Study of the QCD Phase Structure in High-Energy Nuclear Collisions

- Criticality in Heavy-Ion Collisions

Nu Xu

Outline

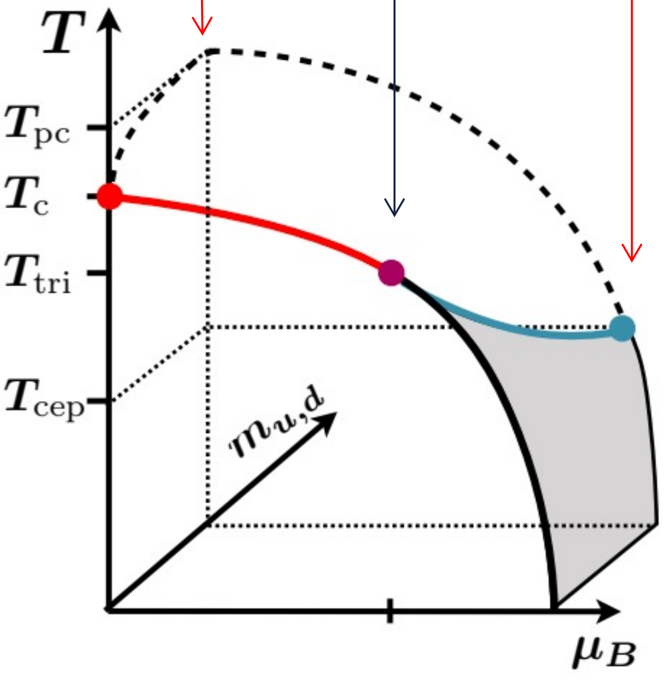
1) **Introduction**

2) Selected Recent Results
   - Collectivity and Baryon Correlation from FXT
   - Criticality from BES-II (collider)

3) Summary

LGT Calculation: QCD Phase Structure

T_C^0 | T_{PC} | T^{TC} | T^{CEP}



F. Karsch *et al.*, 2020

1) QCD transition temperature:
$\mathbf{T_{PC} = 156.5 \pm 1.5\ MeV}$

2) Chiral crossover line

$$T_{PC}(\mu_B) = T_{PC}^0\left[1 - \kappa_2\left(\frac{\mu_B}{T_{PC}^0}\right)^2 - \kappa_4\left(\frac{\mu_B}{T_{PC}^0}\right)^4\right]$$

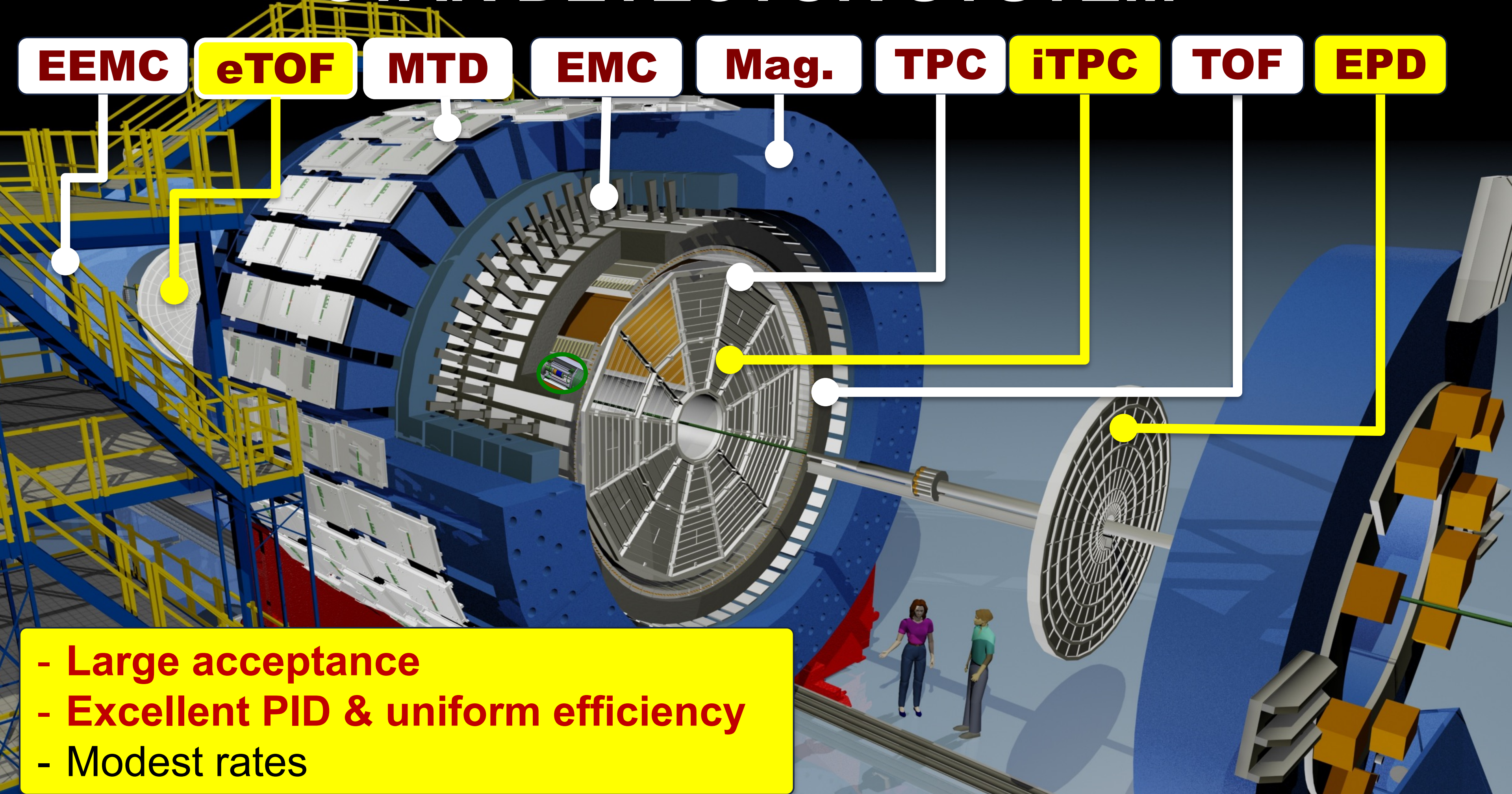
$\kappa_2 = 0.012(4),\ \kappa_4 = 0.00(4)$

3) Chiral transition temperature:
$\mathbf{T_C = 132^{+3}_{-6}\ MeV}$

4) QCD critical end point:
$\mathbf{T^{CEP} < T_C,\quad \mu_B^{CEP} \gtrsim 3T_C}$

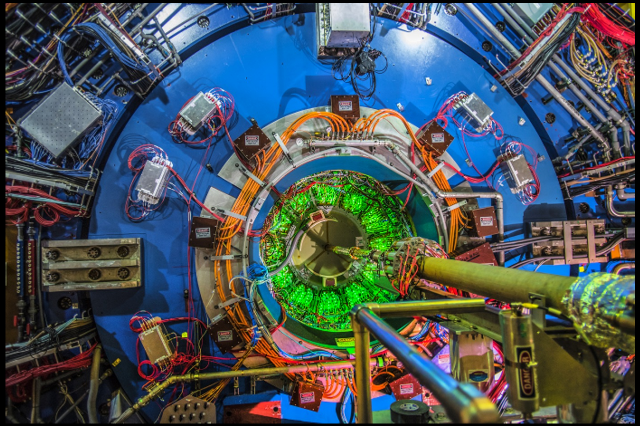
HotQCD: Phys.Lett.**<u>B795</u>**, 15(2019);
Phys. Rev. Lett. **<u>123</u>**, 062002(2019)

STAR DETECTOR SYSTEM



- Large acceptance
- Excellent PID & uniform efficiency
- Modest rates

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

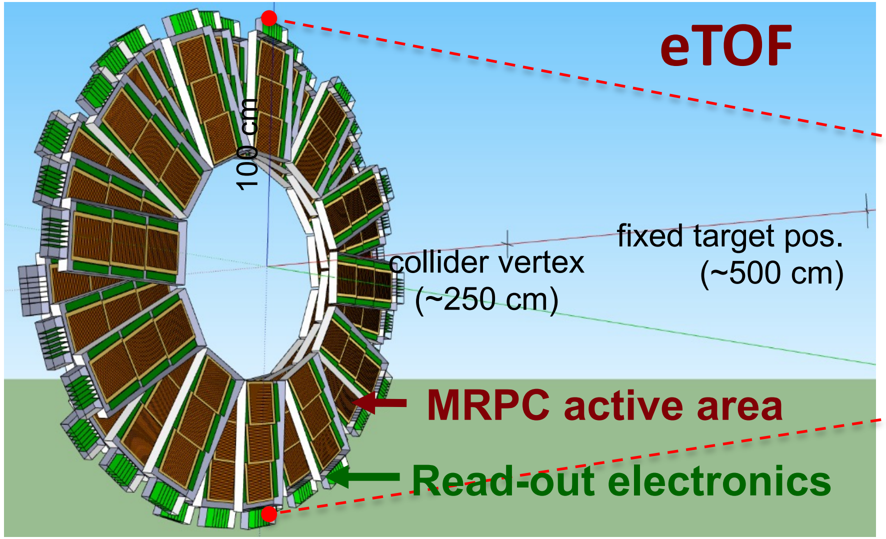
eTOF:
- Forward rapidity coverage
- PID at η = 0.9 to 1.6
- **Borrowed from CBM-FAIR**
- Ready in 2019

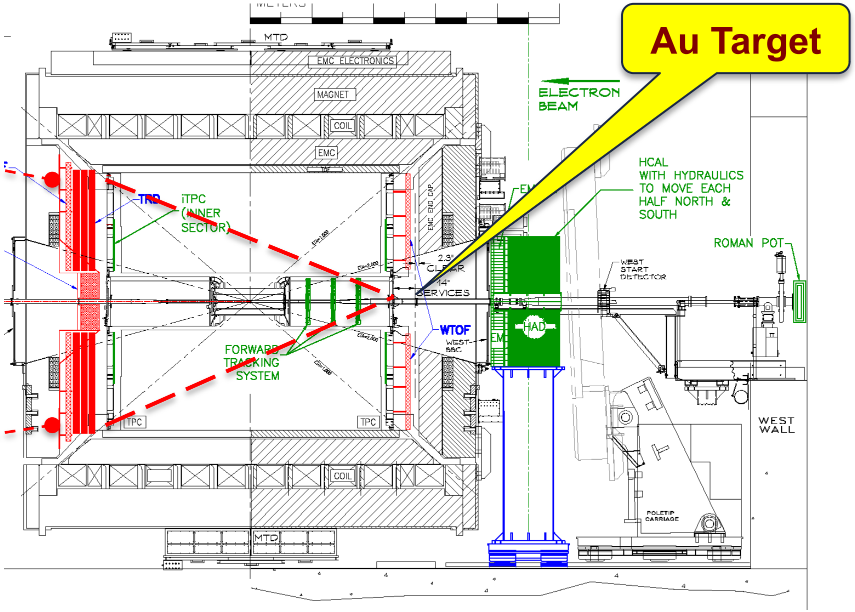
EPD:
- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

1) Enlarge rapidity acceptance
2) Improve particle identification
3) **Enhance centrality/event plane resolution**

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. NIM **A968,** 163970 (2020)

STAR Fixed Target Setup





CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**760 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

STAR BES-I and BES-II Data Sets

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	11.5 (70)	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	9.2 (44.5)	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	7.7 (31.2)	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M / **220**	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M/ **270 M**	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M / **116 M**	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M/ **145 M**	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	11.5	257 M/ **110 M**	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	9.2	160 M/ **78 M**	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	7.7	104 M / **45 M**	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	**260** + 2000 M	**760** MeV	-1.05	Run-18, 21

Most precise data to map the QCD phase diagram

$3 < \sqrt{s_{NN}} < 200$ GeV; $760 > \mu_B > 25$ MeV

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   - Collectivity and Baryon Correlation from FXT
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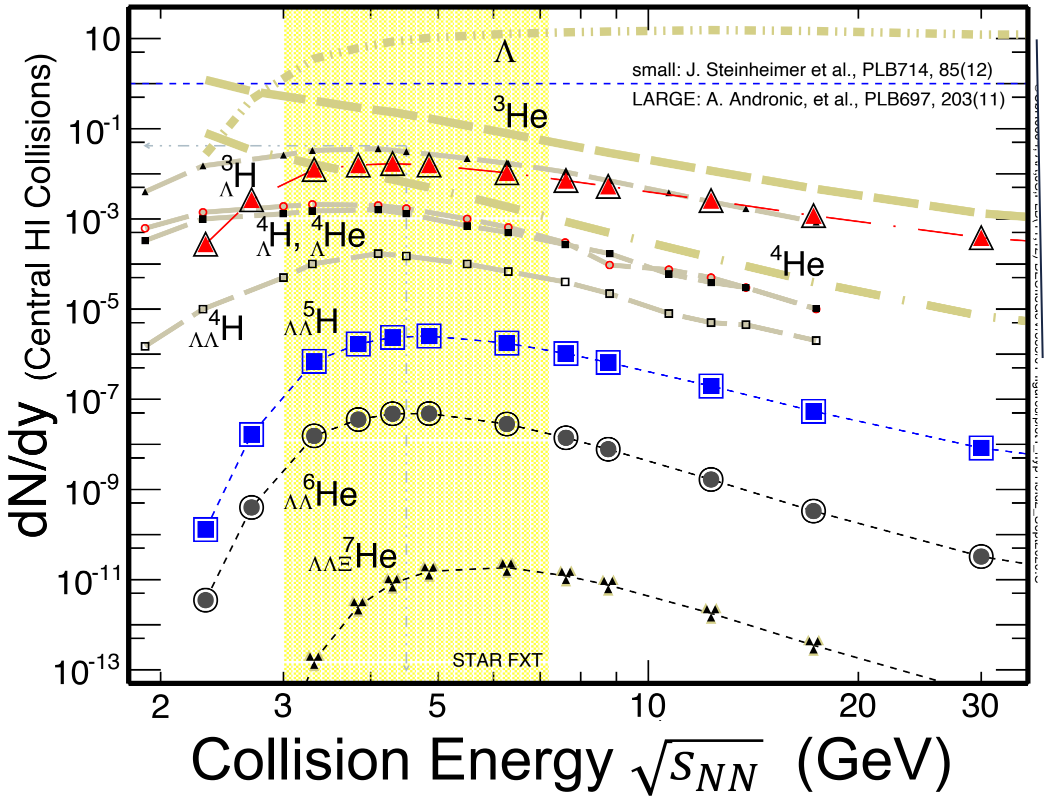
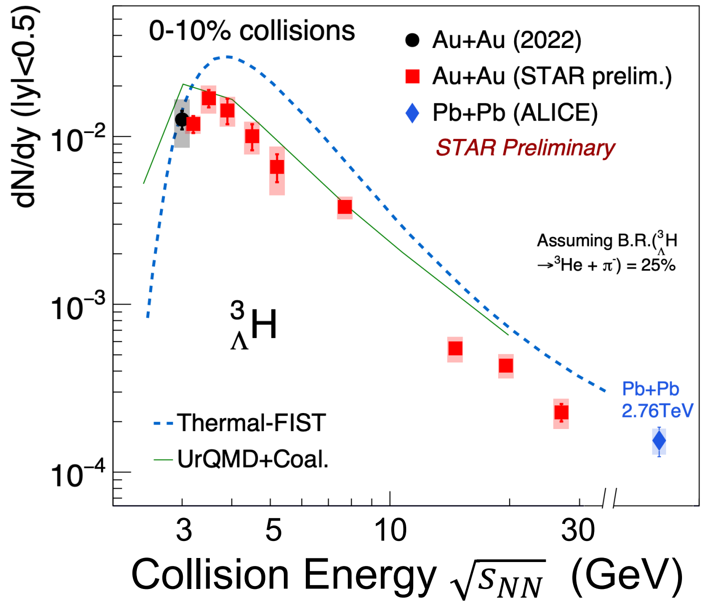
STAR FXT and High Baryon Density Region

A. Andronic *et al.* PL**B697**, 203(2011);
J. Steinheimer *et al.* PL**B714**, 85(2012)



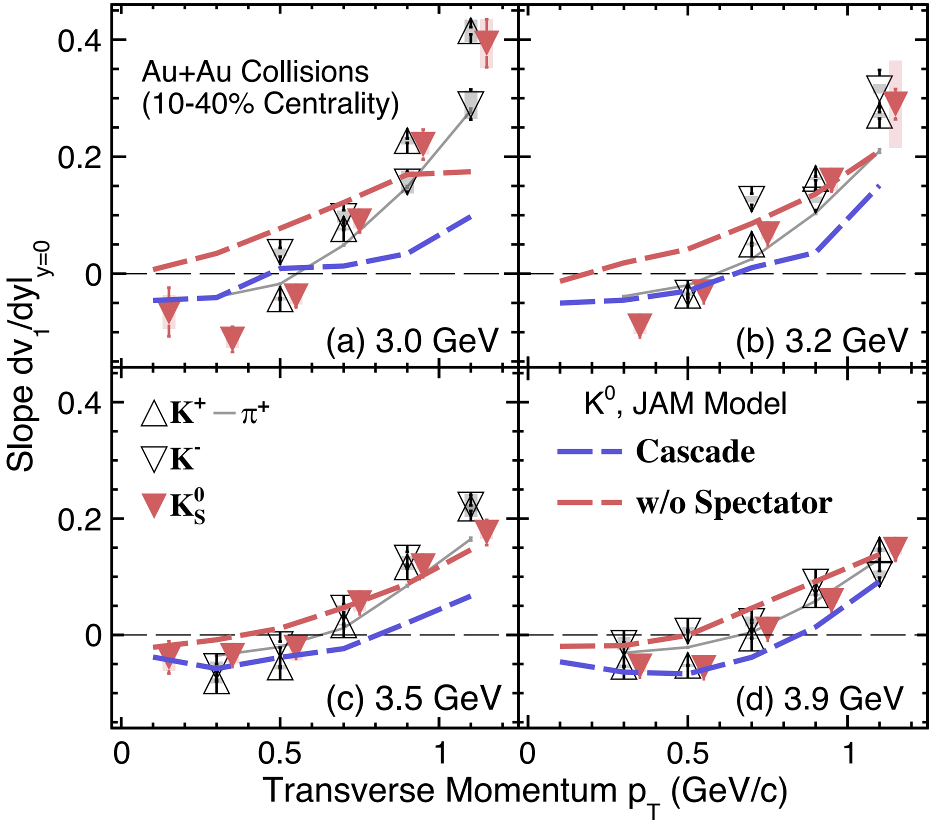
STAR: CPOD2024, SQM2024



1) Hypernucleus: $^{3}_{\Lambda}H$ yields versus energy: peaks at 3.2 GeV;
2) For $\sqrt{s_{NN}} < 10$ GeV, calculations from coalescence more consistent with data

Kaon Anti-Flow at High Baryon Density Region

STAR: CPOD2024, SQM2024



1) A systematic analysis of the p_T dependence of the neutral- and charged-Kaon v_1 from Au+Au collisions at $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV;

2) At $p_T < 0.6$ GeV, all mid-rapidity v1 slopes are negative. Kaon potential was proposed to explain the data, ref.[1,2];

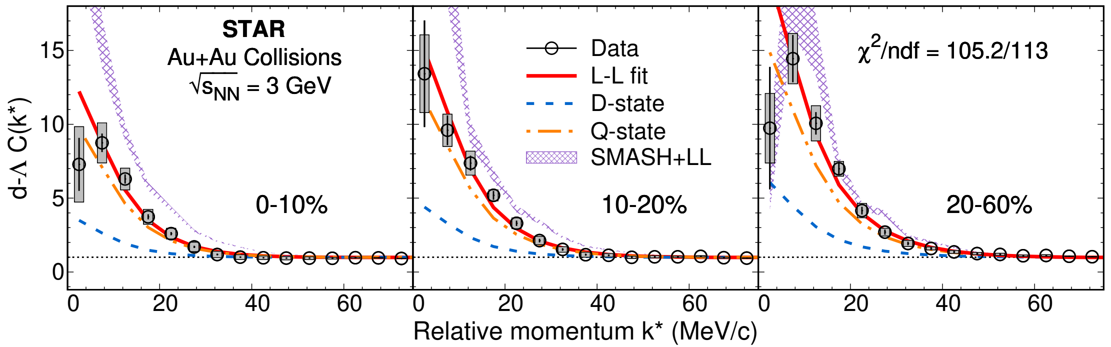
3) JAM model calculations suggest that spectator shadowing, similar to the case of elliptical v_2, plays important role for the negative v_1 slope parameter.

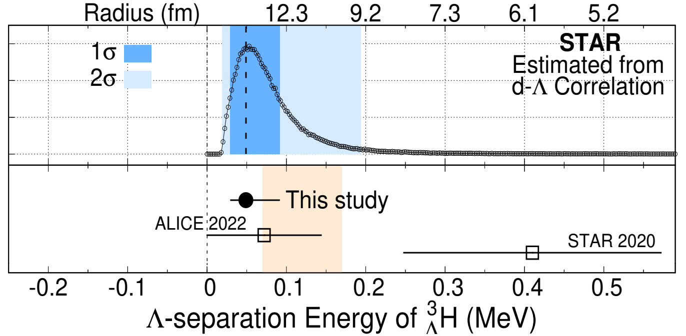
→ Spectator shadowing
→ No Kaon potential is needed

References:

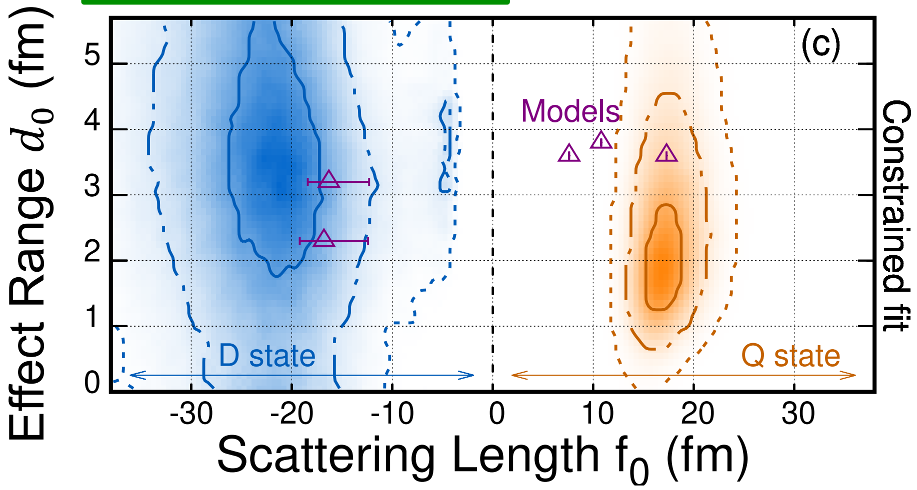
(1) P. Chung *et al.* (E895), PRL **85**, 940(2000);
(2) G.-Q. Li, C. M. Ko, and B.-A. Li, PRL **74**, 235 (1995) and S. Pal, C. M. Ko, Z.-W. Lin, and B. Zhang, PR **C62**, 061903(2000)

$d - \Lambda$ Correlation Functions 3.0 GeV





STAR: CPOD2024



1) Centrality dependence of the $d - \Lambda$ correlation functions from 3.0 GeV Au+Au collisions;
2) For the first time, spin dependent states, *D and Q*, identified experimentally!

→ **New window for studying 3-body interactions in the laboratory**

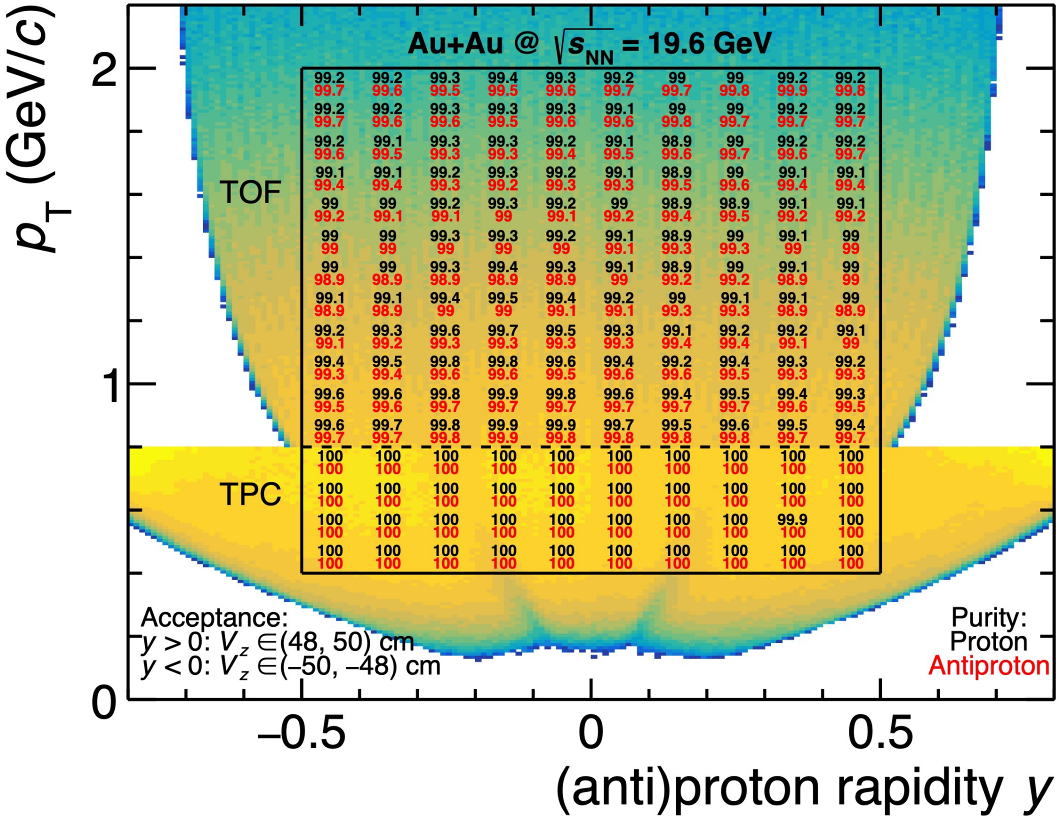
References:

(1) J.M. Lattimer and M. Prakash, Science **304**, 536 (2004);
(2) M. Kohno and H. Kamada, arXiv:2406.13899;
(3) H. W. Hammer, Nucl. Phys. **A705**,173 (2002)

High Moments from BES-II

Precision Measurements of (Net-)Proton Number Fluctuations in Au+Au Collisions at RHIC (STAR Collaboration)

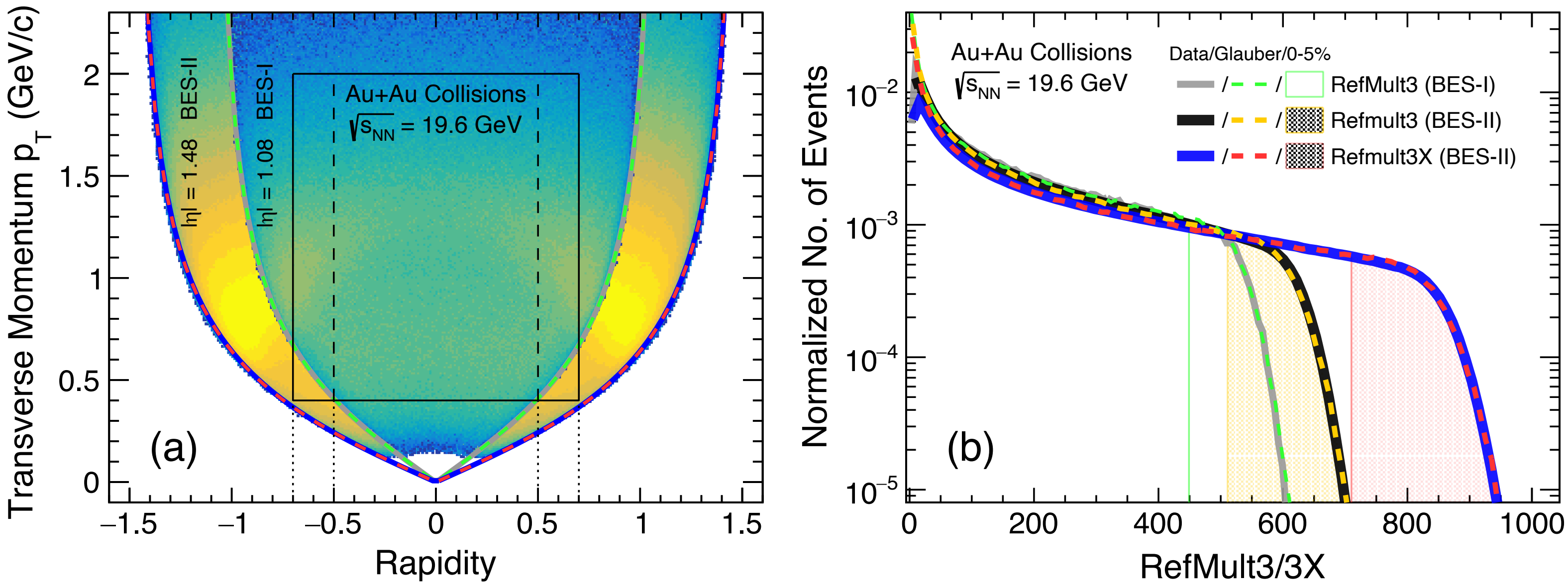
Proton Identification at BES-II



Detector	TPC	TPC+TOF
dE/dx	$\|n\sigma\| < 2$	
m^2 $(GeV/c^2)^2$	NA	0.6 – 1.2
p_T (GeV/c)	0.4 – 0.8	0.8 – 1.2
rapidity	$\|y\| < 0.5$	

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

BES-II: Centrality Determination

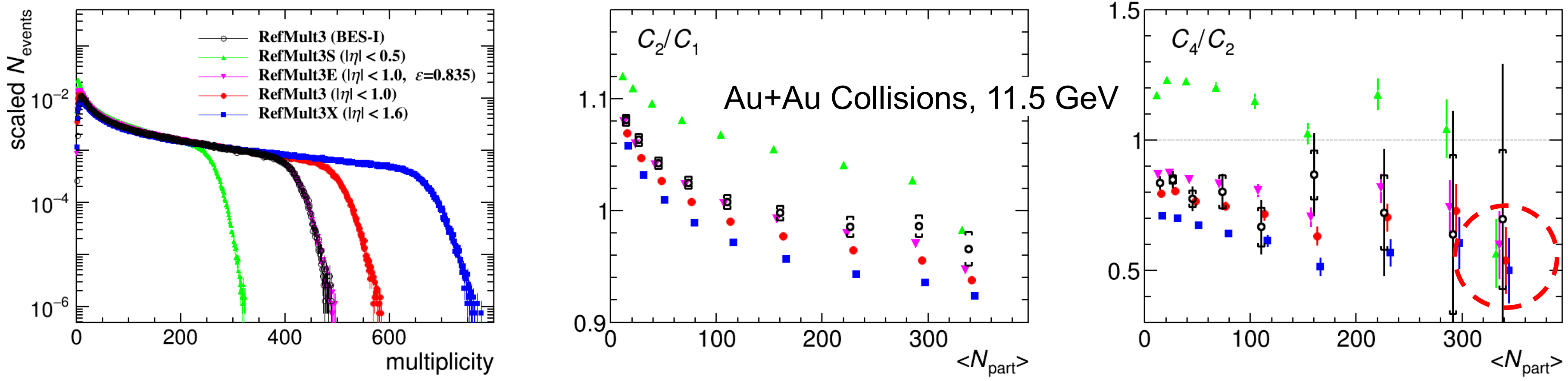


Reference multiplicity measurements **RefMult3**: *TPC measured charge particles except (anti-)protons*

1) RefMult3: (| η |<1.0) for both BES-I and BES-II **2) RefMult3X: (| η |<1.6)** for BES-II

→ Larger acceptance → larger multiplicity → better centrality resolution

BES-II: Centrality Determination



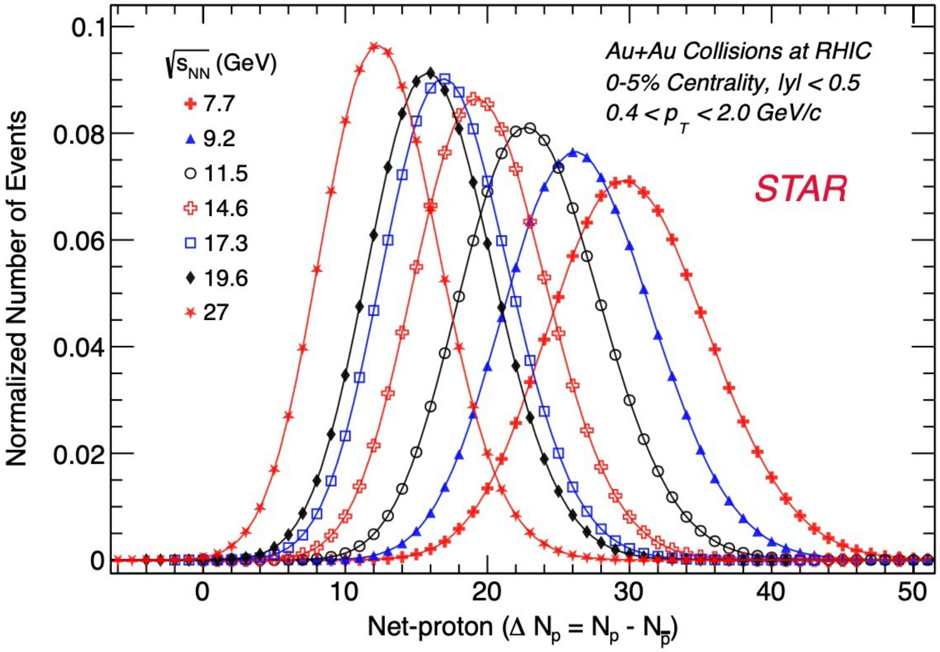
1) Blue squares: BES-II **RefMult3X (| η |<1.6)**
2) Red dots: BES-II **RefMult3 (| η |<1.0)**
3) Pink triangles: BES-II **RefMult3*0.835 (| η |<1.0)** ~ BES-I
4) Black circles: BES-I **RefMult3 (| η |<1.0)**

→ Larger acceptance → larger multiplicity → better centrality resolution!

→ Minimum changes in the C_4/C_2 from the most central collisions

(1) PBM, A. Rustamov and J. Stachel, Nucl. Phys. **A960**, 114(2017); (2) A. Bialas, M. Bleszynski and W. Czyz, Nucl. Phys. **B111**, 461 (1976)

Net-p from BES-II



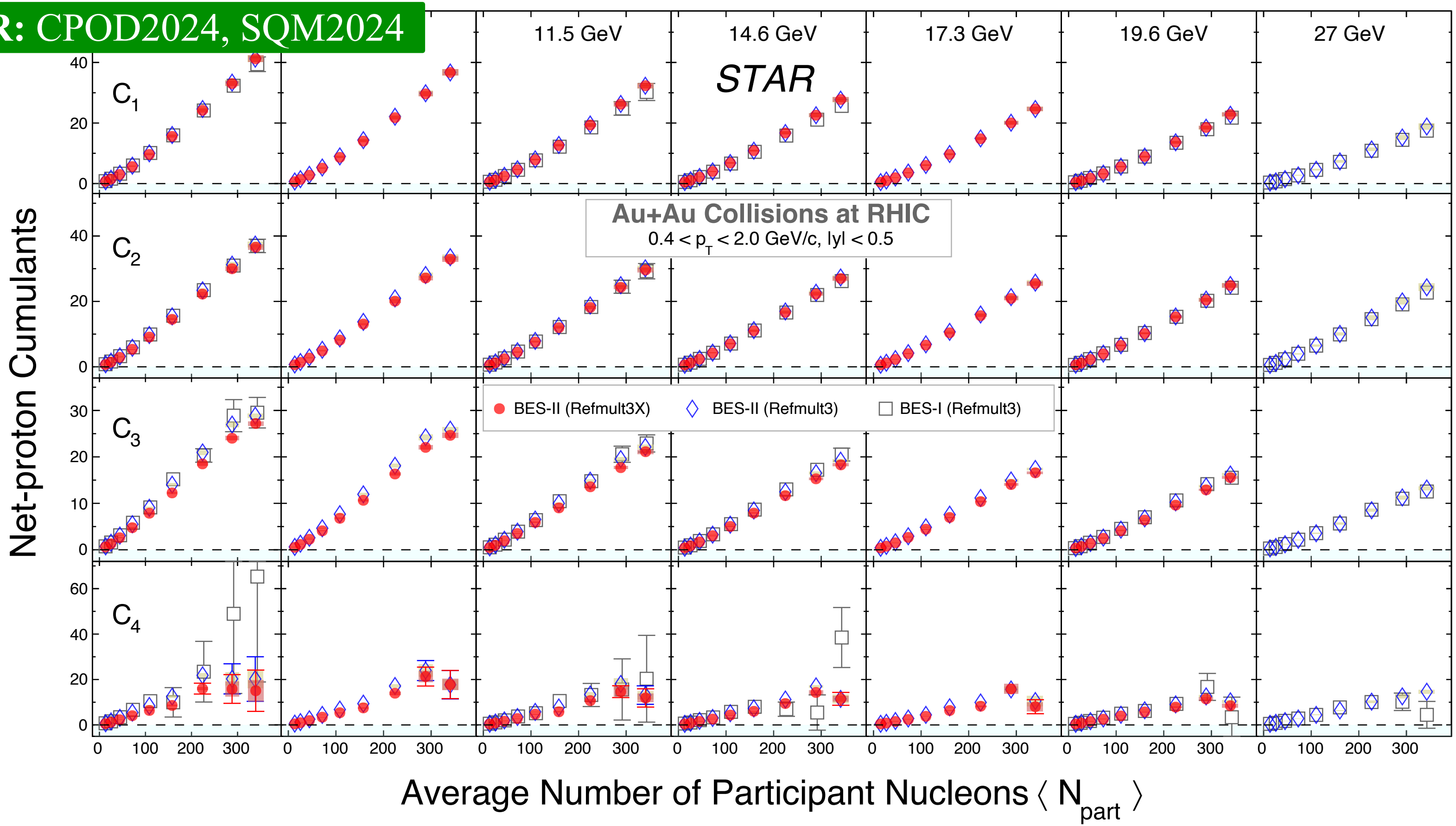
STAR: CPOD2024, SQM2024

1) Raw number distributions from BES-II: Uncorrected for detector efficiency;
2) Mean increases with decreasing collision energy: Effect of baryon stopping;
3) The increase in the width is due to the increase of proton numbers at lower energy

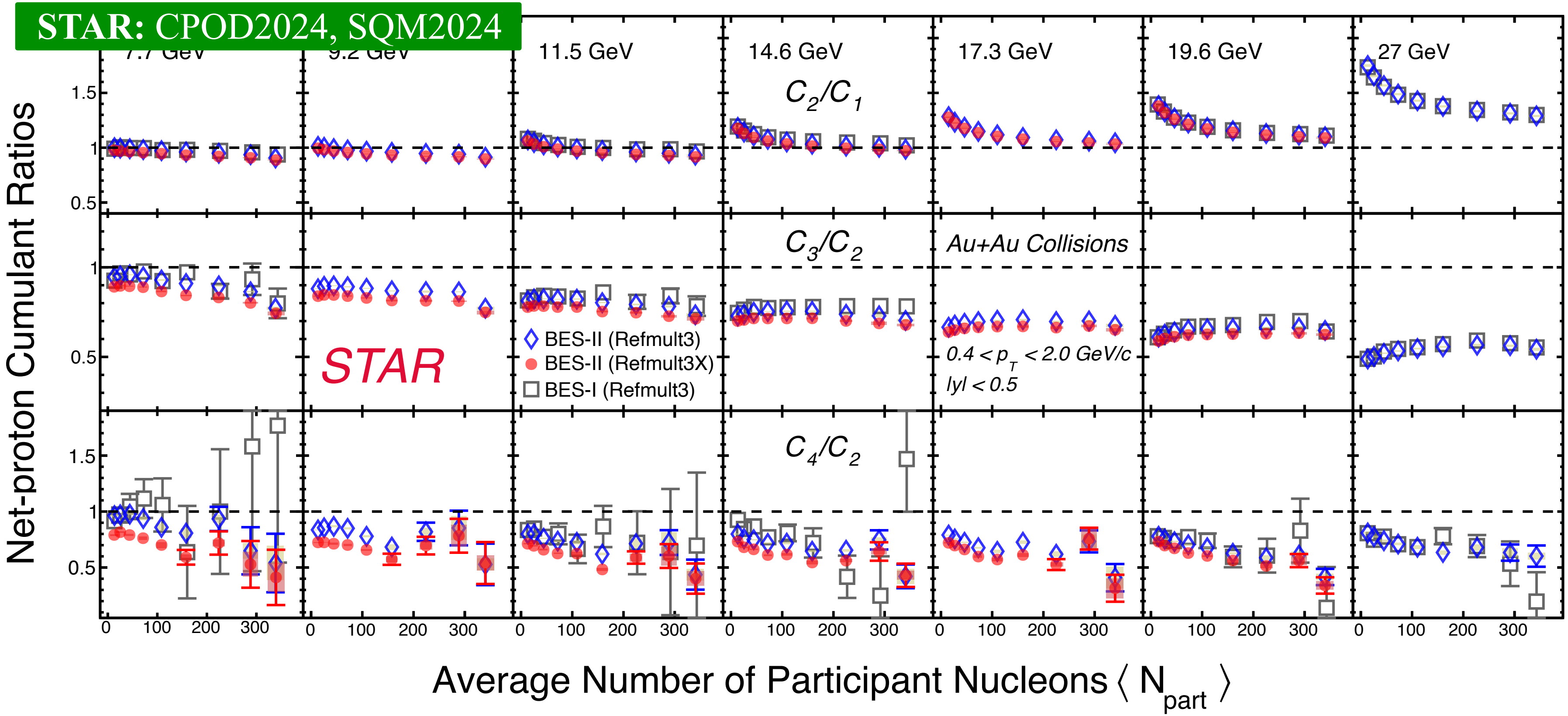
0-5%: C_4/C_2 improvement factor BES-II / BES-I			
7.7 GeV		19.6 GeV	
Stat.	Syst.	Stat.	Syst.
4.7	3.2	4.5	4
*Embedding statistics increased by a factor of 5!			

Cumulants of Net-p from BES-II

STAR: CPOD2024, SQM2024

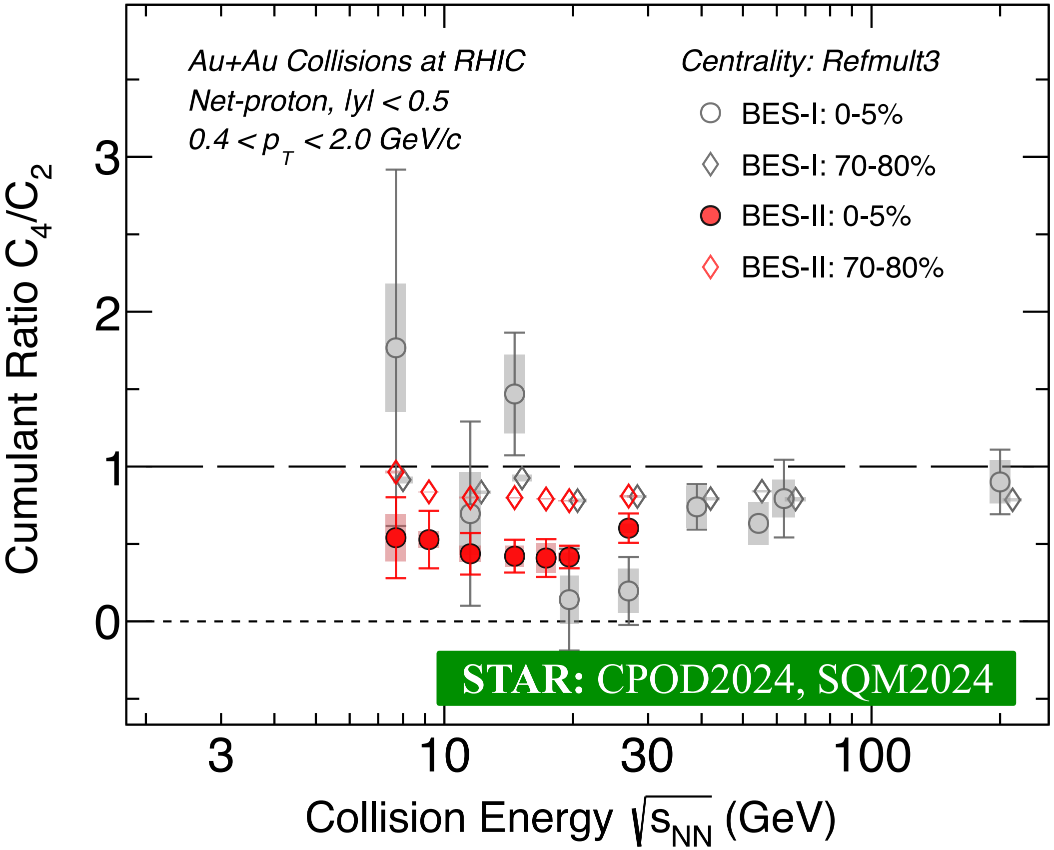


Net-p Cumulant Ratios



In 0-5% central collisions, values of C_4/C_2 are consistent among BES-I and BES-II

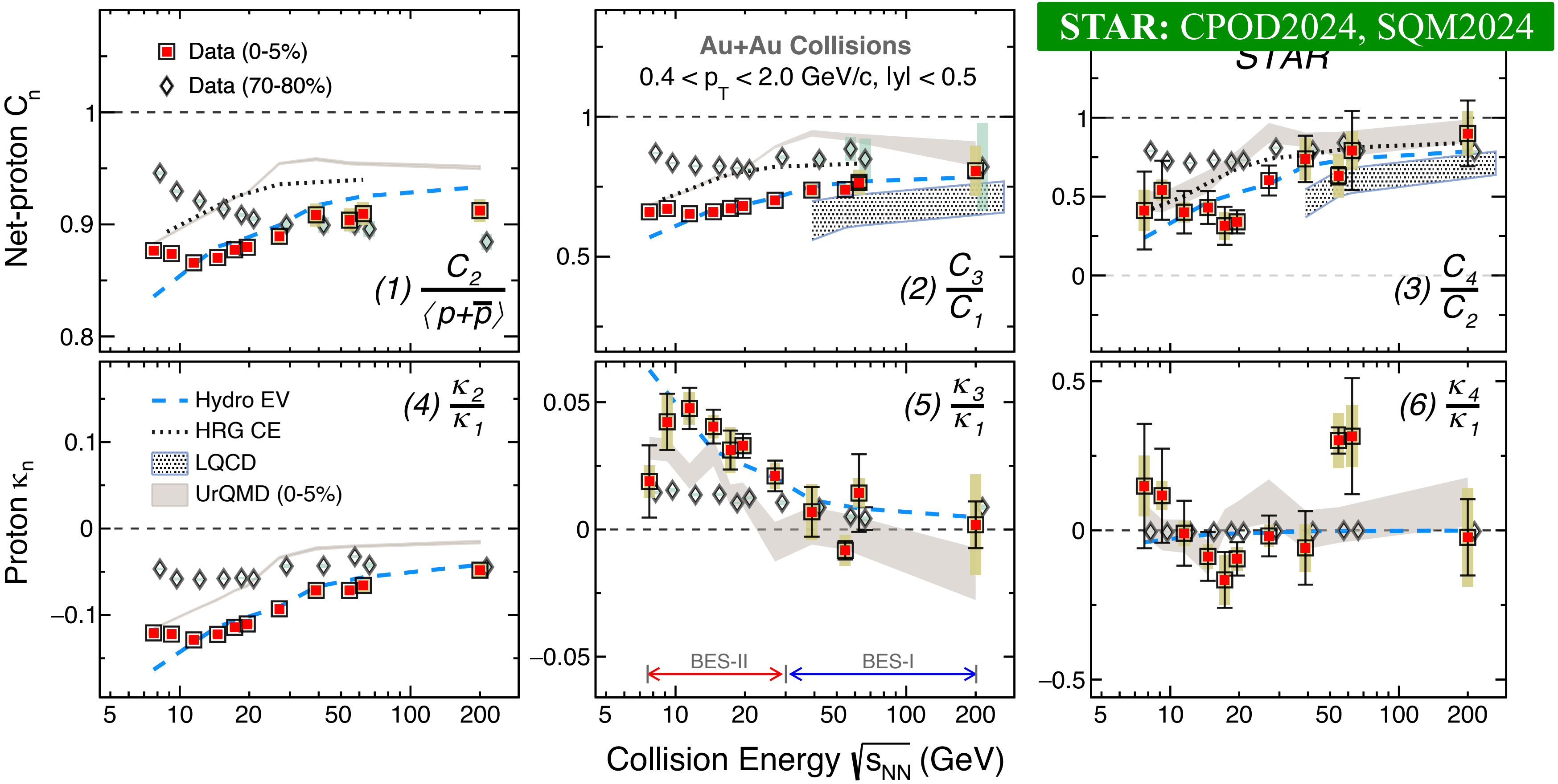
Cumulant Ratios from BES-II and BES-I



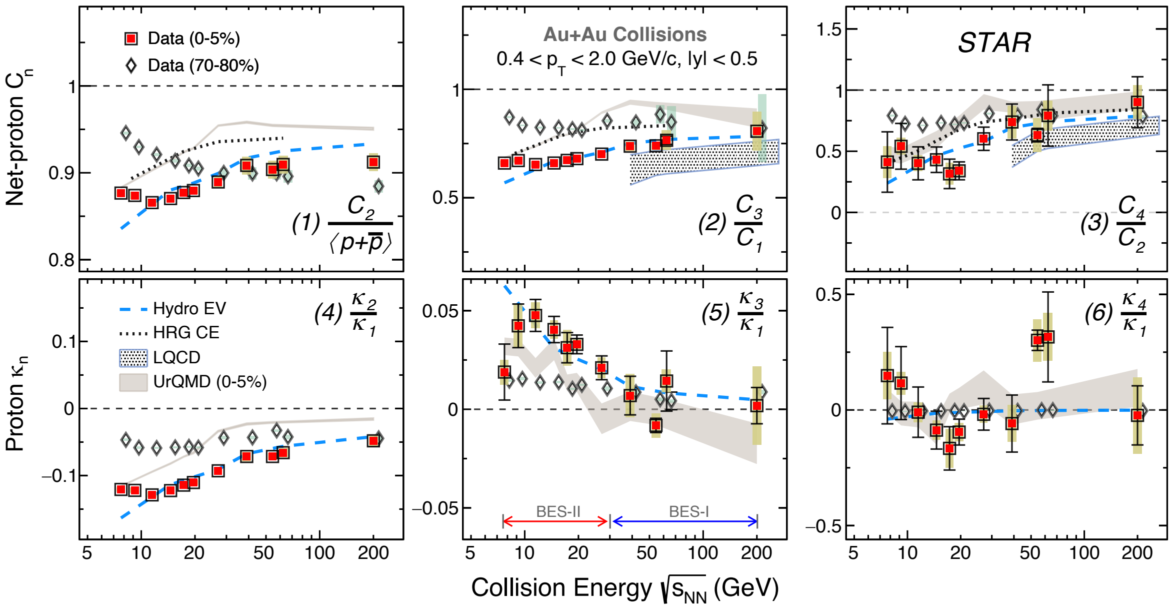
$\sqrt{s_{NN}}$ (GeV)	0-5%	70-80%
7.7	1.0σ	0.9σ
9.2	-	-
11.5	0.4σ	1.3σ
14.6	2.2σ	2.5σ
19.6	0.7σ	0.0σ
27	1.4σ	0.2σ

→ **BES-II and BES-I results are consistent!**

Cumulant and Factorial Cumulant Ratios



Cumulant and Factorial Cumulant Ratios



1) UrQMD: hadronic transport and the results are analyzed in the same way as data. S. Bass *et al.*, Prog. Part. Nucl. Phys., **41**, 255 (1998);

2) HRG CE: P.B. Munzinger *et al.* Nucl. Phys. **A1008**, 122141(2021);

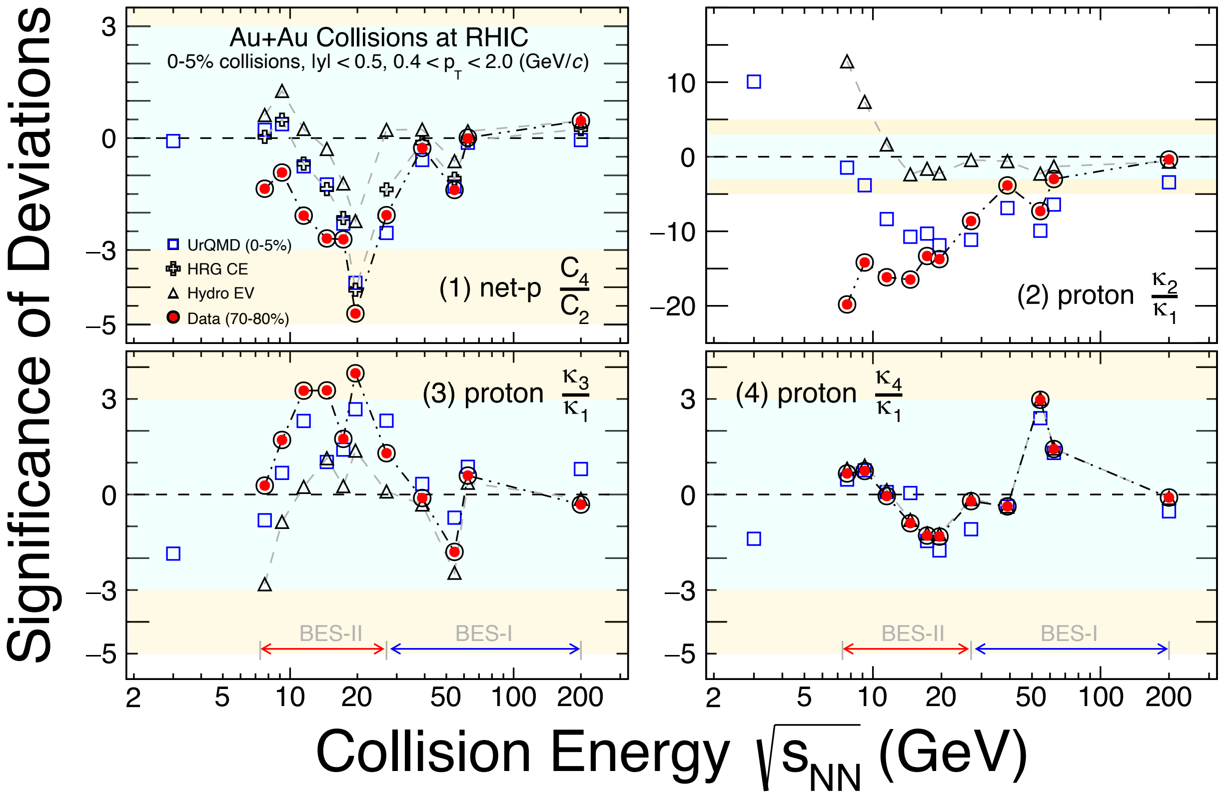
3) Hydro: HRG CE + EV collectivity. V. Vovchenko *et al.*, Phys. Rev. **C105**, 014904 (2022).

4) LQCD: done for net-baryon A. Bazavov *et al.*, Phys. Rev. D101, 074502 (2020).

→ Baryon conservation in all model calculations;

→ All κ_i/κ_1 ratios show clear non-monotonic dependence for proton while anti-protons are close to zero

Comparison with Model Calculations



0-5% central collisions:

1) C_4/C_2 ratios: show minima at 19.6 GeV, 2-5σ depends on reference;
2) All κ_i/κ_1 ($i = 2-4$) ratios show oscillation pattern and suppression for higher order ratios

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Summary

1) Rich physics at large μ_B region:

- Strangeness and EOS;
- Hypernuclei production;
- Baryon correlations;
- …

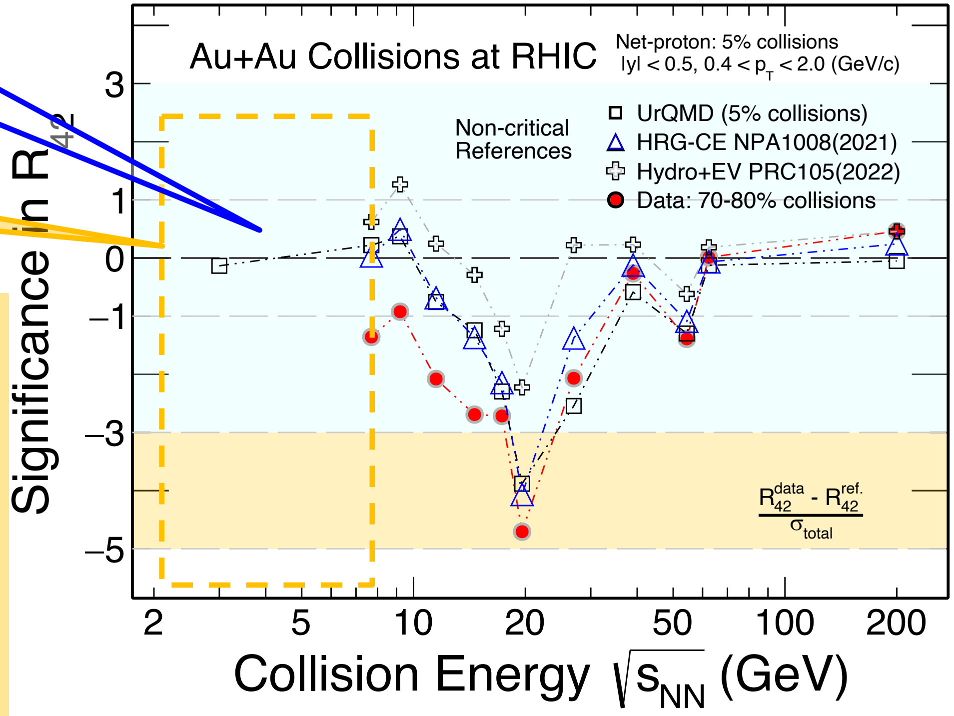
2) QCD critical point:

- BES-II data offered high statistics, better acceptance, centrality resolution and systematic;
- Will do (i) p_T and rapidity scan; (ii) C_5, and C_6 analysis; (iii) complete the FXT data ($\sqrt{s_{NN}}$ = 3 – 3.9 GeV)

Summary

*Predictions on CP at 650 MeV ~ 4 GeV

STAR FXT
HADES
CBM (2028)



"In summary, … Dynamic model calculations including the criticality in needed in order to understand the results from BES-II. On the experiment side, data between $\sqrt{s_{NN}}$ = 3.0 and 8.0 GeV is needed in order to search for the signals of QCD critical point and the 1st-order phase boundary."

* M. Hippert, *et al.*, 2309.00579; X. An *et al.*, NP **A1017** (2022) 122343; W.J. Fu, *et al.*, 2308.15508; F. Gao *et al.*, PR **D104**, (2021) 054022

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// BLUE: Theory // **RED**: Exp. //

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Thank you for your attention!