Proton High-Order Cumulants Results from the STAR Fixed-Target Program

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Quark Matter 2025, Frankfurt, Germany

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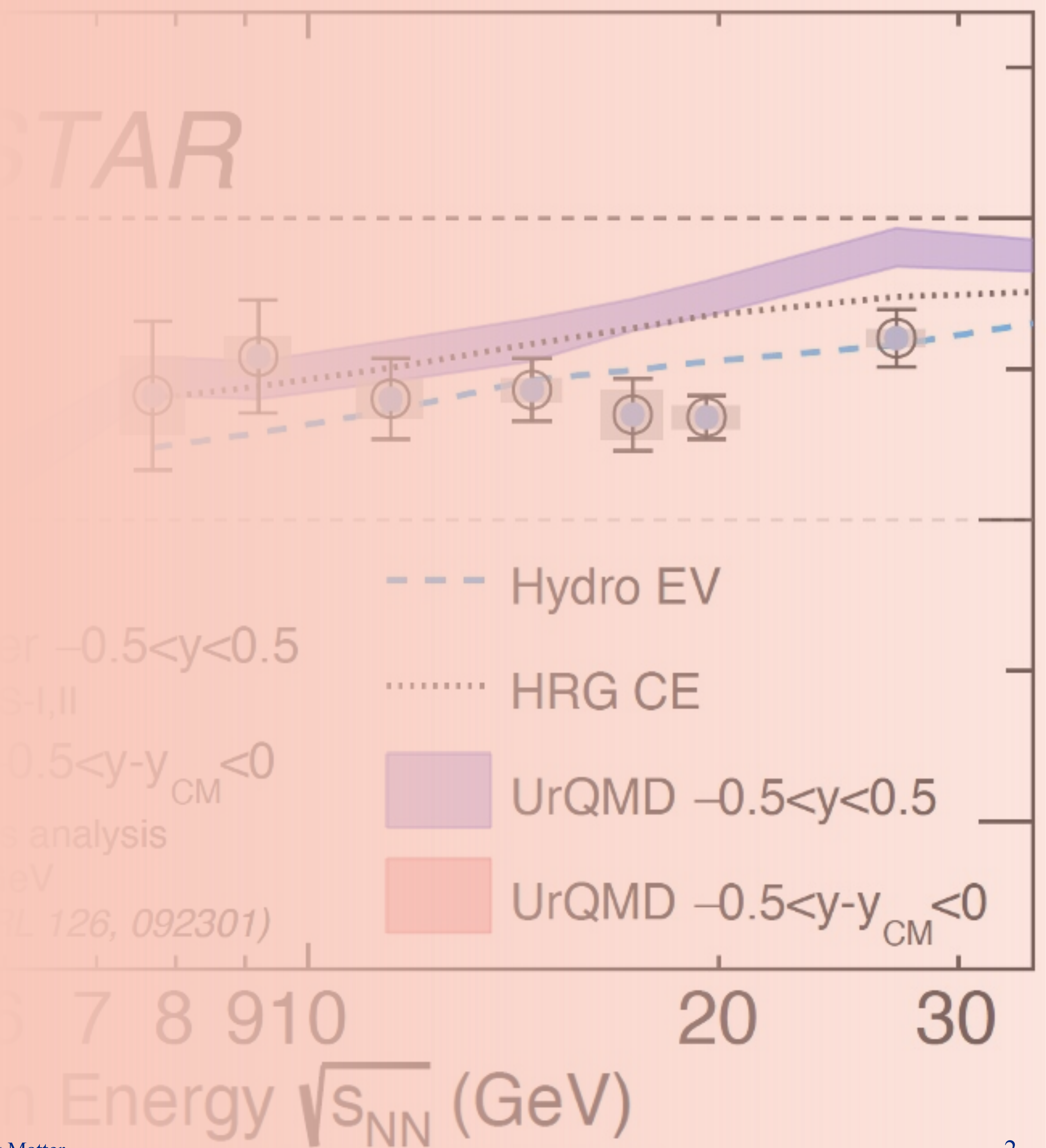
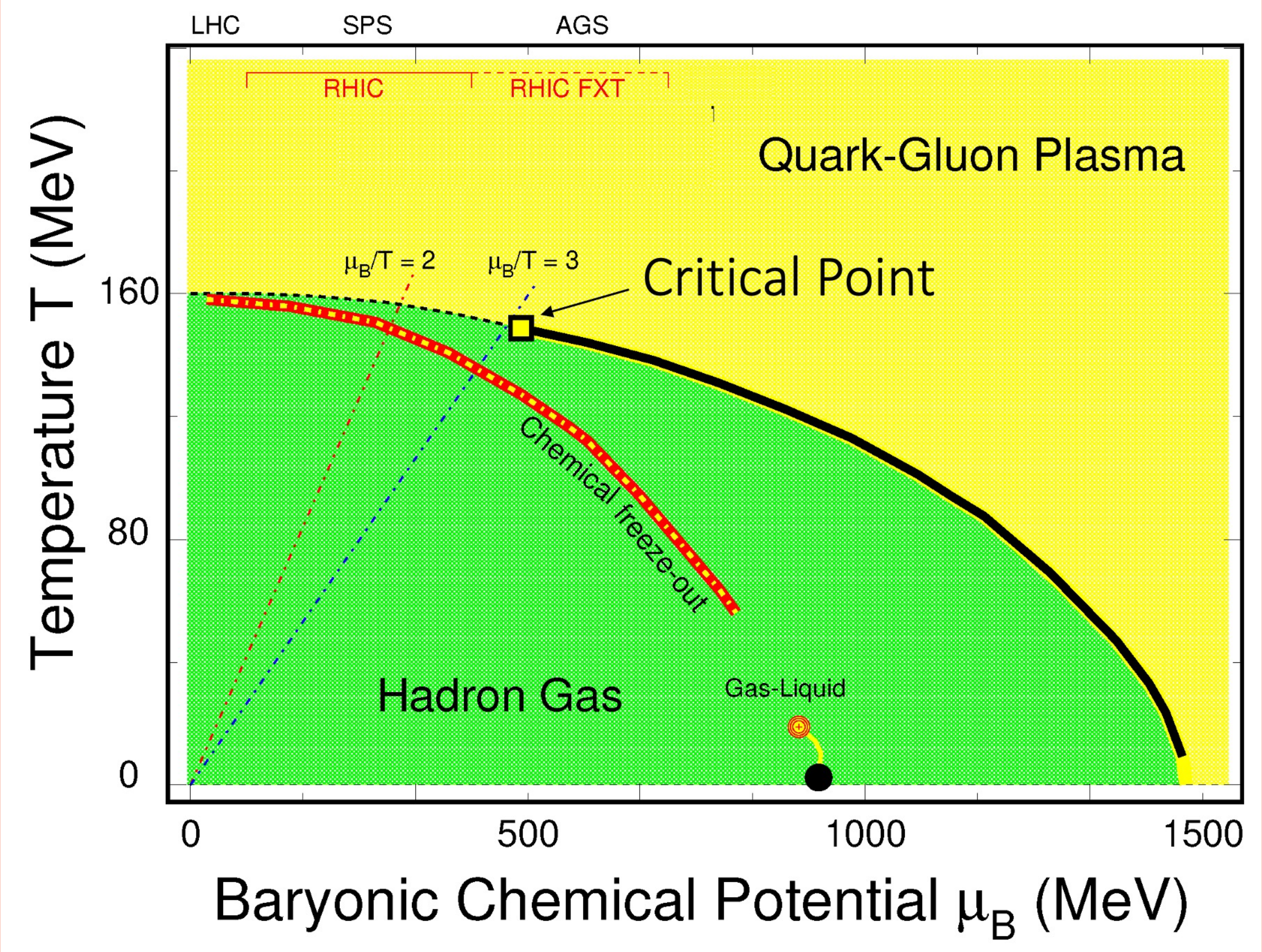
STAR Collaboration

Overview

- QCD Critical Fluctuations
- Beam Energy Scan II Results
- STAR Fixed-Target Program
- New Fixed-Target Results



Phases of QCD Matter



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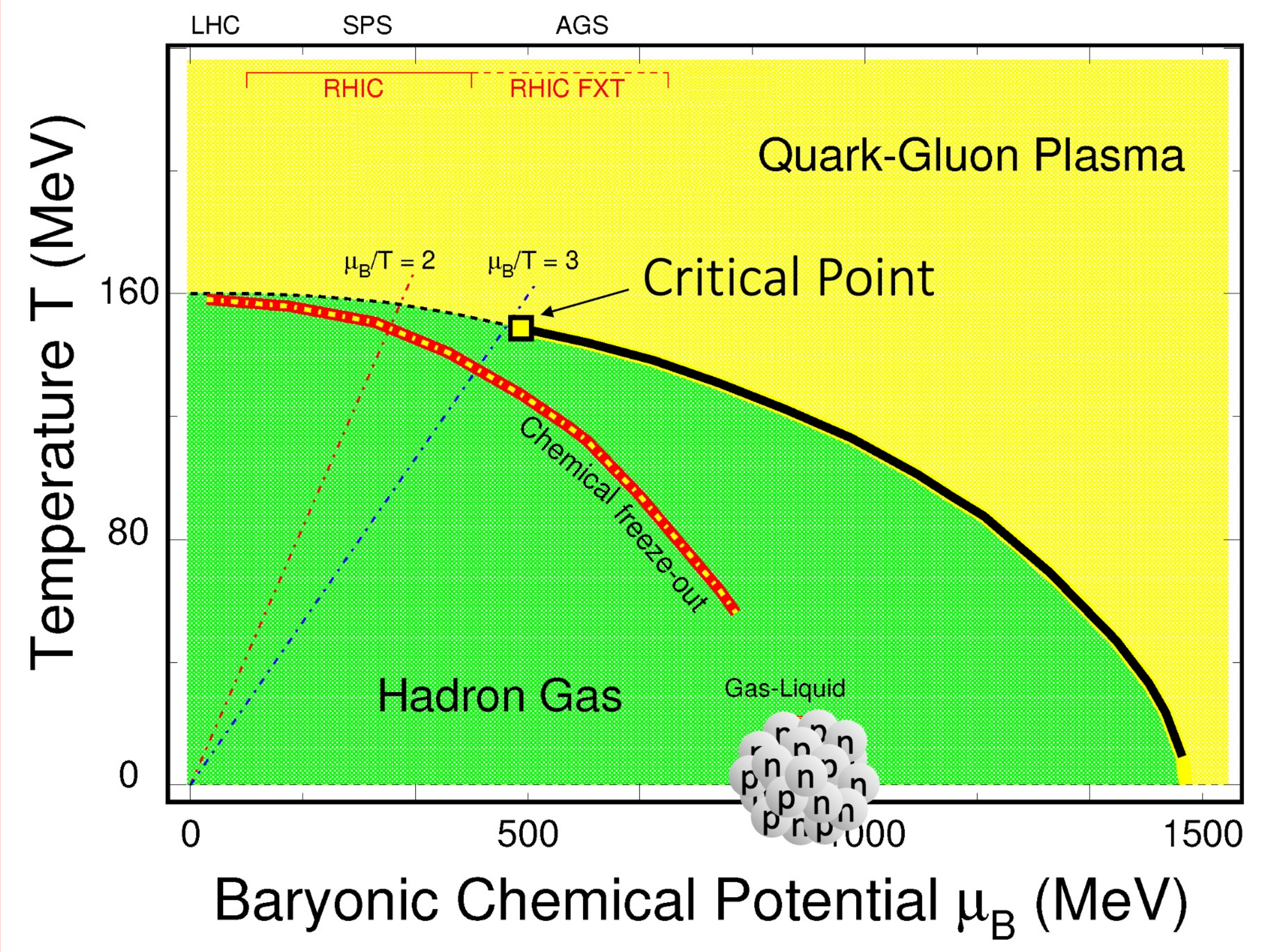

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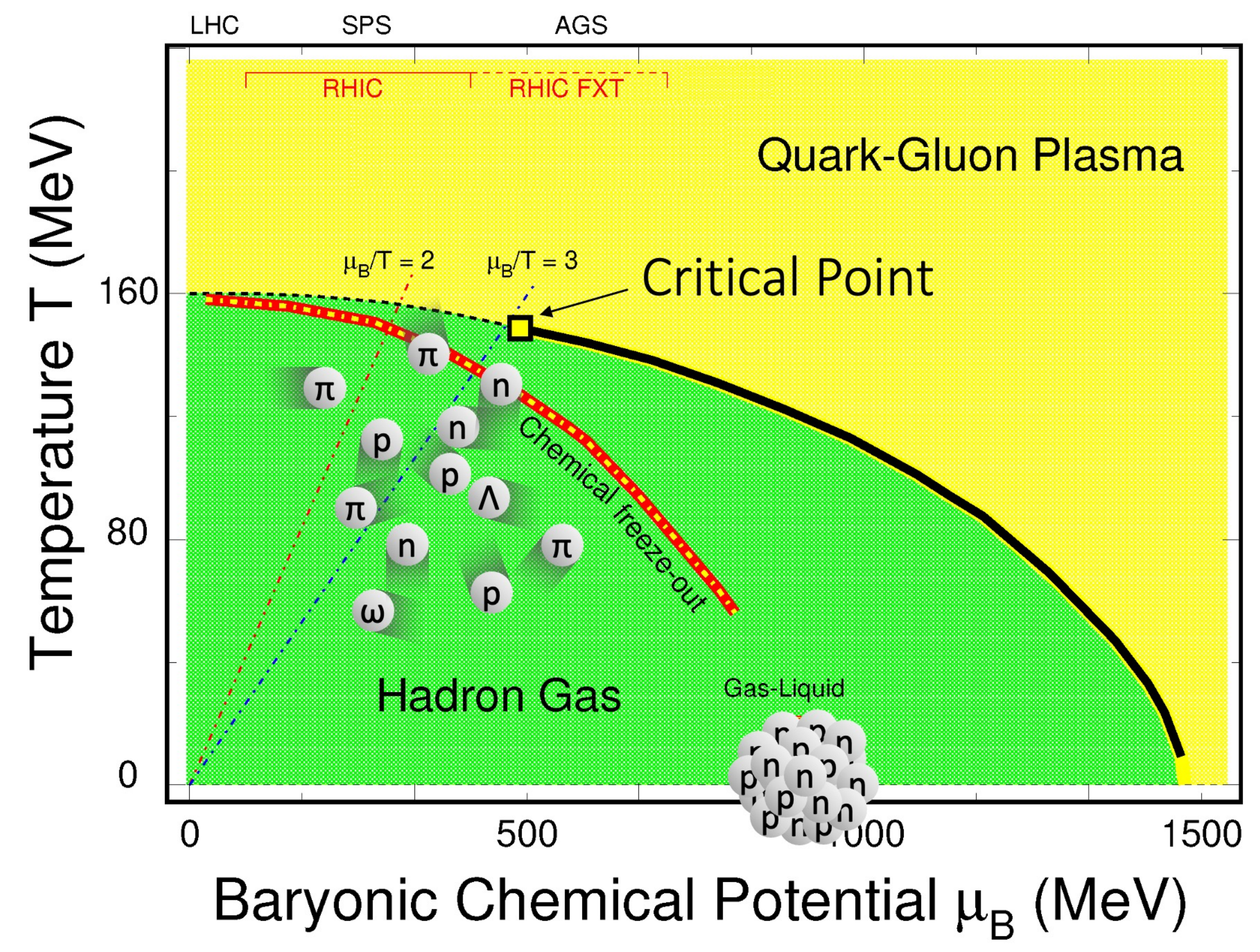

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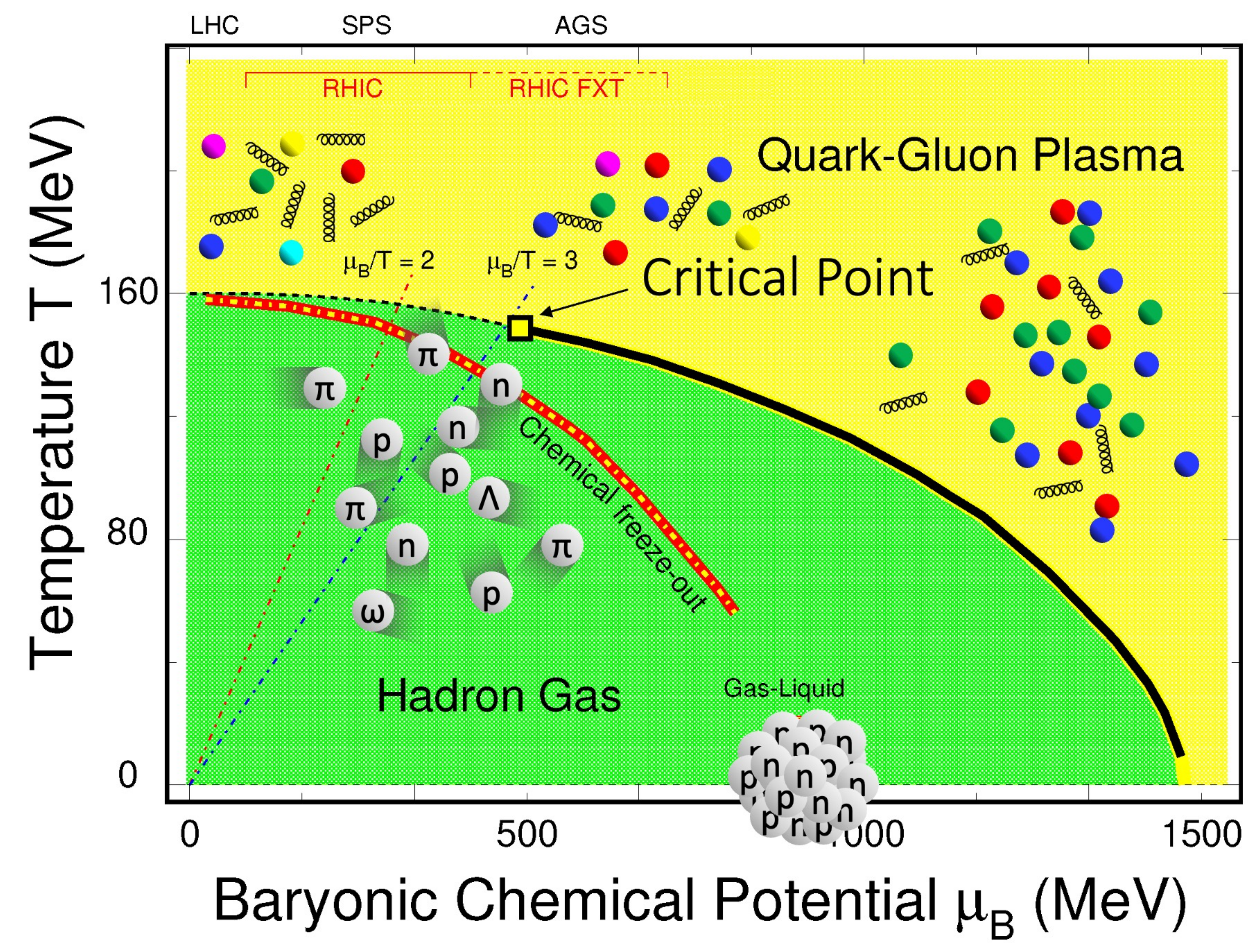

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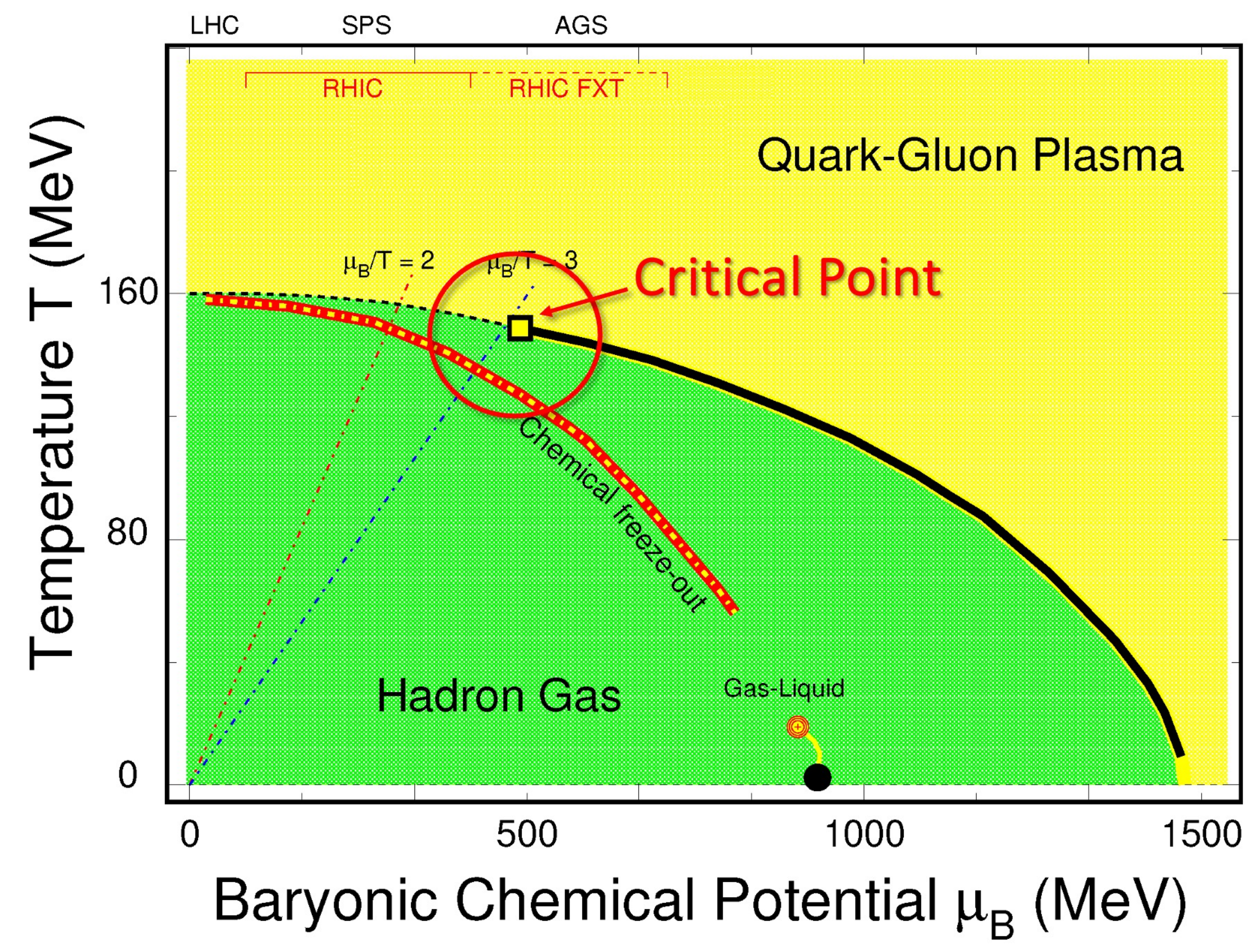

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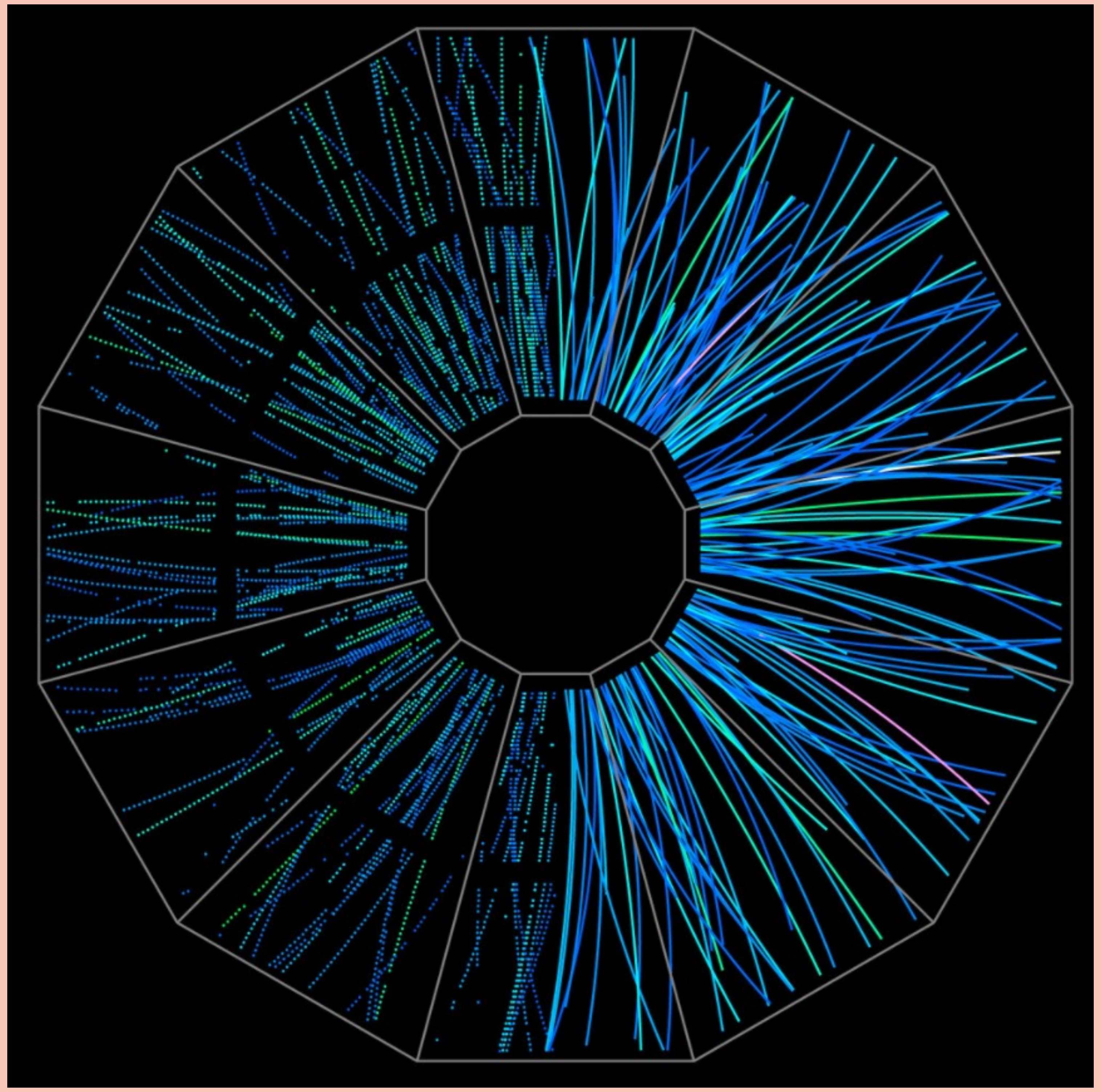
Fluctuations in baryon number

- Distribution of net-baryon number is expected to fluctuate near a critical point
- We measure events sorted by centrality



https://www.bnl.gov/newsroom/news.php?a=214492

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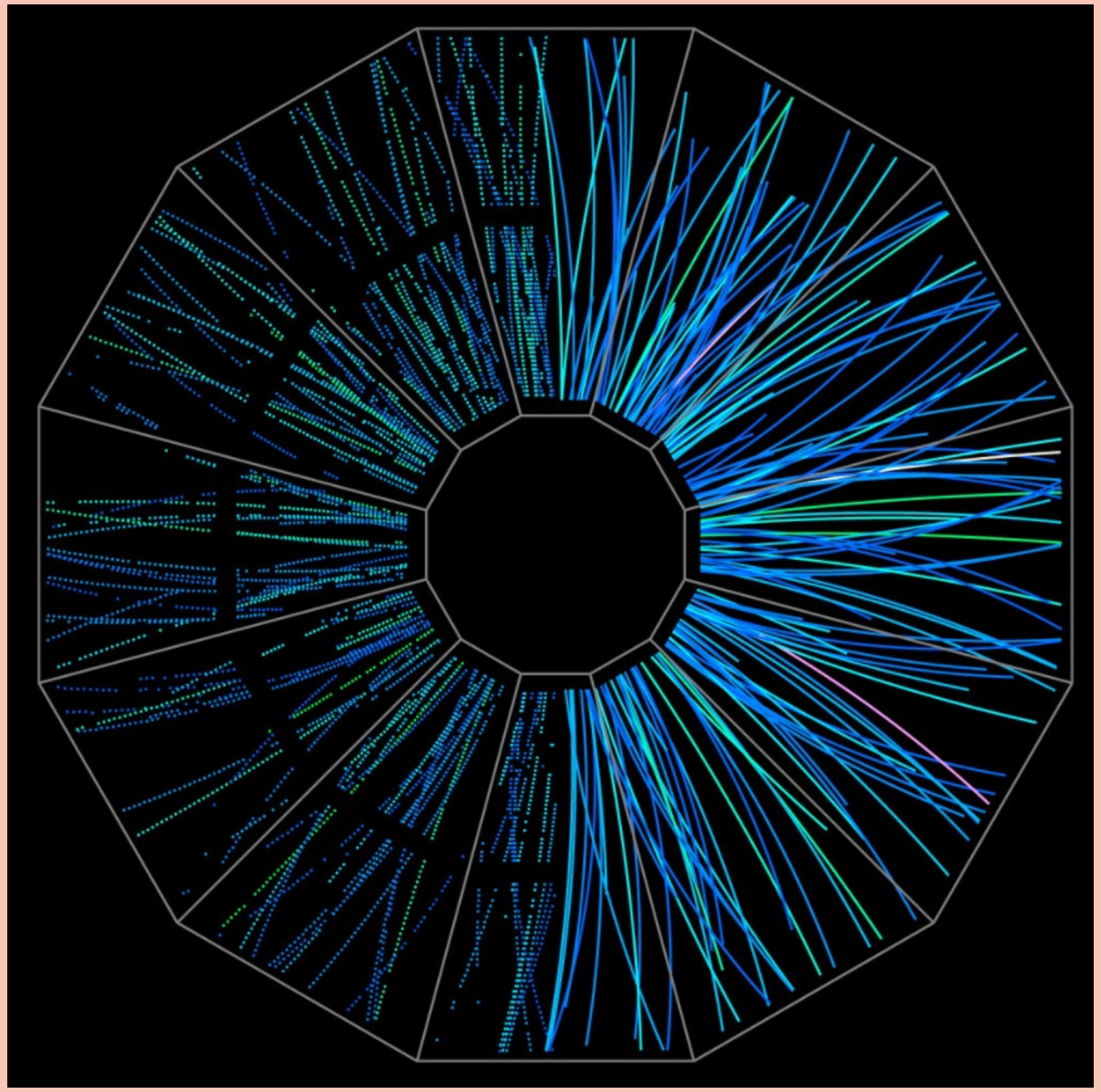

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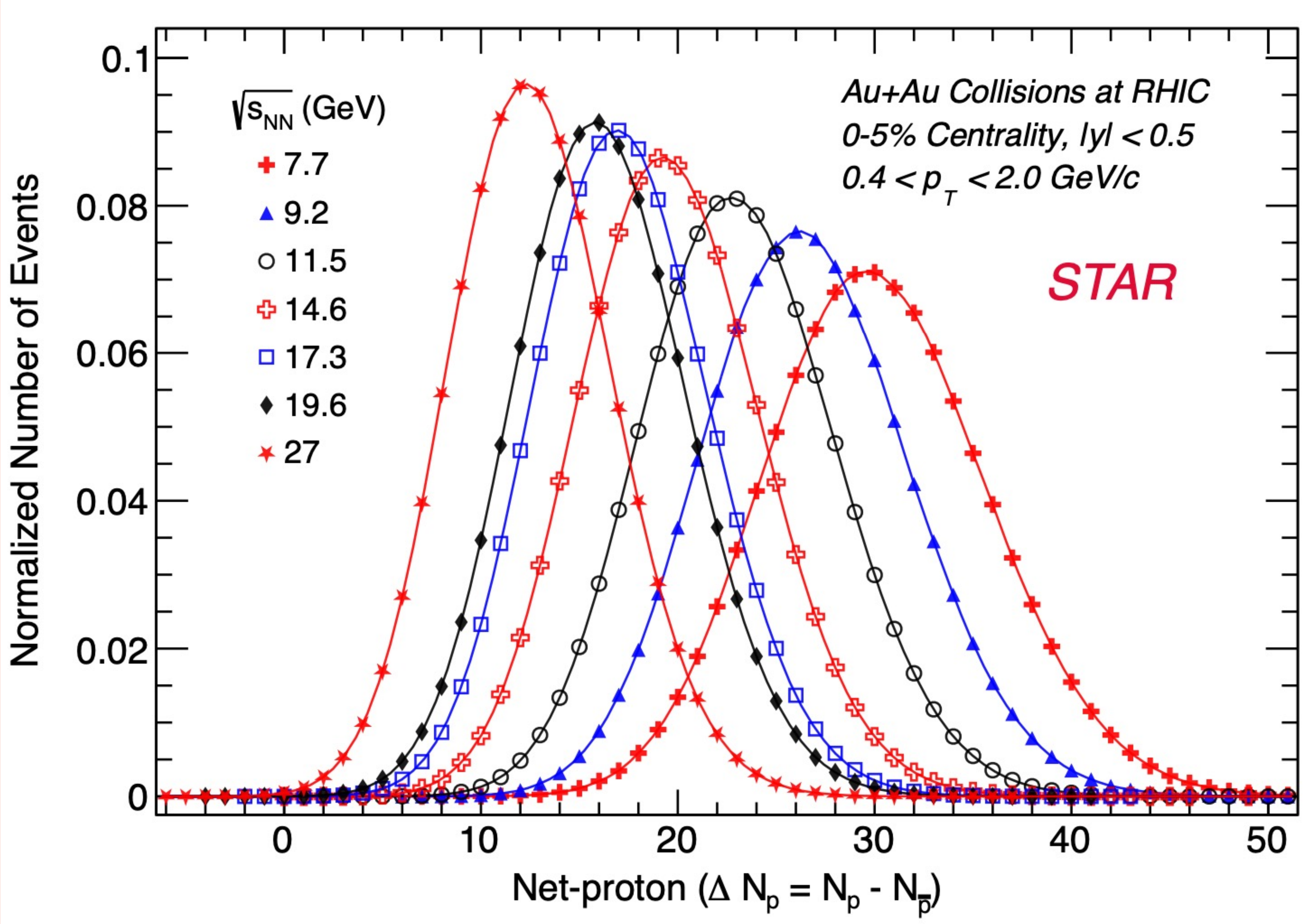

A. Pandav (STAR collaboration), talk at CPOD 2024, https:// conferences.lbl.gov/event/1376/contributions/8772/

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- We measure events sorted by centrality
- Count the number of protons (N_p), antiprotons (N_{pbar}), net-protons(N_p-N_{pbar})
- Measure the mean, variance, skewness, kurtosis…

cumulants

$$C_1 = \langle N \rangle \equiv \mu \ [\text{mean}]$$

$$C_2 = \langle (N-\mu)^2 \rangle \equiv \sigma^2 \ [\text{variance}]$$

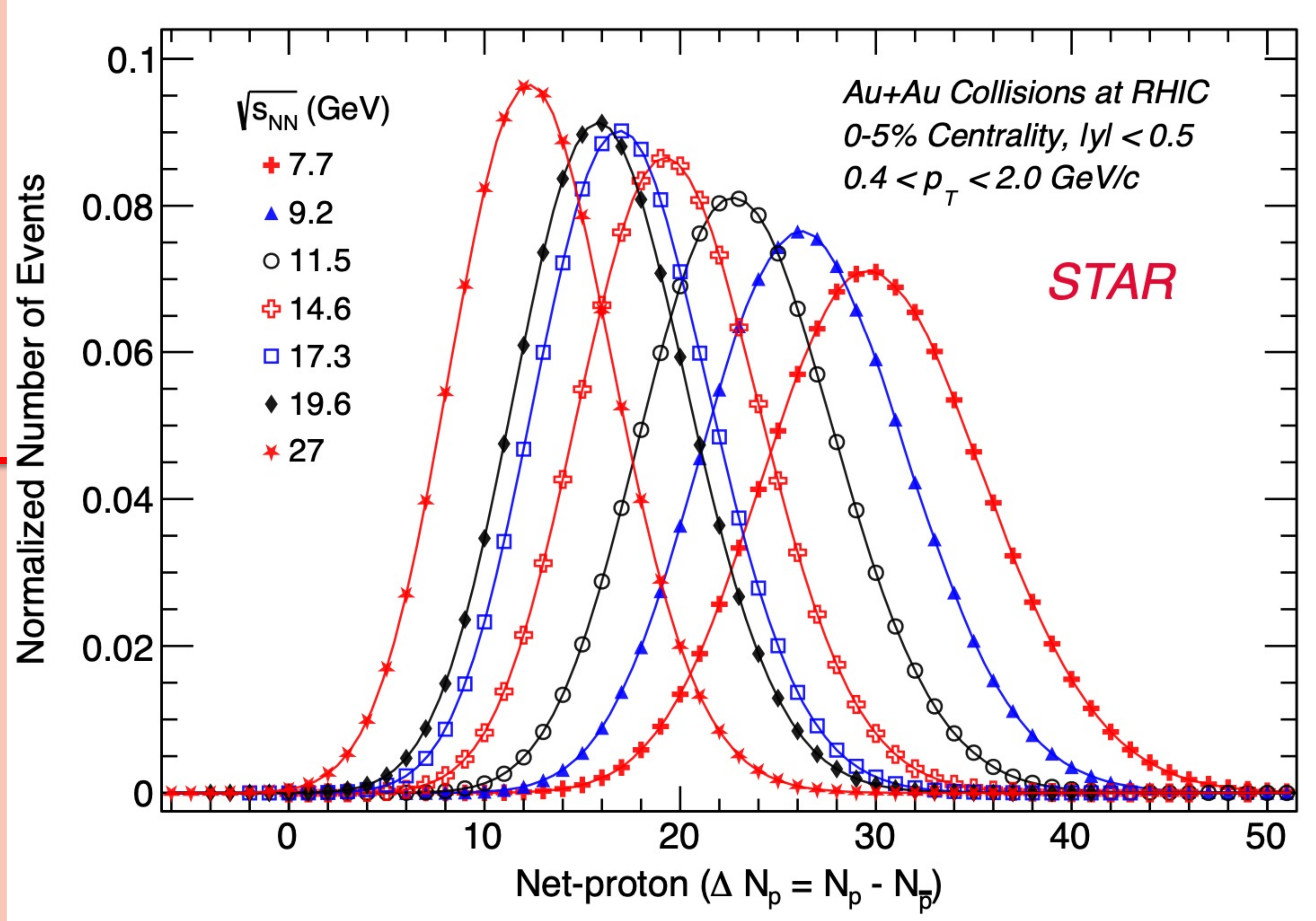
$$C_3 = \langle (N-\mu)^3 \rangle$$

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

standardized moments

$$S\sigma = C_3/C_2 \ [\text{skewness}]$$

$$\kappa\sigma^2 = C_4/C_2 \ [\text{excess kurtosis}]$$



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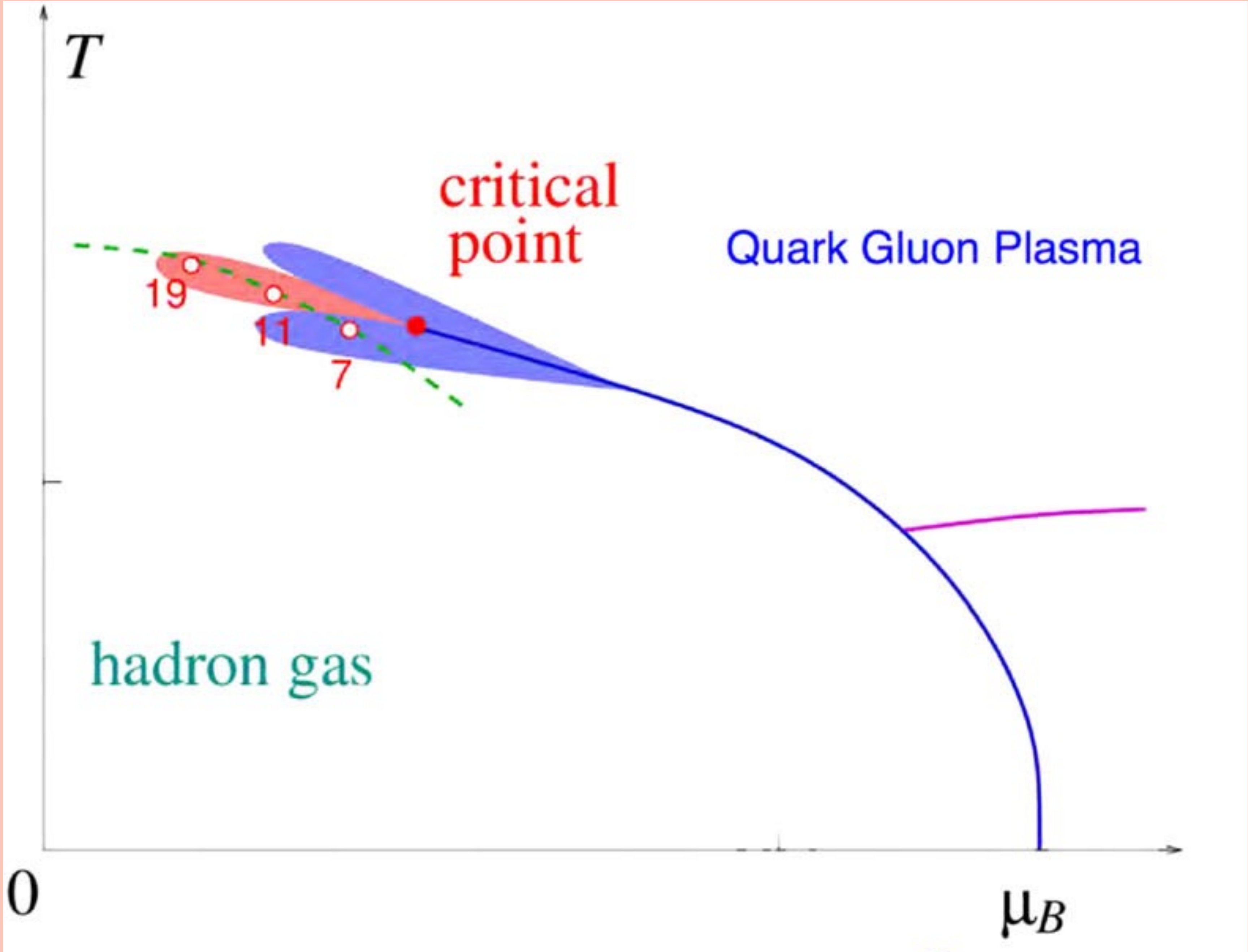
Fluctuations in Proximity to Critical Point

Predicted fluctuation in kurtosis near critical point

QCD Phase Diagram



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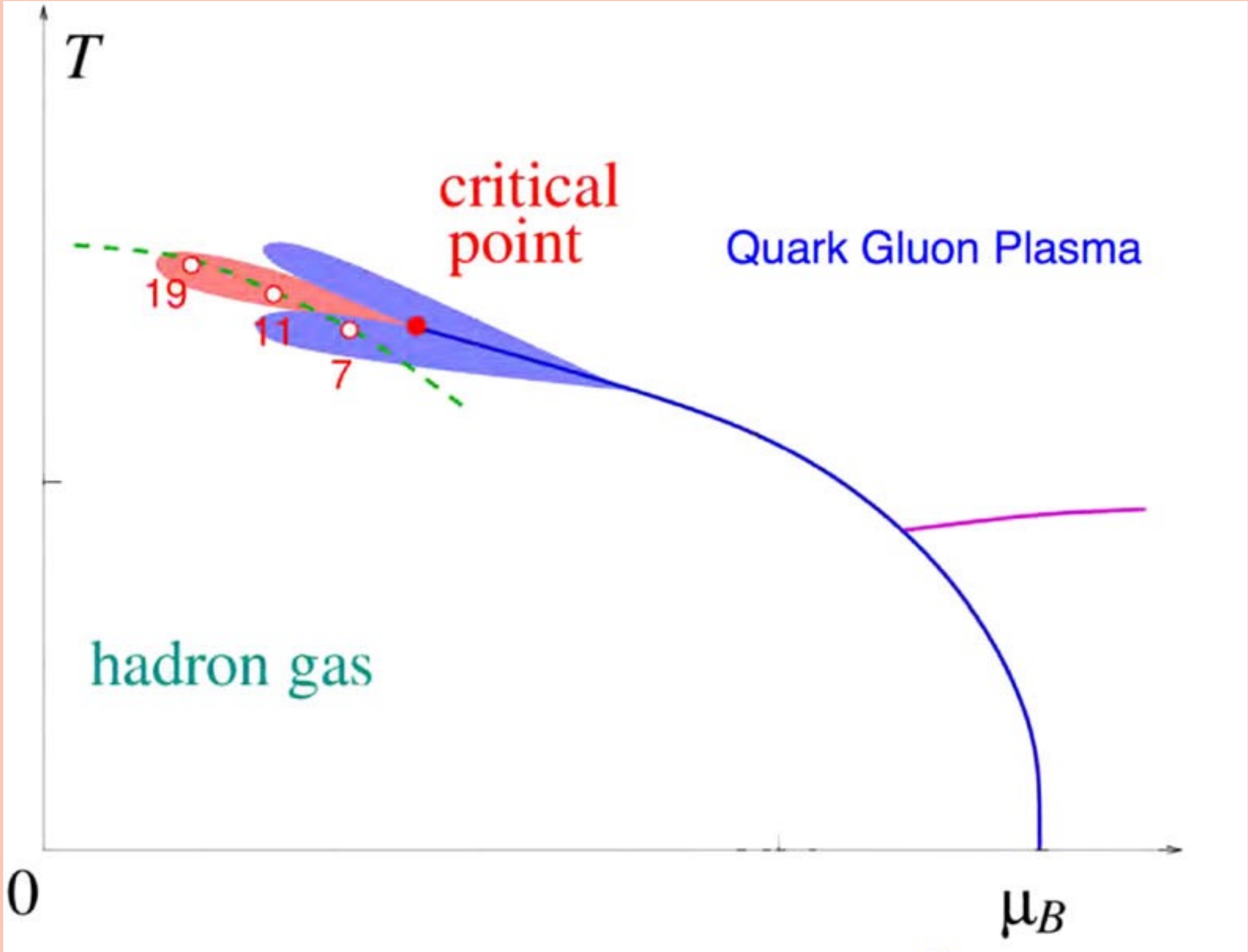

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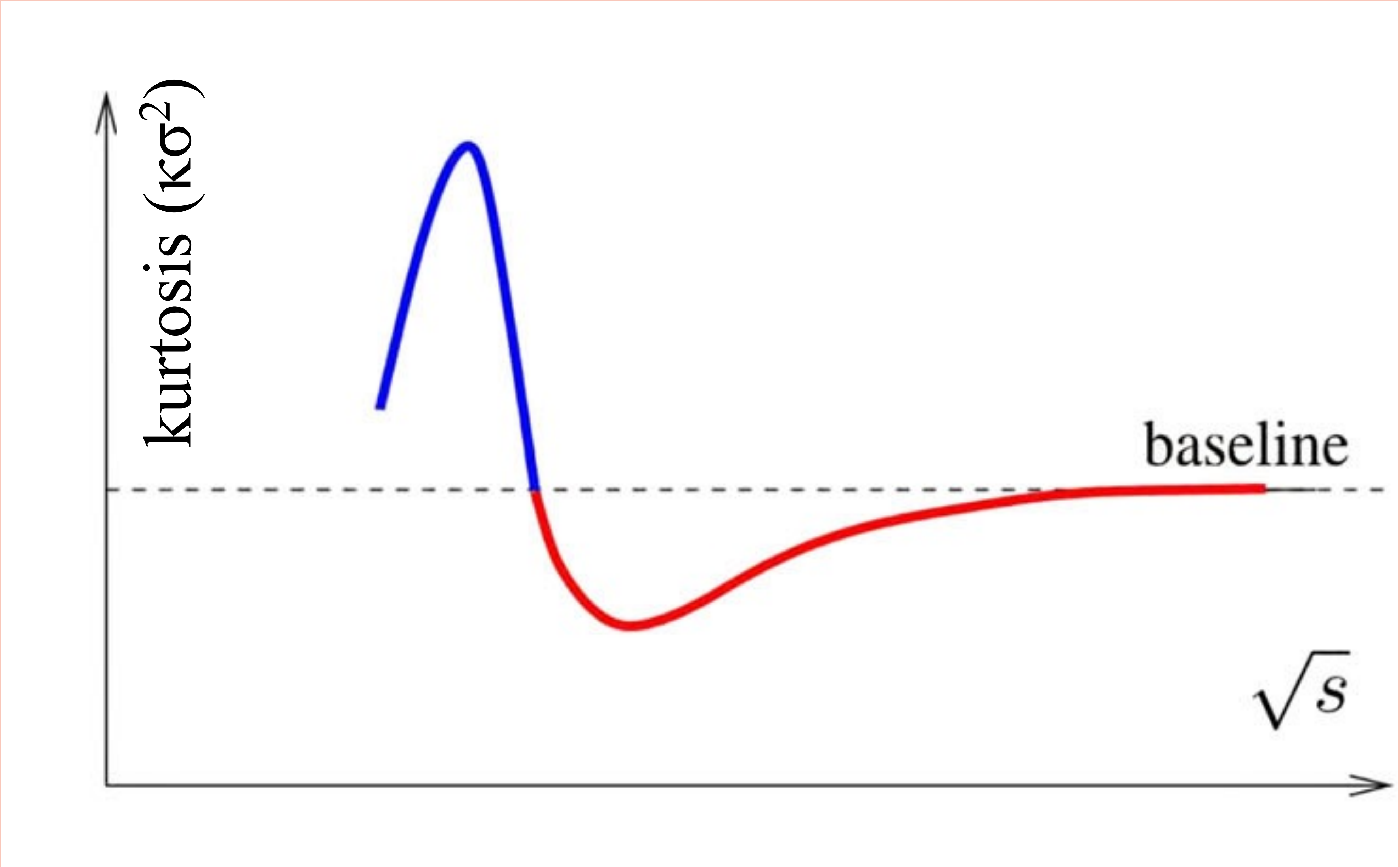

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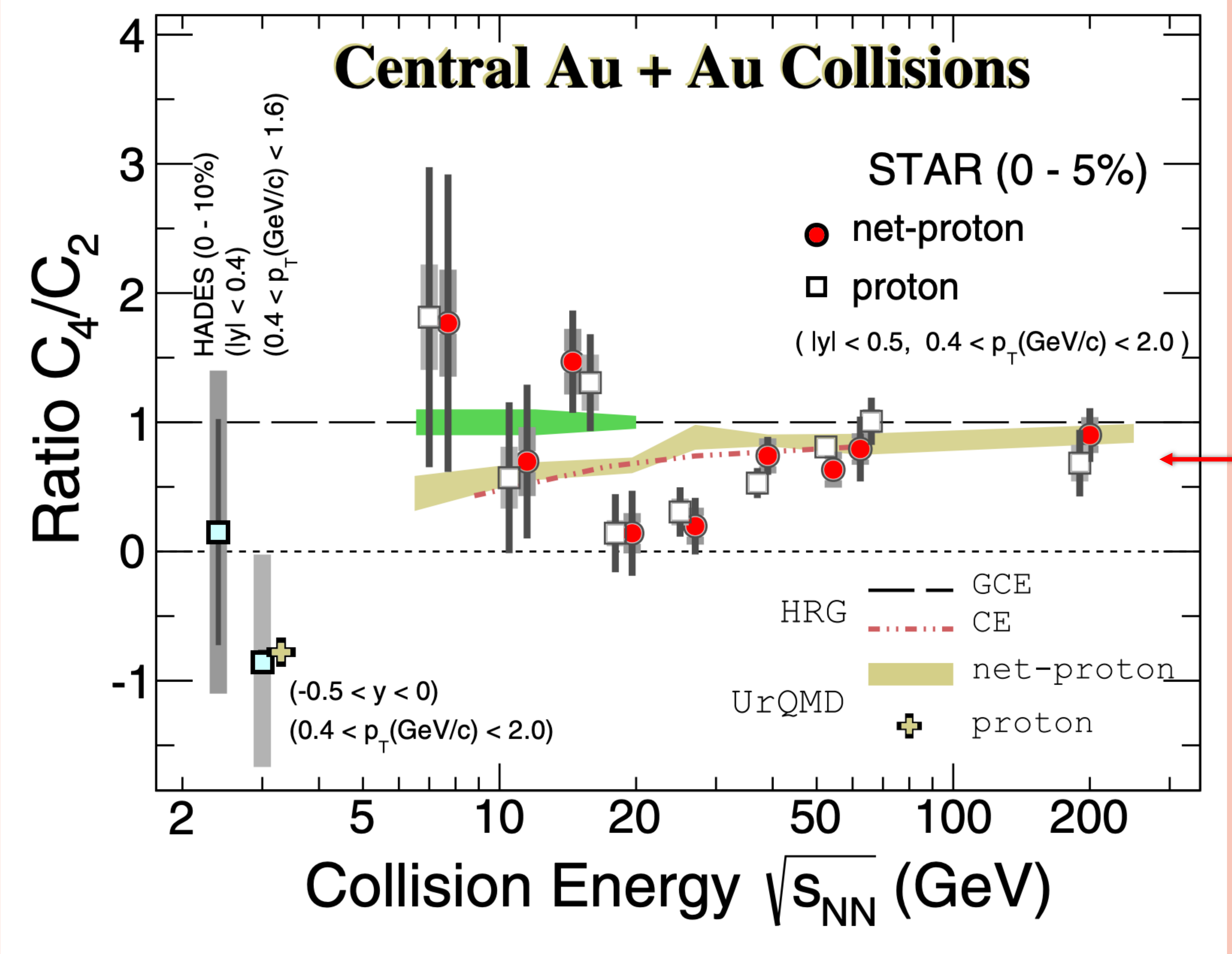
Comparison to Published BES-I Results

Published Results



STAR, Phys. Rev. Lett. 128, 202303 (2022); Phys.Rev.C 107.024908 (2023).
Phys. Rev. Lett. 126, 092301 (2021); Phys. Rev. C 104, 024902 (2021)

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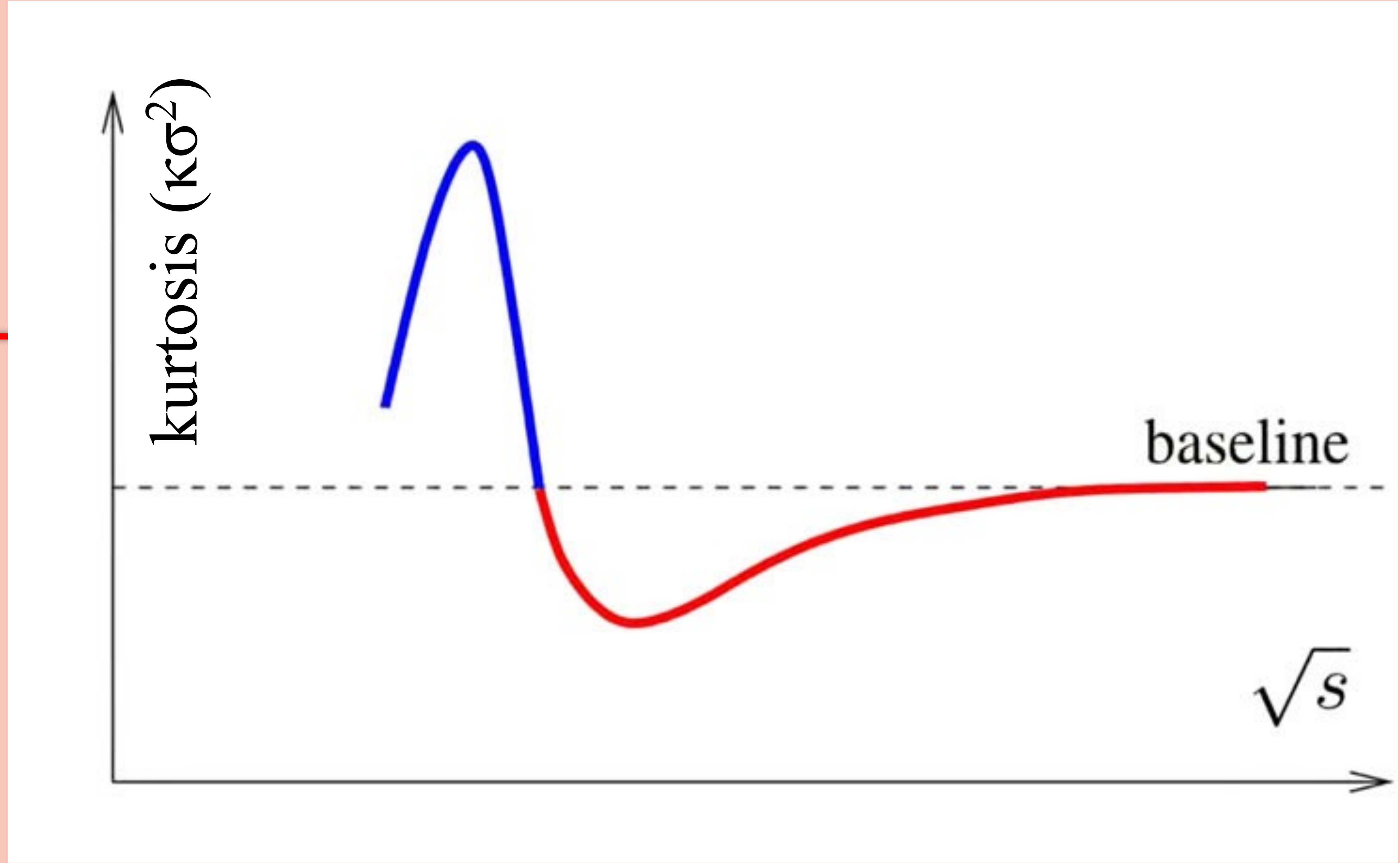

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STAR Beam-Energy Scan II Results

- Recent results from STAR BES-II high-moments shown at CPOD 2024

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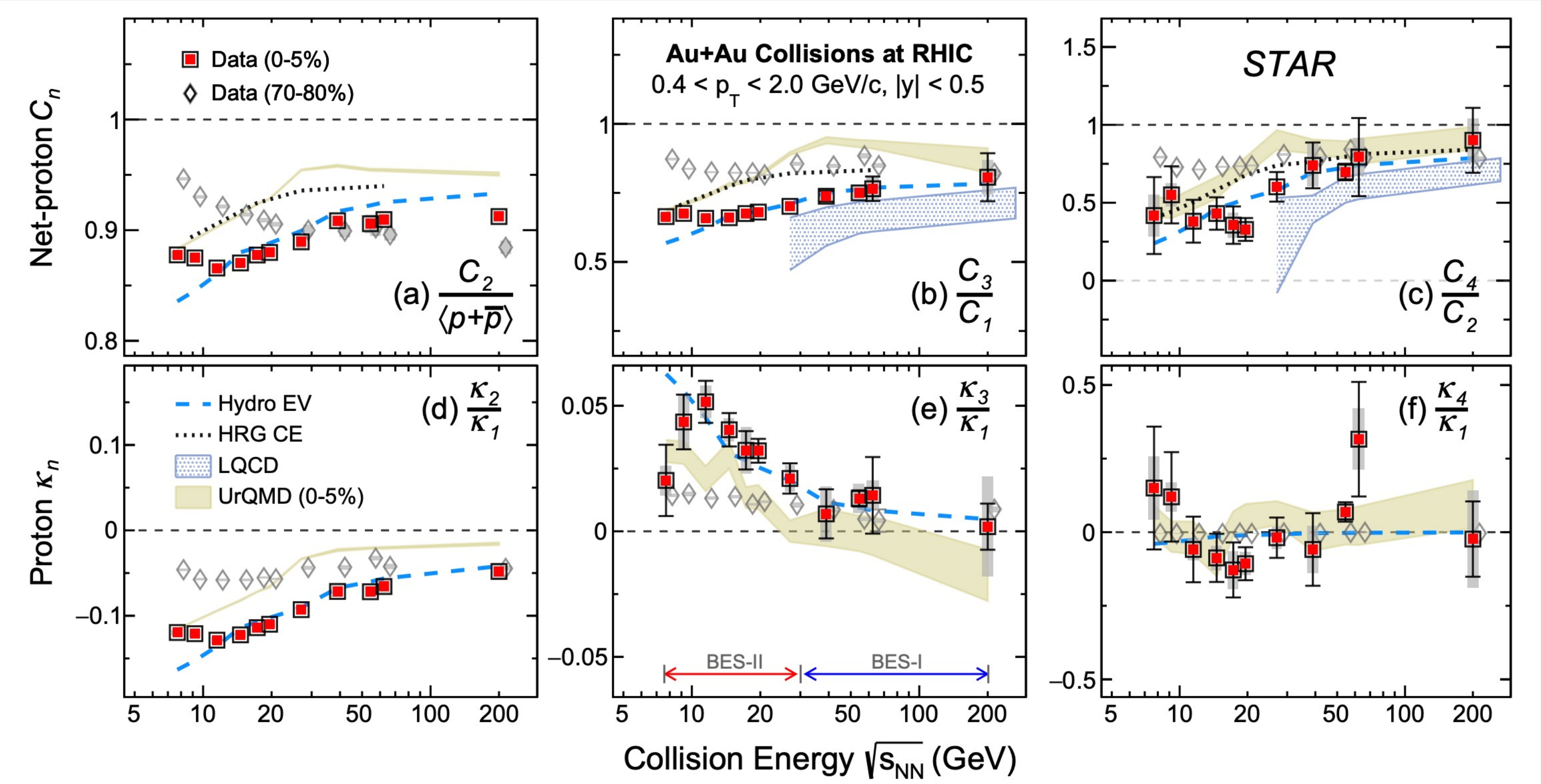
- Deviation from non-critical baselines at 19.6 GeV in C_4/C_2 at 2-5σ



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Theory Estimates for Critical-Point Location

Recent work excludes at 2σ level, CP at μ_B<450 MeV (*arXiv:2502.10267, 2025*)

√s (GeV)	Chemical Potential μ_B (MeV)
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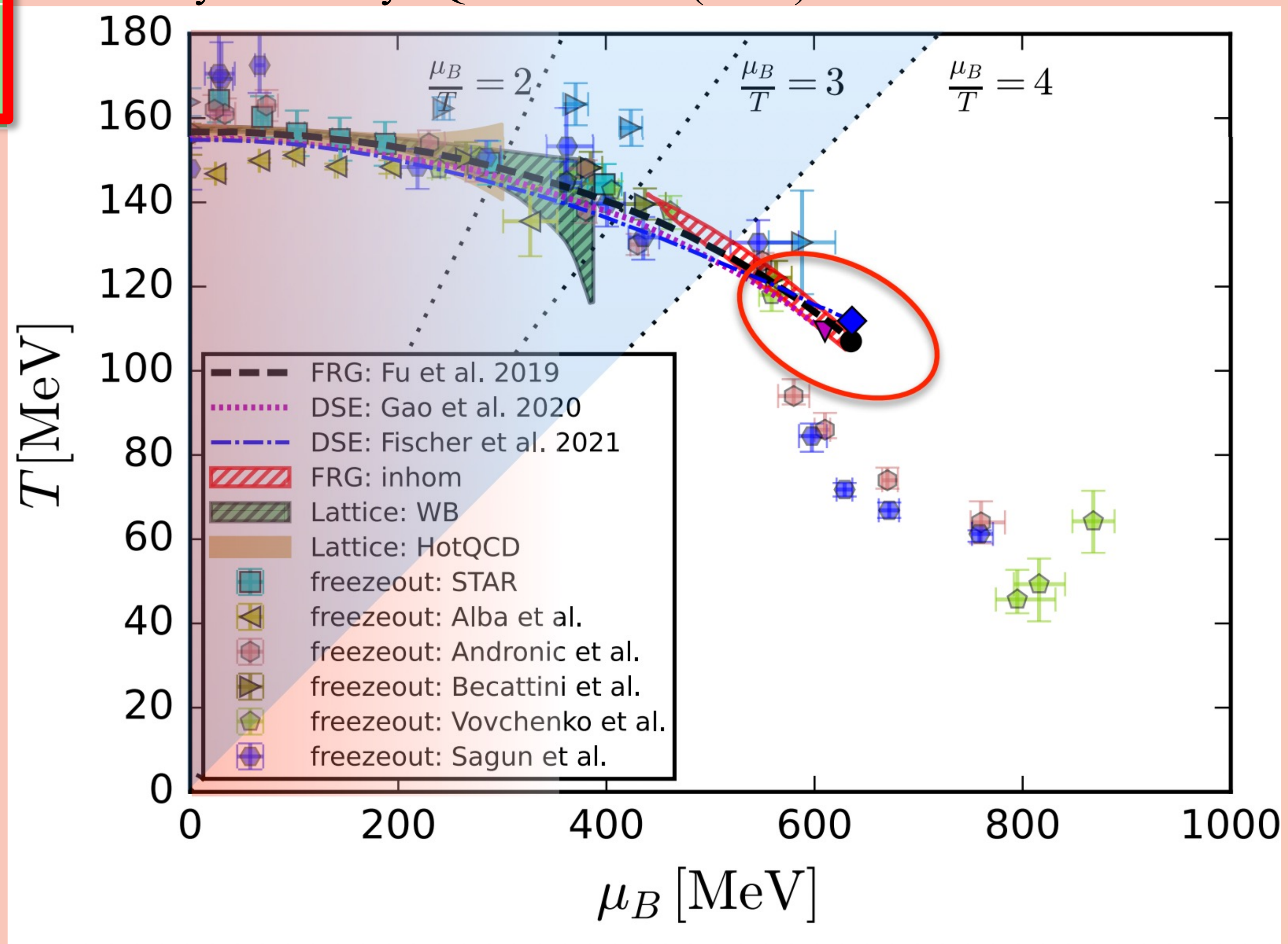

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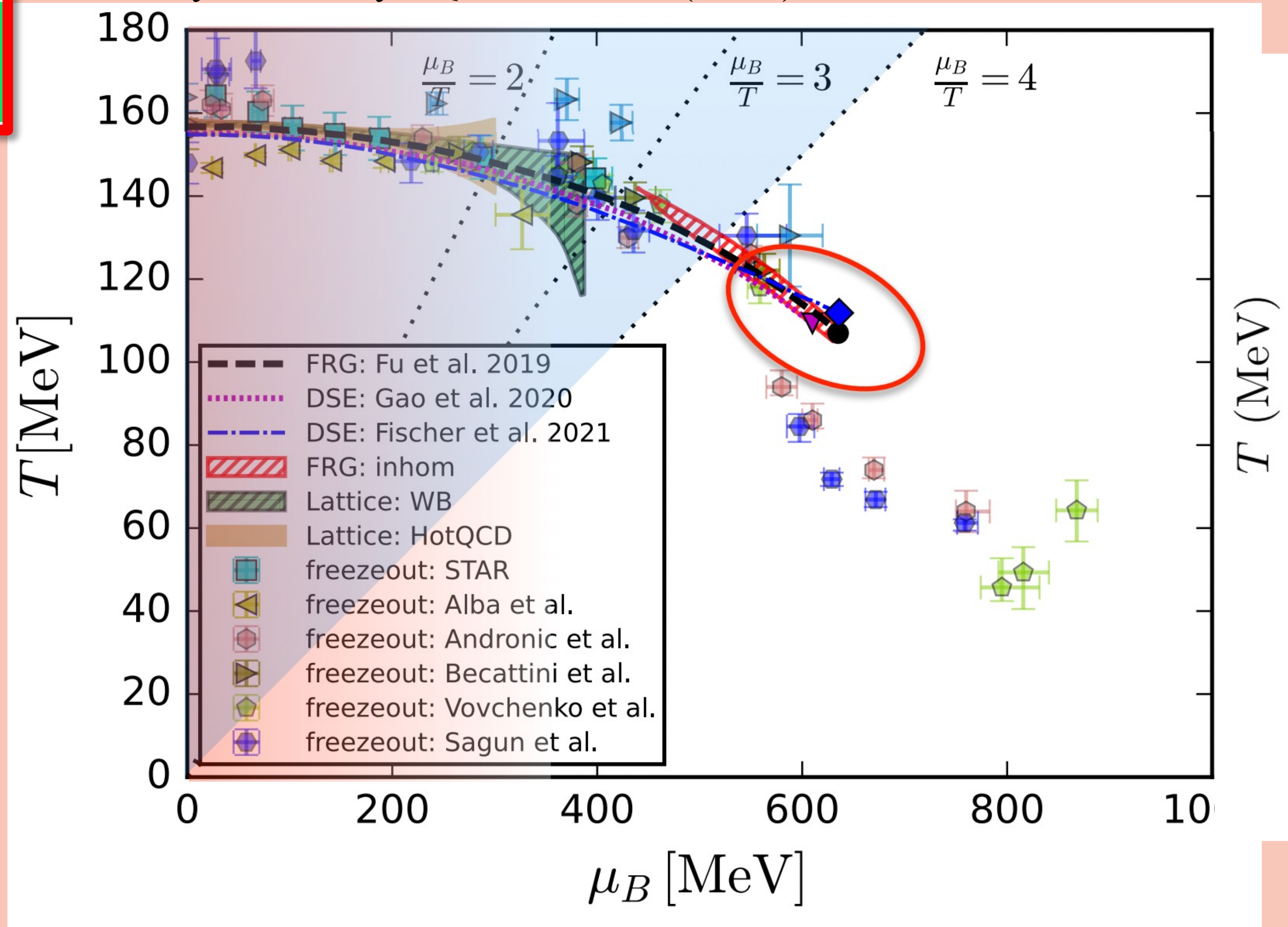

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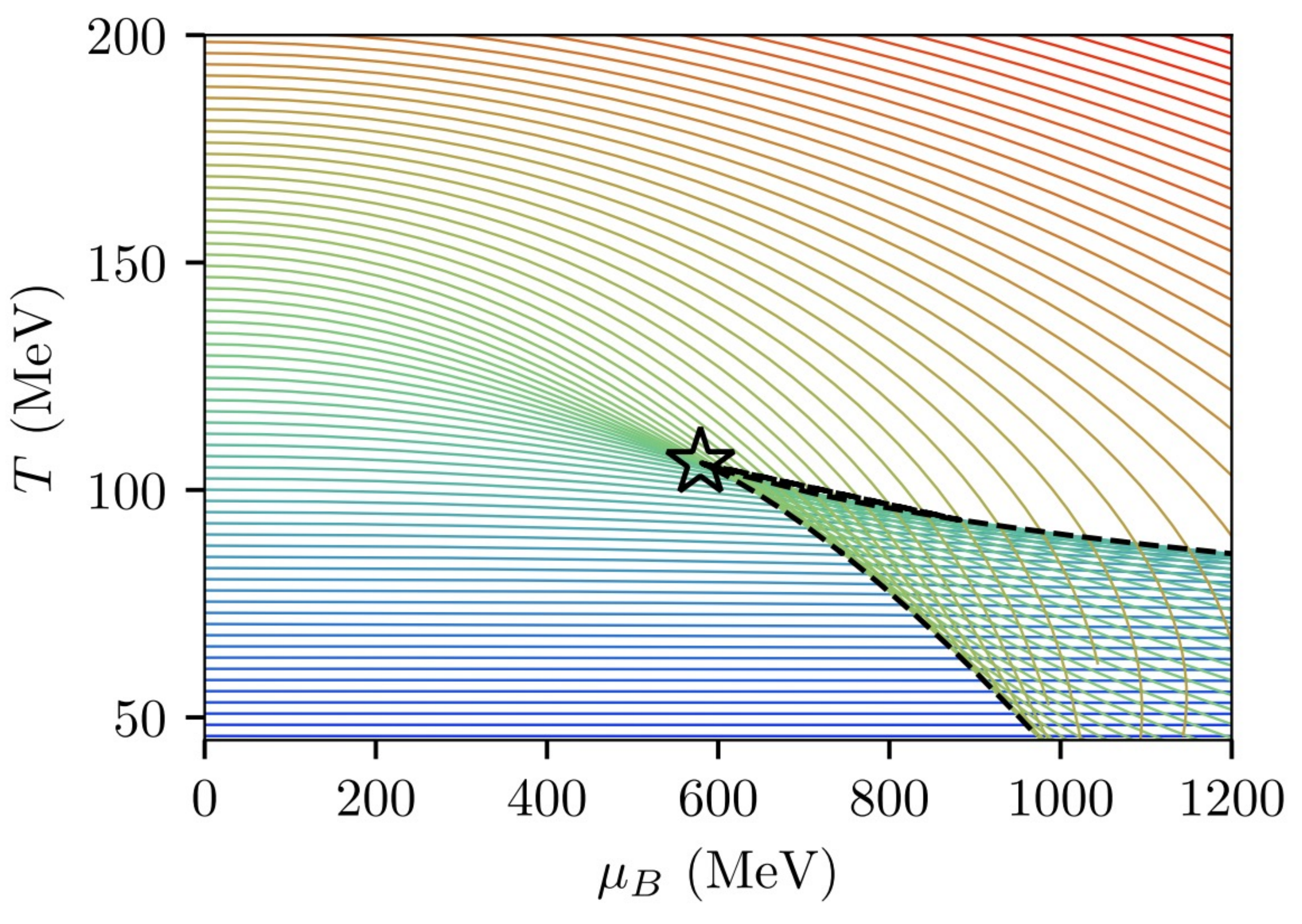

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- J. Goswami: extrapolation using machine-learning model from hot QCD: $\mu_B \cong 600 \pm 80$ MeV

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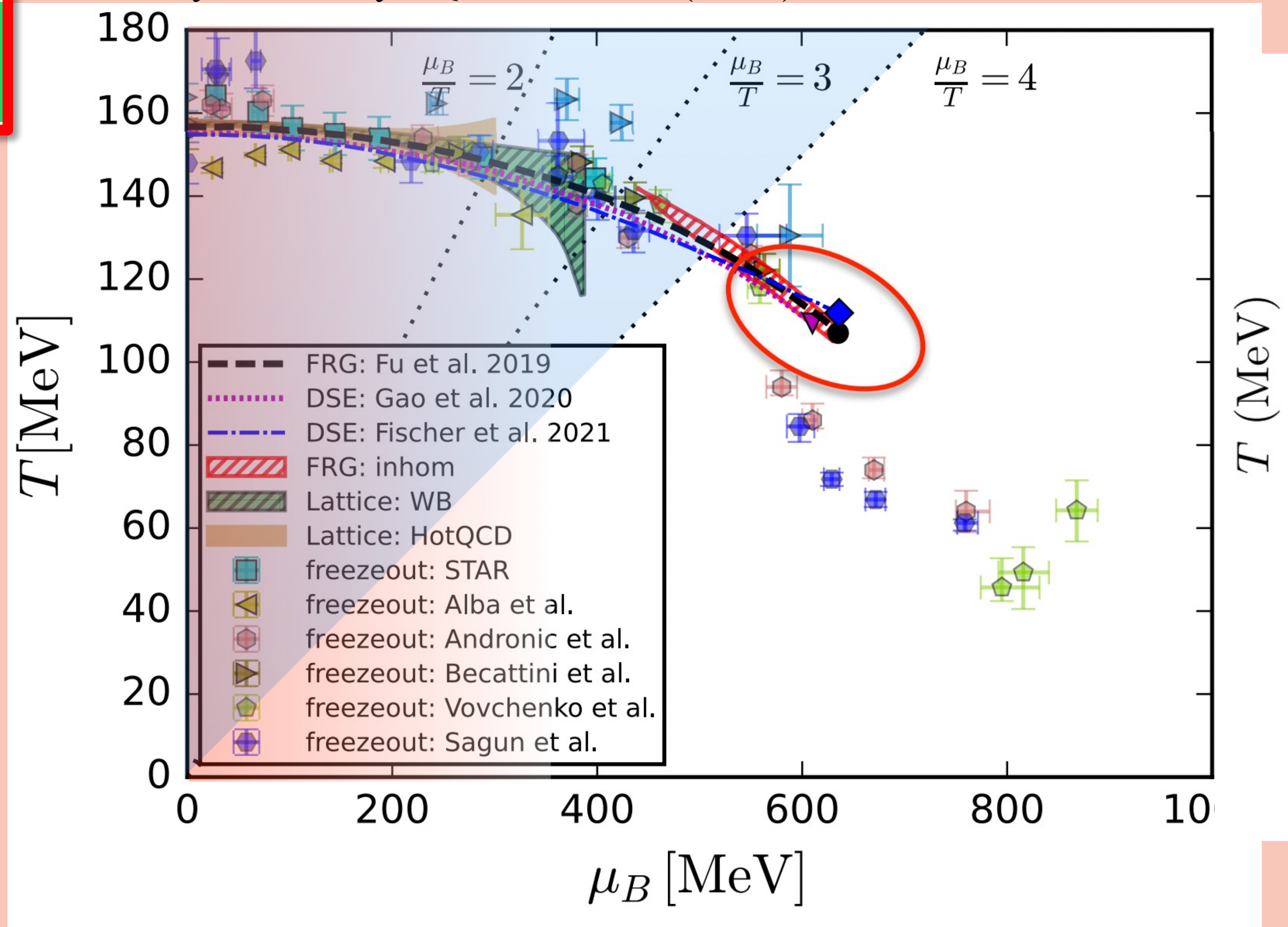

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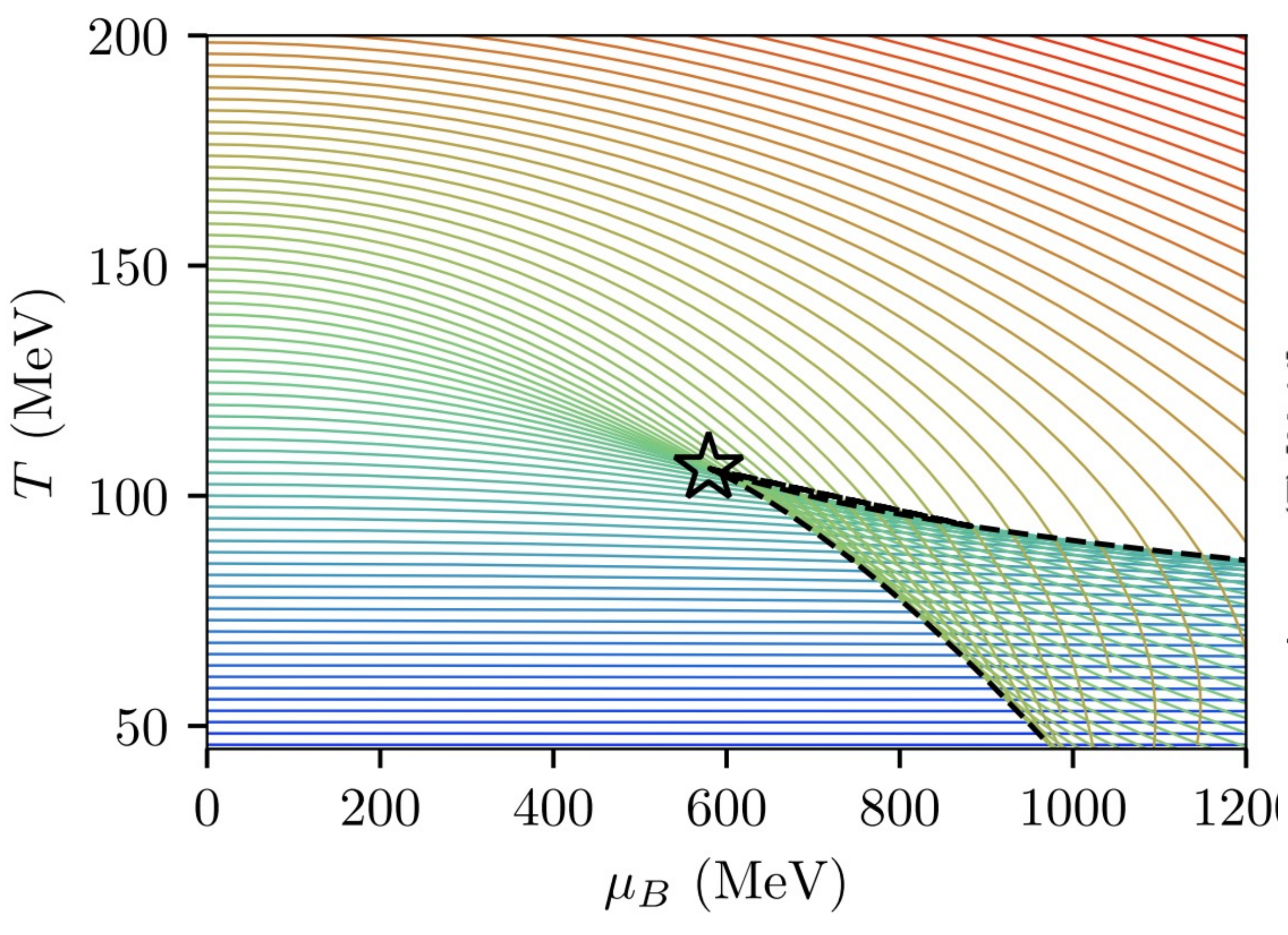
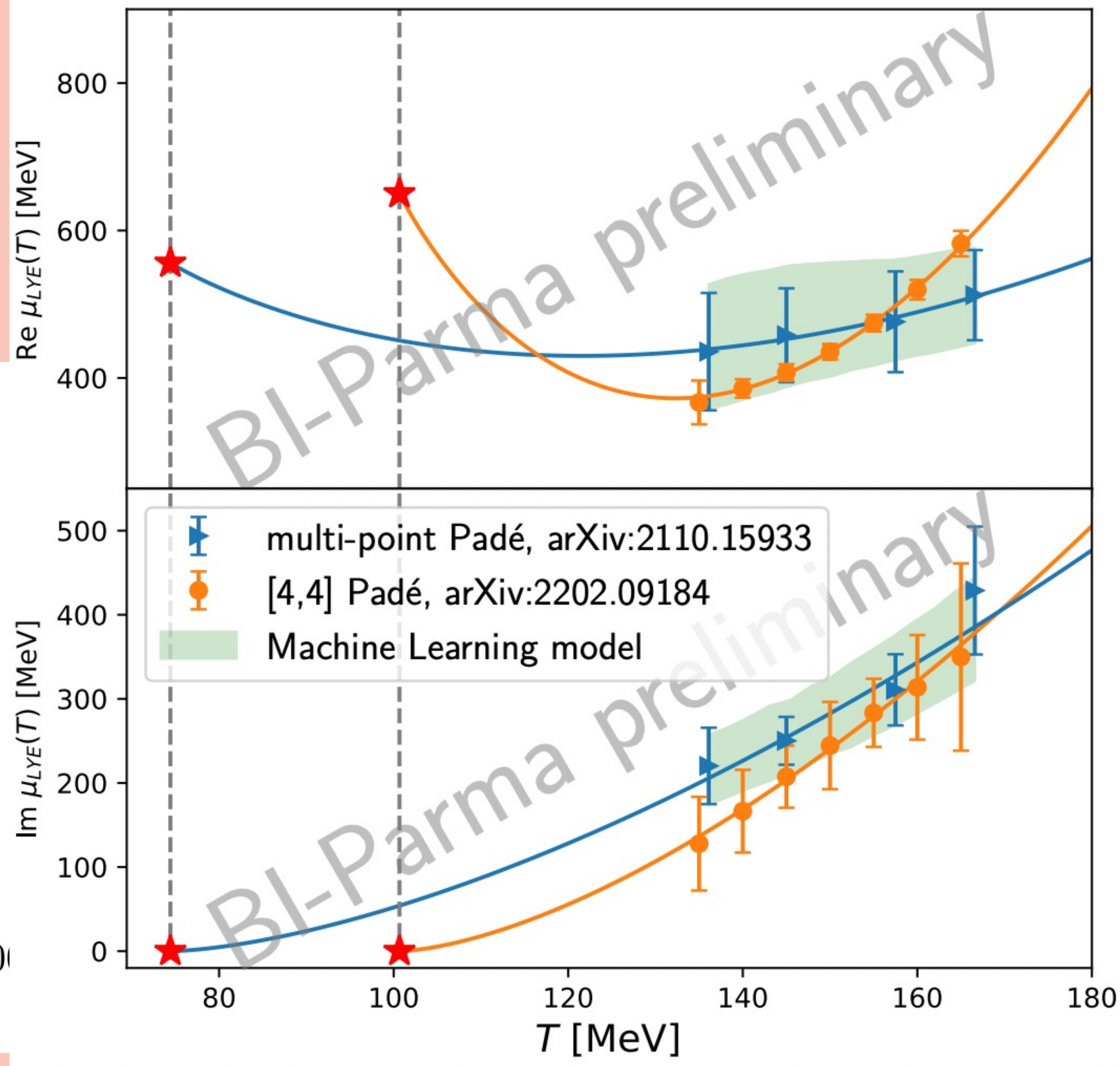


Jishnu Goswami, "Exploring the Critical Points in QCD with Multi-Point Padè and Machine Learning Techniques in (2+1)-flavor QCD" Quark Matter (2023)

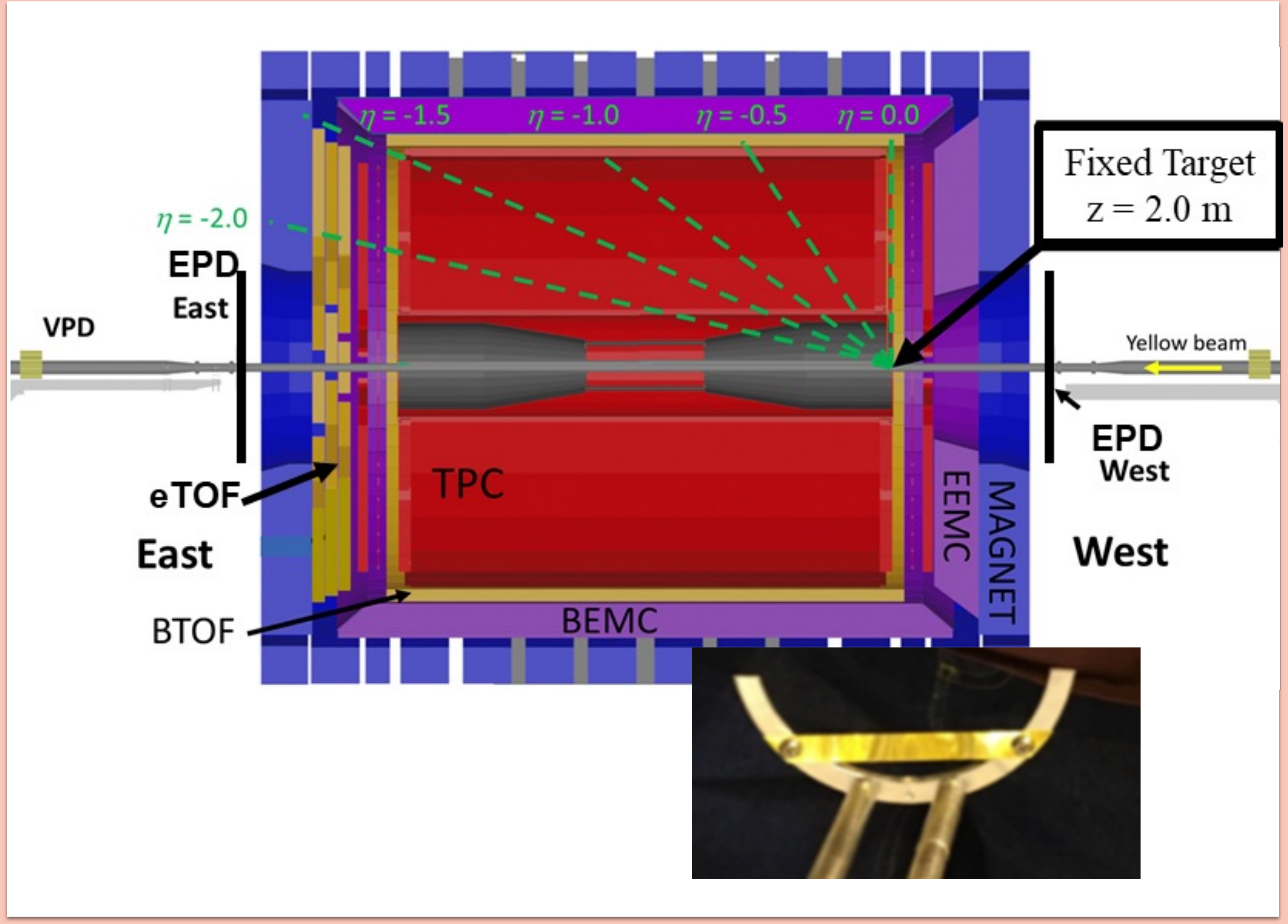


The STAR Fixed-Target Program

Fixed-Target Collisions at STAR

Fixed-Target (FXT) Program at STAR

- Test run with gold target in 2015
- First physics runs at $\sqrt{s_{NN}} = 3.0$ GeV and 7.2 GeV in 2018
- Now have data at 3.0–7.7 GeV



Challenges for FXT

- Shifting asymmetric acceptance w.r.t. midrapidity with collision energy
- At 7.7 GeV, midrapidity moves to edge of Time Projection Chamber (TPC) acceptance

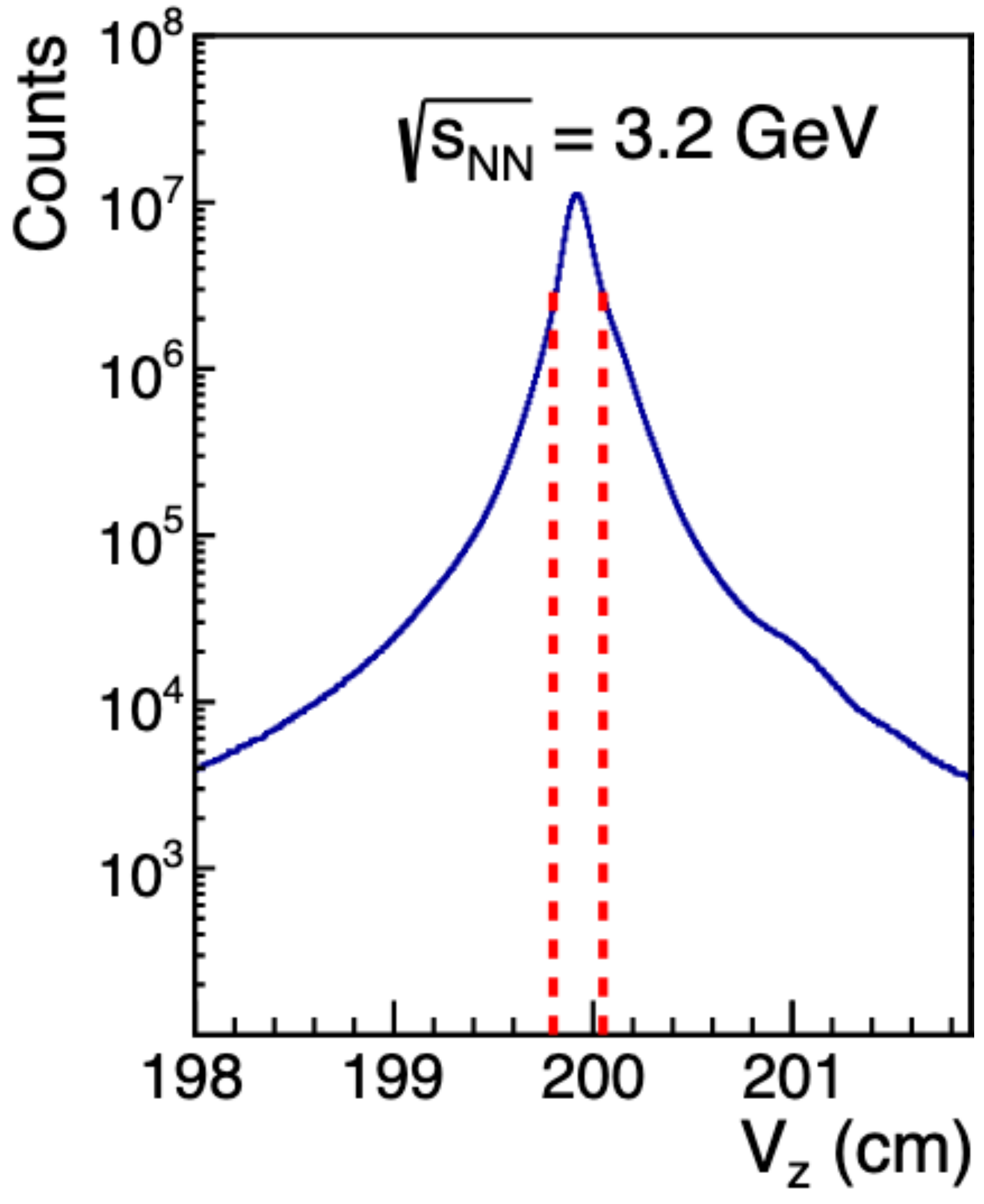
This Fixed-Target Data

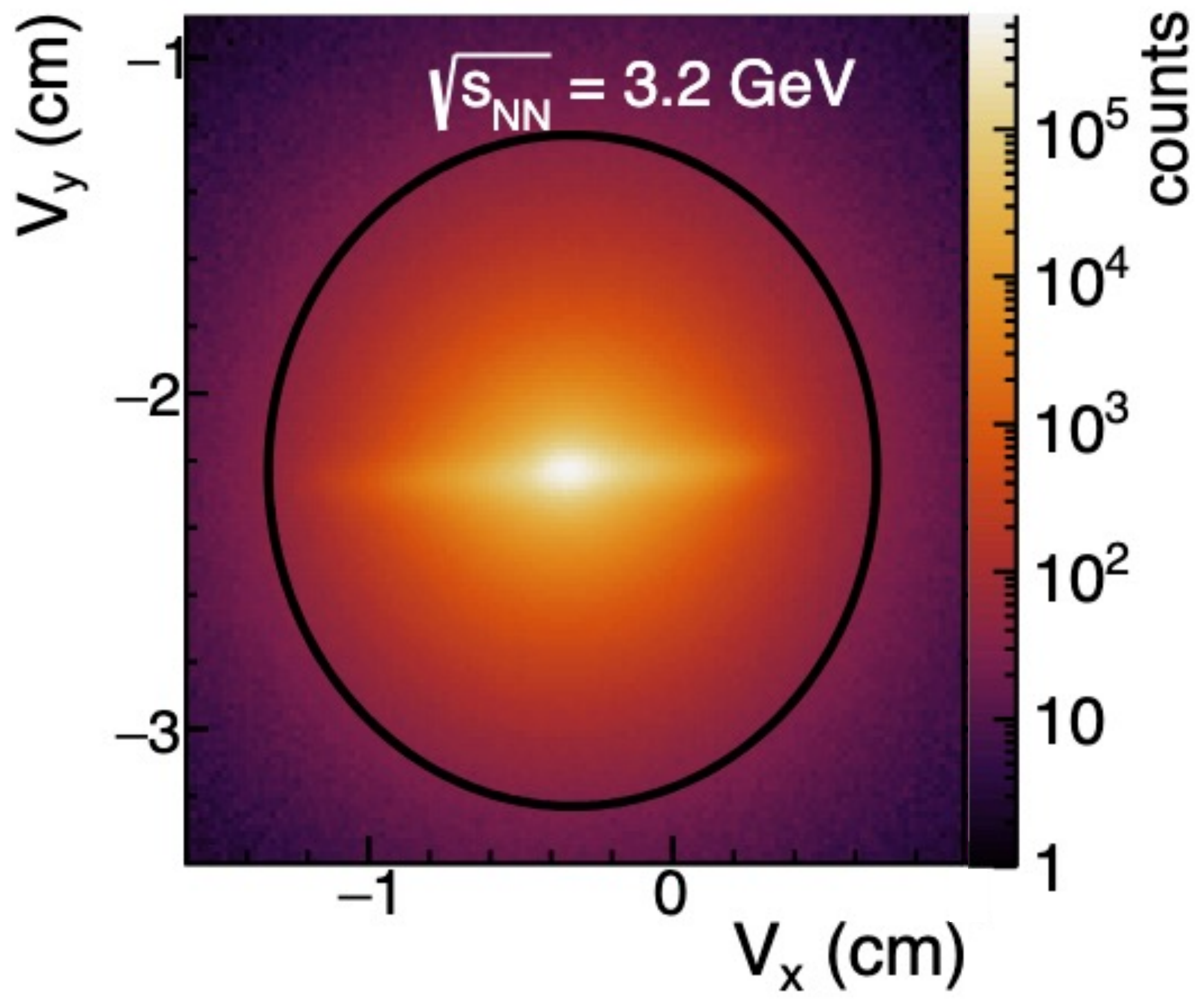
- This analysis looks at three datasets: 3.2, 3.5, 3.9 GeV

Data Set Details

Nominal $\sqrt{s_{NN}}$ (GeV)	Precision $\sqrt{s_{NN}}$ (GeV)	Beam Energy (GeV)	# Good Events	CoM Rapidity	Chemical Pot. μ_B (MeV)
3.2	3.208	4.593	201M	1.139	697
3.5	3.531	5.761	116M	1.254	666
3.9	3.918	7.309	117M	1.375	632

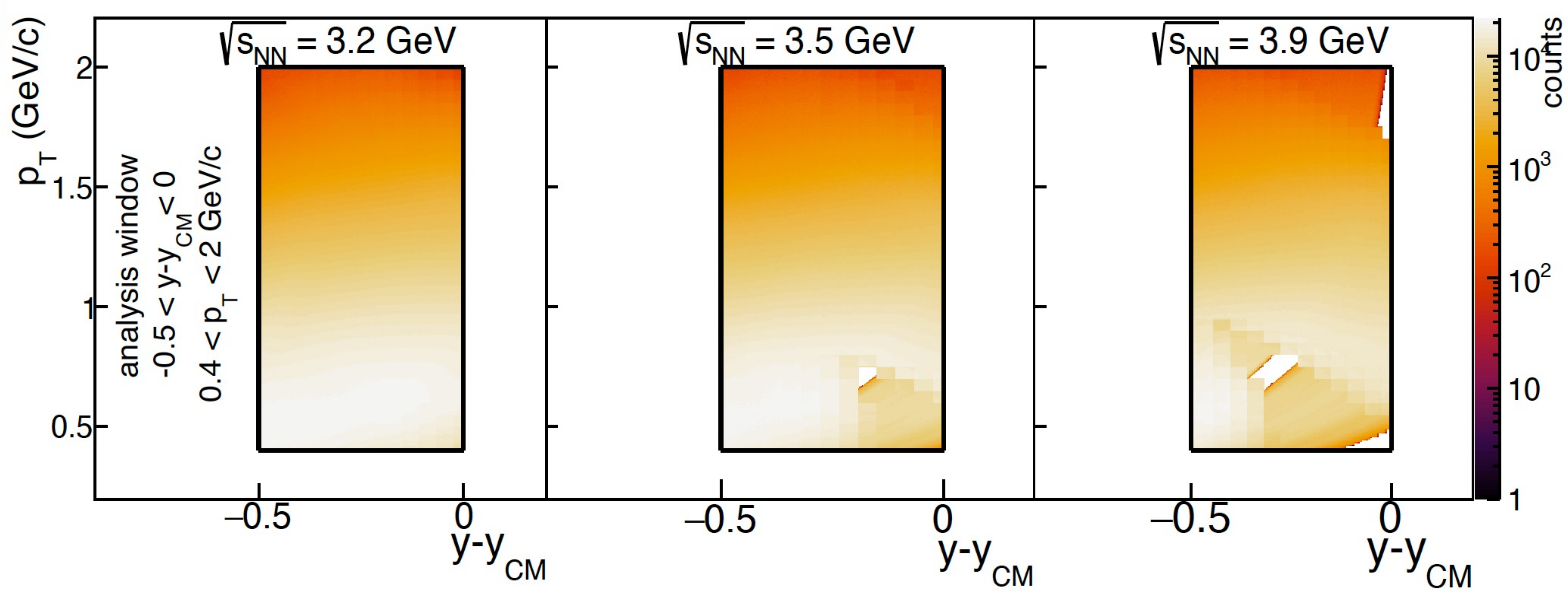
- We select events with vertex centered on target
- $V_z \sim 200$cm
- $V_y \sim -2.2$cm below beam-pipe center





Fixed-Target High-Moments Analysis Window

- Challenging acceptance: detector gaps simulated in UrQMD baseline
- Contamination from pions and deuterons limited
- >90% proton purity in each region of phase space



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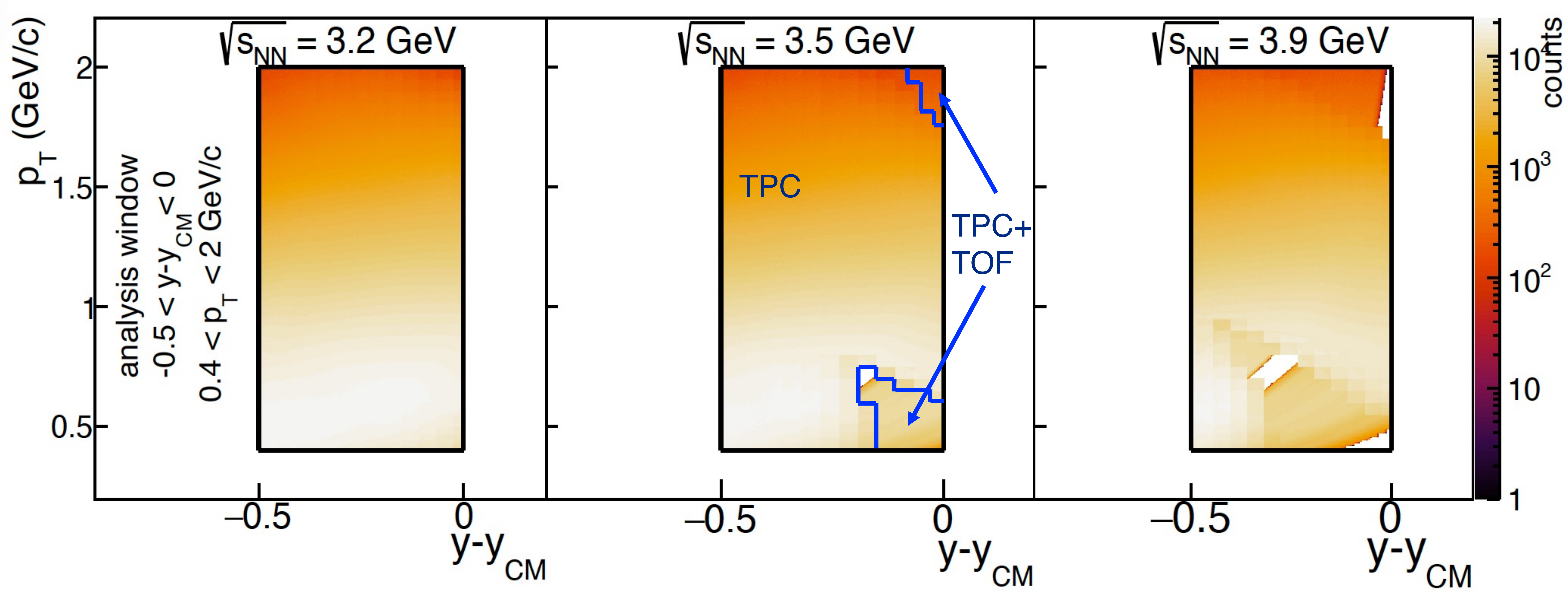
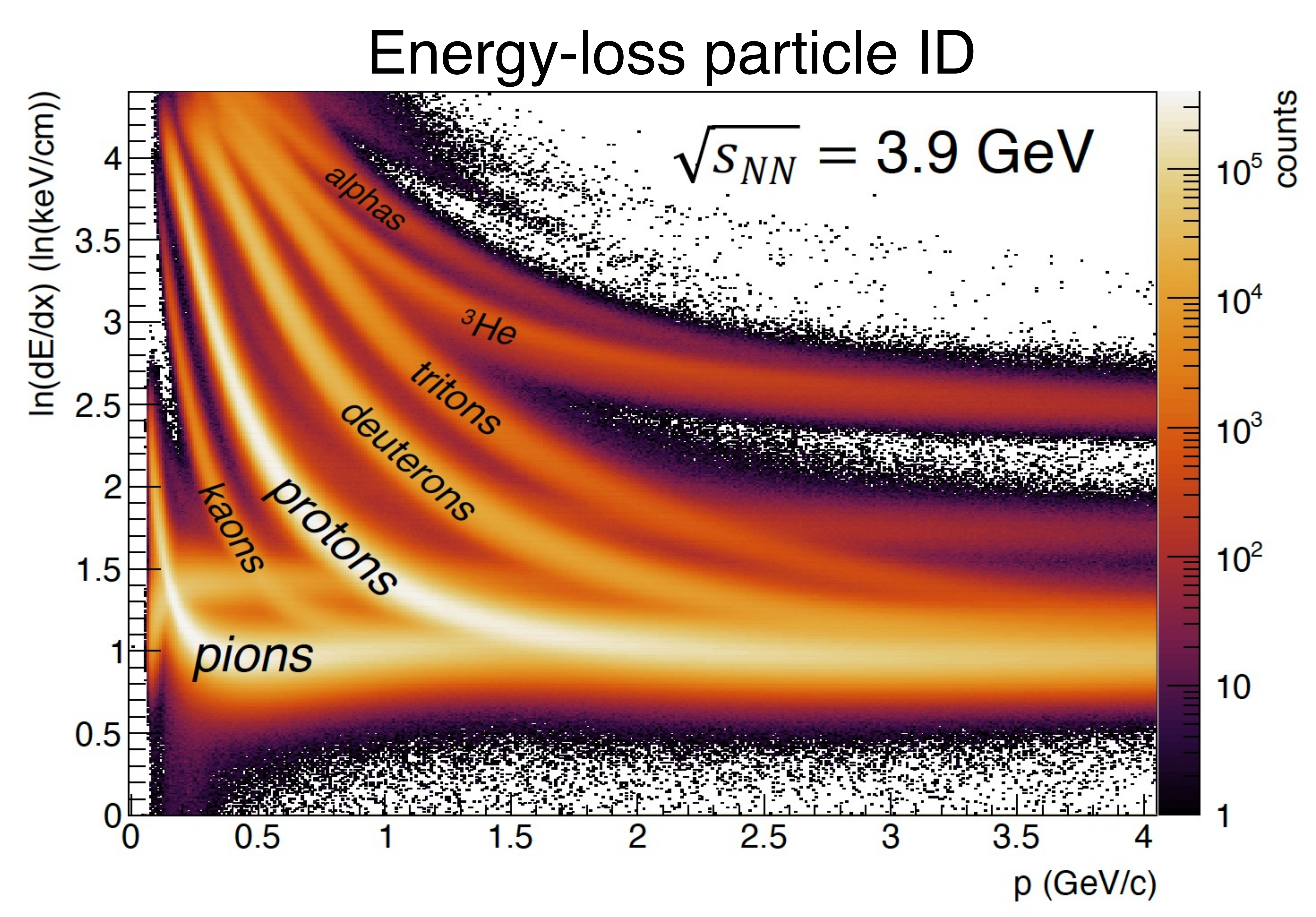
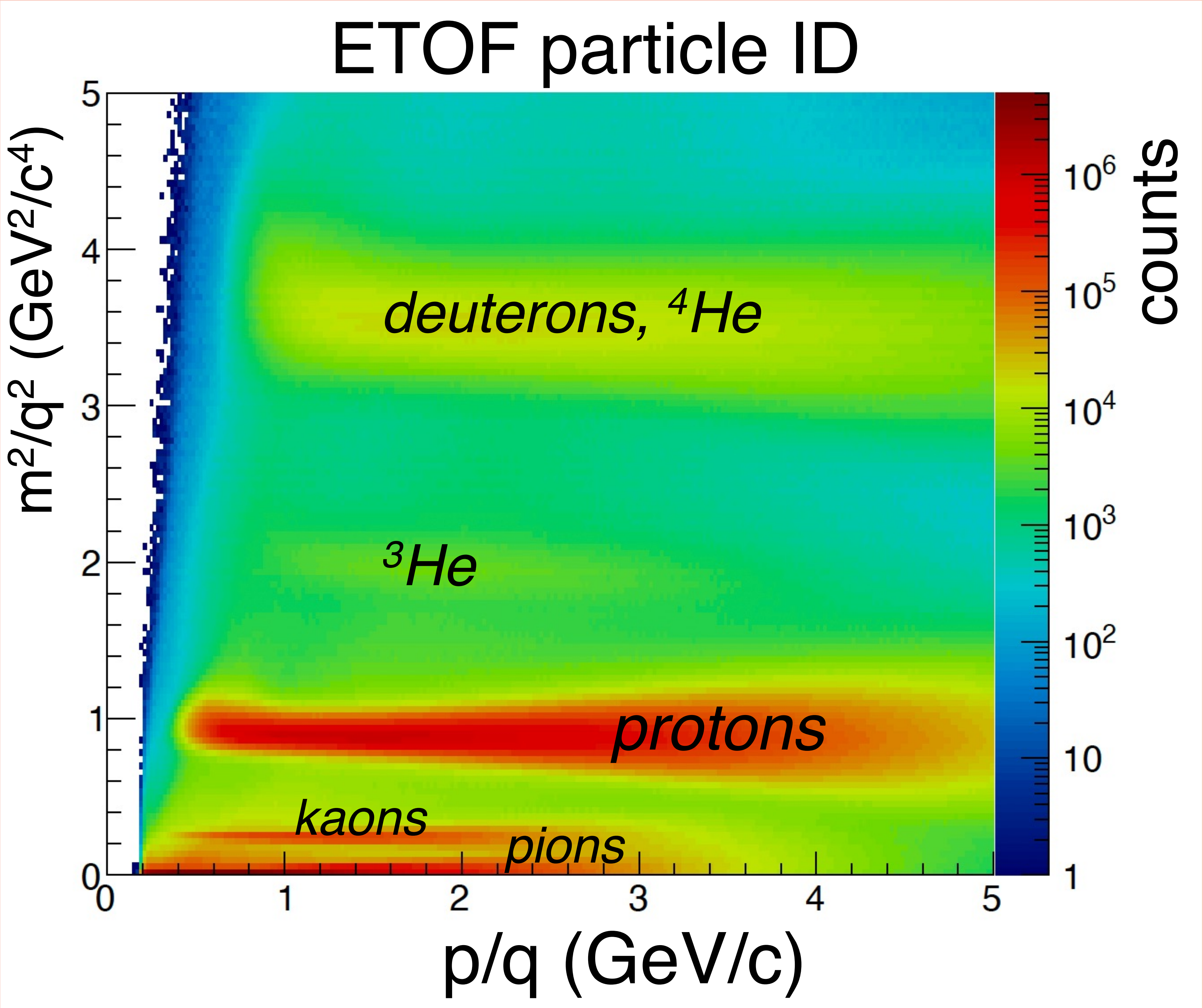


Proton Identification

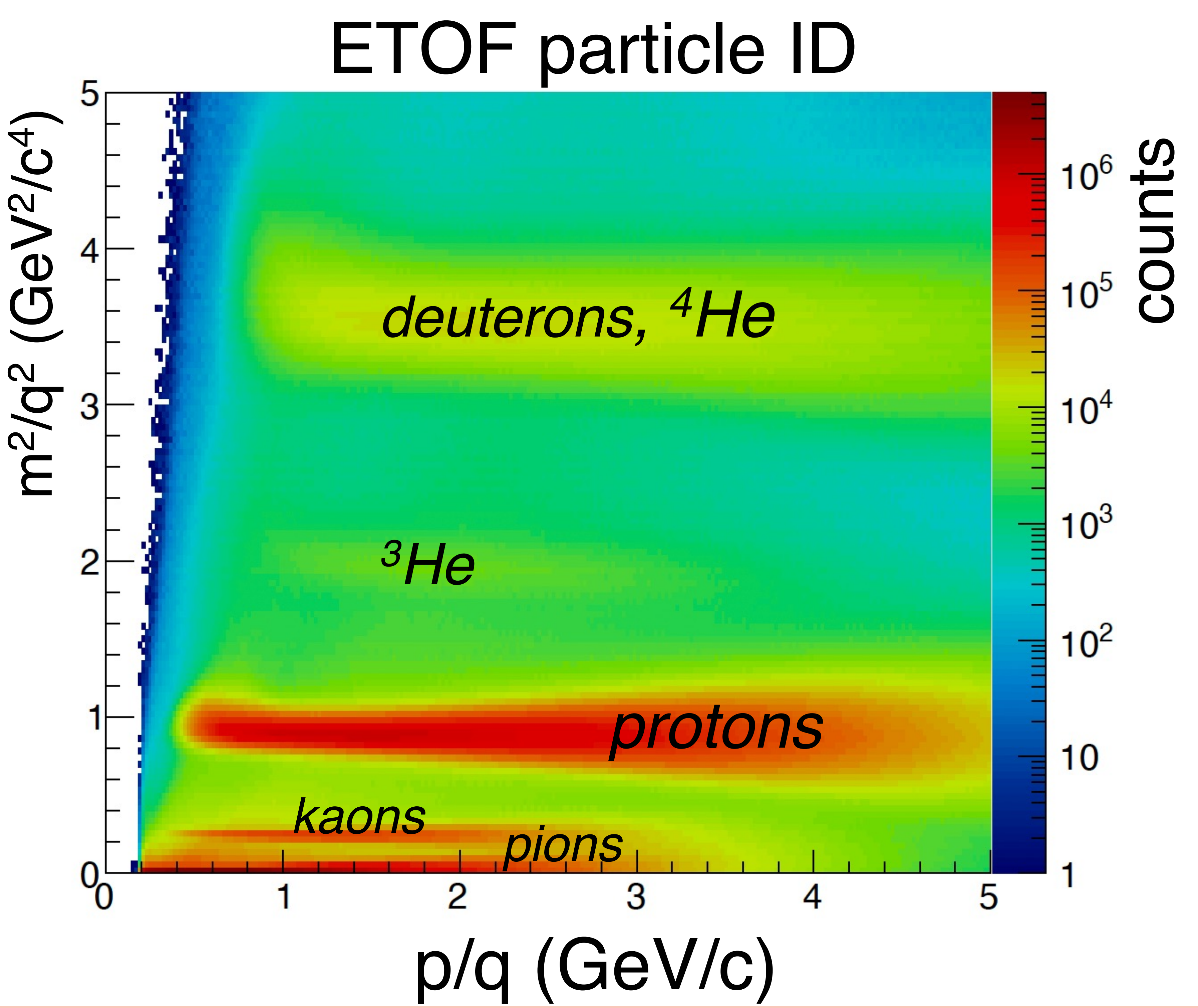
- When pion and deuteron contamination is low, we can use energy-loss in the TPC to identify protons
- When the proton purity dips below 90%, we can use time-of-flight for PID





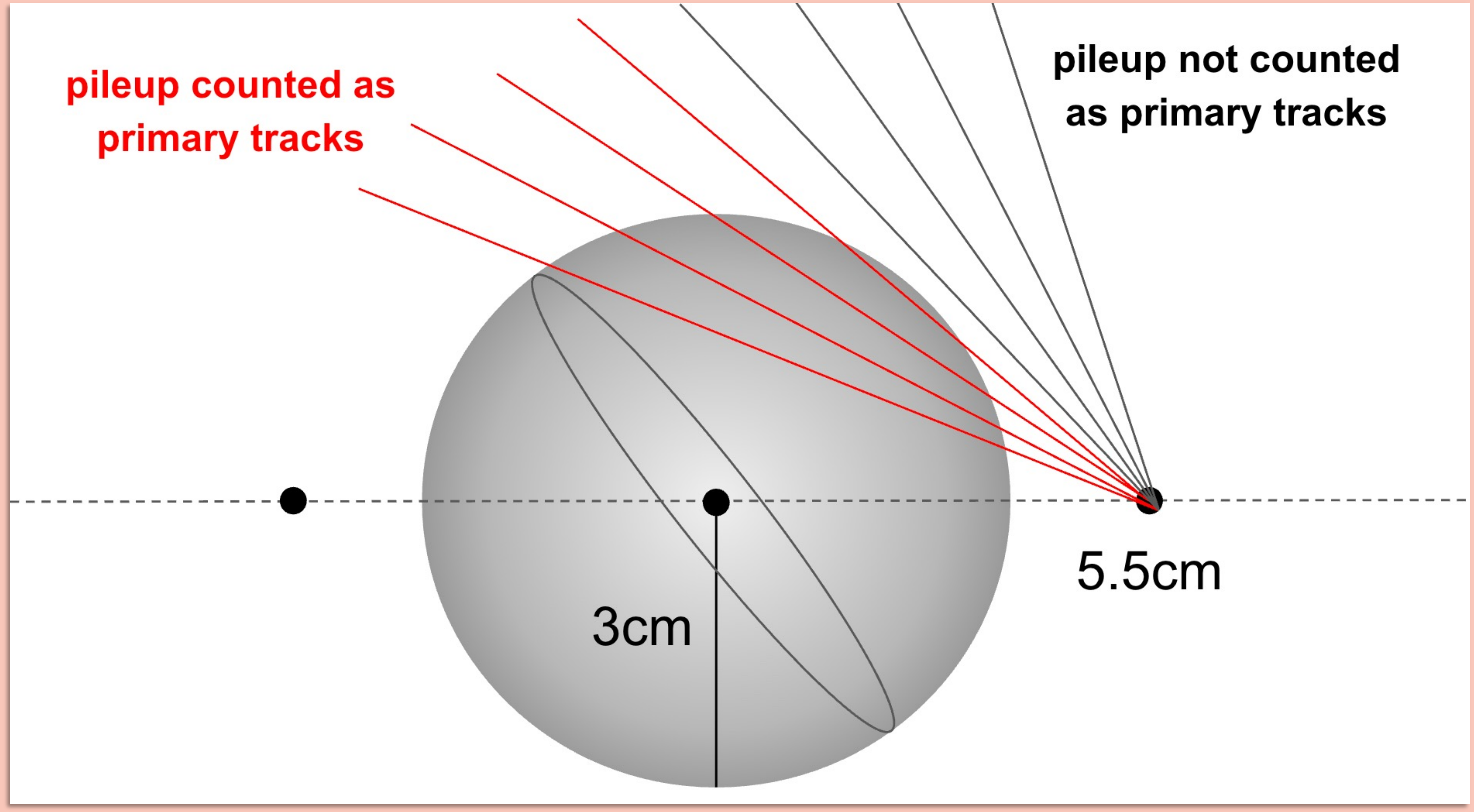
ETOF Details

- CBM-TOF group provided ETOF
- Provides precision particle identification over $1.55<\eta<2.2$
- Collected data for Fixed-Target Program



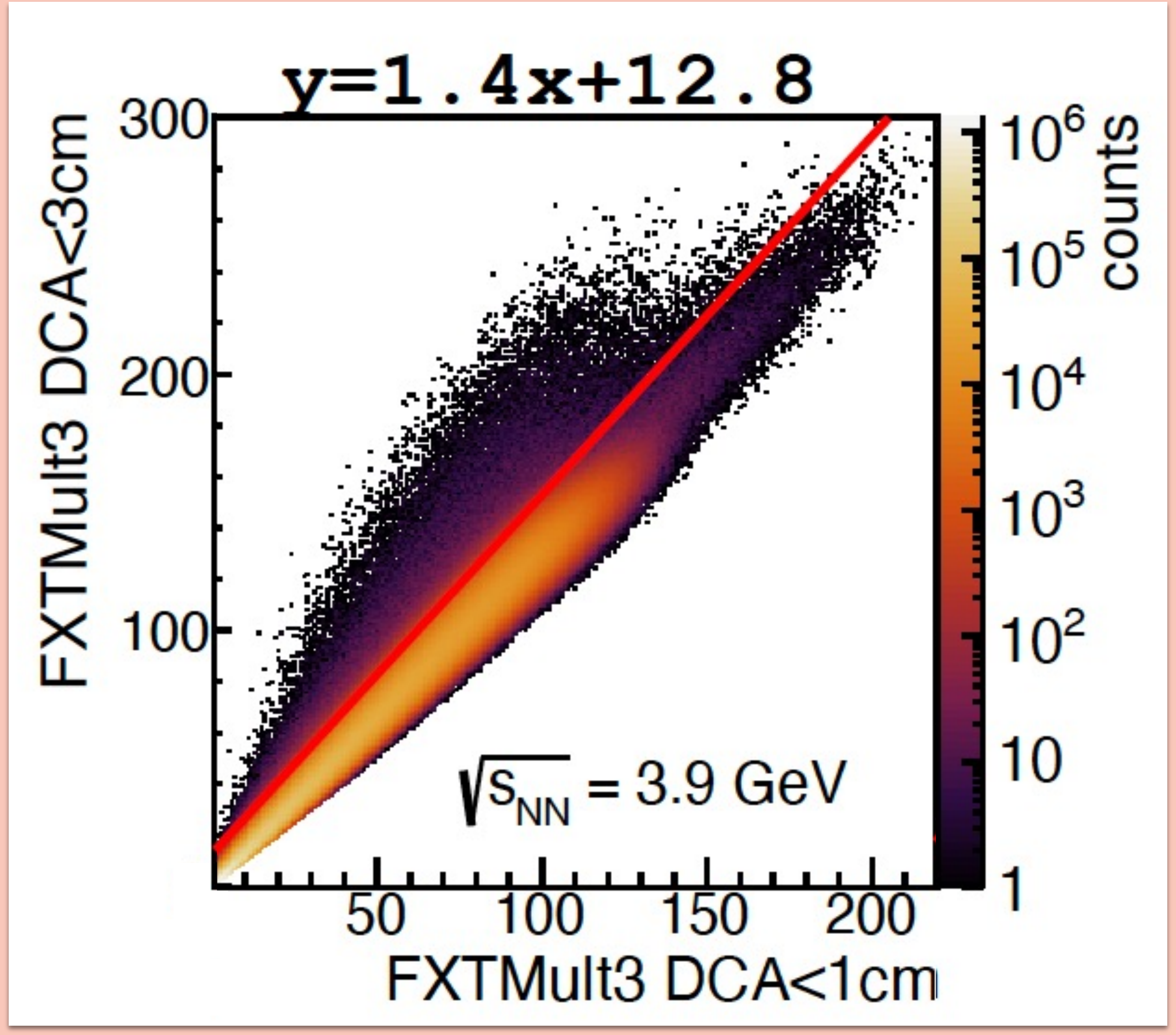
Out-of-Bucket Pileup

- In the Fixed-Target Program, only every 10^{th} bunch was filled
- RHIC clock is 10 MHz, so each bucket is 100ns apart
- Each filled bucket arrives every 1μs
- TPC drift velocity is 5.5 cm/μs
- Pileup tracks from next filled bucket appear shifted by 5.5 cm
- With a 3cm DCA cut, high-rapidity pileup tracks would be counted in primary vertex



Out-of-Bucket Pileup

- We can remove much of this pileup by removing outliers in distribution of multiplicity with DCA<3cm vs. multiplicity with DCA<1cm
- Additionally, iTPC upgrade after 2018 allows us to decrease our DCA cut to 1cm
- This is different from the published 3 GeV cumulants (*PRL 126 092301*)



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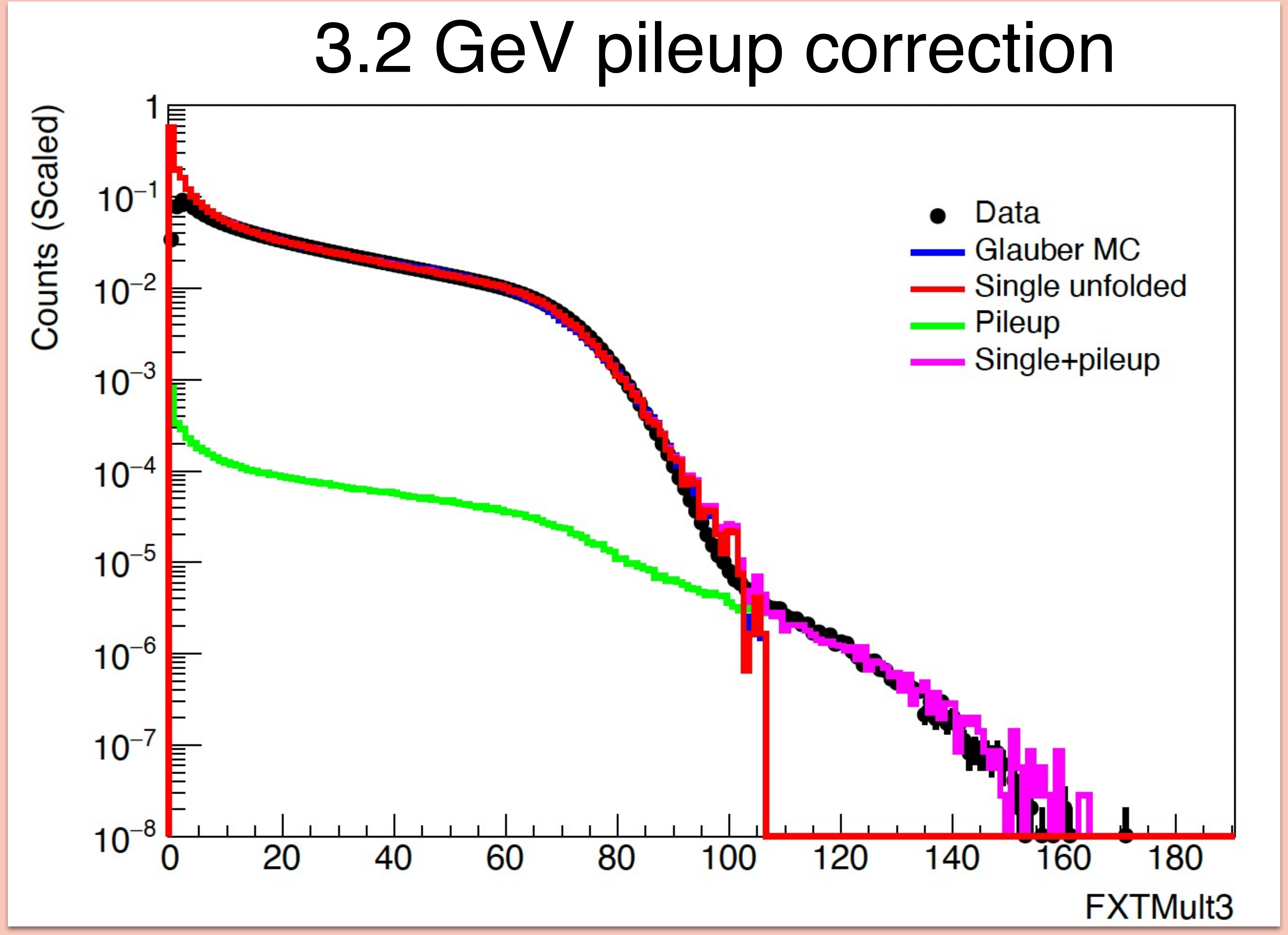

In-Bucket Pileup

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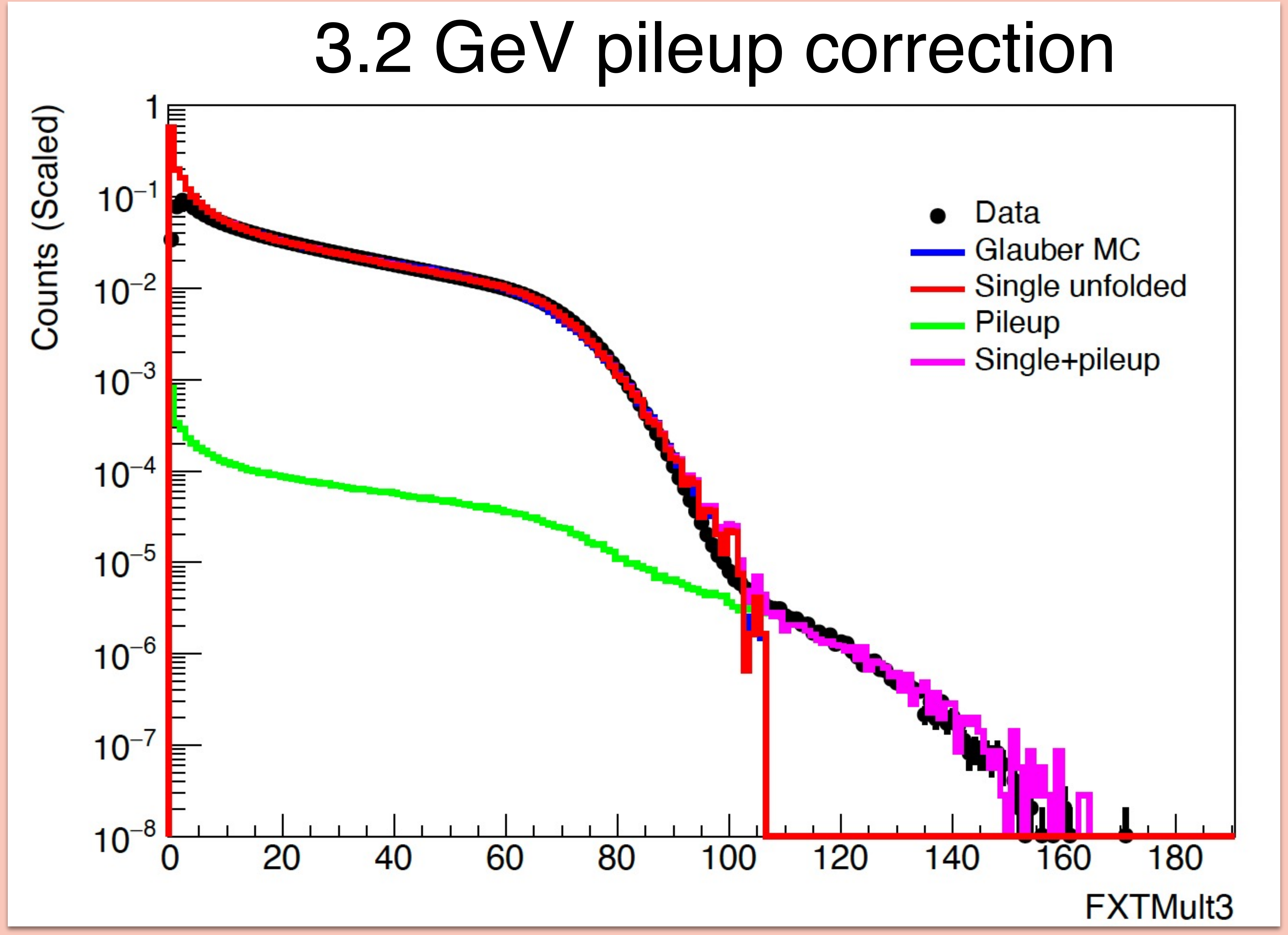
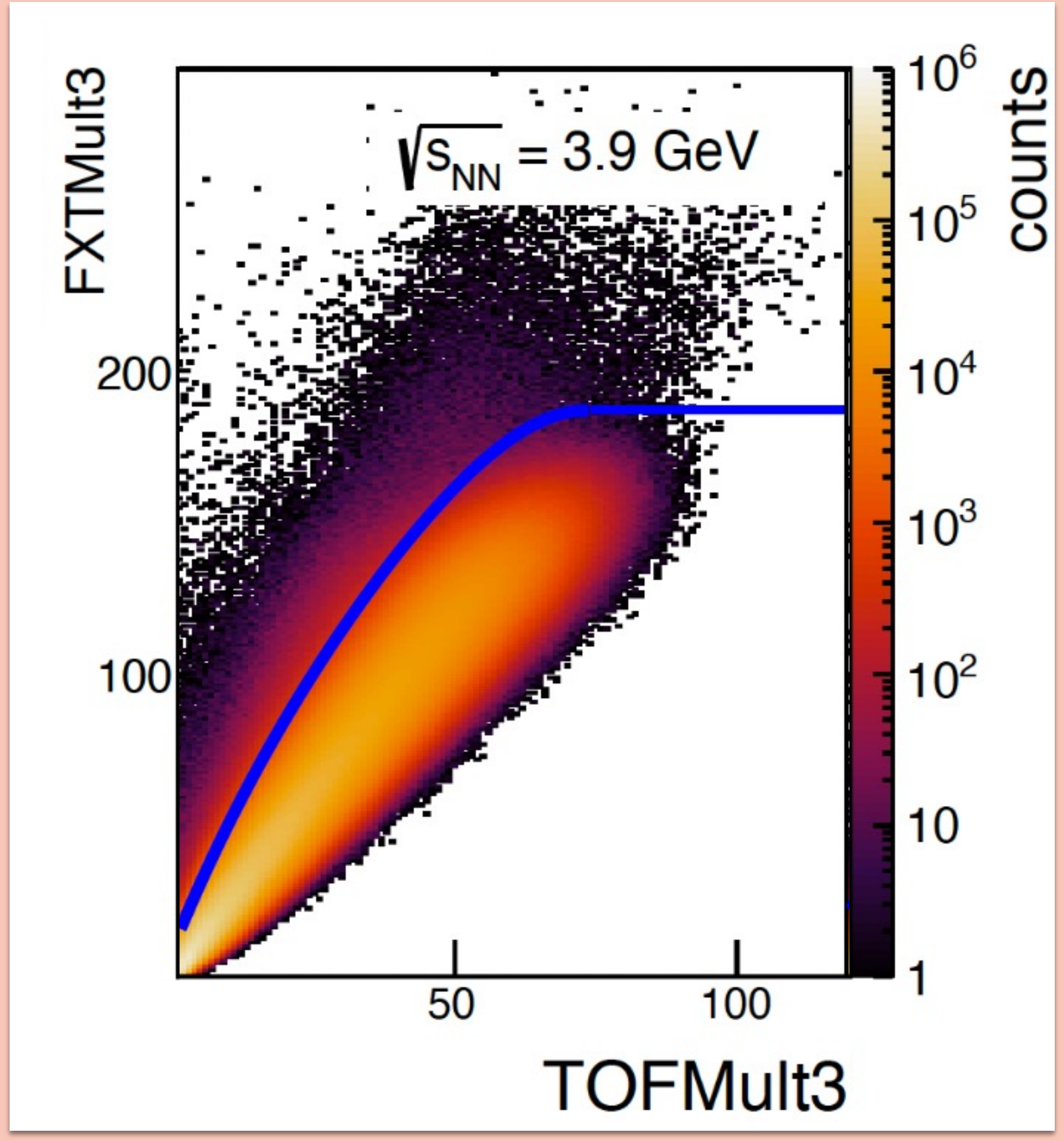
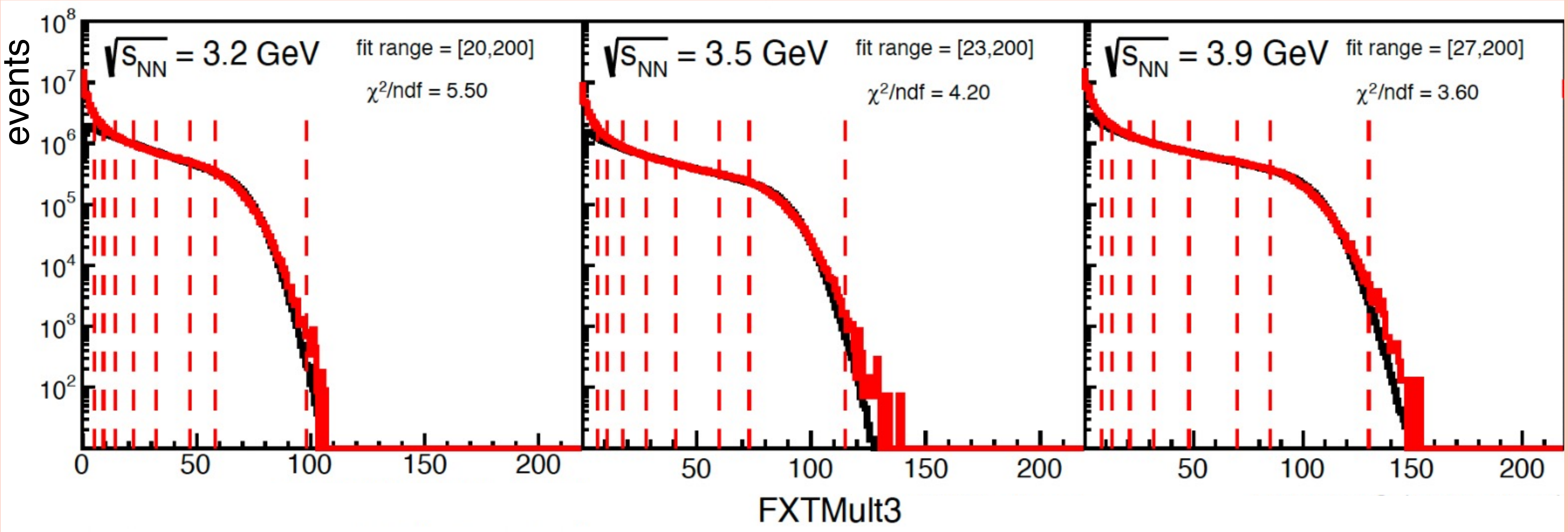
- At 3.5 & 3.9 GeV, pileup is rejected by rejecting outliers in the multiplicity observed by TPC vs multiplicity observed by TOF





Fixed-Target Multiplicity for Centrality Determination

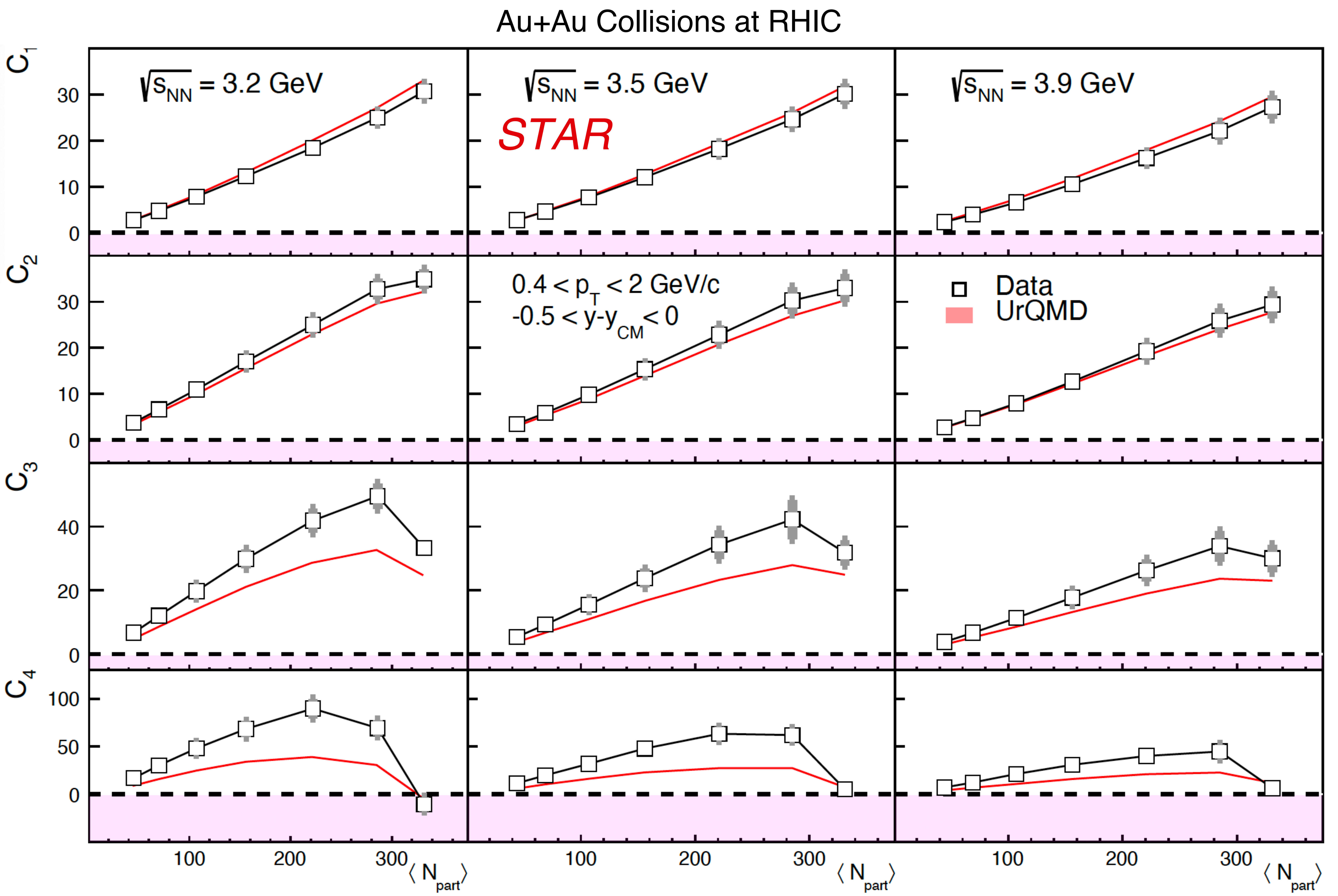
- In fixed-target, multiplicity includes tracks at all η
- FXTMult3: charged-particle multiplicity excluding protons
  - ❑ Distance of closest approach (DCA) to vertex of less than 1cm
  - ❑ Negatively-charged tracks
  - ❑ Low-momentum positive tracks, identified as non-protons
- Multiplicity fit with Glauber + 2-component model for centrality definition



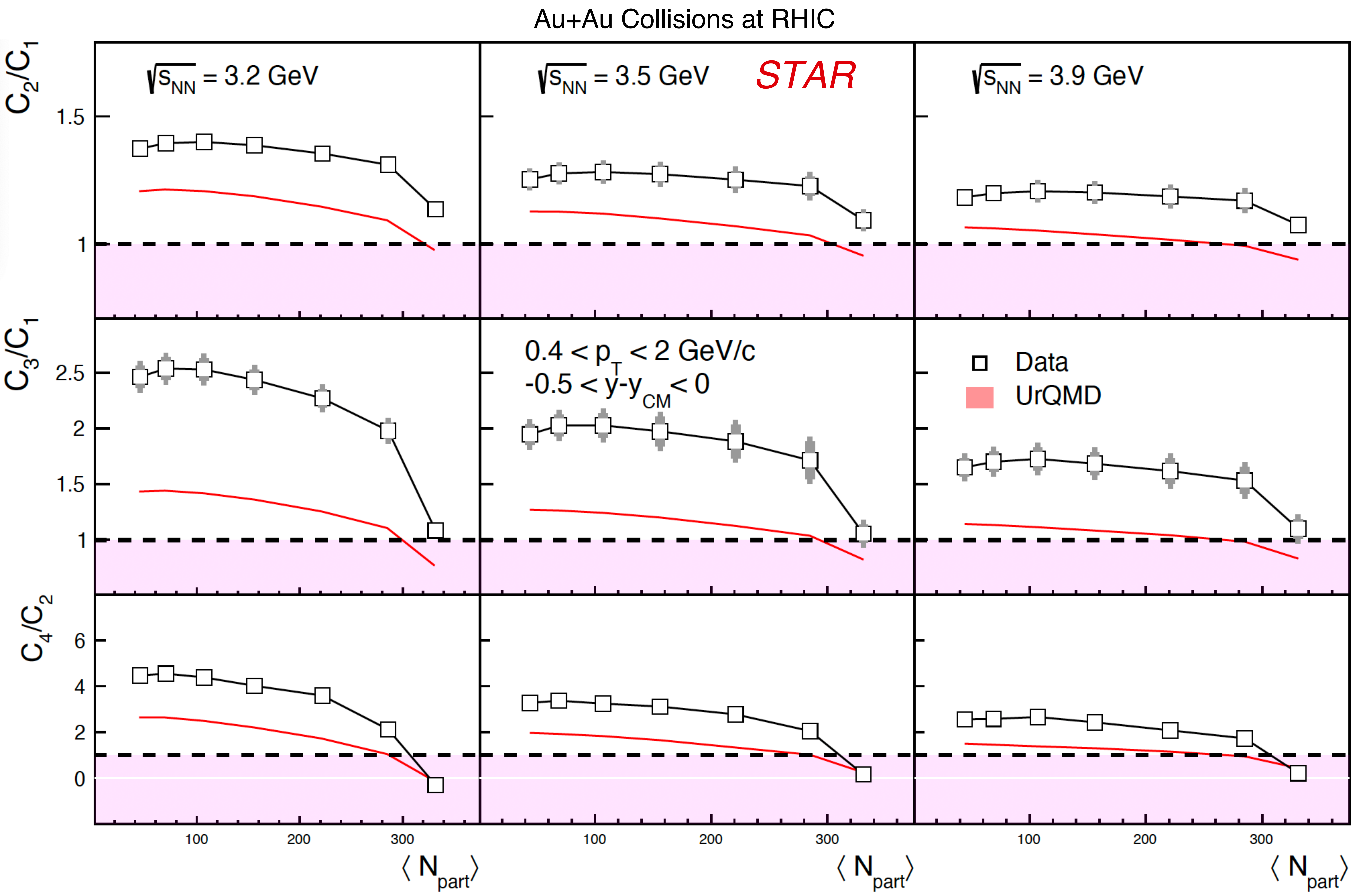
Results

Cumulants vs. Centrality

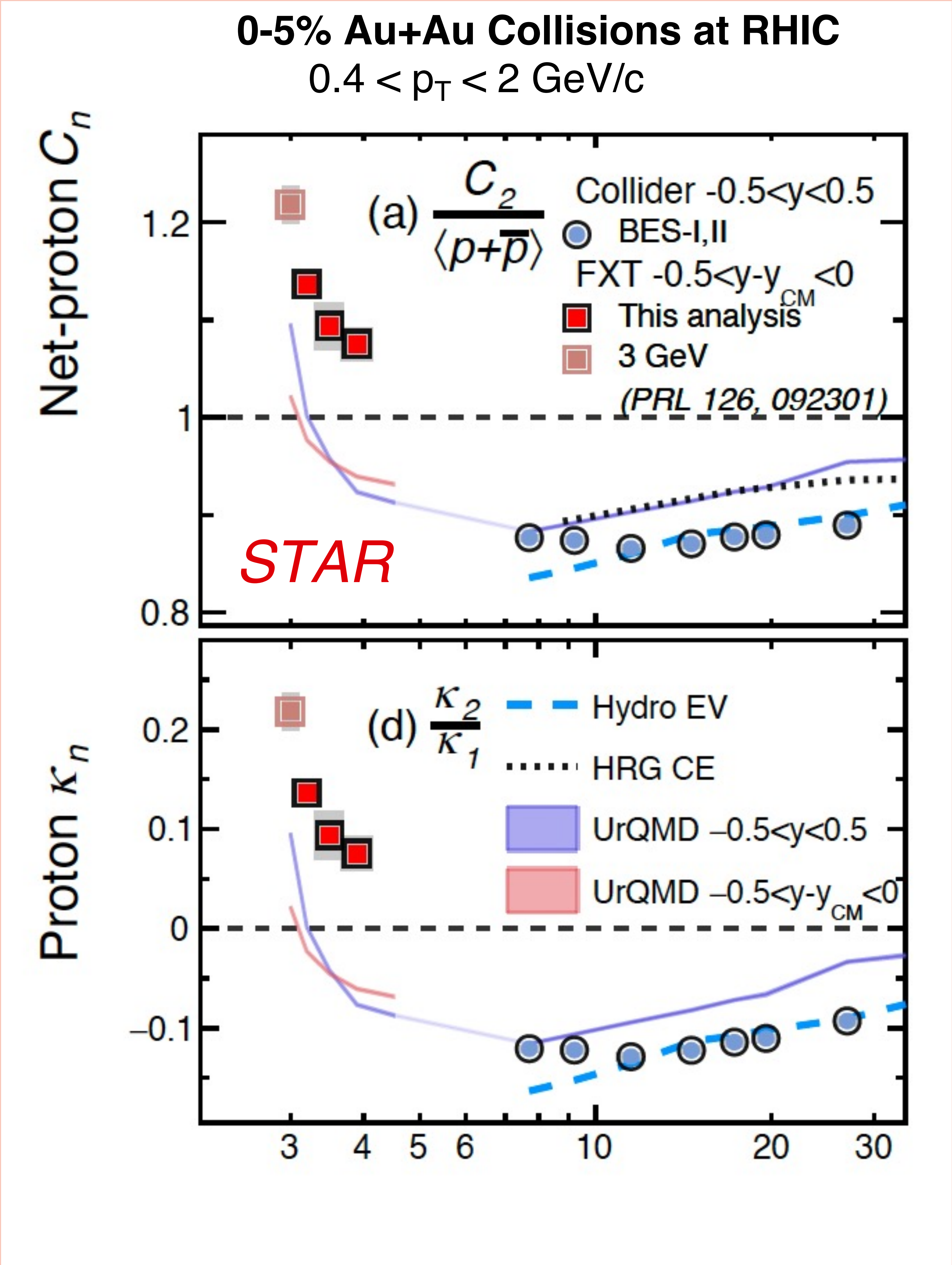
- Central C_3 is notably larger than UrQMD prediction
- Central C_4 is consistent with UrQMD



Cumulant Ratios vs. Centrality



Energy Scan of (Factorial) Cumulants



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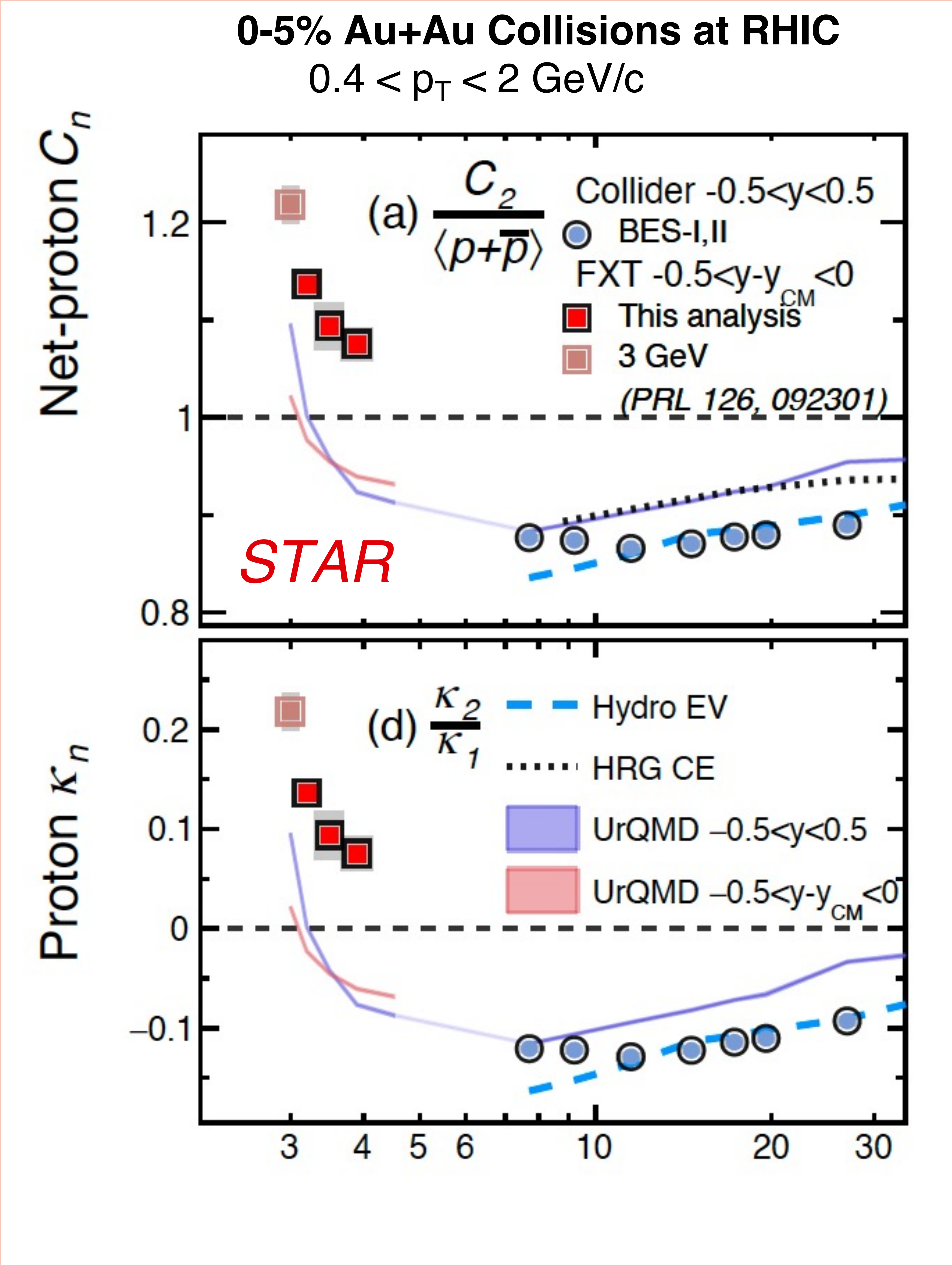

- Fixed-target C_2/C_1 and κ_2/κ_1 monotonically decrease, as predicted by UrQMD

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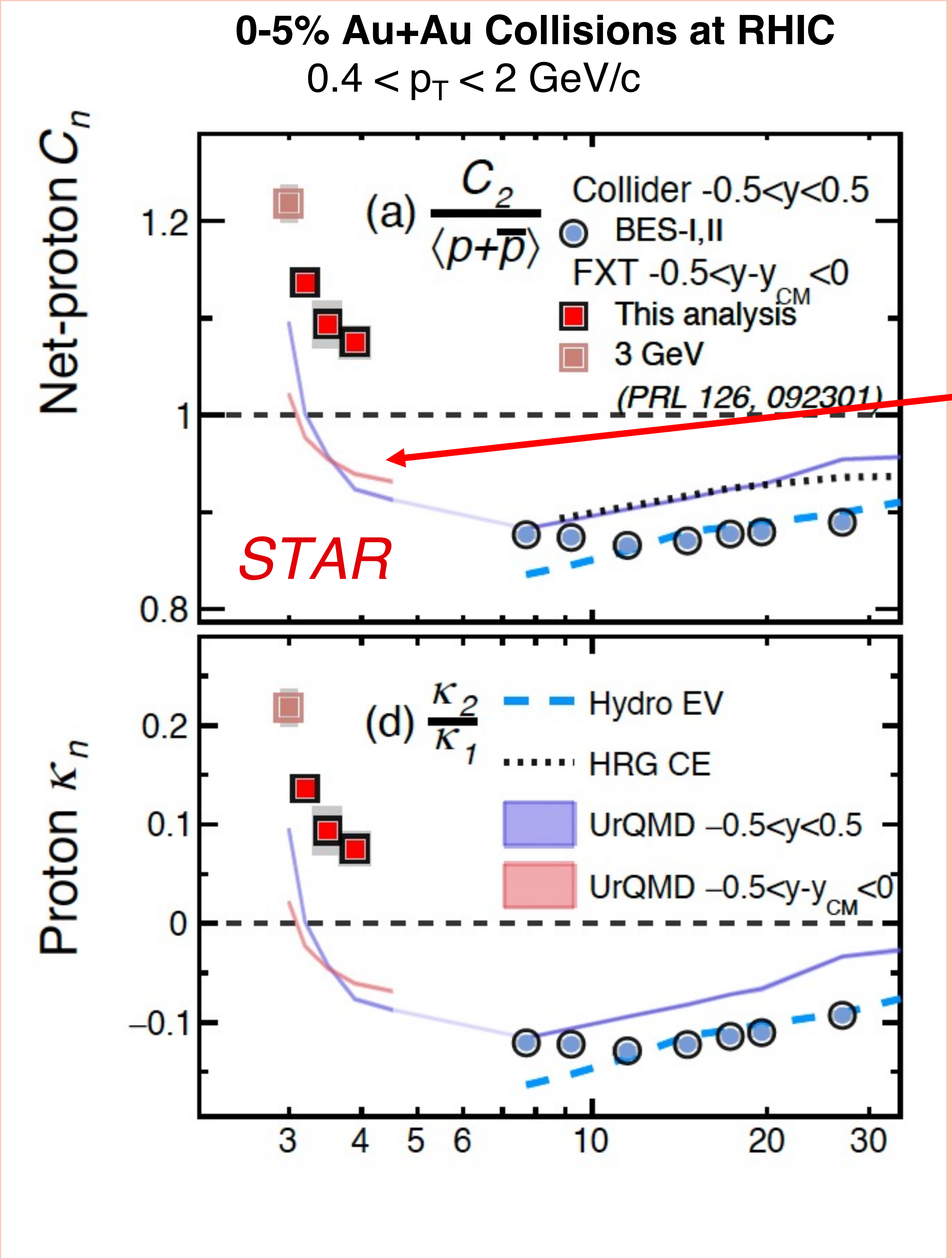

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- Compare against red UrQMD band with half-midrapidity window

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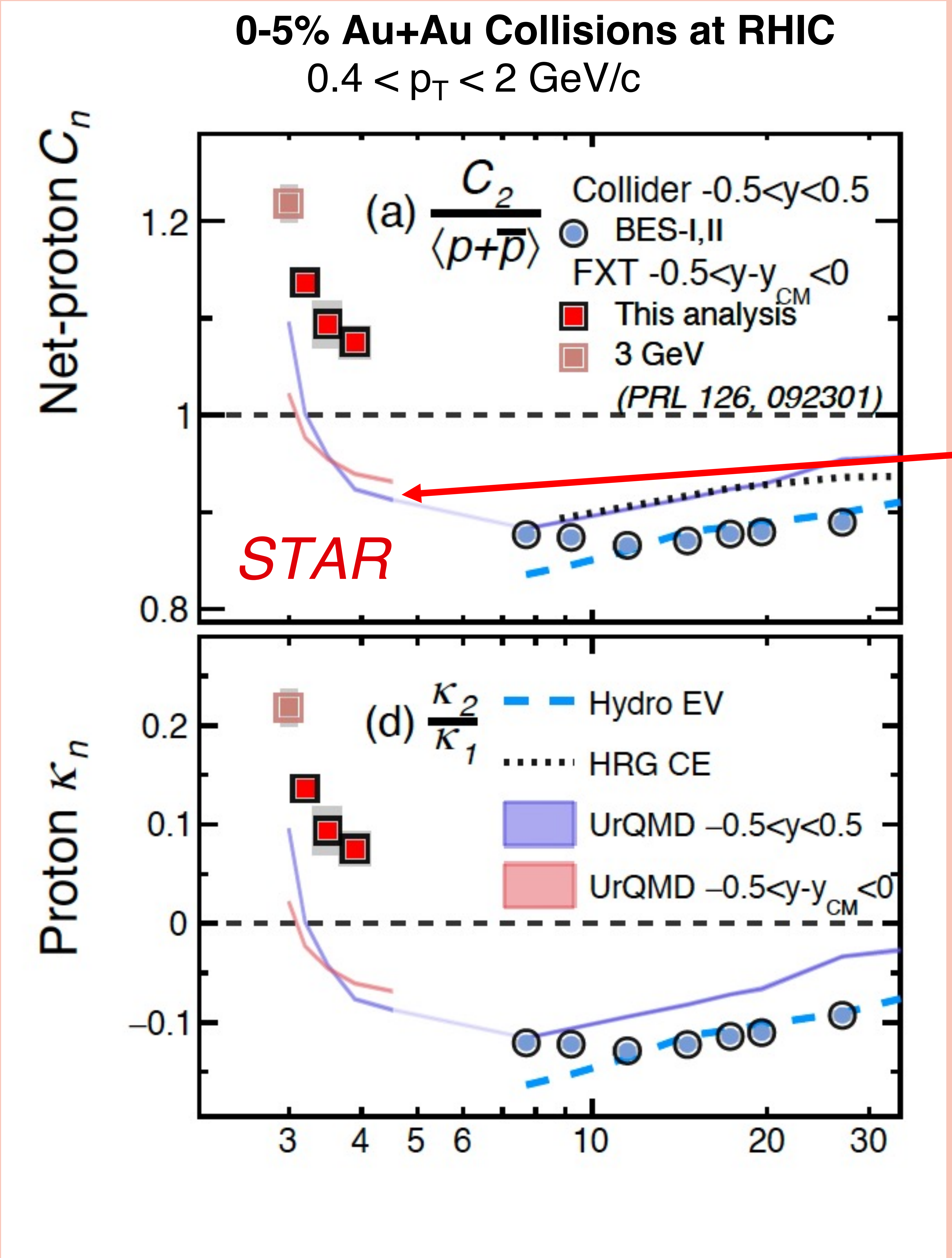

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- Continuation of full midrapidity UrQMD (-0.5<y<0.5) shown in blue

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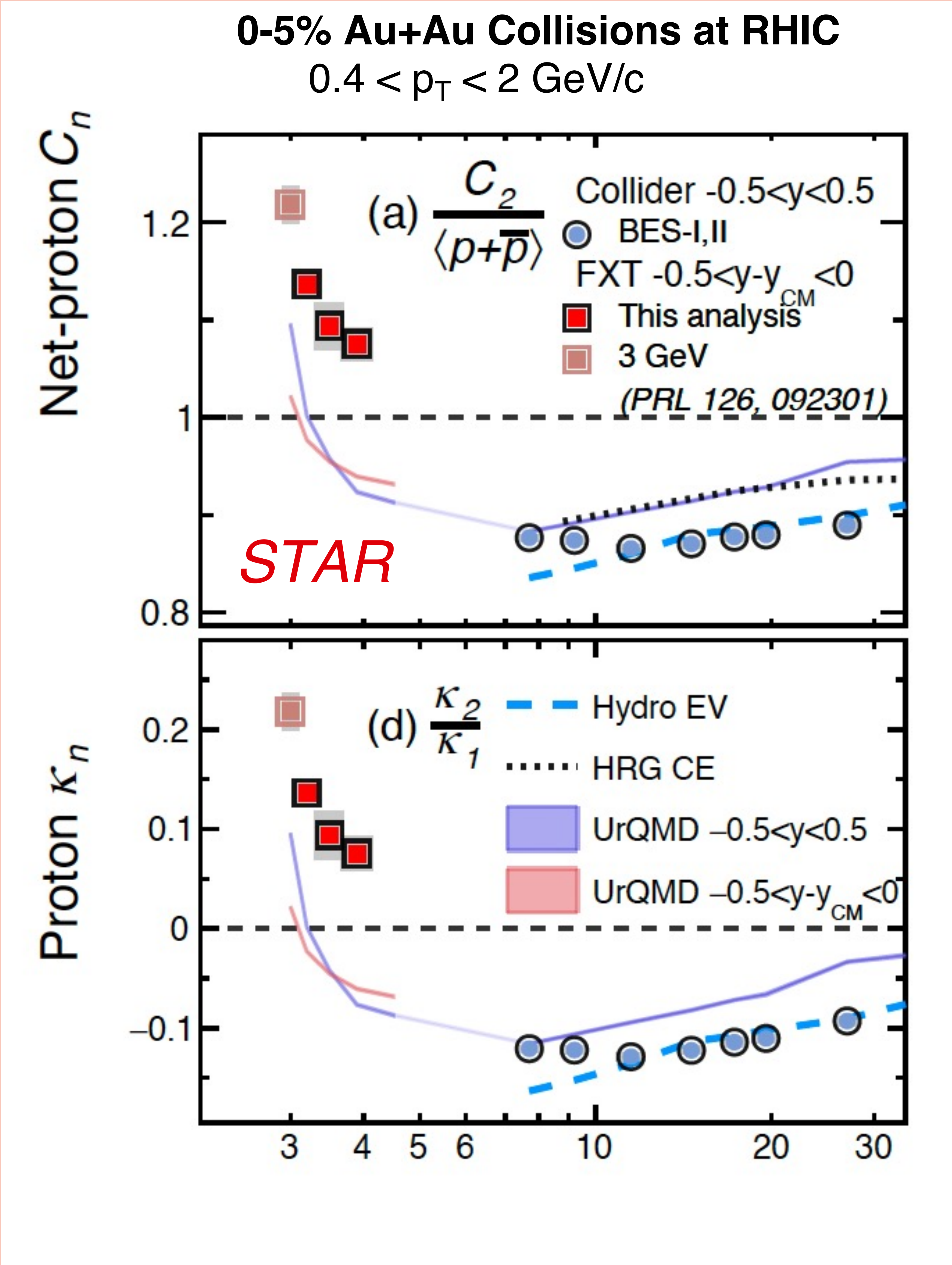

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- Significant enhancement of cumulants above baseline

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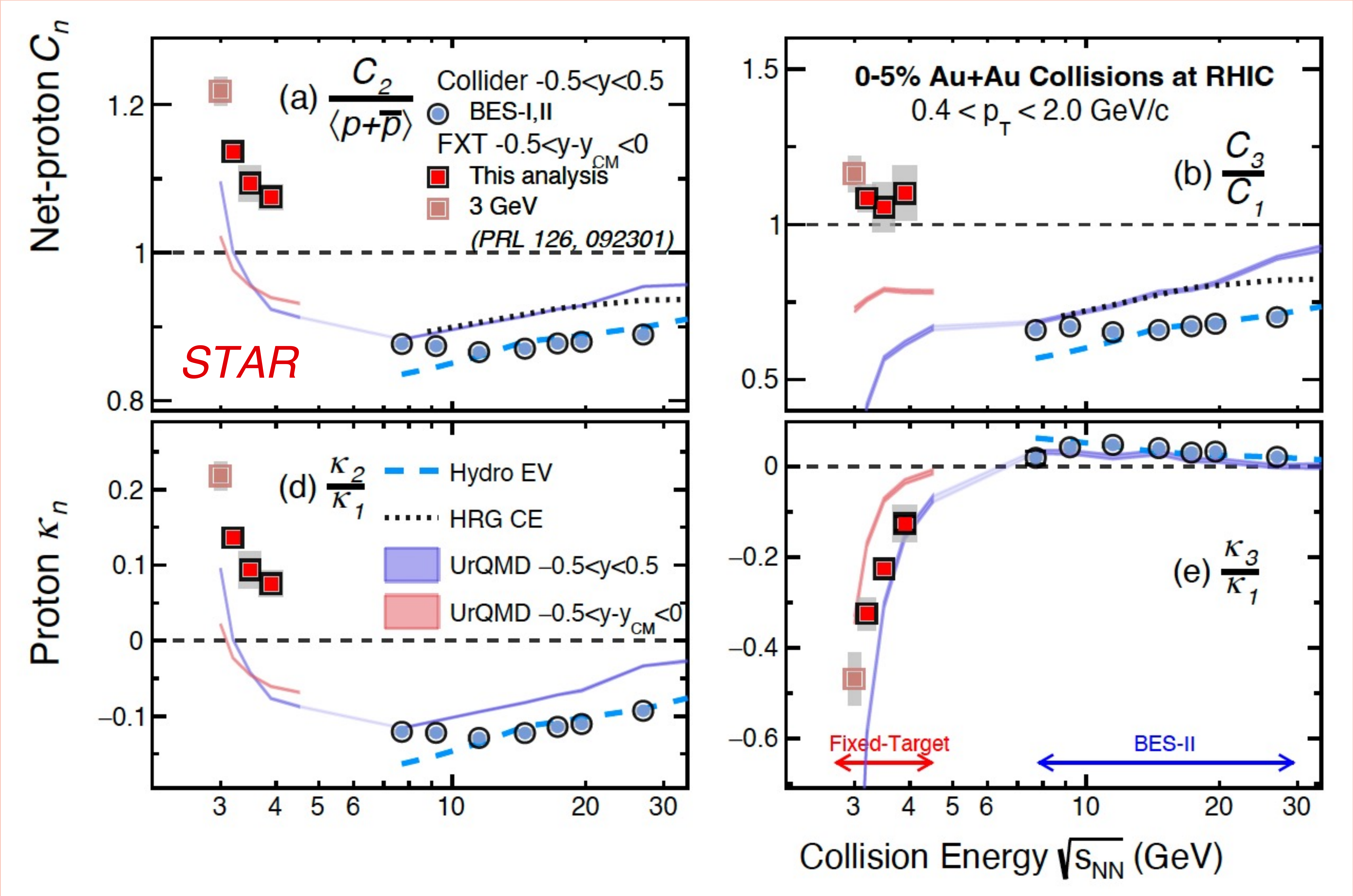

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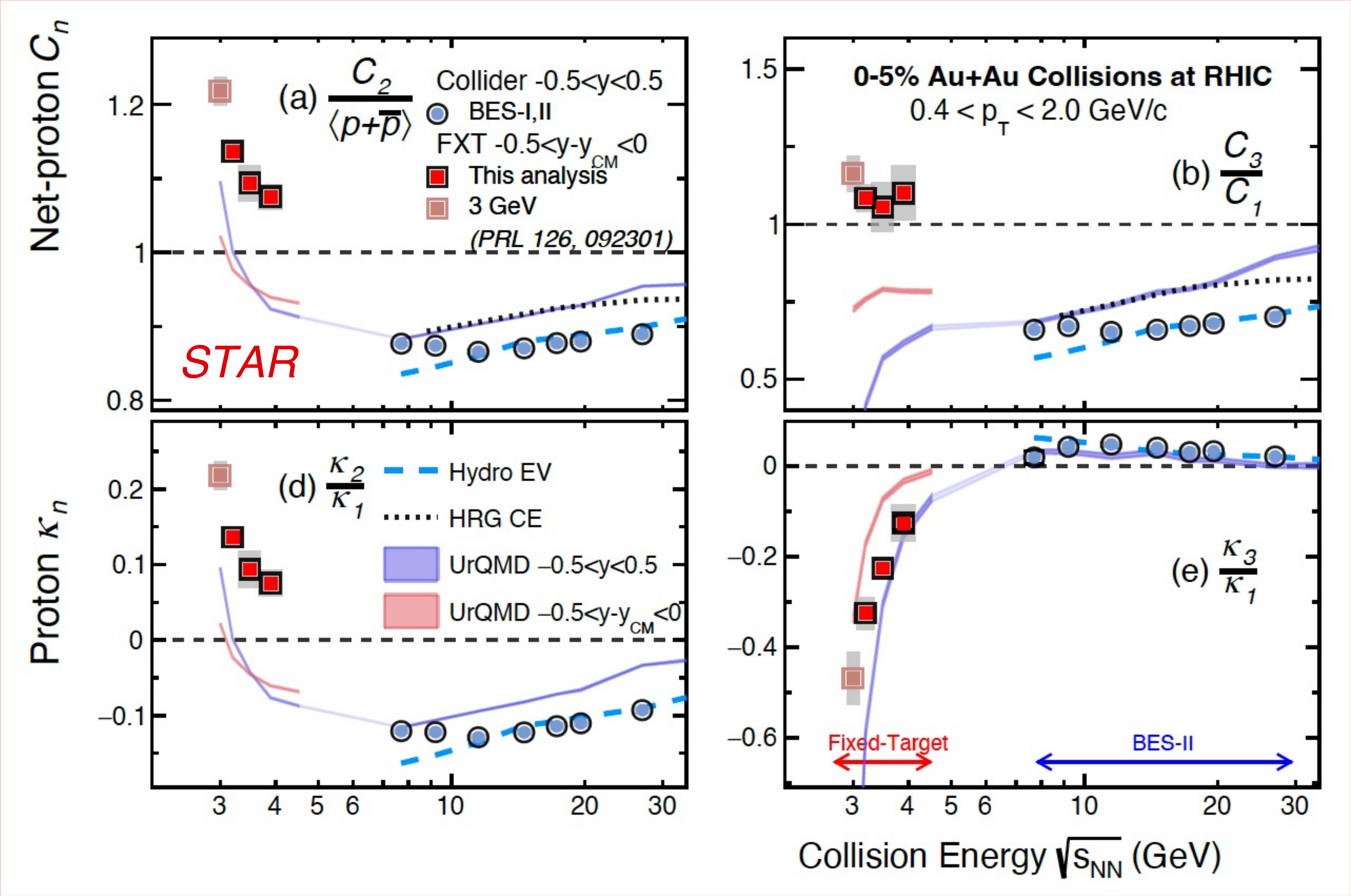
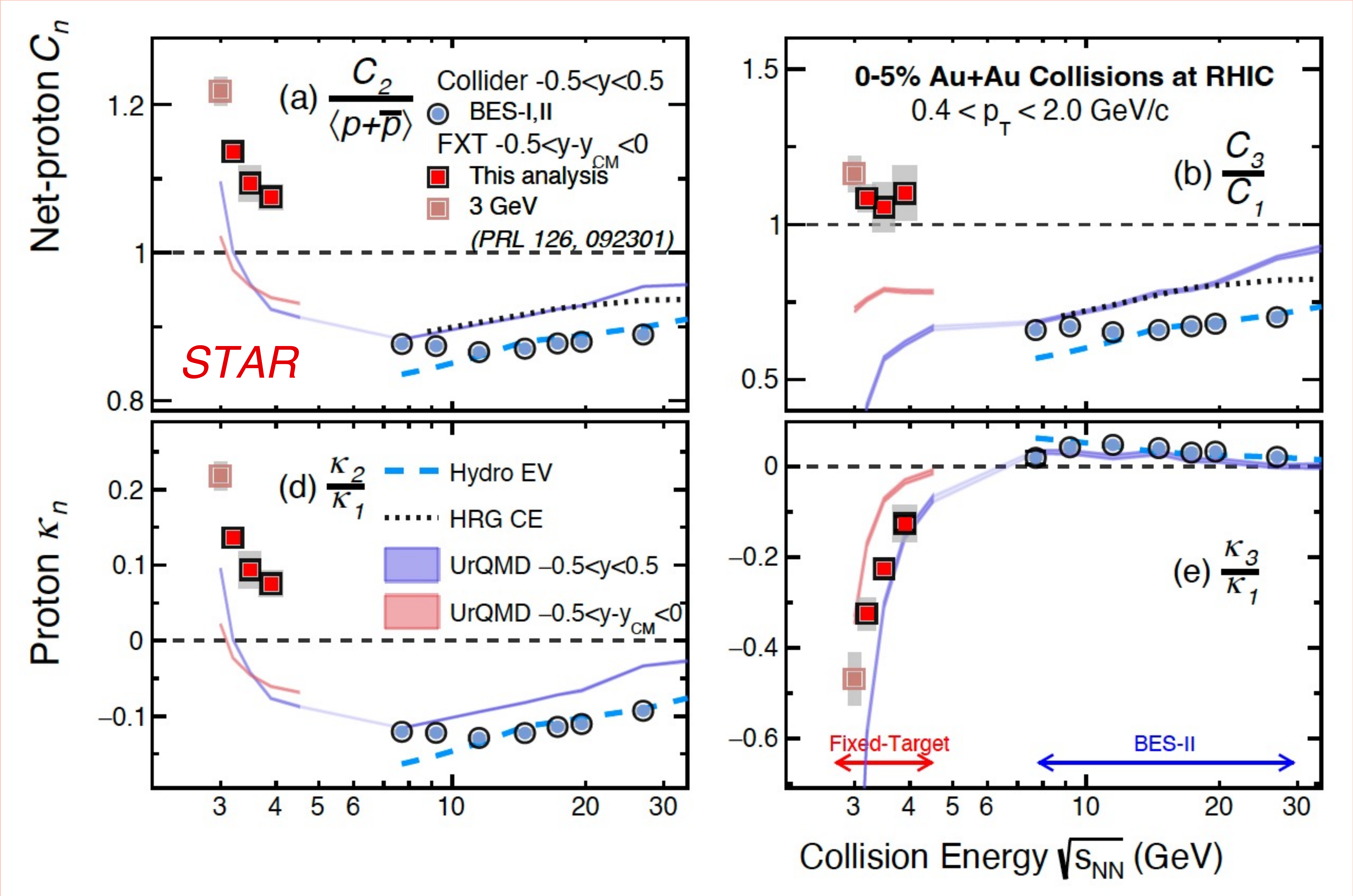


- C_3/C_1 shows no strong energy dependence, similar to UrQMD
- κ_3/κ_1 monotonically increases, as predicted

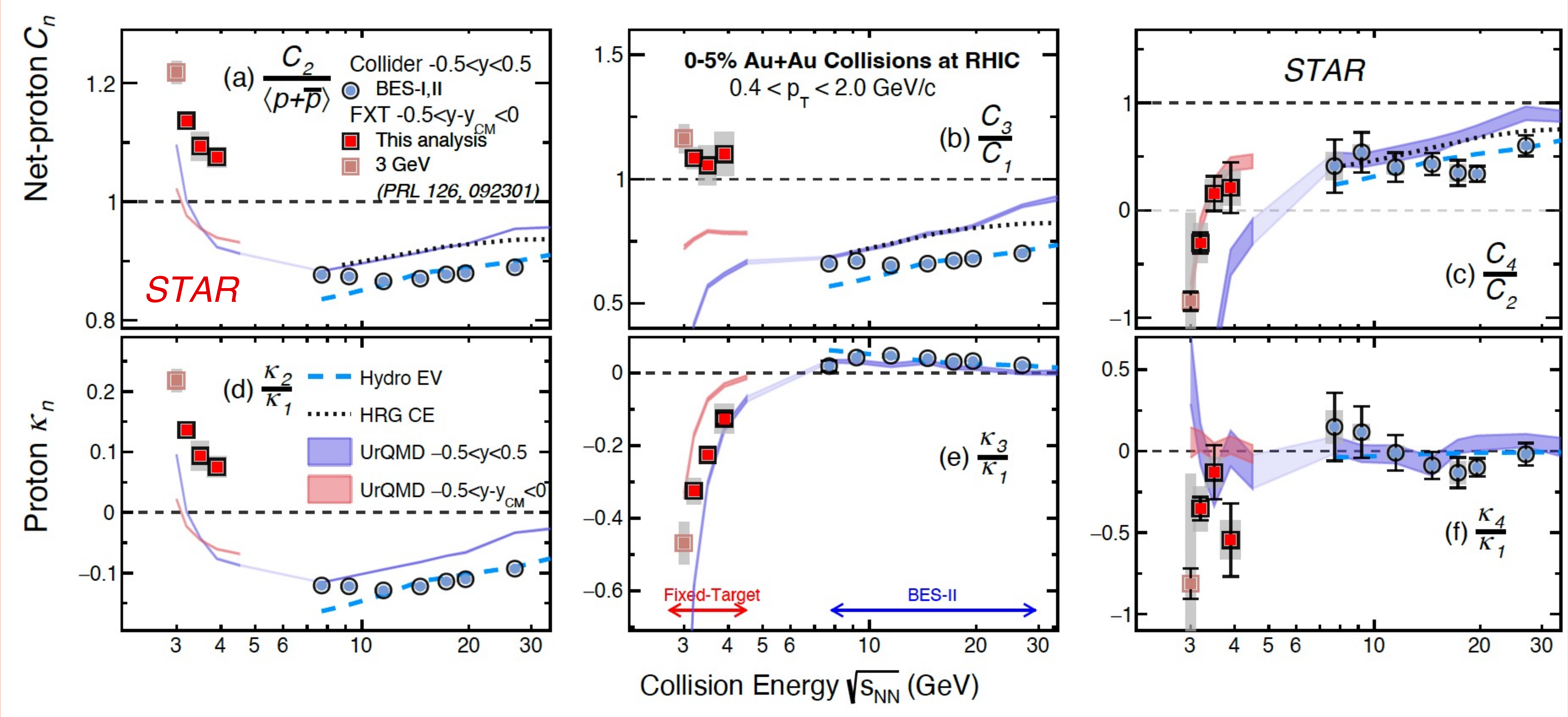
Energy Scan of (Factorial) Cumulants



- C_3/C_1 shows no strong energy dependence, similar to UrQMD
- κ_3/κ_1 monotonically increases, as predicted
- Significant deviations from non-critical baseline at C_3/C_1 and κ_3/κ_1

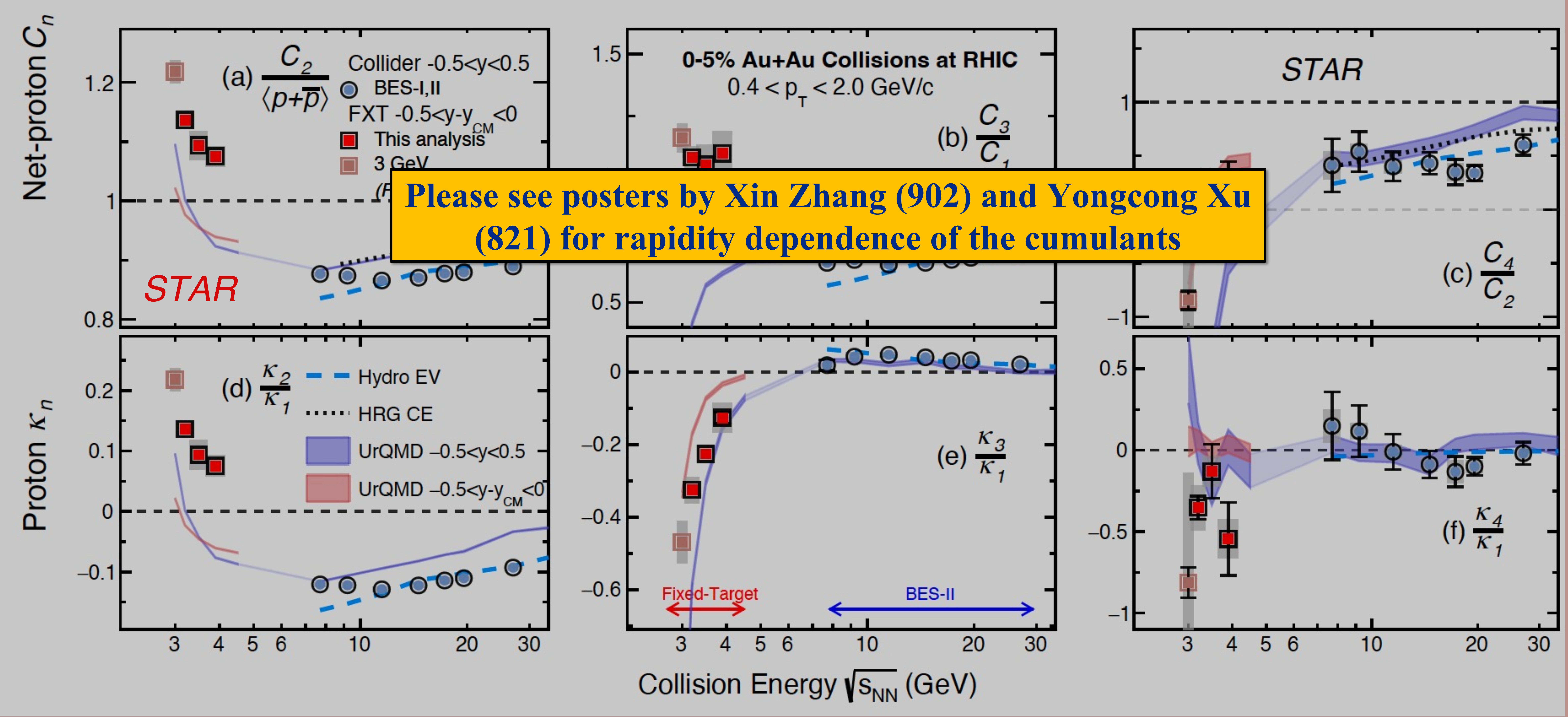
Energy Scan of (Factorial) Cumulants

- C_4/C_2 right on baseline
- κ_4/κ_1 shows no strong energy dependence within uncertainties



Energy Scan of (Factorial) Cumulants

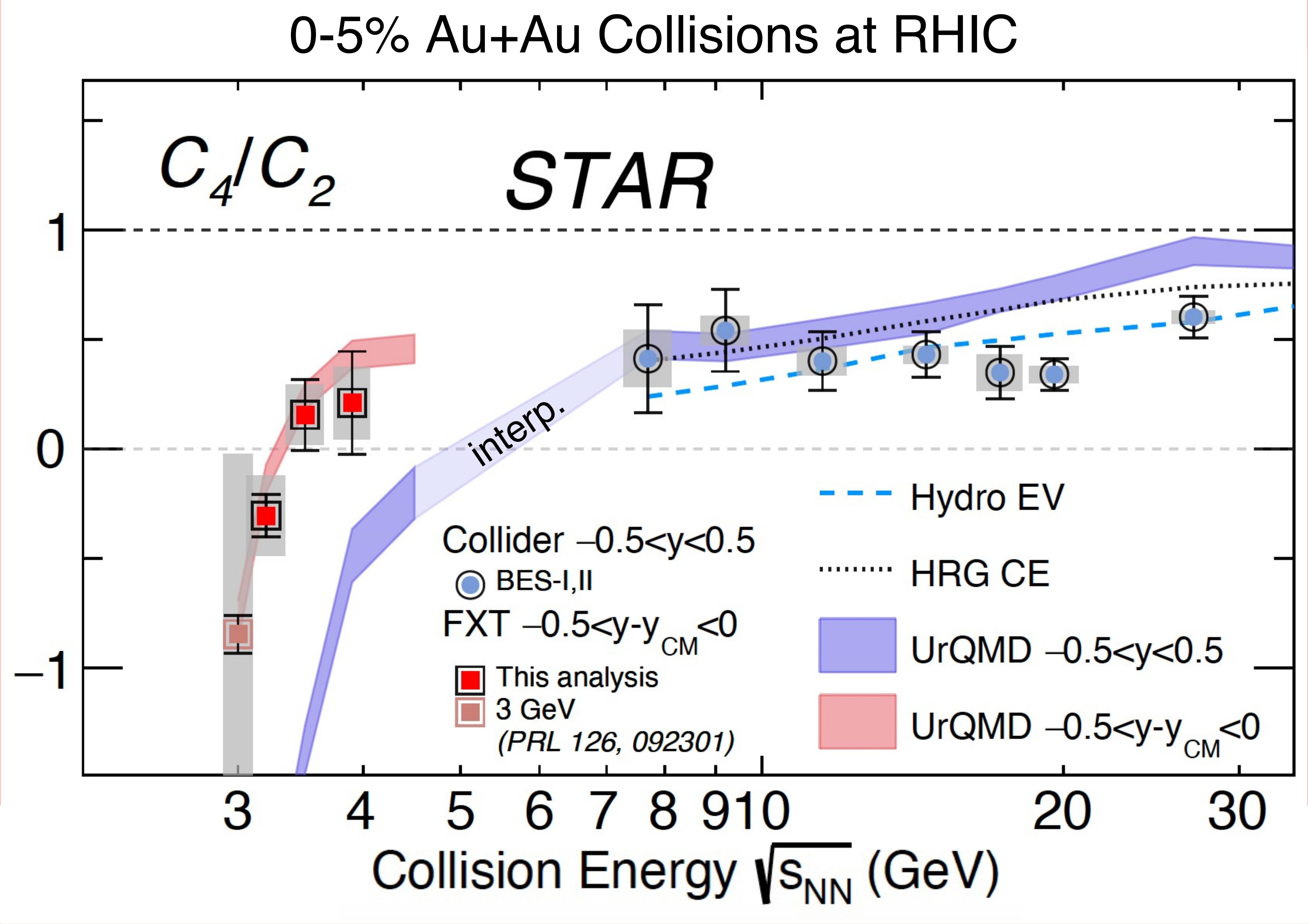
- C_4/C_2 right on baseline
- κ_4/κ_1 shows no strong energy dependence within uncertainties



Please see posters by Xin Zhang (902) and Yongcong Xu (821) for rapidity dependence of the cumulants

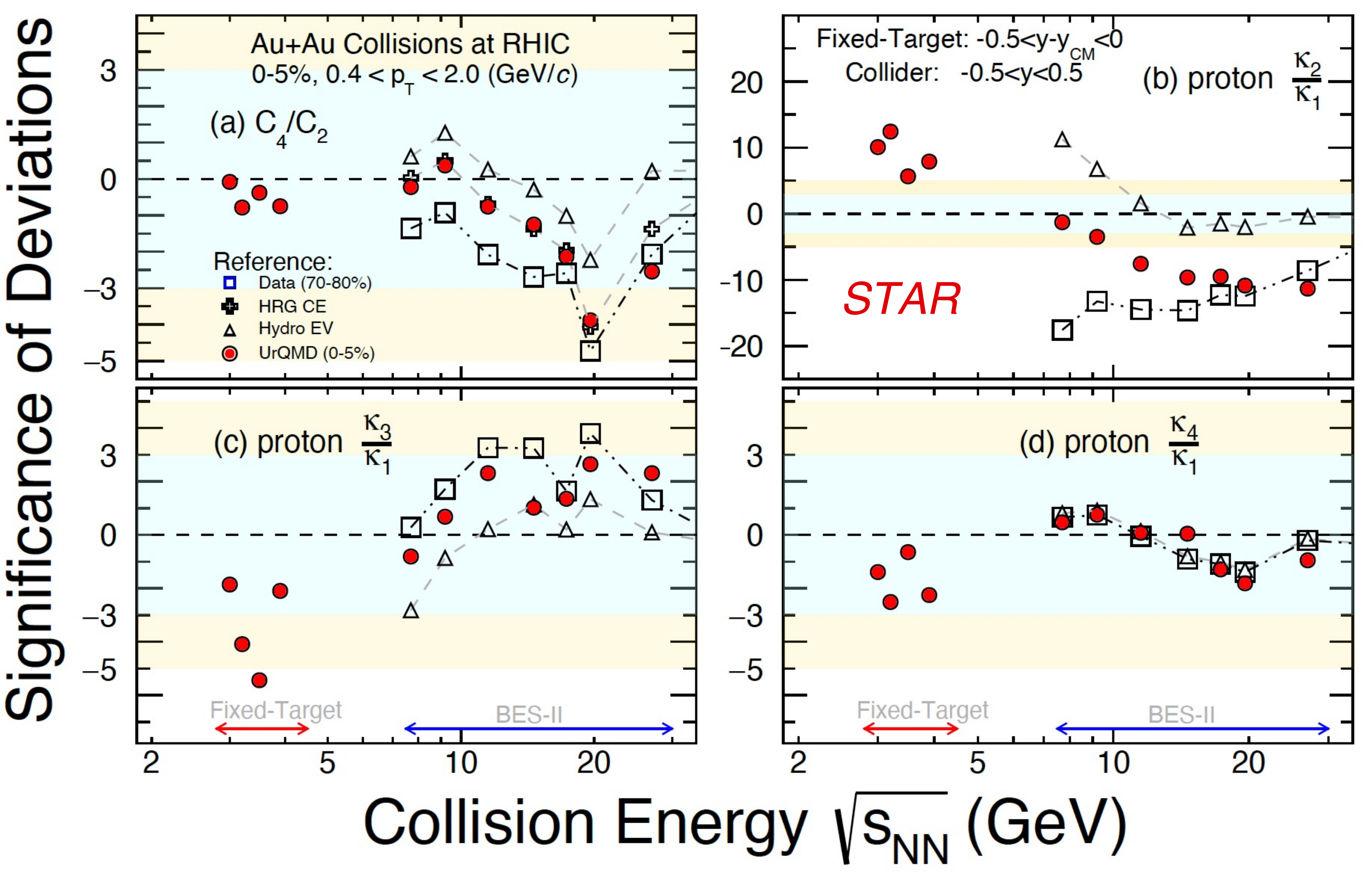
Energy Scan of C_4/C_2

- Central C_4/C_2 is consistent with UrQMD $-0.5<y-y_{CM}<0$
- Systematics are greatly reduced relative to 3.0 GeV (*PRL 126, 092301*)



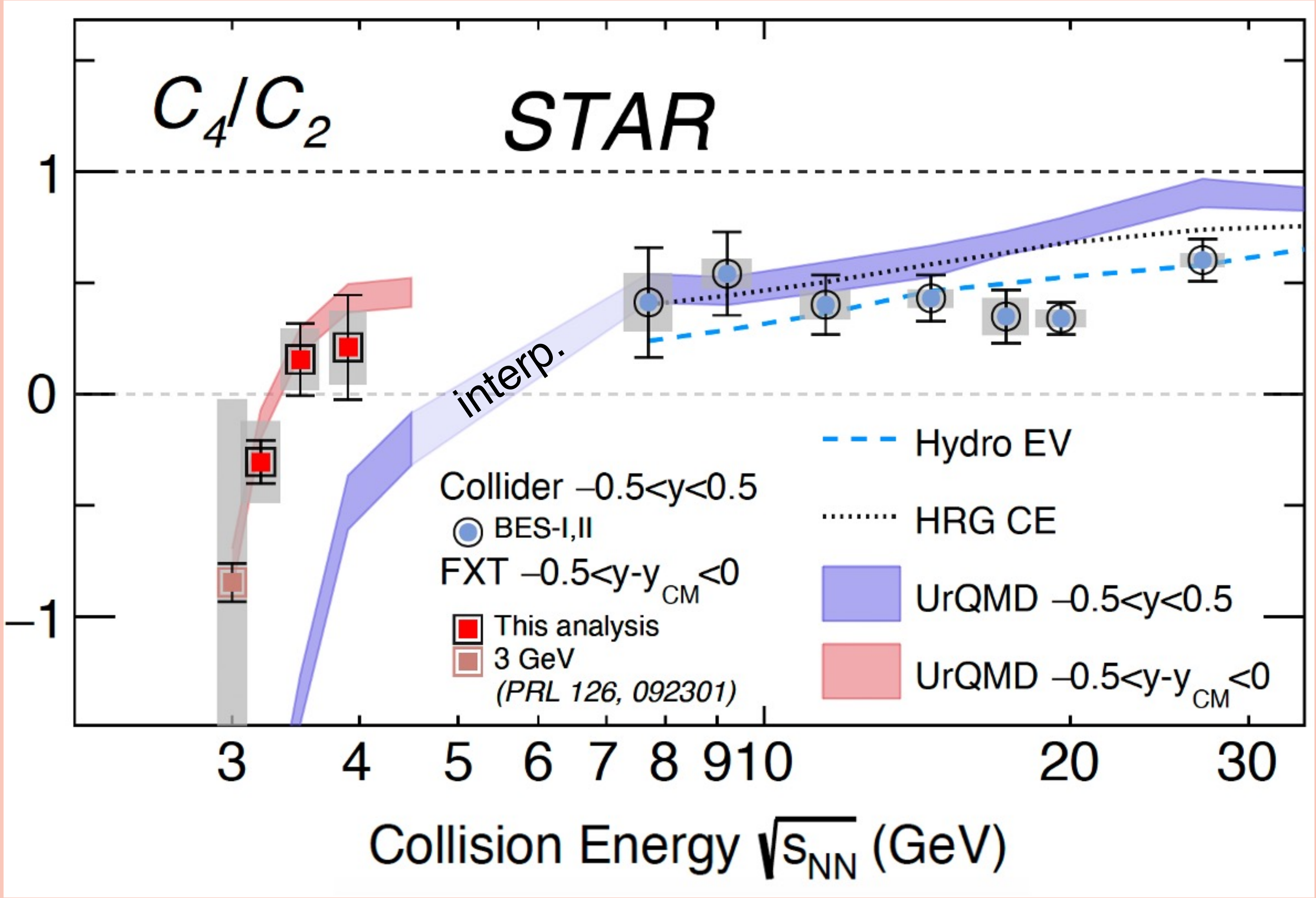
Significance of STAR Fixed-Target Results

- Fixed-Target results have most significant deviations at κ_2/κ_1 and κ_3/κ_1
- Fourth-order deviations are $<3\sigma$



Conclusions

- STAR has measured central proton high-order (factorial) cumulants moments up to fourth order in fixed-target Au+Au collisions at 3.2, 3.5, and 3.9 GeV
- Systematic uncertainty at C_4/C_2 is greatly reduced compared with the published 3 GeV result
  - Central C_4/C_2 is consistent with non-critical UrQMD baseline
  - Significant deviations observed at other orders
  - Cumulants and factorial cumulants are monotonic or the monotonicity is inconclusive



Outlook

- 3 GeV was re-collected in 2021 after the iTPC upgrade and the addition of ETOF
- Full midrapidity ($-0.5<y-y_{CM}<0.5$) analysis can now be performed at 3 GeV, and systematic uncertainty may be reduced
- STAR may extract high-order cumulants at 4.5 GeV, but with larger acceptance gaps
- Interesting behavior at lower orders may be further explored by the CBM experiment at $2.9 - 4.9$ GeV

Thank you!