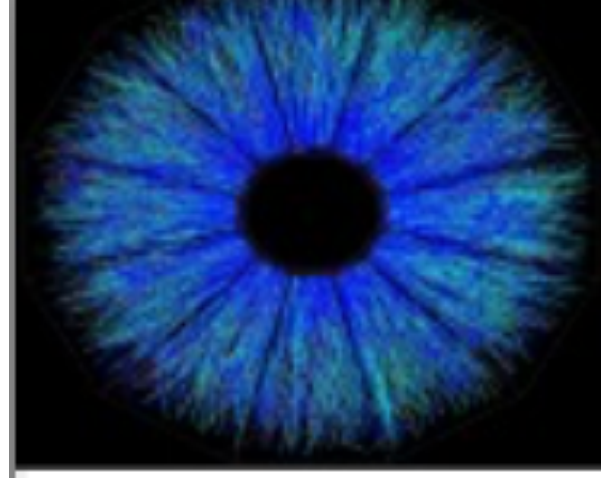
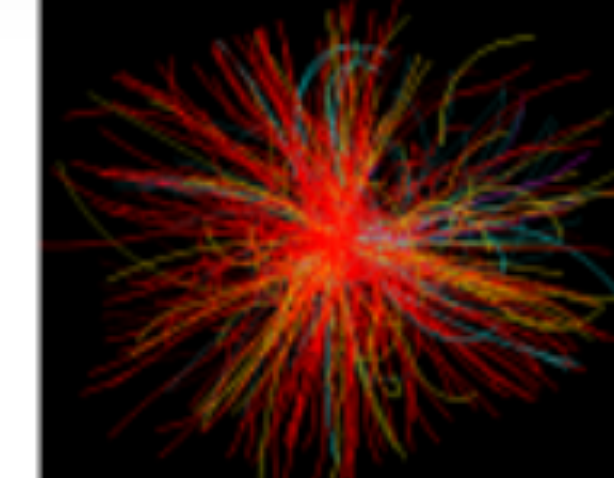




Physics at High Baryon Density (PHD2025)
College of Physical Science and Technology
Central China Normal University, Wuhan
October 16 – 18 , 2025



Probing the QCD Critical Point through (Net-)Proton Fluctuations at RHIC

Yige Huang

Central China Normal University

2025/10/16 - Wuhan - PHD2025

1. Phase Transition & Critical Point

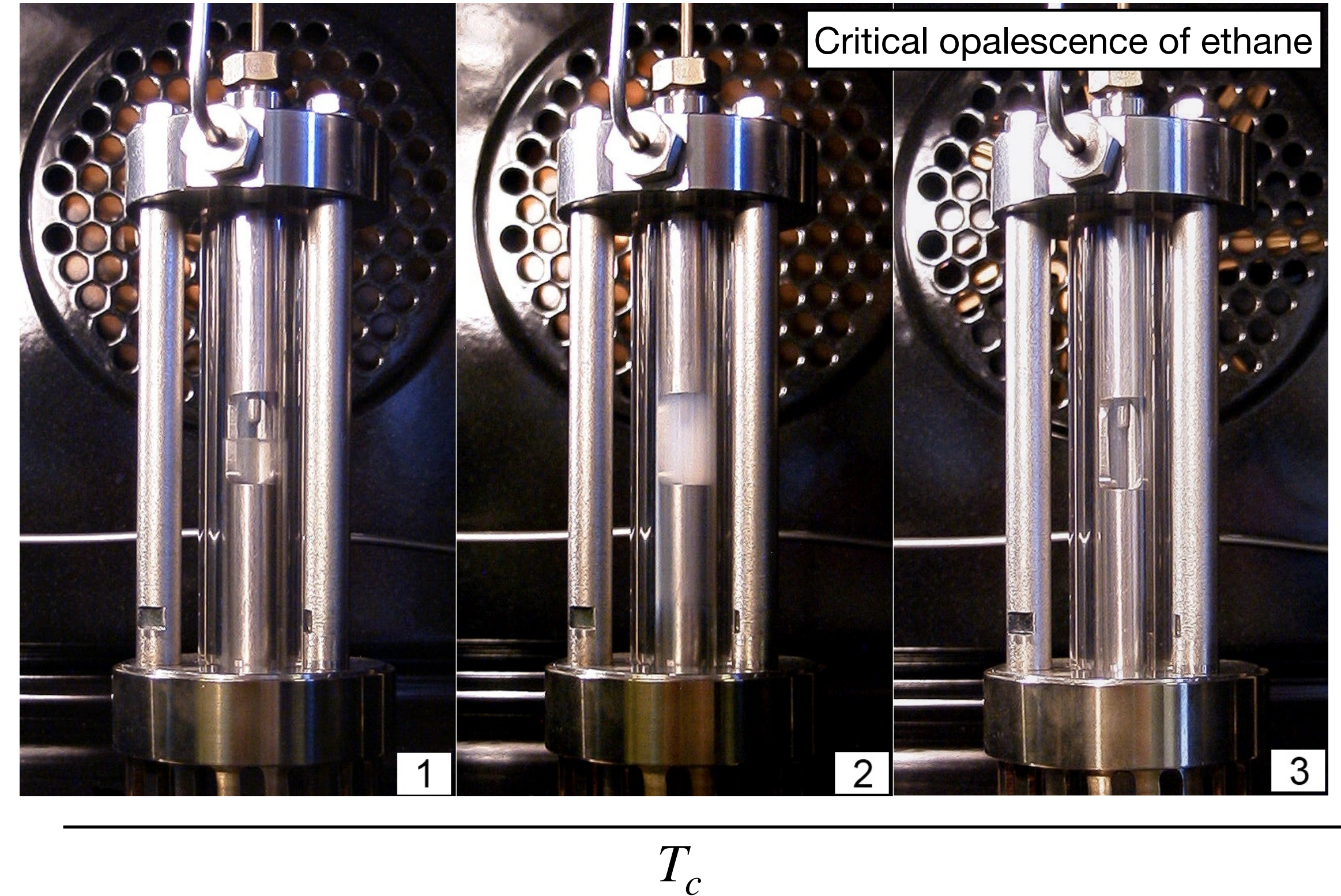
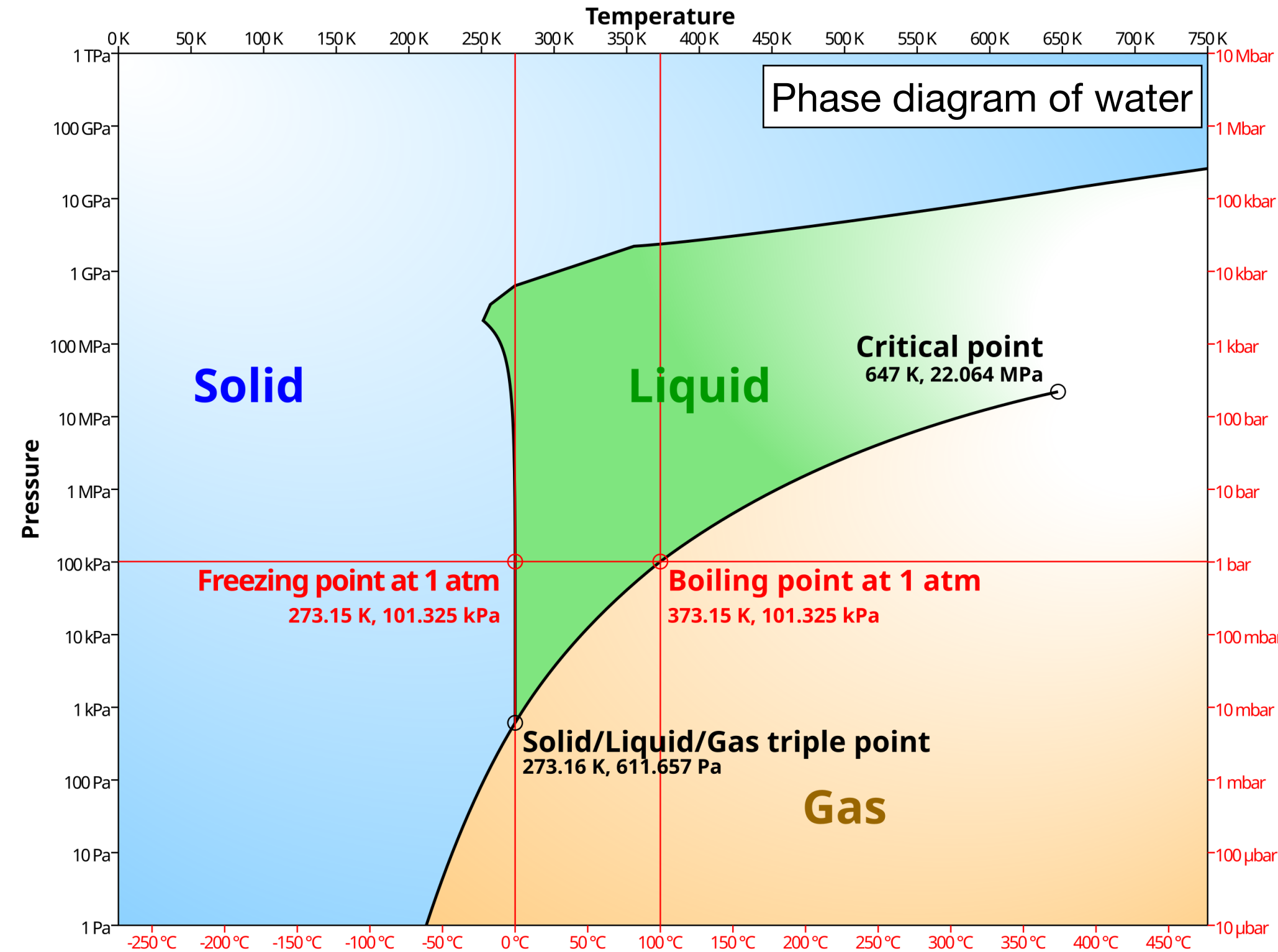
2. RHIC-STAR Experiment

3. Fluctuation Measurements

4. Selected Results

5. Summary & Outlook

Phase Transition & Critical Point



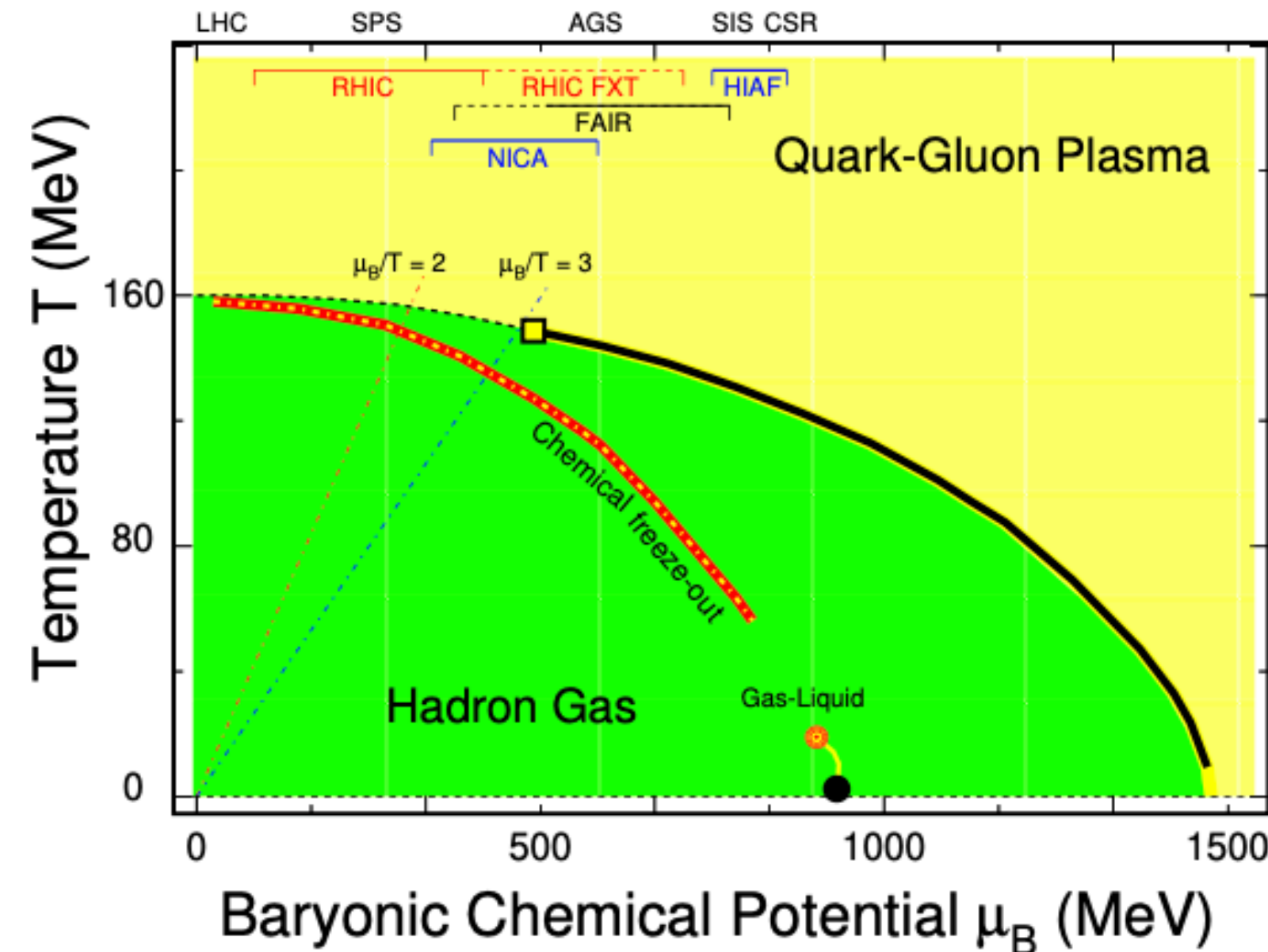
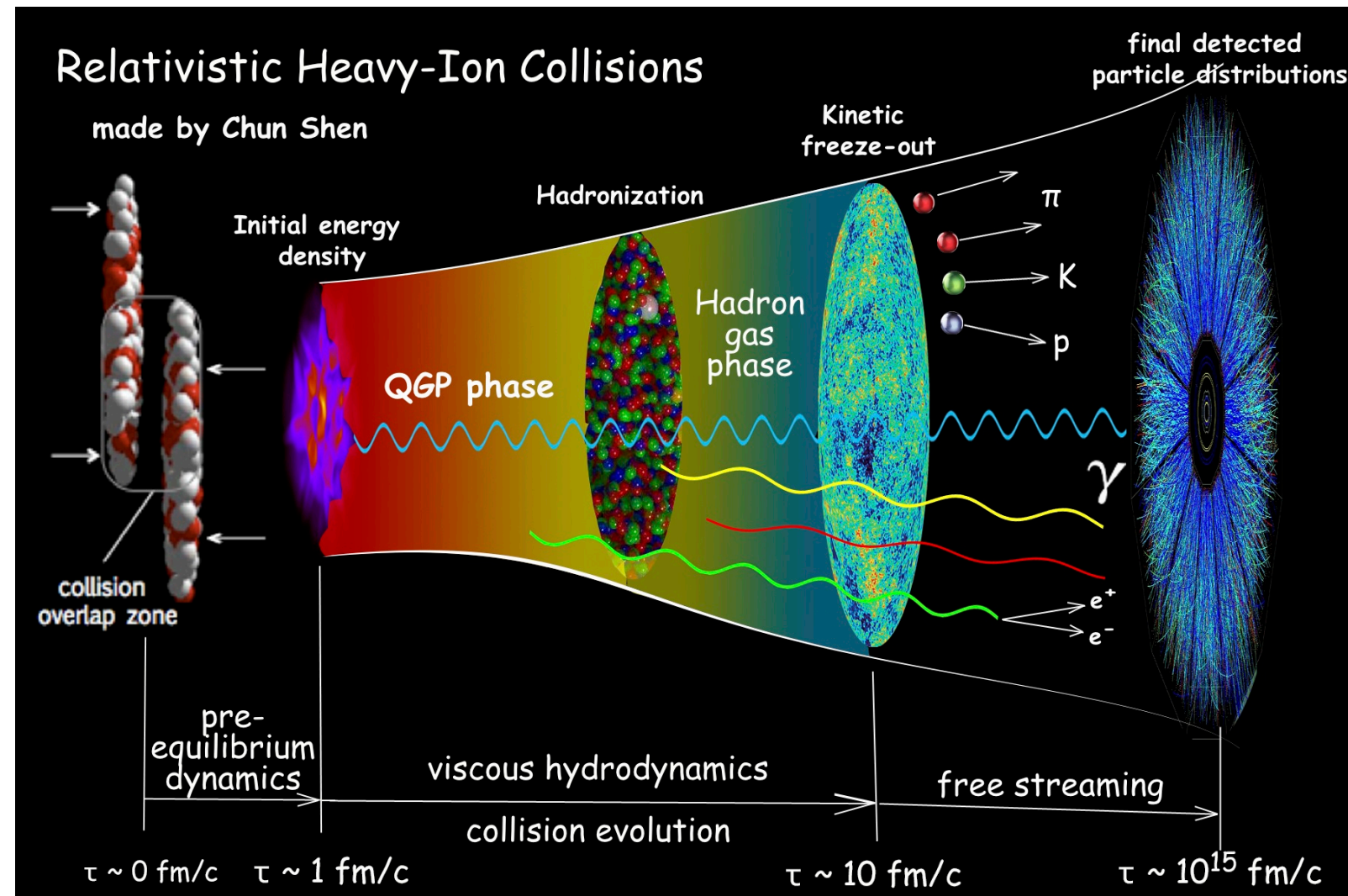
1. Phase transitions can be illustrated with the water phase diagram, including a critical point;
2. Near the critical point, diverging correlation length and enhanced density fluctuations lead to critical opalescence (ethane example).

Phase Transition & Critical Point

Y. Aoki, et al: *Nature* 443 675 (2006)

HotQCD: *PRD* 85 054503 (2012)

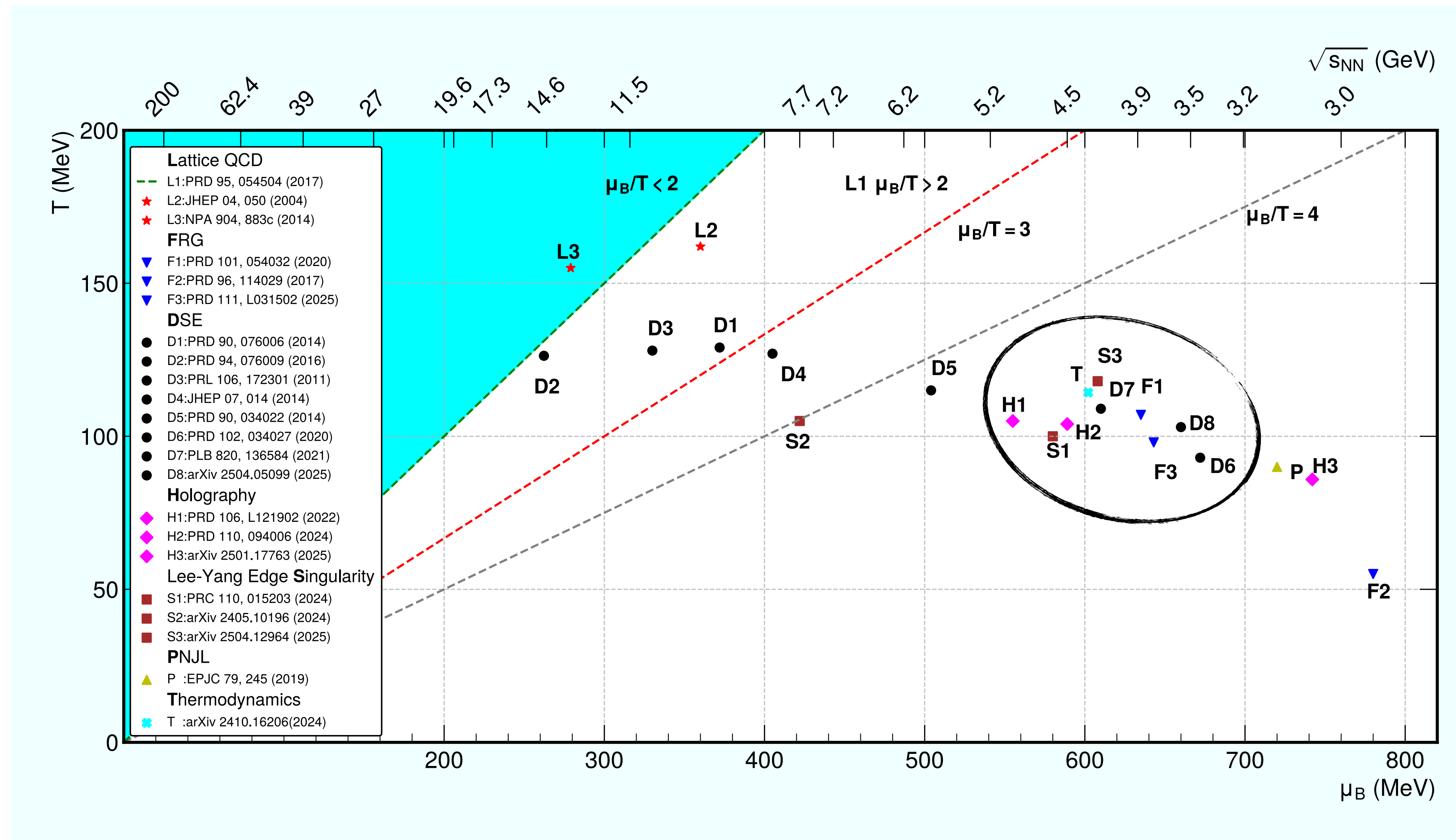
X. Luo, et al: *Particles* 3 278 (2020)



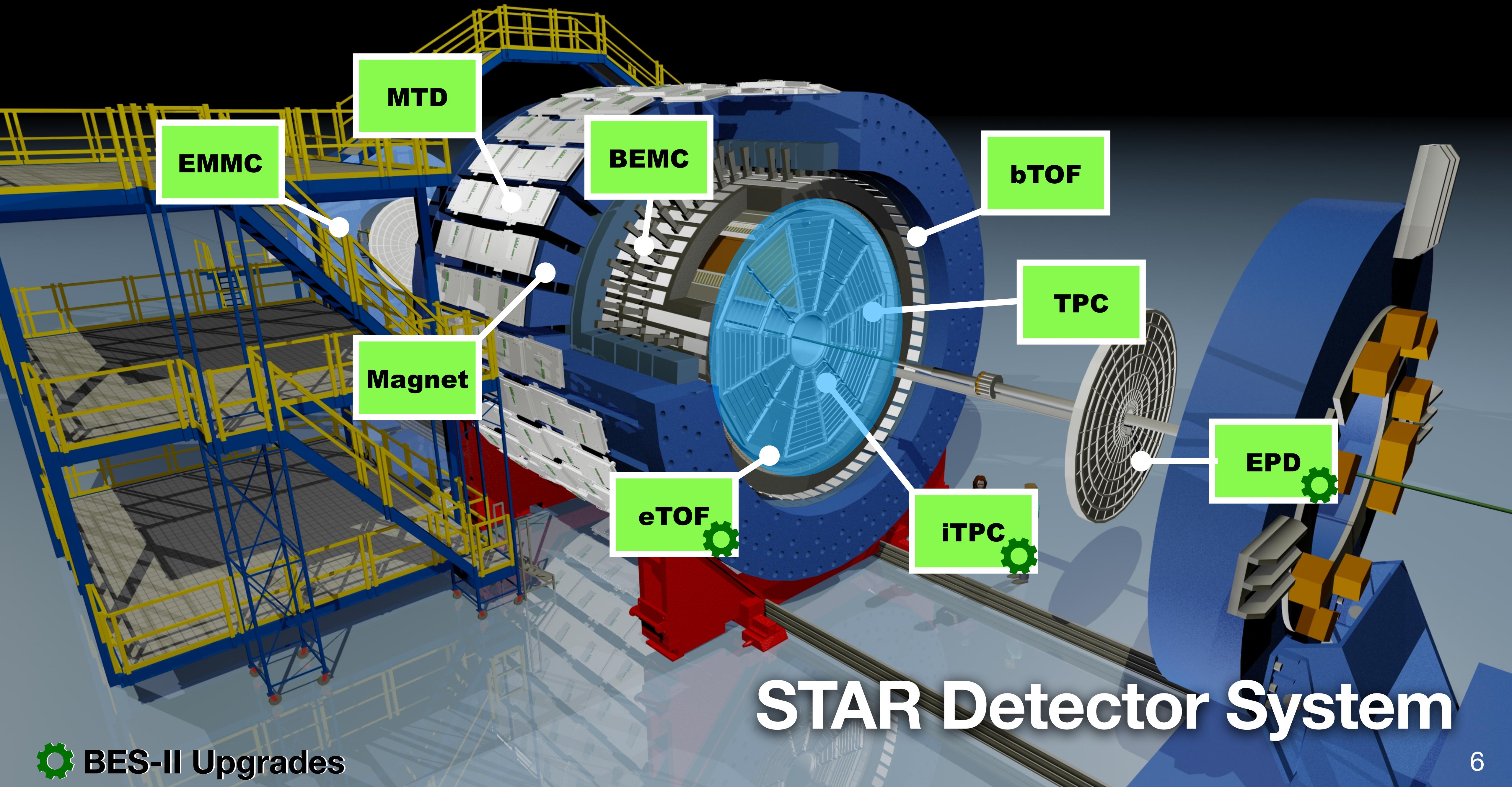
- Lattice QCD: at $\mu_B \sim 0$ MeV, smooth crossover;
- Large μ_B : first-order phase transition and a critical point?

1. Matter at extremely high temperature and density becomes deconfined: quark-gluon plasma (QGP);
2. Study the transition between hadronic matter and QGP: QCD phase diagram;
3. Experiments probe the phase diagram along the chemical freeze-out curve.

Phase Transition & Critical Point



1. Extensive theoretical efforts have been devoted to locating the critical point;
2. Predictions in recent years cluster around $\mu_B \sim 600$ MeV;
3. Experimental confirmation is still required.



EMMC

MTD

BEMC

bTOF

TPC

Magnet

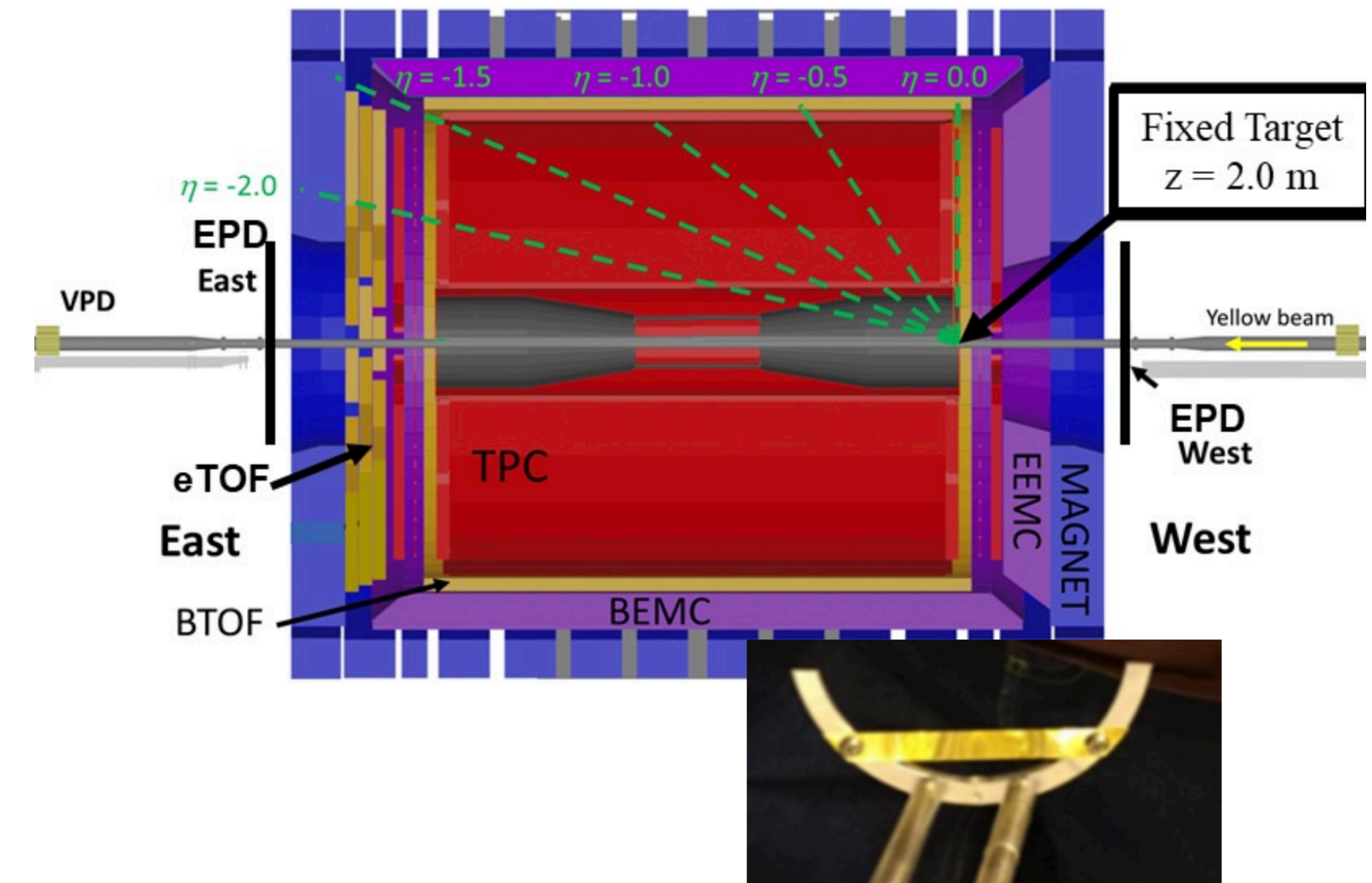
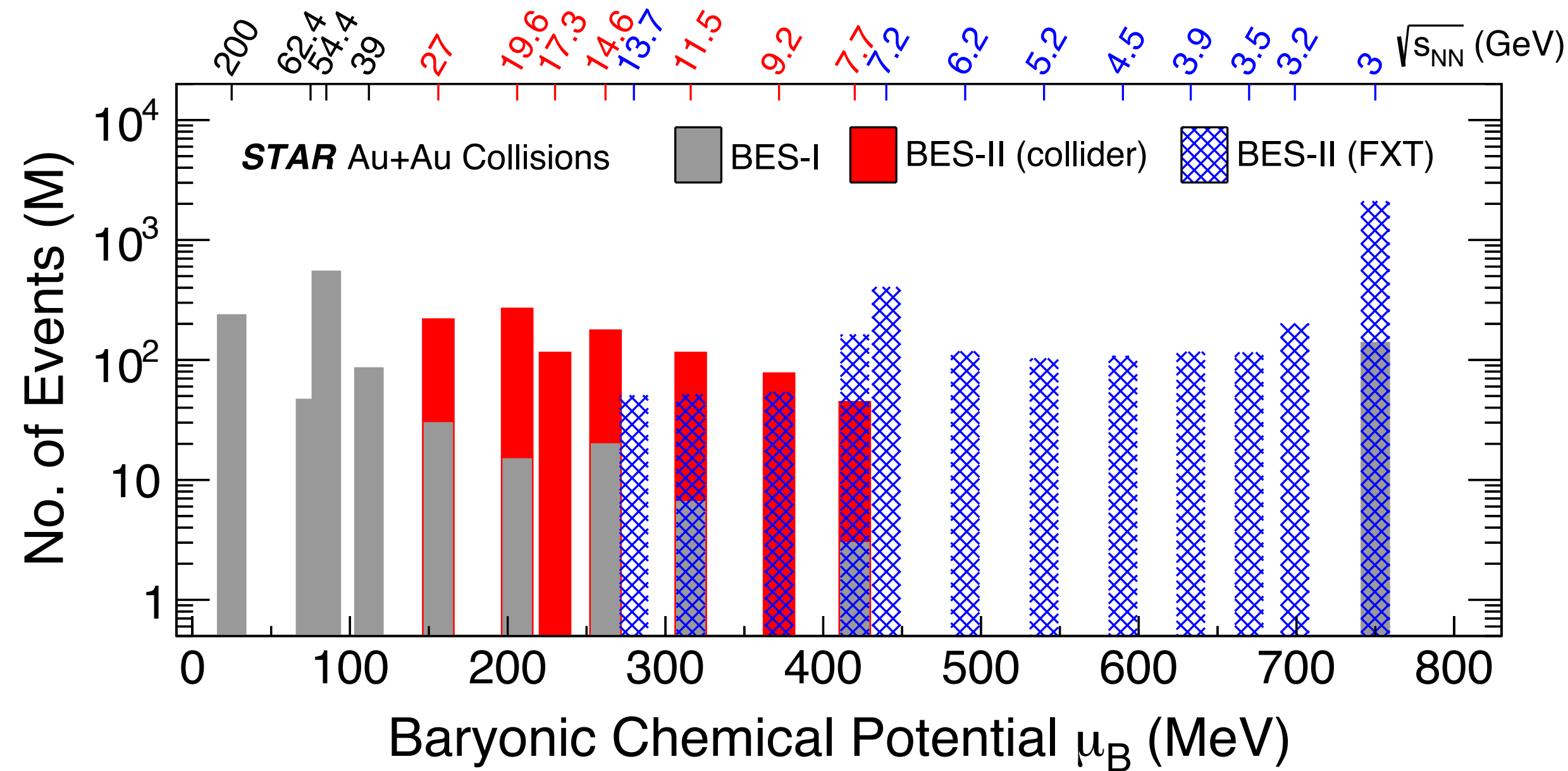
EPD

eTOF

iTPC

STAR Detector System

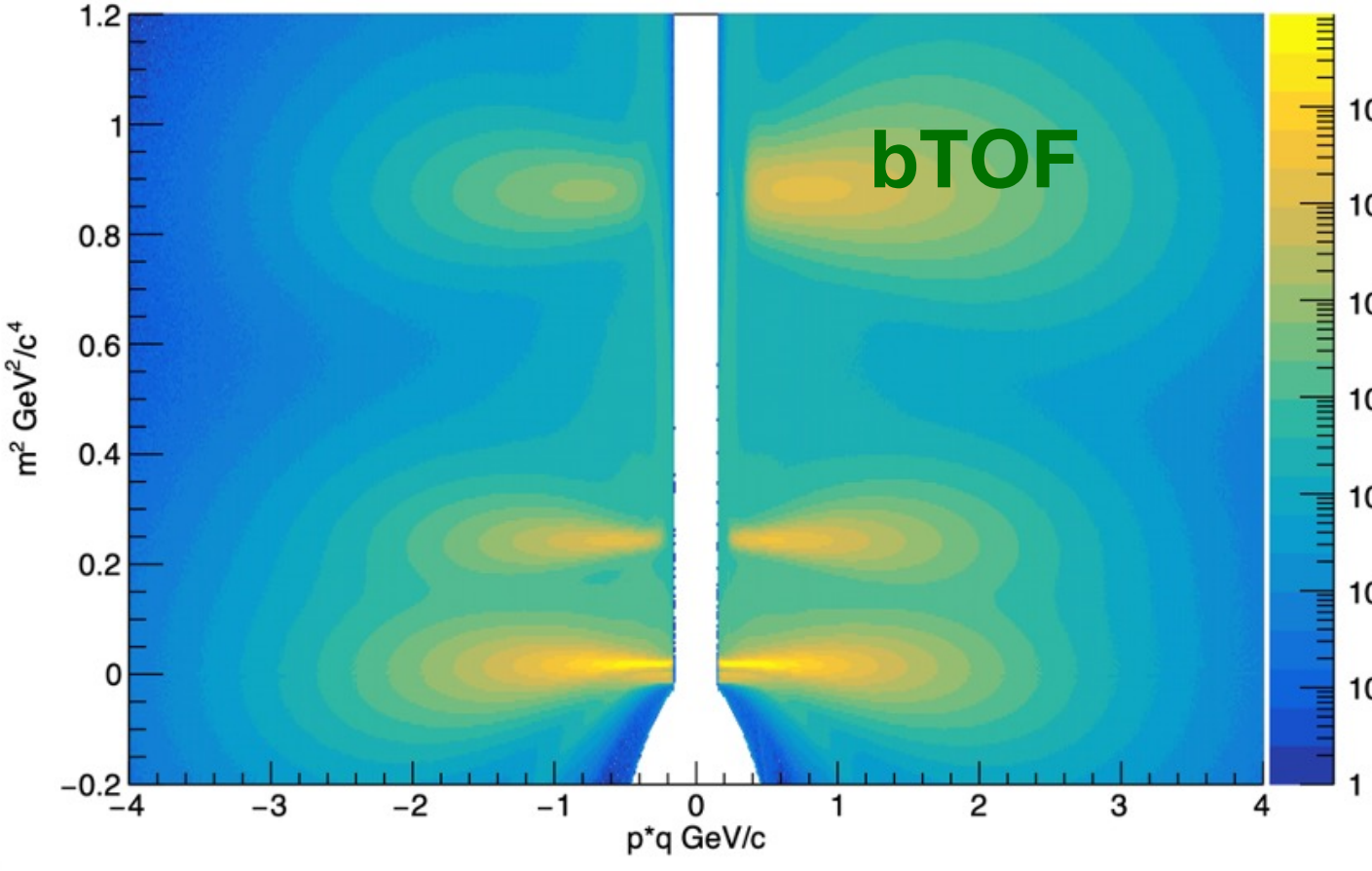
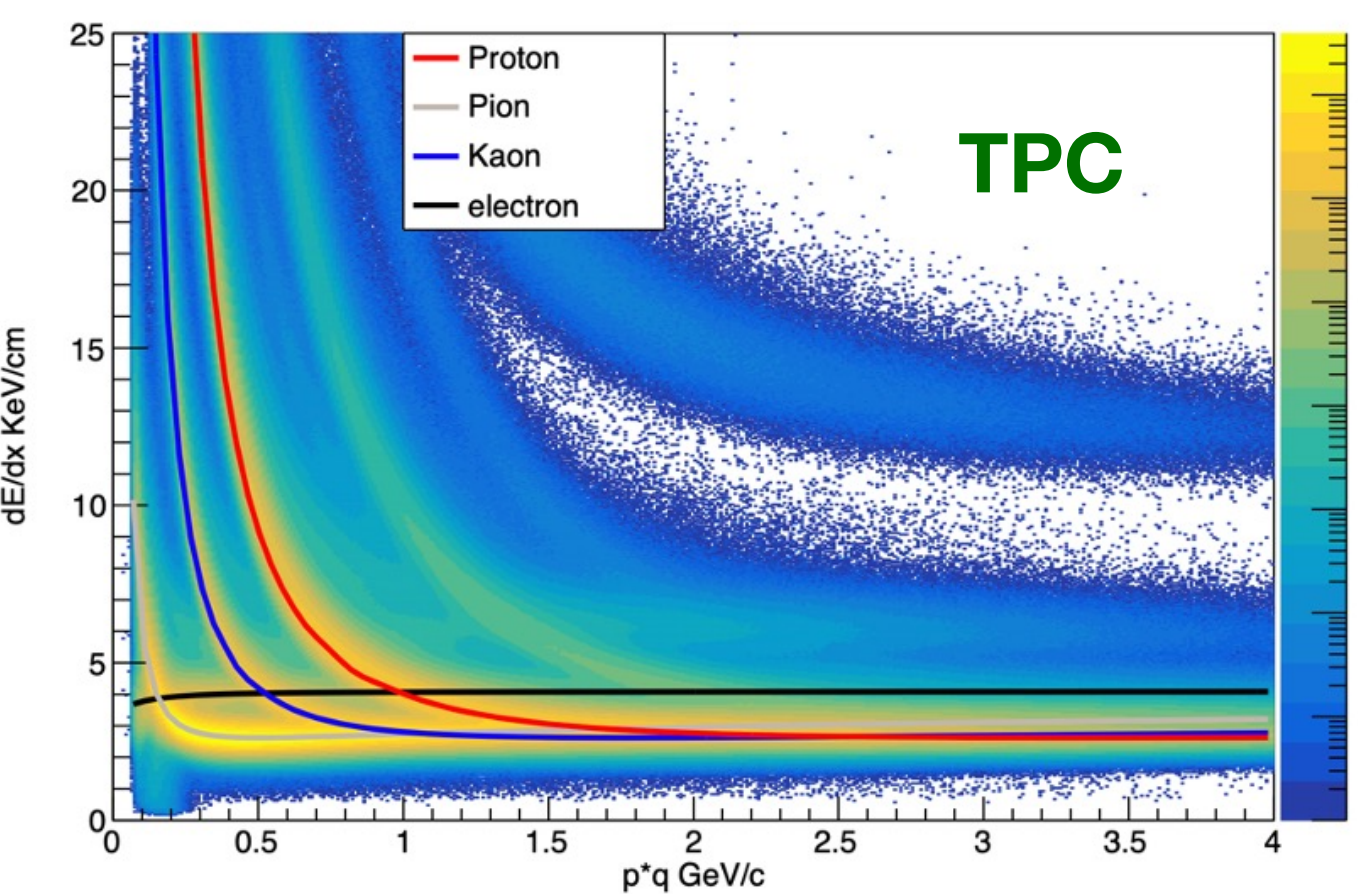
RHIC Beam Energy Scan (BES)



1. BES-I (2010–2014): Au+Au at 7.7 -> 200 GeV
2. BES-II (2018-2021): Au+Au at
 - 1) Collider mode: 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV
 - 2) Fixed-target mode: **3.0, 3.2, 3.5, 3.9, 4.5**, 5.2, 6.2, ..., 13.7 GeV
3. μ_B coverage : 25 — 760 MeV

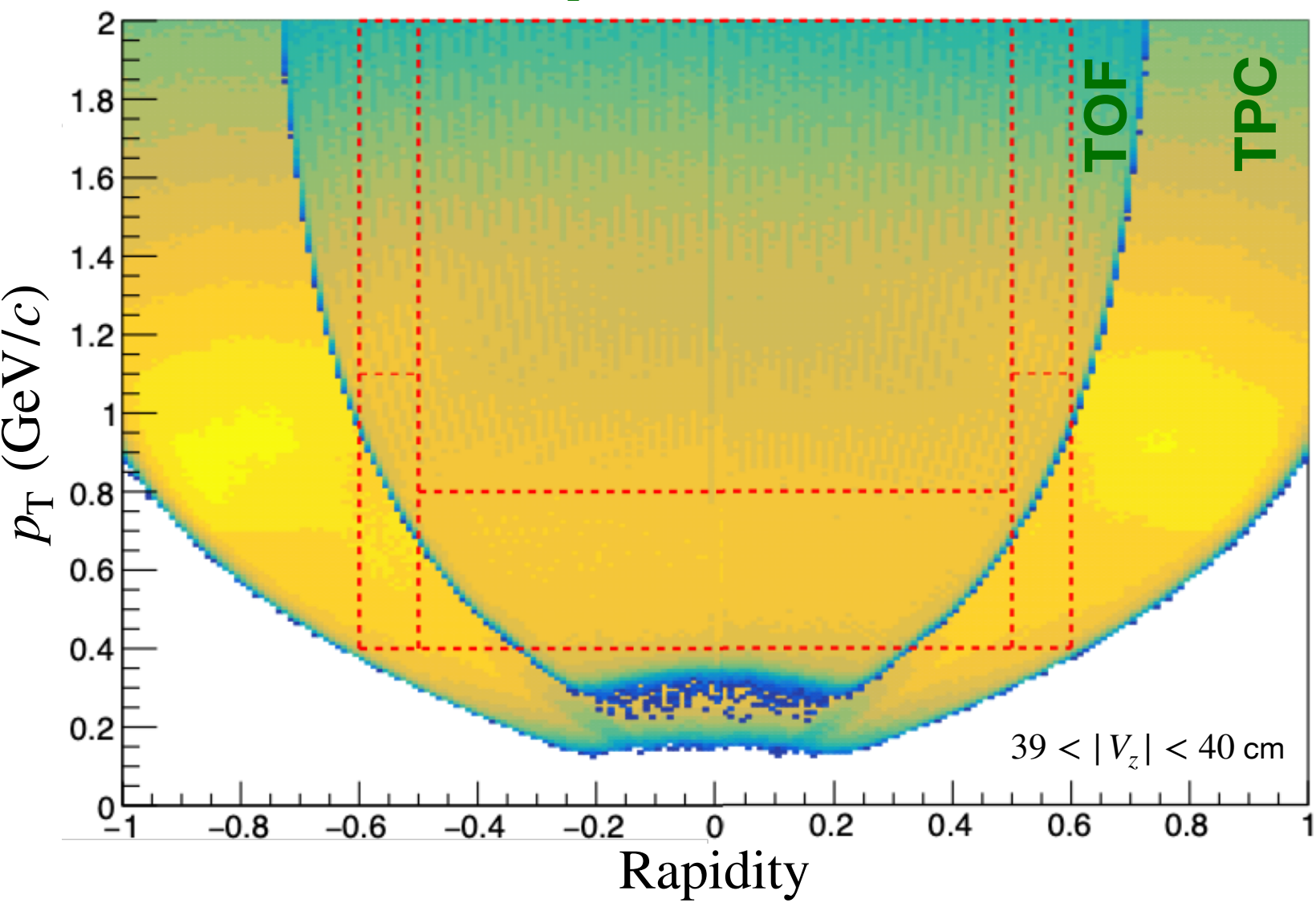
Beam Energy Scan Phase-II (COL Mode)

Particle Identification

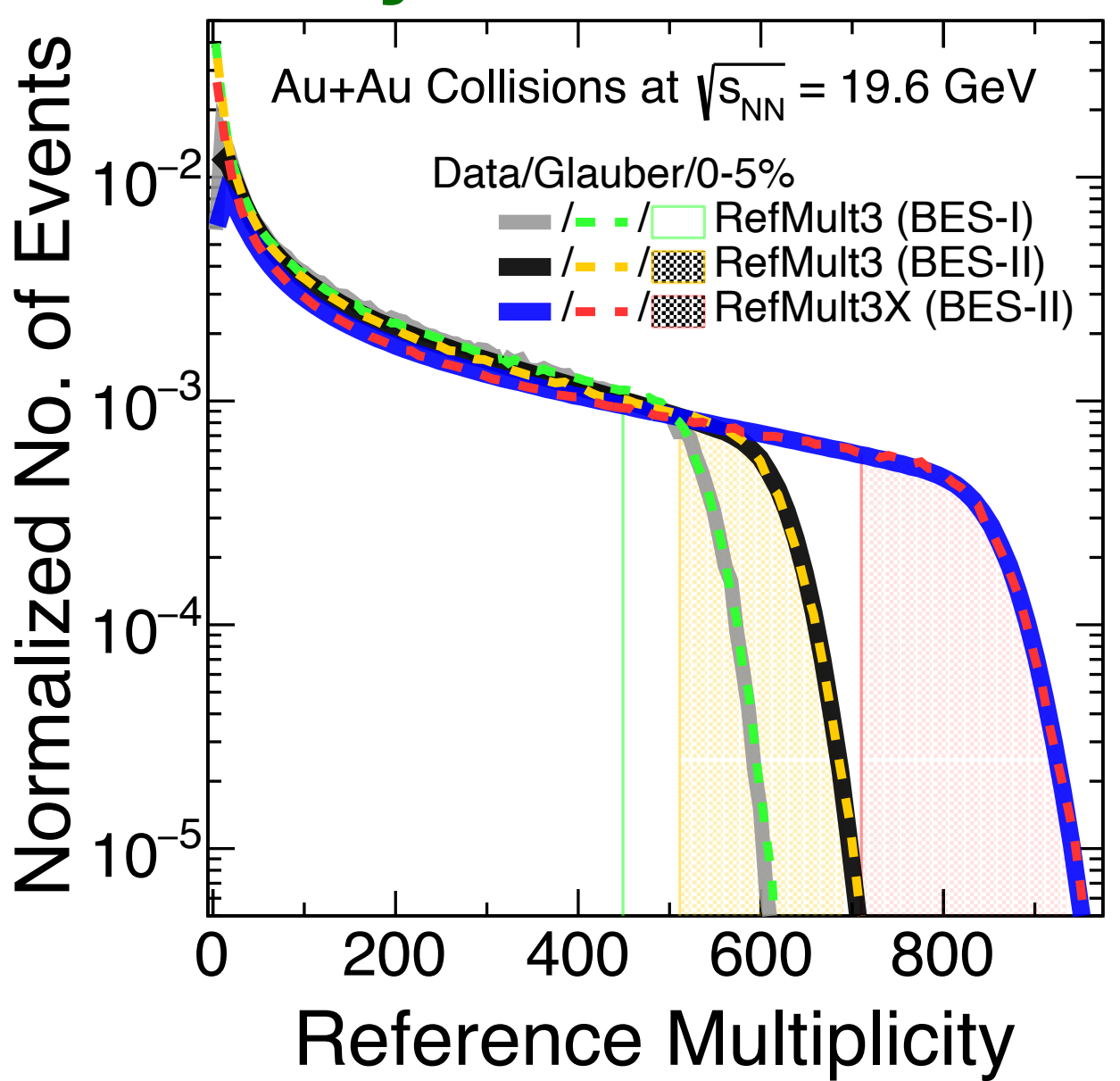


Collider Runs (COL)			Fixed-Target Runs (FXT)		
$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B
200	380 M	25 MeV	13.7 (100)	50 M	280 MeV
62.4	46 M	75 MeV	11.5 (70)	50 M	320 MeV
54.4	1200 M	85 MeV	9.2 (44.5)	50 M	370 MeV
39	86 M	112 MeV	7.7 (31.2)	260 M	420 MeV
27	585 M	156 MeV	7.2 (26.5)	470 M	440 MeV
19.6	595 M	206 MeV	6.2 (19.5)	120 M	490 MeV
17.3	256 M	230 MeV	5.2 (13.5)	100 M	540 MeV
14.6	340 M	262 MeV	4.5 (9.8)	110 M	590 MeV
11.5	57 M	316 MeV	3.9 (7.3)	120 M	633 MeV
9.2	160 M	372 MeV	3.5 (5.75)	120 M	670 MeV
7.7	104 M	420 MeV	3.2 (4.59)	200 M	699 MeV
			3.0 (3.85)	260 + 2000 M	760 MeV

Proton Acceptance



Centrality Definition



1. Excellent PID ensures high proton purity ($> 95\%$);
2. Wide and uniform acceptance;
3. RefMult3(X): multiplicity of charged particles excluding protons (to avoid self-correlation)

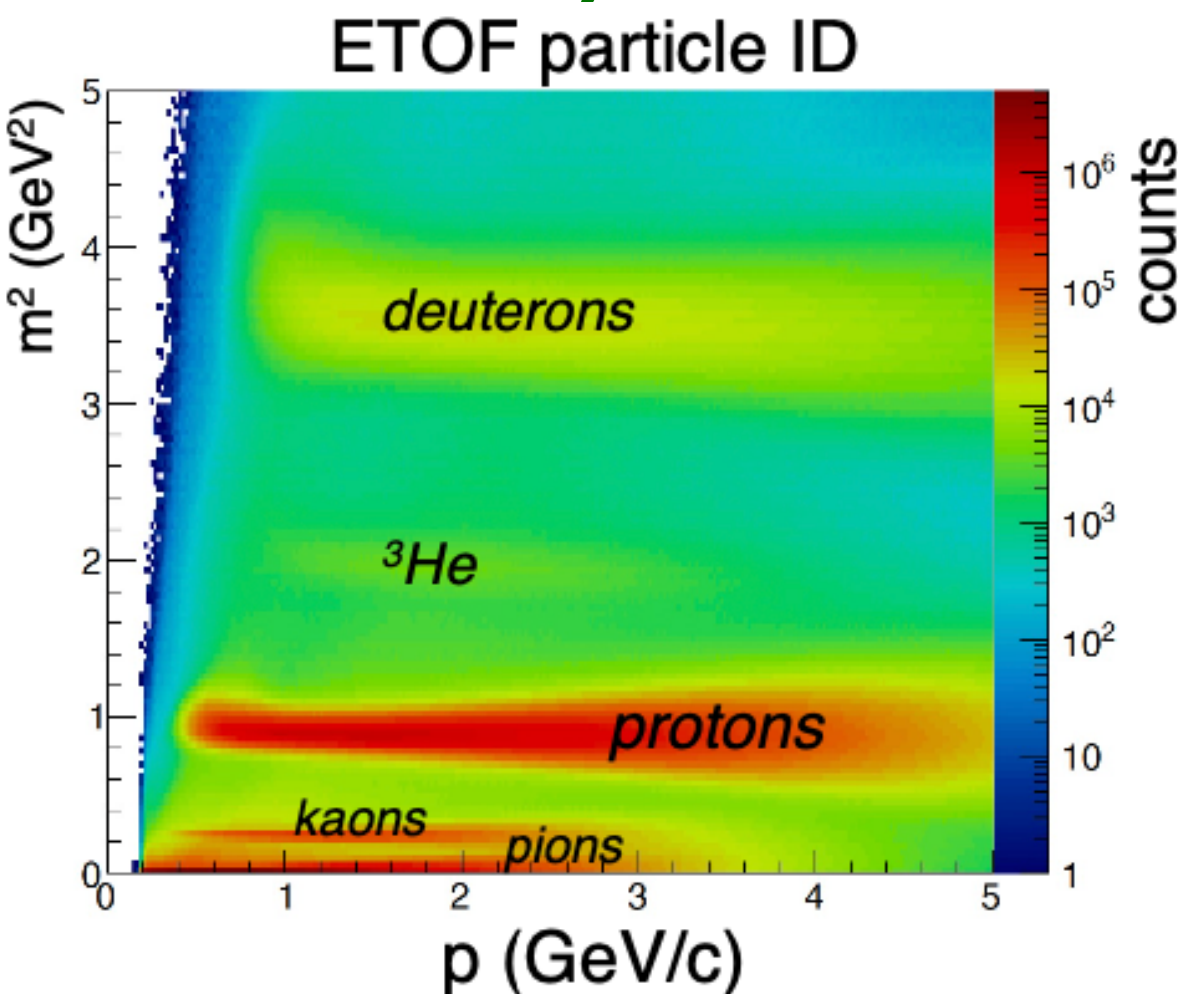
Examples from Au+Au collisions at $\sqrt{s_{NN}} = 19.6$ GeV

Beam Energy Scan Phase-II (FXT Mode)

Particle Identification (Additional to TPC & bTOF)

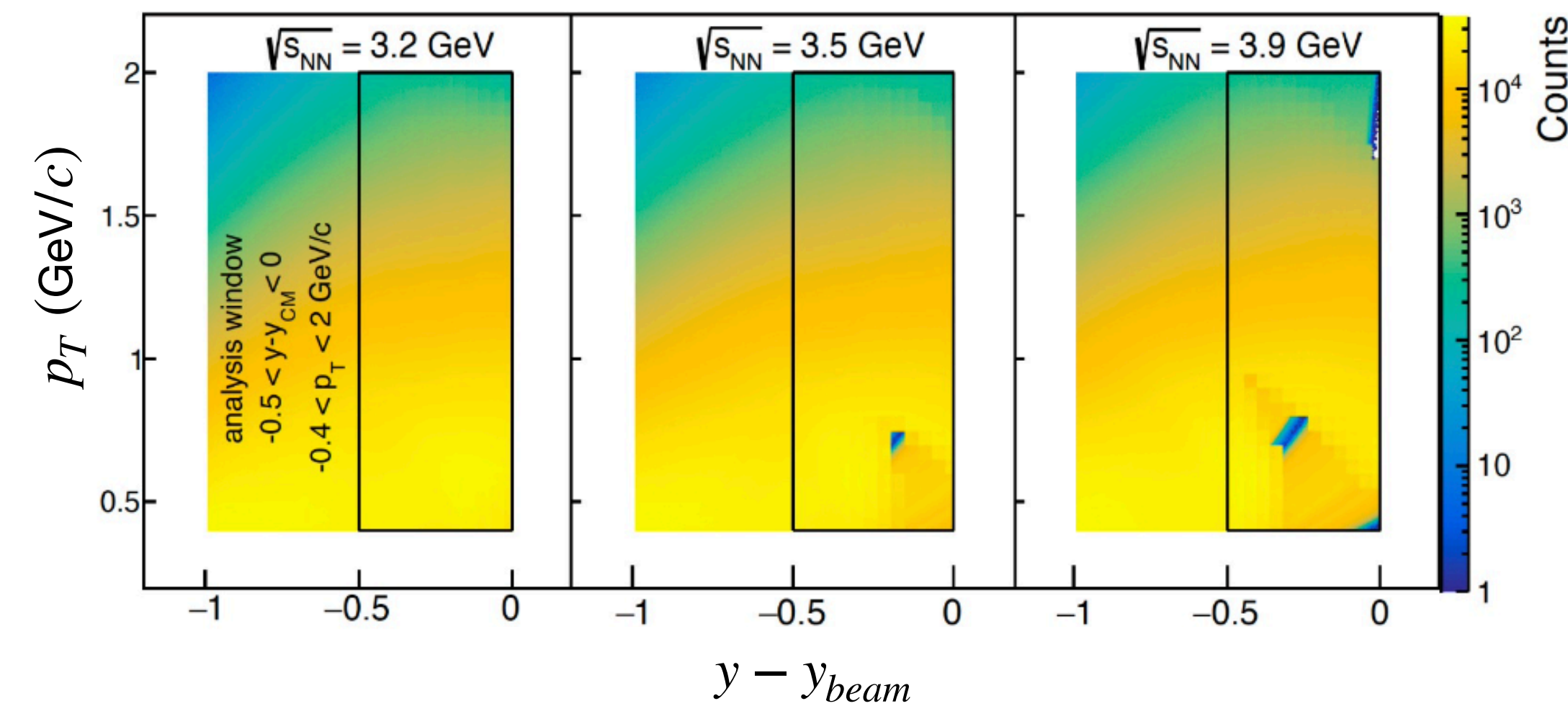


- From CBM-TOF group
- Provides precision PID over $1.55 < \eta < 2.2$
- Collected data for FXT runs

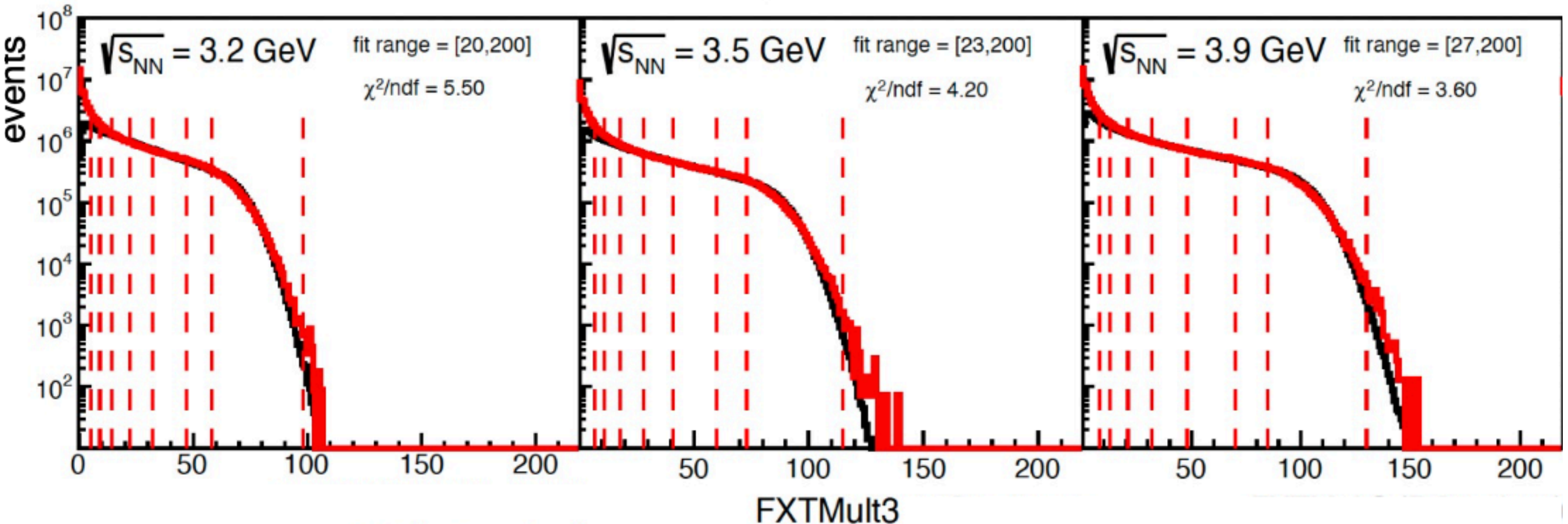


Collider Runs (COL)			Fixed-Target Runs (FXT)		
$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B
200	380 M	25 MeV	13.7 (100)	50 M	280 MeV
62.4	46 M	75 MeV	11.5 (70)	50 M	320 MeV
54.4	1200 M	85 MeV	9.2 (44.5)	50 M	370 MeV
39	86 M	112 MeV	7.7 (31.2)	260 M	420 MeV
27	585 M	156 MeV	7.2 (26.5)	470 M	440 MeV
19.6	595 M	206 MeV	6.2 (19.5)	120 M	490 MeV
17.3	256 M	230 MeV	5.2 (13.5)	100 M	540 MeV
14.6	340 M	262 MeV	4.5 (9.8)	110 M	590 MeV
11.5	57 M	316 MeV	3.9 (7.3)	120 M	633 MeV
9.2	160 M	372 MeV	3.5 (5.75)	120 M	670 MeV
7.7	104 M	420 MeV	3.2 (4.59)	200 M	699 MeV
			3.0 (3.85)	260 + 2000 M	760 MeV

Proton Acceptance



Centrality Definition



Fluctuation Measures

(Central) Moments $\longleftrightarrow$

$$M = C_1, \sigma^2 = C_2$$

$$S = \frac{C_3}{(C_2)^{3/2}}, \kappa = \frac{C_4}{C_2^2}$$

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

$$\frac{C_4}{C_2} = \kappa\sigma^2$$

Cumulants C

$$C_1 = \langle N \rangle$$

$$C_2 = \langle (\delta N)^2 \rangle$$

$$C_3 = \langle (\delta N)^3 \rangle$$

$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

Factorial Cumulants κ

$$\kappa_1 = C_1$$

$$\kappa_2 = -C_1 + C_2$$

$$\kappa_3 = 2C_1 - 3C_2 + C_3$$

$$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$$

N : Event-by-event multiplicity

$$\delta N = N - \langle N \rangle$$

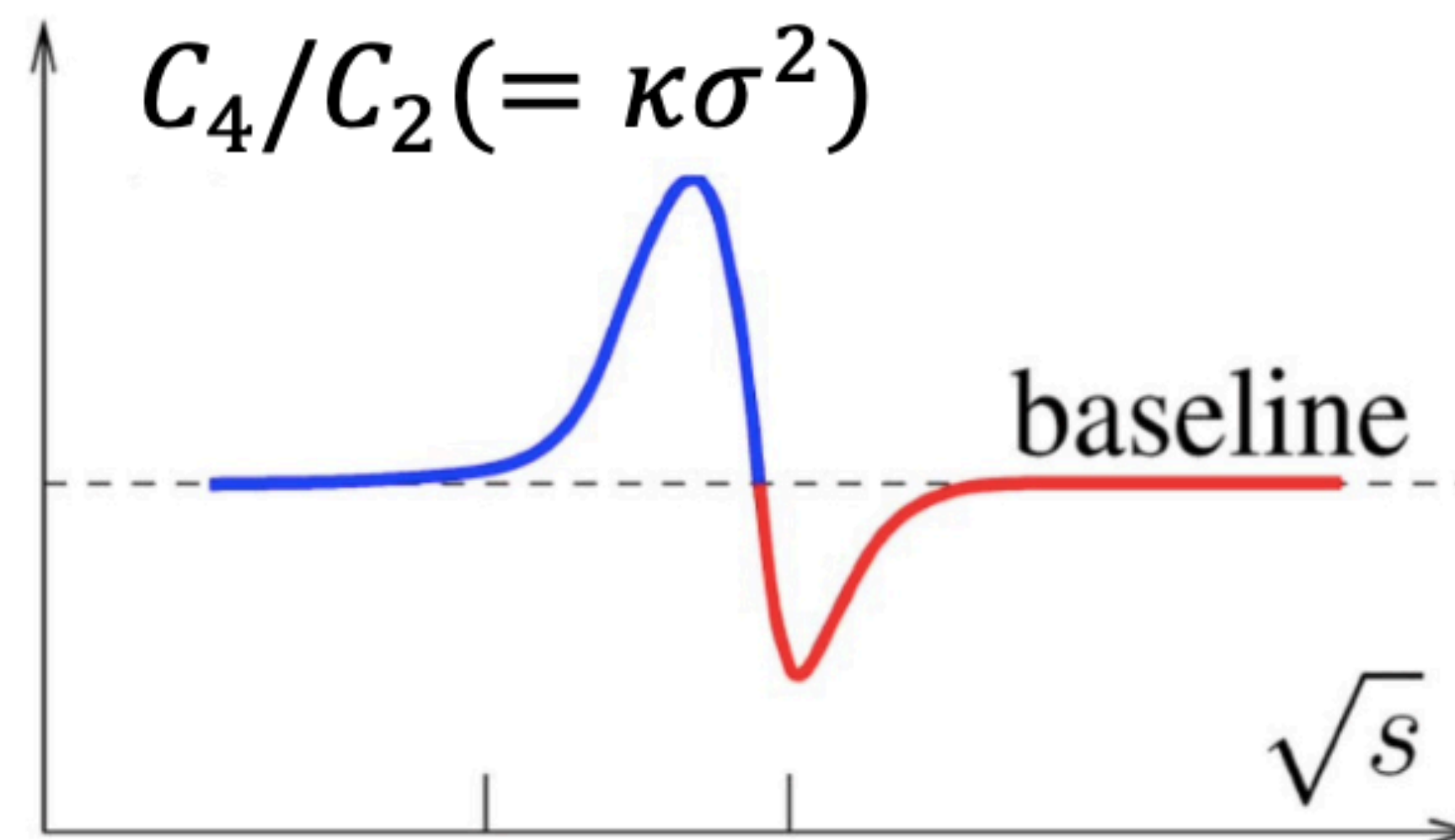
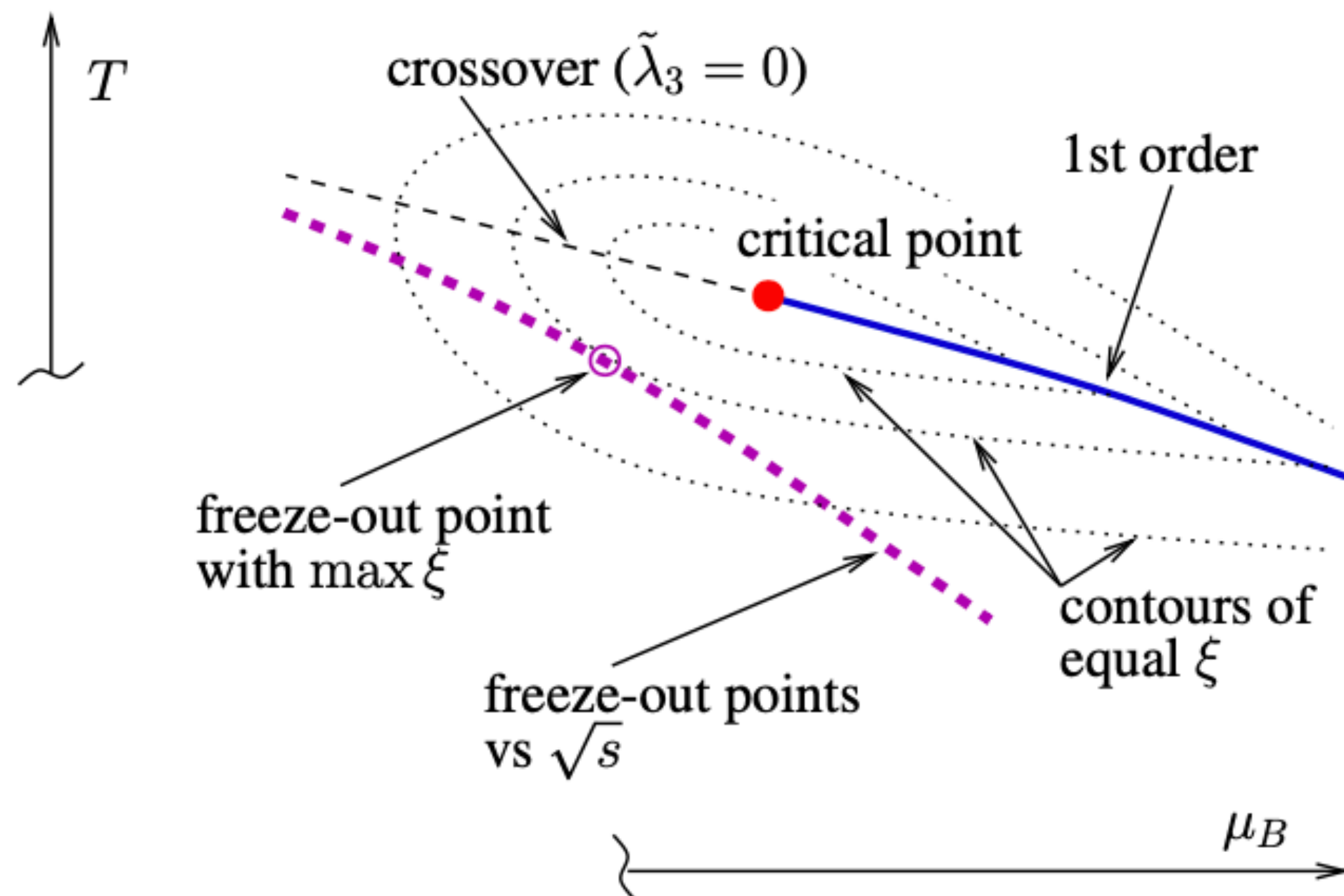
- **Cumulants** quantify the shape of distributions / fluctuations;
- **Factorial cumulants** capture genuine multi-particle correlations.

Fluctuation in Proximity to the Critical Point

Cumulants of Conserved Quantities (B, S, Q)

M. Stephanov: PRL 102 032301 (2009)

M. Stephanov: PRL 107 052301 (2011)



1. Sensitive to correlation length ξ : $C_2 \sim \xi^2$, $C_4 \sim \xi^7$;
2. Directly related to the susceptibility: $\chi_n^{B,S,Q} = C_n^{B,S,Q}/(VT^3)$, $C_4/C_2 = \chi_4/\chi_2$;
3. Non-monotonic energy dependence of C_4/C_2 for the conserved baryon number (using protons as a proxy) indicates the existence of a critical region;
4. Broader energy range and higher statistics in BES-II will help reveal clearer signals.

Fluctuation in Proximity to the Critical Point

Hyper Order Cumulants: Diagnostic of the Phase Transition

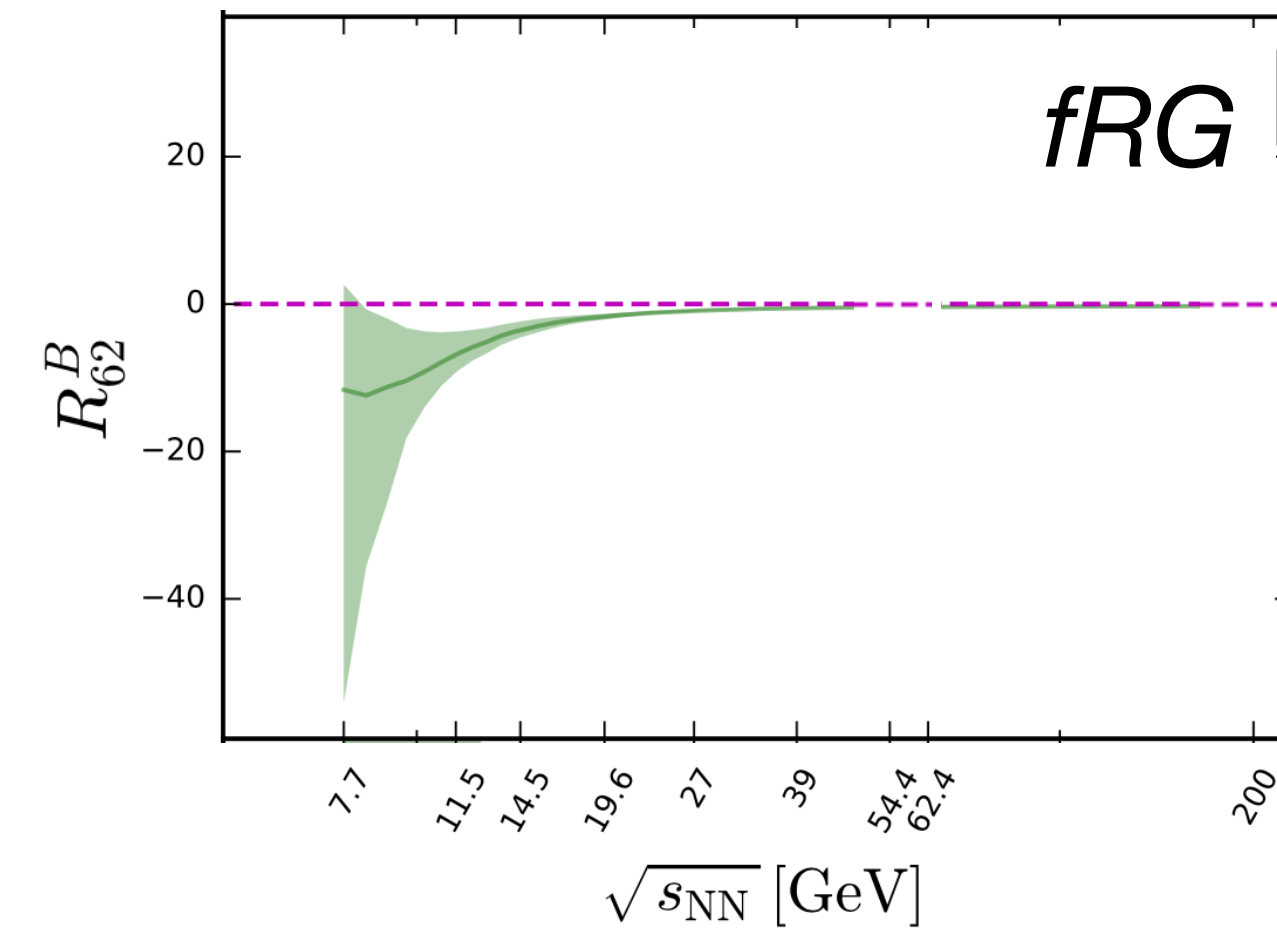
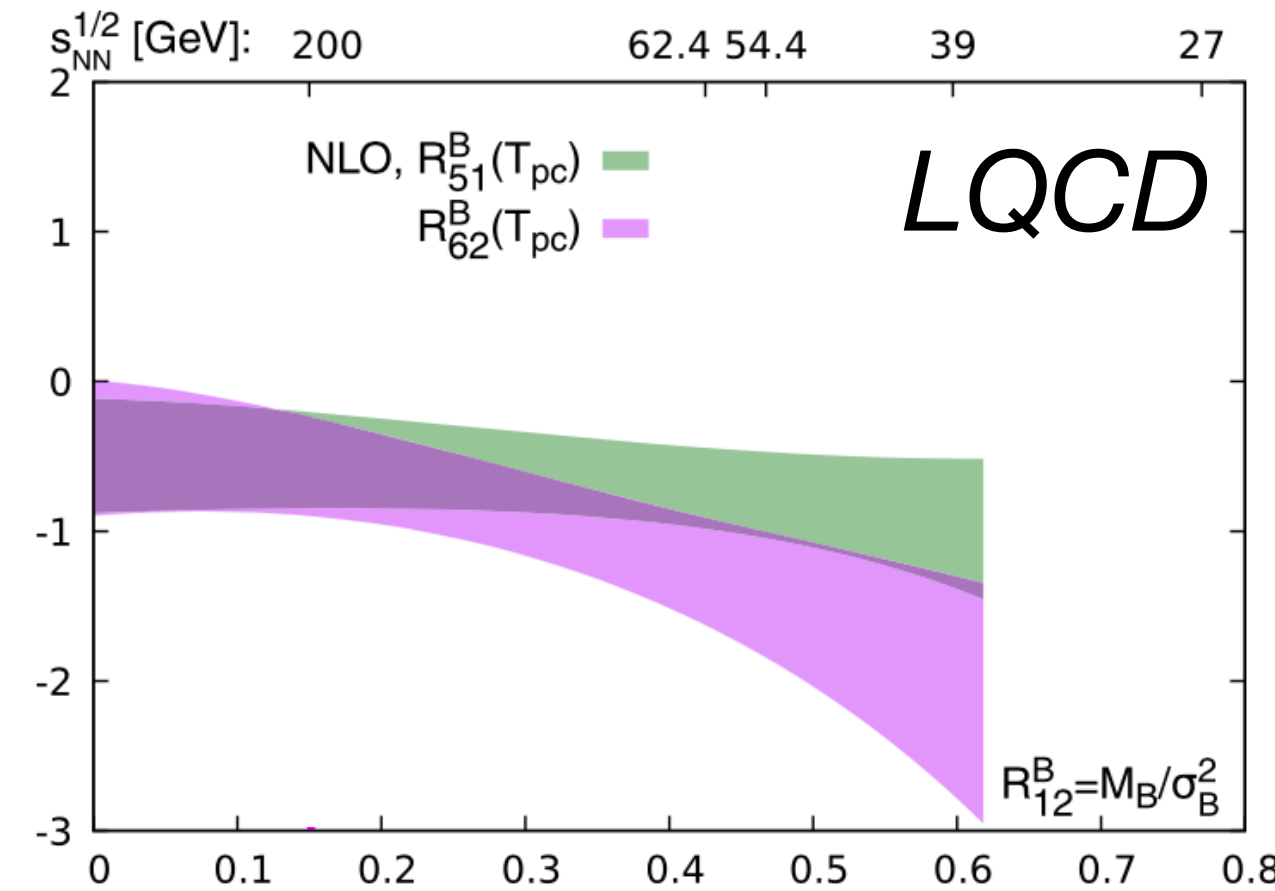
HotQCD: PRD 101 074502 (2020)
W. Fu, et al: PRD 104 094047 (2021)

$$C_5 = \langle (\delta N)^5 \rangle - 5 \langle (\delta N)^3 \rangle \langle (\delta N)^2 \rangle$$

$$C_6 = \langle (\delta N)^6 \rangle - 15 \langle (\delta N)^4 \rangle \langle (\delta N)^2 \rangle - 10 \langle (\delta N)^3 \rangle^2 + 30 \langle (\delta N)^2 \rangle^3$$

$$\kappa_5 = 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5$$

$$\kappa_6 = -120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$$

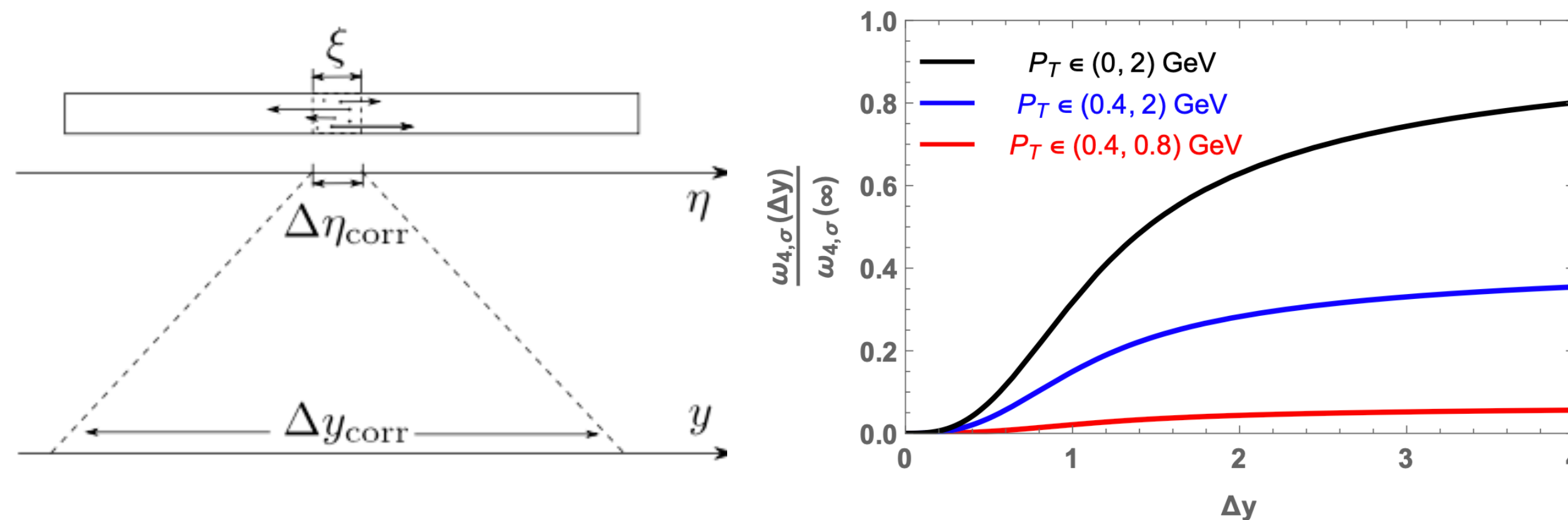


1. Negative C_5/C_1 and C_6/C_2 indicate the smooth crossover nature of the QCD transition;
2. A 7–18 fold increase in statistics in BES-II compared to BES-I will reduce uncertainties and improve the reliability of the results.

Fluctuation in Proximity to the Critical Point

B.Ling and M.A.Stephanov: PRC 93 034915 (2016)

Power-law Behavior: Proton Number Factorial Cumulants in Kinematic Scan



very large Δy_{corr} near the CEP

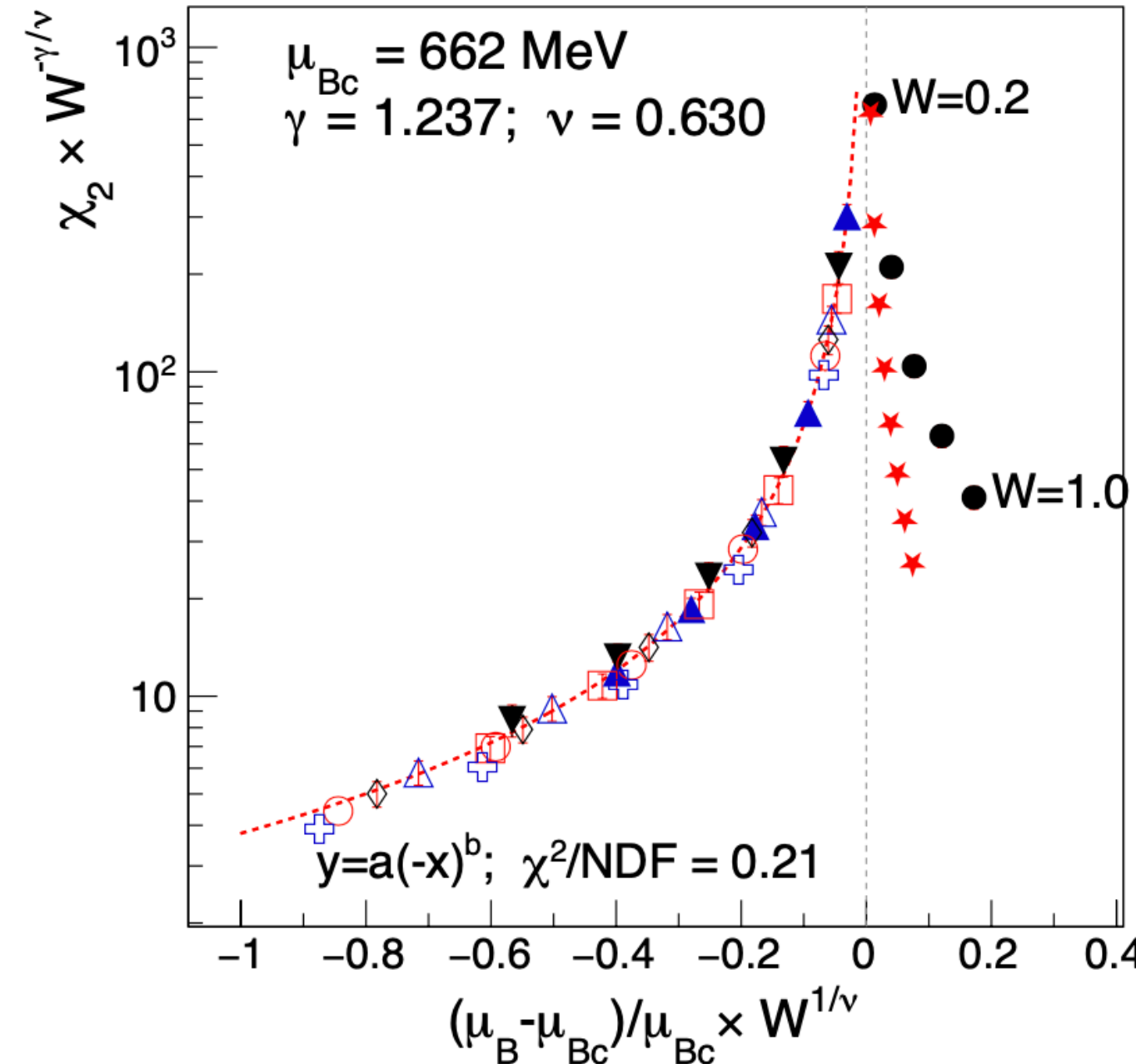
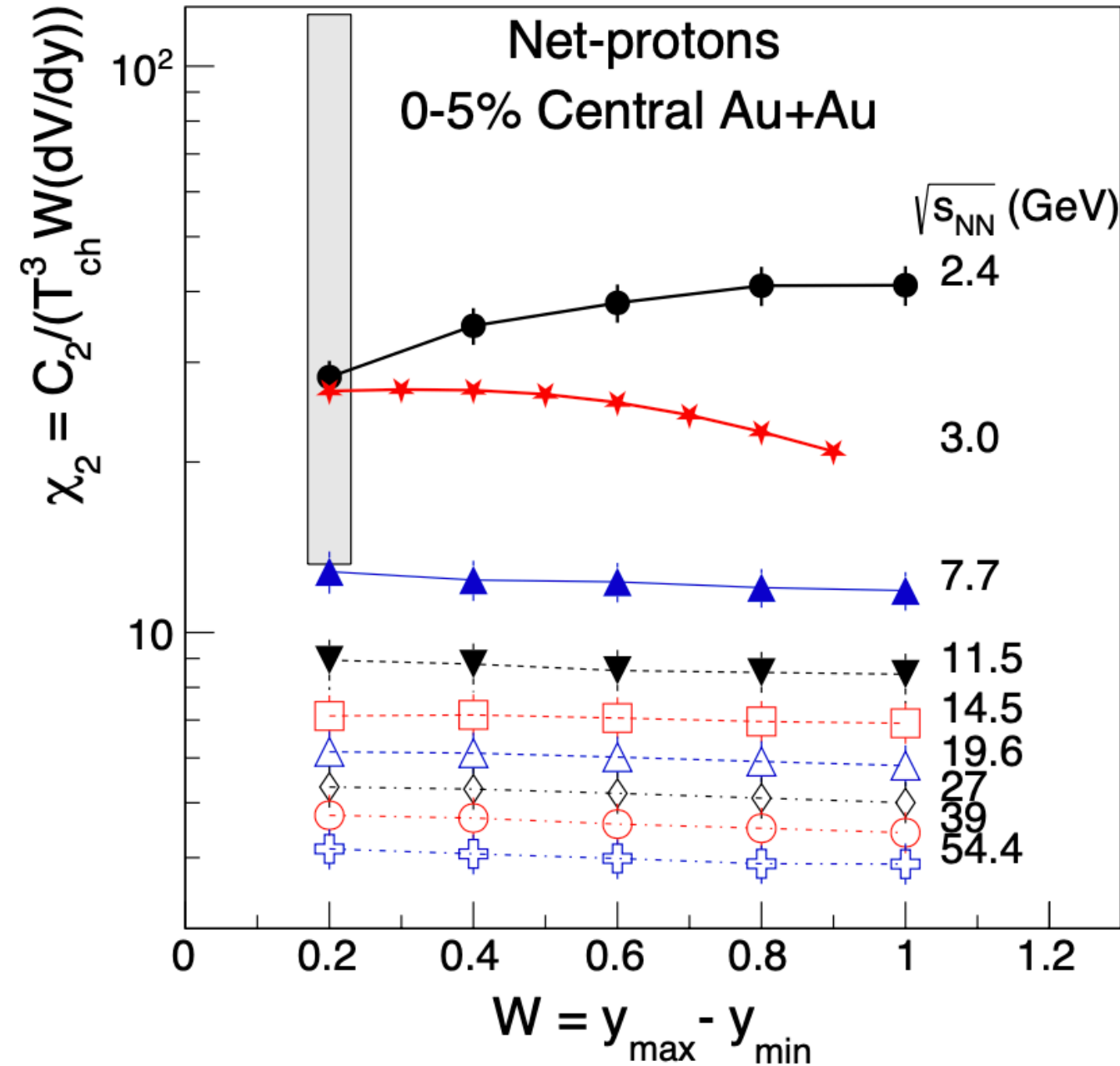
The opposite, small acceptance regime, $\Delta y \ll \Delta y_{corr}$, is easier to describe using the factorial cumulants, $\hat{\kappa}_k$, because they scale as $(\Delta y)^k$ in this regime. The normal cumulants, on the other hand, given by linear combinations of factorial cumulants in Eq. (3), have a more complicated, polynomial dependence on Δy in this regime.

1. Perform a rapidity scan to probe long-range phenomena near the critical point: a wider rapidity window amplifies their contribution;
2. Near the critical point, within small rapidity window $\Delta y \ll \Delta y_{corr}$, we expect $\kappa_n \sim (\Delta y)^n$;
3. BES-II offers wide acceptance for long-range studies and high statistics for reliable fits.

Fluctuation in Proximity to the Critical Point

A.Sorensen and P.Sorensen: arXiv:2405.10278[nucl-th]

Extrapolation the critical point via Finite-Size Scaling Method



$\nu \approx 0.630$ [42]. Based on Eq. (1), if $\chi L^{-\gamma/\nu}$ is plotted as a function of $tL^{1/\nu}$, then data for different system sizes and values of t should collapse on a single universal curve Φ ; the crucial insight for using FSS in finding the critical point is that this can only take place when the correct value of T_c , $\mu_{B,c}$, or $(\frac{\mu_B}{T})_c$ is used in t . Thus, scanning ranges of values of T_c or $\mu_{B,c}$ until the data collapse occurs provides a valuable method to determine the location of a critical point.

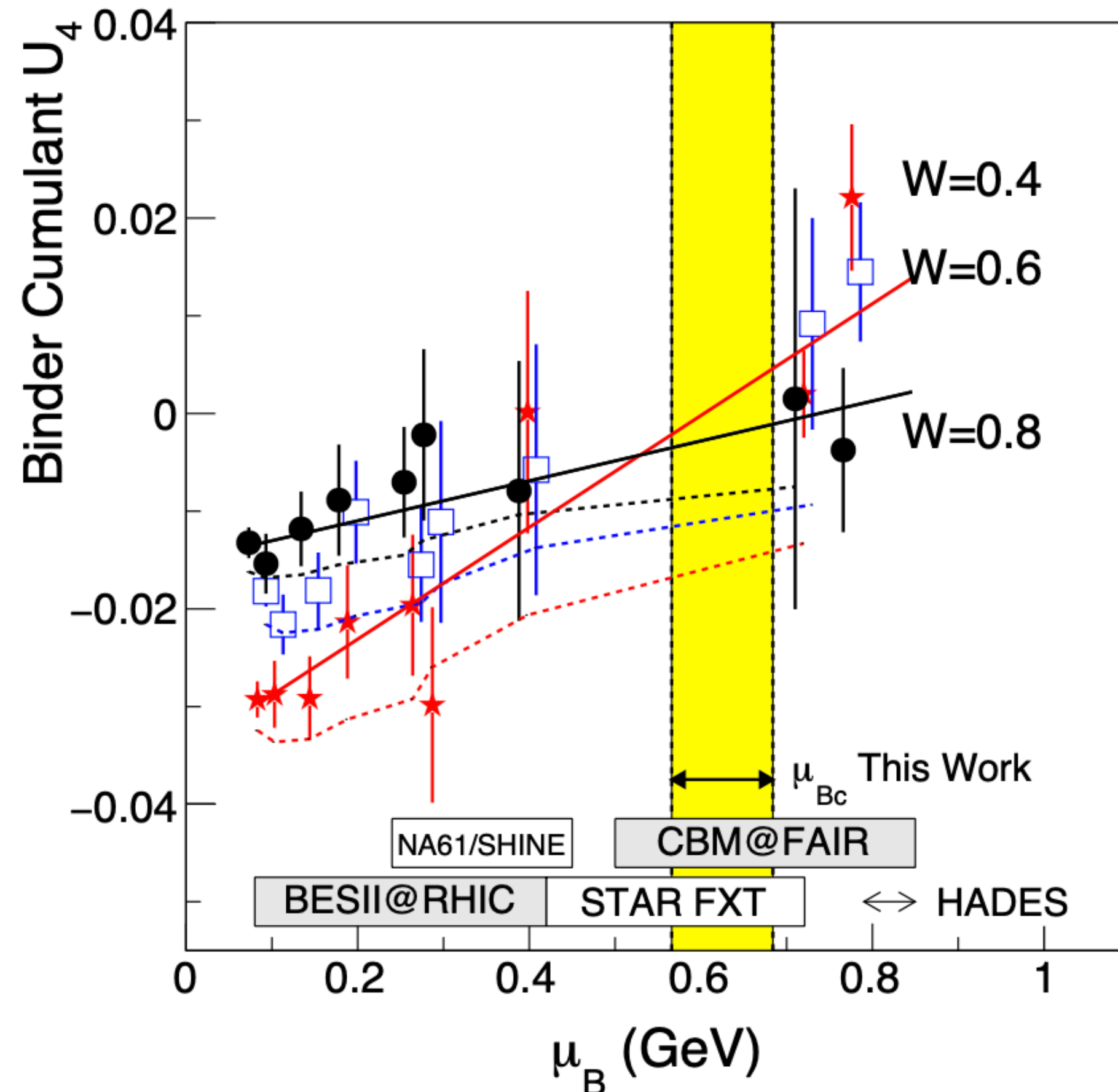
$$\chi(L, t) = L^{\gamma/\nu} \Phi(tL^{1/\nu}), \quad (1)$$

1. Construct susceptibility with measured cumulants and thermal parameters: $\chi_2(W, \mu_{fo}) = \frac{C_2(W, \mu_{fo})}{T_{fo}^3 W dV_{fo}/dy}$;
2. Finite-Size Scaling analysis requires a proper μ_{Bc} to exhibit power-law dependence;
3. STAR BES-II provides sufficient statistics for a precise extrapolation.

Fluctuation in Proximity to the Critical Point

A.Sorensen and P.Sorensen: arXiv:2405.10278[nucl-th]

Intersection Point of the Binder Cumulant



1. $U_4 = -3C_4/C_2^2$;
2. $U_4(\mu_B)$ in different rapidity window (W) is expected to cross at the critical point;
3. An ordering change between left (COL) and right (FXT) is observed in STAR BES-I + STAR FXT 3 GeV + HADES 2.4 GeV Au+Au collisions;
4. High-precision measurements in BES-II will provide further insights.

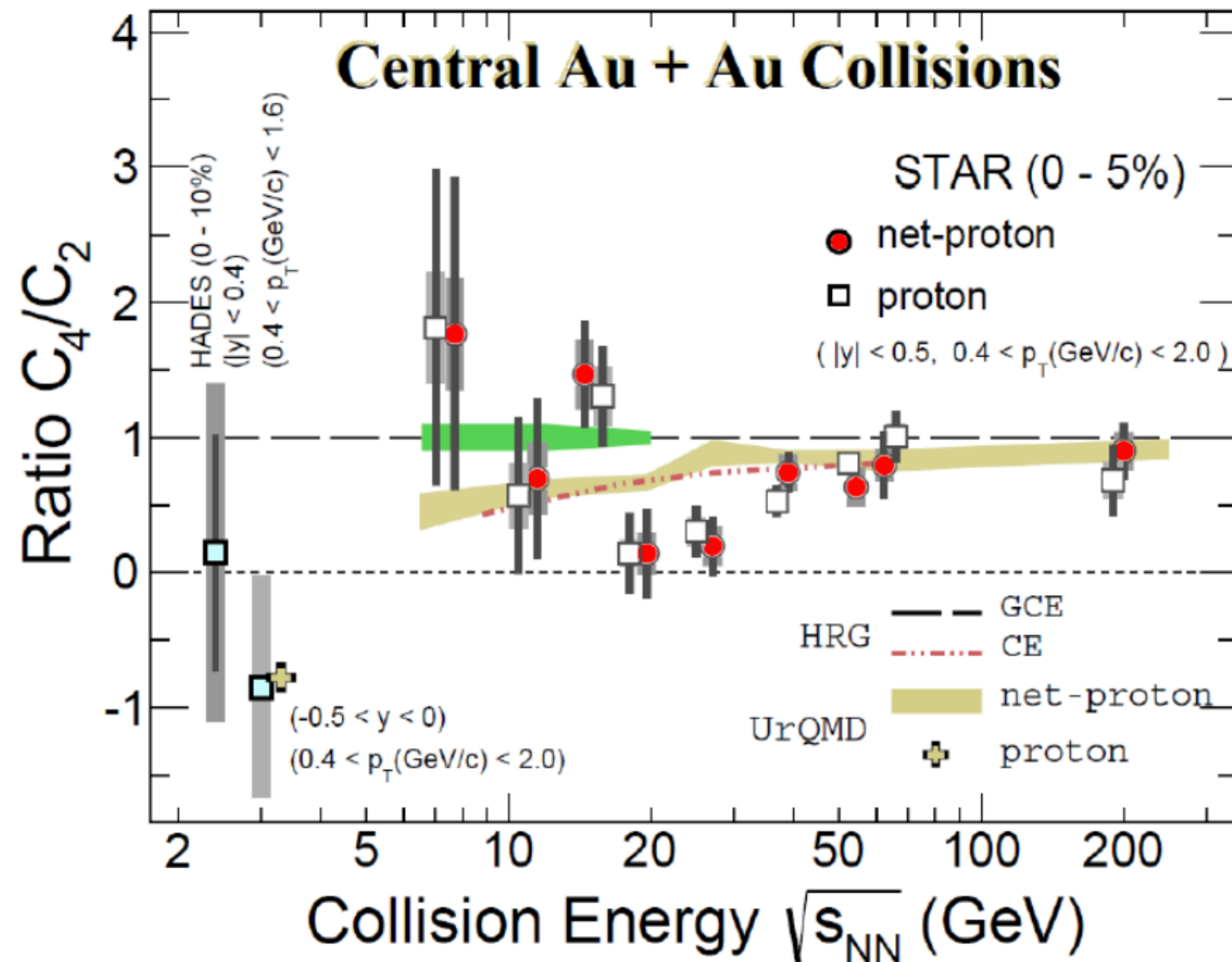
Proton Cumulants @ 3 GeV

STAR: PRL 126 092301 (2021) (BES-I)

STAR: PRL 128 202303 (2022)

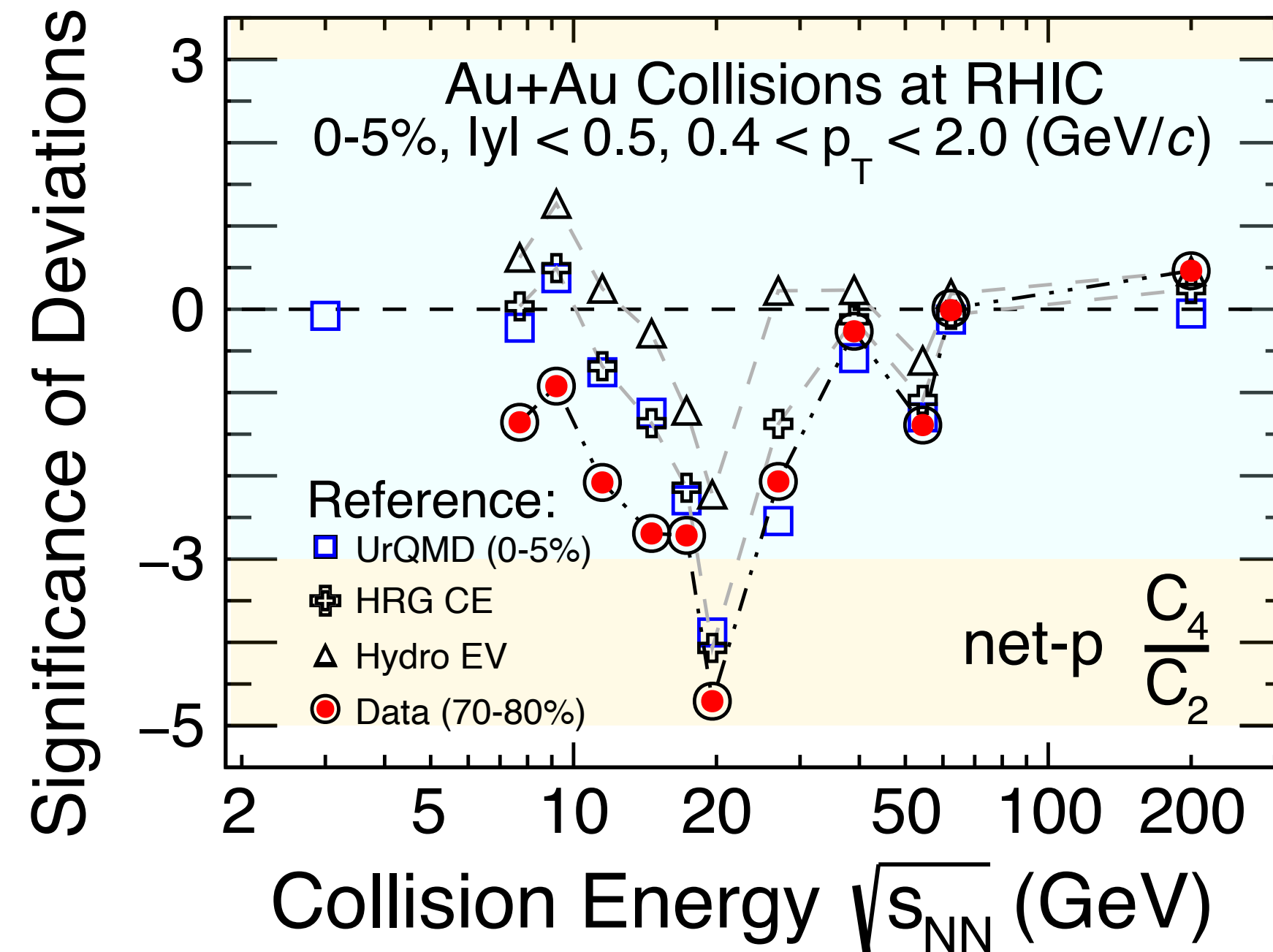
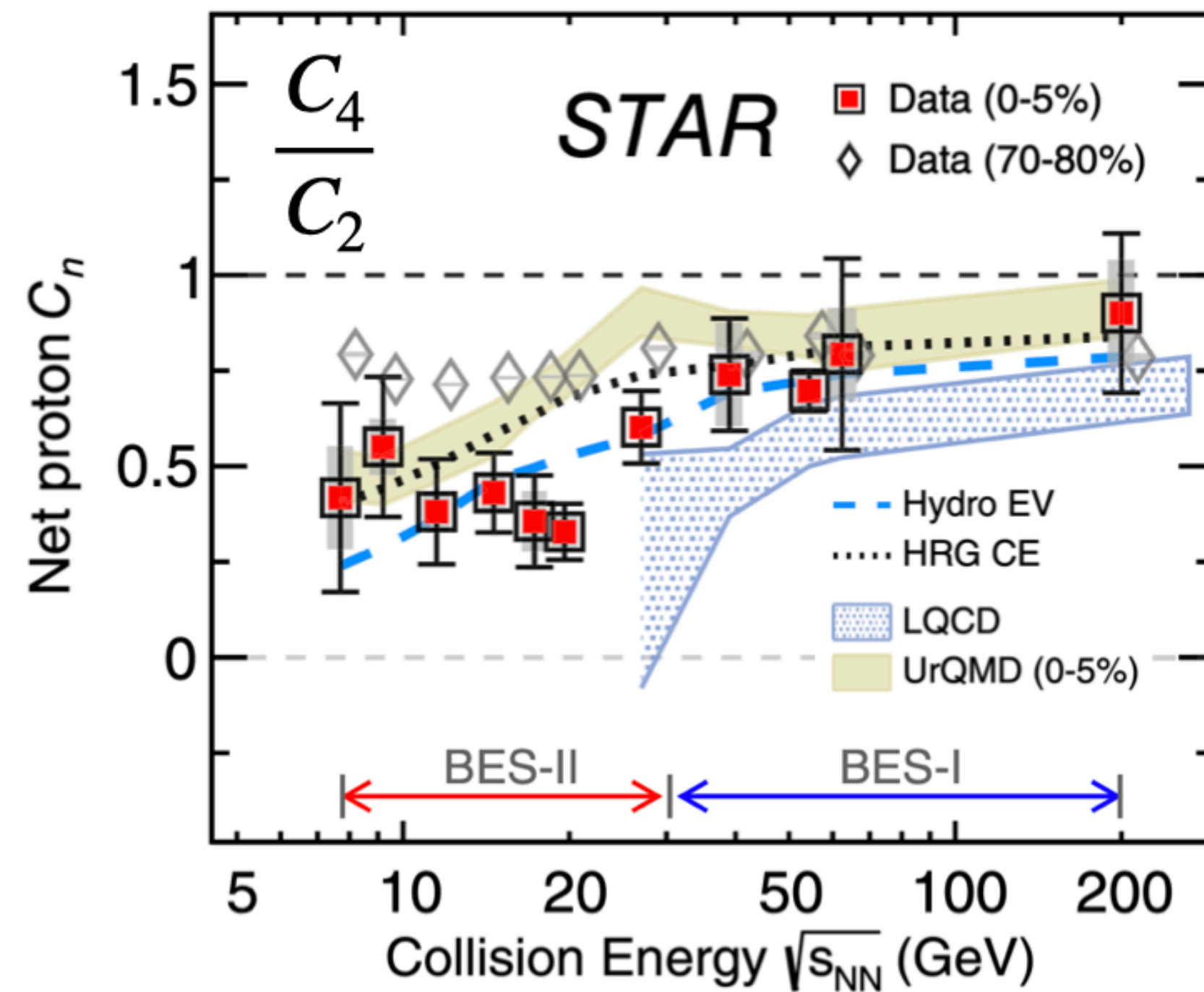
STAR: PRC 107 024908 (2023)

HADES: PRC 102 024914 (2020)



1. As the first fixed-target experiment at STAR, the 3 GeV measurement explores the high baryon density region.
2. This result is well reproduced by UrQMD model, indicating being dominated by hadronic interactions;
3. The QCD critical point, if discovered in heavy-ion collisions, could only exist at energies higher than 3 GeV.

Energy Dependence: BES-II COL Mode



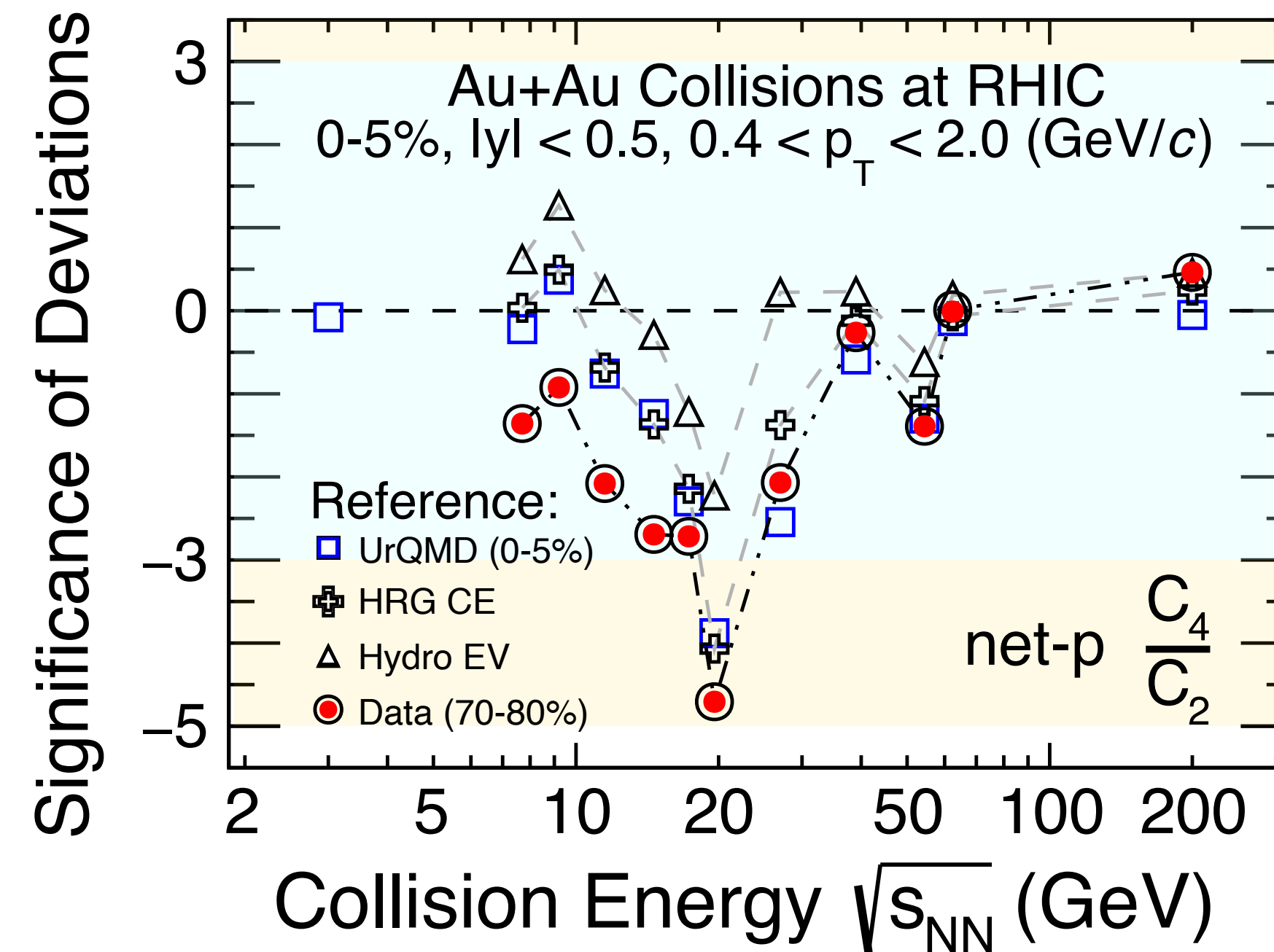
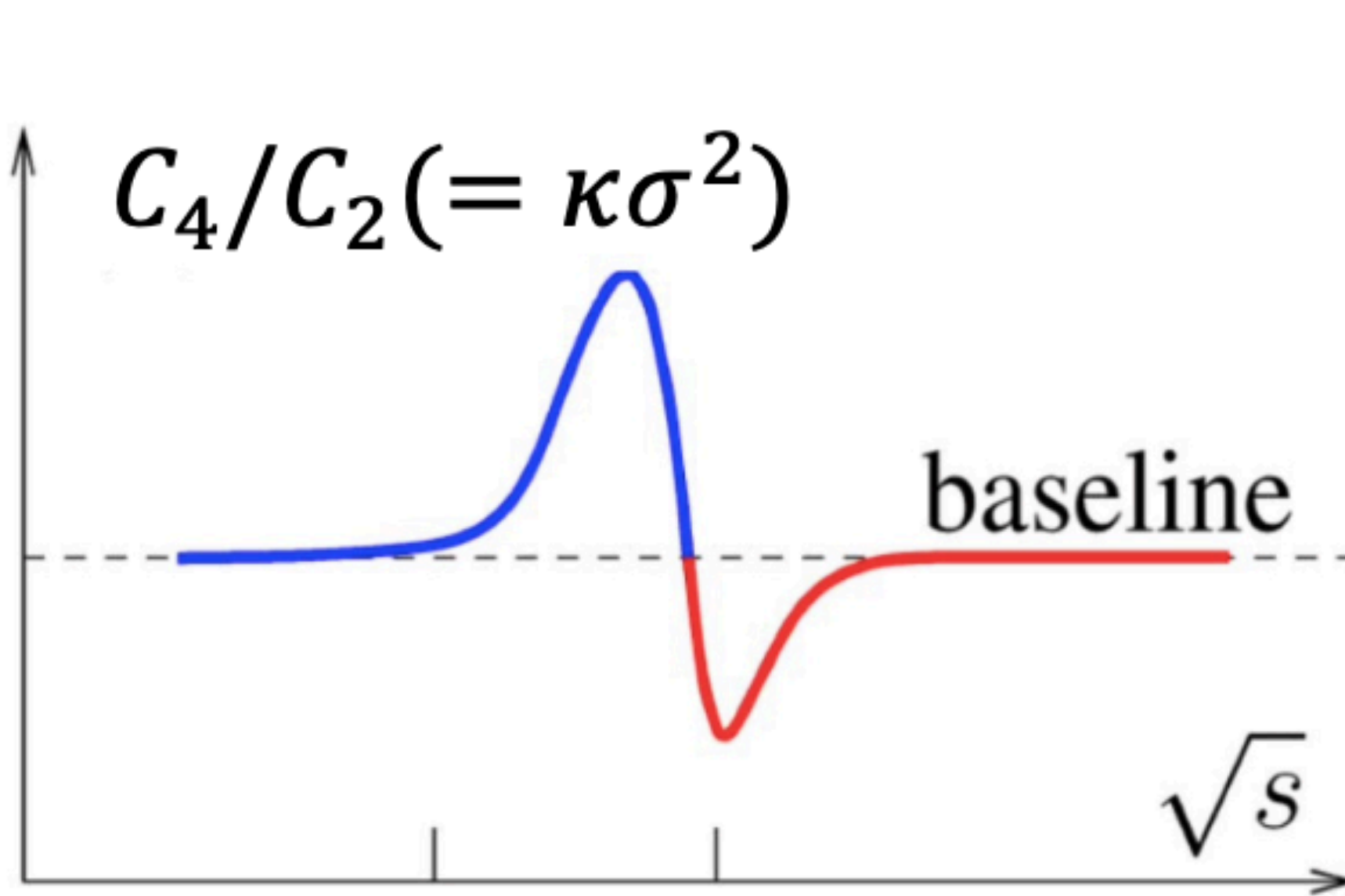
S. Bass, et al: PPNP 41 255 (1998)
P. B. Munzinger, et al: NPA 1008 122141 (2021)
V. Vovchenkov, et al: PRC 105 014904 (2022)
HotQCD: PRD 101 074502 (2020)
STAR: PRL135 142301 (2025)

$$\text{Significance} = \frac{\text{Data} - \text{Ref.}}{\sigma_{\text{total}}}$$

Data: STAR 0-5% Result

1. 4.7 / 3.2 reduction in statistical / systematic uncertainties compared to BES-I;
2. The largest negative deviation occurs at $\sqrt{s_{NN}}=19.6$ GeV w.r.t non-CP references with at most 4.7σ ;

Energy Dependence: BES-II COL Mode



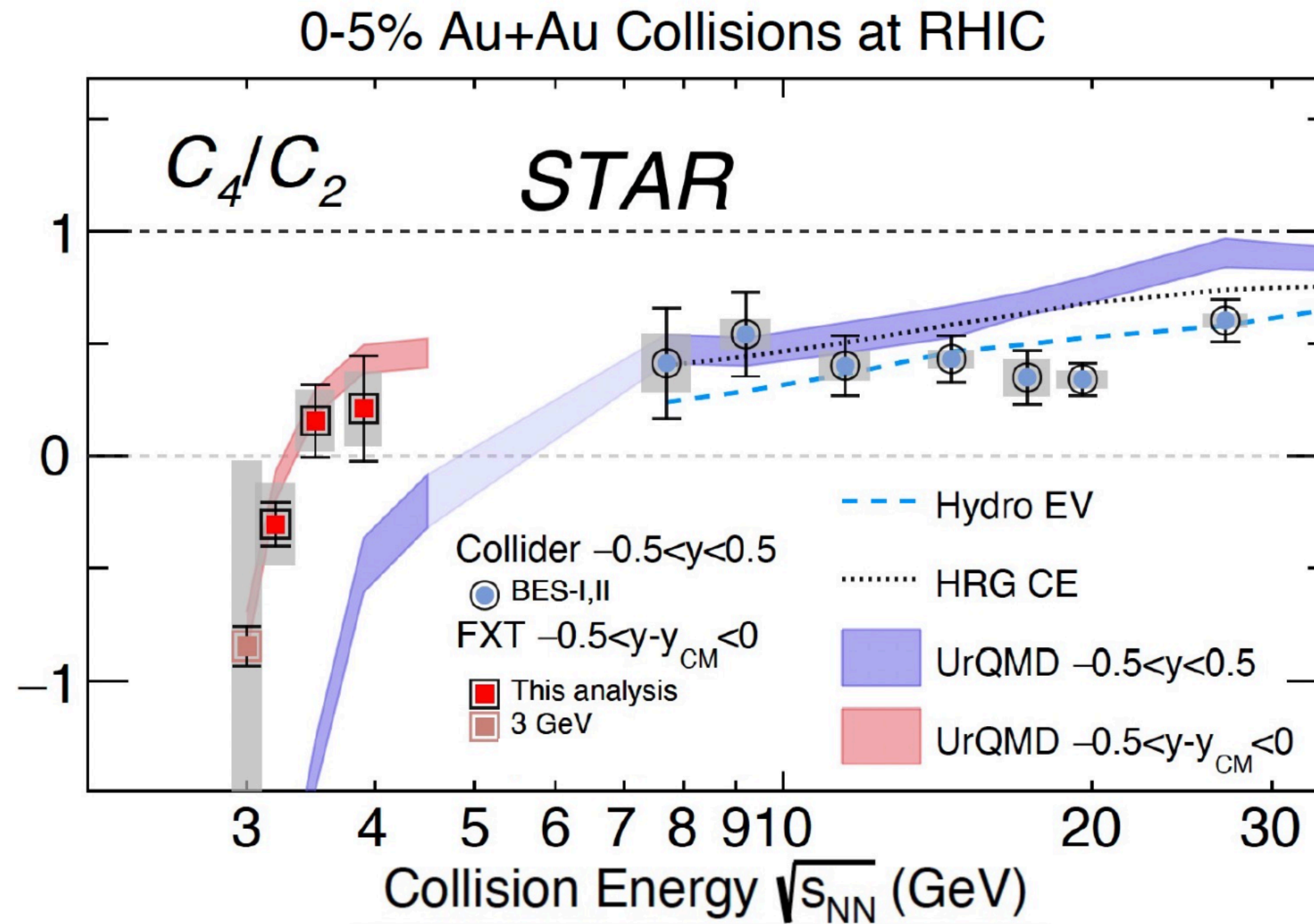
S. Bass, et al: PPNP 41 255 (1998)
 P. B. Munzinger, et al: NPA 1008 122141 (2021)
 V. Vovchenkov, et al: PRC 105 014904 (2022)
 HotQCD: PRD 101 074502 (2020)
STAR: PRL135 142301 (2025)
 M. Stephanov: PRL 102 032301 (2009)

$$\text{Significance} = \frac{\text{Data} - \text{Ref.}}{\sigma_{\text{total}}}$$

Data: STAR 0-5% Result

1. 4.7 / 3.2 reduction in statistical / systematic uncertainties compared to BES-I;
2. The largest negative deviation occurs at $\sqrt{s_{NN}}=19.6$ GeV w.r.t non-CP references with at most 4.7σ ;
3. A **peak** at lower energy / **higher baryon density**? 🤔

Energy Dependence: BES-II FXT Mode

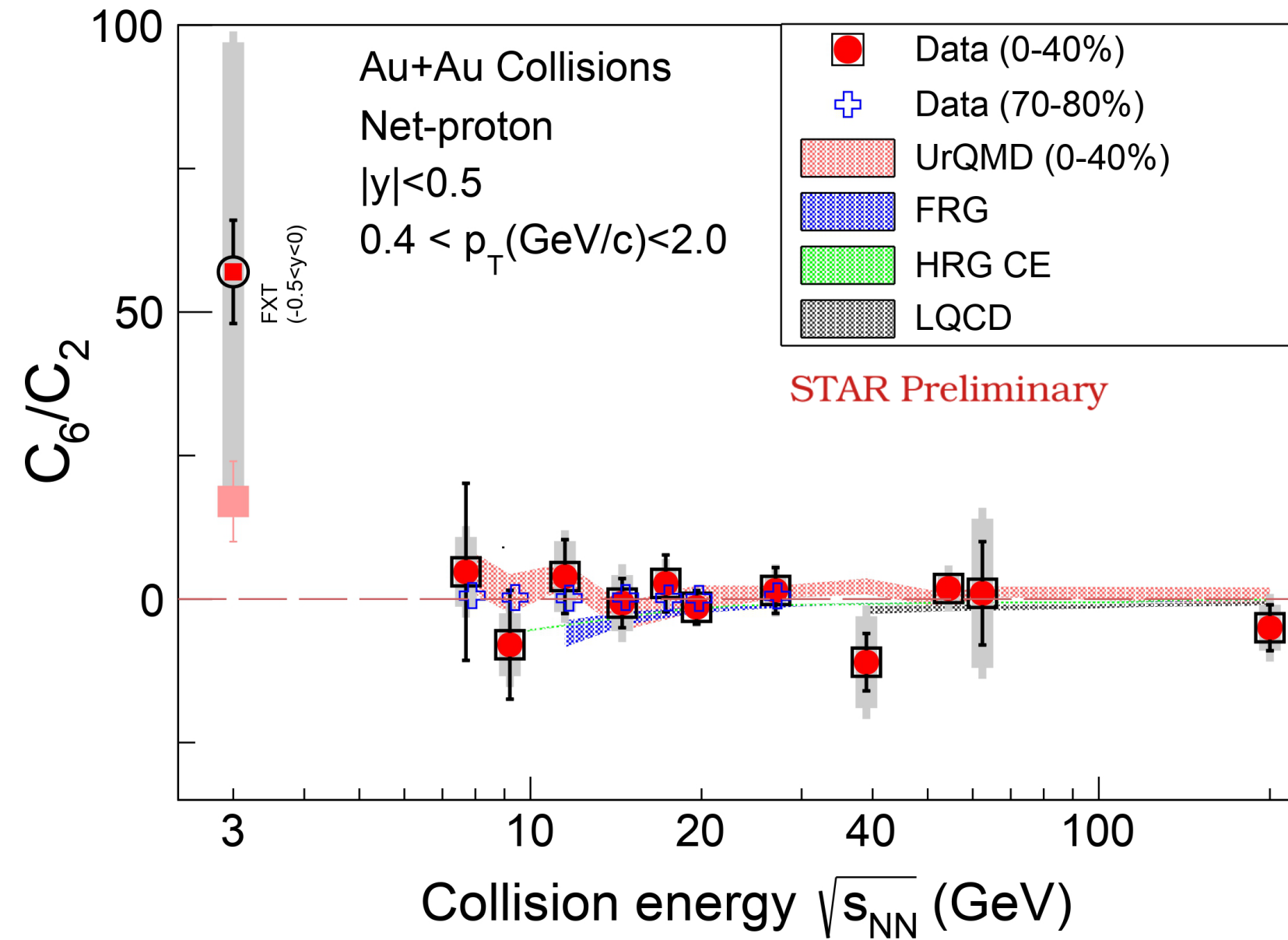
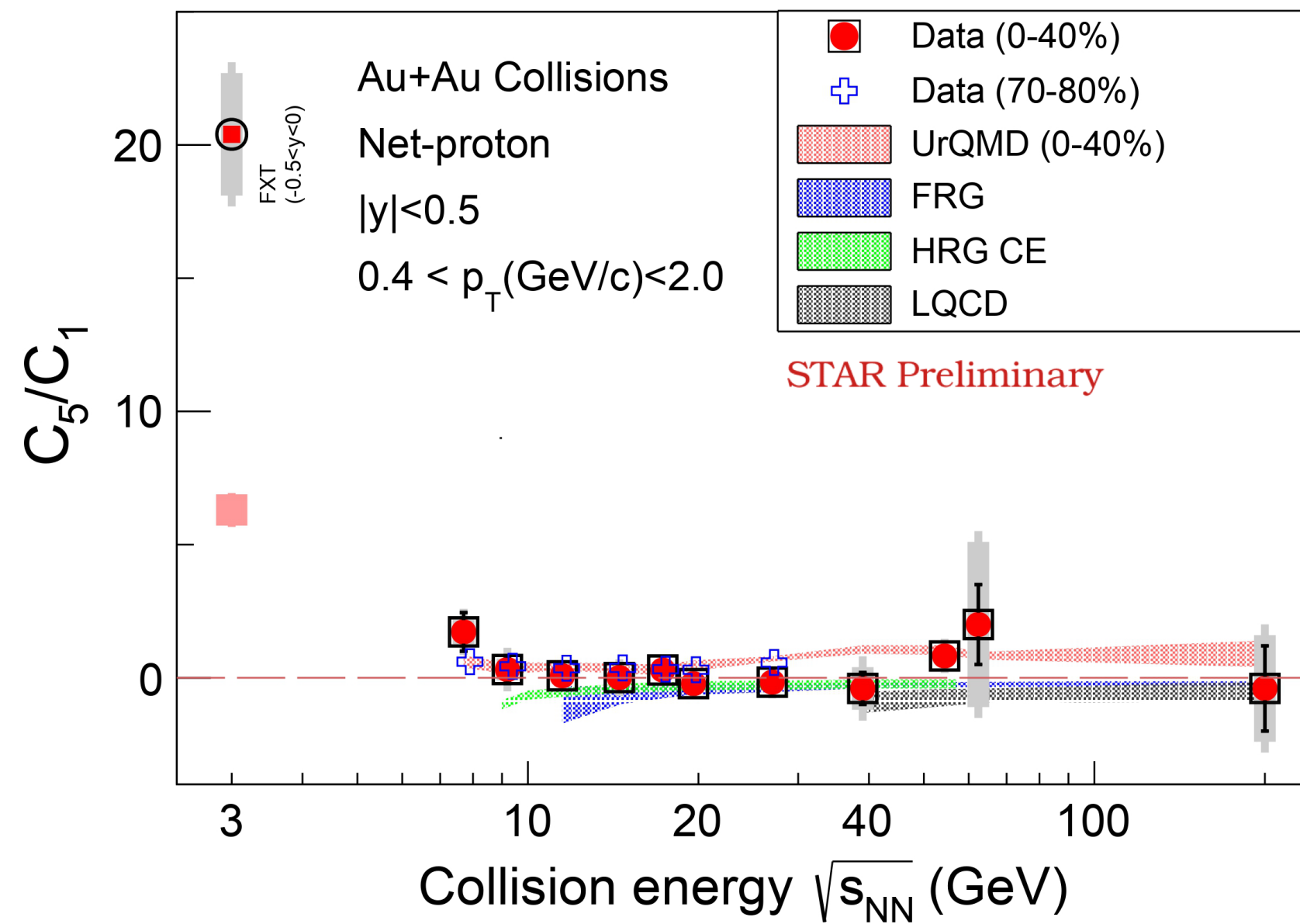


S. Bass, et al: PPNP 41 255 (1998)
P. B. Munzinger, et al: NPA 1008 122141 (2021)
V. Vovchenkov, et al: PRC 105 014904 (2022)
HotQCD: PRD 101 074502 (2020)
STAR: PRL 128 202303 (2022)

Z. Sweger @ QM2025

1. Systematic uncertainty is greatly reduced compared with the published 3 GeV data;
2. Measurements at $\sqrt{s_{NN}}=3.2, 3.5$ and 3.9 GeV are consistent with UrQMD model;
3. Experimental results in the 4 — 8 GeV range are crucial;
4. Analysis of 4.5 GeV and Run21 3 GeV (~ 2 B events) is underway.

Energy Dependence: Hyper-Order Results

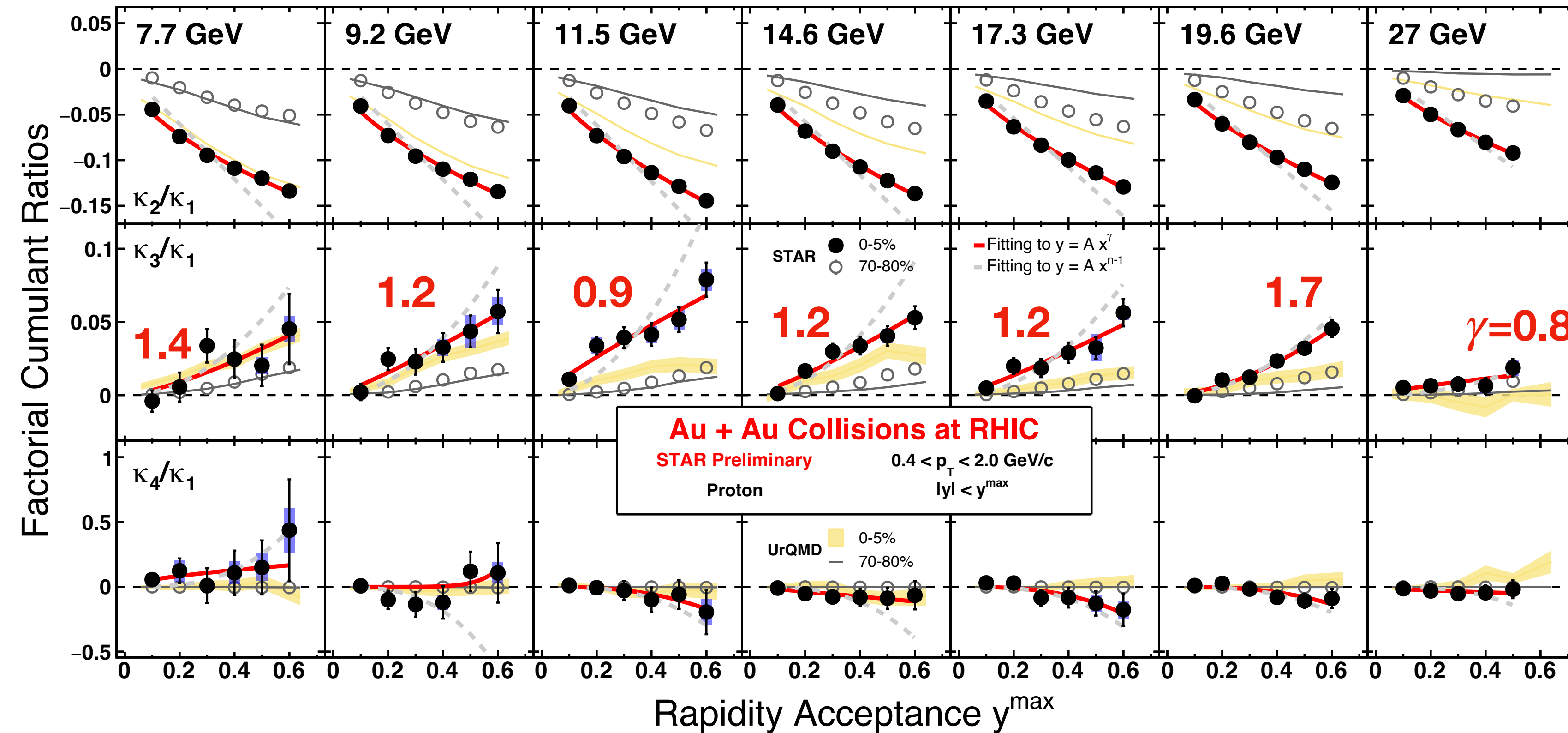


S. Bass, et al: PPNP 41 255 (1998)
 P. B. Munzinger, et al: NPA 1008 122141 (2021)
 W. Fu, et al: PRD 104 094047 (2021)
 HotQCD: PRD 101 074502 (2020)
 STAR: PRC 107 024908 (2023)

B. Mondal @ QM2025

1. Hyper-order values are close to zero;
2. Within 1σ uncertainty, these results (down to 7.7 GeV) are consistent with negative values predicted by LQCD and FRG for a smooth crossover.

Rapidity Scan: Proton Factorial Cumulants



S. Bass, et al: PPNP 41 255 (1998)
 B.Ling and M.A.Stephanov: PRC 93 034915 (2016)

Deep red solid curve

(—): Fitting to $y = Ax^\gamma$

Light gray dashed curve

(- -): Fitting to $y = Ax^{n-1}$

YH @ QM2025

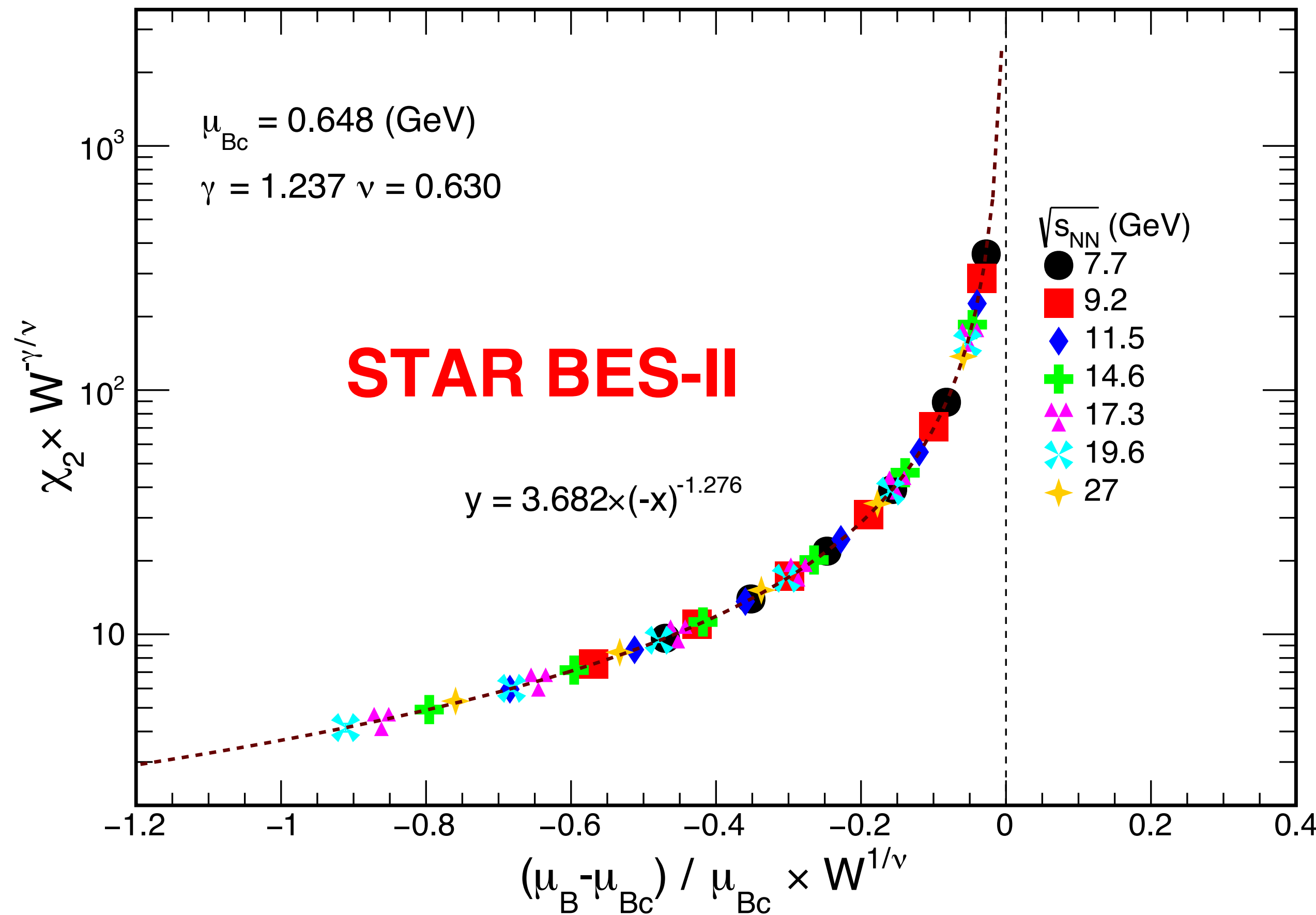
1. UrQMD describes the trend but fails to reproduce STAR data at high energy within large rapidity windows;
2. κ_n/κ_1 as a function of Δy follows the power-law but exhibit smaller exponents compared to the expectation.

Extrapolating the CEP: Finite-Size Scaling

A.Sorensen and P.Sorensen: arXiv:2405.10278[nucl-th]

A.Andronic, et al: Nature 561 7723 321-330 (2018)

J.V.Sengers and J.G.Shanks: Journal of Statistical Physics 137 857 (2009)



YH @ QM2025

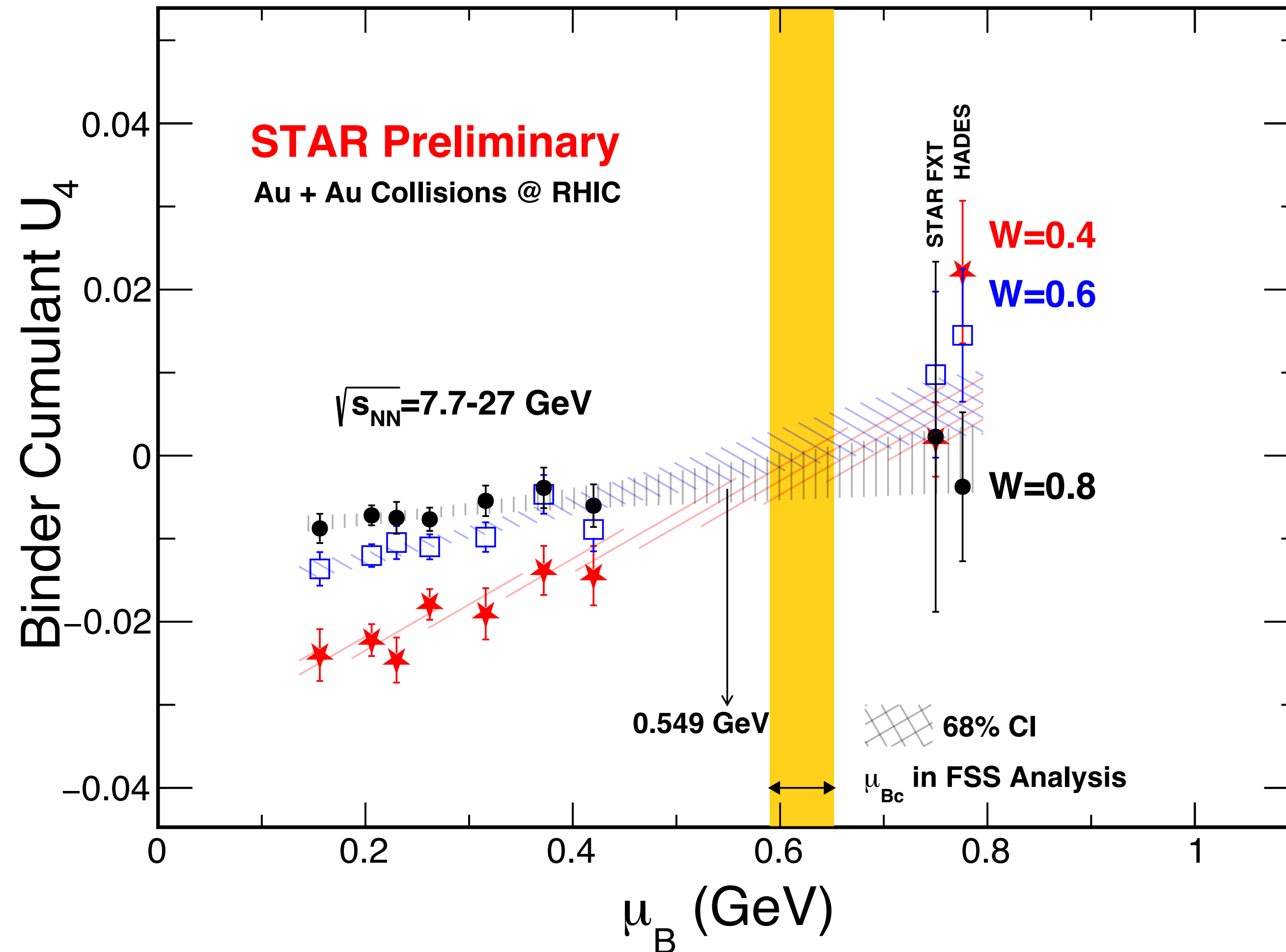
1. $\mu_{Bc} = 648^{+4}_{-3}$ MeV (corresponding to minimum χ^2/NDF), consistent with the fit to BES-I (662^{+22}_{-20} MeV), with a significantly reduced fit uncertainty;
2. With combined fit and systematic uncertainty, a critical μ_B range is given as 590 — 652 MeV.

Ordering Change of Binder Cumulant

A.Sorensen and P.Sorensen: arXiv:2405.10278[nucl-th]

STAR: STAR: PRC 107 024908 (2023)

HADES: HADES: PRC 102 024914 (2020)



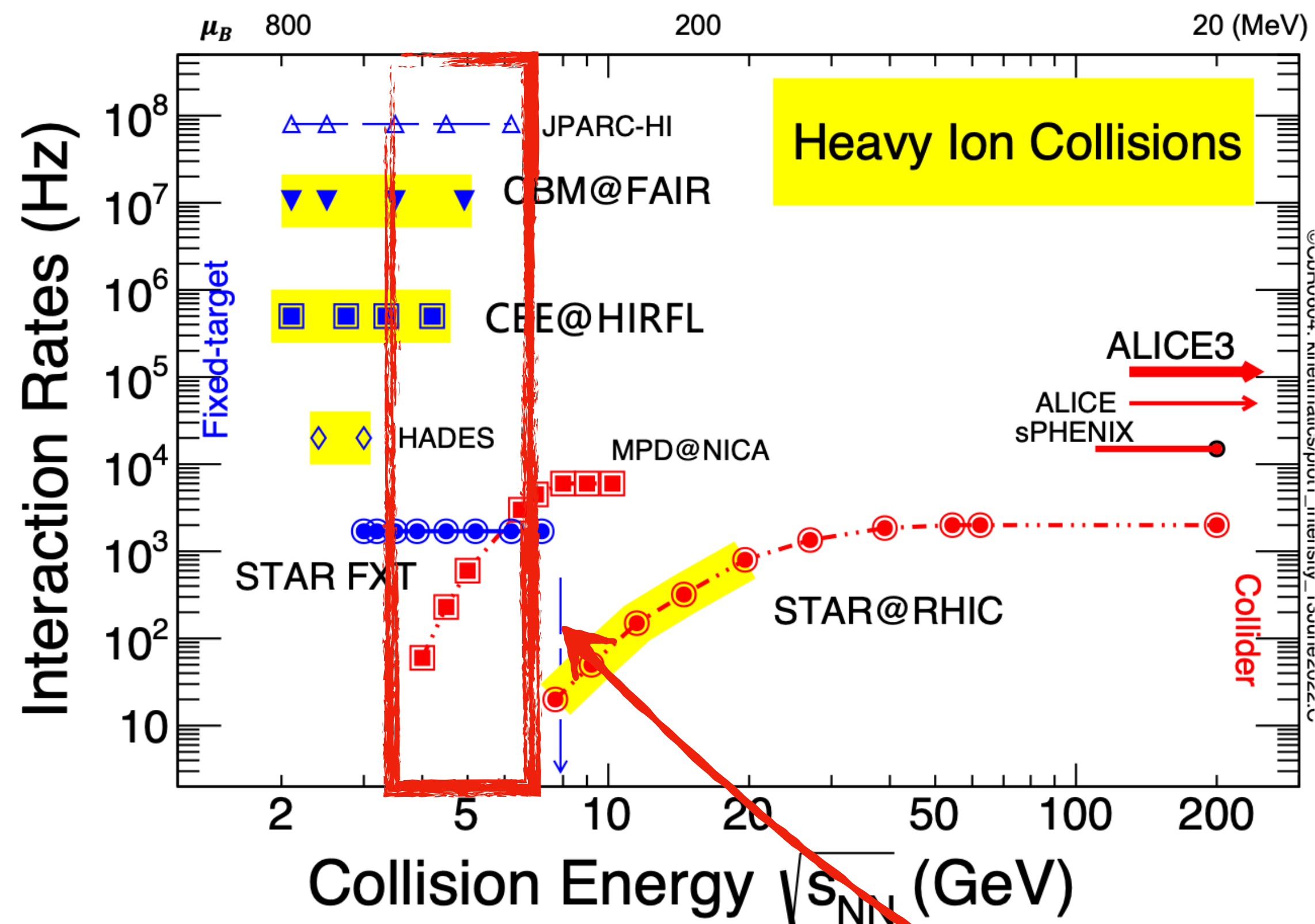
YH @ QM2025

1. Binder cumulant ordering reverses with μ_B : black > blue > red (left), red > blue > black (right);
2. Shaded bands show linear fits with 68% C.I.: 3 bands start to overlap at $\mu_B = 549 \text{ MeV}$;
3. Consistent with extrapolation from finite-size scaling (vertical orange band).

Summary & Outlook

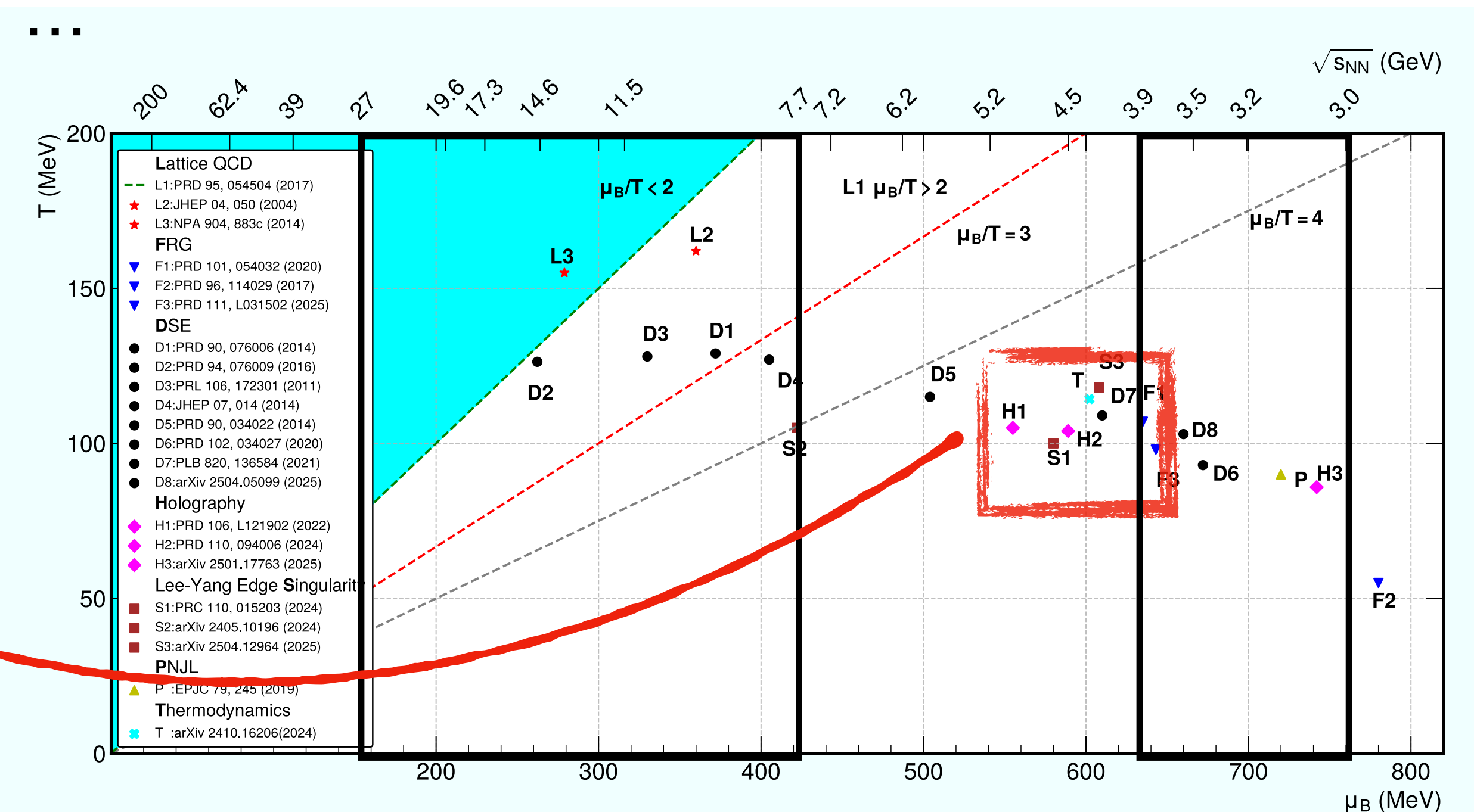
1. STAR reported precision measurements of (net-)proton fluctuations in Au+Au collisions at 3.0 — 3.9 GeV (FXT) and 7.7 — 27 GeV (COL).
 - With better statistics, control on systematics, and centrality resolution.
2. Collider Energies:
 1. Net-proton C_4/C_2 shows largest deviation w.r.t non-CP baselines at 19.6 GeV with $2 - 5\sigma$;
 2. Hyper-order cumulants indicate smooth crossover in the energy range 7.7 — 27 GeV;
 3. Rapidity scan of (net-)proton fluctuations suggests the CEP may lie at higher baryon densities, possibly in a μ_B range 550 — 650 MeV.
3. Fixed-target Energies:
 1. Proton C_4/C_2 are consistent with UrQMD in the energy range 3.0 — 3.9 GeV;
 2. Analysis of 4.5 GeV and high statistics 3 GeV (~2B events) are underway.

Summary & Outlook



Looking forward to the physics at high baryon density!

- China: CEE
- Germany: CBM
- USA: STAR (FXT)
- Russia: MPD



Many Thanks to

RHIC operation team, STAR Collaboration and Theory Colleagues

Daniel Cebra, Xin Dong, Shinichi Esumi, Xiaofeng Luo, Bedanga Mohanty, Bappaditya Mondal, Toshihiro Nonaka, Ashish Pandav, Zarchy Sweger, Fan Si, Zhaohui Wang, Nu Xu, Yongcong Xu, Xin Zhang, Yifei Zhang, Yu Zhang

Thank you for your attention!

