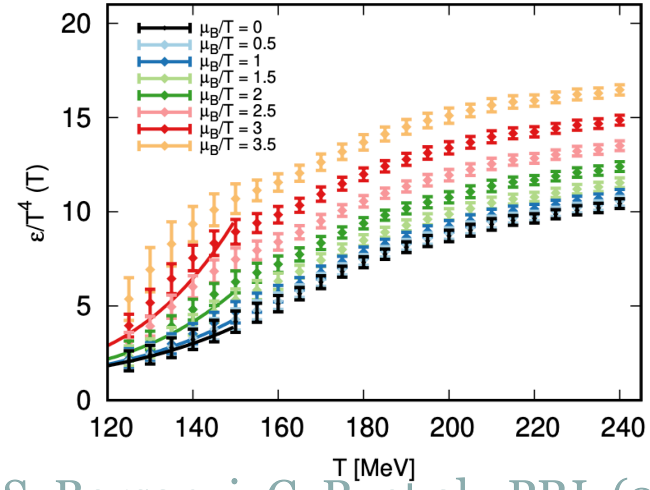


We get all other thermodynamic quantities from the density







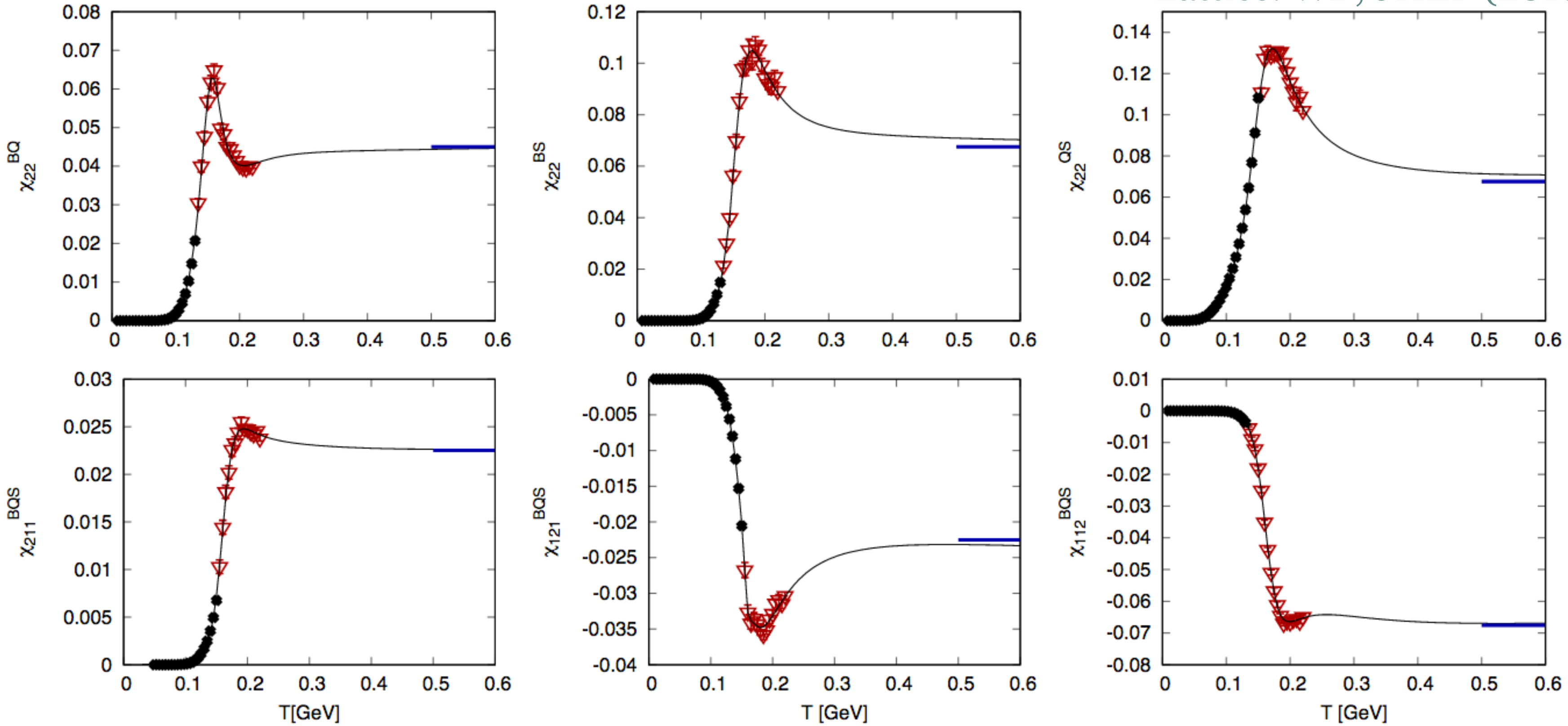
S. Borsanyi, C. R. et al., PRL (2021)

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)

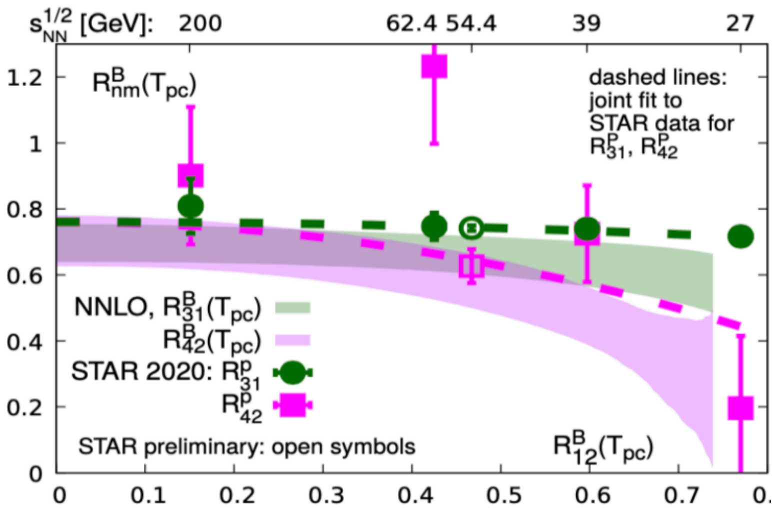


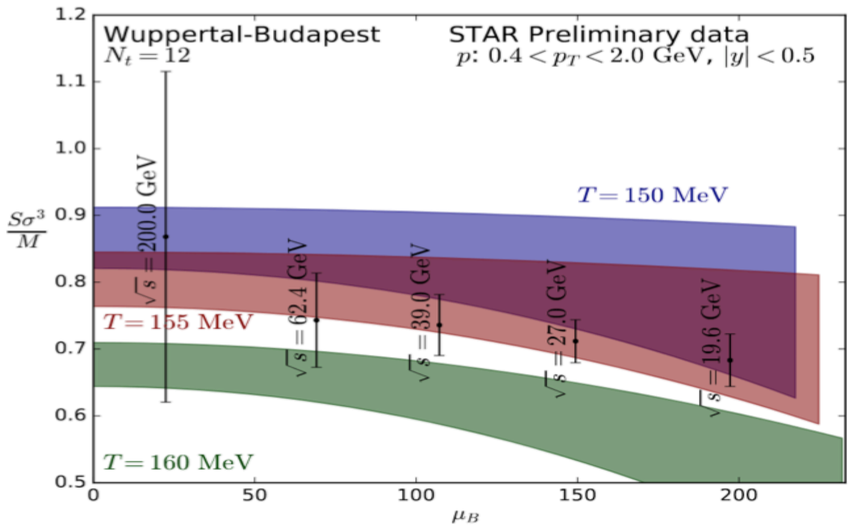
See also A. Monnai et al., PRC (2019)

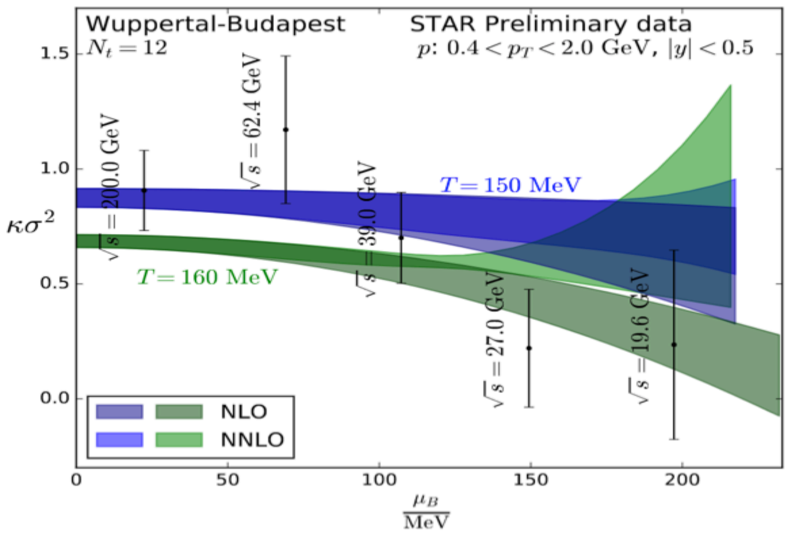
Higher order fluctuations

HotQCD, PRD (2020)

WB, JHEP (2018)







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

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

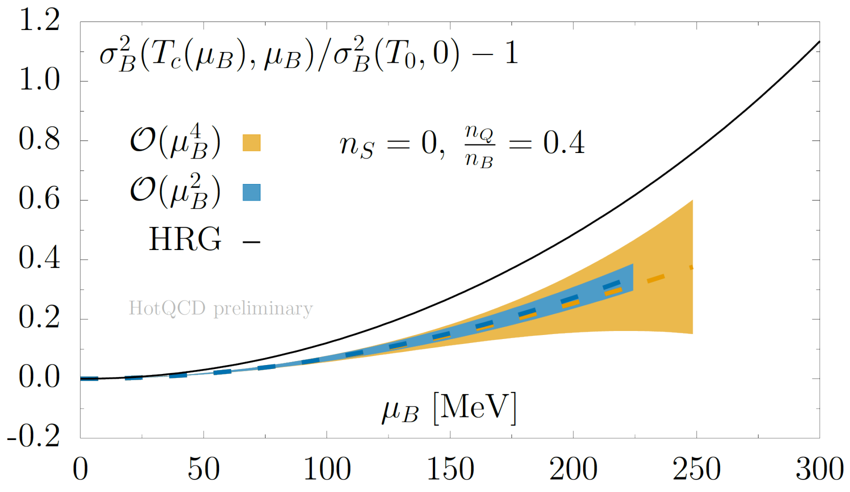
Alternative explanation: canonical suppression

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

Other lattice QCD results

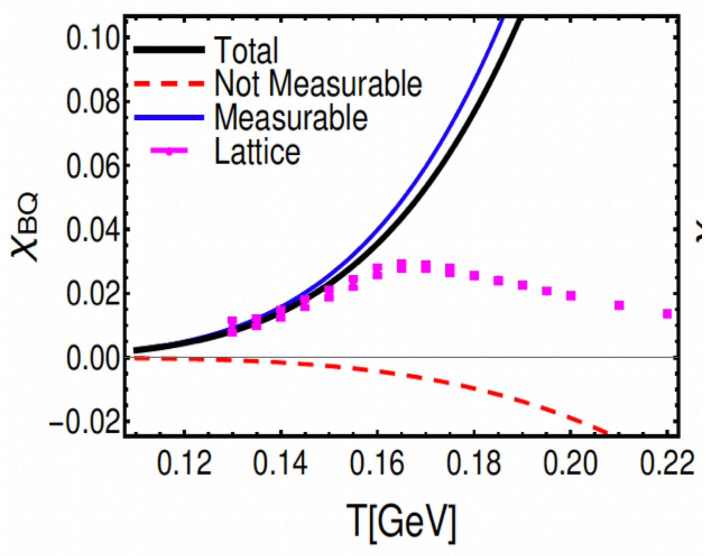
- Fluctuations along the QCD crossover

HotQCD, 1807.05607



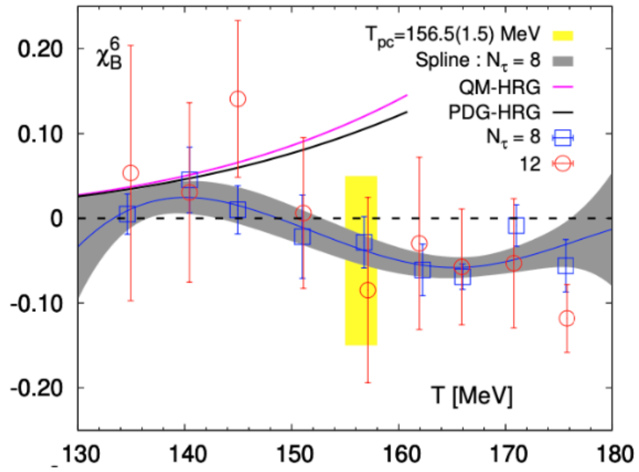
- Off-diagonal correlators

WB, PRD (2020)



- Higher order fluctuations

HotQCD, PRD (2020)



... and many more!

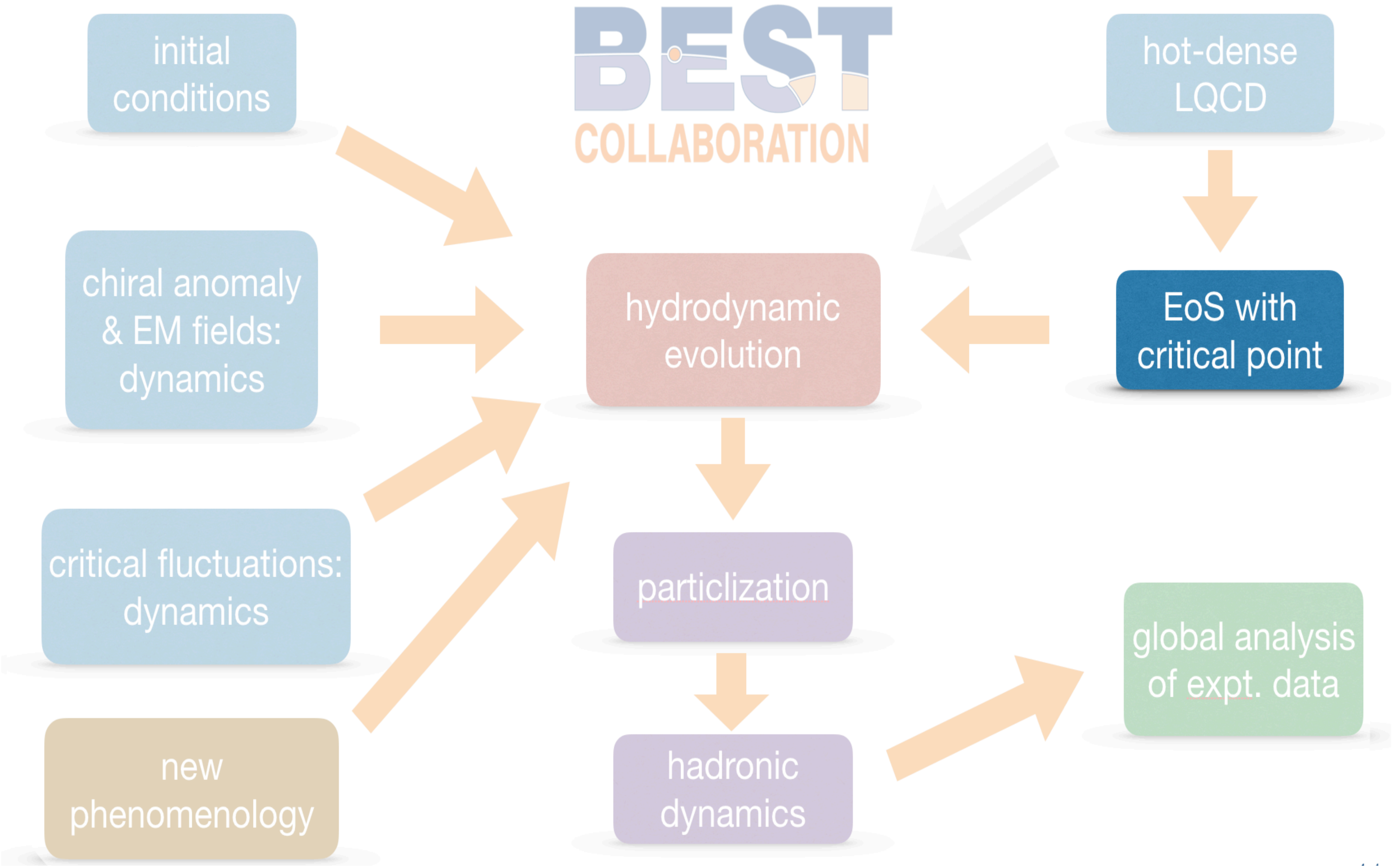
Comparison between theory and experiment

Real world may be complicated

- Critical point beyond the regime probed by lattice
- Non-equilibrium effects important
- Freeze-out, resonances, global charge conservation, etc.

Non-critical contributions: V. Vovchenko et al, 2107.00163

Motivates BEST (non-lattice) theory effort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Strategy

- ✓ We built an equation of state which:
  - ✓ Reproduces the one from lattice QCD up to $O(\mu_B^4)$ (provided by the BEST lattice QCD effort)
  - ✓ Contains a critical point in the 3D Ising model universality class
  - ✓ Can be readily used as input for hydrodynamic simulations to test the effect of the critical point on observables (has been tested by the BEST hydro working group)
- ○ Future hydro simulations and comparison with BESII data will help to constrain the position of the critical point
- ✓ Code available for everybody to use

(download from https://www.bnl.gov/physics/best/resources.php)

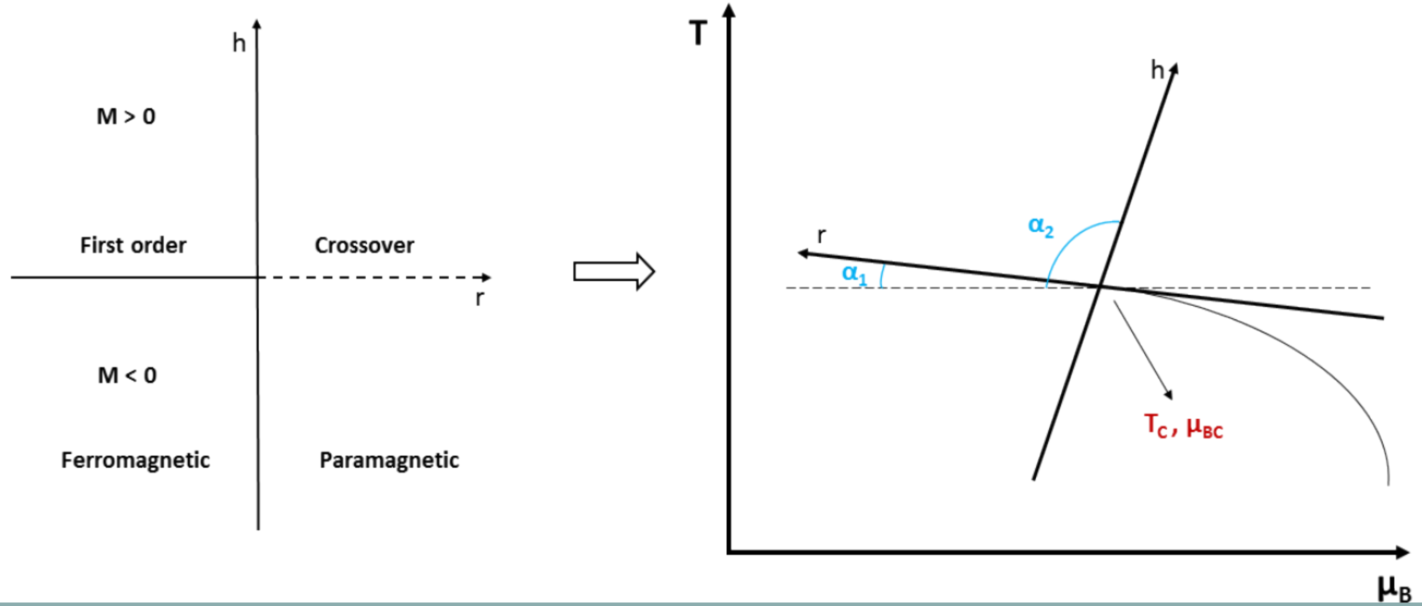
Map the phase diagram

The relation between the Ising model scaling variables (h, r) and the QCD thermodynamic coordinates (T, μ_B), can be expressed in linear form, with the use of **six parameters**:

$$(\mathbf{r}, \mathbf{h}) \longleftrightarrow (\mathbf{T}, \mu_\mathbf{B})$$

$$\frac{T - \mathbf{T_C}}{\mathbf{T_C}} = \mathbf{w}\,(r\rho\,\sin\alpha_1 + h\,\sin\alpha_2)$$

$$\frac{\mu_B - \mu_\mathbf{BC}}{\mathbf{T_C}} = \mathbf{w}\,(-r\rho\,\cos\alpha_1 - h\,\cos\alpha_2)$$



Map the phase diagram

- The number of free parameters is reduced:
  - Assume the shape of transition line is a parabola (good approximation at BES-like energies) → reduce to four parameters:

$$\frac{T_C}{T_C(\mu_B=0)} = 1 + \kappa \left(\frac{\mu_B}{T_C(\mu_B=0)} \right)^2 + \mathcal{O}(\mu_B^4)$$

with the values $T_C(\mu_B=0)=155$ *MeV*, $\kappa=-0.0149$.

- For a chosen value of μ_{BC}, one gets

$$T_C = T_0 + \frac{\kappa}{T_0}\mu_{BC}^2 \qquad \alpha_1 = \tan^{-1}\left(2\frac{\kappa}{T_0}\mu_{BC}\right)$$

- In the following:

$$\mu_{BC} = 350\,\mathrm{MeV} \qquad w = 1 \qquad T_C \simeq 143.2\,\mathrm{MeV}$$

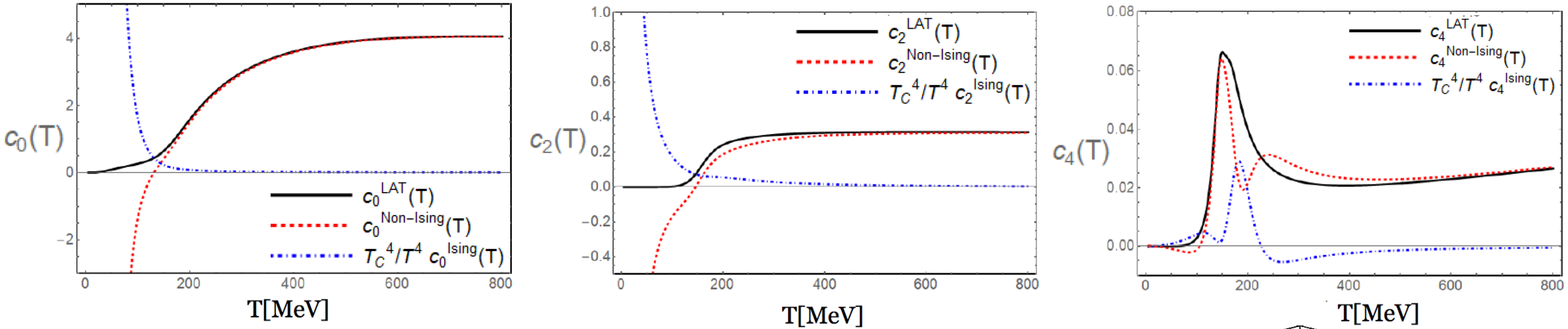
$$\alpha_2 - \alpha_1 = \pi/2 \qquad \rho = 2 \qquad \alpha_1 \simeq 4\,^\circ$$

Expansion coefficients and EoS

P. Parotto, C. R. et al., PRC (2020)

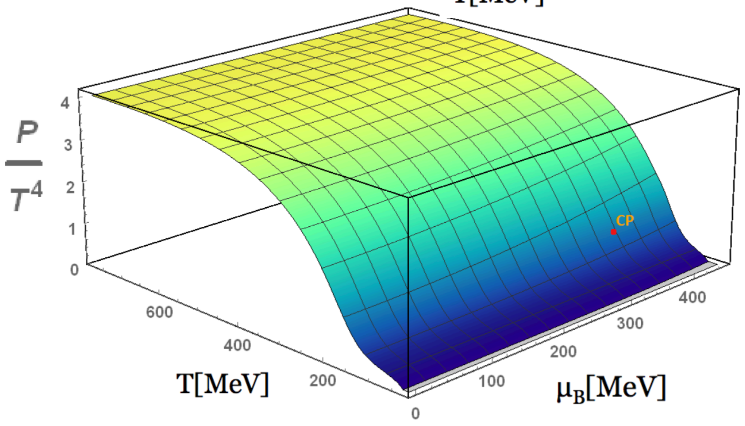
Extract the “regular” contribution as the difference between the lattice and Ising ones

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



Total pressure becomes:

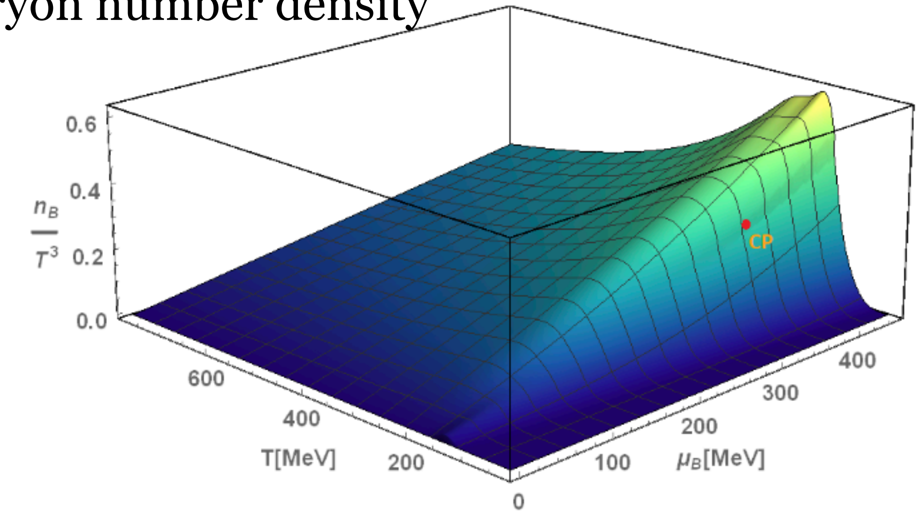
$$P(T,\mu_B) = T^4 \sum_n c^n_{\mathrm{Non\text{-}Ising}}(T) \left(\frac{\mu_B}{T}\right)^n + T_C^4 P_{\mathrm{Ising}}(T,\mu_B)$$



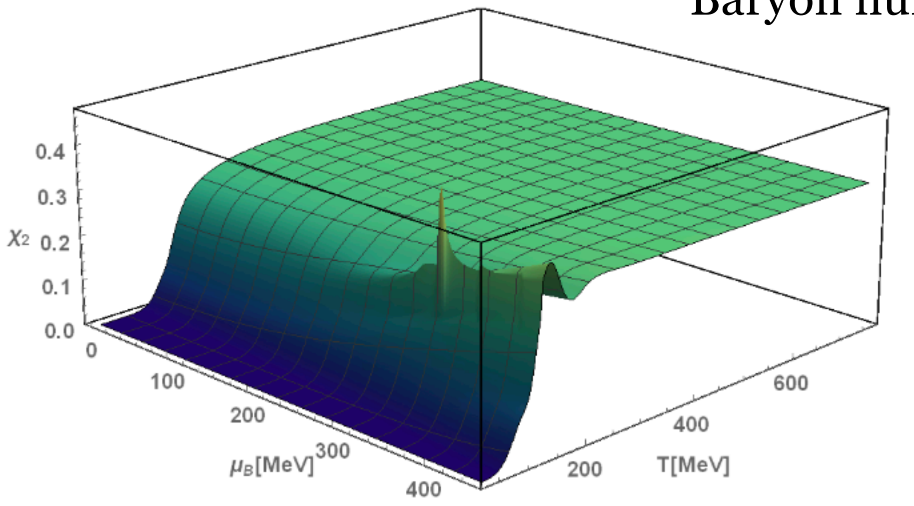
Other thermodynamic observables

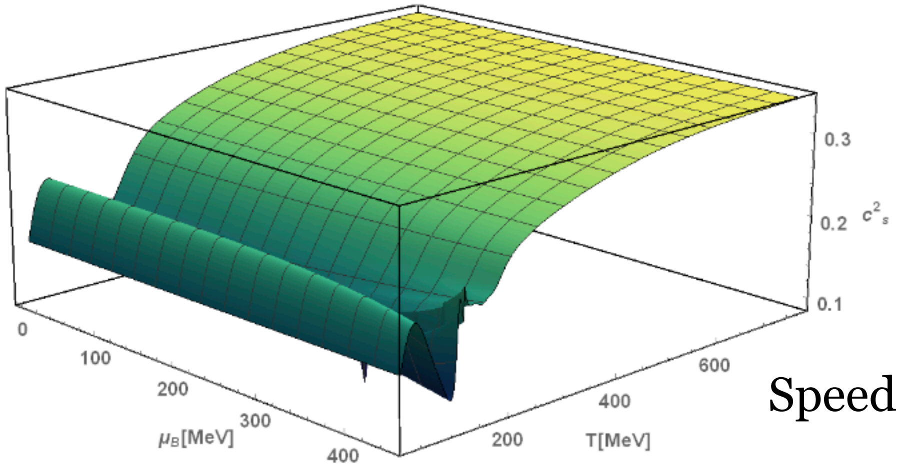
P. Parotto, C. R. et al., PRC (2020)

Baryon number density



Baryon number susceptibility



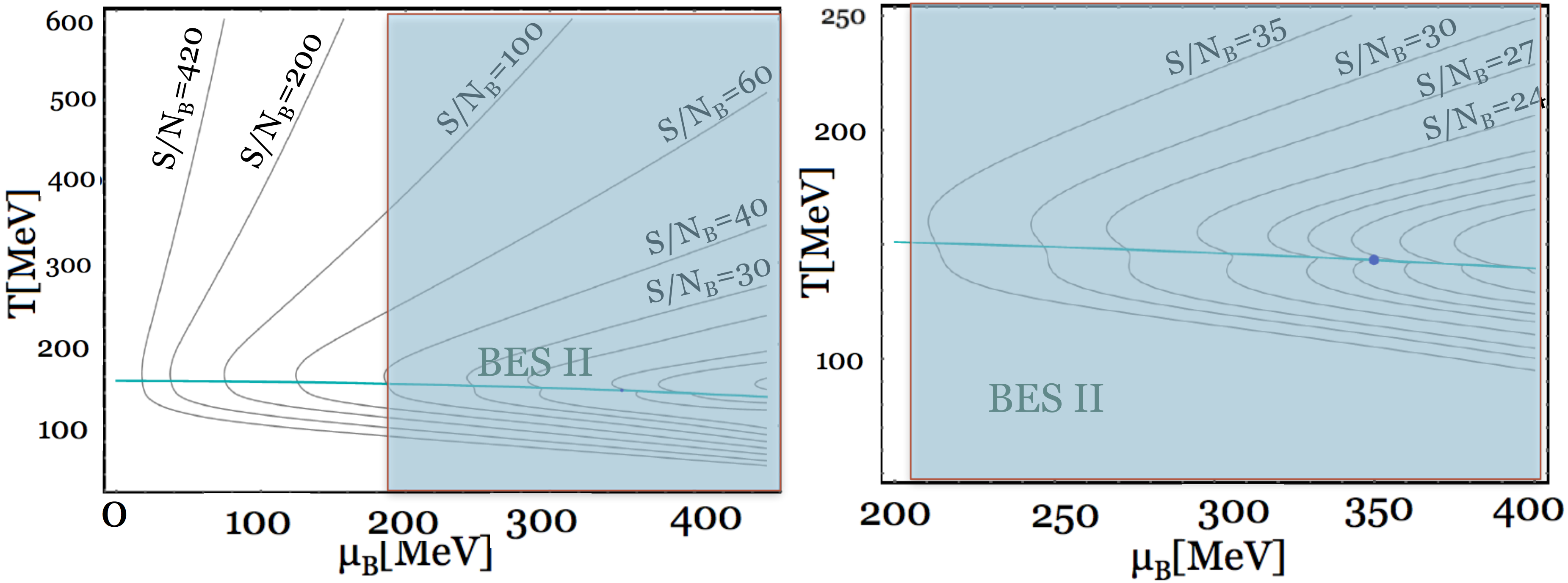


Speed of sound

Final EoS: Isentropic trajectories

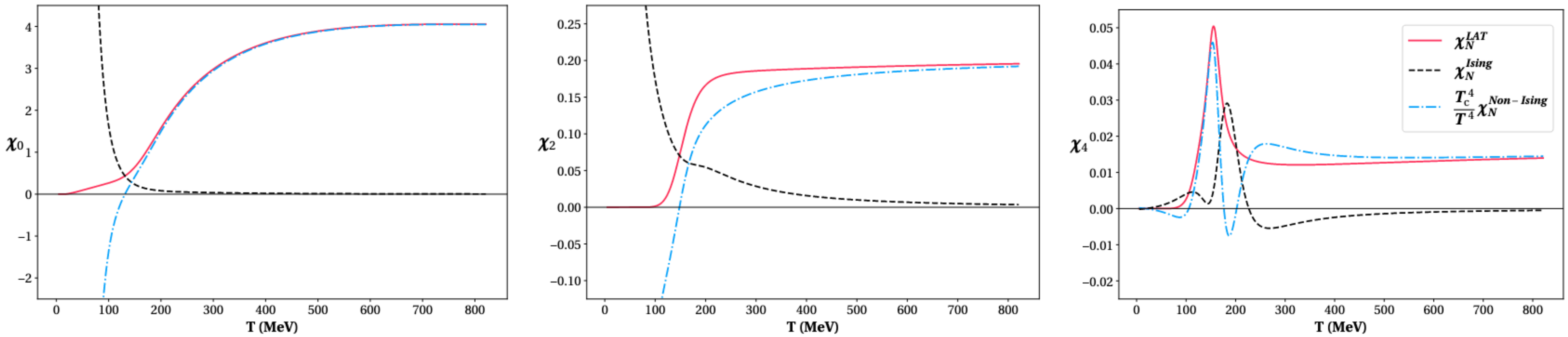
P. Parotto, C. R. et al., PRC (2020)

- 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



Strangeness-neutral EoS

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



Total pressure becomes:

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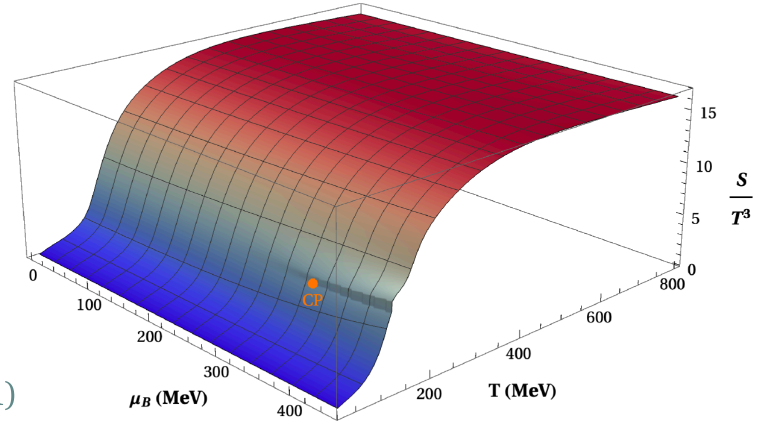
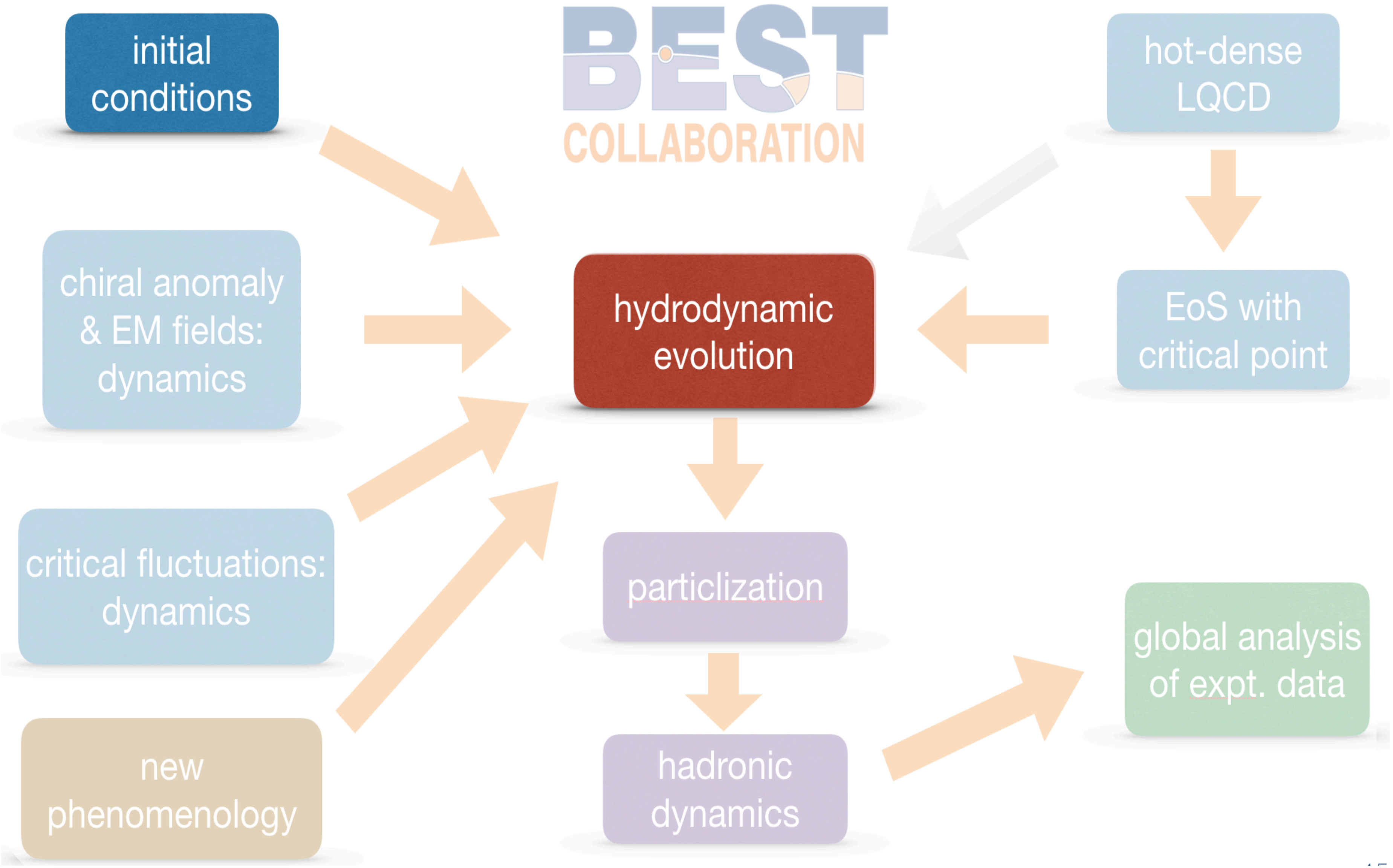


J. Karthein, C. R. et al., EPJ Plus (2021)



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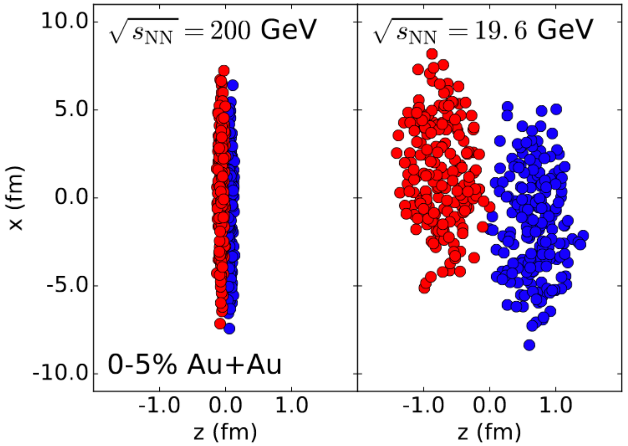
Scientific goals

- 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)

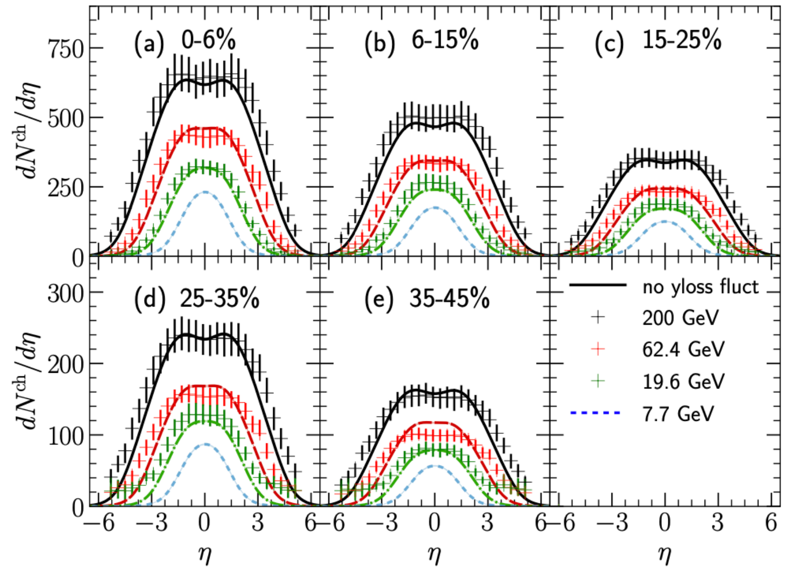
- Extract *transport properties* of nuclear matter at finite baryon density

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

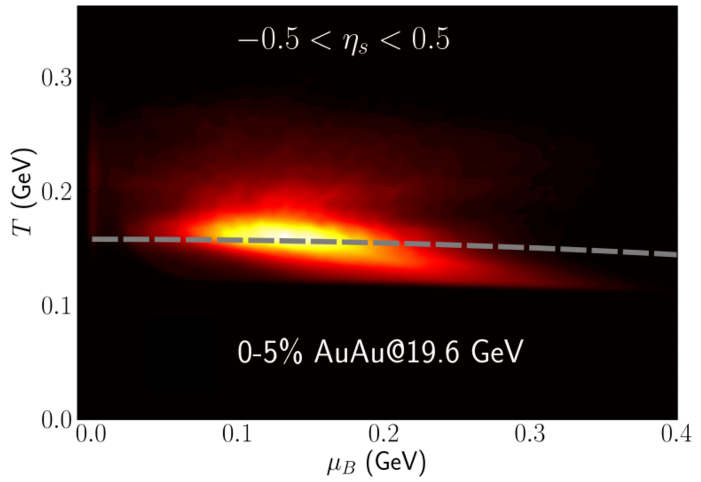
C. Shen, B. Schenke, PRC (2018)
L. Du et al., NPA (2019)



- 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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C. Shen, B. Schenke, PRC (2018);
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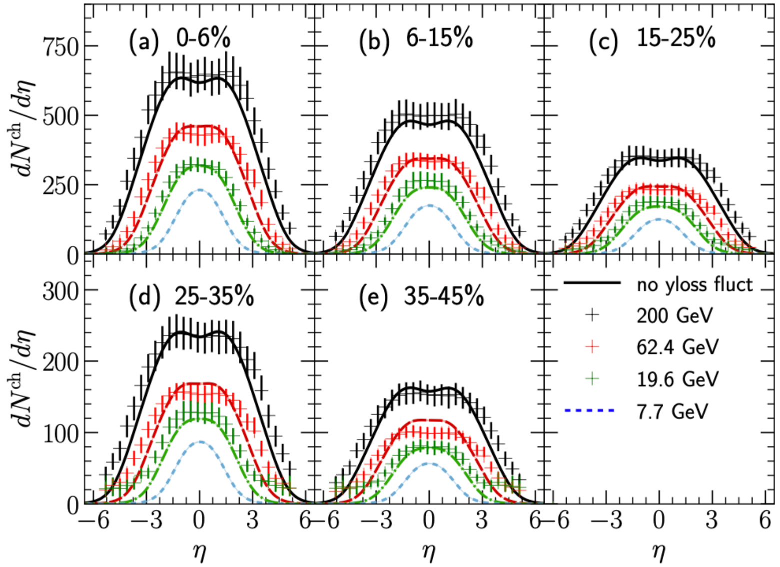
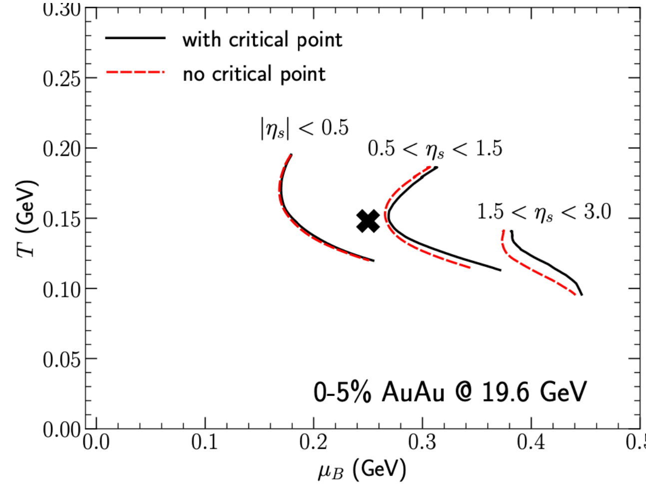
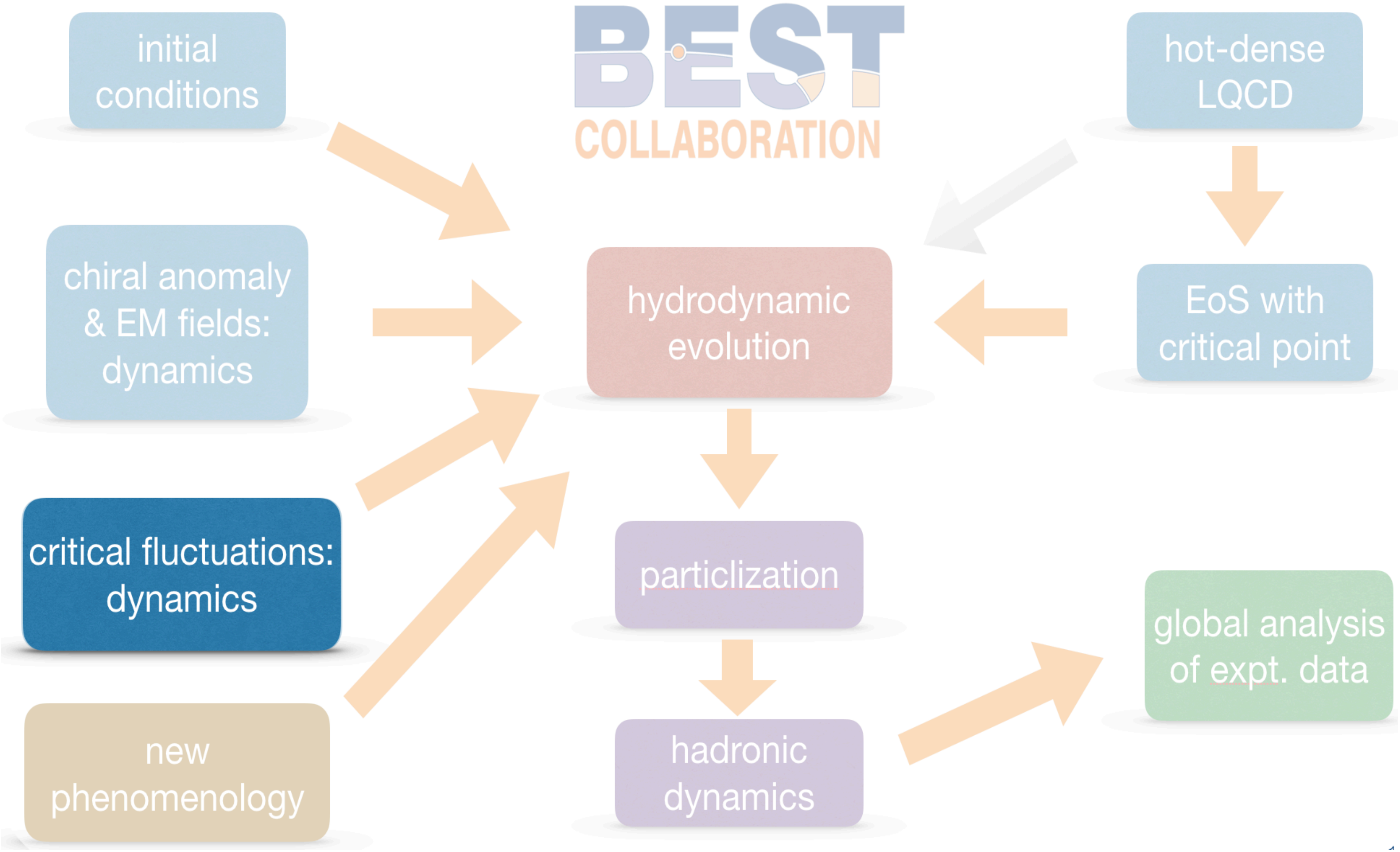





BEST
COLLABORATION
initial conditions
chiral anomaly & EM fields: dynamics
critical fluctuations: dynamics
new phenomenology
hydrodynamic evolution
particlization
hadronic dynamics
hot-dense LQCD
EoS with critical point
global analysis of expt. data

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

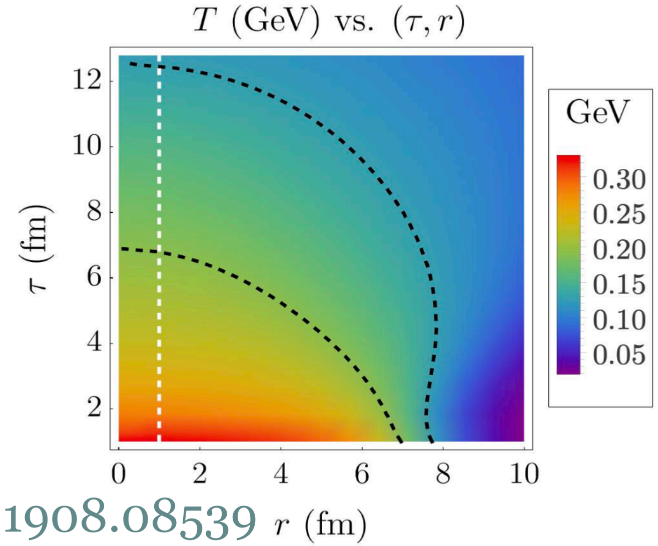
- Solution of stochastic hydro equations using a momentum filter by which fluctuating modes above a cutoff given by a microscopic scale are removed

M. Singh et al., QM2018 proceedings

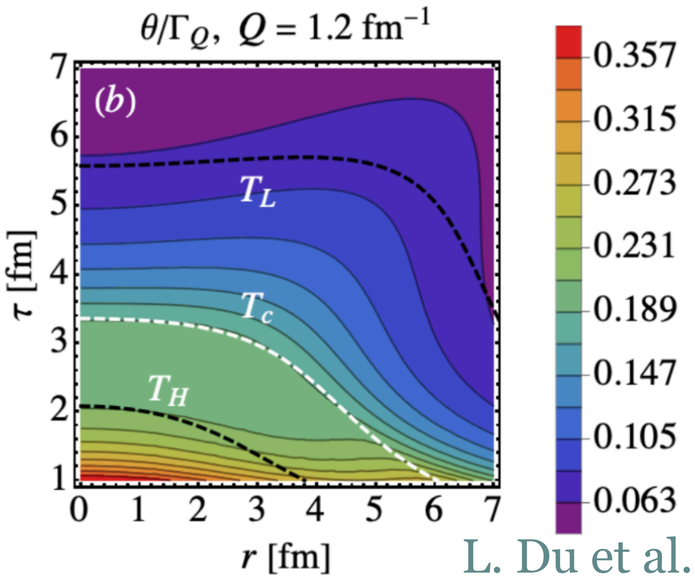
- Solution of full stochastic diffusive equation in a finite-size system with Gaussian white noise: critical slowing down is observed

M. Nahrgang et al., 1804.05728

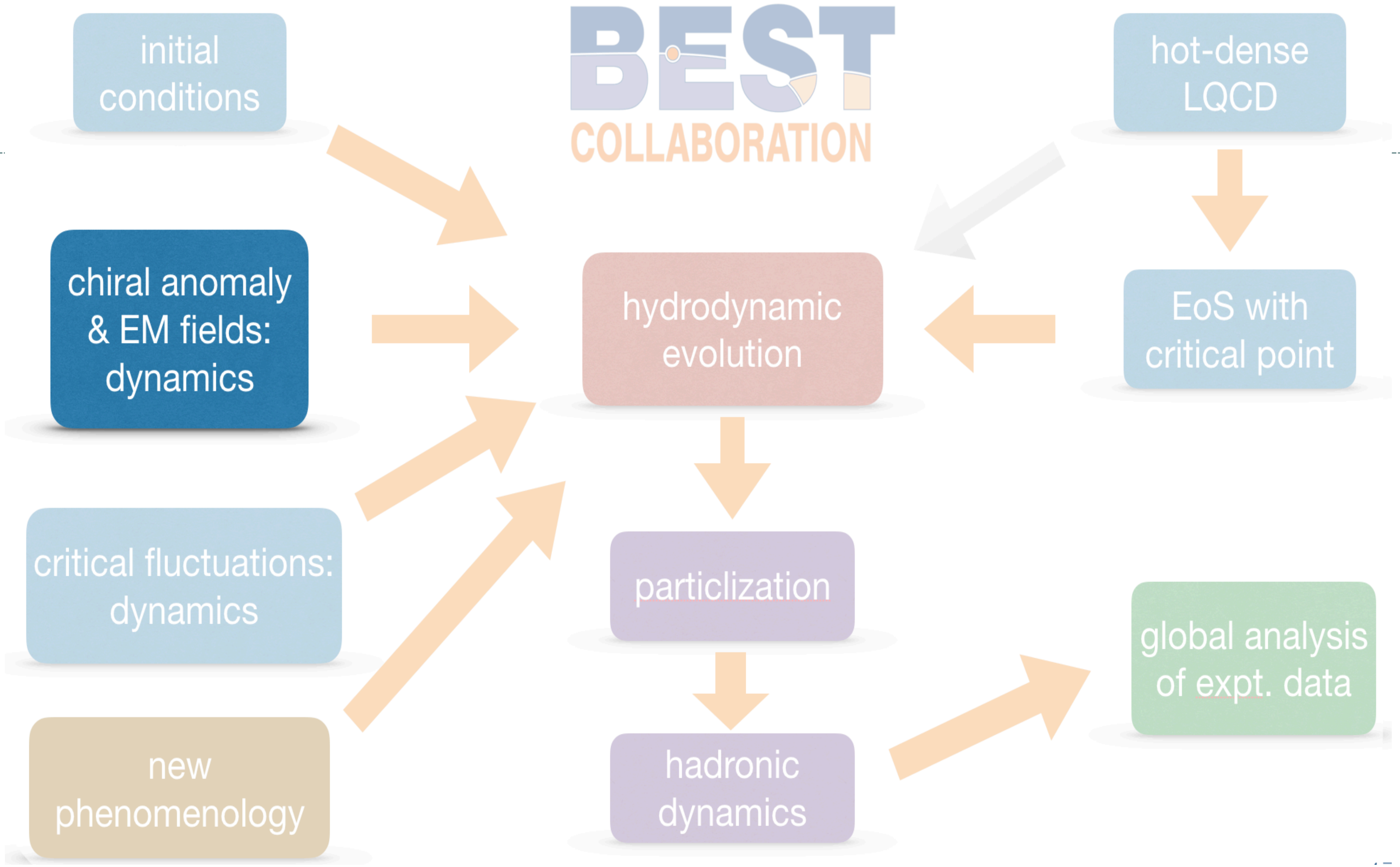
- Hydro+ implemented in two main simulations



K. Rajagopal et al., 1908.08539



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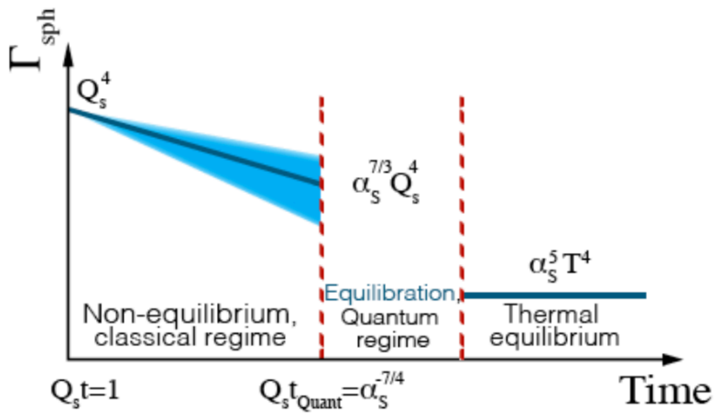
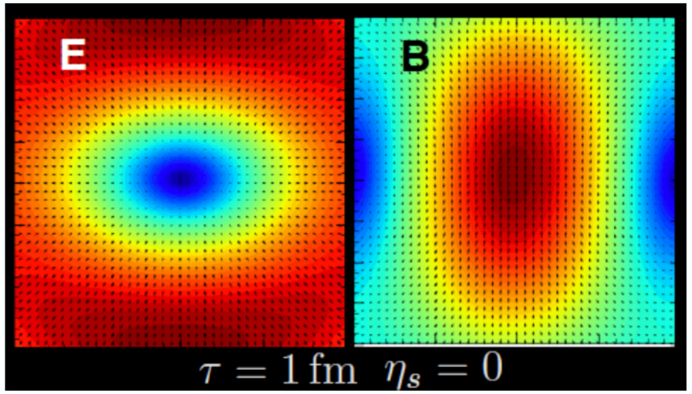
Scientific goals and achievements

- Model fluctuating initial conditions for axial charges

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



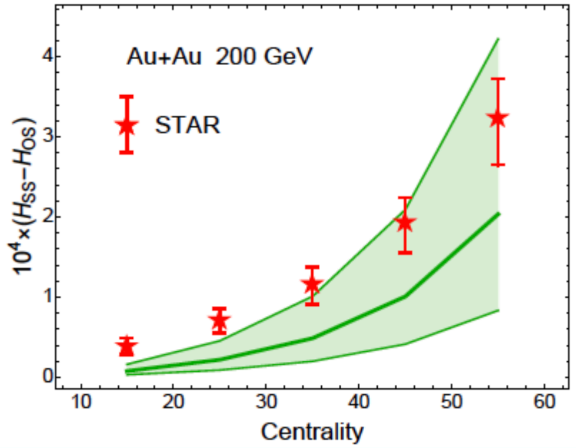


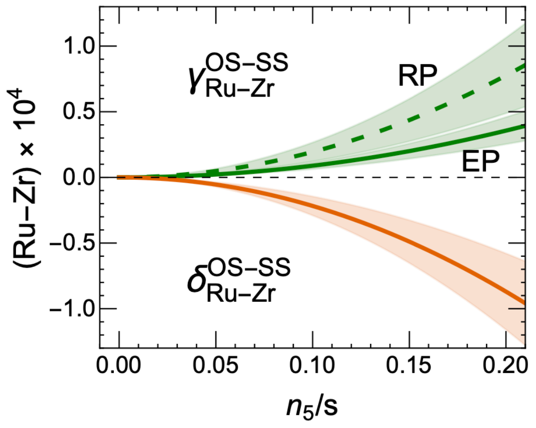
- Develop magneto-hydro code and incorporate anomalous hydro terms, studying the co-evolution of the dynamical magnetic field with the medium

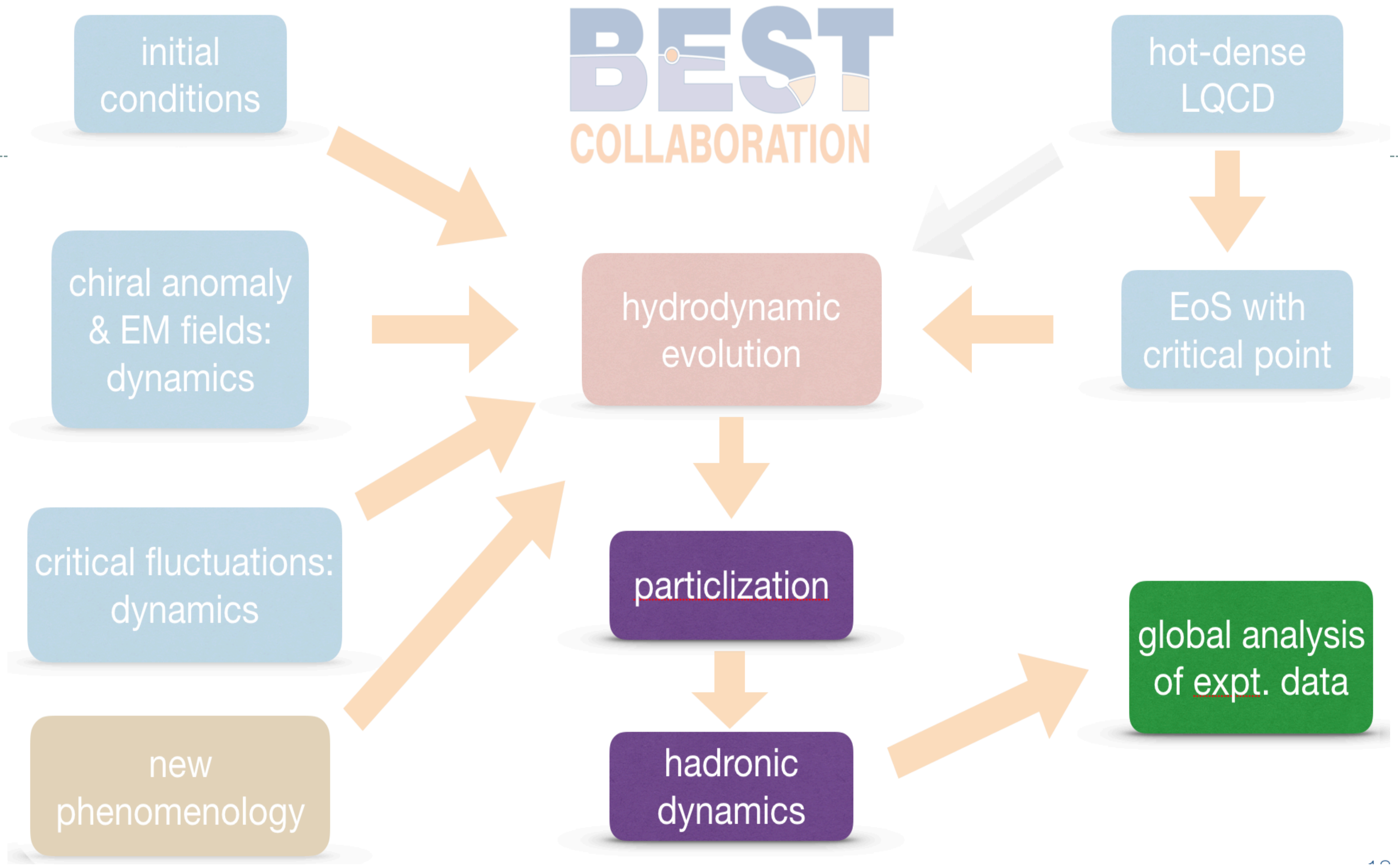
  U. Gursoy et al., PRC (2018)

- 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 et al., 2109.1318

  - Hadronic transport with tunable potentials

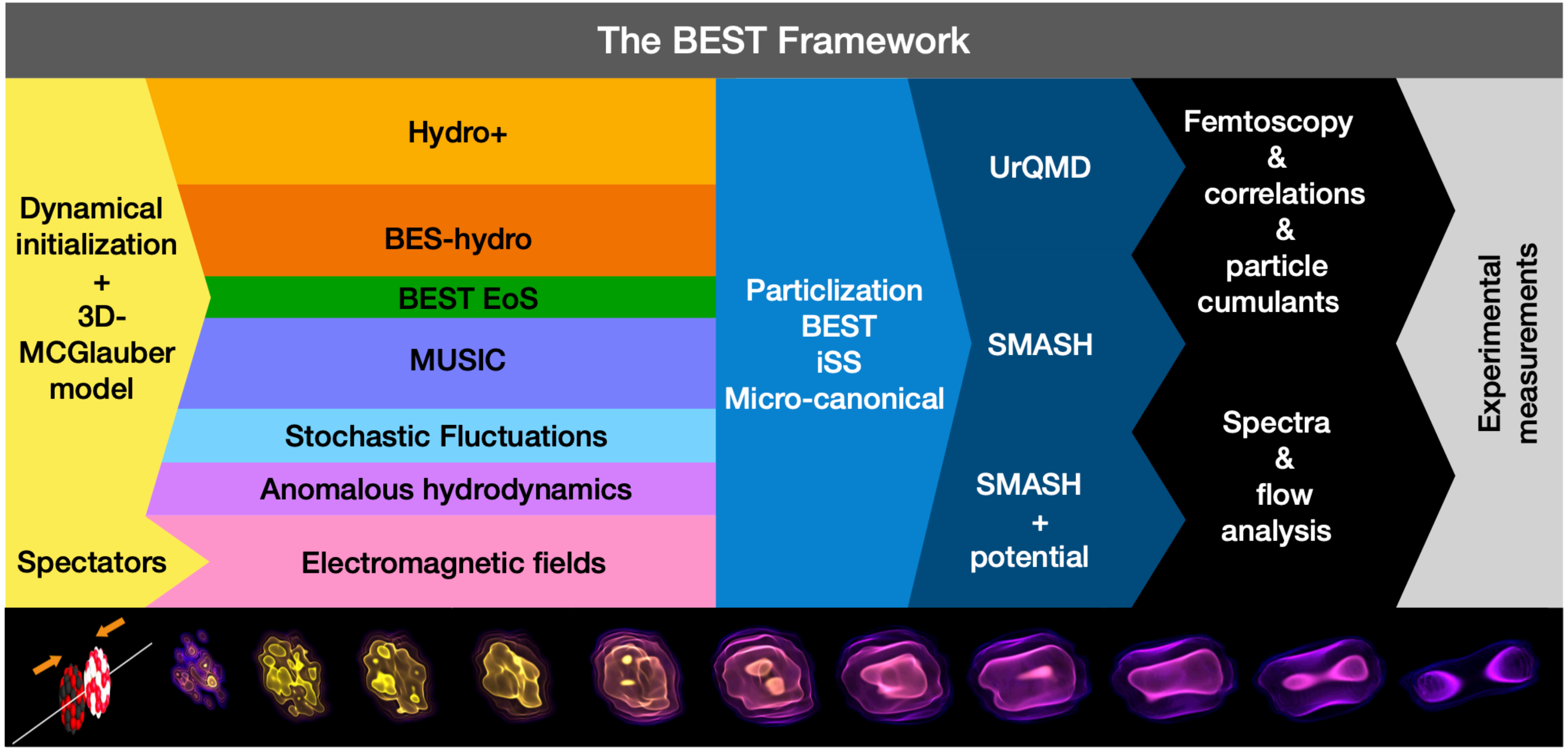
    A. Sorensen, V. Koch, 2011.06635

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

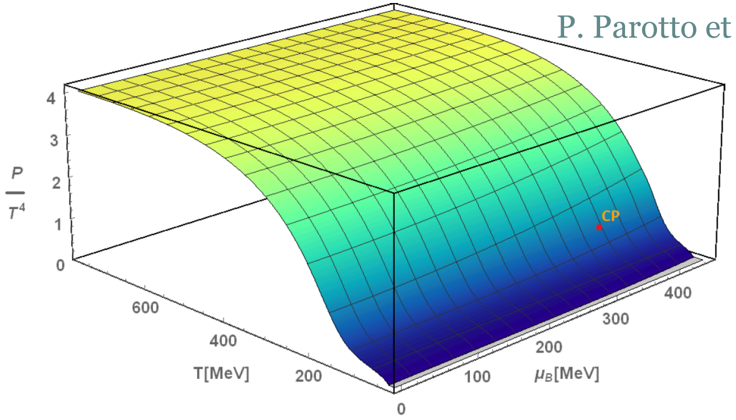


Backup Slides

Two versions of the EoS

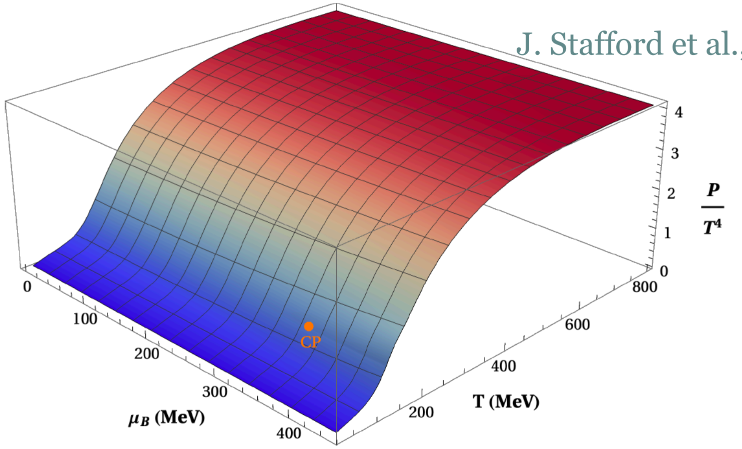
- Finite T and μ_B, but $\mu_S = \mu_Q = 0$

P. Parotto et al., PRC (2020)

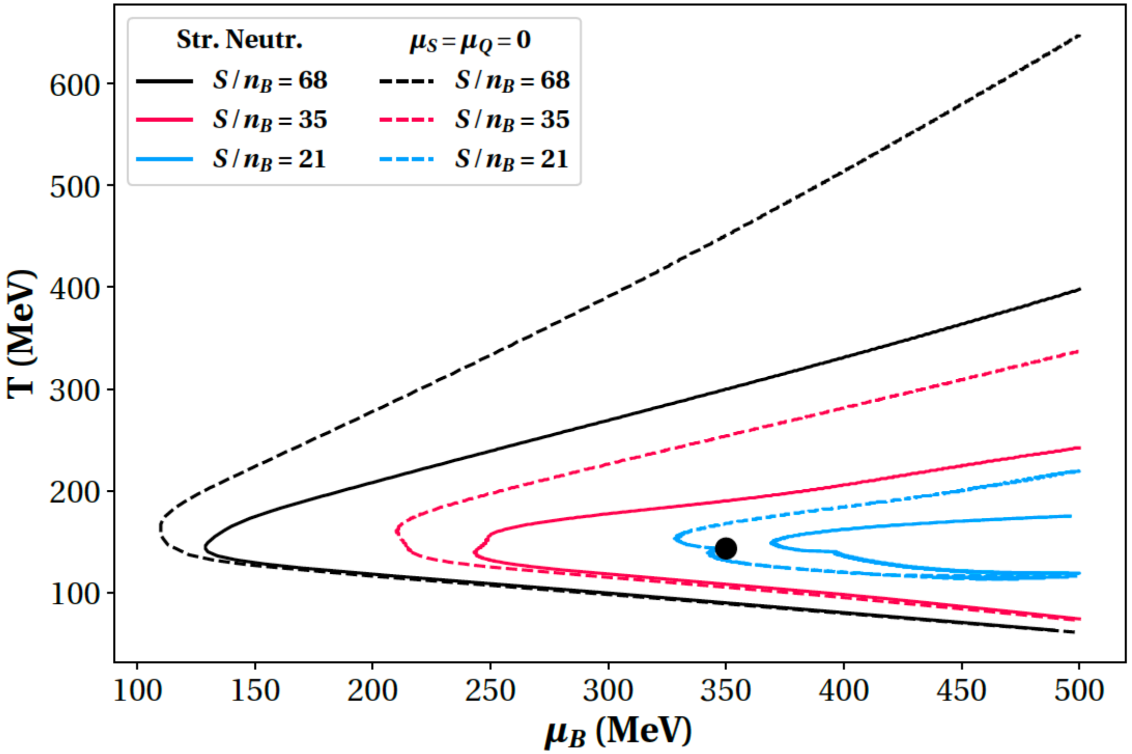


- Finite T, μ_B, μ_S and μ_Q such that $n_S=0$ and $n_Q=0.4n_B$

J. Stafford et al., 2103.08146 (2020)



- Comparing isentropes...

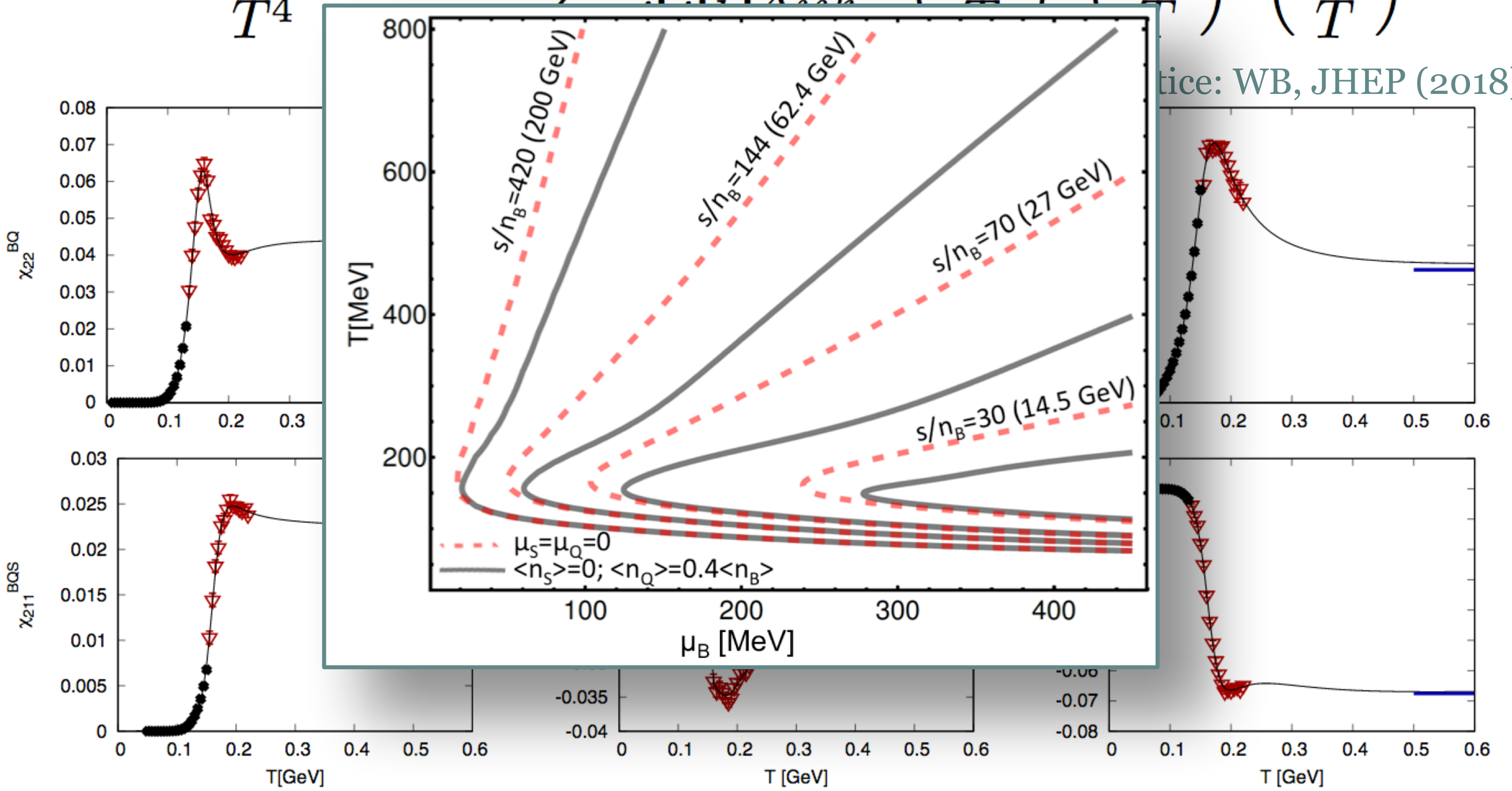


QCD Equation of state for $\mu_B, \mu_S, \mu_Q > 0$

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

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

...tice: WB, JHEP (2018)

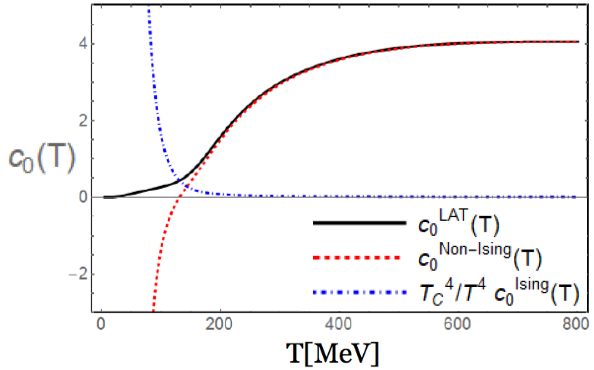


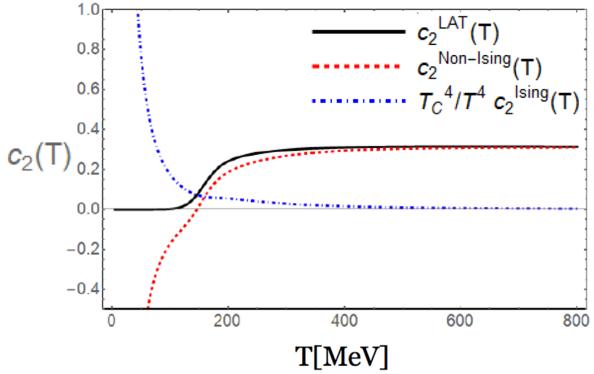
Expansion coefficients and EoS

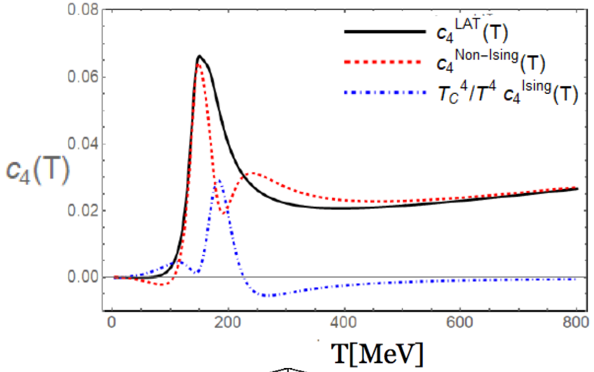
P. Parotto et al.,: PRC (2020)

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

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

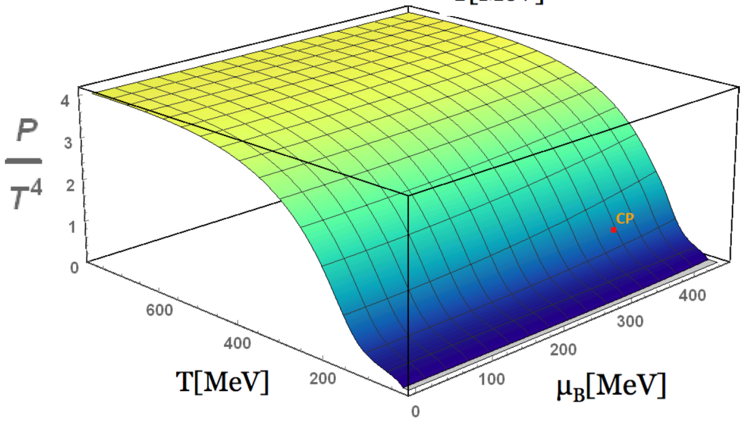






Total pressure becomes:

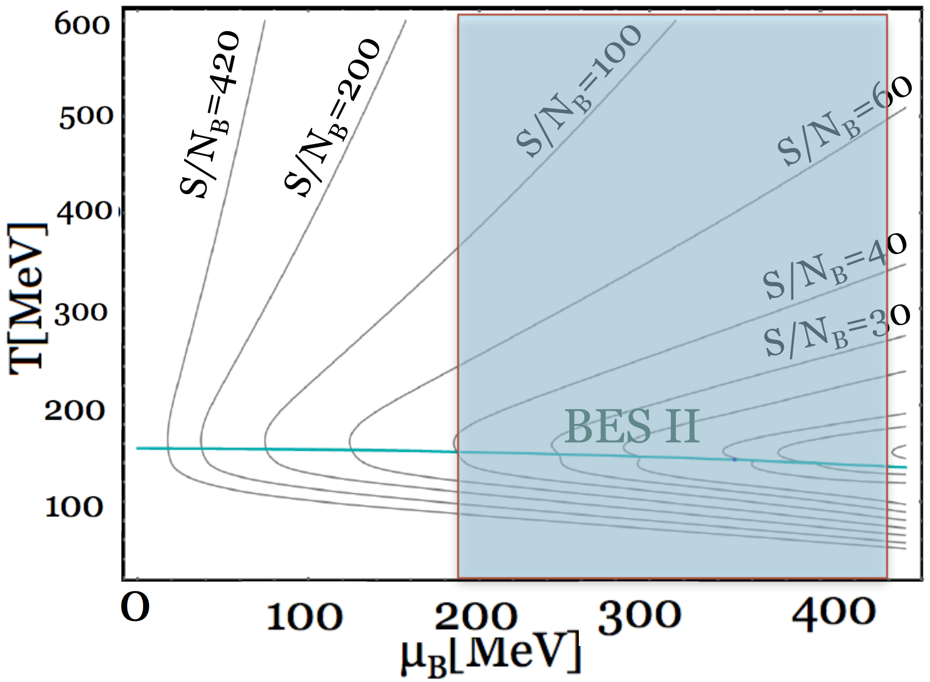
$$P(T,\mu_B) = T^4 \sum_n c^n_{\text{Non-Ising}}(T) \left(\frac{\mu_B}{T}\right)^n + T_C^4 P_{\mathrm{Ising}}(T,\mu_B)$$

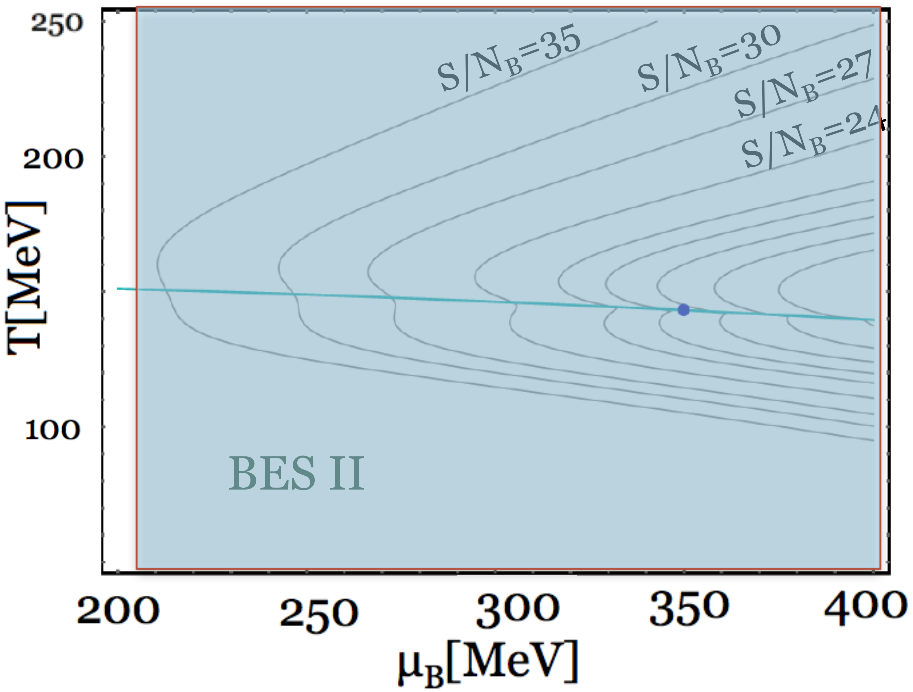


Final EoS: Isentropic trajectories

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



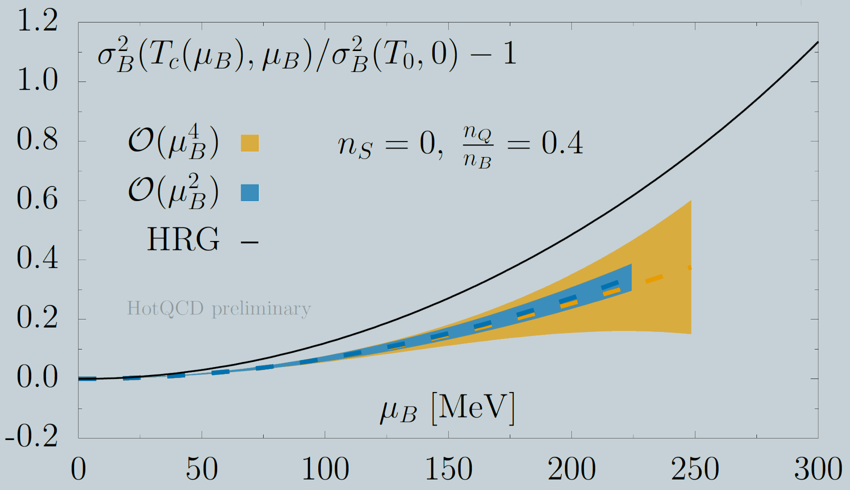


Fluctuations along the QCD crossover

P. Steinbrecher for HotQCD, 1807.05607

Net-baryon variance

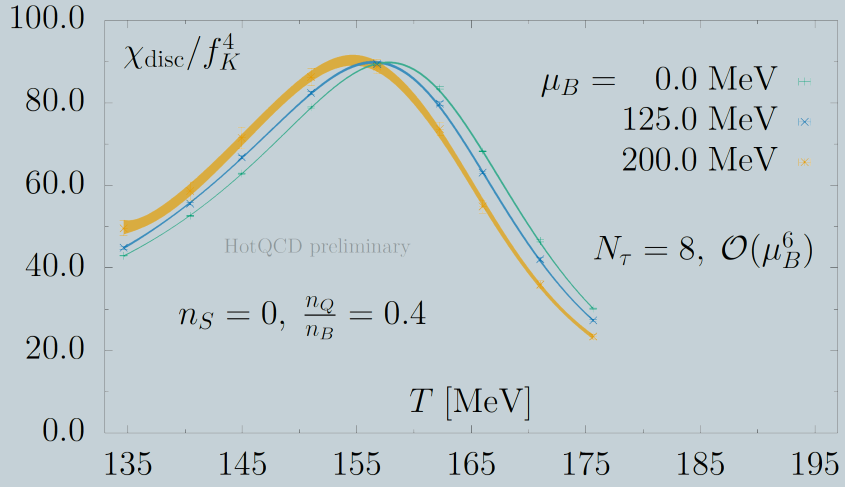
$$\frac{\sigma_B^2(T_c(\mu_B),\mu_B)-\sigma_B^2(T_0,0)}{\sigma_B^2(T_0,0)} = \lambda_2\left(\frac{\mu_B}{T_0}\right)^2 + \lambda_4\left(\frac{\mu_B}{T_0}\right)^4 + \mathcal{O}(\mu_B^6)$$



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

Disconnected chiral susceptibility

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

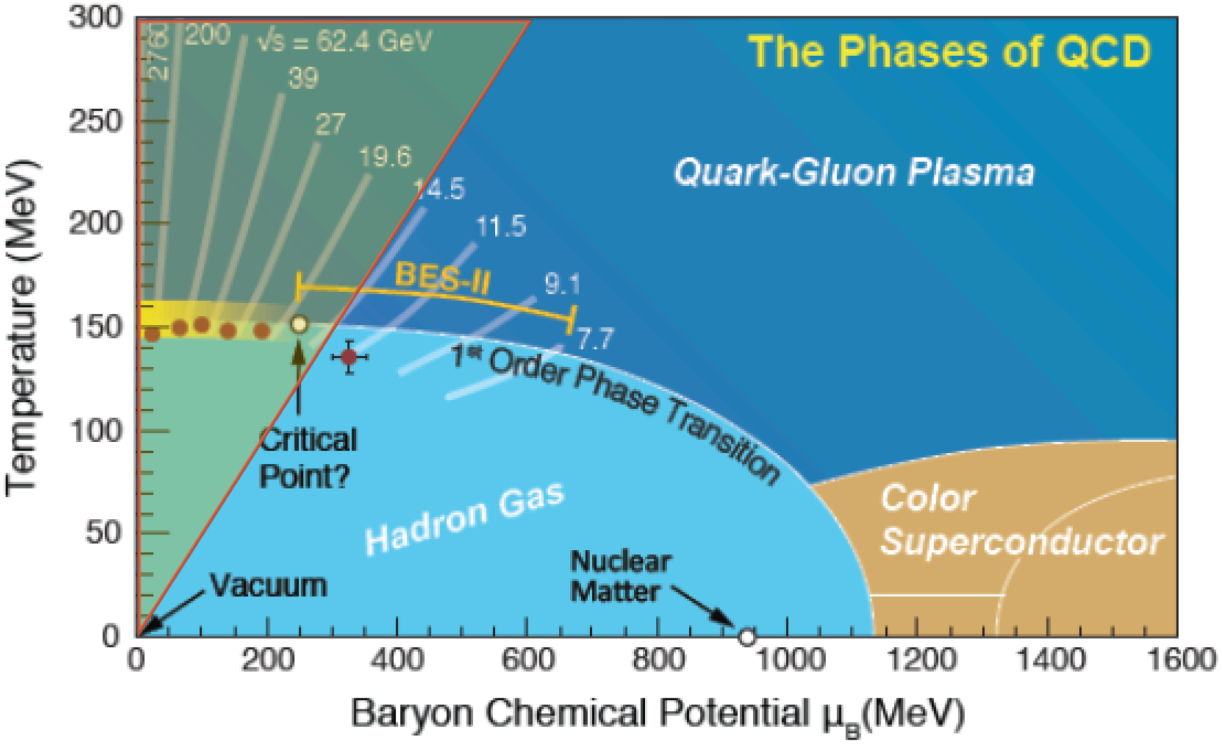


- Peak height expected to increase near the CP
- No sign of criticality

QCD Equation of state for $\mu_B > 0$

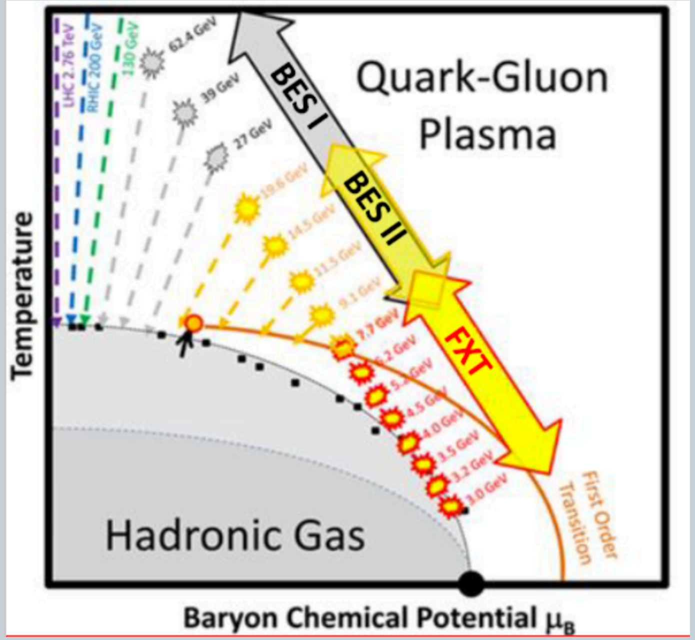
- We now have the equation of state for $\mu_B/T \leq 2$ or in terms of the RHIC energy scan:

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



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

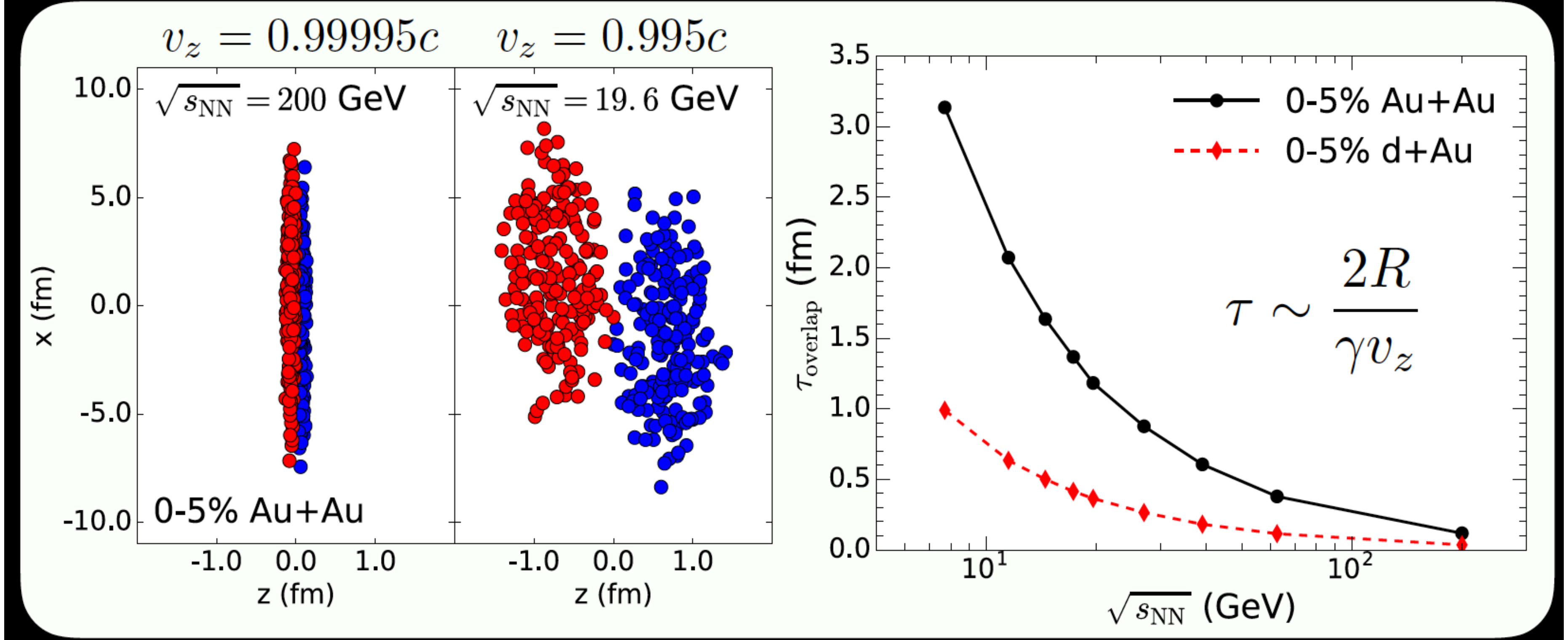
Compilation by D. Cebra

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

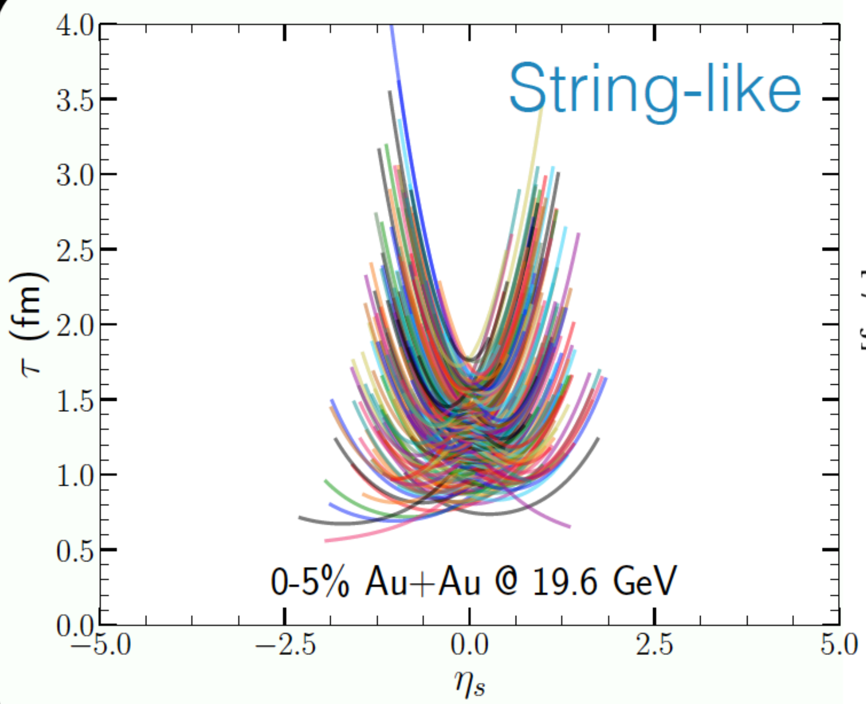


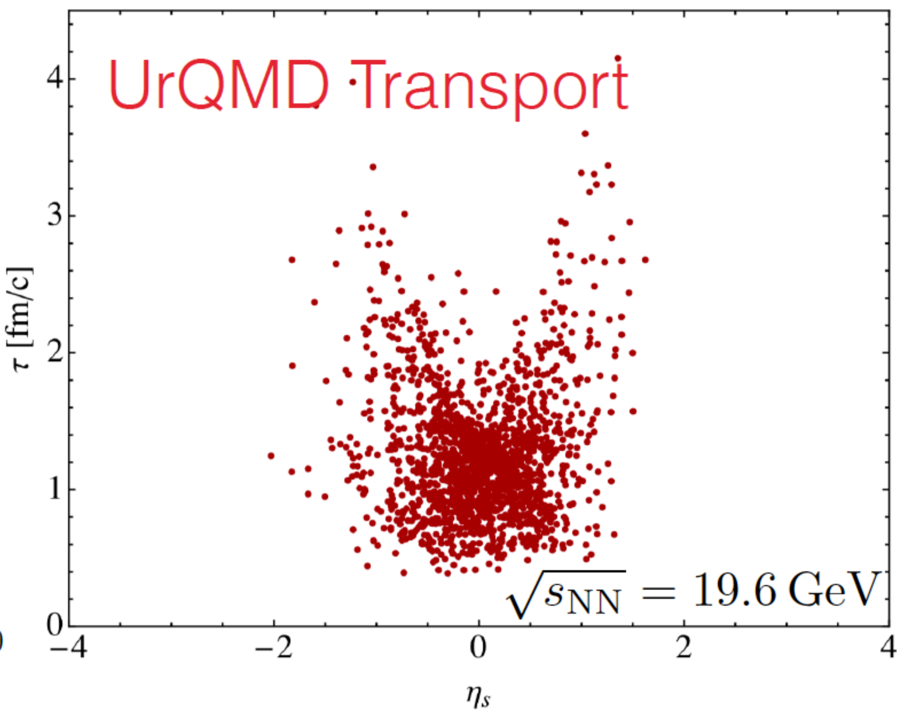
- Nuclei overlapping time is large at low collision energy
- Pre-equilibrium dynamics can play an important role

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



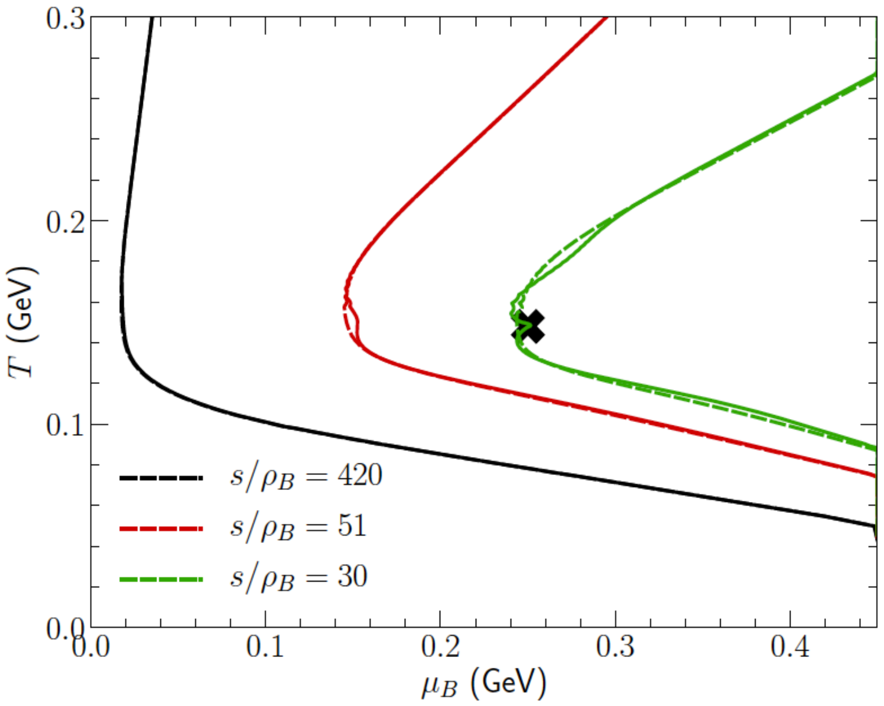


- An extended interaction zone for the energy-momentum sources from the 3D collision geometry

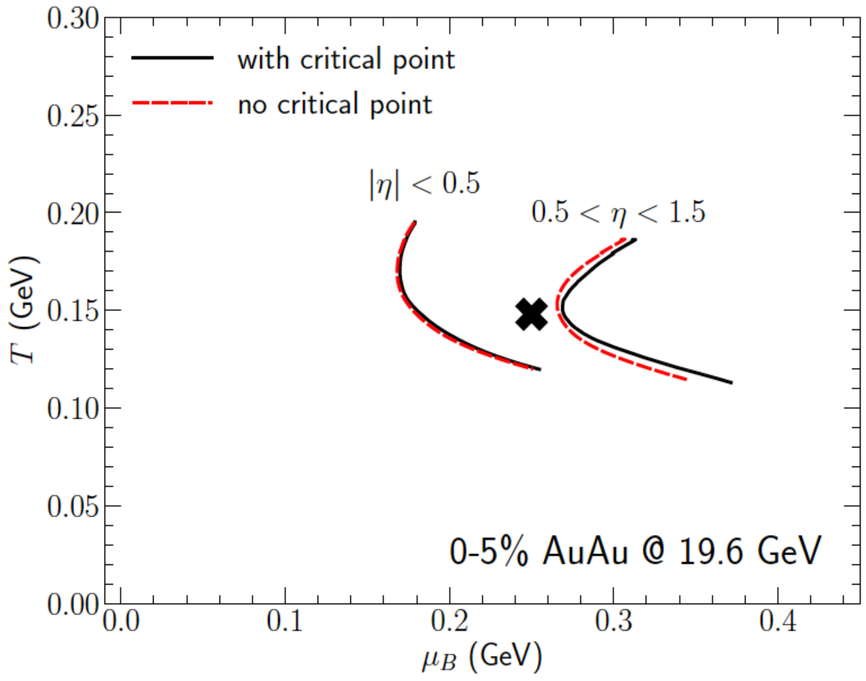
Dynamically interweaves with hydrodynamics

BEST EOS with a critical point

P. Parotto et al., arXiv:1805.05249 [hep-ph]



B. Schenke and C. Shen, in preparation



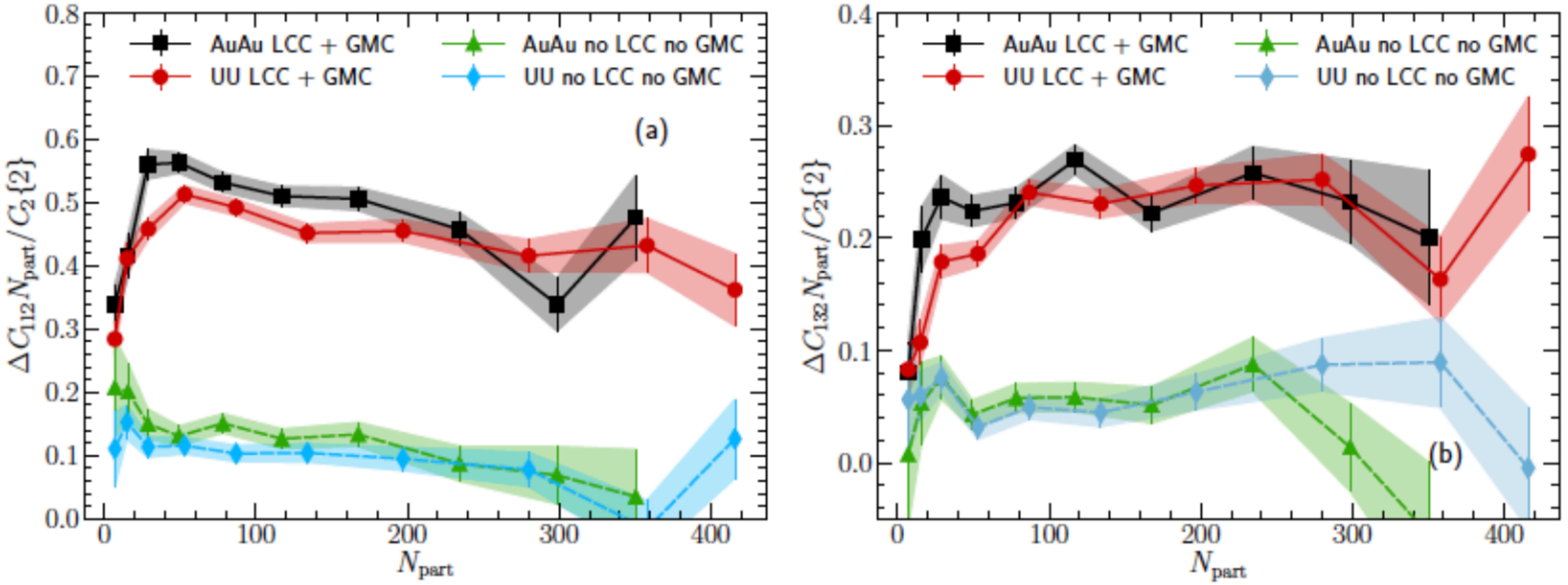
- The BEST EOS is implemented in the state-of-the-art 3D hydrodynamic code (MUSIC)

Visible difference in the fireball trajectories with a critical point

CME Working Group Achievements

Specific Goals #2 & #4:

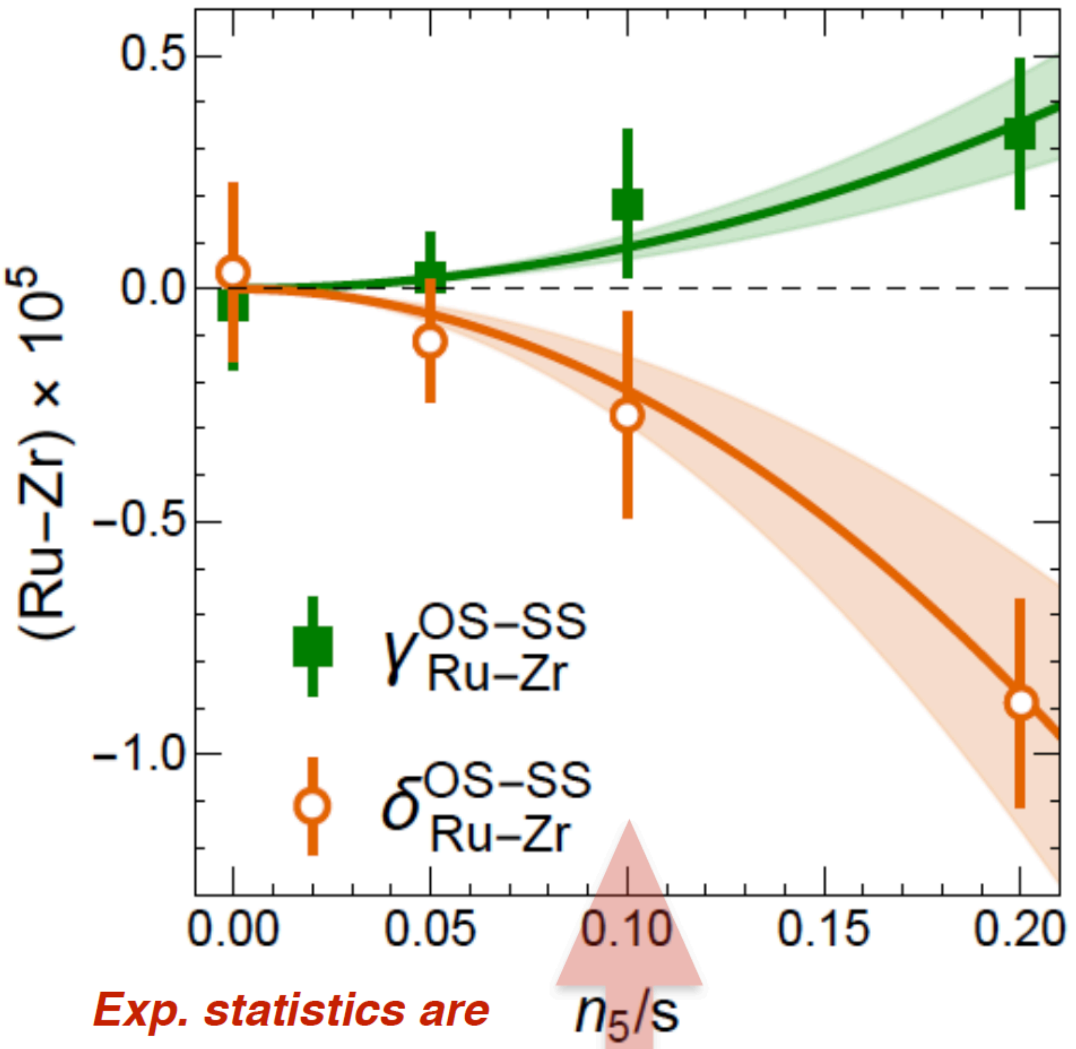
– "…backgrounds"



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

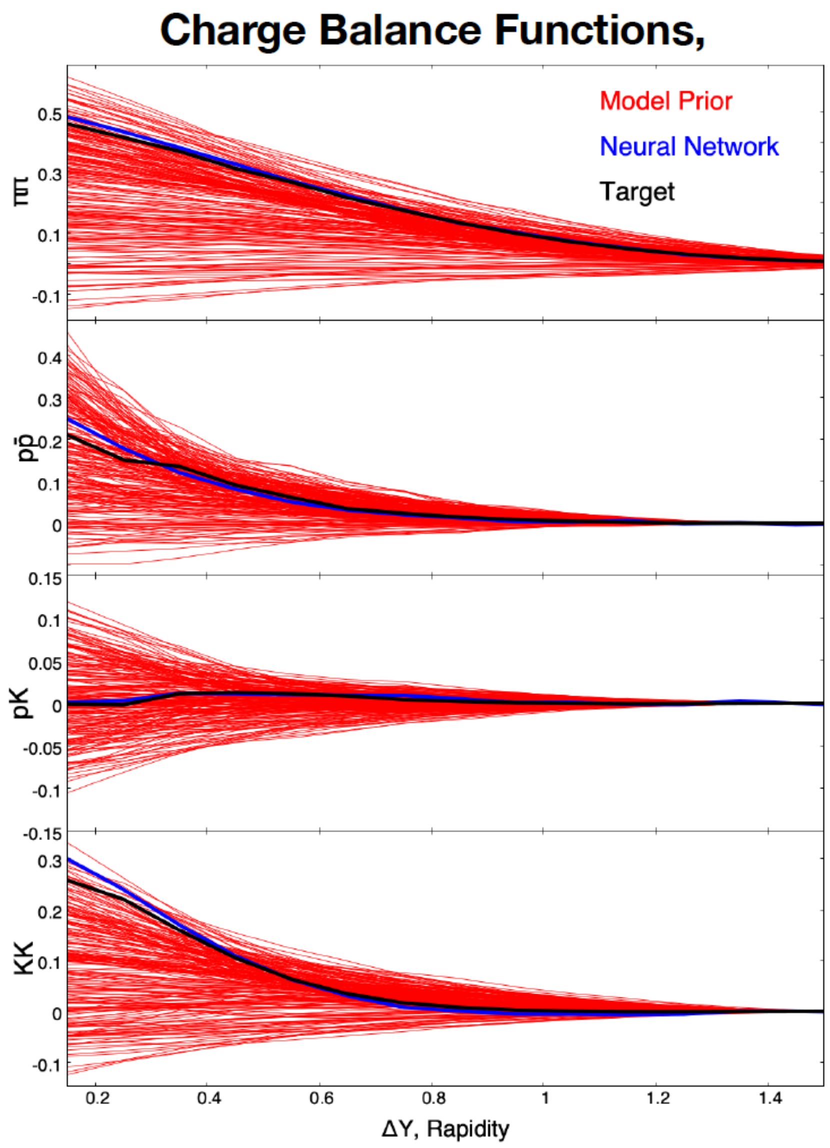
$$\boxed{B_{\pi,\pi}(\Delta y), B_{K,K}(\Delta y), B_{p,p}(\Delta y), B_{p,K}(\Delta y)}$$

Measured by STAR

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

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