Precision Measurement of Net-proton Number Fluctuations in Au+Au Collisions at RHIC

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University of Science and Technology of China

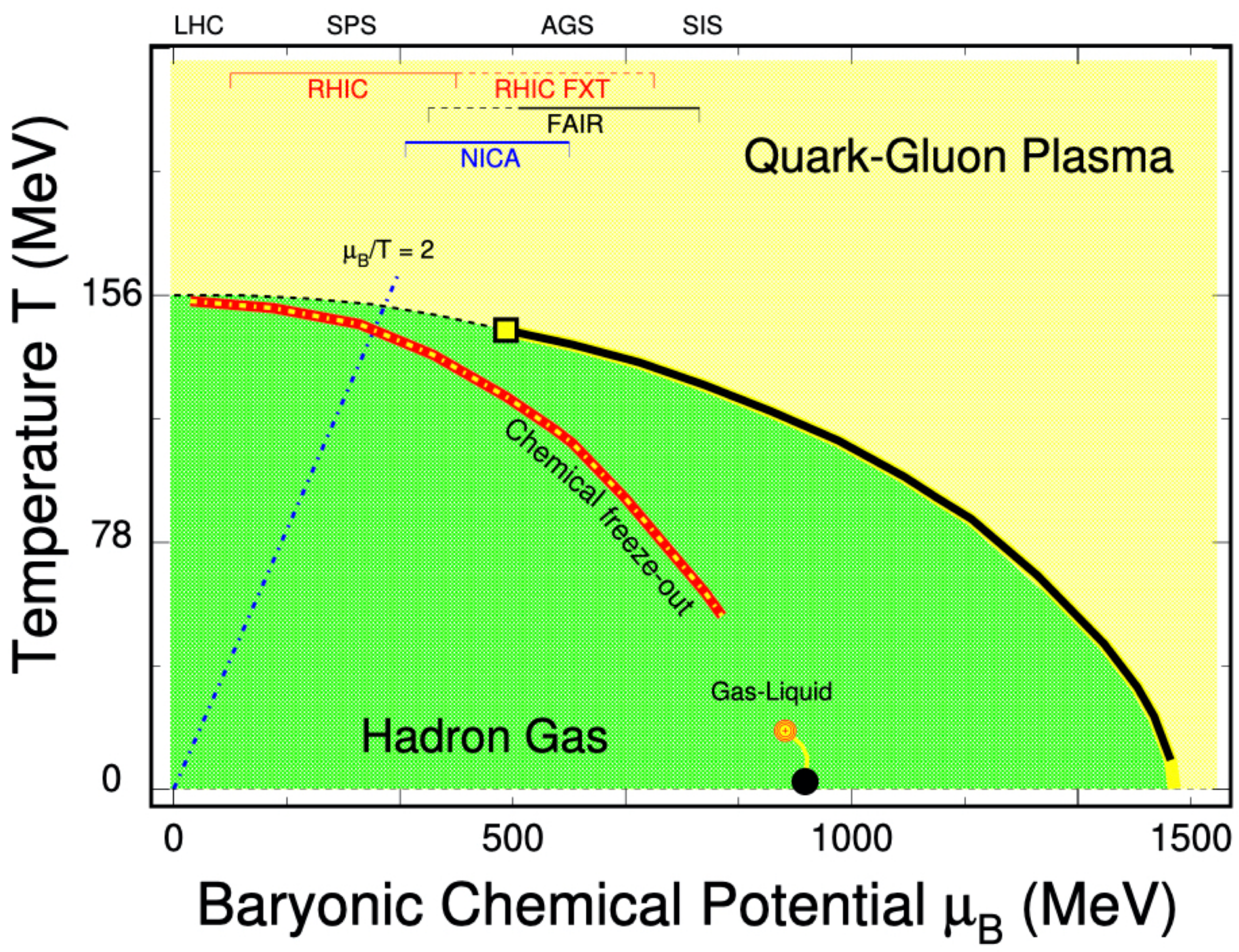
Outline

- Introduction
- Experimental analysis
- Results from BES-II
- Summary and outlook

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France

SQM, June 6, 2024

Introduction: QCD Phase Diagram



Phase diagram of strongly interacting matter

B. Mohanty, N. Xu, arXiv:2101.09210

Key features of phase structure:

- QGP and hadronic phase
- Crossover at small μ_B $(\frac{\mu_B}{T} < 2)$ – compatible to all experimental observations.
- Transition temperature (T_C~156 MeV) – Lattice QCD and verified by exp. chemical freeze-out.
- 1st order phase transition at large μ_B and **critical end point (CEP)** are conjectured.

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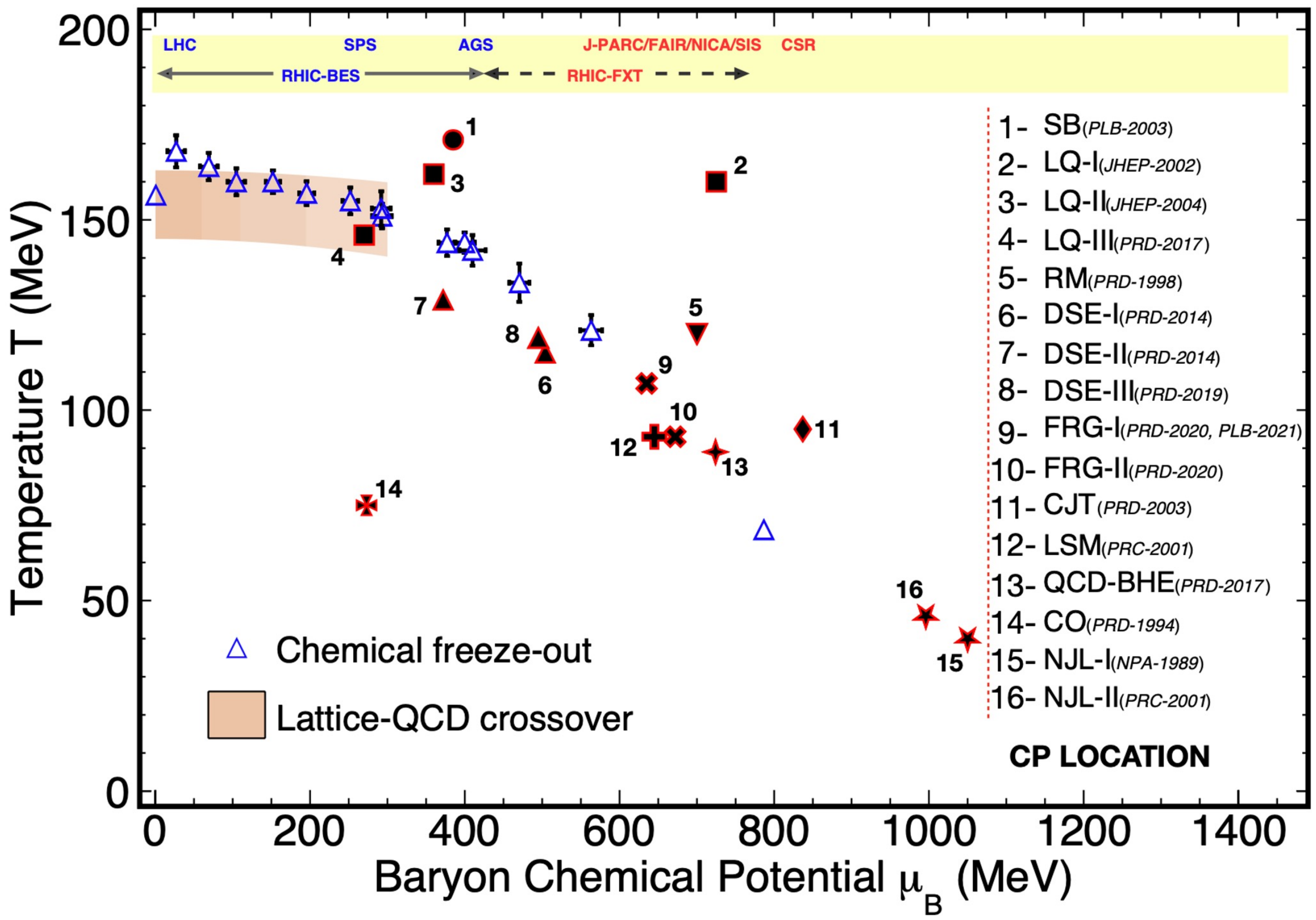

A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

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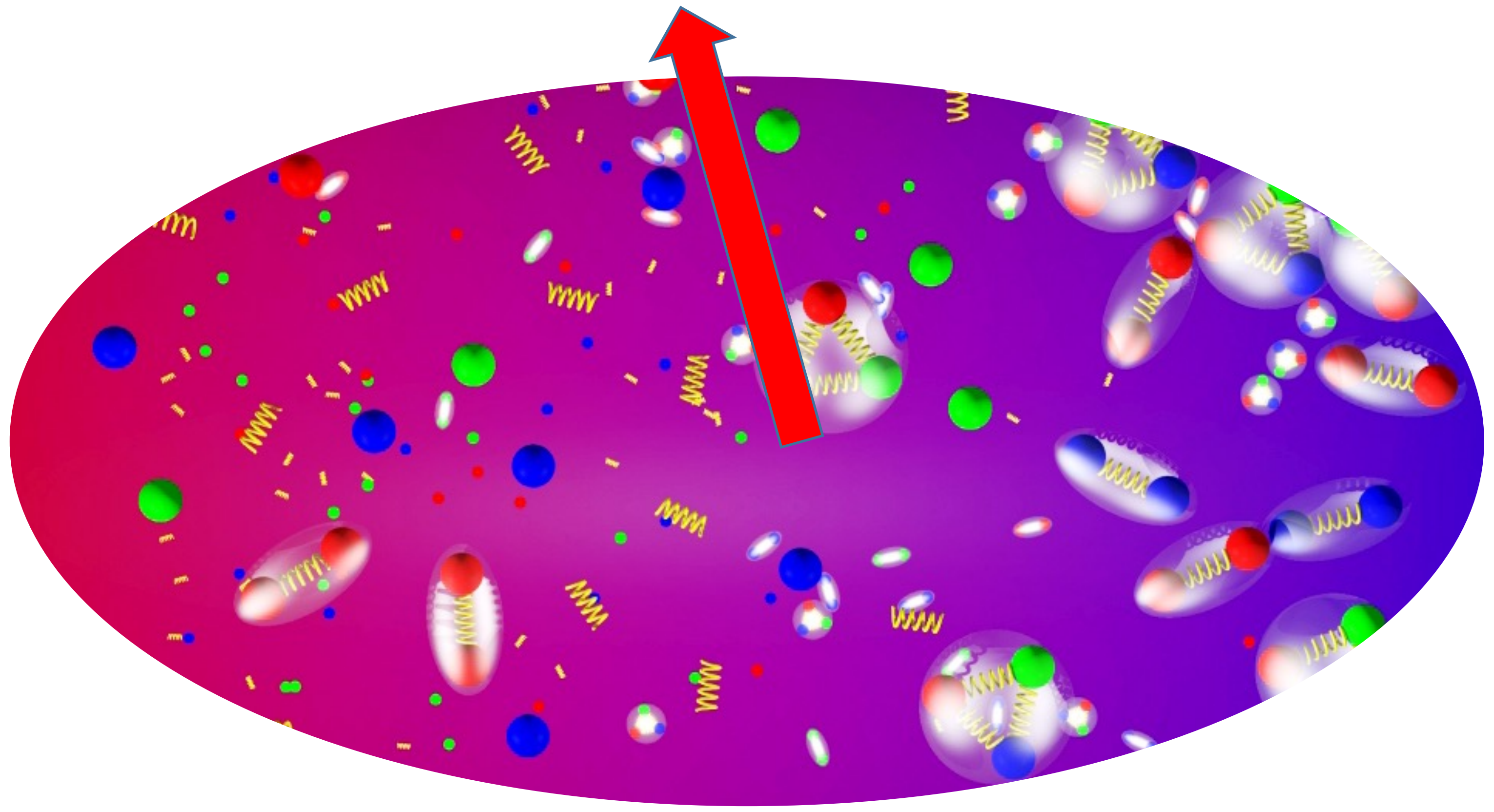
  Sign problem in Lattice QCD at finite μ_B

  Large uncertainties from models to locate the CEP.

Experimentally searching and locating CEP is crucial.

Introduction: Observables

At CEP: correlation length: ξ susceptibilities: χ_n^q **expected to diverge**



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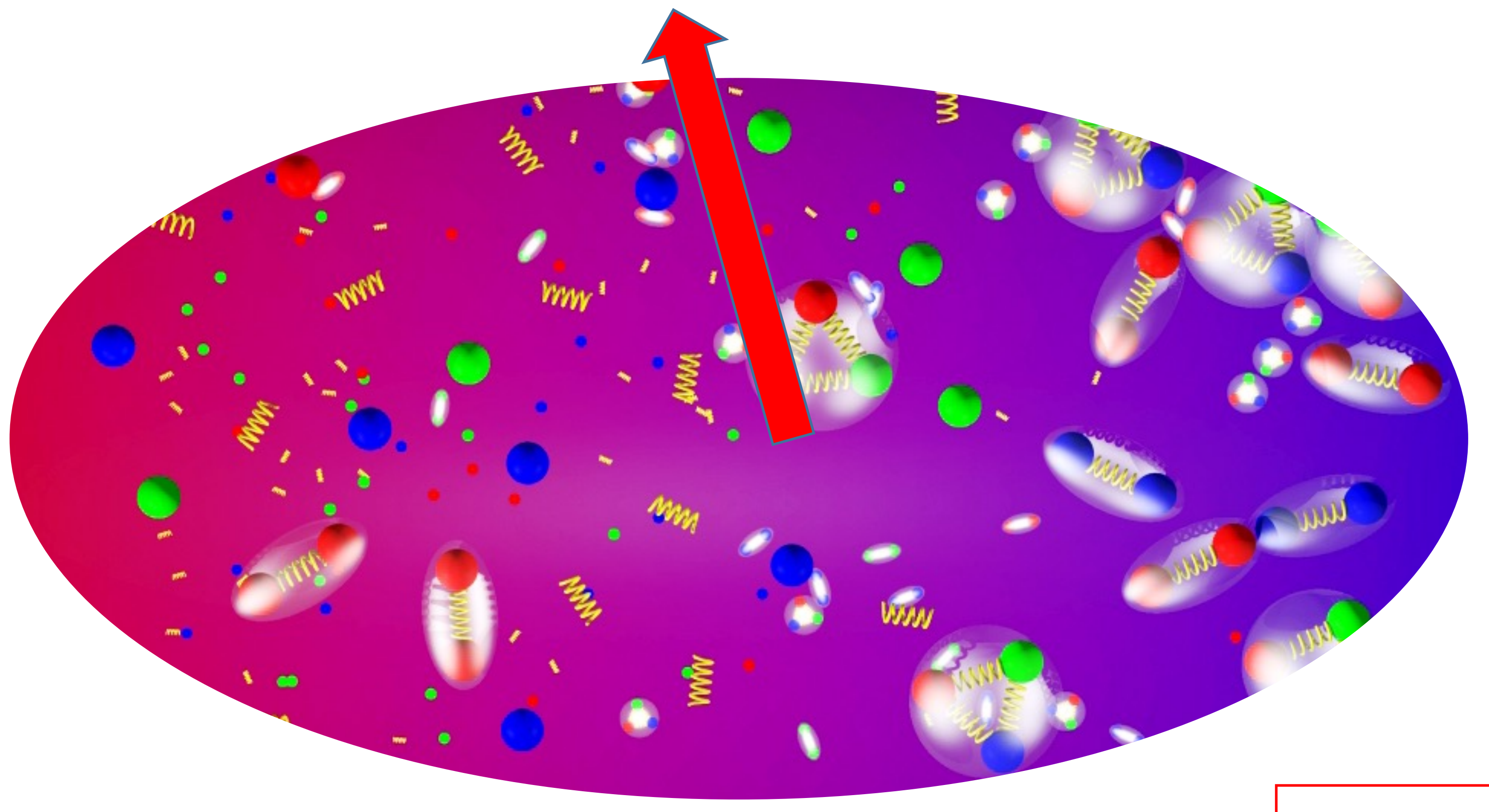
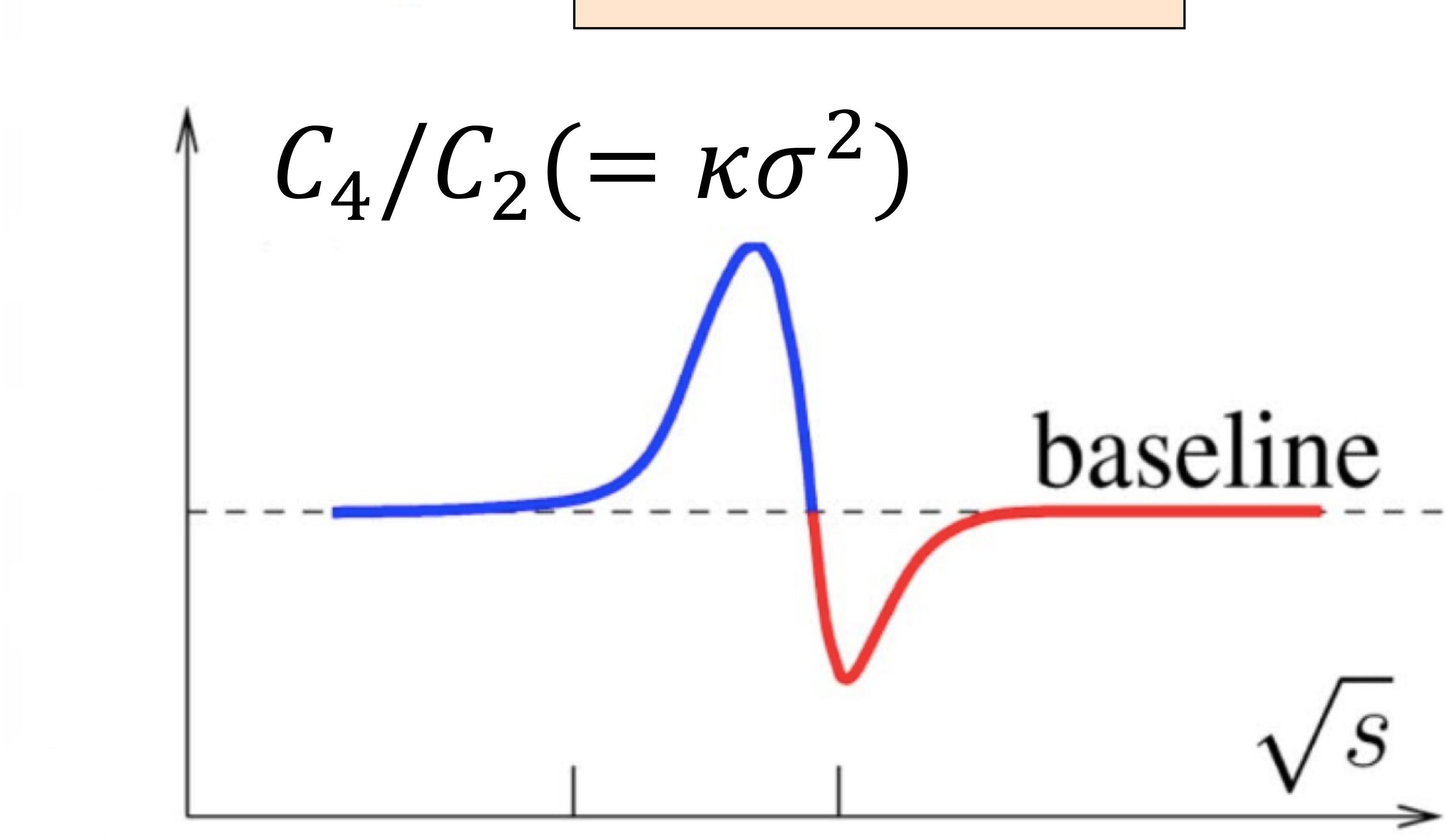


CEP search



M. A. Stephanov, PRL 107 (2011) 052301

$C_2 \sim \xi^2, C_4 \sim \xi^7$

$$\frac{C_{4q}}{C_{2q}} = \frac{\chi_4^q}{\chi_2^q}, \frac{C_{6q}}{C_{2q}} = \frac{\chi_6^q}{\chi_2^q}$$

$q = B, Q, S$

Allow the signal measurable

- Finite size/time effects reduces ξ
  Higher order ➡ more sensitivity
- Direct comparison with lattice QCD, HRG, QCD-based model calculations

Assumption: Thermodynamic equilibrium

Non-monotonic energy dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

R.V. Gavai and S. Gupta, PLB696, 459(11)
S. Ejiri, F. Karsch, K. Redlich, PLB633, 275(06)
A. Bazavov et al., PRL109, 192302(12)
*S. Borsanyi et al., PRL**111**, 062005(13)*

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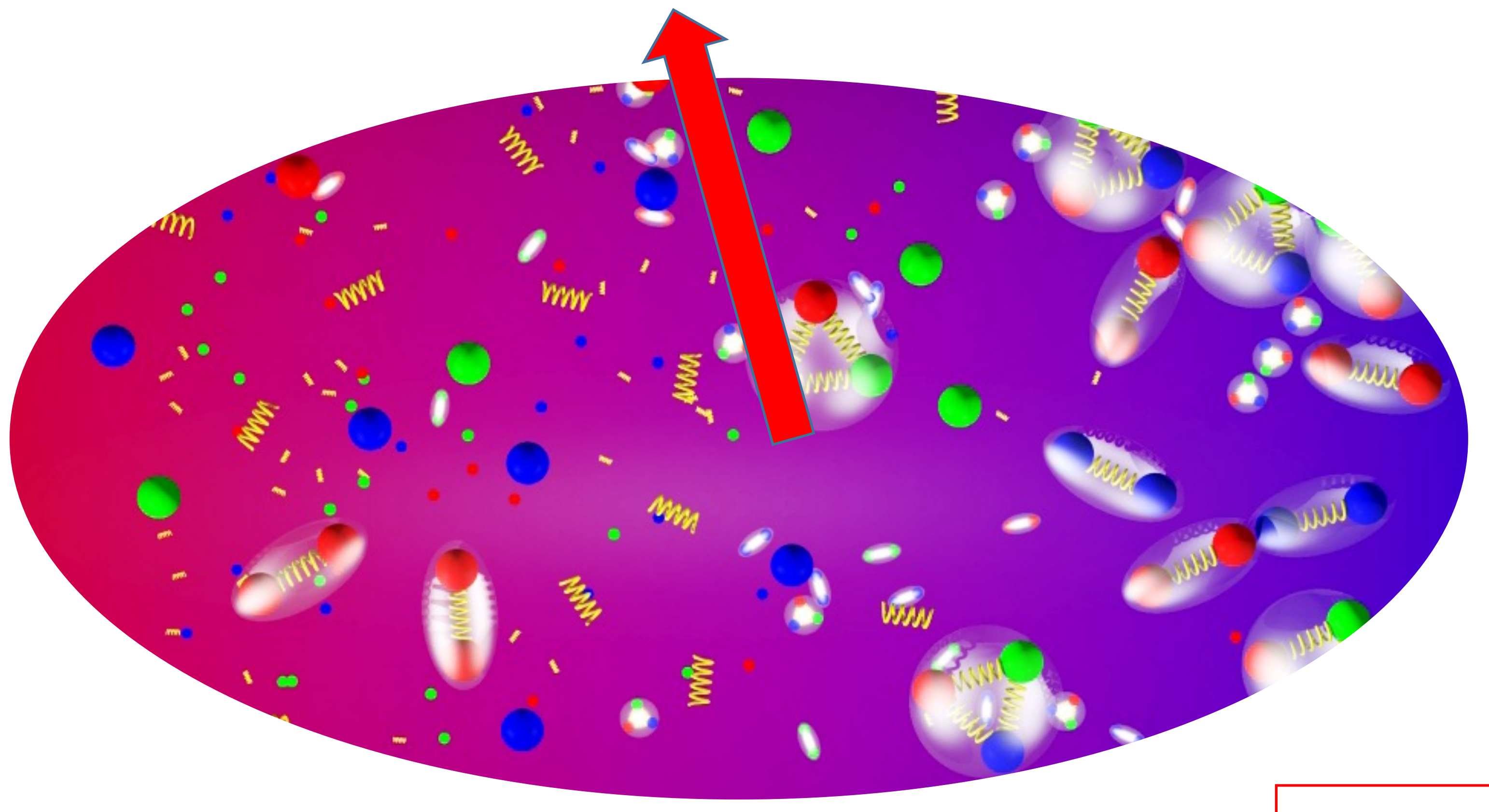

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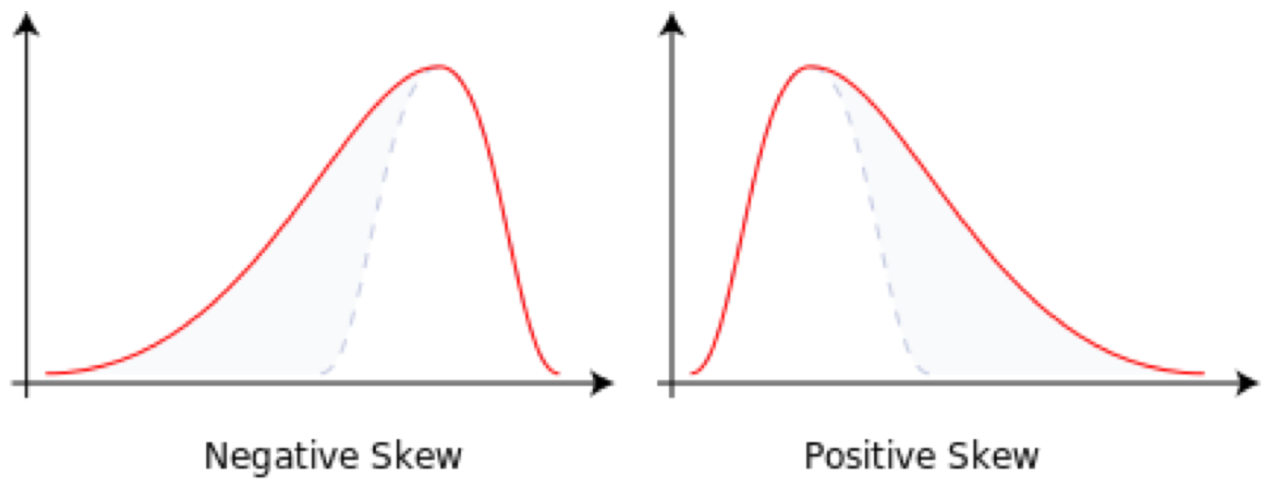
Cumulants

$n =$ *E-by-E net-proton multiplicity*

$C_1 = < n >$
$C_2 = < \delta n^2 >$ $\quad$ $^*\delta n = n - < n >$
$C_3 = < \delta n^3 >$
$C_4 = < \delta n^4 > - 3 < \delta n^2 >$
$C_5 = < \delta n^5 > - 10 < \delta n^3 > < \delta n^2 >$
$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$

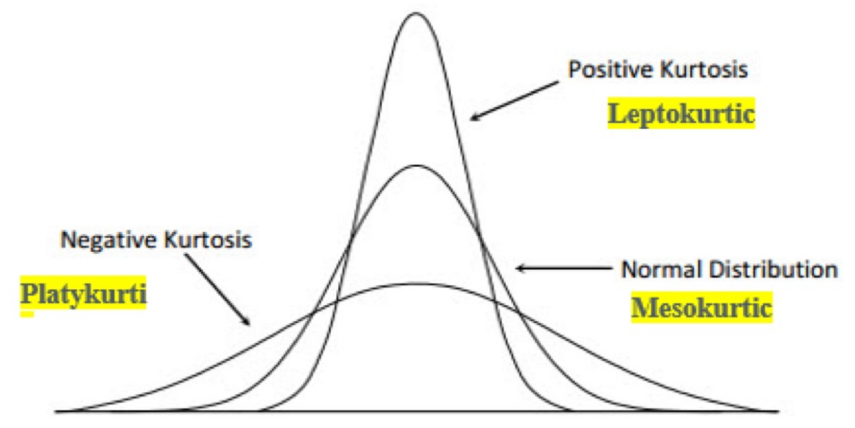
Skewness: Asymmetry

$$S = \langle (\delta N)^3 \rangle / \sigma^3 = C_3/C_2^{3/2}$$



Kurtosis: Peakedness

$$\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 = C_4/C_2^2$$



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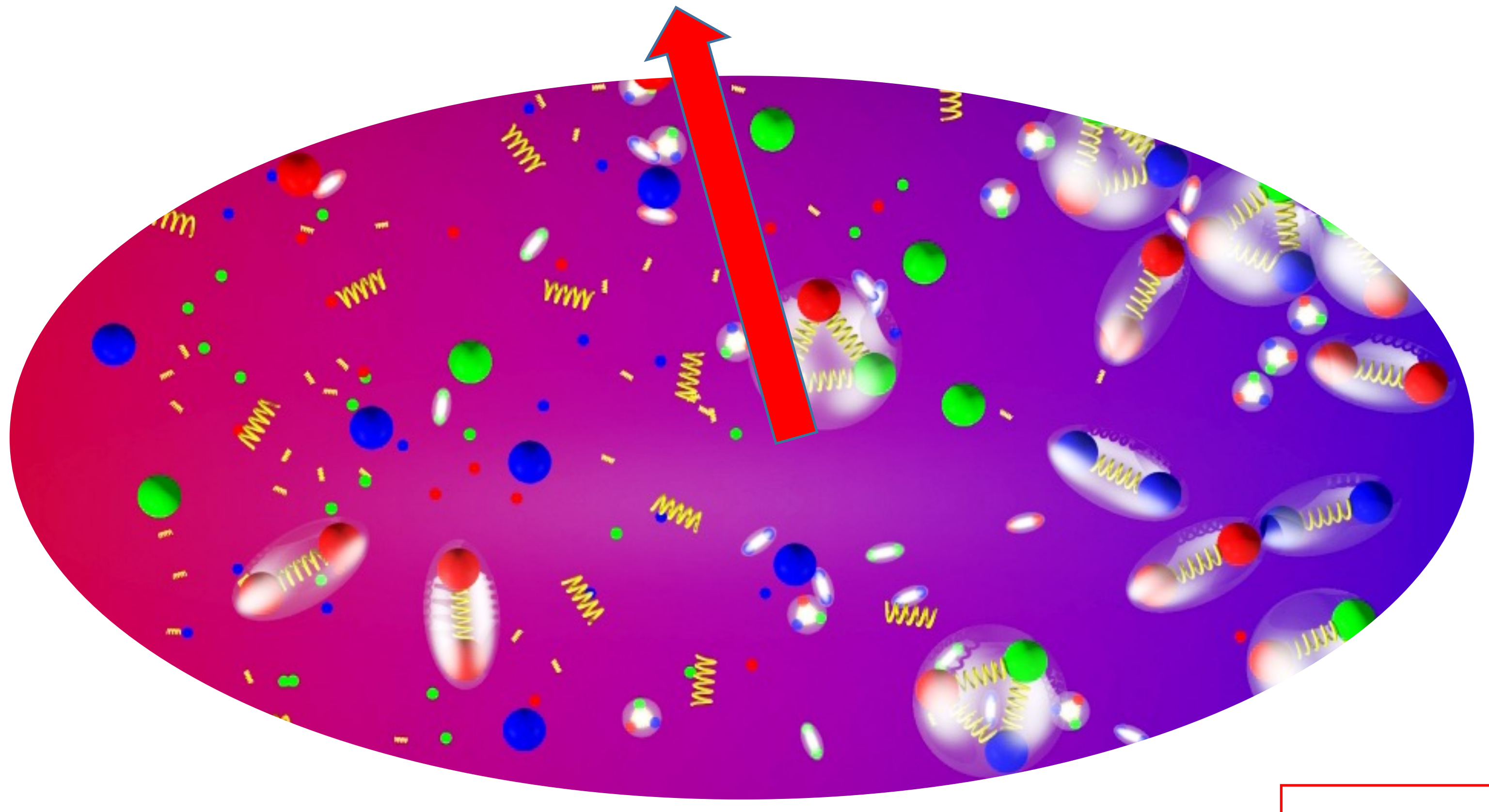

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Factorial cumulants

$n =$ *E-by-E (anti)proton multiplicity*

$\kappa_1 = C_1$

$\kappa_2 = - C_1 + C_2$

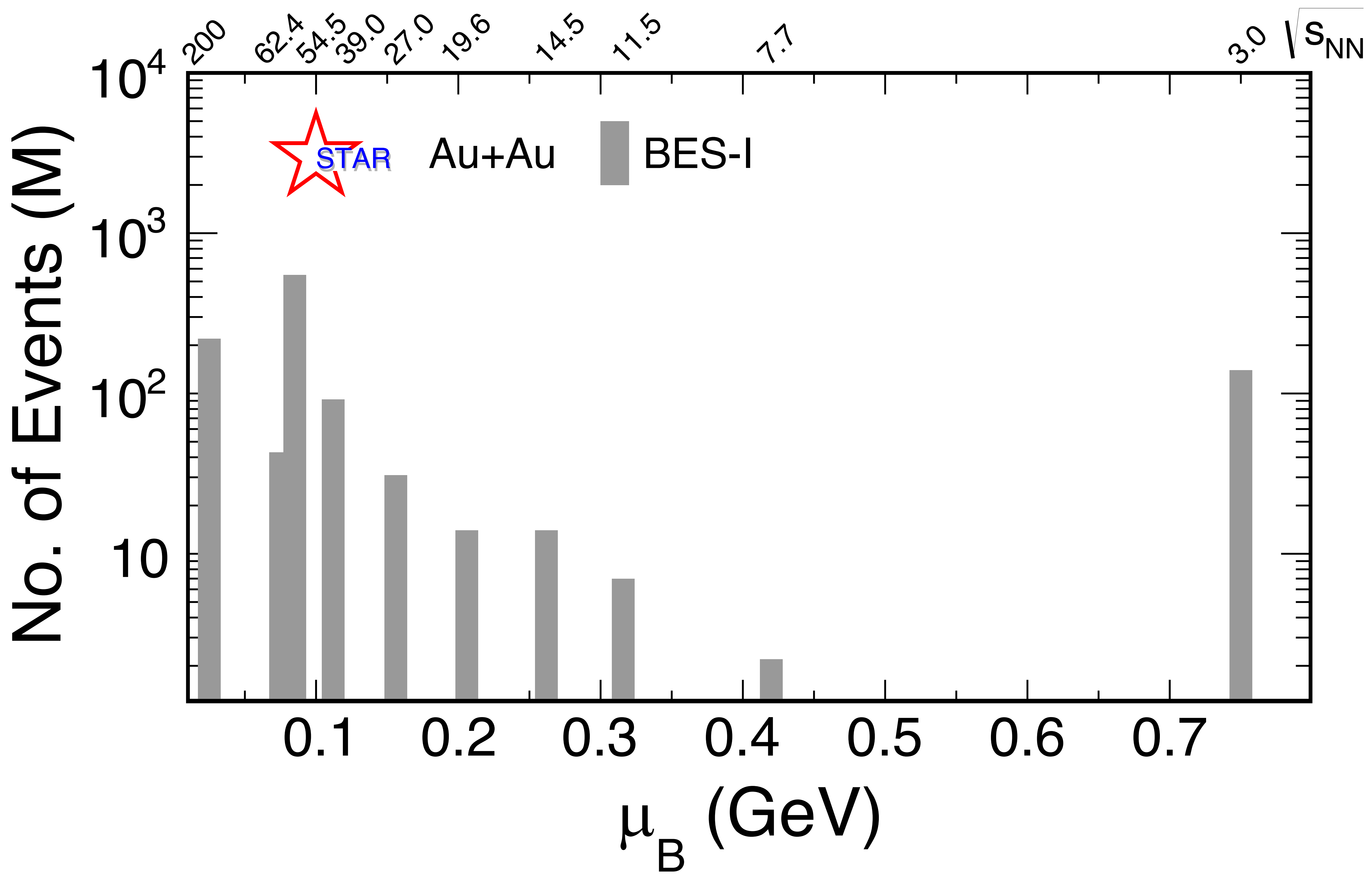
$\kappa_3 = 2C_1 - 3C_2 + C_3$

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

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

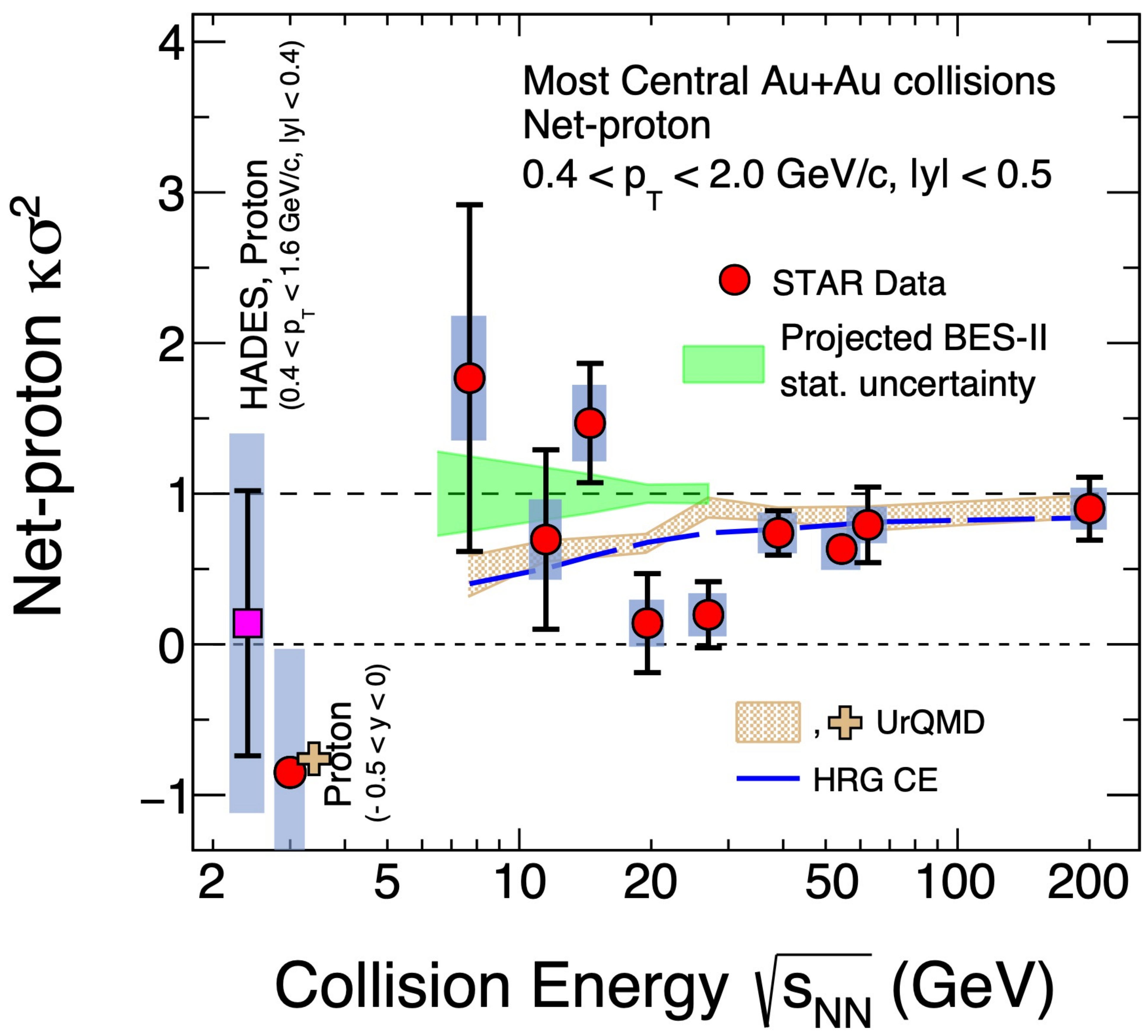
$\kappa_6 = - 120C_1 + 274C_2 - 225C_3 + 85C_4 - 15C_5 + C_6$

Experimental Search for CEP from BES-I



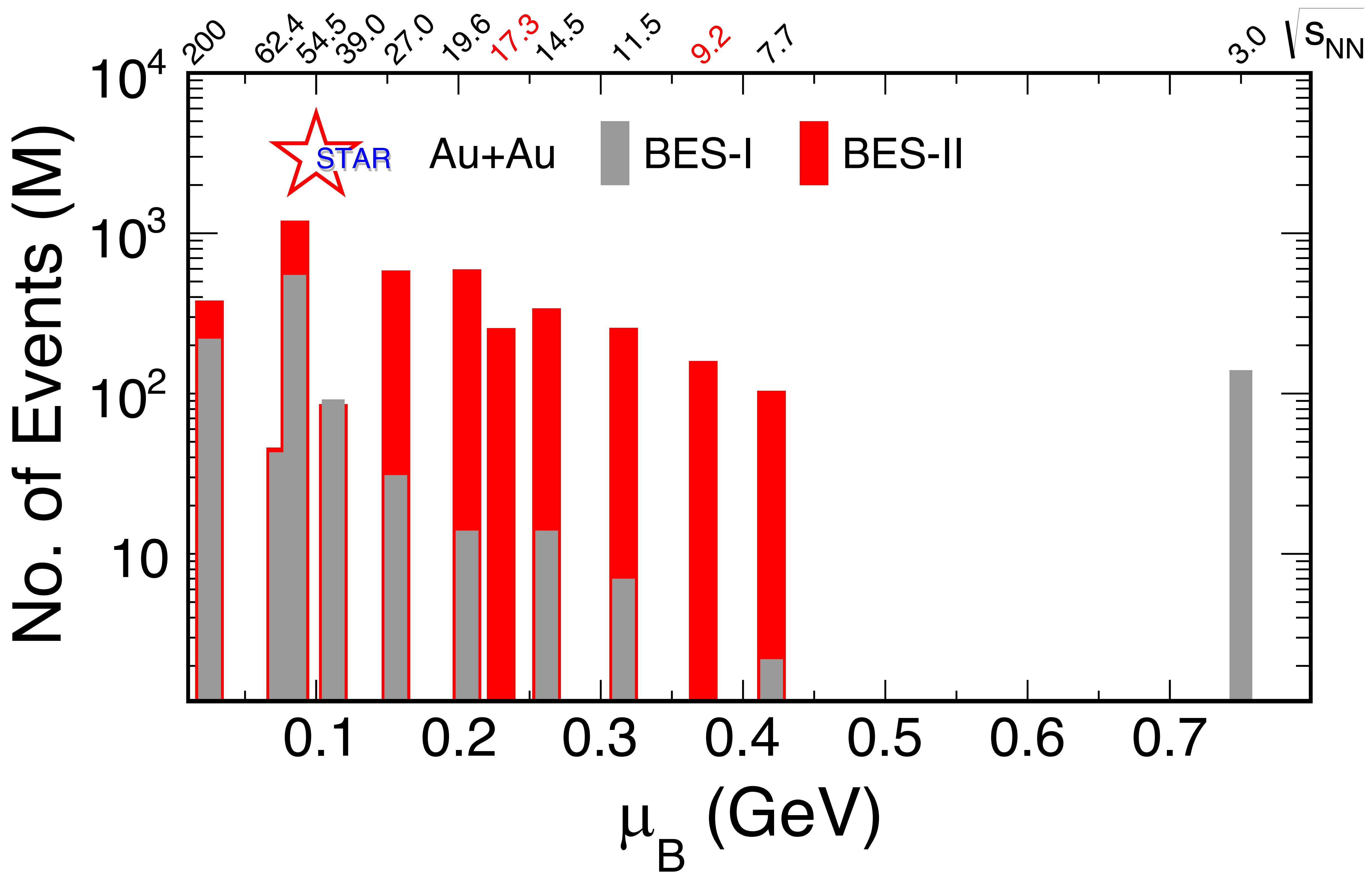
Phase I of BES program (BES-I)

STAR : PRL 127, 262301 (2021), PRC 104, 24902 (2021)
: PRL 128, 202302 (2022), PRC 107, 24908 (2023)
HADES: PRC 102, 024914 (2020)



- Non-monotonic distribution in central collisions from BES-I 200 to 7.7 GeV (3σ).
- Proton C_4/C_2 consistent with UrQMD at 3 GeV.
- Non-CEP models with baryon conservation show a monotonic dependence vs. collision energy.

STAR BES-II program: Precision Measurement



Phase I of BES program (BES-I)

Phase II of BES program (BES-II) Collider mode

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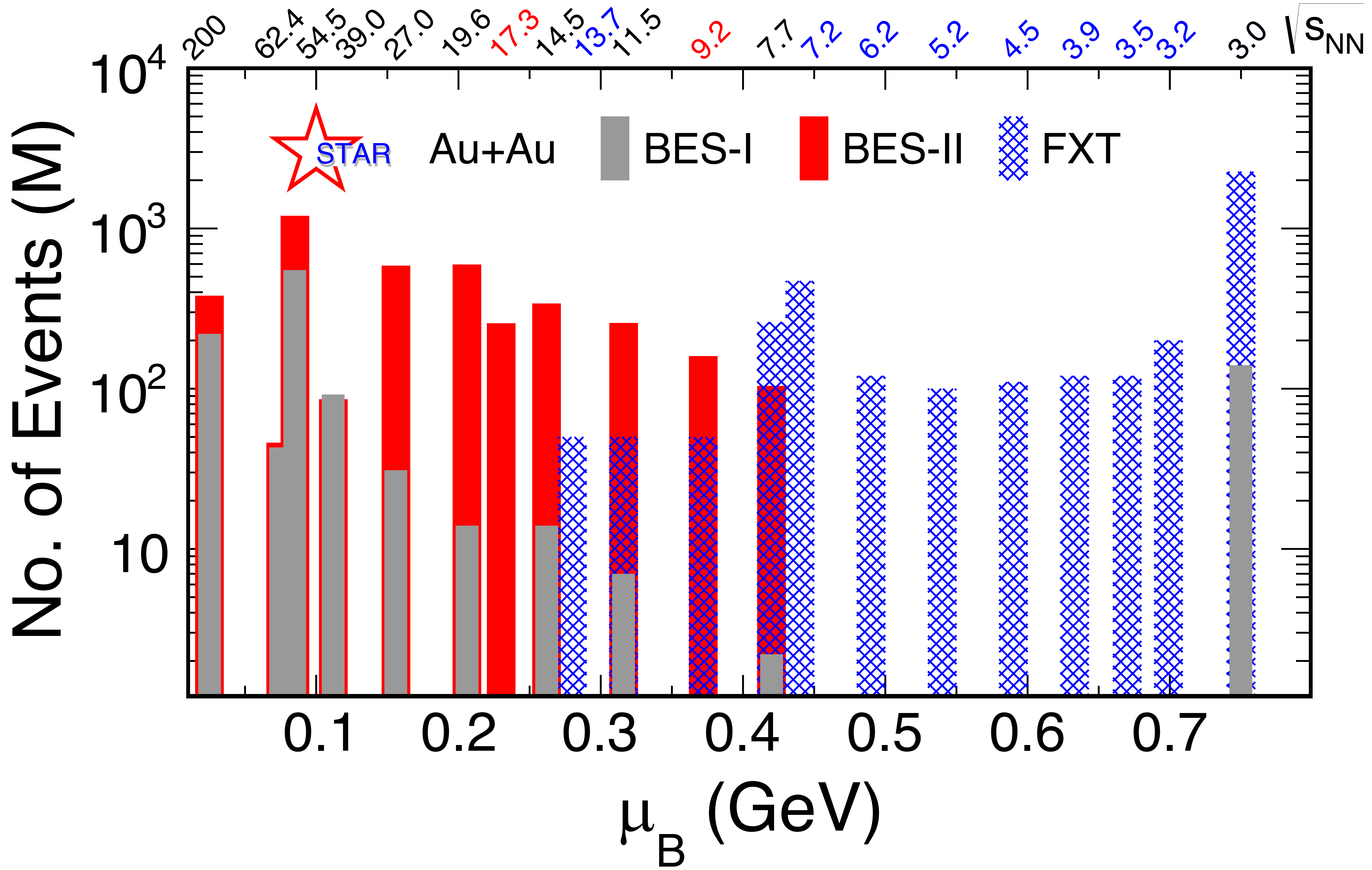

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Phase II of BES program (BES-II) Collider mode

Fixed Target program (FXT)

$3 \leq \sqrt{s_{NN}}(\text{GeV}) \leq 200 \rightarrow 750 \geq \mu_B(\text{MeV}) \geq 25$

High precision, widest μ_B coverage to date

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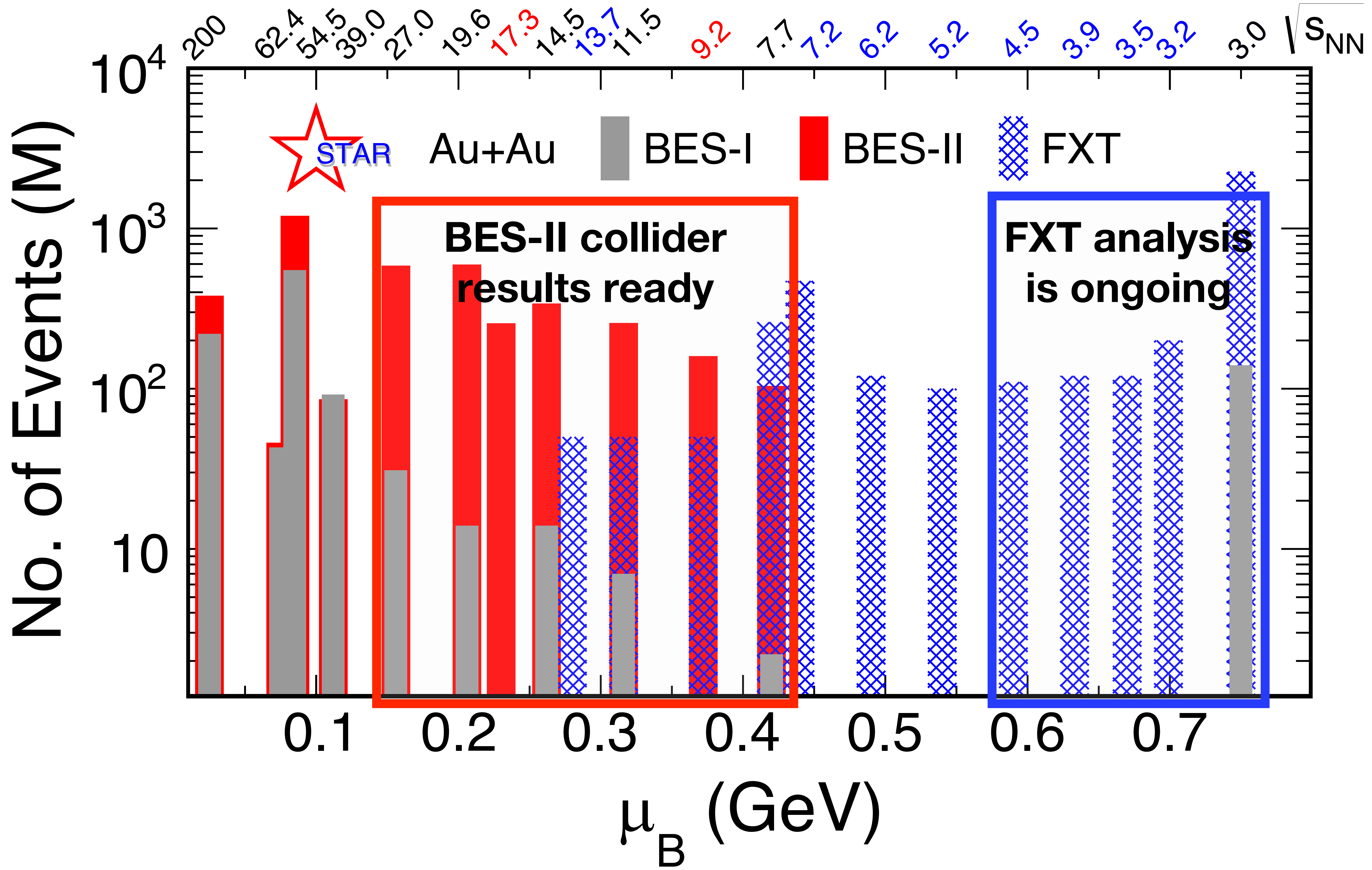

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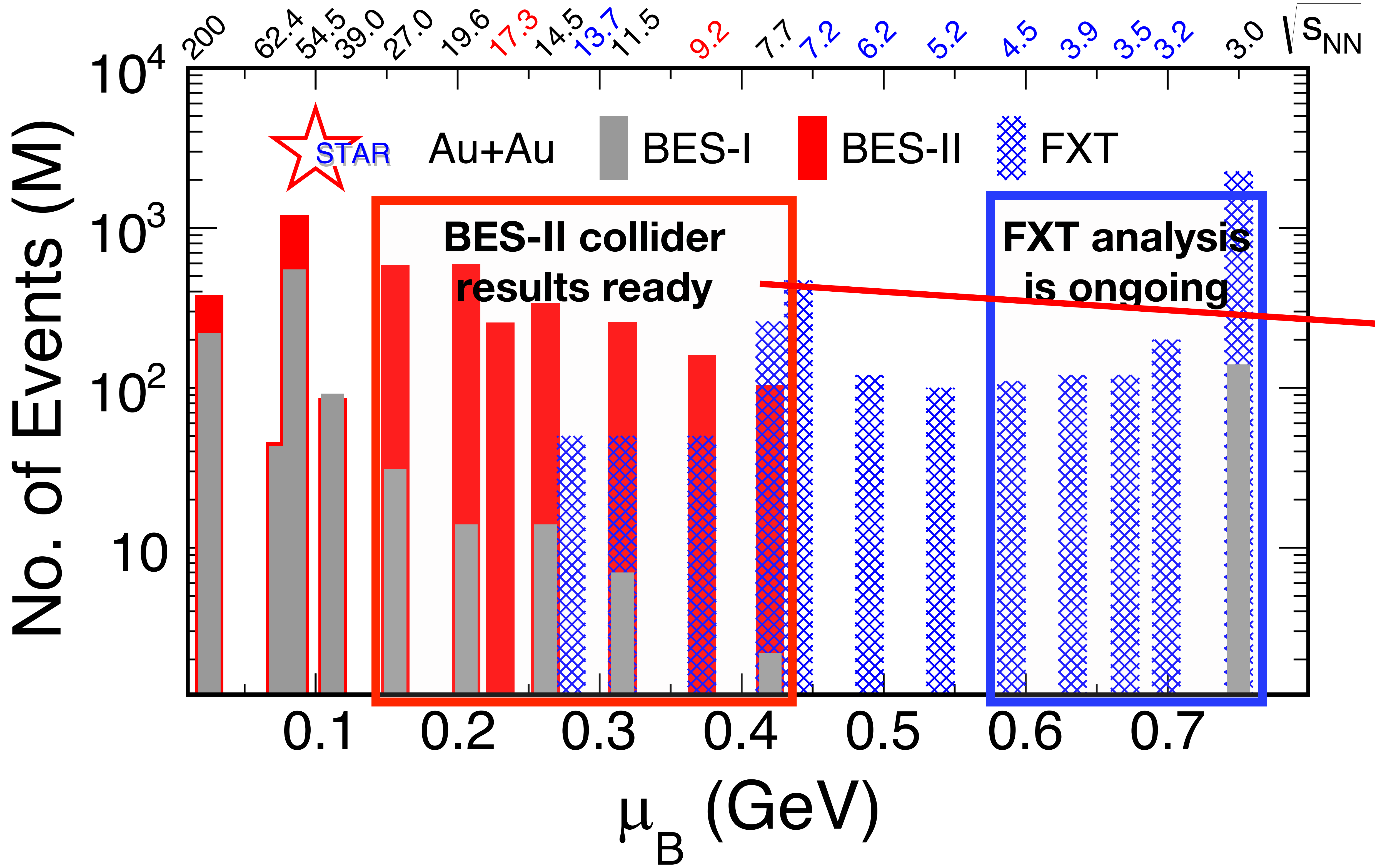

μ_B

Phase I of BES program (BES-I)

Phase II of BES program (BES-II)

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Events used for net-proton fluctuation studies (Collider runs)
BES-II vs BES-I

$\sqrt{s_{NN}}$ (GeV)	Events BES-I (10^6)	Events BES-II (10^6)
7.7	3	**45**
9.2	-	**78**
11.5	7	**110**
14.5	20	**178**
17.3	-	**116**
19.6	15	**270**
27	30	**220**

~x10-18 larger statistics
9.2 and 17.3 GeV added to energy scan

High precision, widest μ_B coverage to date

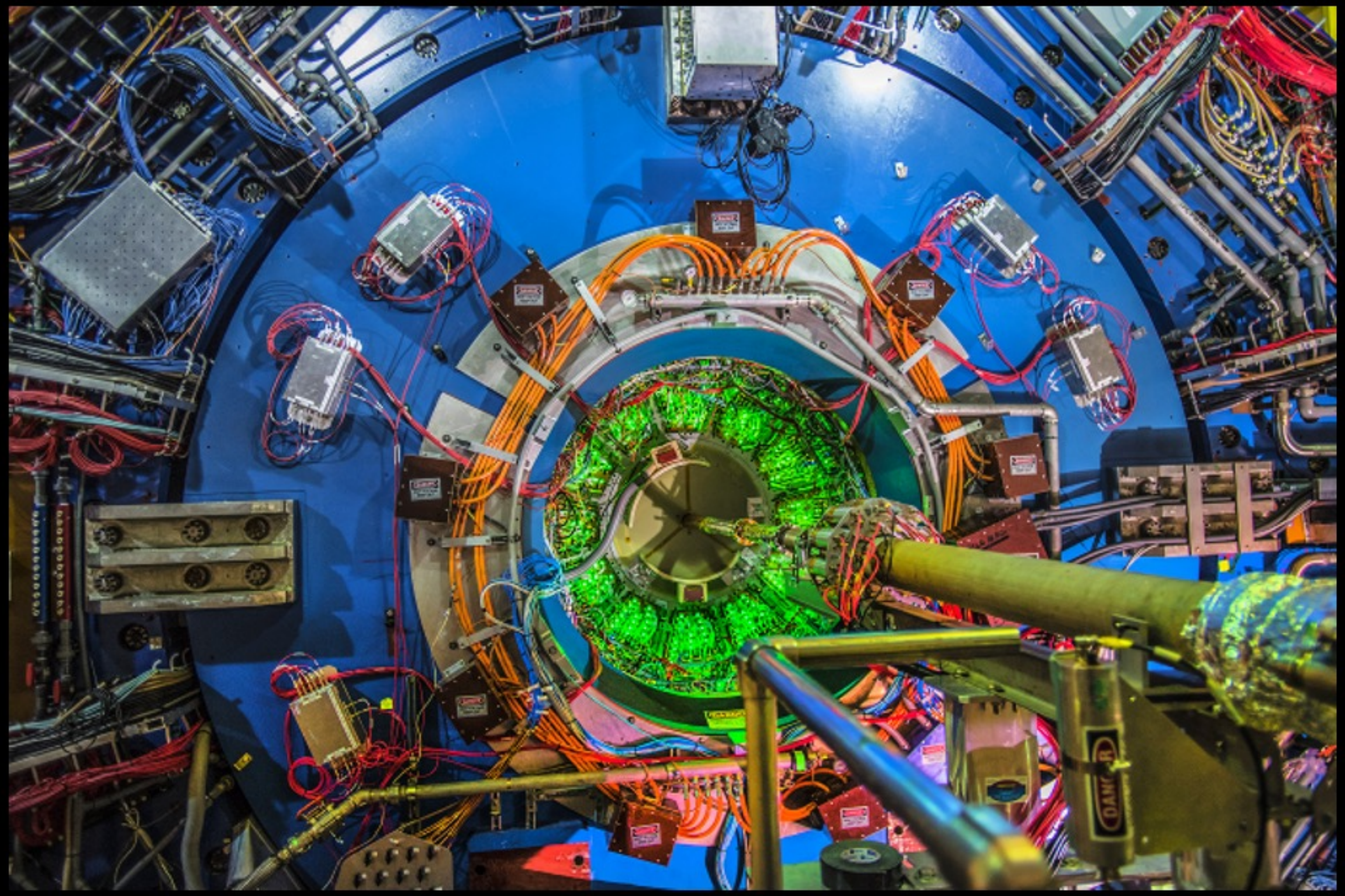
STAR Detector: BES-II Upgrade

Wide and uniform acceptance

Excellent PID and tracking

Modest rates

STAR Major Upgrades for BES-II



iTPC:
- Improves dE/dx
- Extends η coverage from 1.0 to 1.6
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

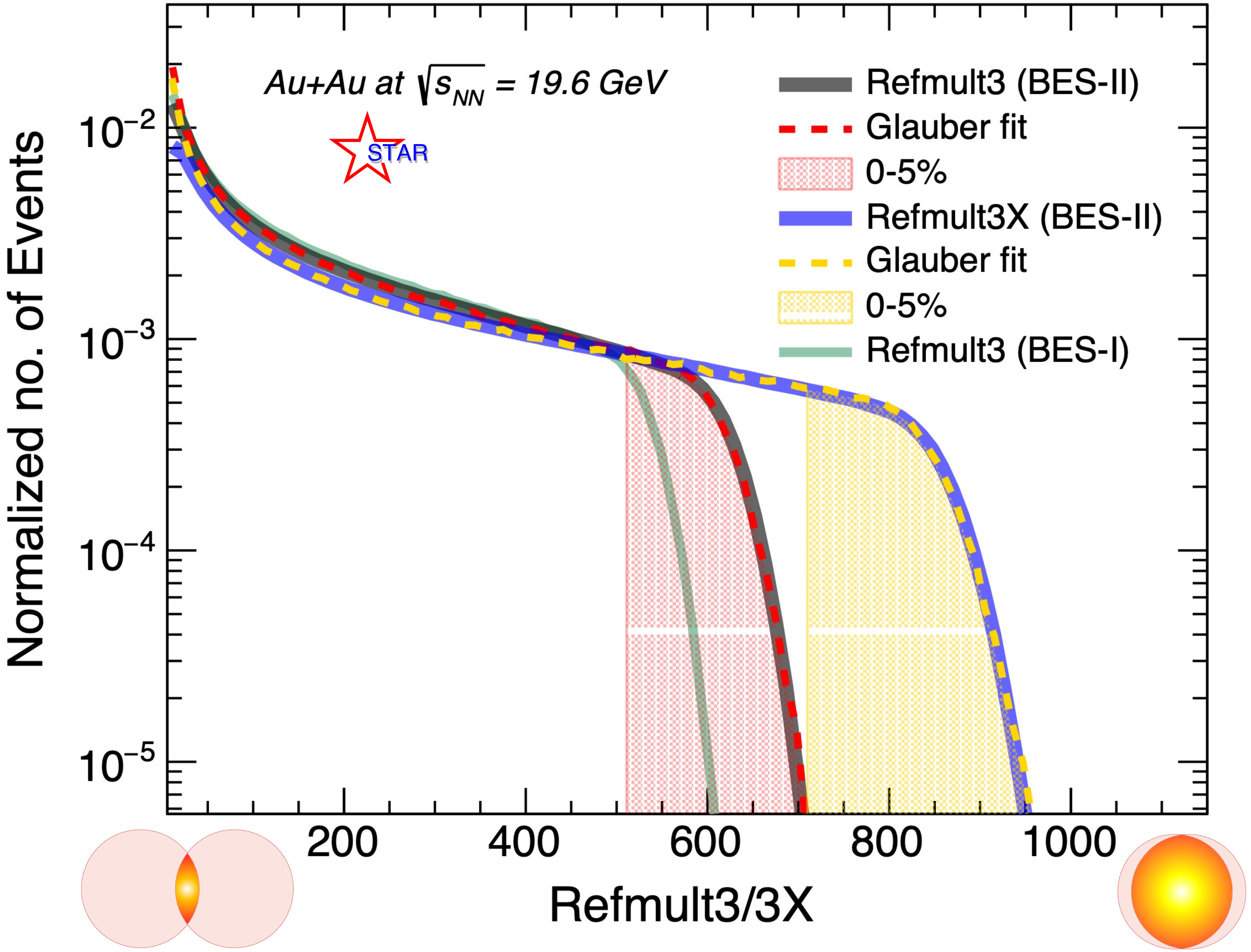
eTOF:
- Forward rapidity coverage
- PID at η = 1.05 to 1.5
- Borrowed from CBM-FAIR
- Ready in 2019

EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

1) Enlarge rapidity acceptance: $|\eta| \leq 1.0 \rightarrow |\eta| \leq 1.6$
2) Improve particle identification: $p_T \geq 125$ MeV/c $\rightarrow p_T \geq 60$ MeV/c
3) Enhance centrality/event plane resolution, suppress auto correlations
4) Enable the fixed-target program: $\mu_B \leq 420$ MeV $\rightarrow \mu_B \leq 750$ MeV

Centrality Definition

- Defined using charged particle multiplicity measured by STAR
- Exclude protons and antiprotons to avoid self correlation



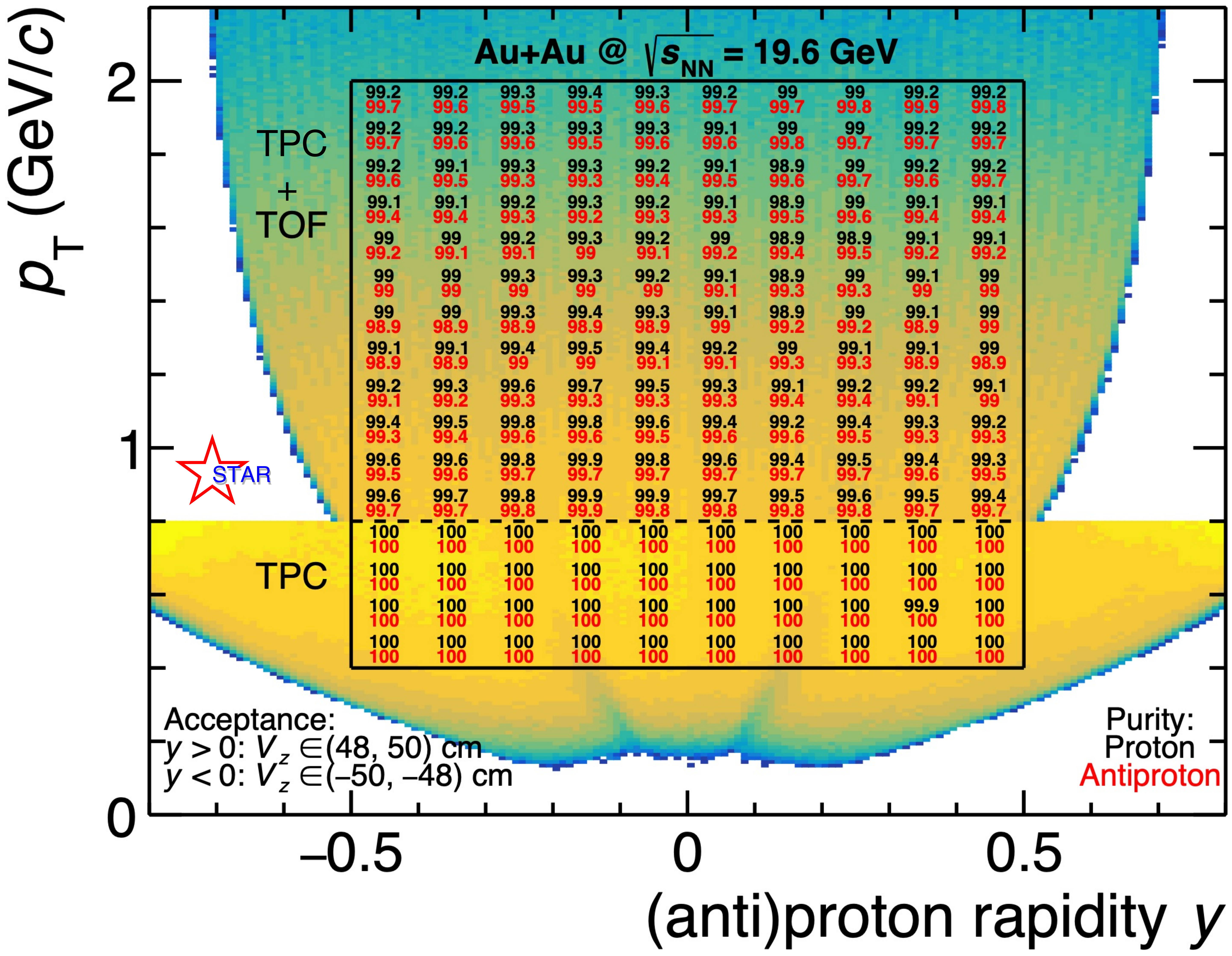
Two centrality definitions with different acceptance:

Refmult3		Refmult3X
Charged particle multiplicity excluding protons		
BES-I	BES-II	BES-II
w/o iTPC	w/ iTPC	w/ iTPC
$\|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.6$

Refmult3X (BES-II) > Refmult3 (BES-II) > Refmult3 (BES-I)

Best centrality resolution

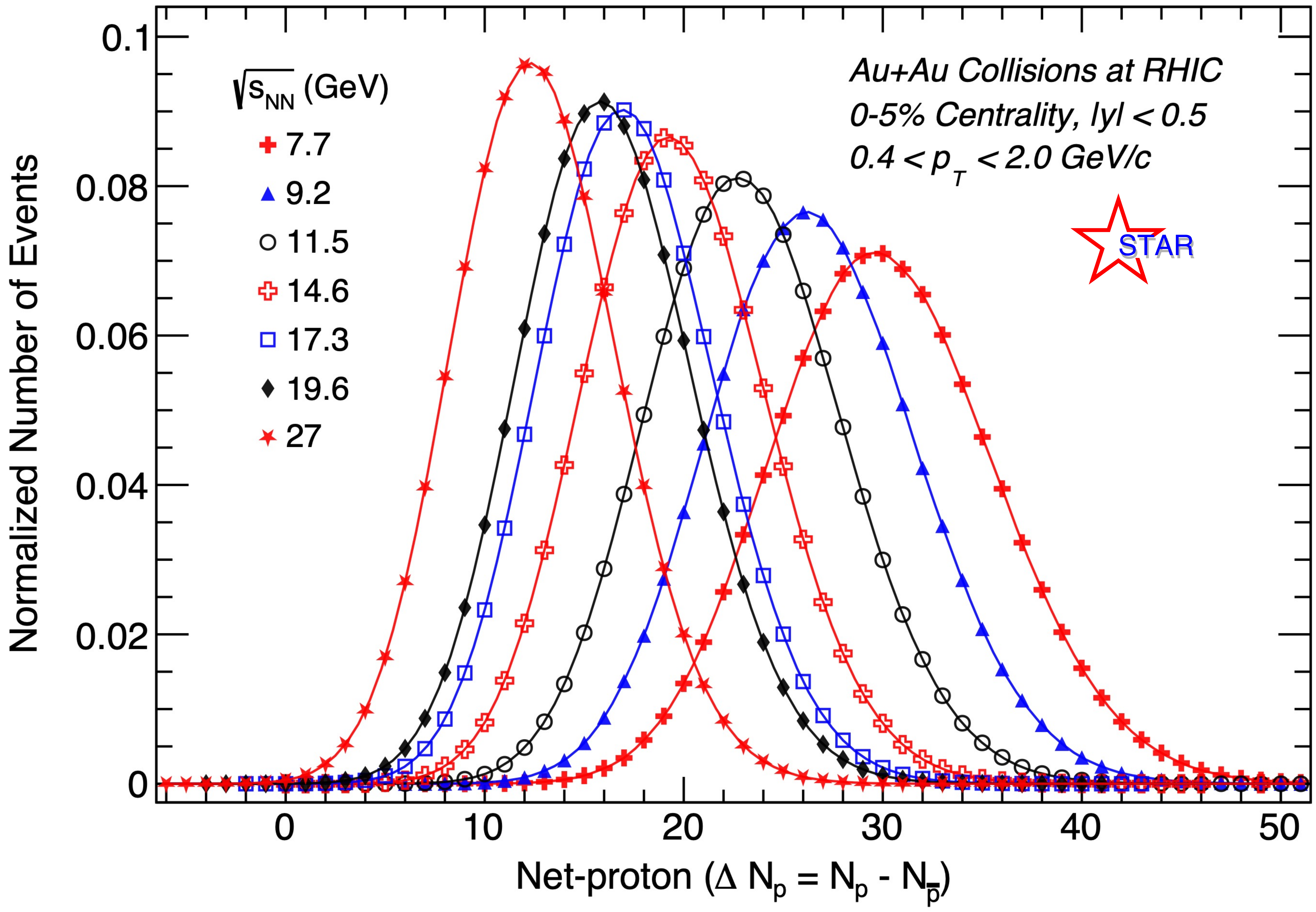
Proton Identification



p_T (GeV/c)	0.4 – 0.8	0.8 – 2.0
rapidity	$\lvert y\rvert < 0.5$	
detector	TPC	TPC+TOF
dE/dx	$\lvert n\sigma\rvert < 2$	
mass^2 (GeV^2/c^4)	/	0.6 – 1.2

- Uniform acceptance for (anti-) protons $|y|<0.5$ with $|Vz| < 50$cm
- (anti-)protons identified using TPC dE/dx + TOF
- Bin-by-bin purity > 99% in the full acceptance range and all energies

Event-by-Event Net-proton Number Distribution



- Raw net-proton number distributions from BES-II: Uncorrected for detector efficiency
- Mean increases with decreasing collision energy: Effect of baryon stopping

Improved statistics and systematics

- Better statistics:
  ~x10 – 18 larger statistics compared with BES-I $Stat.error\, C_r \propto \frac{\sigma^r}{\sqrt{N}}$ *STAR, PRC 104 (2021) 024902*

- Larger acceptance and improved tracking
  Benefit from iTPC upgrade
  ~10% higher proton efficiency compared to BES-I
  Better control on uncertainty on efficiency: 2% compared to 5% in BES-I

- Better centrality resolution
  Corrected for finite centrality bin with event-number-weighted average

$C_n = \sum_r w_r C_{n,r}$
where $w_r = n_r / \sum_r n_r$, n=1,2,3,4…
Here, n_r is no. of events in r^{th} multiplicity bin

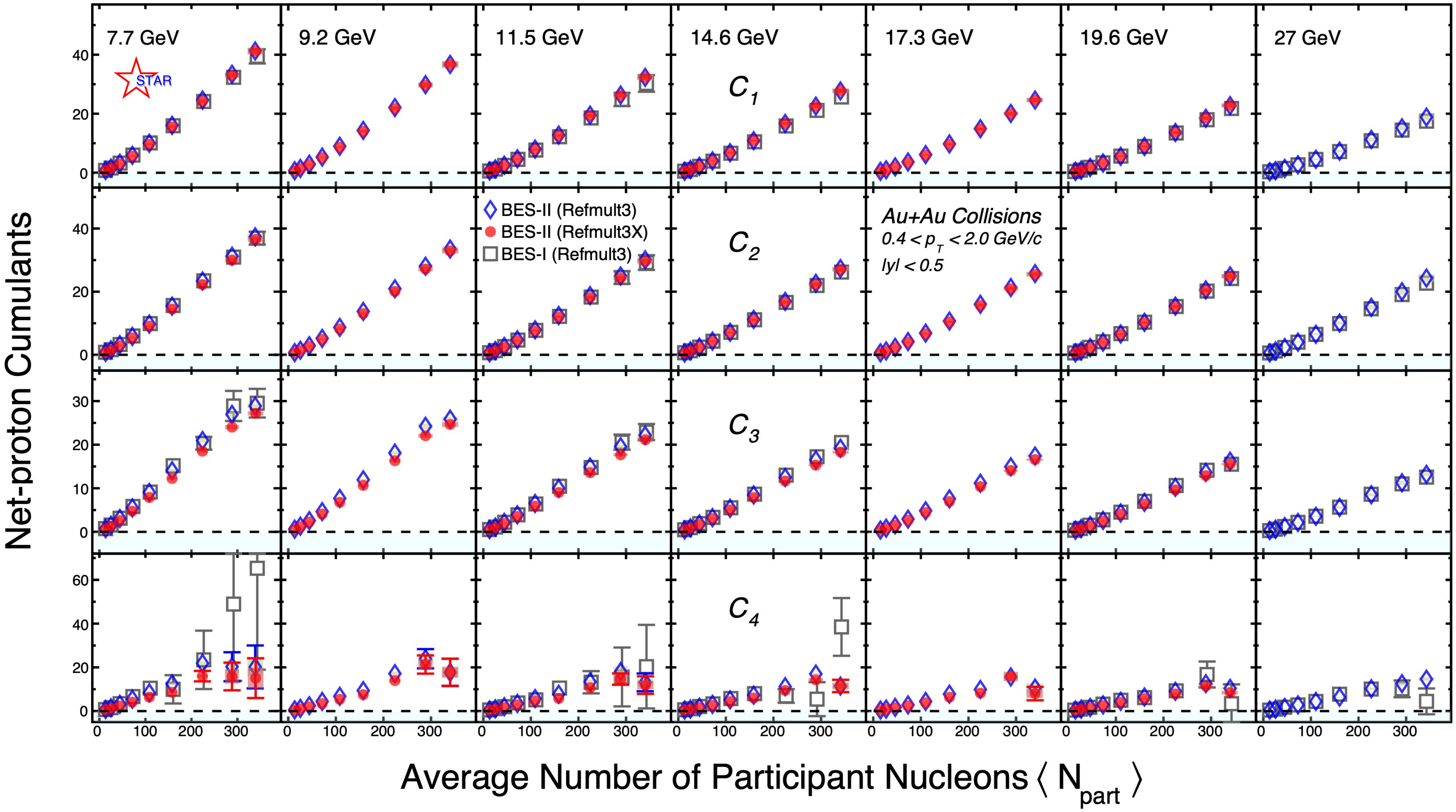
X. Luo, T Nonaka, PRC 99 (2019), X. Luo et al, J.Phys. G 40, 105104 (2013)

Reduction factor in uncertainties on 0-5% C_4/C_2: BES-II vs BES-I

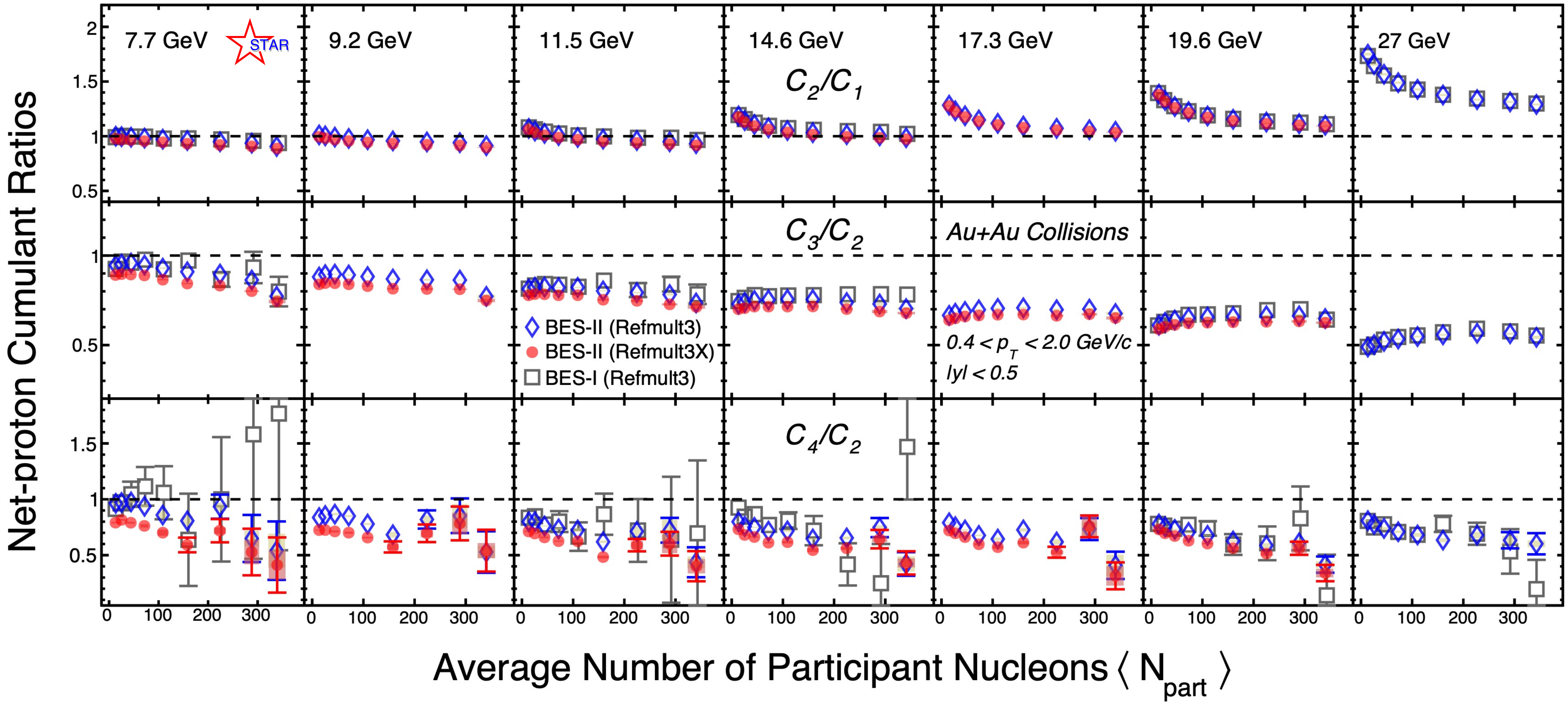
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

Latest Net-proton Fluctuation Results from STAR BES-II

Cumulants vs Centrality and Collision Energies



Cumulant ratios vs Centrality and Collision Energies

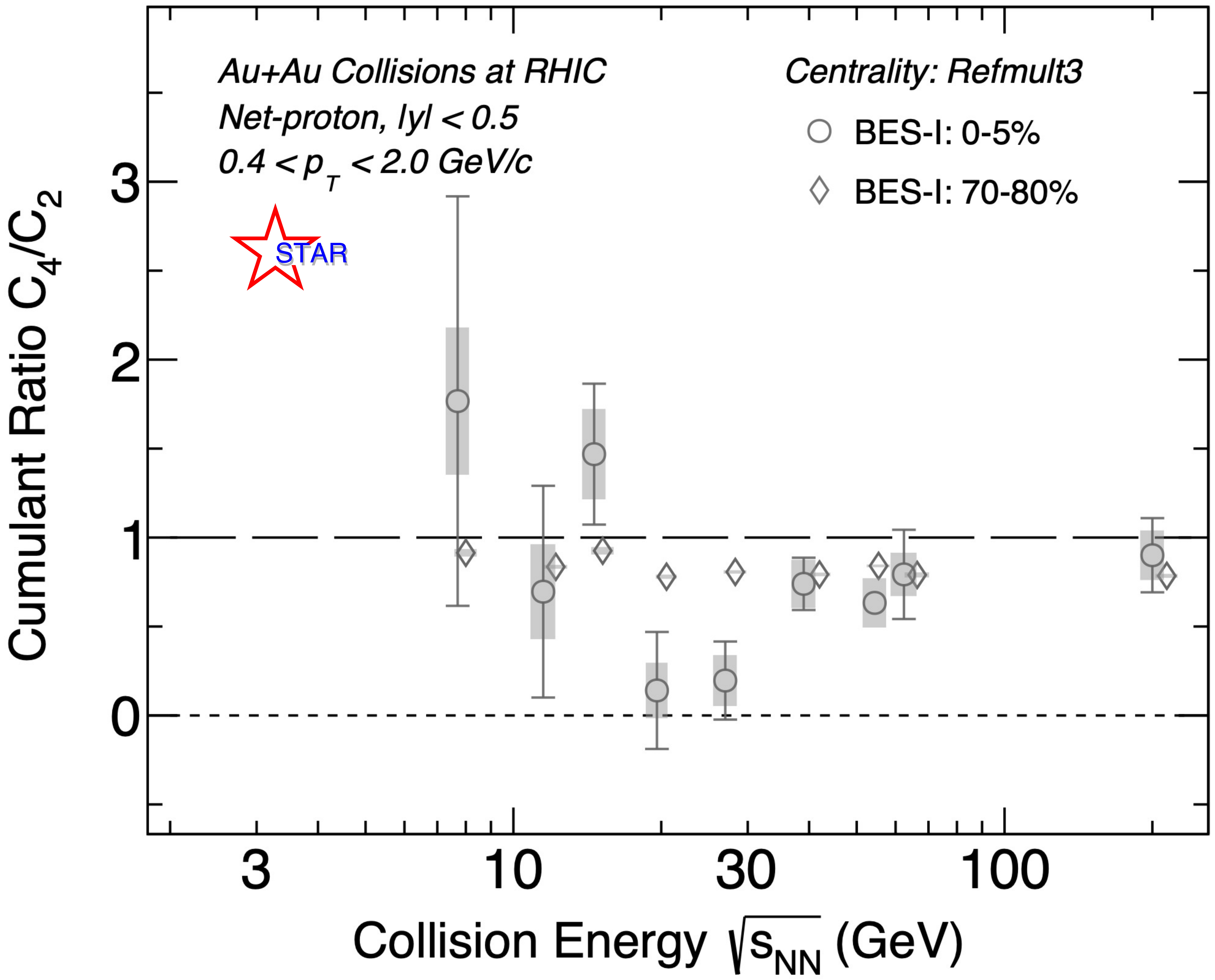


- Precision measurements: smooth variation across centrality and collision energy observed.
- Higher centrality resolution leads to lower ratios (especially in mid central collisions):

  Results from Refmult3X (BES-II) < Refmult3 (BES-II) < Refmult3 (BES-I)

- For 0-5% C_4/C_2 , weak effect of centrality resolution seen.

Energy Dependence of C_4/C_2: Comparison with BES-I



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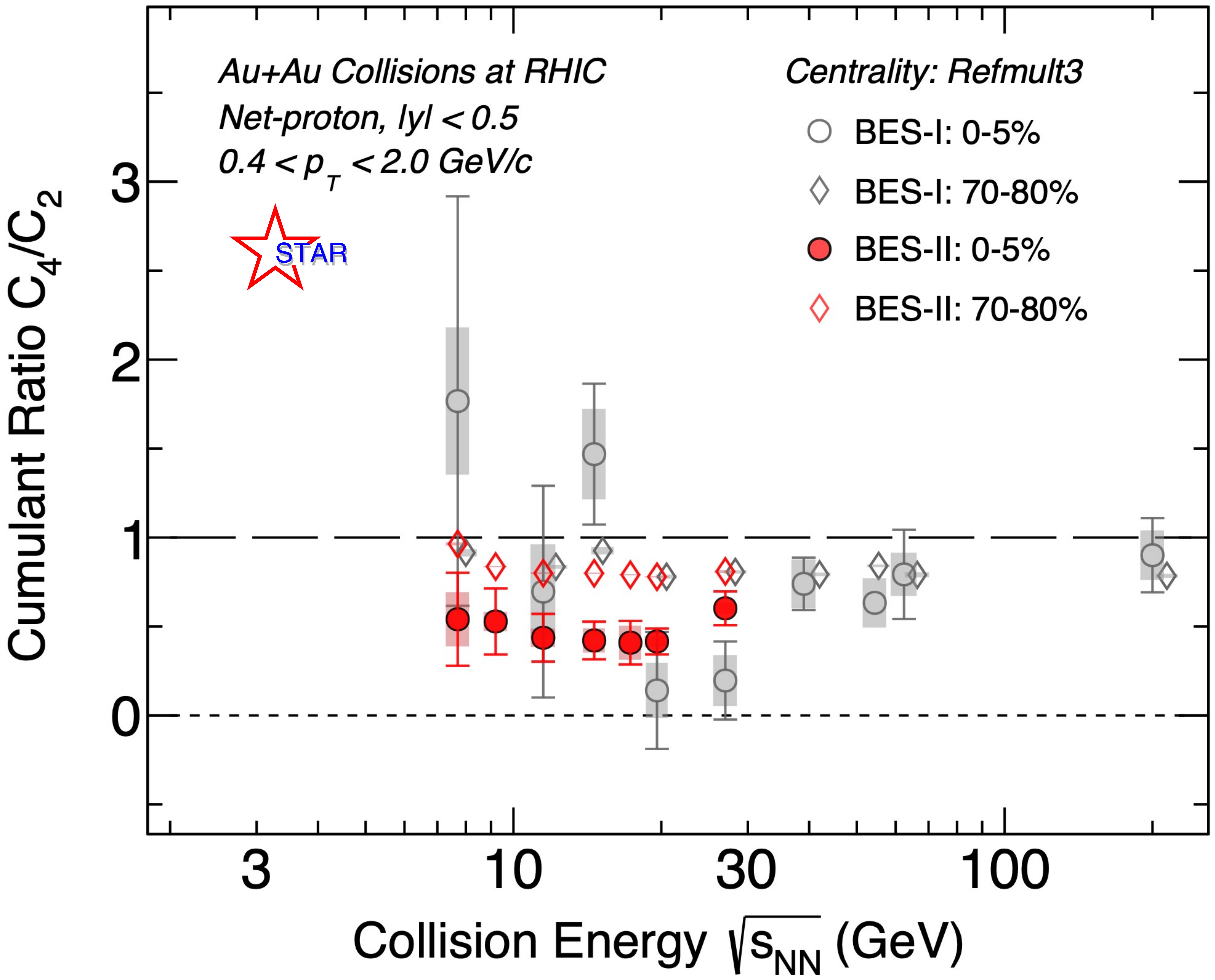
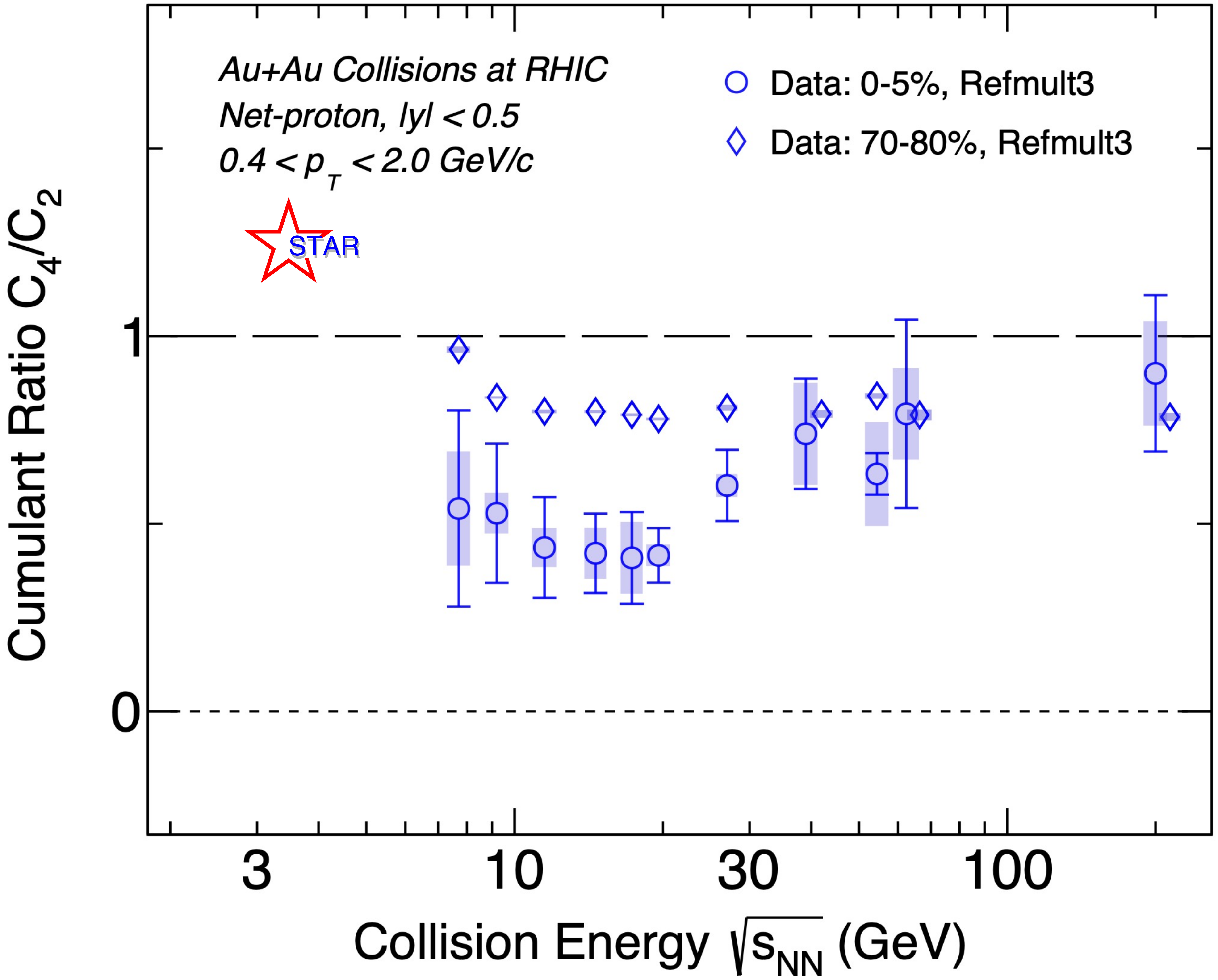


Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

- BES-II results consistent with BES-I within uncertainties.

Effect of Centrality Resolution on C_4/C_2



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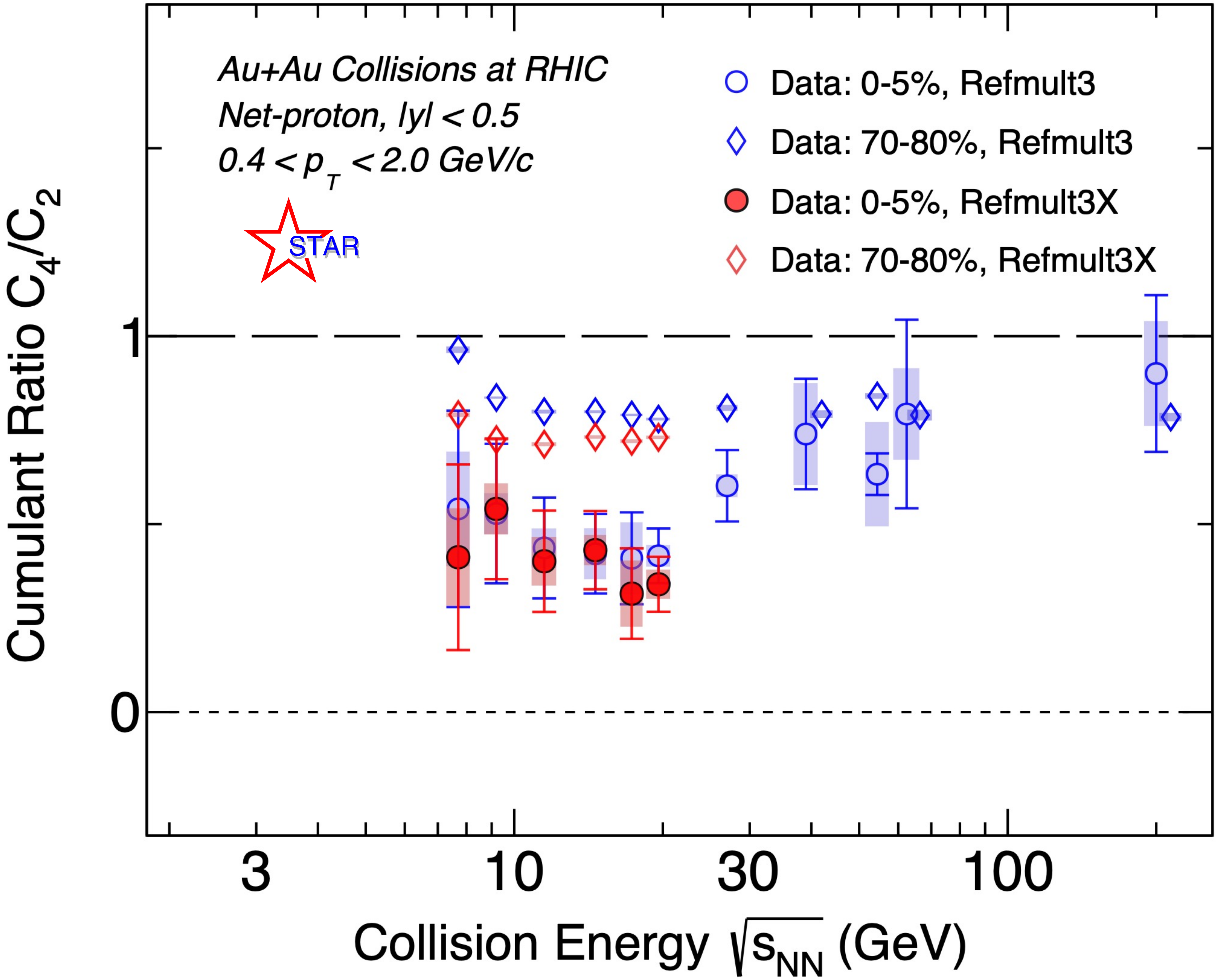
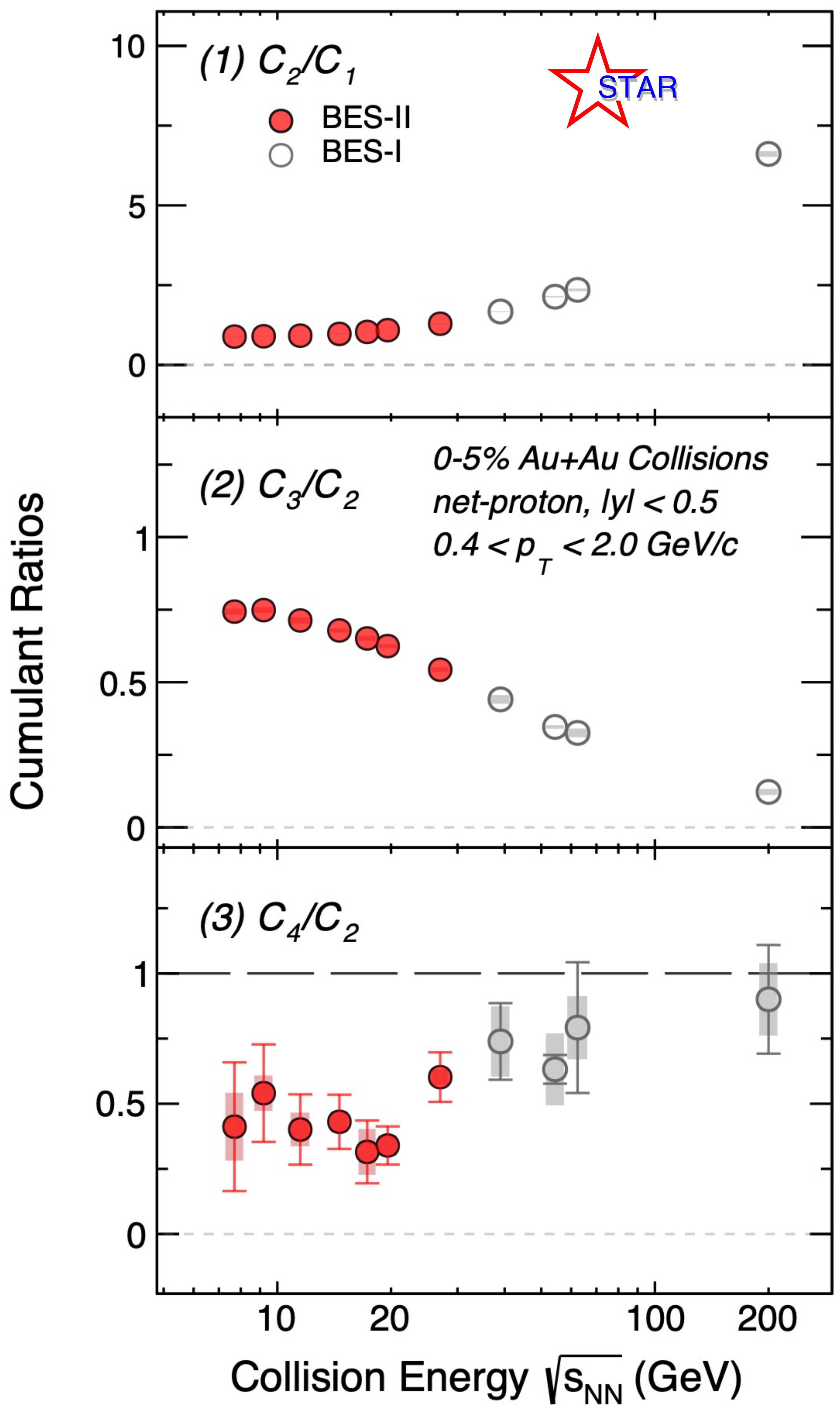


- 0–5% centrality C_4/C_2 results show good agreement between Refmult3 and Refmult3X: **weak effect of centrality resolution.**
- Difference in 70–80% due to centrality resolution impact.

BES-II results shown hereafter are with Refmult3X

Energy Dependence: Model Comparison

Net-proton cumulant ratios



- Smooth variation vs $\sqrt{s_{NN}}$ in C_2/C_1 and C_3/C_2 observed. C_4/C_2 decreases with decreasing energy.

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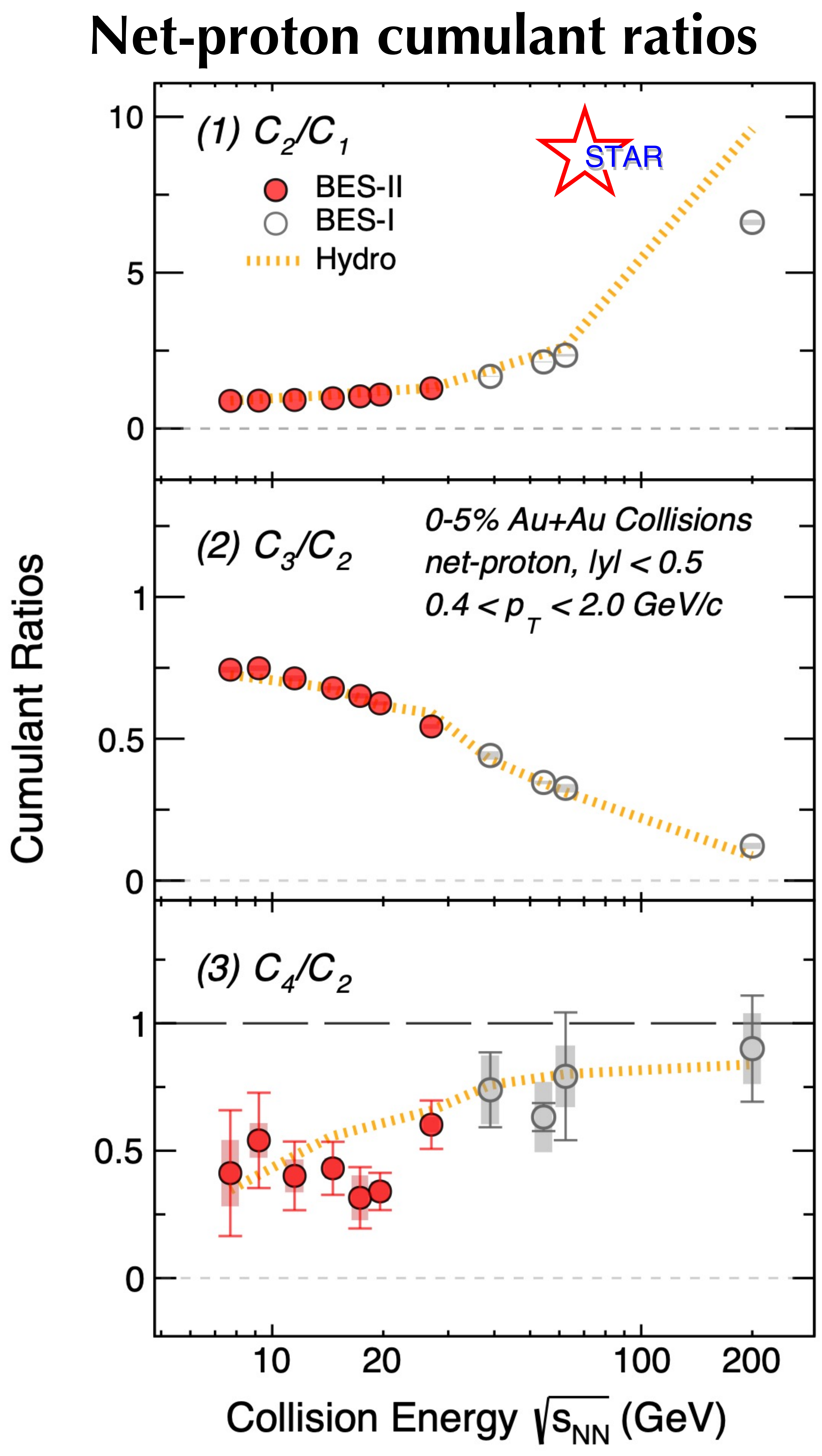

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V. Vovchenko et al, PRC 105, 014904 (2022)

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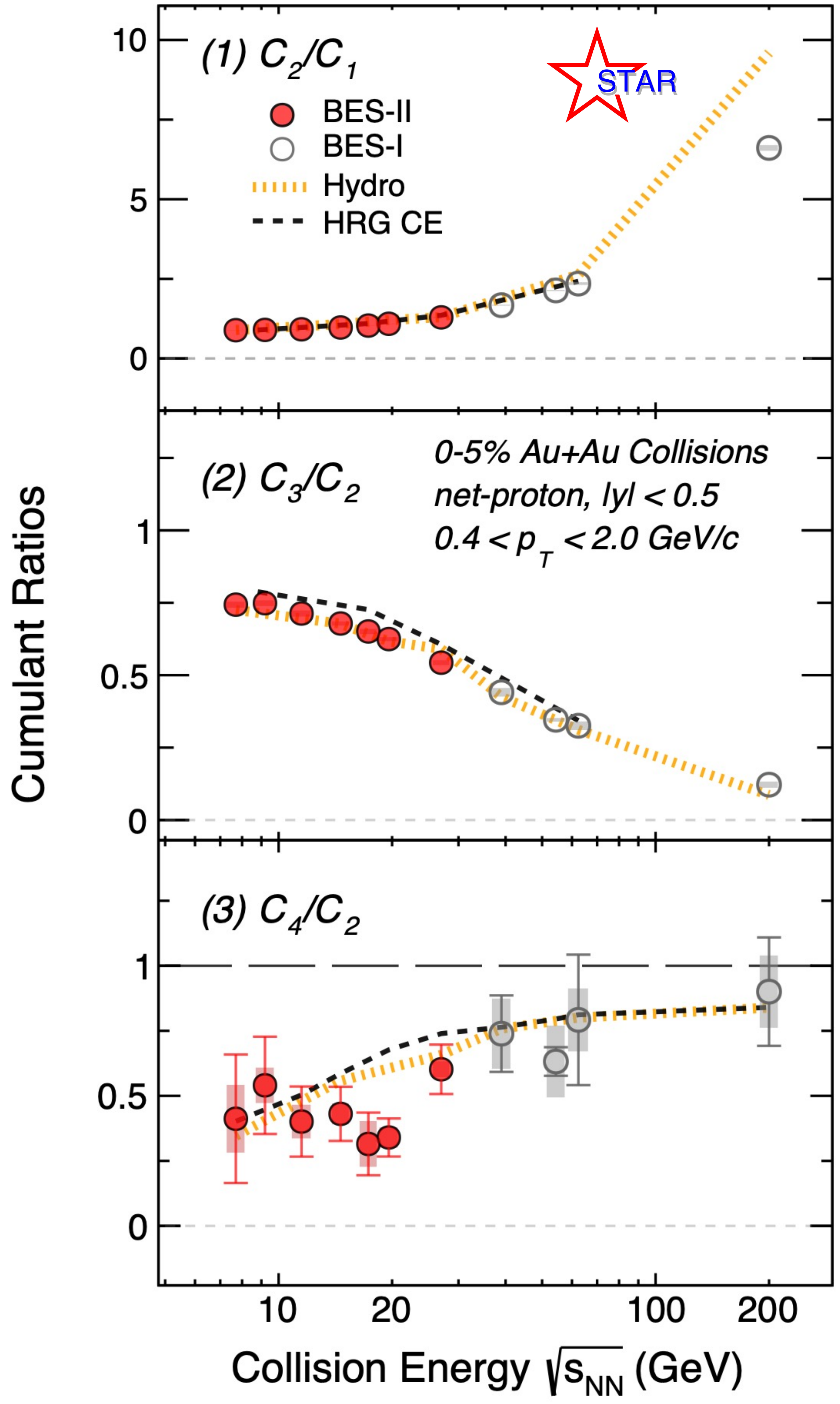

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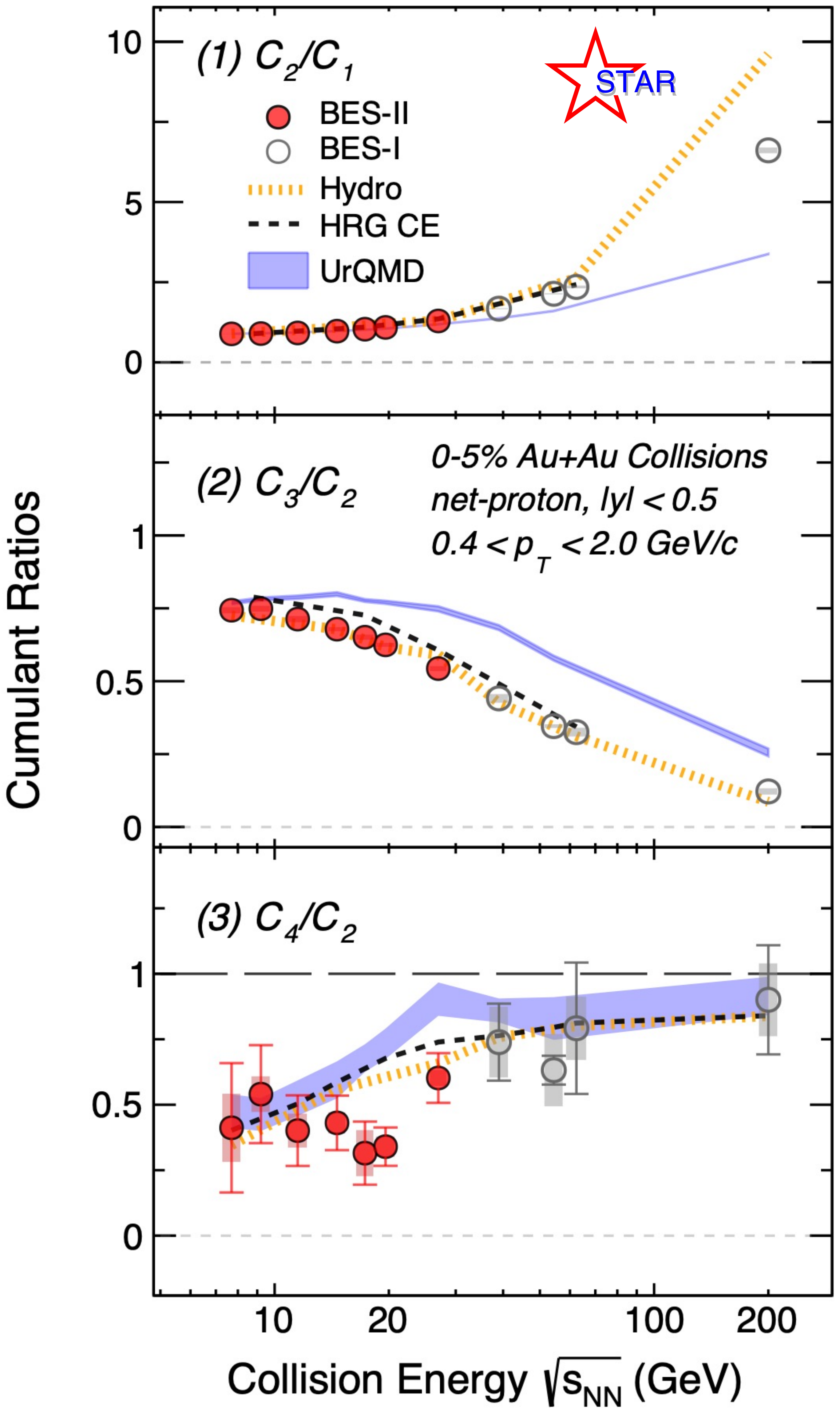

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C. UrQMD: Hadronic transport model

Bass S., et al. Prog. Part. Nucl. Phys., 41, 255 (1998)

(All models include baryon number conservation)

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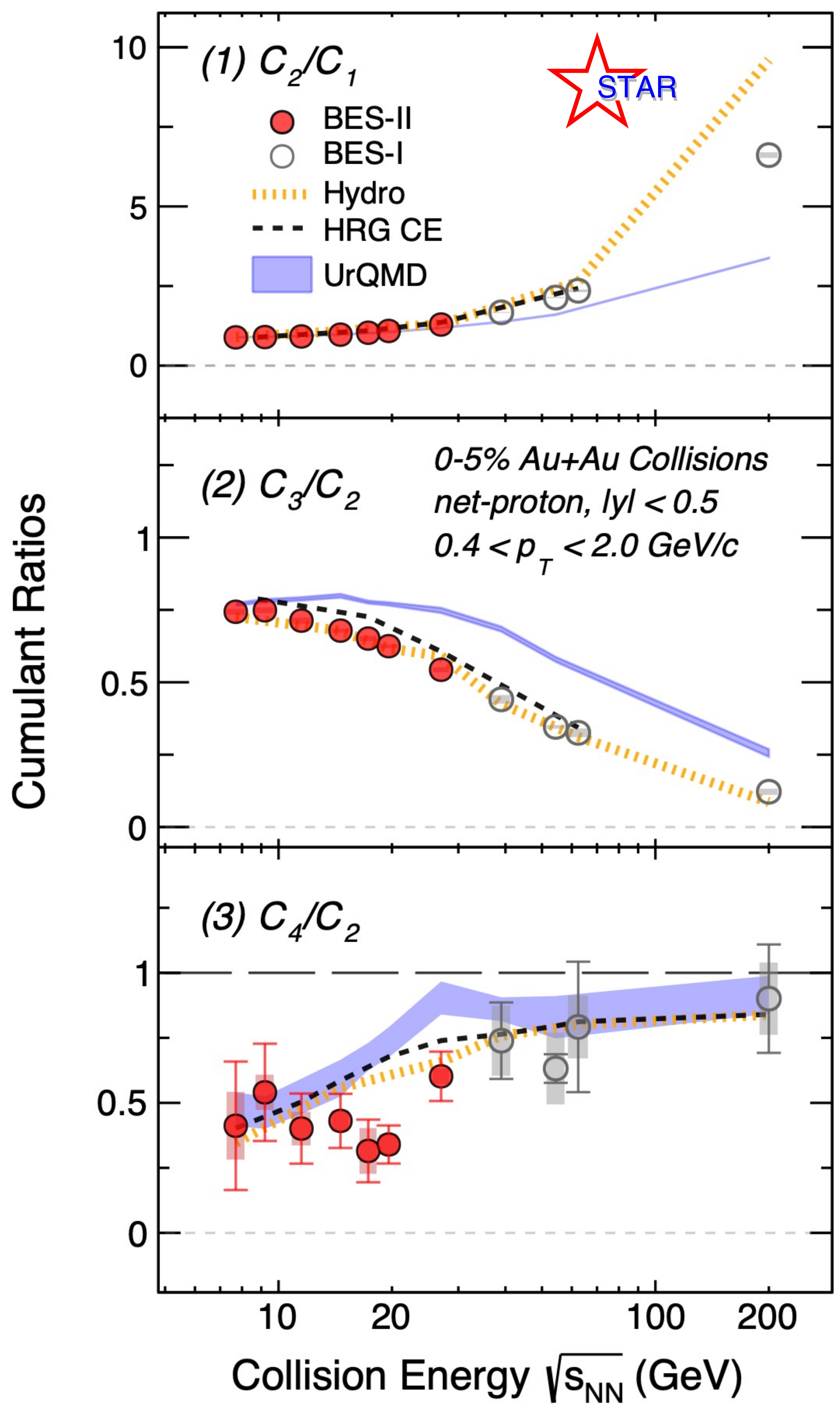
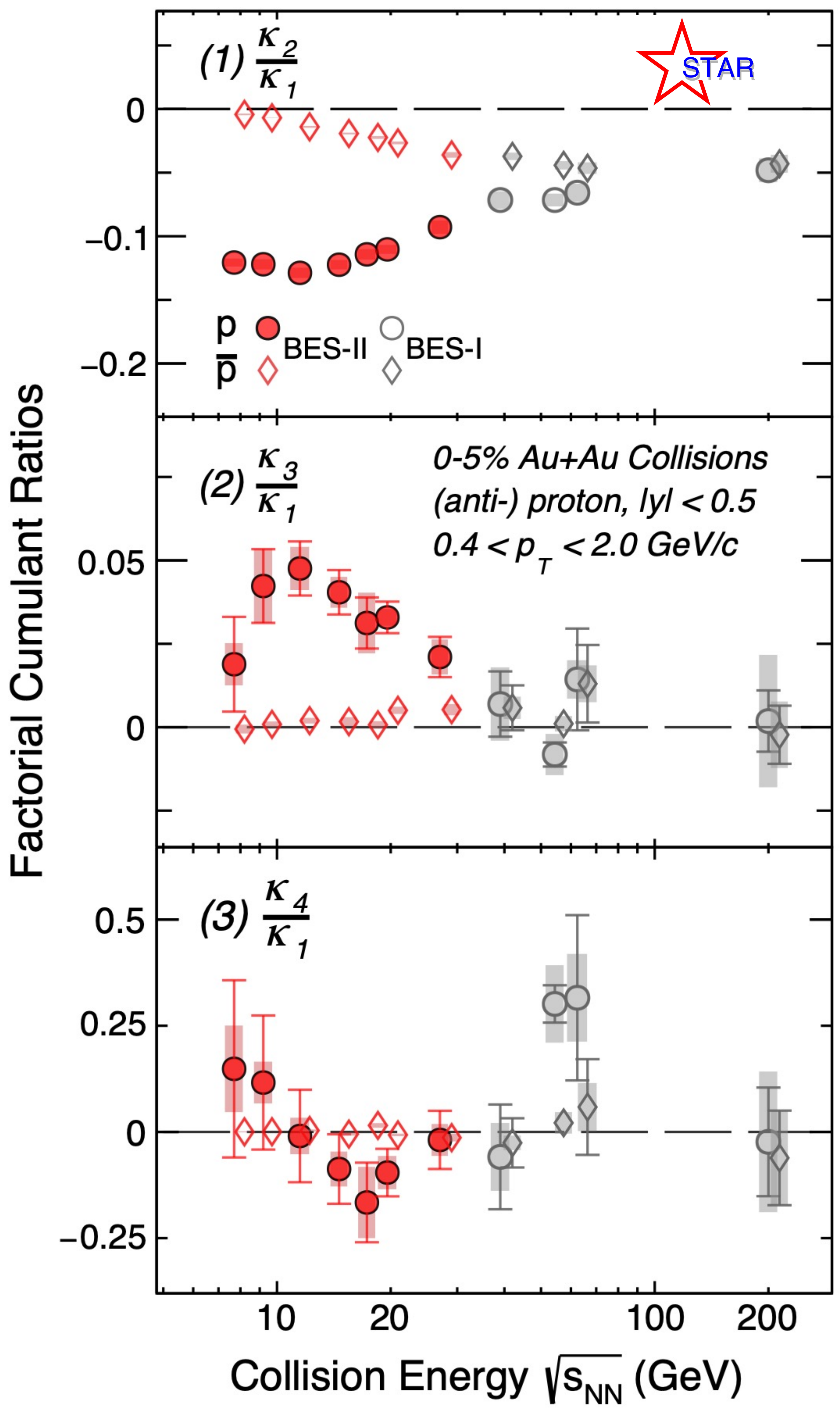


(anti)proton factorial cumulant ratios



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  (All models include baryon number conservation)
- Proton factorial cumulant ratios deviates from Poisson baseline at 0.
  Antiproton κ_3/κ_1, κ_4/κ_1 closer to 0.

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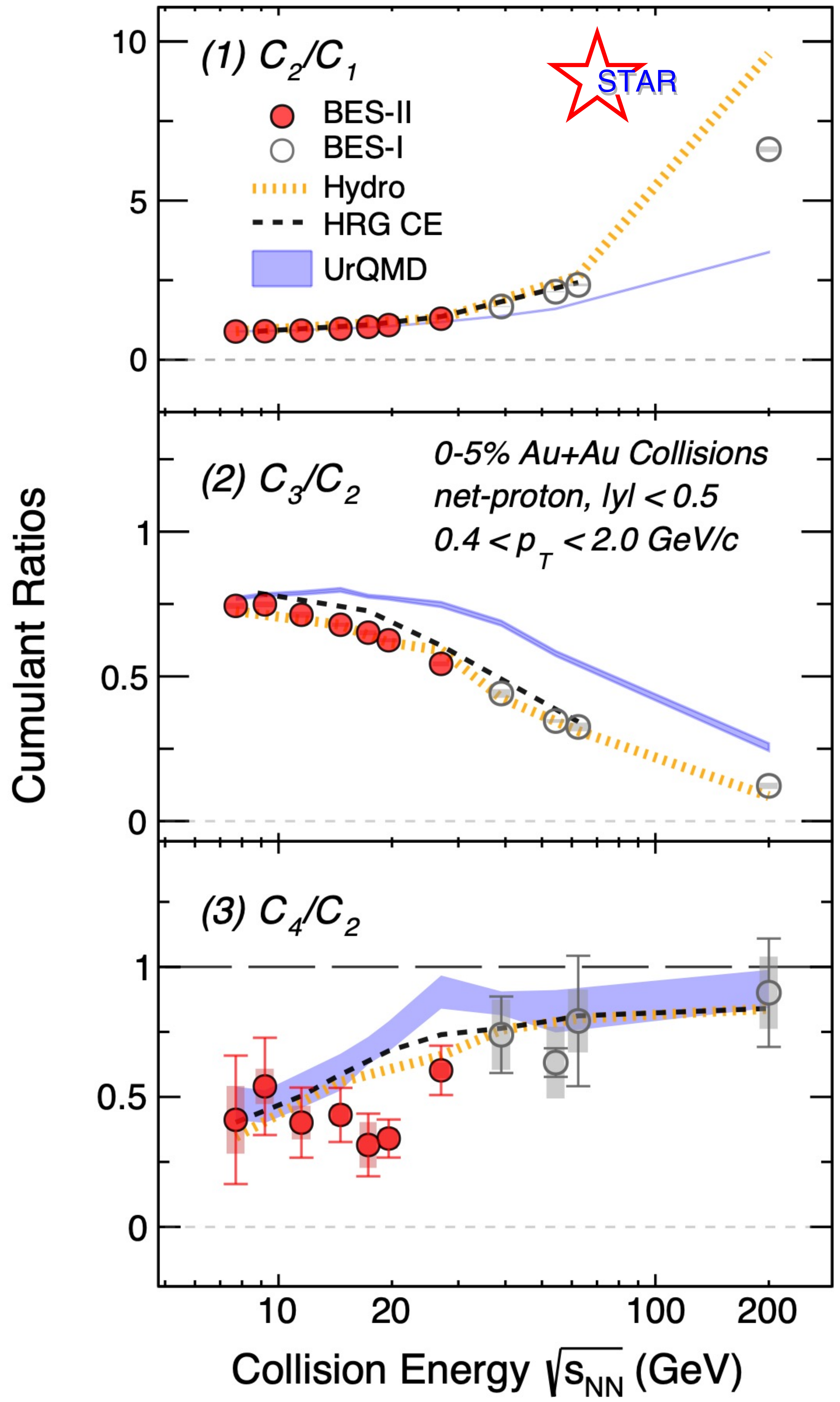
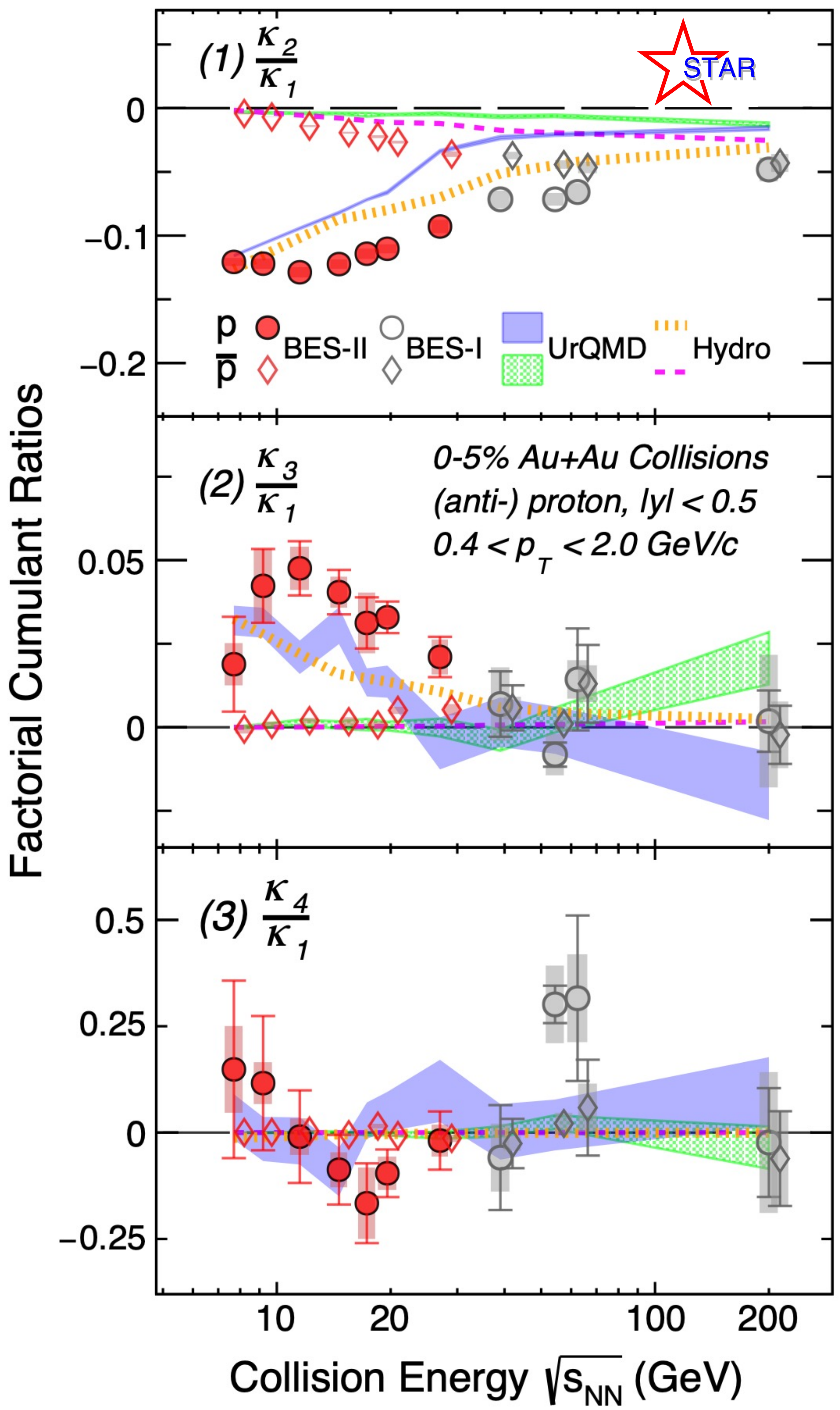
Net-proton cumulant ratios

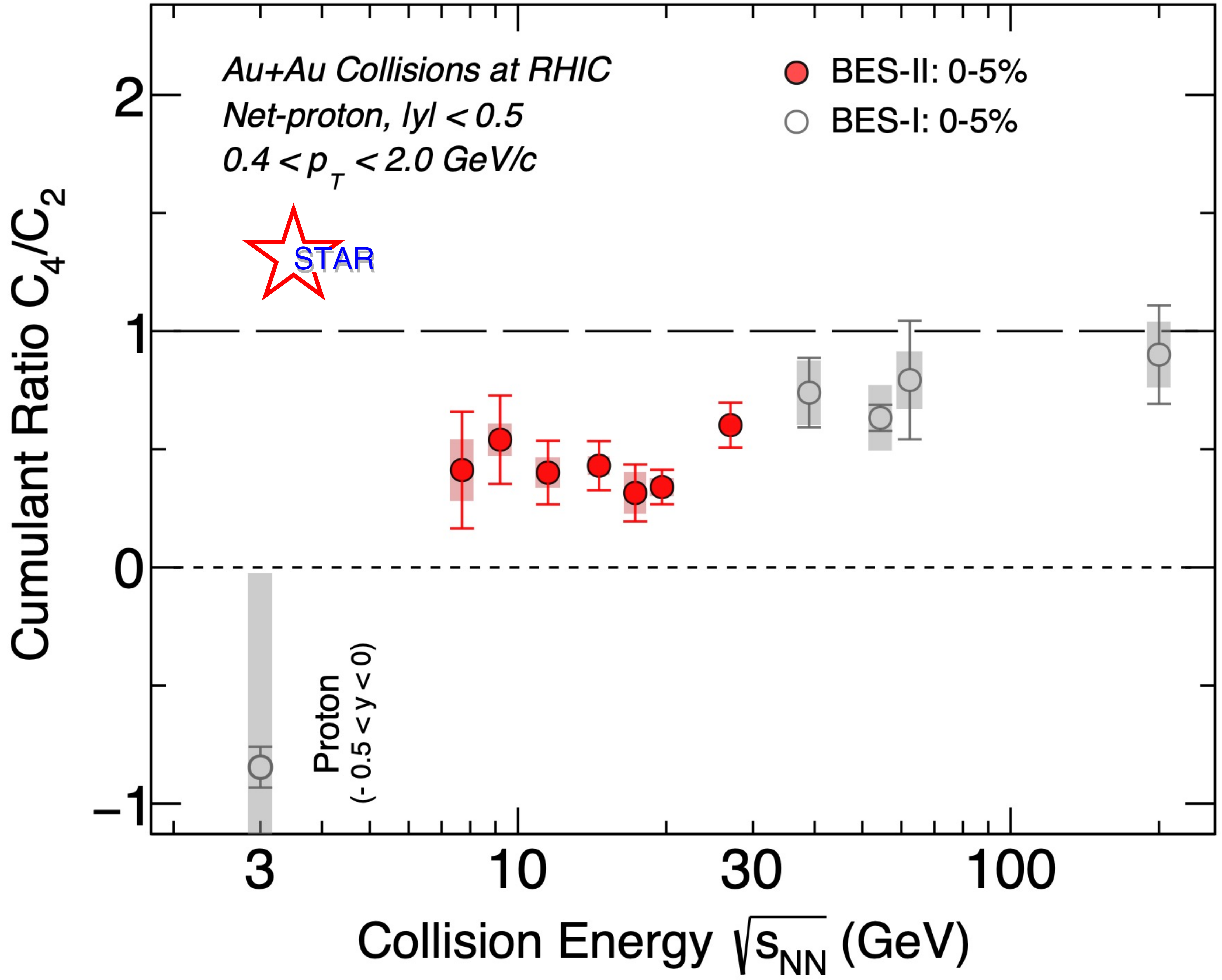


(anti)proton factorial cumulant ratios

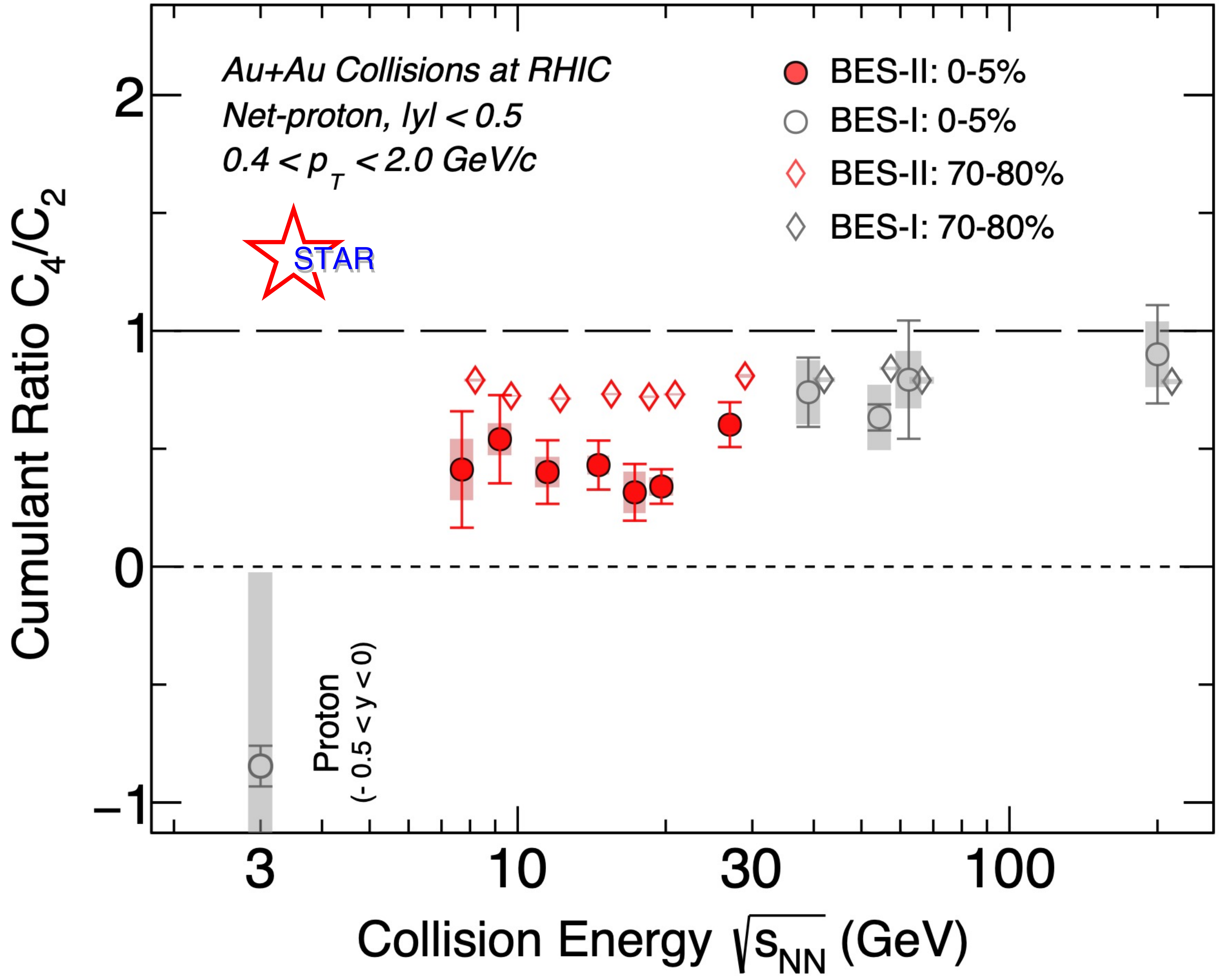


- Smooth variation vs $\sqrt{s_{NN}}$ in C_2/C_1 and C_3/C_2 observed. C_4/C_2 decreases with decreasing energy.
- Non-CP models used for comparison:
  - A. Hydro: Hydrodynamical model
    V. Vovchenko et al, PRC 105, 014904 (2022)
  - B. HRG CE: Thermal model with canonical treatment of baryon charge P. B Munzinger et al, NPA 1008, 122141 (2021)
  - C. UrQMD: Hadronic transport model
    Bass S., et al. Prog. Part. Nucl. Phys., 41, 255 (1998)
  - (All models include baryon number conservation)
- Proton factorial cumulant ratios deviates from Poisson baseline at 0.
  Antiproton κ_3/κ_1, κ_4/κ_1 closer to 0.
- Baryon number conservation may shift the non-CEP model baseline but won 't create criticality.

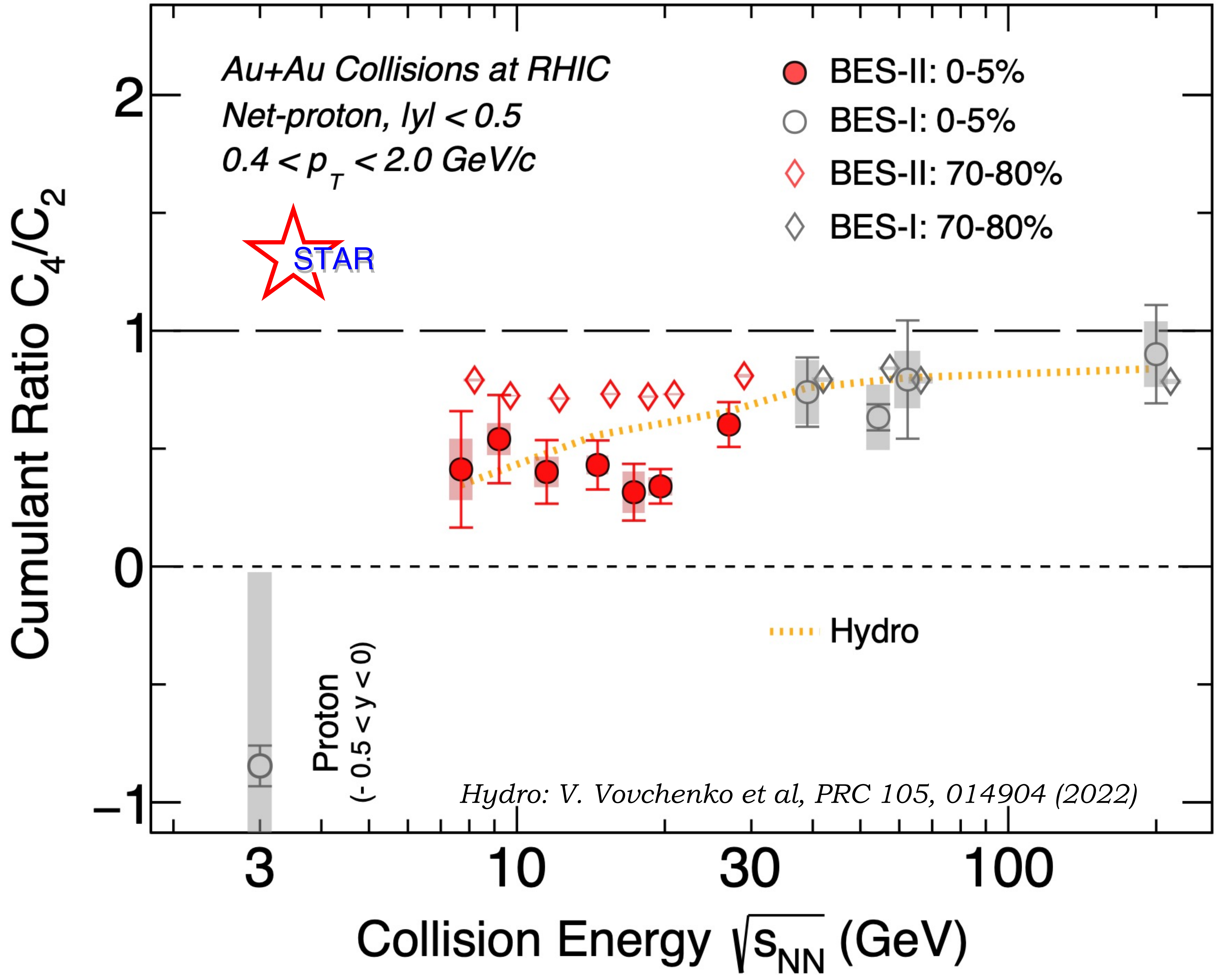
Energy Dependence of C_4/C_2



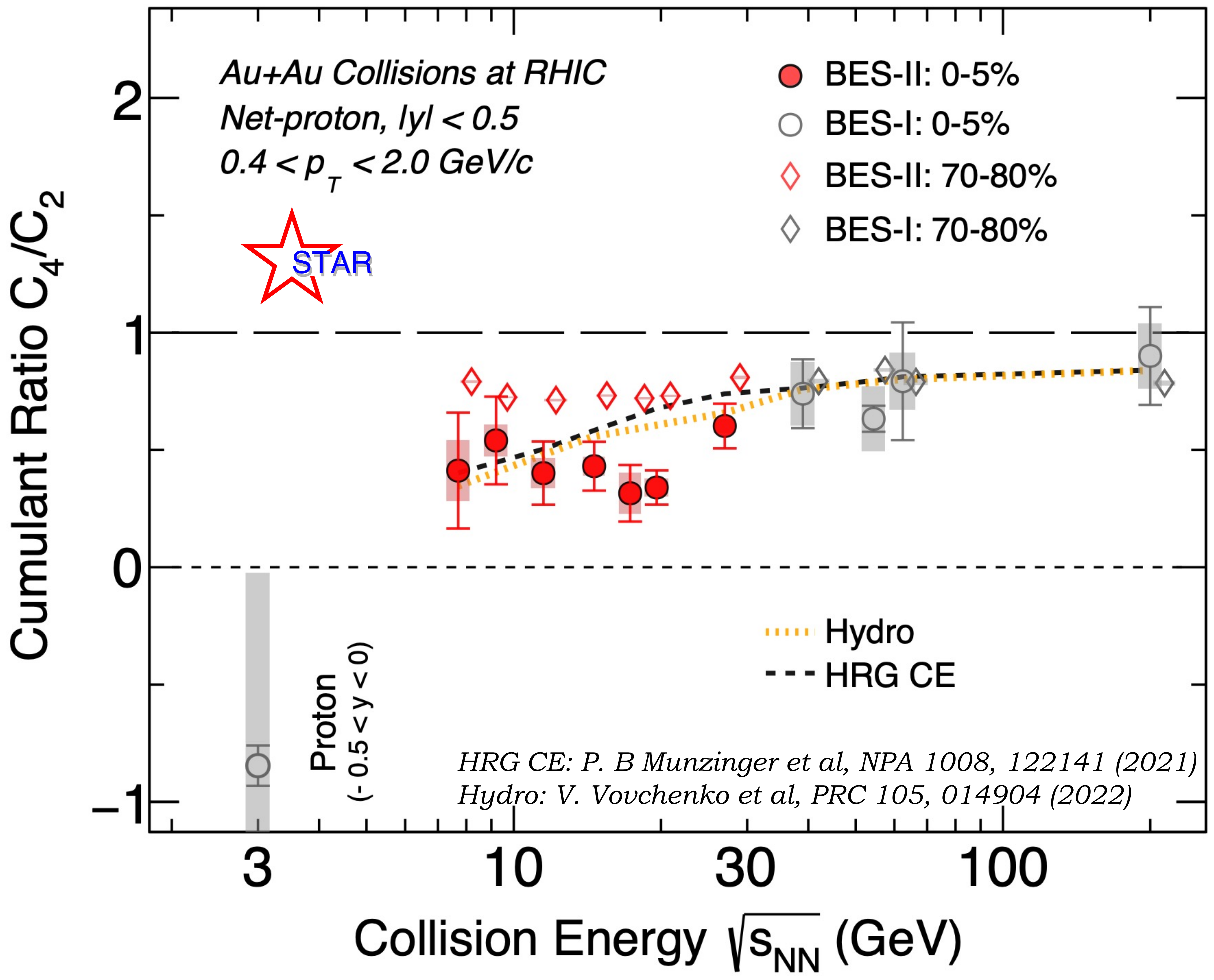
Energy Dependence of C_4/C_2



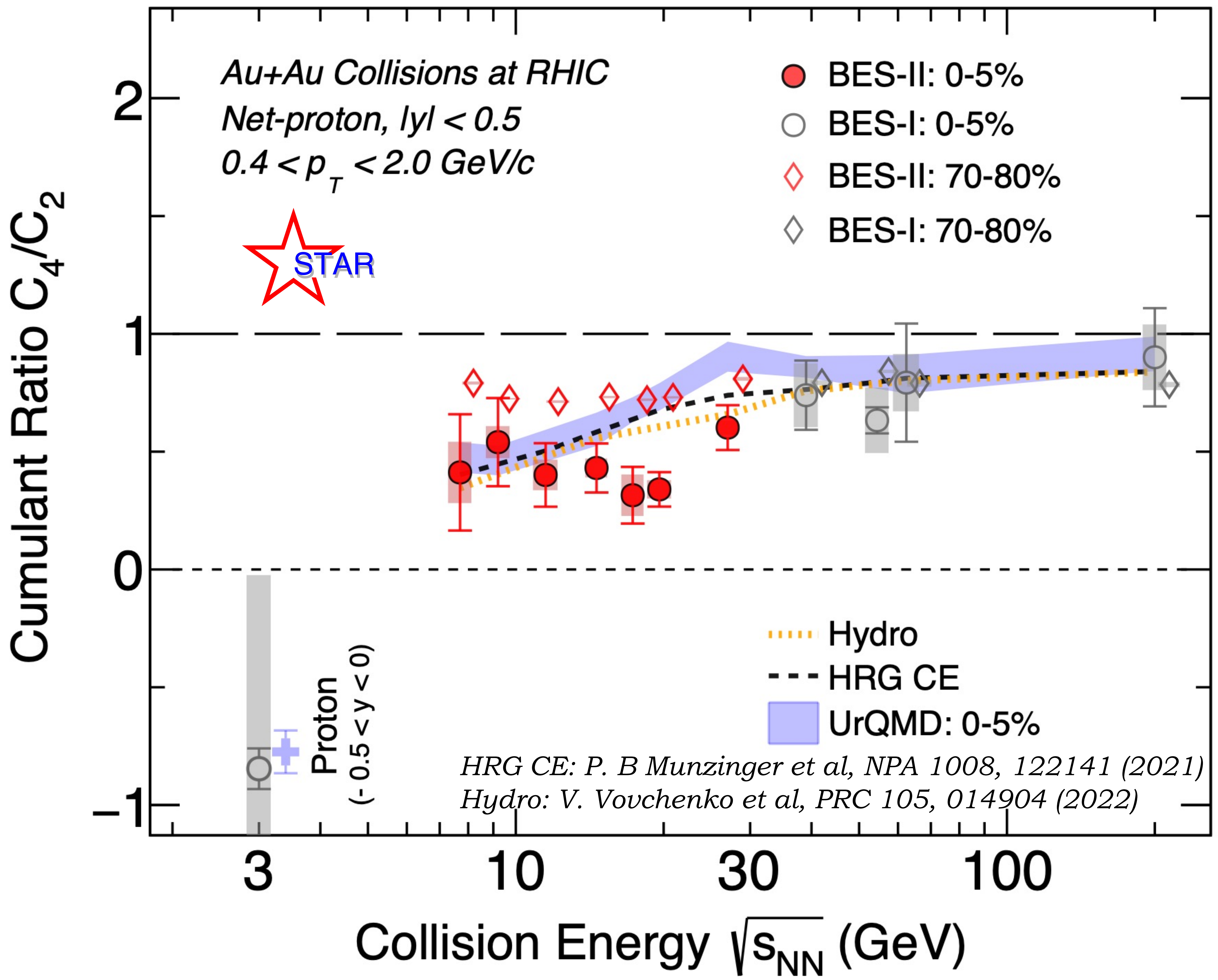
Energy Dependence of C_4/C_2



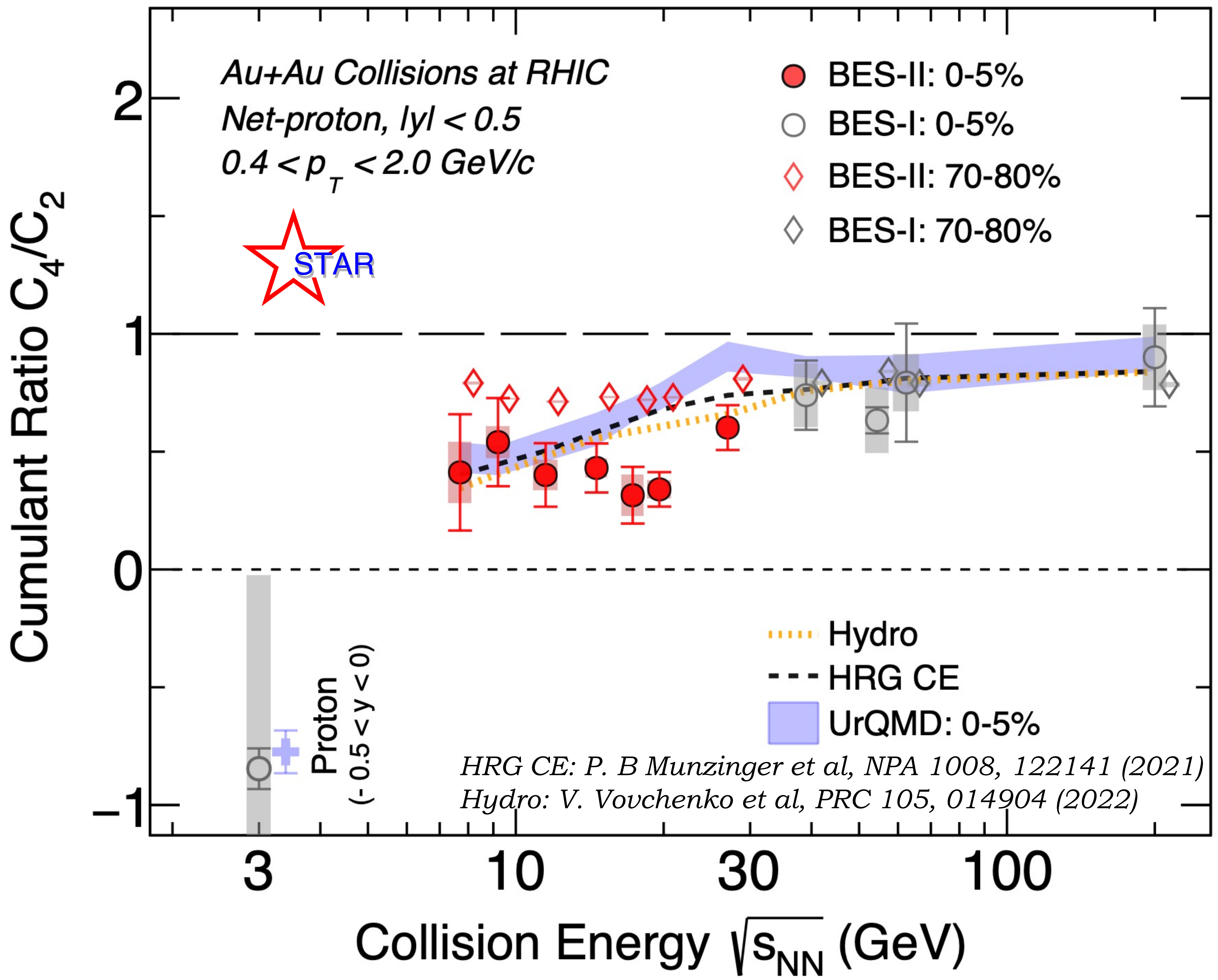
Energy Dependence of C_4/C_2

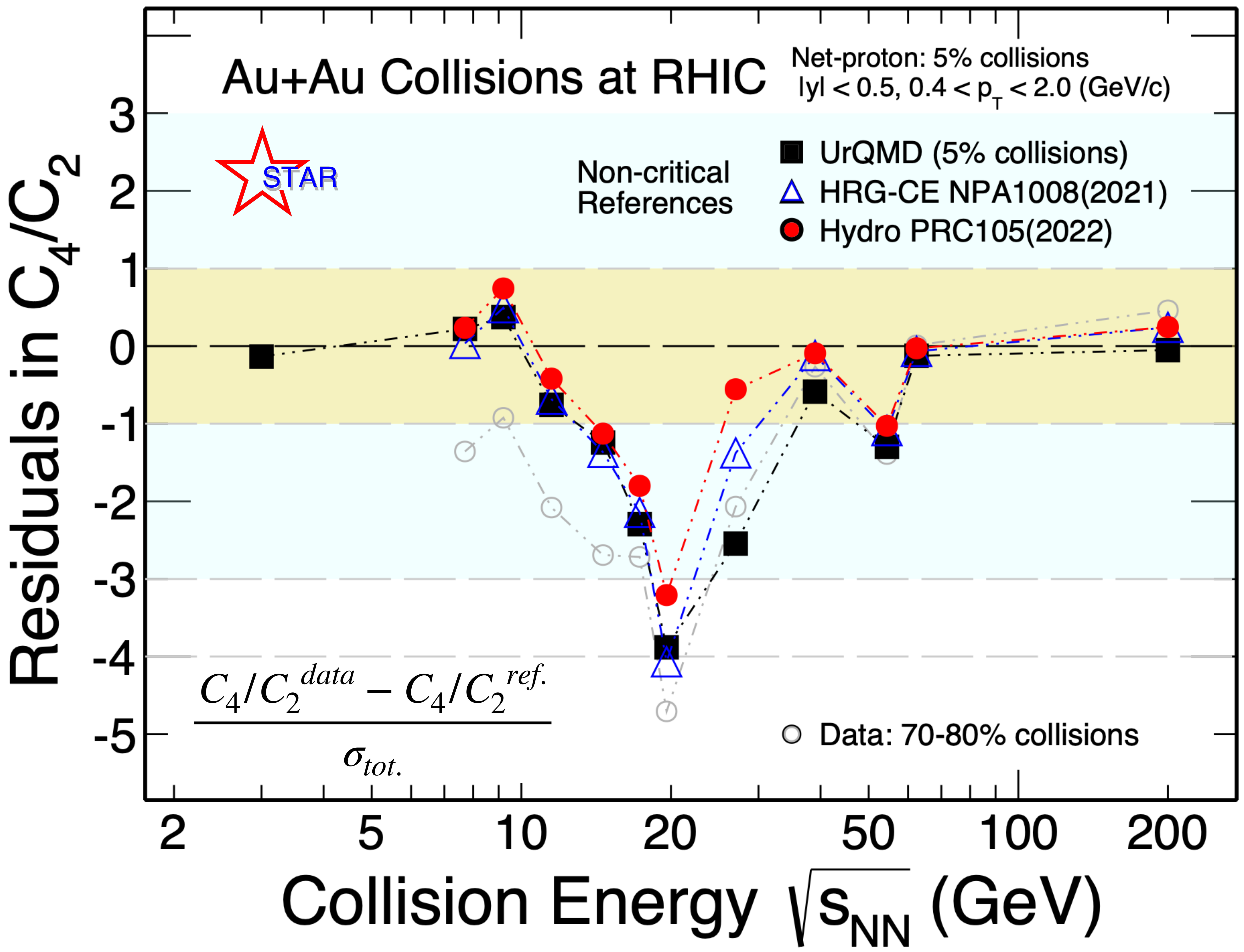


Energy Dependence of C_4/C_2



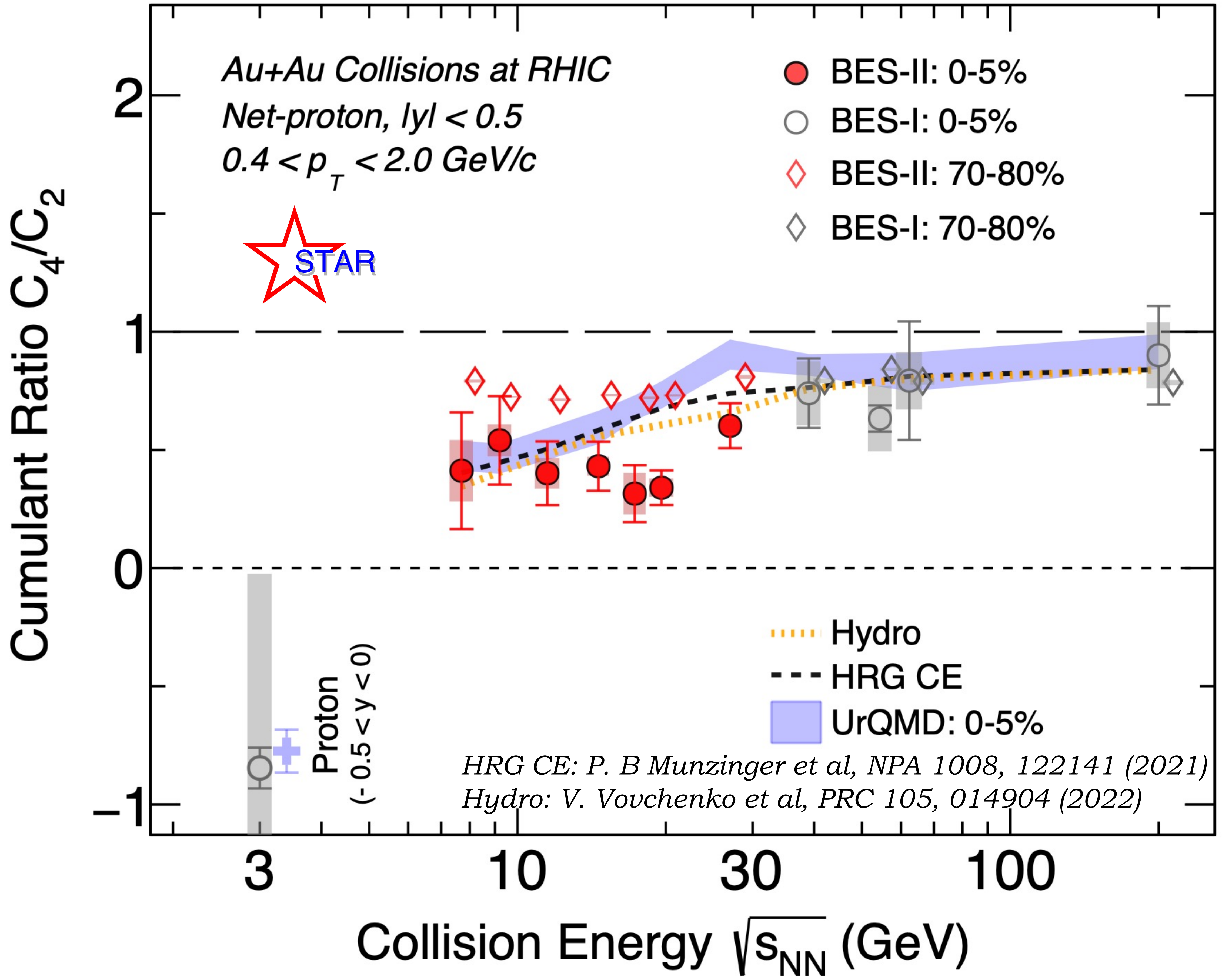
C_4/C_2: Quantifying Deviation from Non-CP Models

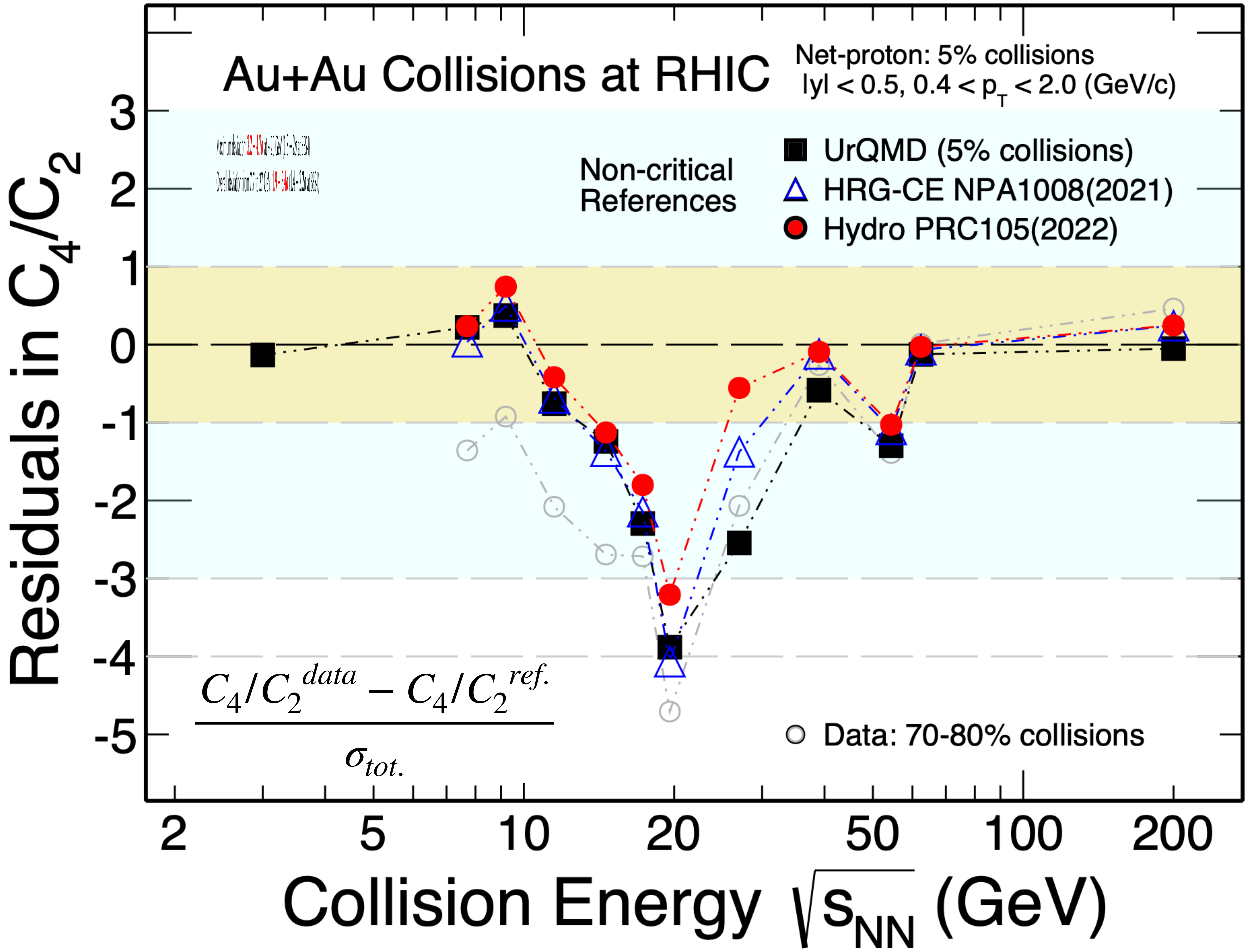




C_4/C_2 shows minimum around ~20 GeV comparing to non-CEP models and 70-80% data.

C_4/C_2: Quantifying Deviation from Non-CP Models

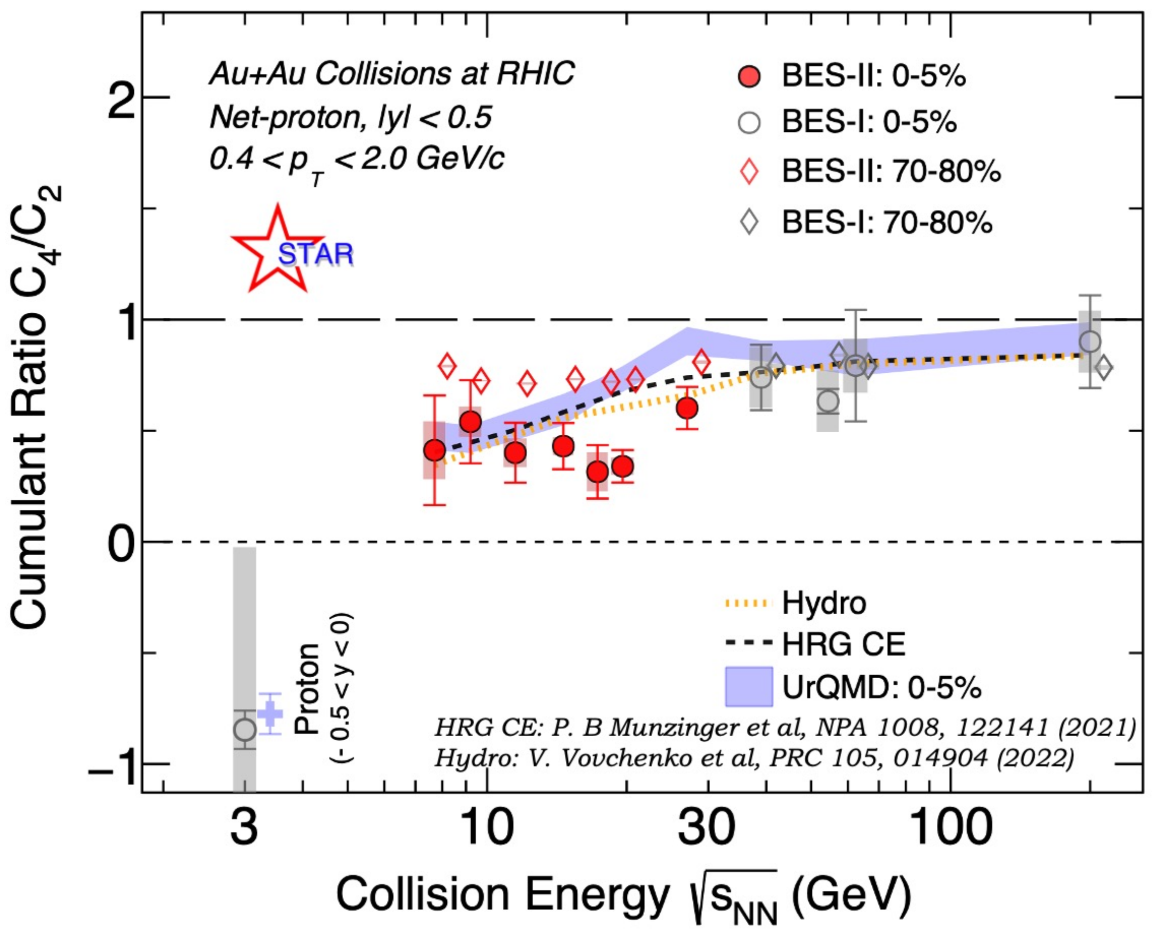


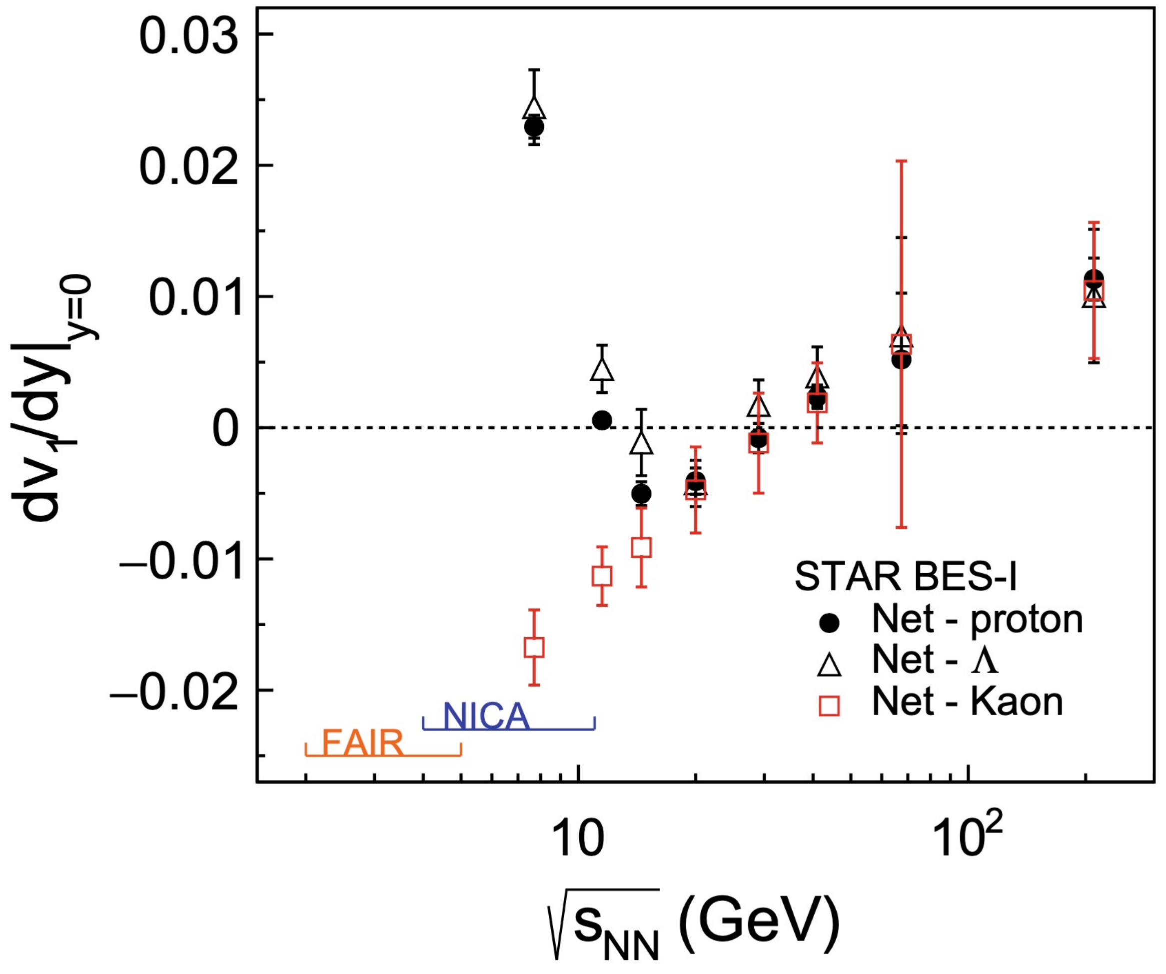


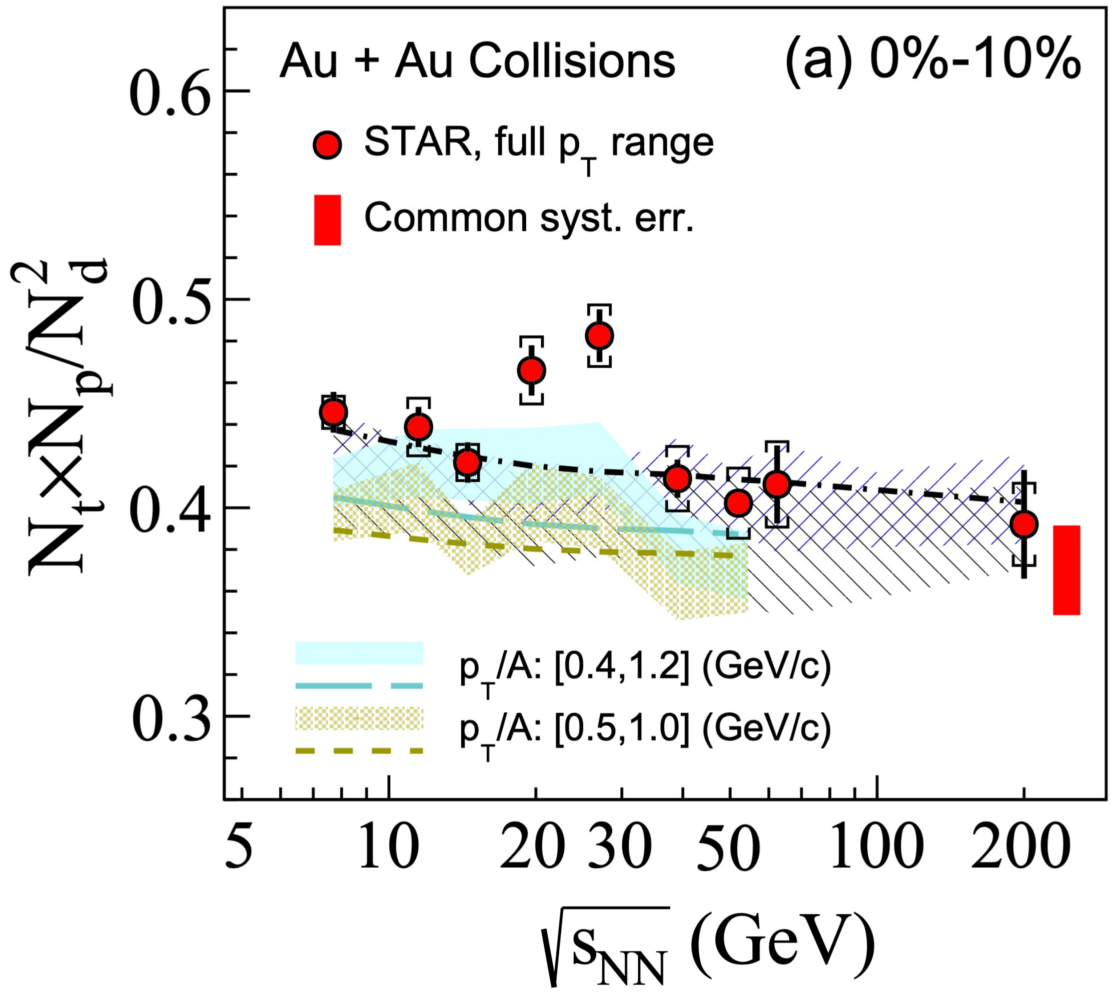
C_4/C_2 shows minimum around ~20 GeV comparing to non-CEP models and 70-80% data.

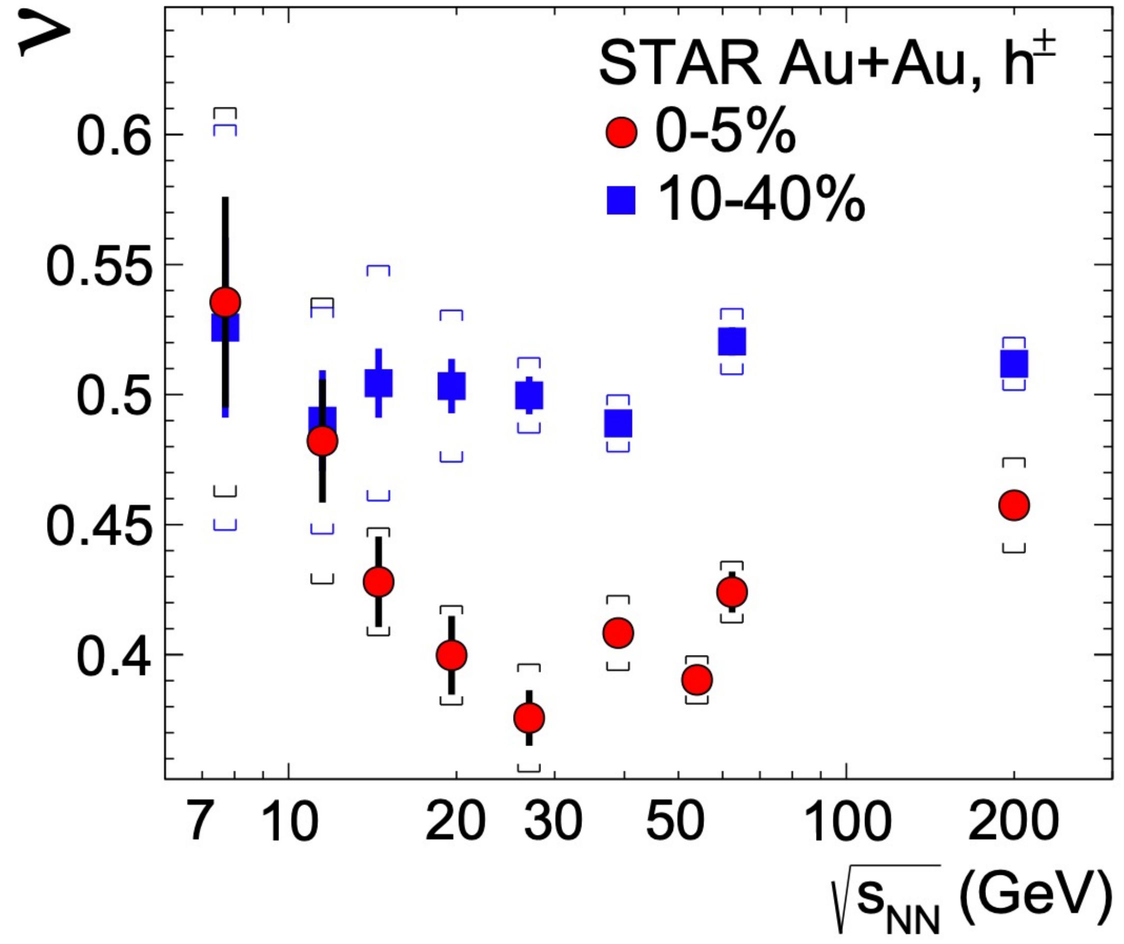
- Maximum deviation: $3.2 - 4.7\sigma$ at ~ 20 GeV ($1.3 - 2\sigma$ at BES-I)
- Overall deviation from 7.7 to 27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

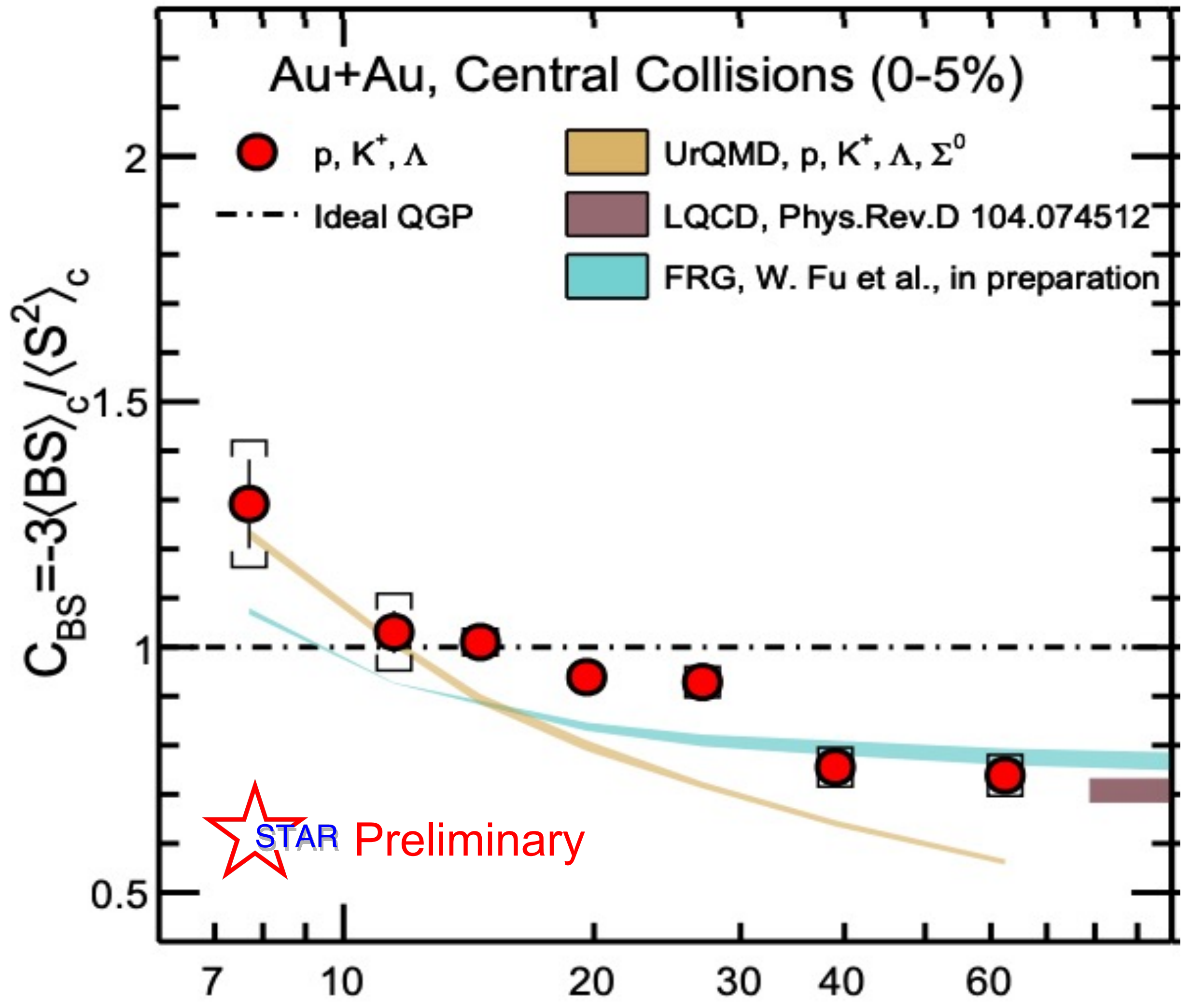
Independent Observables: Common Structure











Common structure seen for all the independent measurements:
- Non-monotonic distributions vs. collision energy.
- Peak or dip structure around 20 – 30 GeV w.r.t non-CEP model.

Direct flow slope: *STAR PRL 112, 162301 (2014), PRL 120, 062301 (2018)*

Light nuclei yield ratio: *STAR PRL 130, 202301 (2023)*

Charged particle intermittency: *STAR PLB 845 (2023)*

Baryon-Strangeness Correlation: *Hanwen Feng, CPOD 2024*

Summary and Outlook

Summary:

- Precision measurement of net-proton number fluctuations vs . centrality and collision energy in Au+Au collisions from STAR BES-II reported. Compared to BES-I, we have
  better statistical precision, better centrality resolution, better control on systematics!

- Net-proton C_4/C_2 in 0-5% central collisions show a maximum deviation in 0-5% data w.r.t. various non-CEP model calculations and 70-80% data is observed at $\sqrt{s_{NN}}$ = 20 GeV with a significance level of $3.2 - 4.7\sigma$.

Outlook:

- Extend measurements to even higher orders of fluctuations: $C_n, \kappa_n (n = 1 - 6)$.

- Examine transverse momentum dependence and rapidity dependence of fluctuations.

- Complete the measurements in Au+Au collisions at fixed target (FXT) energies.

Acknowledgements

RHIC operation for successfully completing collection of BES-II data,

Tremendous work from the analysis group,

Organizers for giving this opportunity.

Thank you for your attention !