Anomalous suppression of mean p_T fluctuations potentially signals QCD CEP

Li Yan

Institute of Modern Physics, Fudan Univerity

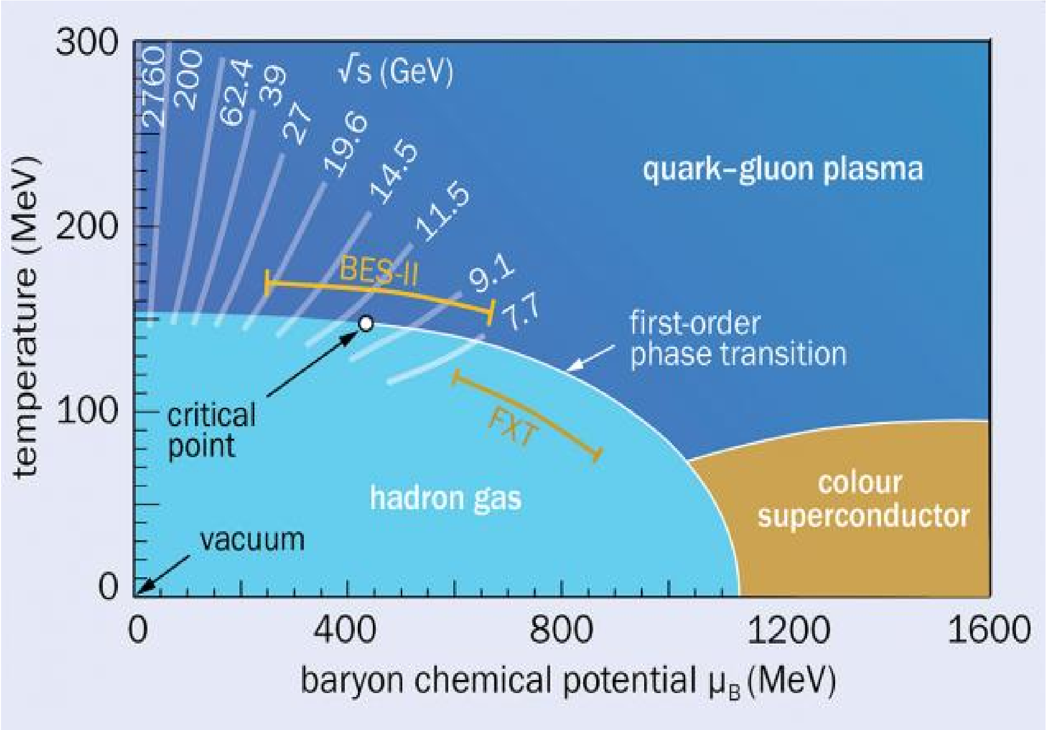
"QCD critical point and hydro evolution"

Yukawa Institute for Theoretical Physics, Kyoto, Jun. 2, 2026

with Yu-Shan Mu

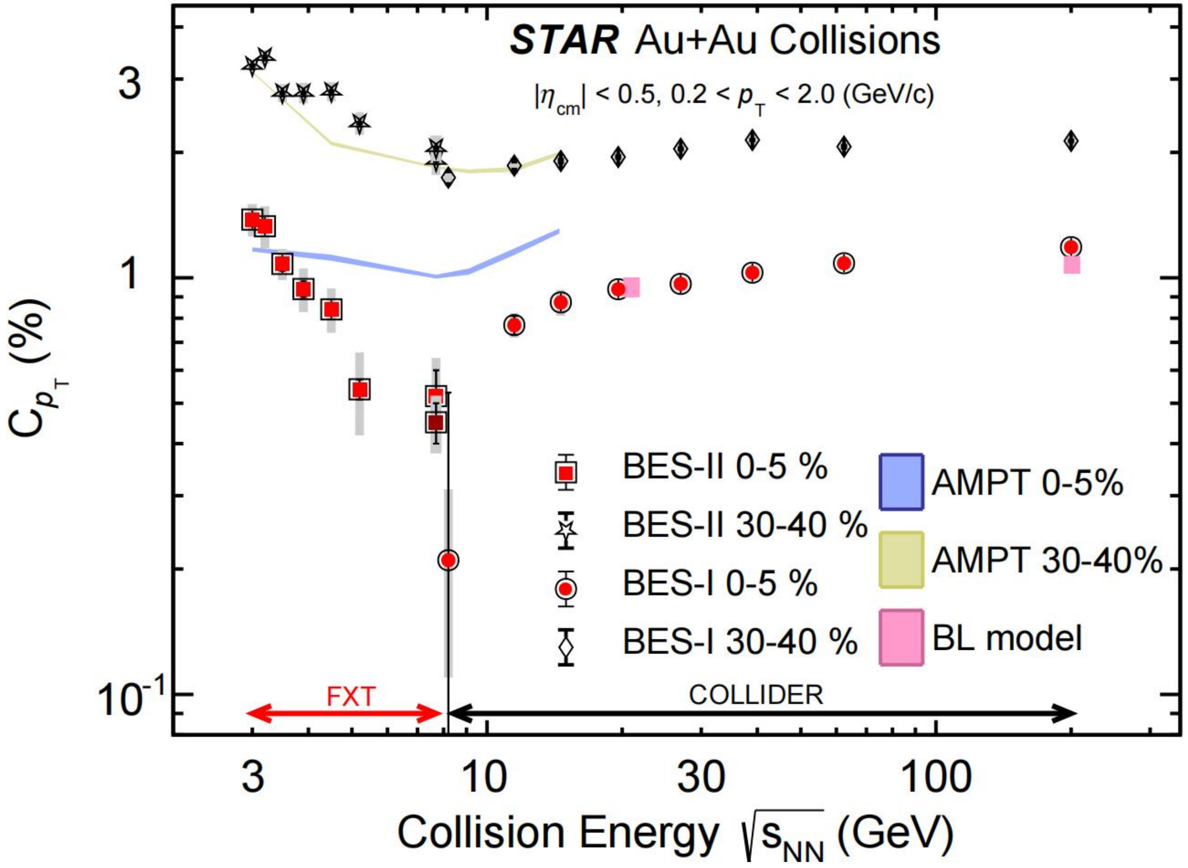
Introduction

- QCD phases and BES:



[STAR collaboration, 2604.06434]

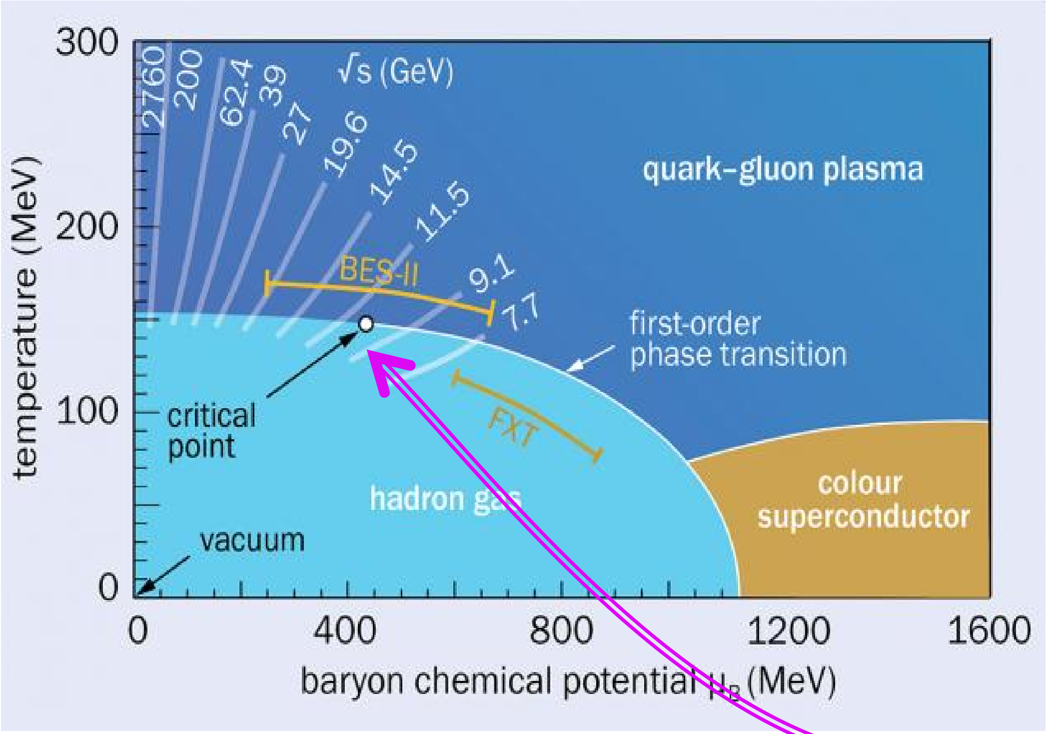
[p_T] fluctuations



* Well identified non-monotonic signatures in BES are associated with QCD CEP.

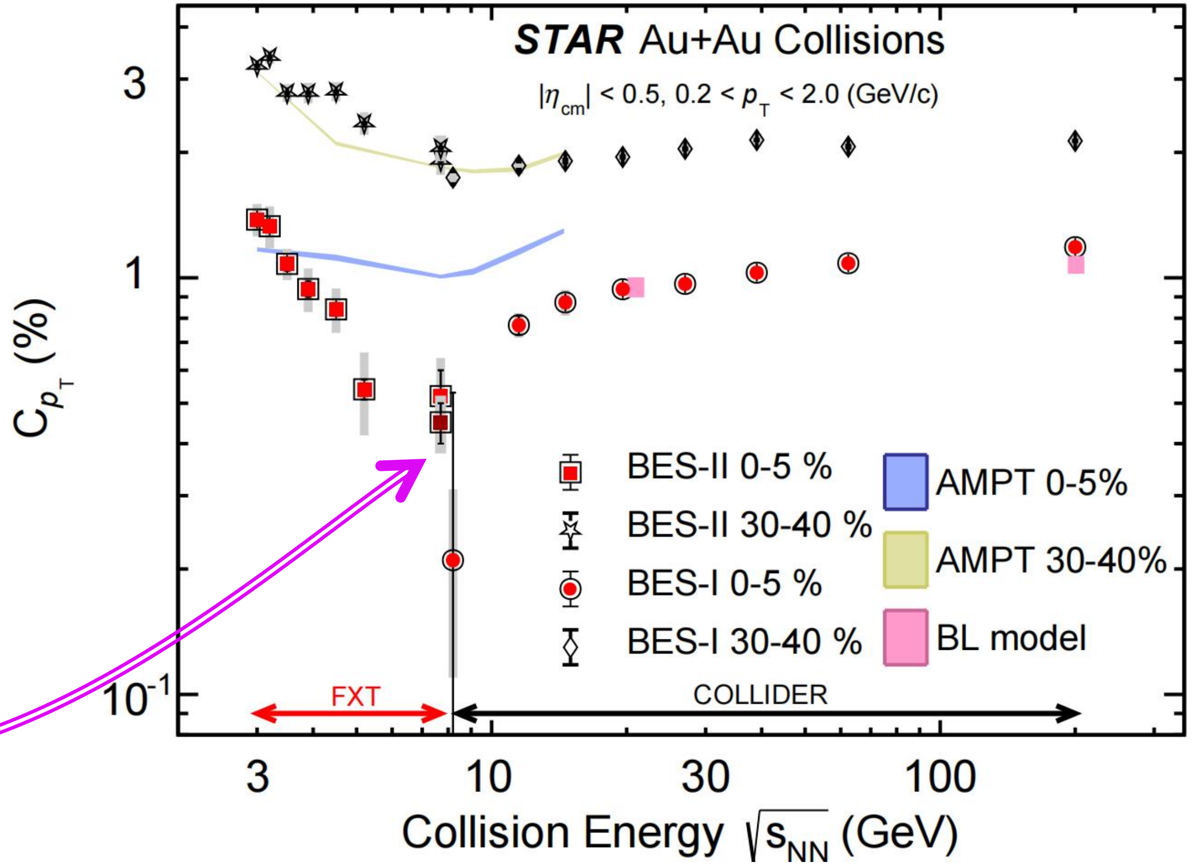
Introduction

- QCD phases and BES:



[STAR collaboration, 2604.06434]

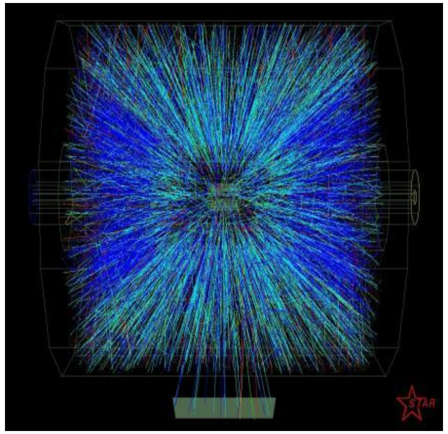
[p_T] fluctuations



* Well identified non-monotonic signatures in BES are associated with QCD CEP.

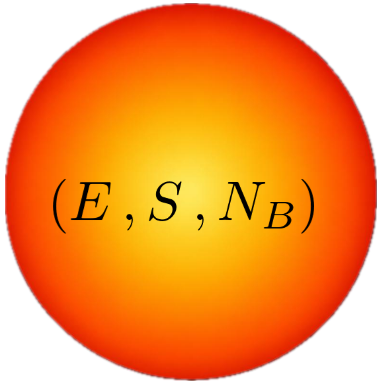
Particles from heavy-ion collisions = an effective QCD fireball

$(E\,,S\,,N_B)$



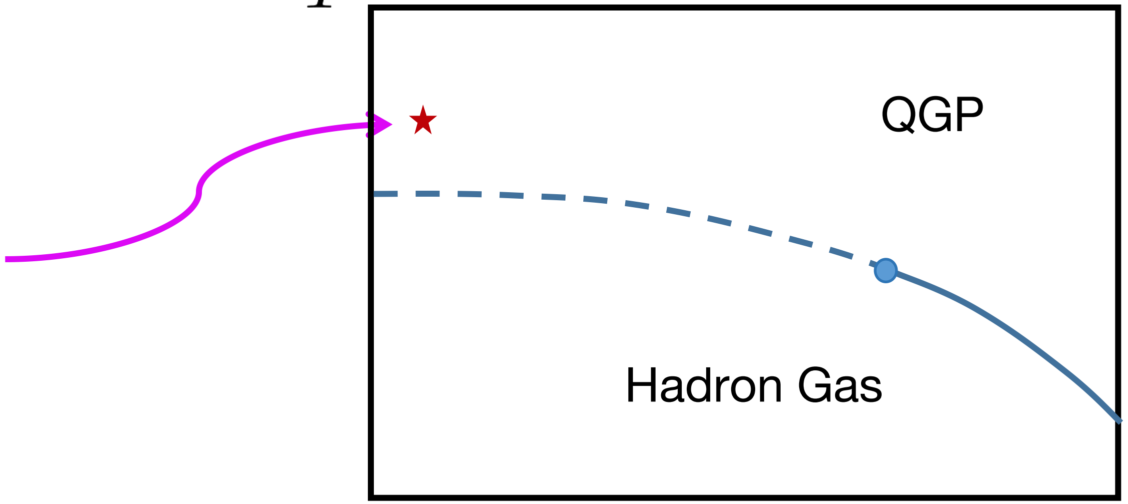
$([p_T]\,,N_{ch}\,,N_B)$

$\leftrightarrow$



(T,μ_B,V)

T



μ_B

- In heavy-ion collisions, each collision produces a dynamcial state: Multi-Particle final State (MPS).
- Multi-Particle State is thermally equivalent to an effective smooth and uniform QCD fireball:

$$E^{\rm MPS} = E^{\rm eff} = \underbrace{e(T,\mu_B)}_{\rm QCD\ EoS}V\,, \quad S^{\rm MPS} = S^{\rm eff} = \underbrace{s(T,\mu_B)}_{\rm QCD\ EoS}V\,, \quad N_B^{\rm MPS} = N_B^{\rm eff} = \underbrace{n_B(T,\mu_B)}_{\rm QCD\ EoS}V$$

MPS in ultra-central collisions (UCC) detect QCD thermodynamic response

E.g., speed of sound: ($\mu_B \approx 0$, LHC energies and top RHIC energies)

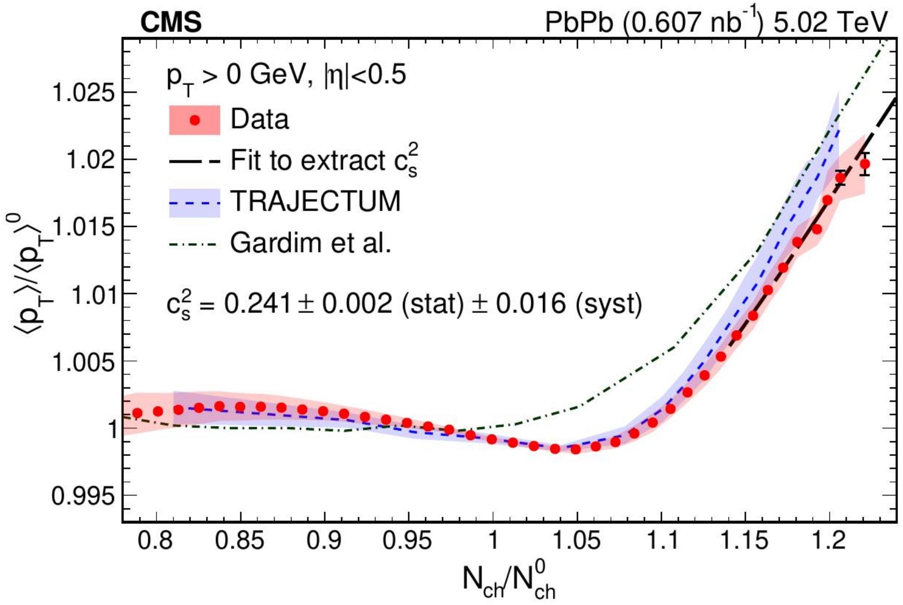
- Initial-state quantum fluct. introduce variations in energy from event to event: ΔE (or ΔS):

$$\text{const. V} \Rightarrow \underbrace{\Delta T}_{\text{resp.}} = \underbrace{C_V^{-1}}_{\text{thermal resp. func.}} \underbrace{(T\Delta S)}_{\text{source}} = \frac{c_s^2}{S}(T\Delta S)\,, \qquad C_V \sim \chi_{ee}$$

[CMS collaboration, 2401.06896]

- Further related to exp., $[p_T]$ vs N_{ch} in UCC measures c_s:

$$\Delta \log[p_T] = c_s^2 \Delta \log N_{ch}$$

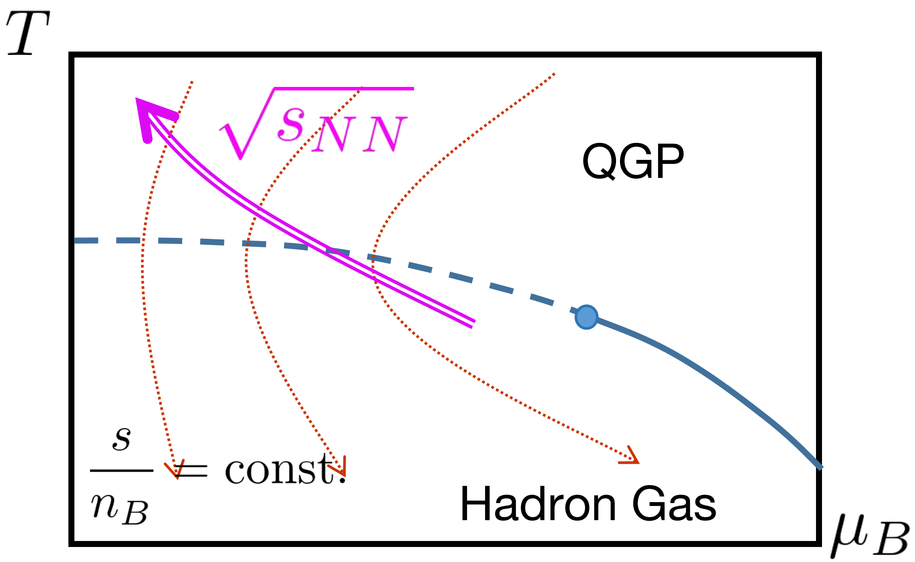


- Assumptions and conditions:

1. Linear correlations: $[p_T] \sim T$, $N_{ch} \sim S$
2. Saturated effective volume in UCC: V = const.

[F. Gardim et al, 19',]

Thermodynamical resp. with finite baryon chemical potential



- Isentropic condition: A QCD fireball close to local equilibrium (hydro) evolves approximately with a constant s/n_B

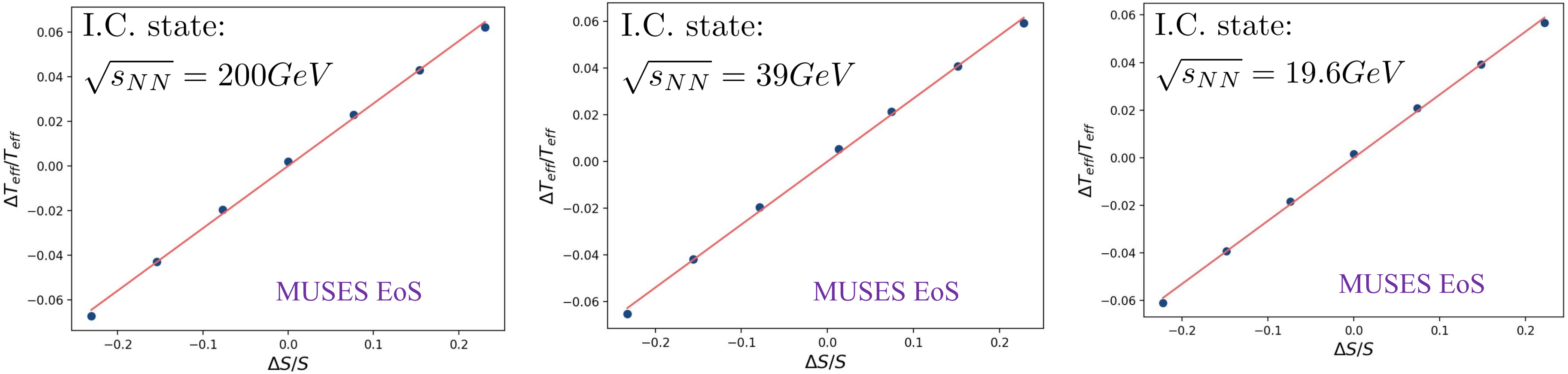
$$\sigma \equiv \frac{s}{n_B}$$

- Dissipations alter the condition, but not much.

- Fundamental thermodynamic relations and the constant s/n_B condition,

$$\begin{cases} de = Tds + \mu_B dn_B \\ dP = sdT + n_B d\mu_B \end{cases} \rightarrow \quad Ts\left(1 + \underbrace{\left(\frac{\partial \mu_B}{\partial T}\right)_\sigma}_{\equiv \lambda} \sigma^{-1}\right) d\log T = c_s^2 Ts\left(1 + \frac{\mu_B}{T}\sigma^{-1}\right) d\log s$$

Thermodynamical resp. with finite chemical potential



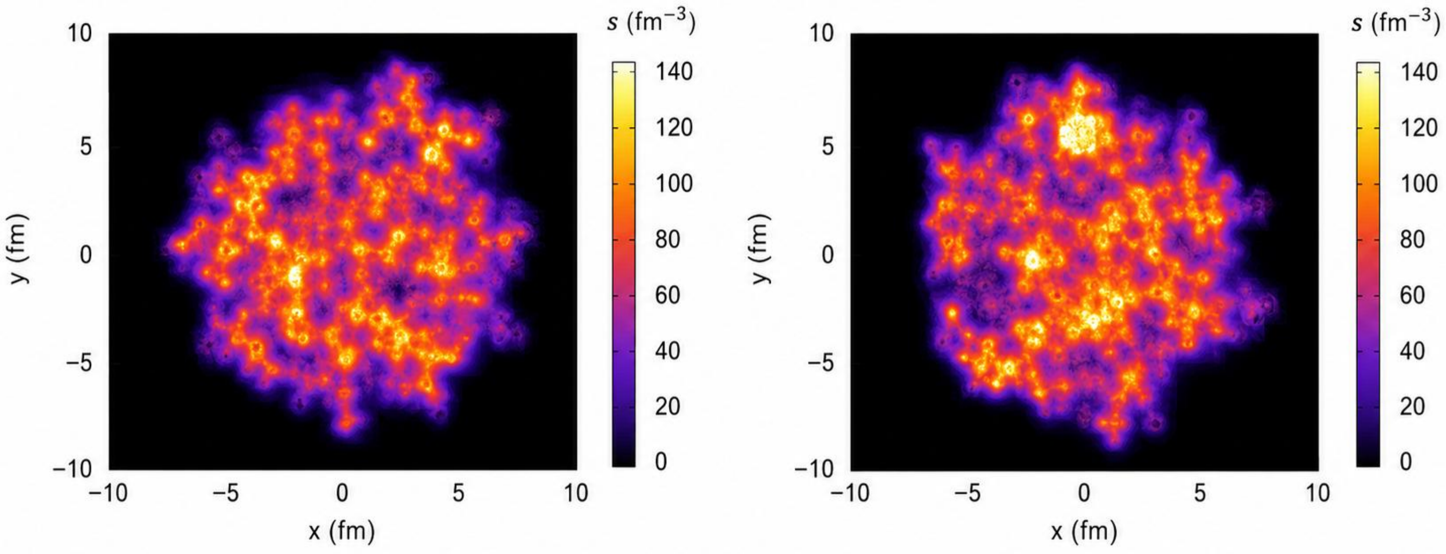
[MUSES EoS, 2402.0863]

- Accounting for the condition of constant volume: $s \to S/V$, $\sigma \to S/N_B$

$$d \log T = \frac{c_s^2 \left(1 + \frac{\mu_B}{T}\sigma^{-1}\right)}{1 + \lambda\sigma^{-1}} d \log S \quad \Leftrightarrow \quad dT = \underbrace{\frac{c_s^2}{S} \frac{1 + \frac{\mu_B}{T}\sigma^{-1}}{1 + \lambda\sigma^{-1}}}_{C_\sigma^{-1}} T dS$$

where C_σ is the generalized heat capacity with finite chemical potential wrt the isentropic condition

The effect of initial-state fluctuations



Au-Au: $\sqrt{s_{NN}} = 200GeV$

$b = 0$ fm

$\Delta S \approx 0$

- Initial-state fluctuations are of quantum origin, and provide the dominant fluct. in the fireball.
- Initial-state fluctuations are associated with S, they appear in the resp. relation accordingly,

$$d\log T = \frac{c_s^2\left(1+\frac{\mu}{T}\sigma^{-1}\right)}{1+\lambda\sigma^{-1}} d\log S + \frac{\delta_0}{1+\lambda\sigma^{-1}}$$

* The effect of thermal fluct. are expected sub-leading, and are not considered in this work.

The thermodynamic resp. with finite μ_B in $[p_T]$ vs N_{ch}

- Accounting for the linear correlations ($[p_T] \sim T$ and $N_{ch} \sim S$), we find in UCC,

$$\Delta \log[p_T] = \frac{c_s^2 \left(1 + \frac{\mu}{T}\sigma^{-1}\right)}{1 + \lambda\sigma^{-1}} \Delta \log N_{ch} + \frac{\delta}{1 + \lambda\sigma^{-1}} + \underbrace{\delta'}_{\text{All other fluct.}}$$

- Observations:

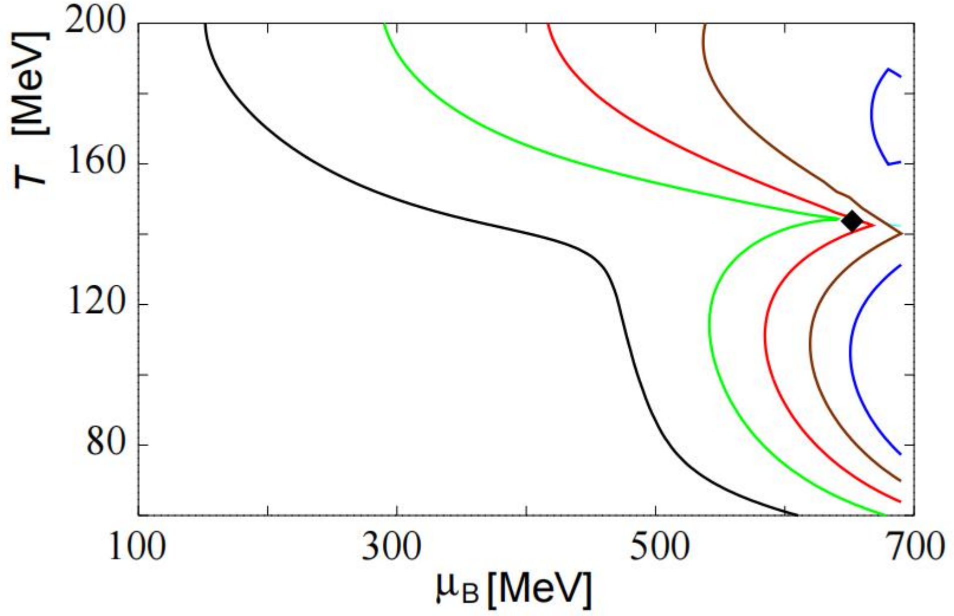
1. Linear correlation is determined by $1/C_\sigma$. (NB: approaching QCD CEP, C_σ \propto $C_V \sim \xi^{0.17}$)
2. Fluctuations (from both ΔN_{ch} and δ) are suppressed by $1/(1 + \lambda/\sigma)$. (NB: λ is singular around QCD CEP.)

- Predictions for UCC:

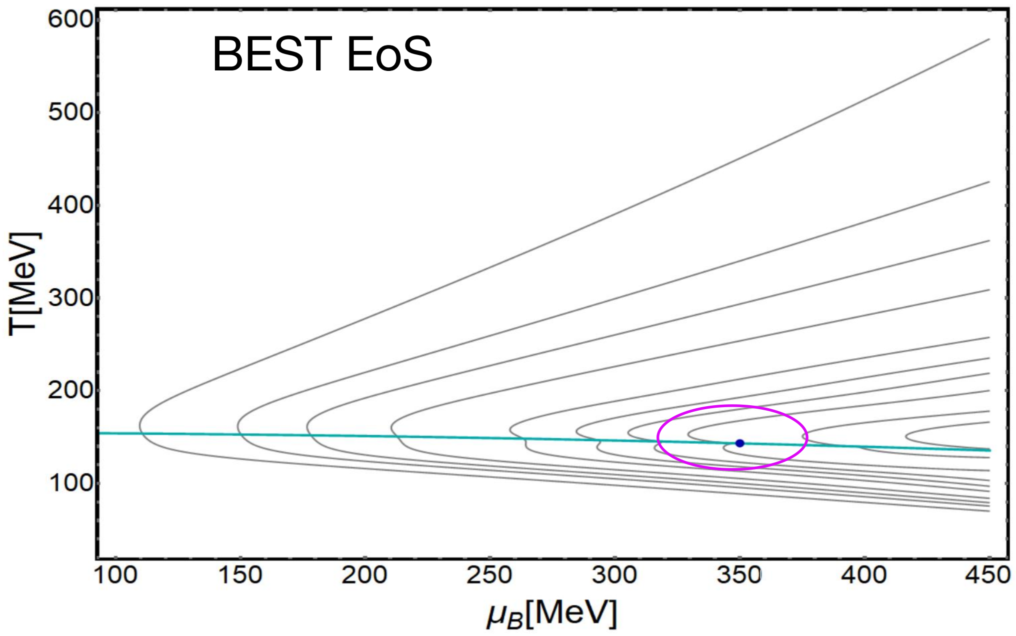
1. Linear correlation between $[p_T]$ and N_{ch} is reduced around QCD CEP.
2. Fluctuations of $[p_T]$ are suppressed around QCD CEP due to $1/(1 + \lambda/\sigma)$.

Critical properties of λ

[C. Nonaka and M. Asakawa, nuch-th/0410078]



[BEST collaboration, 1805.05259]

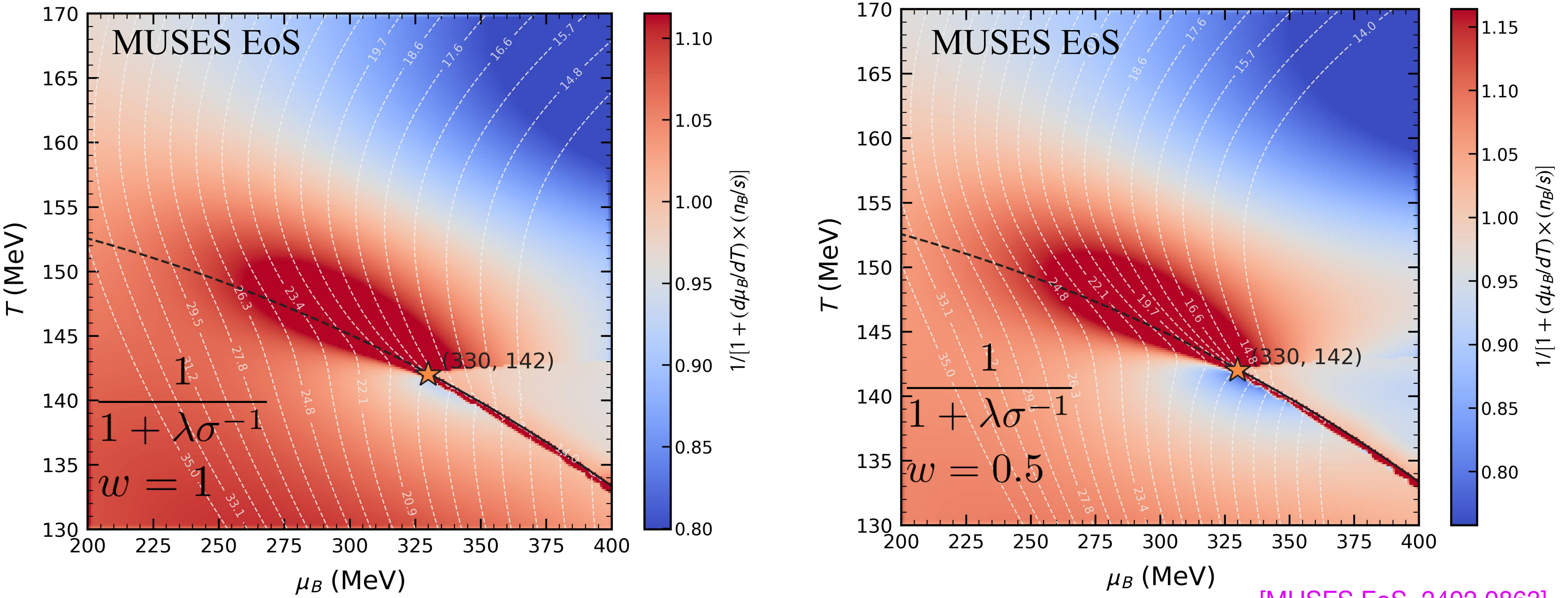


- Naive understanding: |λ| maximizes due to the "focusing effect" of s/n_B lines around CEP. (Qualitative)

$$\lambda = \left(\frac{\partial \mu_B}{\partial T}\right)_\sigma \quad \Leftrightarrow \quad \text{slope along the const. } \frac{s}{n_B} \text{ line}$$

- Pricise value of λ relies on non-universal behavior near CEP. (Quantitative)

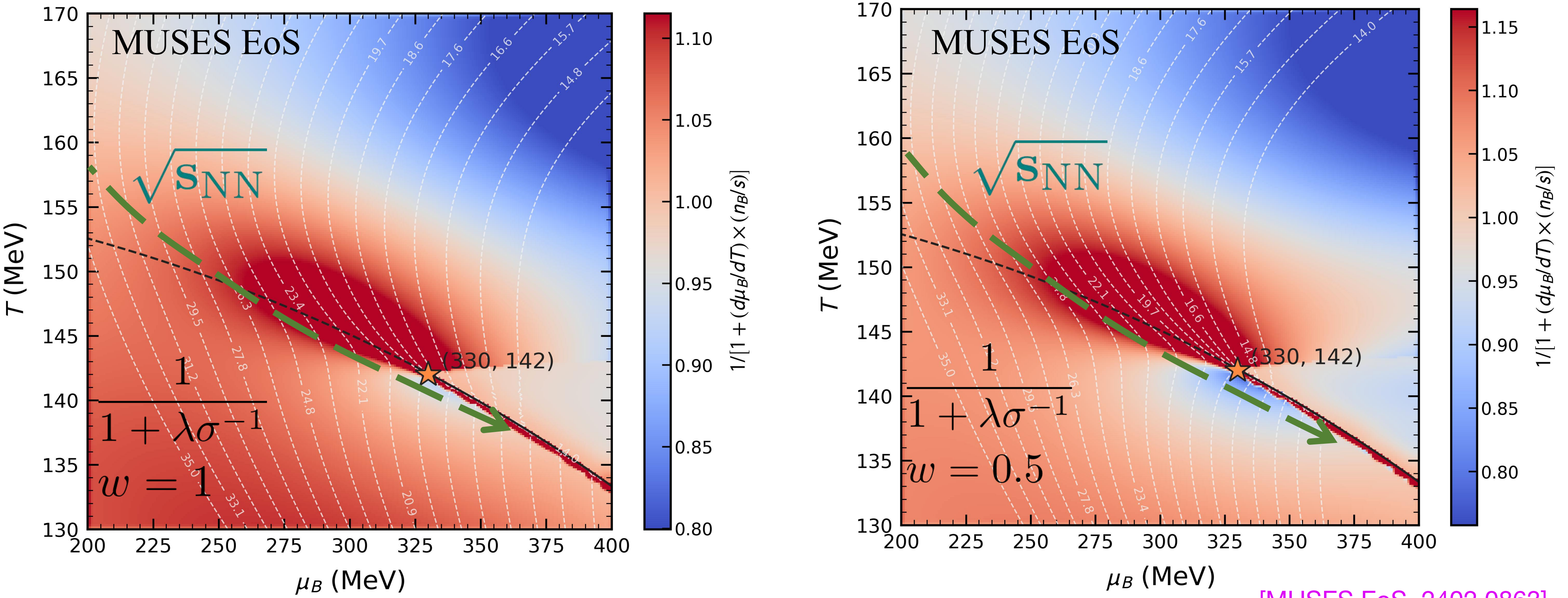
The suppression factor 1/(1 + λ/σ) in QCD phases: plateau and basin



[MUSES EoS, 2402.0863]

- Location of CEP is chosen regarding S/N_B at 7.7 GeV.
- Criticality of the CEP relies on parameter w in MUSES EoS.

The suppression factor 1/(1 + λ/σ) in QCD phases: plateau and basin



[MUSES EoS, 2402.0863]

- Location of CEP is chosen regarding S/N_B at 7.7 GeV.
- Criticality of the CEP relies on parameter w in MUSES EoS.

Validation using Hybrid Hydro modeling (2+1D)

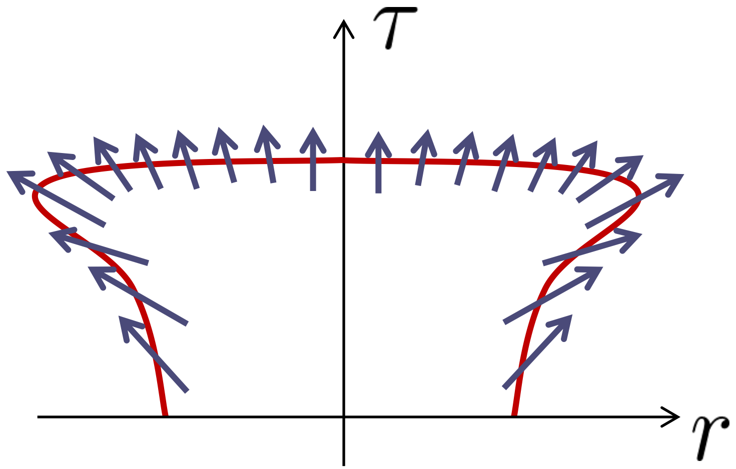
$T^{\mu\nu}$, J_B^{μ}

T_c, μ_{Bc}, w and ρ [MUSES EoS, 2402.0863]

TRENTo + MUSIC + MUSES EoS + iSS + UrQMD

sample *s* and n_B independently, τ_0 ~ nucleus crossing time, *k* increases monotonically

- Extract *T* and μ_B from the hydro freeze-out surface

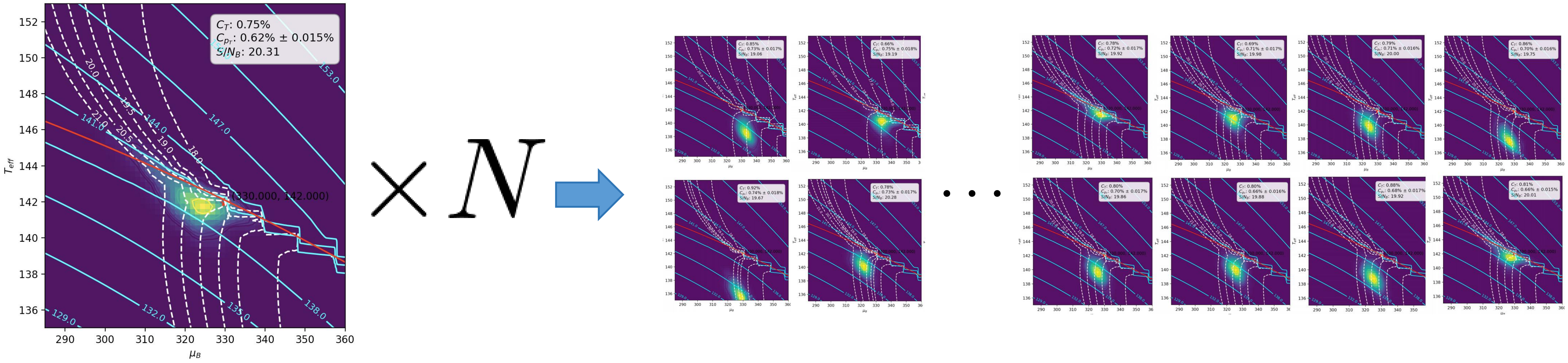


$$\begin{cases} E = \int_\Sigma d\sigma_\mu T^{0\mu} = e^{EOS}(T,\mu_B)V \\ S = \int_\Sigma d\sigma_\mu s^\mu = s^{EOS}(T,\mu_B)V \\ N_B = \int_\Sigma d\sigma_\mu n_B^\mu = n_B^{EOS}(T,\mu_B)V \end{cases}$$

* We consider (at least transient) thermalization of QCD system above 3.5 GeV in BES.

[(NCQ scaling) STAR collaboration, 2504.02531]

Assuming 7.7 GeV is special ...



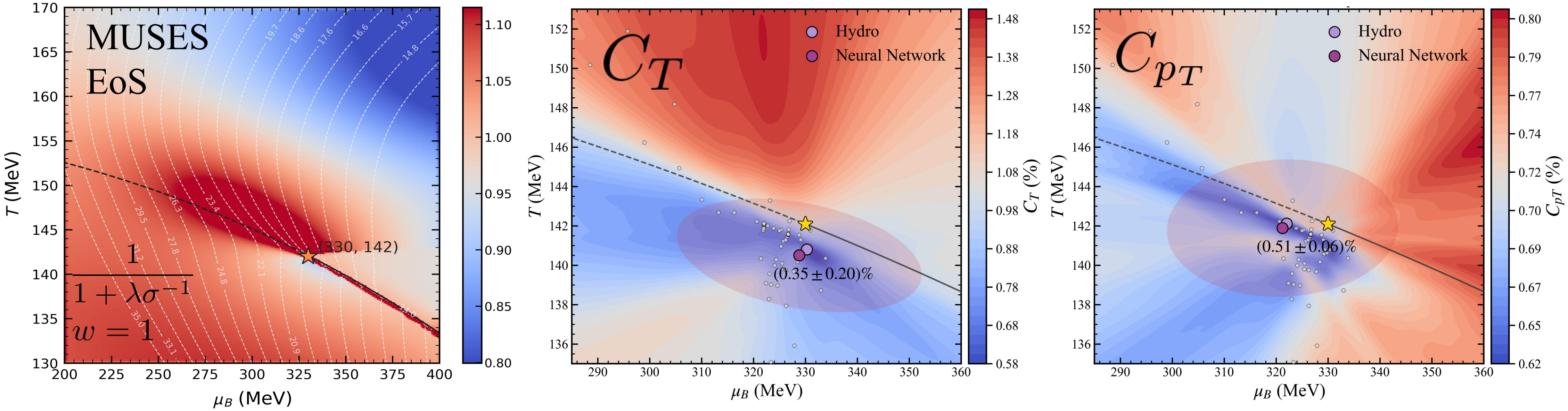
- Scan QCD phases around 7.7 GeV: with <N$_{ch}$>, <N$_B$> and <[p$_T$]> tuned according to STAR exp.
- Accounting for errors, we roughly have for 7.7 GeV 0-5% events, S/N$_B$ ≈ 20 ± 1

  for **w = 1.0** in MUSES → $T_c \sim 142$MeV, $\mu_{Bc} \sim 330$ MeV

- EbE simulations of 0-5% central Au-Au collision EbE (1k events, N ~ 70 sets) and def.

$$C_T \equiv \sqrt{\langle(\delta T)^2\rangle}/\langle T\rangle \qquad C_{p_T} \equiv \sqrt{\langle(\delta[p_T])^2\rangle}/\langle[p_T]\rangle$$

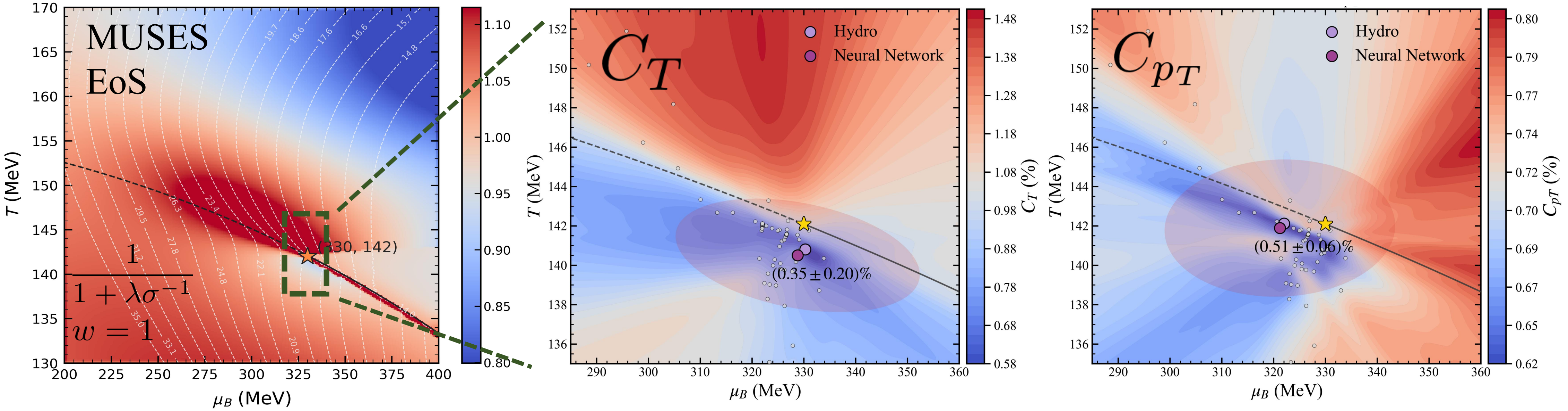
Reconstruct the “plateau and basin” from hydro + EoS



- White symbols correspond to raw hydro results.
- Distribution recontructed using NN to interpolate hydro results and estimate the minimum.
- Distribution of $C_T \neq$ Distribution of C_p,

$$[p_T] = aT(1 + b\frac{\mu_B}{T} + \ldots)$$

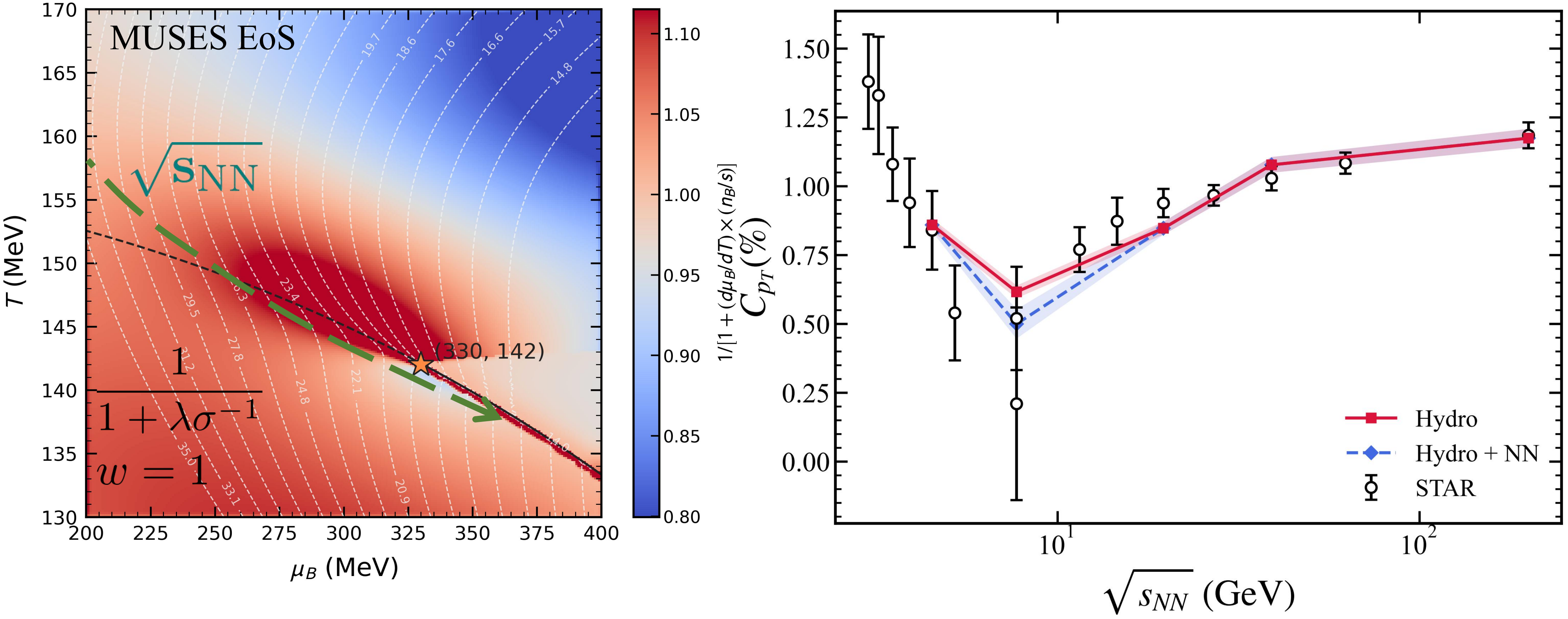
Reconstruct the "plateau and basin" from hydro + EoS



- White symbols correspond to raw hydro results.
- Distribution recontructed using NN to interpolate hydro results and estimate the minimum.
- Distribution of $C_T \neq$ Distribution of C_{p_T}

$$[p_T] = aT(1 + b\frac{\mu_B}{T} + \ldots)$$

Extend to other energies



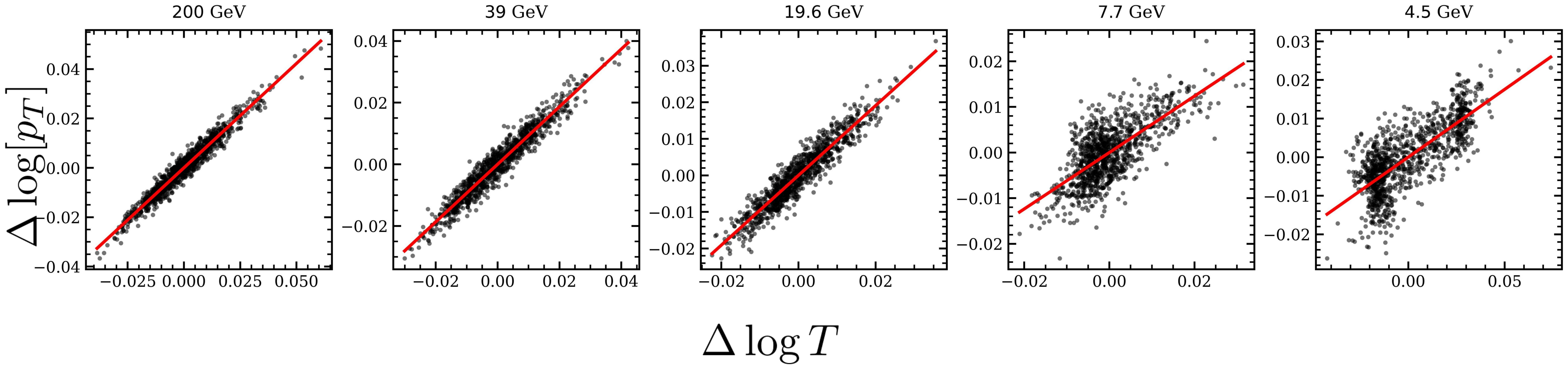
Hydro parameters are chosen such that they vary monotonically with respect to $\sqrt{s_{NN}}$.

Summary

- Anomalous suppression of mean p_T fluctuations potentially signals QCD CEP ==> Qualitative True

- Quantitative analyses, such the location of CEP, requires more rigorous treatment of hydro modeling and model parameters (Bayesian analyses), effect of thermal fluct., etc.

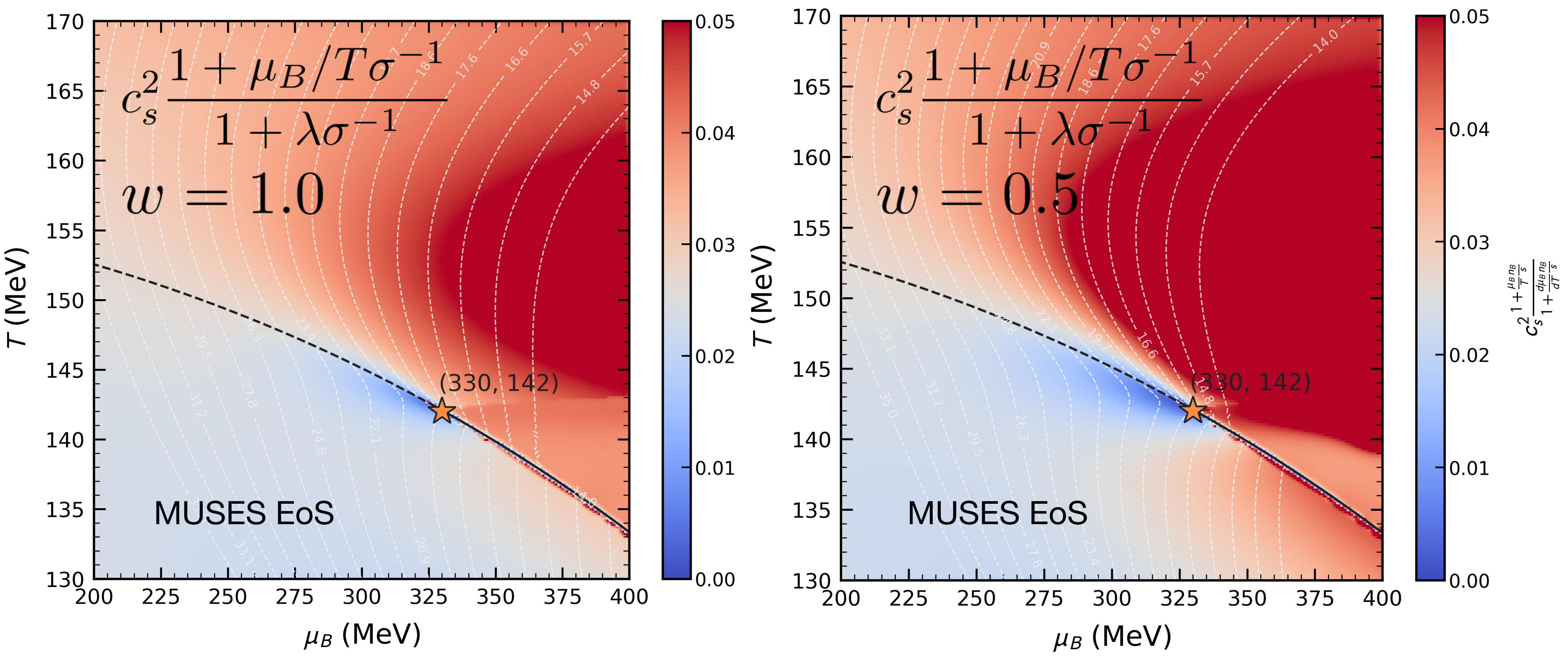
Linear correlations between $[p_T]$ and T



$$[p_T] = aT + b \quad \rightarrow \quad \Delta \log T = \Delta \log[p_T]$$

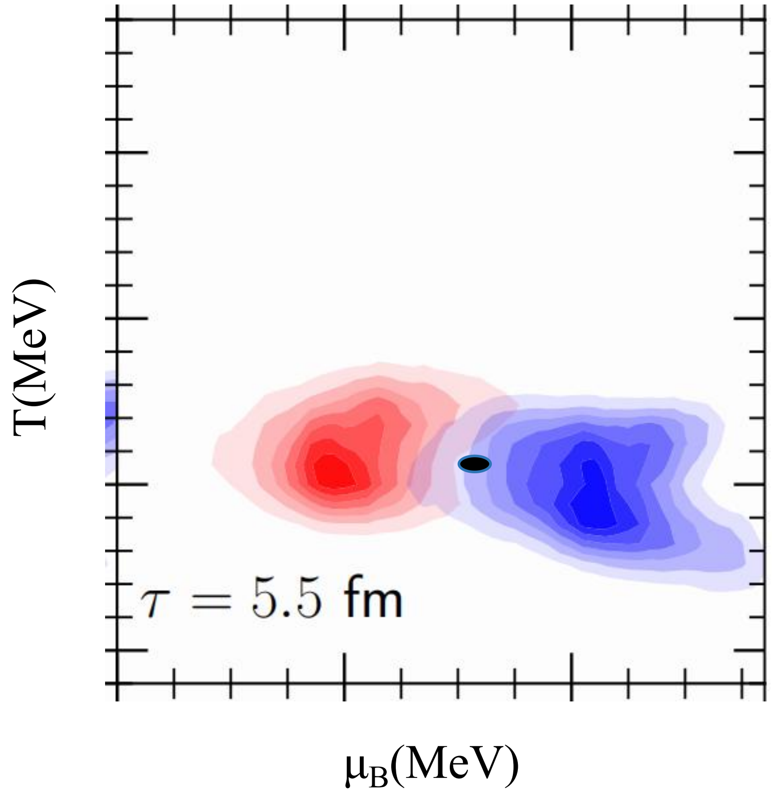
$$[p_T] = aT\left(1 + b\frac{\mu_B}{T} + \dots\right) \quad \not\rightarrow \quad \Delta \log T = \Delta \log[p_T]$$

Linear coefficient ~ $1/C_\sigma$



Why thermal fluctuations are sub-leading

1 event



VS

1k events