中国科学院大学
University of Chinese Academy of Sciences



Mei Huang

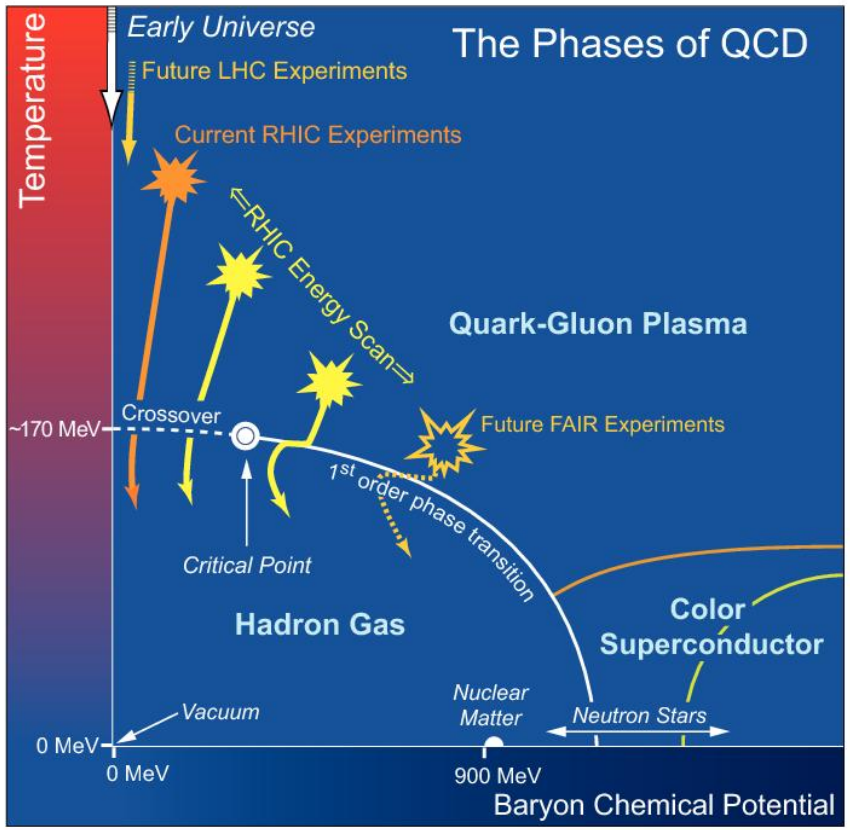
University of Chinese Academy of Sciences

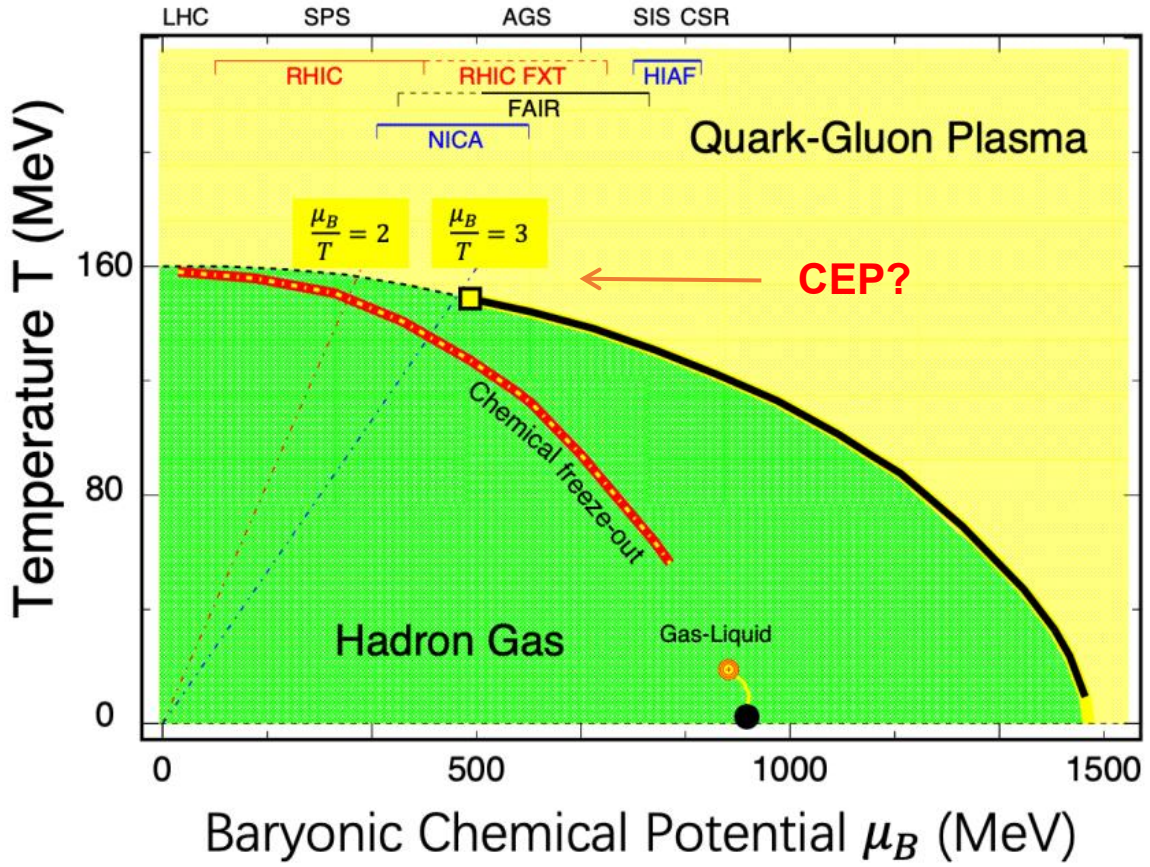
arXiv:e-Print: 2404.02397 [hep-ph]

Collaborators: Yifan Shen, Wei Chen, Kun Xu, Xiangyu Wu

iHIC2024, Tsinghua Uni., July 13-16, 2024

QCD phase diagram & searching for the CEP

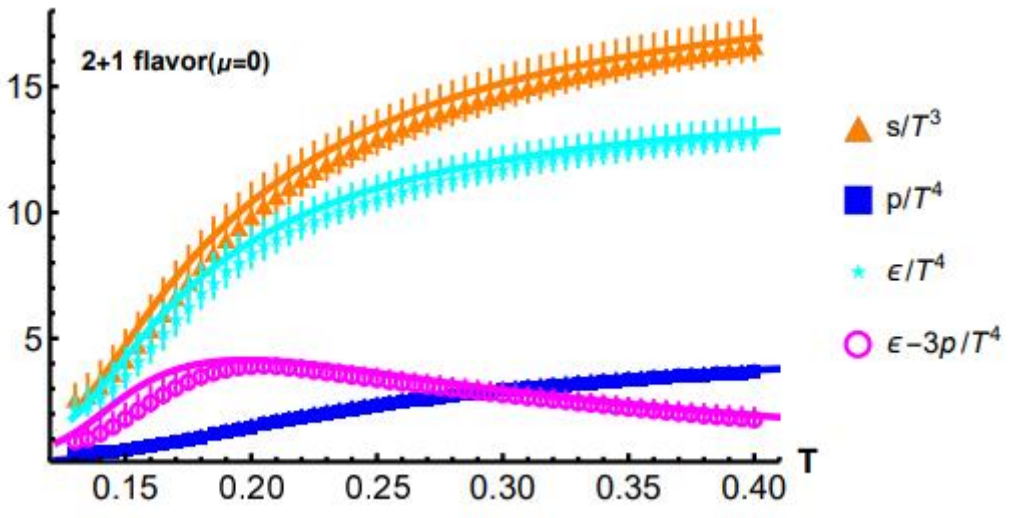




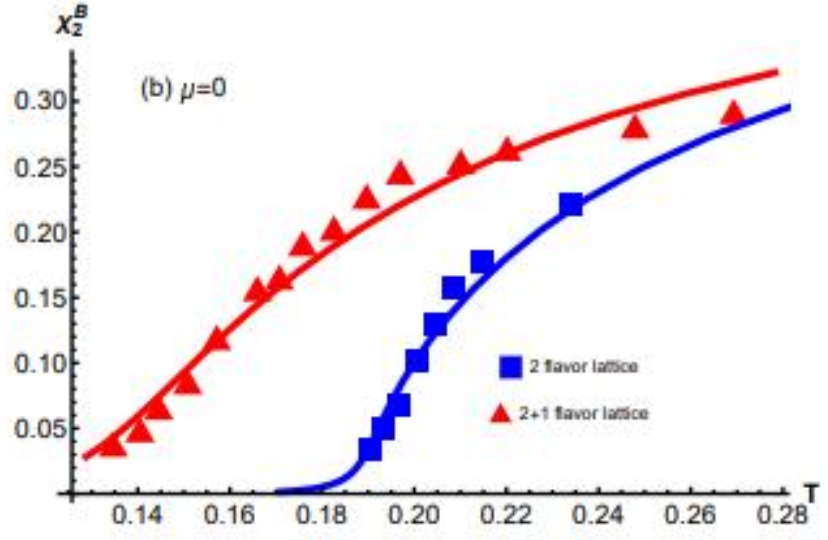
LQCD (Frithjof Karsch) & nonperturbative theoretical calculations (Jan Pawlowski)

Strategy of model calculations (rPNJL model, DSE-fRG,fRG,holographic QCD models):

1, Fit model paraters with Lattice QCD EOS and baryon number susceptibility at zero chemical potential;
2,Predictions at finite baryon number chemical potential.



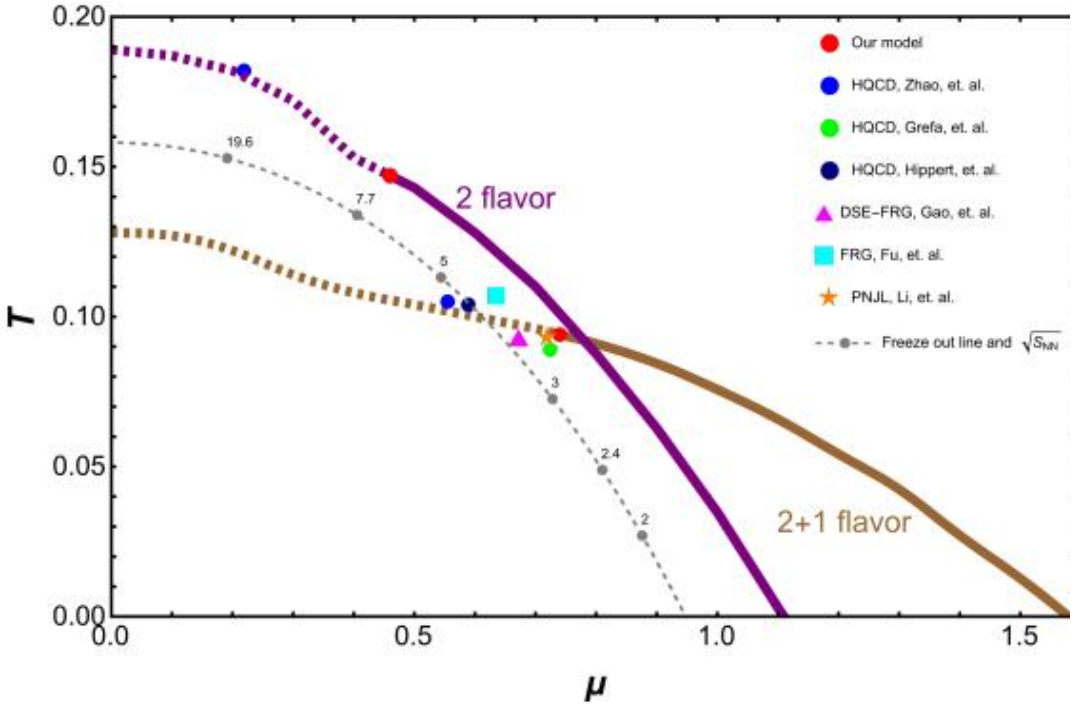
Determine Tc at mu=0

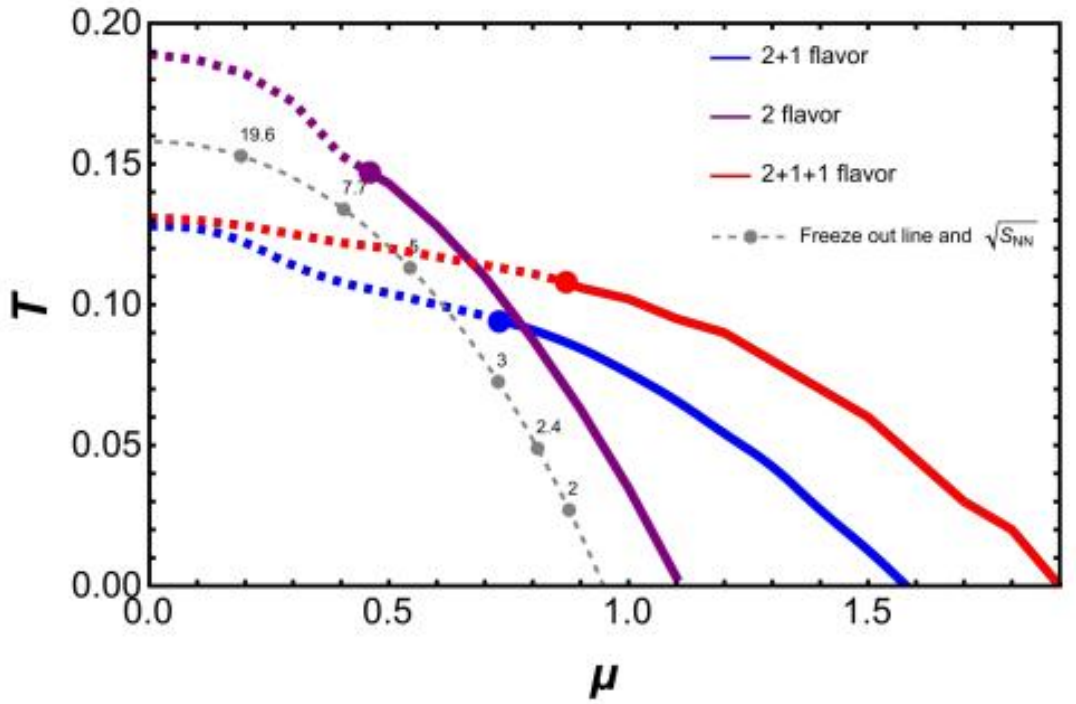


Determine mu dependent Tc

QCD:X—Ø C ◯Ø, M.H.,
P ▷ S.R ◯ .D 109 (2024) 5, L051902, ◯−
P◎=Ø :2401.06417

Locations of CEP from rPNJL model,holographic QCD models, DSE-fRG,fRG converge at around (Tc~100MeV, mu_B^c~700 MeV)





R◯⊔. D 104, 034002 (2021), ∠◎X⊟⊔.2102.12042 [∅ ⊏⊐Ⓛ−⊿⊿⊿], M. H⊟ⓅⓅ◯◎⊿⊿, J. G◎◯//∠, T. A. M∠∅∅⊟∅/∅/, J. N□◎□∅⊿∠, J. N□◎□∅⊿∠−H□Ⓢ⊿⊿Ⓛ◯◎, I. P□◎⊿⊿⊟ⓁⓁ□ V∠◺◺¢—◯◺◺, C. R∠⊿⊿⊿⊟, R. R□—/∅/◯Ⓜ□∅⊿⊿, ∠∅⌓ M. T◎—⊕⊟ⓁⓁ□ (2023) ∠◎X⊟⊔:2309.00579 [∅—▱Ⓛ−⊿⊿⊿], Y.−Q. Z⊿∠□, S. H◯, D. H□—, L. L⊟, ∠∅⌓ Z. L⊟, JHEP 04, 115 (2023), ∠◎X⊟⊔:2212.14662 [⊿◯Ⓟ−Ⓟ⊿] ◎PNJL:Z⊿⊟⊥⊟∅ L⊟, K—∅ X—, X⊟∅▷∠∅/∅/ W∠∅/∅/ ∠∅⌓ MH, ∠◎X⊟⊔:1801.09215

DSE−//RG: F. G∠□ ∠∅⌓ J. M. P∠∨Ⓛ□∨Ⓢ∩⊟, P⊿▷Ⓢ. R◯⊔. D 102, 034027 (2020), ∠◎X⊟⊔:2002.07500 [⊿◯Ⓟ−Ⓟ⊿]

Net proton number fluctuations near critical point

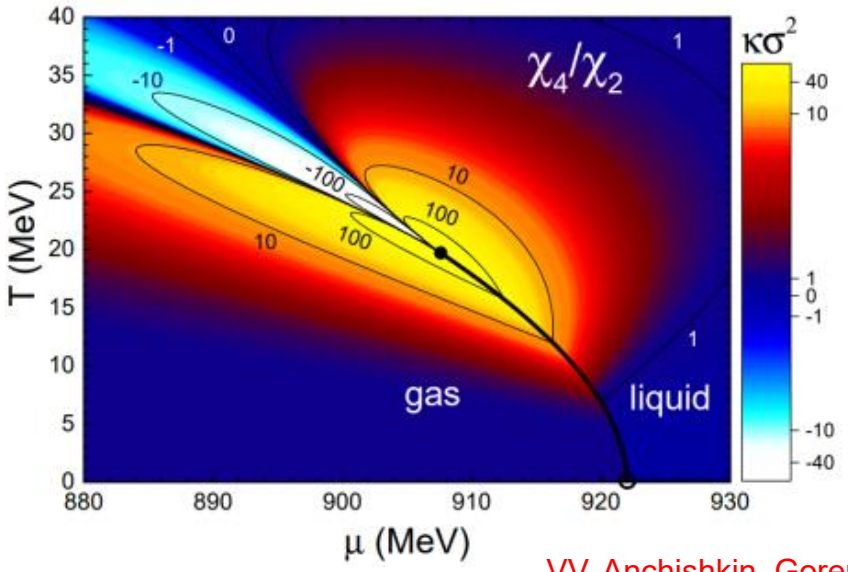
$$K_N = \ln(e^{tN}) = \sum_{n=1}^{\infty} k_n \frac{t^n}{n!}$$

$$k_n \propto \frac{\partial^n (\ln Z^{gce})}{\partial \mu^n}$$

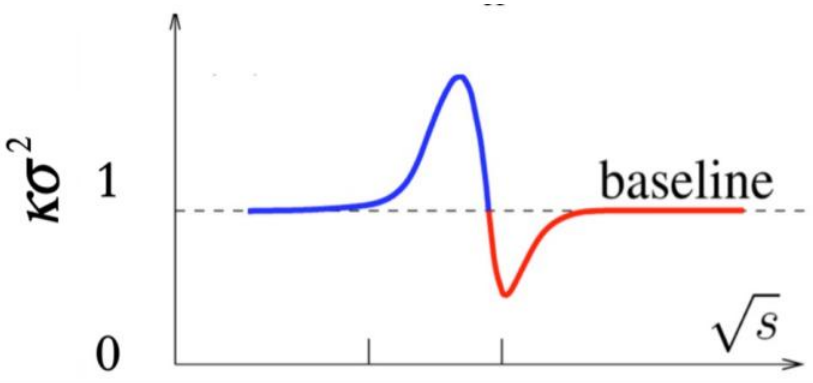
$$\ln Z^{gce}(T,V,\mu) = \ln[\sum_N e^{\mu N/T} Z^{ce}(T,V,N)]$$

$$C_1 = \langle N \rangle = M$$
$$C_2 = \langle (\Delta N)^2 \rangle = \sigma^2$$
$$C_3 = \langle (\Delta N)^3 \rangle = S\sigma^3$$
$$C_4 = \langle (\Delta N)^4 \rangle - 3C_2^2 = \kappa\sigma^4$$

$$\frac{\sigma^2}{M} = \frac{C_2}{C_1}, S\sigma = \frac{C_3}{C_2}, \kappa\sigma^2 = \frac{C_4}{C_2}$$

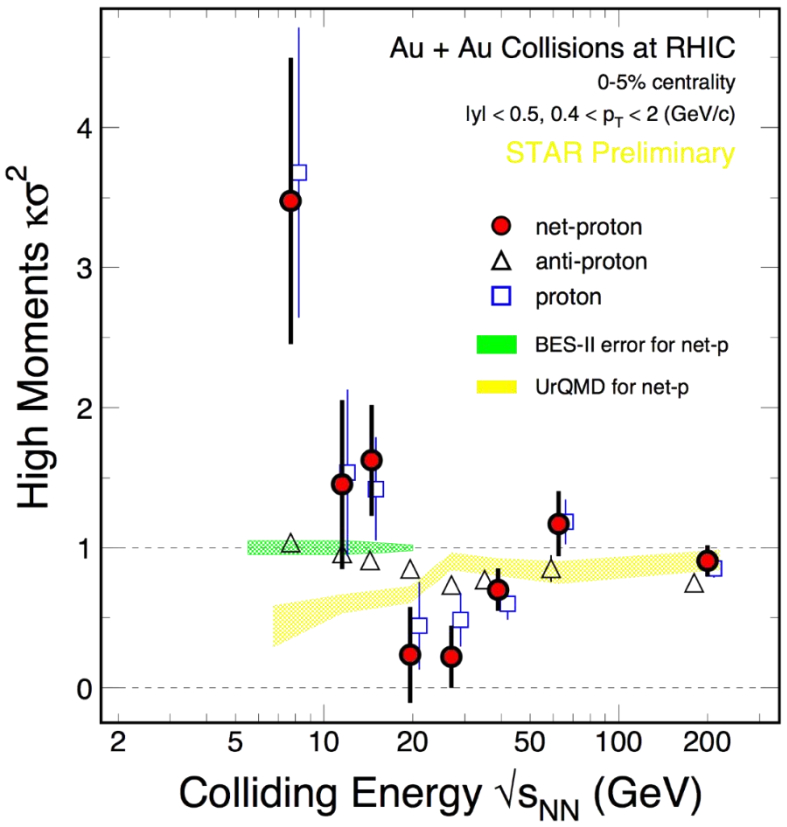


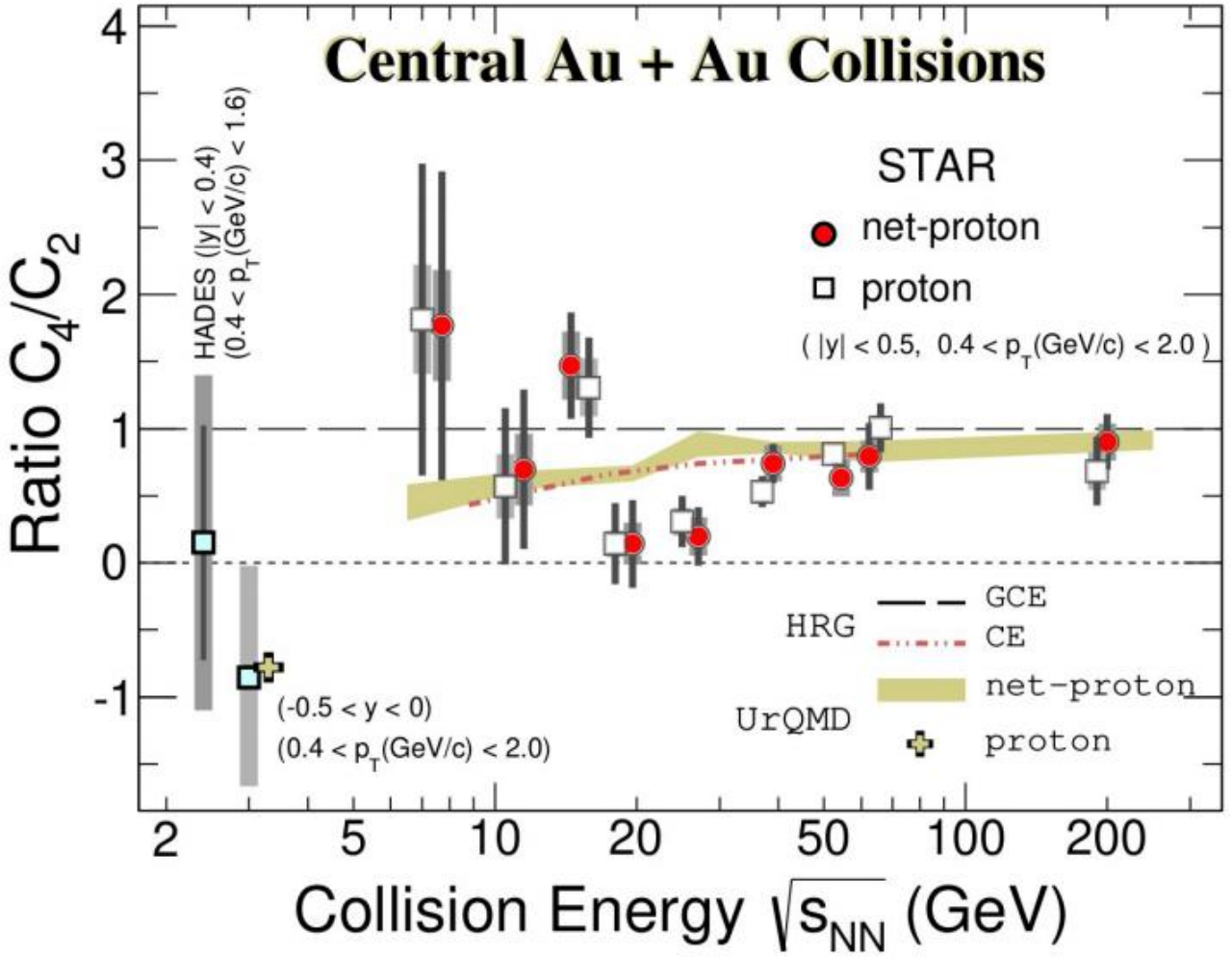
VV, Anchishkin, Gorenstein, Poberezhnyuk, PRC 92, 054901 (2015)



M.A.Stephanov,PRL107,052301(2011)

Fluctuations near critical point (dip-peak structure)





STAR: PRL112, 32302(14);
PRL113,092301(14);
X.F.Luo, N.Xu, arXiv:1701.02105

Nonmonotone → Critical End Point signature ?

STAR:
Phys. Rev. Lett. 126 (2021) 092301
Phys. Rev. Lett. 128 (2022) 202303

EoS from Polyakov-loop-Nambu-Jona-Lasinio(PNJL) Model

Zhibin Li, Kun Xu, Xinyang Wang, Mei Huang. Eur.Phys.J.C 79 (2019) 3, 245

(μ_{Bc} = 720MeV, T_c= 93MeV)

Thermal Potential of PNJL Model:

$$\Omega_{\rm PNJL} = U(\Phi,\bar{\Phi},T) + g_s\sum_f\sigma_f^2 - \frac{g_D}{2}\sigma_u\sigma_d\sigma_s + 3\frac{g_1}{2}(\sum_f\sigma_f^2)^2 + 3g_2\sum_f\sigma_f^4 - 6\sum_f\int_{-\Lambda}^{\Lambda}\frac{d^3p}{(2\pi)^3}E_f$$
$$- 2T\sum_f\int_{-\infty}^{\infty}\frac{d^3p}{(2\pi)^3}\times\left\{\ln\left[1+3\Phi e^{-\frac{E_f-\mu_f}{T}}+3\bar{\Phi}e^{-2\frac{E_f-\mu_f}{T}}+e^{-3\frac{E_f-\mu_f}{T}}\right]+\right.$$
$$\left.\ln\left[1+3\bar{\Phi}e^{-\frac{E_f+\mu_f}{T}}+3\Phi e^{-2\frac{E_f+\mu_f}{T}}+e^{-3\frac{E_f+\mu_f}{T}}\right]\right\}$$

Effective mass:

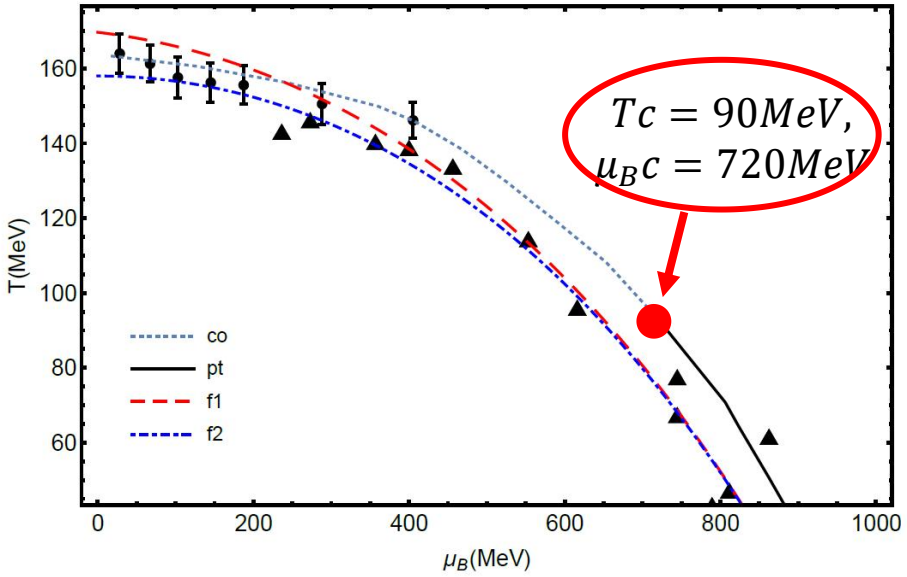
$$M_f = m_f - 2g_s\sigma_f + \frac{g_D}{4}\sigma_{f+1}\sigma_{f+2} - 2g_1\sigma_f(\sum_{f'}\sigma_{f'}^2) - 4g_2\sigma_f^3$$

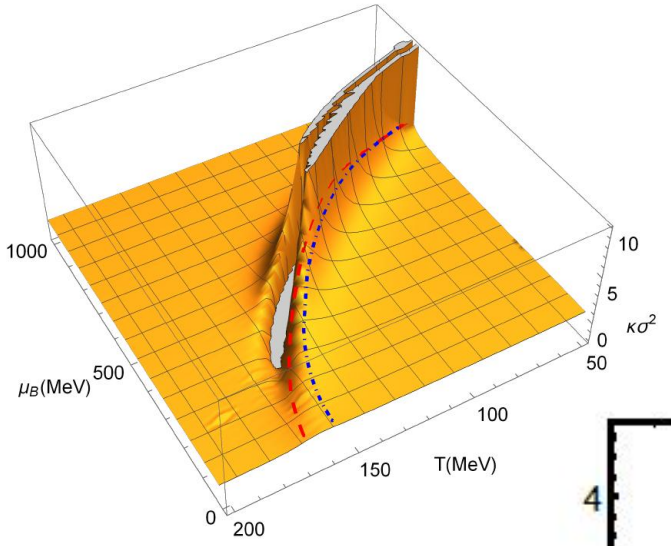
Polyakov loop:

$$\frac{U}{T^4} = -\frac{b_2(T)}{2}\bar{\Phi}\Phi - \frac{b_3}{6}(\Phi^3+\bar{\Phi}^3) + \frac{b_4}{4}(\Phi\bar{\Phi})^2$$

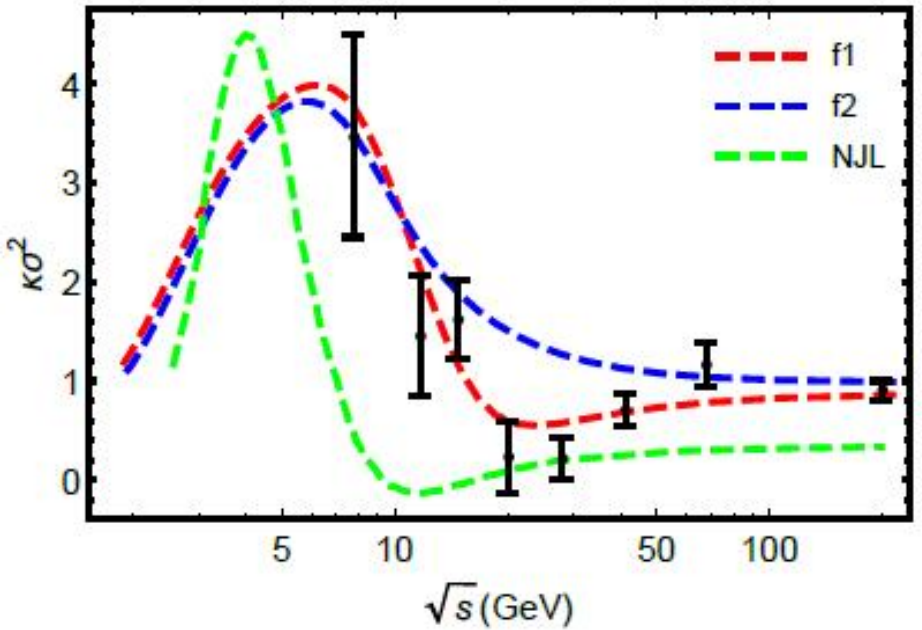
1, Fit model paraters with Lattice QCD EOS and baryon number susceptibility at zero chemical potential;
2,Predictions at finite baryon number chemical potential.

Critical End Point





Sensitivity of freeze out lines



Two freeze out lines fitted to BES-I data and other experimental data

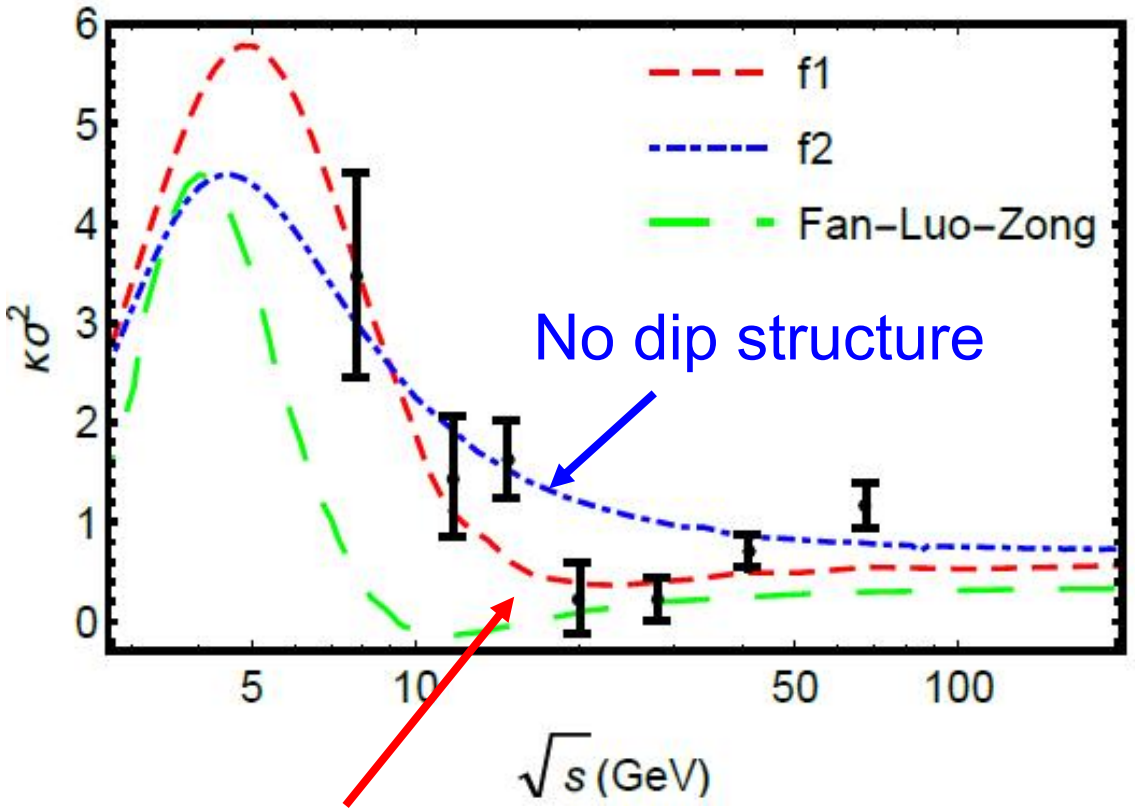
f1: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4 - 0.013(0.948 - \mu)^2$

f2: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4$ X. L—□ ∠∅⌓ N. X—, [∠◎X⊟⊔:1701.02105]

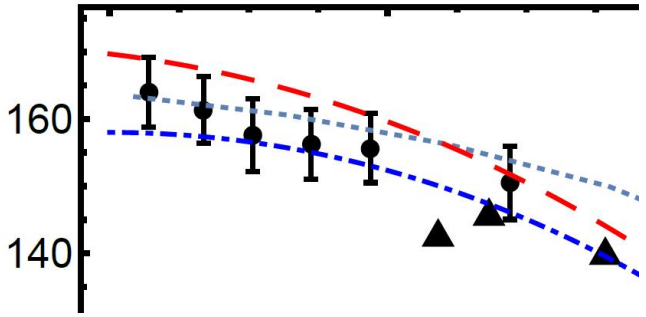
S. Das [STAR Collaboration], EPJ Web Conf. 90, 08007 (2015) arXiv:1412.0499 [nucl-ex]
V. V. Begun, V. Vovchenko and M. I. Gorenstein, J. Phys. Conf. Ser. 779, no. 1, 012080 (2017) [arXiv:1609.04827 [nucl-th]].

Z↗⊟⊥⊟∅ L⊟, K—∅ X—, X⊟∅▷∠∅/∅ W∠∅/∅ ∠∅⌓ M○⊟ H—∠∅/∅, ∠◎X⊟⊔:1801.09215, EPJC 2019

Kurtosis along freeze-out lines



Sensitivity of freeze out lines



f1 cross the phase boundary while f2 not!

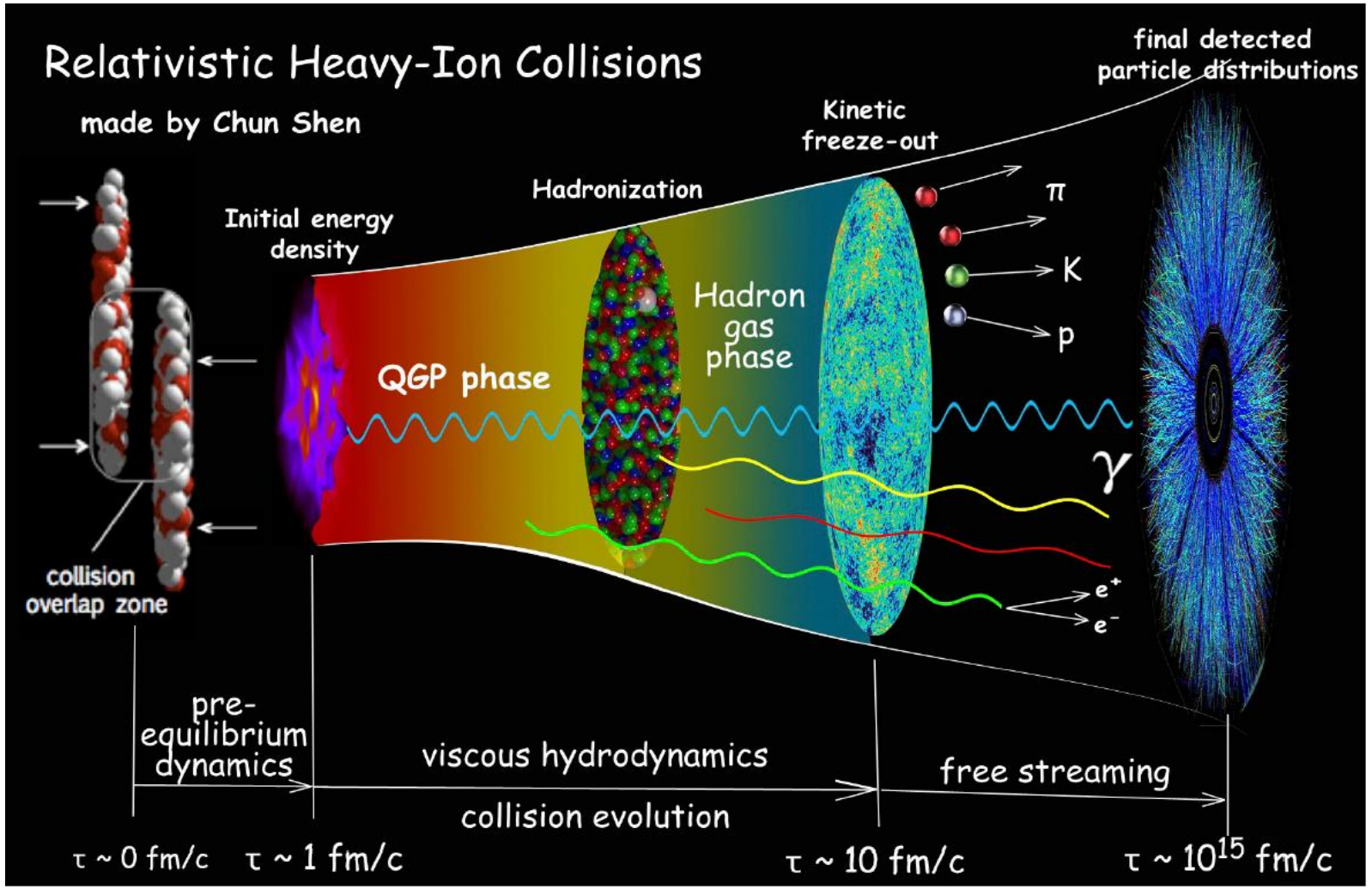
Z⇗⇌ ⊥⇌Ø L⇌, K—Ø X—,
X⇌Ø▷∠Ø/Ø W∠Ø/Ø
∠Ø⌓ M○⇌ H—∠Ø/Ø,
∠◎X⇌⊔:1801.09215

1、Agree well with BES-I data! --->equilibrium result can describe the experimental data!!!

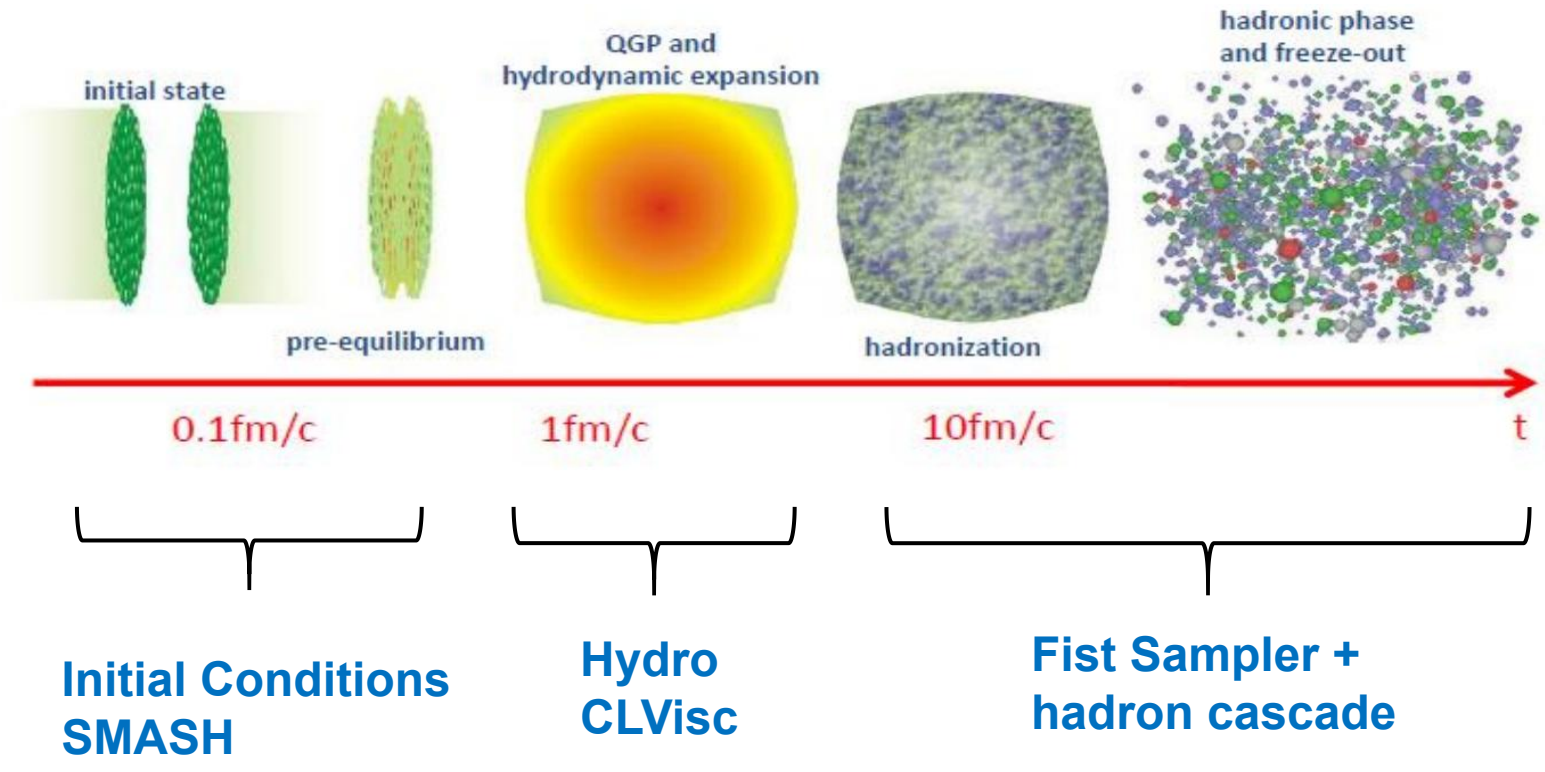
2、The dip structure is sensitive to the relation between the freeze-out line and the phase boundary

Relativistic Heavy-Ion Collisions

Relativistic heavy-ion collisions → hot QCD matter and its phase transition



Hybrid Model



Hydrodynamics (CLVisc)

Conservation laws of energy-monmentum and net baryon current：

$$\nabla_\mu T^{\mu\nu} = 0 \qquad \text{with} \qquad T^{\mu\nu} = eU^\mu U^\nu - P\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\nabla_\mu J^\mu = 0 \qquad \text{with} \qquad J^\mu = nU^\mu + V^\mu$$

$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta_v \sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma_\alpha^{\nu>} + \frac{9}{70}\frac{4}{e+p}\pi_\alpha^{<\mu}\pi^{\nu>\alpha}$$

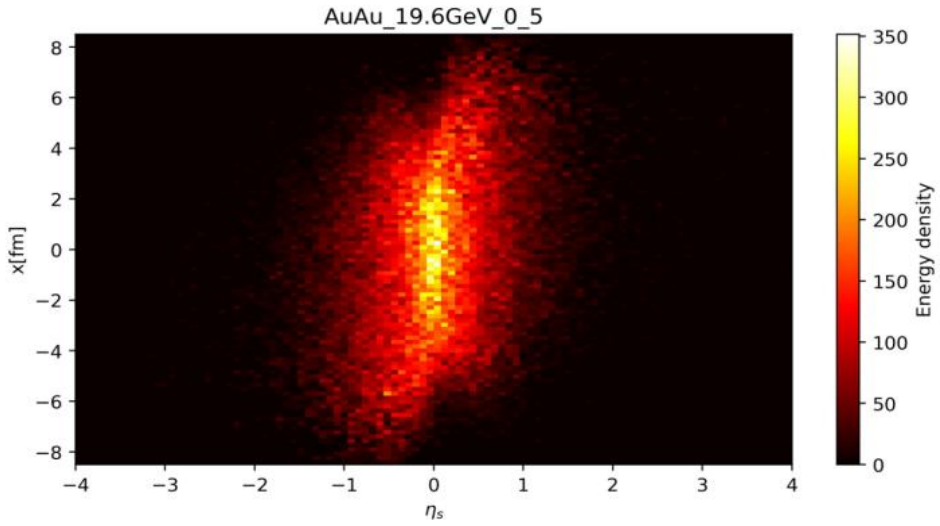
$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

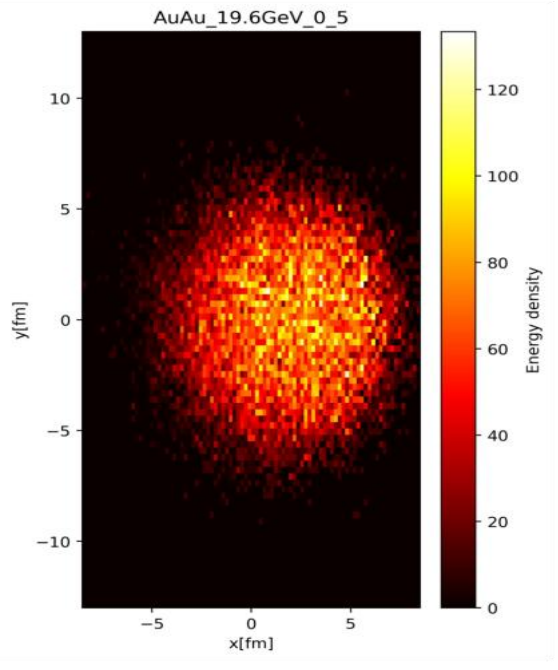
Input:
1. Initial conditions
2. EoS

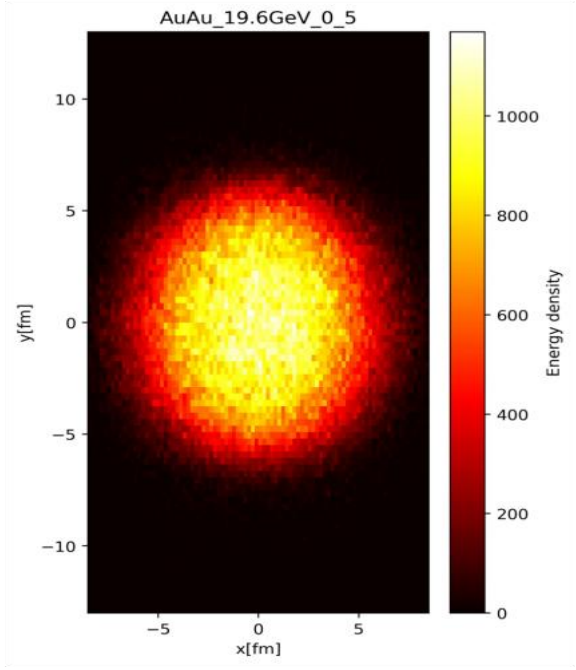
L.Pang et al, Phys.Rev. C86 (2012) 024911
L.Pang et al, Phys. Rev. C 97, 064918 (2018)
X.Wu et al, Phys. Rev. C 105, 034909 (2022)

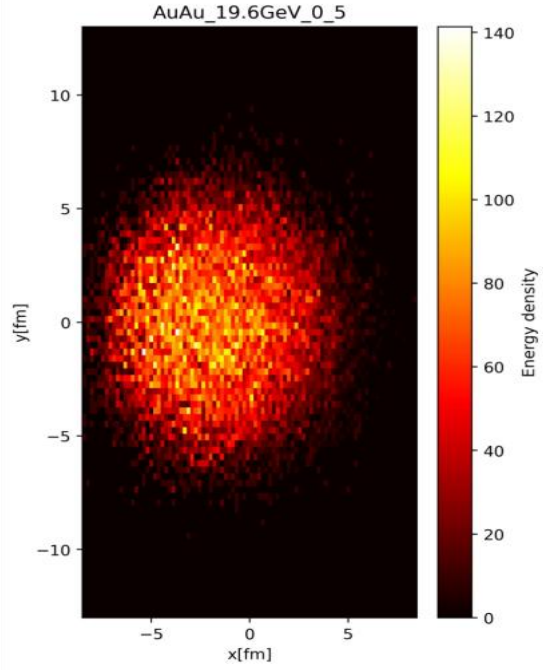
Initial Condition (SMASH)

J. Weil et al,
Phys. Rev. C 94, 054905 (2016)









SMASH as initial condition

energy density distribution at tau=1.22 fm in 0-5%Au+Au collision in 19.6GeV with different eta_s

1,EoS with CEP： Polyakov-loop-Nambu-Jona-Lasinio(PNJL) Model

Thermal Potential of PNJL Model:

Zhibin Li, Kun Xu, Xinyang Wang, Mei Huang. Eur.Phys.J.C 79 (2019) 3, 245

(μ_{Bc} = 720MeV, T_c= 93MeV)

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2, EOS without CEP： numerical equation of state (NEOS) with multiple charges: net baryon (B), strangeness (S) and electric charge (Q)(NEOS-BQS) based on the lattice QCD EoS from the HotQCD collaboration

Particlization

When the local energy density drops below the freezeout energy density (we set ef rz=0.4 GeV/fm3), the Cooper-Frye formula is used to obtain the momentum distribution of particles:

$$\frac{dN}{dY p_T dp_T d\phi} = \frac{g_i}{(2\pi)^3} \int_\Sigma p^\mu d\Sigma_\mu f_{eq} \left(1 + \delta f_\pi + \delta f_V\right)$$

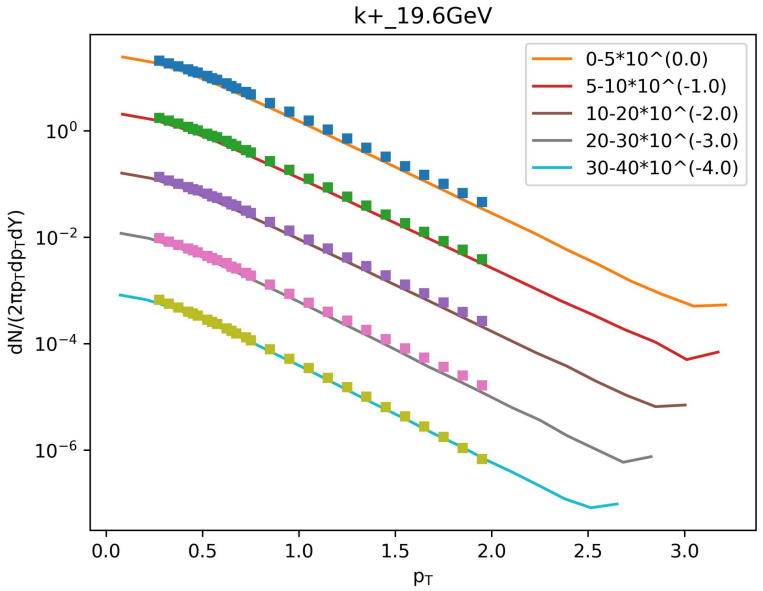
Use Thermal-FIST package, which maintains exact global conservation (under the canonical ensemble) of conserved charges, such as baryon number, electric charge, strangeness, and charm, to sample the momentum distribution of thermal hadrons

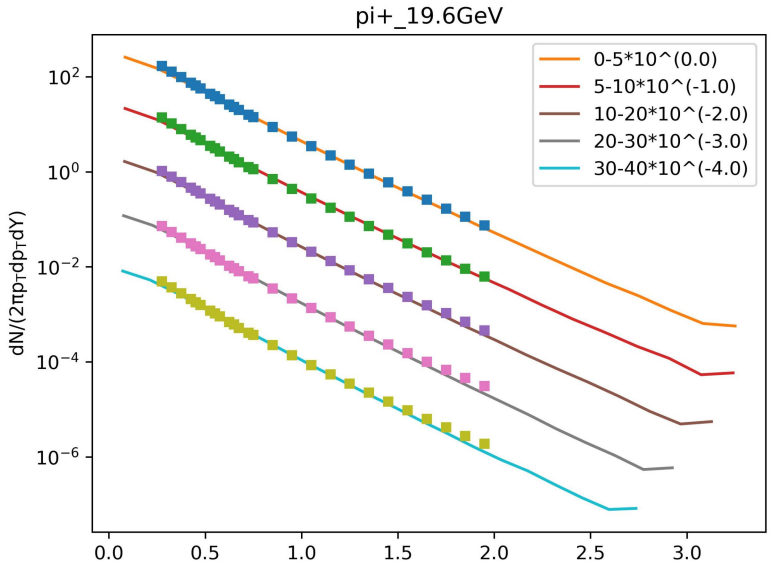
Parameters Table

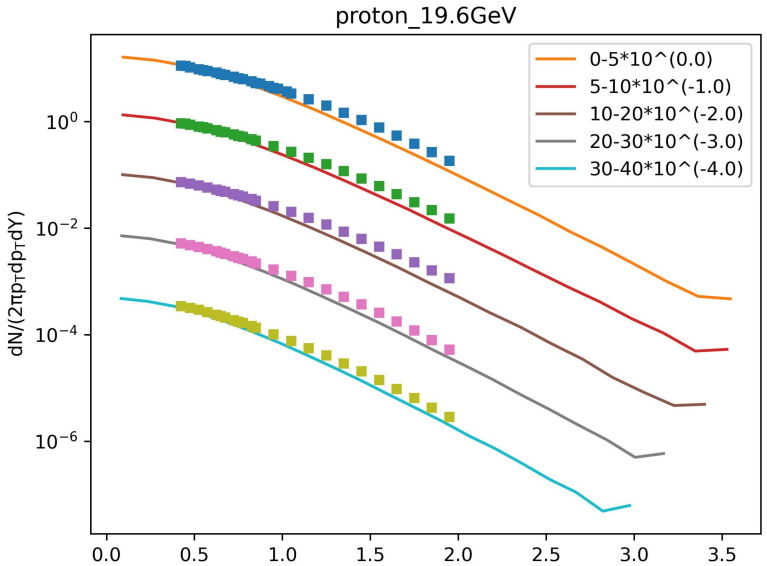
$\sqrt{s_{NN}}[GeV]$	$\tau_0[fm/c]$	$R_\perp[fm]$	$R_\eta[fm]$	η/s
7.7	3.2	1.4	0.5	0.2
14.5	1.65	1.4	0.5	0.2
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08

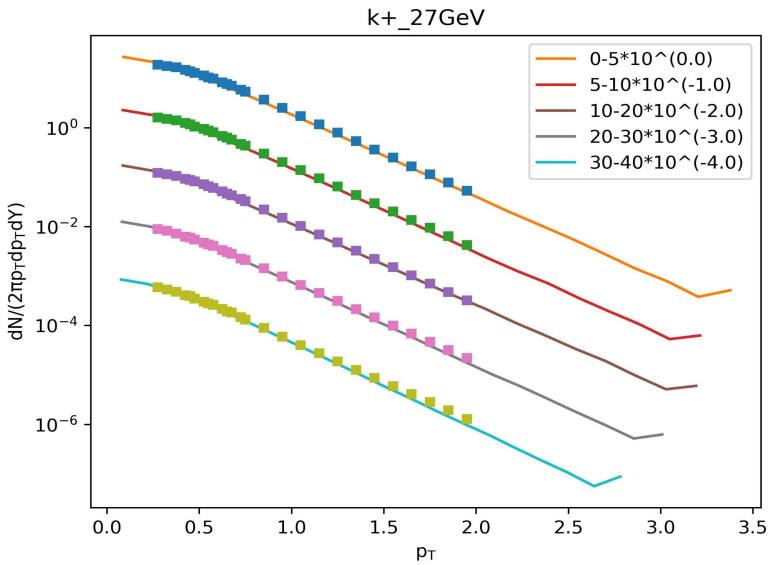
Identified particle spectra

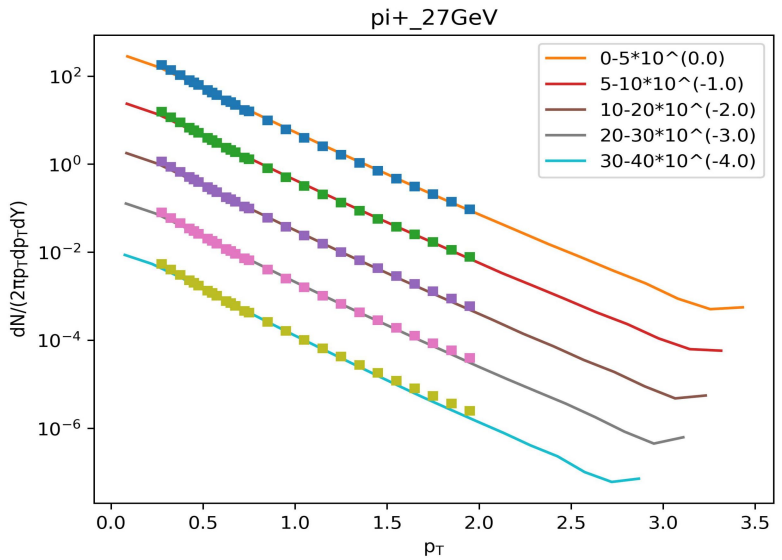
lines from simulation, points from STAR data,
and in agreement with experimental datas

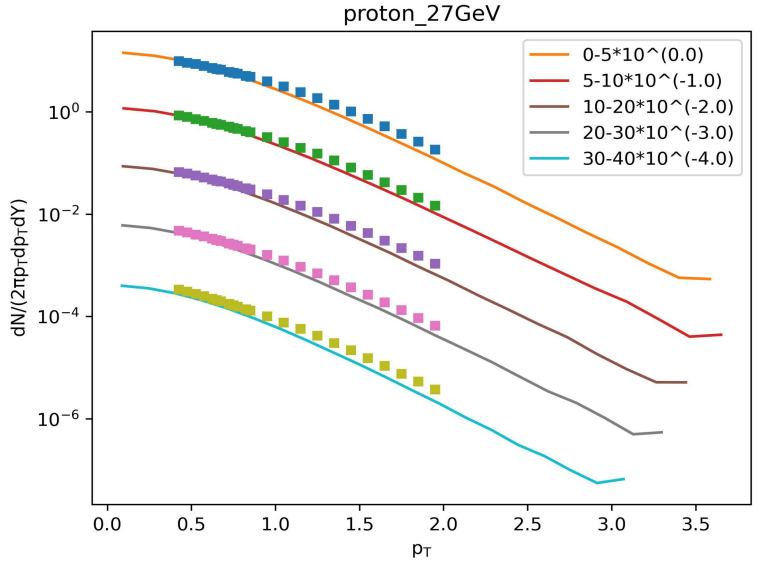






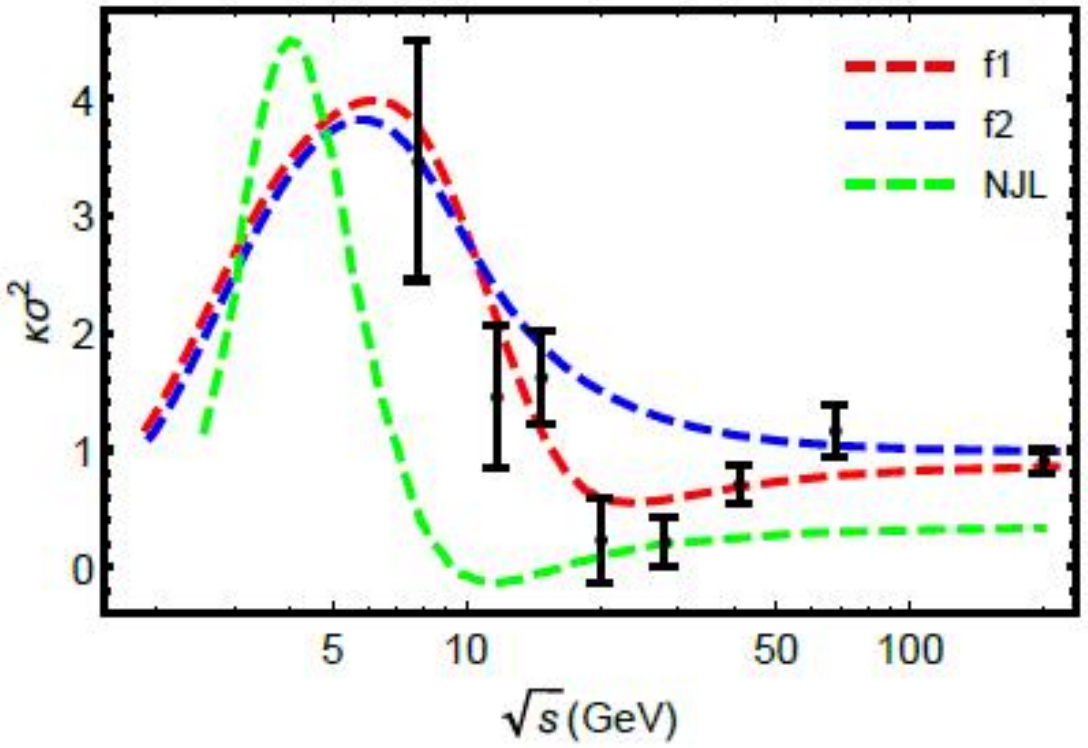


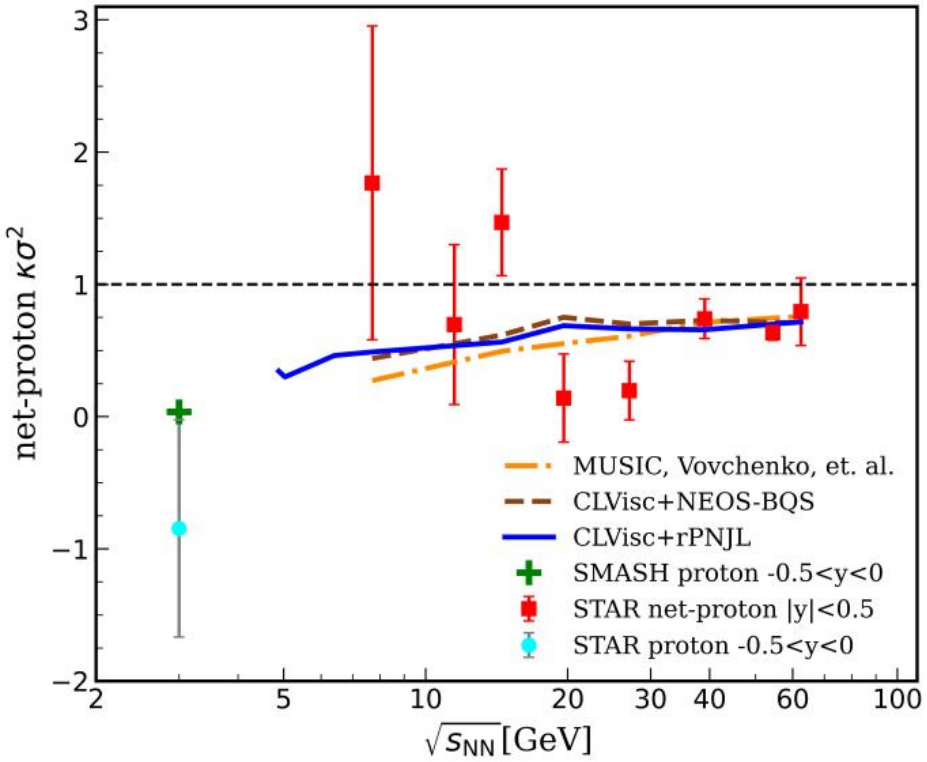




Disappearance of the peak structure and EOS independent!

Struggled several years!





Z⇗⇐ ⊥⇐∅ L⇐, K—∅ X—,
X⇐∅⊳ ∠∅⊘ W∠∅⊘ ∠∅⌓
M◯⇐ H—∠∅⊘,
∠◎X⇐⊔:1801.09215, EPJC 2019

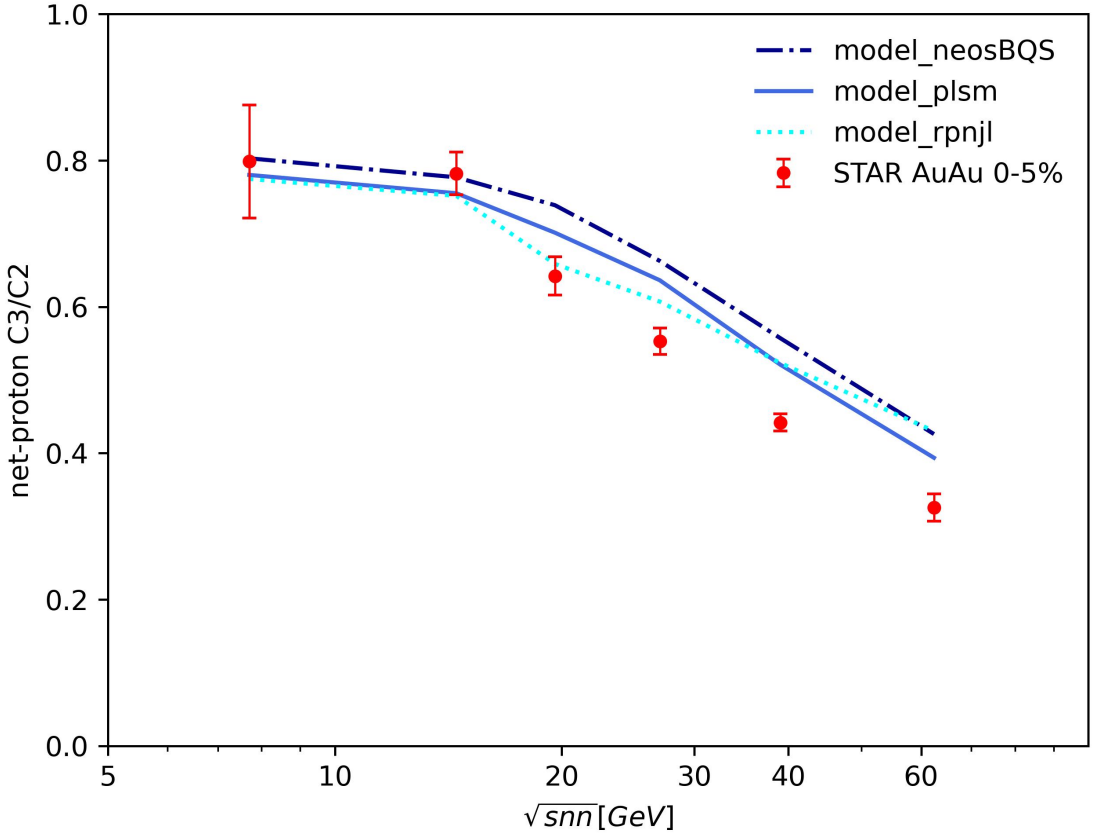
Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH, arXiv:e-Print: 2404.02397 [hep-ph]

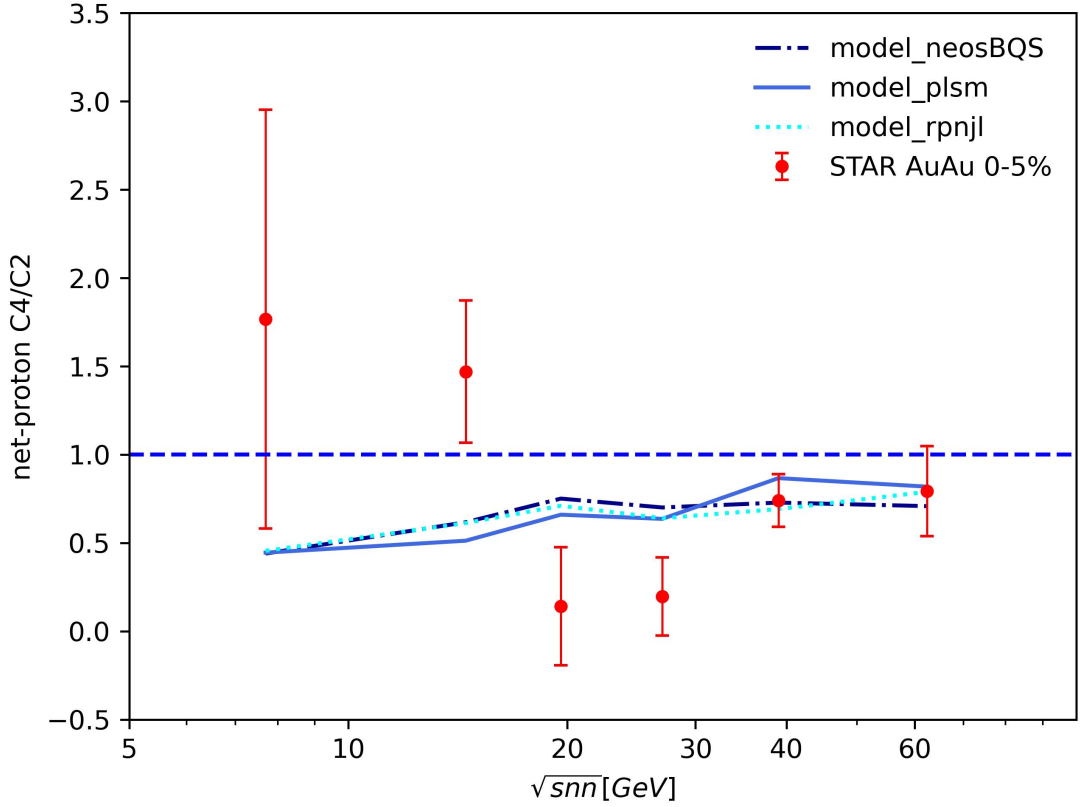
MUSIC: different hydrodynamics model

V. Vovchenko, V. Koch, and C. Shen, Phys. Rev.C 105, 014904 (2022)

Disappearance of the peak structure and EOS independent!

Central Au+Au Collisions





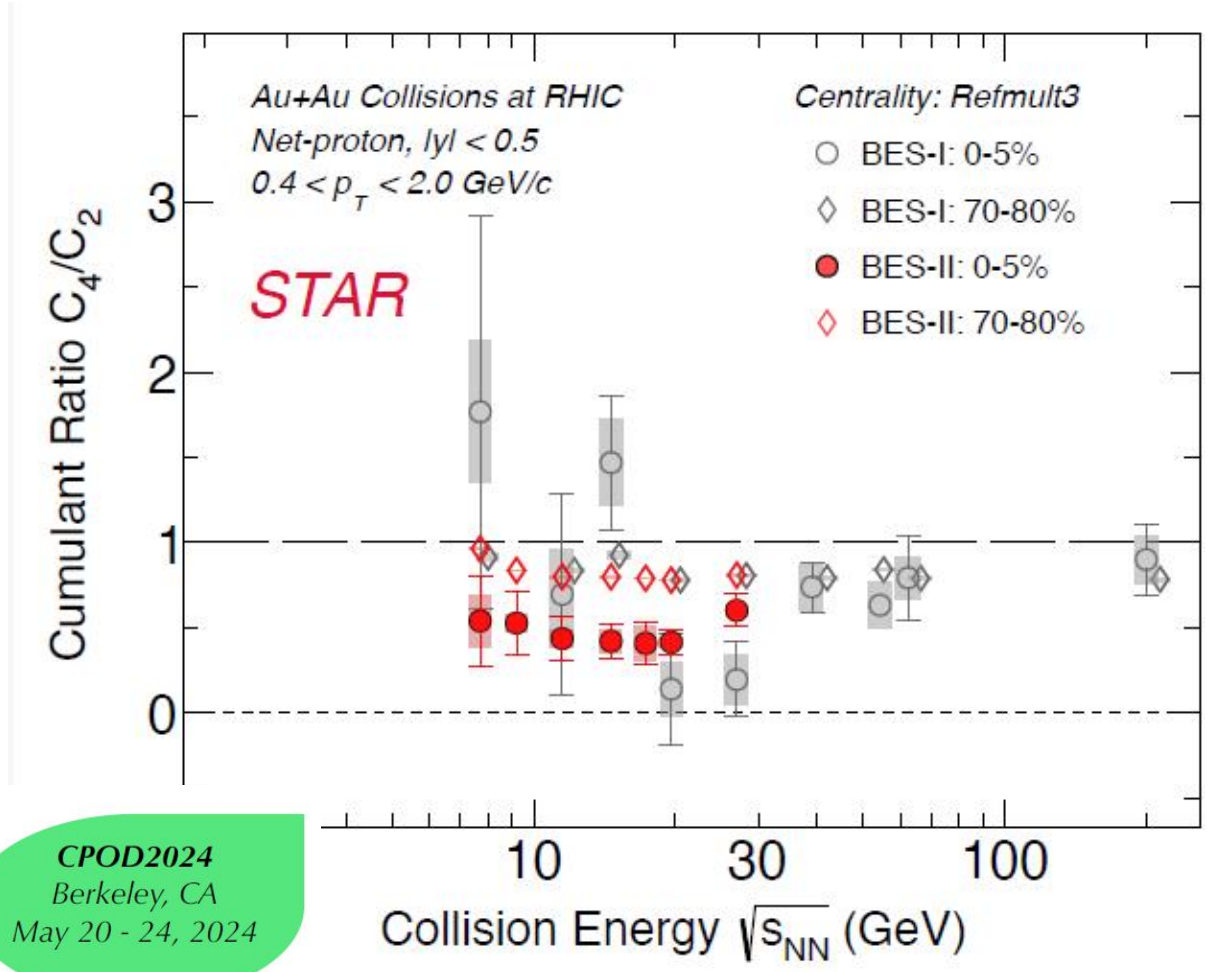
NEOS-BQS: cross-over without CEP

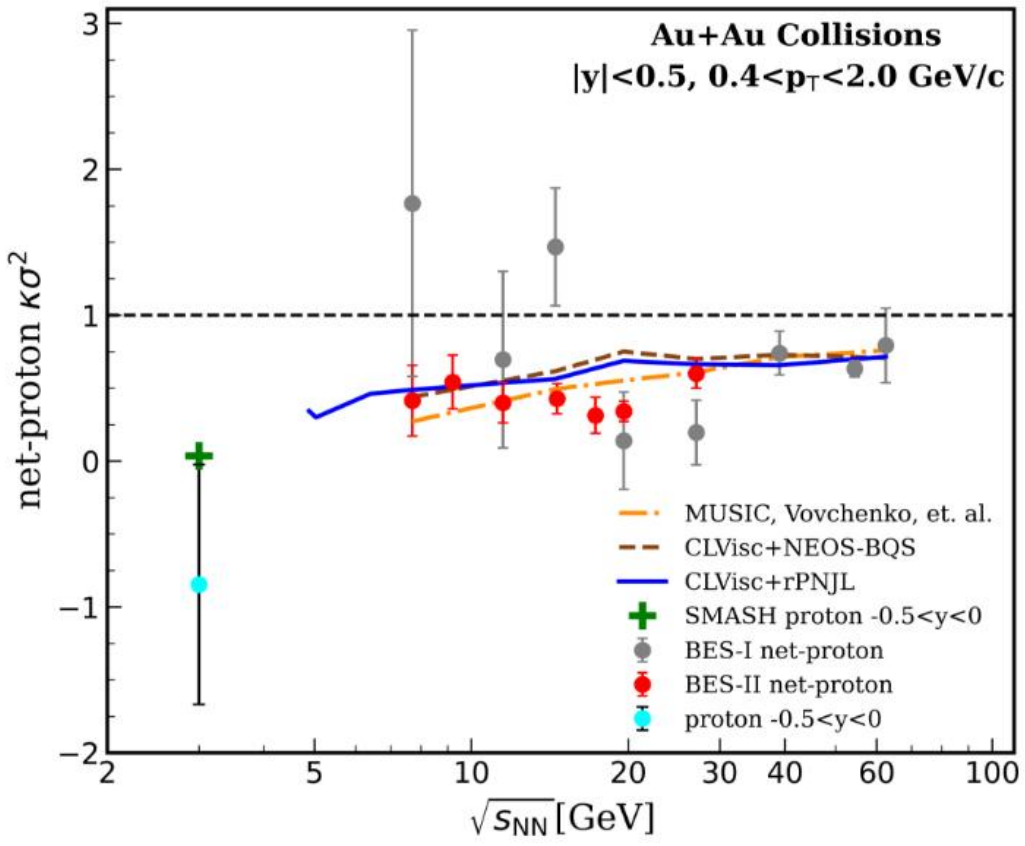
A. Monnai, B. Schenke, and C. Shen, Phys. Rev. C 100, 024907 (2019)

Polyakov linear sigma model: 1st phase transition **(μ_E = 139.5MeV, T_E= 188MeV)**

H. Mao, J.Jin, M.Huang, J.Phys.G37:035001,2010

Disappearance of the peak structure and EOS independent!



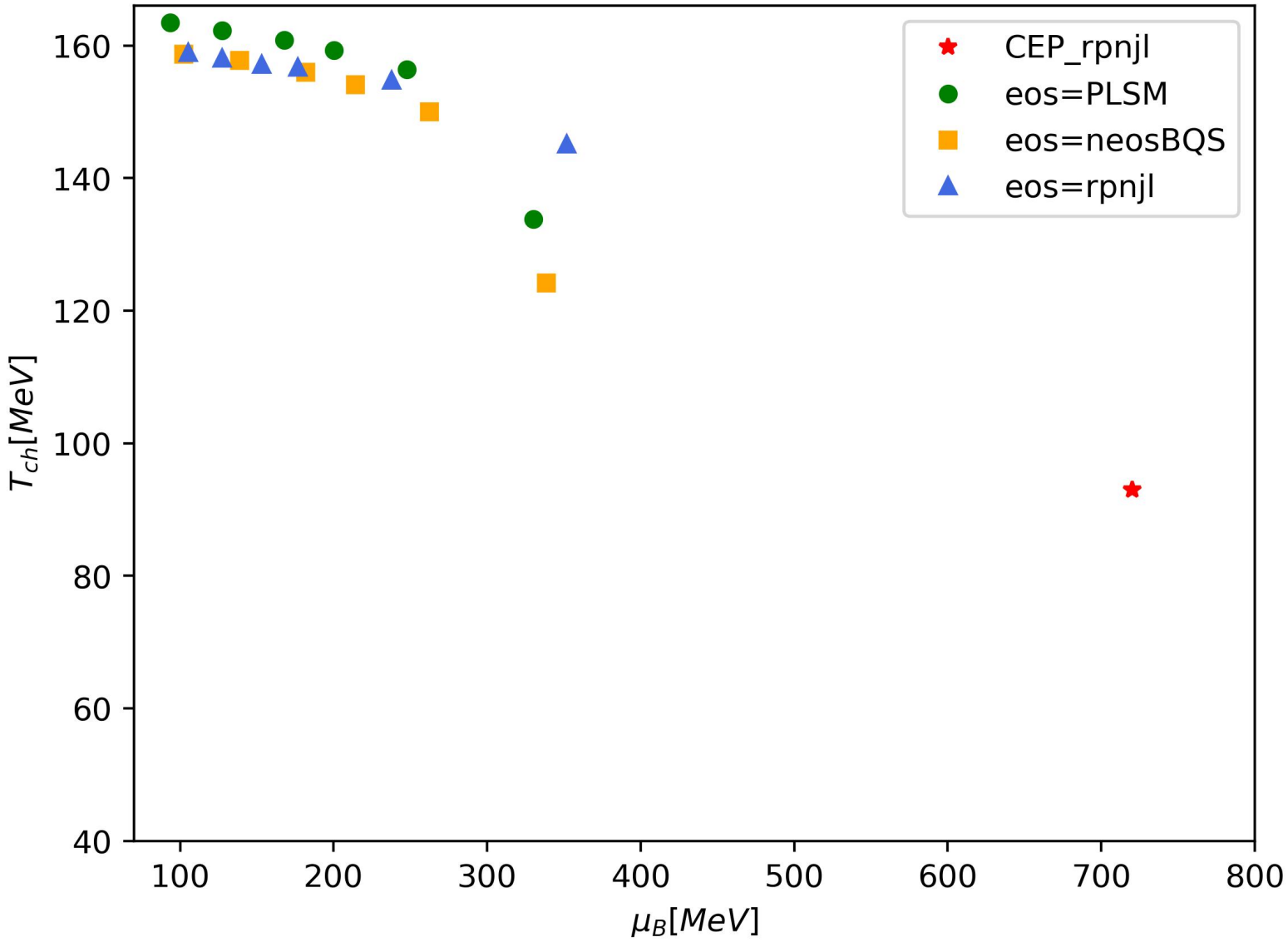


CPOD2024
Berkeley, CA
May 20 - 24, 2024

Ashish Pandav for STAR Collaboration
Lawrence Berkeley National Laboratory
May 21, 2024

Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH,
arXiv:e-Print: 2404.02397 [hep-ph]

Hydrodynamics including EoS with or w/o CEP



EoS from PNJL:

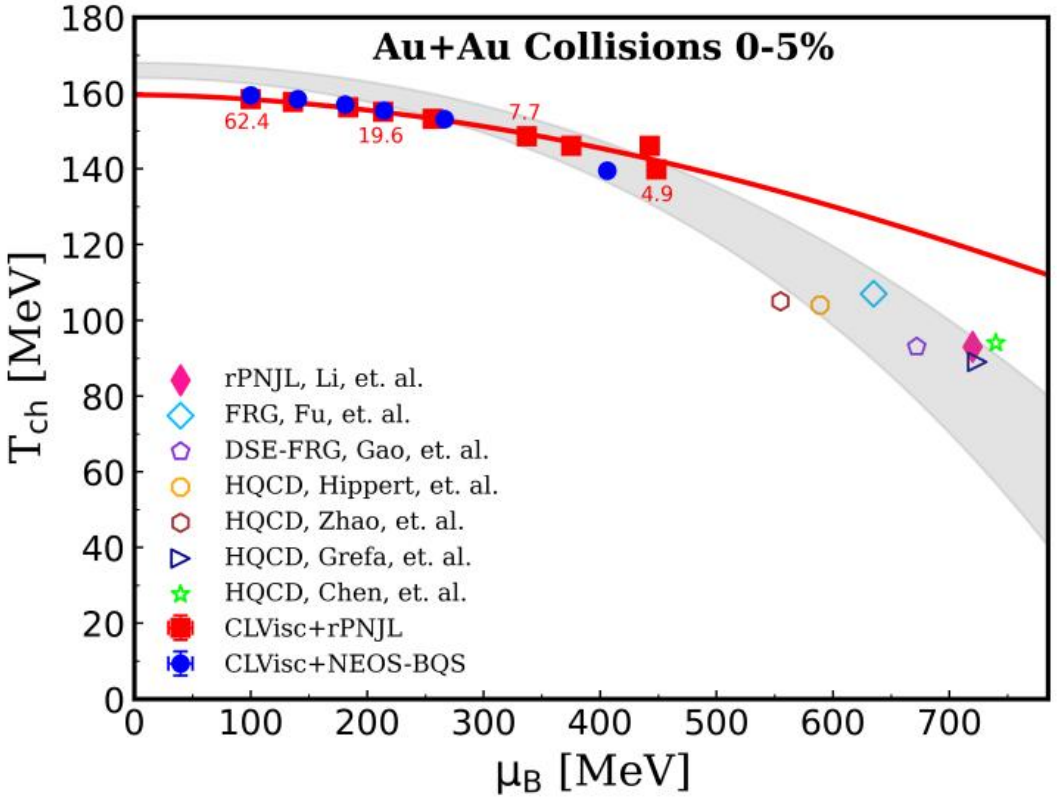
μ_{Bc} = 720MeV, T_c= 93MeV

EoS from PLSM:

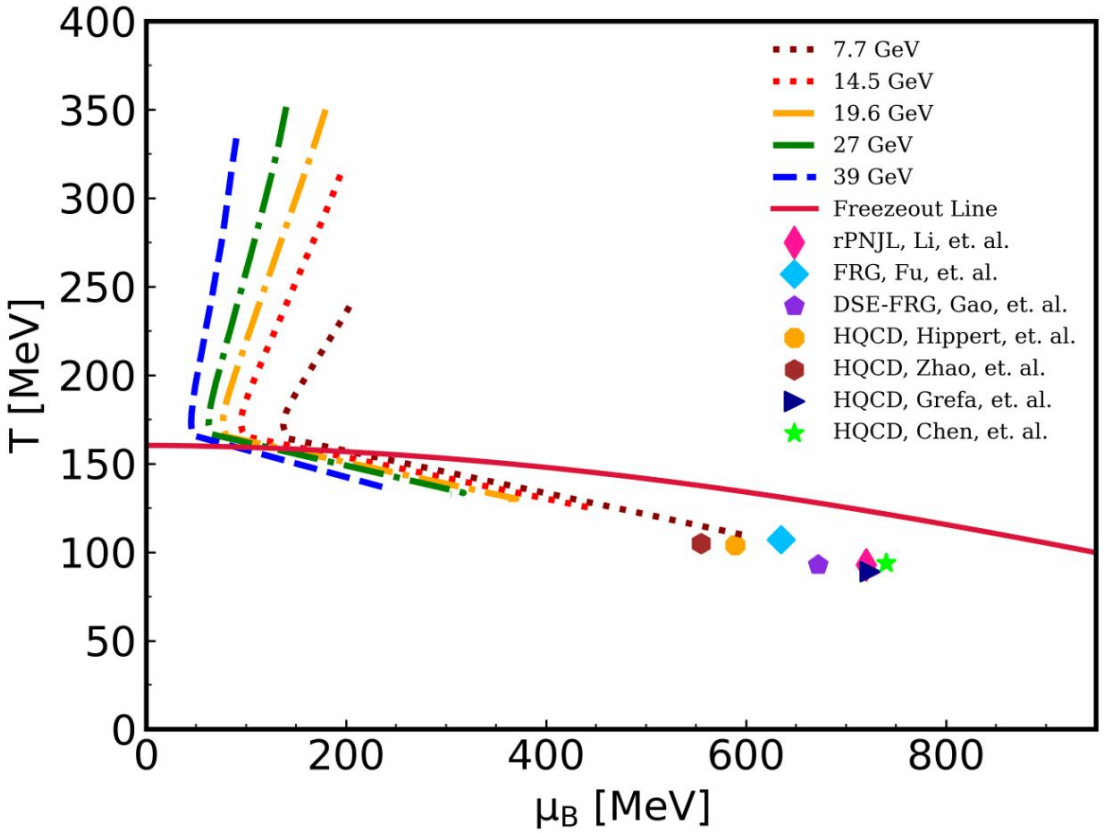
μ_E = 139.5MeV, T_E= 188MeV

To Far

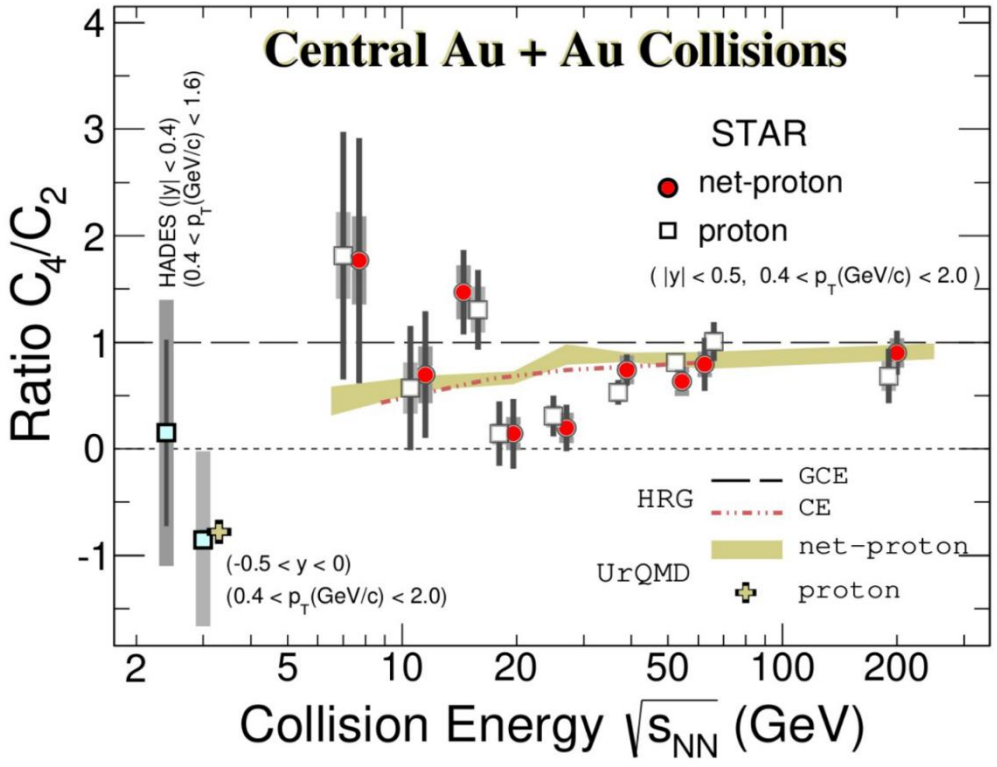
Signature washed out by hadronization?

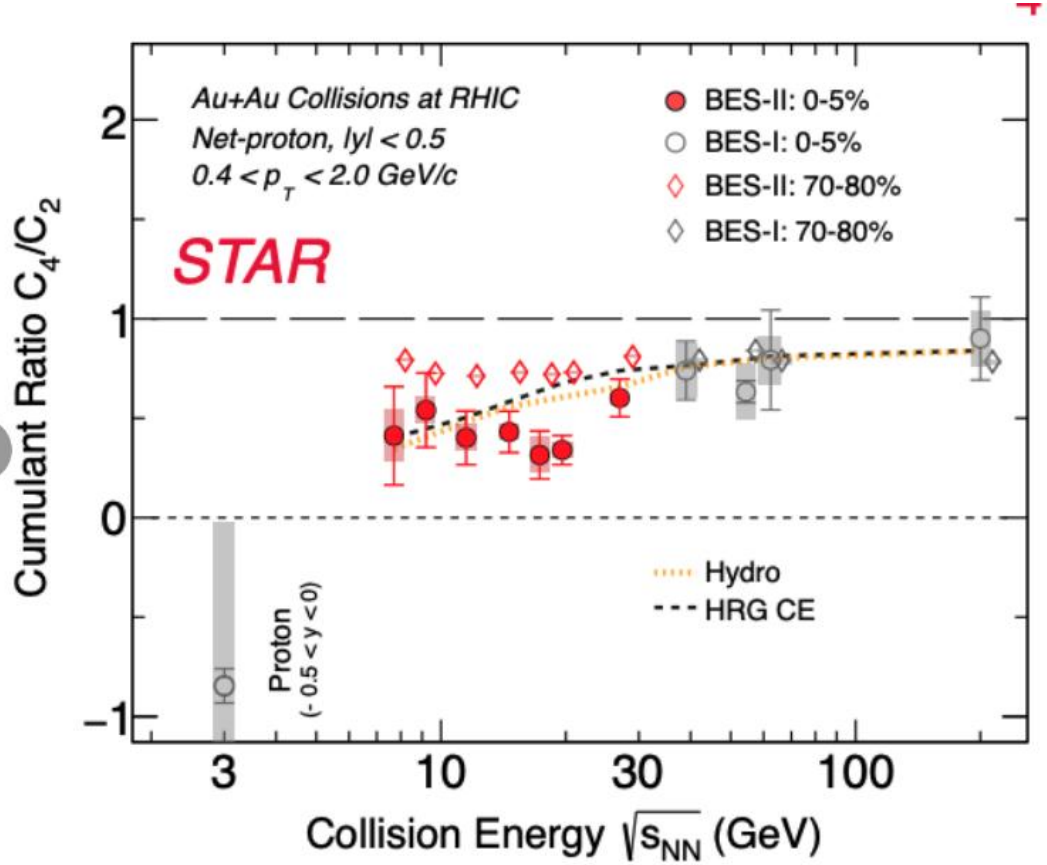


isentropic evolution line suggested by Horst Stoecker



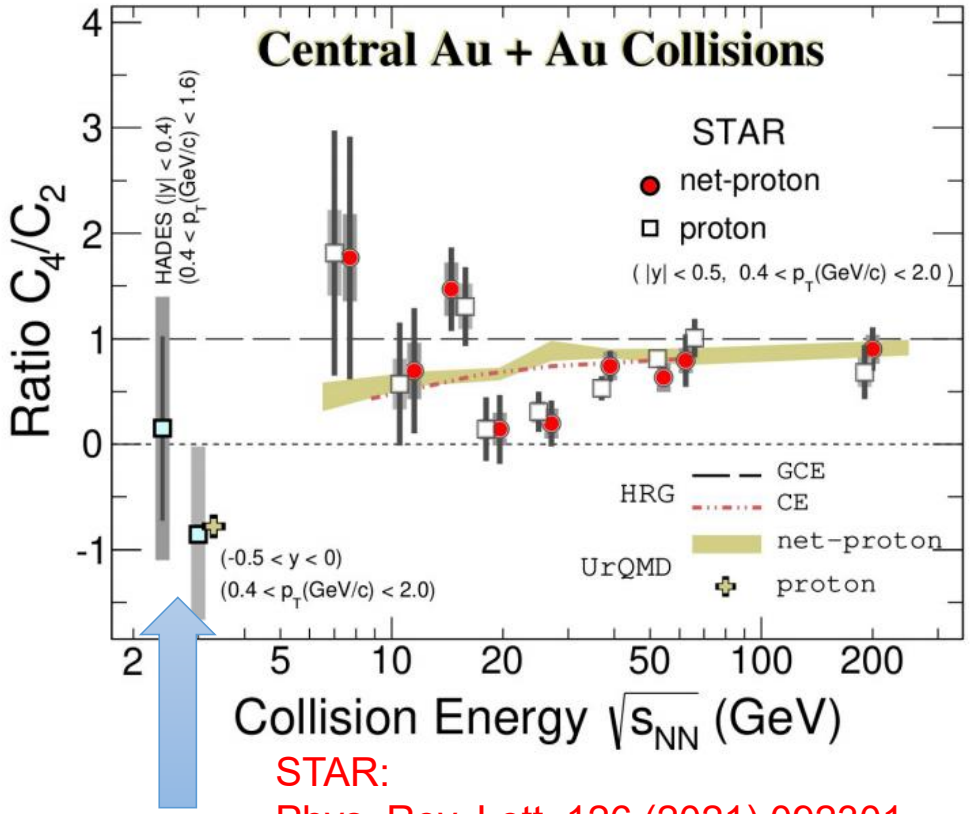
Disappearance of the peak structure!





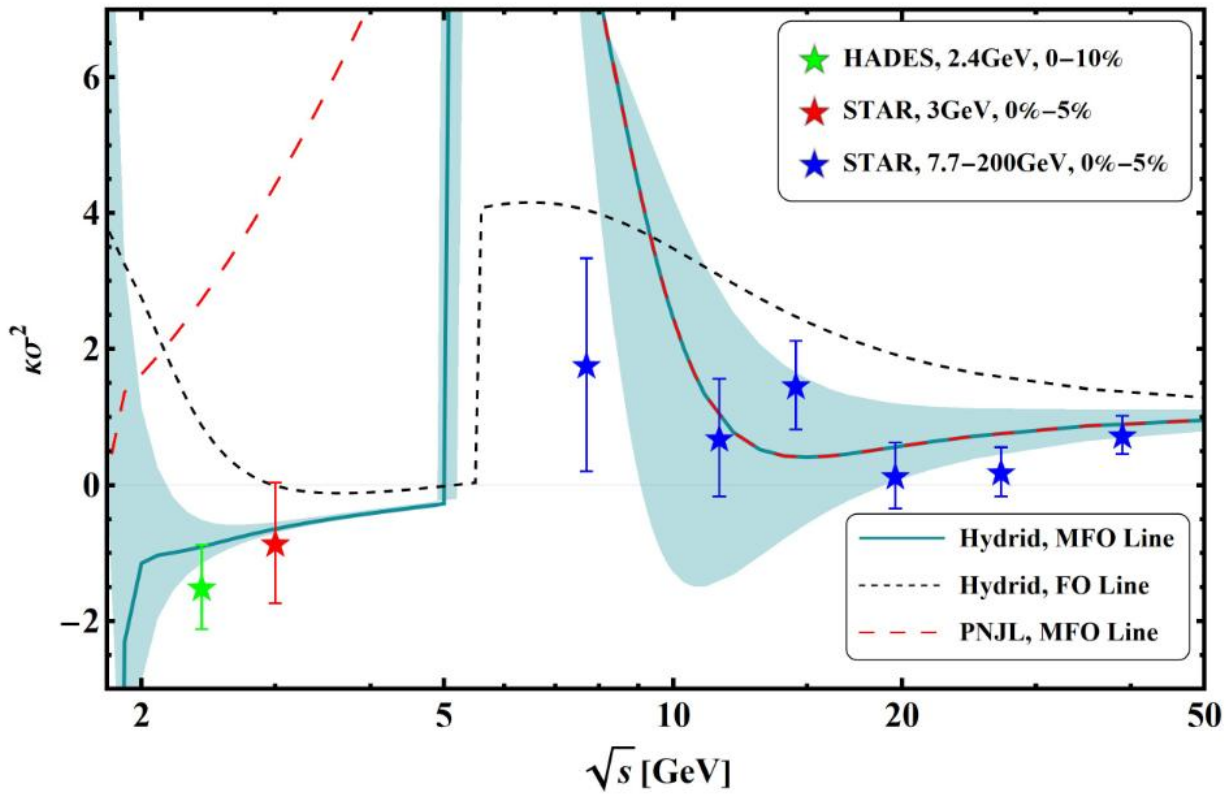
Outlook

Hydrodynamics simulation
+
EoS with liquid-gas phase



STAR:
Phys. Rev. Lett. 126 (2021) 092301
Phys. Rev. Lett. 128 (2022) 202303

Kun Xu, Mei Huang,
arxiv: 2307.12600



Kun Xu's Talk

Summary

1. Theoretical calculations from different methods give a convergent location of CEP on (T,mu) phase diagram

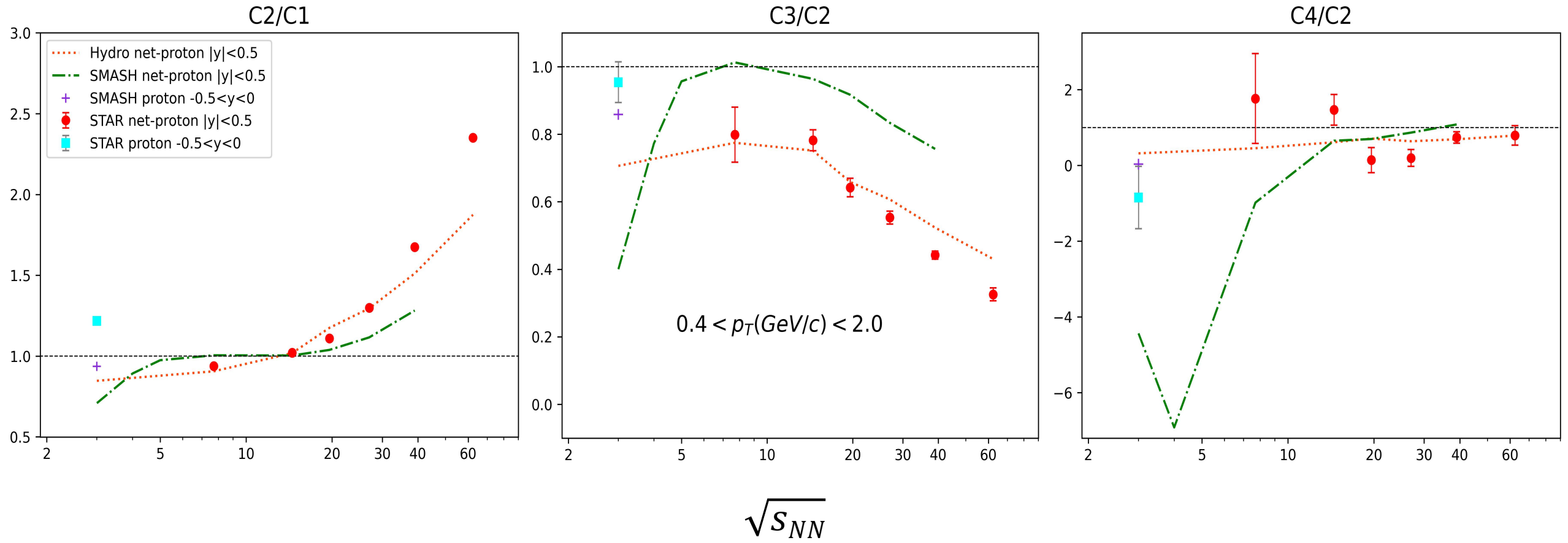
2. Considering hydro evolution of the real state of collisions, no exact signature of CEP is found, the results are no of EOS independent

3. Need extra work

Thanks for attention!

Different Evolutions (Hydro vs SMASH)

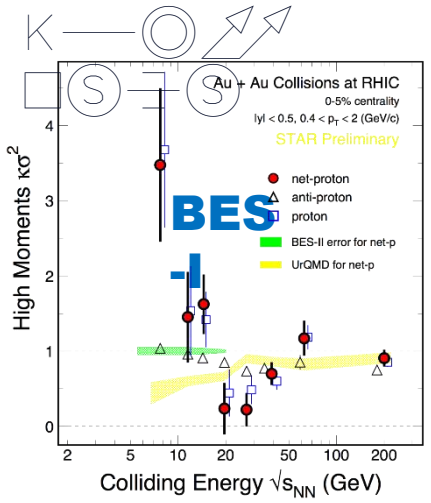
Central Au+Au Collisions



No fluctuation in low energy And from SMASH in low energy, values become minus

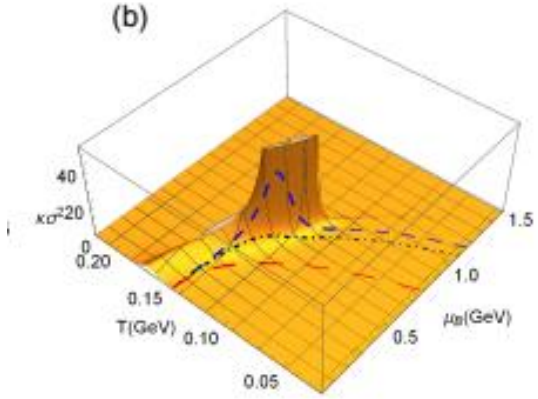
QCD phase structure at finite baryon chemical potential

CEP searching at HICs

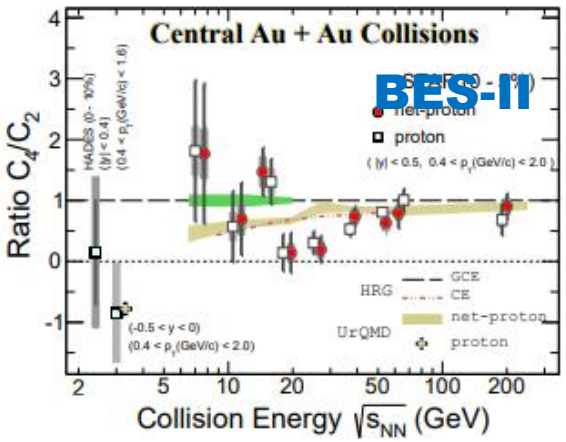


STAR: **PRL112**, 32302(14);

CEP of chiral phase transition

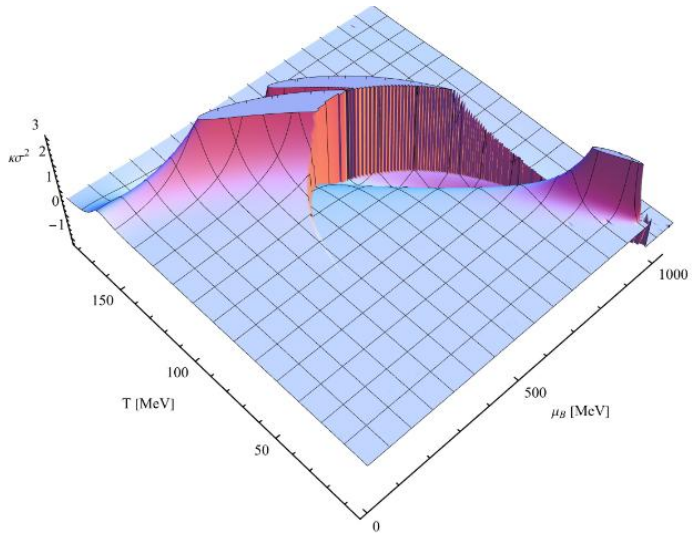


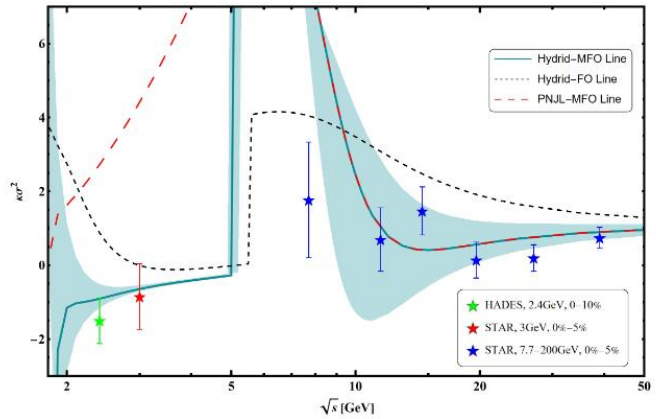
Z.B.Li et.al, Chin.Phys.C 42 (2018) 1, 013103； EPJC 79，2019



STAR: Phys. Rev. Lett. 128 (2022) 202303

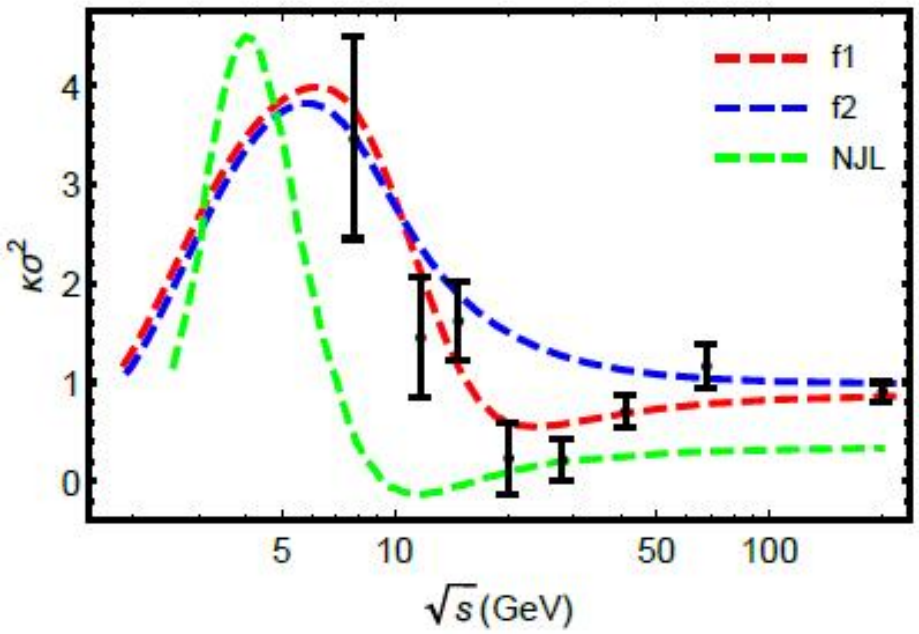
CEP of chiral phase transition meets CEP of nuclear liquid-gas phase transition!

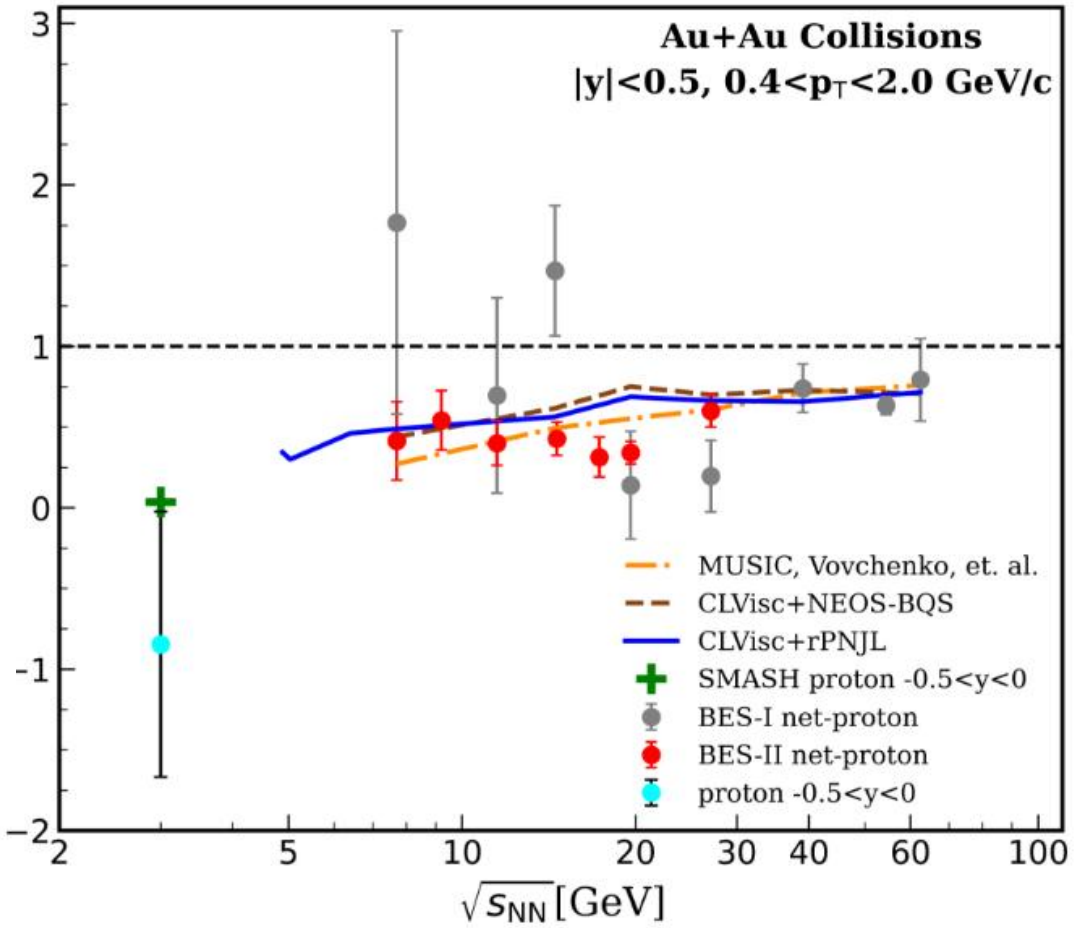




Kun Xu, Mei Huang, to appear soon

Disappearance of the peak structure and EOS independent!

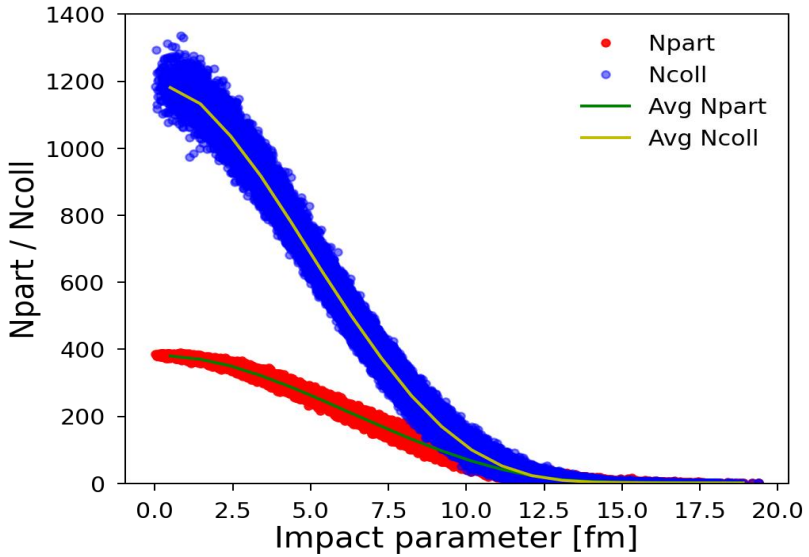




Z⇗⇐⊥⇐∅ L⇐, K—∅ X—, X⇐∅⊢▷∠∅/∅ W∠∅/∅ ∠∅⌓ M○⇐ H—∠∅/∅, ∠◎X⇐⊔:1801.09215, EPJC 2019

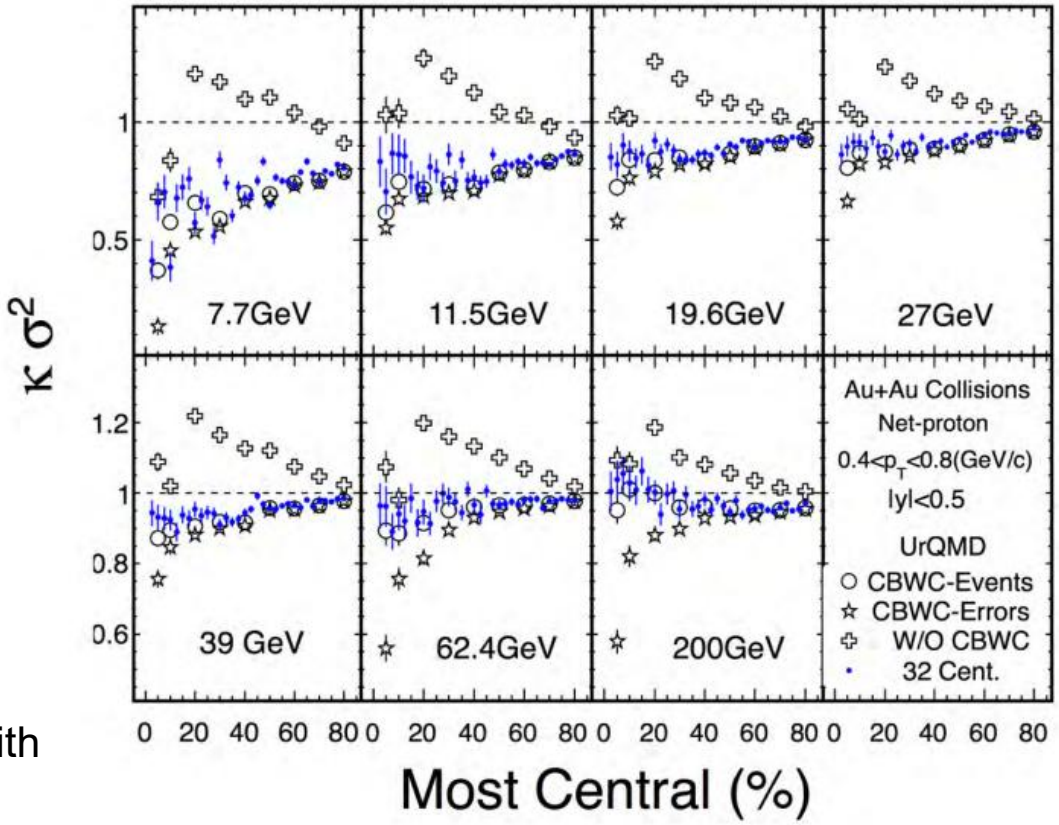
The centrality bin width correction

from Glauber model:



N_{part} ,N_{coll} have large fluctuation → Cumulants can be affected by events with different impact parameters/participants (volume fluctuations).

X.F.Luo, N.Xu, Nucl. Sci. Tech. 28, 112 (2017)



$$C_n = \frac{\sum_{r=N_1}^{N_2} n_r C_n^r}{\sum_{r=N_1}^{N_2} n_r} = \sum_{r=N_1}^{N_2} \omega_r C_n^r$$