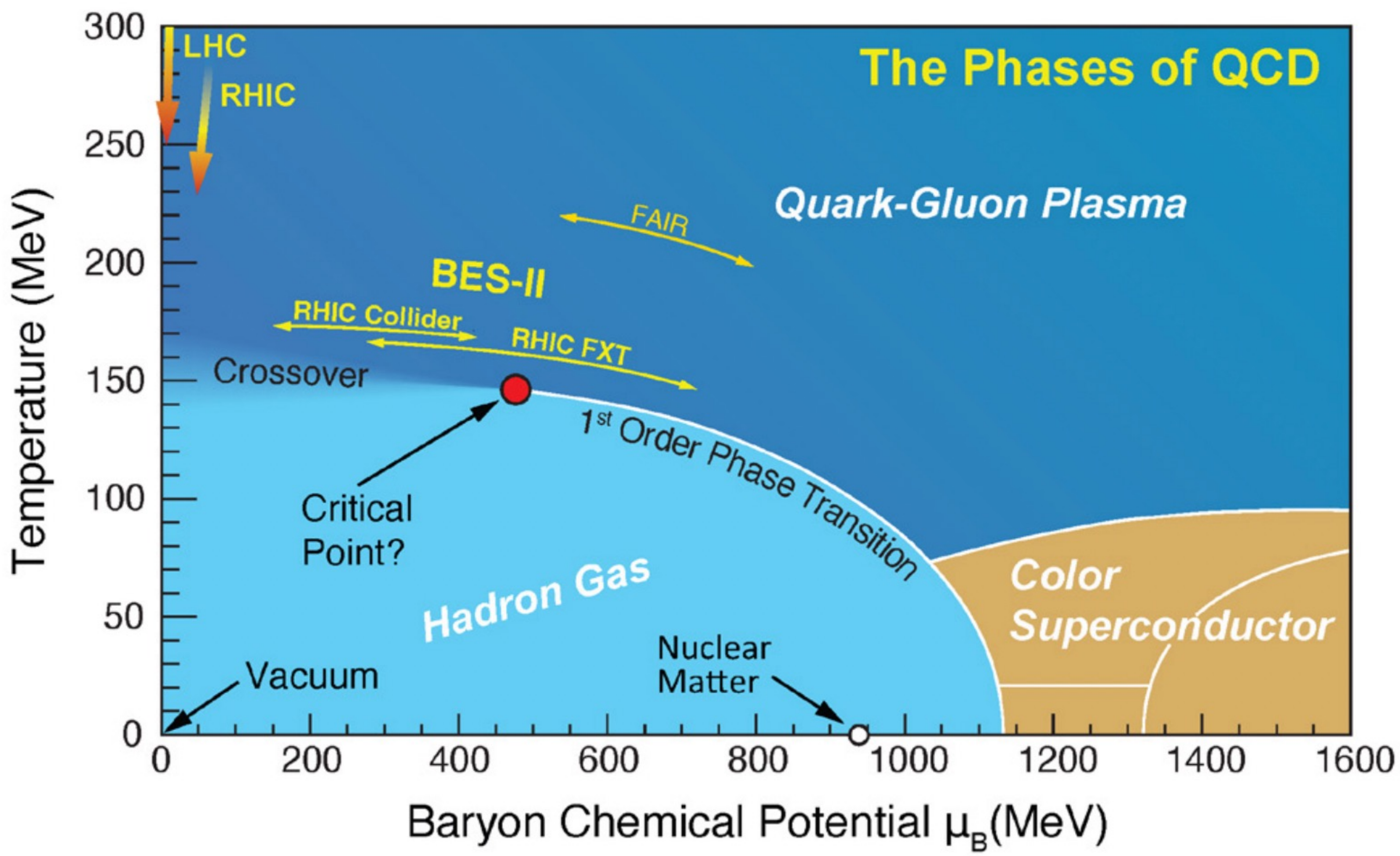
Recent Proton Fluctuation Results from Beam Energy Scan II at RHIC

Xin Dong (Lawrence Berkeley National Laboratory)



Outline

1) Introduction
   - QCD Critical End Point and Beam Energy Scan (BES) at RHIC

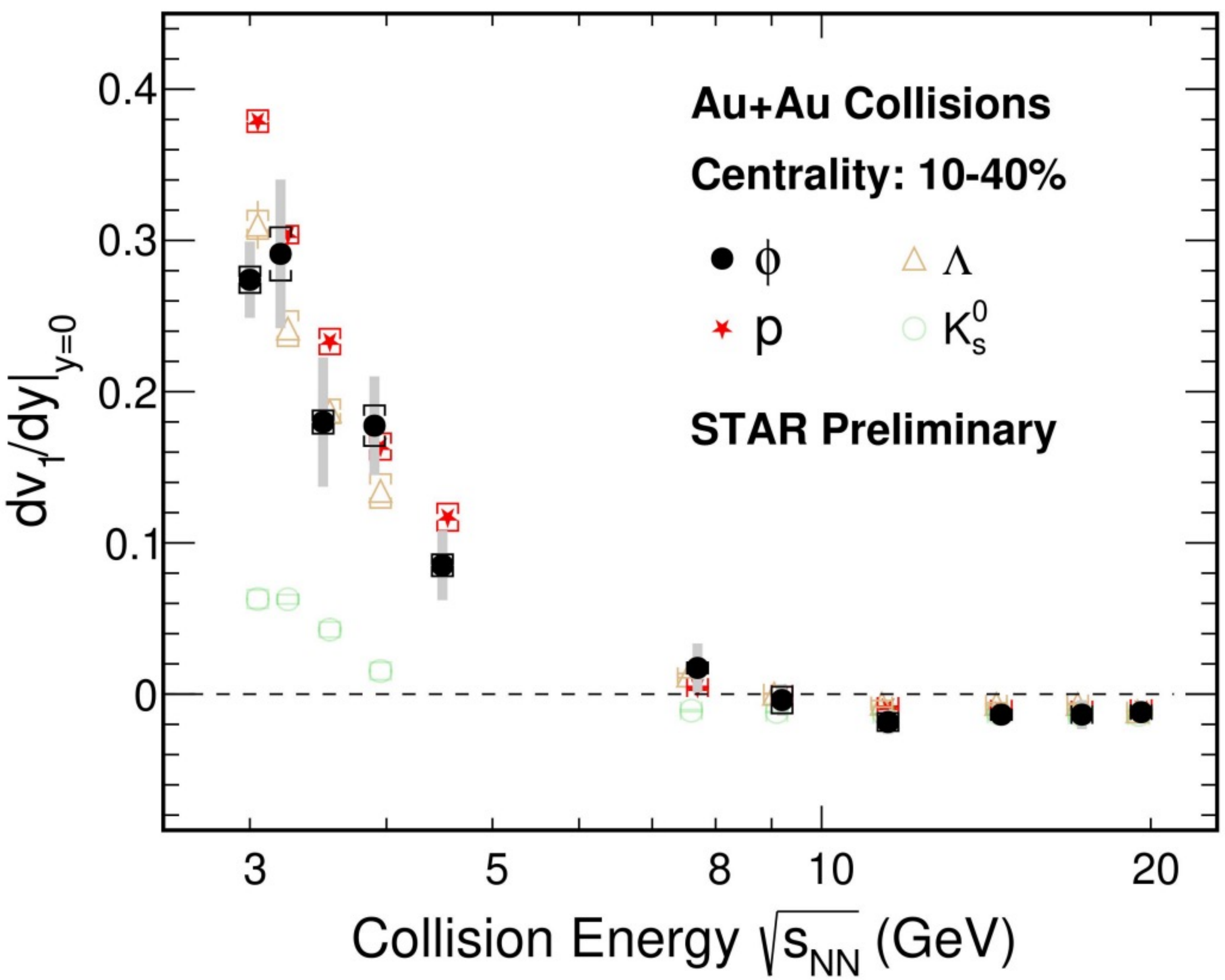
2) Recent Highlights from RHIC BES-II
   - (Net-)Proton fluctuations at collider energies
   - New proton fluctuations at fixed-target energies

3) Summary and Future Prospective

STAR, arXiv: 2504.00817; QM 2025 talks: Yige Huang, Zachary Sweger
QM 2025 posters: Fan Si, Bappaditya Mondal, Xin Zhang, Yongcong Xu

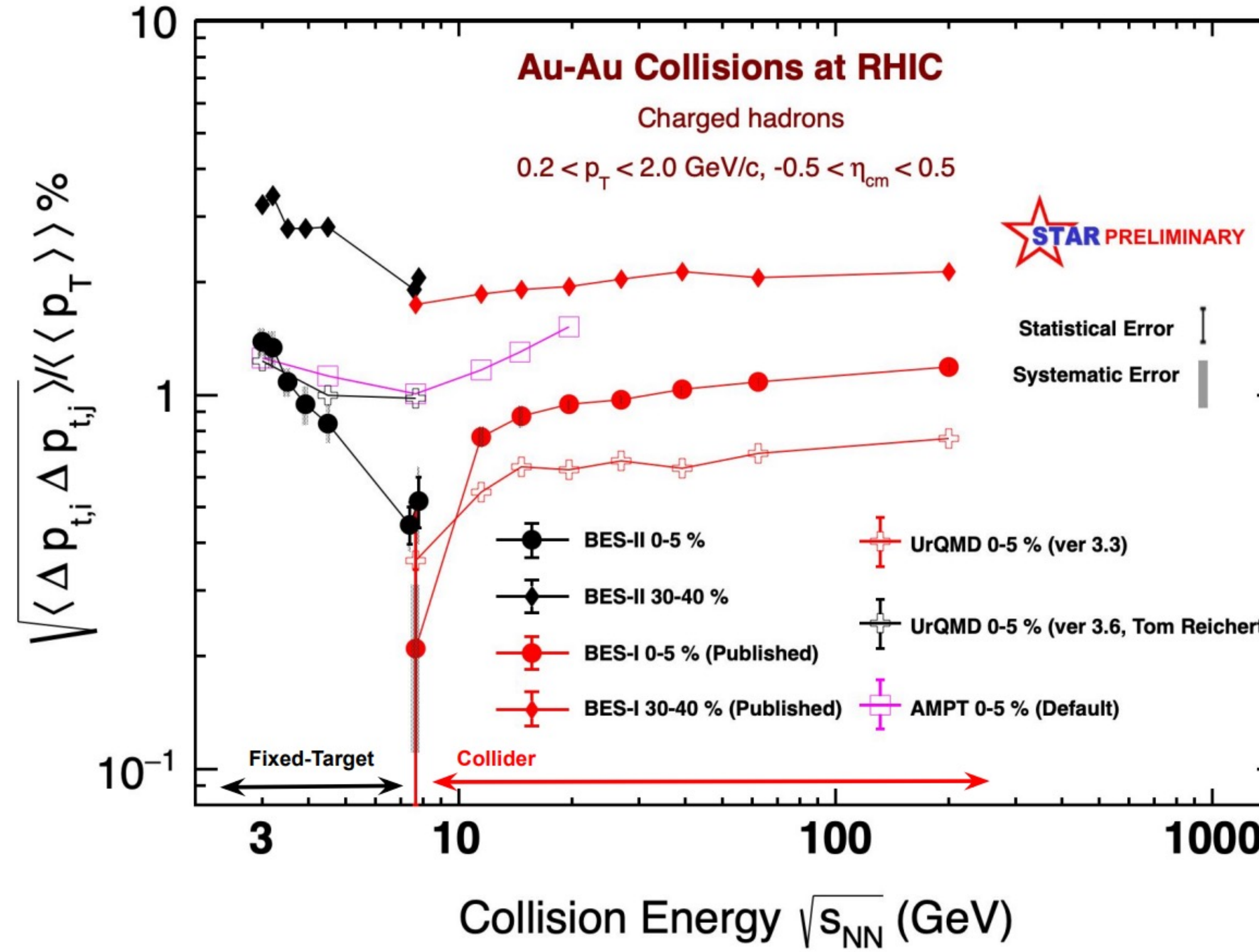
Appetizers

Guangyu Zheng (STAR), QM25 Poster ID 696



$v_1(\phi) \sim v_1(p) \sim v_1(\Lambda)$

Rutik Manikandhan (STAR), QM25 Poster ID 774



non-monotonic energy dependence of p_T-p_T fluctuation

Critical End Point Search Observable - Cumulants

At critical point with an infinite system
- correlation length should diverge
- susceptibilities should diverge

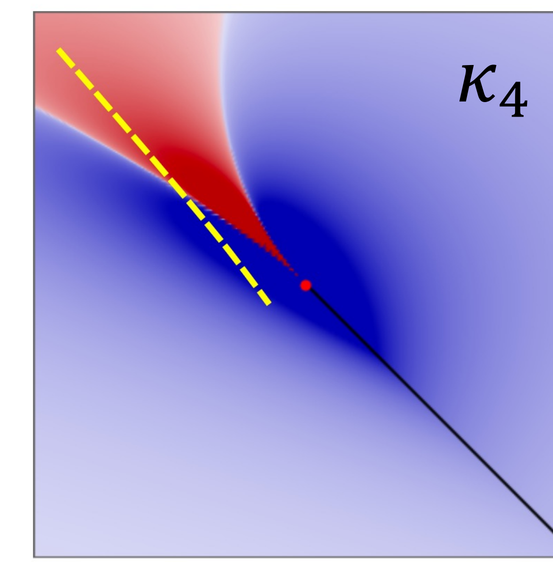
$$\chi_n^B = -\frac{1}{3^n}\frac{\partial^n f/T^4}{\partial \hat{\mu}_q^n}$$

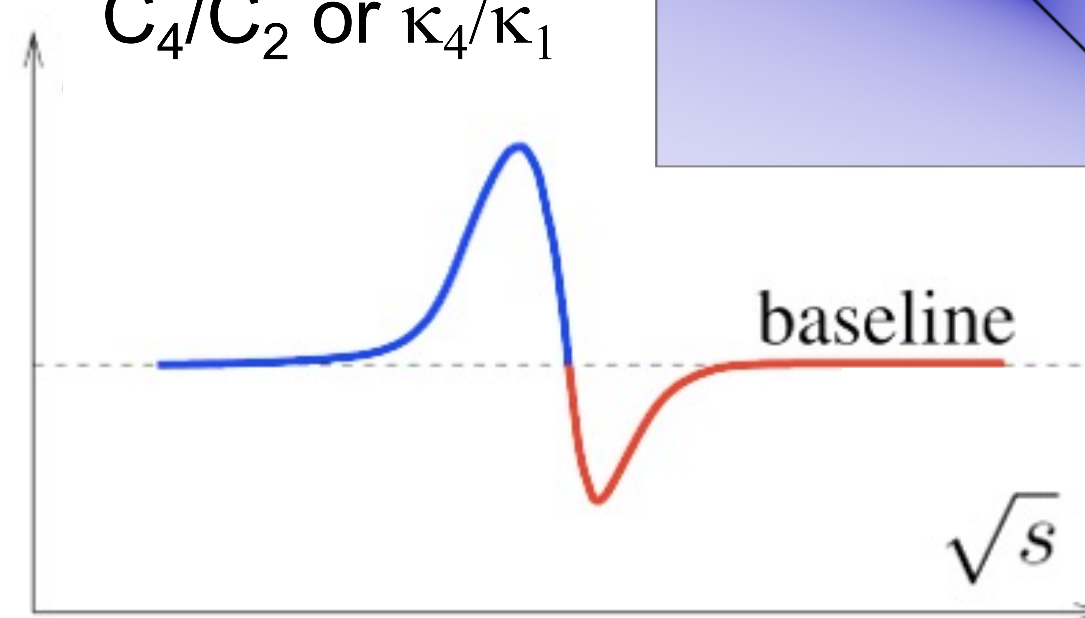
Proposed Experimental Observables:

Moments of conserved quantities: net-***B***, net-***S***, net-***Q*** etc.
- directly related to the susceptibility ratios
  - calculable from Lattice QCD
- sensitive to correlation lengths

$$\begin{aligned}
\text{mean}: \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance}: \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness}: \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3 / C_2^{3/2}, \\
\text{kurtosis}: \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4 / C_2^2.
\end{aligned}$$

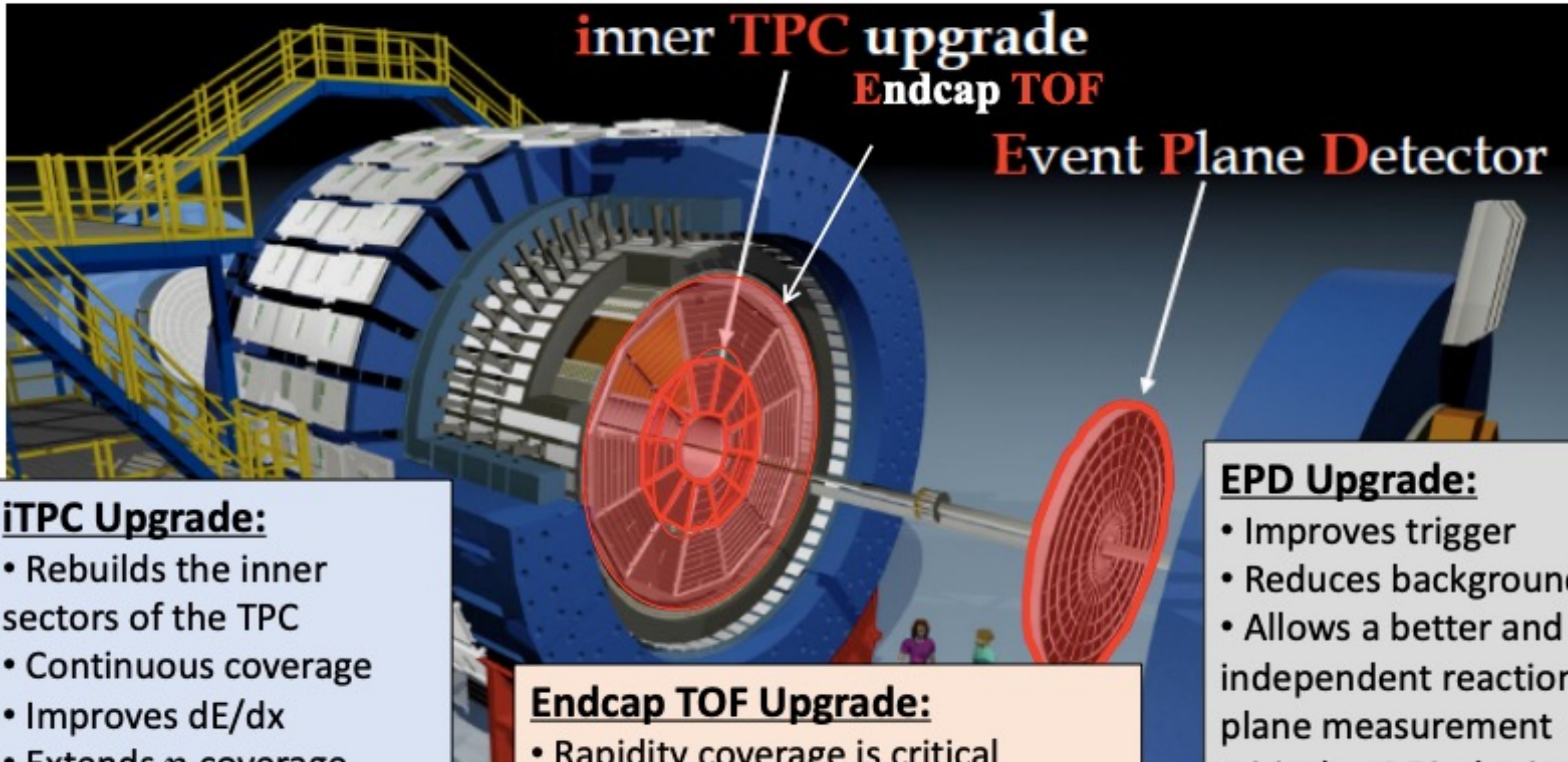
Notation: Cumulants: $C_{1,2,\ldots}$
Factorial Cumulants: $\kappa_{1,2,\ldots}$





M. A. Stephanov, PRL 102 (2009) 032301

STAR Detectors at BES-II



iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-off from 125 MeV/c to 60 MeV/c

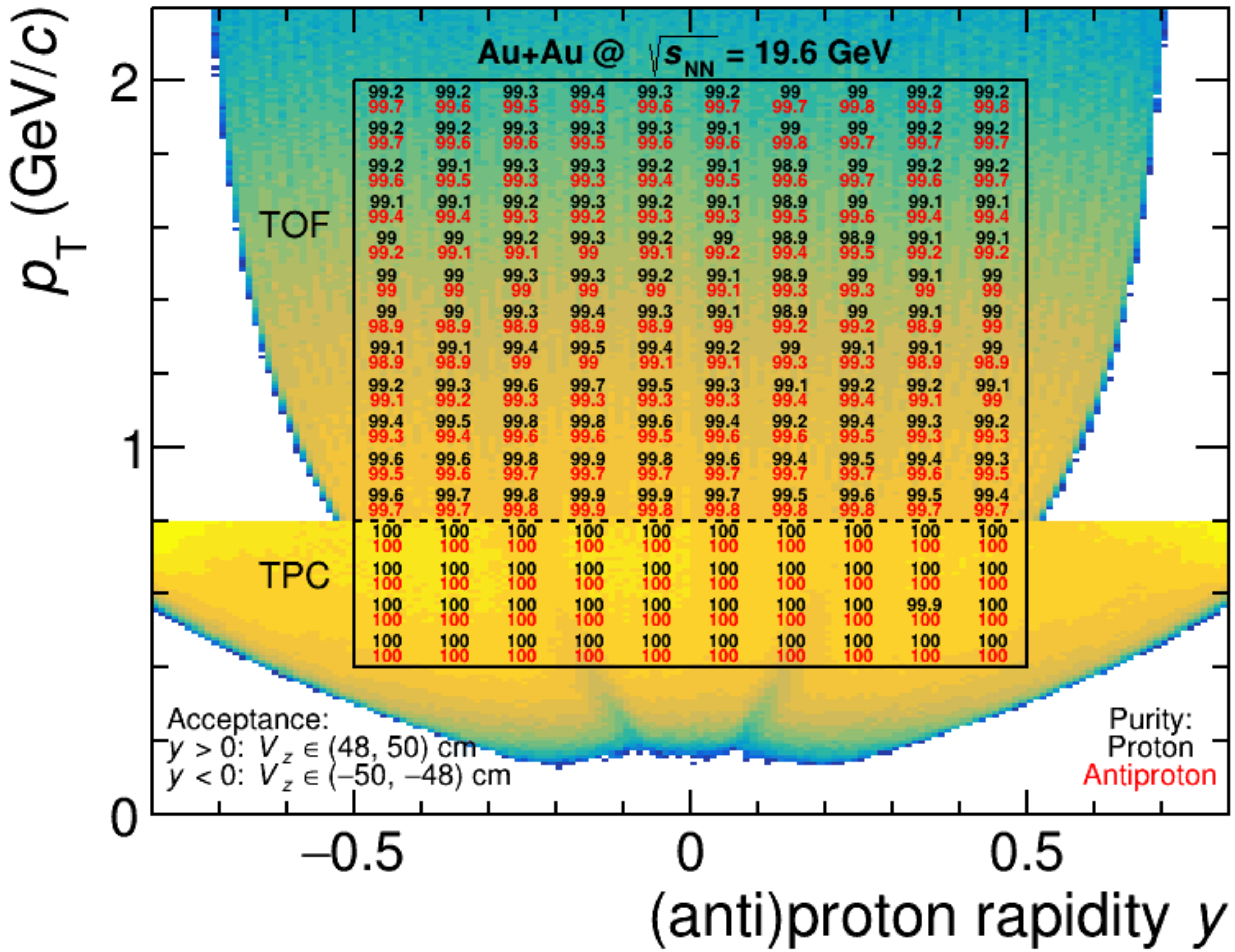
Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

High Statistics BES-II Datasets (2019 – 2021)

Au+Au Collisions at RHIC							
Collider Runs				**Fixed-Target Runs**			
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B
1	**200**	380 M	**25** MeV	**1**	13.7 (100)	50 M	280 MeV
2	62.4	46 M	75 MeV	**2**	11.5 (70)	50 M	316 MeV
3	54.4	1200 M	85 MeV	**3**	9.2 (44.5)	50 M	372 MeV
4	39	86 M	112 MeV	**4**	7.7 (31.2)	260 M	420 MeV
5	27	585 M	156 MeV	**5**	7.2 (26.5)	470 M	440 MeV
6	19.6	595 M	206 MeV	**6**	6.2 (19.5)	120 M	490 MeV
7	17.3	256 M	230 MeV	**7**	5.2 (13.5)	100 M	540 MeV
8	14.6	340 M	262 MeV	**8**	4.5 (9.8)	110 M	590 MeV
9	11.5	257 M	316 MeV	**9**	3.9 (7.3)	120 M	633 MeV
10	9.2	160 M	372 MeV	**10**	3.5 (5.75)	120 M	670 MeV
11	7.7	104 M	420 MeV	**11**	3.2 (4.59)	200 M	699 MeV
				12	**3.0** (3.85)	**260** + 2000 M	**750** MeV

Proton Identification and Purity



1) Uniform acceptance for (anti-) protons $|y|<0.5$ with $|V_z| < 50$cm

2) (anti-)protons identified using TPC dE/dx + TOF

3) Bin-by-bin purity > 99% in the full acceptance range and all energies

(Anti-)Proton Acceptance:
$|y| < 0.5$, *and*
$0.4 < p_T < 2$ GeV/c

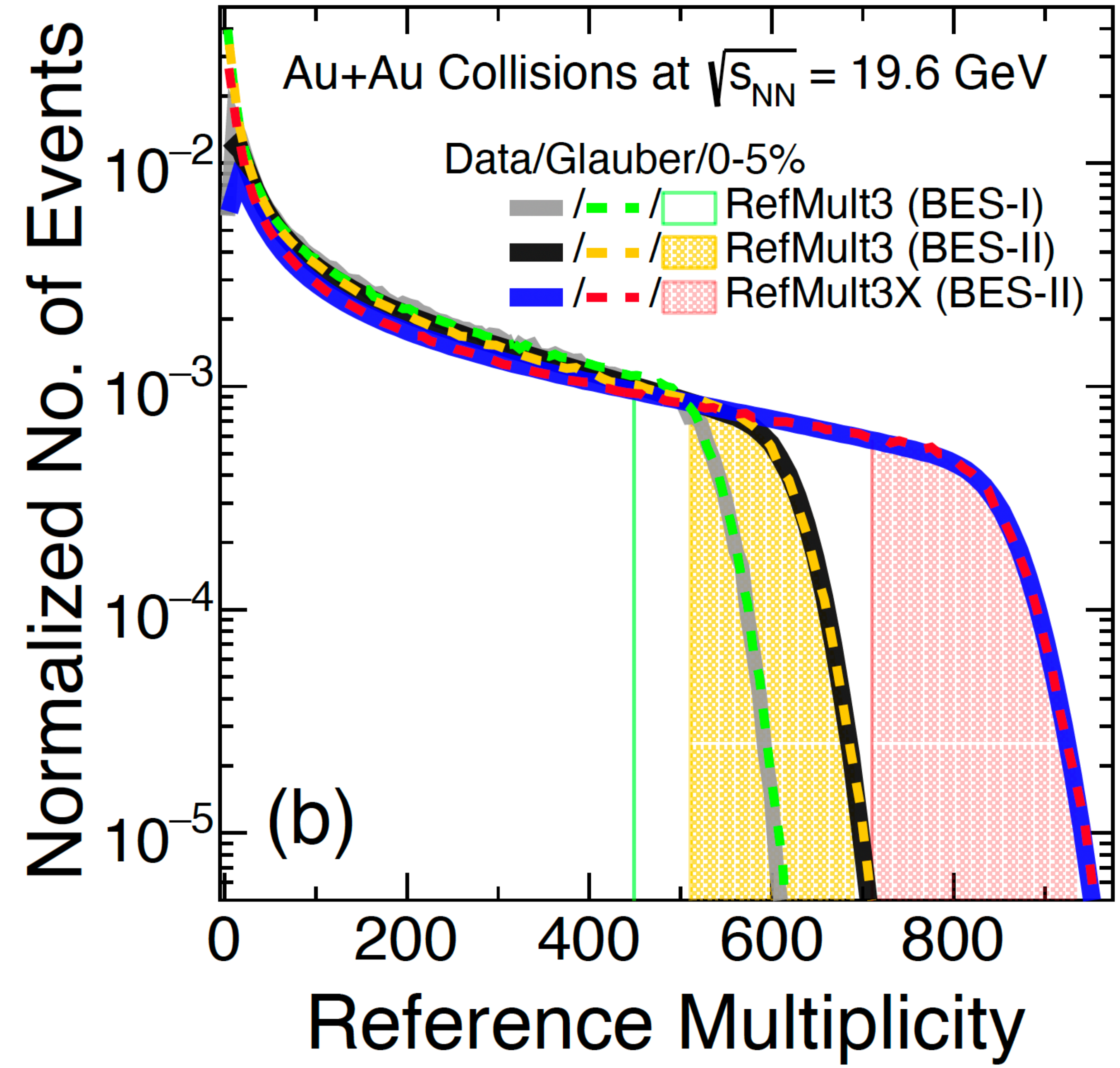
Collision Centrality for Proton Number Fluctuations

Charged particle multiplicity fit to MC Glauber to determine collision centrality
Exclude protons/antiprotons to avoid self correction

STAR: 2504.00817

RefMult3: Charged particles excluding protons within $|\eta| \leq 1.0$ (BES-I)

RefMult3X: Charged particles excluding protons within $|\eta| \leq 1.6$ (BES-II)



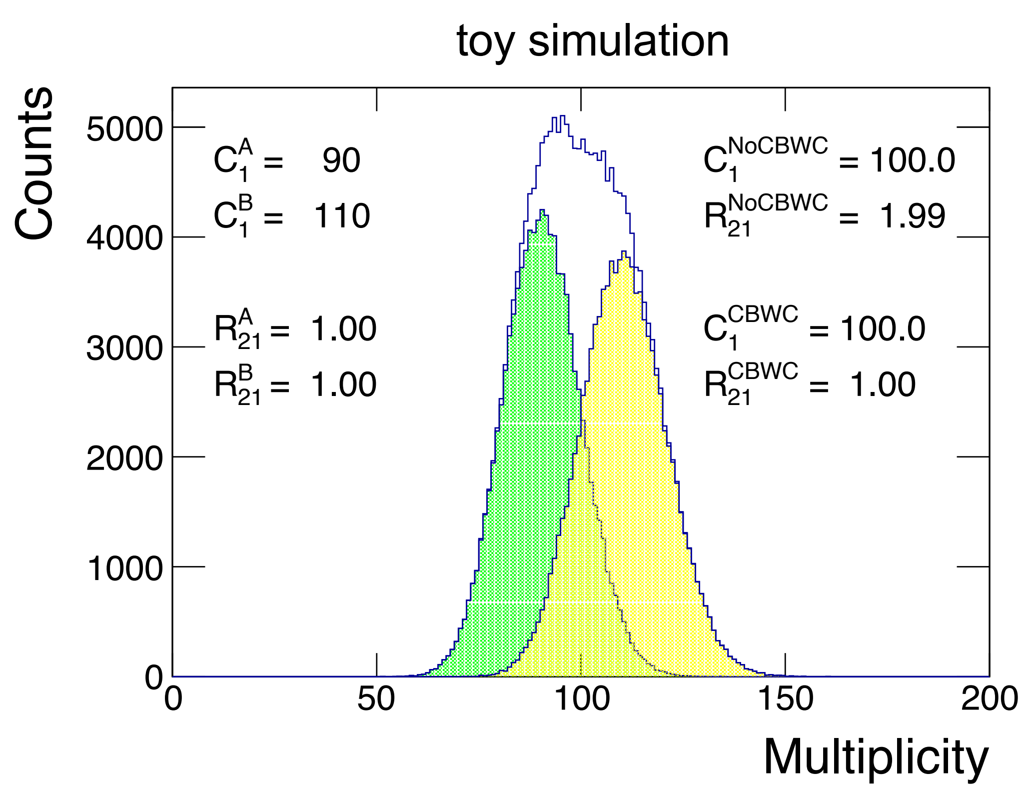
Multiplicity order:
Refmult3X^{BES-II} > Refmult3^{BES-II} > Refmult3^{BES-I}
→ Better centrality resolution with Refmult3X^{BES-II}

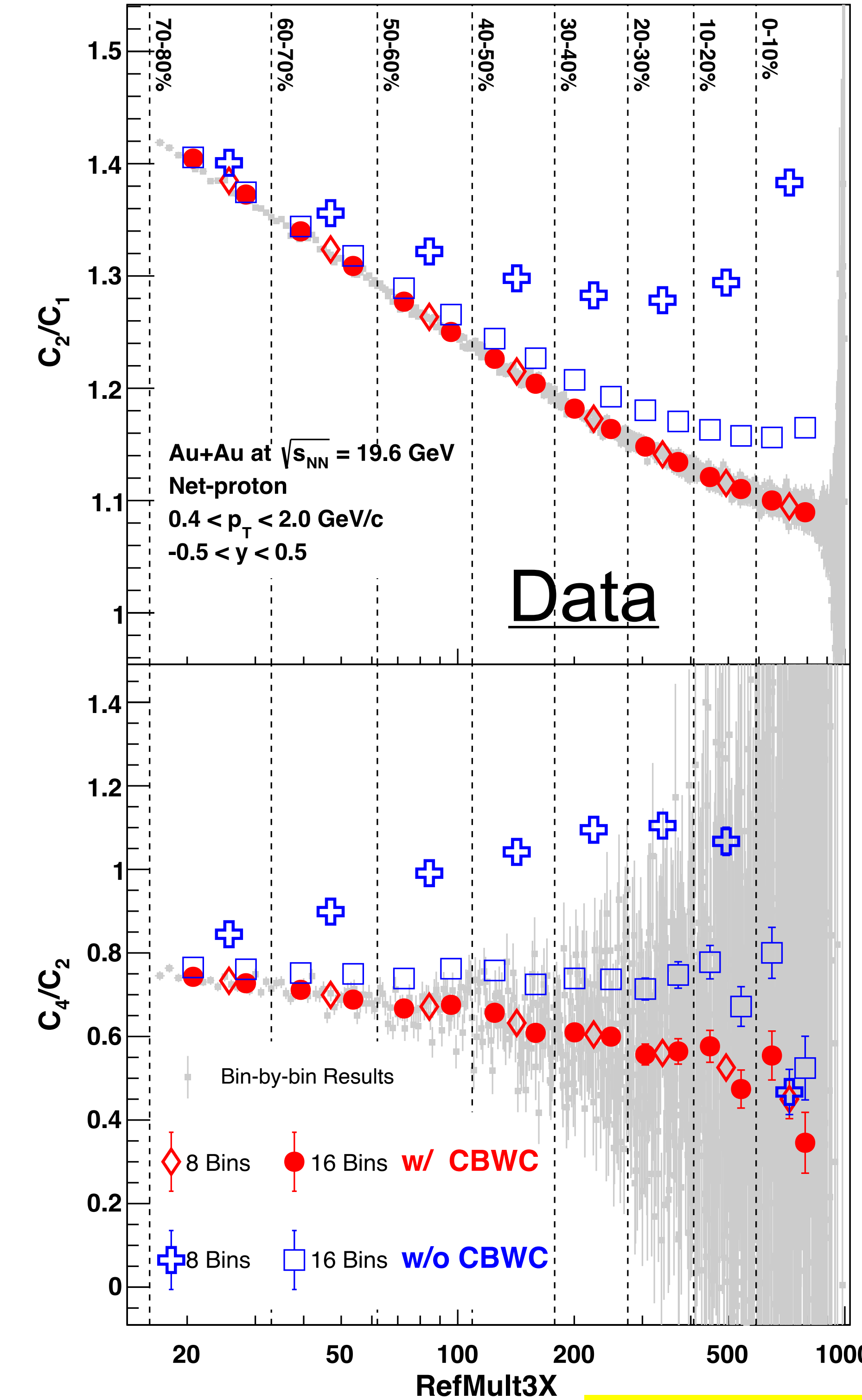
Centrality-Bin-Width-Correction

CBWC -> Centrality-Bin-Width-Average (CBWA)

$$C_n = \frac{\sum_r n_r C_n^r}{\sum_r n_r} = \sum_r \omega_r C_n^r \qquad\qquad \omega_r = n_r / \sum_r n_r$$

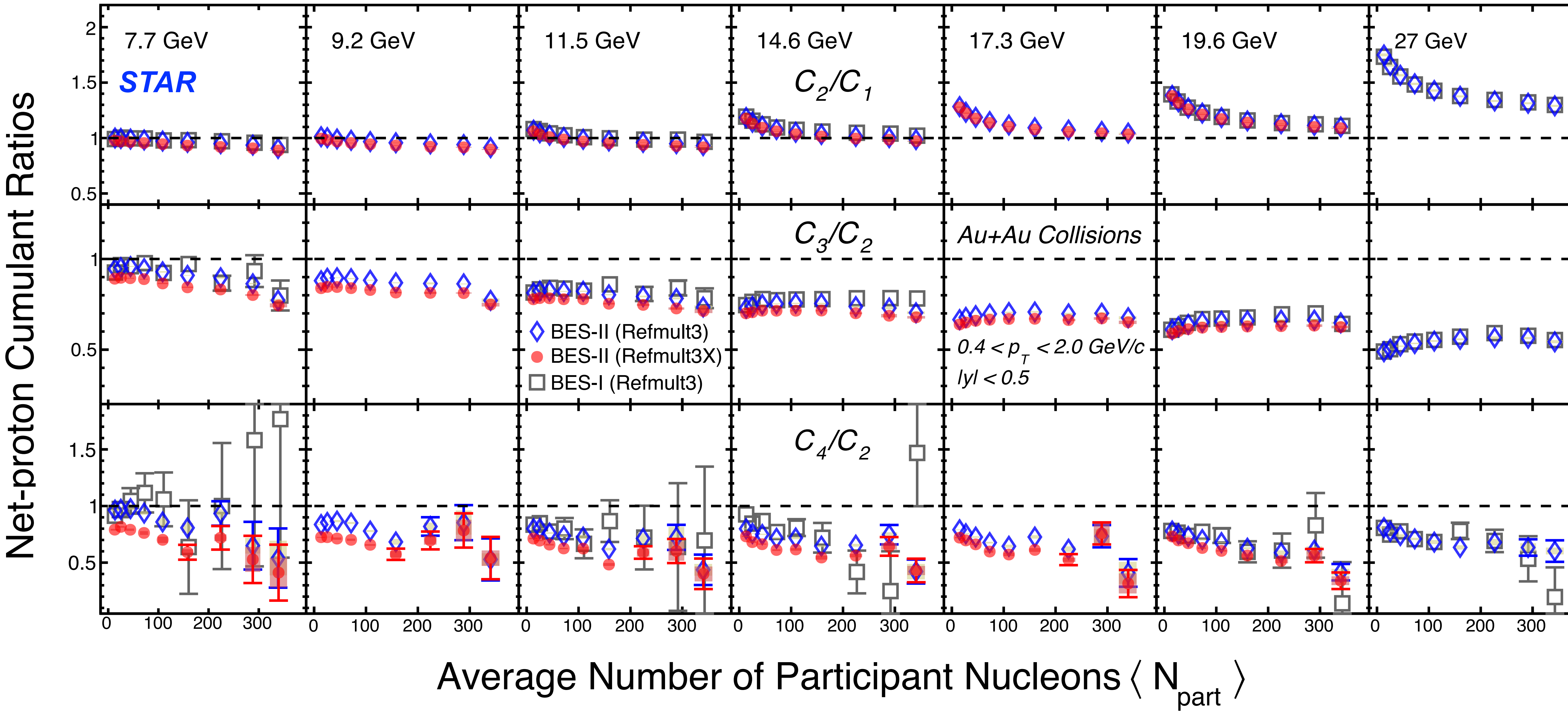
The average method is to remove the trivial dependence of the measured cumulants on the choice of centrality bin size.





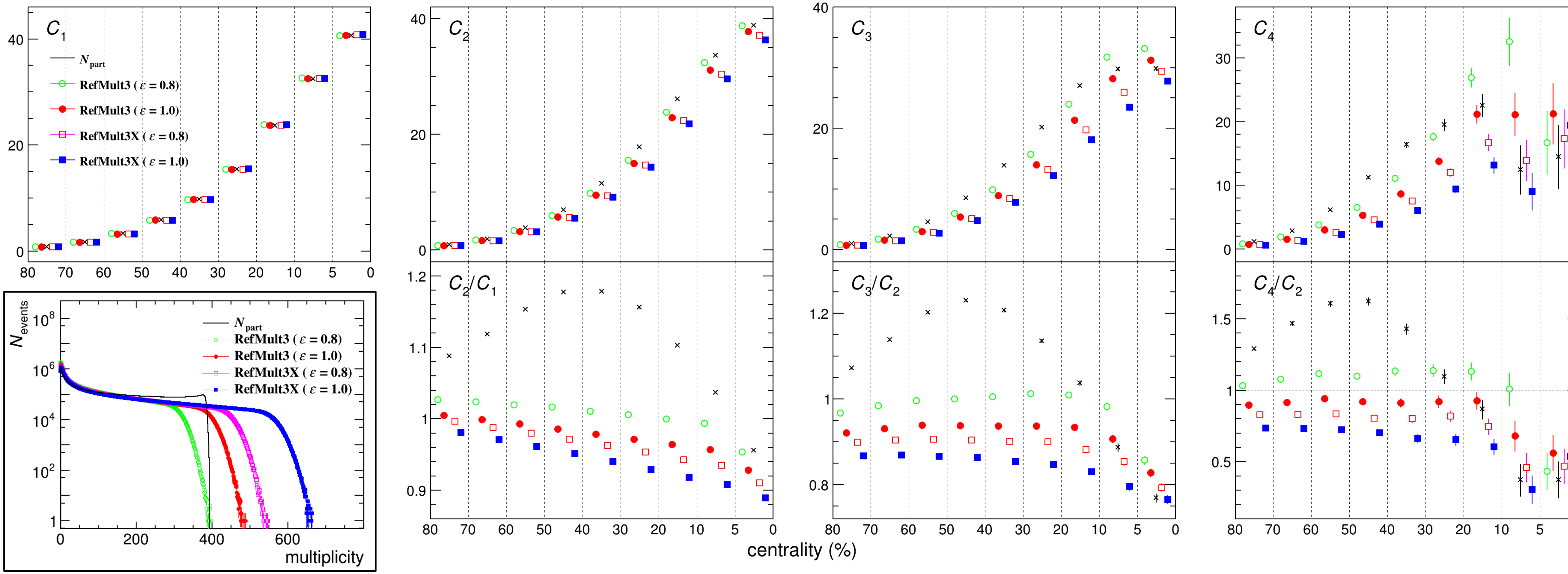
STAR: 2504.00817

Net-proton Cumulant Ratios from BES-II



1) Significantly improved precision in BES-II measurements
2) Centrality resolution impact: $\text{Refmult3X}^{\text{BES-II}} < \text{Refmult3}^{\text{BES-II}} < \text{RefMult3}^{\text{BES-I}}$
3) C_4/C_2 in 0-5% centrality, results are consistent – weak resolution effect

Centrality Resolution Study (UrQMD 7.7 GeV)



Centrality resolution from worst to best: ○ < ● < □ < ■

- Clear centrality resolution ordering: better resolution => lower cumulants/ratios

Net-proton Cumulant Ratios Compared to Models

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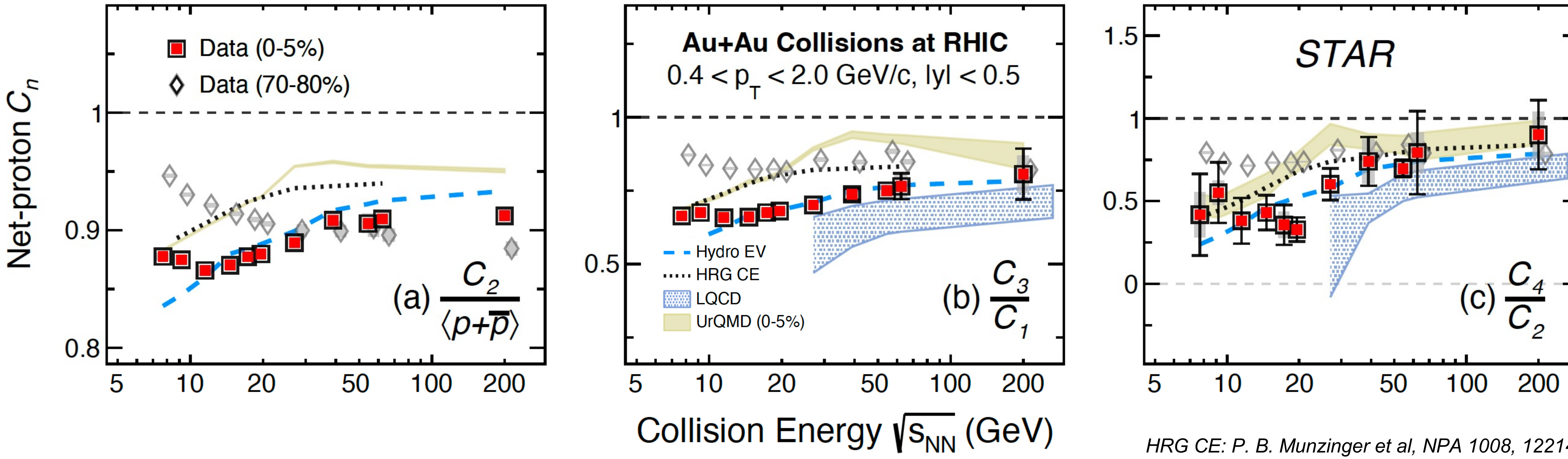


HRG CE: P. B. Munzinger et al, NPA 1008, 122141 (2021)
Hydro EV: V. Vovchenko et al, PRC 105, 014904 (2022)
LQCD: D. Bollweg et al, PRD 110, 054519 (2024)

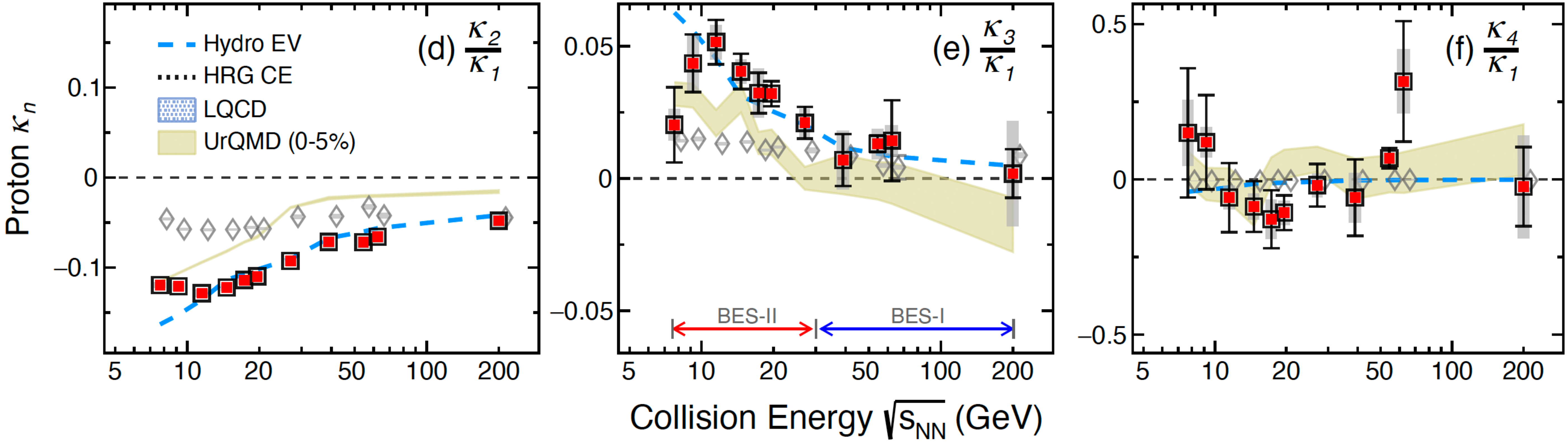
In 0-5% central Au+Au collisions

1) Net-proton C_4/C_2 shows deviation from non-CP references at ~ 20 GeV!
   - references: Hydro(+EV), HRG-CE, UrQMD, and 70-80% data
   - energy dependence trend driven by baryon number conservation

2) Net-proton $C_2/\langle p+\bar{p}\rangle$, C_3/C_1 show deviations from non-CP models too, especially below 11.5 GeV.

Proton/Anti-proton Factorial Cumulant Ratios

STAR: 2504.00817

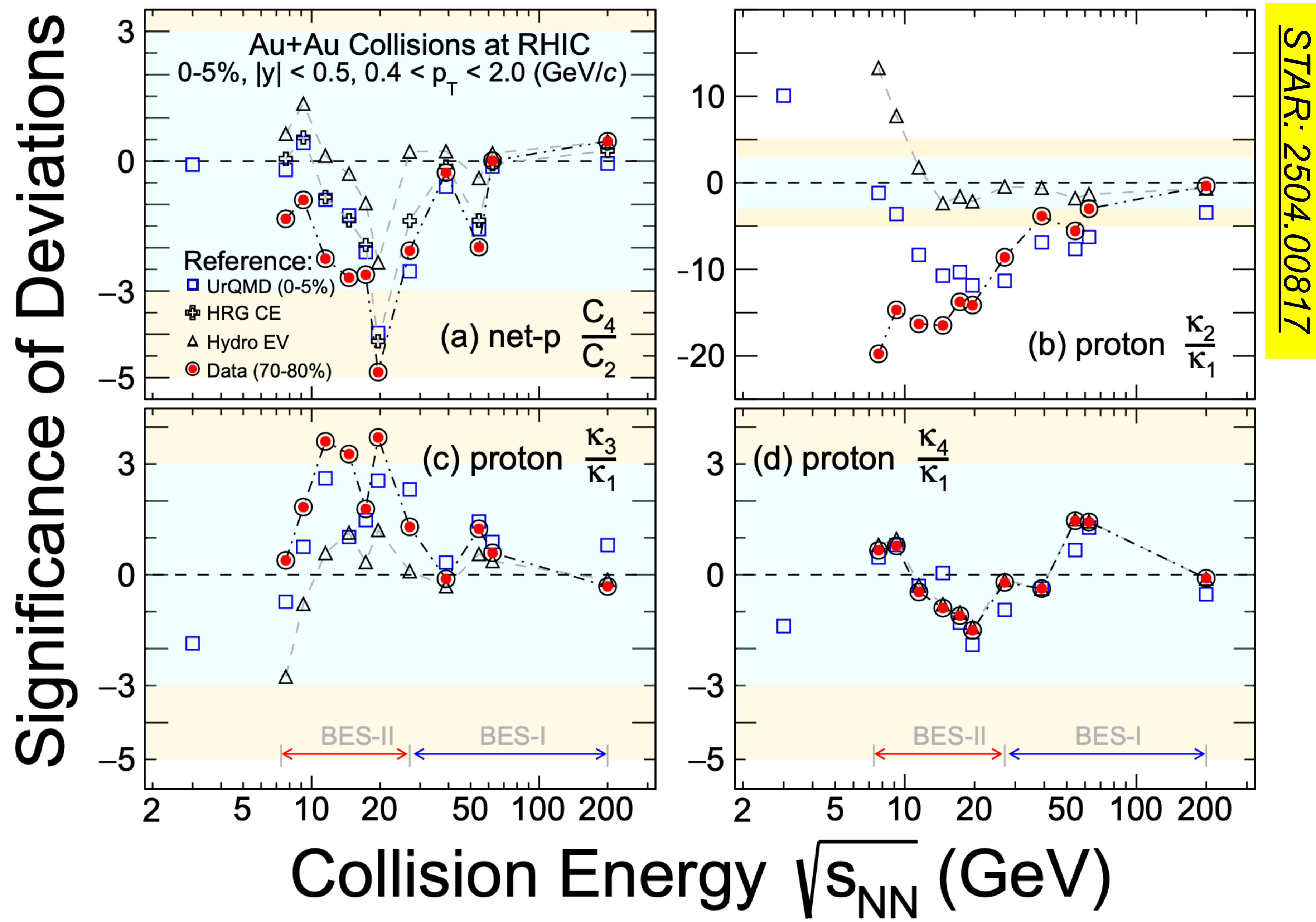


HRG CE: P. B. Munzinger et al, NPA 1008, 122141 (2021)
Hydro EV: V. Vovchenko et al, PRC 105, 014904 (2022)
LQCD: D. Bollweg et al, PRD 110, 054519 (2024)

In 0-5% central Au+Au collisions

Proton factorial cumulant ratios deviates from non-CP references
- hint of non-monotonicity in κ_2/κ_1, κ_3/κ_1 at low energies

Quantify Deviations



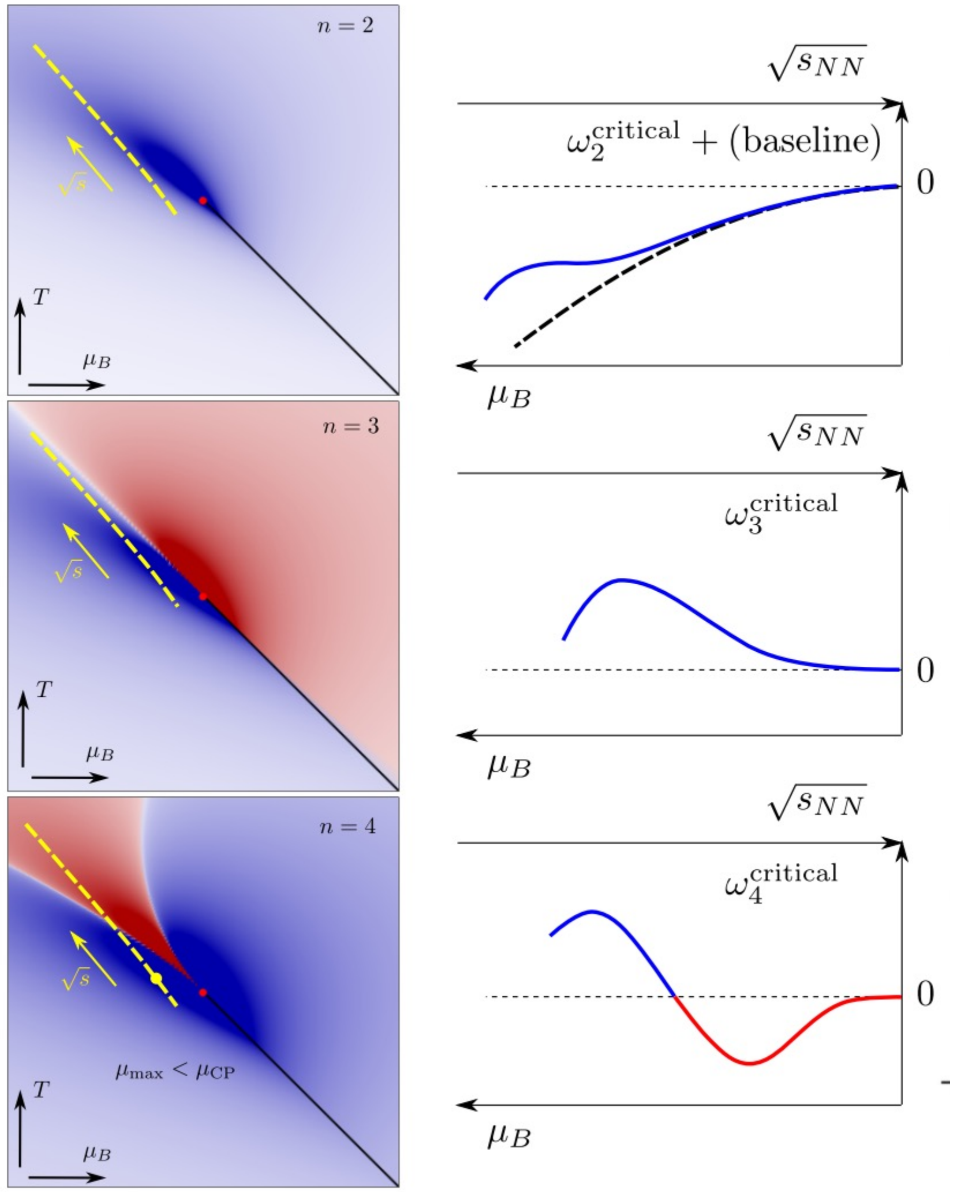
1) C_4/C_2 shows a minimum at ~20 GeV comparing to non-CP models/70-80% data

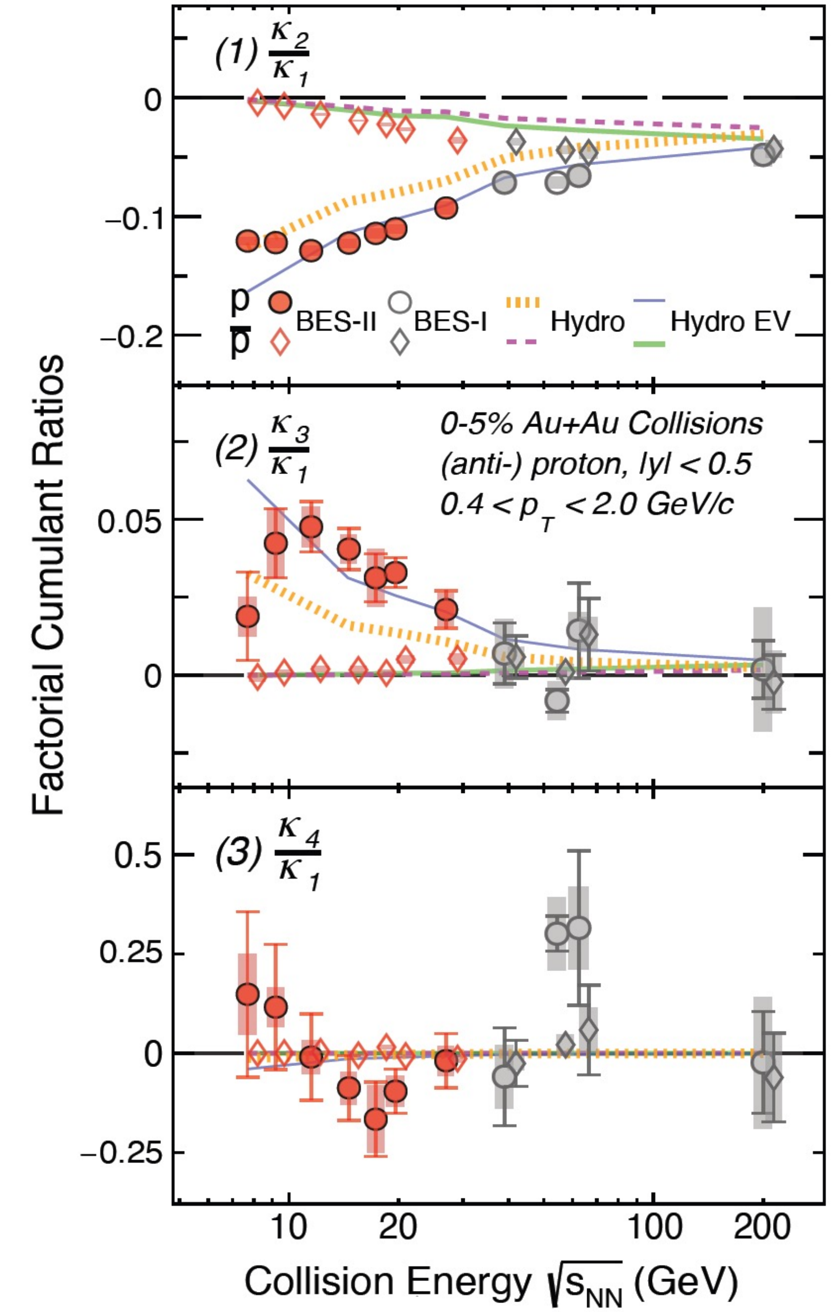
- Maximum deviation: **2 – 5 σ** at 20 GeV (1.3 – 2σ at BES-I)

2) Deviations also seen in proton κ_2/κ_1, κ_3/κ_1 etc.

Resemblance of CP Anticipated Signal?

M. Stephanov, arXiv:2410.02861

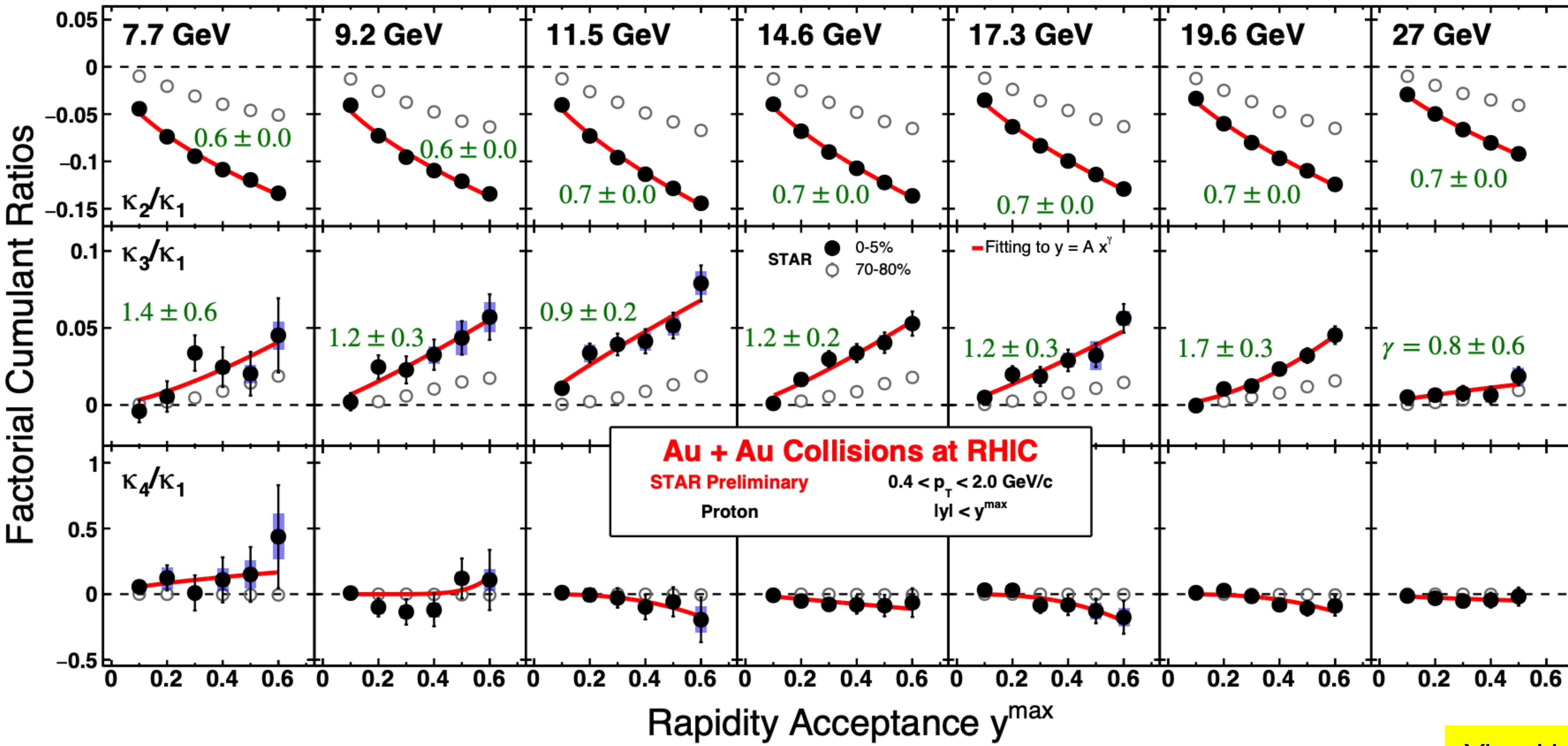




Critically needed:

1) Control on the non-CP reference
2) Dynamical predictions including CP

Proton Factorial Cumulant Ratios vs. Rapidity Window

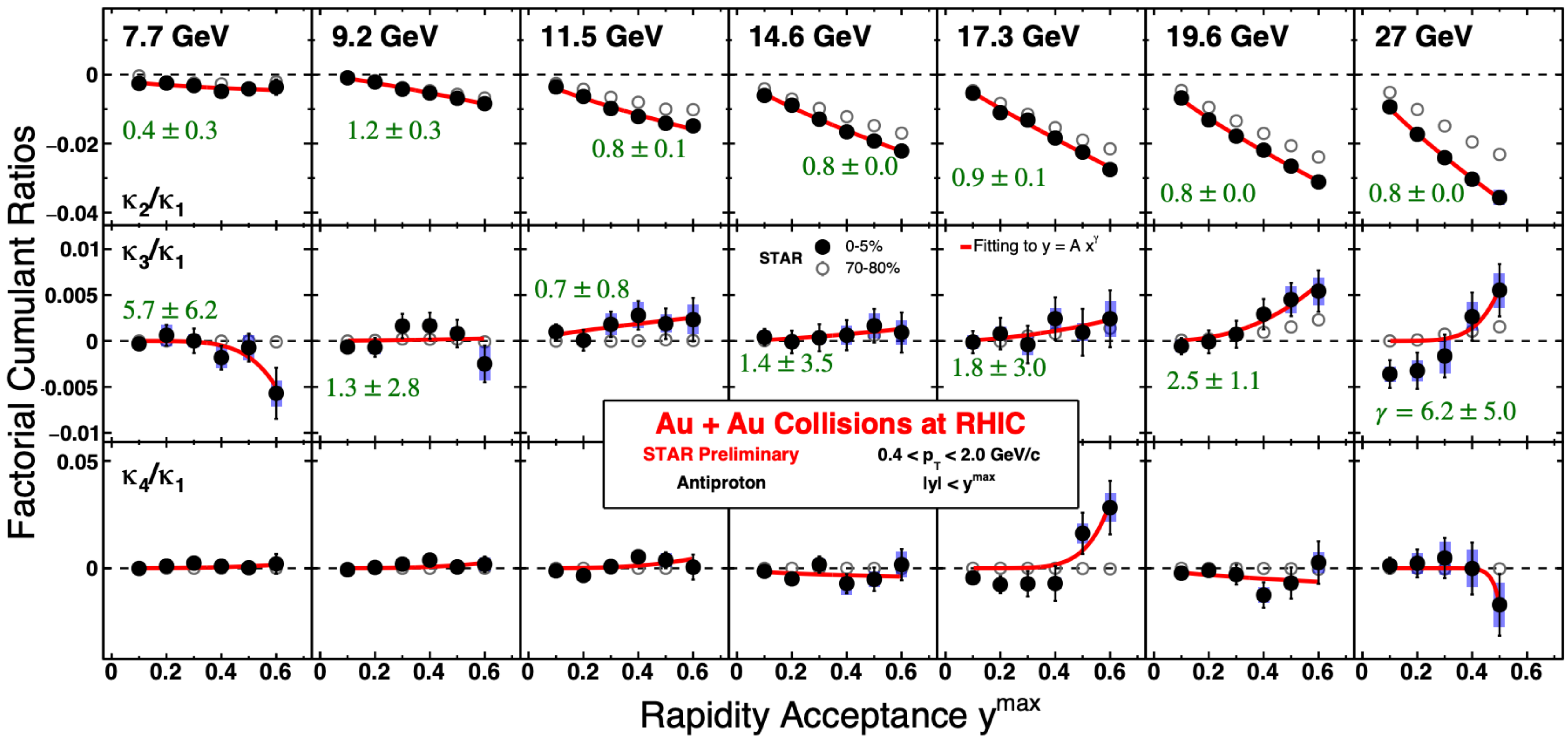


Yige Huang, QM25

1) Proton κ_n/κ_1 follows a power increase vs. Δy

2) Power constant smaller than simple expectation (n-1)

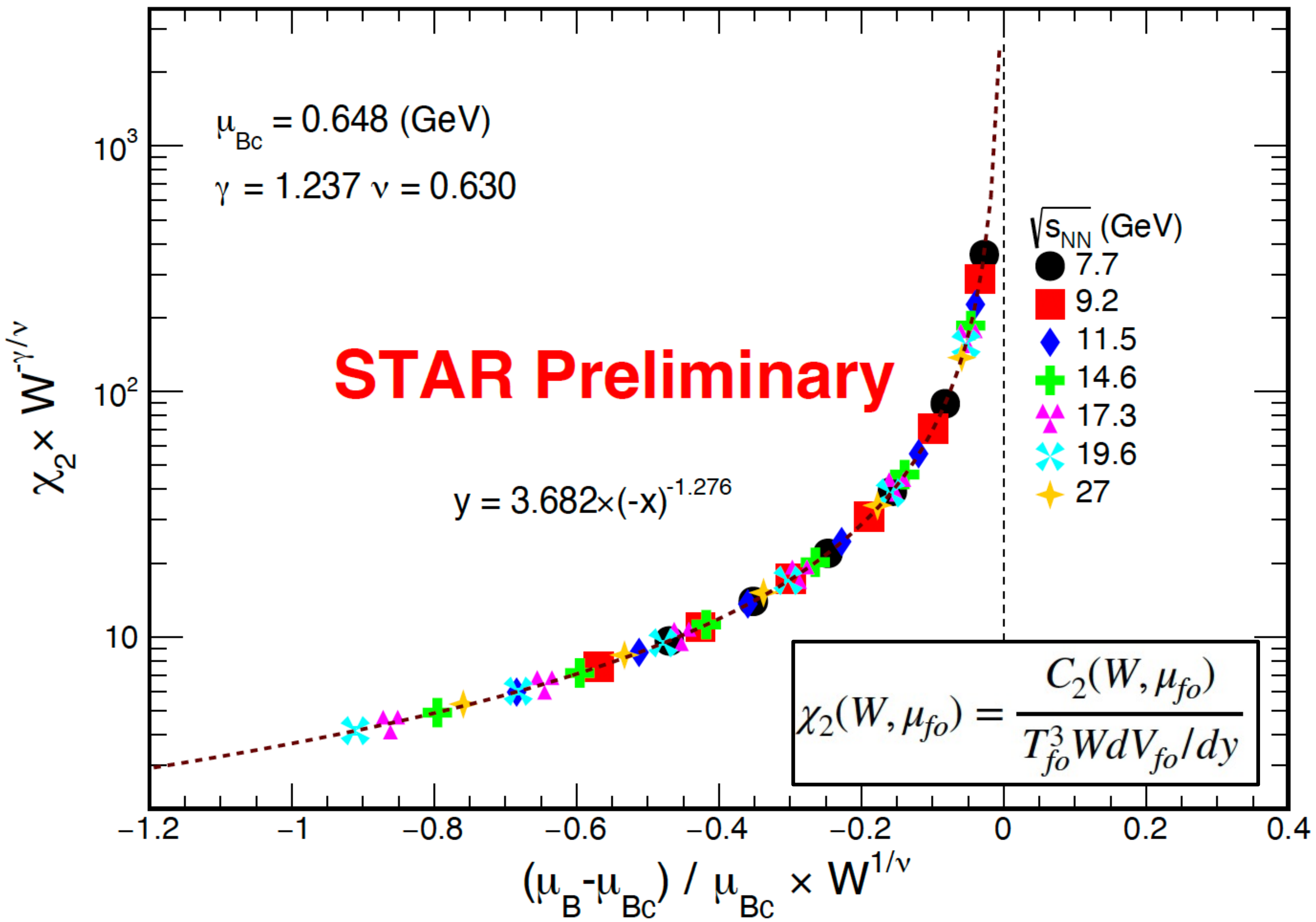
Anti-Proton Factorial Cumulant Ratios

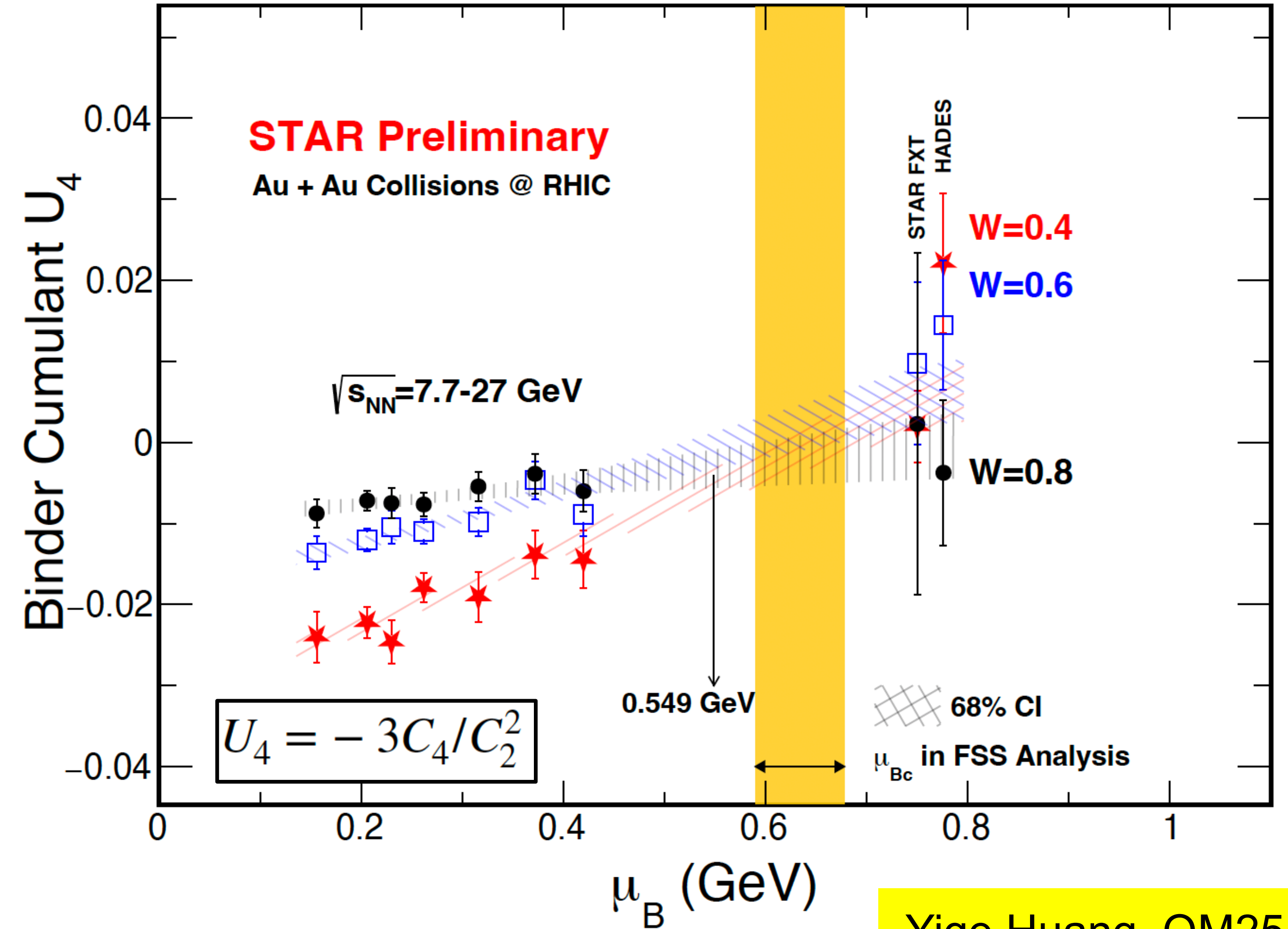


1) Anti-proton κ_n/κ_1 follows a power vs. Δy

2) Power constant for κ_2/κ_1 smaller than simple linear expectation (n-1)

Finite Size Scaling Study





Yige Huang, QM25

A. Sorensen and P. Sorensen, arXiv: 2405.10278

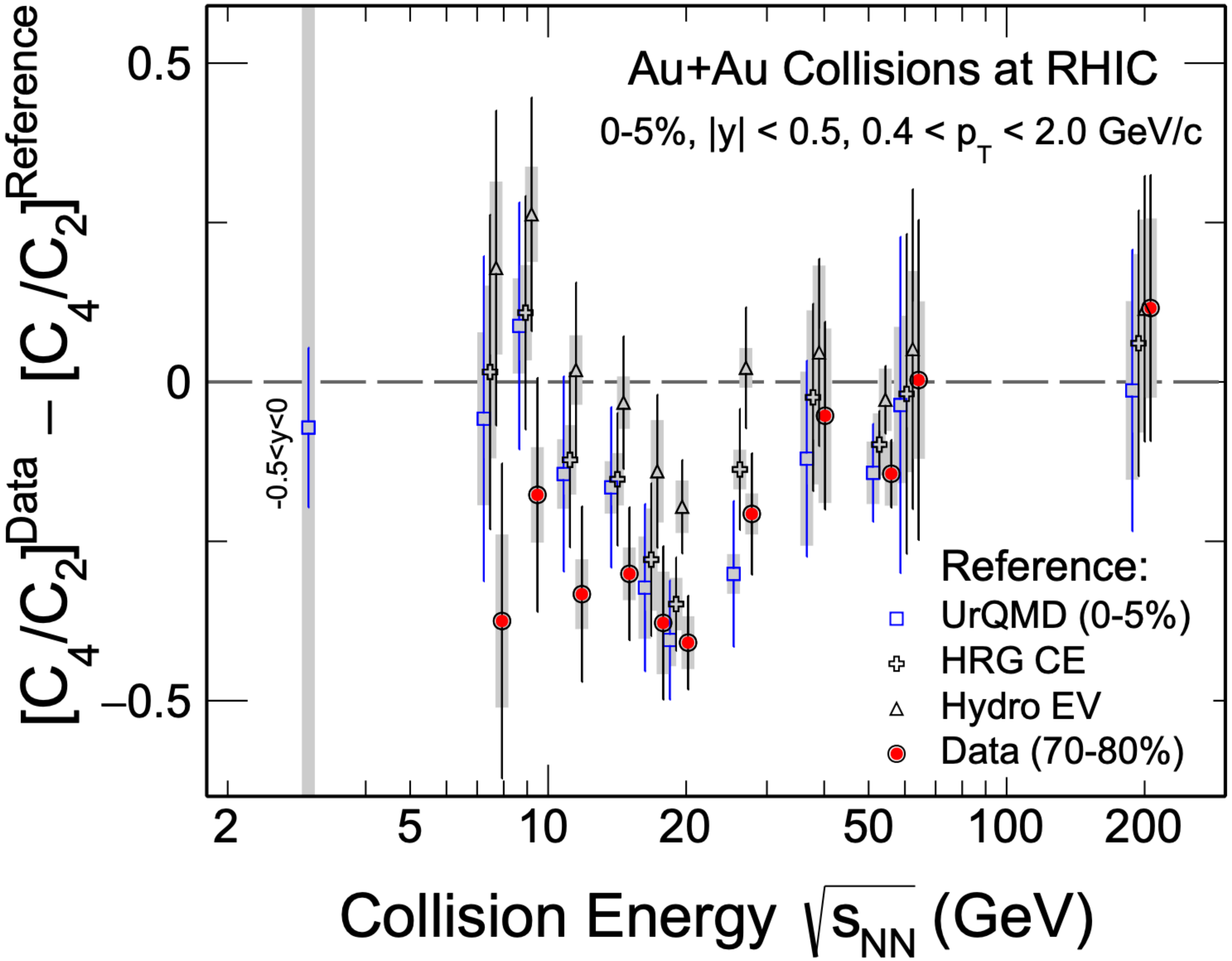
1) Finite size scaling study for C_2 based on thermodynamic behavior

$$\mu_{Bc} = 648^{+30/+2}_{-24/-58} \text{ MeV}$$

2) Consistent estimation from Binder cumulants fit results

Pushing Towards Lower Energies

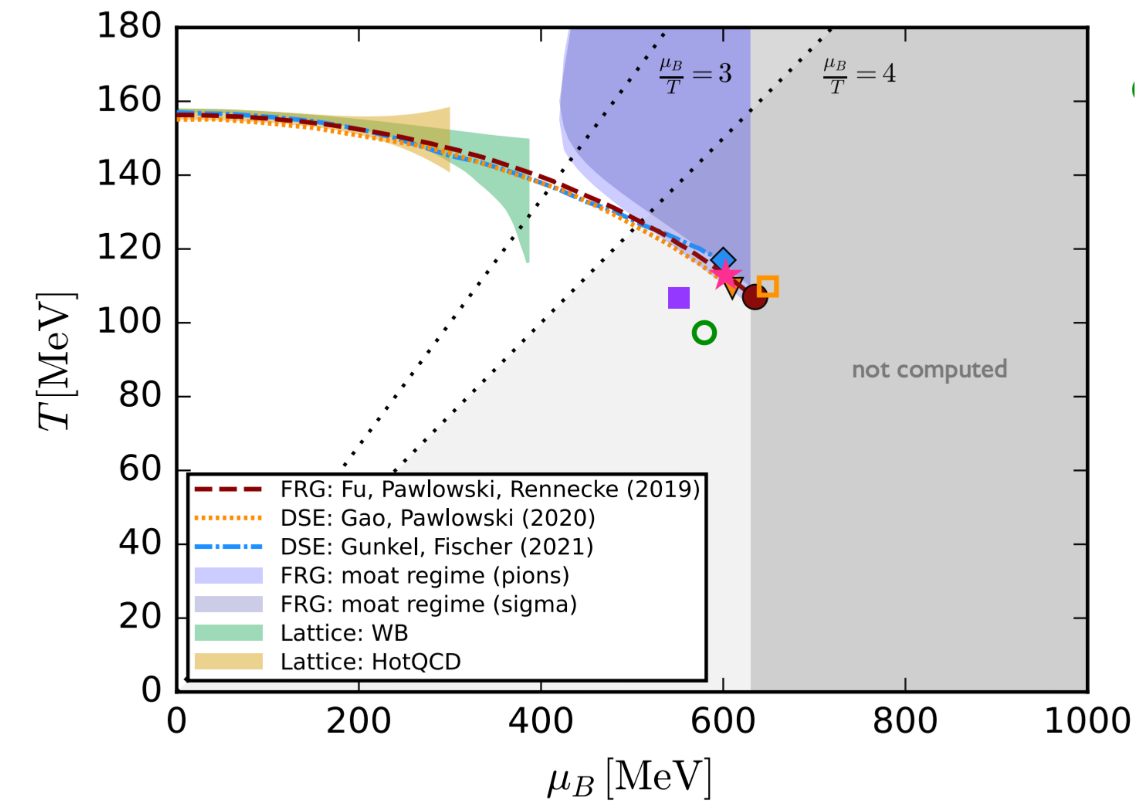
STAR: 2504.00817



Latest predictions:

μ_B^{CEP}: ~ 420 – 750 MeV

T^{CEP}: ~ 90 – 120 MeV

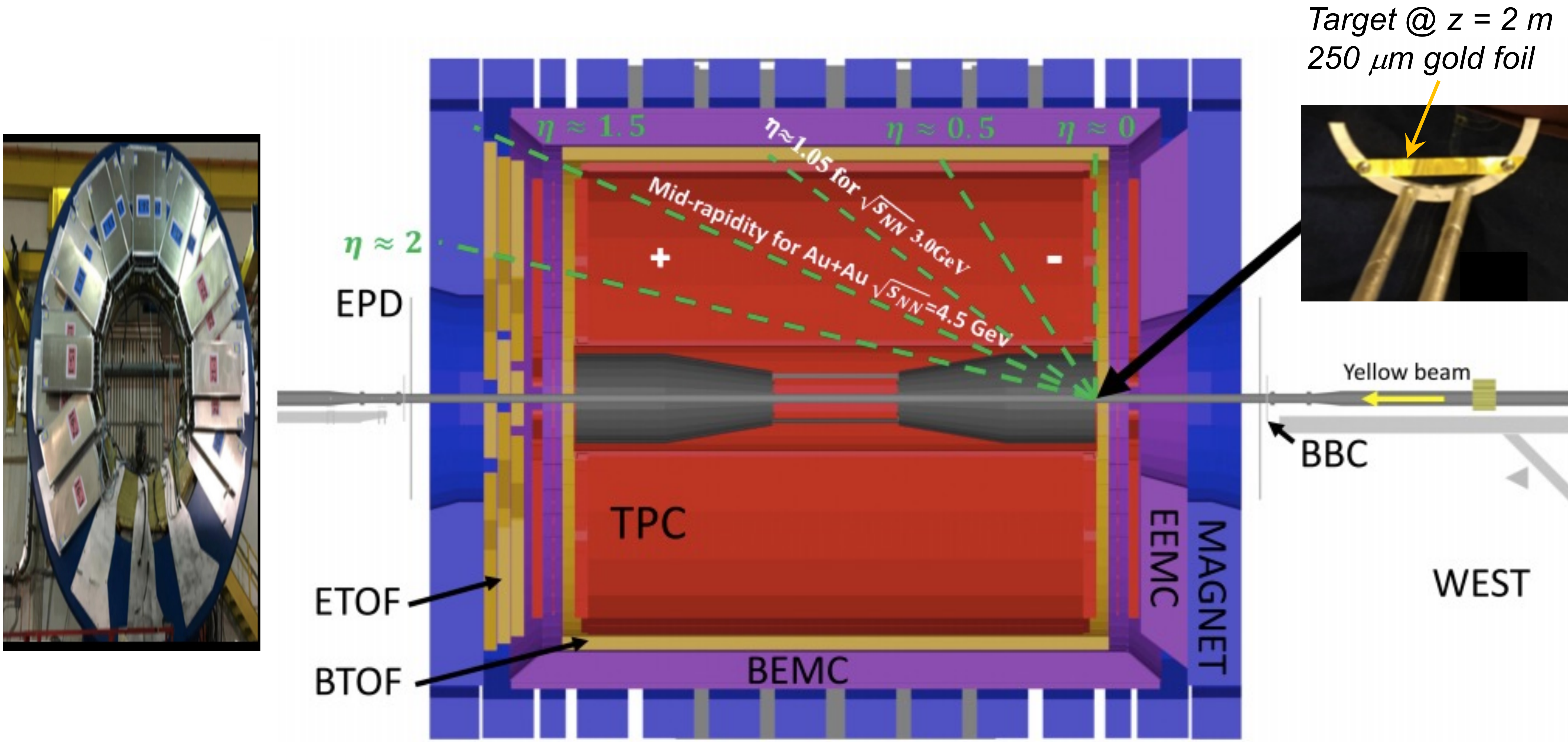


F. Rennecke, QM 2025

To establish the oscillation evidence of proton fluctuation measurements:

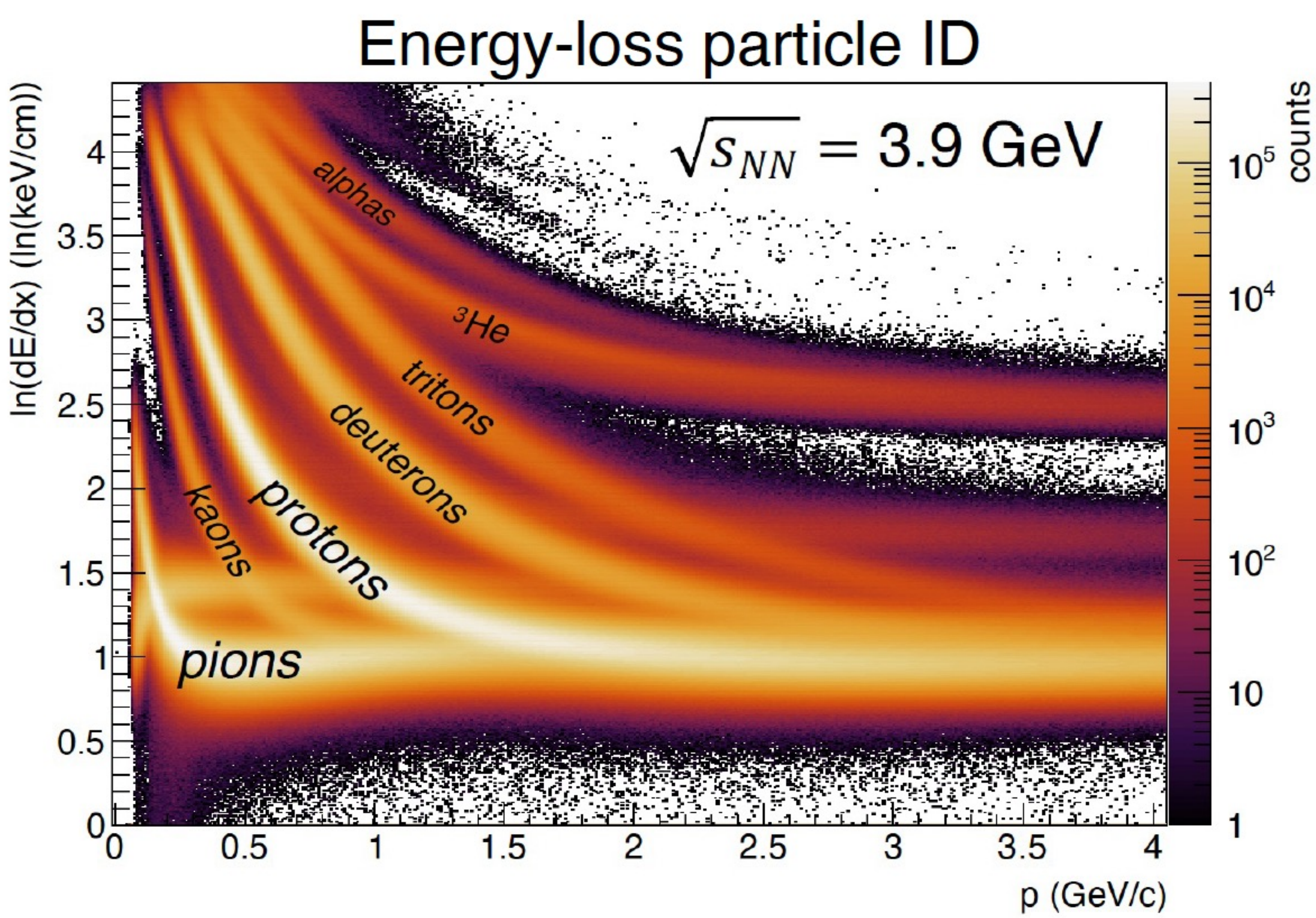
→ **Precision measurements between 3-10 GeV!**

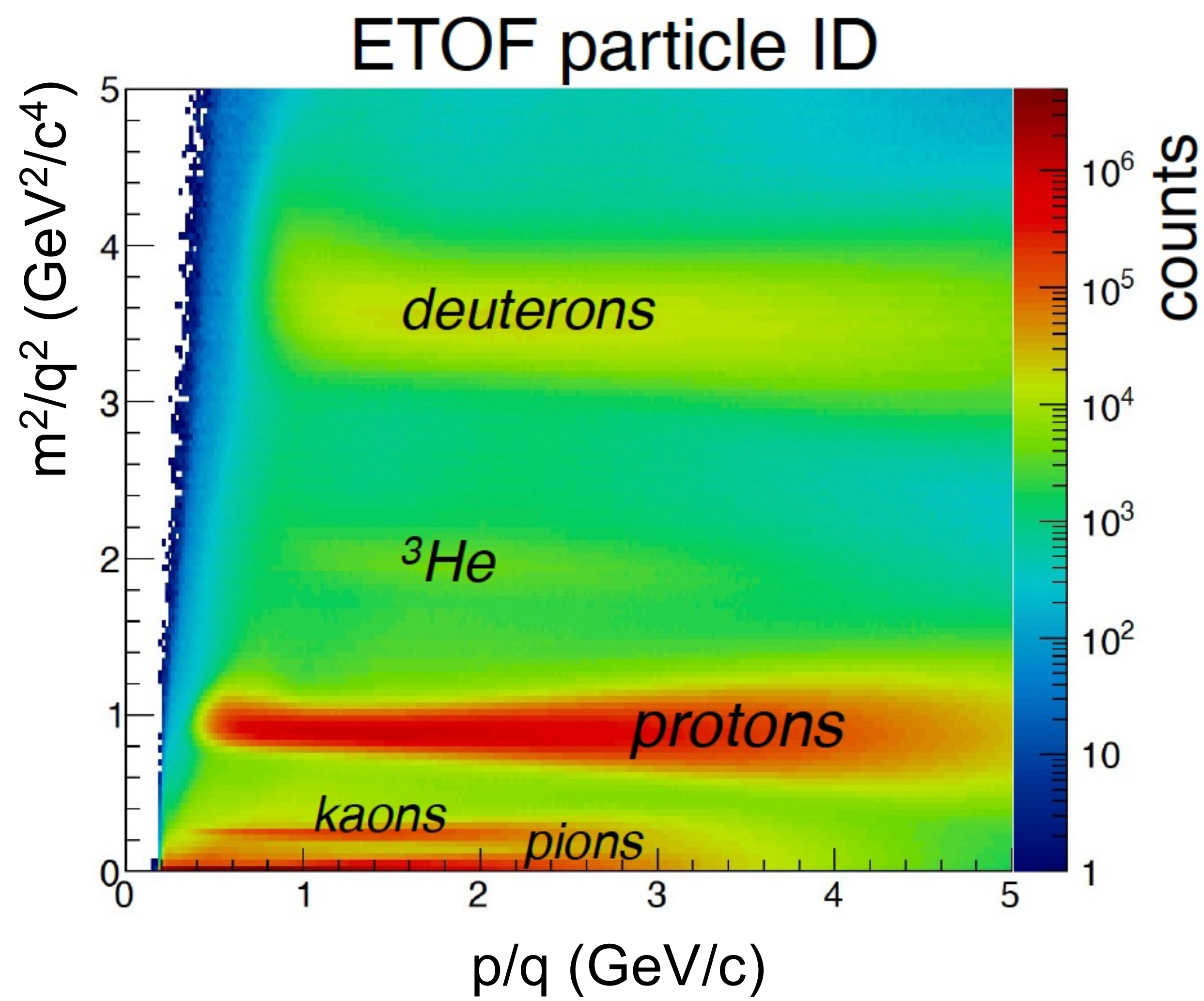
STAR Fixed-Target (FXT) Program



ETOF provided by CBM-FAIR, crucial for BES-II, especially for the FXT program

Proton Identification



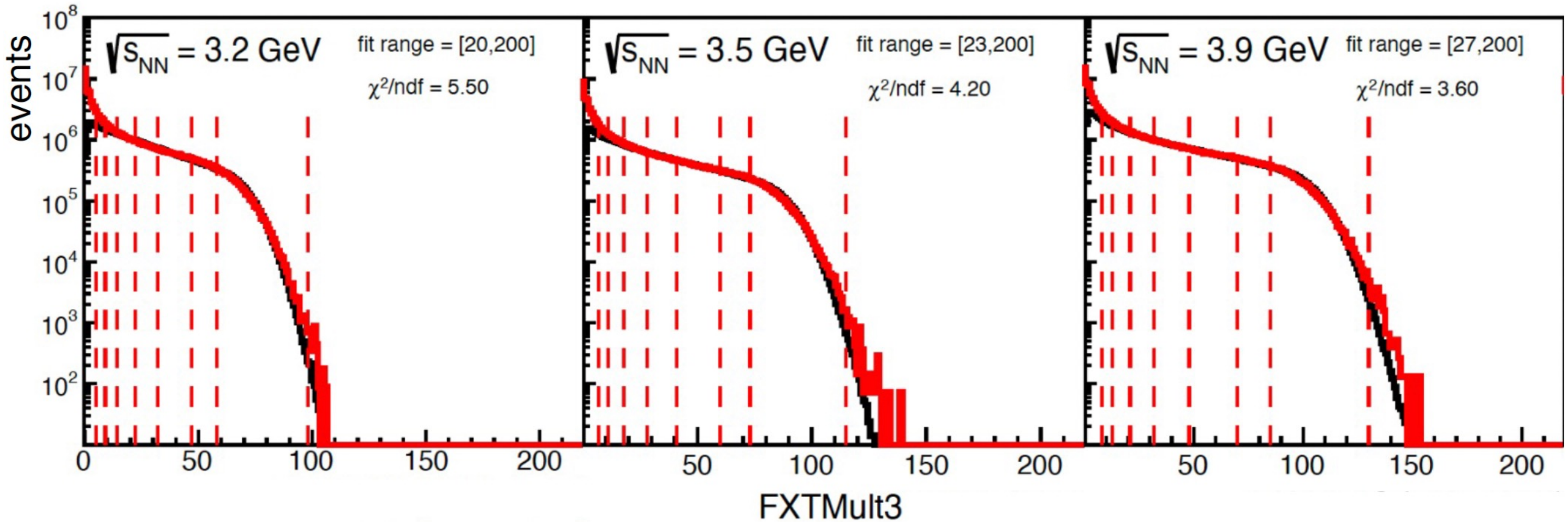


1) eTOF modules constructed for CBM-TOF detector

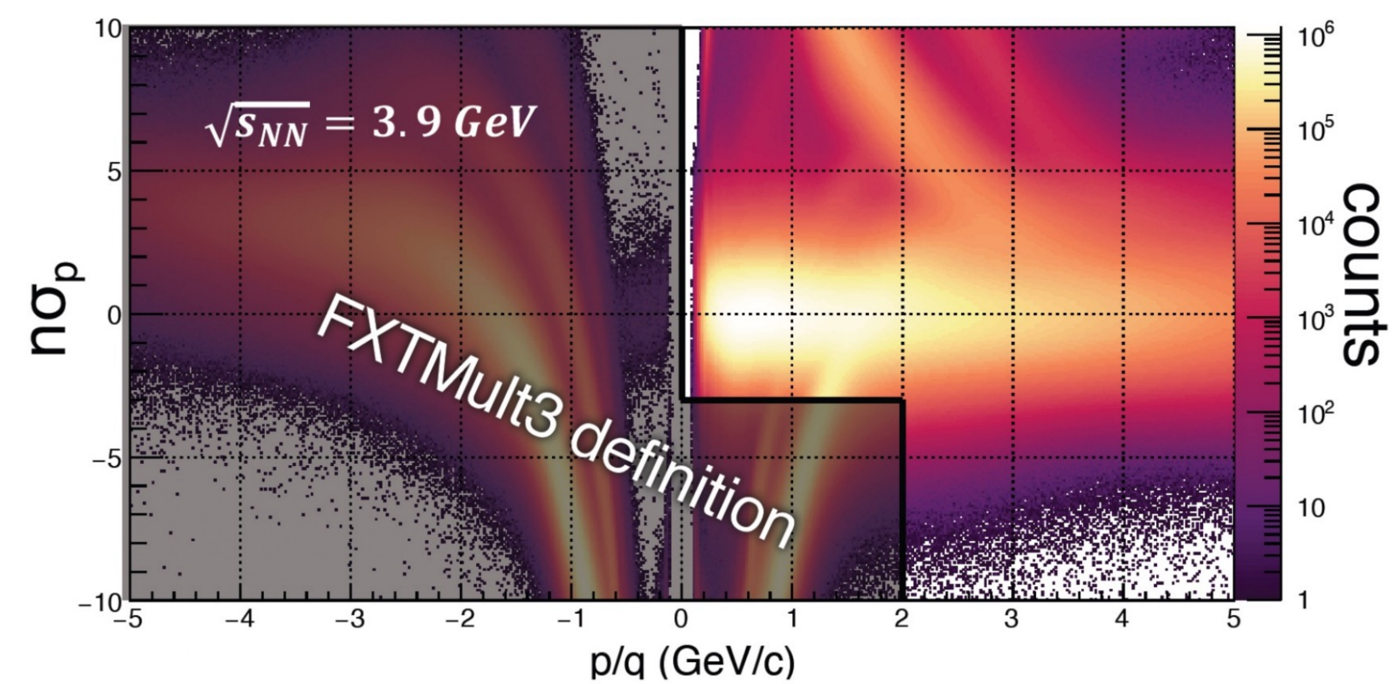
2) Physics running during 2020-2021 runs, crucial for hadron/light nuclei identification at FXT energies

3) Good detector performance (timing resolution, matching efficiency, stability)

Centrality Determination

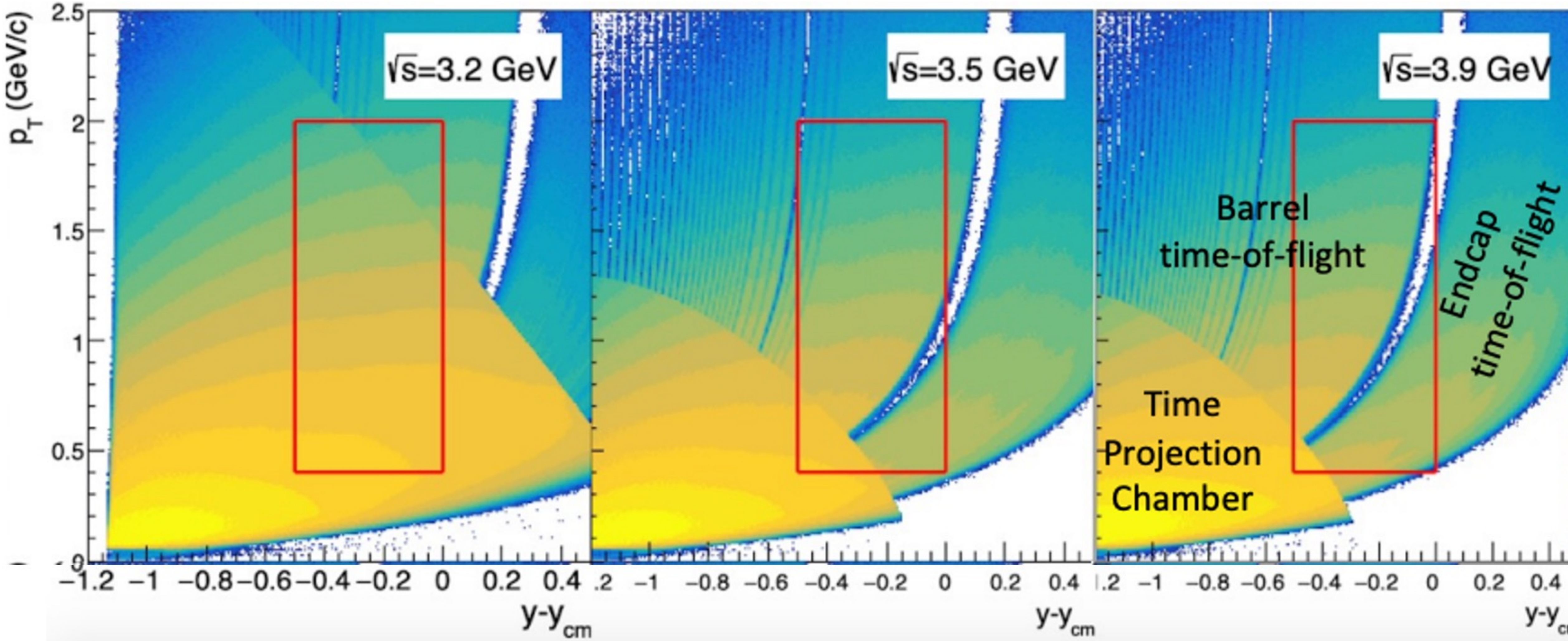


FXTMult3: all h^- and, h^+ excluding protons/*d*/*t*.. within STAR detector



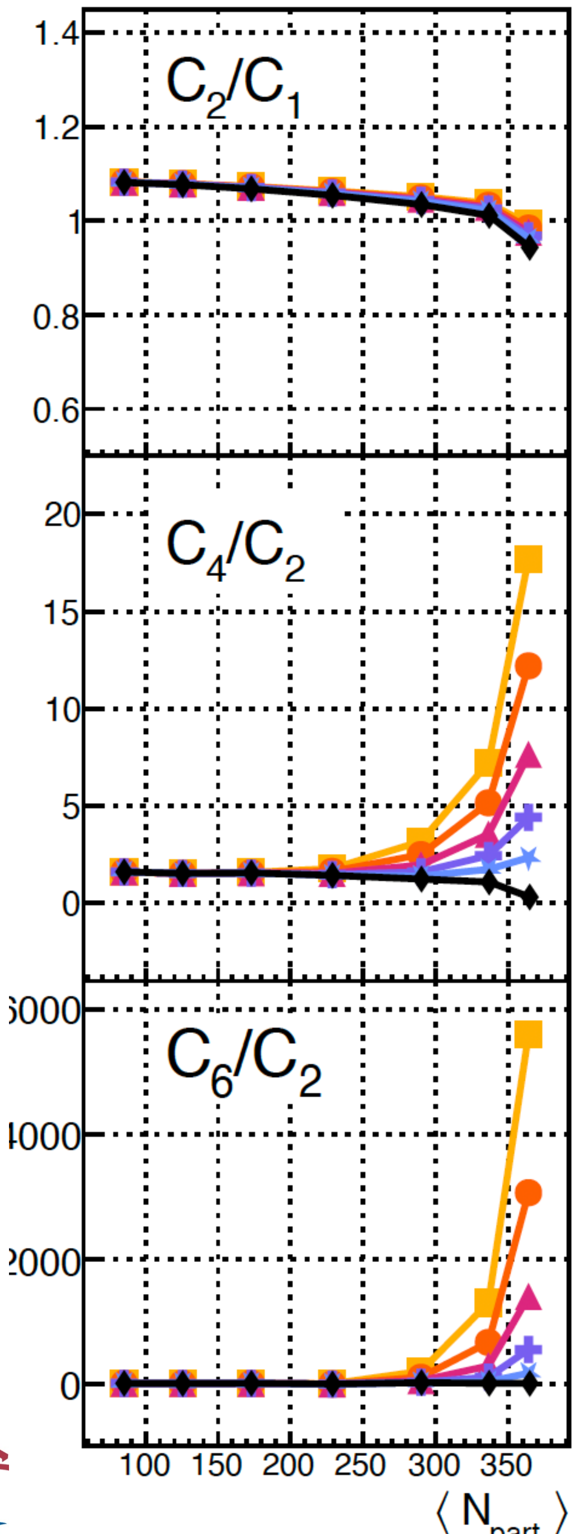
Experimental Challenges

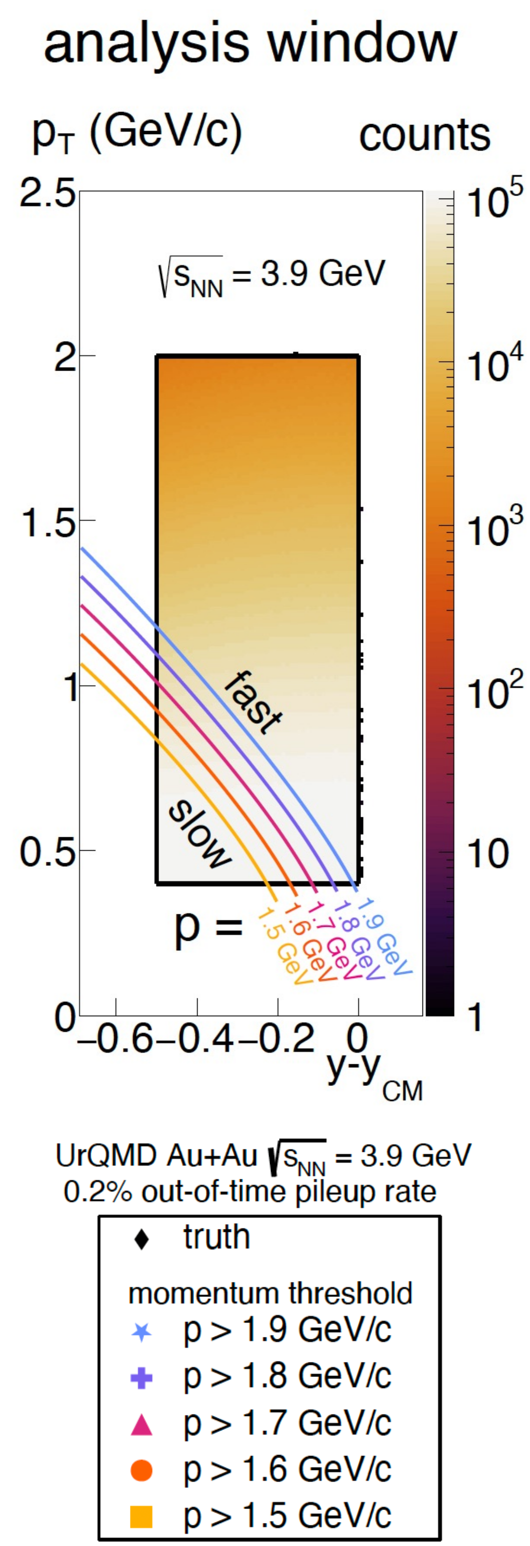
Conventional method for particle identification

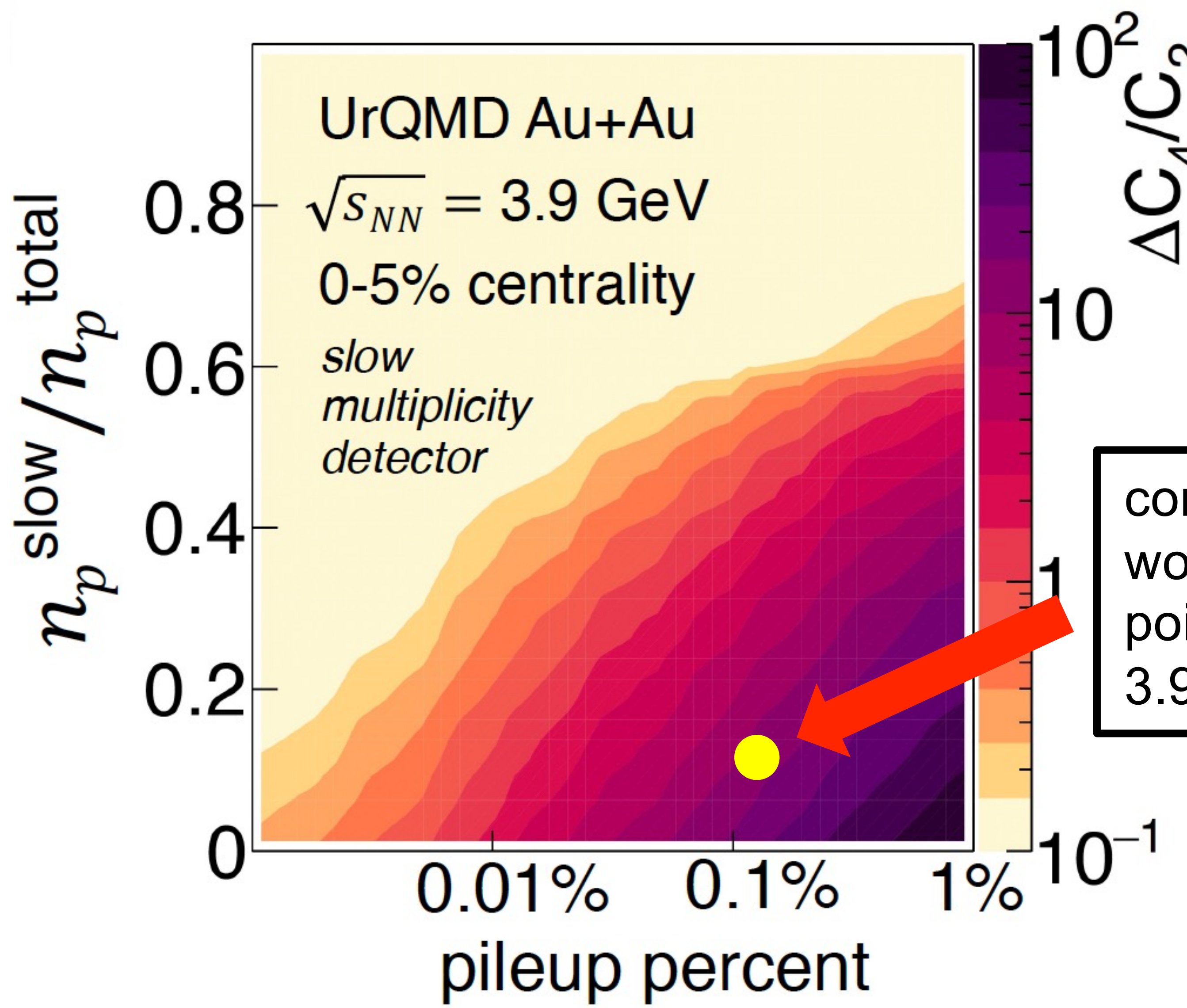


1) Pileup + mixed usage of fast/slow detectors for centrality / PID
2) Evolving proton acceptance in different collision energies
3) Acceptance gaps between detector boundaries (e.g. b/eTOF)

Impact of Pileup + Mixed Use of Fast/Slow Detectors





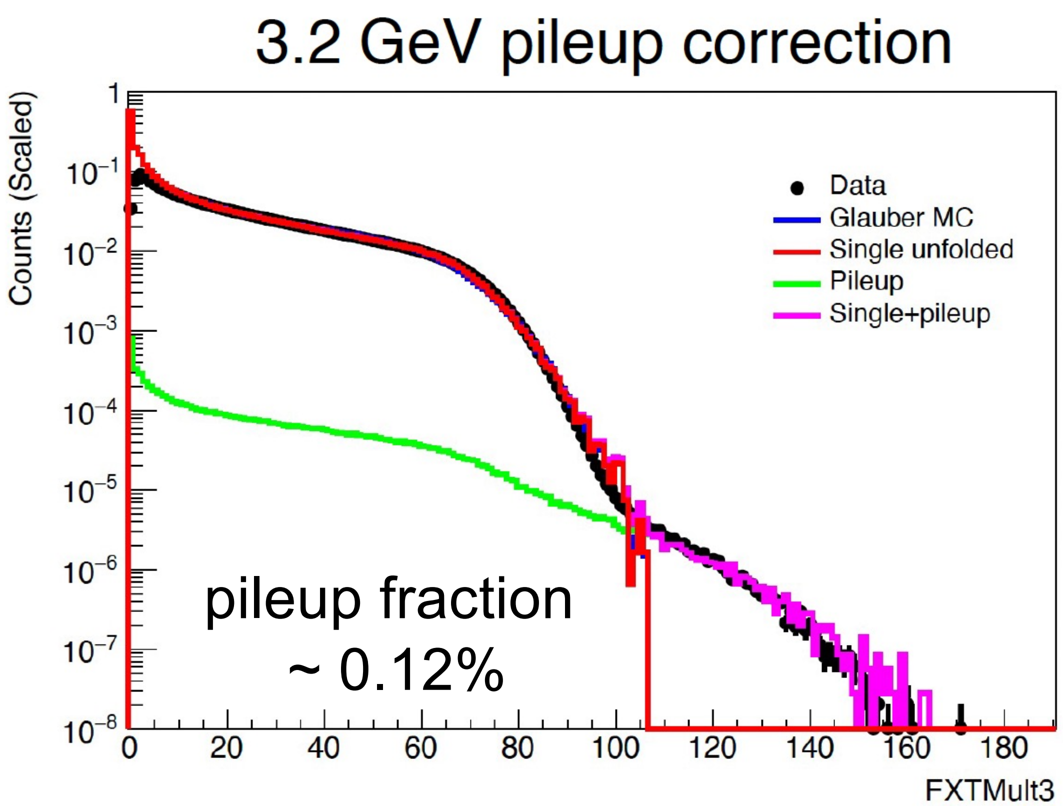


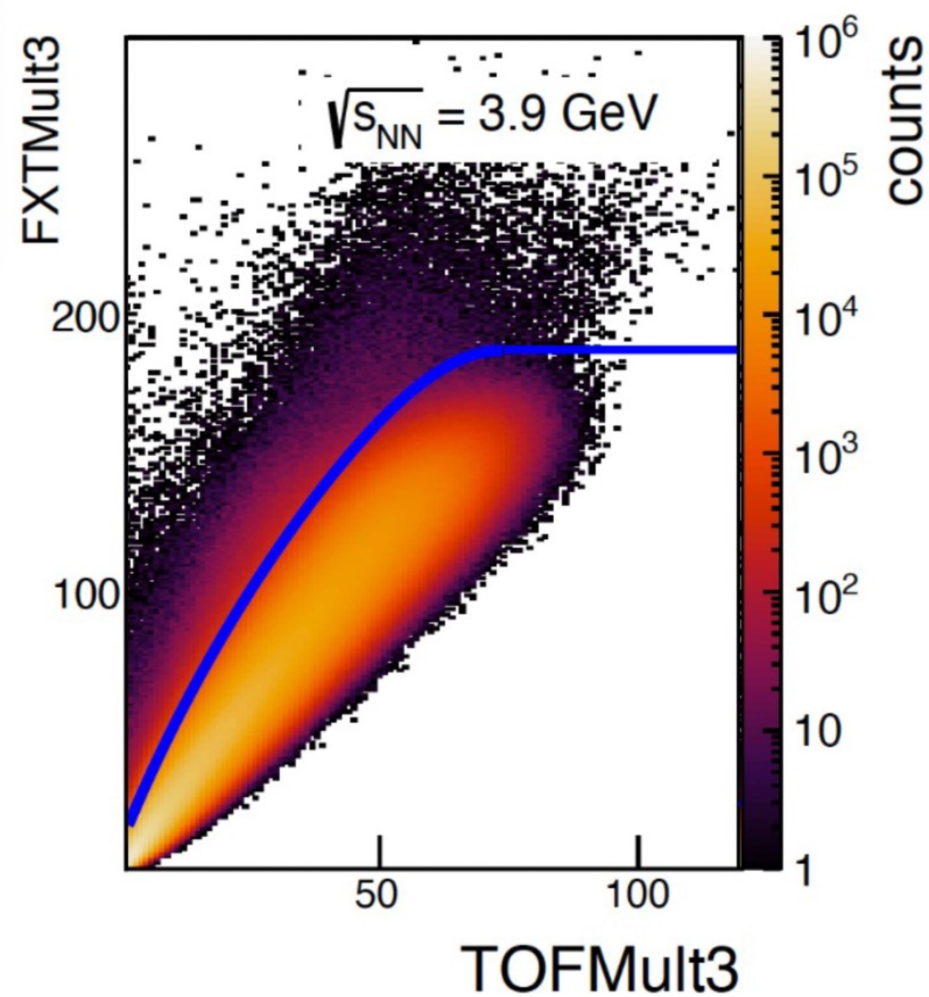
conv. working point at 3.9 GeV

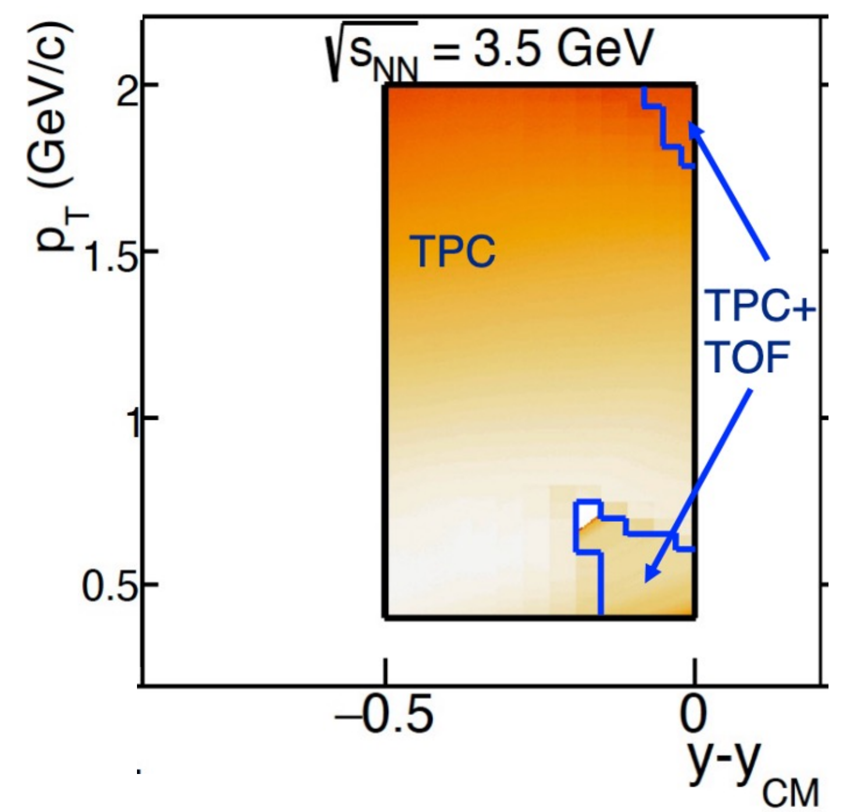
Z. Sweger et al, PRC 111 (2025) 034902

mixed use of fast/slow detectors + pileup can distort measured high order cumulants significantly!

Experimental Strategies



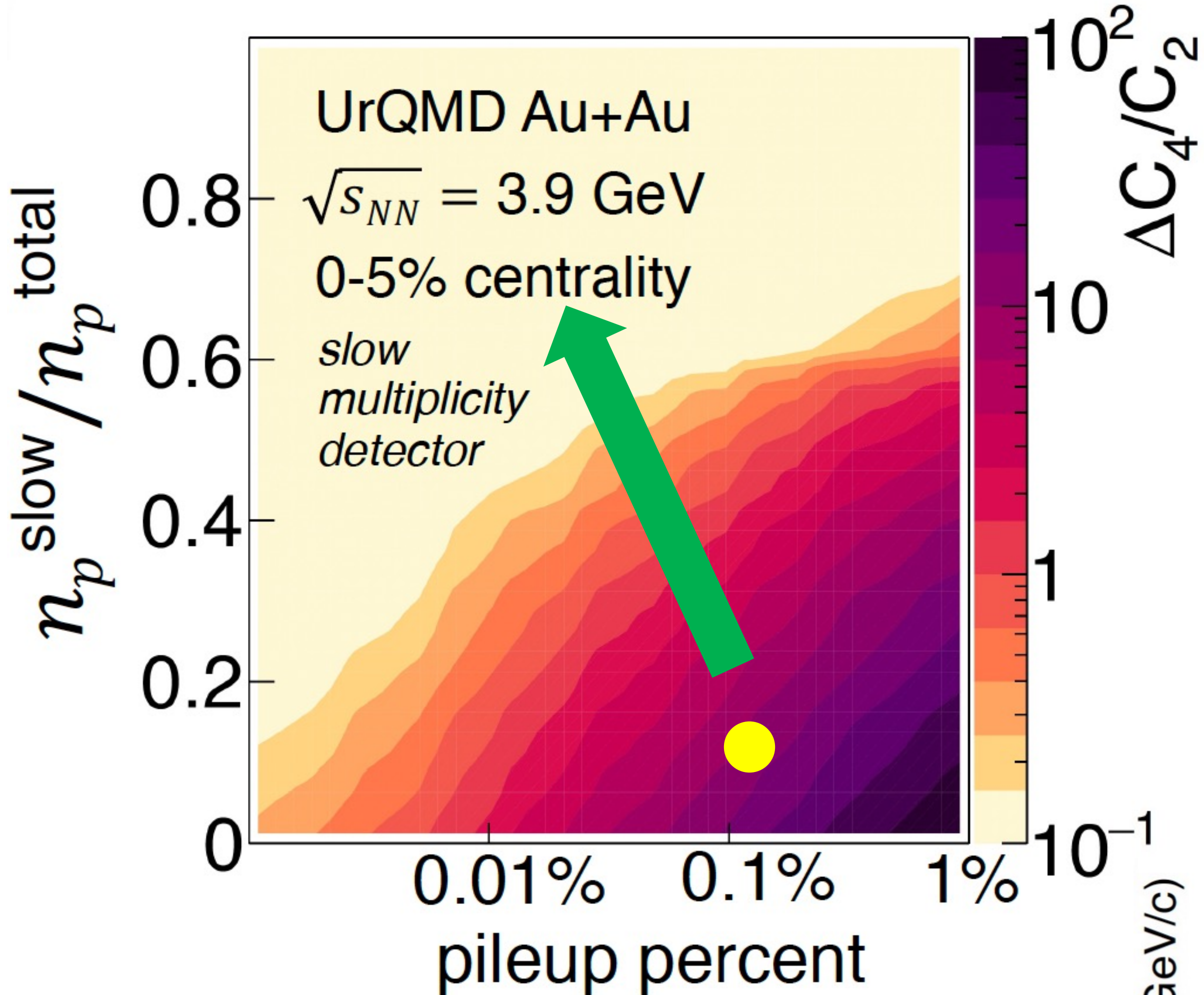




dynamic dE/dx selection to maximize TPC PID and ensure >90% purity

1) 3.2 GeV -> Nearly all protons are identified by TPC -> Pileup correction
2) 3.5, 3.9 GeV -> Rely on strongly proton identified by b/eTOF -> Pileup rejection
3) Maximize the usage of TPC dE/dx PID to reduce fast/slow mismatch

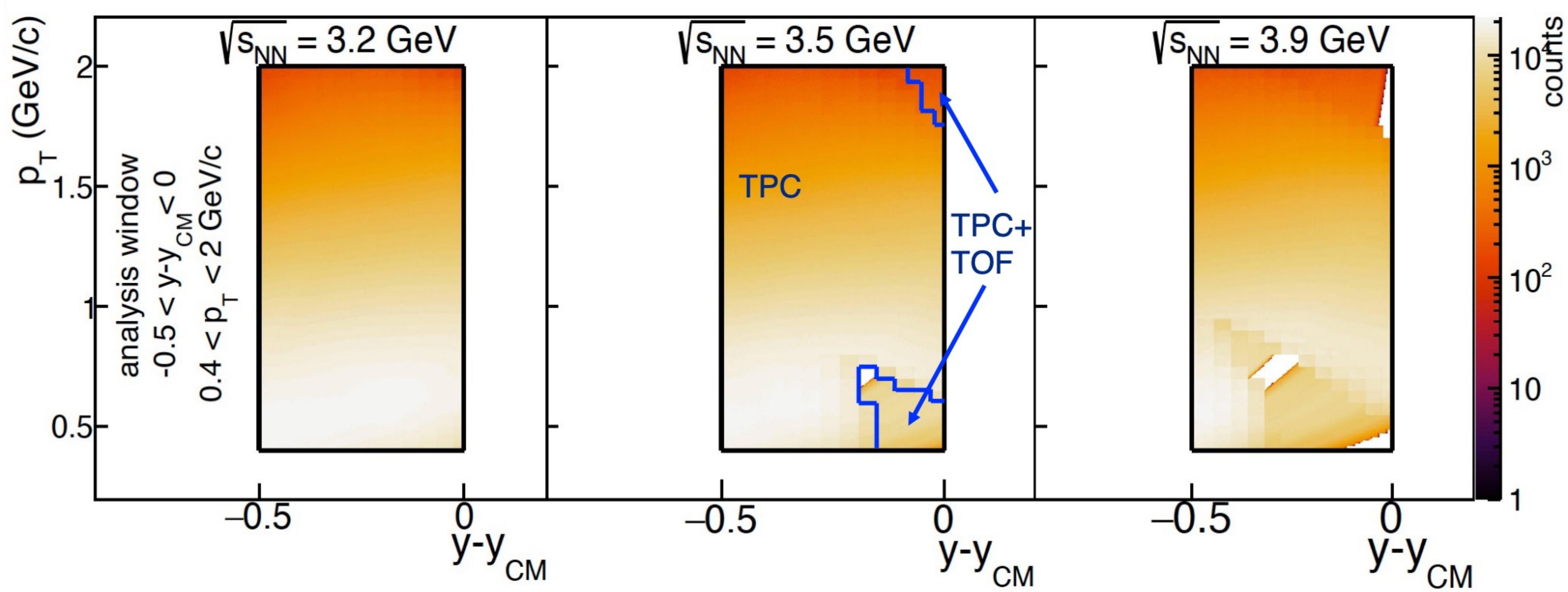
Experimental Methods to Mitigate Challenges



1) reject pileup
2) maximize use of TPC PID

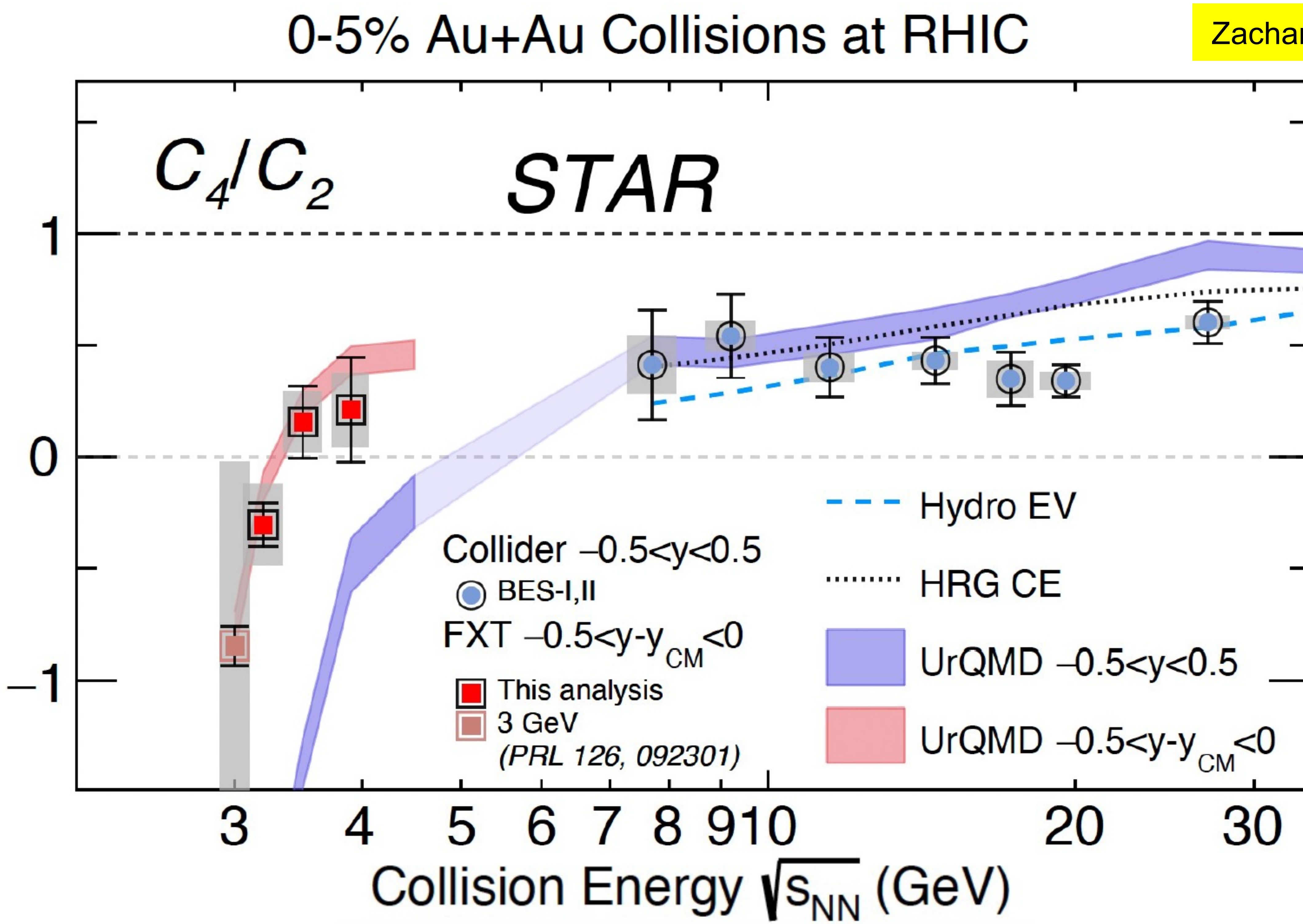
1) Good midrapidity proton acceptance at 3.2, 3.5, 3.9 GeV.

2) Remaining acceptance holes included in model calculations for comparisons.

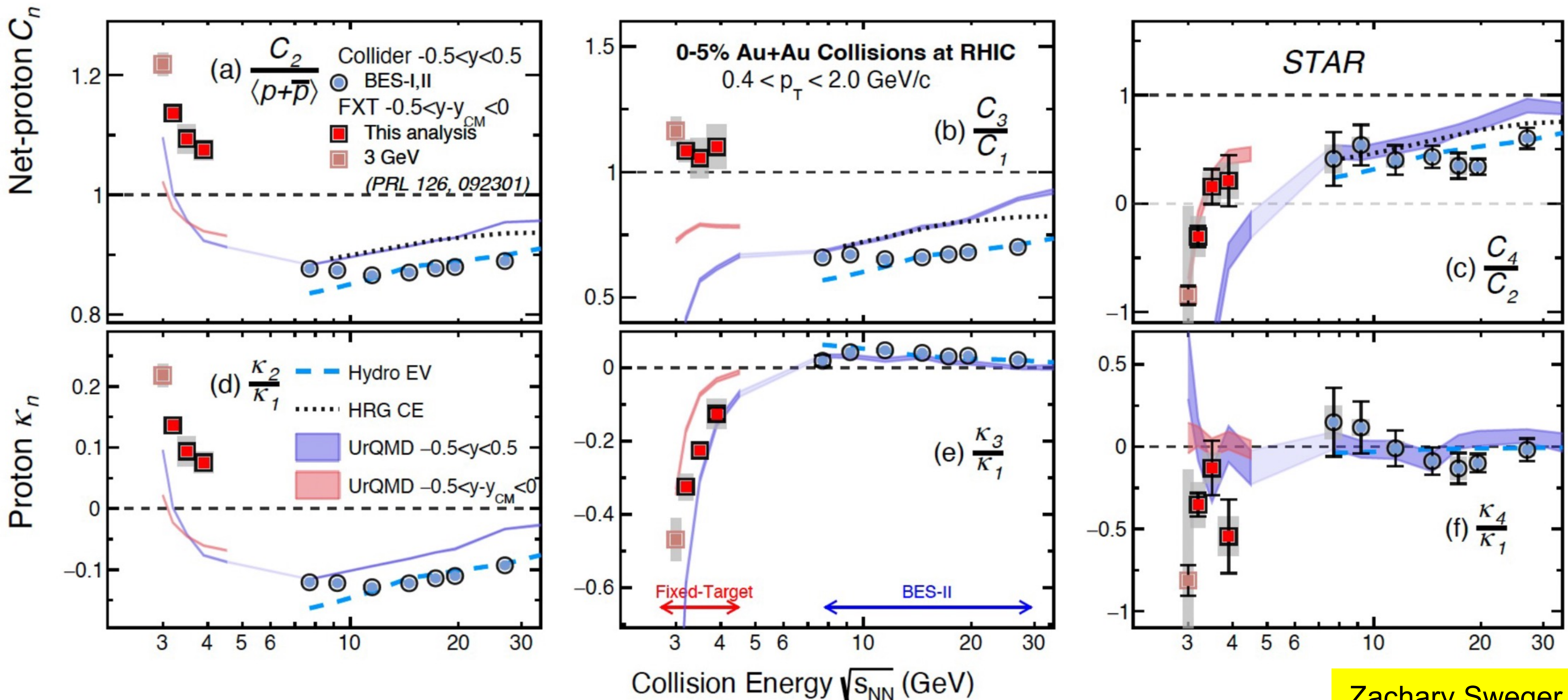


Proton C_4/C_2 from FXT Energies

Zachary Sweger, QM25



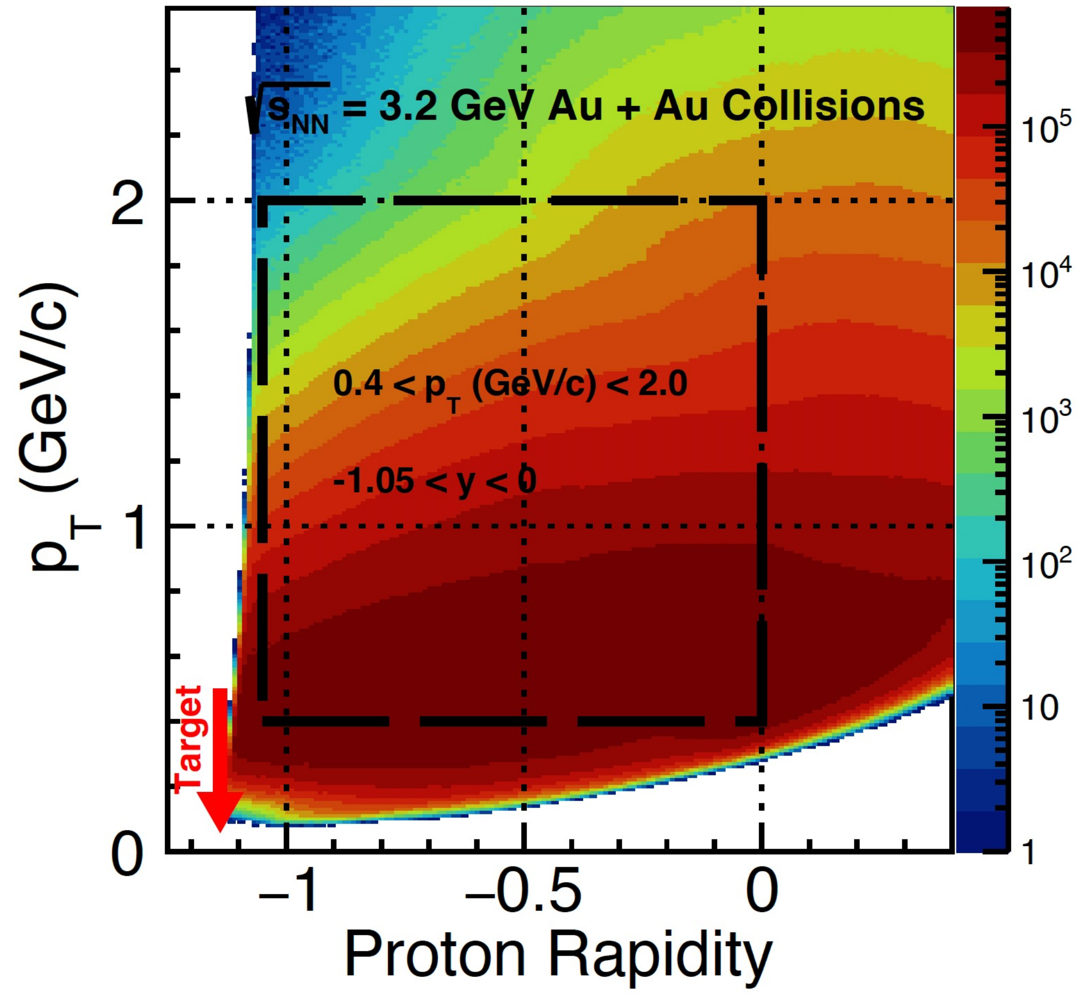
Proton (Factorial) Cumulant Ratios from FXT Energies

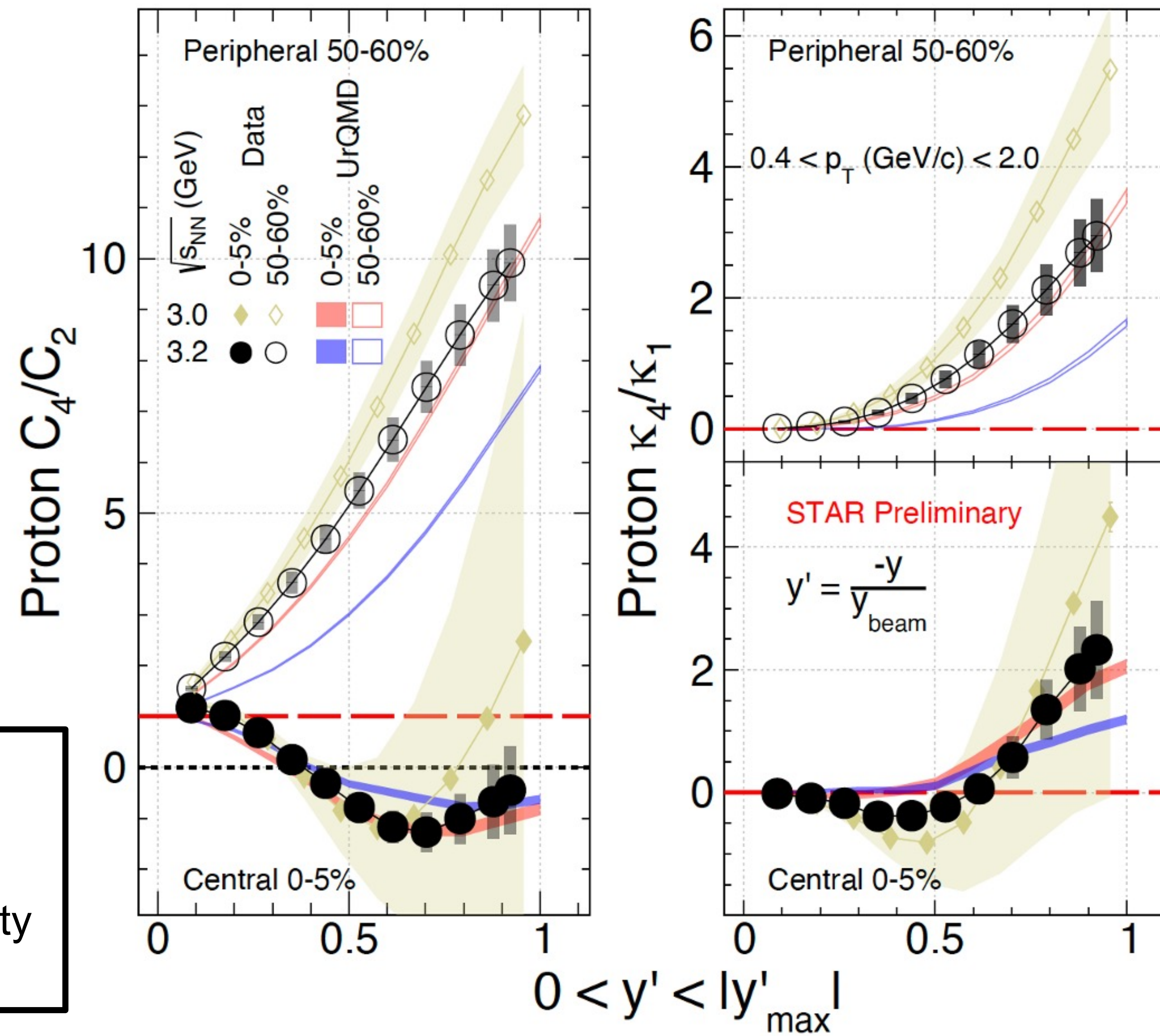


Zachary Sweger, QM25

At 3.0 – 3.9 GeV central collisions:
1) Proton (factorial) cumulants at 2nd and 3rd order deviates from UrQMD
2) Proton C_4/C_2, κ_4/κ_1 consistent with UrQMD

From Mid-rapidity to Target-rapidity





1) Rapidity coverage from mid-y to target-y
   - evolution from hot to cold medium properties

2) Data challenges UrQMD to describe full rapidity dependence, especially near target region.

Xin Zhang, Yongcong Xu, QM25

Summary

STAR presented new precision measurements of (net-)proton fluctuations from BES-II including all collider energies + several FXT energies

- better statistics, better systematics, better centrality resolution

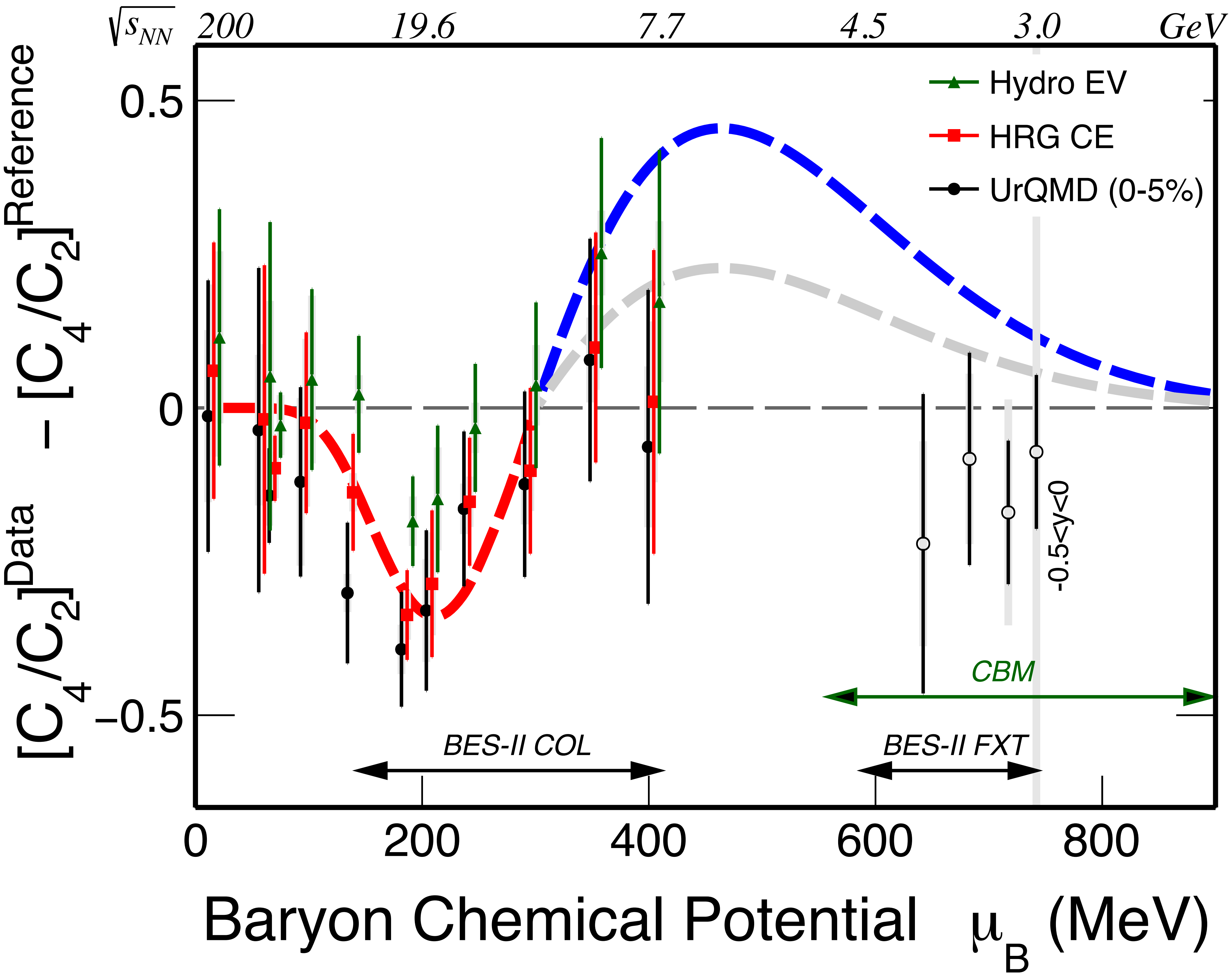
1) At collider energies, net-proton C_4/C_2 in central collisions show deviations from non-CP references (models or peripheral data) at 2-5σ at 19.6 GeV.

- Larger deviations are observed in lower order factorial cumulant ratios.

2) At FXT energies, proton C_4/C_2 in central collisions are consistent with UrQMD calculations at 3.0 – 3.9 GeV.

- Deviations are seen in lower order (factorial) cumulant ratios.

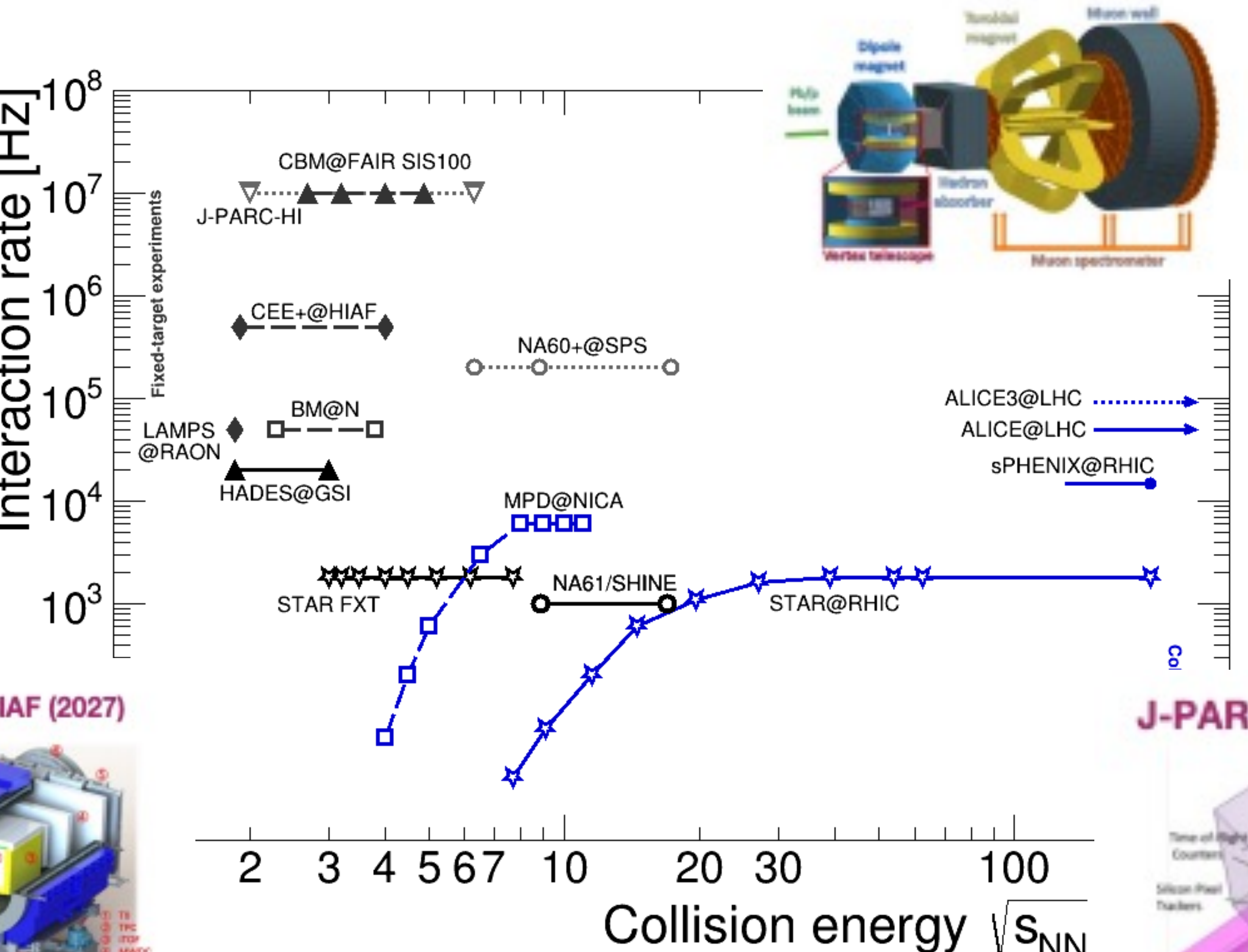
Quest for QCD Critical Point Search – To Be Continued



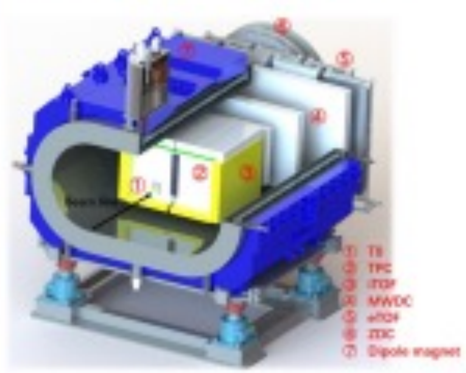
Future High μ_B Experiments

CBM/HADES at SIS100 (2028)

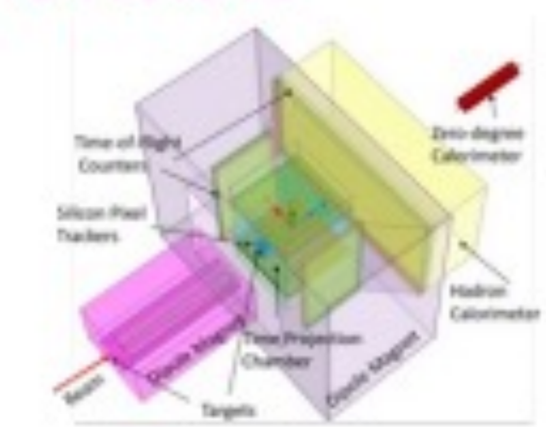
NA60+ at SPS (>2030, after LHC LS3)



CEE+ at HIAF (2027)



J-PARC-HI



Acknowledgements

Many Thanks to:

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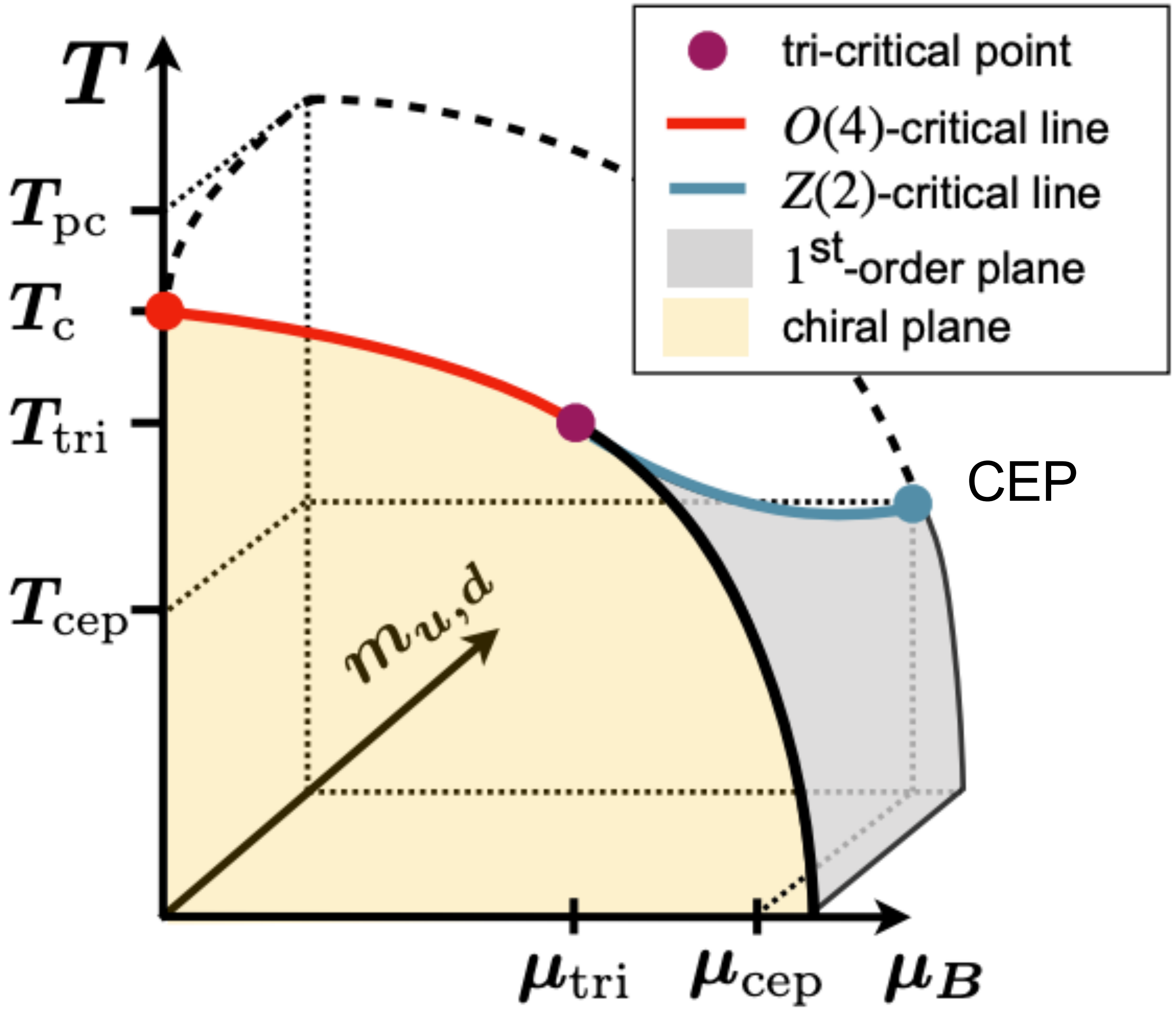
STAR Collaboration

Theory Colleagues

Backup

- Not Used

QCD Critical End Point (CEP or CP)



At μ_B = 0, cross over phase transition – Lattice QCD
- compatible to all experimental observations

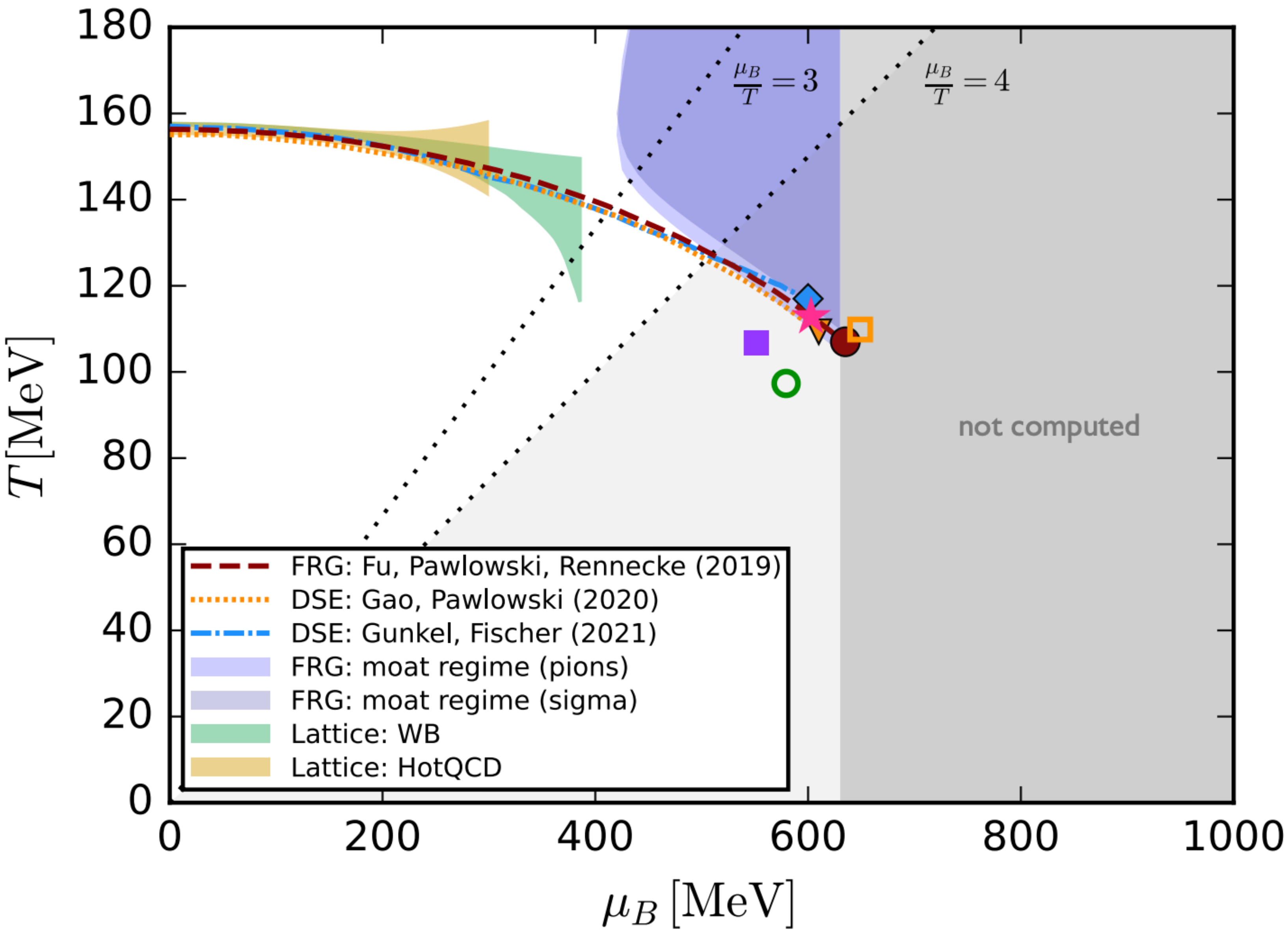
At finite μ_B: sign problem in Lattice QCD
Tyler expansion method
- estimate as of 2023 LRP:

$$T_{CEP} < 140\text{MeV}\ ,\ \mu_B^{CEP} > 400\text{MeV}$$

$$\frac{\mu_B}{T} > 3$$

H.T. Ding et al, PRD 109 (2024) 114516

Recent Theoretical Predictions on QCD CEP



Courtesy of F. Rennecke, QM 2025

Challenges for full LQCD at high μ_B, various approaches for CEP predictions:

1) Alternative method in LQCD

2) DSE/FRG functional methods

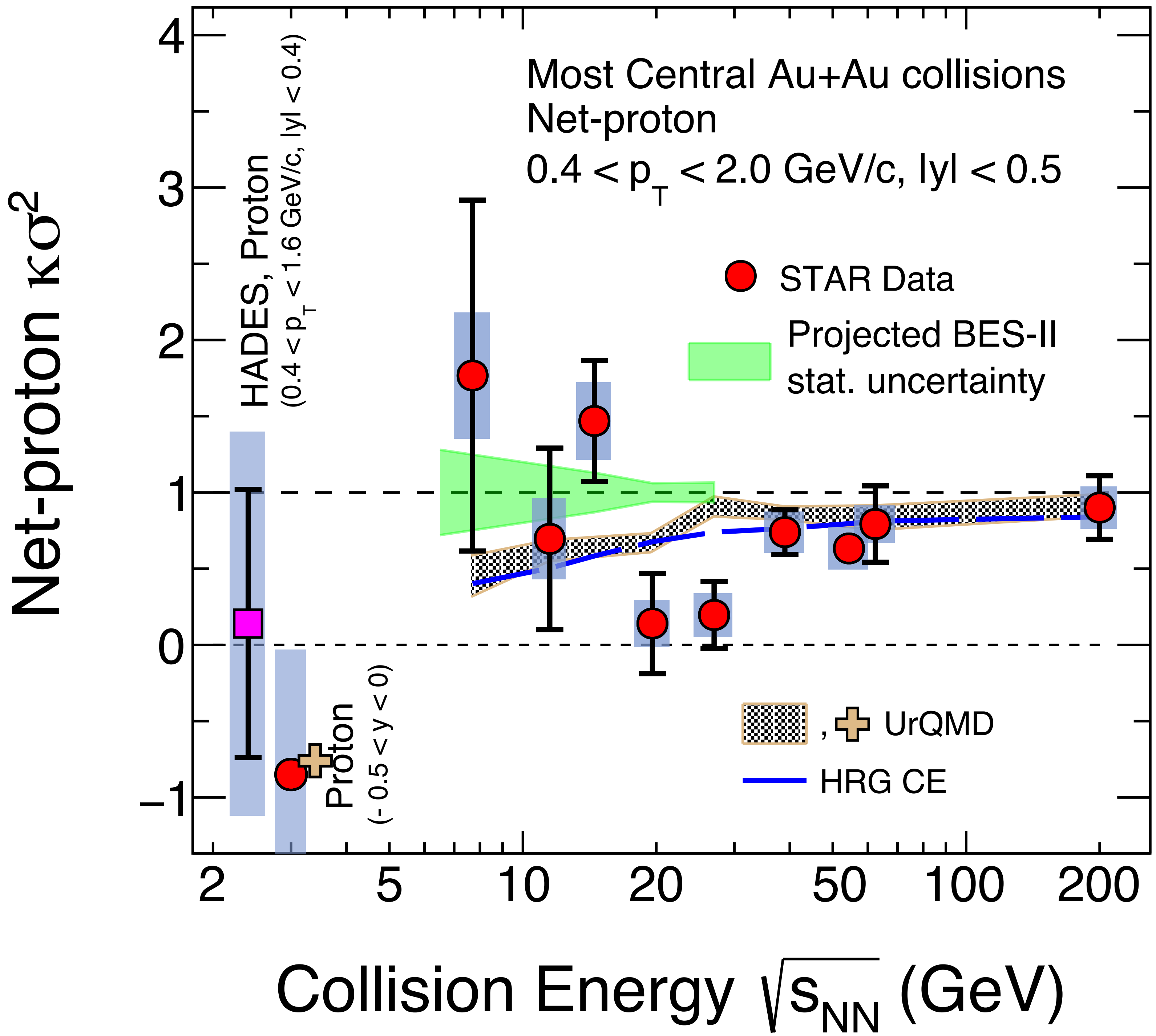
3) Holography

4) Thermodynamic scaling fit

Latest estimation from different methods:

μ_B^{CEP}: ~ 500 – 700 MeV
T^{CEP}: ~ 90 – 120 MeV

Higher Moments of Net-protons from BES-I (2010-2017)



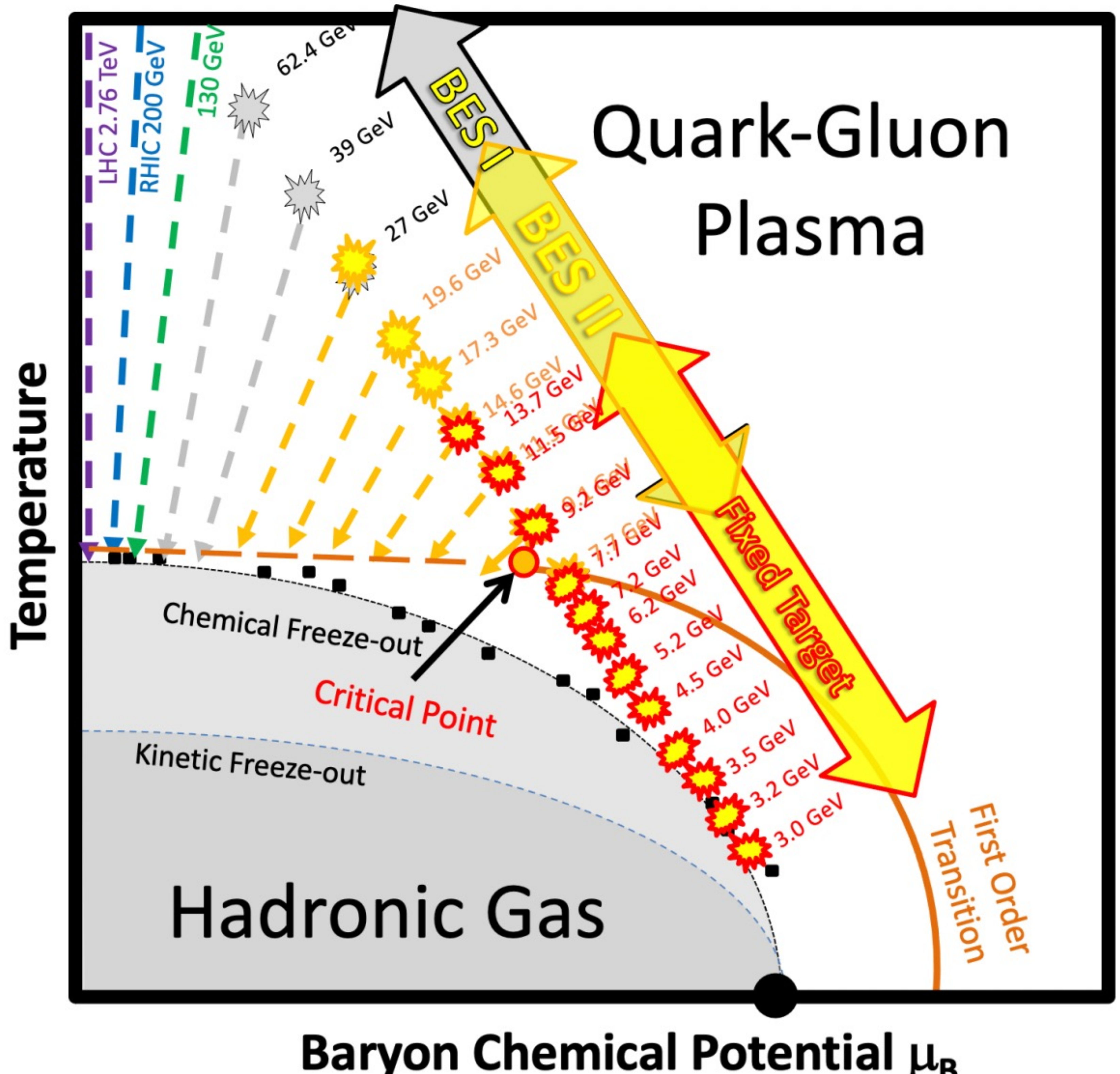
1) Hint of non-monotonic distribution vs. collision energy for $\kappa\sigma^2$ (C_4/C_2) in central collisions from BES-I

2) Proton C_4/C_2 consistent with UrQMD at 3 GeV

3) UrQMD/HRG-CE (non-CP) shows a monotonic dependence vs. energy
- *baryon conservation affects the baseline*

STAR, PRL 126 (2021) 092301, PRL 128 (2022) 202303
HADES, PRC 102 (2020) 024914

Beam Energy Scan (BES) Program at RHIC



BES-I (2010 – 2014):

μ_B: 70 – 400 MeV

62.4, 39, 27, 19.6, 14.6, 11.5, 7.7

BES-II (2018 – 2021):

μ_B: 150 – ~750 MeV

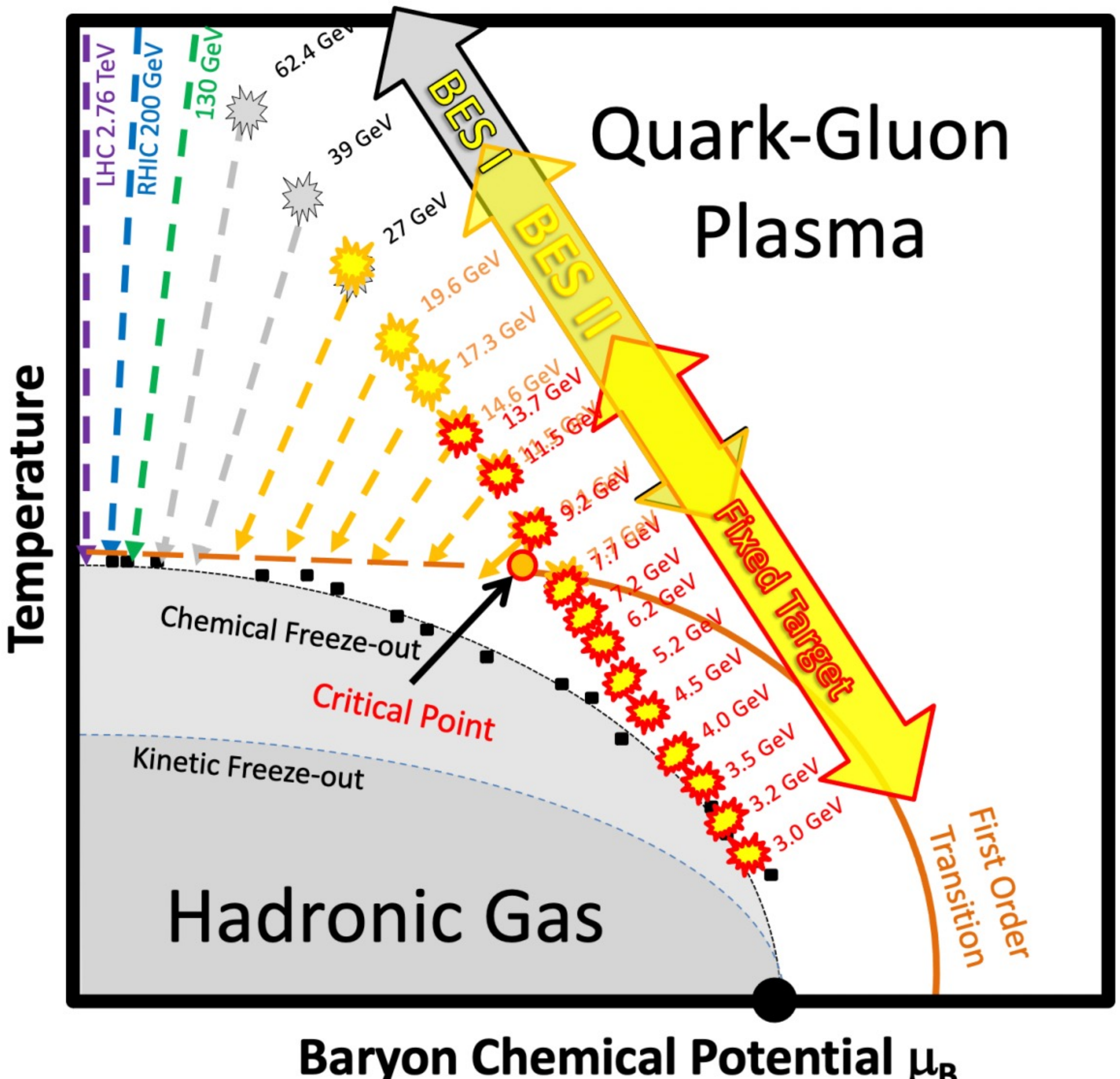
Collider mode

27, 19.6, 17.3, 14.6, 11.5, 9.2, 7.7

Fixed Target mode

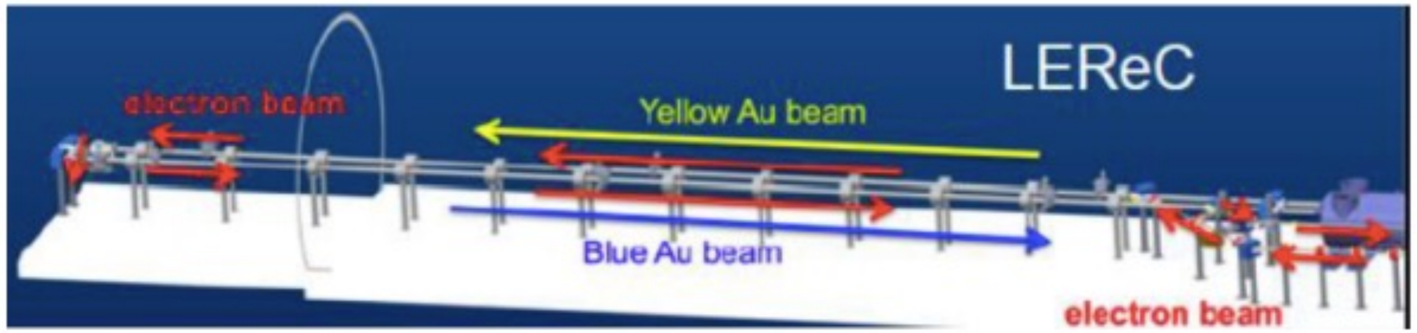
13.7, 11.5, 9.2, 7.7, 7.2, 6.2, 5.2, 4.5, **3.9, 3.5, 3.2, 3.0**

RHIC Beam Energy Scan



	$\sqrt{s_{NN}}$ (GeV)	Beam E (GeV)	# of Good Events	BES-I
2017	54.4		1350 M	
2018	27		560 M	70 M
	7.2	26.5 (FXT)	155 M	
	3.0	3.85 (FXT)	258 M	
2019	19.6		582 M	36 M
	14.6		324 M	20 M
	7.7	31.2 (FXT)	50.6 M	
	3.9	7.3 (FXT)	52.7 M	
	3.2	4.59 (FXT)	201 M	
2020	11.5		235 M	12 M
	9.2		162 M	
	7.7	31.2 (FXT)	112 M	
	7.2	26.5 (FXT)	317 M	
	6.2	19.5 (FXT)	118 M	
	5.2	13.5 (FXT)	103 M	
	4.8	11.5 (FXT)	235 M	
	4.5	9.8 (FXT)	108 M	
	3.9	7.3 (FXT)	117 M	
	3.5	5.75 (FXT)	116 M	
2021	17.3		250 M	
	7.7		101 M	5 M
	13.5	100 (FXT)	50.7 M	
	11.5	70 (FXT)	51.7 M	
	9.1	44.5 (FXT)	53.9 M	
	3.0	3.85 (FXT)	2.0 B	

Electron Cooling - LEReC

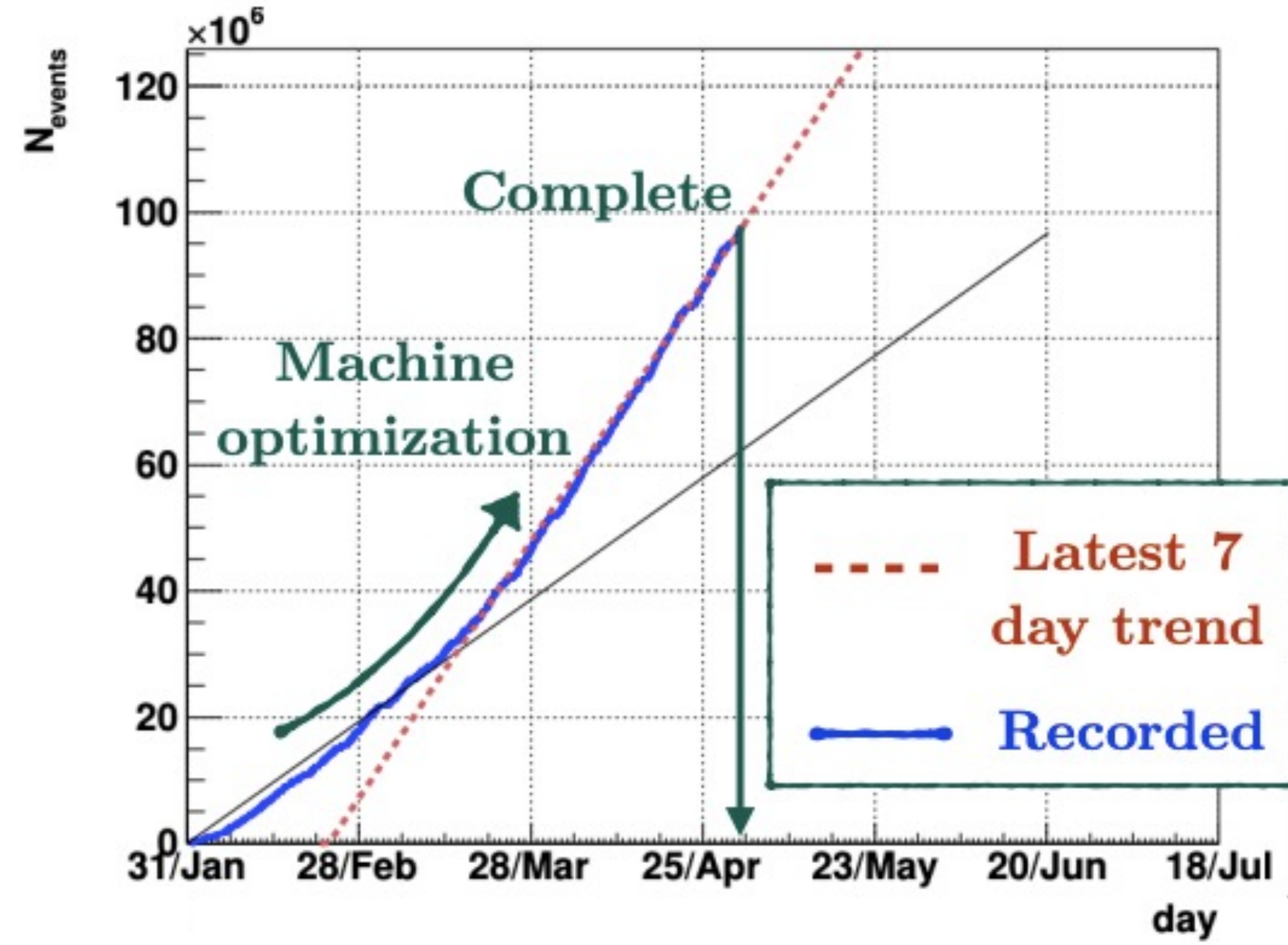


LEReC – Low Energy RHIC electron Cooling

Good Event Rate (Hz)

$\sqrt{s_{NN}}$ (GeV)	BES-I	BES-II
19.6	80	500
17.3	-	400
14.6	25	190
11.5	20	120
9.2	6	40
7.7	7	30

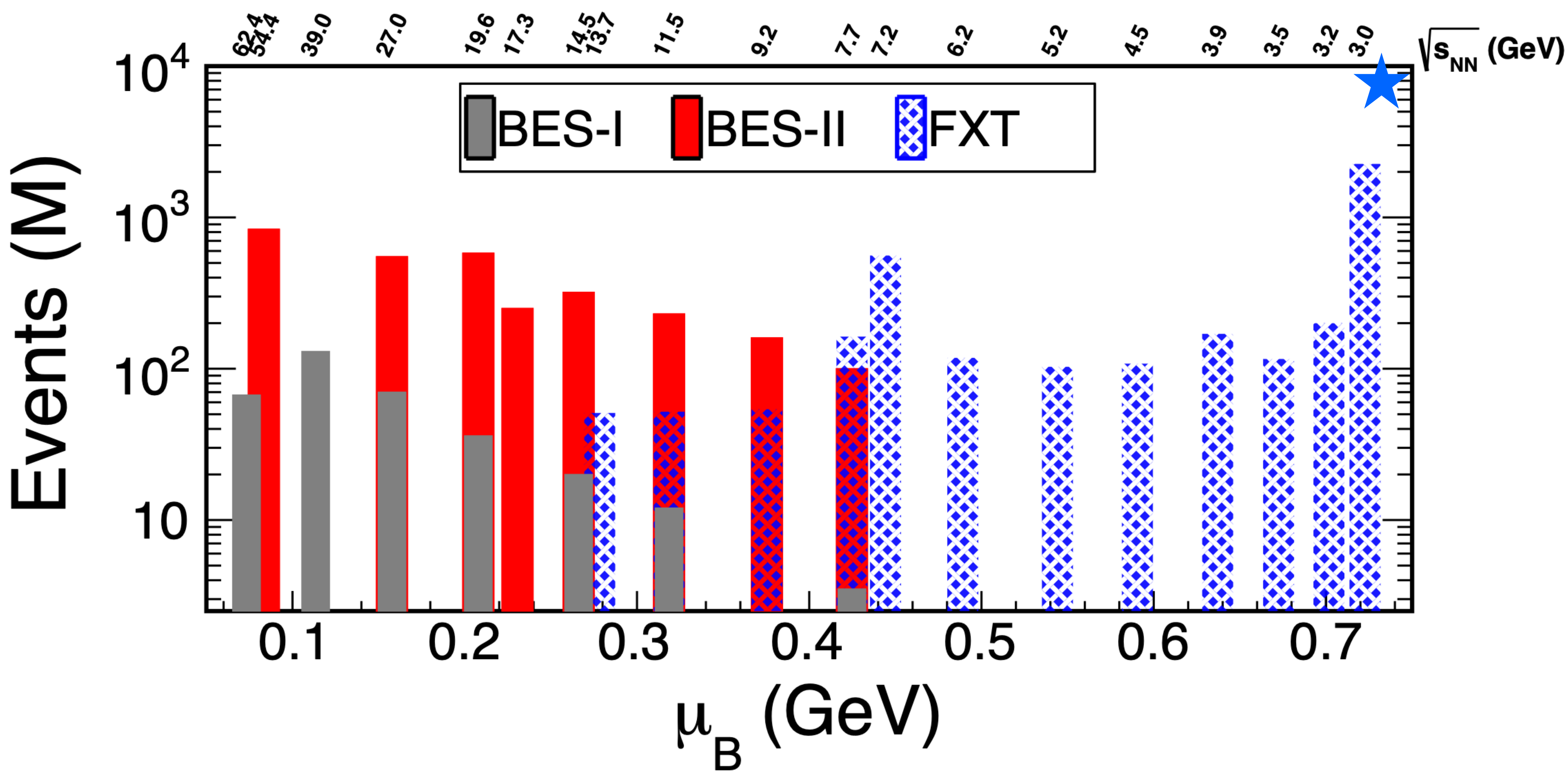
Au+Au 7.7 GeV in 2021



7.7 GeV goal finished within 12.1 weeks!
(estimated 20 weeks)

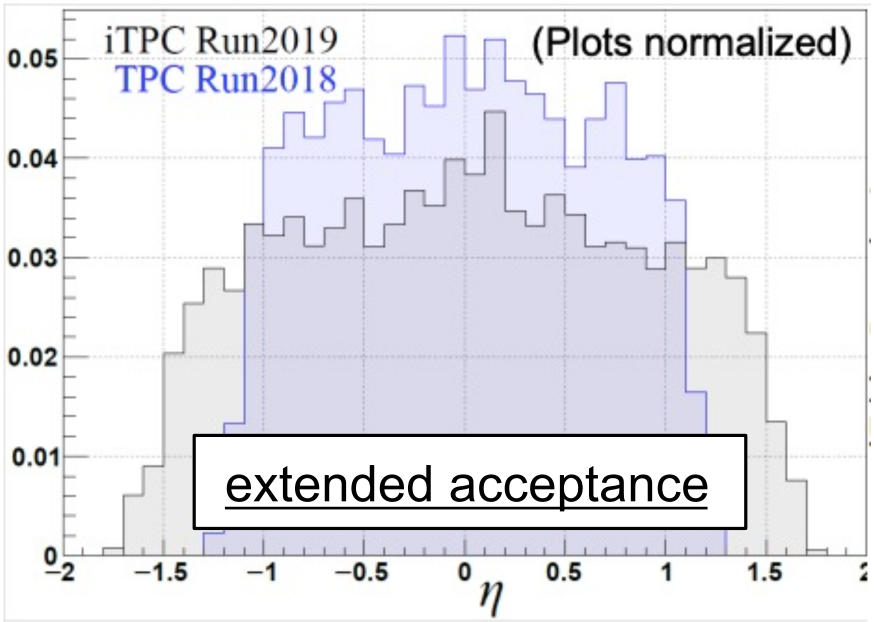
Datasets from Beam Energy Scan Phase-II

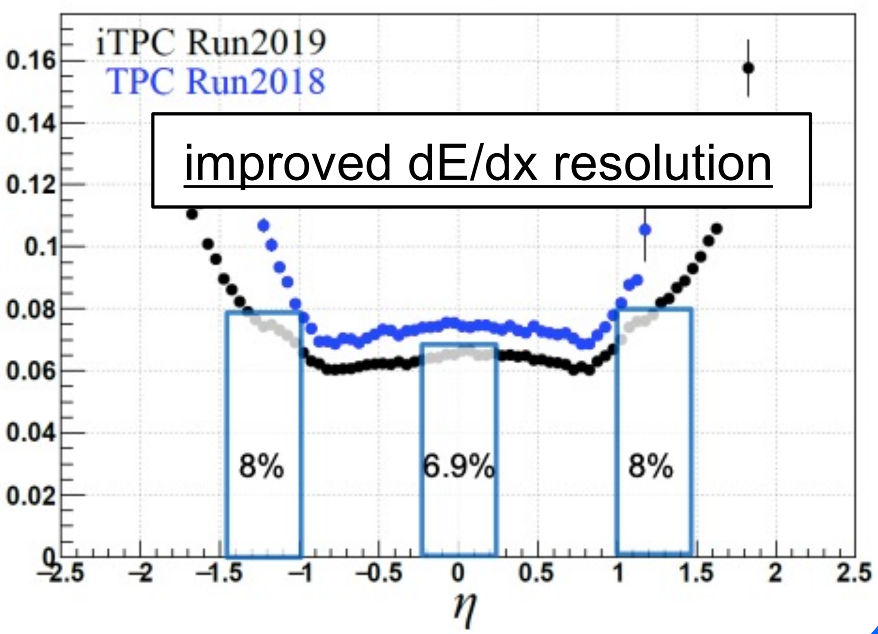
- x10-20 more statistics compared to BES-I at collider energies
- 8 collider energies (7.7 – 54.4 GeV) / 12 fixed-target energies (**3.0** - 13.5 GeV)



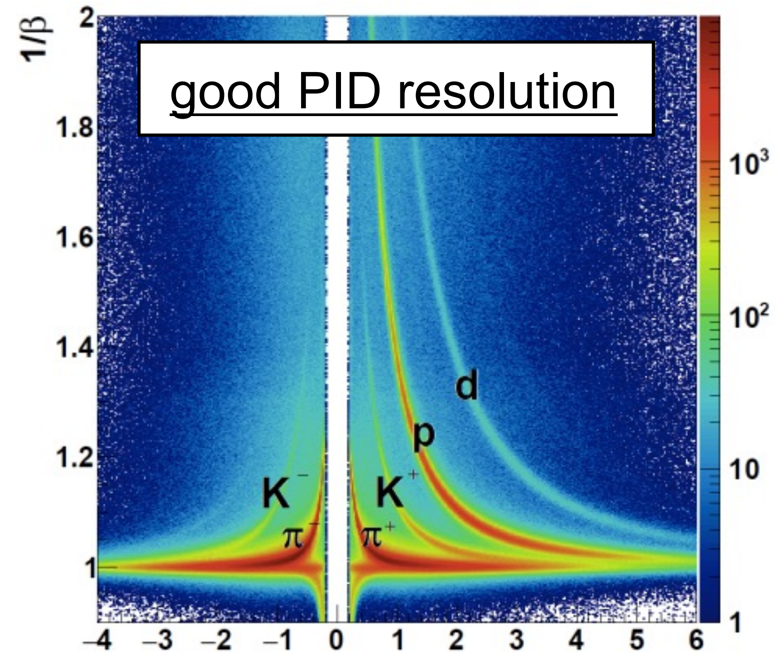
Detector Performance

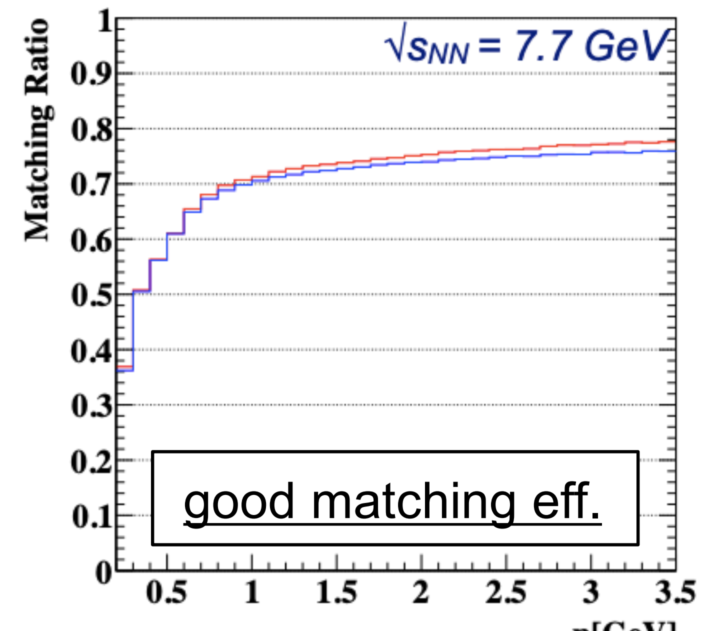
iTPC (2019+)



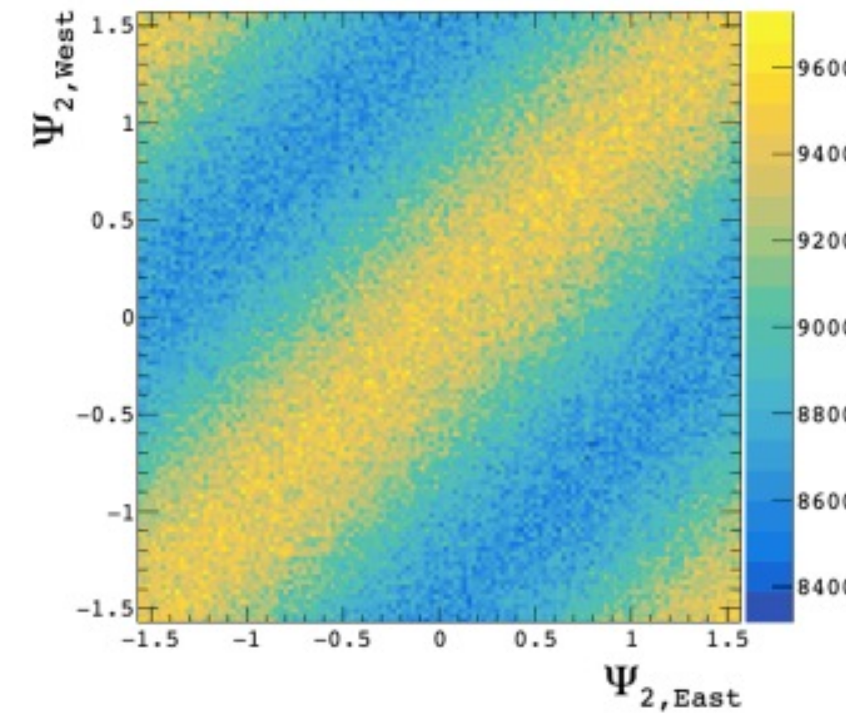


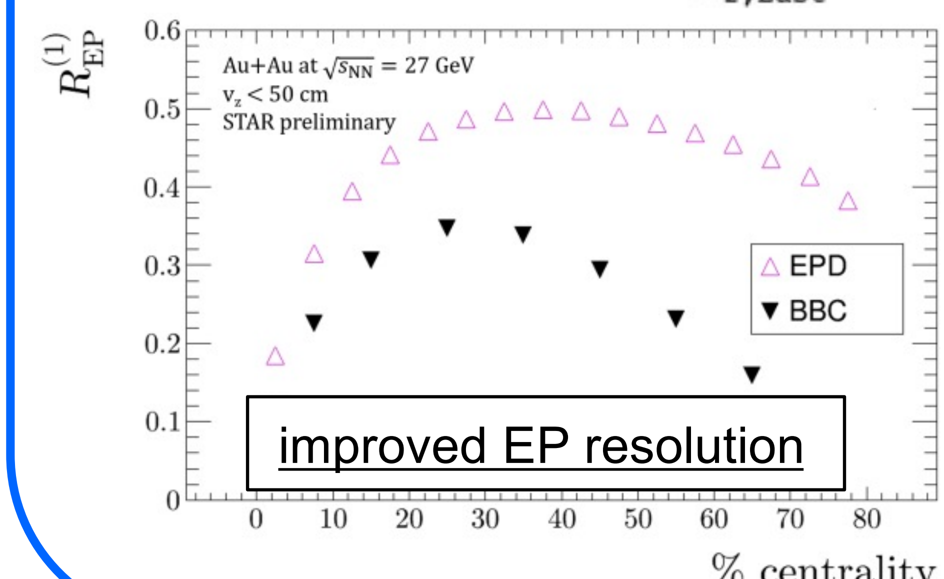
eTOF (2019+)



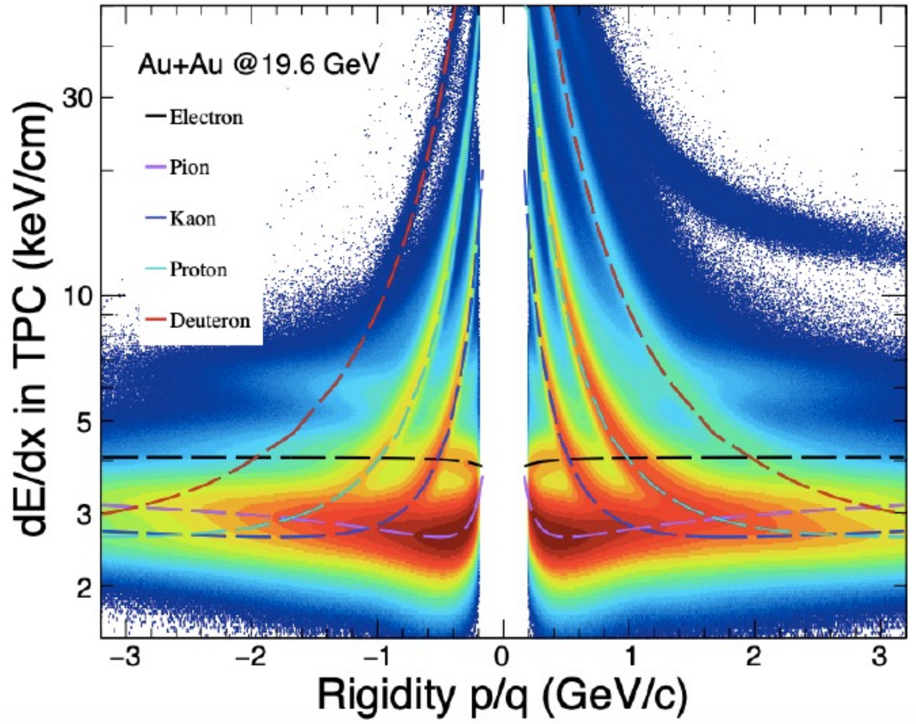


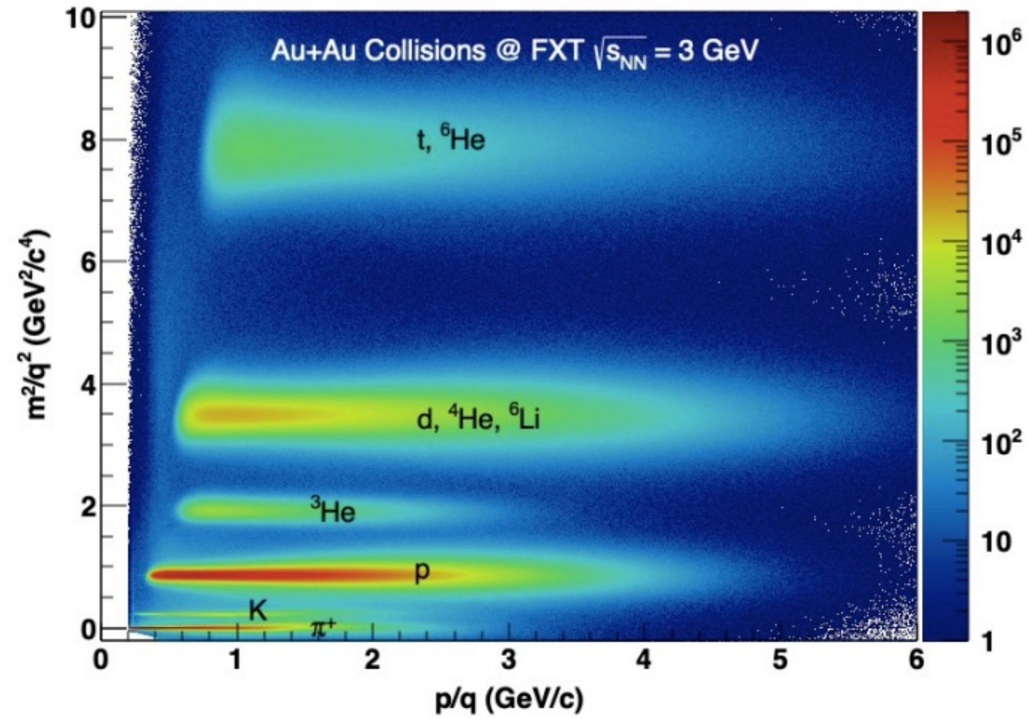
EPD (2018+)

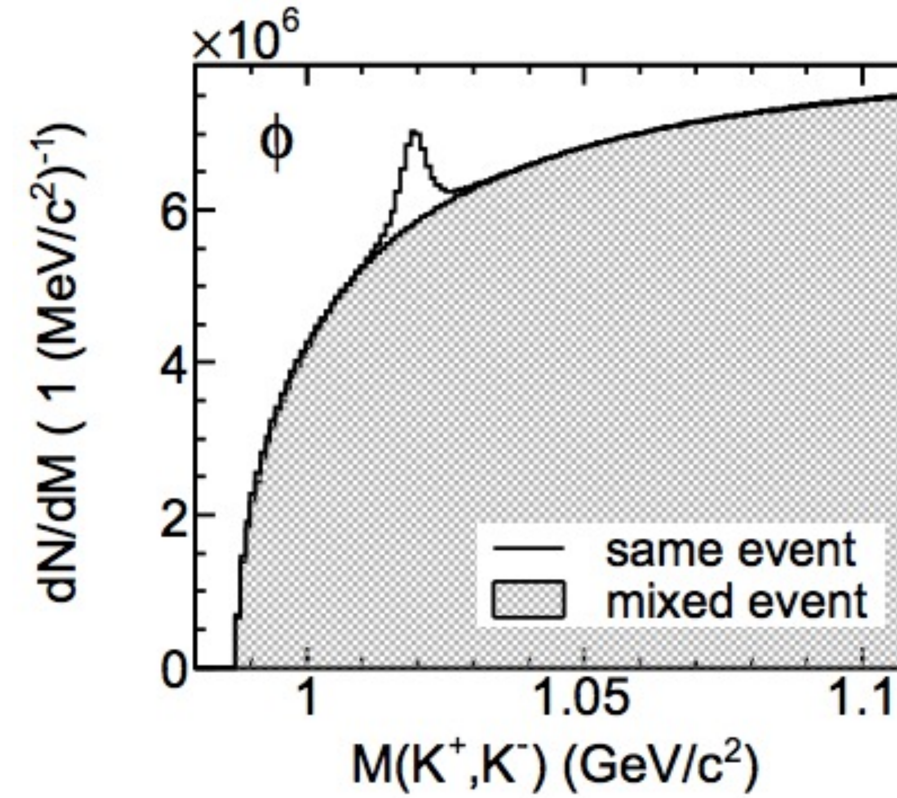




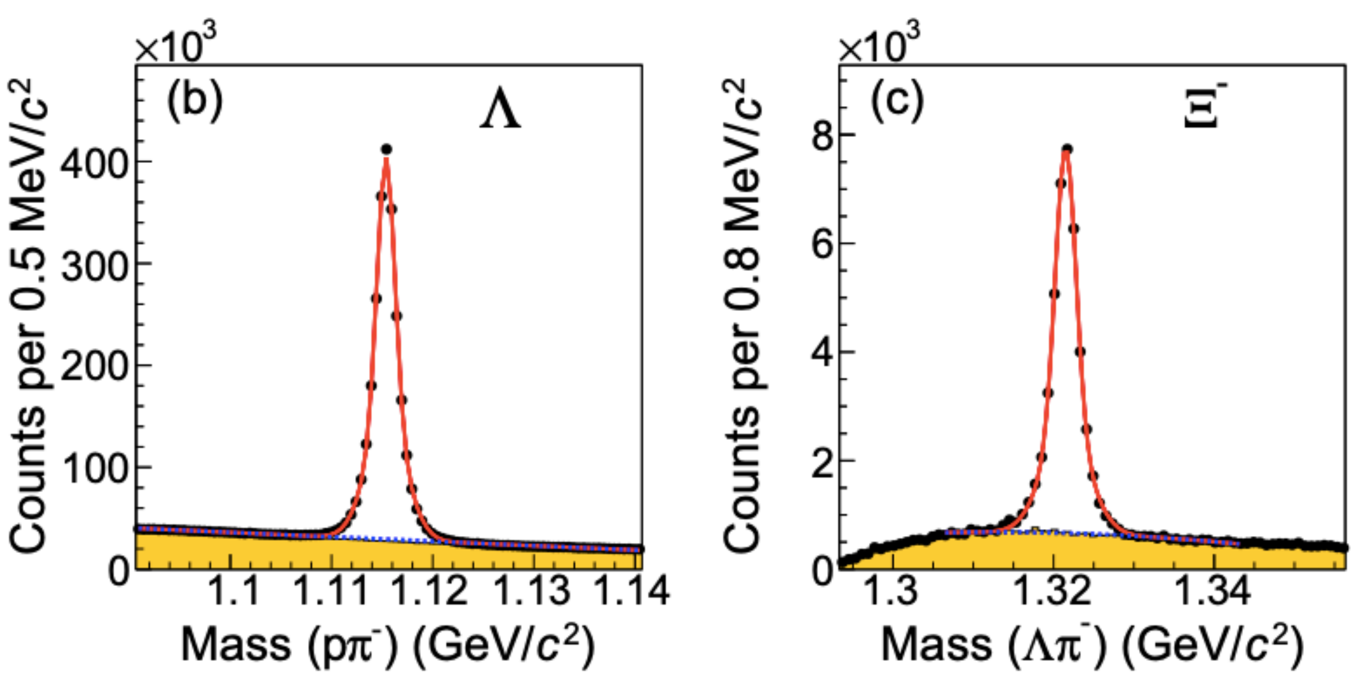
Particle Identification



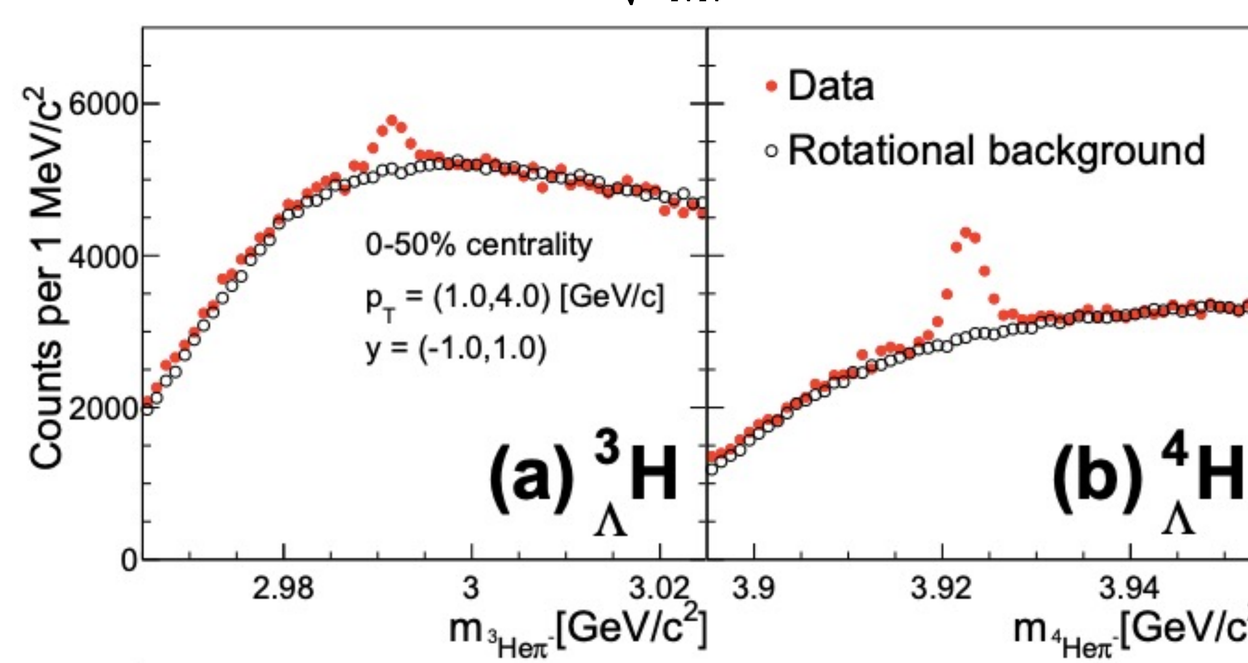




STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), |y|<0.5



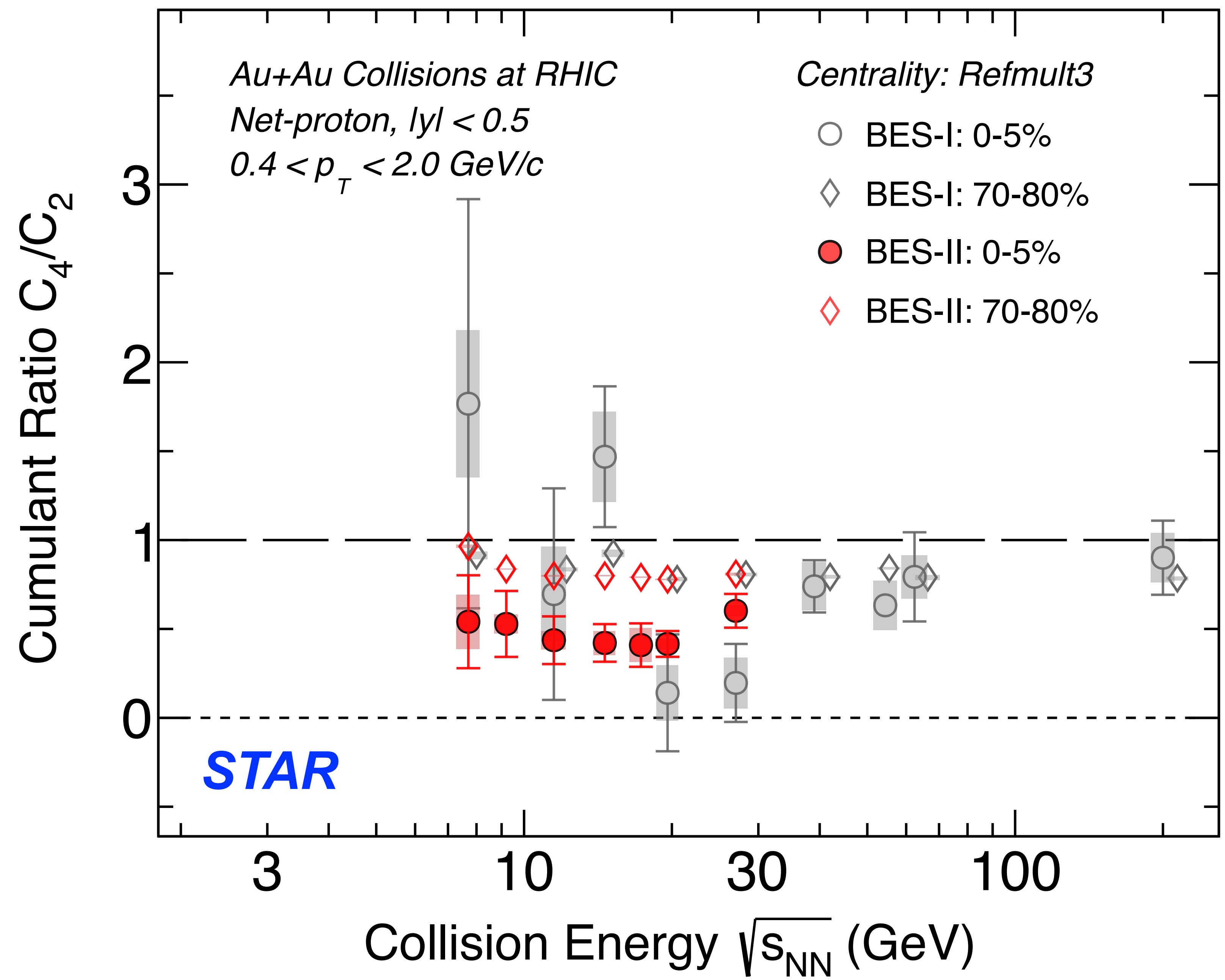
Au+Au $\sqrt{s_{NN}}$ = 3.0 GeV



Comparison between BES-I and BES-II

consistency test BES-II vs. BES-I

$\sqrt{s_{NN}}$ (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



At 0-5% centrality (Refmult3), C_4/C_2 from BES-II consistent with BES-I, with significantly improved statistical and systematic uncertainties!

Better Statistics and Better Systematics

Better statistics:

i) a factor of 10-18 larger event statistics
ii) ~ 10% tracking efficiency improvement

$$\text{error}(C_m) \propto \frac{\sigma^m}{\sqrt{N}\ \varepsilon^\alpha}$$

STAR, PRC 104 (2021) 024902

Better systematics:

i) tracking efficiency uncertainty 5% -> 2%
ii) tracking/PID performance improvement

benefit from iTPC upgrade

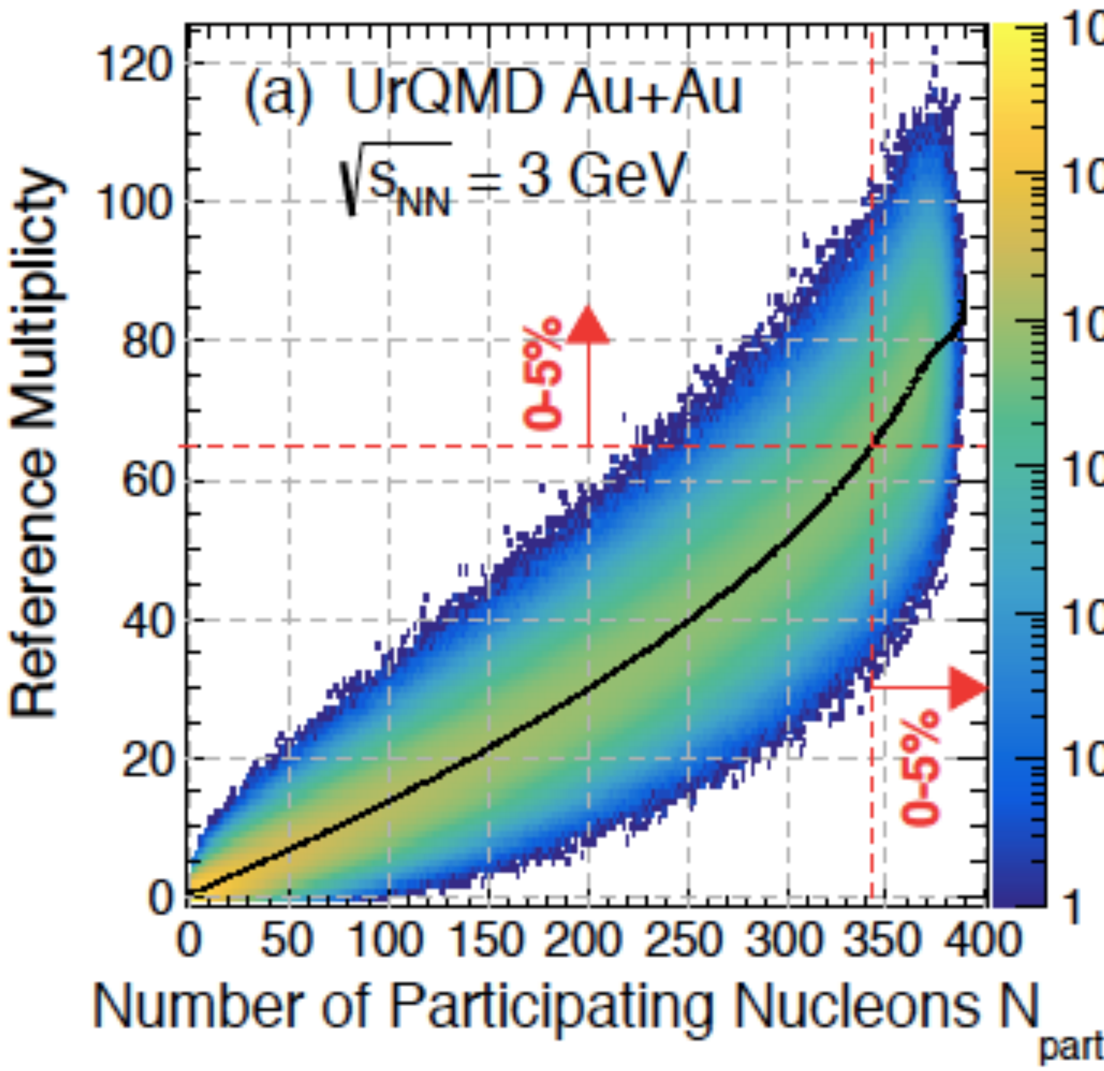
Better centrality resolution

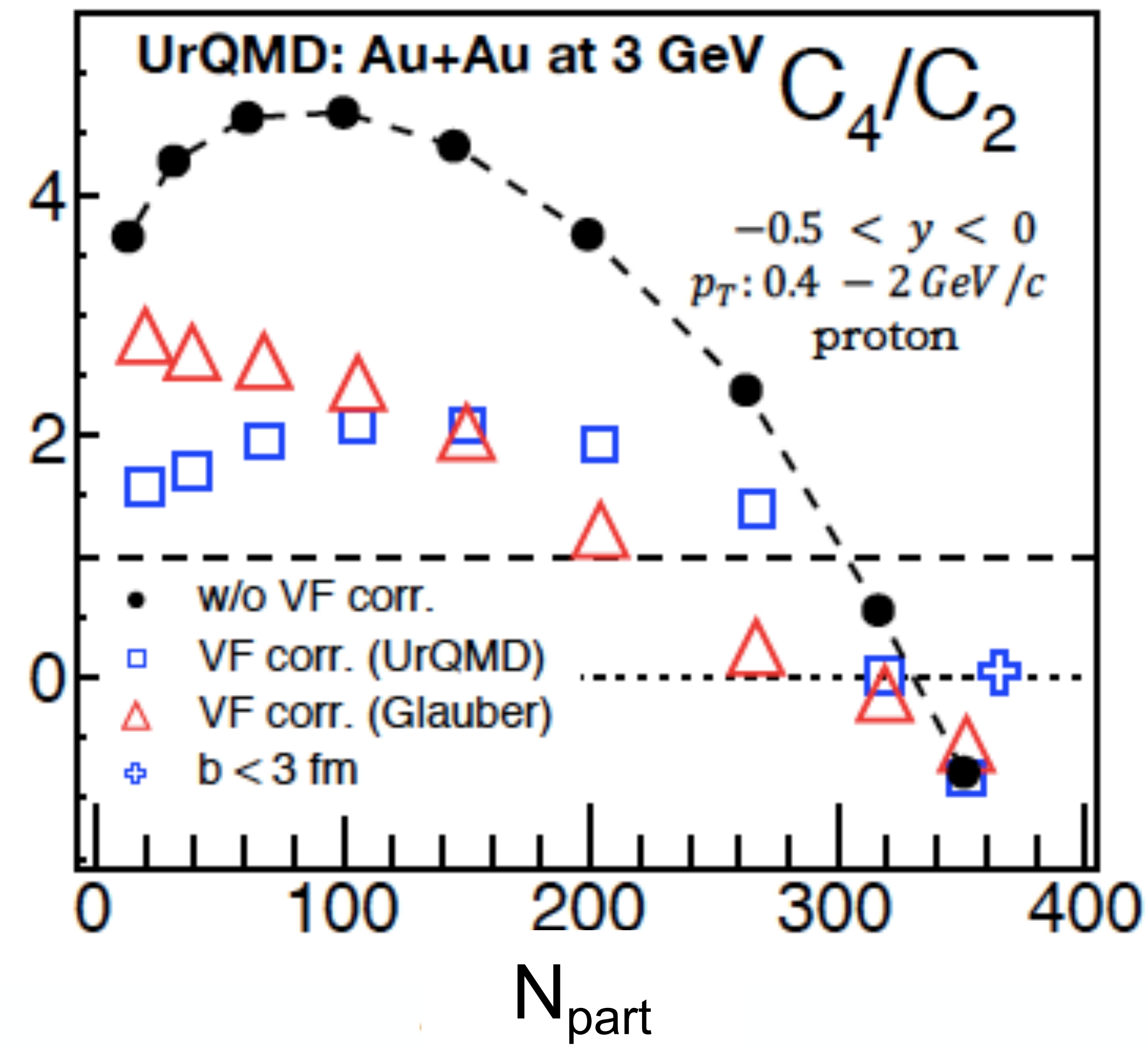
Reduction factor in uncertainties on 0-5% C_4/C_2 :
BES-II vs BES-I

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

Physics Challenges – Initial Volume Fluctuations

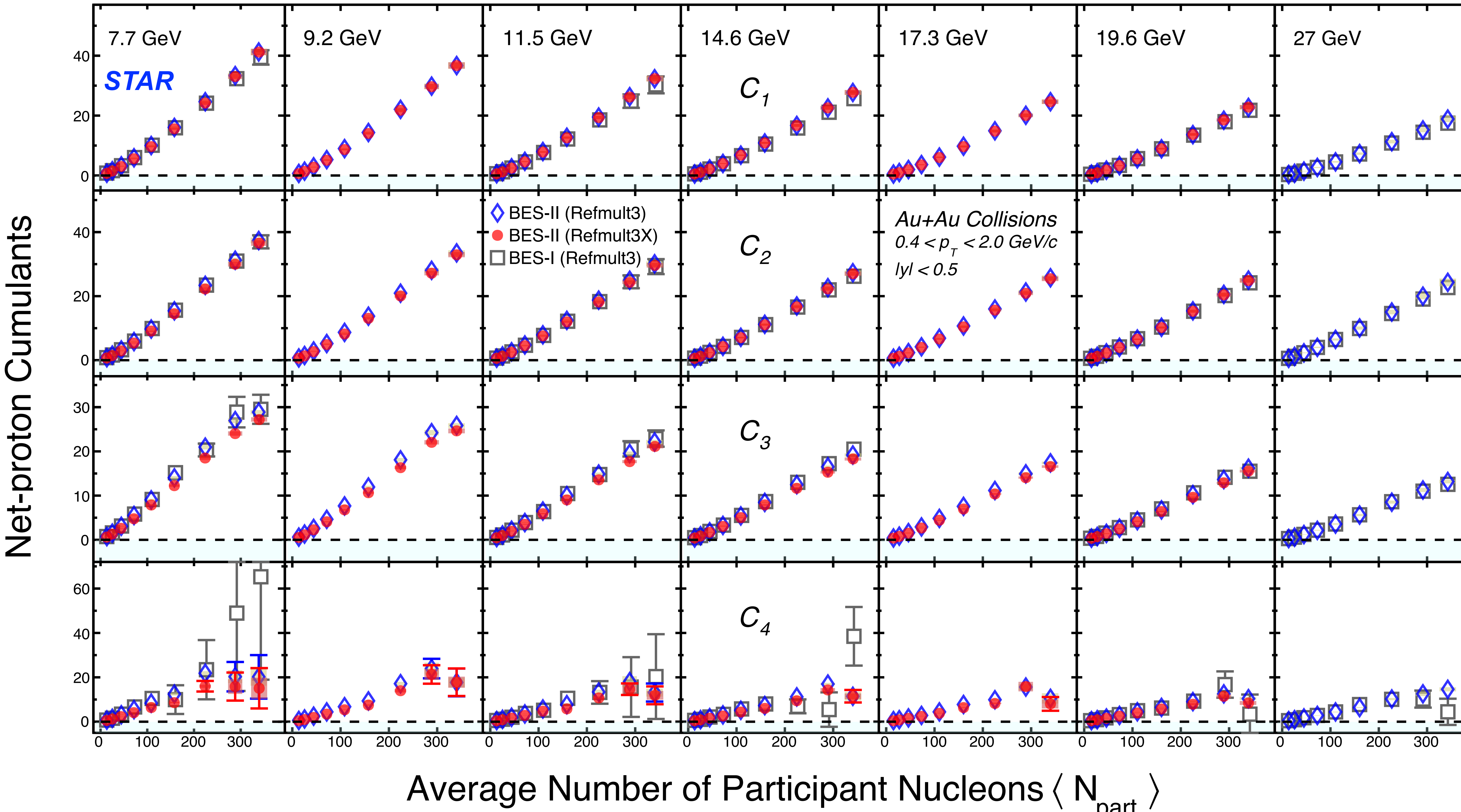
STAR, PRC 107 (2023) 024908





Low collision energies → much reduced multiplicity
→ worsened centrality resolution / large volume fluctuation
Currently corrections rely on models (model-dependence)
→ A data-driven way to assess the IVF?

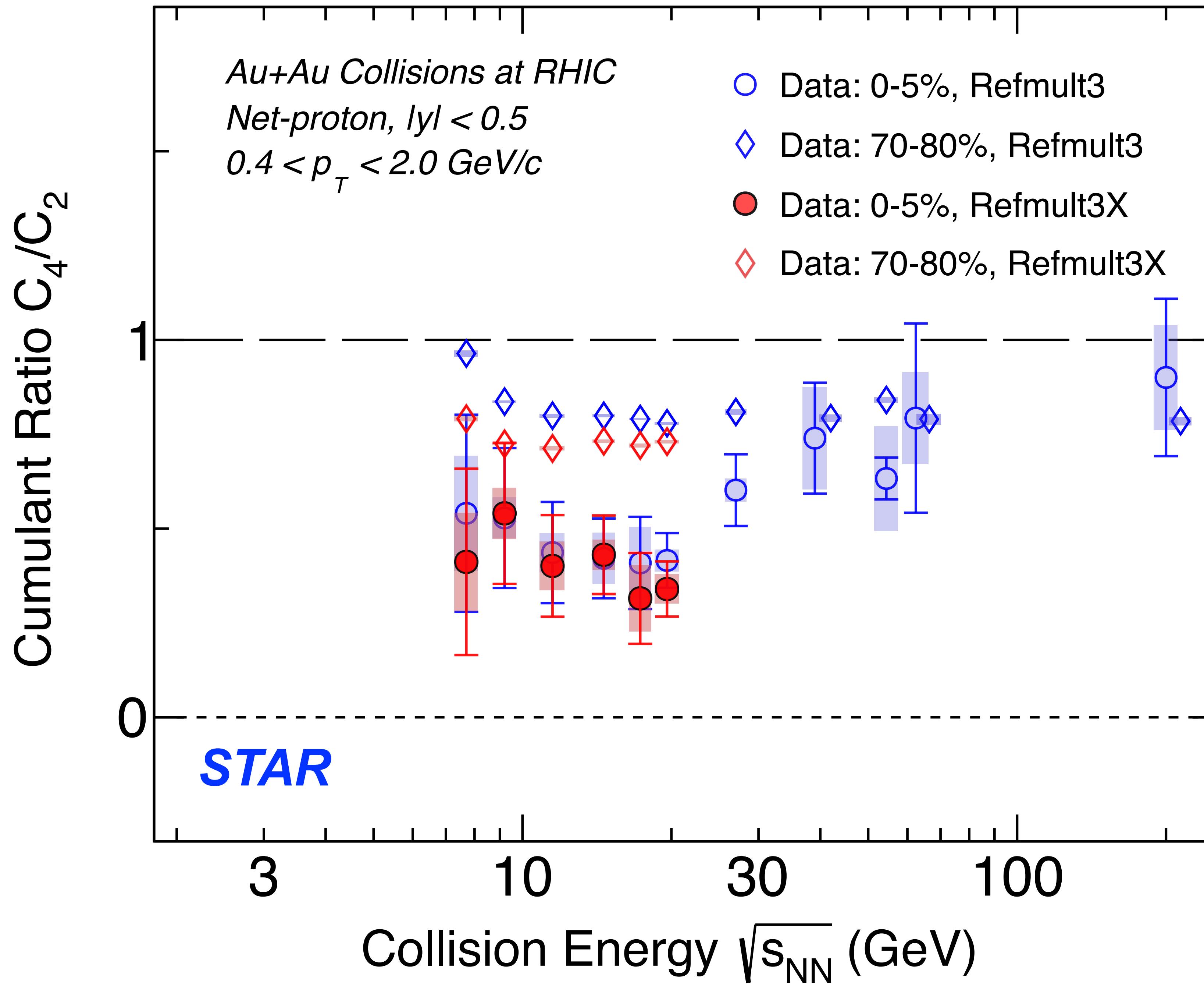
Net-proton Cumulants from BES-II



BES-II Measurements: Refmult3 vs. Refmult3X

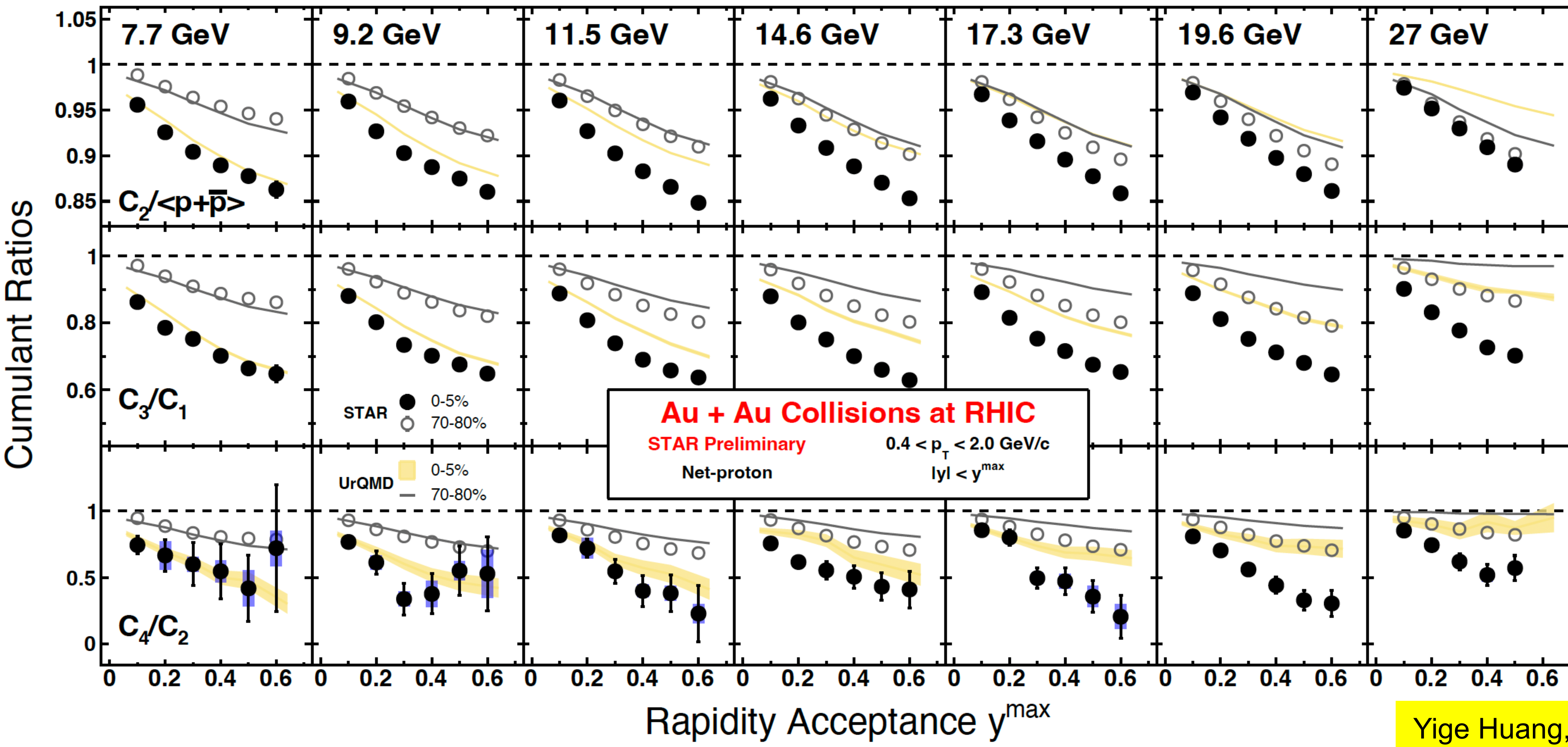
1) C_4/C_2 in 0-5% centrality: results between Refmult3X and Refmult3 agree with each other!

2) Difference seen in 70-80% due to centrality resolution impact.



Results from Refmult3X are represented hereafter

Net-proton Cumulant Ratios vs. Rapidity Window

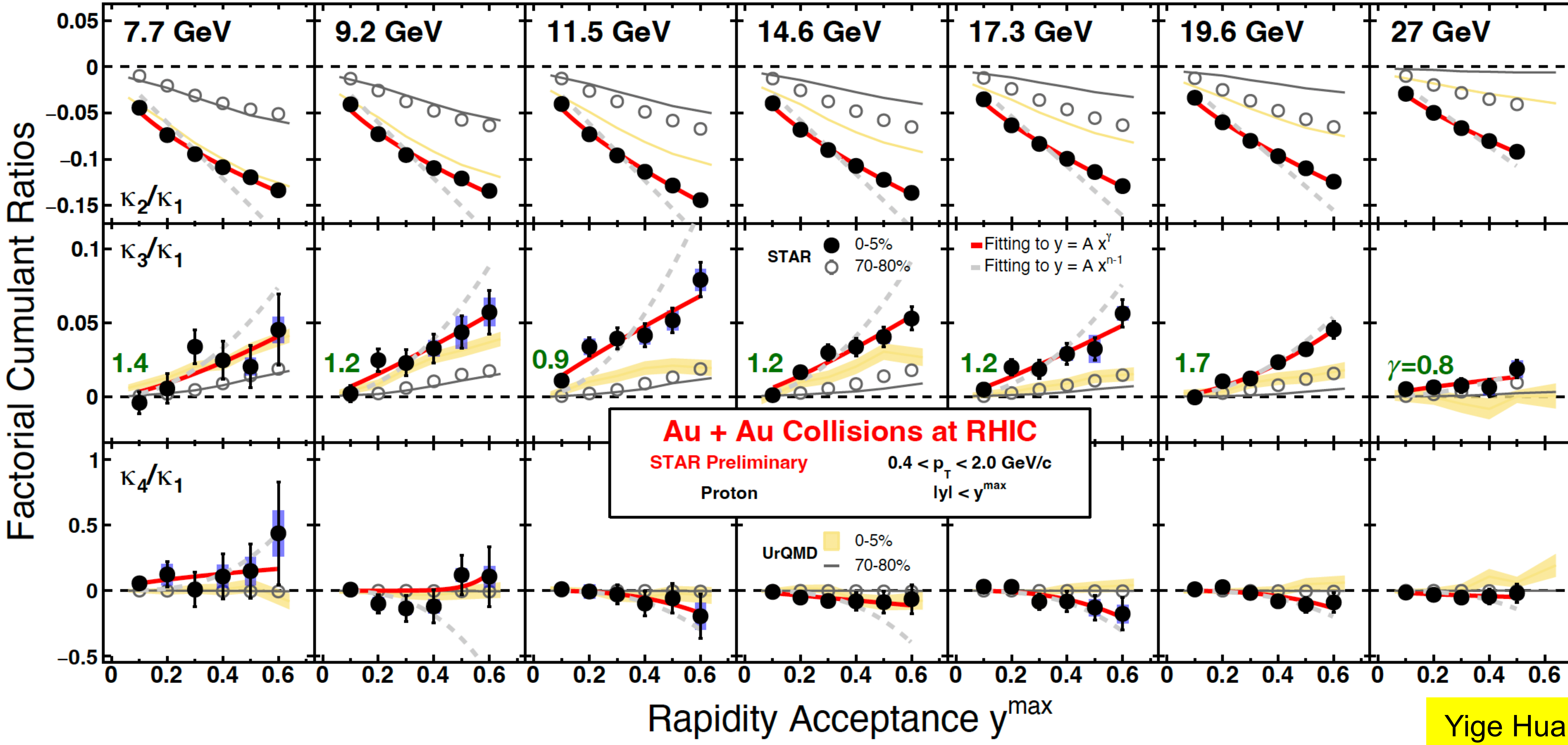


Yige Huang, QM25

1) Net-proton cumulant ratios grow with increasing Δy window

2) UrQMD calculations smaller compared to data at 17.3, 19.6 and 27 GeV

Proton Factorial Cumulant Ratios vs. Rapidity Window

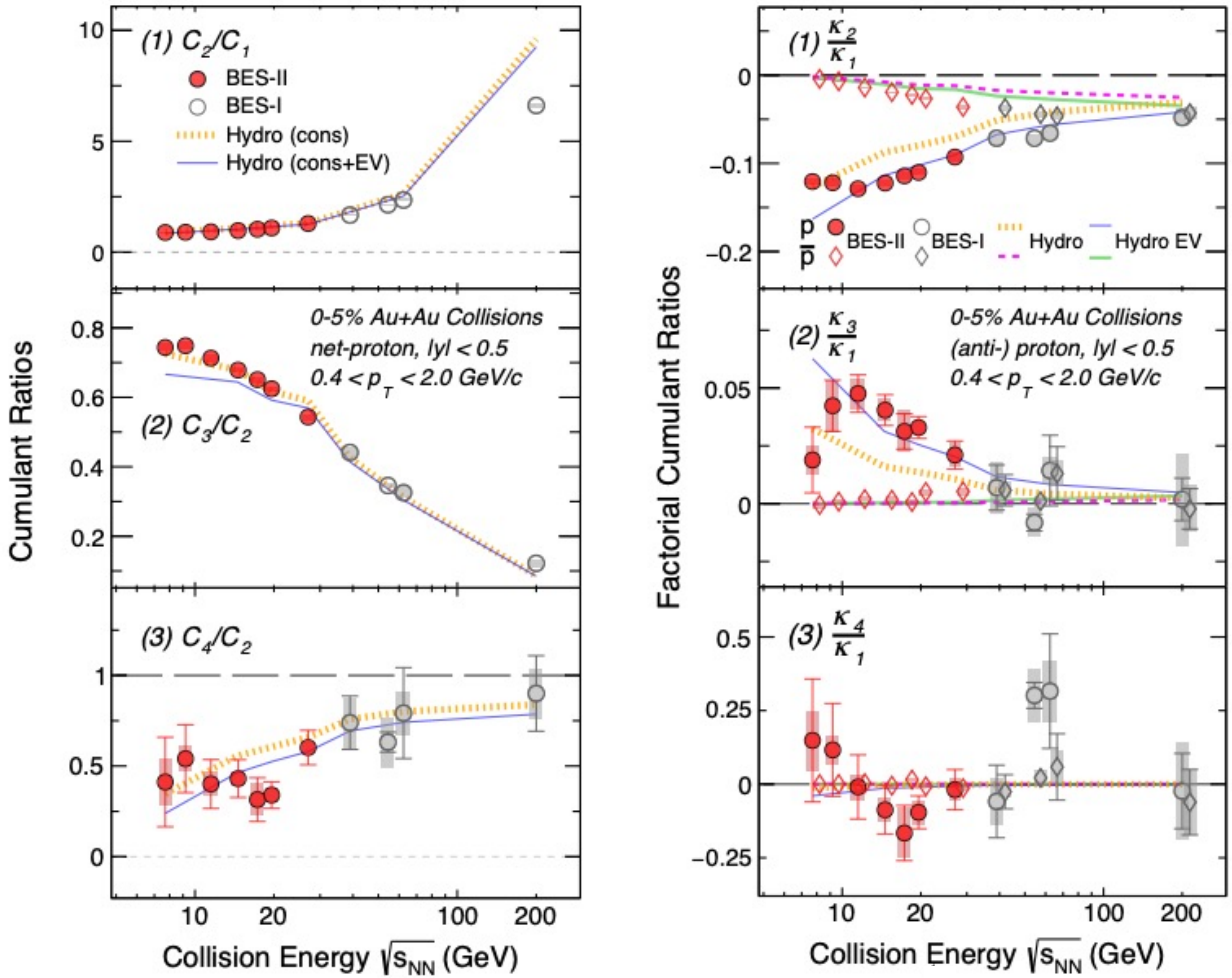


Yige Huang, QM25

1) Proton κ_n/κ_1 follows a power increase vs. Δy

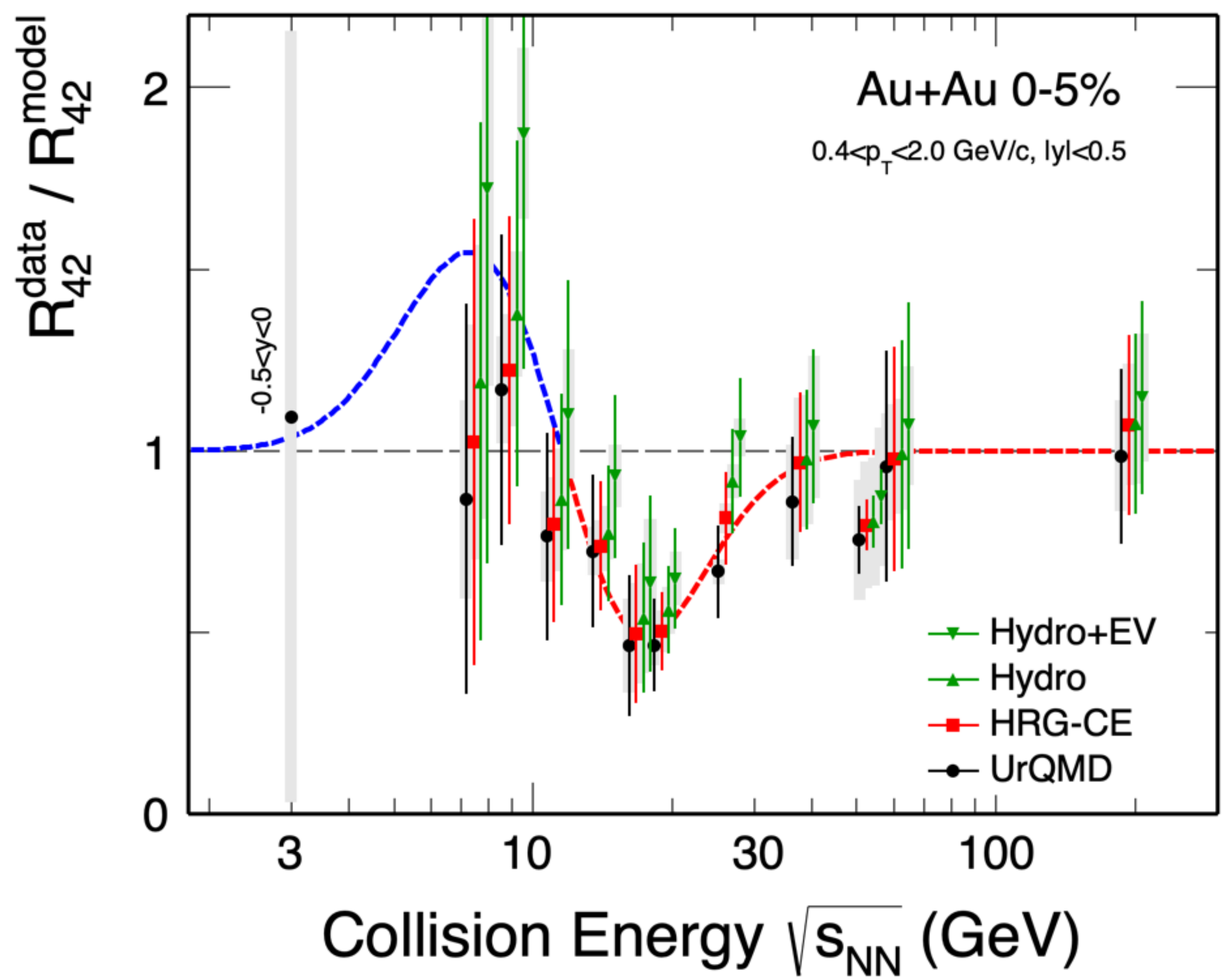
2) Power constant smaller than simple expectation (n-1)

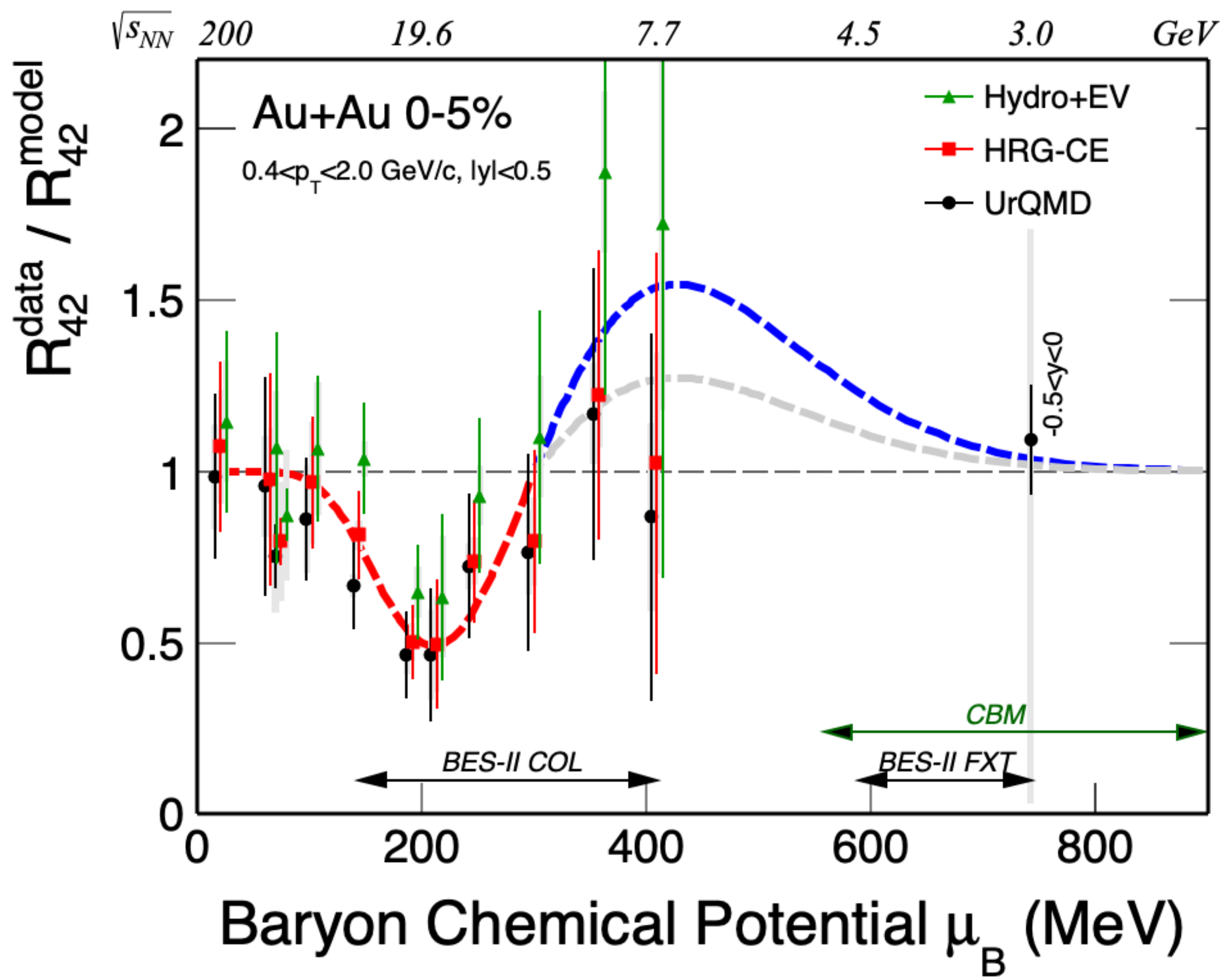
Comparison w/ Hydro and Hydro+EV



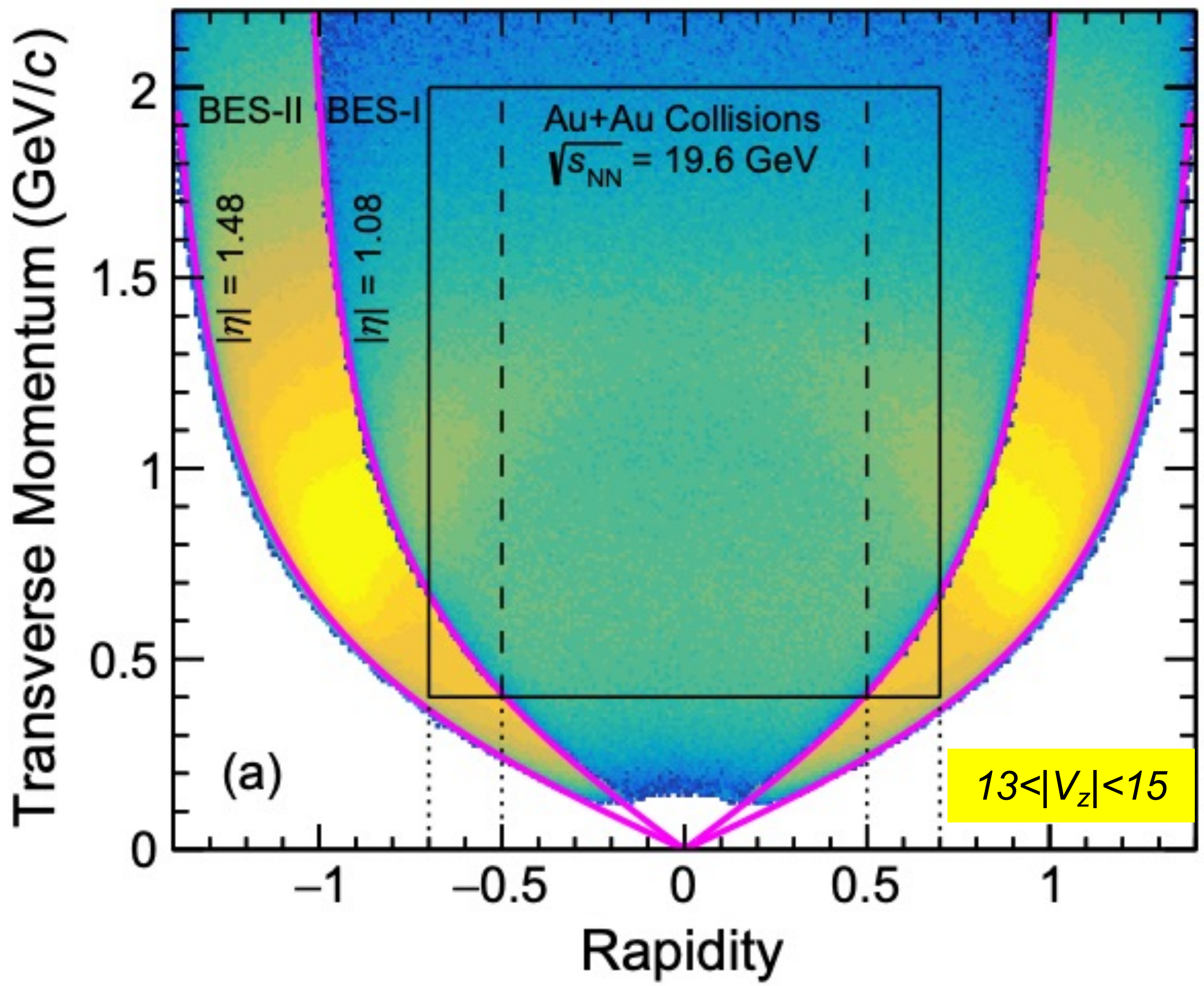
V. Vovchenko et al, PRC 105, 014904 (2022)

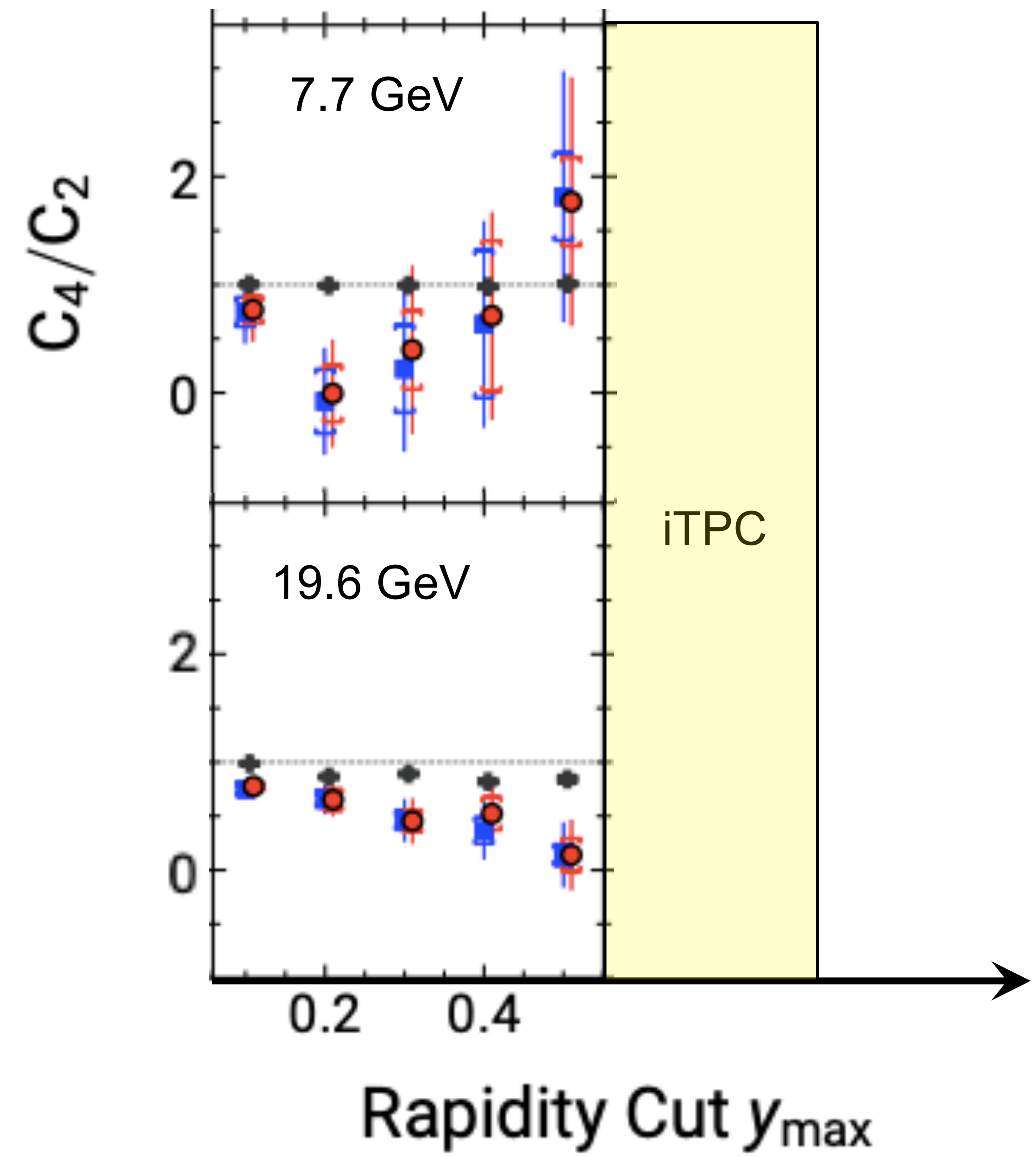
Comparison w/ Hydro+EV





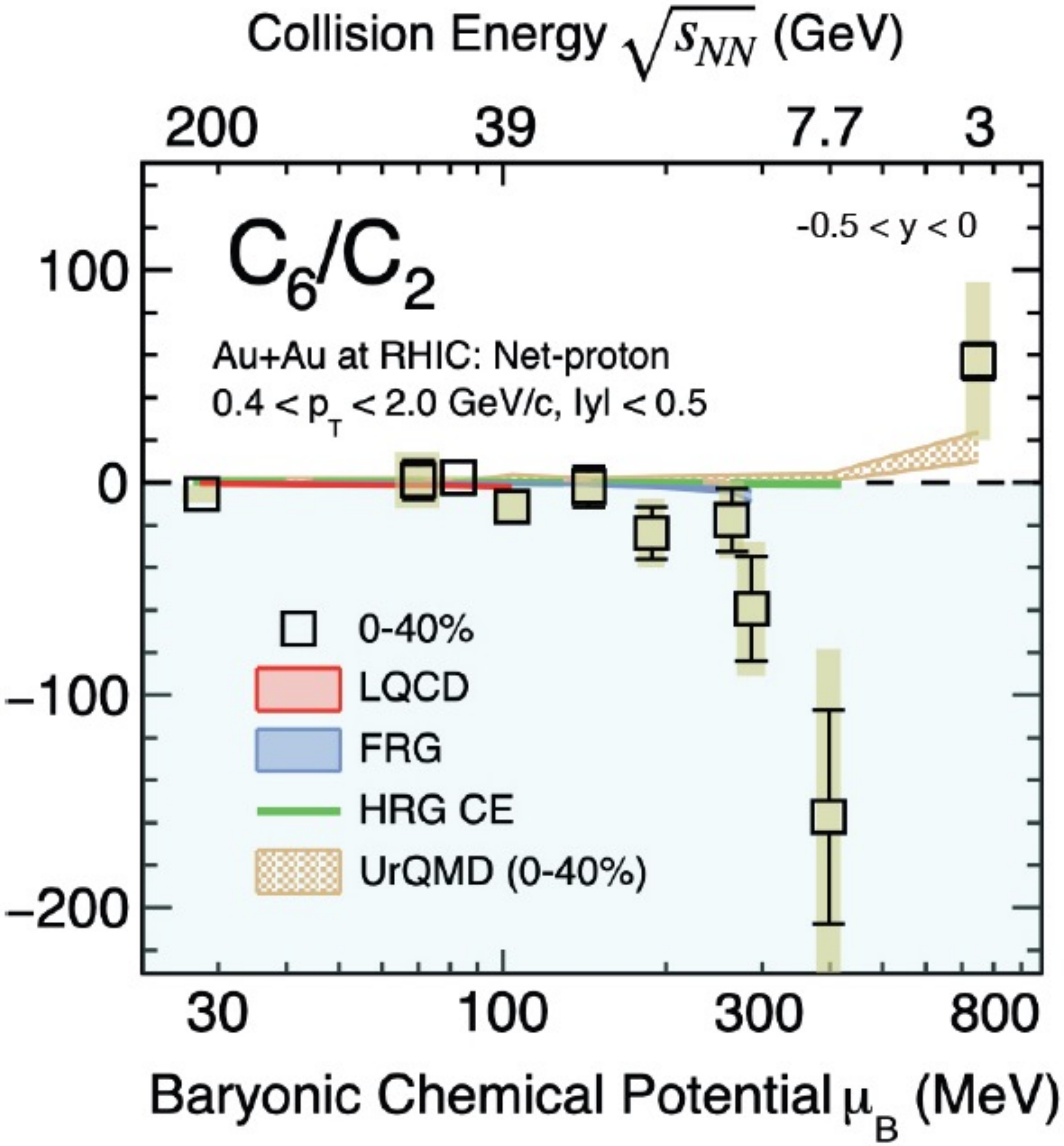
Kinematic Scan (Rapidity / p_T) – New at QM25

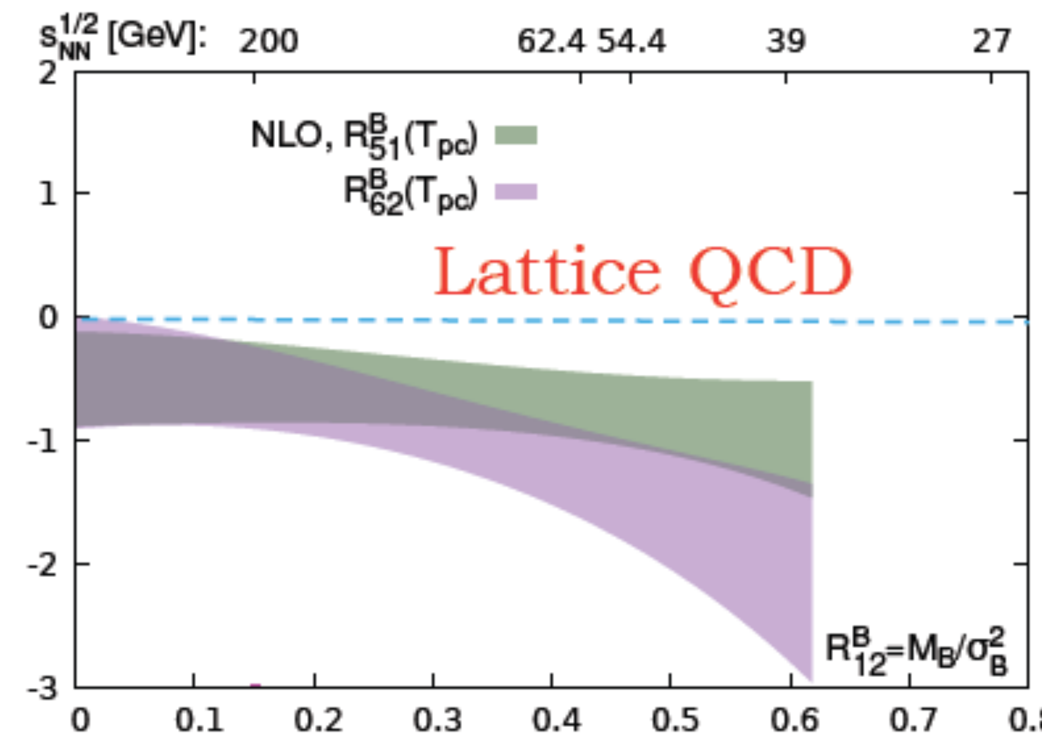




1) CP induced fluctuation expected a characteristic dependence vs. accept. window size
2) BES-II with iTPC upgrade extends the rapidity window coverage for this study

Hyper-order Cumulant Ratios – BES-I



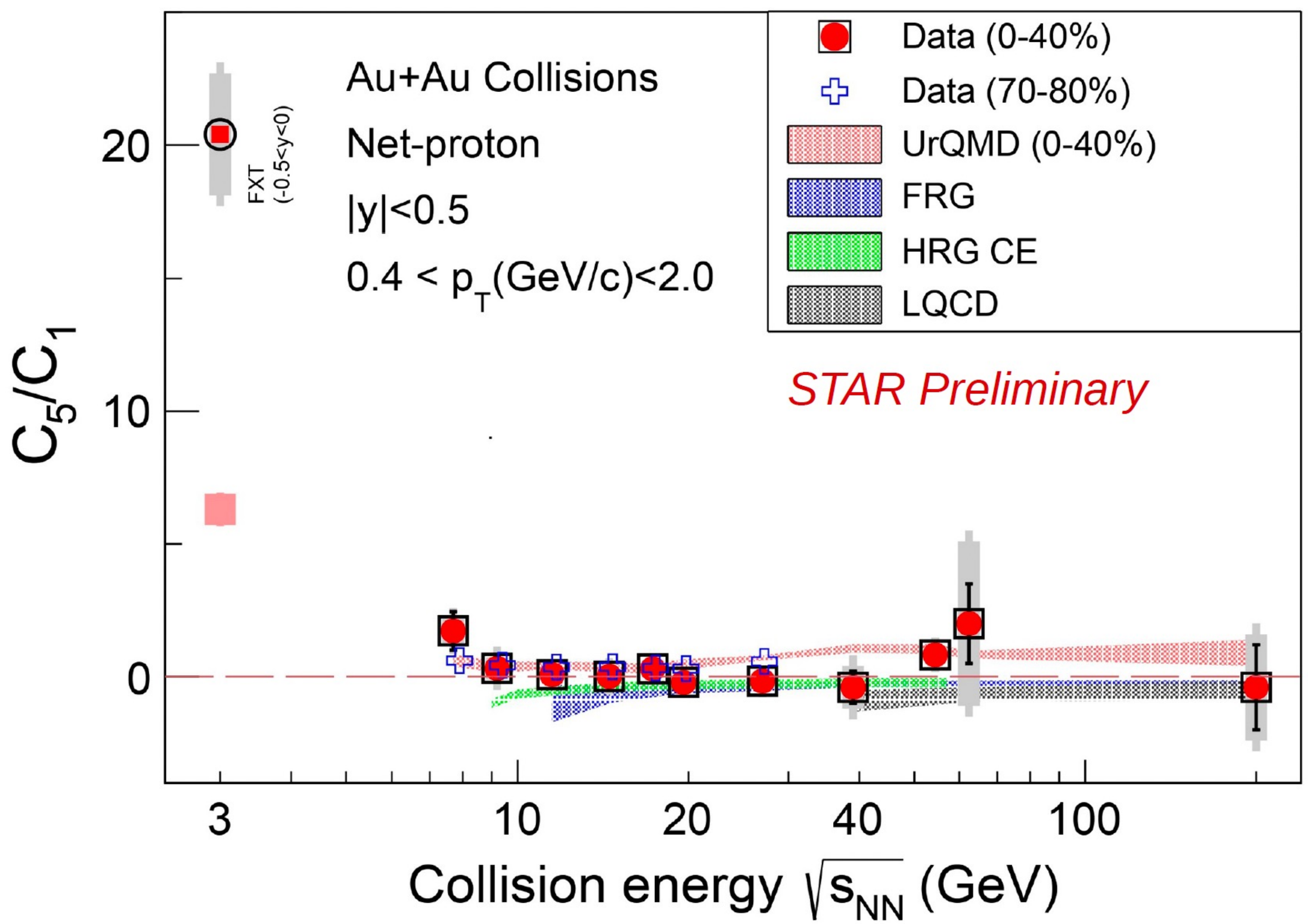


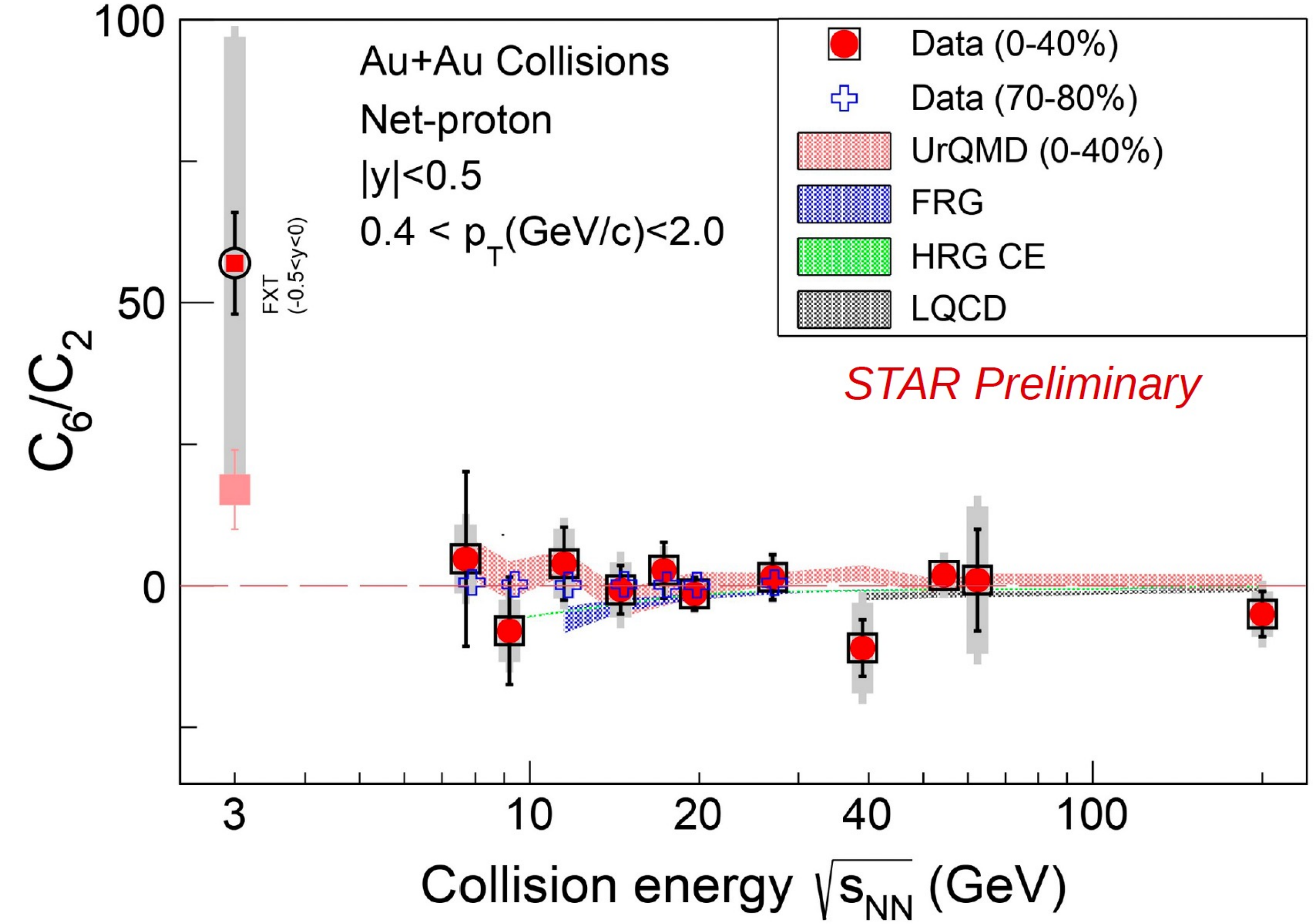
1) Increasingly negative C_6/C_2 down to 7.7 GeV (1.7σ) – consistent with LQCD

2) $C_6/C_2 > 0$ at 3 GeV, consistent with UrQMD calculation

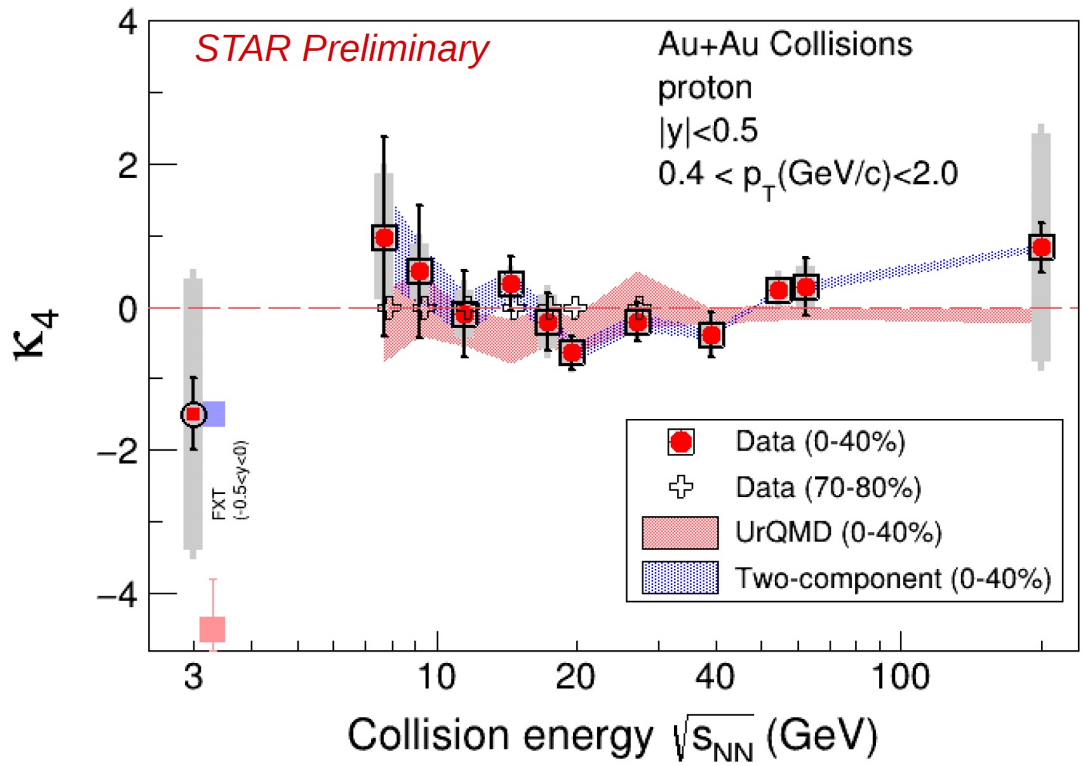
STAR, PRL 127 (2021) 262301 (2021), PRL 130 (2023) 082301

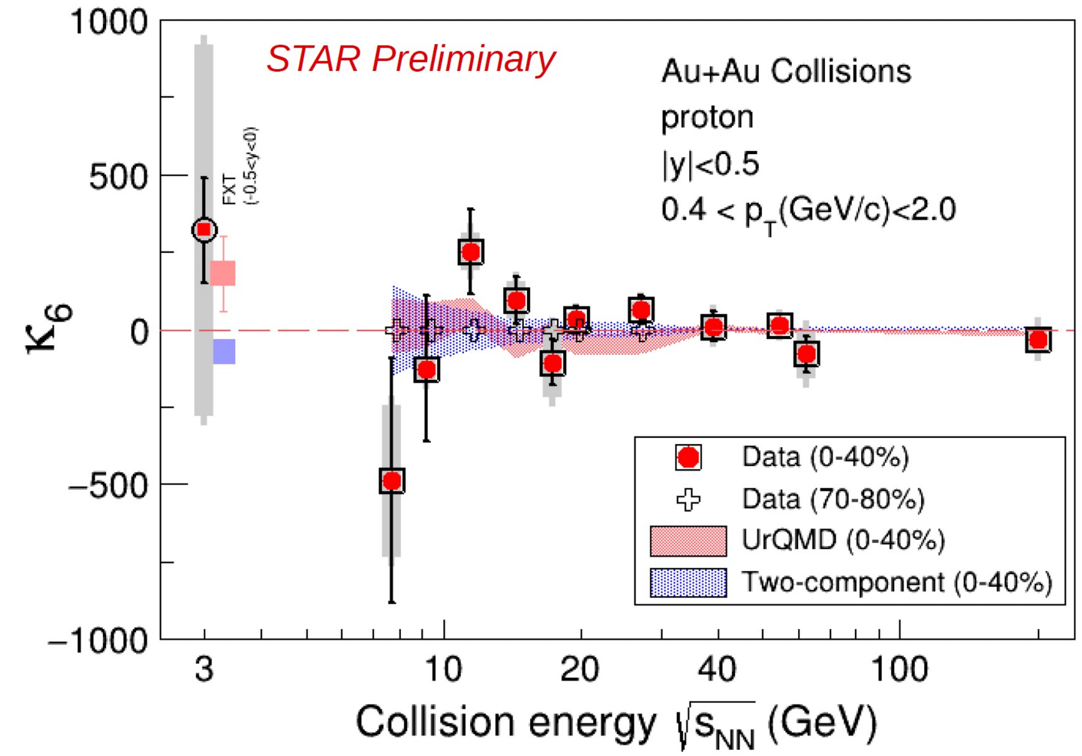
New Precision Measurement of Hyper-Order Cumulants

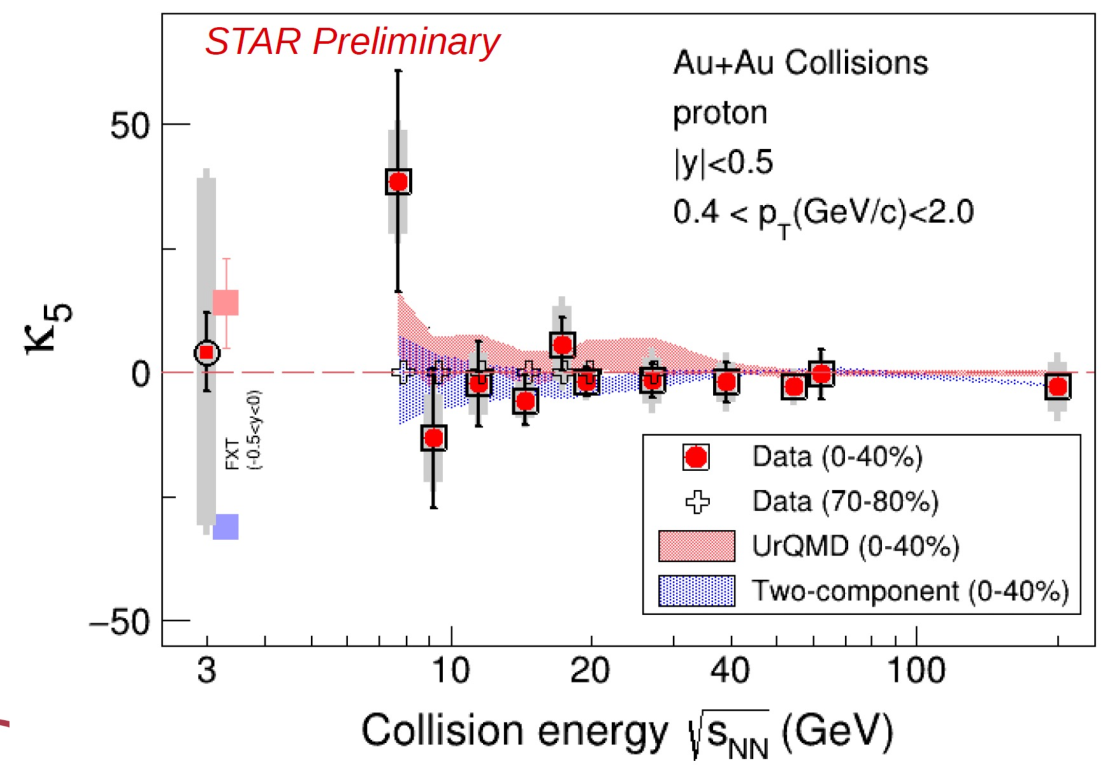




Proton Factorial Cumulants



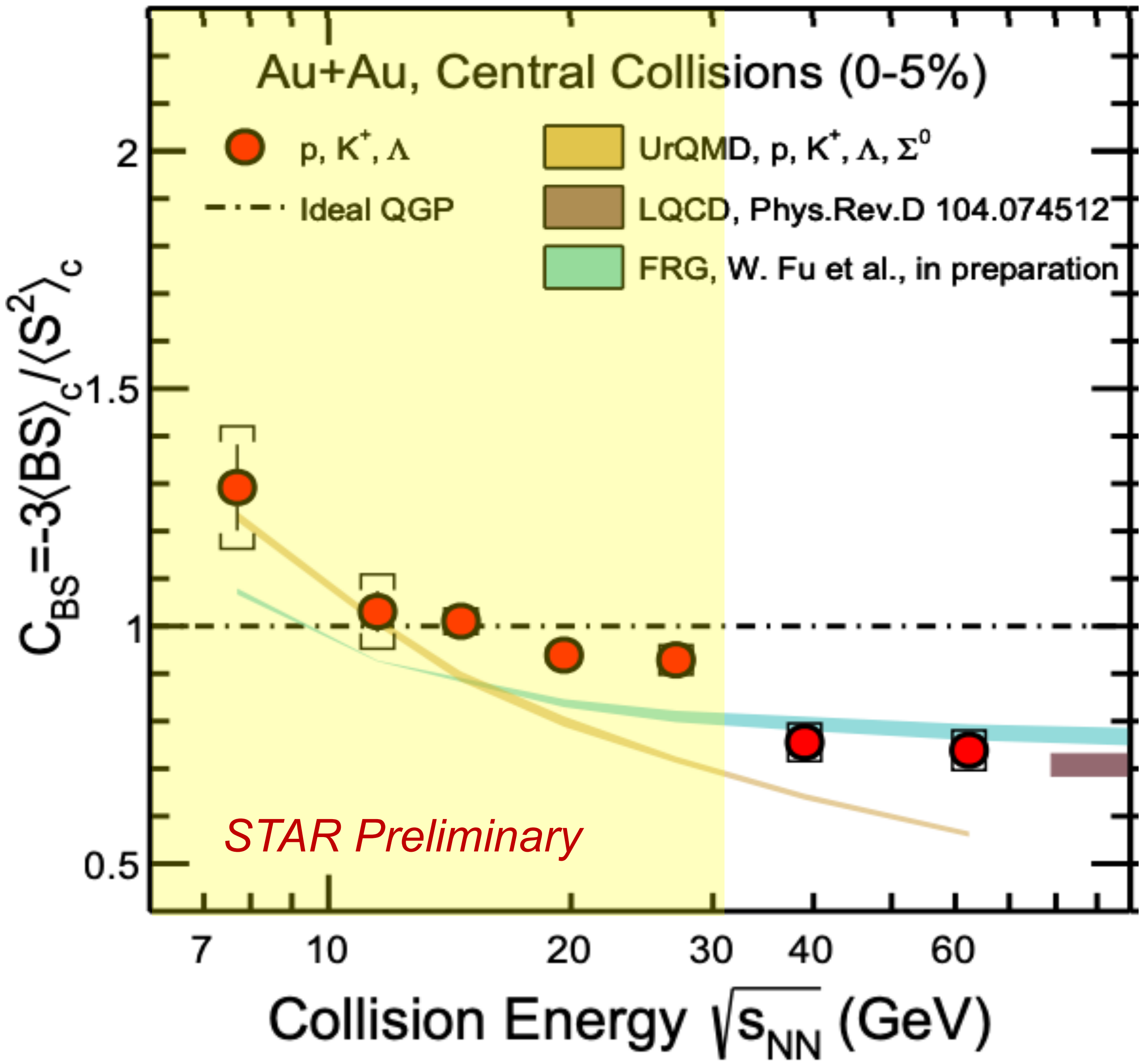




Possible EoS Change vs. Energy in Other Observables

STAR, CPOD 2024

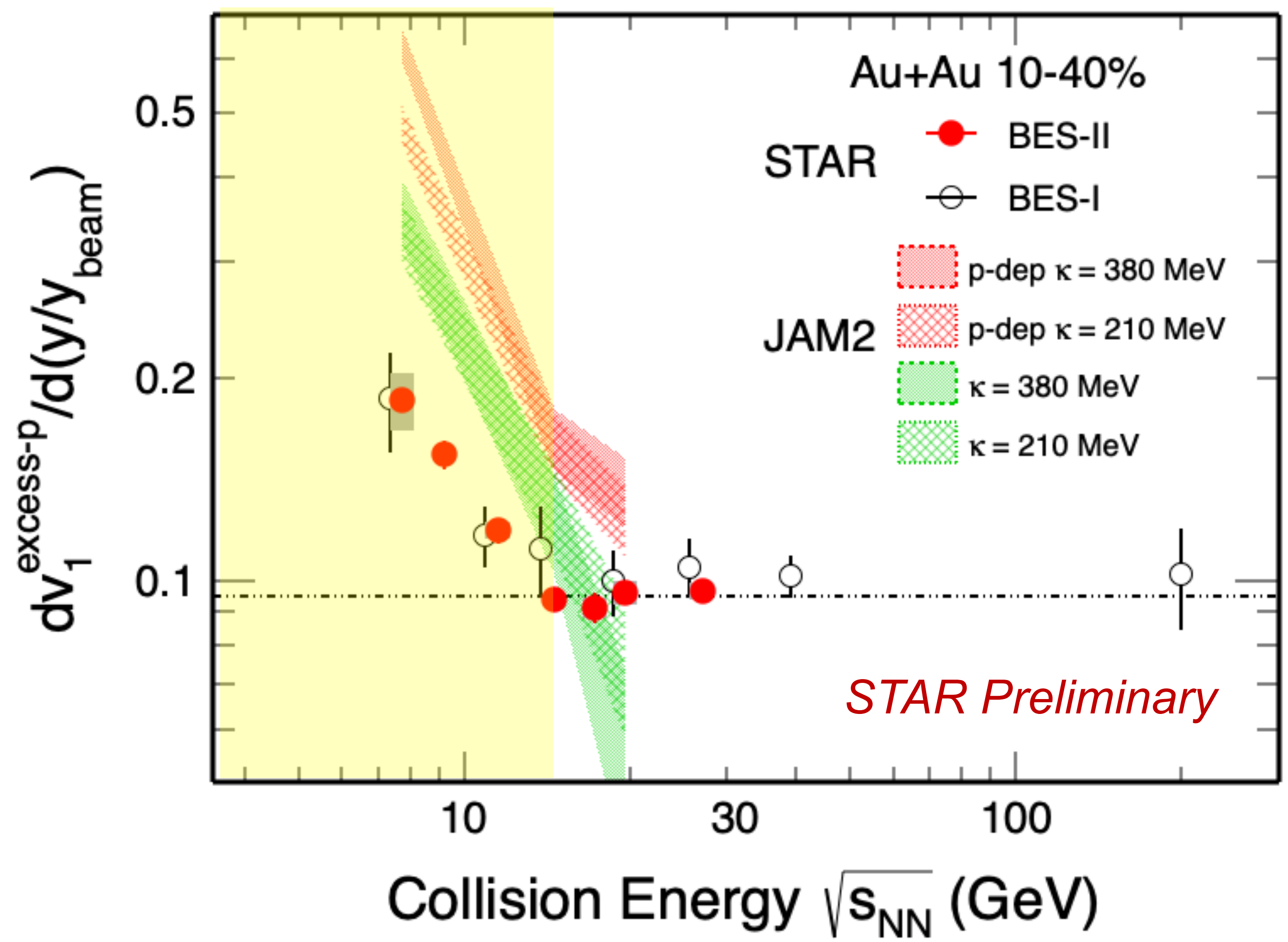
Baryon-Strangeness Correlation



C_{BS} consistent with FRG/LQCD at high energies, deviates at 27 GeV and below

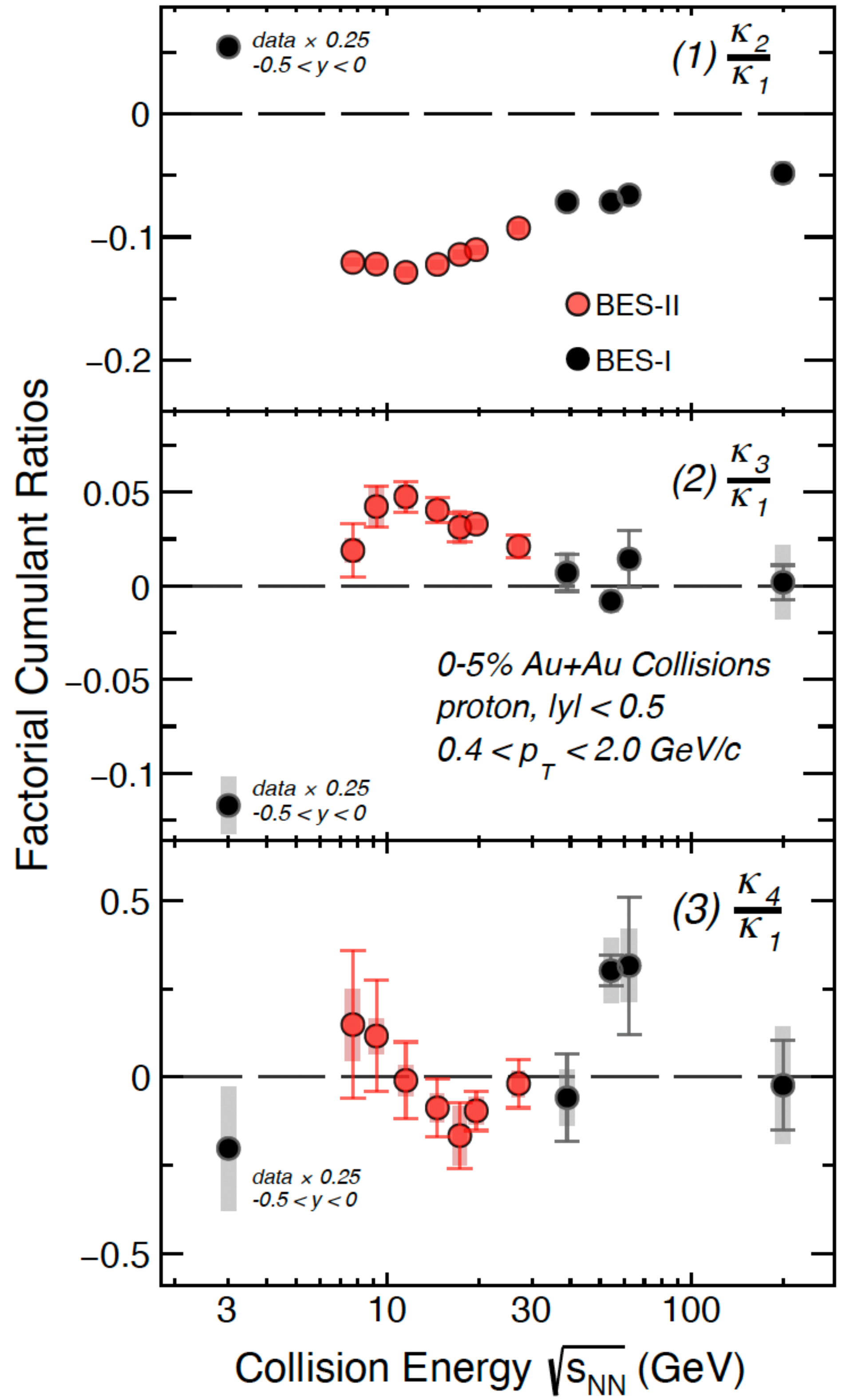
Excess-p v_1 slope

$$v_1^{\mathrm{excess}-p} = \frac{v_1^p - v_1^{\bar{p}}}{1-r} \qquad r = \bar{p}/p$$

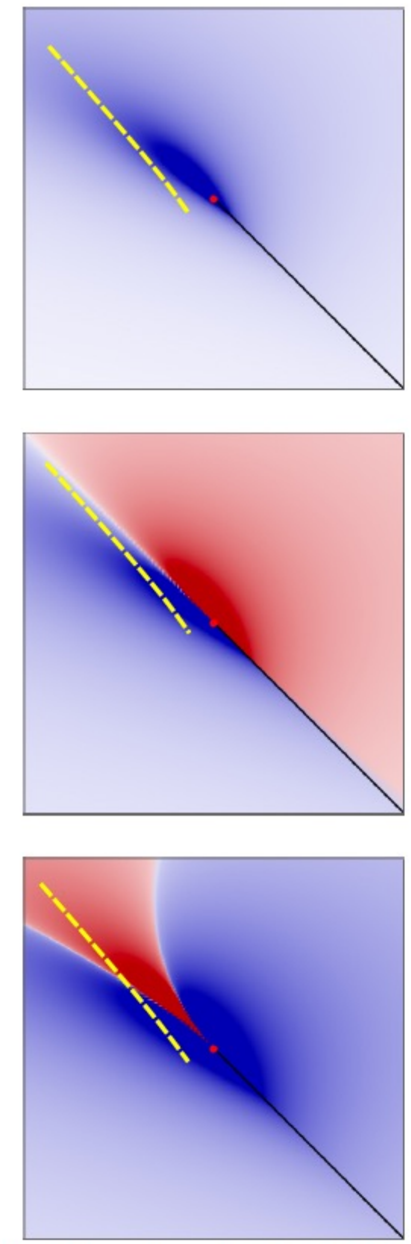


Excess-p v_1 slope shows a scaling at >=14.6 GeV, and the scaling breaks at < 14.6 GeV

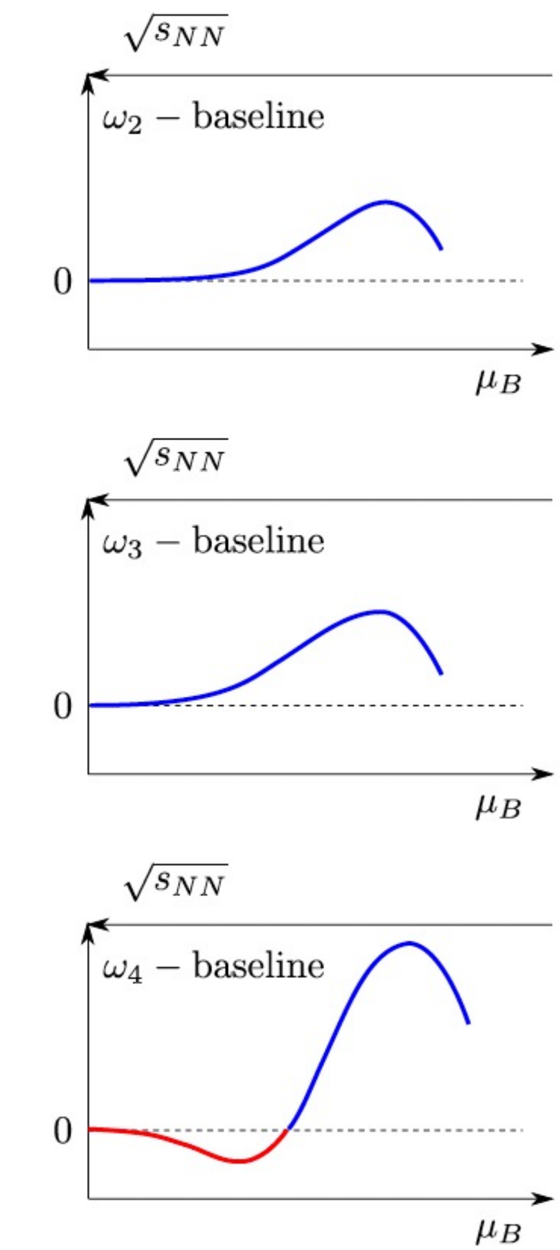
Comparisons with 3 GeV Data Points Included



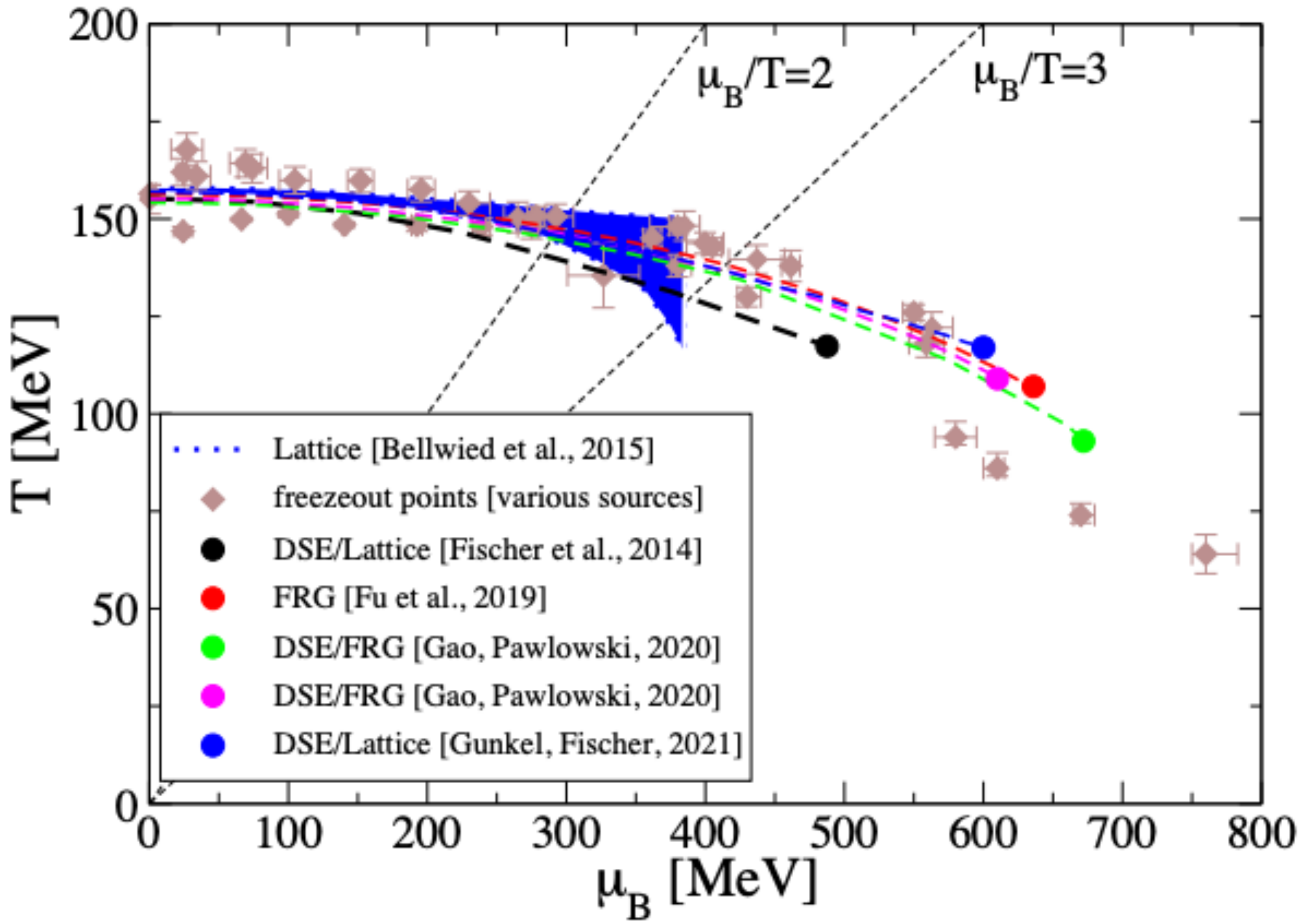
M. Stephanov, CPOD 2024

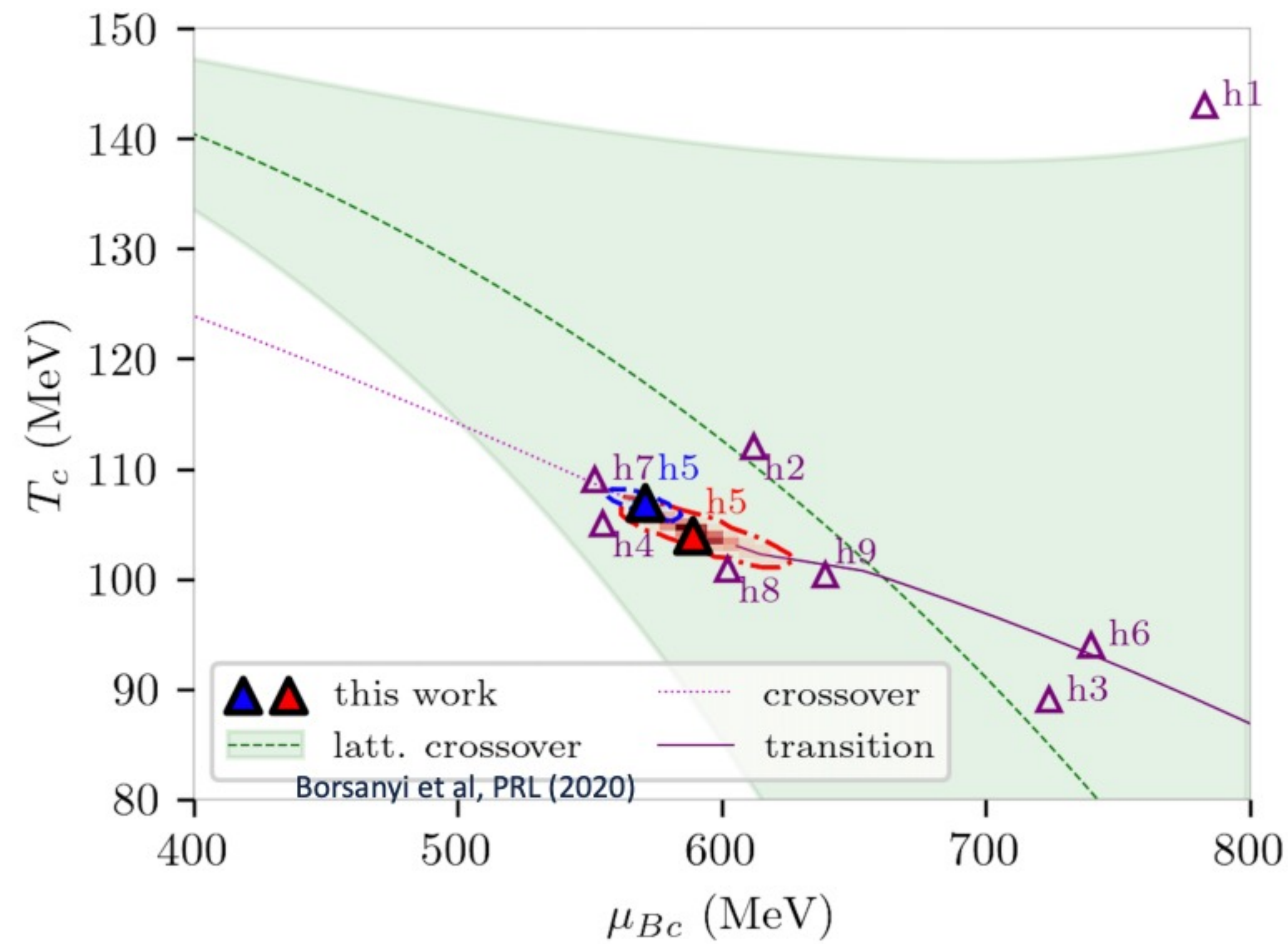


Bzdak et al review 1906.00936

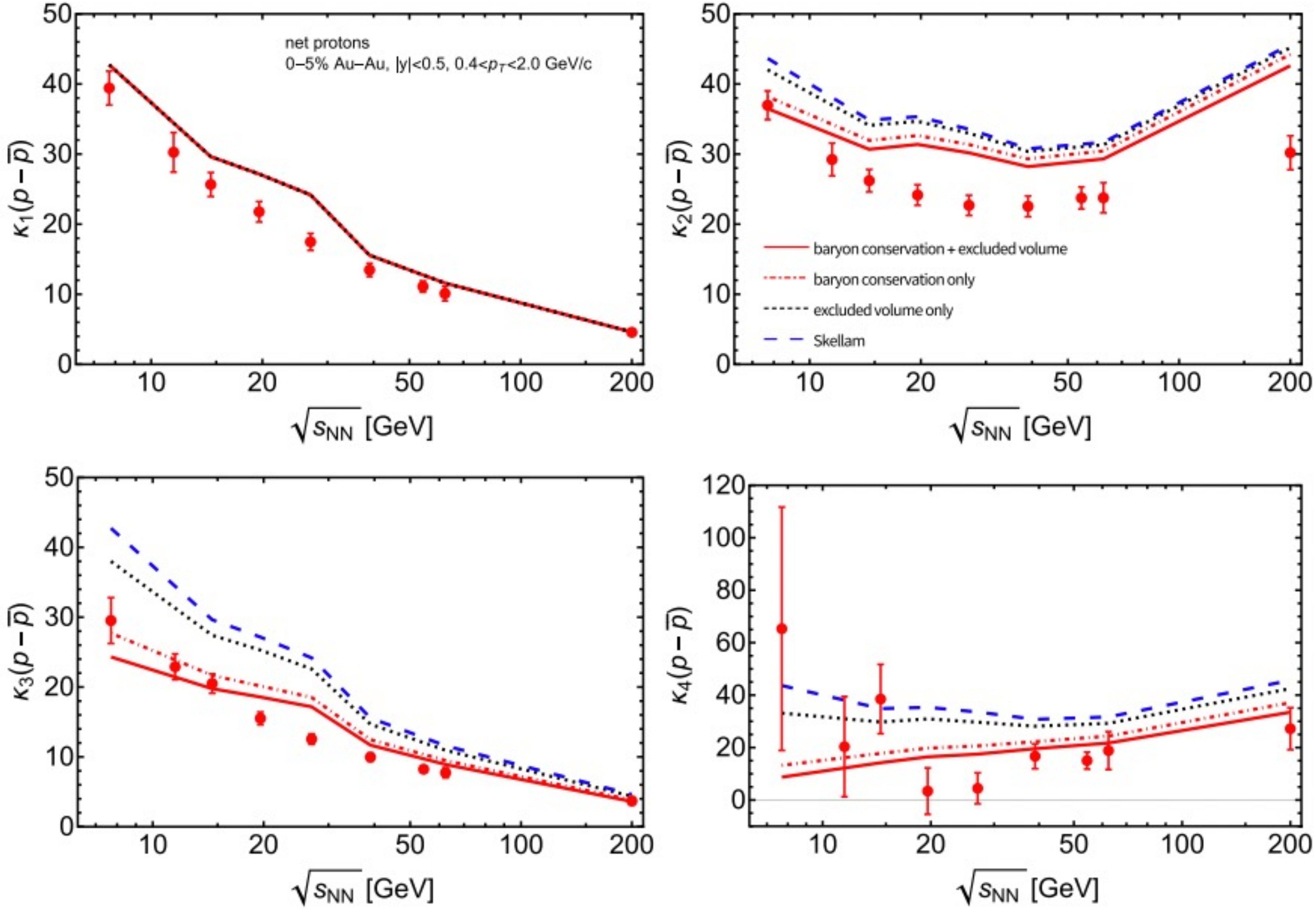


CEP Predictions from DSE/FRG and Holograph





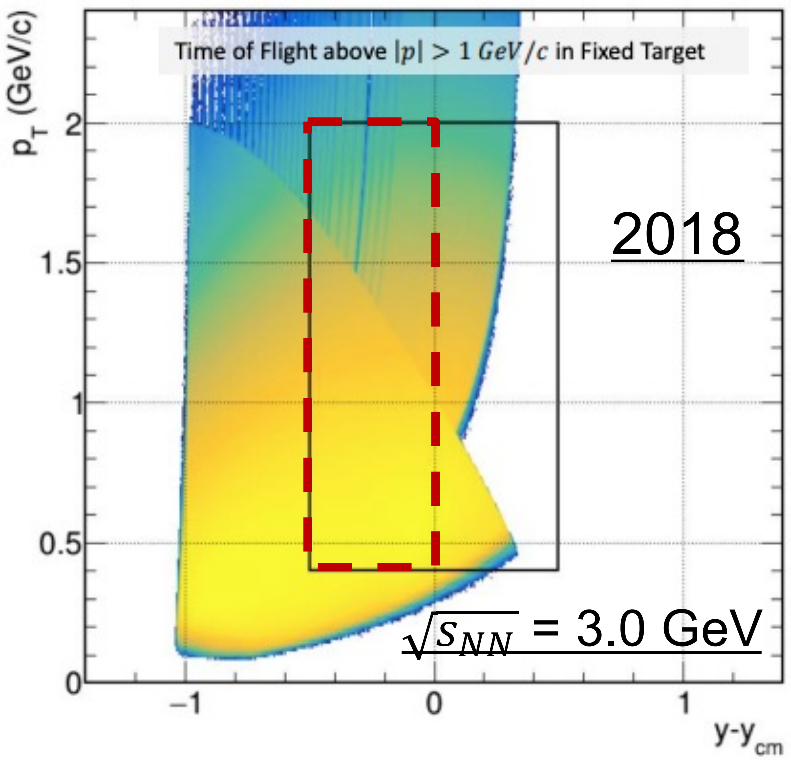
Hydro (Baryon Cons. + EV)

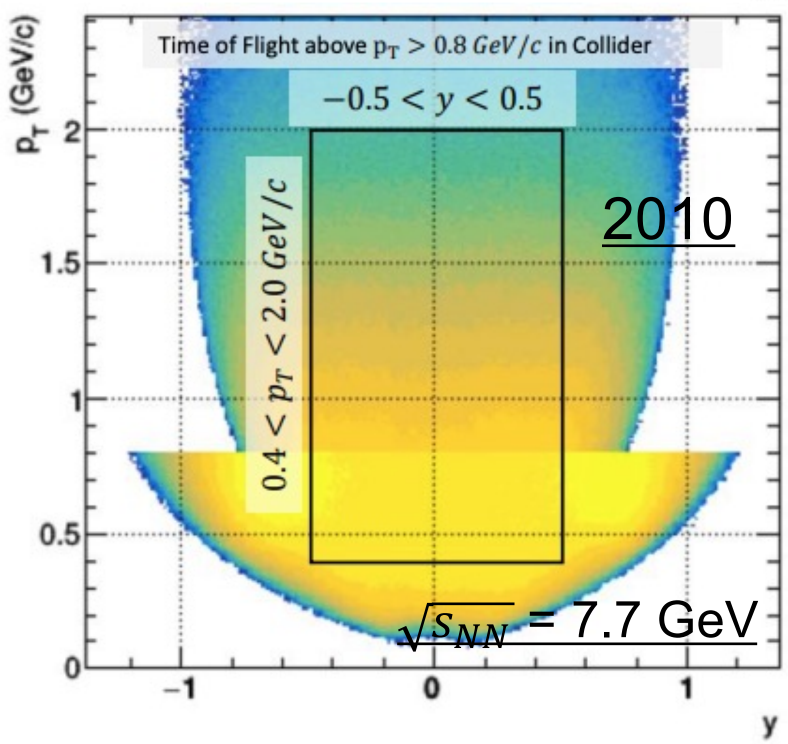


V. Vovchenko et al, PRC 105, 014904 (2022)

High Moments Measurements in FXT Dataset

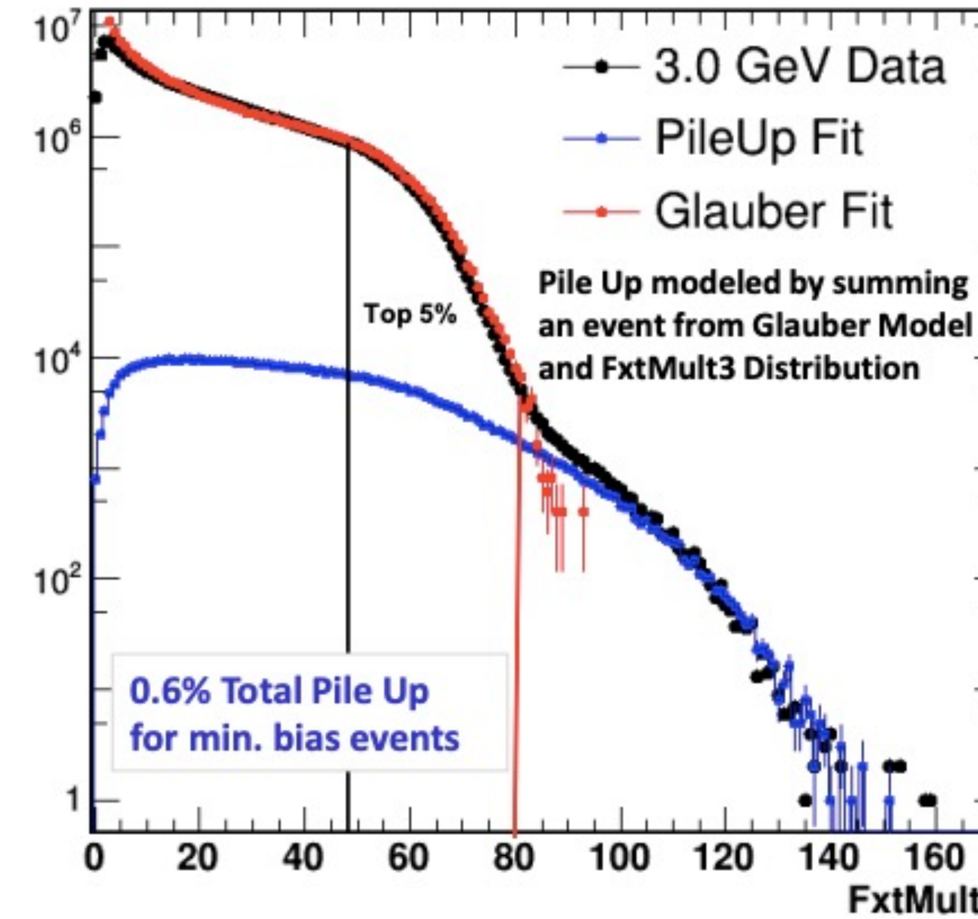
Proton Acceptance





"Pile-up" effect

Sam Heppelmann, Yu Zhang

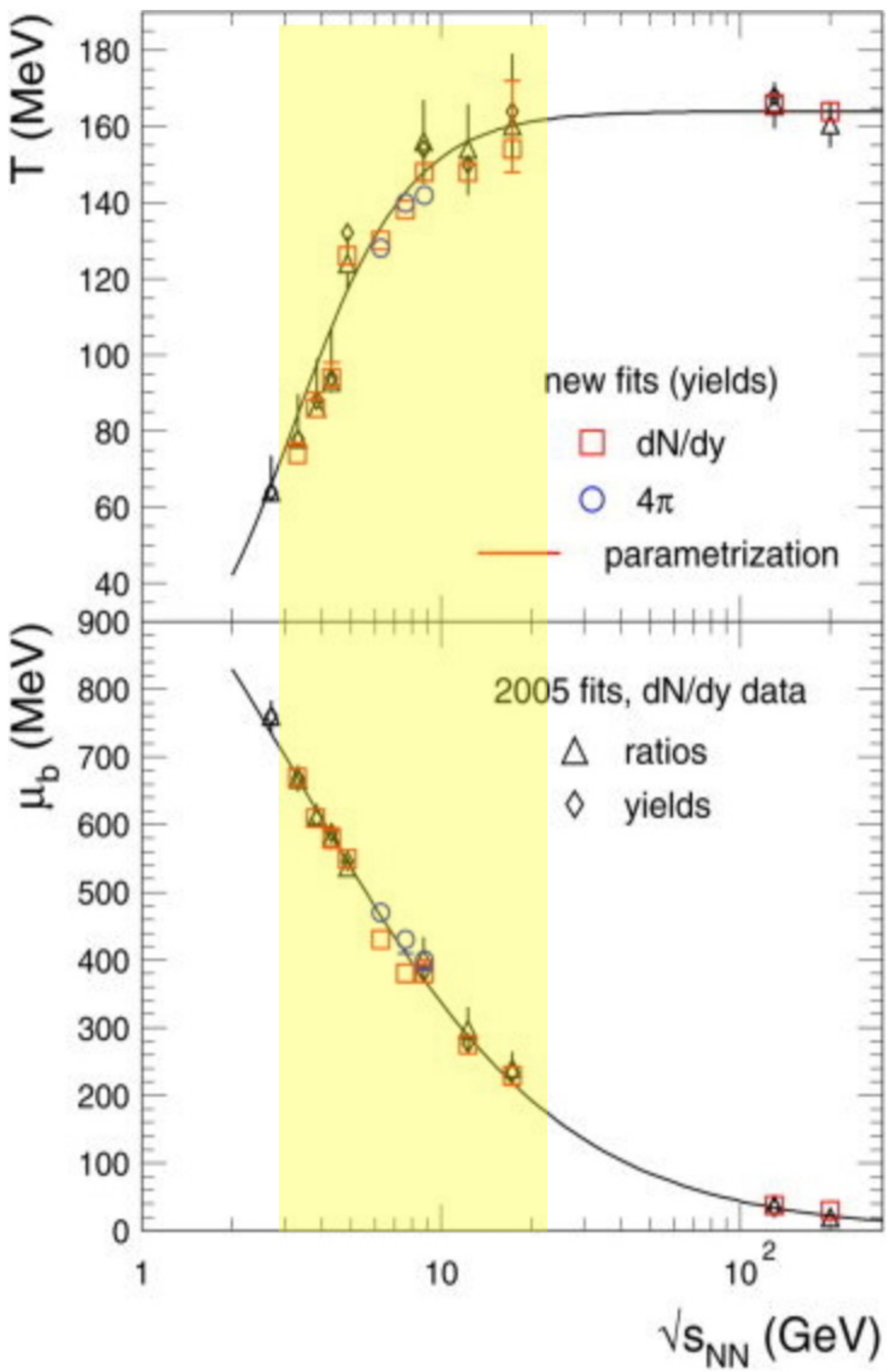


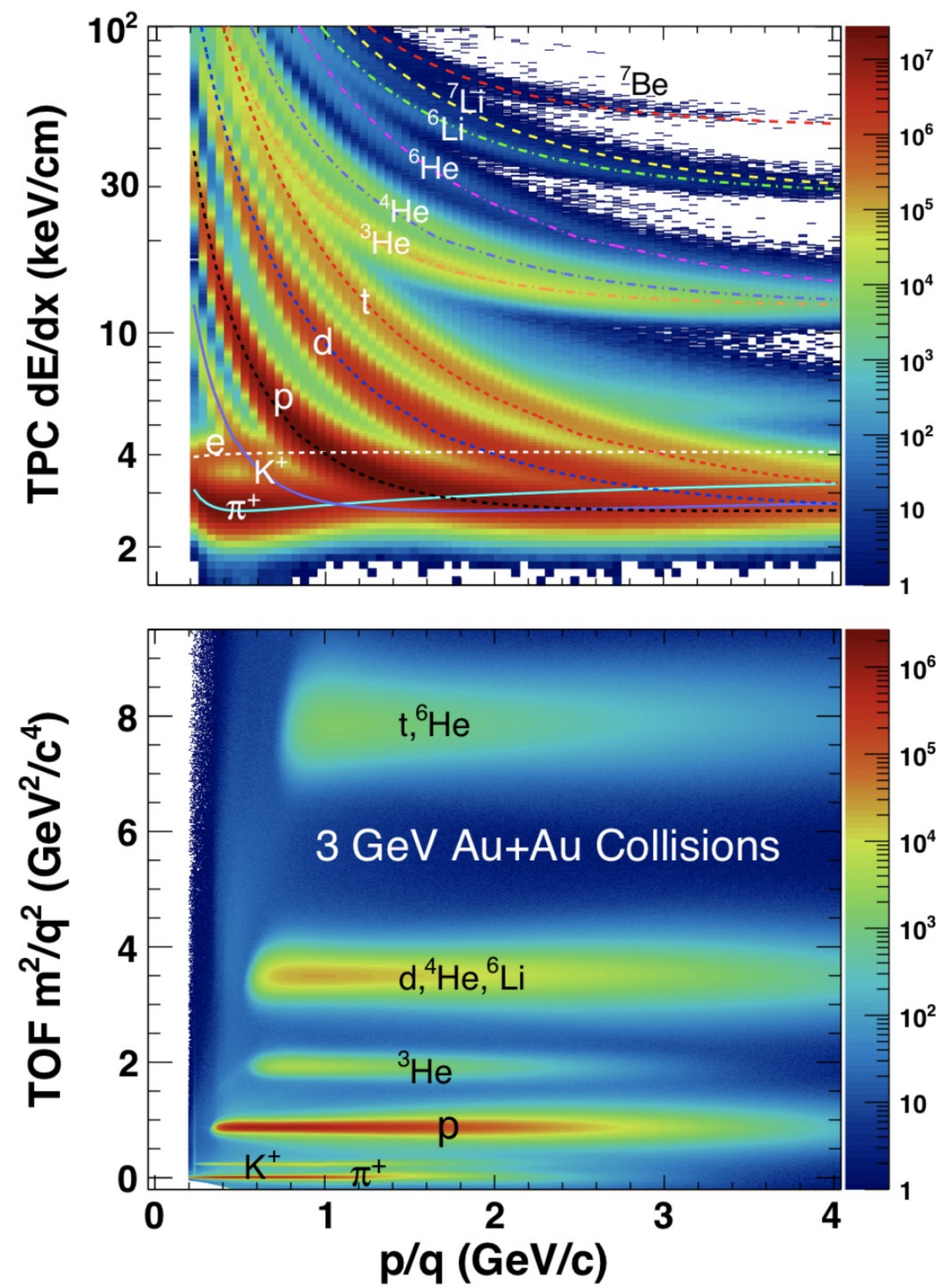
- "Two-component" unfolding technique

  T. Nonaka et al, NIMA 984 (2020) 164632
- Controllable precision on pile-up level $(0.6\ \pm 0.1)\%$ with centrality dependence

  - negligible in collider data

Opportunity of Studying Baryon Interactions in BES





A. Andronic et. al. PLB 673 (2009) 142

STAR, arXiv: 2311.11020