



QCD phase diagram within functional QCD

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Dalian University of Technology

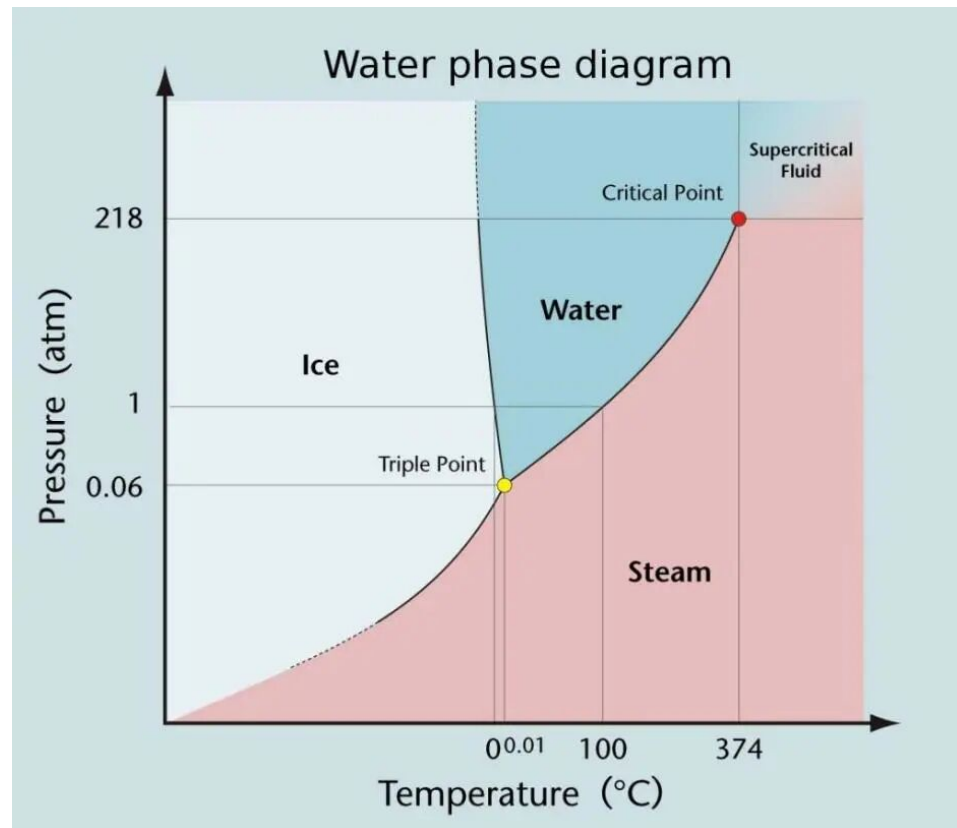
极端条件下的QCD 研讨会, 烟台, August 18 – 21, 2026

Based on:

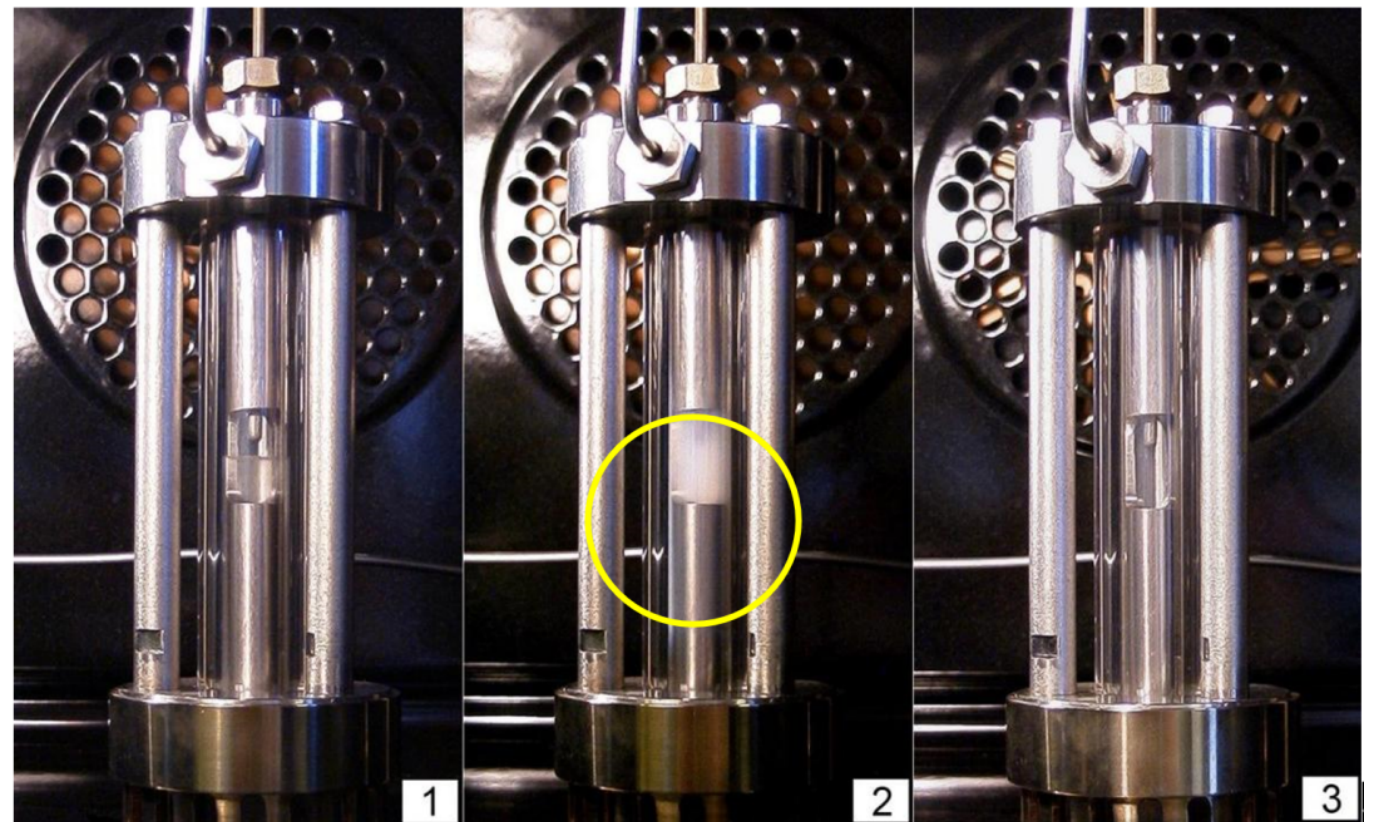
WF, Xiaofeng Luo, Jan M. Pawłowski, Fabian Rennecke, Shi Yin, *PRD* 111 (2025) L031502, arXiv: 2308.15508;
WF, Jan M. Pawłowski, Robert D. Pisarski, Fabian Rennecke, Rui Wen, Shi Yin, *PRD* 111 (2025) 094026, arXiv:2412.15949;
Rui-zhe Zha, Shi Yin, Shanjin Wu, Lipei Du, Xiaofeng Luo, WF, arXiv:2607.26912;
Zi-ning Wang, Li-jun Zhou, Chuang Huang, Rui Wen, Shi Yin, WF, arXiv:2607.07354.
WF, Chuang Huang, Jan M. Pawłowski, Fabian Rennecke, Rui Wen, Shi Yin, arXiv:2603.13455.

Phase of matter and phase transitions

Phase diagram of water



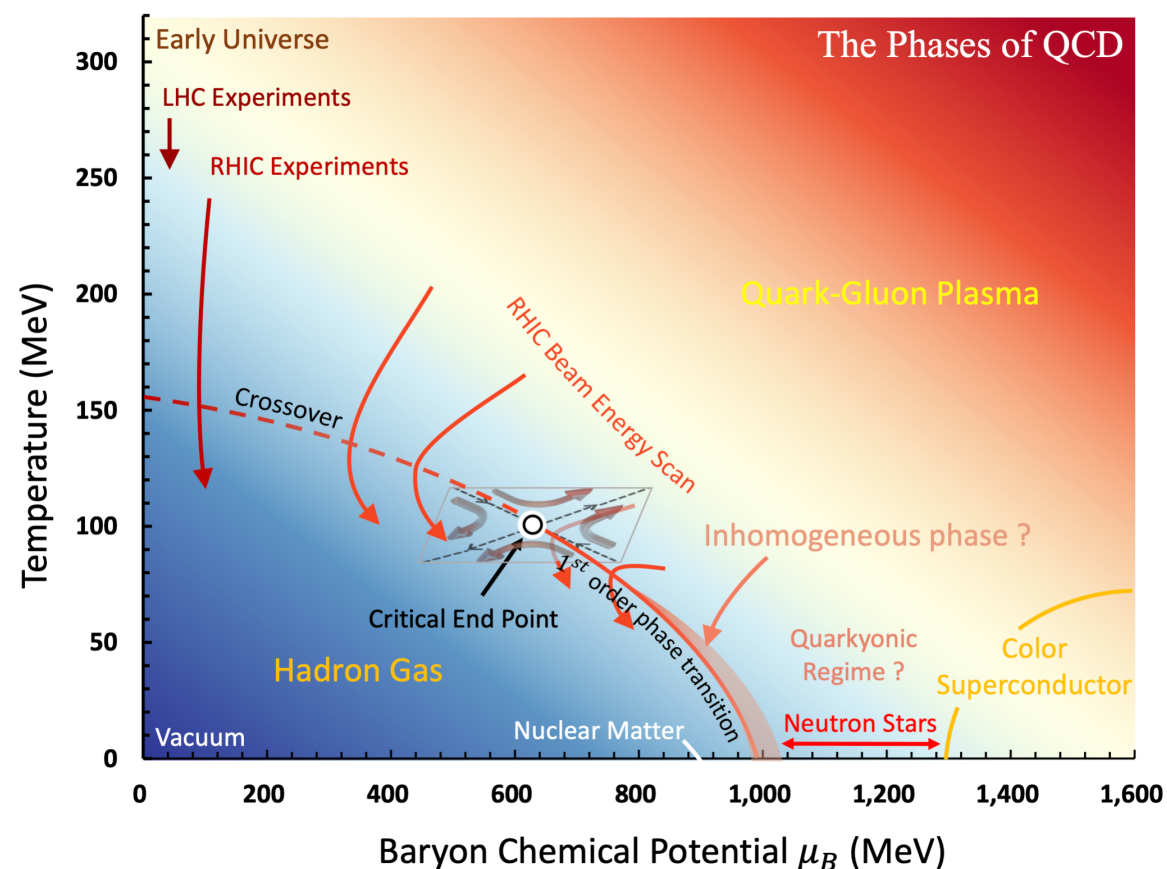
Critical opalescence (临界乳光) from ethane



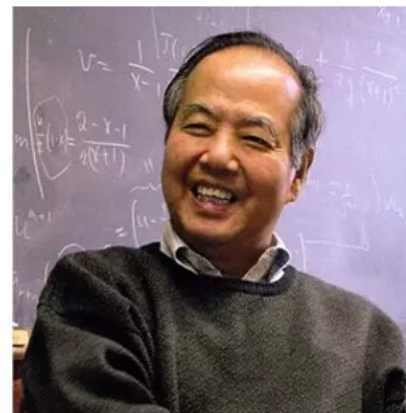
- Critical phenomenon was first discovered by French physicist de la Tour (德拉图) in 1822, more than 200 years ago.

QCD phase diagram

QCD phase diagram



李政道先生早在上世纪70年代提出利用重离子碰撞激发真空研究QCD相变

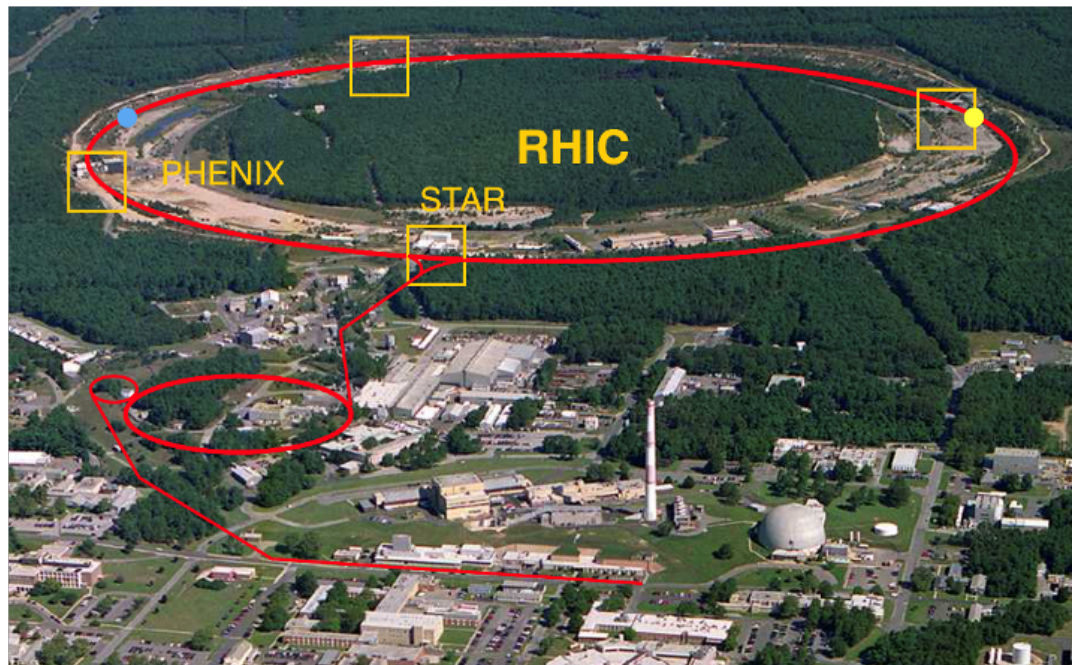


核子重如牛，对撞生新态
---李政道

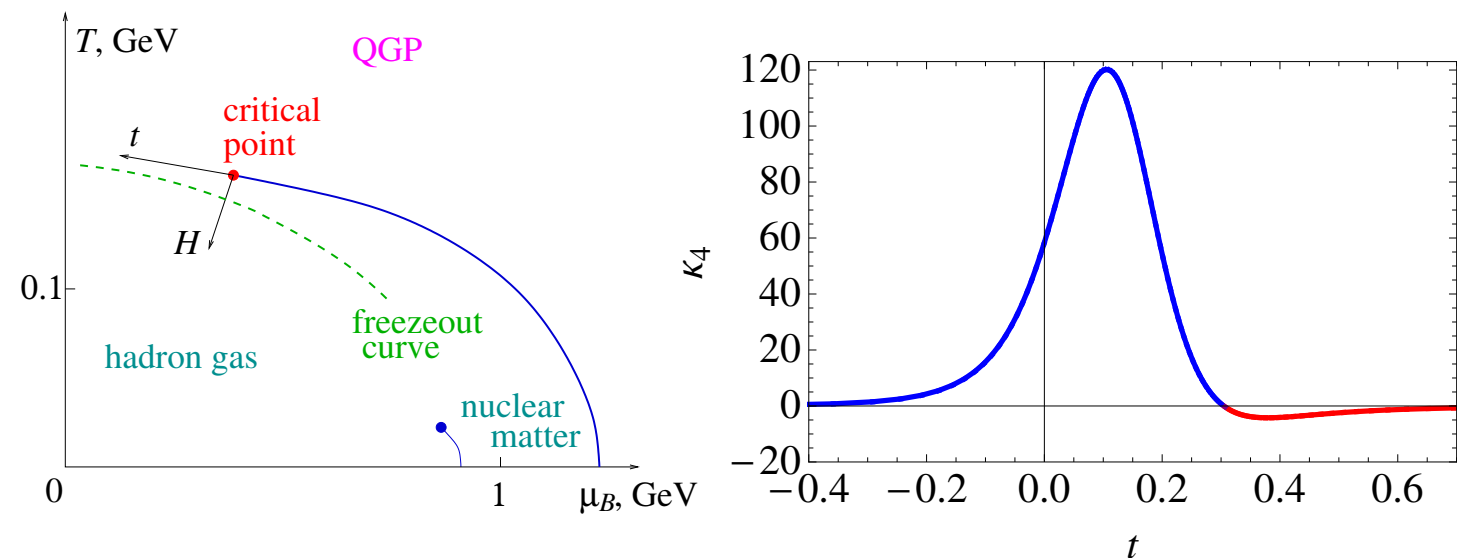
- Studies of QCD phase diagram play a important role in exploring the nature of strong interactions, compact stars, the evolution of early universe, etc.

Search of CEP in heavy-ion collision experiments

Relativistic Heavy-Ion Collider (RHIC)



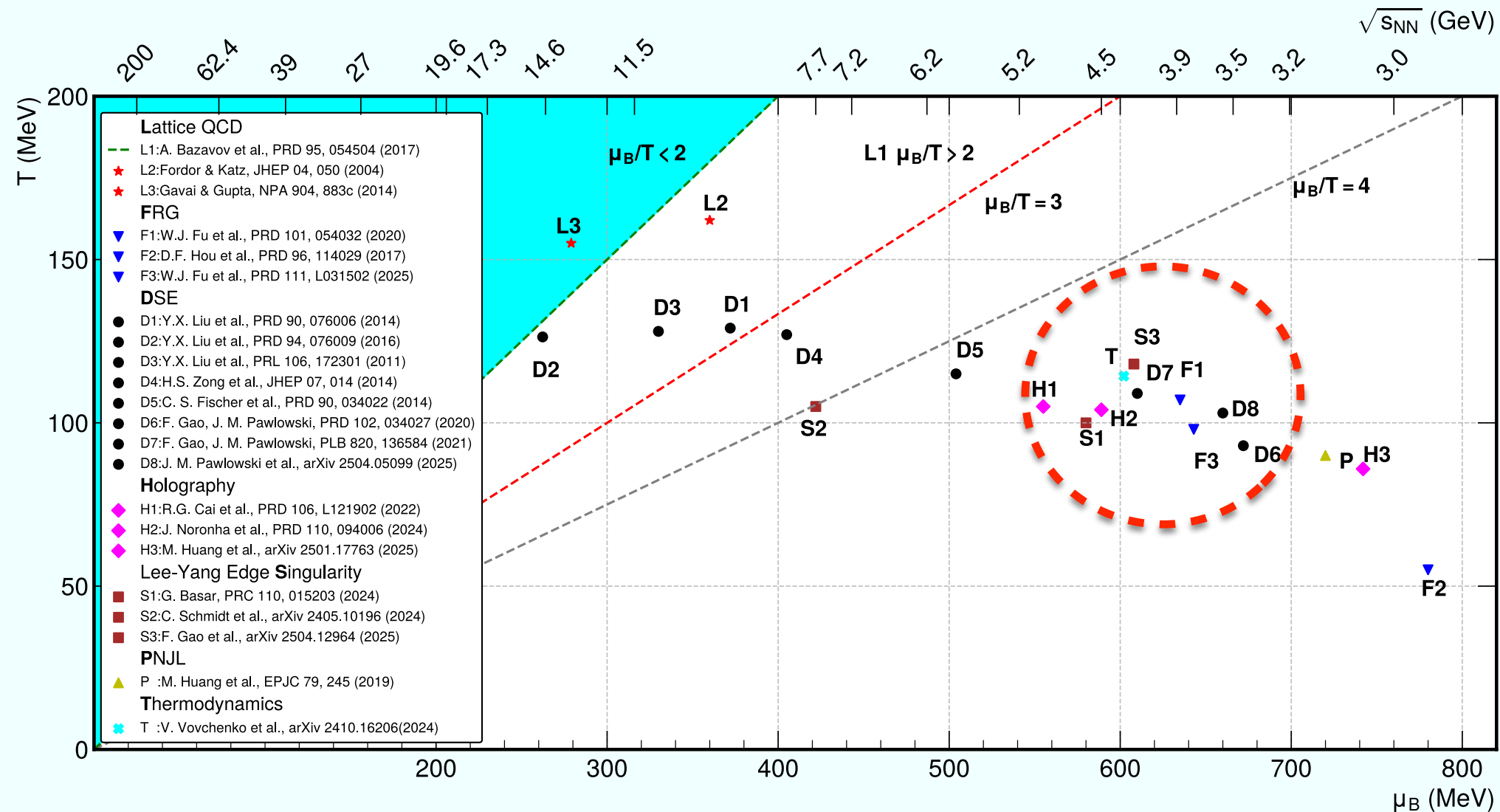
Fluctuation observables



Non-monotonicity:
M. Stephanov, *PRL* 107 (2011) 052301

- A non-monotonic dependence of fluctuations on the collision energy is expected when the system passes through the QCD critical point.

Theoretical predictions of CEP



By courtesy of Xiaofeng Luo

- There have been continuous efforts for more than two decades to predict the location of CEP from theoretical computations, and researchers in China have made significant contributions.

Outline

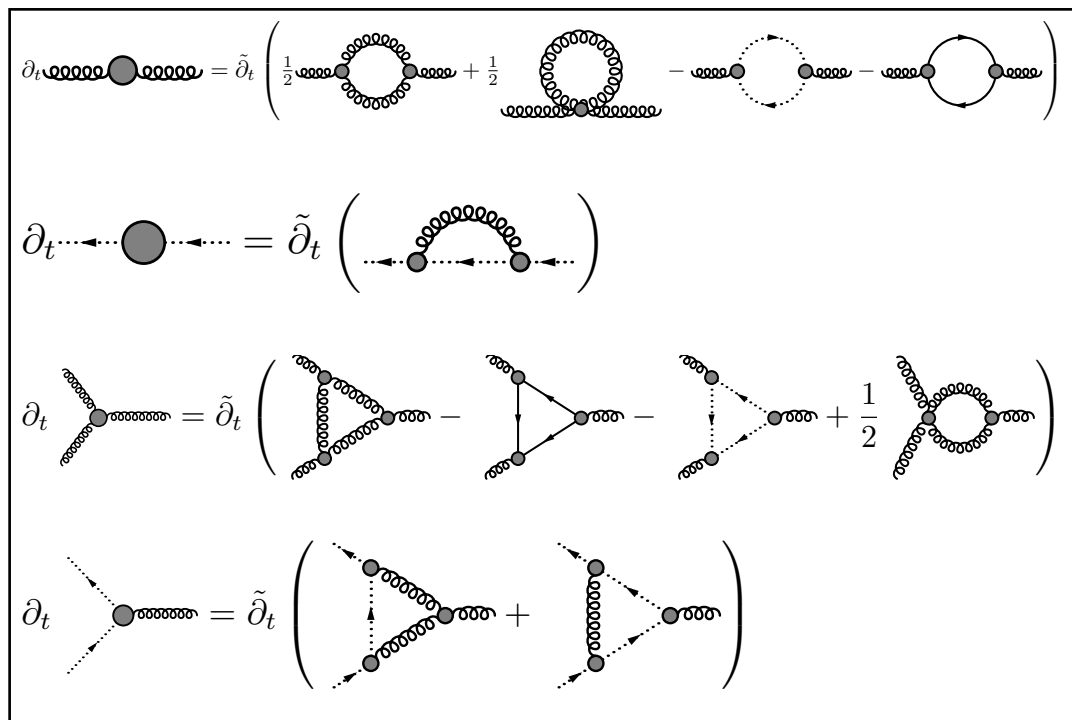
- **Introduction**
- **Recent estimates of the location of CEP**
- **Fluctuation observables**
- **Moat regime**
- **Summary and outlook**

QCD within fRG

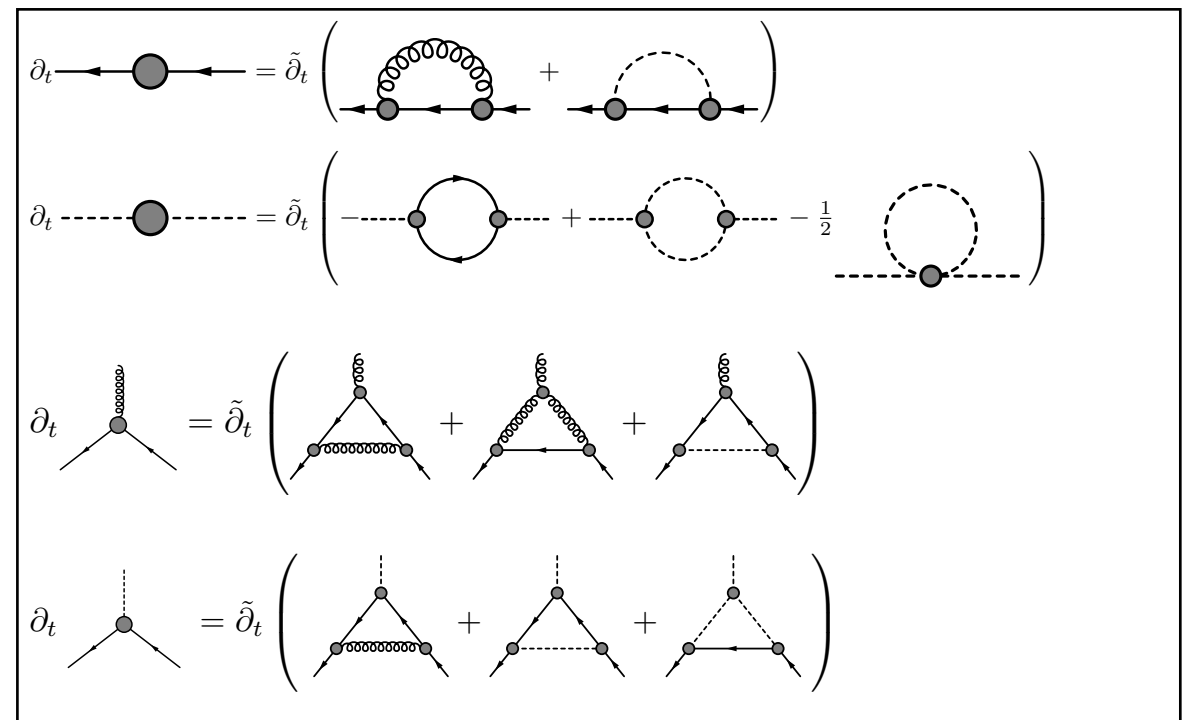
QCD flow equation:

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{(orange loop)} - \text{(dotted loop)} - \text{(solid loop)} + \frac{1}{2} \text{(blue loop)}$$

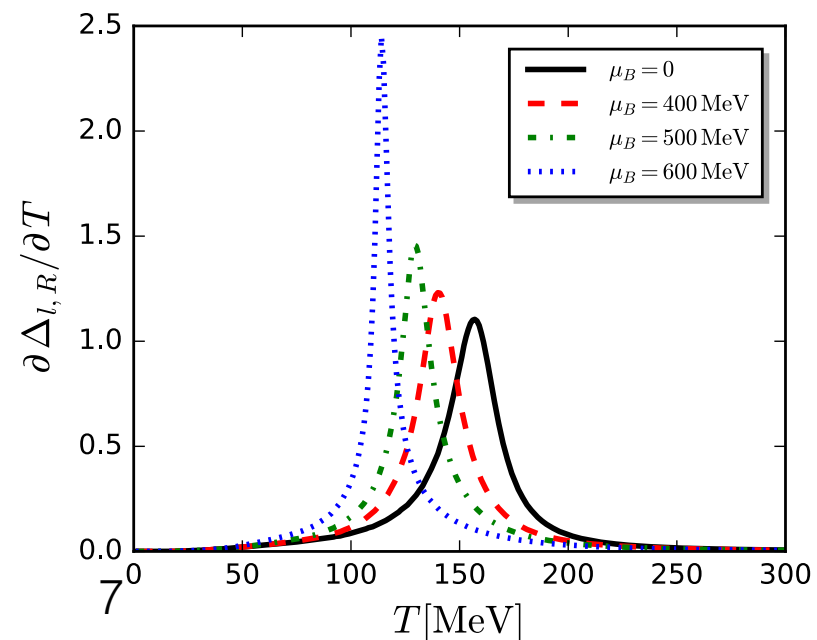
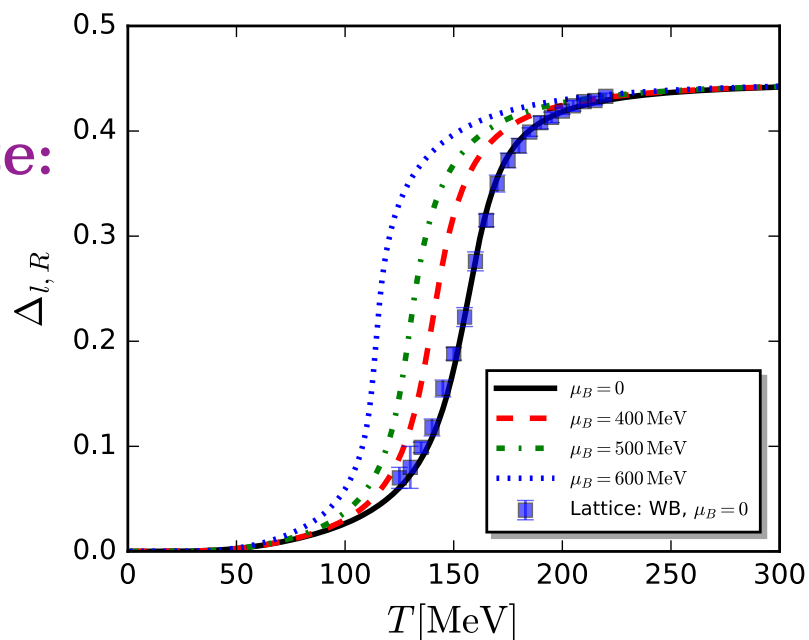
Glue sector:



Matter sector:



Quark condensate:

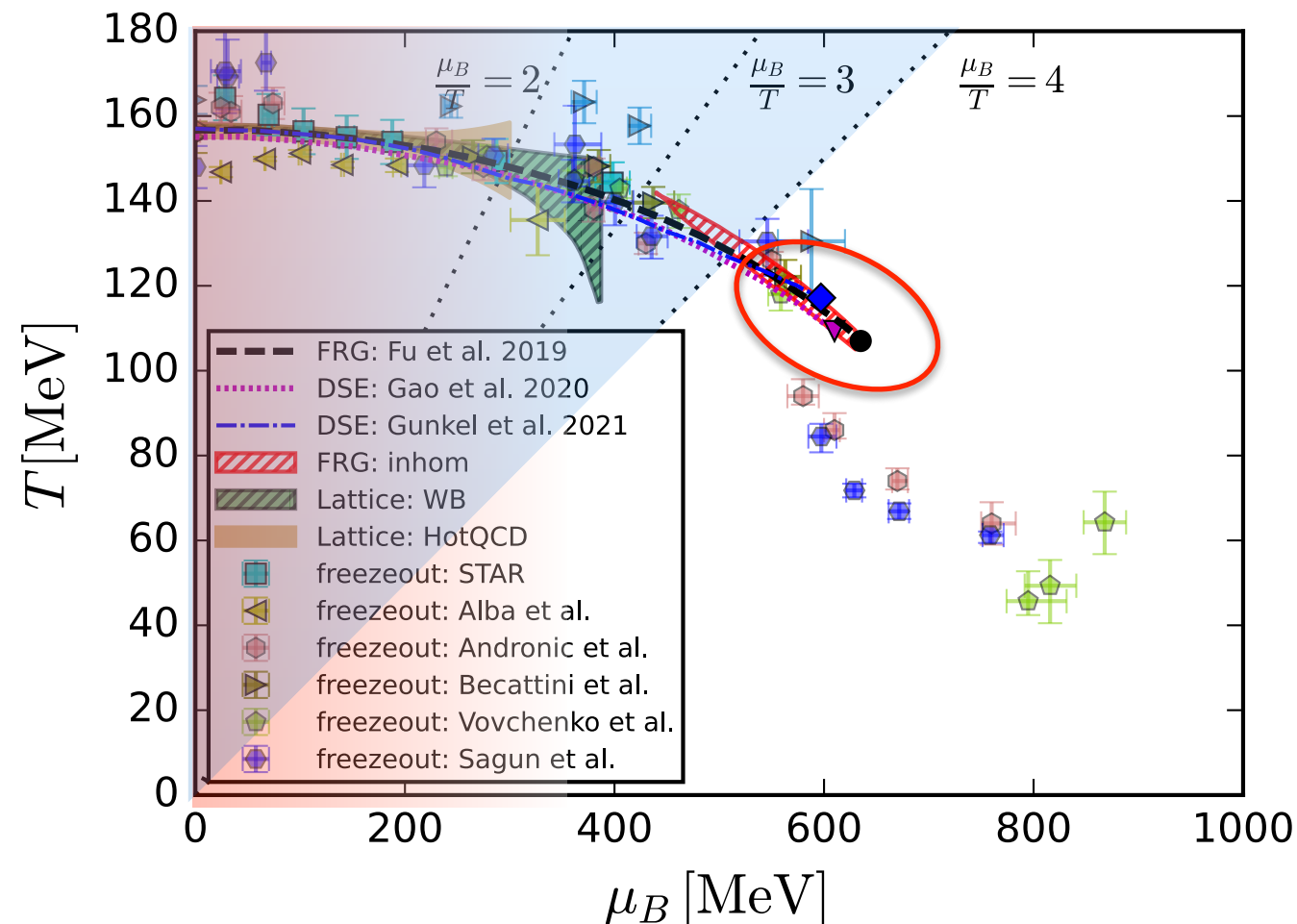


fRG: WF, Pawłowski, Rennecke,
PRD 101 (2020) 054032

Lattice: Borsanyi *et al.* (WB),
JHEP 09 (2010) 073

Quantitative errors analysis in fRG:
Ihssen, Pawłowski, Sattler, Wink,
arXiv:2408.08413

CEP from functional QCD around the year 2020



Passing through strict benchmark tests in comparison to lattice QCD at vanishing and small μ_B .

Regime of quantitative reliability of functional QCD with $\mu_B/T \lesssim 4$.

Estimates of the location of CEP from first-principles functional QCD:

fRG:

$$\bullet (T, \mu_B)_{\text{CEP}} = (107, 635) \text{ MeV}$$

WF, Pawłowski, Rennecke, *PRD* 101 (2020) 054032, arXiv:1909.02991

DSE:

$$\blacktriangledown (T, \mu_B)_{\text{CEP}} = (109, 610) \text{ MeV}$$

Gao, Pawłowski, *PLB* 820 (2021) 136584, arXiv:2010.13705

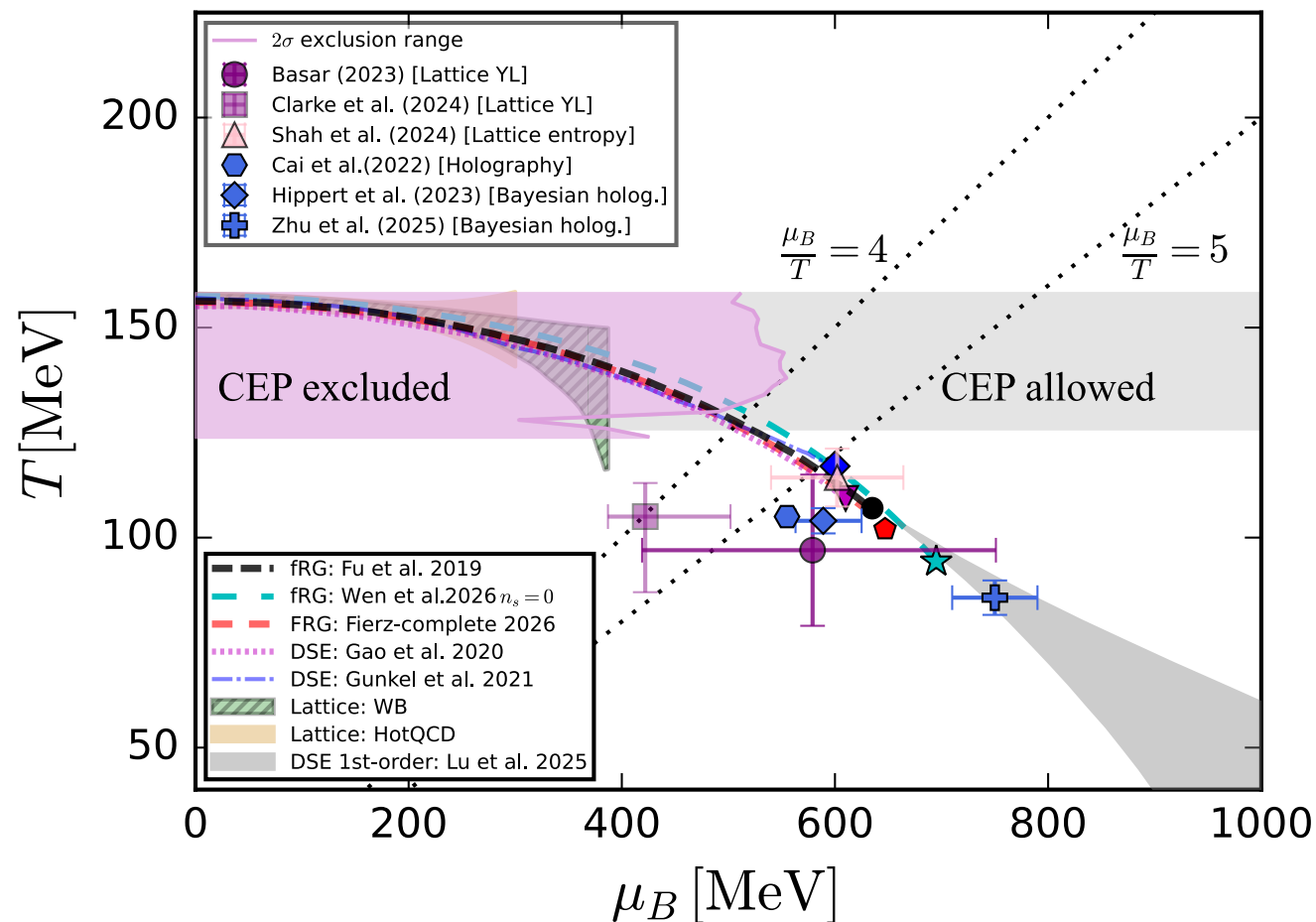
$$\blacklozenge (T, \mu_B)_{\text{CEP}} = (117, 600) \text{ MeV}$$

Gunkel, Fischer, *PRD* 104 (2021) 054022, arXiv:2106.08356

- Recent studies of QCD phase structure from both fRG and DSE have shown convergent estimate for the location of CEP:

$$(T, \mu_B)_{\text{CEP}} \approx (110 \pm 10, 630 \pm 30) \text{ MeV}$$

CEP from different approaches



Functional QCD (recent results):

fRG:

Pawlowski *et al.*, arXiv:2512.20510.

Fu *et al.*, arXiv:2603.13455; Wang *et al.*, arXiv:2607.07354.

DSE:

Lu *et al.*, *PRD* 113 (2026) 054019, arXiv:2504.05099.

Lu *et al.*, arXiv:2603.09336.

- Combined results of different approaches indicate the location of CEP is **not favored in the region $\mu_B/T \lesssim 4 \sim 5$.**

Lattice extrapolation:

Yang-Lee edge singularities

$$(T, \mu_B)_{\text{CEP}} = (97^{+18}_{-18}, 579^{+172}_{-160}) \text{ MeV}$$

Basar, *PRC* 110 (2024) 015203, arXiv:2312.06952.

$$(T, \mu_B)_{\text{CEP}} = (105^{+8}_{-18}, 422^{+80}_{-35}) \text{ MeV}$$

Clarke *et al.*, *PRD* 112 (2025) L091504, arXiv:2405.10196.

$$T_{\text{CEP}} \leq 103 \text{ MeV (84 \% level) or no CEP}$$

Adam *et al.*, arXiv:2507.13254.

Contours of constant entropy density

$$(T, \mu_B)_{\text{CEP}} = (114.3 \pm 6.9, 602.1 \pm 62.1) \text{ MeV}$$

Shah *et al.*, *PRC* 113 (2026) L012201, arXiv:2410.16206.

No CEP at $\mu_{B\text{CEP}} < 450 \text{ MeV}$ at the 2σ level

Borsanyi *et al.*, *PRD* 112 (2025) L111505, arXiv:2502.10267.

(Bayesian) holography:

$$(T, \mu_B)_{\text{CEP}} = (105, 555) \text{ MeV}$$

Cai *et al.*, *PRD* 106 (2022) L121902, arXiv:2201.02004.

$$(T, \mu_B)_{\text{CEP}} = (104 \pm 3, 589^{+36}_{-26}) \text{ MeV (95\% level)}$$

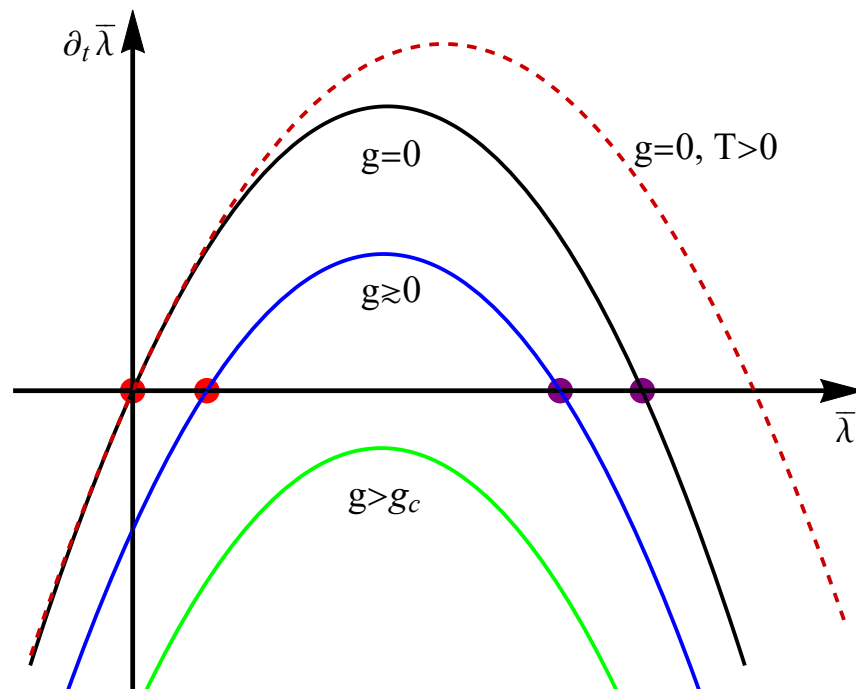
Hippert *et al.*, *PRD* 110 (2024) 094006, arXiv:2309.00579.

$$(T, \mu_B)_{\text{CEP}} = (81.6 - 89.8, 710 - 790) \text{ MeV (95\% level)}$$

Zhu *et al.*, *PRD* 112 (2025) 026019, arXiv:2501.17763.

Four-quark interactions and chiral symmetry breaking

Beta function of four-quark couplings:



Braun, Gies, *JHEP* 06 (2006) 024.

$$\partial_t \bar{\lambda} = (d-2)\bar{\lambda} - a\bar{\lambda}^2 - b\bar{\lambda}g^2 - cg^4,$$

Four-quark interactions

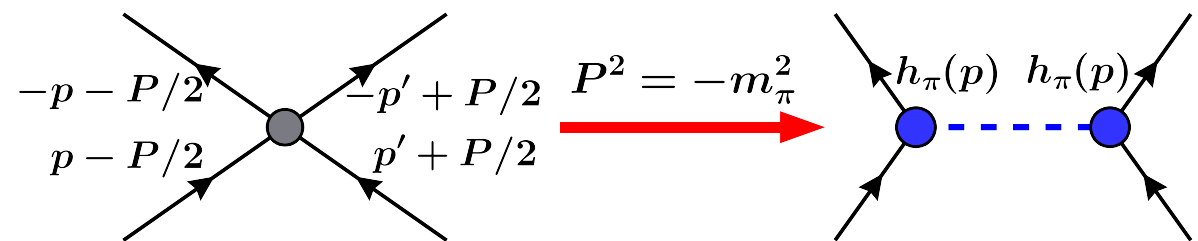
$$\Gamma_{4q} = - \int_x \sum_{\alpha \in \mathcal{F}} \lambda_\alpha \mathcal{T}_{ijmn}^{(\alpha)} \bar{q}_{li} q_{lj} \bar{q}_{lm} q_{ln}$$

with Fierz-complete four-quark basis of ten tensors

$$\mathcal{F} = \left\{ \sigma, \pi, a, \eta, (V \pm A), (V - A)^{\text{adj}}, \right. \\ \left. (S \pm P)^{\text{adj}}_-, (S + P)^{\text{adj}}_+ \right\}$$

Yukawa couplings via dynamical hadronization

$$\Gamma_{\bar{q}q\phi} = h_\sigma \bar{q}_l T^0 \sigma q_l + h_\pi \bar{q}_l i\gamma_5 \vec{T} \cdot \vec{\pi} q_l$$

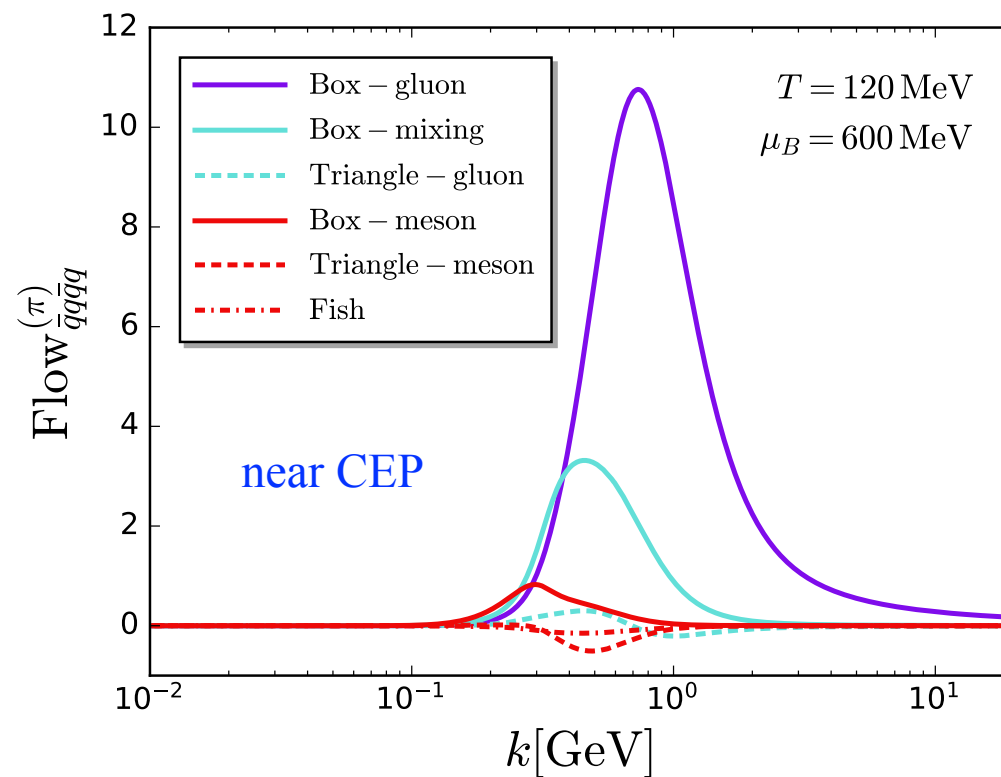
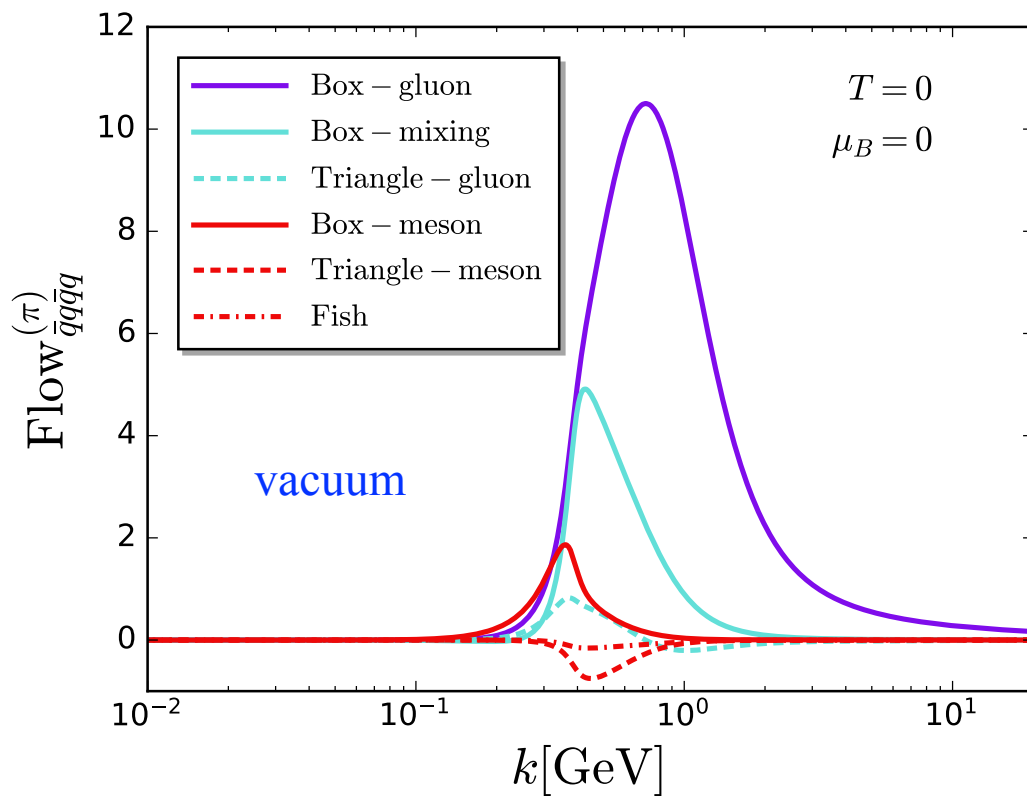
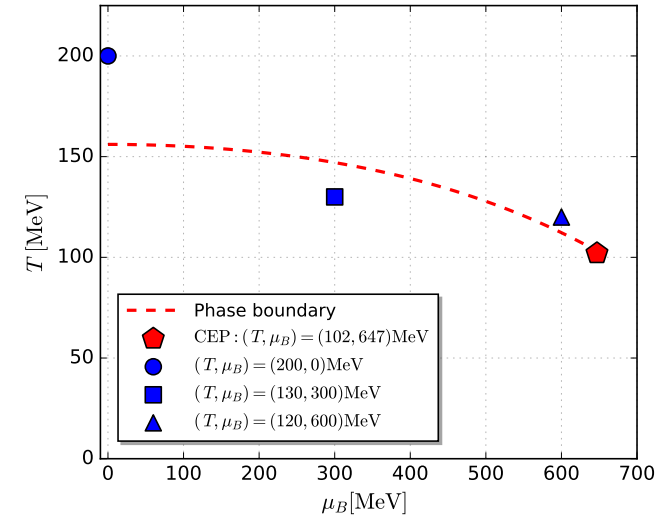


Wang, Zhou, Huang, Wen, Yin, WF, arXiv:2607.07354.

Four-quark flows

Flow equations of four-quark vertices:

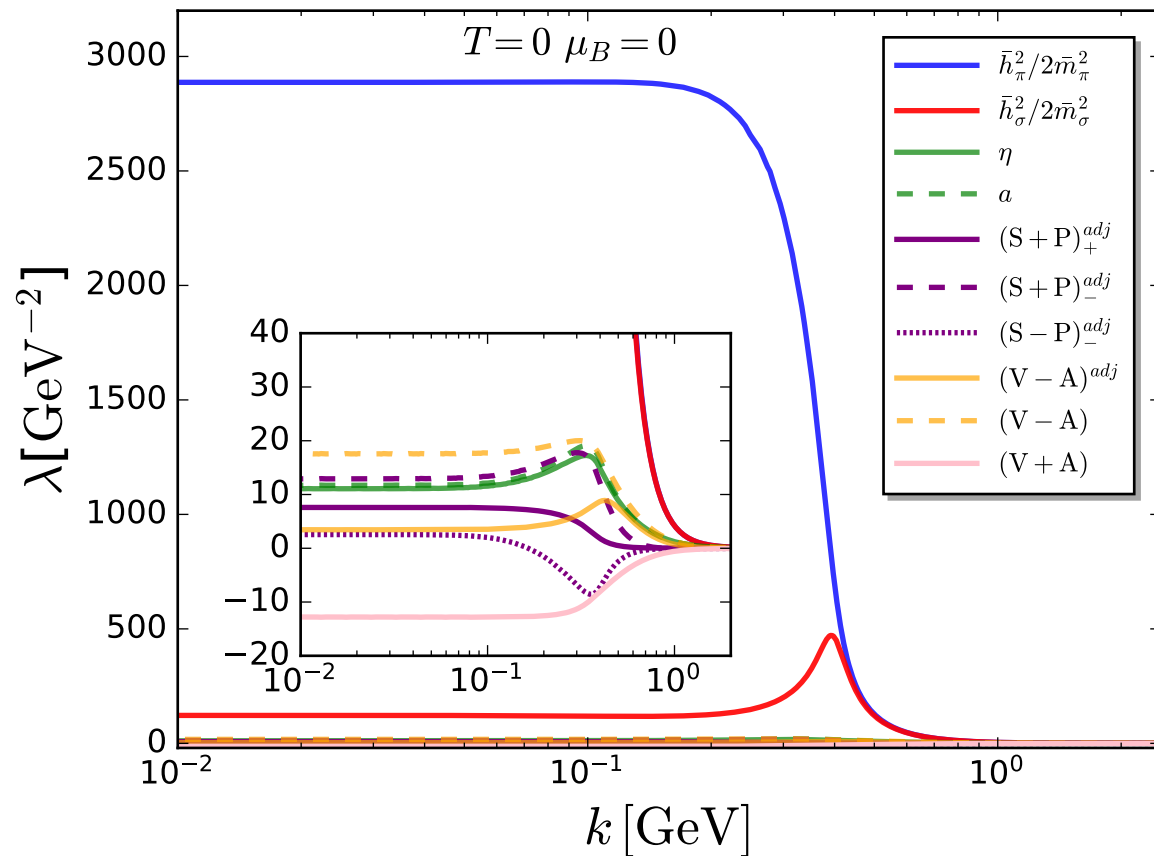
$$\partial_t \left(\text{Diagram: Four-quark vertex} \right) = \tilde{\partial}_t \left(\text{Diagram: Box-gluon} + \text{Diagram: Box-meson} + \text{Diagram: Triangle-gluon} + \text{Diagram: Triangle-meson} + \text{Diagram: Fish} \right)$$



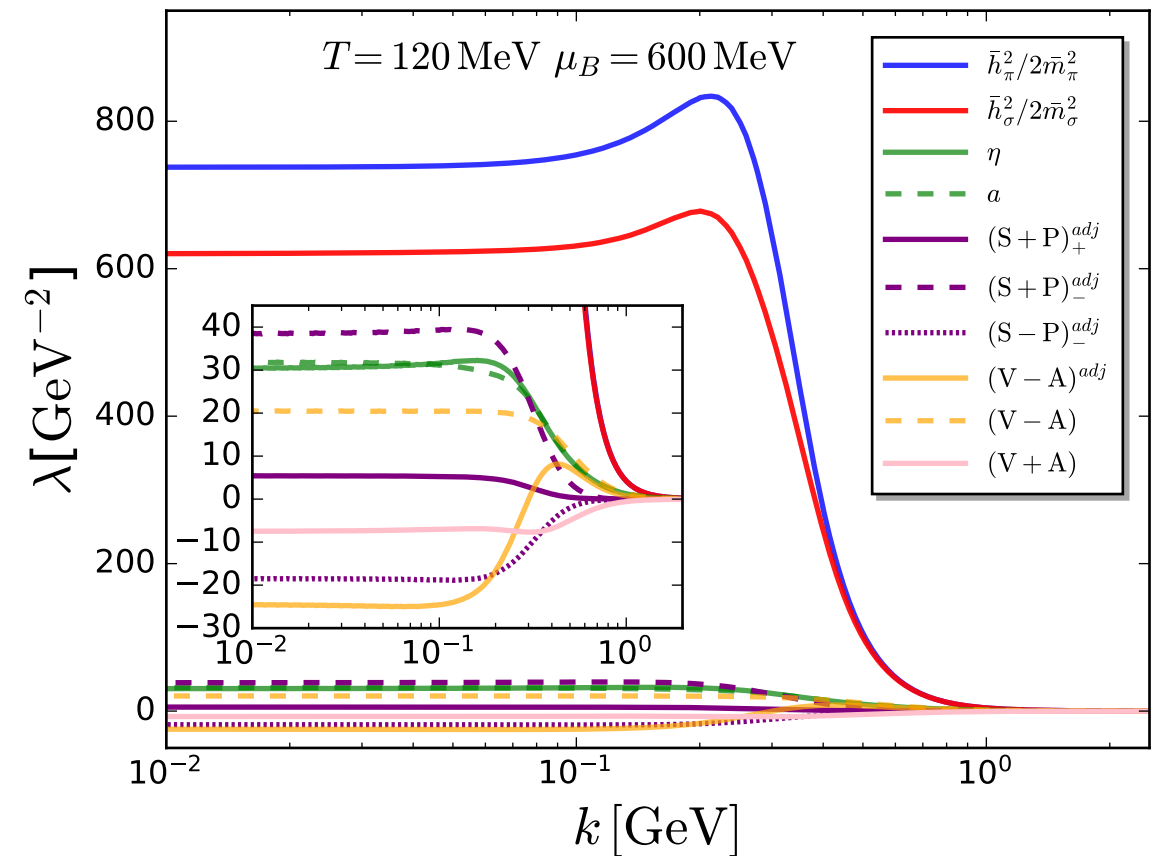
- Diagrams of gluon and meson interactions show dominance at different RG scales.

Four-quark couplings of different channels

Four-quark couplings in the vacuum:



Four-quark couplings near CEP:

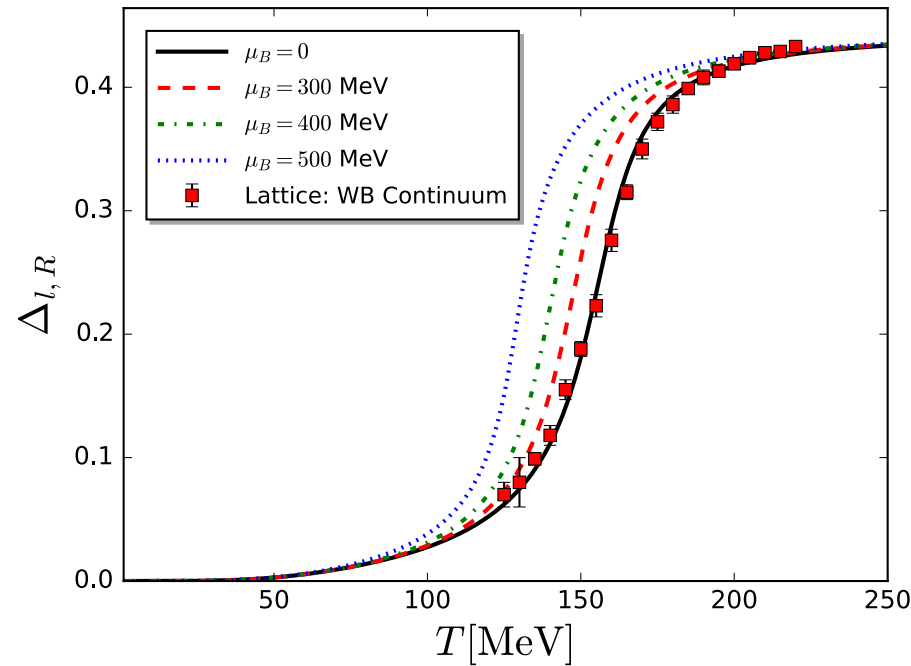


- The **pion** and **sigma** channels play the dominant roles.
- Channels other than the scalar-pseudoscalar channels become **more relevant** towards CEP.

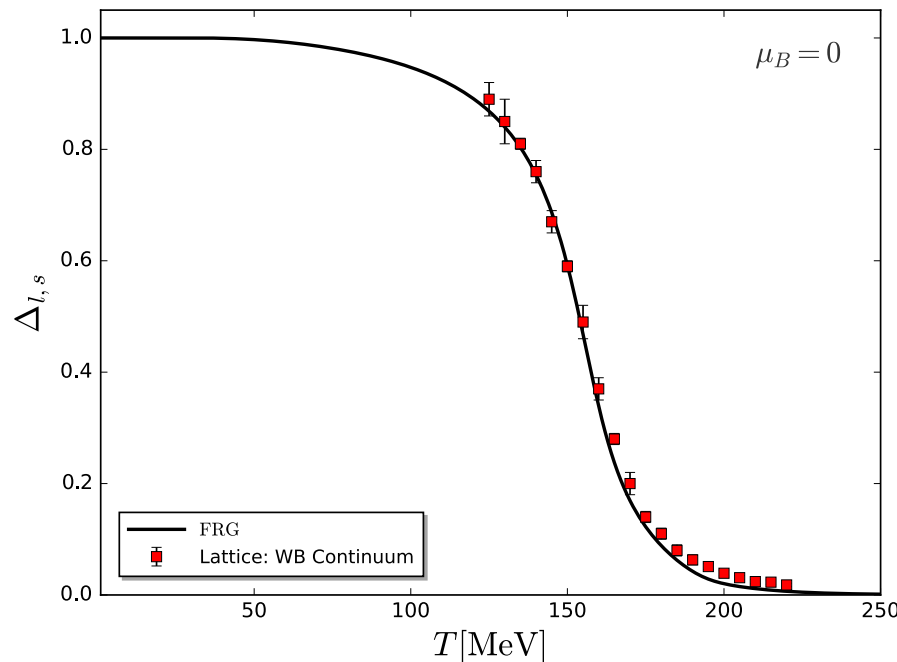
Wang, Zhou, Huang, Wen, Yin, WF, arXiv:2607.07354.

QCD phase diagram with Fierz-complete four-quark interactions

Light quark condensate:



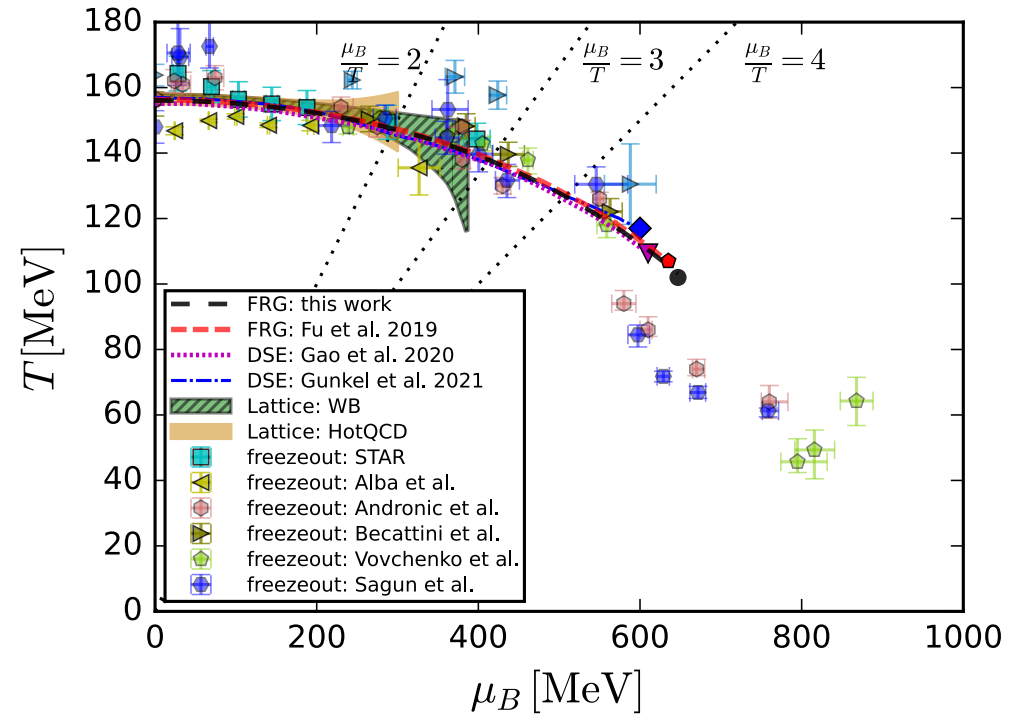
Reduced condensate:



fRG: Wang, Zhou, Huang, Wen, Yin, WF, arXiv:2607.07354.

Lattice: S. Borsanyi *et al.*, *JHEP* 09 (2010) 073.

QCD phase diagram:



Phase boundary:

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

Curvature coefficients:

$$\kappa_2 = 0.0151(1), \quad \kappa_4 = 0.00023(2)$$

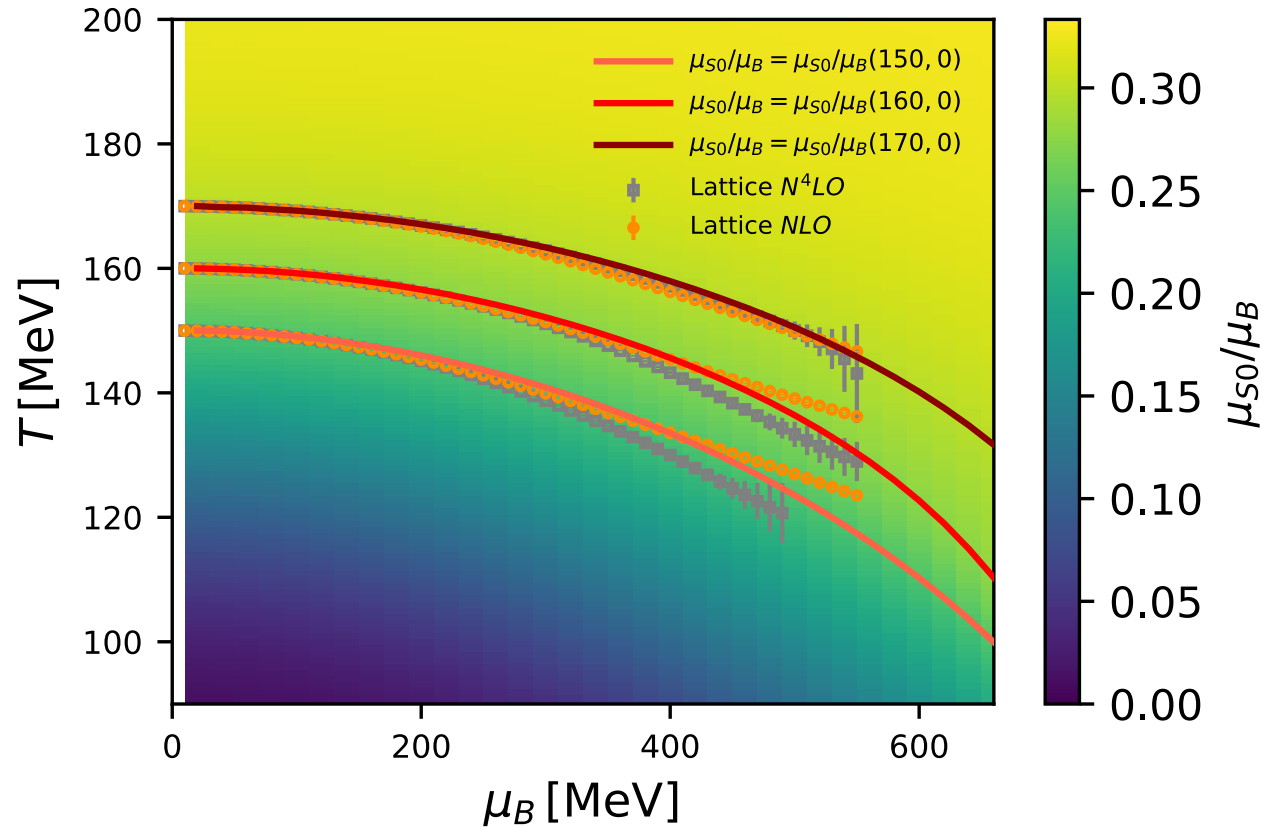
CEP:

$$(T_{\text{CEP}}, \mu_{B,\text{CEP}}) = (102, 647) \text{ MeV}$$

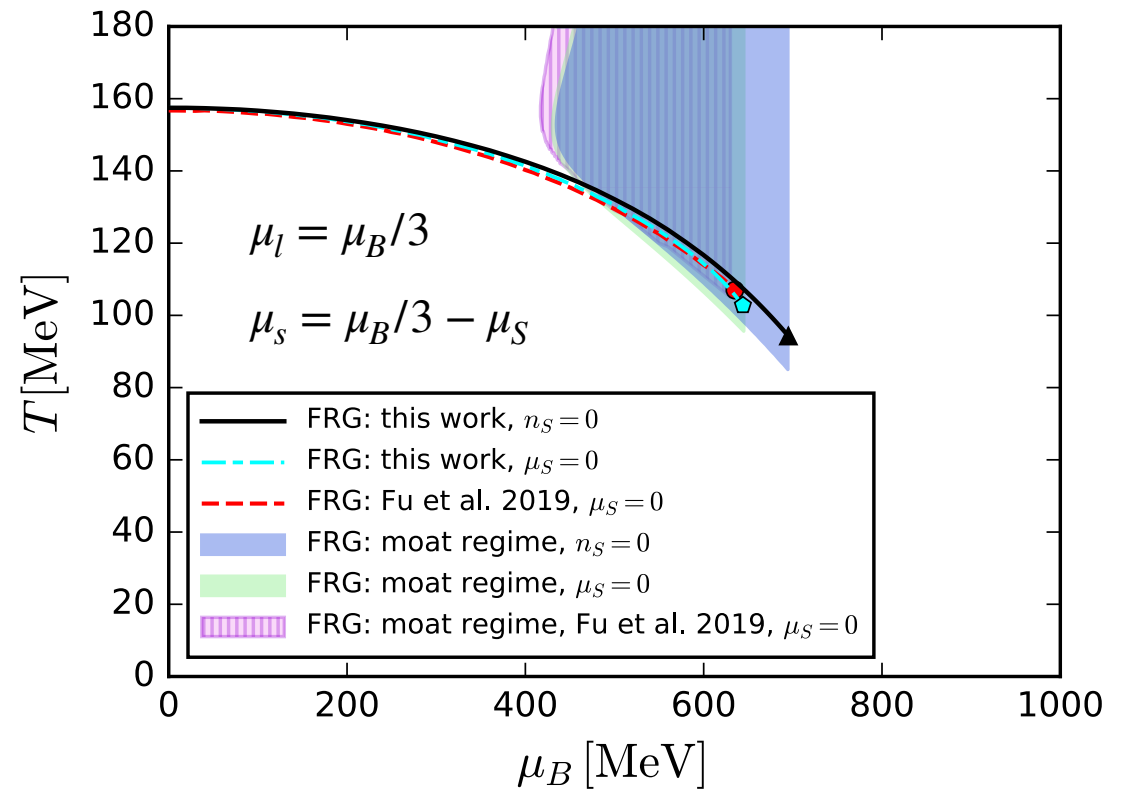
- The dynamics of Fierz-complete four-quark interactions **increases** a bit the curvature of the phase boundary, and moves the CEP to location of **larger** baryon chemical potential and **smaller** temperature.

CEP and strangeness neutrality

μ_S with constraint $n_S = 0$



Phase diagram with $n_S = 0$



Curvature of the phase boundary:

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

fRG: $\frac{\kappa_2^{n_S=0}}{\kappa_2^{\mu_S=0}} = 0.897(20)$ **Lattice:** $\frac{\kappa_{2,\text{lat}}^{n_S=0}}{\kappa_{2,\text{lat}}^{\mu_S=0}} = 0.893(35)$

- Strangeness neutrality **flattens** a bit the phase boundary and moves CEP to **larger** μ_B .

$\mu_S = 0:$ $(T, \mu_B)_{\text{CEP}} = (102, 644) \text{ MeV}$



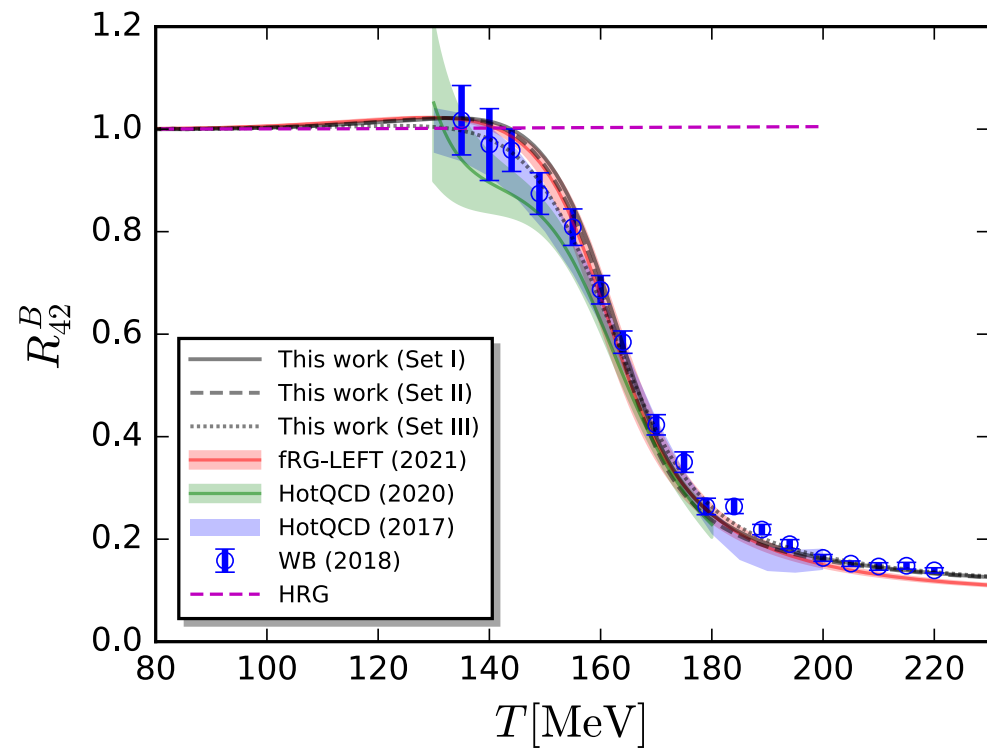
$n_S = 0:$ $(T, \mu_B)_{\text{CEP}} = (92, 696) \text{ MeV}$

fRG: WF, Huang, Pawłowski, Rennecke, Wen, Yin, arXiv:2603.13455.

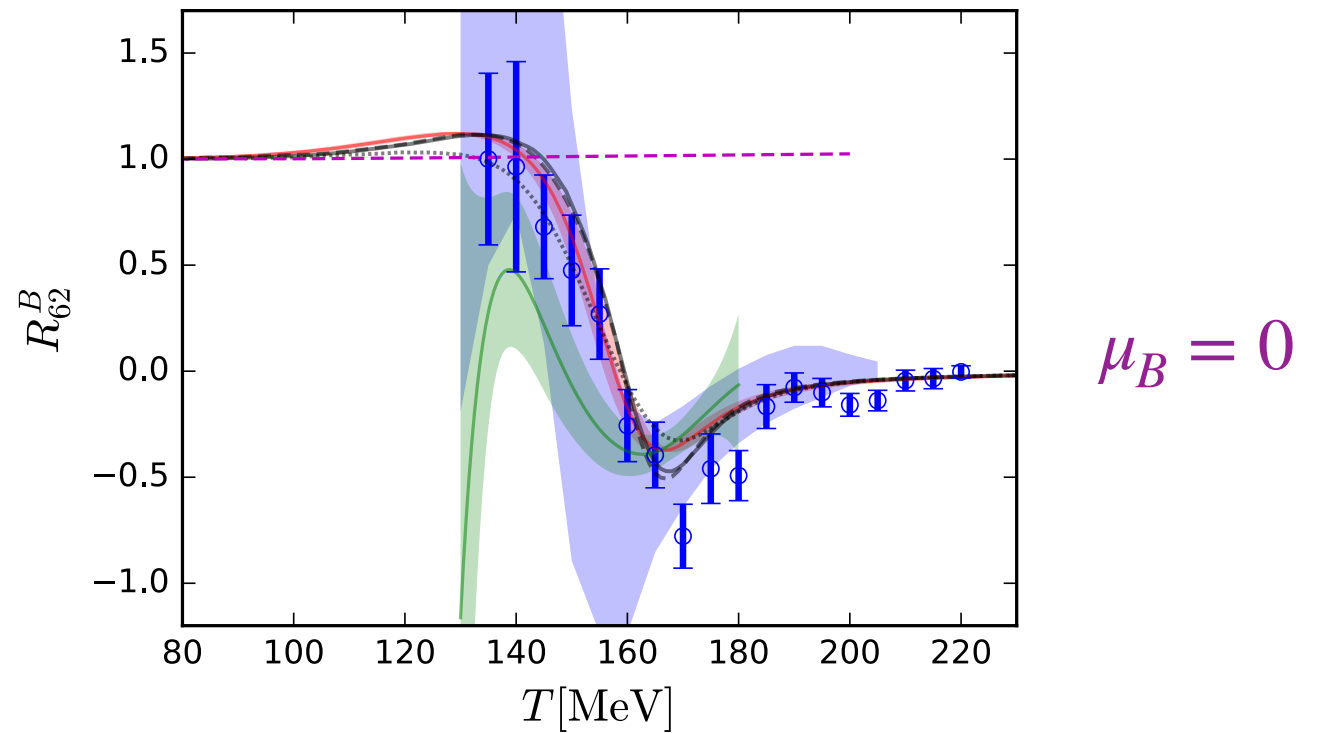
Lattice: Ding *et al.*, *PRD* 109 (2024) 114516, arXiv:2403.09390.

Lattice: Borsanyi *et al.*, arXiv:2510.26455.

Baryon number fluctuations



fRG: WF, Luo, Pawłowski, Rennecke, Yin, *PRD* 111 (2025) L031502, arXiv: 2308.15508; WF, Luo, Pawłowski, Rennecke, Wen, Yin, *PRD* 104 (2021) 094047.



HotQCD: A. Bazavov *et al.*, *PRD* 95 (2017), 054504; *PRD* 101 (2020), 074502.

WB: S. Borsanyi *et al.*, *JHEP* 10 (2018) 205.

Baryon number fluctuations

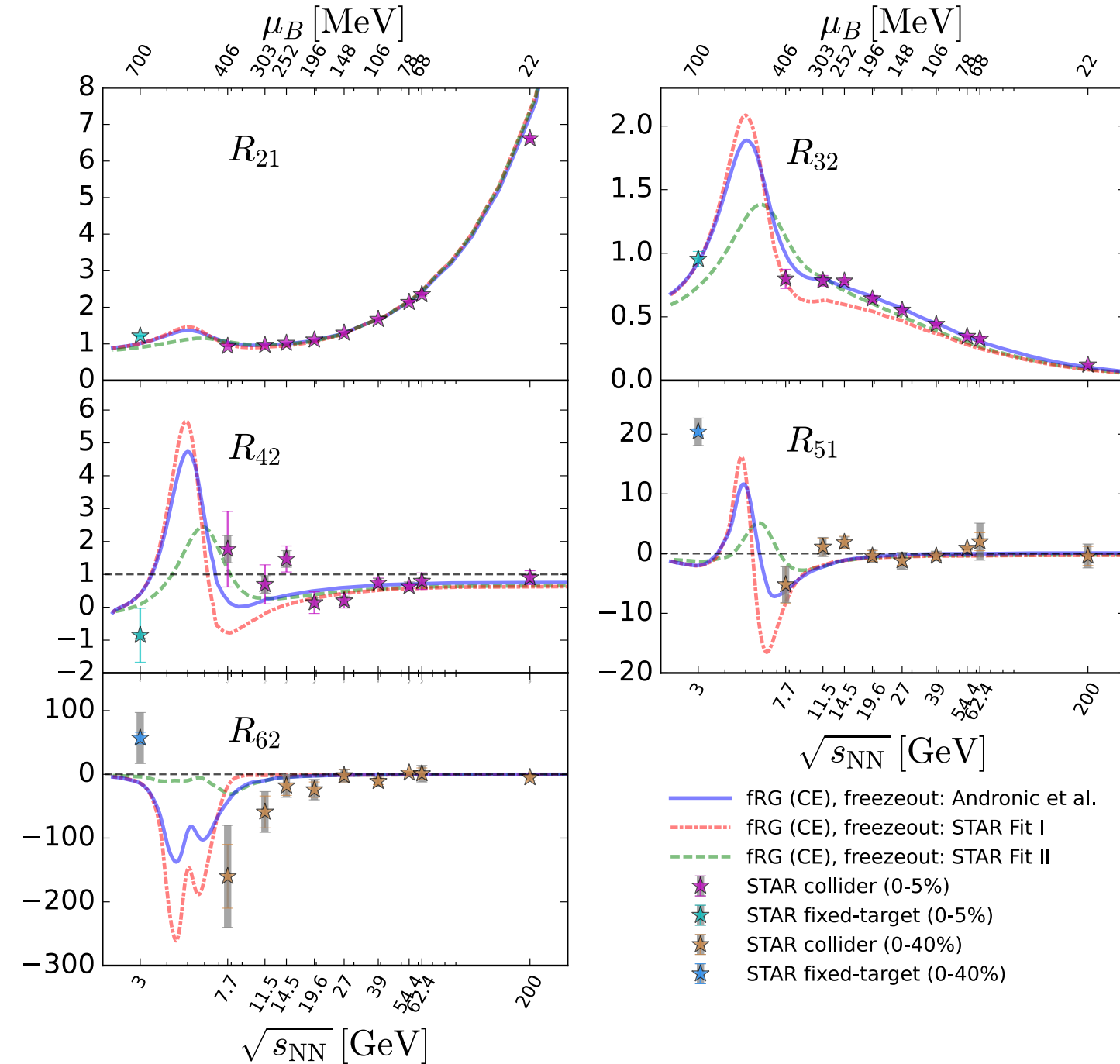
$$\chi_n^B = \frac{\partial^n}{\partial (\mu_B/T)^n} \frac{p}{T^4} \quad R_{nm}^B = \frac{\chi_n^B}{\chi_m^B}$$

Relation to the cumulants

$$\frac{M}{VT^3} = \chi_1^B, \quad \frac{\sigma^2}{VT^3} = \chi_2^B, \quad S = \frac{\chi_3^B}{\chi_2^B \sigma}, \quad \kappa = \frac{\chi_4^B}{\chi_2^B \sigma^2},$$

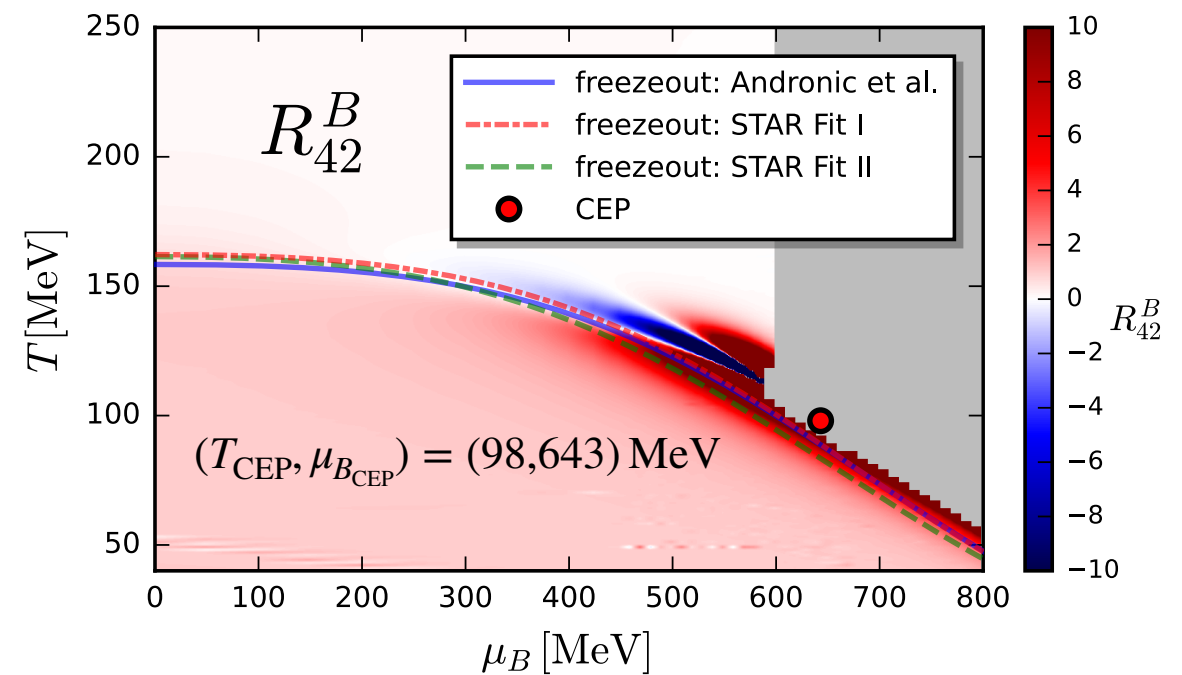
- In comparison to lattice results and our former results, the improved results of baryon number fluctuations at vanishing chemical potential in the QCD-assisted LEFT are **convergent** and **consistent**.

Fluctuations at the freeze-out curve



fRG: WF, Luo, Pawlowski, Rennecke, Yin, *PRD* 111 (2025) L031502, arXiv: 2308.15508.

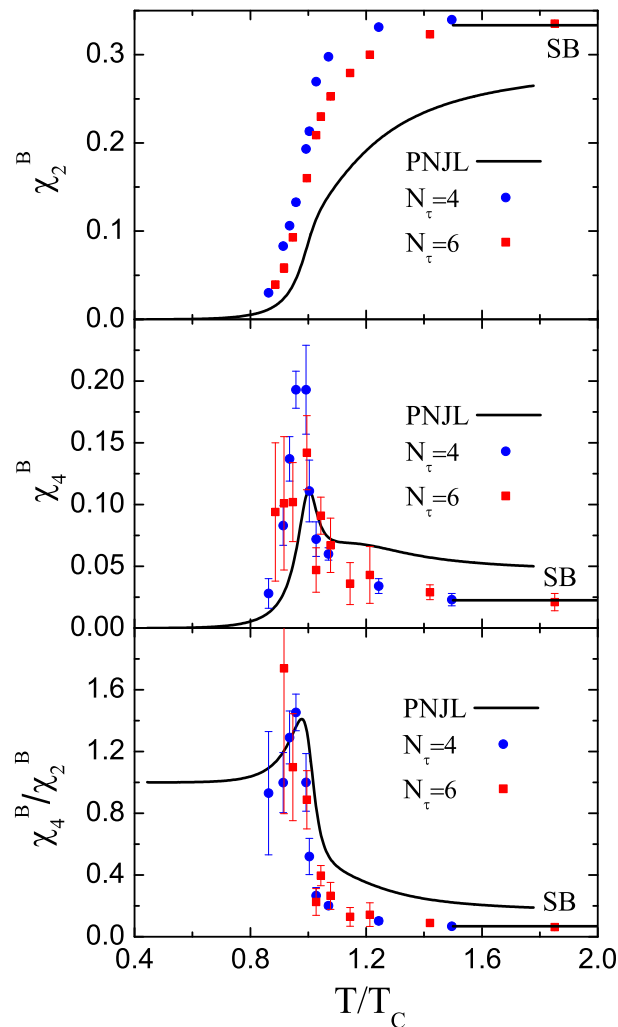
STAR: Adam *et al.* (STAR), *PRL* 126 (2021) 092301;
Abdallah *et al.* (STAR), *PRL* 128 (2022) 202303;
Aboona *et al.* (STAR), *PRL* 130 (2023) 082301.



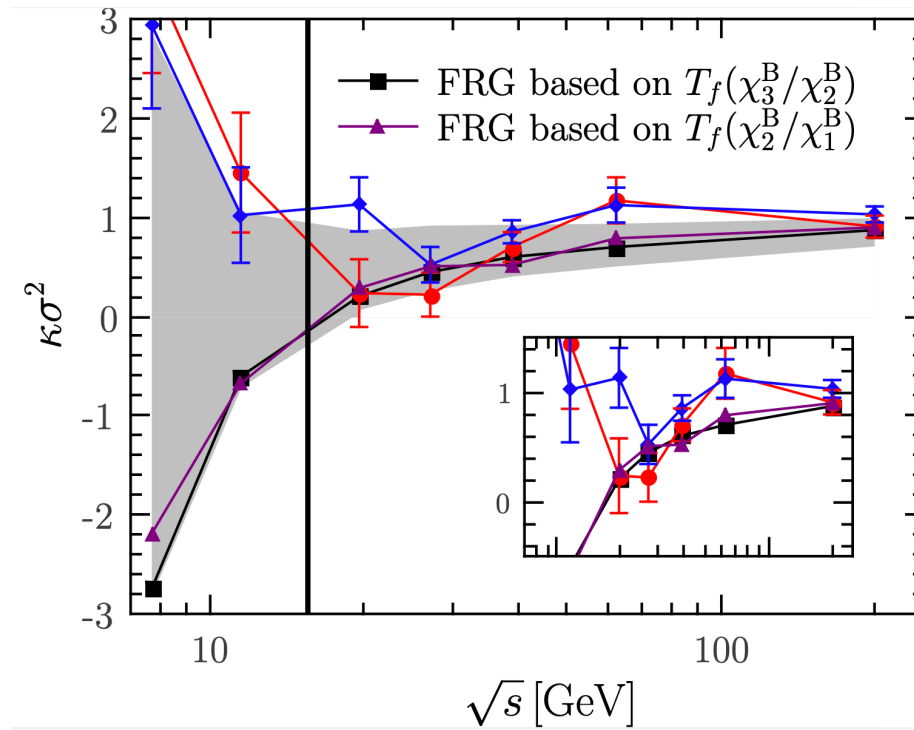
- Peak structure is found in 3 GeV $\lesssim \sqrt{s_{NN}} \lesssim 7.7$ GeV.
- Position of peak in R_{42} is $\mu_{B_{\text{peak}}} = 536, 541$ and 486 MeV for the three freeze-out curves, significantly smaller than $\mu_{B_{\text{CEP}}} = 643$ MeV.

C₄/C₂: Kurtosis of fluctuations

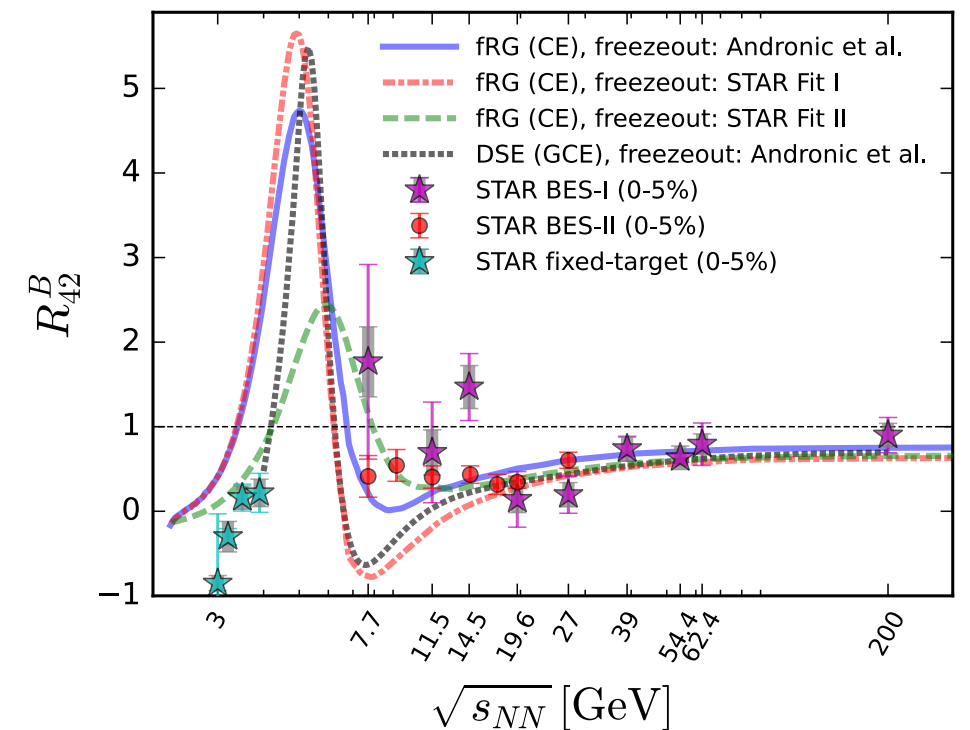
Net baryon (proton) number kurtosis:



Mean field: WF, Yu-xin Liu, Yue-Liang Wu, *PRD* 81 (2010) 014028, arXiv: 0910.5783.



fRG: WF, Pawłowski, *PRD* (rapid communications) 93 (2016) 091501, arXiv: 1512.08461.



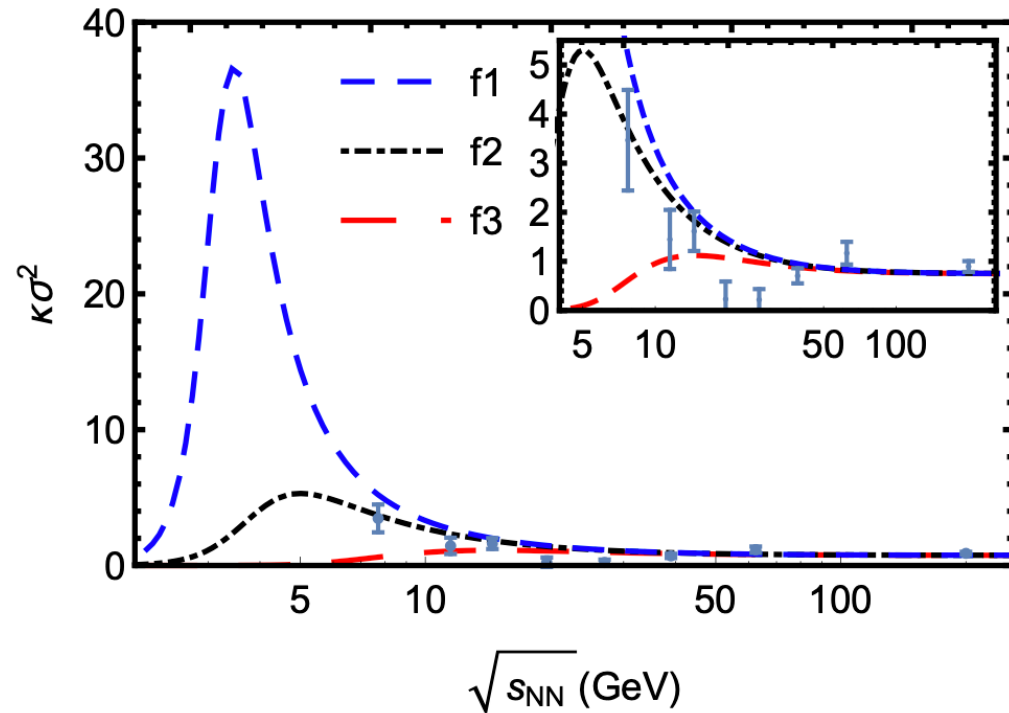
STAR: *PRL* 135 (2025) 142301, arXiv:2504.00817.

fRG: WF, Luo, Pawłowski, Rennecke, Yin, *PRD* 111 (2025) L031502, arXiv: 2308.15508.

- A peak structure is predicted in the energy regime of fixed-target experiments, i.e. $3 \text{ GeV} \lesssim \sqrt{s_{\text{NN}}} \lesssim 7.7 \text{ GeV}$. Experimental search of this peak is very important.

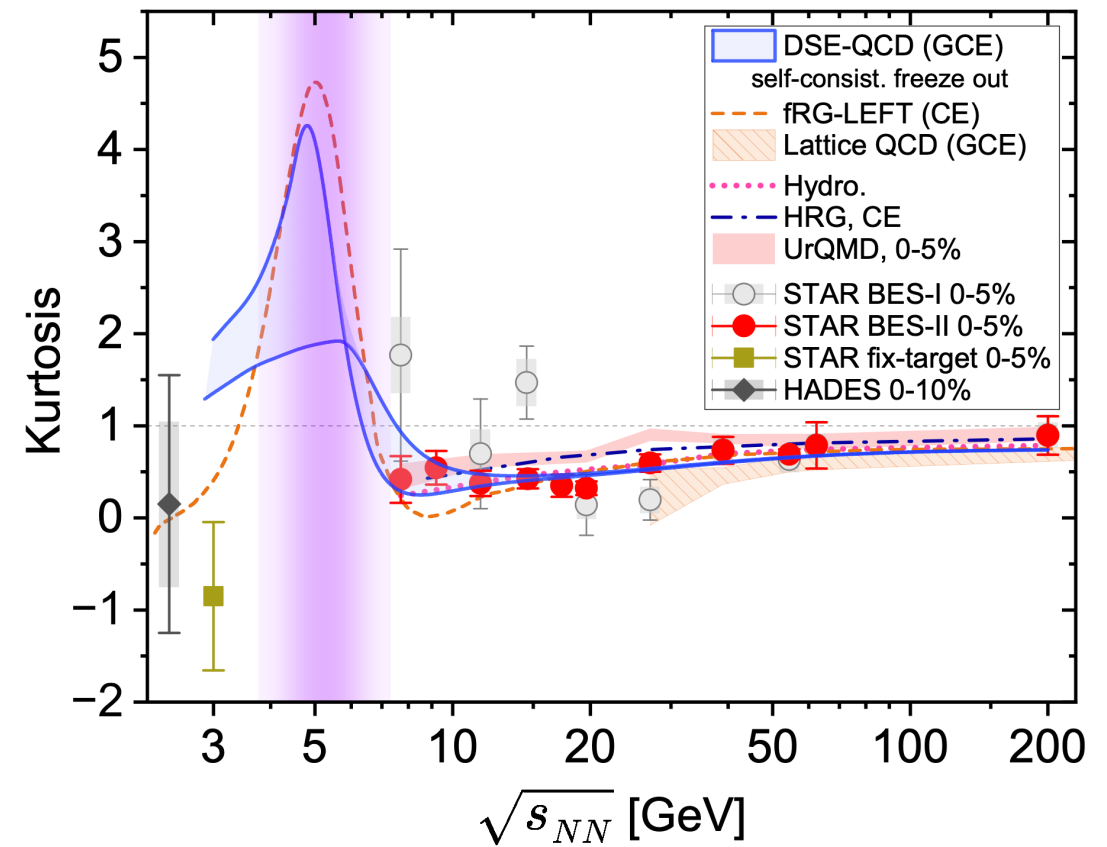
Baryon number kurtosis from different approaches

Holography:



Zhibin Li, Yidian Chen, Danning Li, Mei Huang,
CPC 42 (2018) 0131, arXiv:1706.02238;
Zhibin Li, Kun Xu, Xinyang Wang and Mei Huang,
EPJC 79 (2019) 245, arXiv:1801.09215.

DSE:

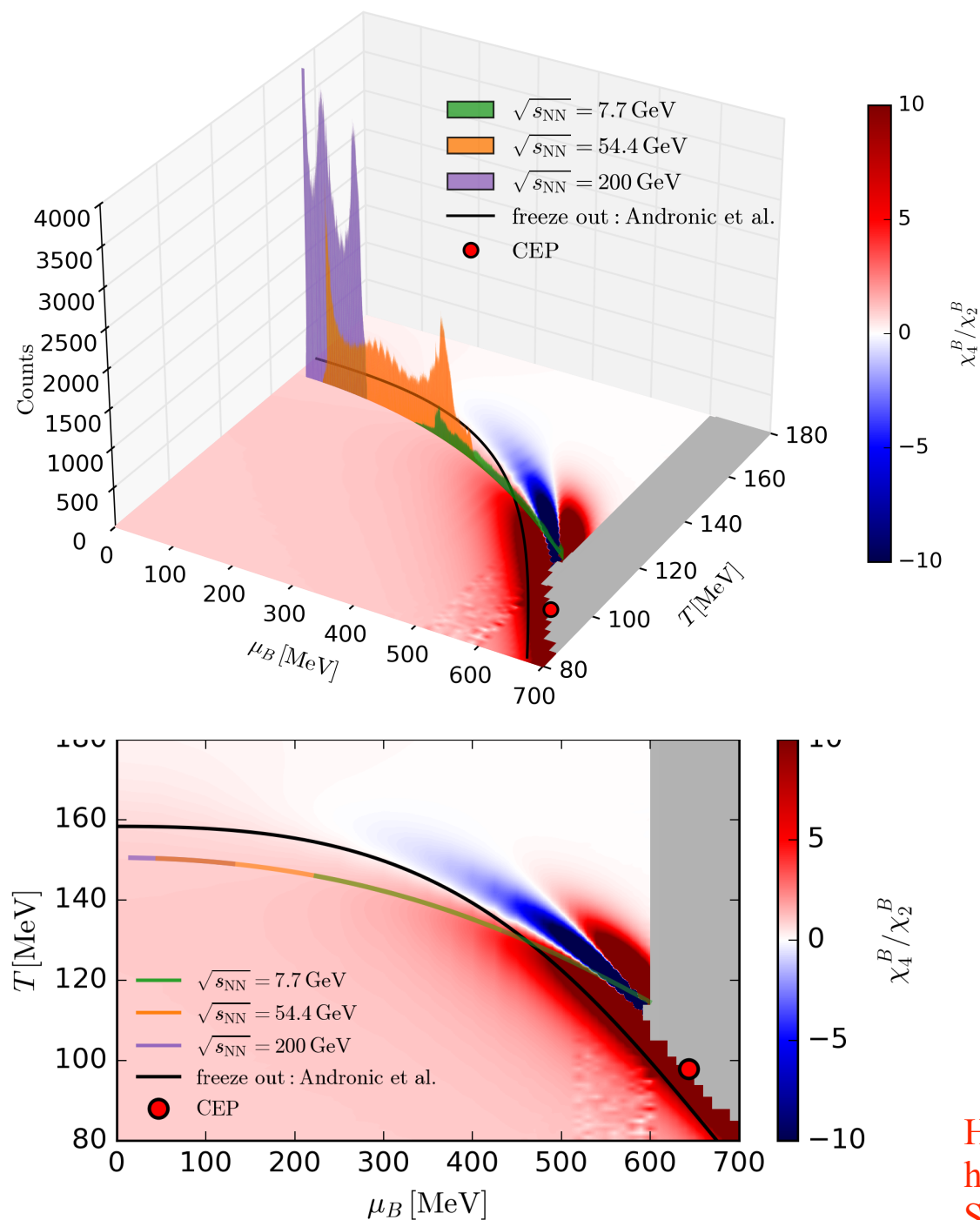


DSE: Lu, Fischer, Gao, Liu, Pawłowski, arXiv:2603.09336; Lu, Gao, Liu, Pawłowski, *PRD* 113 (2026) 054019, arXiv:2504.05099.

- A peak structure is also found in the results from holography and DSE.

Critical fluctuations + hydrodynamics

Fluid elements distributed
on the phase diagram:



Effects included:

- **Hypersurface elements** of different T and μ_B obtained from hydrodynamics simulations

$$\delta C_n^{B\pm, gce}(x_i) = \delta V_i^{\text{eff}} T^3(x_i) \chi_n^{B\pm}(x_i).$$

- Implementing the baryon number fluctuations calculated from **fRG**

$$\chi_n^{B\pm} = \frac{\chi_n^{B\pm, HRG}}{\chi_n^{B, HRG}} \chi_n^{B, fRG}.$$

- Using the Cooper-Frye formula to determine the probability within an **acceptance window** of momenta and rapidity $p_{\text{acc}}(x_i; \Delta p_{\text{acc}})$.
- Using the **isospin randomization** to calculate the (anti)proton cumulants.
- **Global baryon number conservation** via the subensemble acceptance method (SAM).

HRG+hydro: Vovchenko, Koch, Shen, *PRC* 105 (2022) 014904, arXiv:2107.00163.

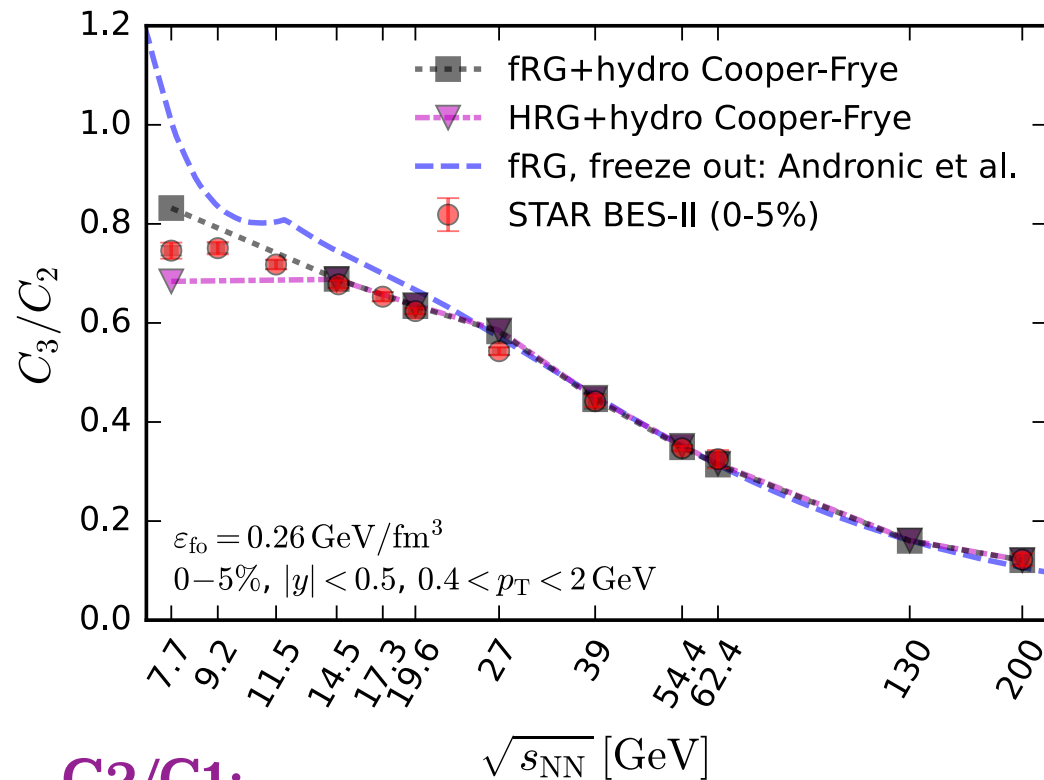
hydro: Du, Gao, Jeon, Gale, *PRC* 109 (2024) 014907, arXiv:2302.13852.

SAM: Vovchenko, Savchuk, Poberezhnyuk, Gorenstein, Koch, *PLB* 811 (2020) 135868.

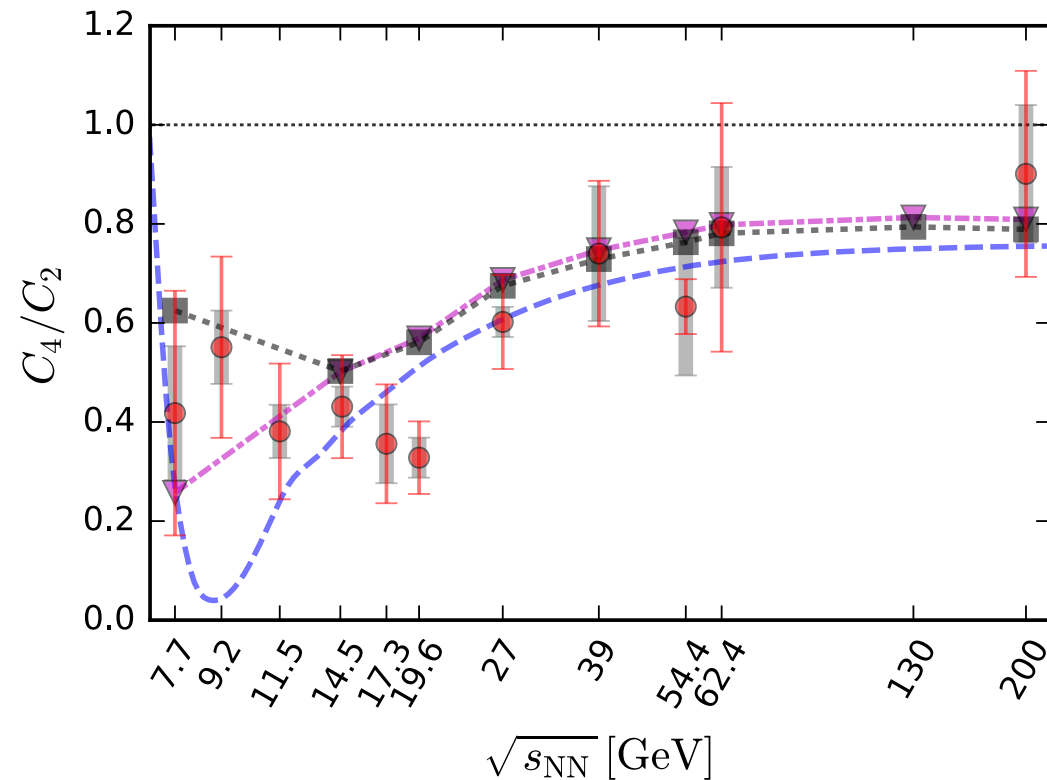
fRG+hydro: Zhao, Yin, Wu, Du, Luo, WF, arXiv:2607.26912.

Critical net-proton fluctuations with hydrodynamics

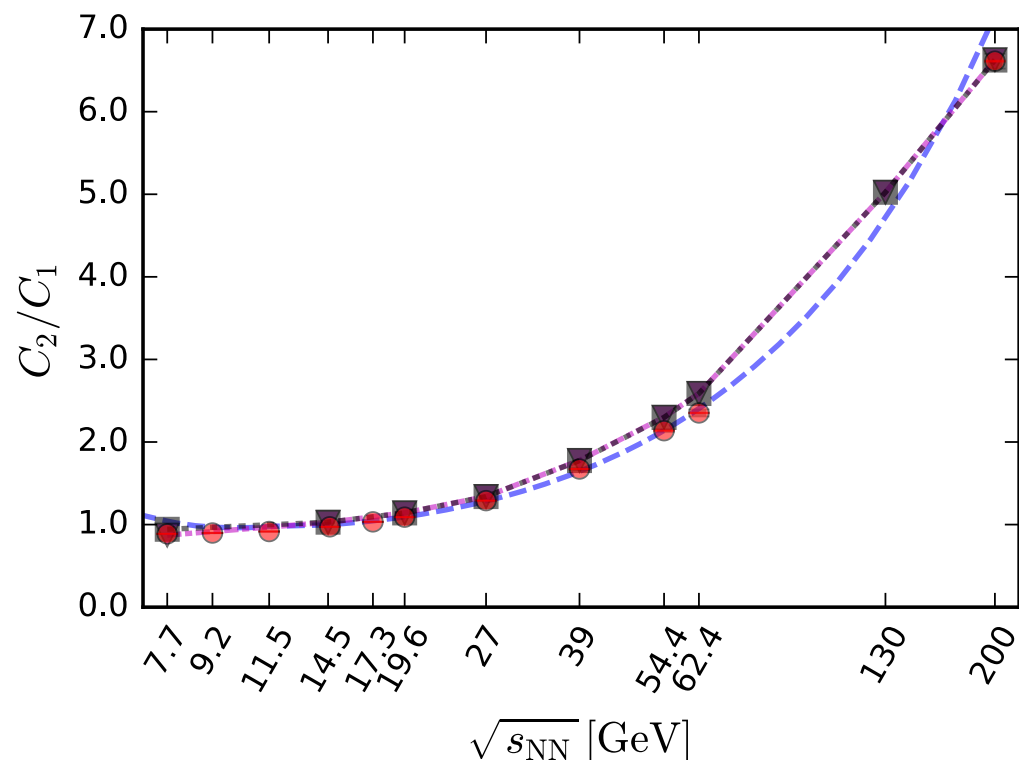
C_3/C_2 :



C_4/C_2 :



C_2/C_1 :

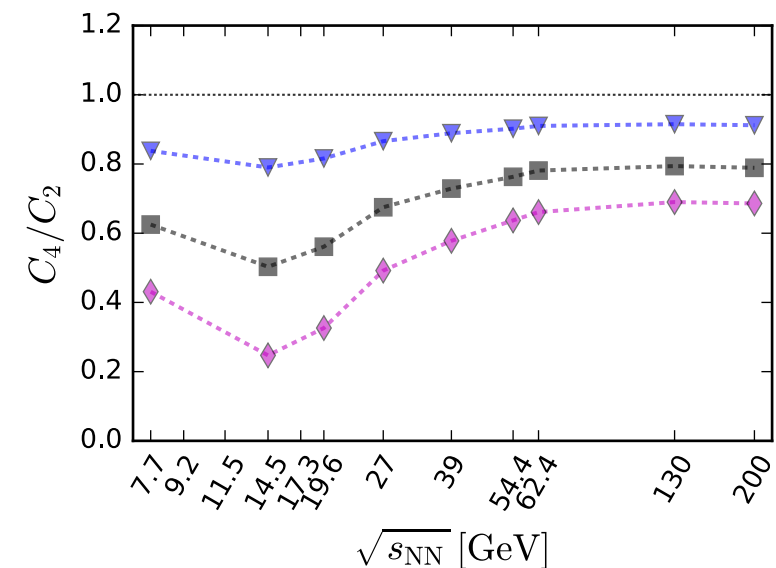
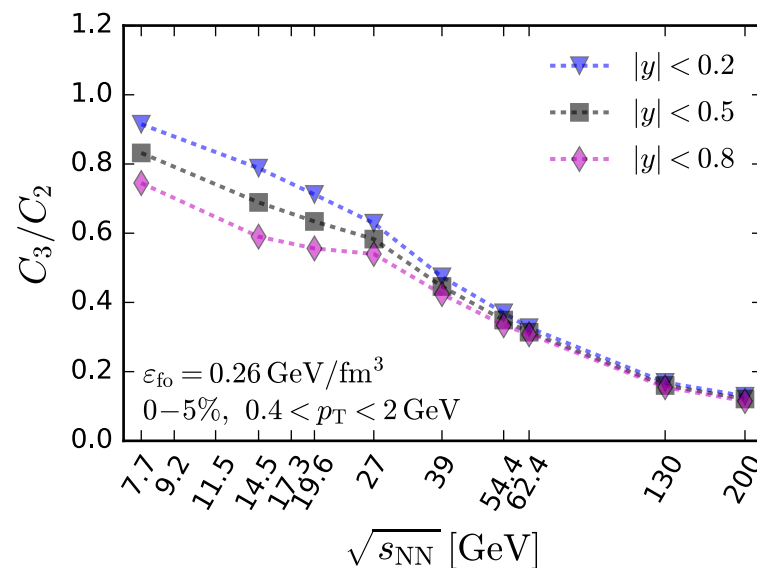
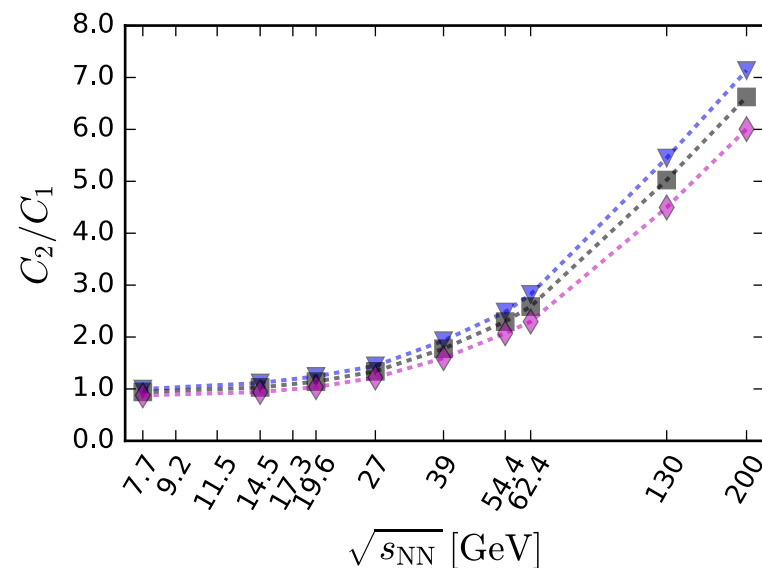


- **Non-monotonic** dependence is observed in fRG+hydro, in comparison to the HRG+hydro.
- In comparison to the critical fluctuations computed on the parametrized freeze-out curve, fRG+hydro shows a **better agreement** with the experimental data.

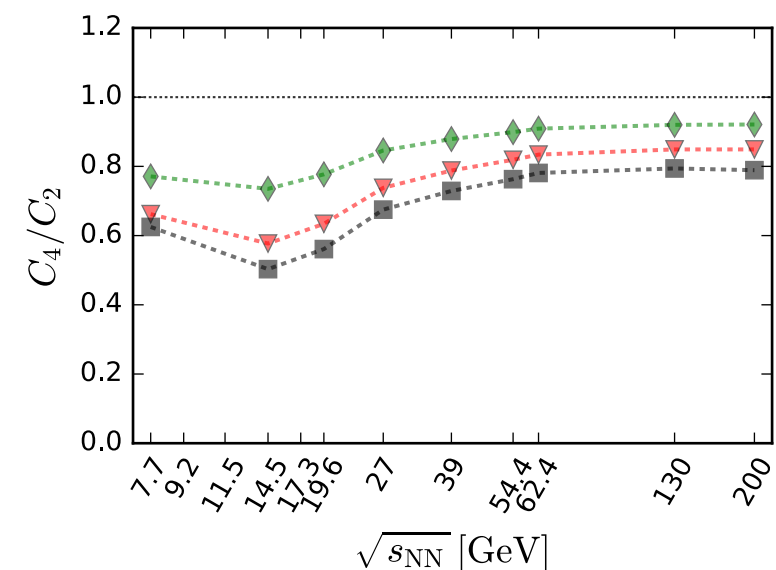
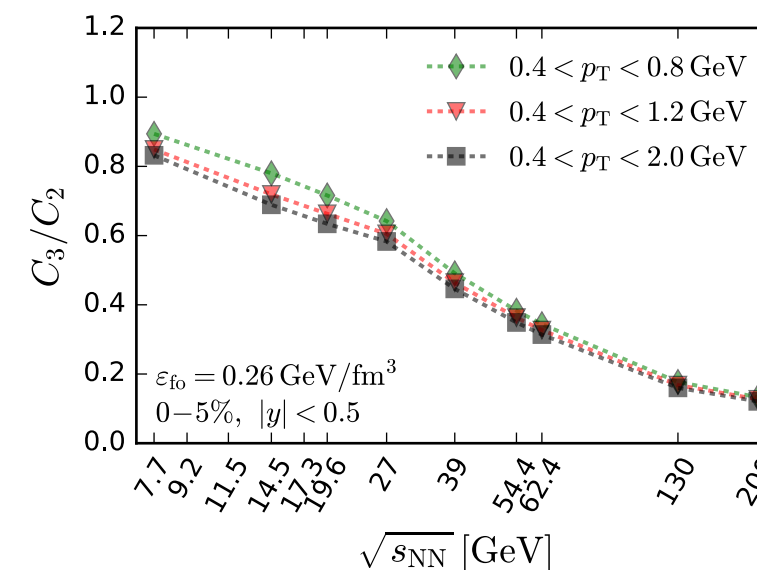
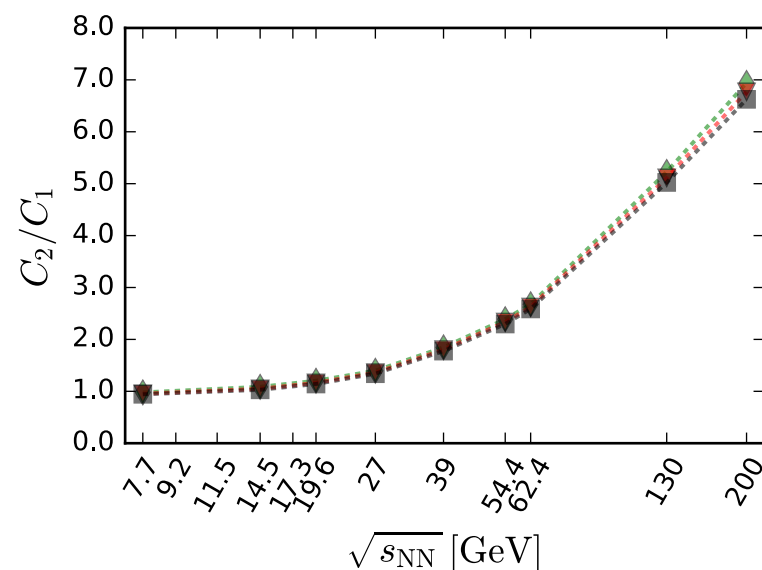
fRG+hydro: Zhao, Yin, Wu, Du, Luo, WF, arXiv:2607.26912.

fRG+hydro: Acceptance dependence

Rapidity:



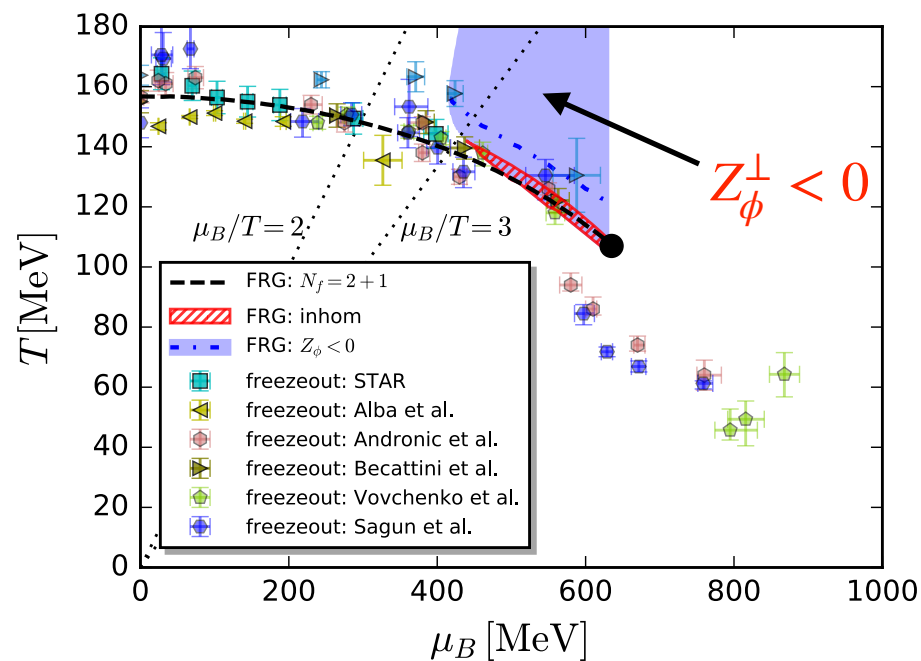
Transverse momentum:



- C_3/C_2 , C_4/C_2 are **suppressed** with the increase of the acceptance window due to the global baryon conservation effect.
- The non-monotonic dependence of C_4/C_2 does **not** depend on the acceptance window.

Moat regime in QCD phase diagram

Moat (护城河) regime:



Indicated in QCD calculations:

WF, Pawłowski, Rennecke, *PRD* 101 (2020) 054032.



Mesonic two-point correlation function:

$$\Gamma_{\phi\phi}^{(2)}(p) = [Z_\phi^\parallel(p_0, \mathbf{p}) p_0^2 + Z_\phi^\perp(p_0, \mathbf{p}) \mathbf{p}^2] + m_\phi^2$$

with

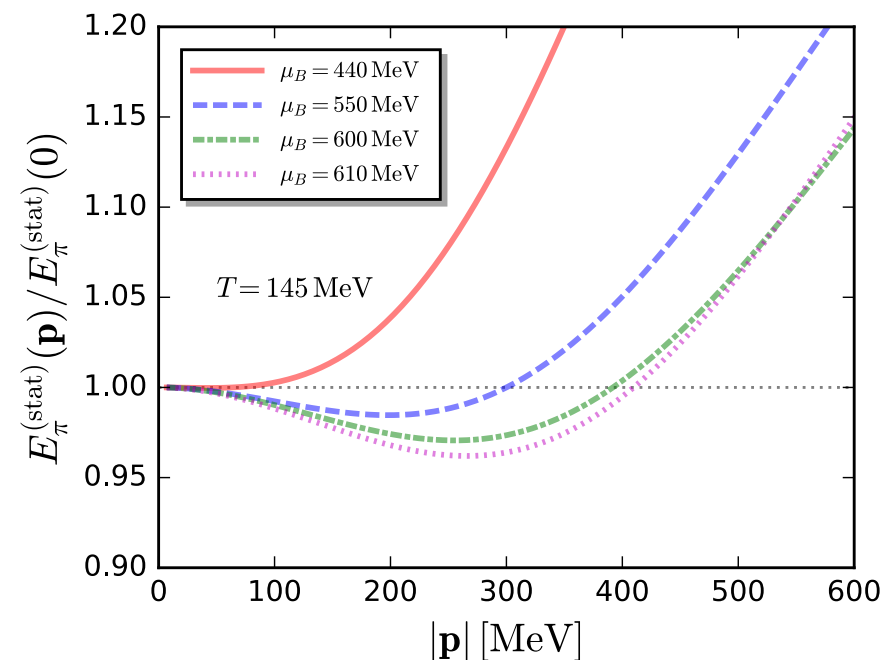
$$\Gamma_{\phi\phi,k}^{(2)} = \frac{\delta^2 \Gamma_k[\Phi]}{\delta\phi\delta\phi} \Big|_{\Phi=\Phi_{\text{EoM}}}$$

Phenomenology:

Pisarski, Rennecke, *PRL* 127 (2021) 152302;

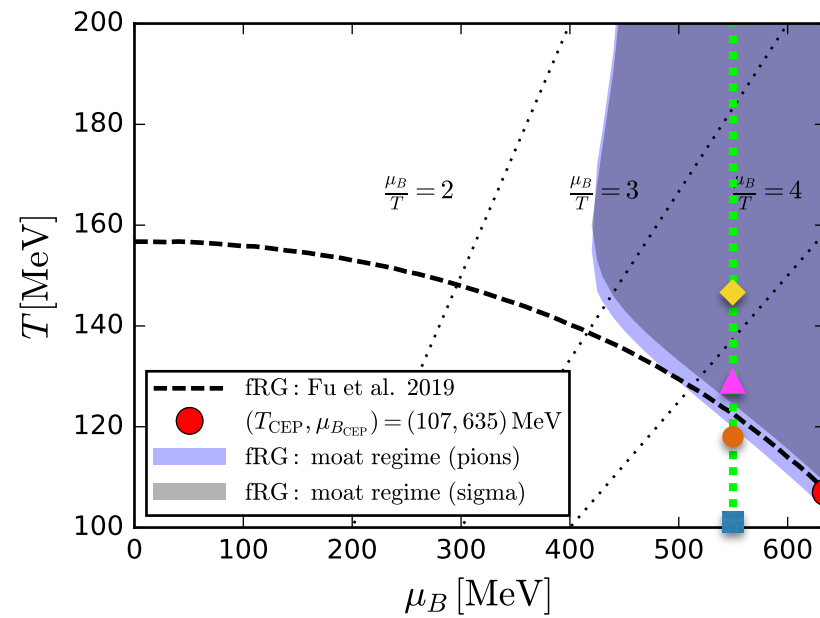
Rennecke, Pisarski, Rischke, *PRD* 107 (2023) 116011.

Dispersion relation:



WF, Pawłowski, Pisarski, Rennecke, Wen, Yin, *PRD* 111 (2025) 094026.

Spectral functions in moat regime

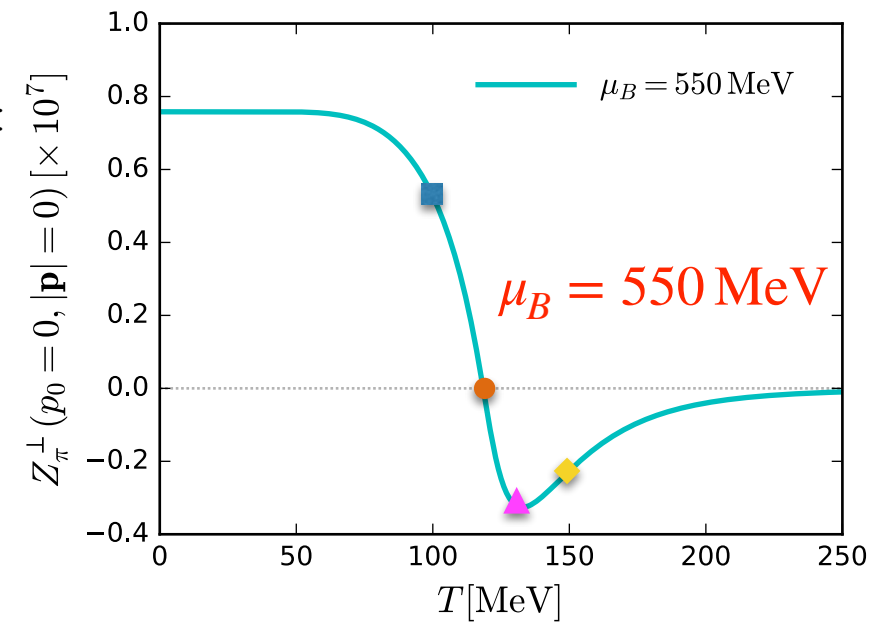


Analytic continuation on the flow equation:

$$G_\phi^R(\omega, \vec{p}) = \lim_{\epsilon \rightarrow 0^+} G_\phi(-i(\omega + i\epsilon), \vec{p})$$

Spectral functions of mesons:

$$\rho_\phi(\omega, \vec{p}) = \frac{1}{\pi} \text{Im} G_\phi^R(\omega, \vec{p})$$

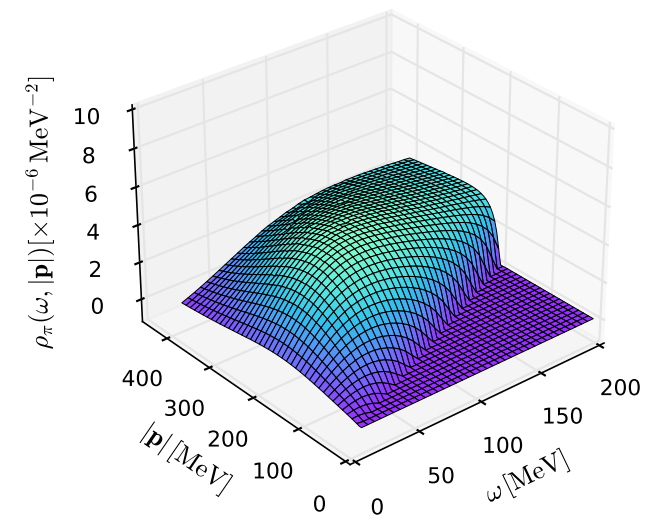
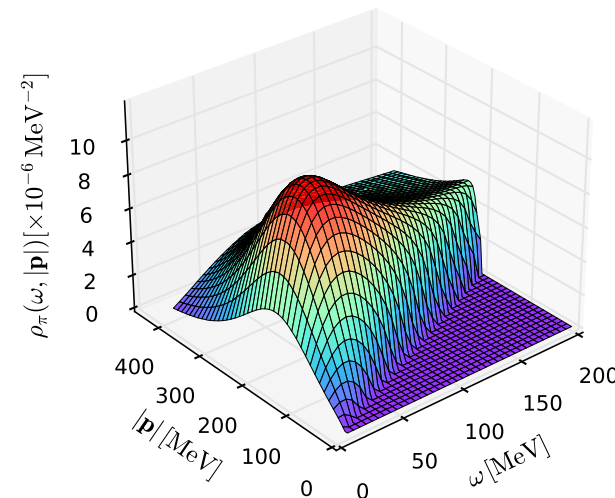
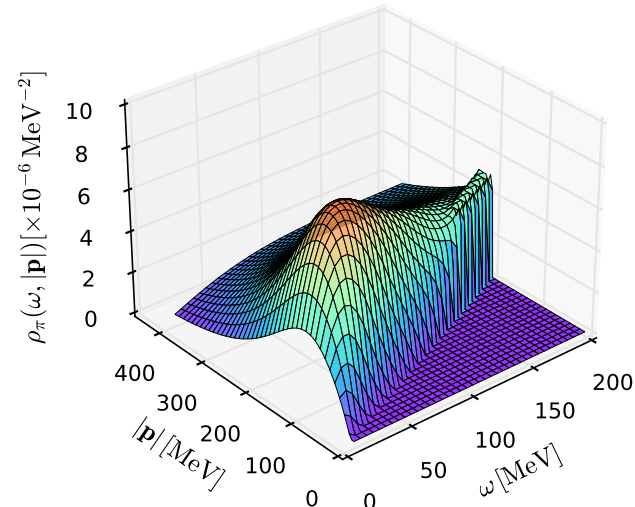
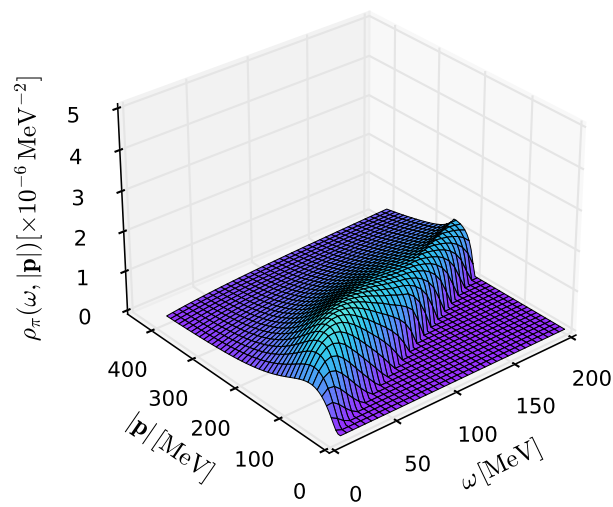


■ $T = 100$ MeV

● $T = 120$ MeV

▲ $T = 130$ MeV

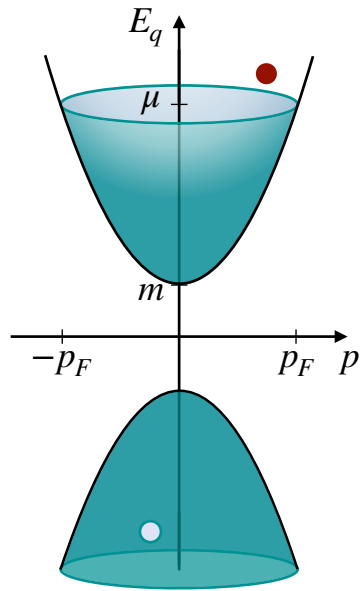
◆ $T = 150$ MeV



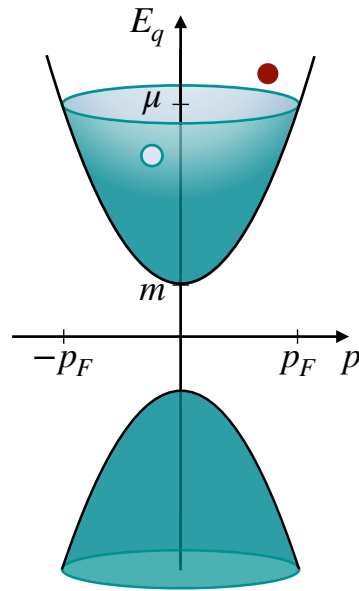
WF, Pawłowski, Pisarski, Rennecke, Wen, Yin, *PRD* 111 (2025) 094026.

Landau damping and moat regime

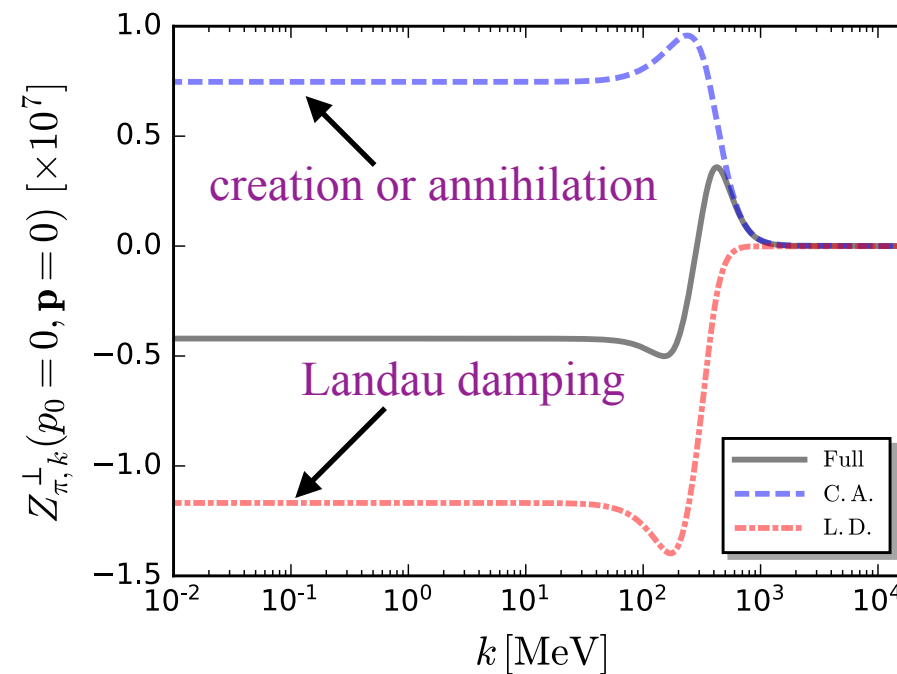
Creation-annihilation
process:



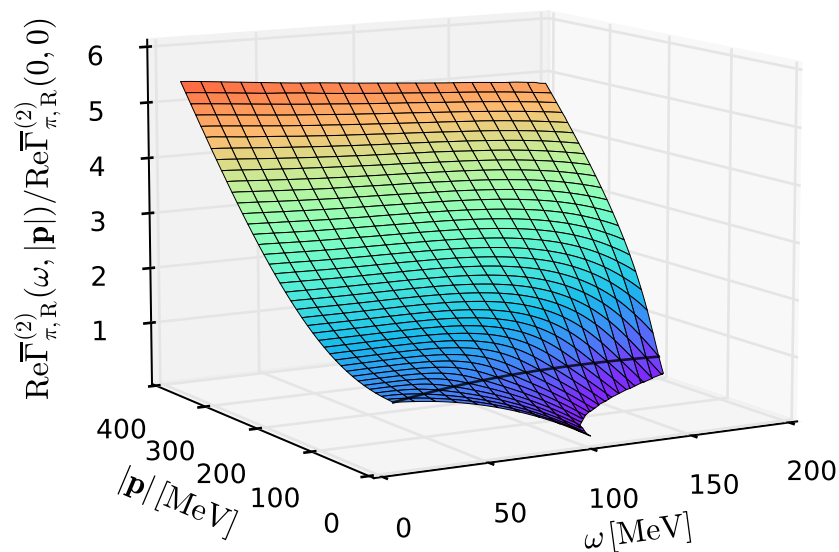
Landau damping
(particle-hole)
process:



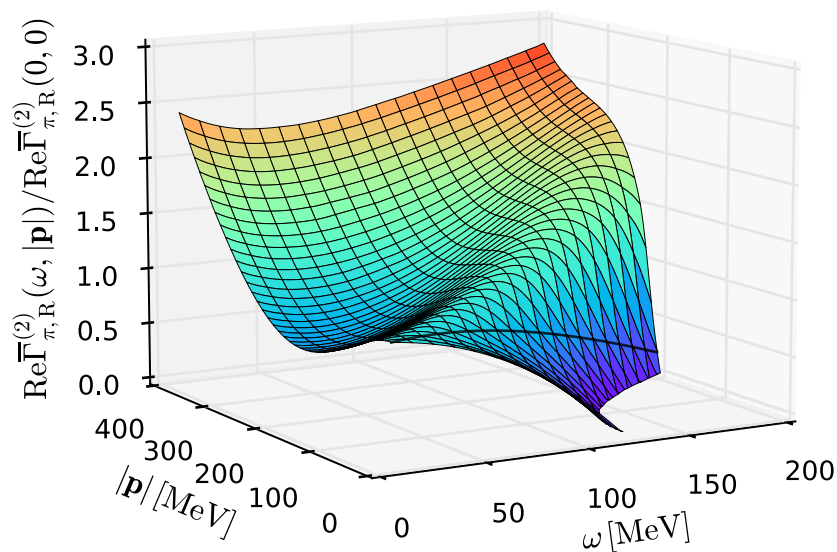
Contributions from two processes:



Real part of $\Gamma_{\phi\phi,R}^{(2)}(p_0, \mathbf{p})$:



Normal: $\mu_B = 0, T = 160 \text{ MeV}$

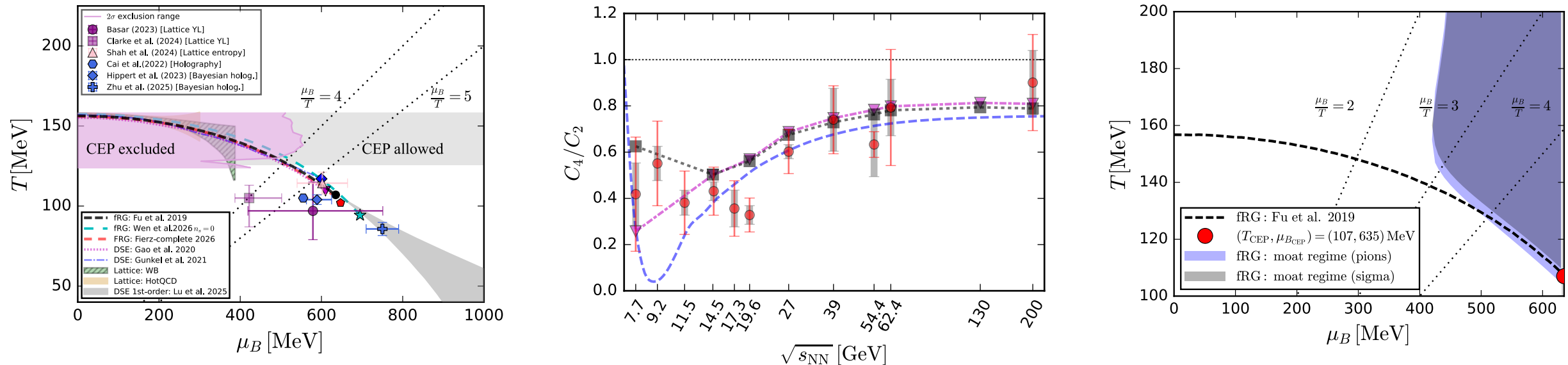


Moat: $\mu_B = 630 \text{ MeV}, T = 114 \text{ MeV}$

- Moat regime is found to arise from **Landau damping** of quarks in thermal bath in the regime of large baryon chemical potential.

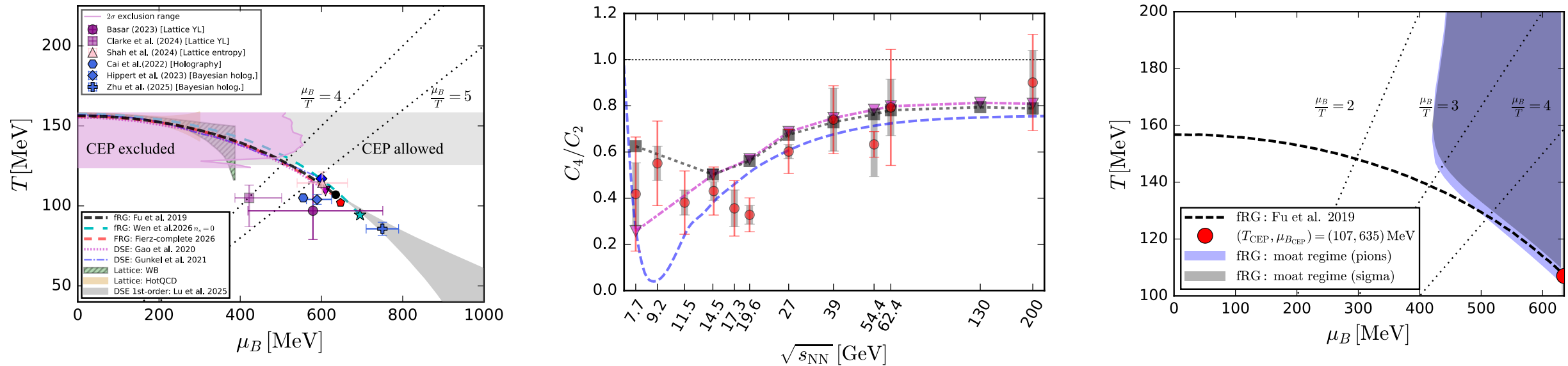
WF, Pawłowski, Pisarski, Rennecke, Wen, Yin, *PRD* 111 (2025) 094026.

Summary and outlook



- ★ Combined results of different approaches, including functional QCD, lattice, holography, indicate that the location of CEP is not favored in the region $\mu_B/T \lesssim 4 \sim 5$.
- ★ A non-monotonic dependence on the collision energy is observed in net-proton fluctuations calculated with fRG and hydrodynamics.
- ★ Moat regime is found to arise from Landau damping of quarks in thermal bath in the regime of large baryon chemical potential.

Summary and outlook



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Thank you very much for your attentions!

致谢

理论:

Gaoqing Cao (曹高清), Hao-Lei Chen (陈浩磊), Yong-rui Chen (陈永睿), Lipei Du (杜立配), Fei Gao (高飞), Chuang Huang (黄闯), Mei Huang (黄梅), Xu-Guang Huang (黄旭光), Yu-xin Liu (刘玉鑫), Guo-Liang Ma (马国亮), Jan M. Pawlowski, Robert D. Pisarski, Fabian Rennecke, Yang-yang Tan (谈阳阳), Zi-ning Wang (王子宁), Rui Wen (温睿), Shi Yin (尹诗), Li-jun Zhou (周力军), Peng-fei Zhuang (庄鹏飞)...

实验:

Jinhui Chen (陈金辉), Xiaofeng Luo (罗晓峰), Nu Xu (许怒), Chunjian Zhang (张春健)...

The 3rd International Workshop on Physics at High Baryon Density (PHD2026, 第三屆高重子密度物理國際研討會)

Nov 10 – 13, 2026
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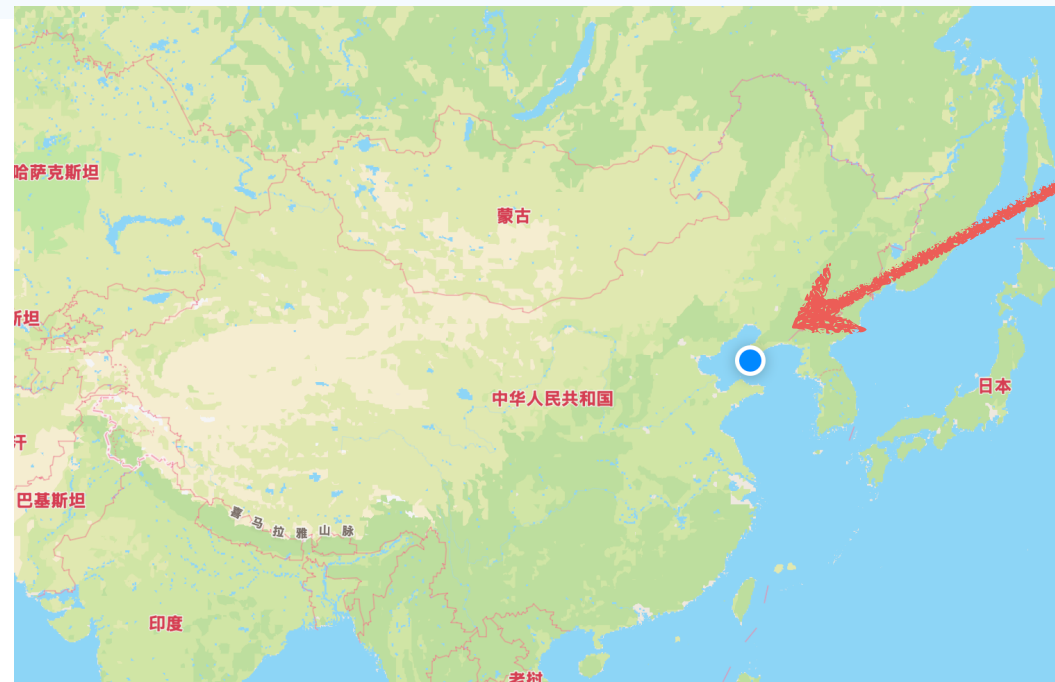
Physics Topics :

- 1) QCD Phase Structure at High Baryon Density
- 2) Nuclear Matter at High Density and Equation of State
- 3) Dynamical Evolution of Heavy-ion Collisions
- 4) Nuclear Matter Under Extreme External Fields
- 5) Hadron Properties in Nuclear Medium
- 6) Nuclear Physics in Compact Stars

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Dalian!



Dalian



Backup

Functional renormalization group

Functional integral with an IR regulator

$$Z_k[J] = \int (\mathcal{D}\hat{\Phi}) \exp \left\{ -S[\hat{\Phi}] - \Delta S_k[\hat{\Phi}] + J^a \hat{\Phi}_a \right\}$$

$$W_k[J] = \ln Z_k[J]$$

regulator:

$$\Delta S_k[\varphi] = \frac{1}{2} \int \frac{d^4 q}{(2\pi)^4} \varphi(-q) R_k(q) \varphi(q)$$

flow of the Schwinger function:

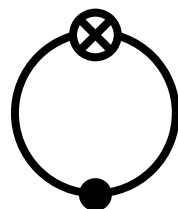
$$\partial_t W_k[J] = -\frac{1}{2} \text{STr} \left[(\partial_t R_k) G_k \right] - \frac{1}{2} \Phi_a \partial_t R_k^{ab} \Phi_b$$

Legendre transformation:

$$\Gamma_k[\Phi] = -W_k[J] + J^a \Phi_a - \Delta S_k[\Phi]$$

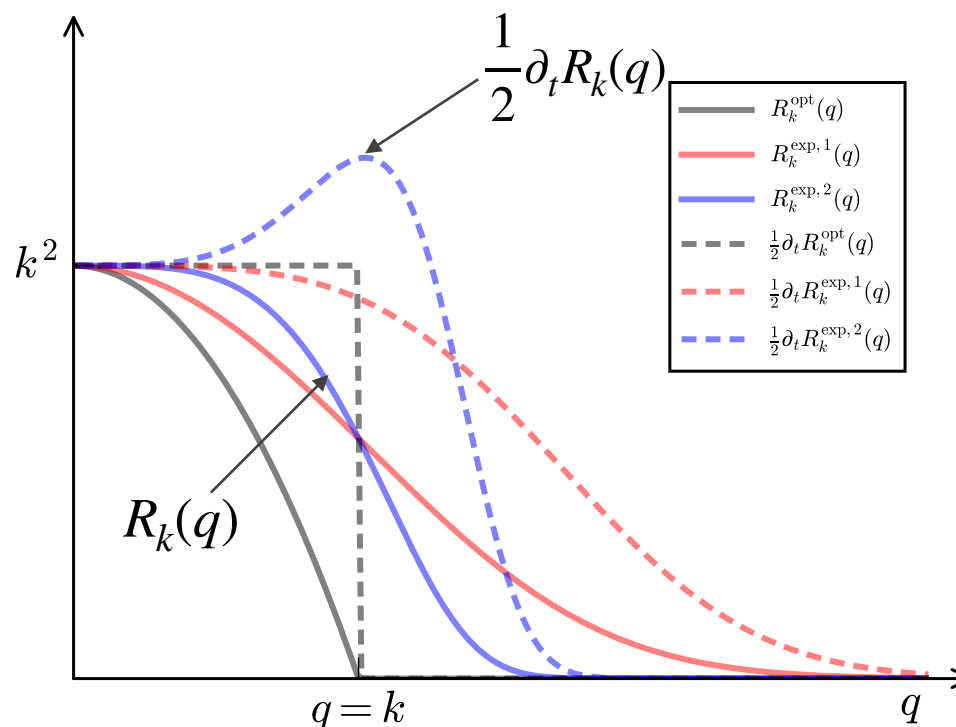
flow of the effective action:

$$\partial_t \Gamma_k[\Phi] = \frac{1}{2} \text{STr} \left[(\partial_t R_k) G_k \right] = \frac{1}{2}$$

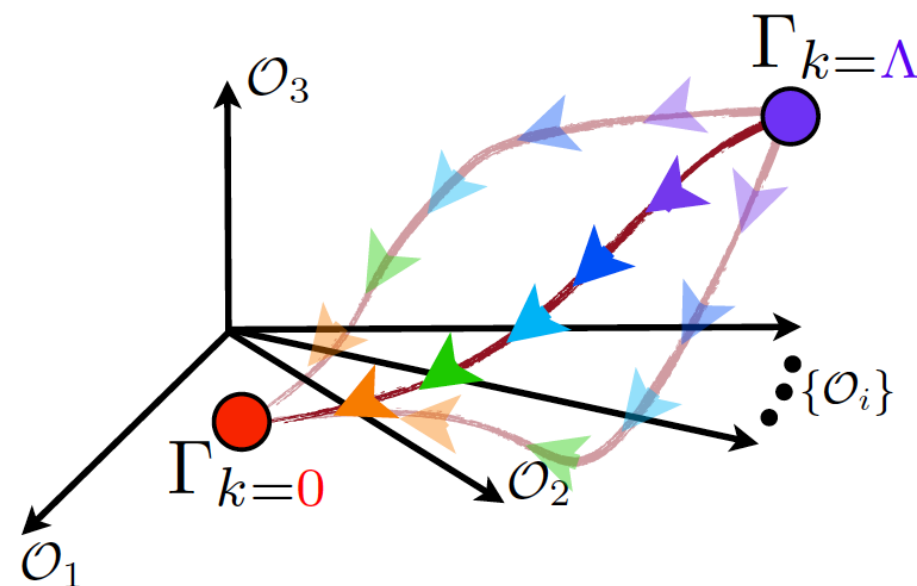


Wetterich formula

C. Wetterich, *PLB*, 301 (1993) 90



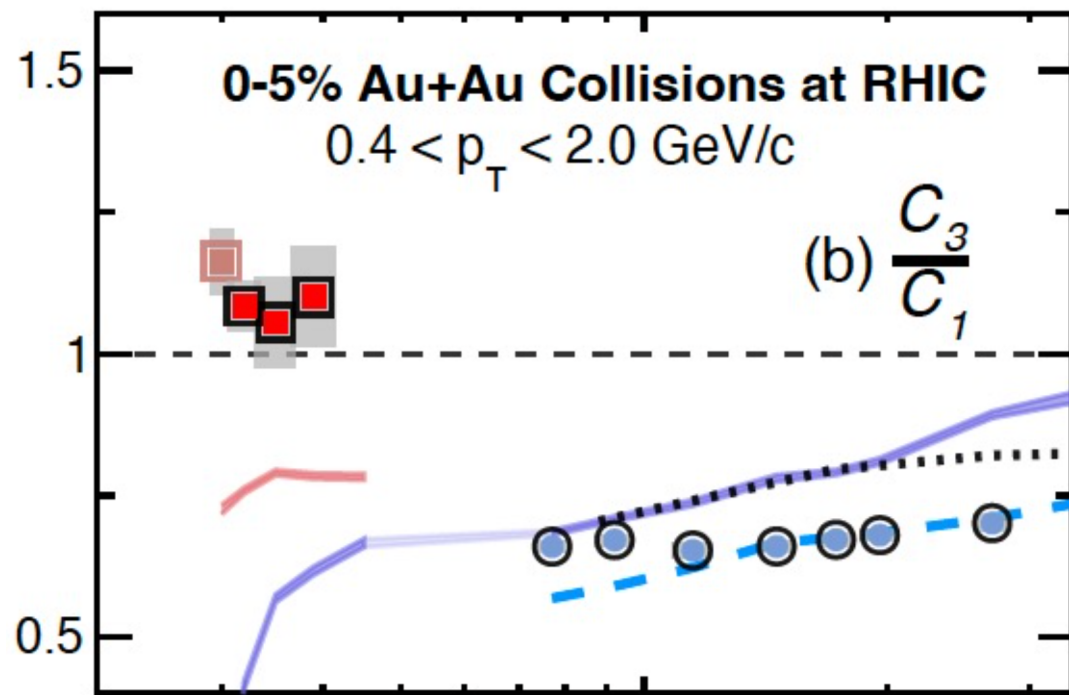
$$G_{k,ab} = \gamma^c_a \left(\Gamma_k^{(2)}[\Phi] + \Delta S_k^{(2)}[\Phi] \right)^{-1}_{cb},$$



Review: WF, *CTP* 74 (2022) 097304,
arXiv: 2205.00468 [hep-ph]

C₃/C₁: Comparison to STAR data

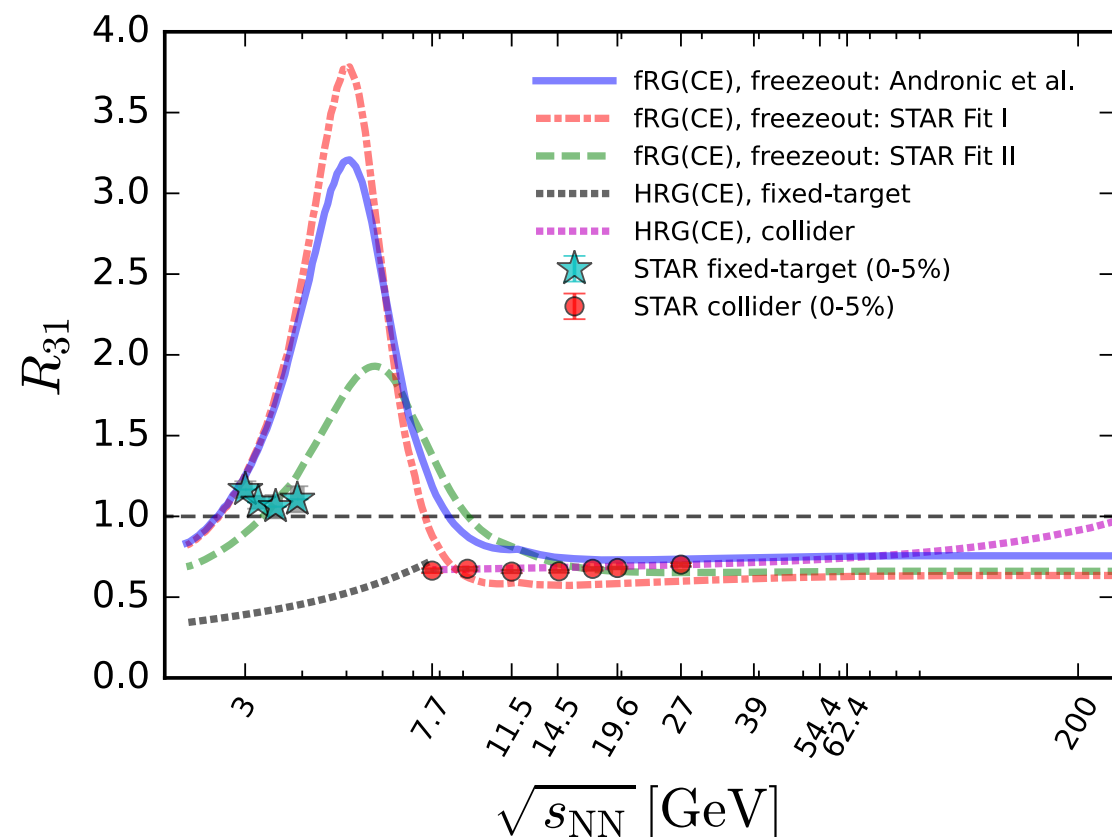
STAR data and UrQMD (baseline):



STAR: Z. Sweger, Quark Matter 2025

STAR: arXiv:2504.00817

fRG (critical) and HRG (baseline):



fRG: WF, Luo, Pawłowski, Rennecke, Yin, *PRD* 111 (2025) L031502, arXiv: 2308.15508; Zhao, Yin, WF, in preparation

- Significant deviations from both the non-critical baseline results in UrQMD and HRG.
- fRG results are in accordance with data.