Searching the QCD critical point with the net-proton multiplicity fluctuations

Shanjin Wu(吴善进)

Lanzhou University

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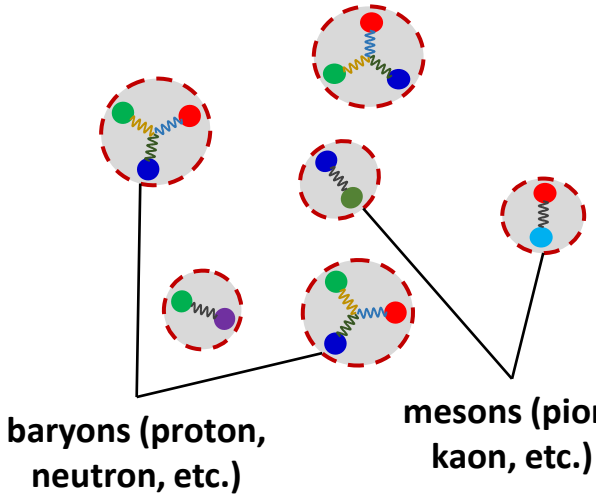
Exploring QCD phase diagram in Heavy-Ion Collisions

Phases of the QCD matter

Hadron

Confinement

Chiral symmetry breaking



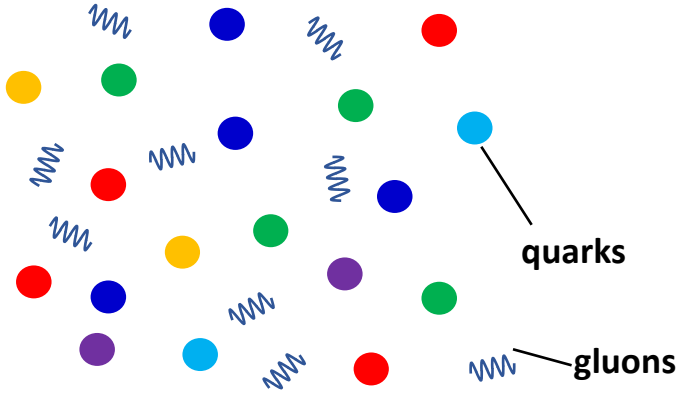
$T_c \sim 2 \times 10^{12} K$

Phase transition

Quark gluon plasma

Deconfinement

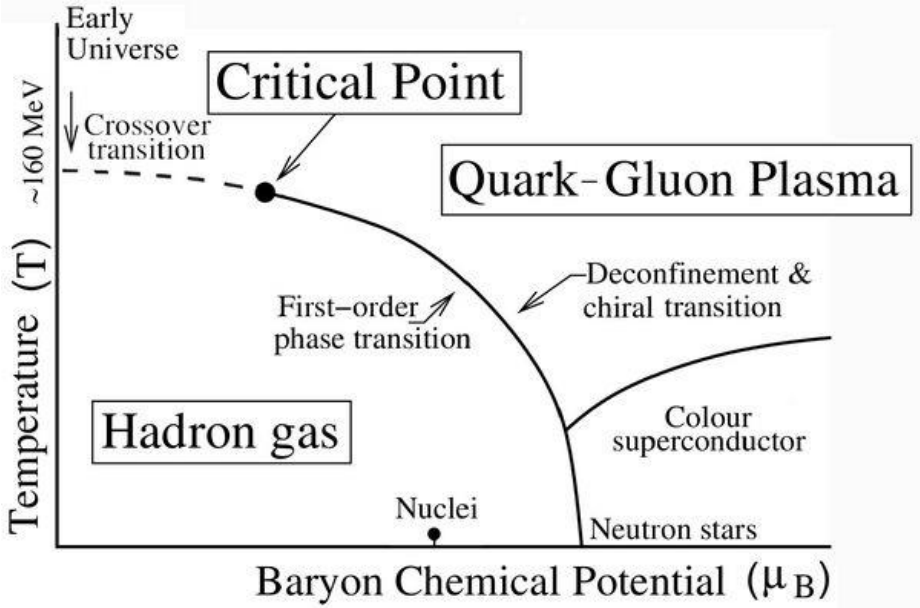
Chiral symmetry restoration



QCD phase diagram

- **small μ_B and $T \sim 155$MeV**(Lattice QCD):
  - Crossover (2nd order phase transition)
- **large μ_B** (Effective models: DSE,fRG)
  - 1st order phase transition

→ **Critical point**

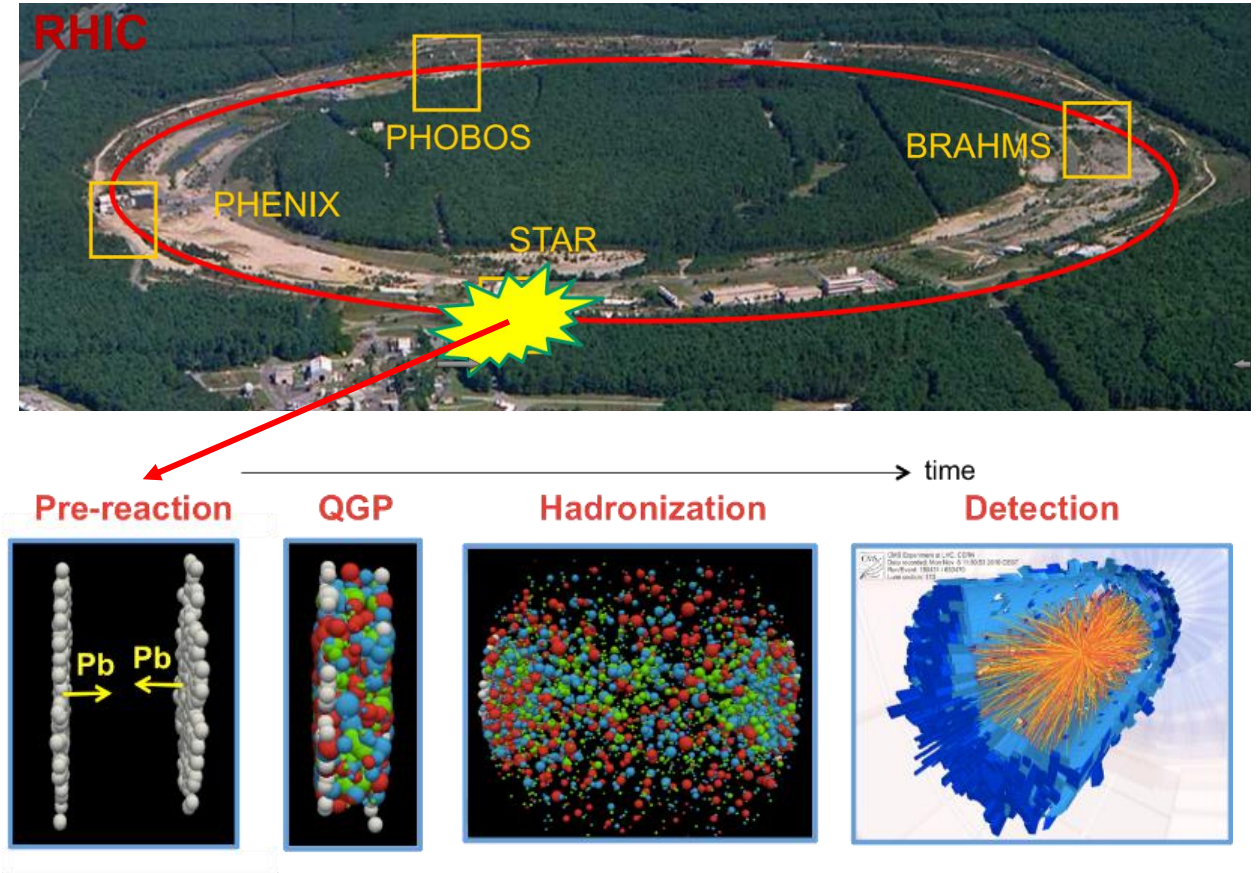


- Lattice QCD: sign problem at large μ_B
- Effective models: parameters dependent

→ **Heavy-ion collisions :**

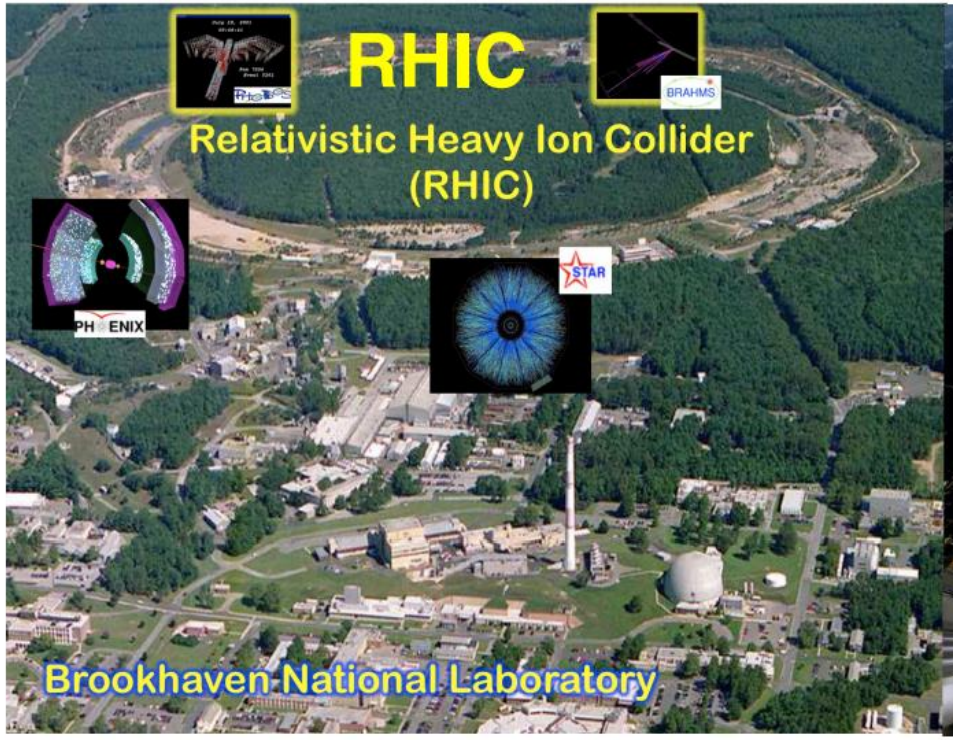
- tuning $\sqrt{s_{NN}}$,mapping $T-\mu$ phase diagram:
  RHIC(BES),NICA,FAIR,J_PARC,HIAF….

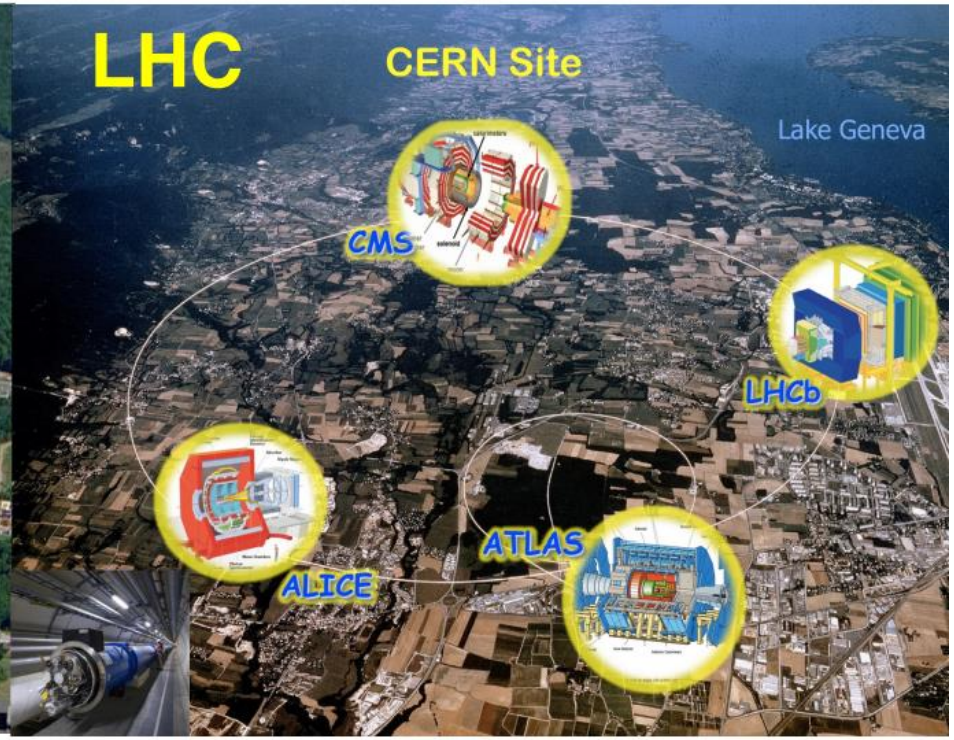
Stages of Heavy-Ion collisions



Experimental and theoretical studies shows the QGP has been created.

Facilities of relativistic heavy-ion collisions





First collisions in 2000

- Diameter 1.2 km
- pp, dAu, CuCu, AuAu, UU, OO, …
- $\sqrt{s_{NN}}$ ~ **0.007 – 0.2 TeV**
- 99.995% speead of light

First collisions in 2010

- Diameter 8.6 km
- pp, PbPb, pPb, XeXe
- $\sqrt{s_{NN}}$ ~ **5 – 8 TeV**
- 99.9999991% speead of light

“Standard model” in Heavy-ion collisions: Hydrodynamics

Initial condition for
$e(x,t_0), p(x,t_0), n(x,t_0), u^\mu(x,t_0)$

Transport Coefficients
η, ζ, κ

Relativistic Navier-Stokes Equation for
$e(x,t), n(x,t), u^\mu(x,t)$

EoS for $e(p,n)$

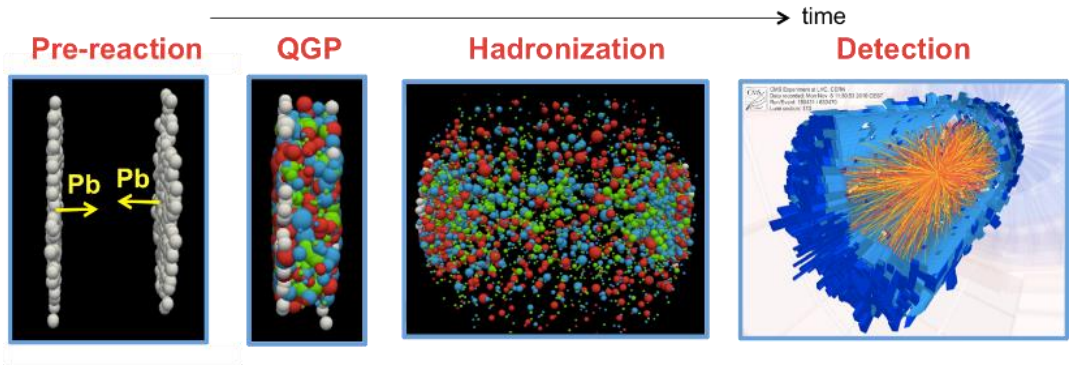
Other d.o.f

Particle distribution $f(p)$

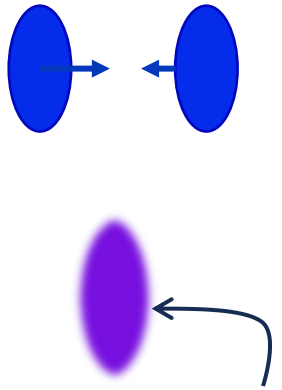
Observable

Where QCD comes in?

- **EoS** (Lattice QCD, fRG, Dyson-Schwinger)
- **Transport coefficients** (Lattice QCD, Hard Thermal Loops)
- **Initial condition** (Nuclear Theory)
- **Other d.o.f**

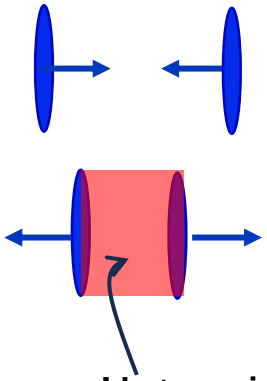


Why heavy-ion collisions can search QCD critical point?



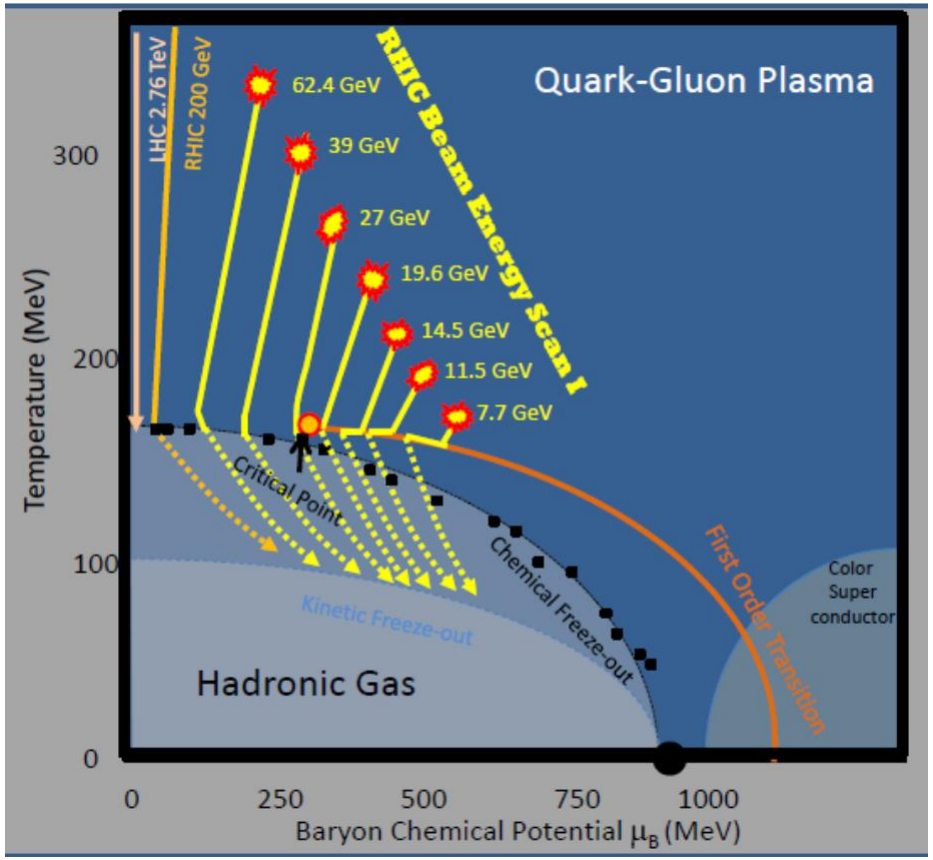
Low energy collisions
Lots of nucleons from boost nucleus, only part of anti-nucleon from QCD vacuum
Nucleon≫ Anti-Nucleon: large μ_B

Hot and dense region
Nucleon≫ Anti-Nucleon



High energy collisions
Most of the nucleon anti-nucleon pairs from QCD vacuum
Nucleon~ Anti-Nucleon: small μ_B

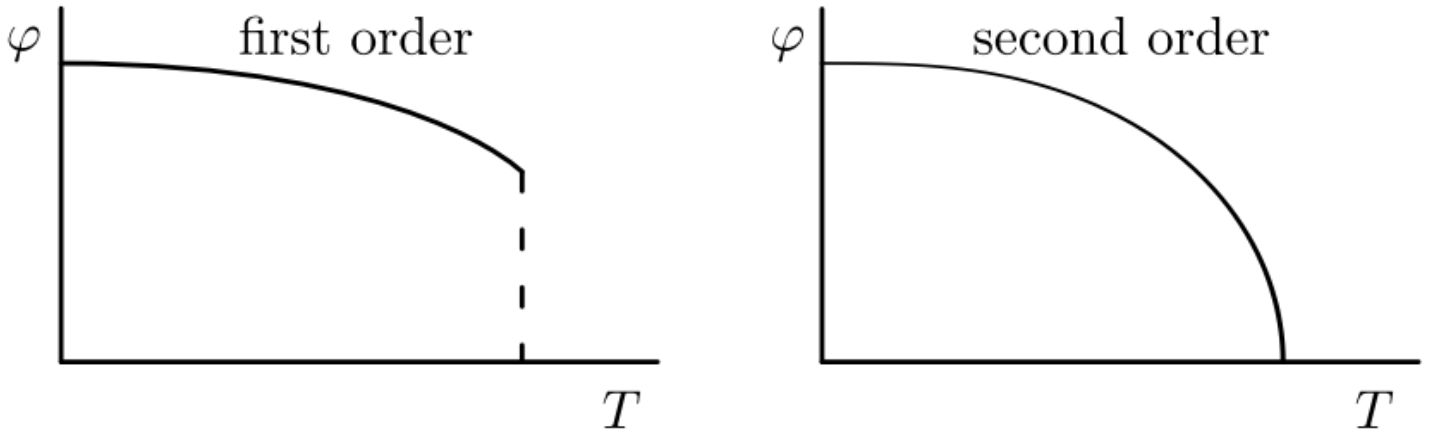
Hot region
Nucleon~ Anti-Nucleon



=>Tuning $\sqrt{s_{NN}}$, scan the QCD phase diagram

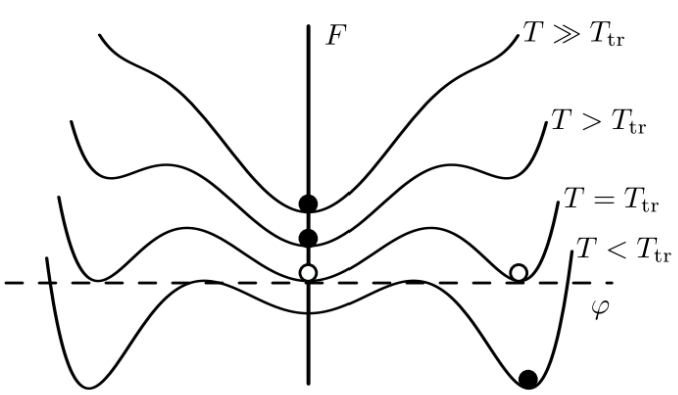
The observable of QCD phase transition in Heavy-Ion Collisions

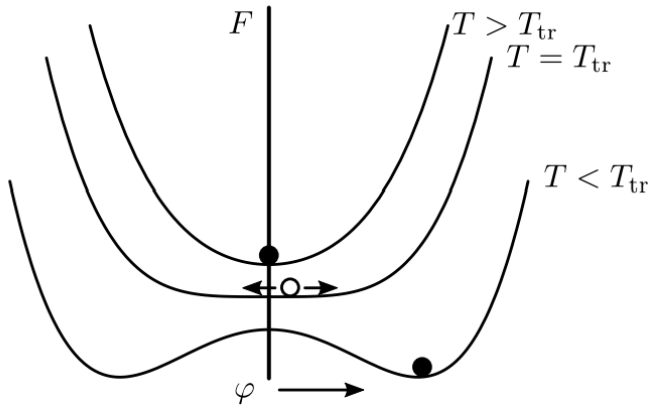
Theory of phase transition



Lev Landau

Order parameter: identify symmetry and symmetry breaking

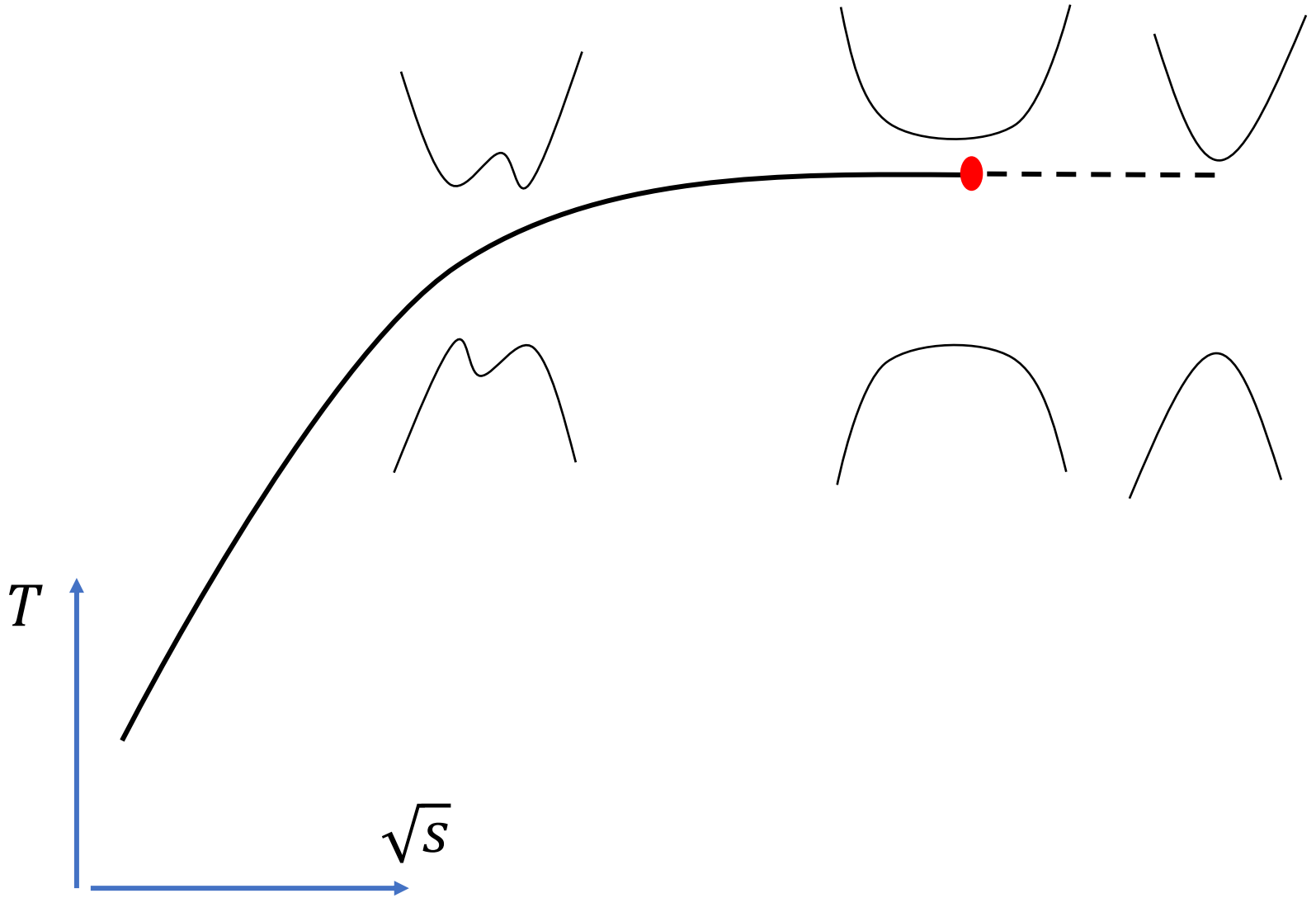




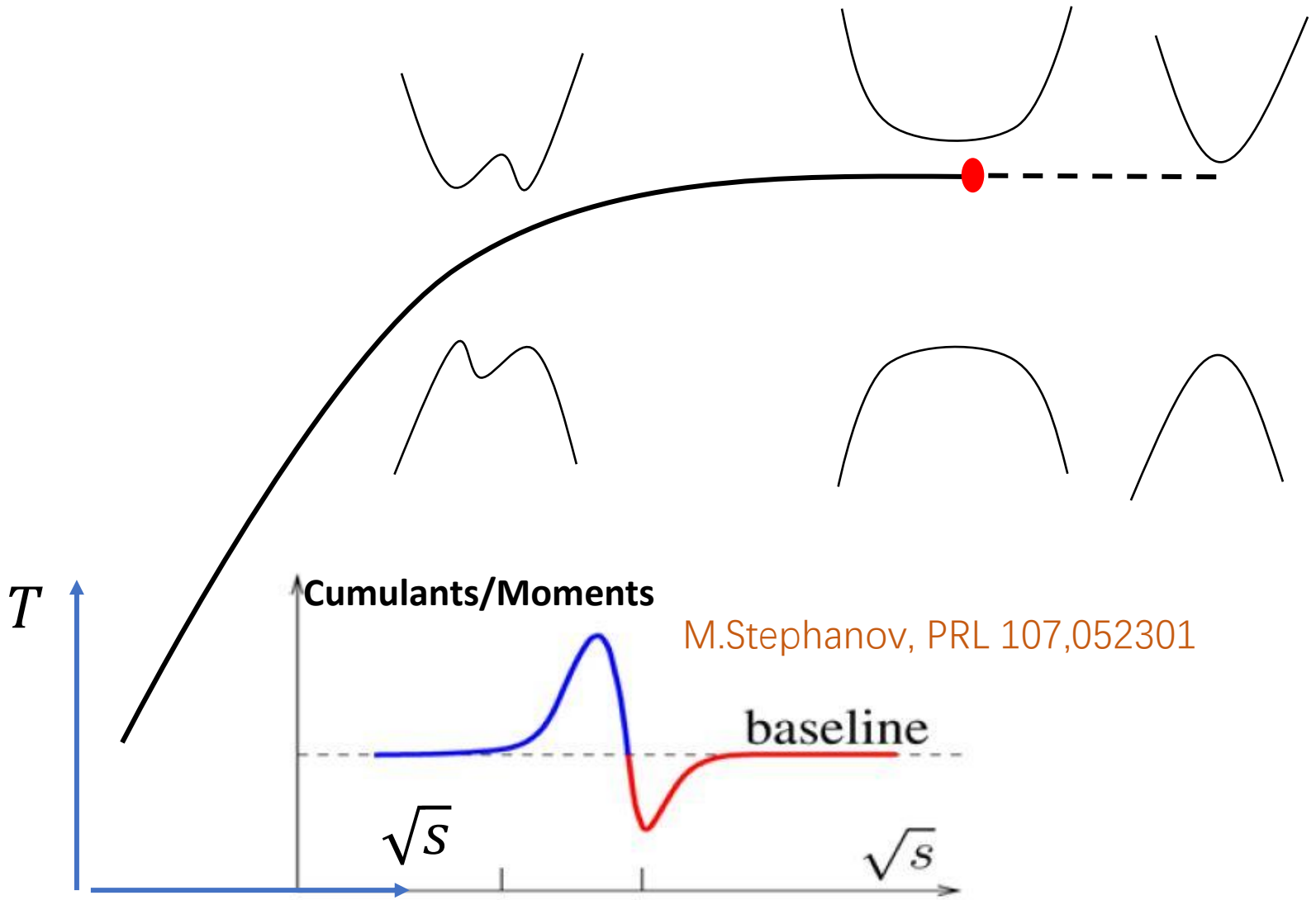
Lessons:

1. Different shape of distribution(free energy) in different region of phase diagram
2. Large fluctuations near critical point

QCD phase diagram

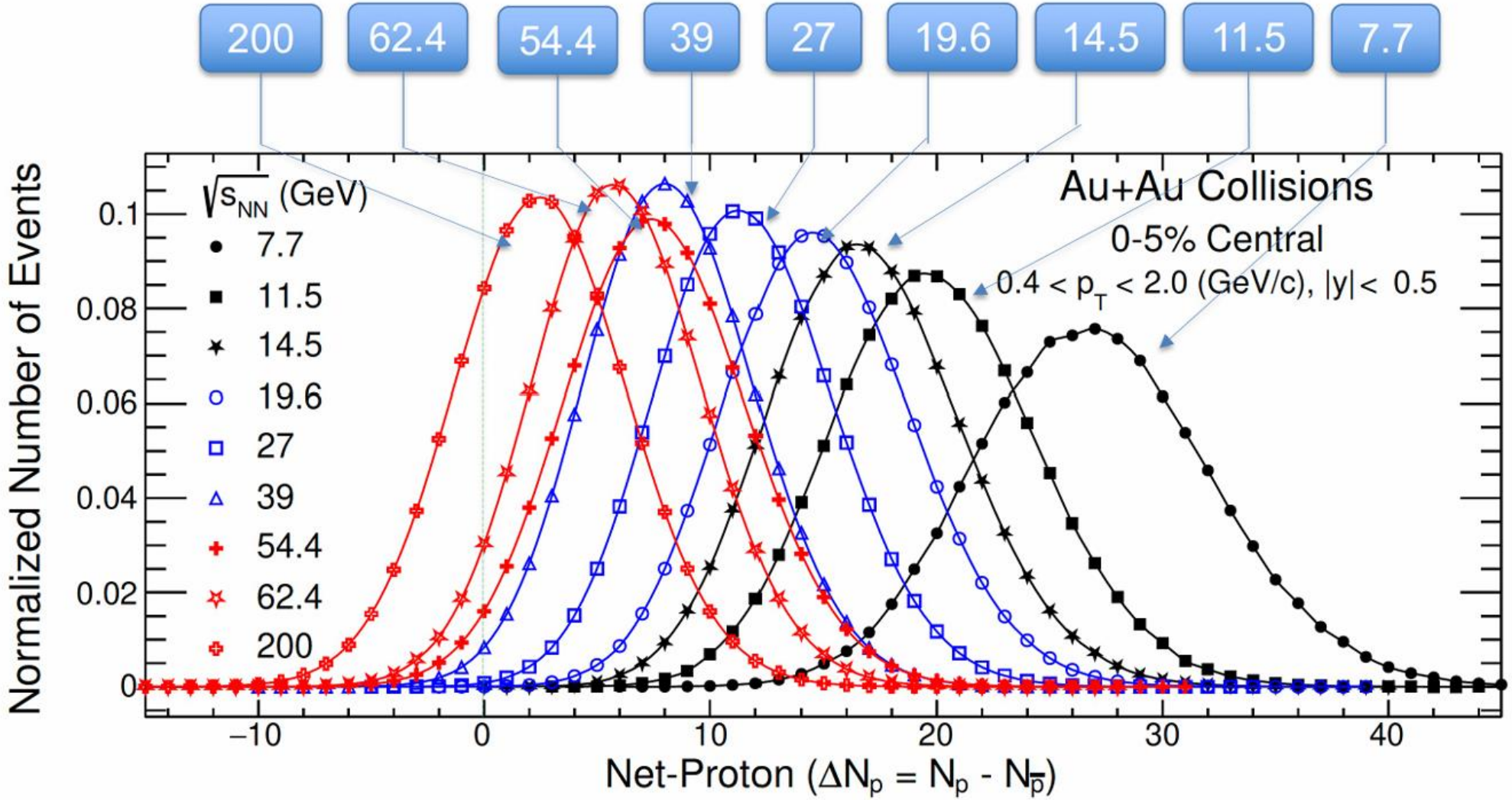


QCD phase diagram



M.Stephanov, PRL 107,052301

Event-by-event Multiplicity distribution



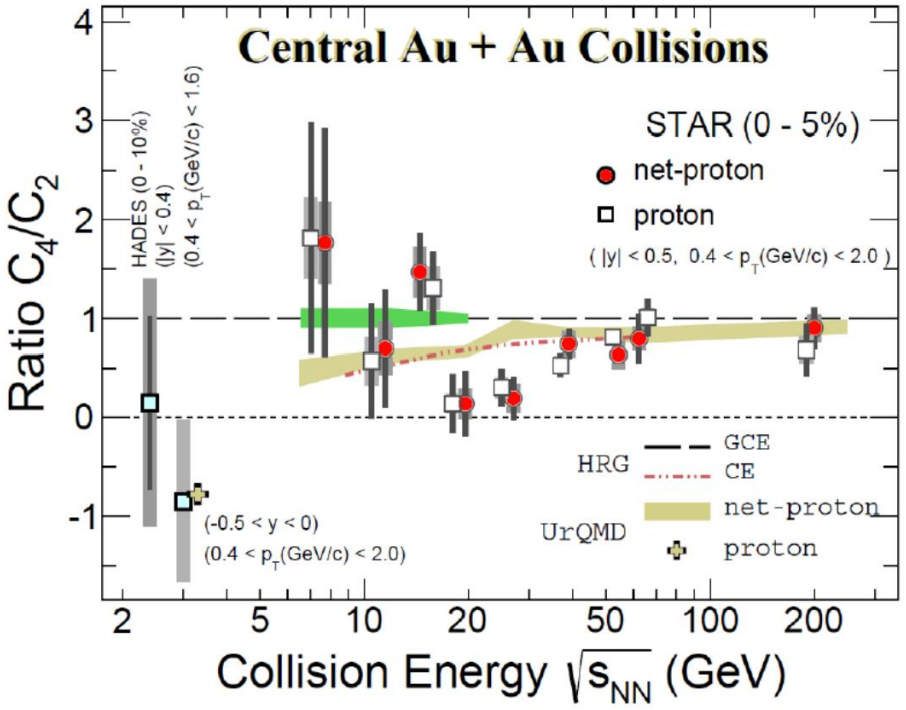
STAR, PRL126, 092301 (2021) STAR, 2101.12413 (long paper)

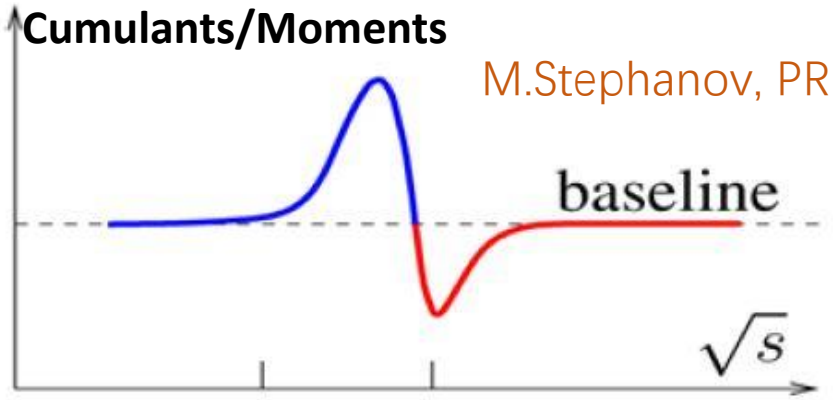
QCD phase diagram

→ **Scanning QCD phase diagram :**

- Shape of net-proton multiplicity distribution and the observable of QCD phase transition
- Preliminary agrees with experiments

Beam Energy Scan first phase (BES-I)





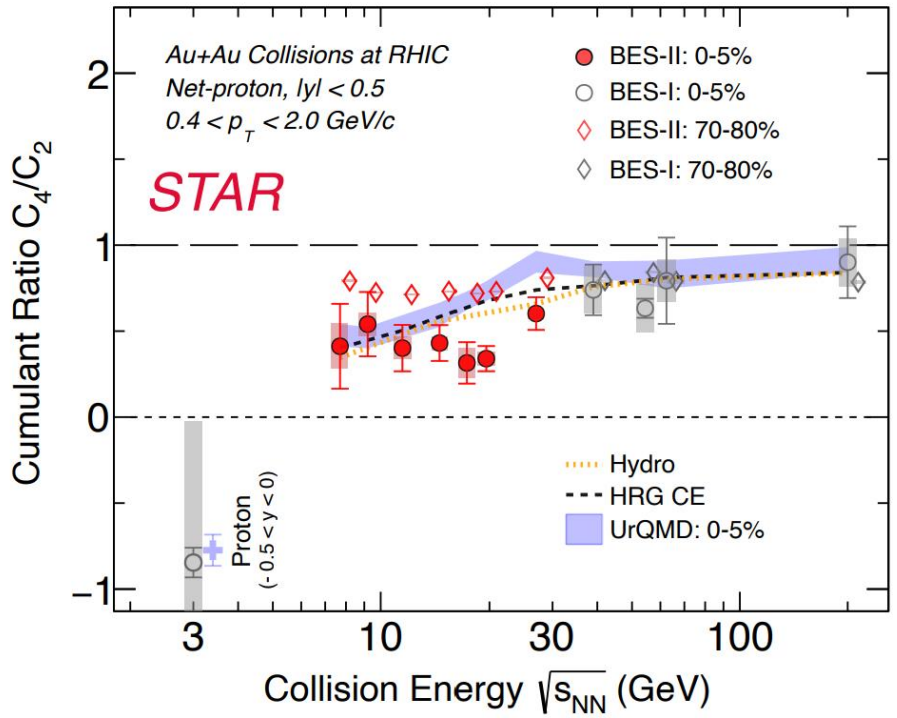
M.Stephanov, PRL 107,052301

STAR, PRL 126,092301
STAR,PRL 128,202303

Recent experiment progress

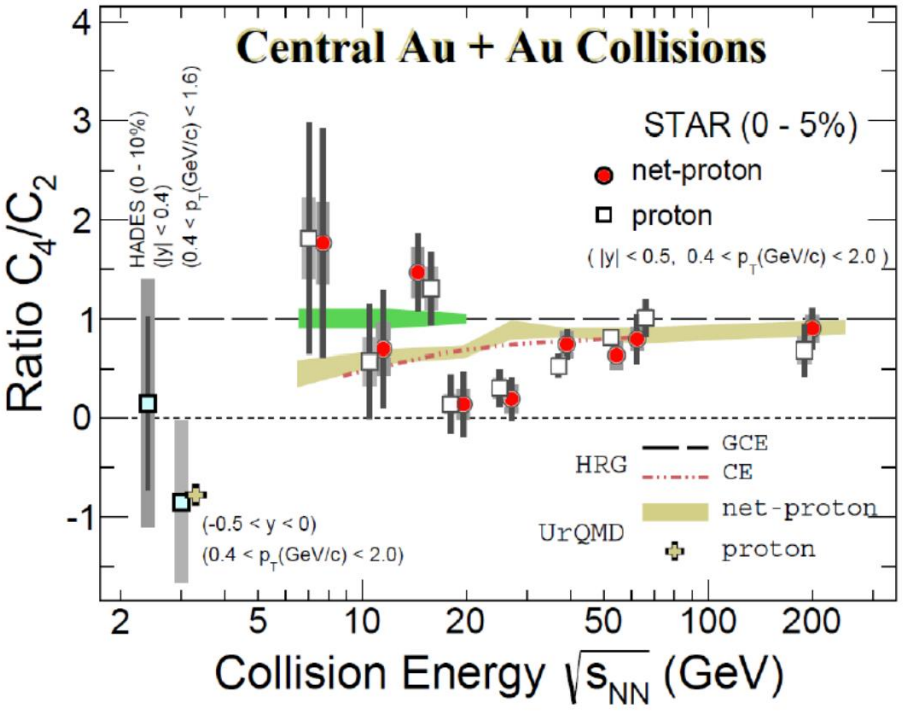
Net-proton fluctuations near critical point

- Higher statistics and detector acceptance



STAR, CPOD 2024

- Kurtosis at BESI

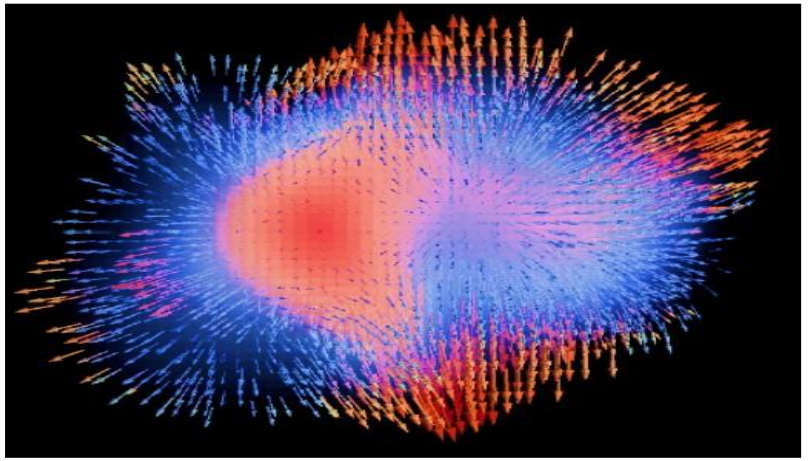


STAR, PRL 126,092301
STAR,PRL 128,202303

Possible solution: heavy-ion collisions is complex system

QGP fireball system in heavy-ion experiments

- QGP fireball system created in heavy-ion experiments is not an ideal system:
  - Fast expanding
  - Finite size
  - Inhomogeneous temperature and chemical potential
  - Volume fluctuation and quantum fluctuations
  - Conservation contamination

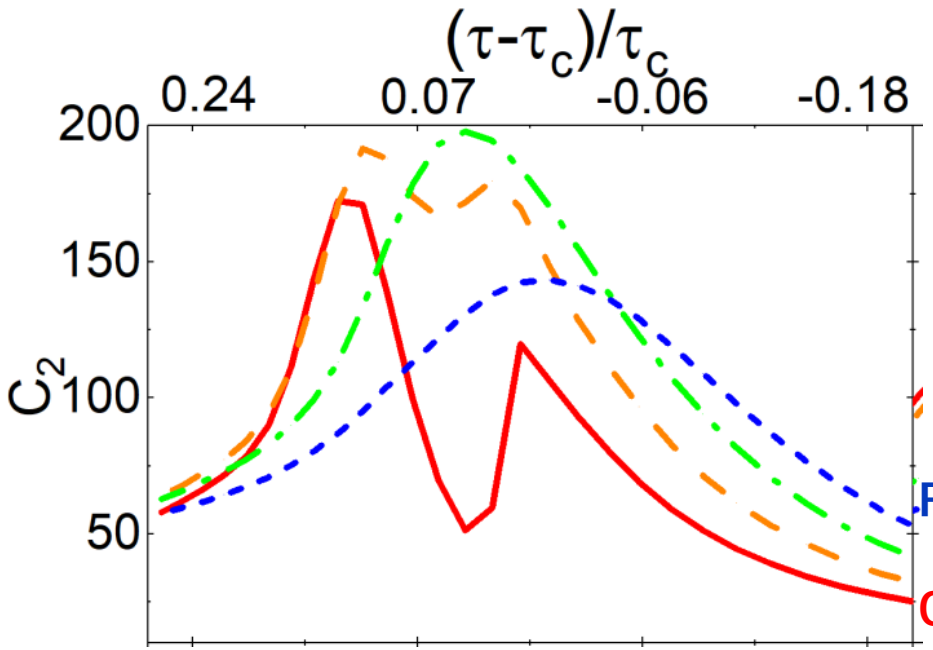


Fast expanding effects

Lijia Jiang,Shanjin Wu and Huichao Song,NPA.2017.06.047

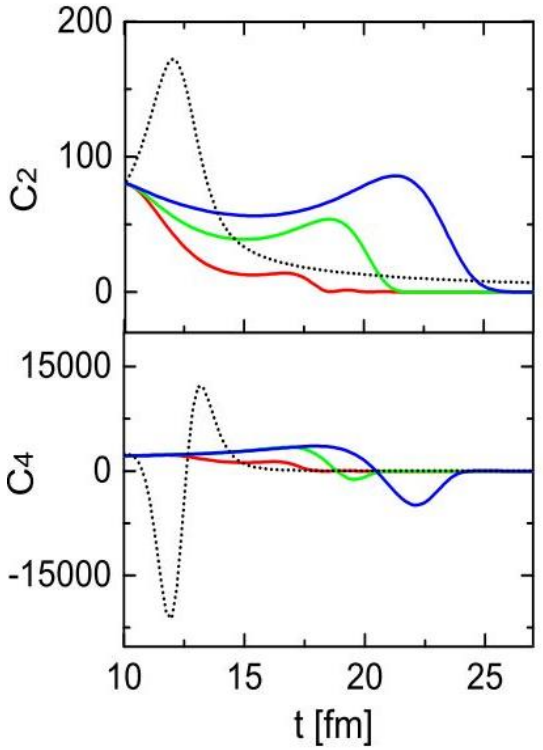
- Expanding effects suppress the fluctuations
- Expanding effects reverse the sign
- Expanding effects move the maximum fluctuations

Shian Tang, Shanjin Wu, Huichao Song, PRC(2023)



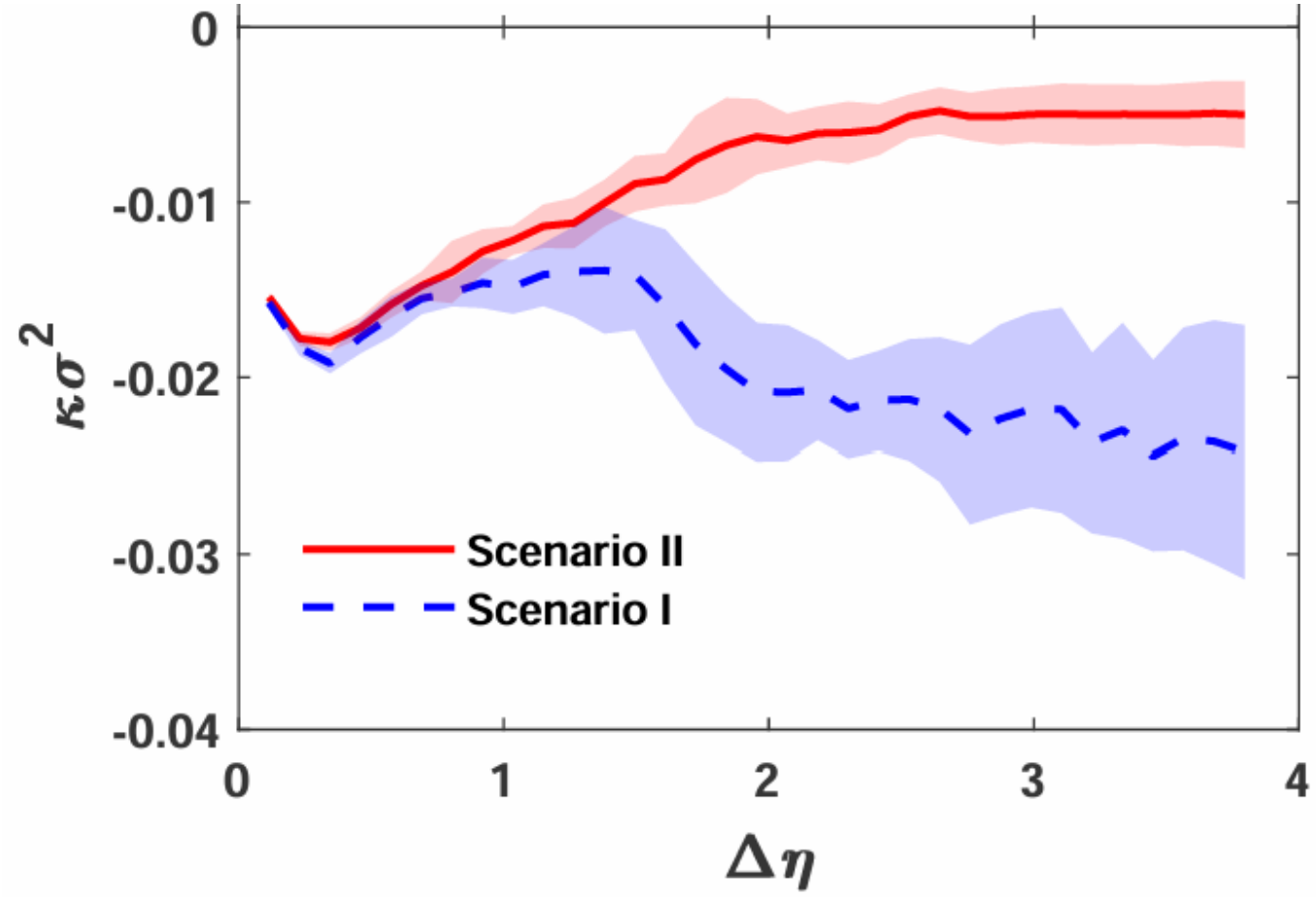
Far from CP

Close to CP



Inhomogeneous T and mu effects

- Inhomogeneous T and mu effects enhances the magnitude of fluctuations



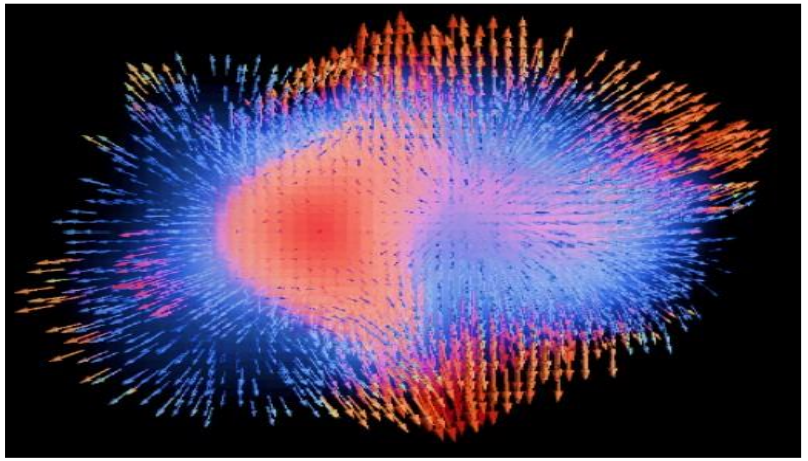
Uniform QGP

Shanjin Wu, arXiv:2406.12325

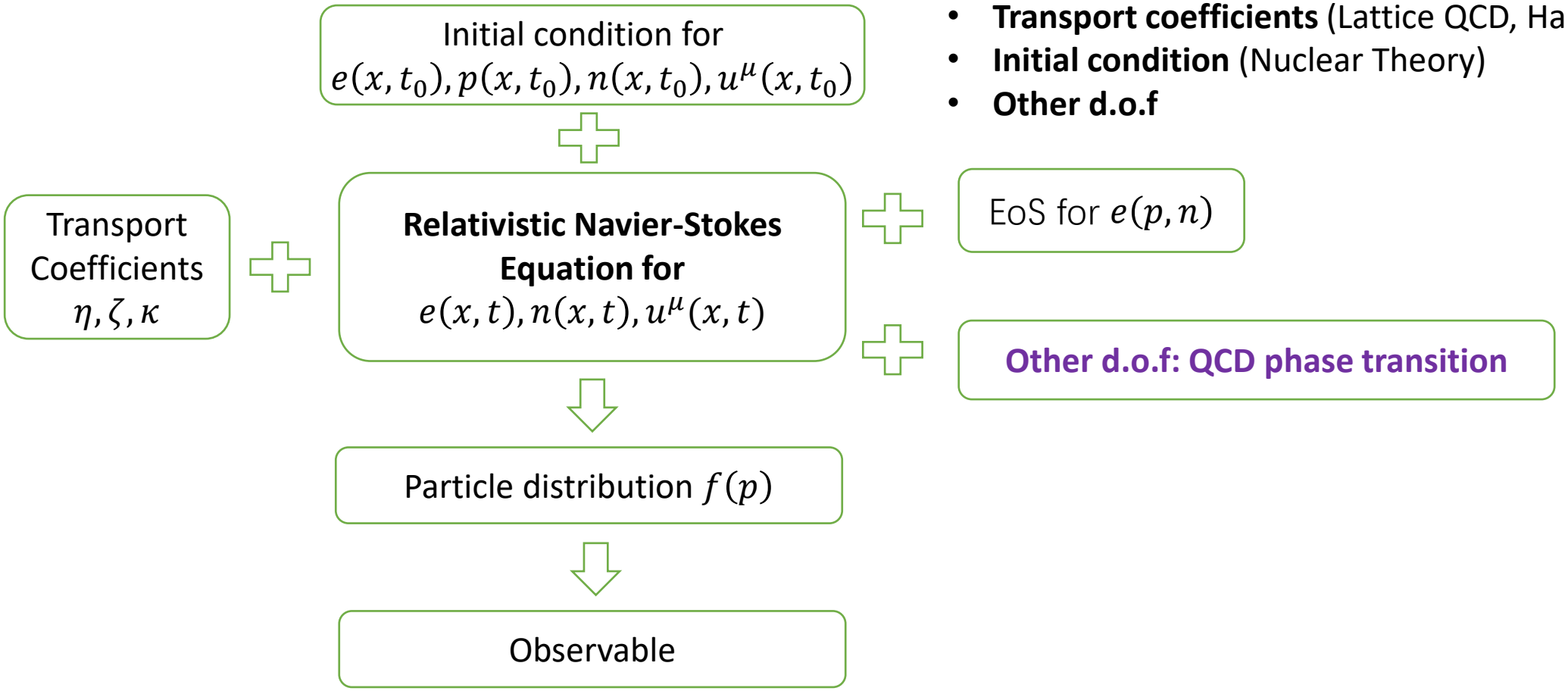
Inhomogeneous QGP

QGP fireball system in heavy-ion experiments

- QGP fireball system created in heavy-ion experiments is not an ideal system:
  - Fast expanding
  - Finite size
  - Inhomogeneous temperature and chemical potential
  - Volume fluctuation and quantum fluctuations
  - Conservation contamination
- Build a model to describe all these effects



“Standard model” in Heavy-ion collisions: Hydrodynamics



Where QCD comes in?

- **EoS** (Lattice QCD, fRG, Dyson-Schwinger)
- **Transport coefficients** (Lattice QCD, Hard Thermal Loops)
- **Initial condition** (Nuclear Theory)
- **Other d.o.f**

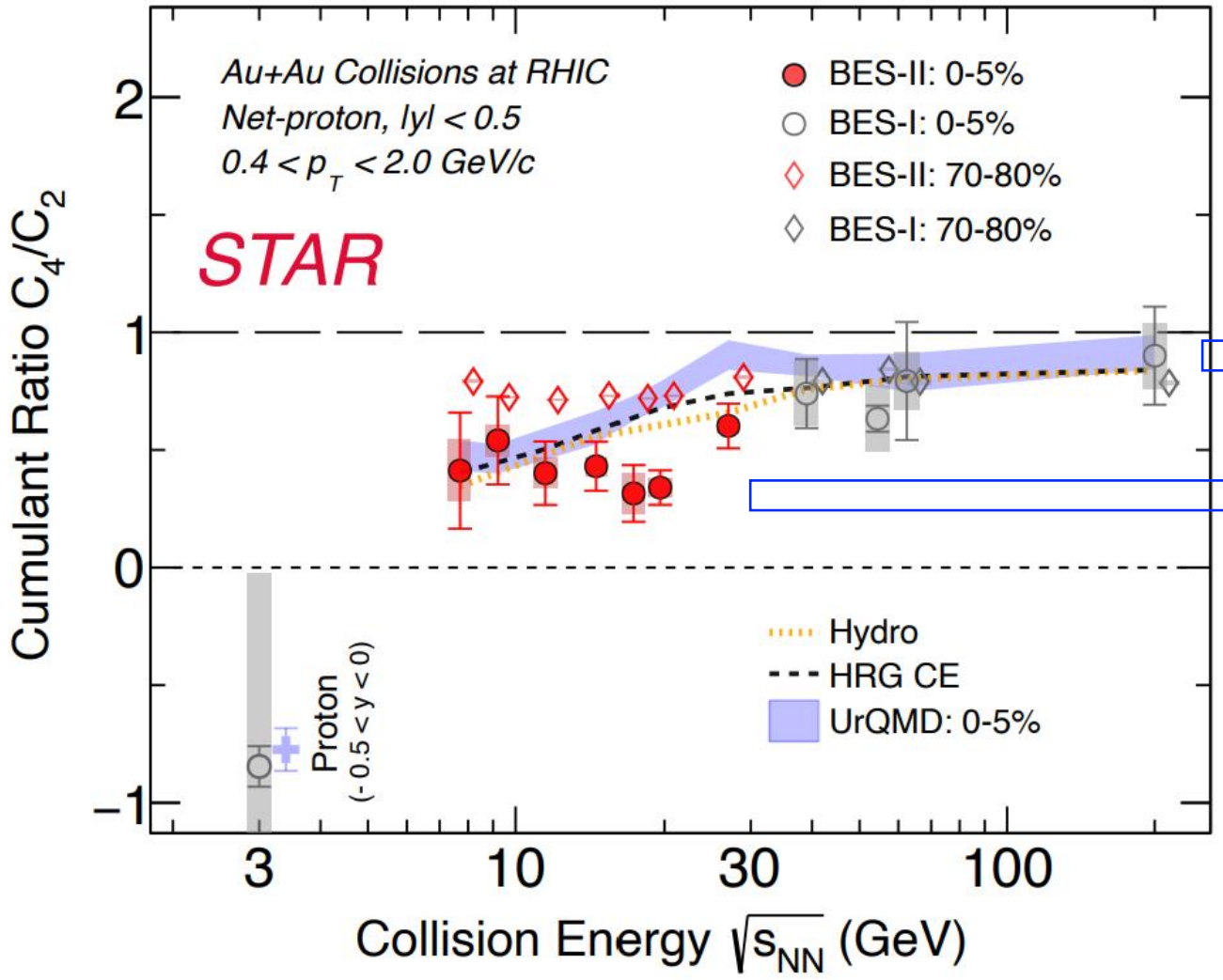
Dynamical models near QCD critical point

Modeling in expanding QGP: **Hydrodynamics + Critical fluctuations**

- **Model A** (order parameter field)
  S.Mukherjee et al15' 16', L.Jiang et al17', S.Wu et al 19', S.Tang et al 23',
- **Model B** (conserved field)
  M.Sakaida et al 17', S.Wu et al 19', M.Nahrgang et al 19', G.Pihan et al 22'…
- **Model H** (conserved order parameter field + momentum+…)
  it is hard and in progress
- **Non-equilibrium chiral hydrodynamics** (hydro + order parameter)
  M. Nahrgang et al 11'12'14'16'19'
- **Hydro+, hydro++…** (hydro + slow modes)
  M. Stephanov et al 18'19'20', N. Abbasi et al 22', L. Du et al 20',……
- **Fluctuating hydrodynamics** (hydro + noise)
  J.Kapusta et al 12',12', K.Murase et al 13', X.An et al 19',21'…
- **Hydro-kinetics** (deterministic fluctuating hydro)
  D.Teaney et al 17'18'19'22'…

See reviews: e.g. Lipei Du et al. 2402.10183; Xin An et al., 2108.13867; Shanjiu Wu, et al.,2104.13250; Marcus Bluhm et al., 2001.08831; Adam Bzdak et al.,1906.00936;M.Asakawa et al.,1512.05308

Experiment measurements and theory efforts



STAR, CPOD 2024

Hydro without Critical

Building Hydro with Critical

Summary

- QCD phase diagram is an exciting area with rich physics required exploration.
- Preliminary agreements between experiments and theory suggesting the existing critical point and first order phase transition at finite baryon chemical potential.
- More comprehensive study is required for the conclusive observation of QCD critical point.

Thank you!