University of Chinese Academy of Sciences

Searching for CEP at NICA?

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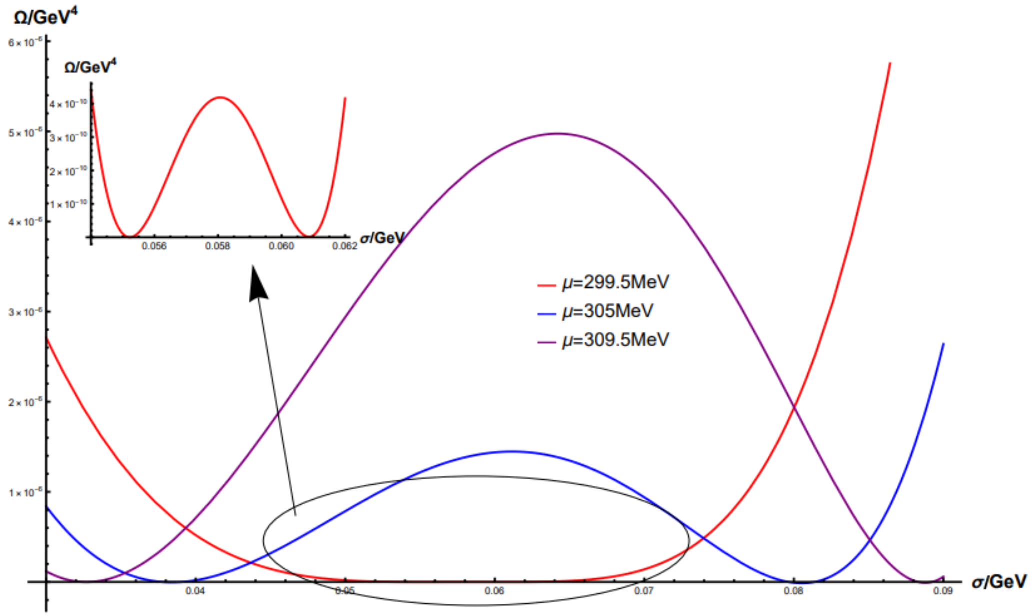
arXiv:e-Print: 2404.02397 [hep-ph]

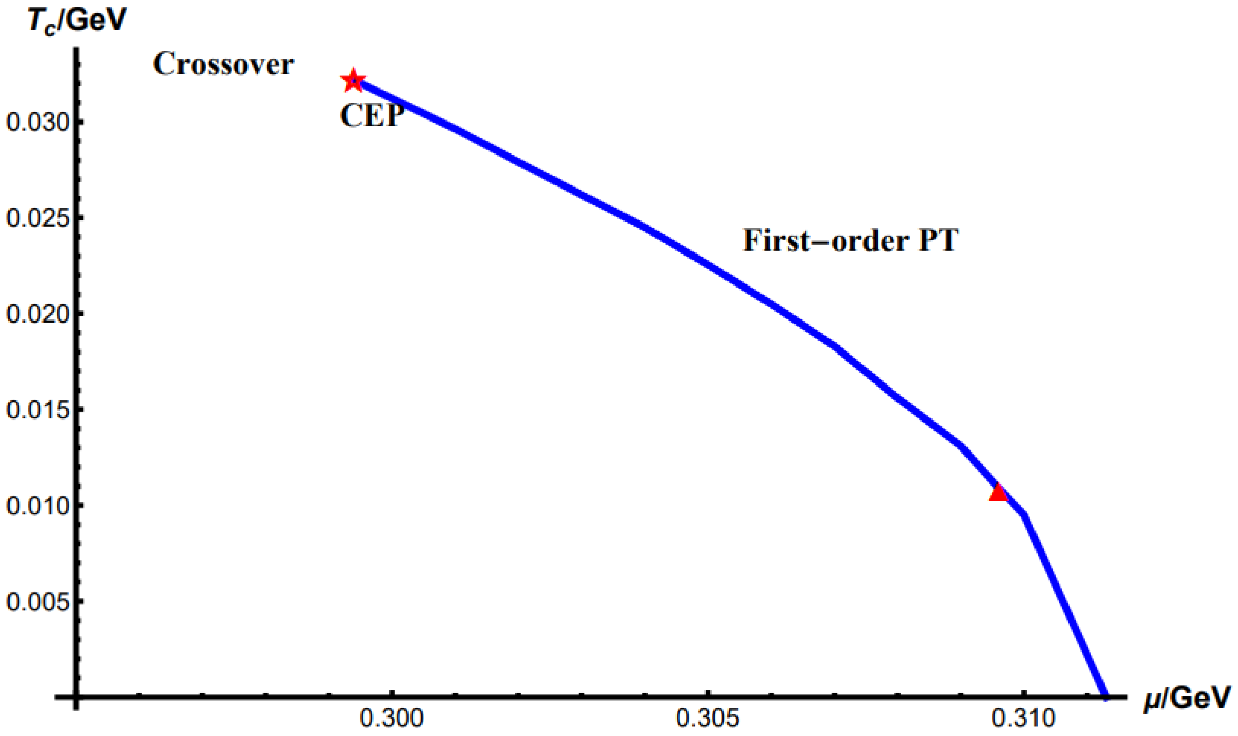
Collaborators: Yifan Shen, Wei Chen, Kun Xu, Xiangyu Wu

The 2nd China-Russia Joint Workshop on NICA Facility, Qingdao，Sep. 10-12, 2024

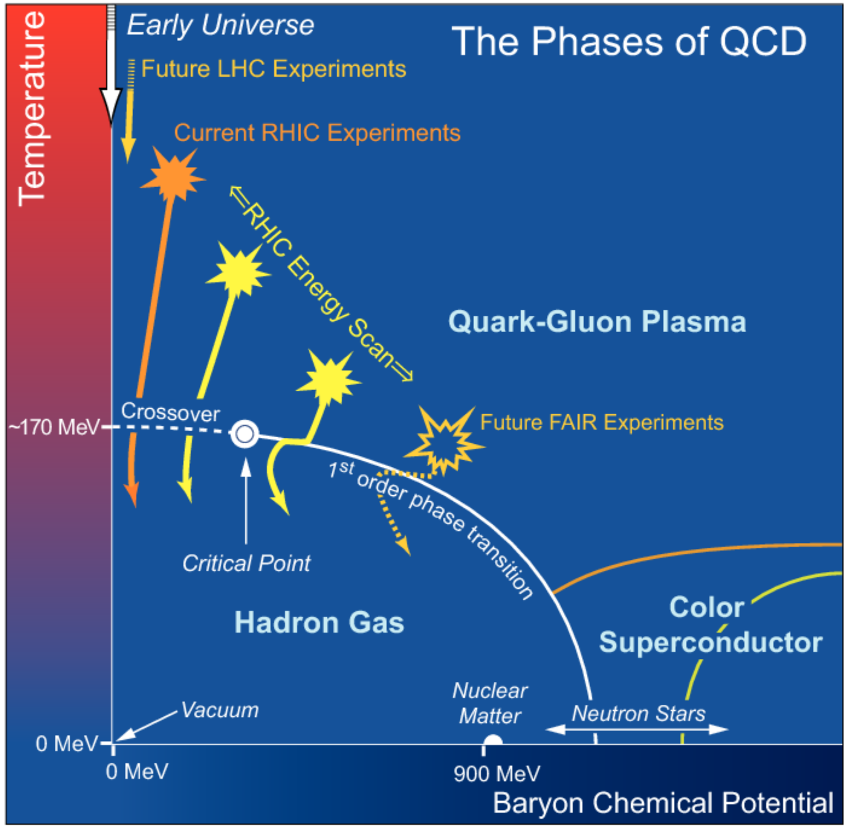
Existence of CEP at high baryon chemical potential

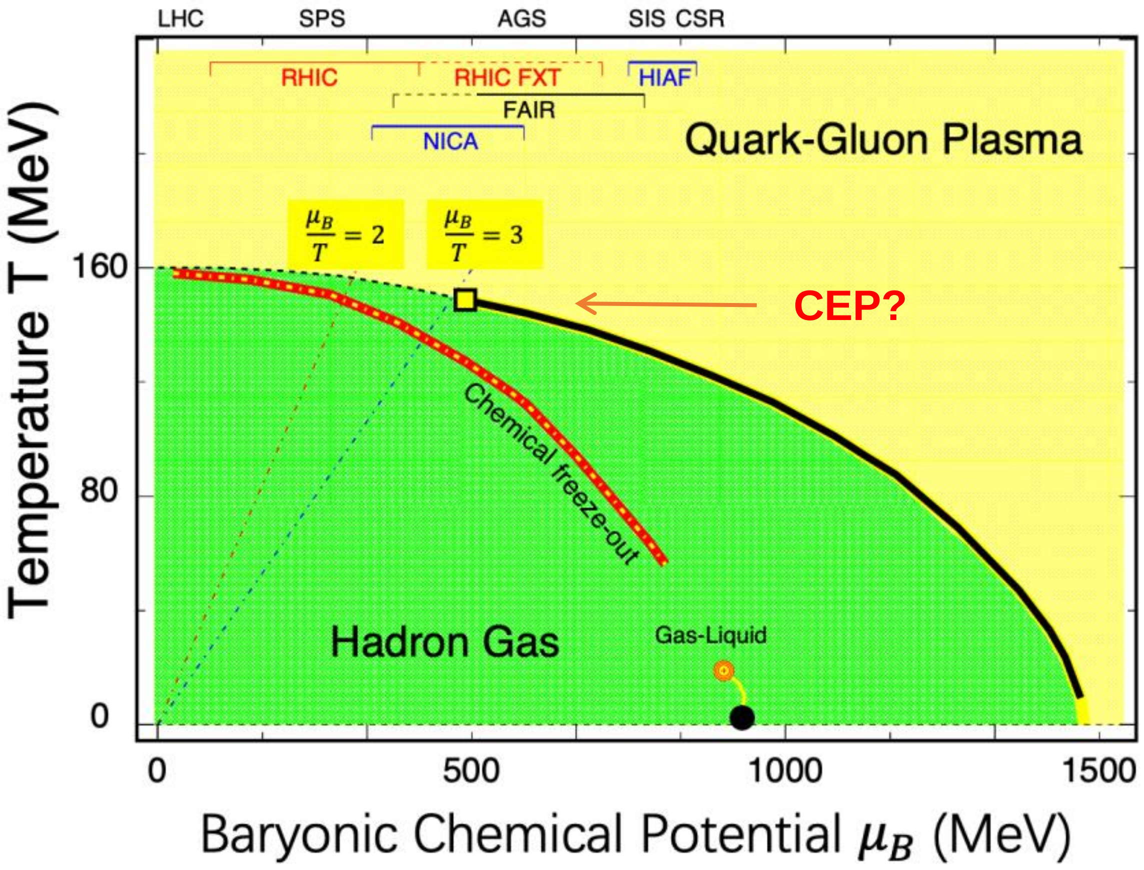


Barrier develops when mu increases, indicating 1st-order phase transition.



QCD phase diagram & searching for the CEP



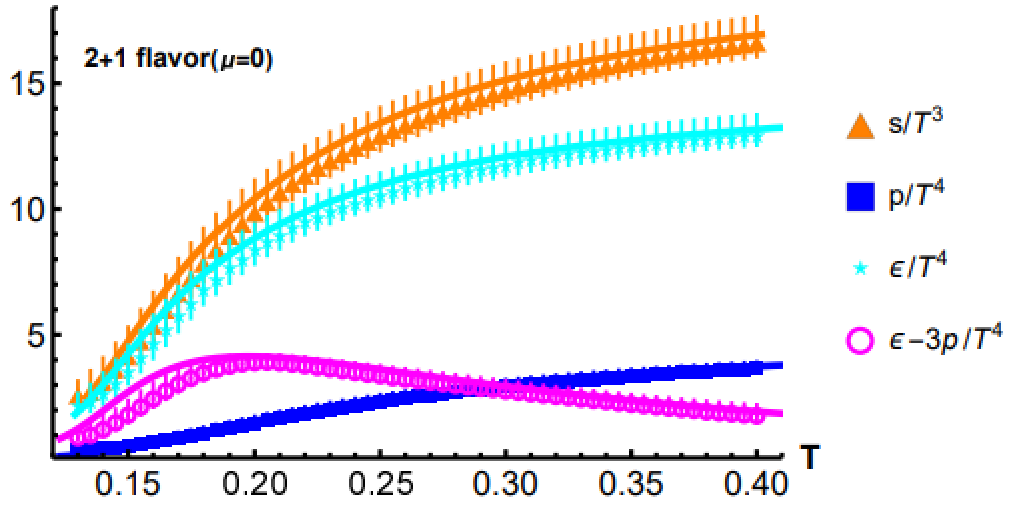


Theoretical predictions for the location of CEP

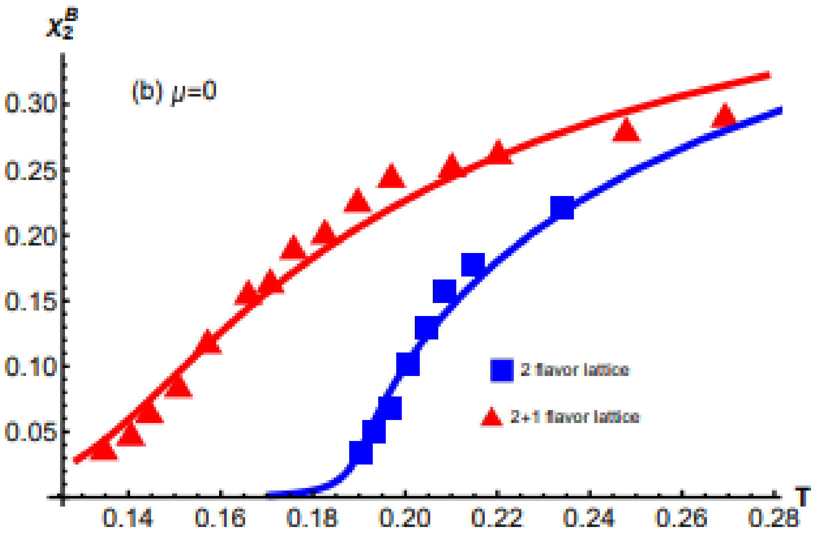
LQCD & nonperturbative theoretical calculations

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.



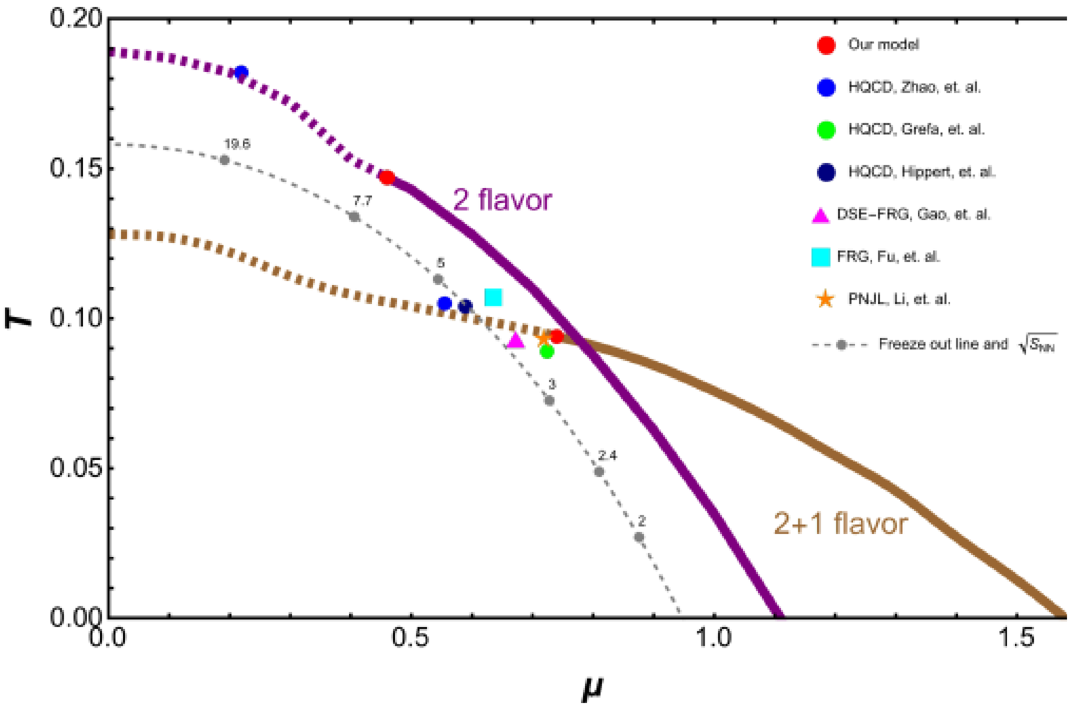
Determine Tc at mu=0

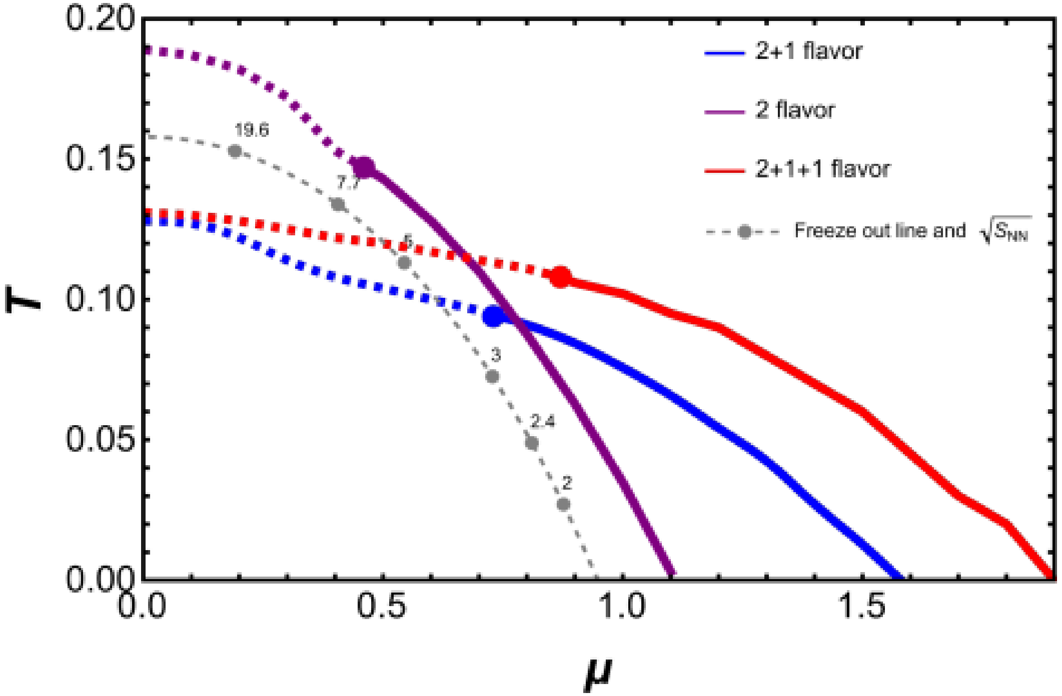


Determine mu dependent Tc

hQCD:Xun Chen, M.H., Phys.Rev.D 109 (2024) 5, L051902, e-Print:2401.06417

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





hQCD:Xun Chen, M.H., Phys.Rev.D 109 (2024) 5, L051902, e-Print:2401.06417 [hep-ph];e-Print: 2405.06179 [hep-ph]

J. Grefa, J. Noronha, J. Noronha-Hostler, I. Portillo, C. Ratti, and R. Rougemont, Phys. Rev. D 104, 034002 (2021), arXiv:2102.12042 [nucl-th]; M. Hippert, J. Grefa, T. A. Manning, J. Noronha, J. Noronha-Hostler, I. Portillo Vazquez, C. Ratti, R. Rougemont, and M. Trujillo (2023) arXiv:2309.00579 [nucl-th], Y.-Q. Zhao, S. He, D. Hou, L. Li, and Z. Li, JHEP 04, 115 (2023), arXiv:2212.14662 [hep-ph]

rPNJL:Zhibin Li, Kun Xu, Xinyang Wang and MH, arXiv:1801.09215

DSE-fRG: *F. Gao and J. M. Pawlowski, Phys. Rev. D 102, 034027 (2020), arXiv:2002.07500 [hep-ph].*

fRG:W.-j. Fu, J. M. Pawlowski, and F. Rennecke, Phys. Rev. D 101, 054032 (2020), arXiv:1909.02991 [hep-ph].

Net proton number fluctuations near critical point

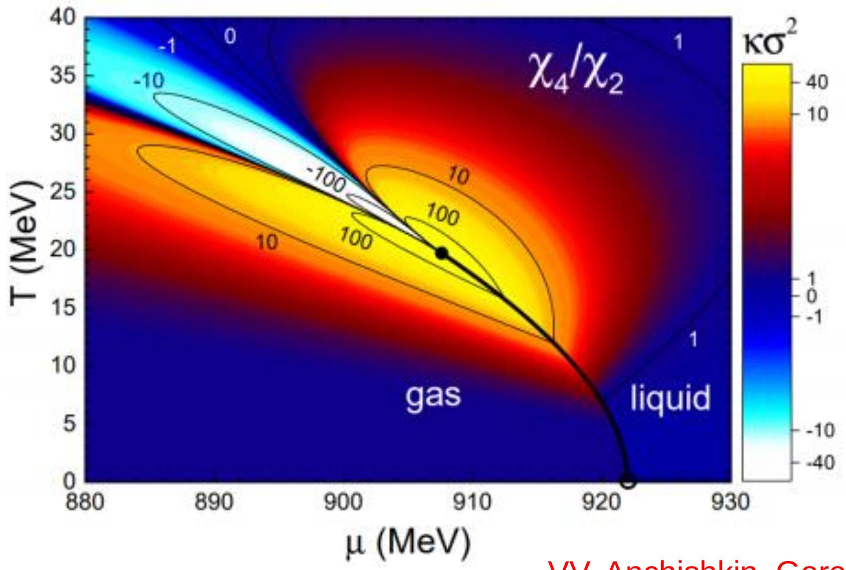
$$K_N = \ln(e^{tN}) = \sum_{n=1}^{\infty} k_n \frac{t^n}{n!}$$

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

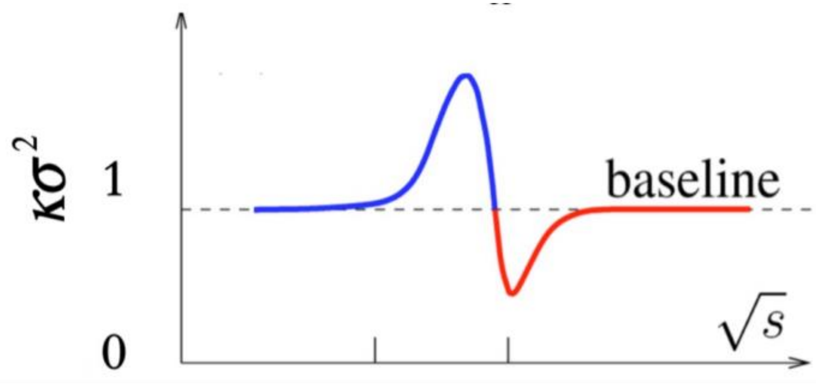
$$k_n \propto \frac{\partial^n(\ln Z^{gce})}{\partial \mu^n}$$

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

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



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



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

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:

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

Effective mass:

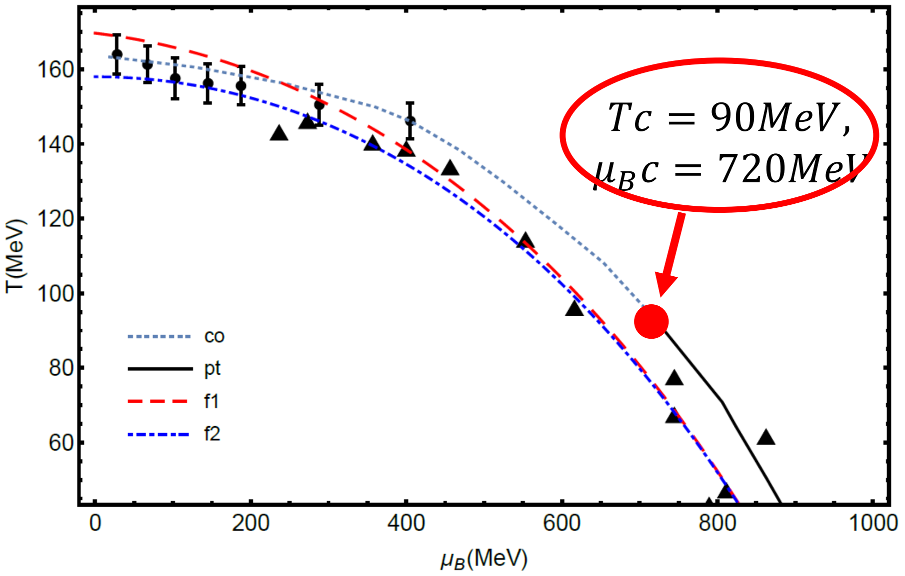
$$M_f = m_f - 2g_s\sigma_f + \frac{g_D}{4}\sigma_{f+1}\sigma_{f+2} - 2g_1\sigma_f(\textstyle\sum_{f'}\sigma_{f'}^2) - 4g_2\sigma_f^3$$

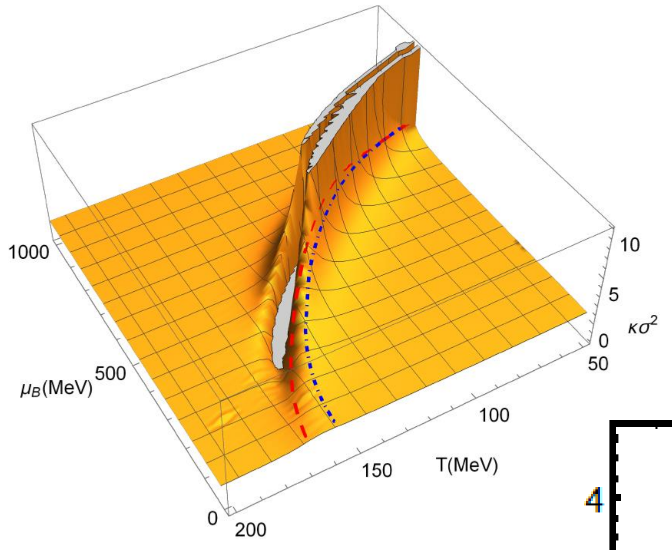
Polyakov loop:

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

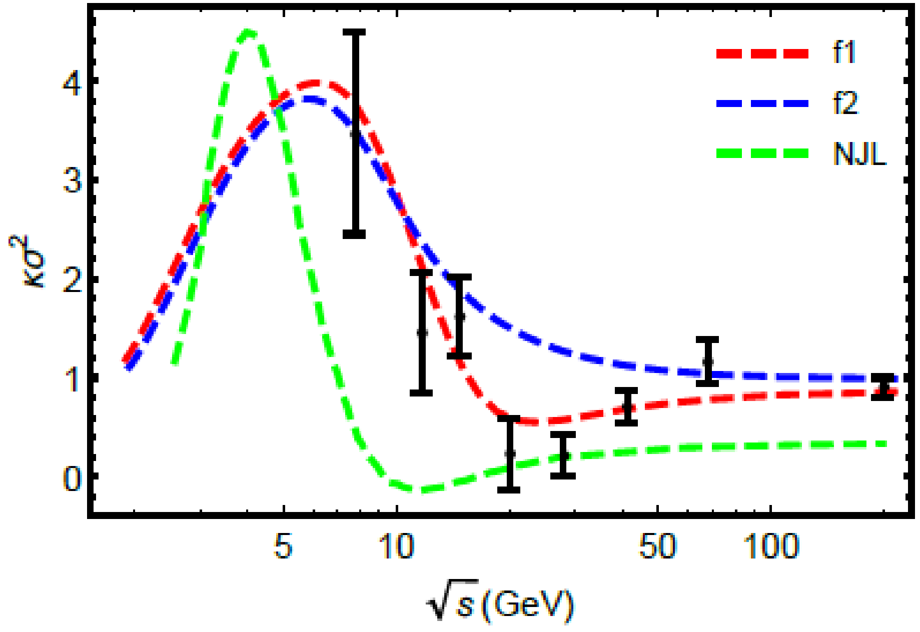
1, Fit model paraters with Lattice QCD EOS and baryon number susceptibility at zero chemical potential;
2,Predictions at finite baryon number chemical potential.

Critical End Point





Sensitivity of freeze out lines



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

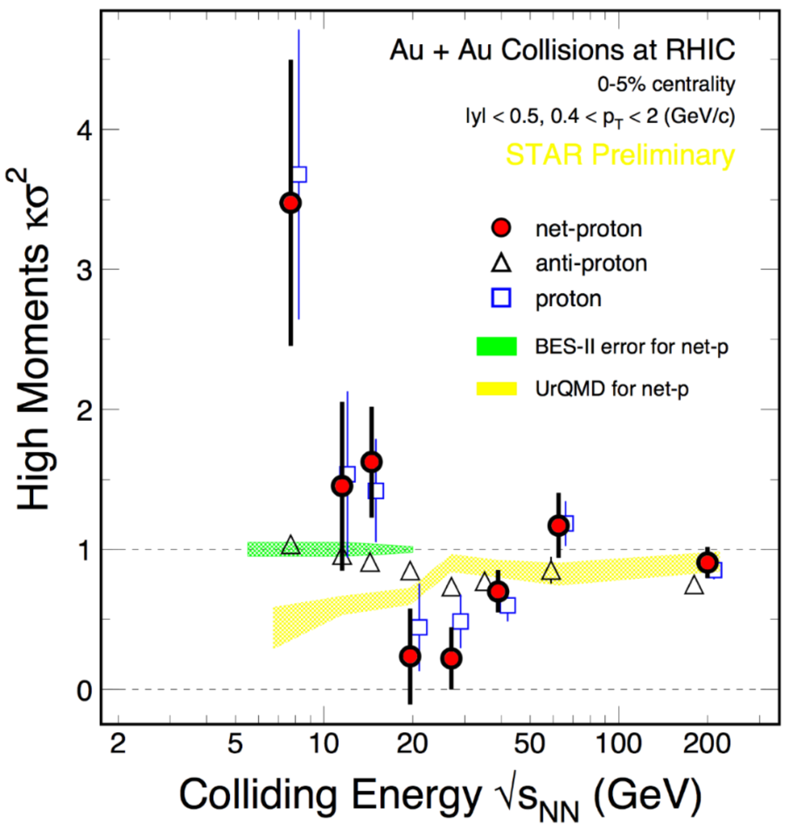
f1: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4 - 0.013(0.948 - \mu)^2$

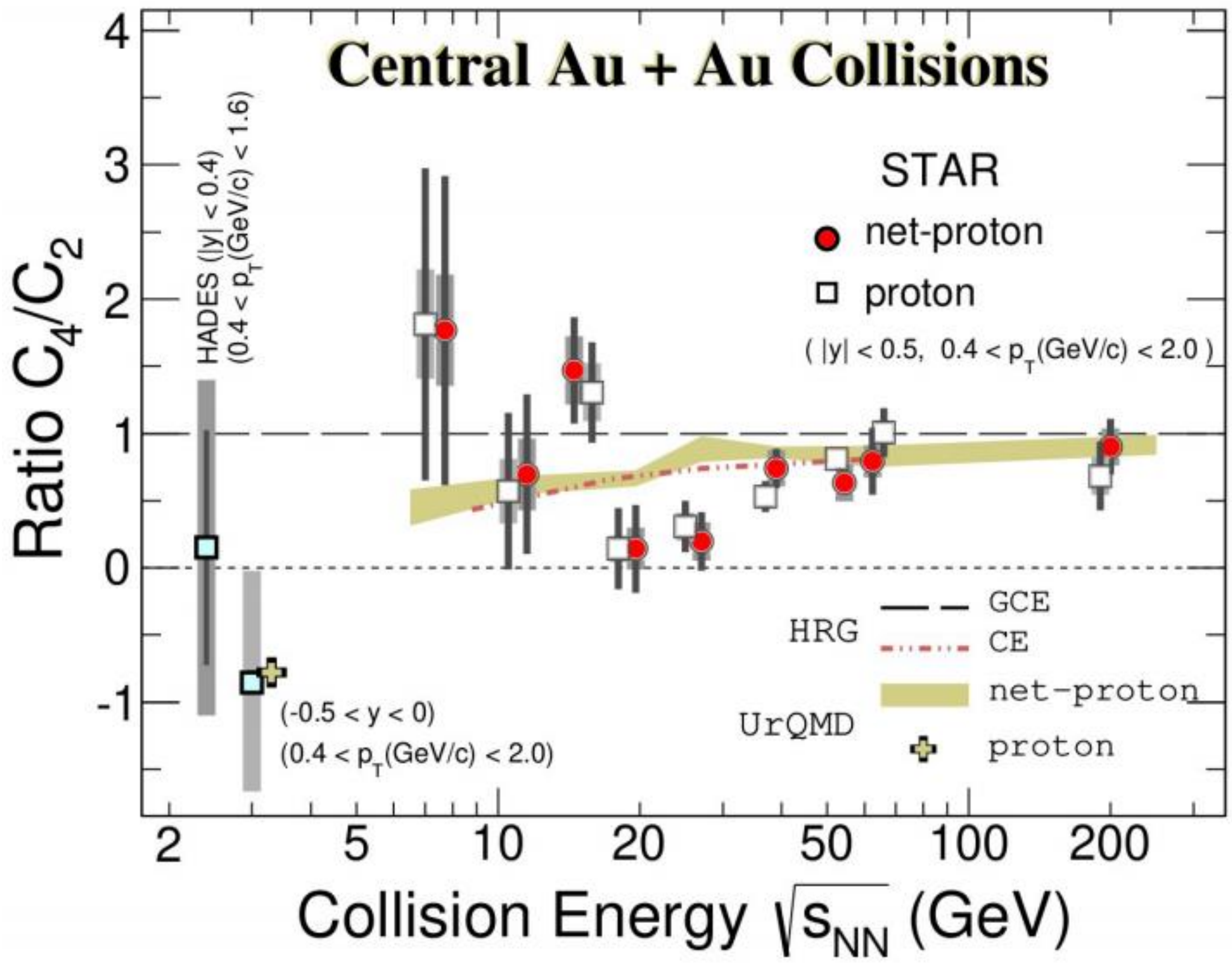
f2: $T(\mu) = 0.158 - 0.14\mu^2 - 0.04\mu^4$ X. Luo and N. Xu, [arXiv:1701.02105]

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]].

Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215， EPJC 2019

Fluctuations near critical point (dip-peak structure)



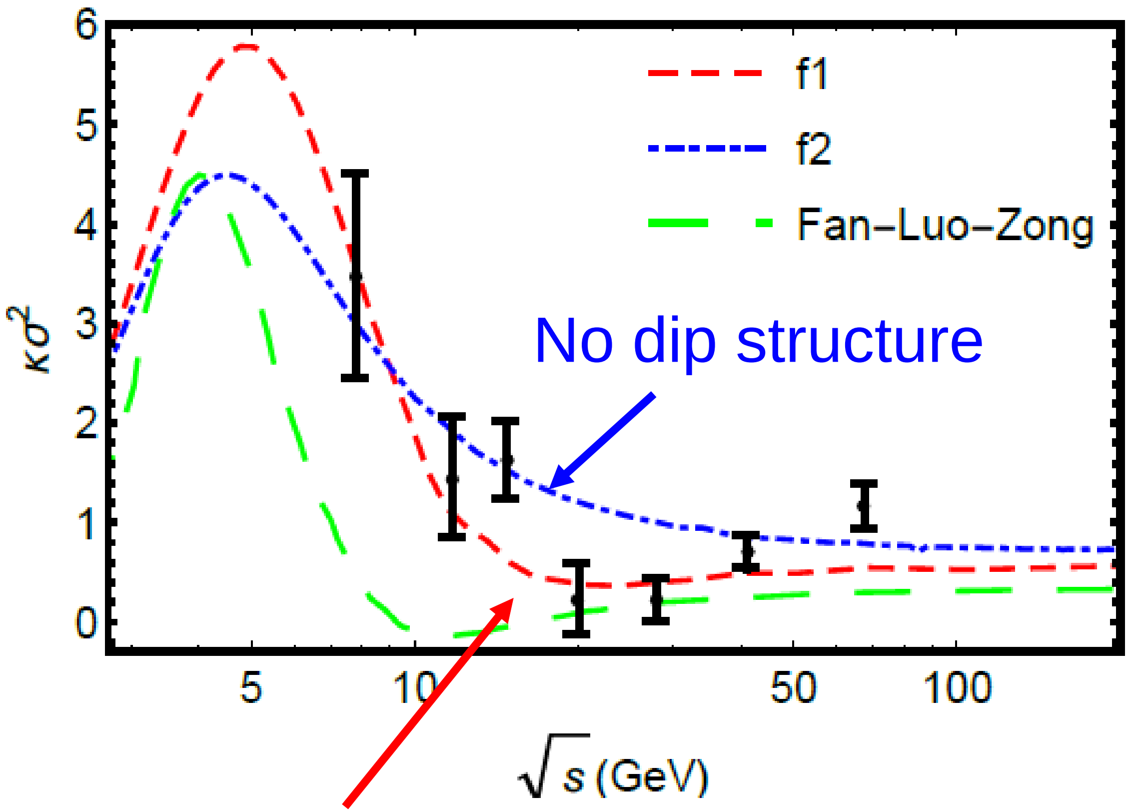


STAR: PRL112, 32302(14);
PRL113,092301(14);
X.F.Luo, N.Xu, arXiv:1701.02105

Nonmonotone → Critical End Point signature ?

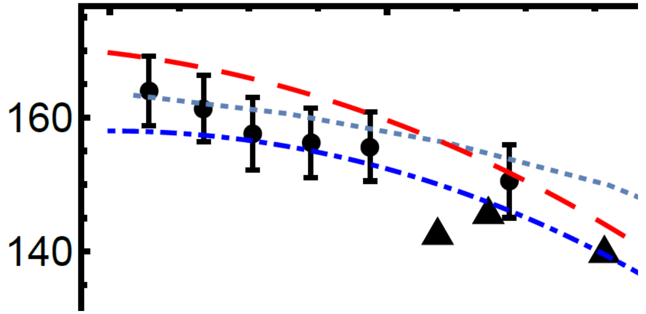
STAR:
Phys. Rev. Lett. 126 (2021) 092301
Phys. Rev. Lett. 128 (2022) 202303

Kurtosis along freeze-out lines



Dip-peak structure

Sensitivity of freeze out lines



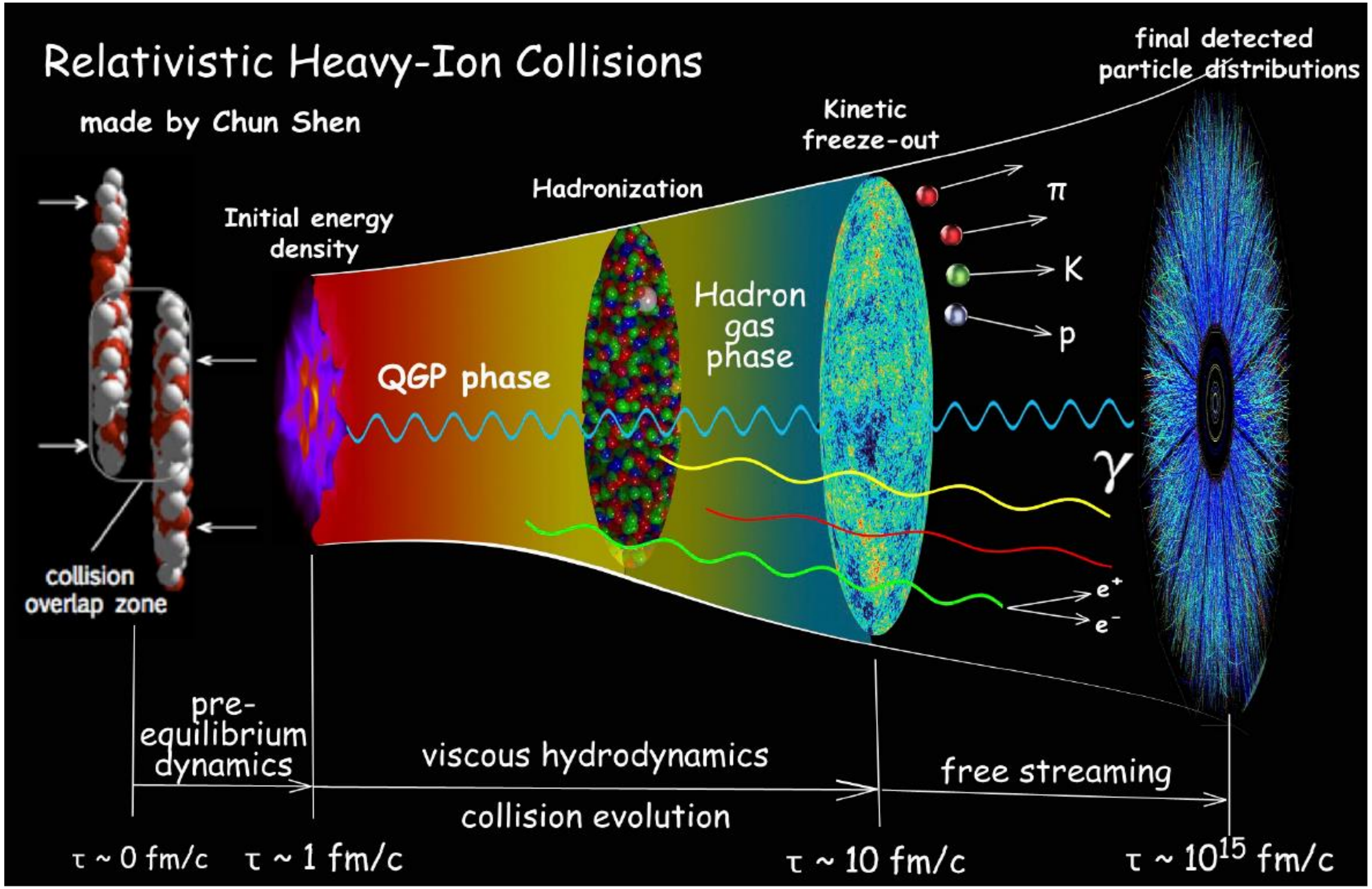
f1 cross the phase boundary while f2 not!

Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215

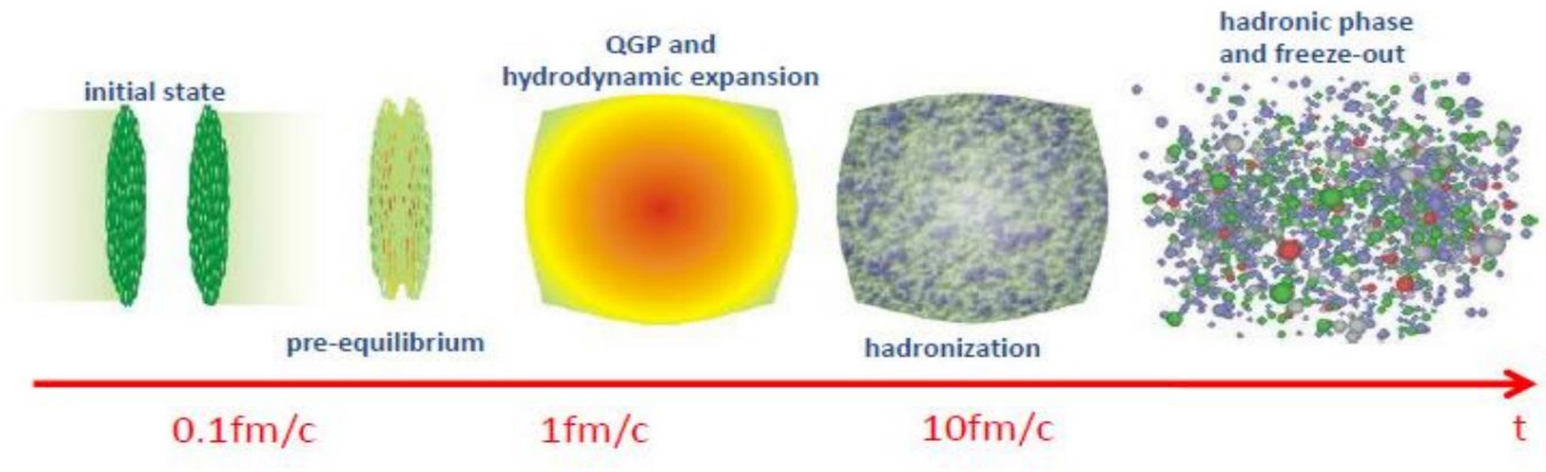
1、Agree well with BES-I data! --->equilibrium result can describe the experimental data!!!
2、The dip structure is sensitive to the relation between the freeze-out line and the phase boundary

Relativistic Heavy-Ion Collisions

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



Hybrid Model



Initial Conditions
SMASH

Hydro
CLVisc

Fist Sampler +
hadron cascade

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

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

Hydrodynamics (CLVisc)

Conservation laws of energy-monmentum and net baryon current：

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

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

Input:

1. Initial conditions

2. EoS from rPNJL model (carry CEP information)

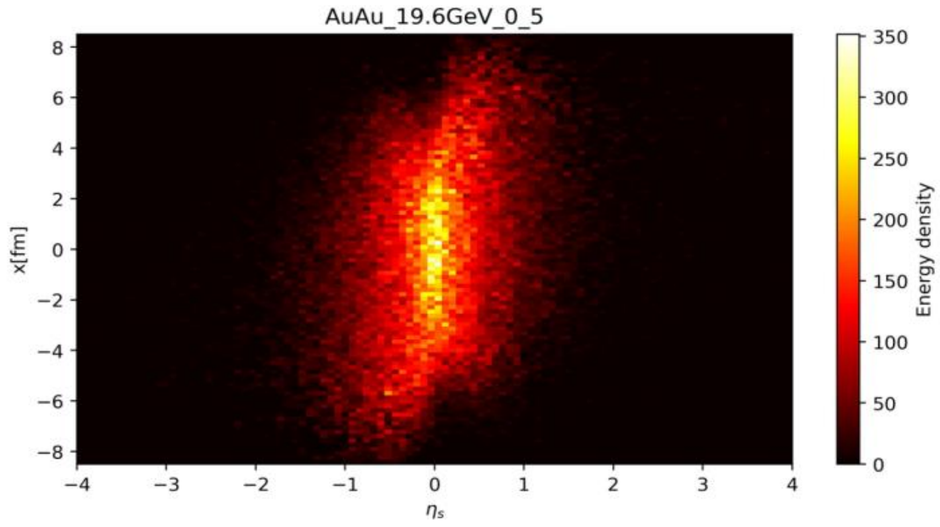
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - \eta_v \sigma^{\mu\nu}) - \frac{4}{3}\pi^{\mu\nu}\theta - \frac{5}{7}\pi^{\alpha<\mu}\sigma_\alpha^{\nu>} + \frac{9}{70}\frac{4}{e+p}\pi_\alpha^{<\mu}\pi^{\nu>\alpha}$$

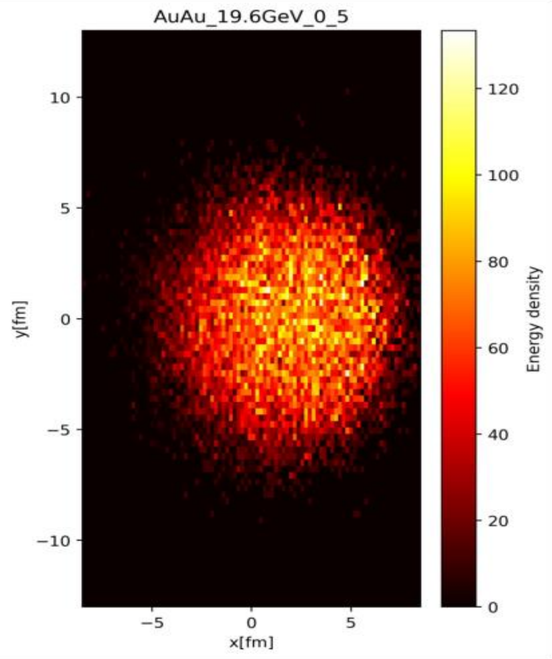
$$\Delta^{\mu\nu} DV_\nu = -\frac{1}{\tau_V}\left(V^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - V^\mu\theta - \frac{3}{10}V_\nu\sigma^{\mu\nu}$$

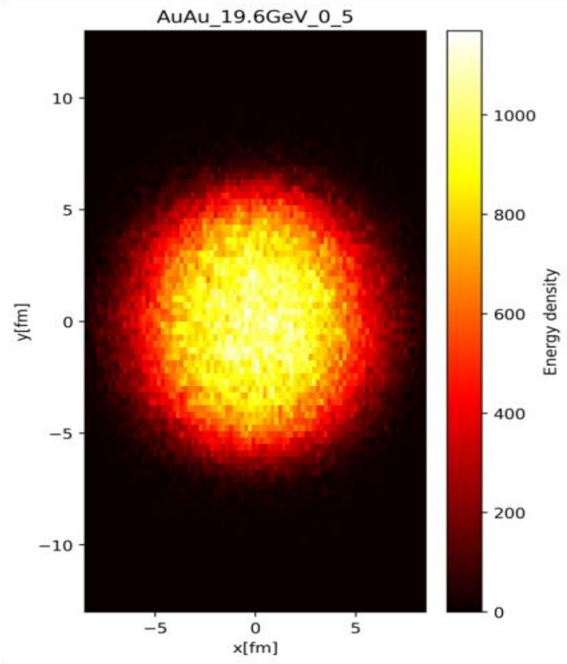
L.Pang et al, Phys.Rev. C86 (2012) 024911
L.Pang et al, Phys. Rev. C 97, 064918 (2018)
X.Wu et al, Phys. Rev. C 105, 034909 (2022)

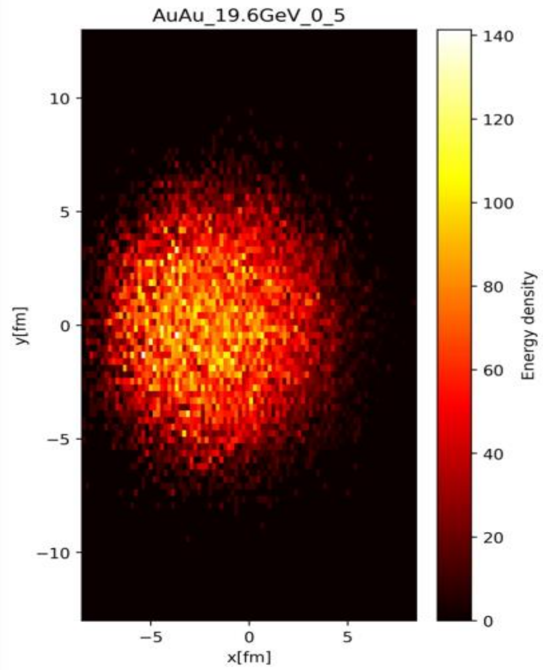
Initial Condition (SMASH)

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)

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

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:

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

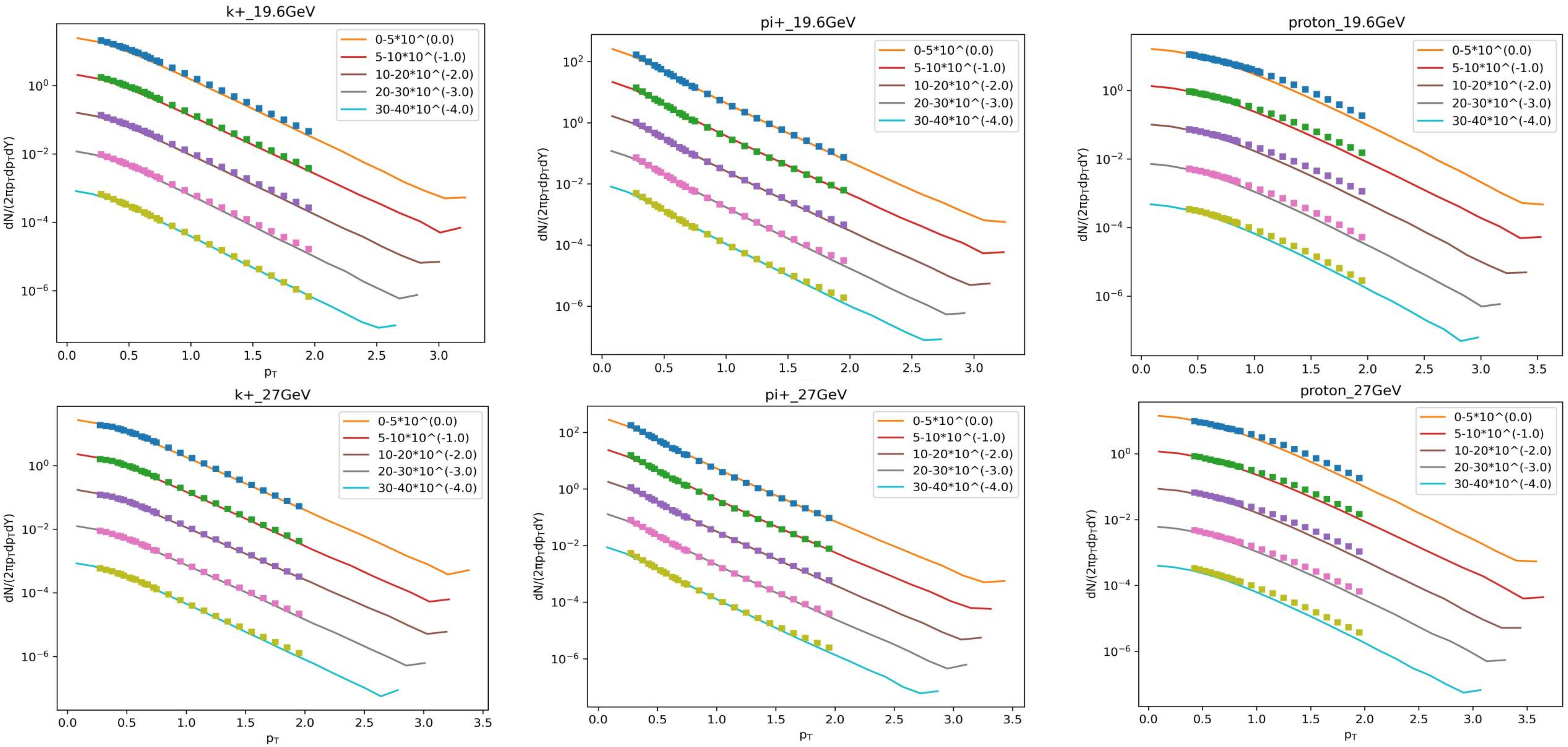
Use Thermal-FIST package, which maintains exact global conservation (under the canonical ensemble) of conserved charges, such as baryon number, electric charge, strangeness, and charm, to sample the momentum distribution of thermal hadrons

Parameters Table

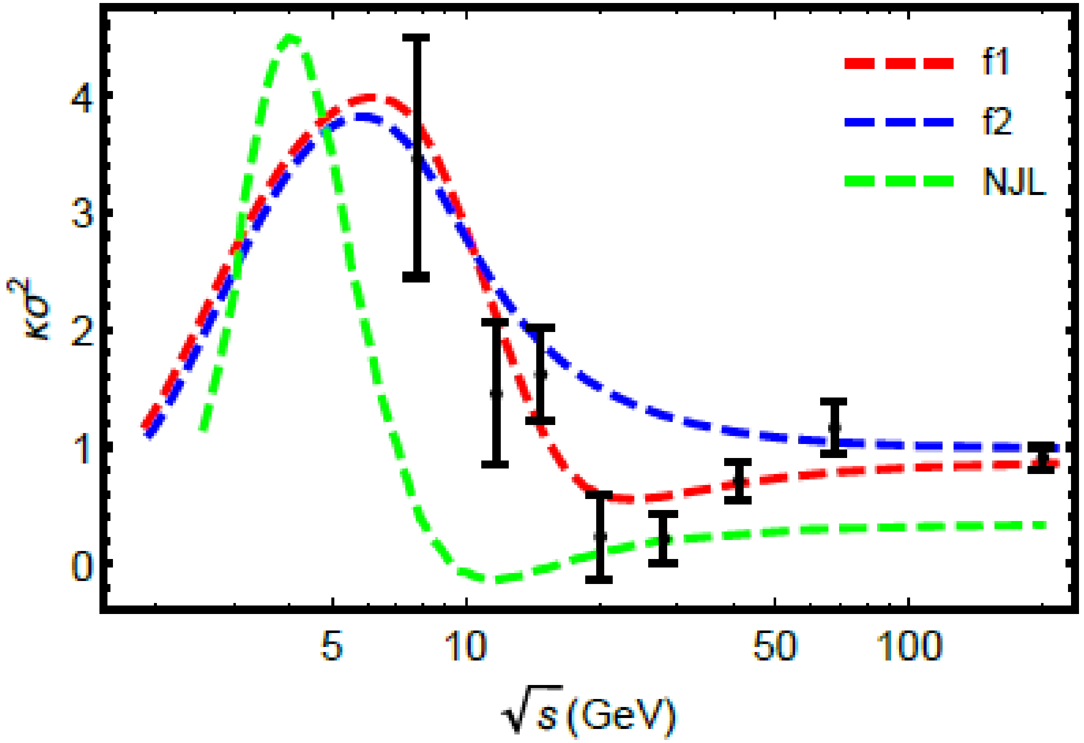
$\sqrt{s_{NN}}[GeV]$	$\tau_0[fm/c]$	$R_\perp[fm]$	$R_\eta[fm]$	η/s
7.7	3.2	1.4	0.5	0.2
14.5	1.65	1.4	0.5	0.2
19.6	1.22	1.4	0.5	0.15
27	1.0	1.2	0.5	0.12
39	0.9	1.0	0.7	0.08
62.4	0.7	1.0	0.7	0.08

Identified particle spectra

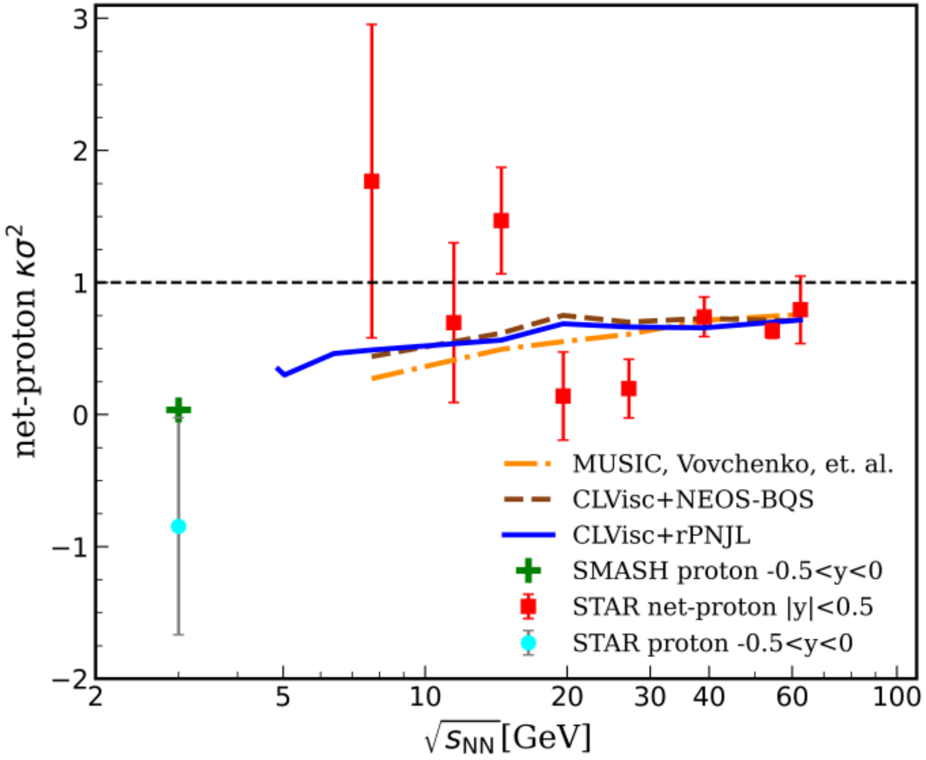
lines from simulation, points from STAR data, and in agreement with experimental datas



Above 7.7 GeV, no peak structure and EOS independent



Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215， EPJC 2019



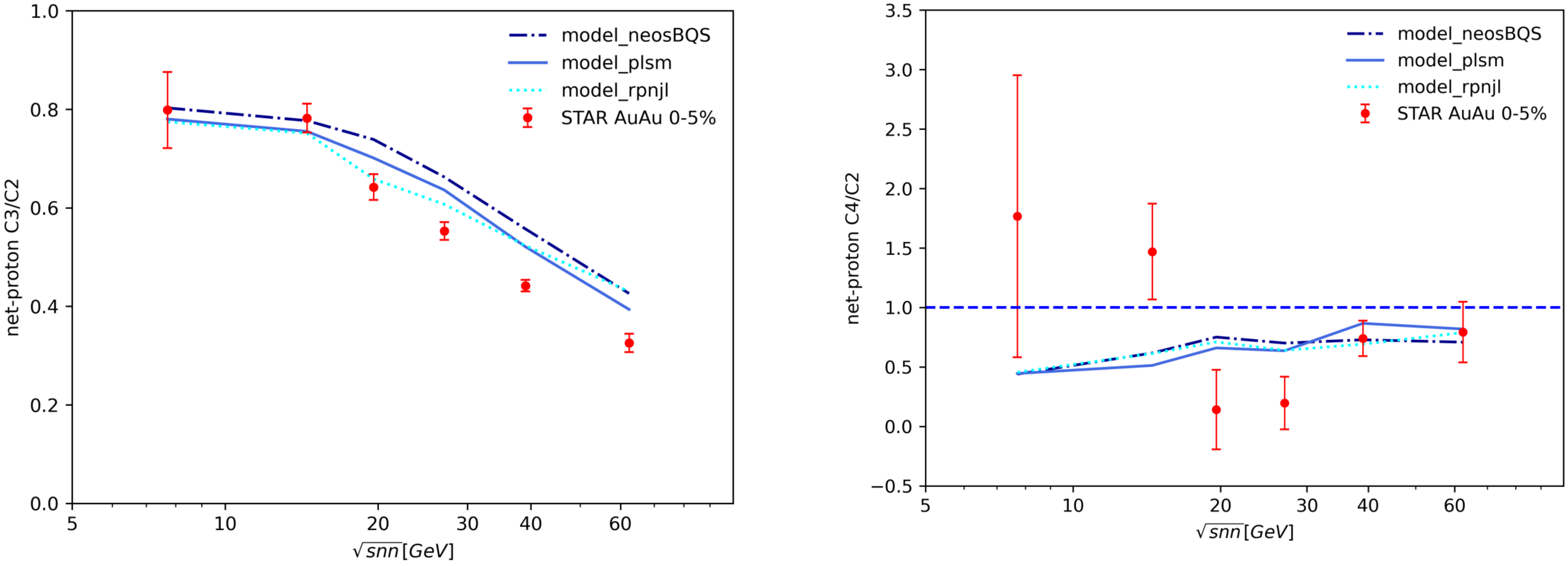
Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH, arXiv:e-Print: 2404.02397 [hep-ph]

MUSIC: different hydrodynamics model

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

Above 7.7 GeV, no peak structure and EOS independent

Central Au+Au Collisions



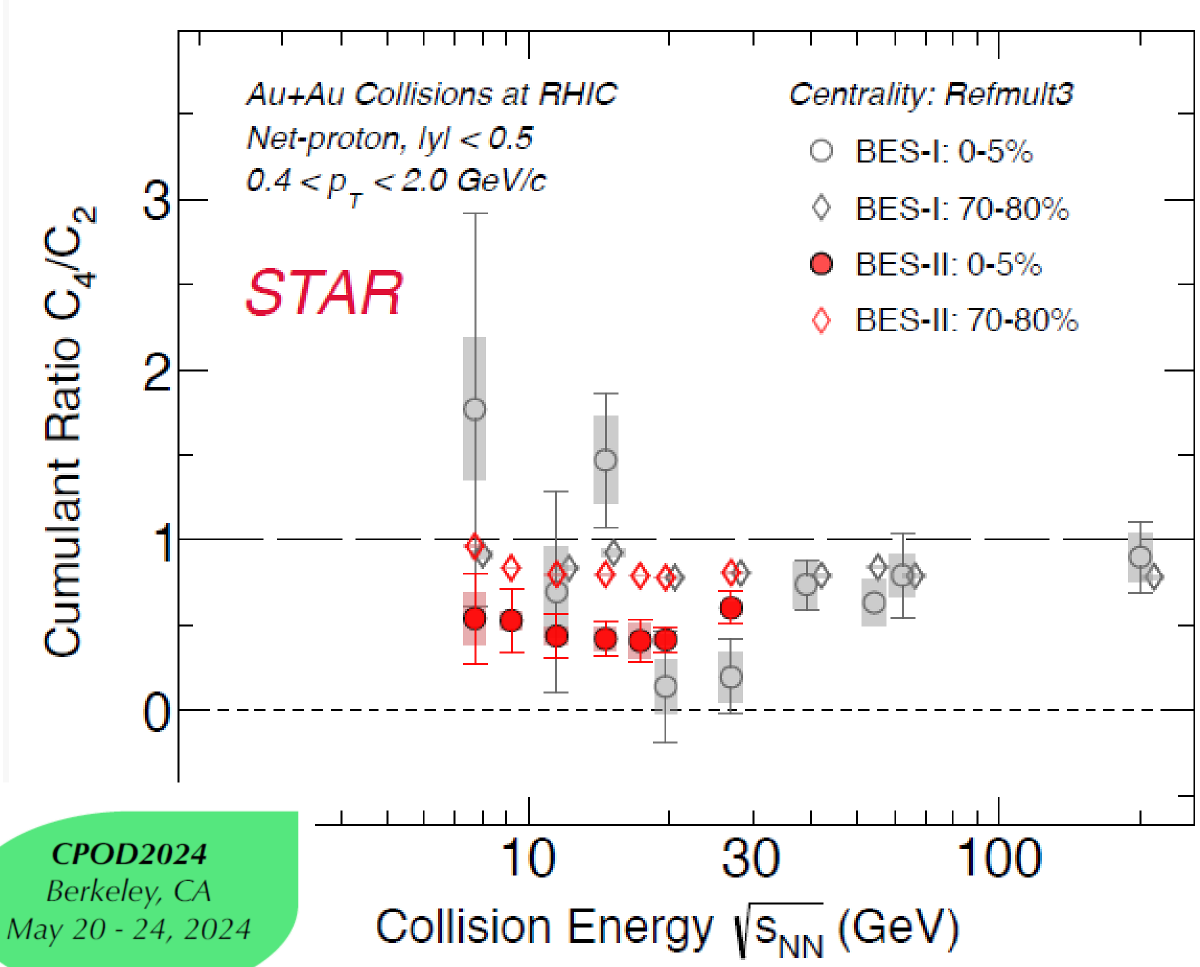
NEOS-BQS: cross-over without CEP

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

Above 7.7 GeV, in agreement with newest Exp. results!



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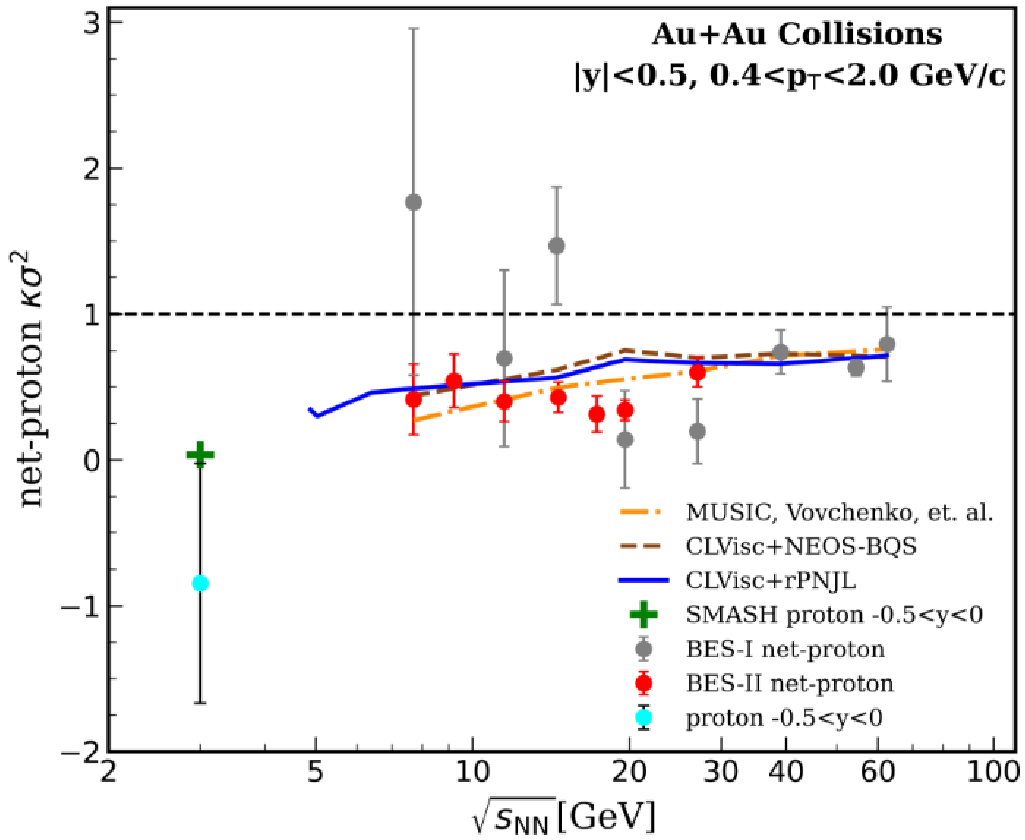
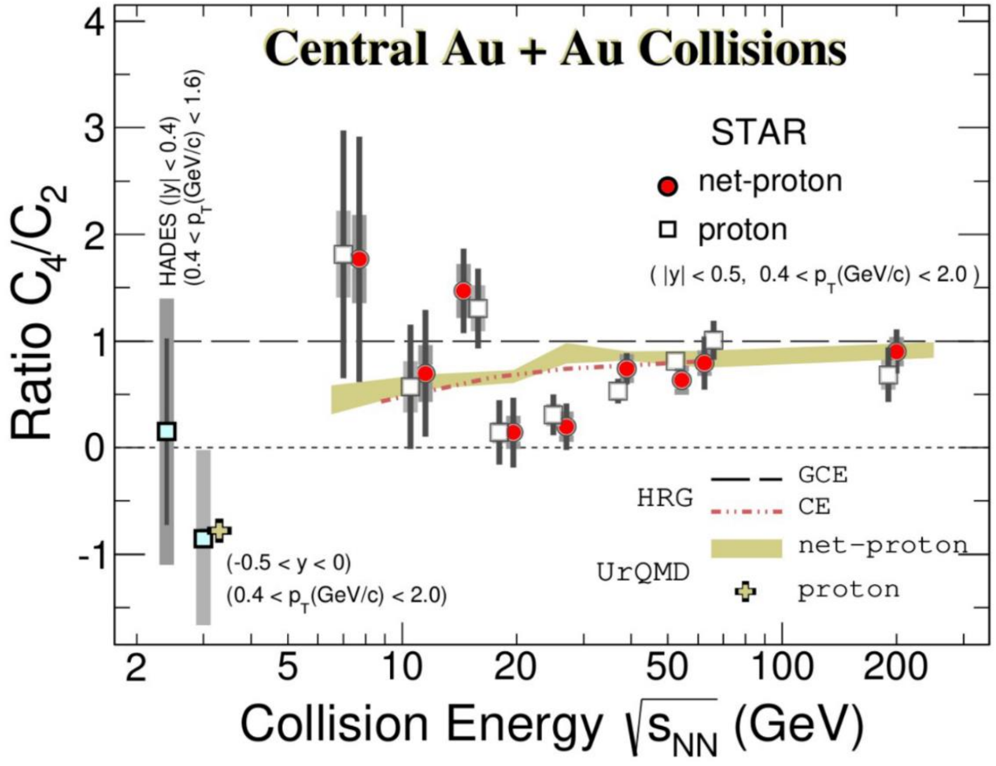
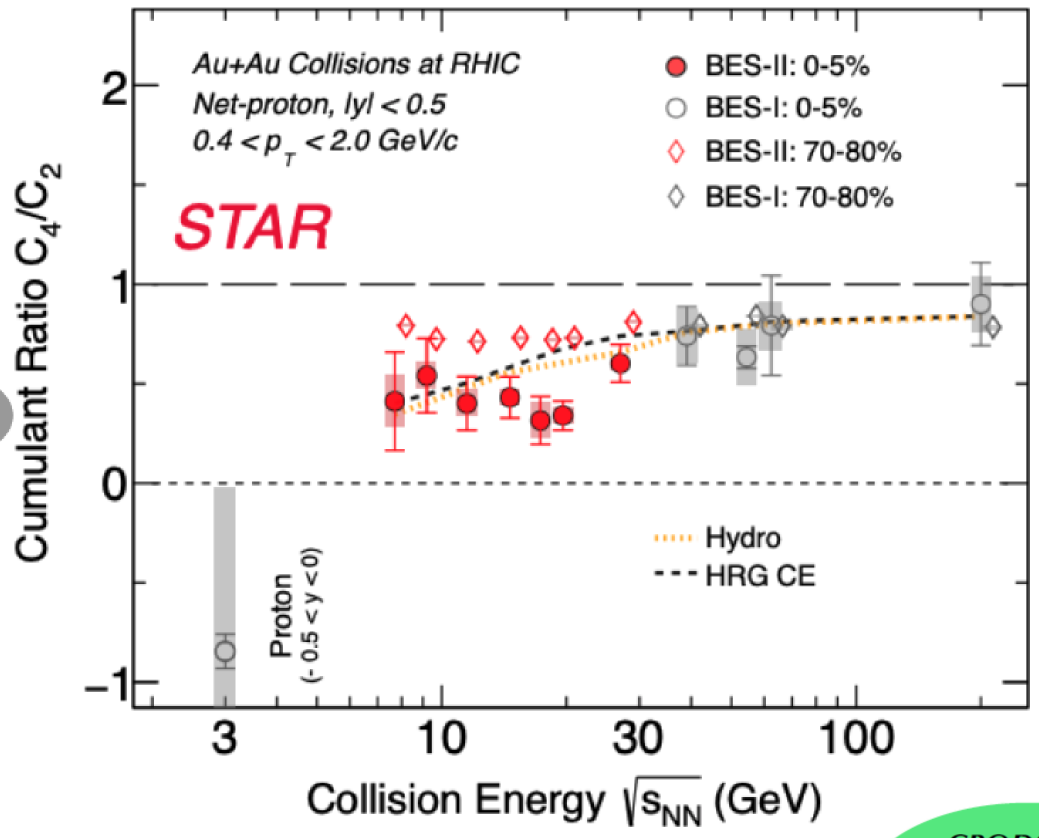
May 20 - 24, 2024



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

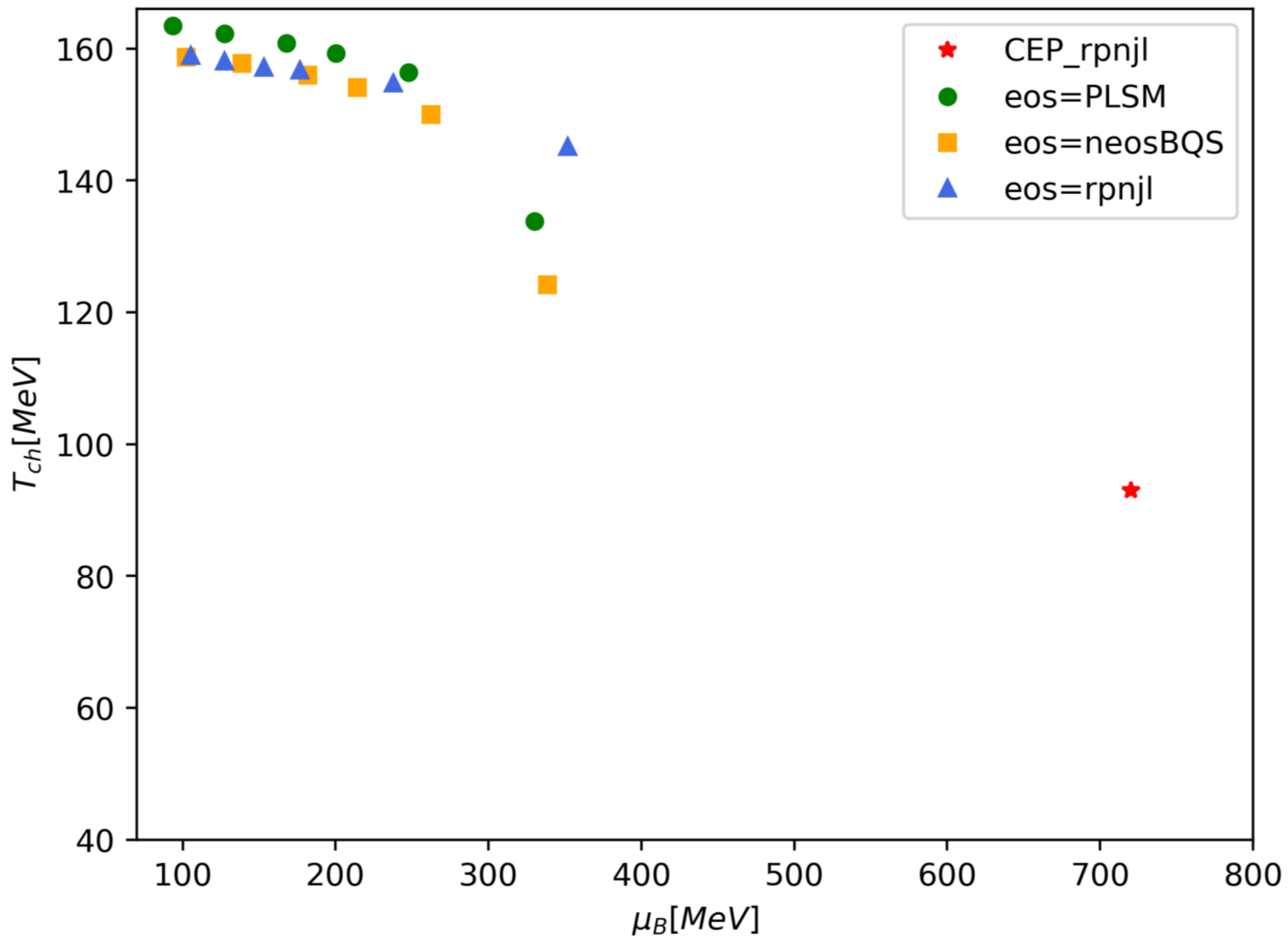
Yifan Shen, Wei Chen, Xiangyu Wu, Kun Xu, MH,
arXiv:e-Print: 2404.02397 [hep-ph]





CPOD2024
Berkeley, CA
May 20 - 24, 2024

How to understand the result? CEP is too far away from freezeout?



EoS from PNJL:

μ_{Bc} = 720MeV, T_c= 93MeV

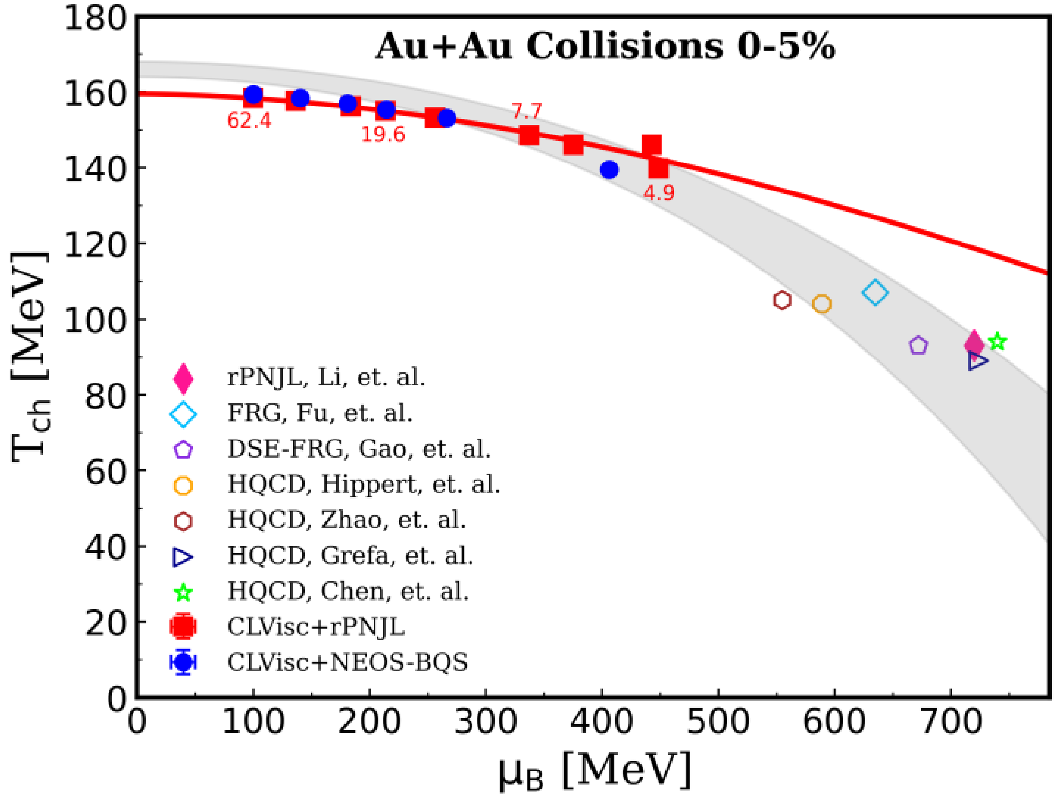
EoS from PLSM:

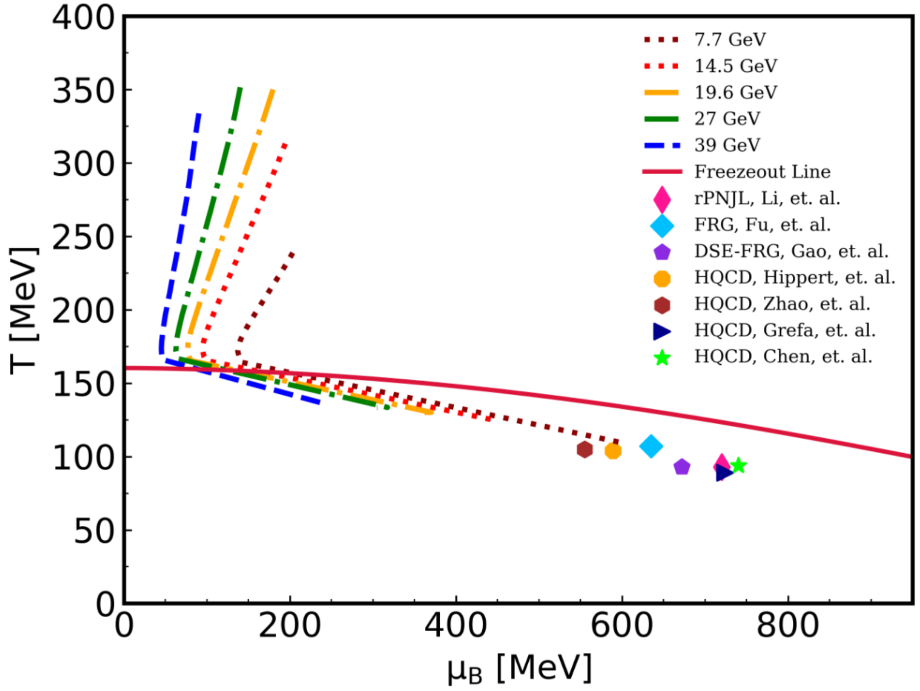
μ_E = 139.5MeV, T_E= 188MeV

To Far

Signature washed out by hadronization?

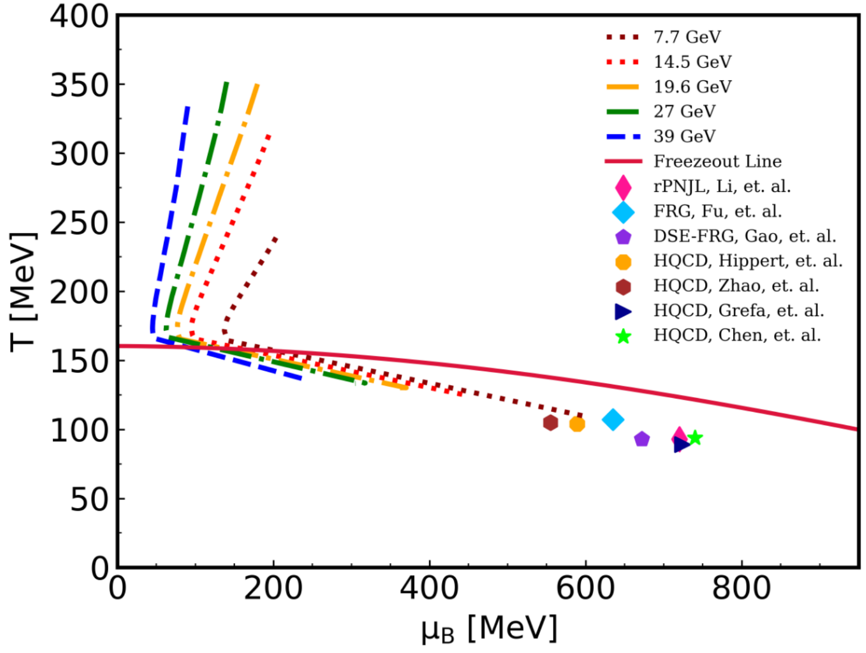
CEP is far away?

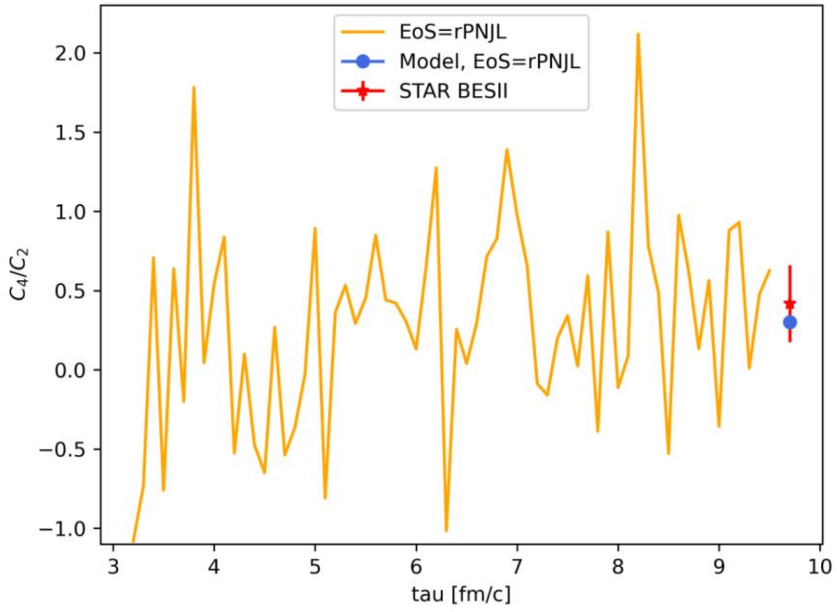




isentropic evolution line

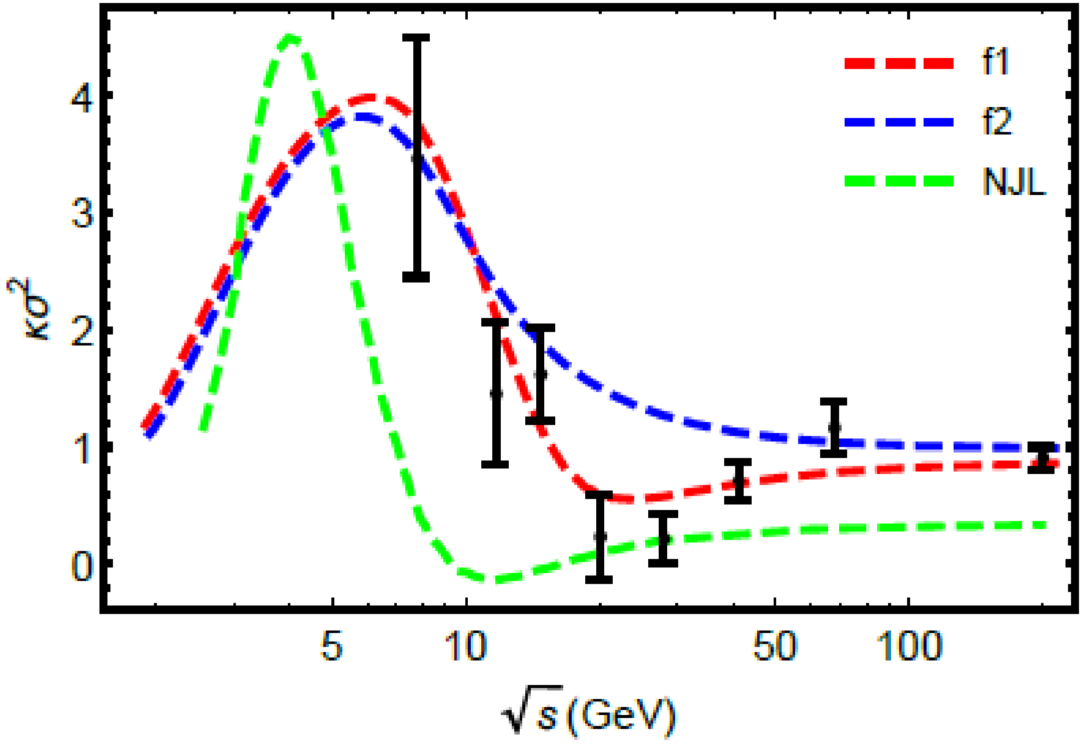
Can C4/C2 reflect the information of CEP during the evolution ?



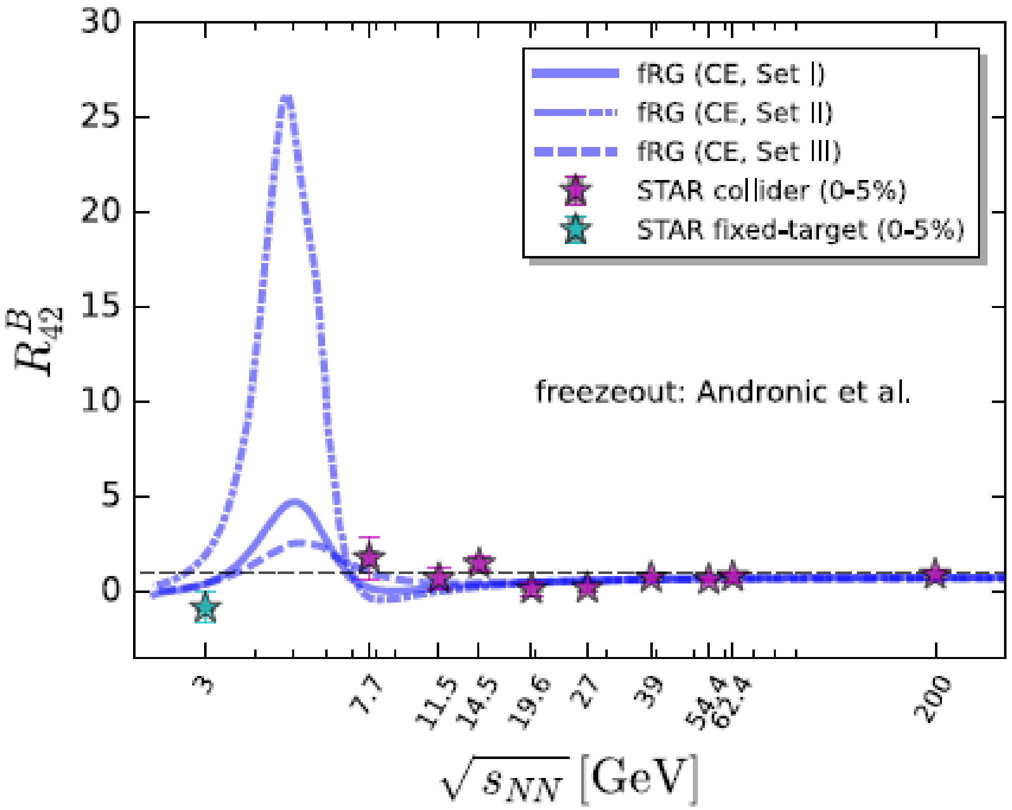


isentropic evolution line

Waiting for the result around 5GeV (NICA) !



rPNJL, Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215， EPJC 2019

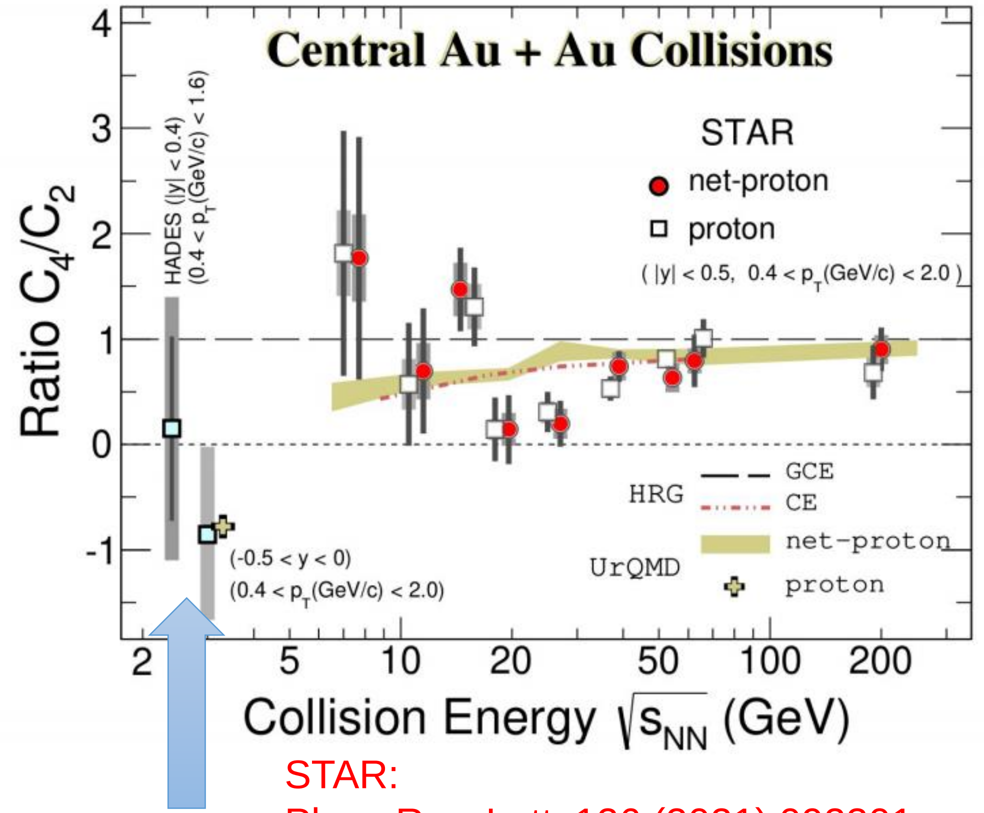


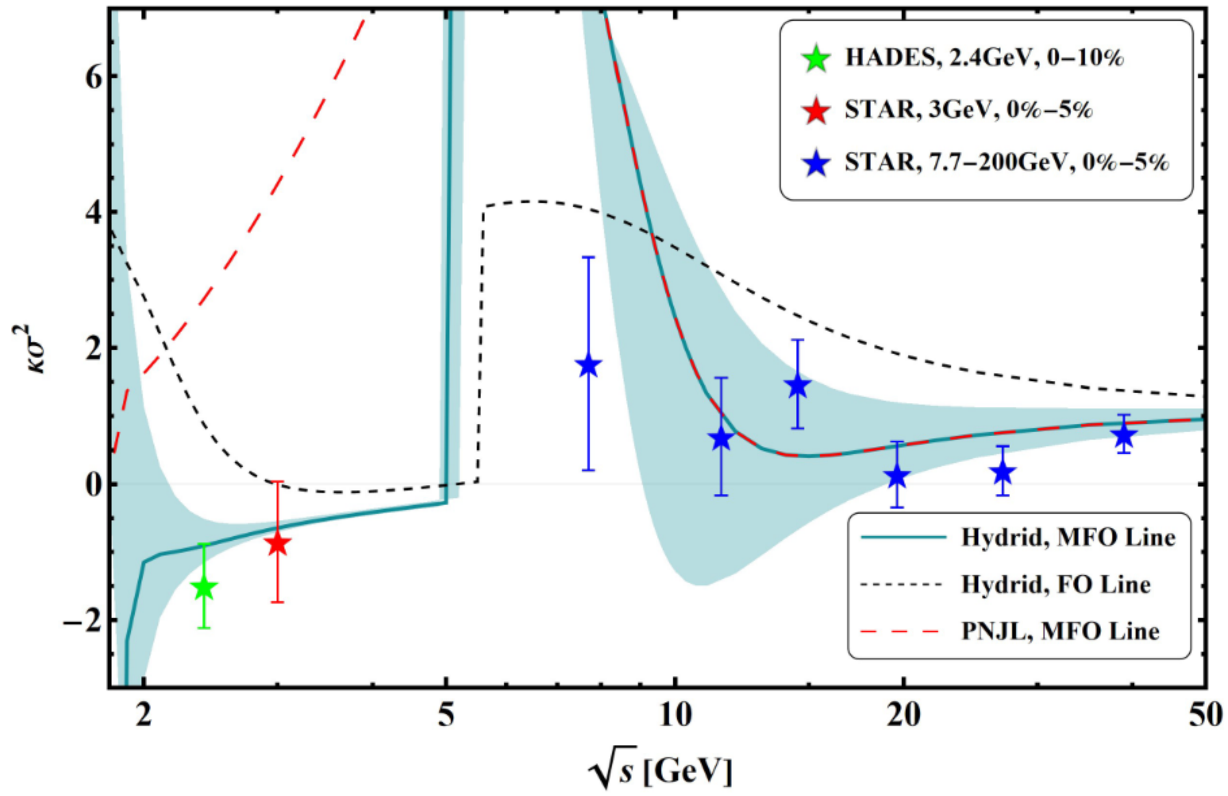
fRG, Weijie Fu, Luo, Pawlowski, Rennecke, Yin, arXiv: 2308.15508

Outlook

Hydrodynamics simulation
+
EoS with liquid-gas phase

Kun Xu, Mei Huang,
arxiv: 2307.12600





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

Summary

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

2. Considering hydro evolution of the realistic HIC collisions, no explicit signature of CEP is found above 7 GeV, the results are kind of EOS independent.

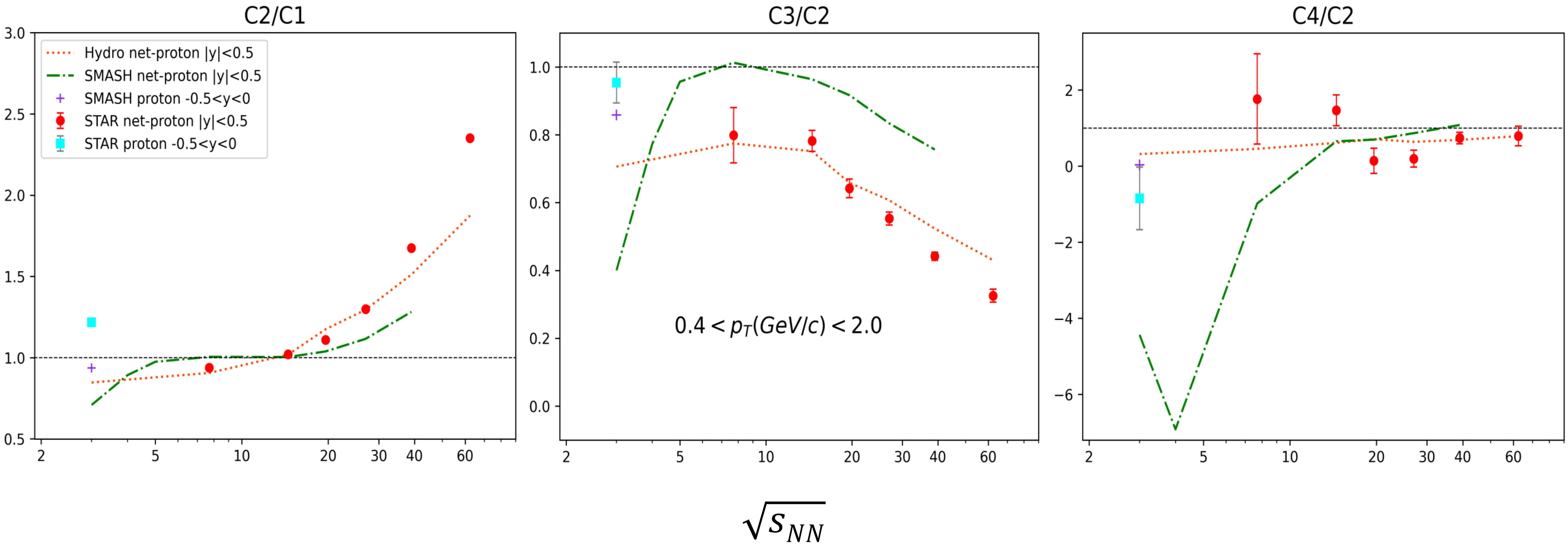
3. Expect eperiment results around 5GeV !

3. More signatures needed, photon/dilepton emission?

Thanks for attention!

Different Evolutions (Hydro vs SMASH)

Central Au+Au Collisions

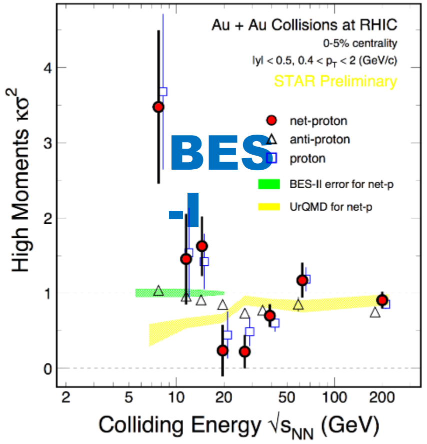


No fluctuation in low energy   And from SMASH in low energy, values become minus

QCD phase structure at finite baryon chemical potential

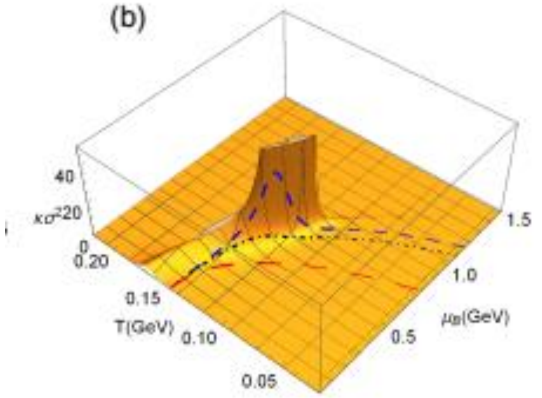
CEP searching at HICs

Kurtosis

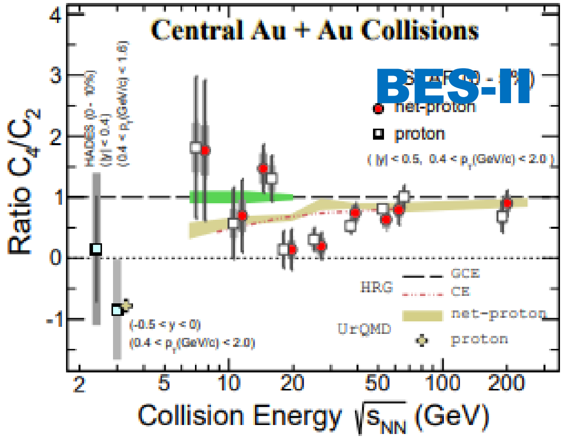


STAR: **PRL112**, 32302(14);

CEP of chiral phase transition

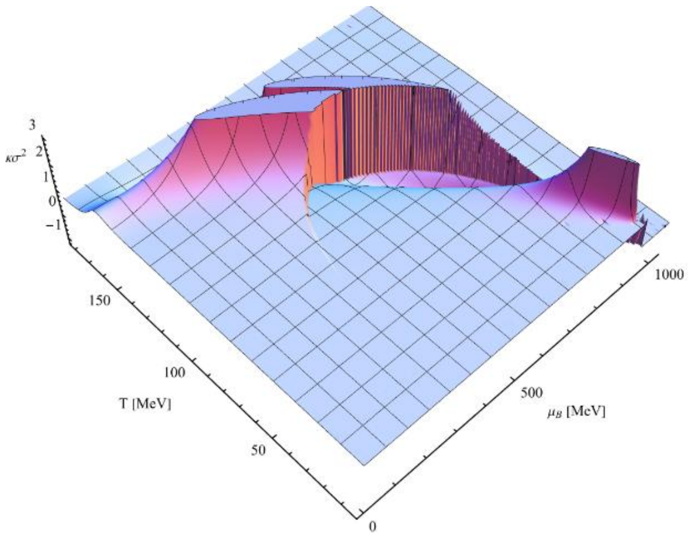


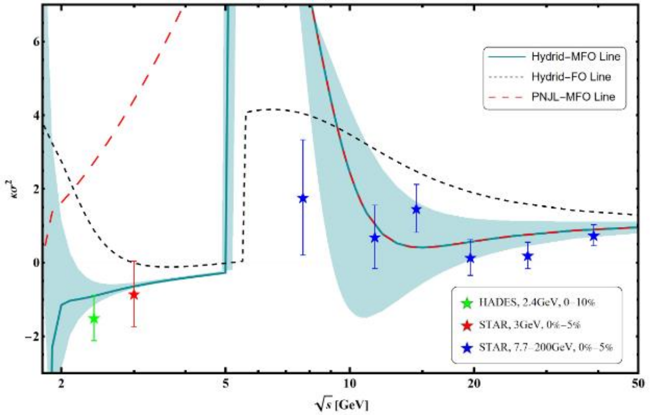
Z.B.Li et.al, Chin.Phys.C 42 (2018) 1, 013103； EPJC 79，2019



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

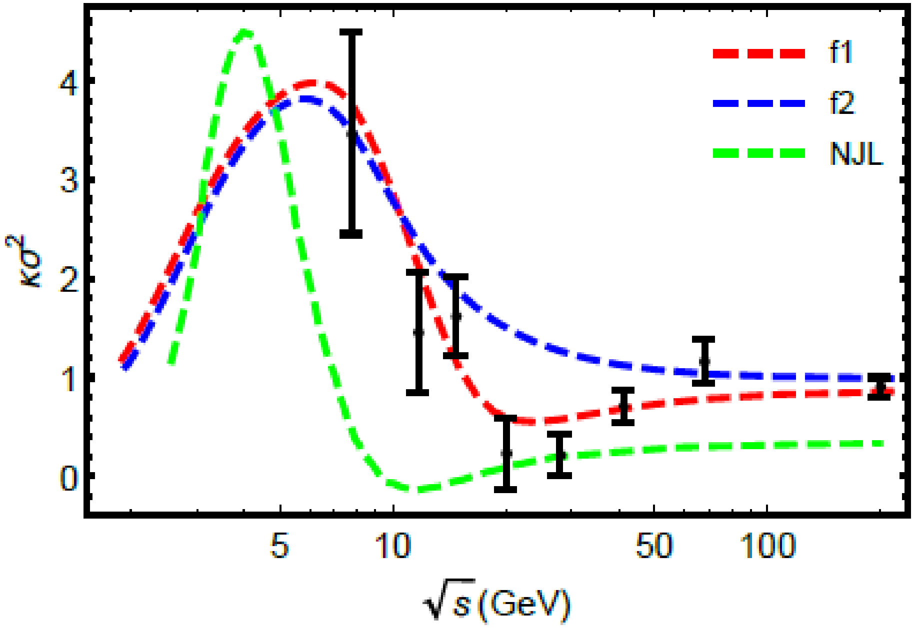
CEP of chiral phase transition meets CEP of nuclear liquid-gas phase transition!

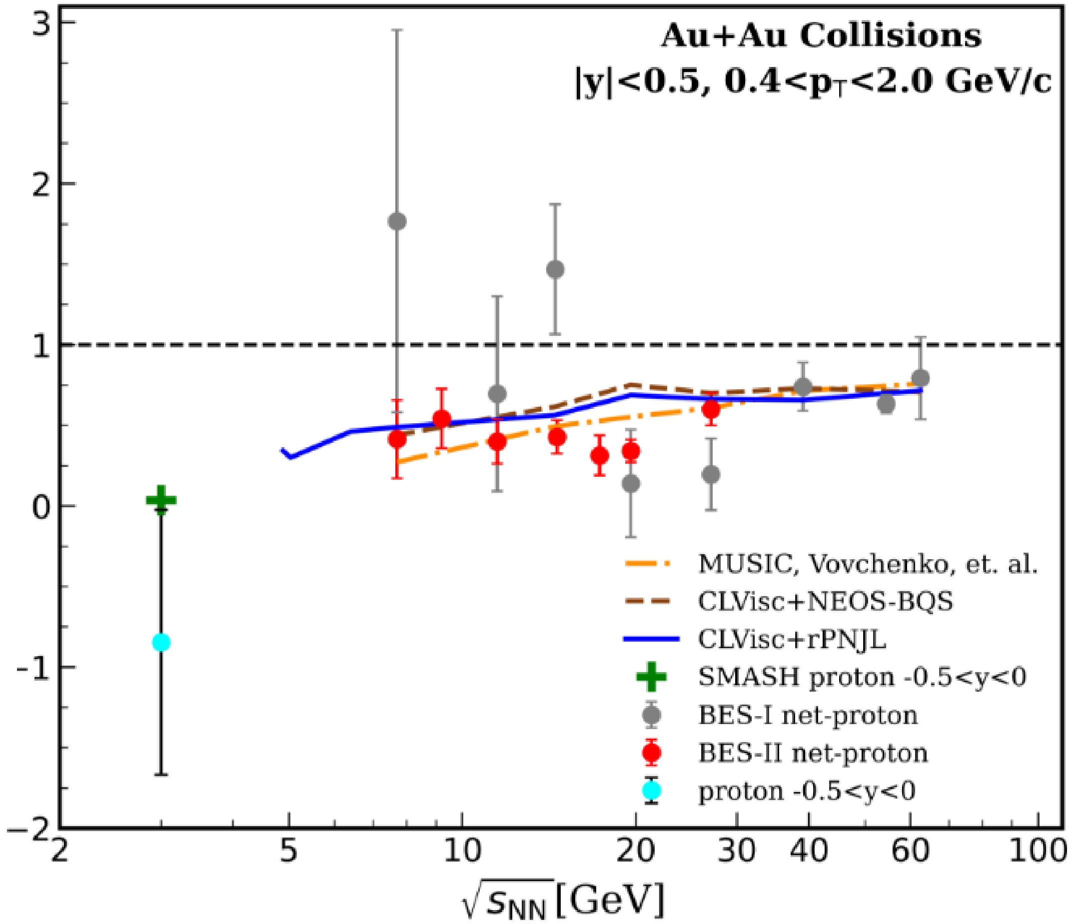




Kun Xu, Mei Huang, to appear soon

Disappearance of the peak structure and EOS independent!

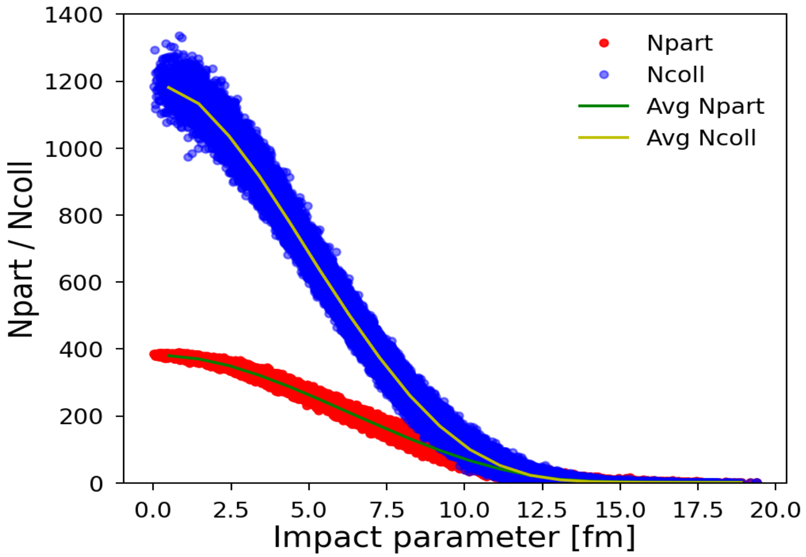




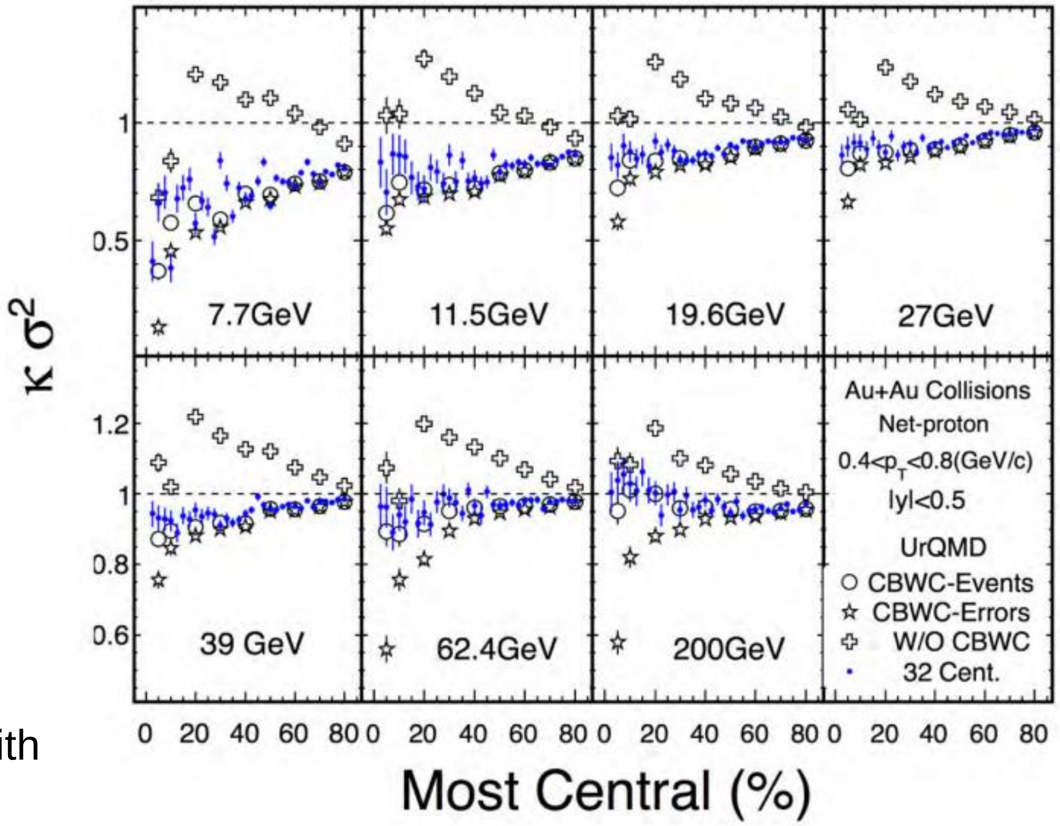
Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang, arXiv:1801.09215， EPJC 2019

The centrality bin width correction

from Glauber model:



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



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

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