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

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Lawrence Berkeley National Laboratory
May 28, 2024

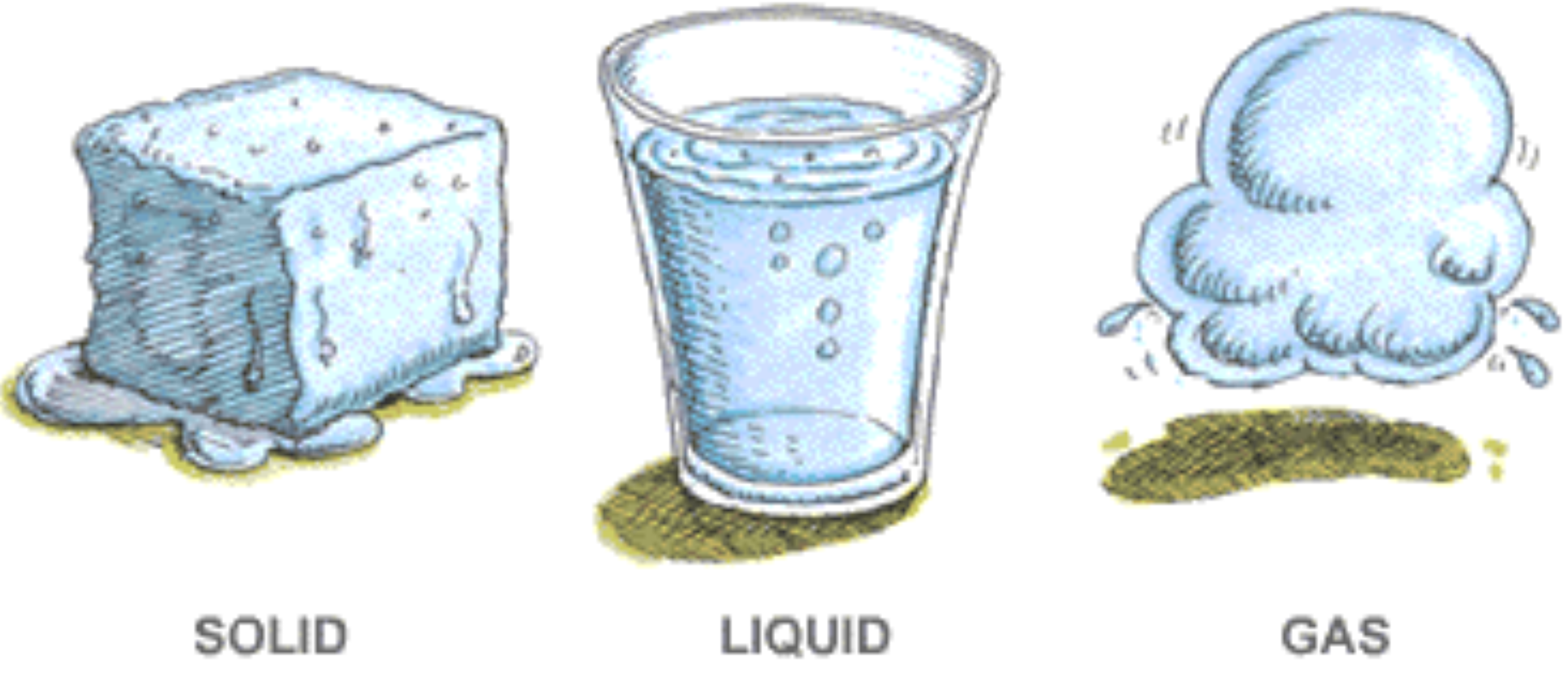
RHIC-BES
Online Seminar

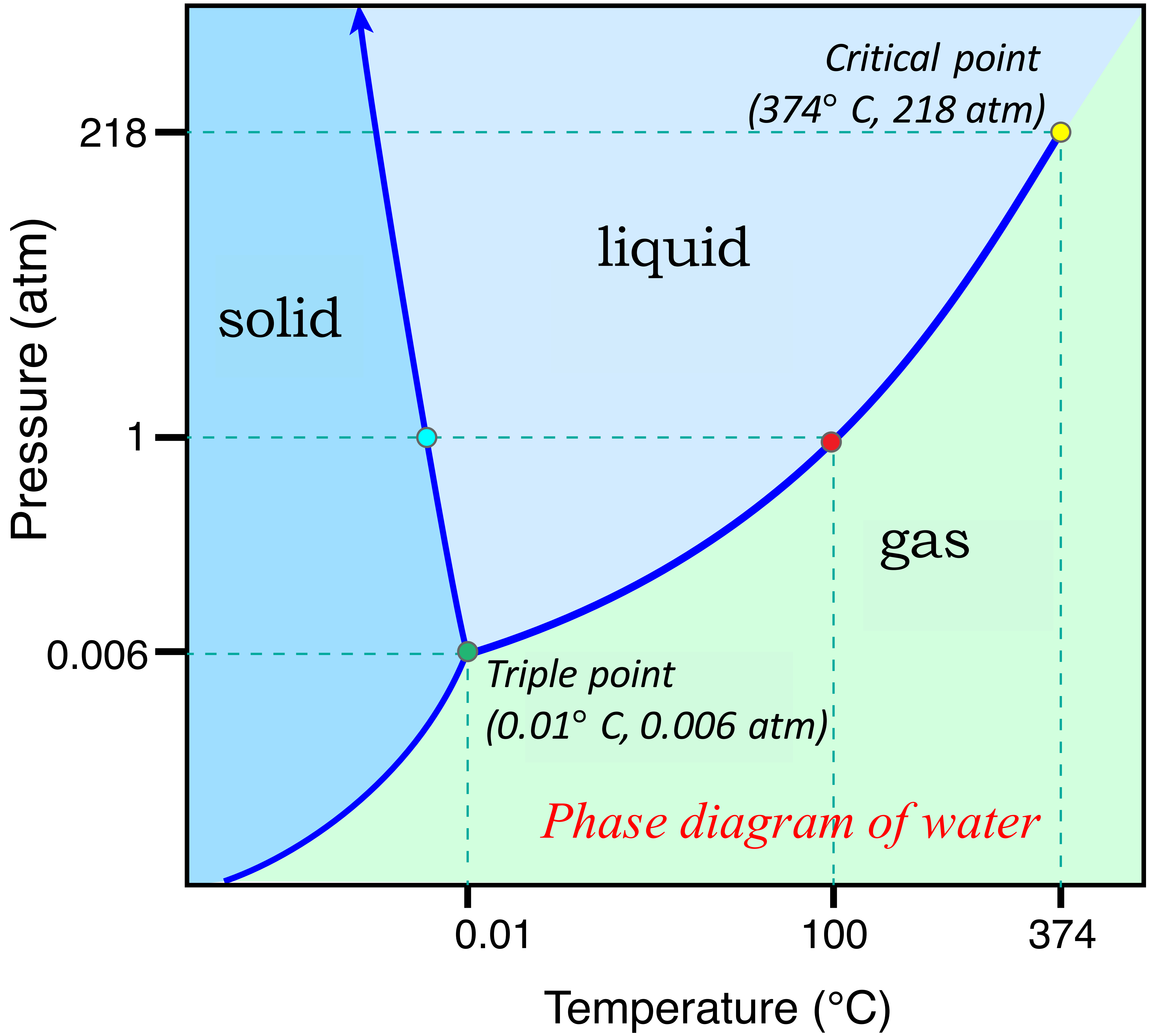
BERKELEY LAB

STAR

Outline

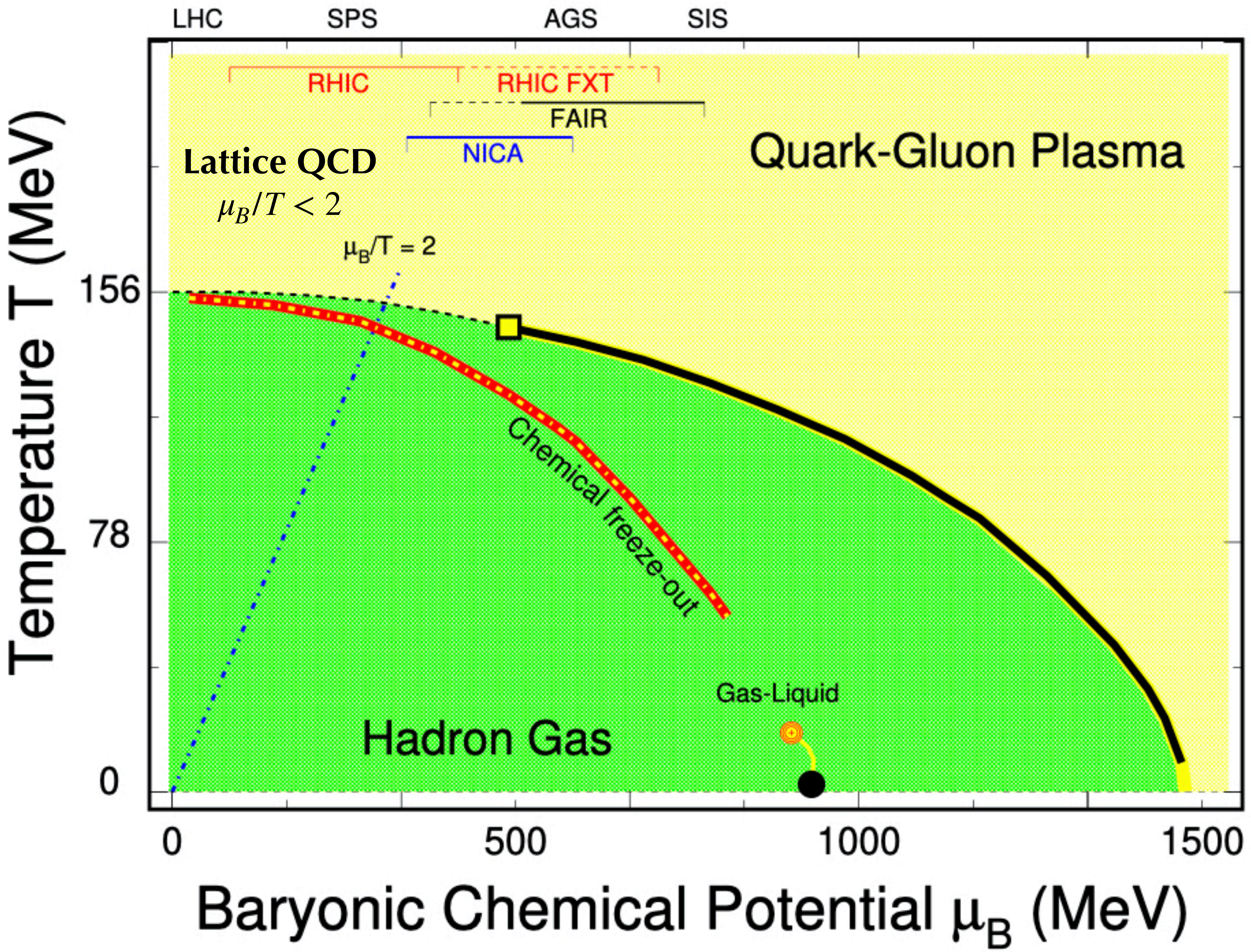
Introduction: Phase Transition in water





- ☐ Underlying interaction electromagnetic
- ☐ Precise understanding available

Introduction: QCD Phase Diagram



B. Mohanty, N. Xu, arXiv:2101.09210

Lattice QCD →

Models →

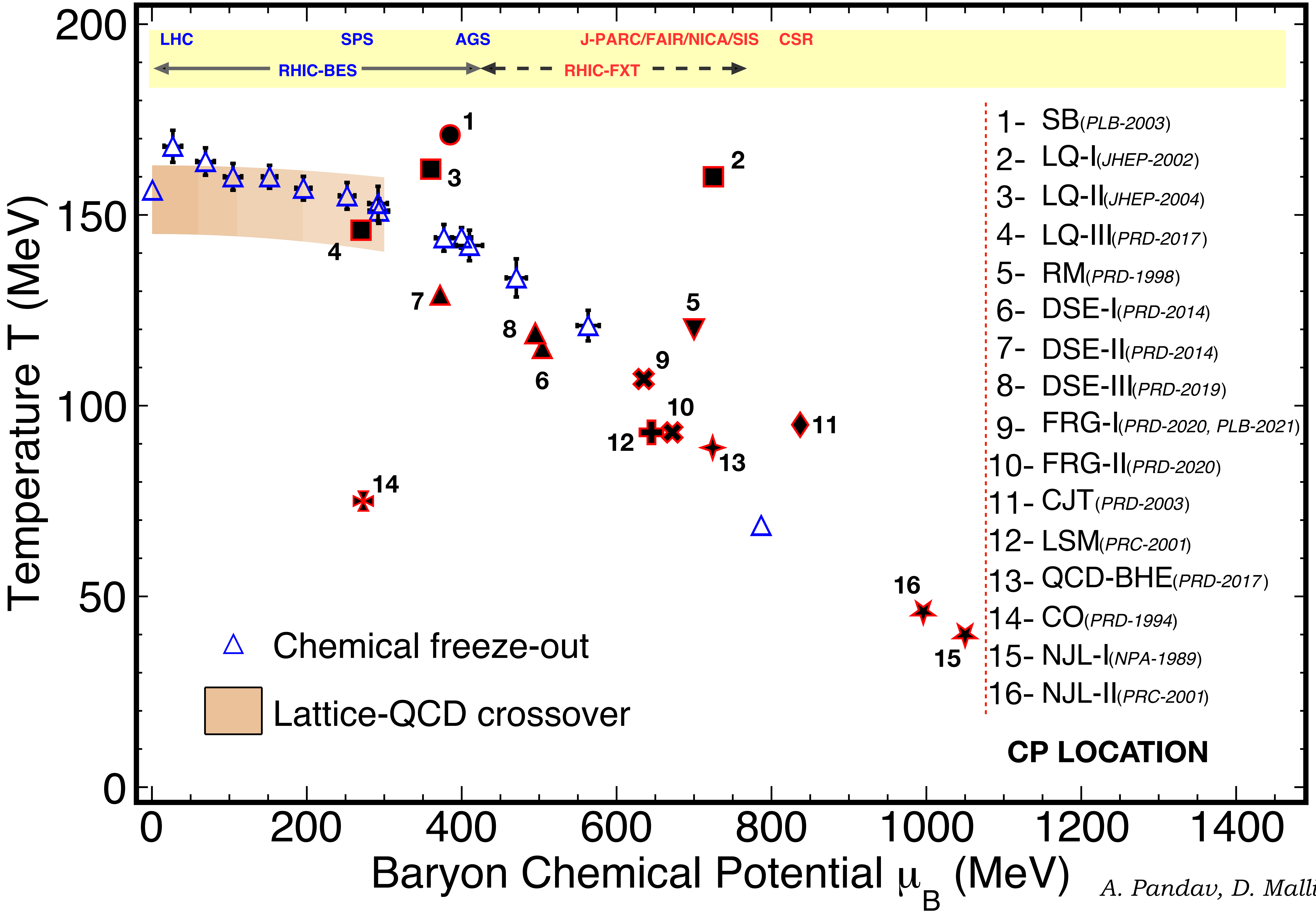
Phase structure:

- QGP and hadronic phase ✓
- Transition temperature (T_c) ✓
- Crossover at small μ_B ($\frac{\mu_B}{T} < 2$) ✓
- 1st order P.T. at large μ_B ?
- **Critical end point** ?

☐ Phase diagram of strongly interacting matter

☐ Largely conjectured

Introduction: QCD Critical Point

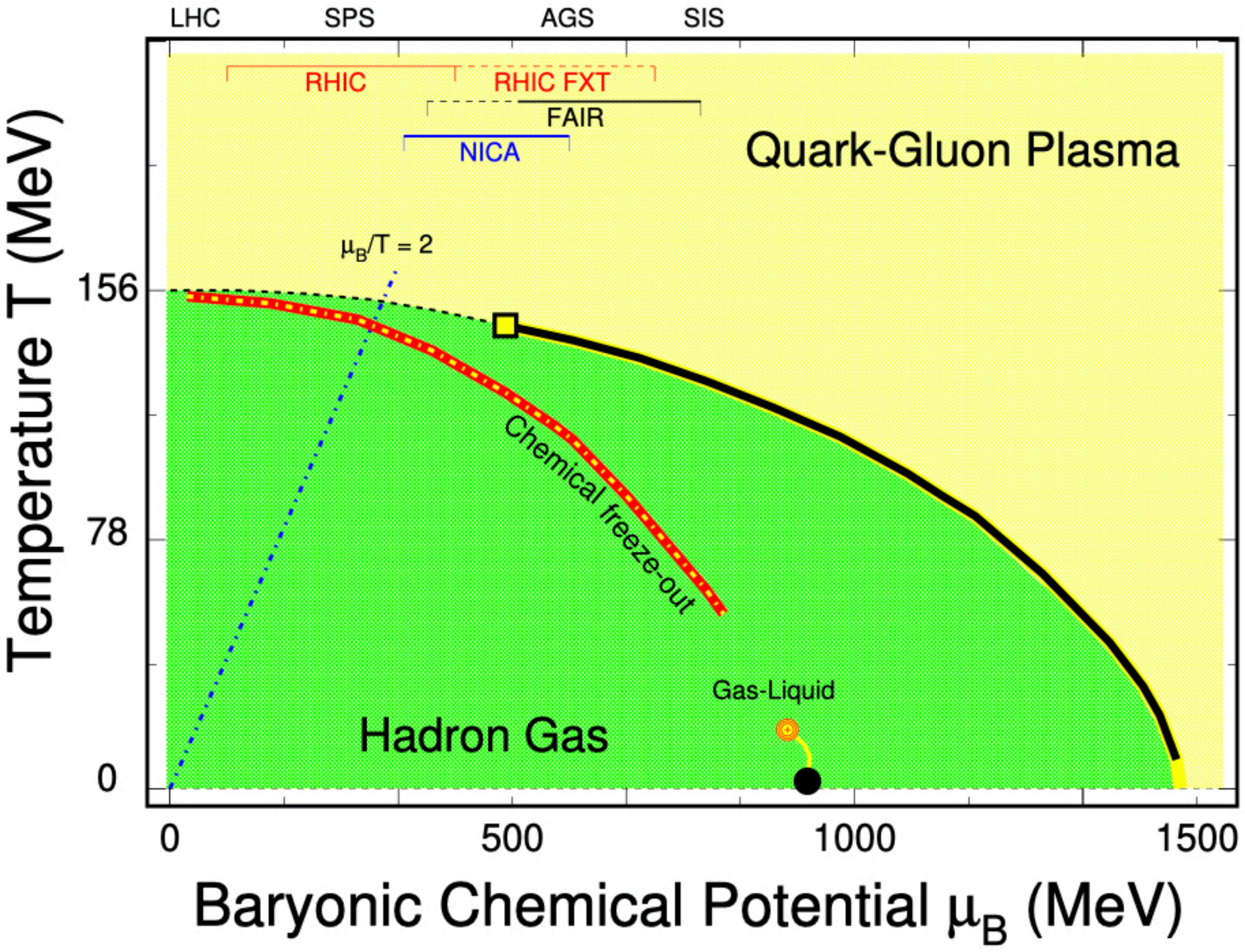


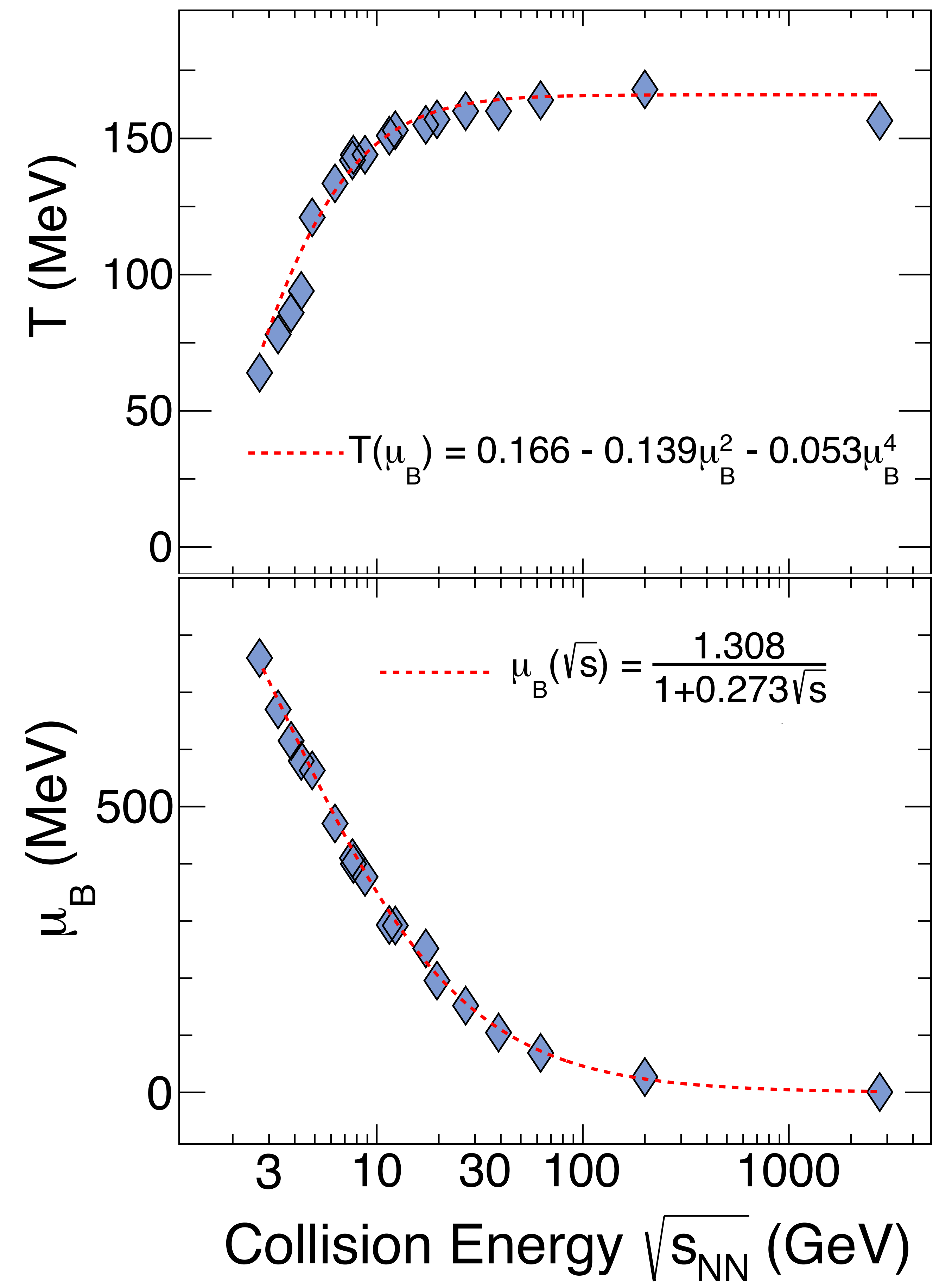
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

- Lattice calculations at high μ_B suffer from sign problem
- Effective models have several underlying assumptions/ approximations

☐ Theory predictions in $\mu_B - T$ plane. **Experimental search very important.**

Introduction: Experimentally accessing Phase Diagram



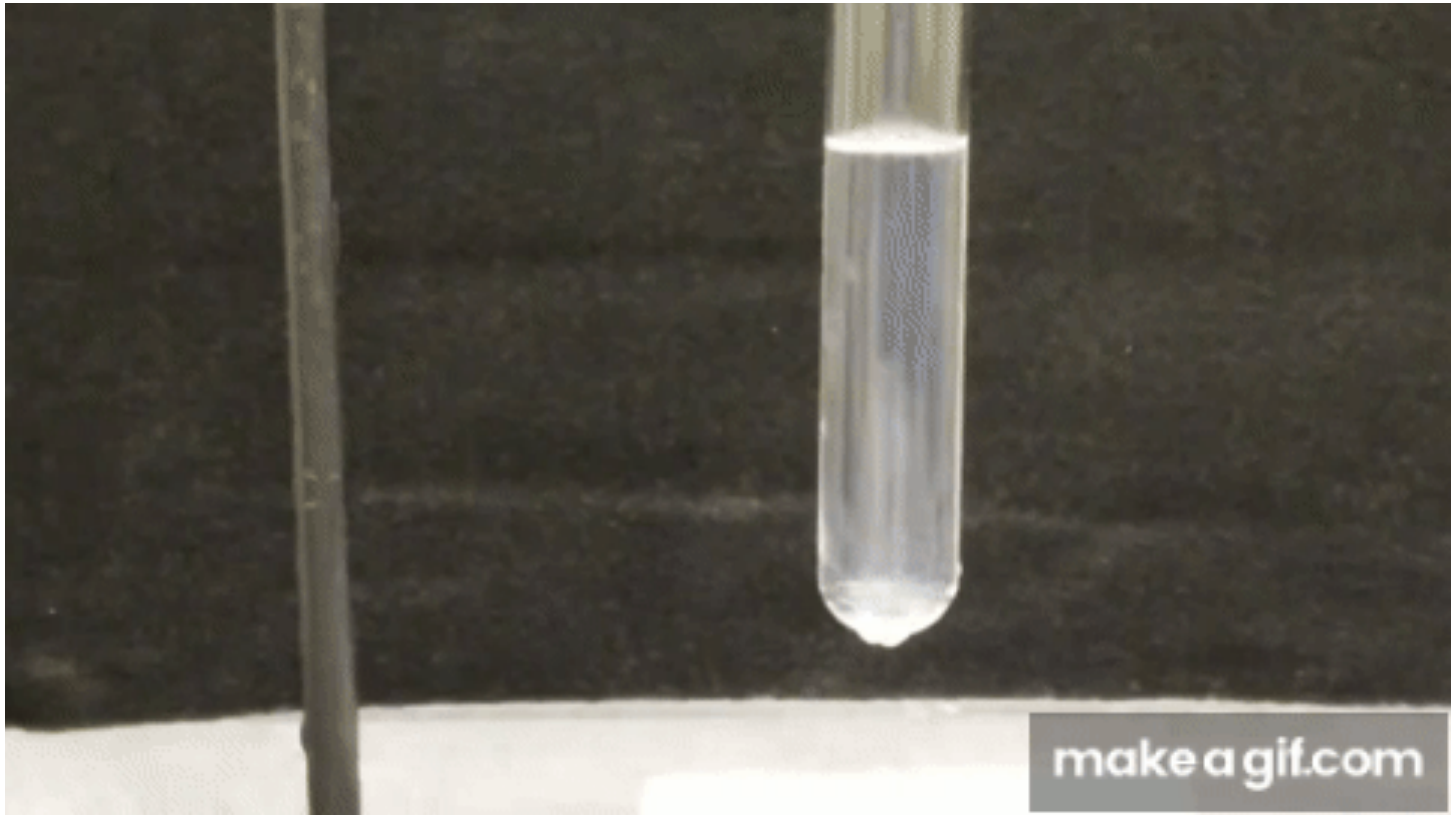


B. Mohanty, N. Xu, arXiv:2101.09210, A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)

P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302

- Varying collision energy, impact parameter, rapidity acceptance, collision species, varies T and μ_B of system created
- Study energy/centrality/rapidity/species dependence of CP sensitive observables

Fluctuations near CP:



Development of long range density fluctuations,

Divergence of correlation length, thermodynamic response functions (susceptibility, compressibility etc)

Enhanced fluctuations expected near CP.

How to quantify fluctuations? measure cumulants.

Critical Opalescence: CO_2 appears milky white

T. Andrews. Phil. Trans. Royal Soc.,1869, 159:575.

Cumulants:

- Cumulants: $n =$ ***net-proton multiplicity in an event***

$$C_1 = < n >$$

$$C_2 = < \delta n^2 >$$

$*\delta n = n - < n >$

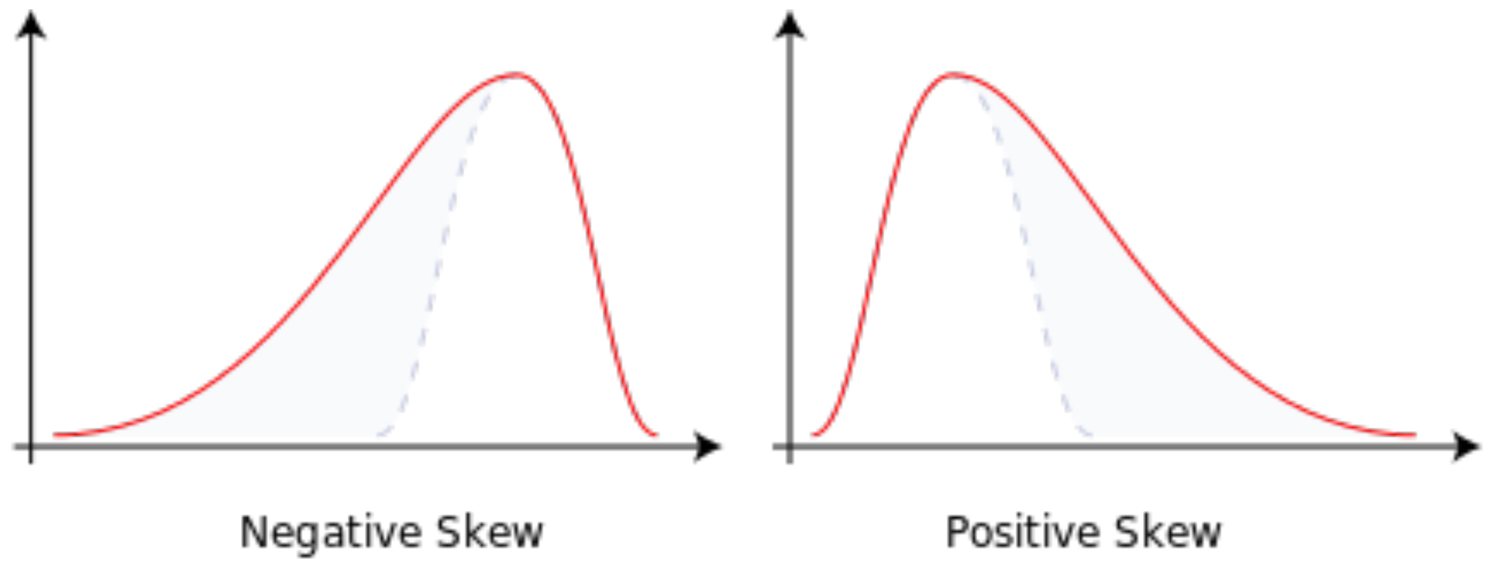
$$C_3 = < \delta n^3 >$$

$$C_4 = < \delta n^4 > - 3 < \delta n^2 >$$

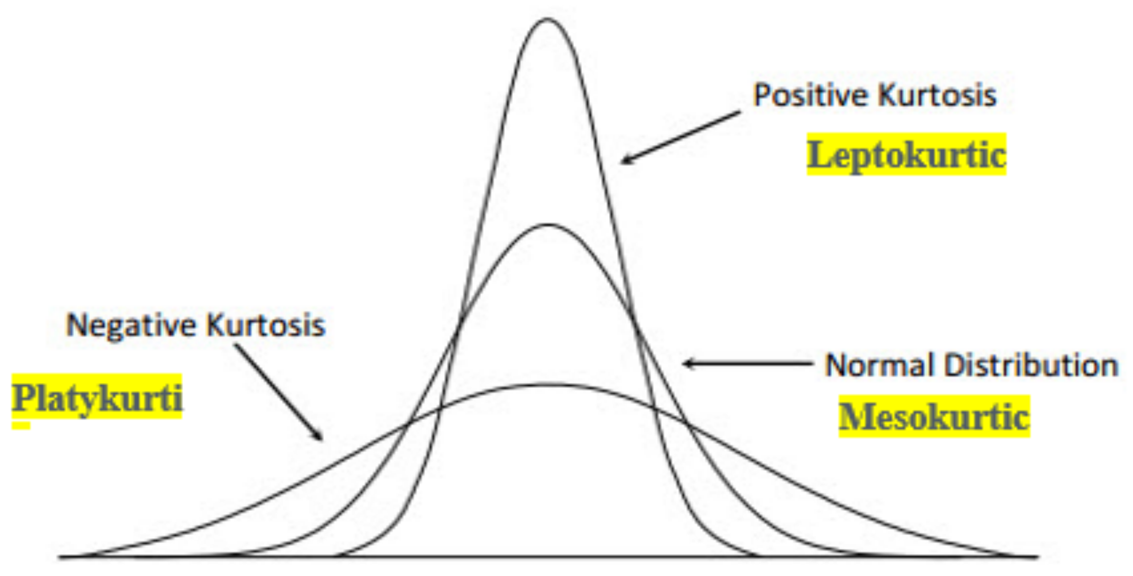
$$C_5 = < \delta n^5 > - 10 < \delta n^3 > < \delta n^2 >$$

$$C_6 = < \delta n^6 > - 15 < \delta n^4 > < \delta n^2 > - 10 < \delta n^3 >^2 + 30 < \delta n^2 >^3$$

Skewness: Asymmetry



Kurtosis: Peakedness



- Factorial cumulants (irreducible correlation function):

$$\kappa_1 = C_1$$

$$\kappa_2 = - C_1 + C_2$$

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

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

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

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

Cumulants and CP Search:

Related to correlation length: $C_2 \sim \xi^2, C_4 \sim \xi^7$

Finite size/time effects reduces ξ

Higher order ⟶ more sensitivity

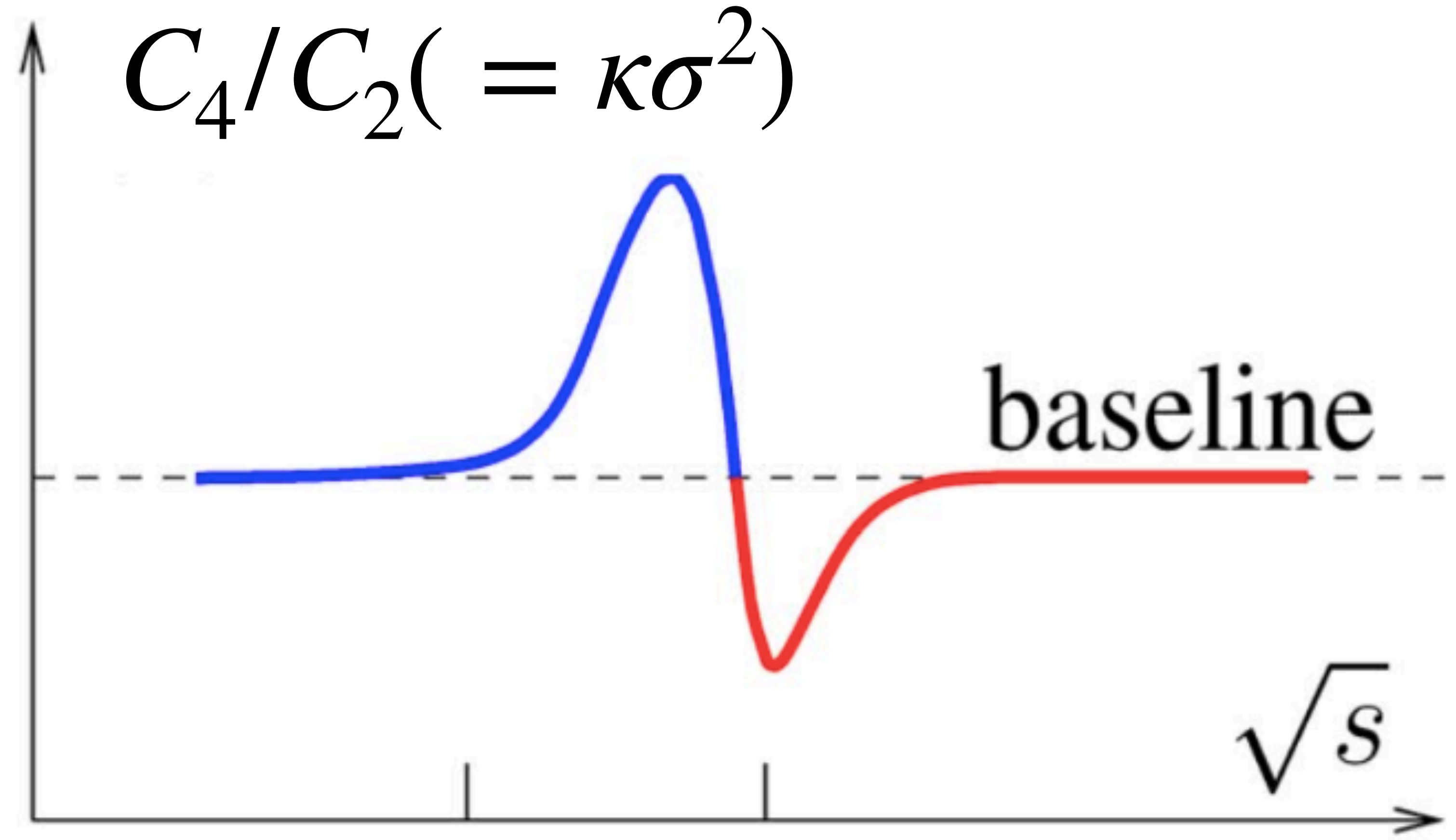
$q = B, Q, S$

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

Direct comparison with lattice QCD, HRG, QCD-based model calculations

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)*

CP search



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

Assumption: Thermodynamic equilibrium

Non-monotonic $\sqrt{s_{NN}}$ **dependence** of C_4/C_2 of conserved quantity - **existence of a critical region**

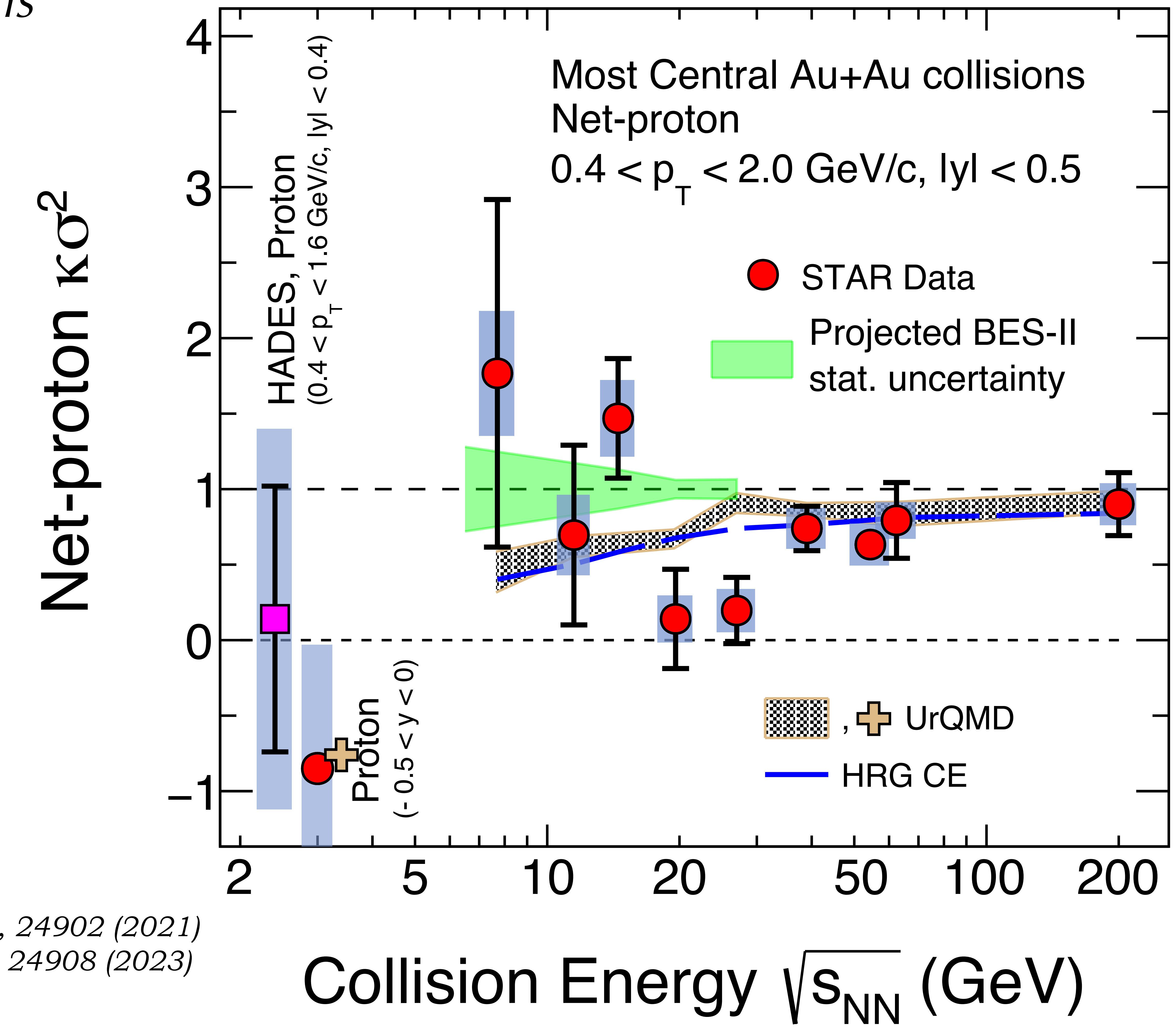
Experimental search for CP: BES Scan at STAR-RHIC

Phase I of BES program (BES-I): *Au+Au collisions*

J. Cleymans, et. al, PRC. 73, 034905 (2006)

$\sqrt{s_{NN}}$ (GeV)	Events (10^6)	μ_B (MeV)
200	220	25
62.4	43	75
54.4	550	85
39	92	112
27	31	156
19.6	14	206
14.5	14	262
11.5	7	316
7.7	2.2	420
3.0	140	750

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



Observed hint of non-monotonic trend in BES-I (3 σ): consistent with model expectation with a CP
Robust conclusion require confirmation from precision measurement from BES-II.
Extend reach to even lower collision energies with FXT energies

STAR BES-II Program: Precision Measurements

Au+Au Collisions at RHIC							
Collider Runs				**Fixed-Target Runs**			
Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)	Sl. no.	$\sqrt{s_{NN}}$ (GeV)	No. of collected events (millions)	μ_B (MeV)
1	**200**	380	**25**	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
				12	**3.0** (3.85)	**260** + 2000	**750**

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

High precision, widest μ_B coverage to date

STAR BES-II Program: Precision Measurements

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Au+Au Collisions at RHIC

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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**

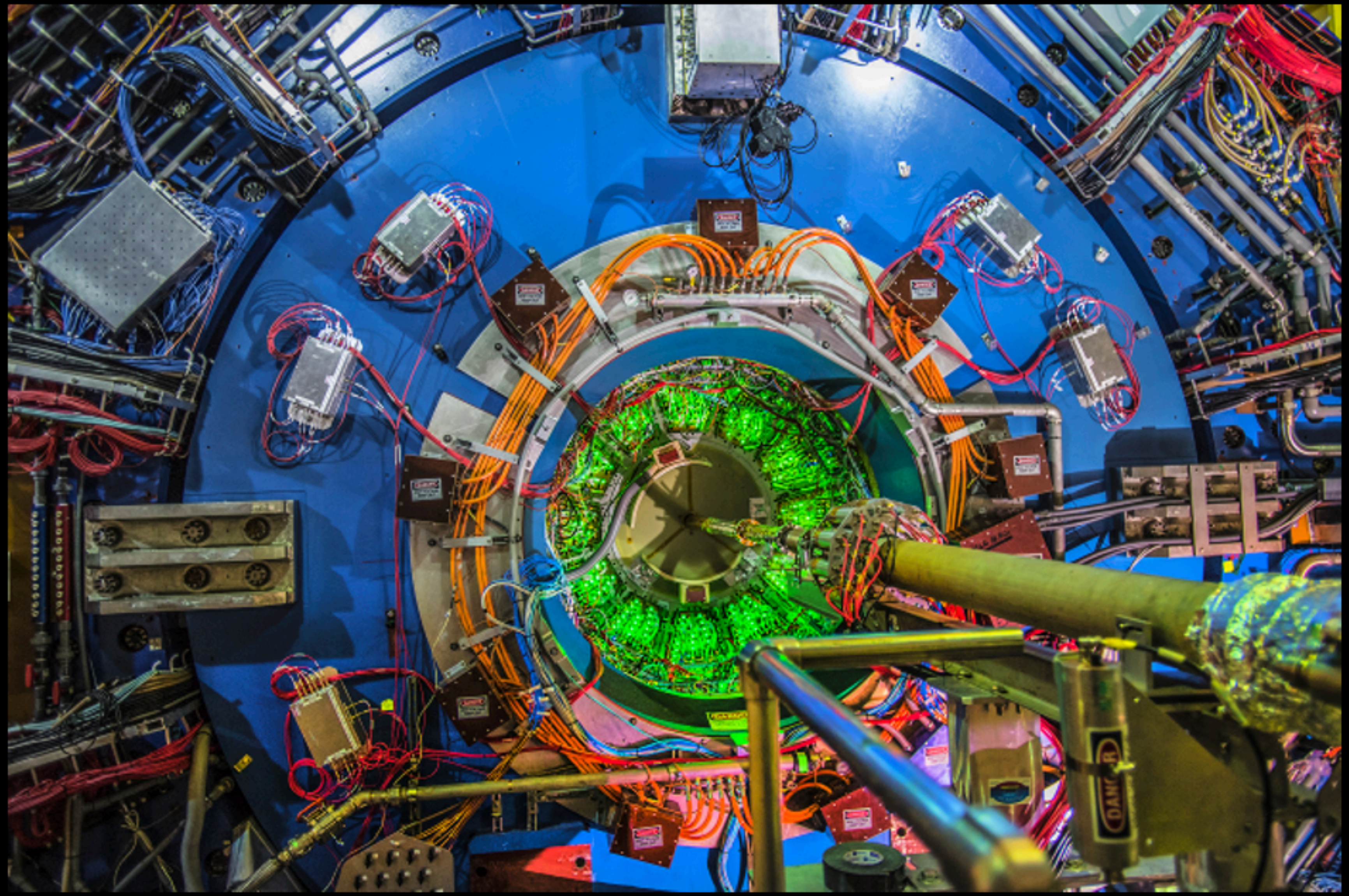
~10-18 fold improvement in statistics
9.2 and 17.3 GeV added to energy scan

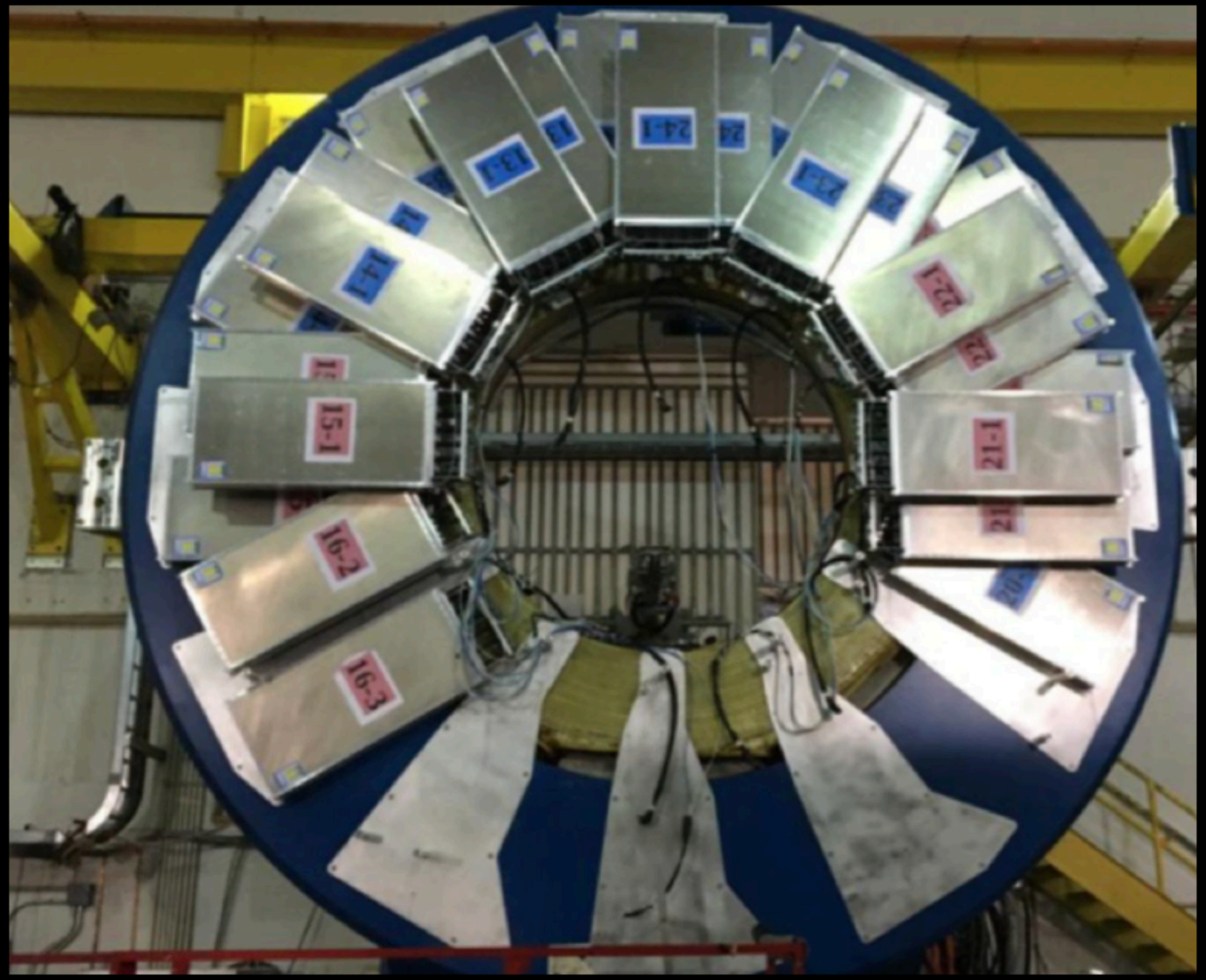
$$3 \leq \sqrt{s_{NN}}\ (GeV) \leq 200 \ \rightarrow 750 \geq \mu_B\ (MeV) \geq 25$$

High precision, widest μ_B coverage to date

STAR Detector: BES-II Upgrade

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

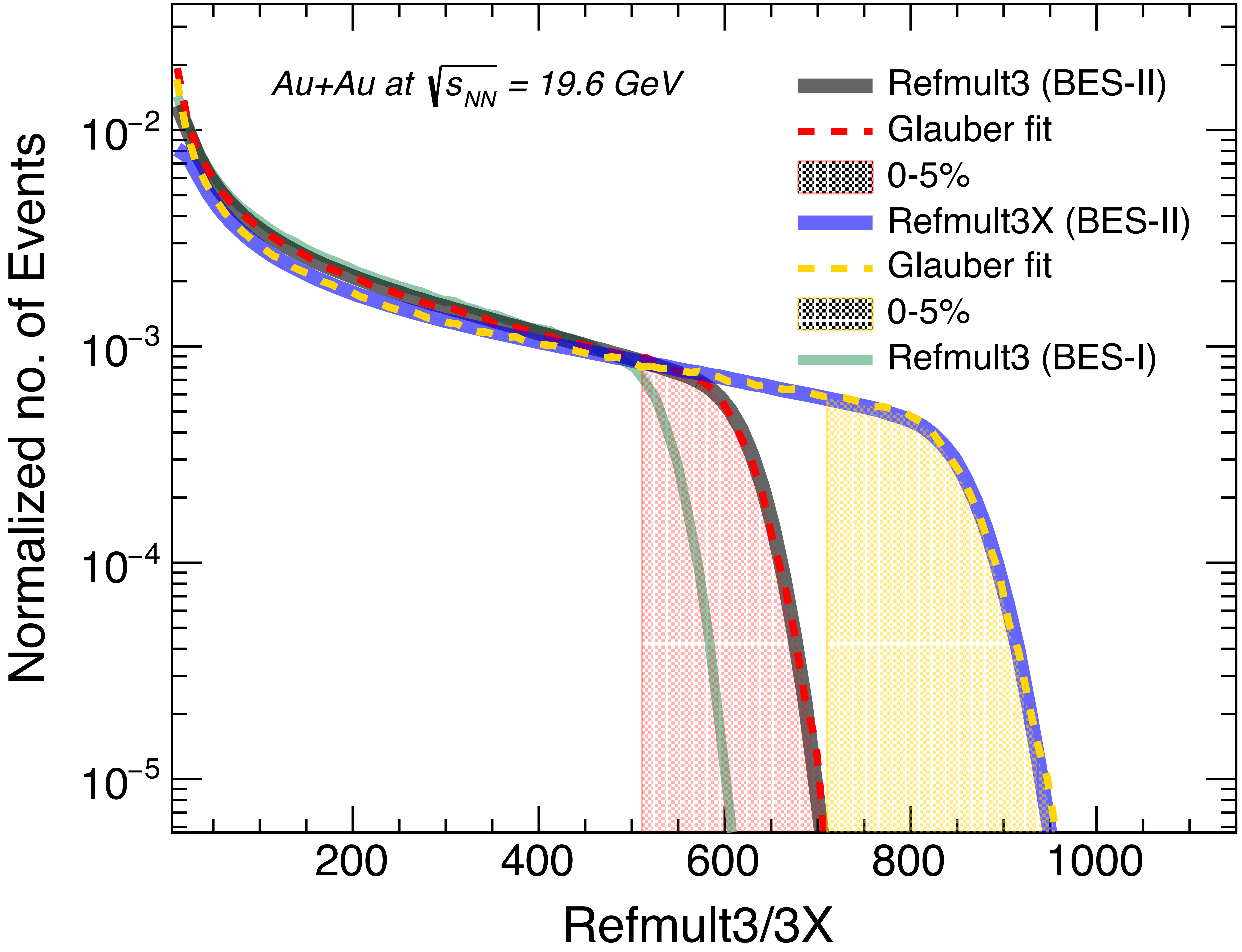
eTOF:
- Forward rapidity coverage
- PID at η = 1.05 to 1.5
- Borrowed from CBM-FAIR
- Ready in 2019

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:

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



Two choices of centrality

Refmult3: Charged particle multiplicity excluding protons measured within $|\eta| < 1.0$

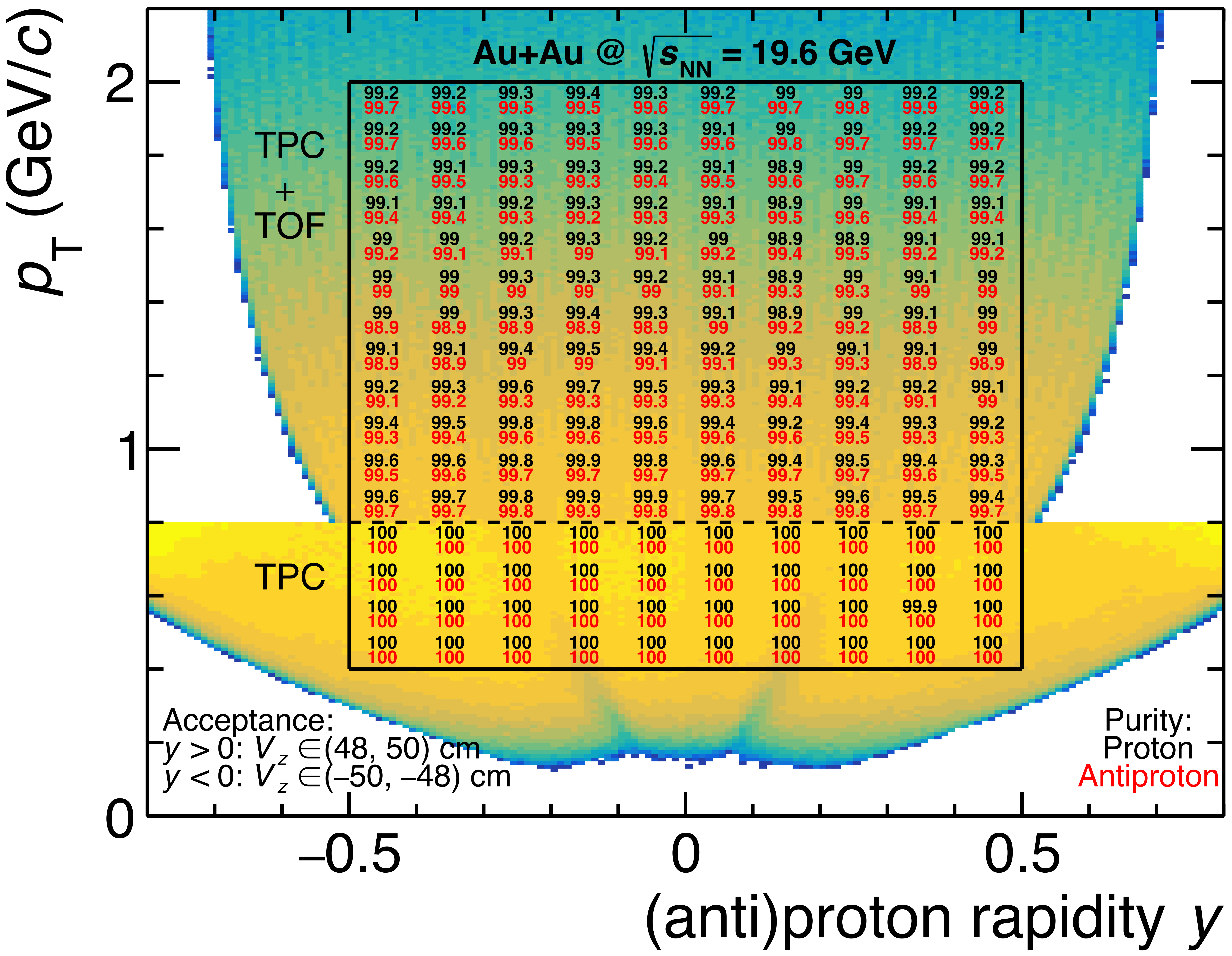
Refmult3X: Charged particle multiplicity excluding protons measured within $|\eta| < 1.6$

Possible due to iTPC upgrade

Larger multiplicity leads to better centrality resolution:

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

Proton Selection:



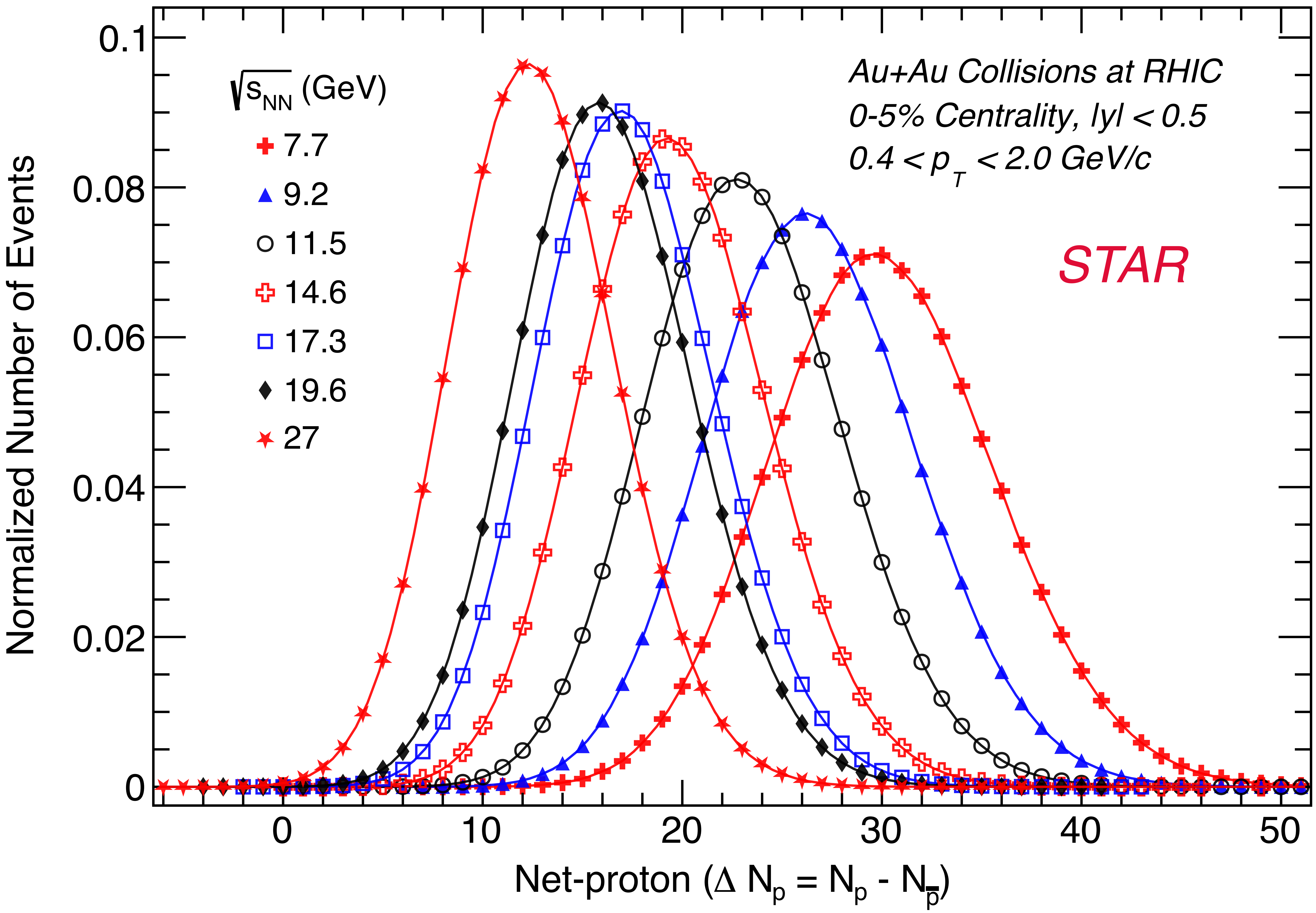
TPC and TOF detector used for identifying protons over
$p_T = 0.4 - 2.0\ GeV/c$, and $|y| < 0.5$

$p_T = 0.4 - 0.8\ GeV/c$ (PID using TPC)
Using dE/dx measurements → $|n\sigma| < 2$

$p_T = 0.8 - 2.0\ GeV/c$ (using TPC+TOF)
In addition to TPC, $mass^2$ from TOF used
→ $0.6 < mass^2 < 1.2\ GeV^2/c^4$

Bin-by-bin
proton/antiproton purity > 99%

Event-by-event Net-proton Distribution:



Raw net-proton distributions from BES-II: Uncorrected for detector efficiency

Mean increases with decreasing collision energy: Effect of baryon stopping

Larger width leads to larger Stat. uncertainties

$$Stat.error\ C_r \propto \frac{\sigma^r}{\sqrt{N}}$$

Corrections:

- Corrected for detector efficiency

Binomial detector efficiency response considered
~10% higher proton efficiency compared to BES-I
Better control on uncertainty on efficiency: 2% compared to 5% in BES-I

- Corrected for PID cut efficiency

$PID_{eff} = S_a/S_{tot}$
S_a = area under $|n\sigma_p| < 2.0$
S_{tot} = total area under $n\sigma_p$ distribution($|n\sigma_p| < 5.0$)

- Corrected for finite centrality bin width

$$C_n = \sum_r w_r C_{n,r}$$
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

Percentage stat. and sys. error in net-proton cumulants at 0-5% centrality

$\sqrt{s_{NN}}$	7.7 GeV		19.6 GeV	
	% stat. error	% sys. error	% stat. error	% sys. error
C_2/C_1	0.1%	0.3%	0.06%	0.3%
C_3/C_2	2.1%	1.3%	0.7%	1%
C_4/C_2	61%	29%	22%	11%

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

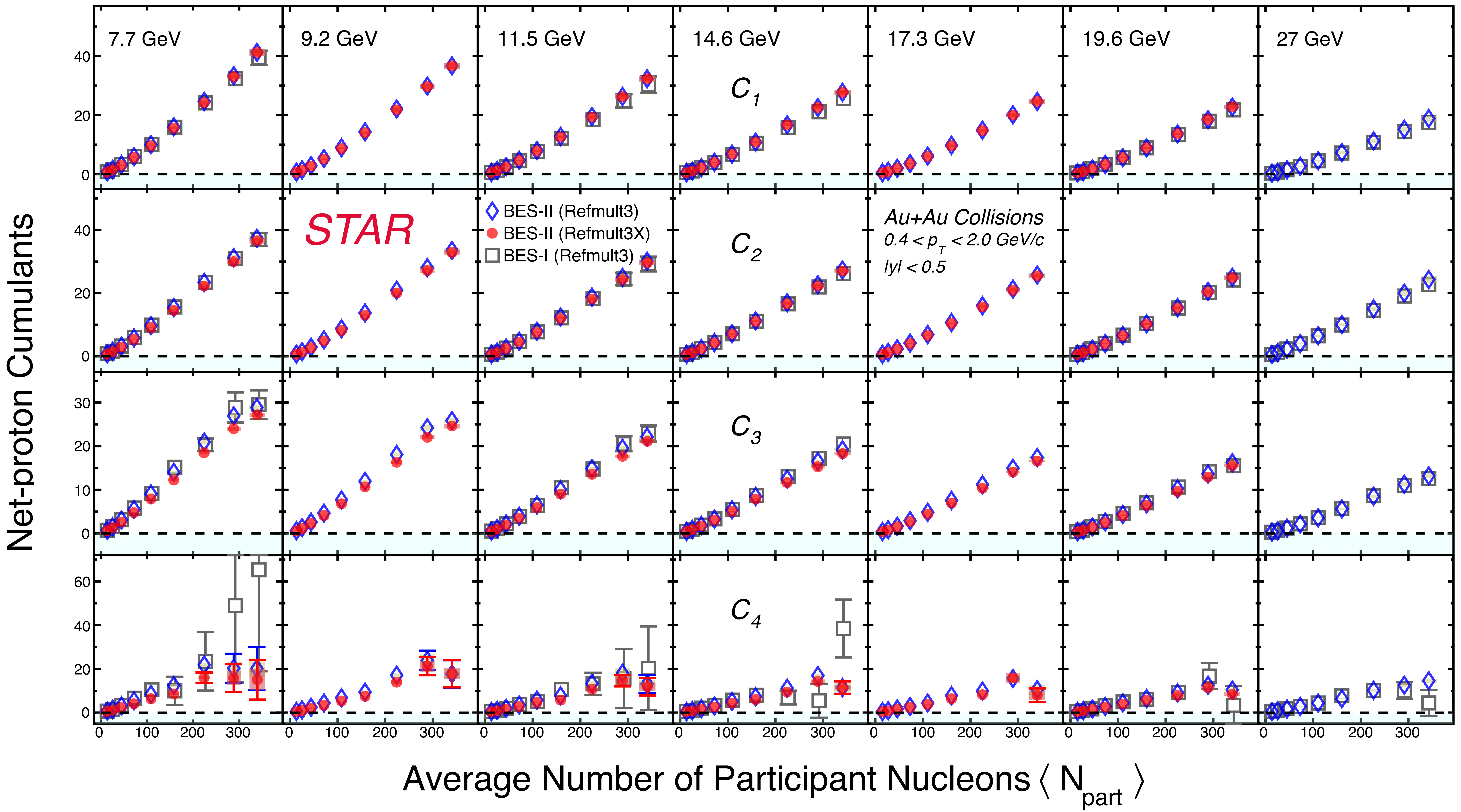
7.7 GeV		19.6 GeV	
stat. error	sys. error	stat. error	sys. error
4.7	3.2	4.5	4

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

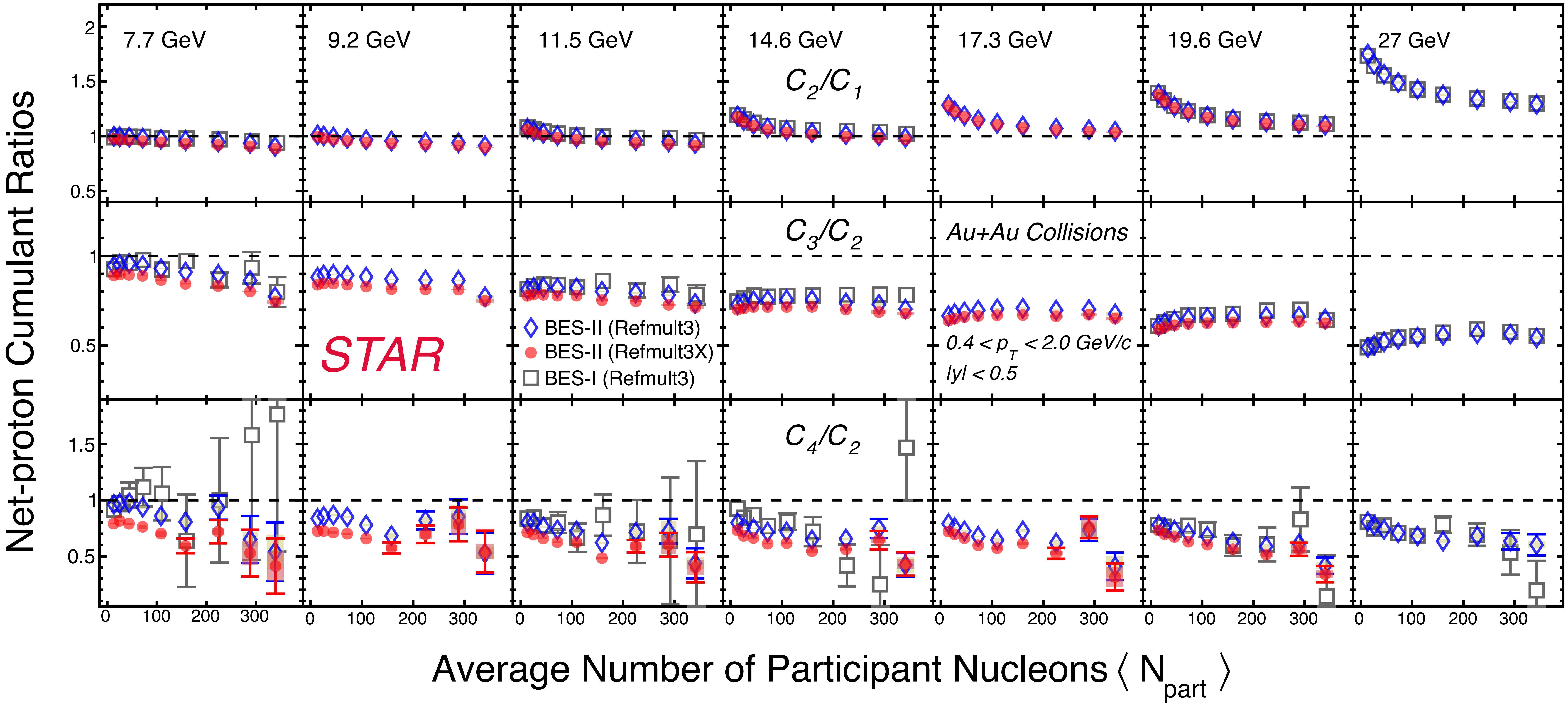
Latest Net-proton Fluctuation

Results from BES-II:

Centrality Dependence and comparison with BES-I

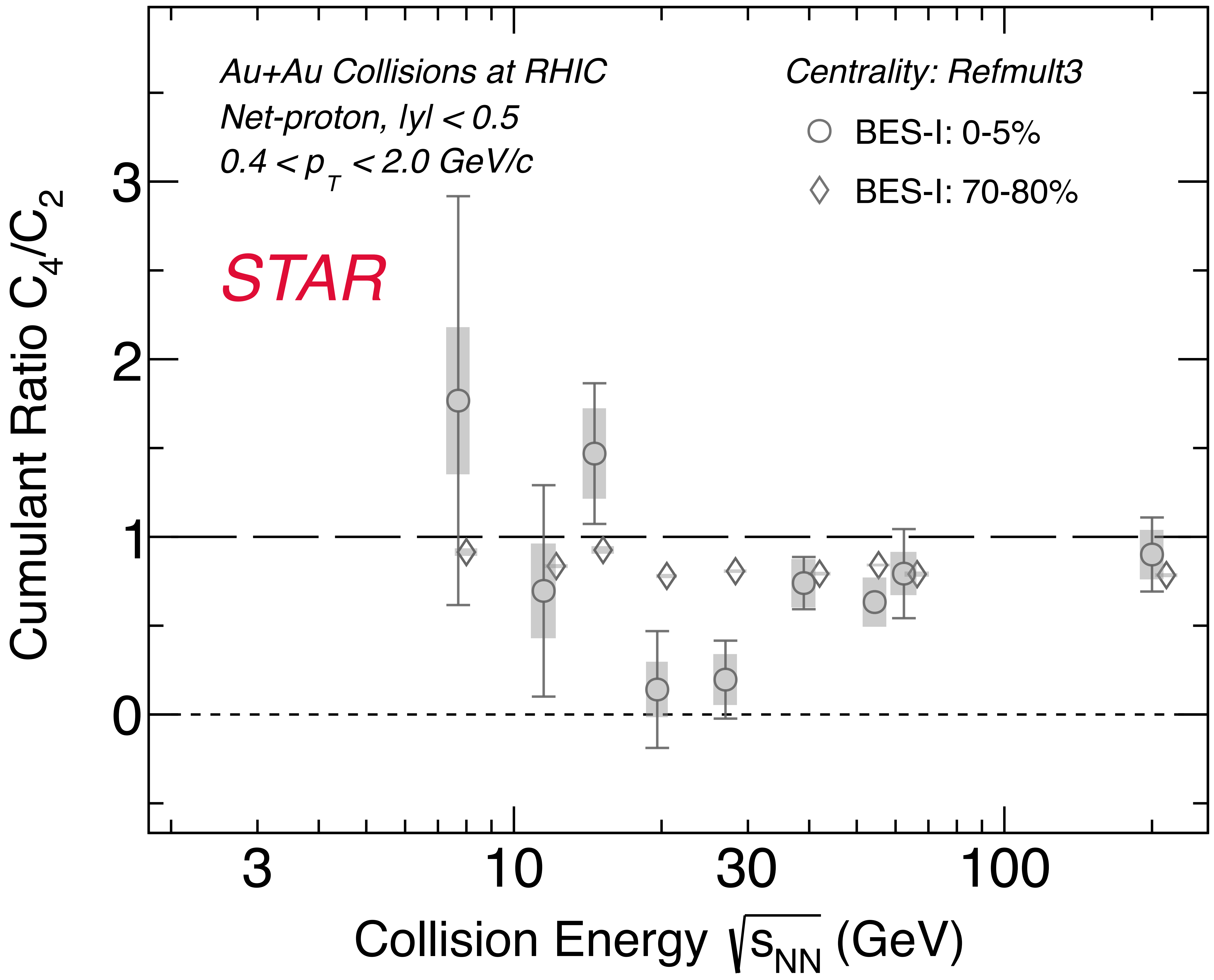


Centrality Dependence and comparison with BES-I

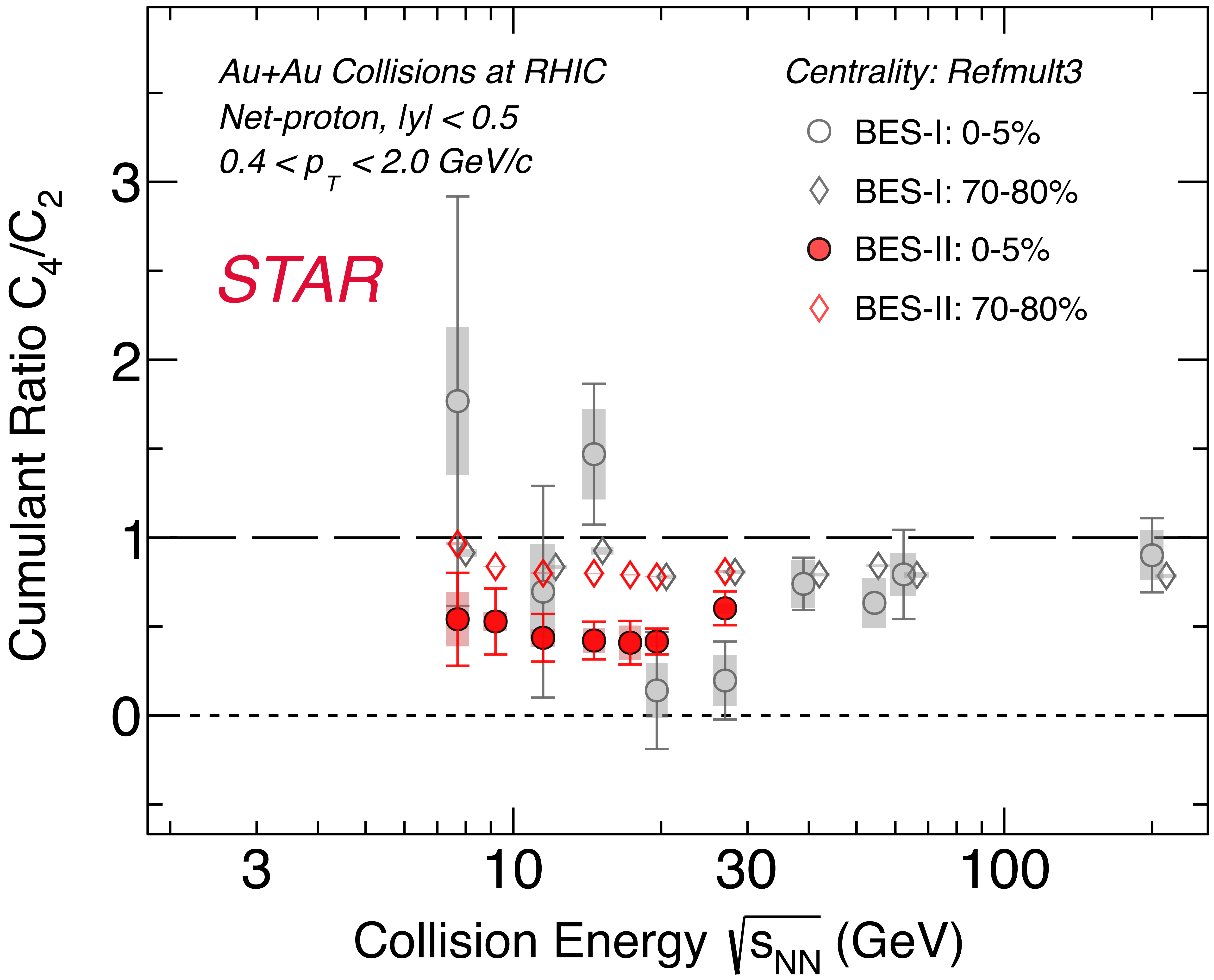


1. Precision measurements: smooth variation across centrality and collision energy observed.
2. Higher centrality resolution leads to lower ratios (especially in mid central collisions):
   Results from Refmult3X (BES-II) < Refmult3 (BES-II) < Refmult3 (BES-I)
3. For 0-5% C_4/C_2, weak effect of centrality resolution seen.

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



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

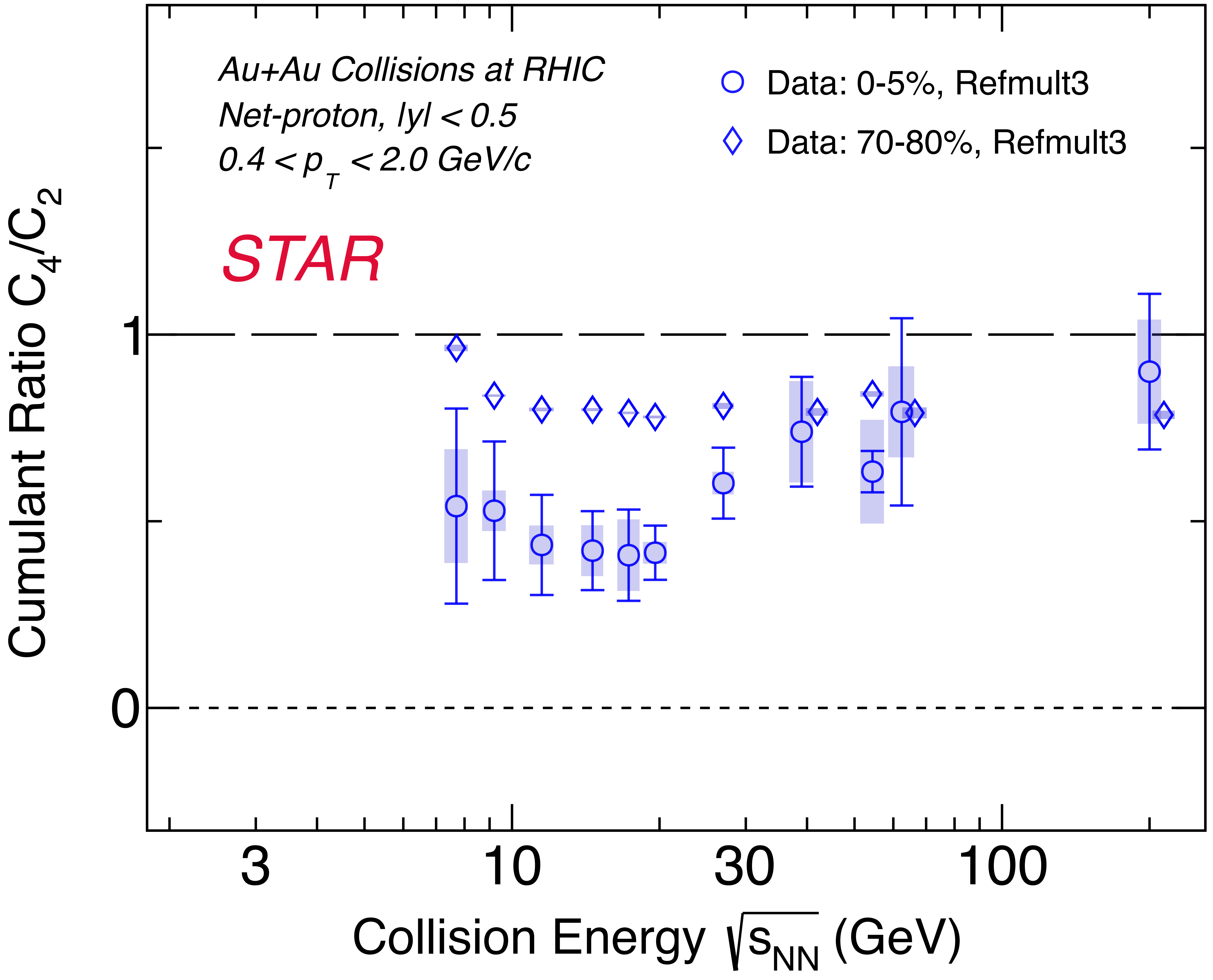


Deviation between BES-II and BES-I data

$\sqrt{s_{NN}}$ (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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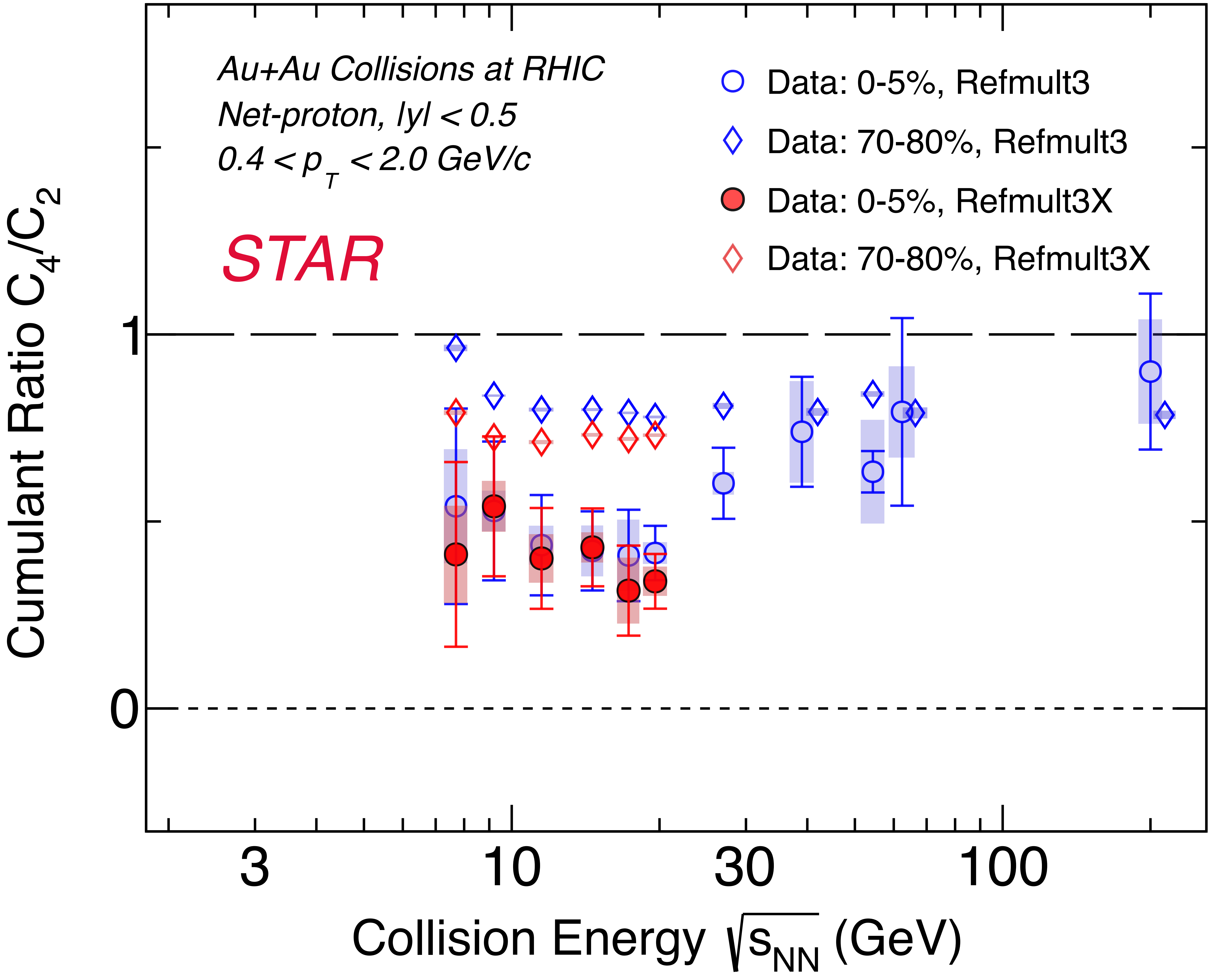
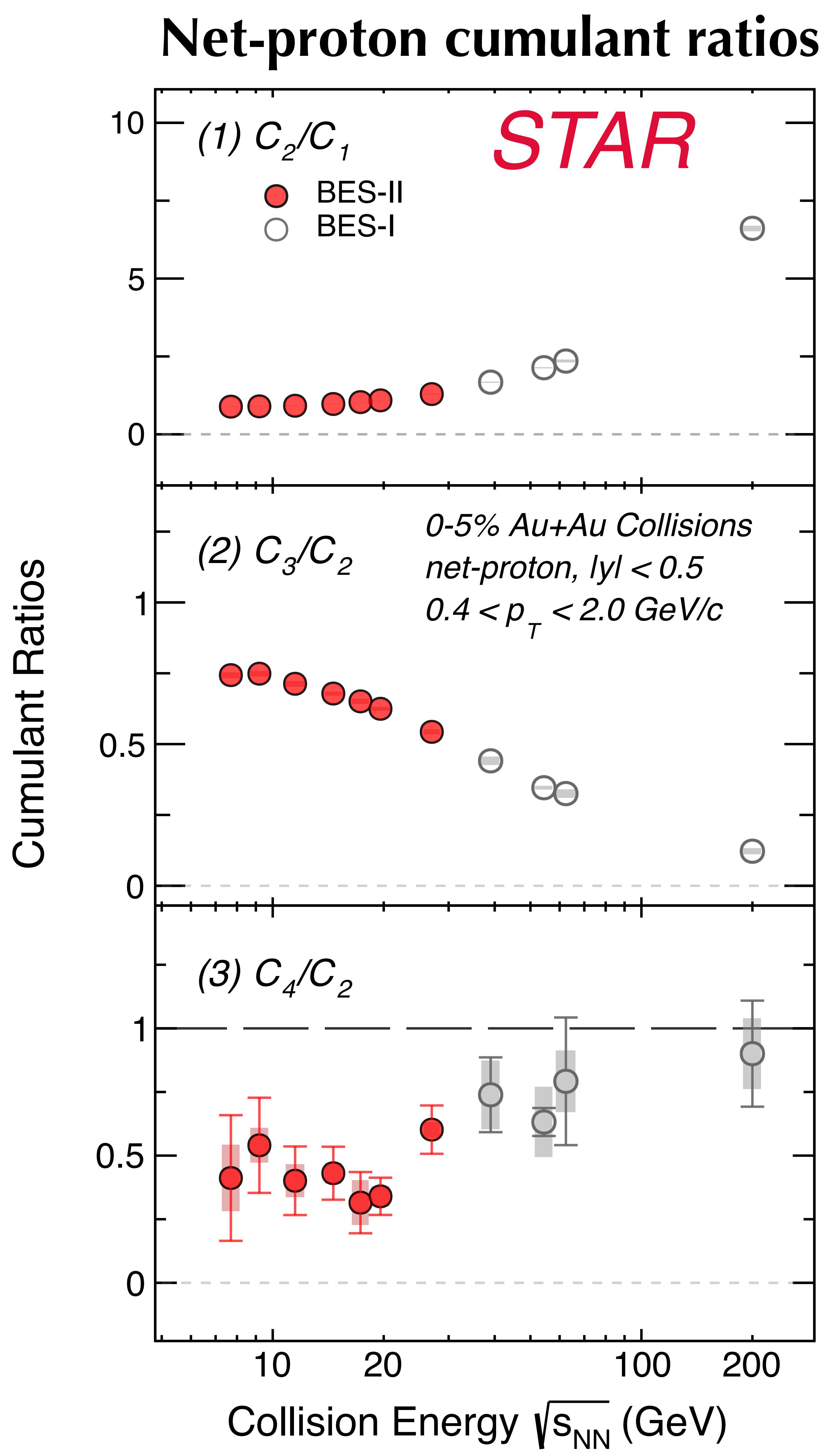


1. **0-5% centrality** C_4/C_2 results show good agreement between Refmult3 and Refmult3X: **weak effect of centrality resolution.**

2. BES-II results shown hereafter are with Refmult3X

Energy Dependence: Model Comparison



HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
Hydro: V. Vovchenko et al, PRC 105, 014904 (2022)

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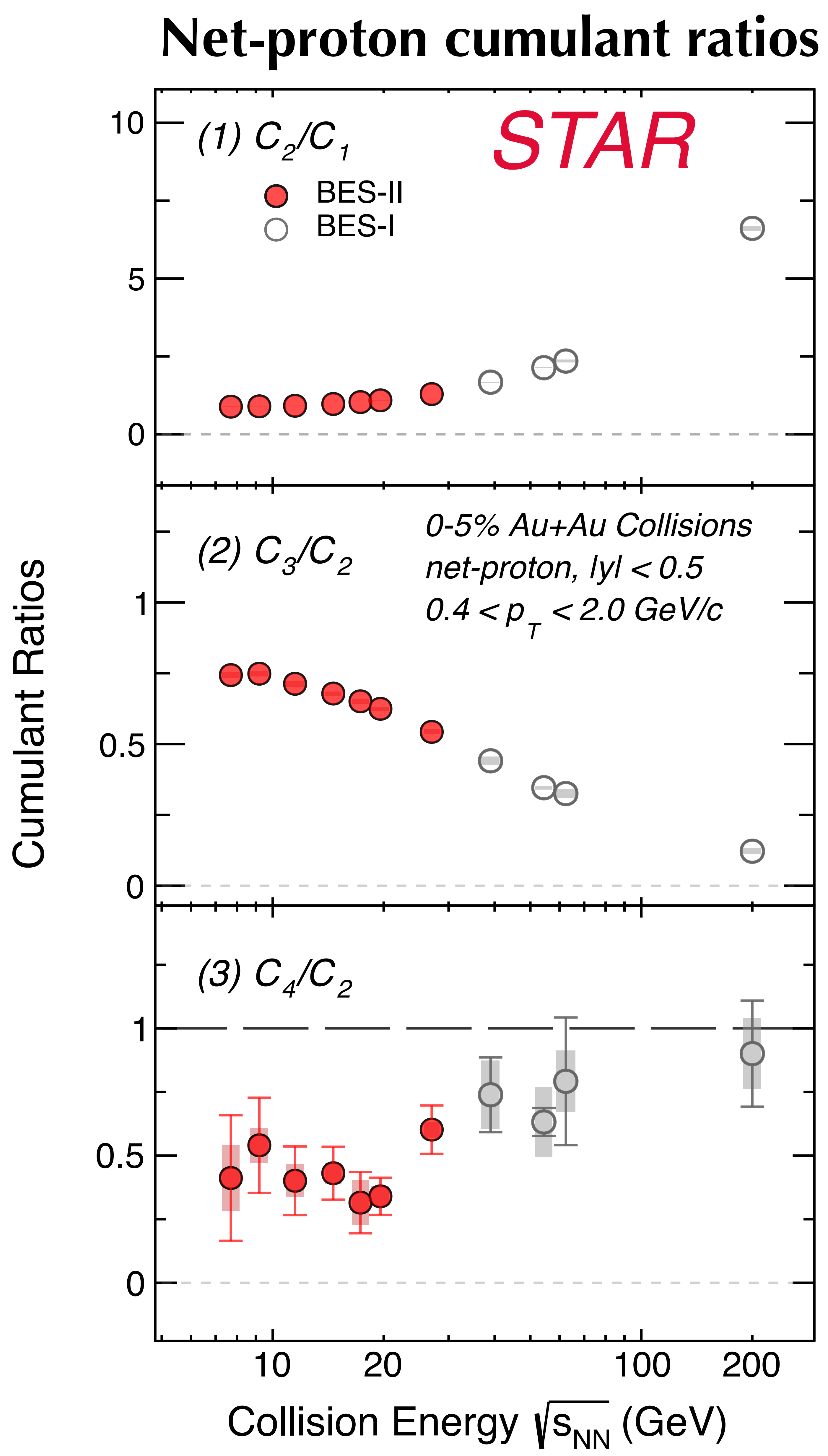

1. Smooth variation vs $\sqrt{s_{NN}}$ in C_2/C_1 and C_3/C_2 observed. C_4/C_2 decreases with decreasing $\sqrt{s_{NN}}$.

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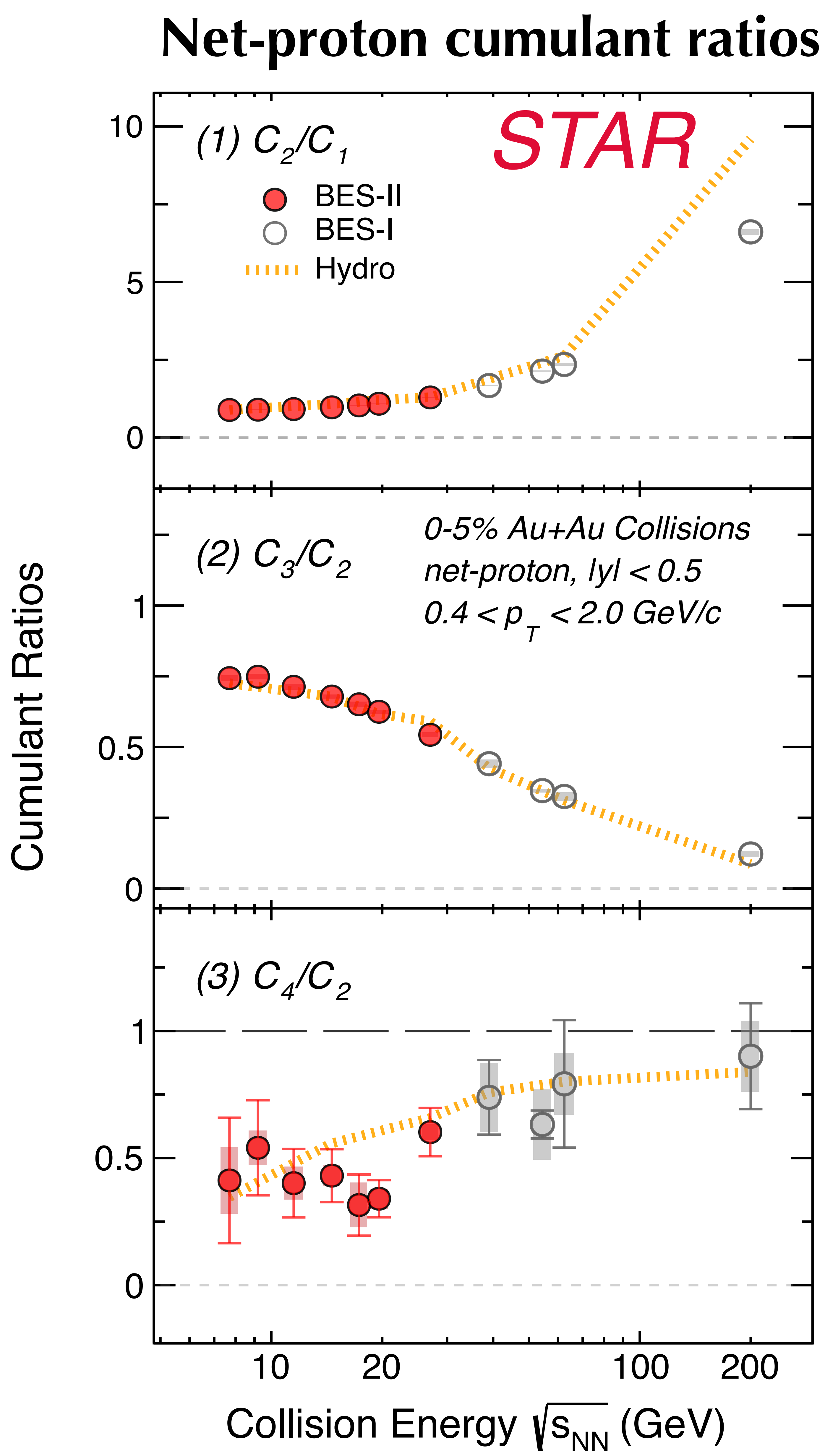

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2. Non-CP models used for comparison:

A. Hydro: Hydrodynamical model

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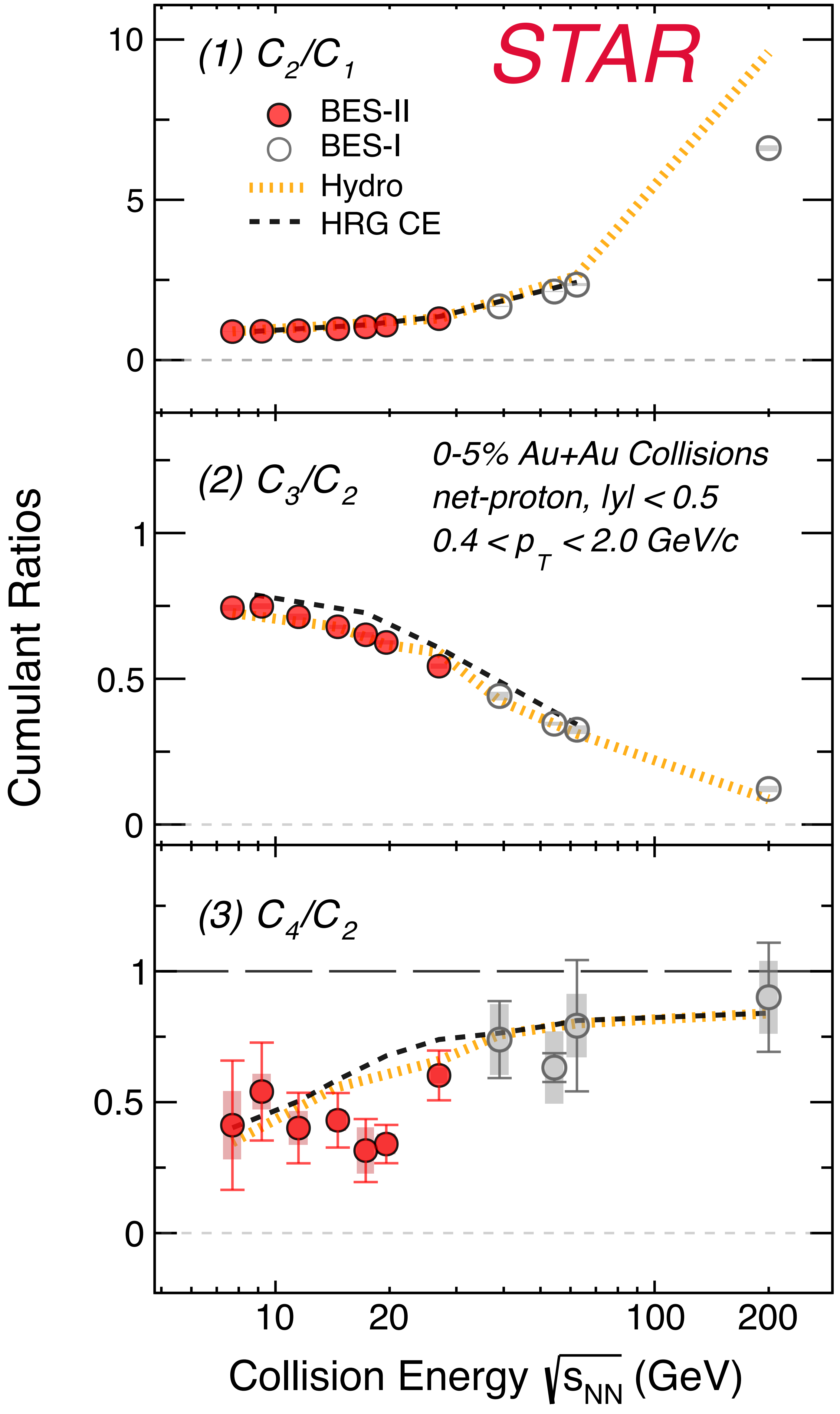
Energy Dependence: Model Comparison

Net-proton cumulant ratios



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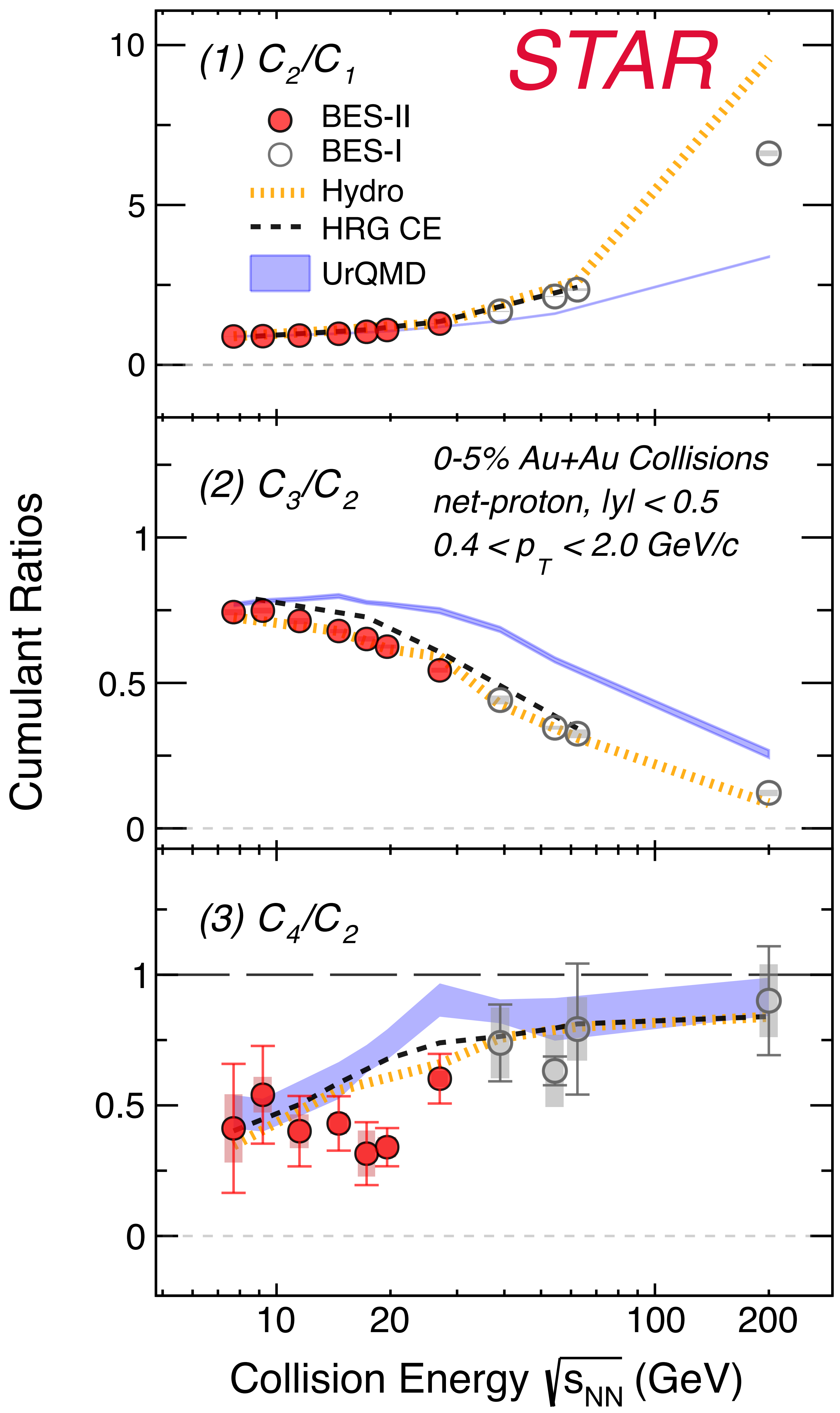

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B. HRG CE: Thermal model with canonical treatment of baron charge

C. UrQMD: Hadronic transport model

(All models include baryon number conservation)

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
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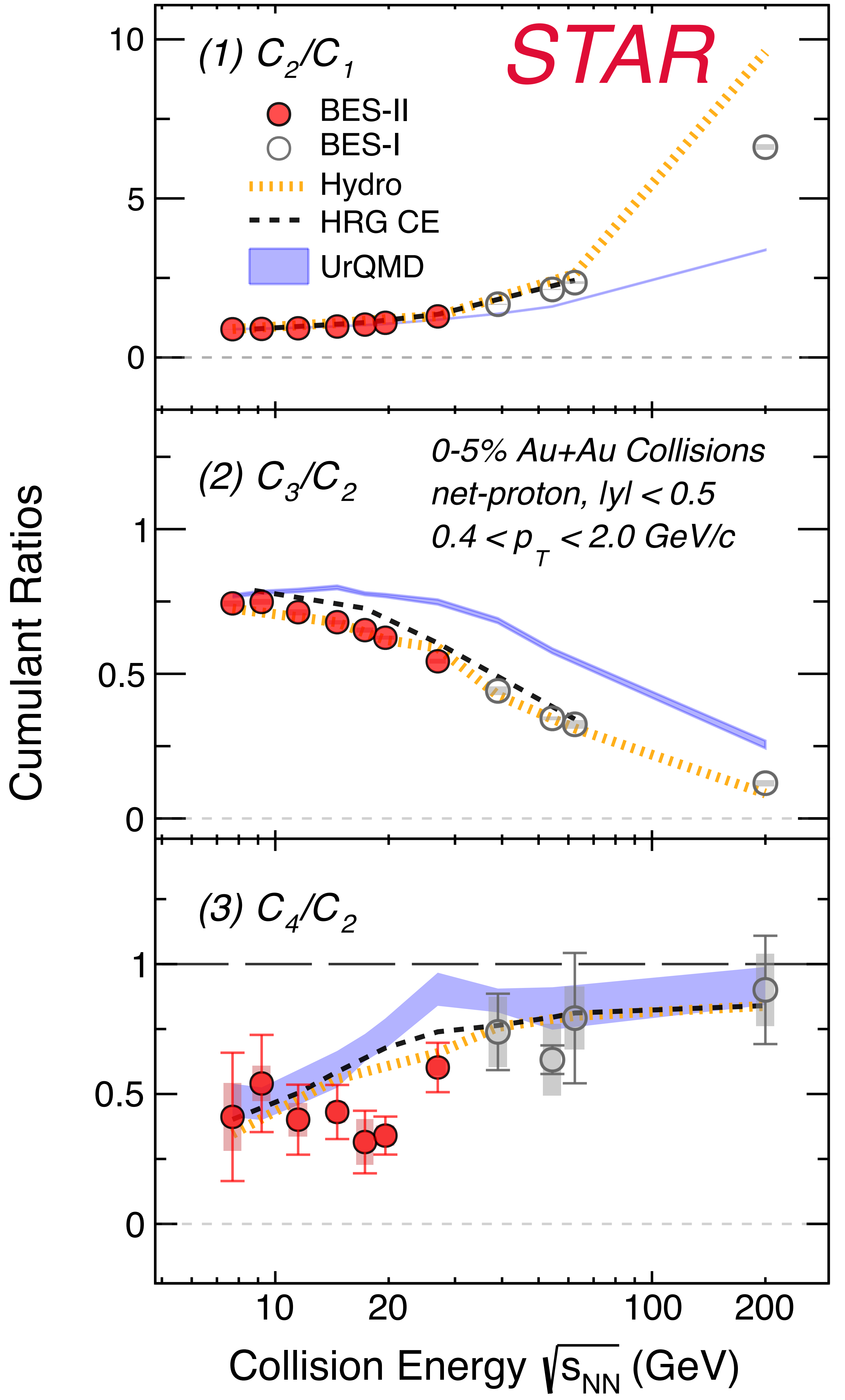
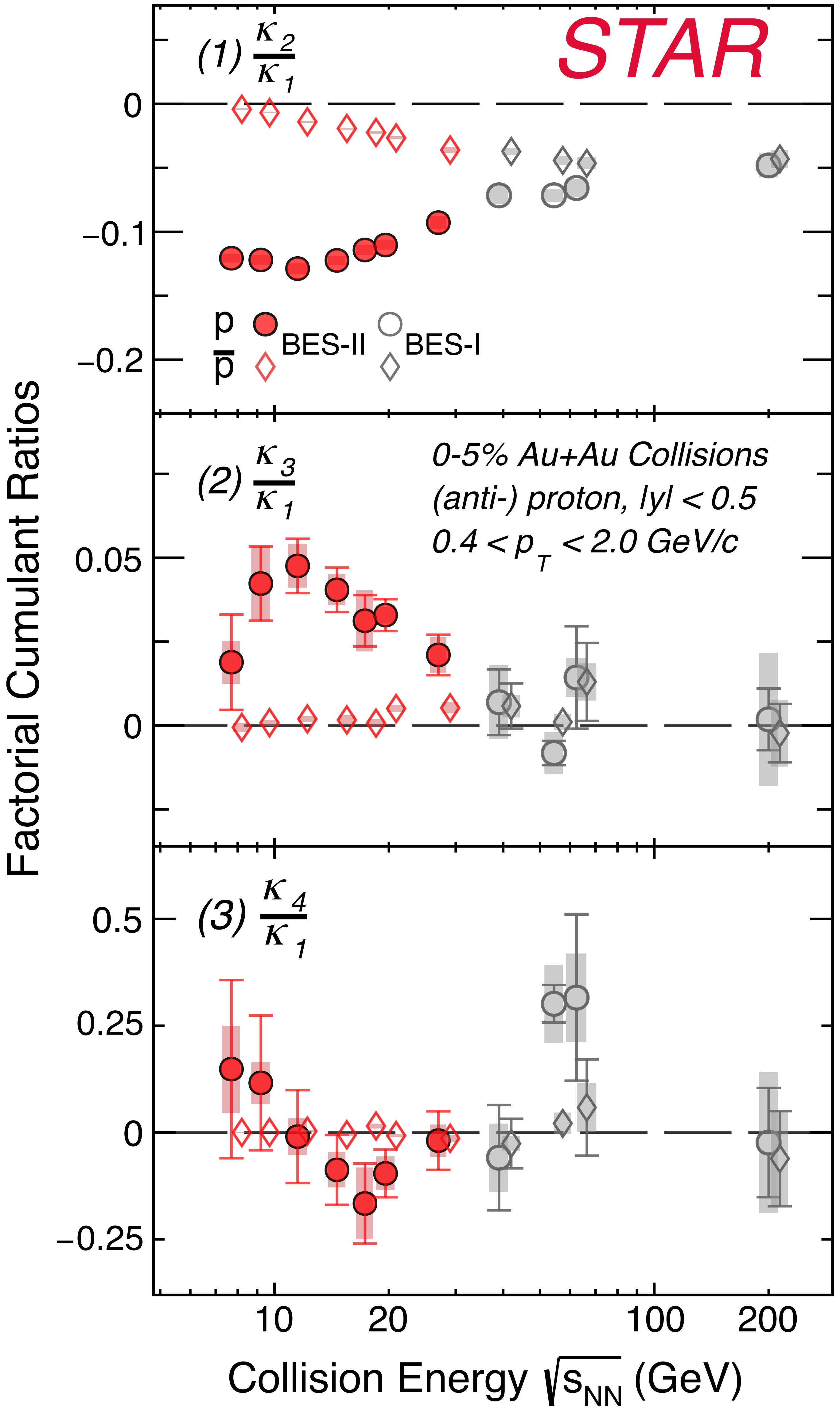
Energy Dependence: Model Comparison

Net-proton cumulant ratios



Proton/antiproton factorial cumulant ratios



1. Smooth variation vs $\sqrt{s_{NN}}$ in C_2/C_1 and C_3/C_2 observed. C_4/C_2 decreases with decreasing $\sqrt{s_{NN}}$.
2. Non-CP models used for comparison:
   - A. Hydro: Hydrodynamical model
   - B. HRG CE: Thermal model with canonical treatment of baron charge
   - C. UrQMD: Hadronic transport model

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

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
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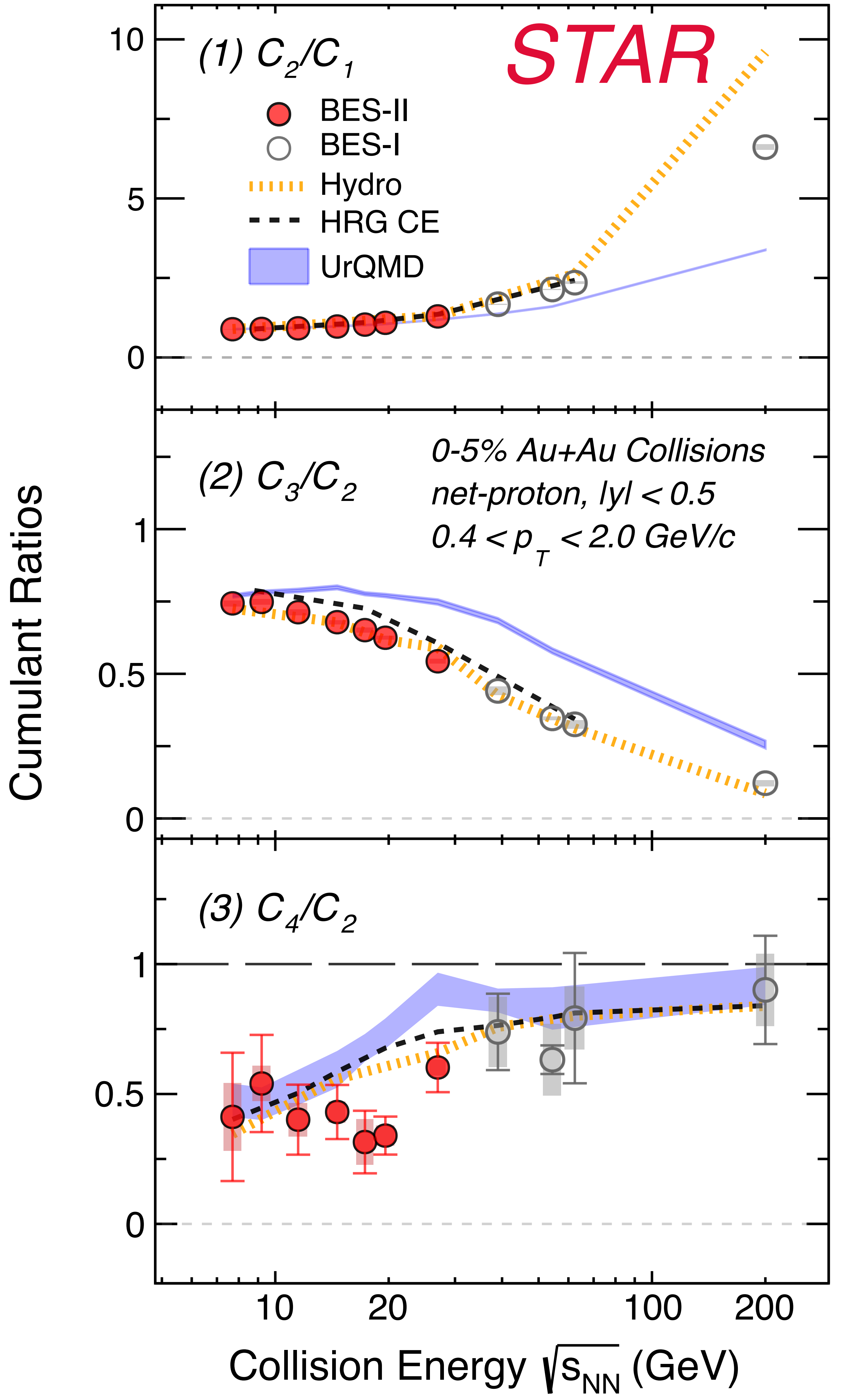
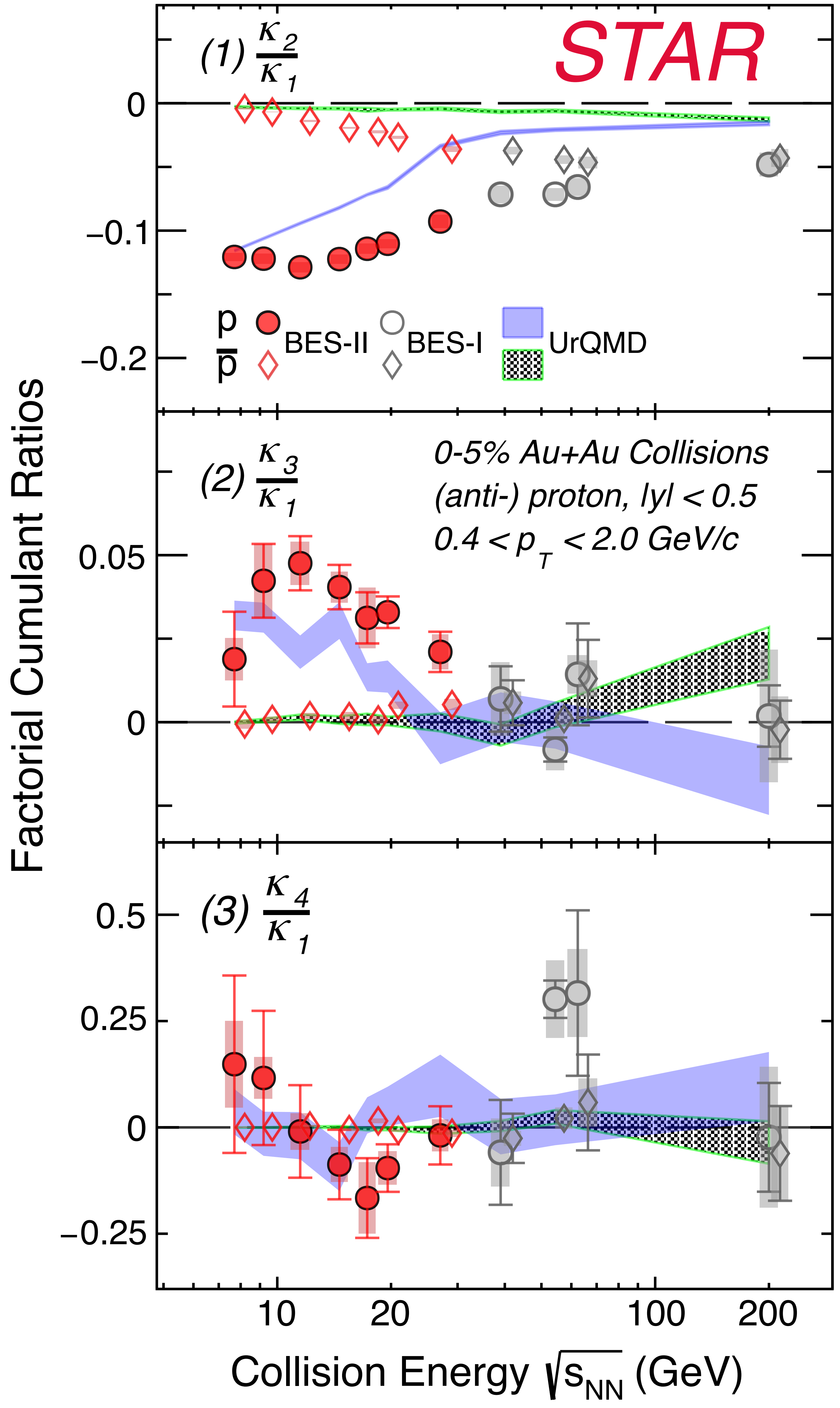
Energy Dependence: Model Comparison

Net-proton cumulant ratios



Proton/antiproton factorial cumulant ratios



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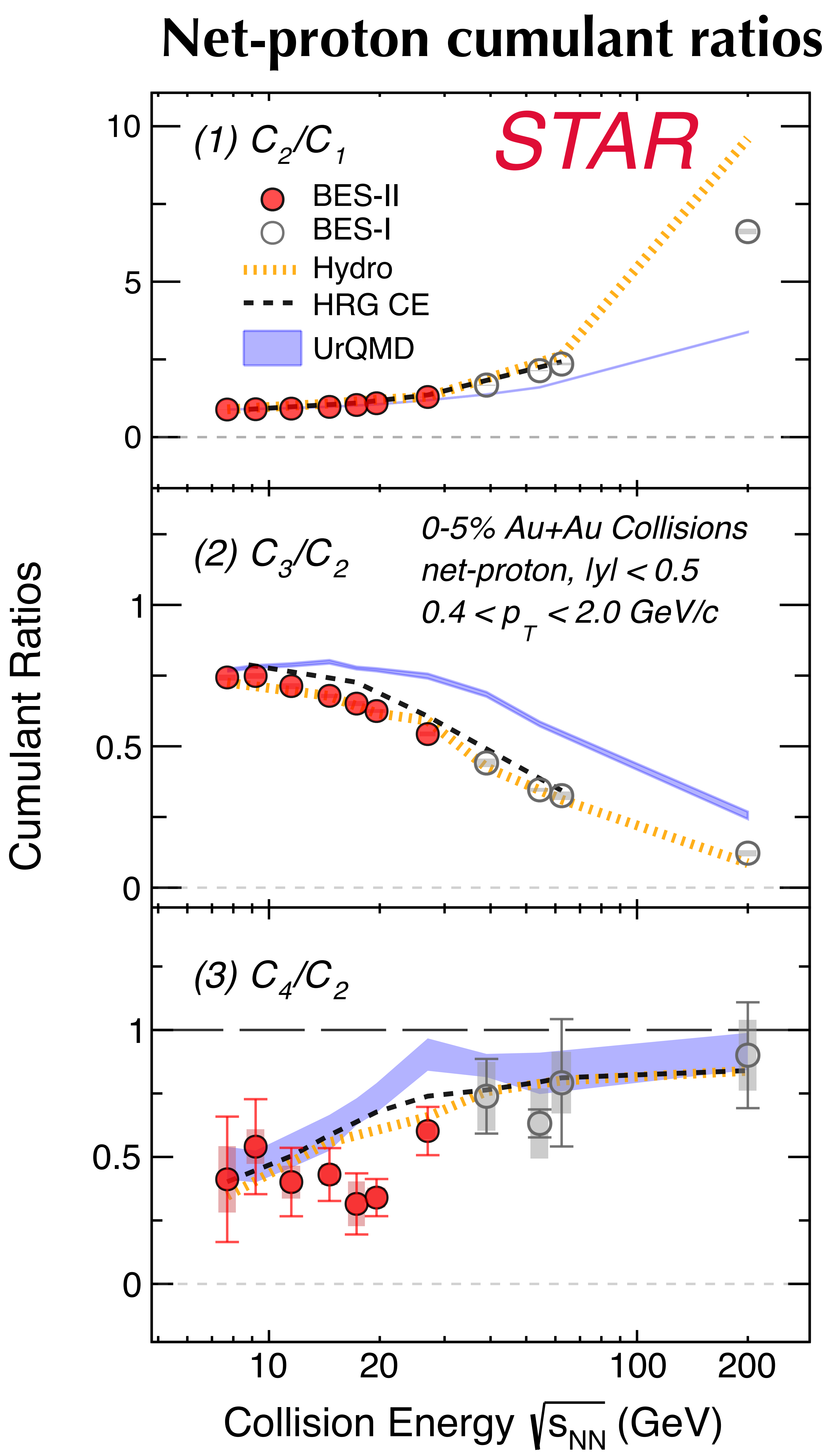

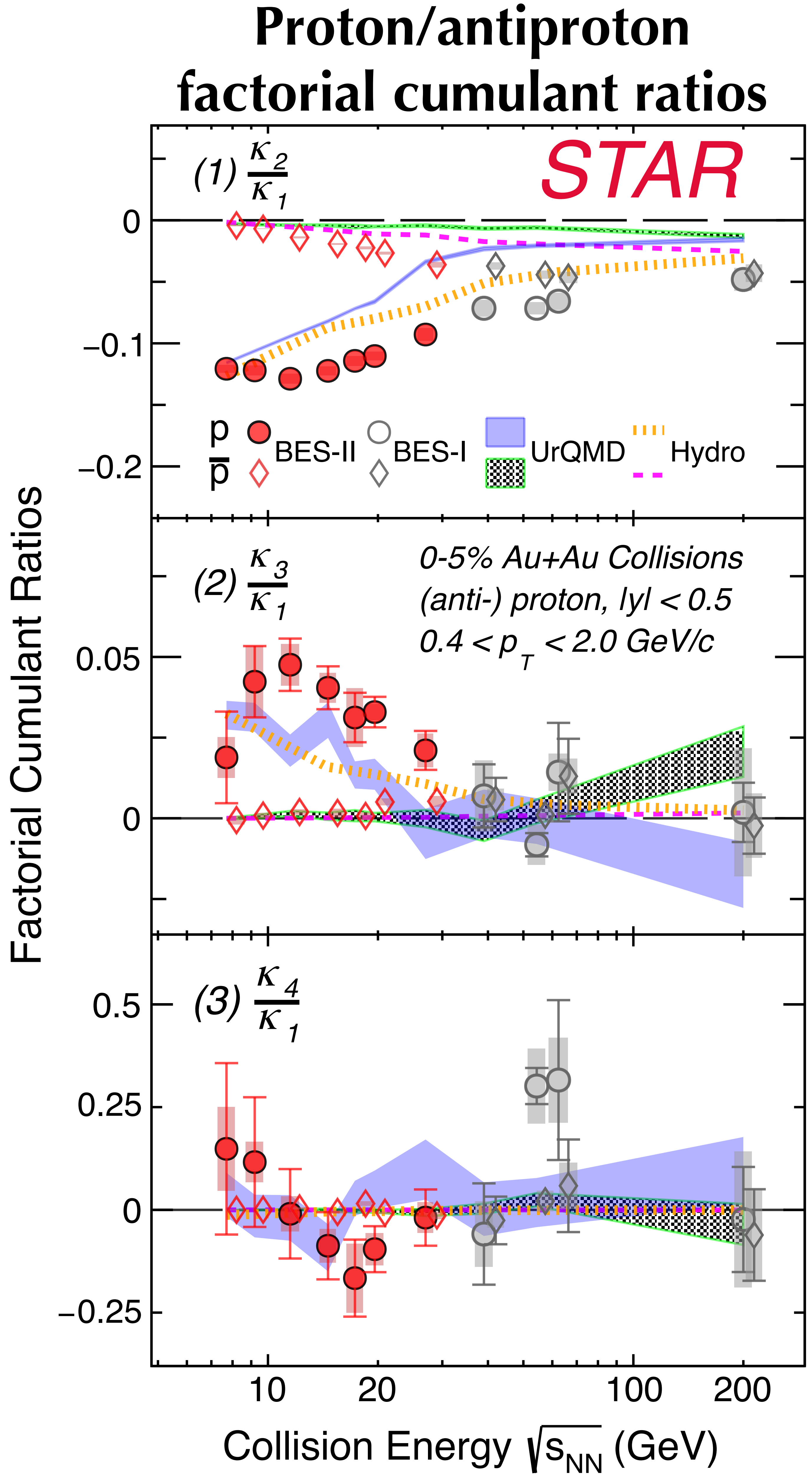

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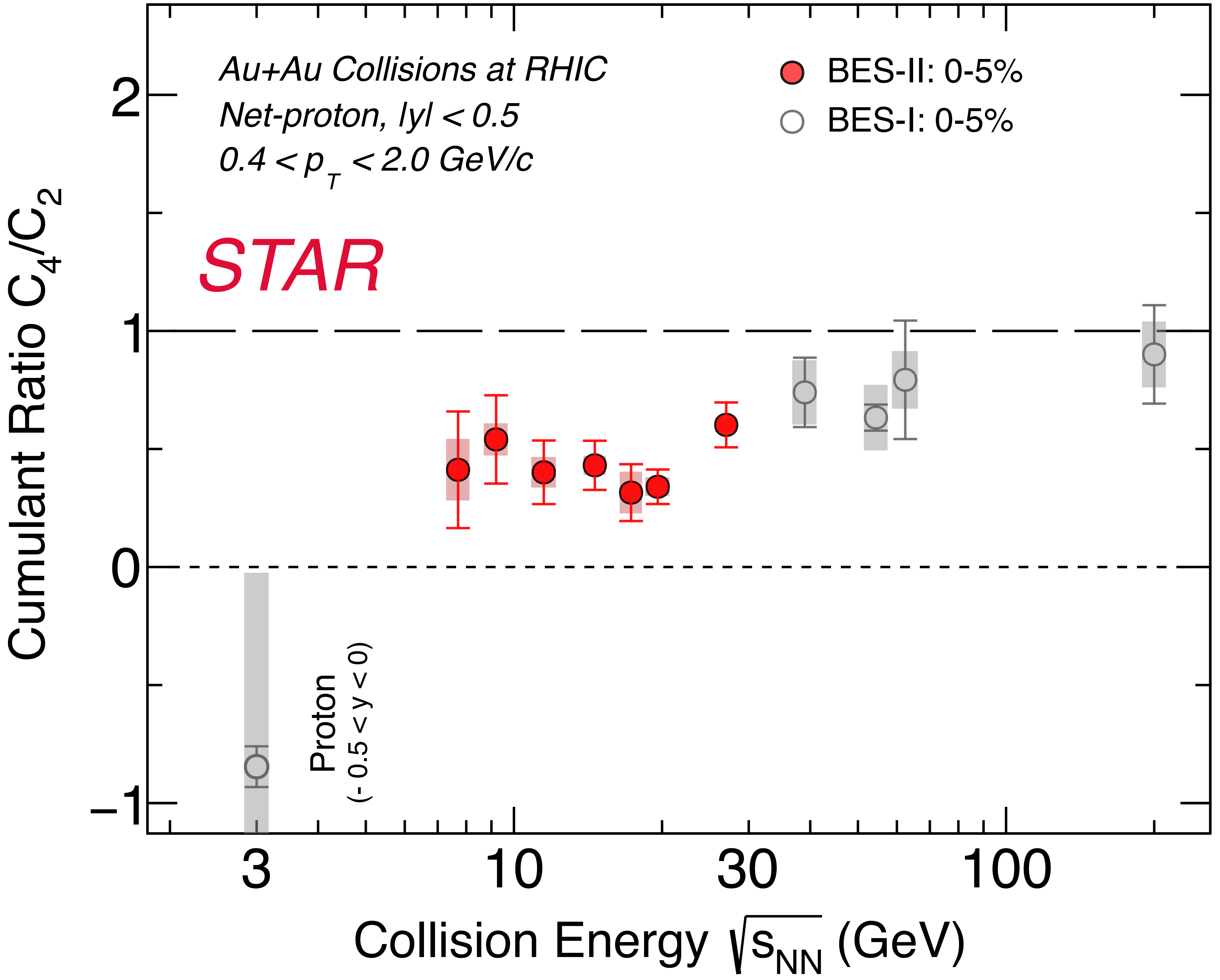
Energy Dependence of C_4/C_2: Quantifying deviation



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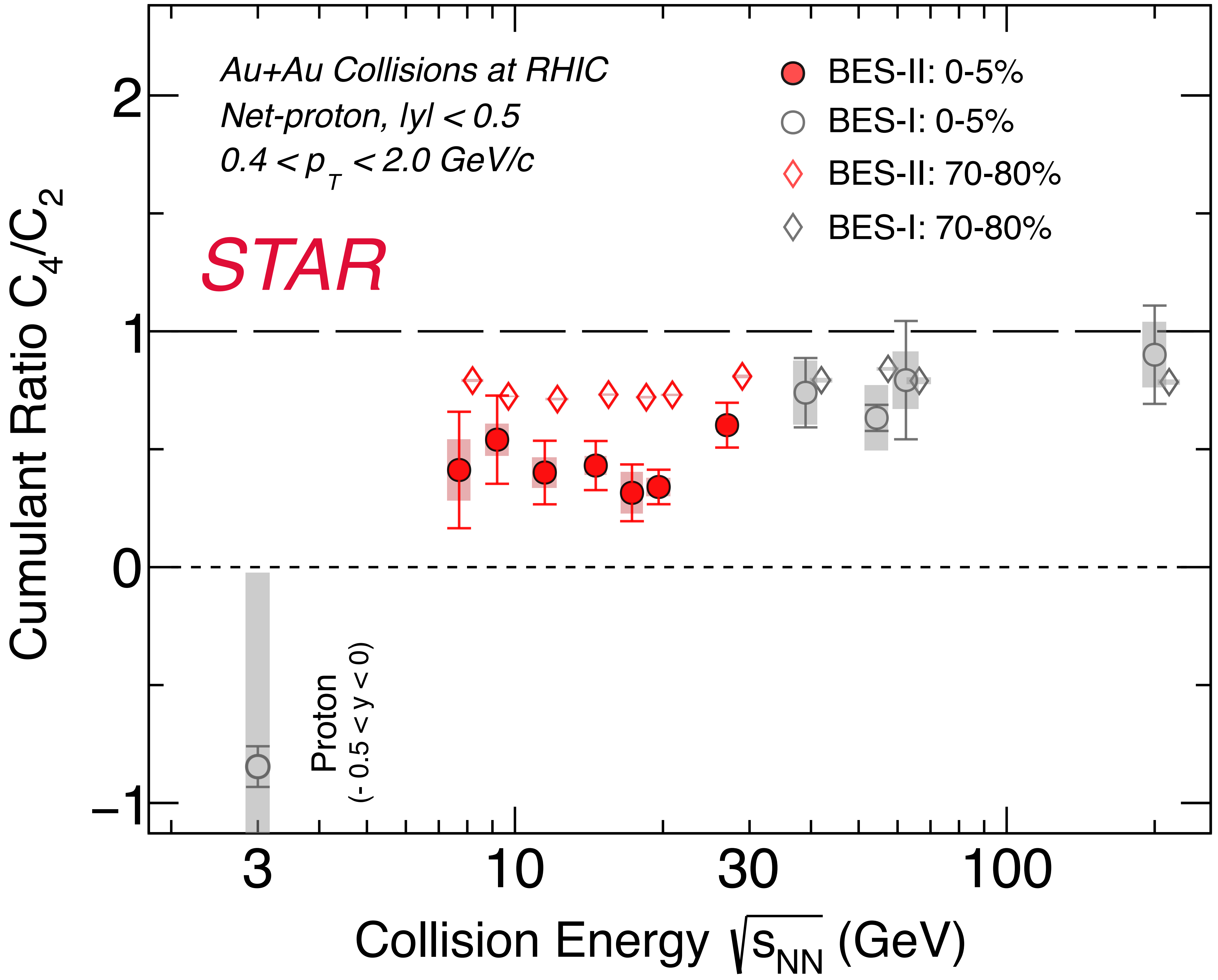

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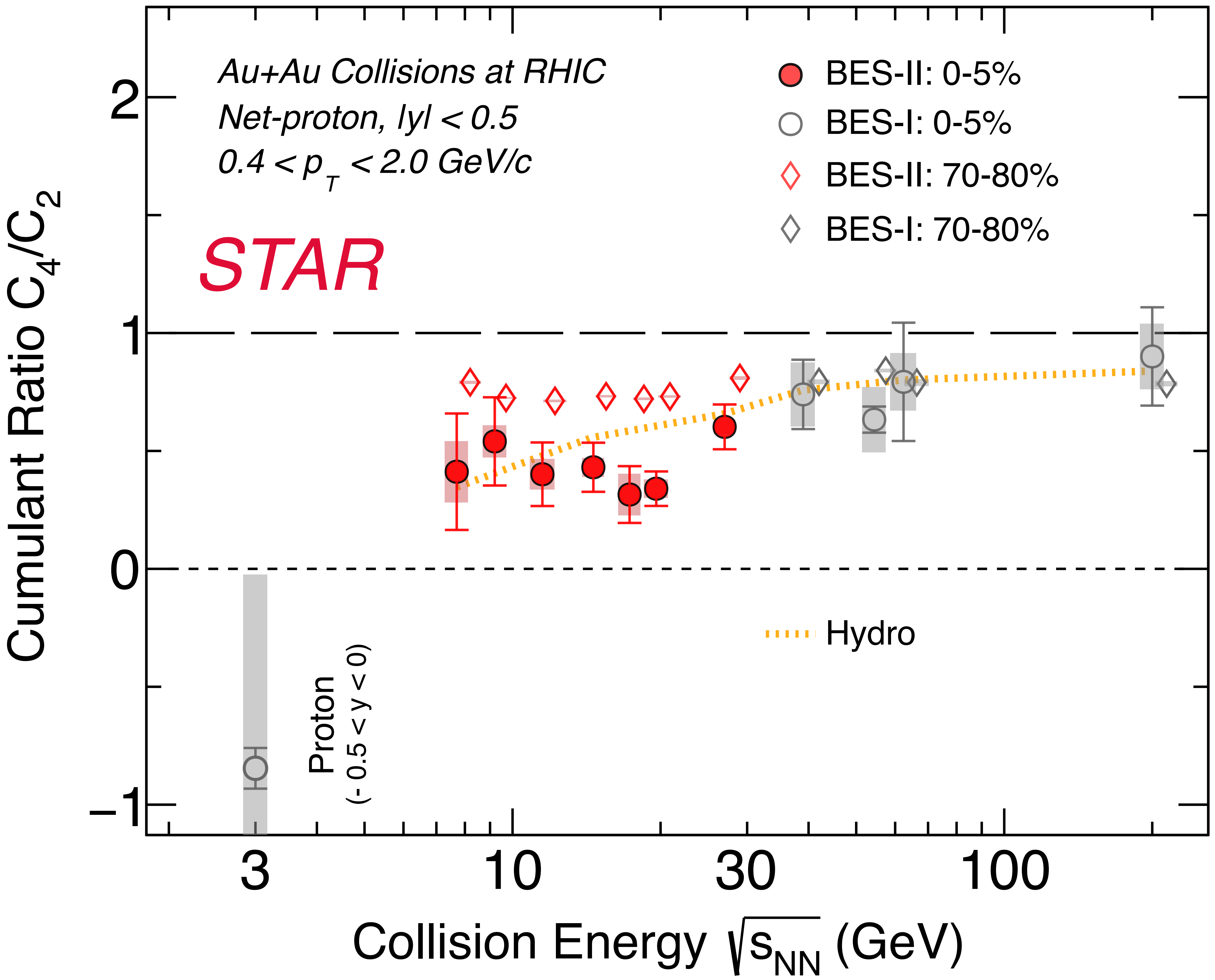

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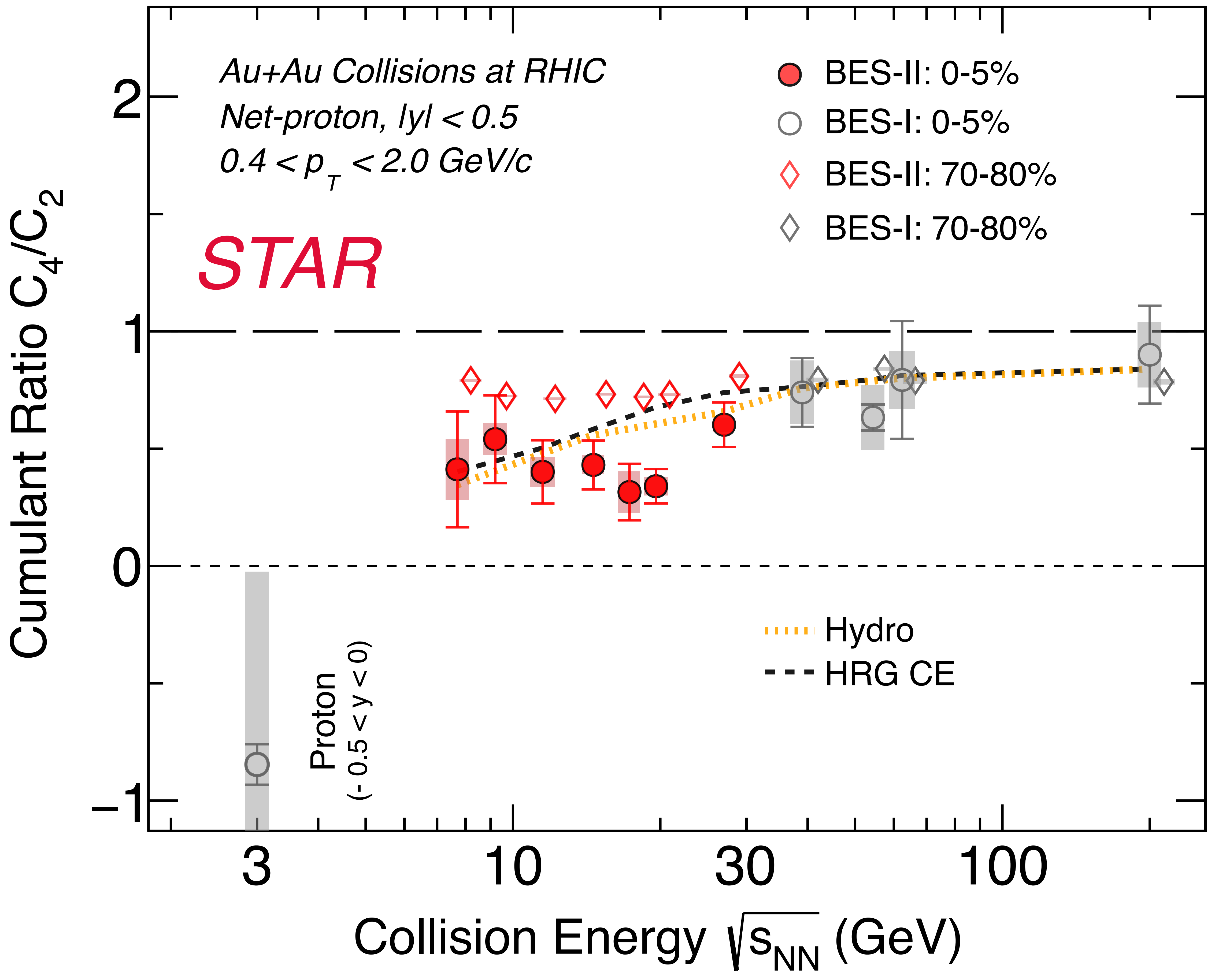

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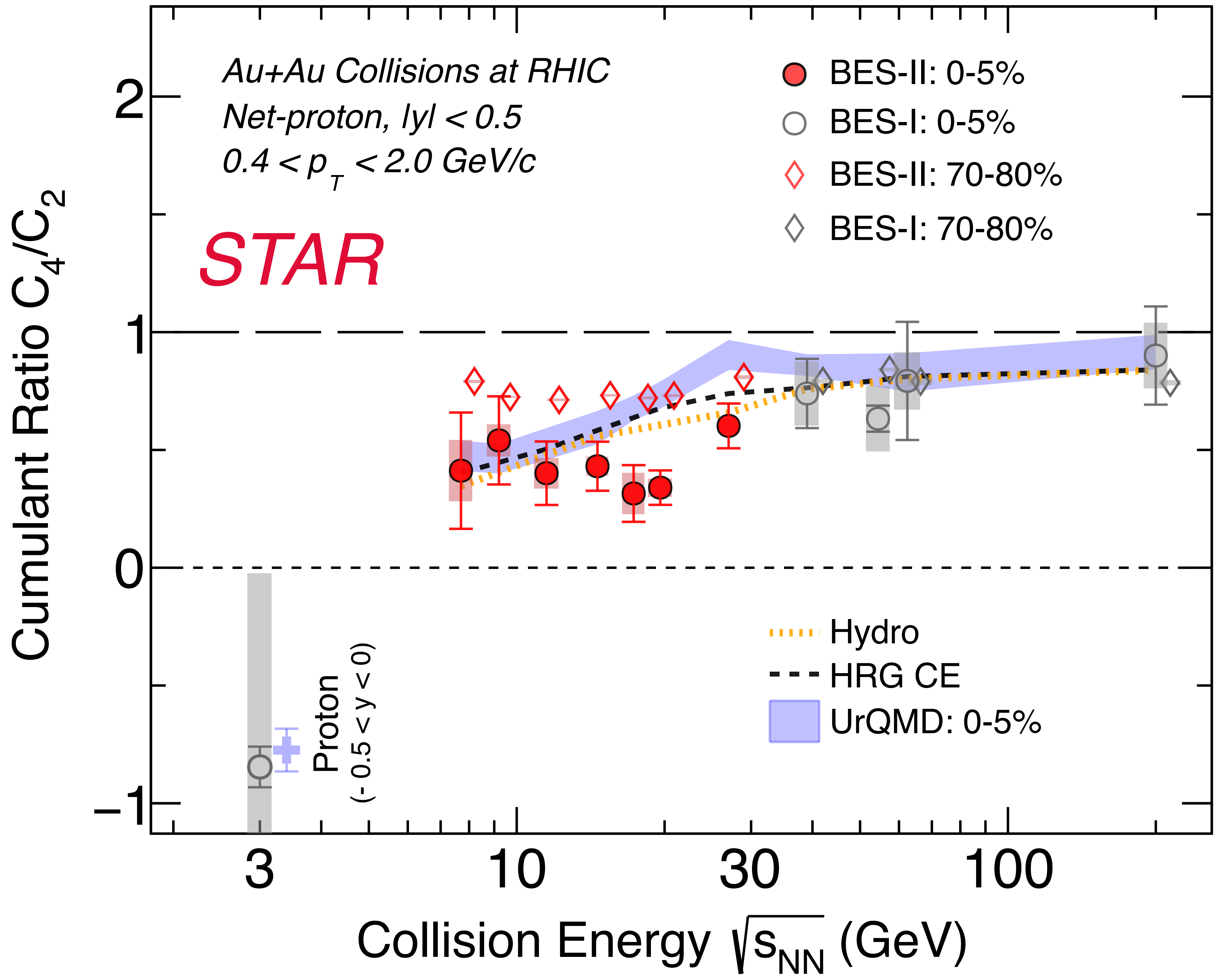

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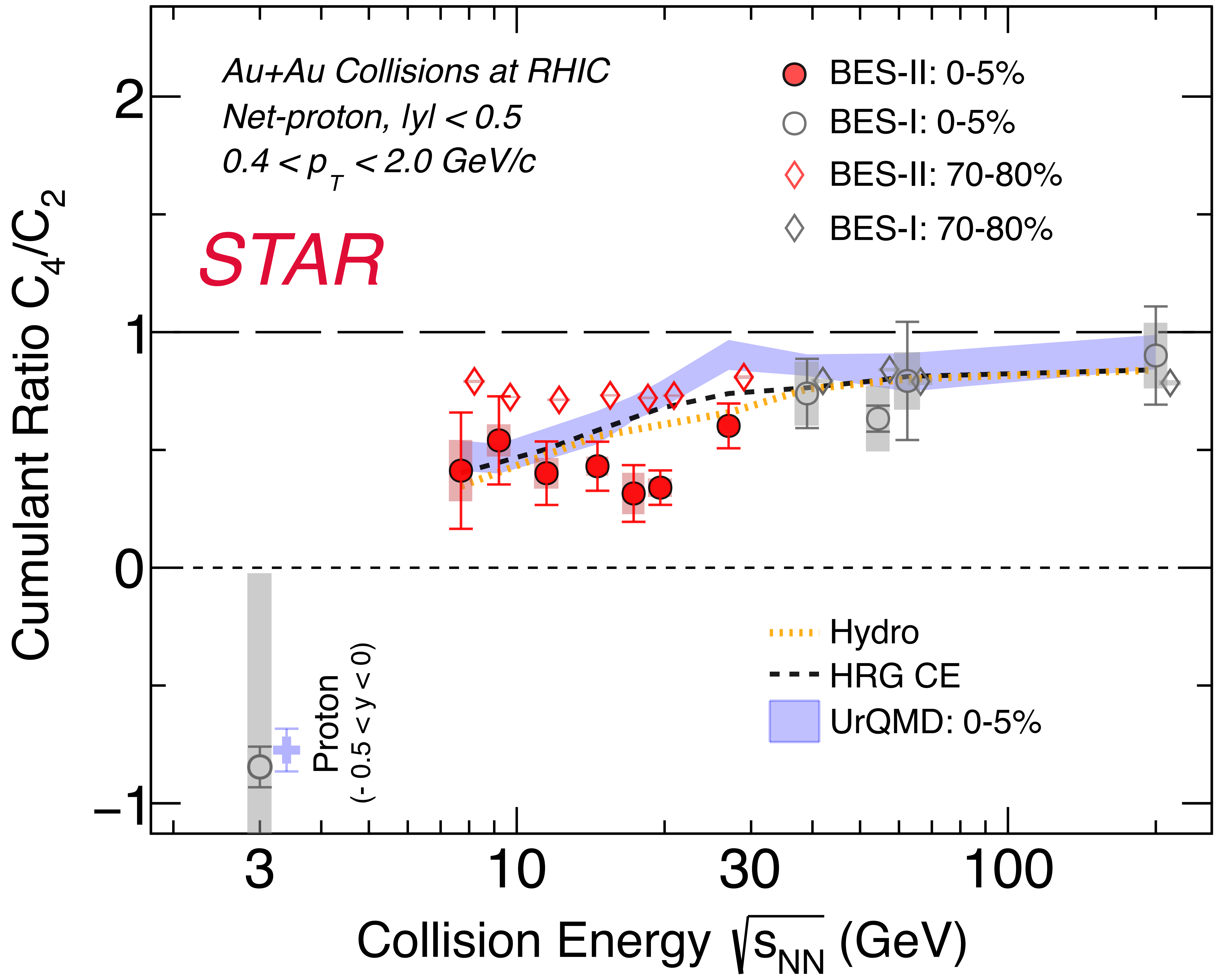

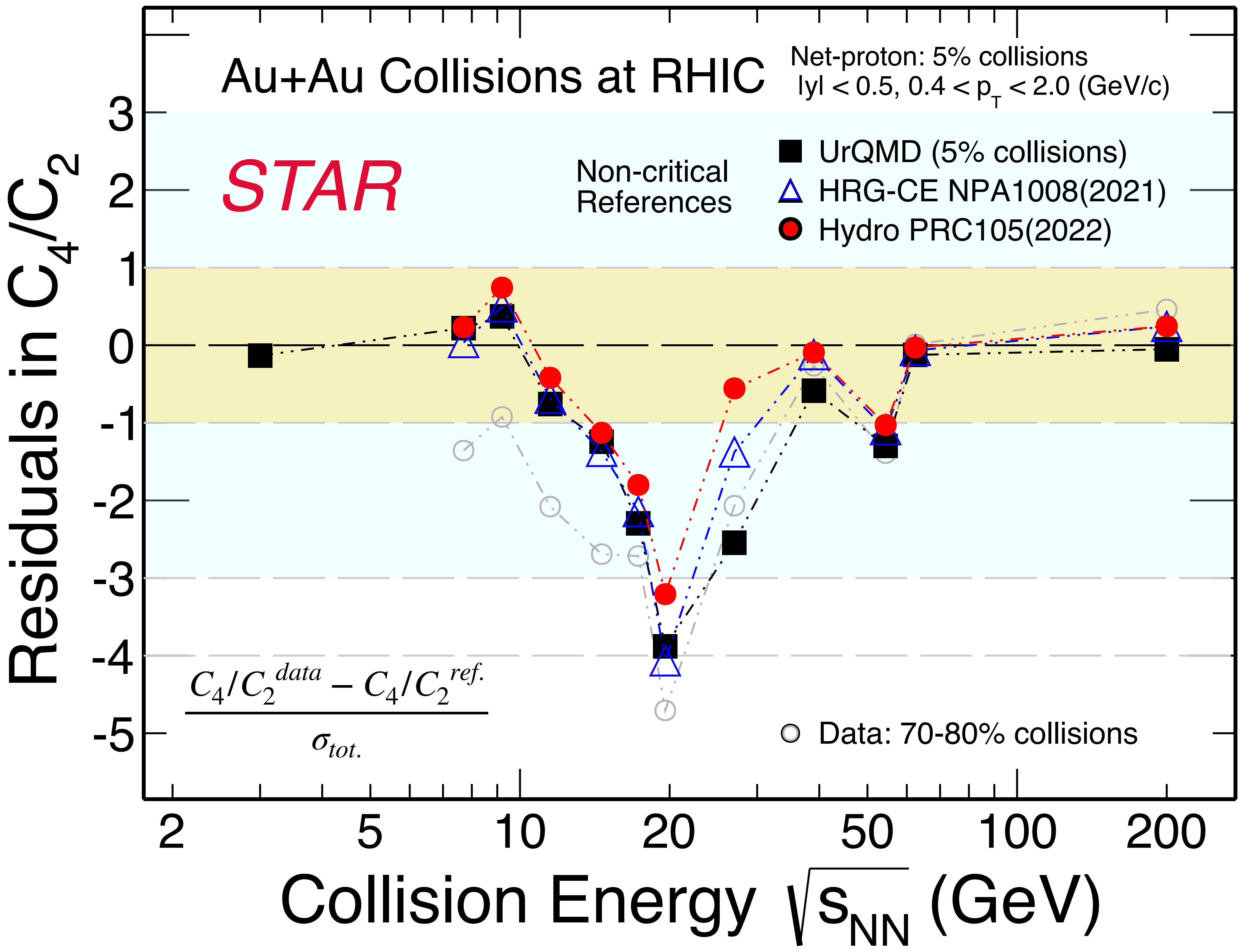

C_4/C_2 shows minimum around ~20 GeV comparing to non-CP models, 70-80% data

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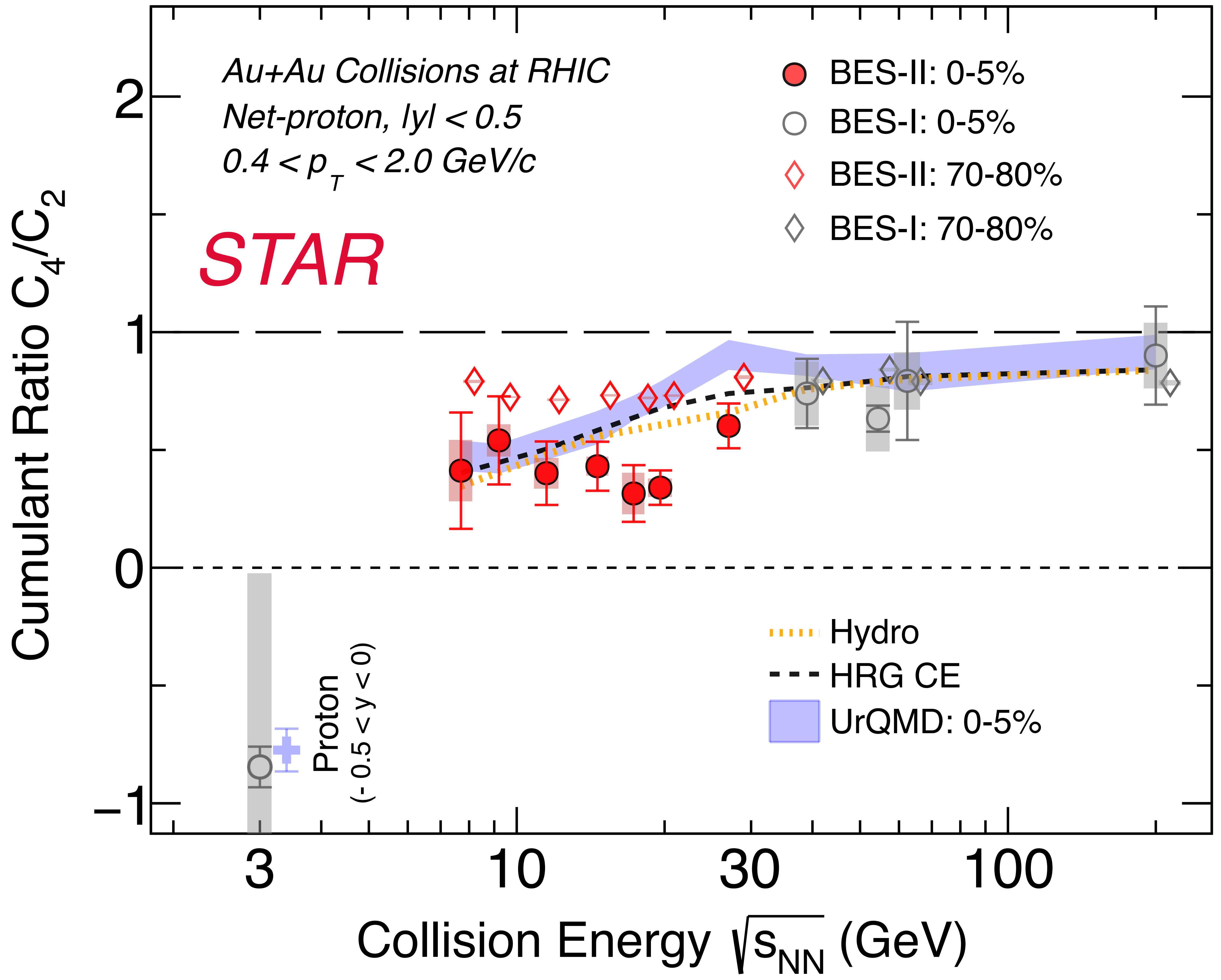

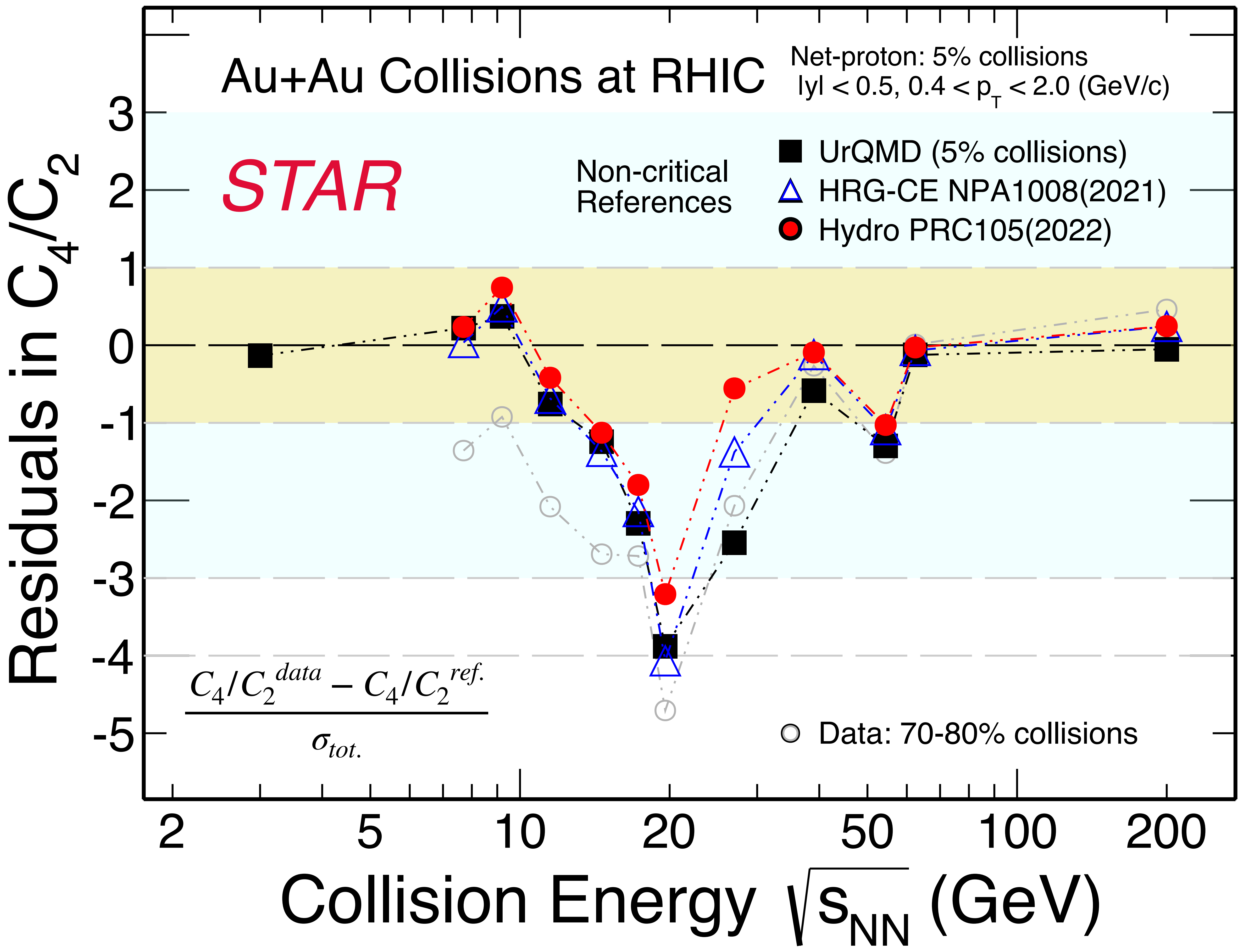

C_4/C_2 shows minimum around ~20 GeV comparing to non-CP models, 70-80% data

1. Maximum deviation: $3.2 - 4.7\sigma$ at $\sqrt{s_{NN}} = 20$ GeV ($1.3 - 2\sigma$ at BES-I)

2. Overall deviation from $\sqrt{s_{NN}} = 7.7$ -27 GeV: $1.9 - 5.4\sigma$ ($1.4 - 2.2\sigma$ at BES-I)

HRG CE: P. B Munzinger et al, NPA 1008, 122141 (2021)
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Summary and Outlook:

Summary:

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

2. Measured net-proton C_4/C_2 in 0-5% central collisions do not show deviation above non-CP model calculations. Maximum deviation in 0-5% data w.r.t. various non-CP 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:

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

2. Examine transverse momentum dependence and rapidity dependence of fluctuations.

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

Acknowledgements:

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

Organizers for giving this opportunity.

Thank you all for listening.

Back UP