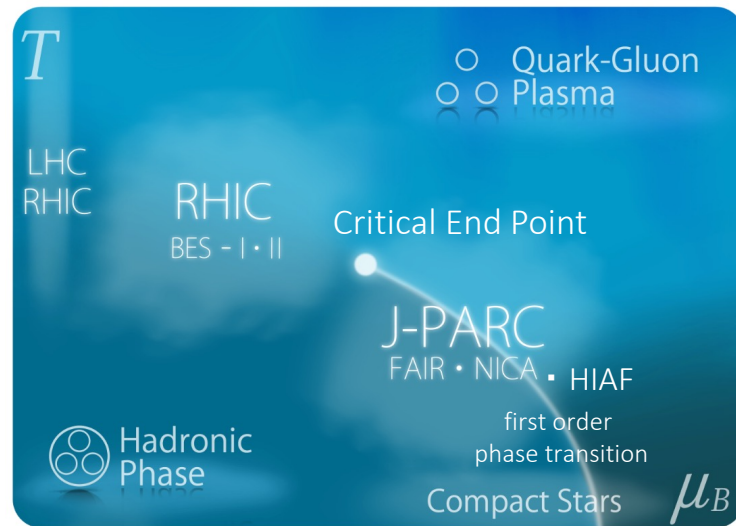




Recent results from Beam Energy Scan Program at RHIC



Shinichi Esumi, University of Tsukuba,
Institute of Physics, Faculty of Pure and Applied Sciences,
Tomonaga Center for the History of the Universe (TCHoU)



The STAR experiment

at the Relativistic Heavy Ion Collider, Brookhaven National Laboratory



筑波大学

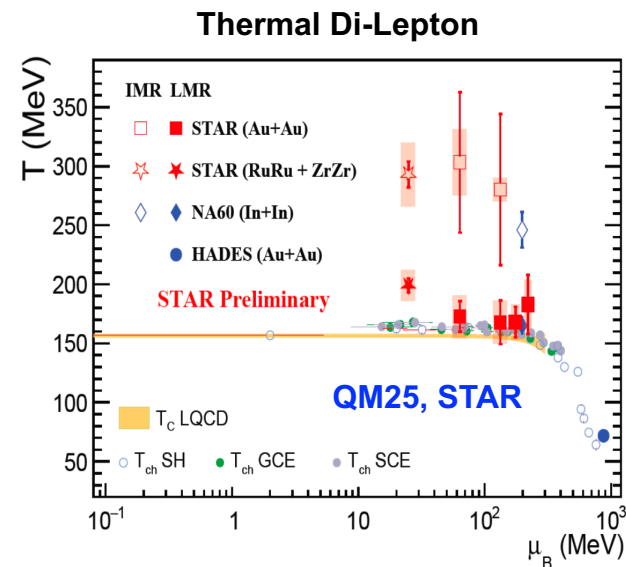
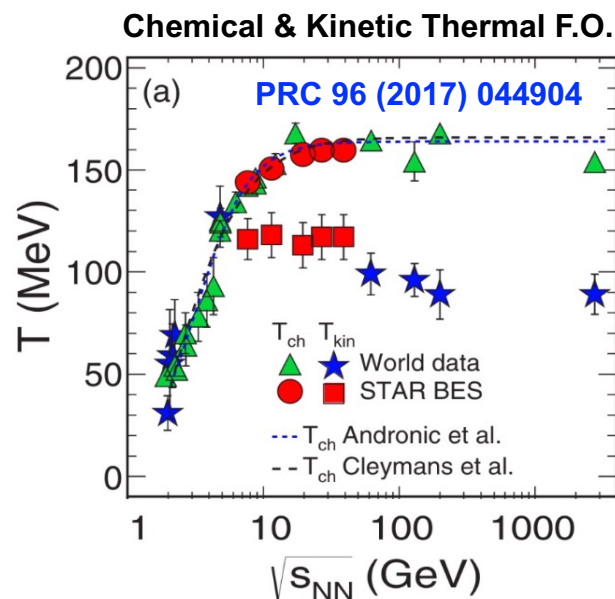
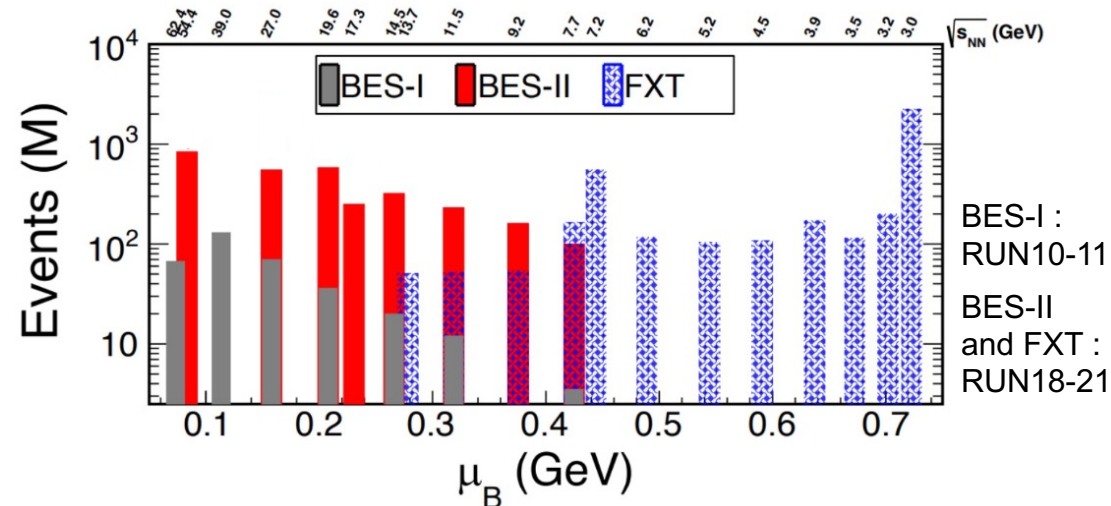
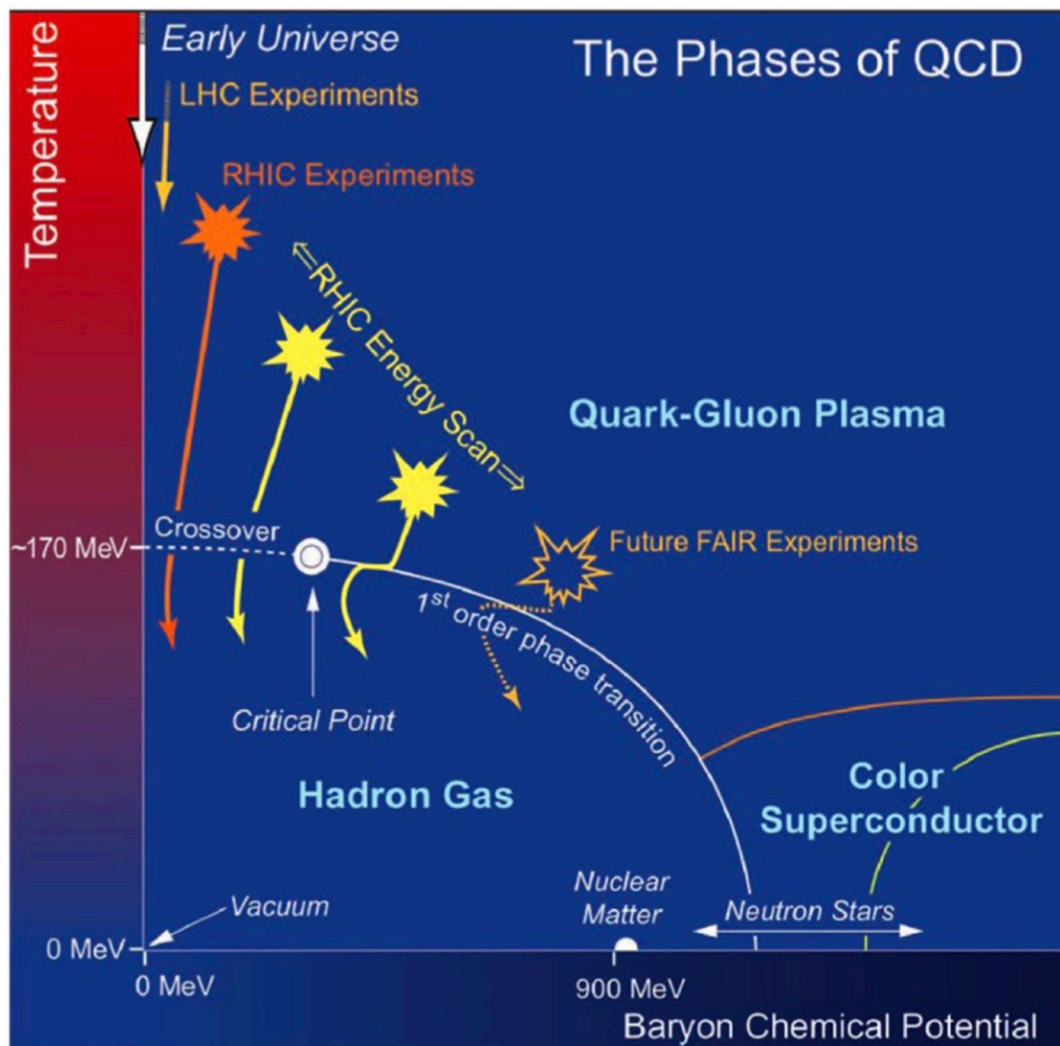
宇宙史研究センター

Tomonaga Center for the History of the Universe

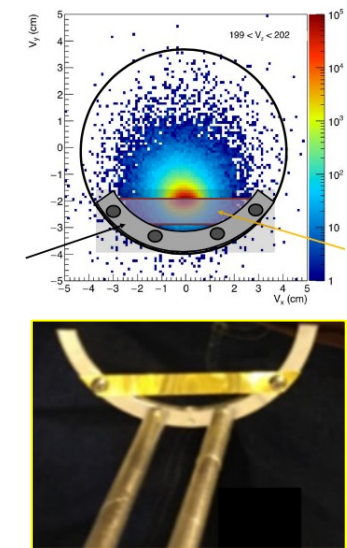
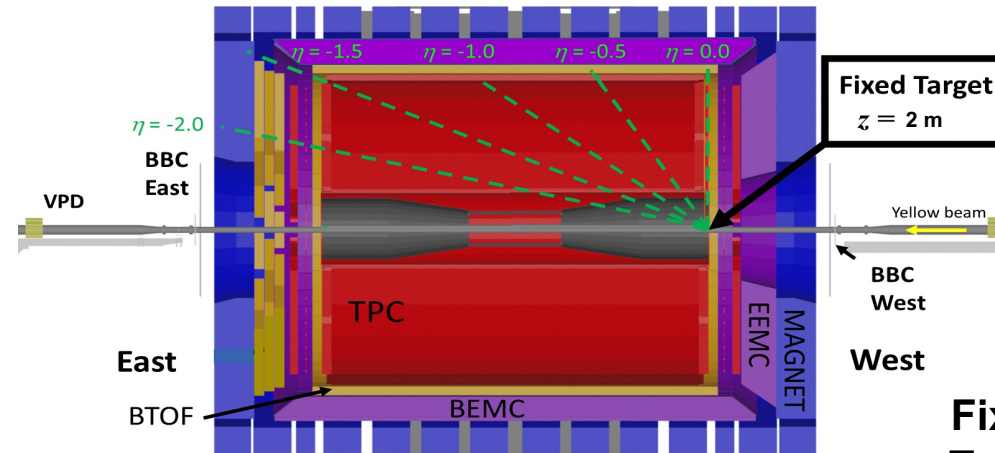


筑波大学
University of Tsukuba

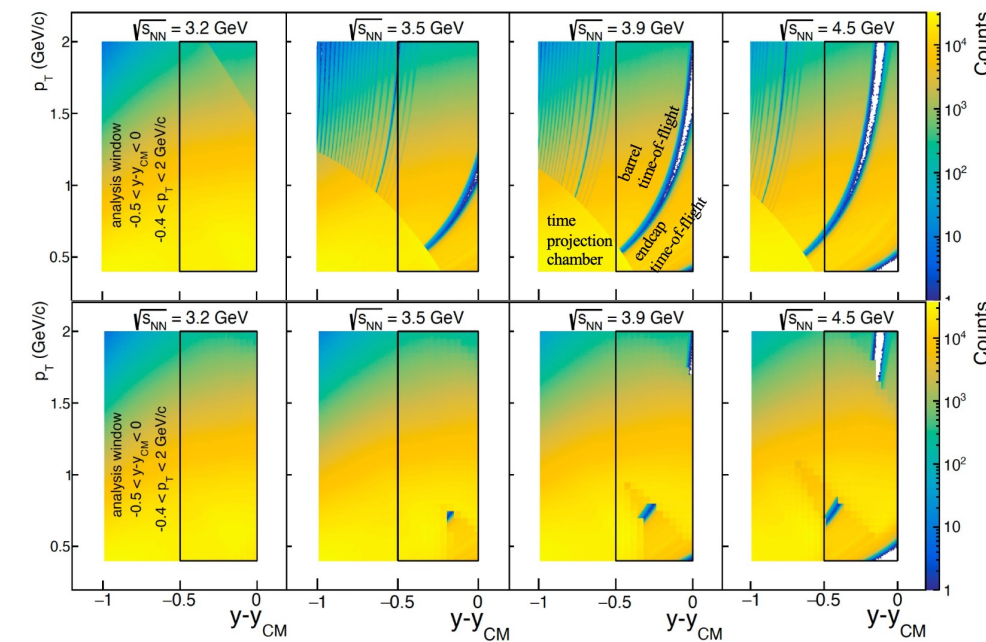
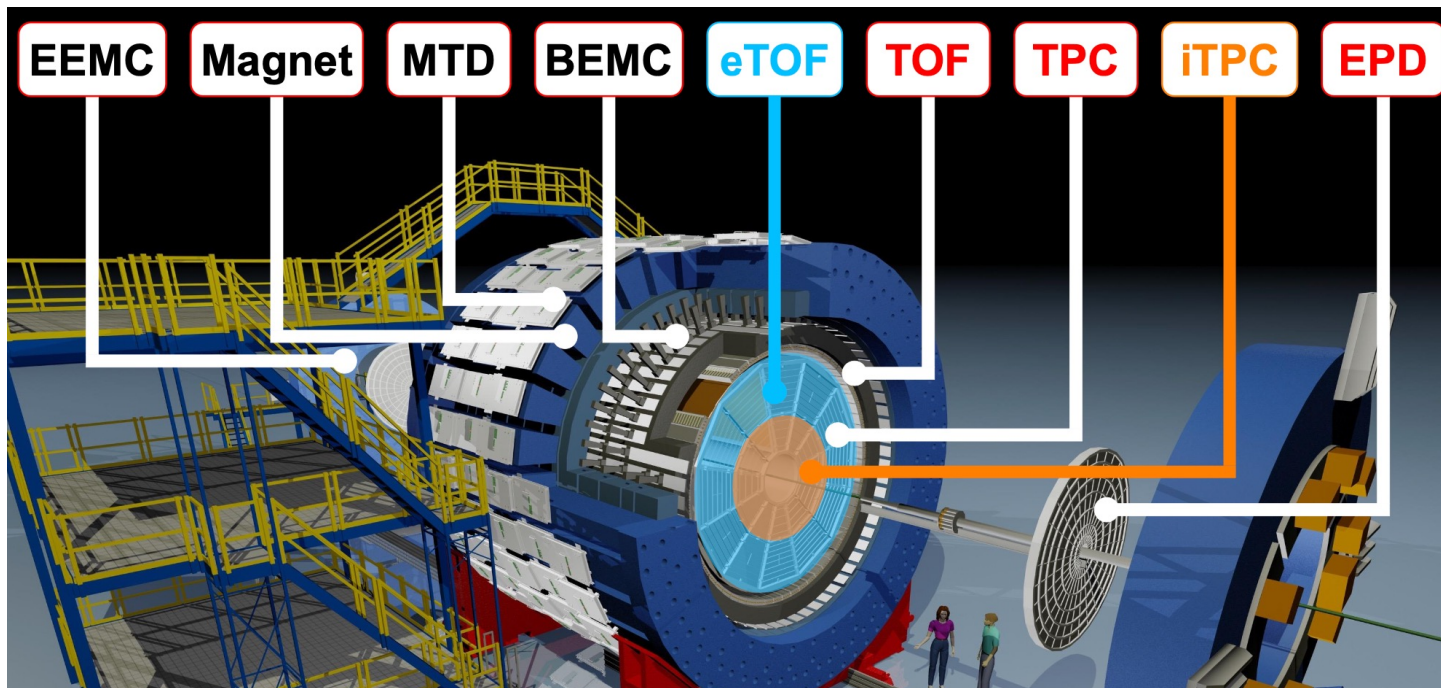
Beam Energy Scan Program at RHIC (from BES-I to BES-II)



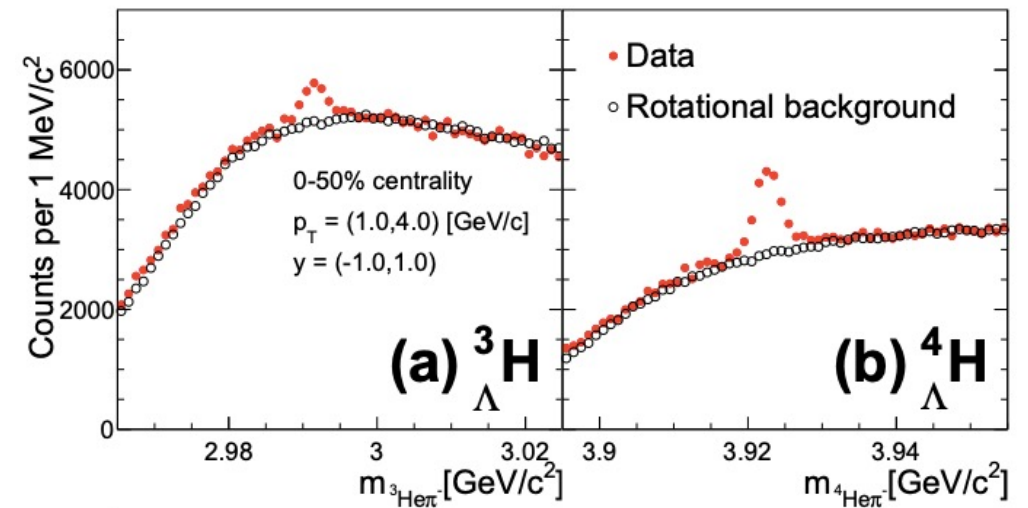
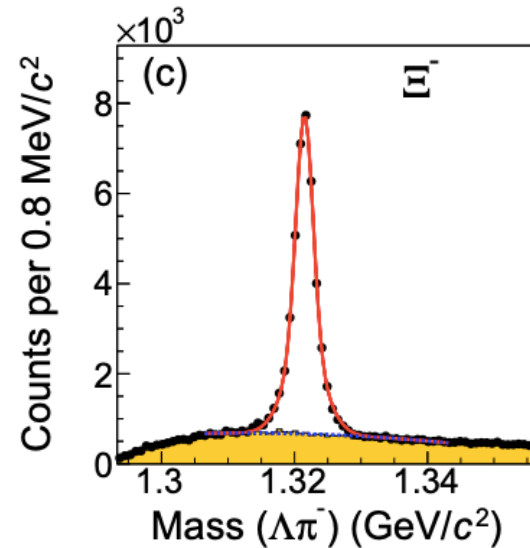
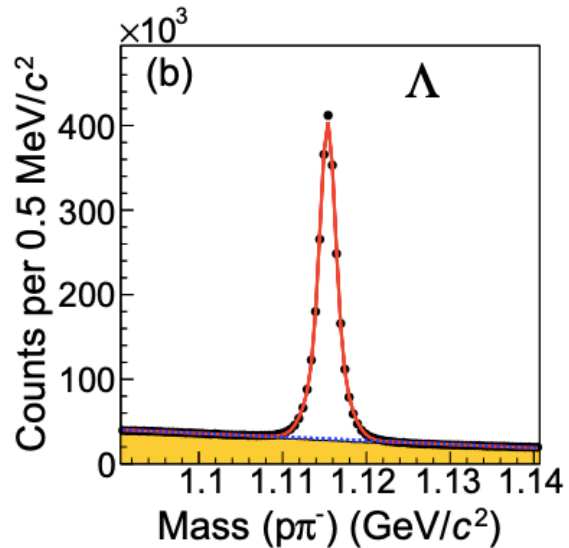
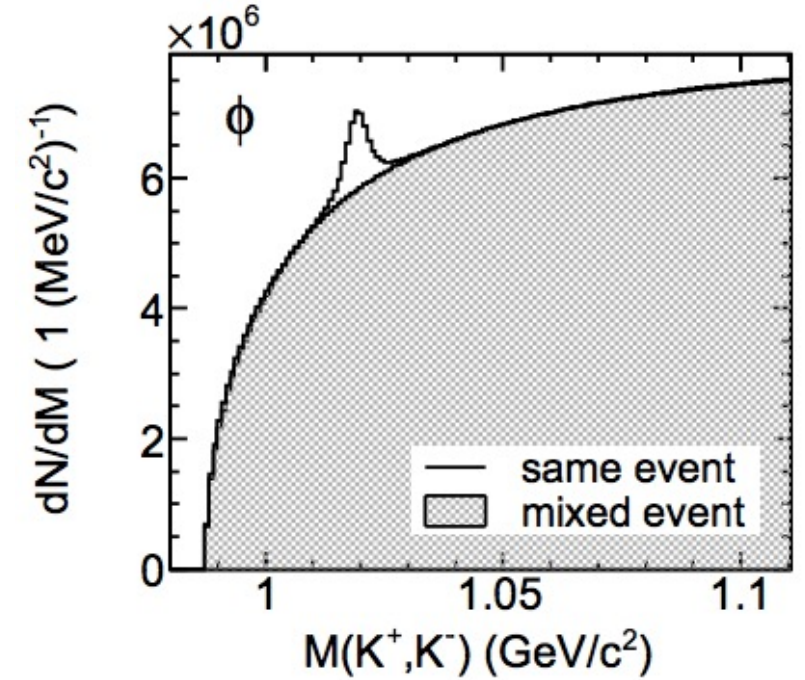
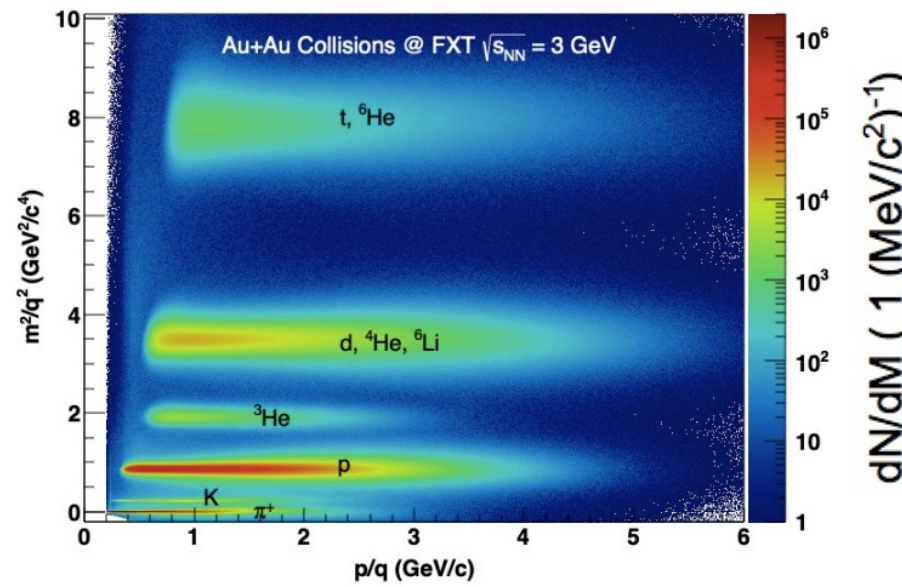
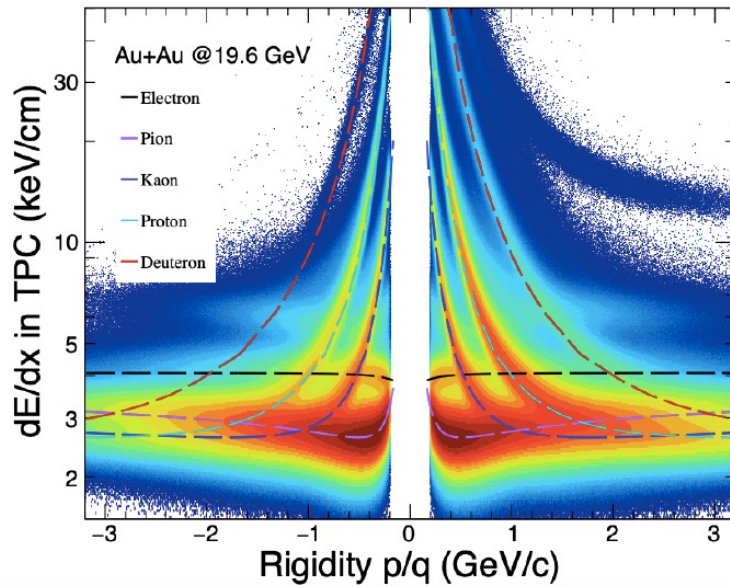
STAR experimental setup (COL/FXT)



Fixed Target at STAR



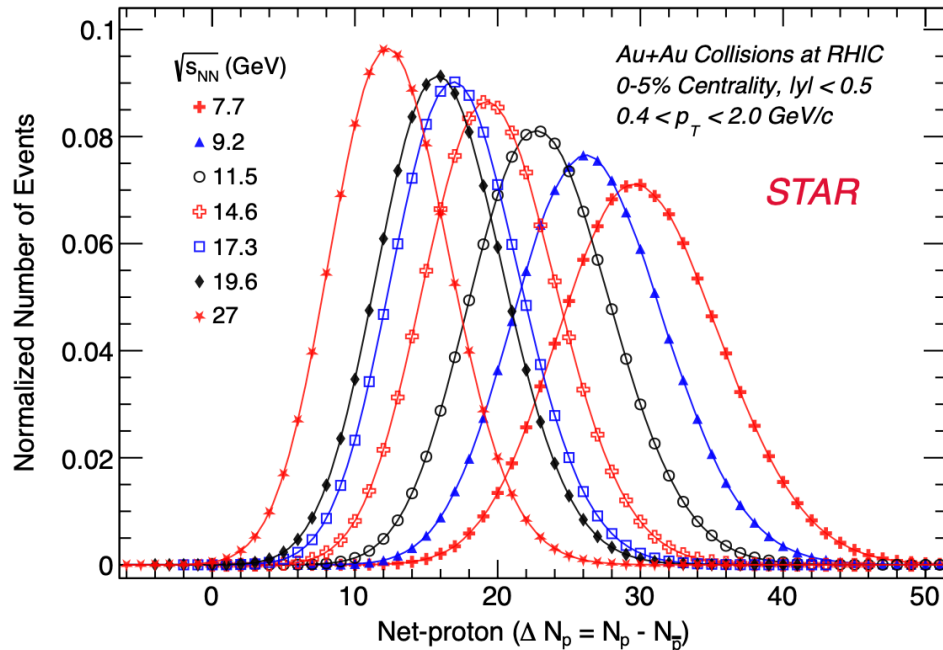
Particle identification in STAR



Net-proton kurtosis

At critical point with an infinite system

- correlation length should diverge
- susceptibilities should diverge



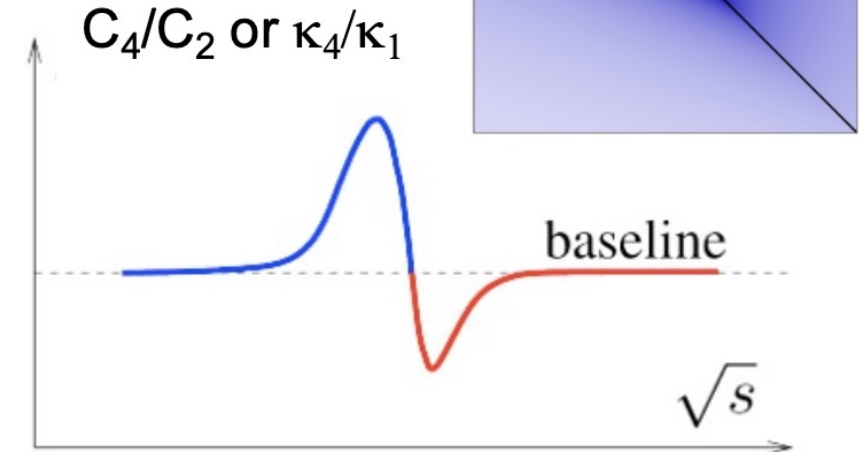
Proposed Experimental Observables:

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

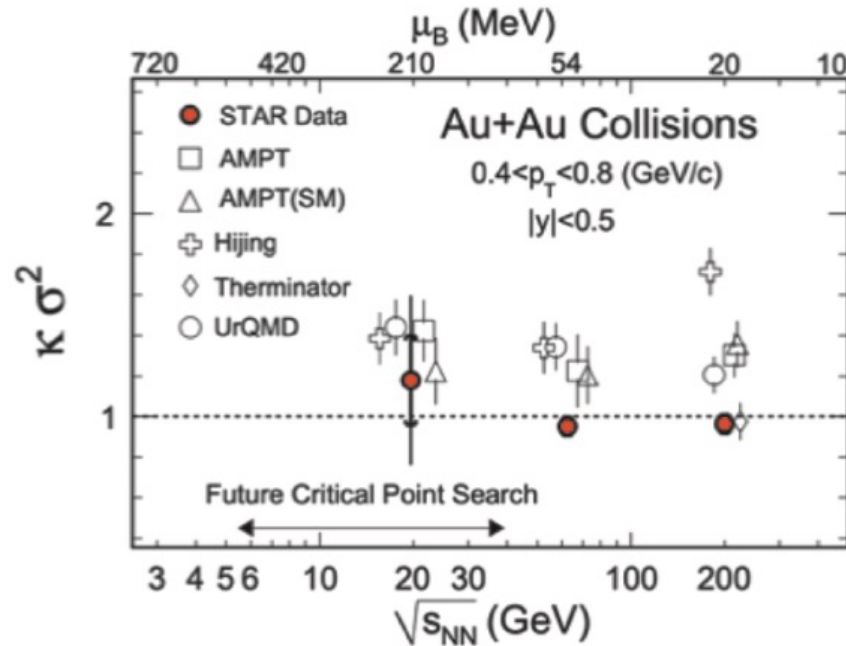
mean : $M = \langle N \rangle$	$= C_1,$
variance : $\sigma^2 = \langle (\delta N)^2 \rangle$	$= C_2,$
skewness : $S = \langle (\delta N)^3 \rangle / \sigma^3$	$= C_3 / C_2^{3/2},$
kurtosis : $\kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3$	$= C_4 / C_2^2.$

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

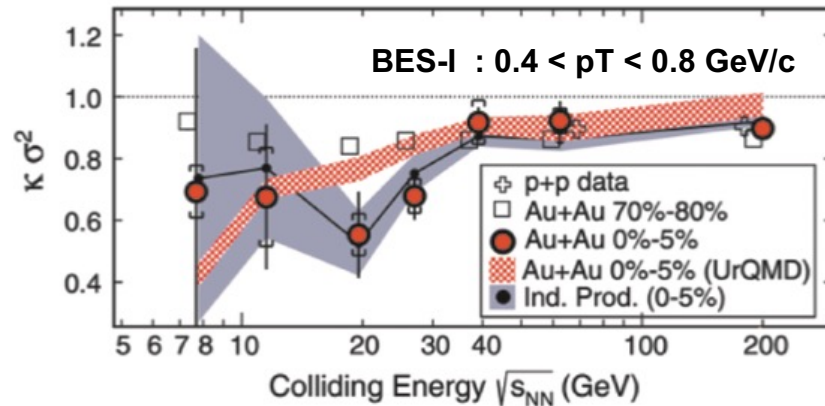


M. A. Stephanov, PRL 102 (2009) 032301

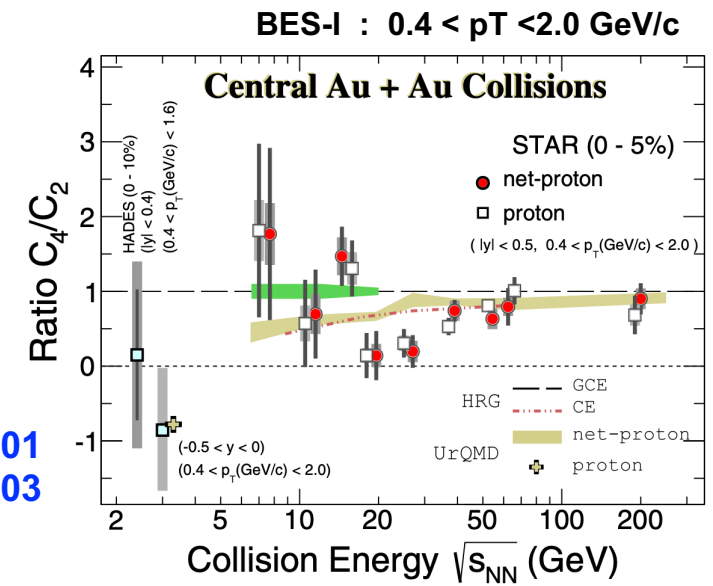
History of net-proton kurtosis results in STAR



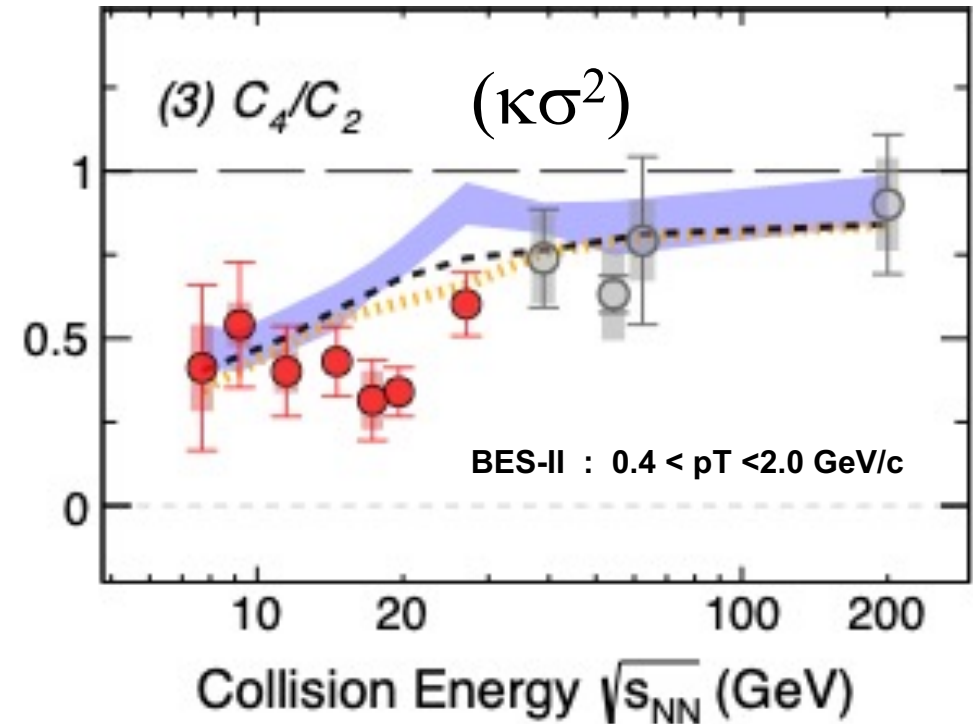
PRL 105
(2010) 022302



PRL 112
(2014) 032302



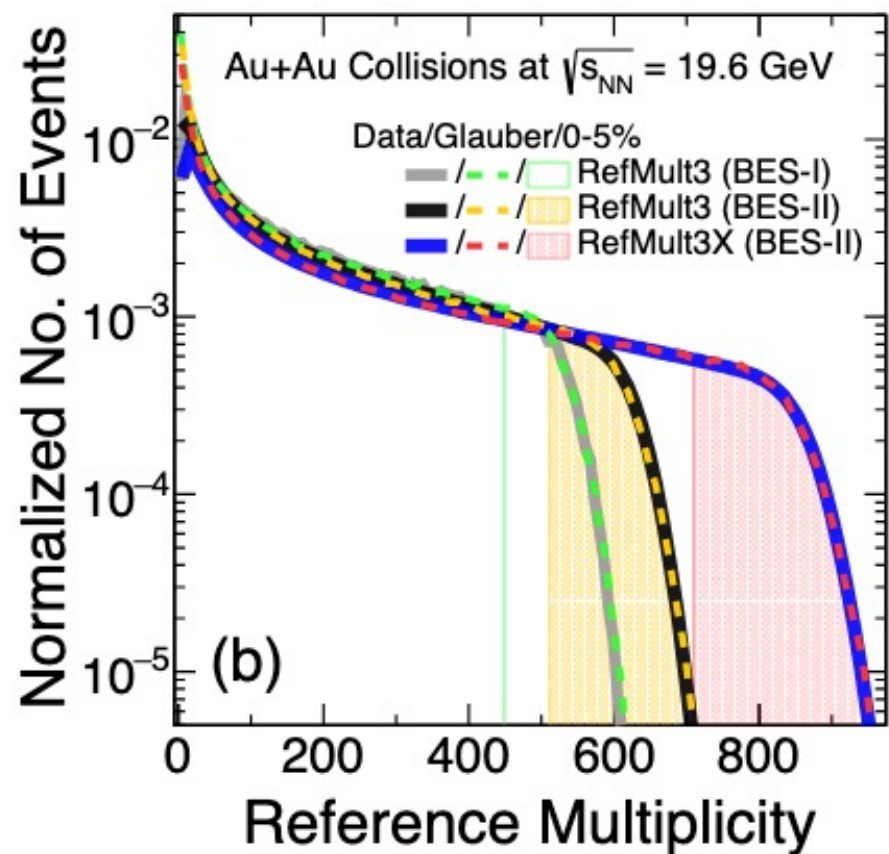
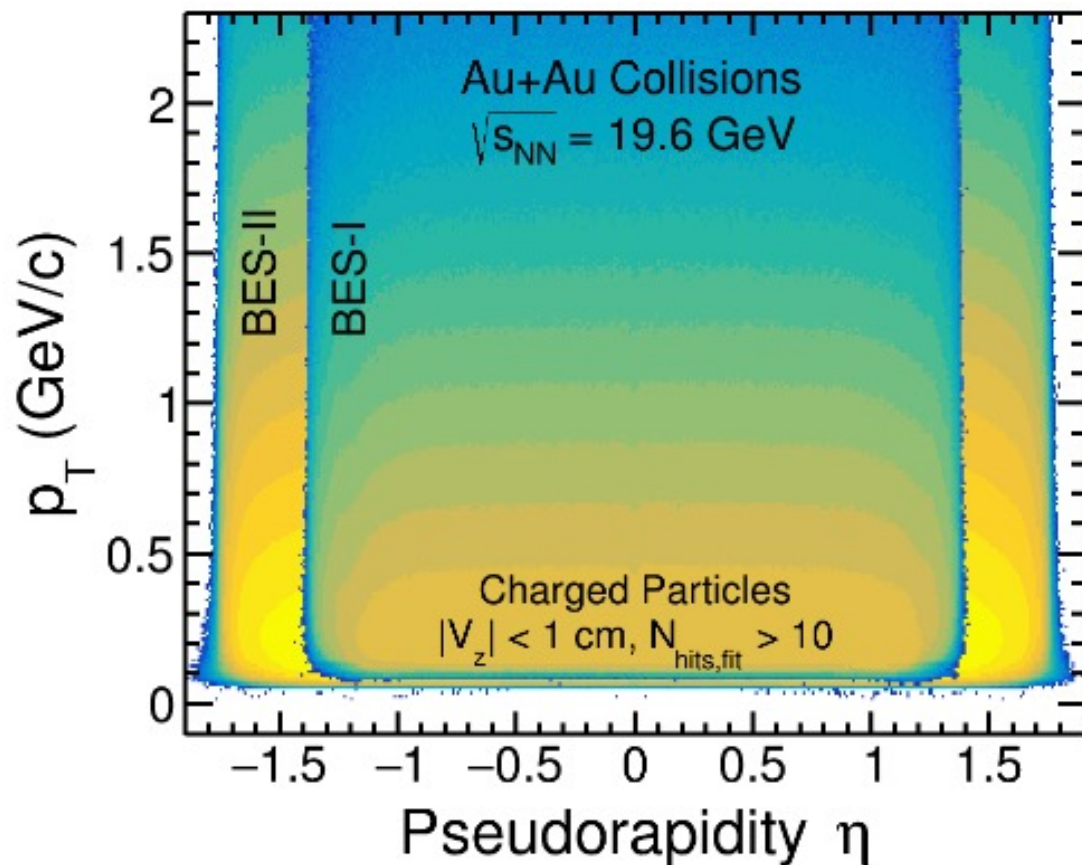
PRL 126 (2021) 092301
PRL 128 (2022) 202303



CPD2024
SQM2024

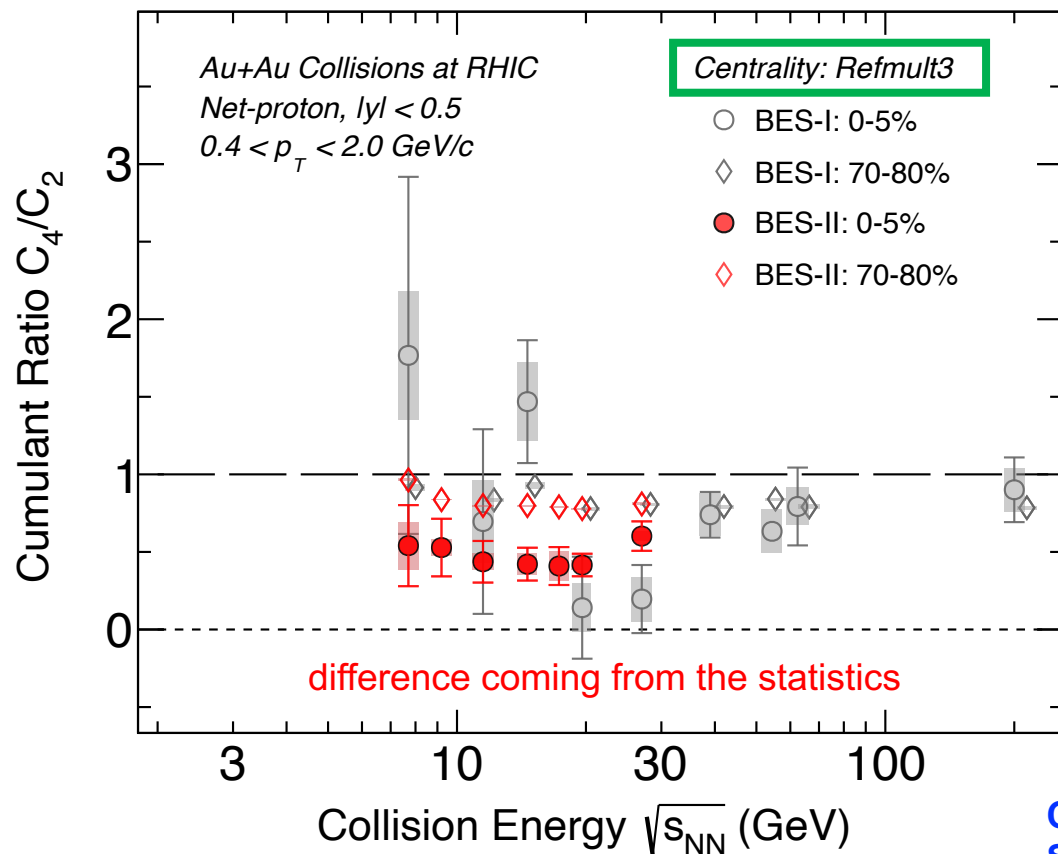
Inner TPC upgrade for wider rapidity coverage at STAR

enough resolution for large θ angle tracks escaping from the endcap



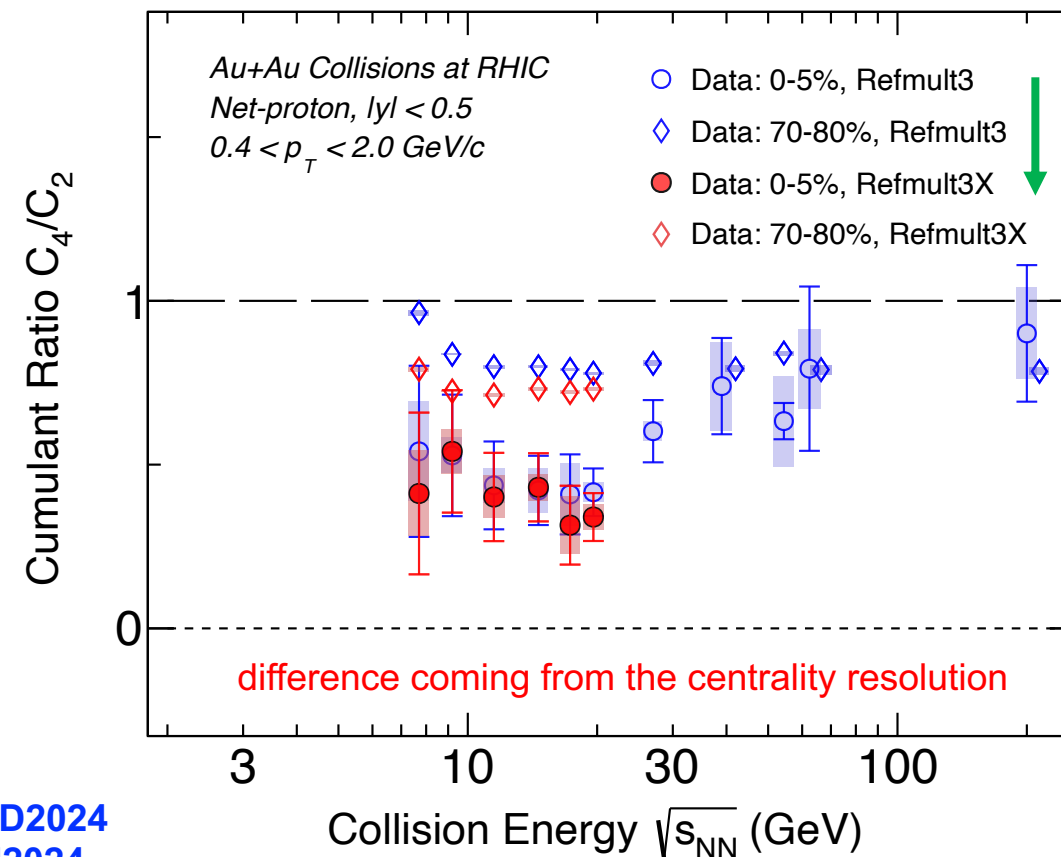
$|\eta| < 1.0$ (or 1.6) excluding protons for RefMult3 (or 3X)

Comparison between BES-I and BES-II results

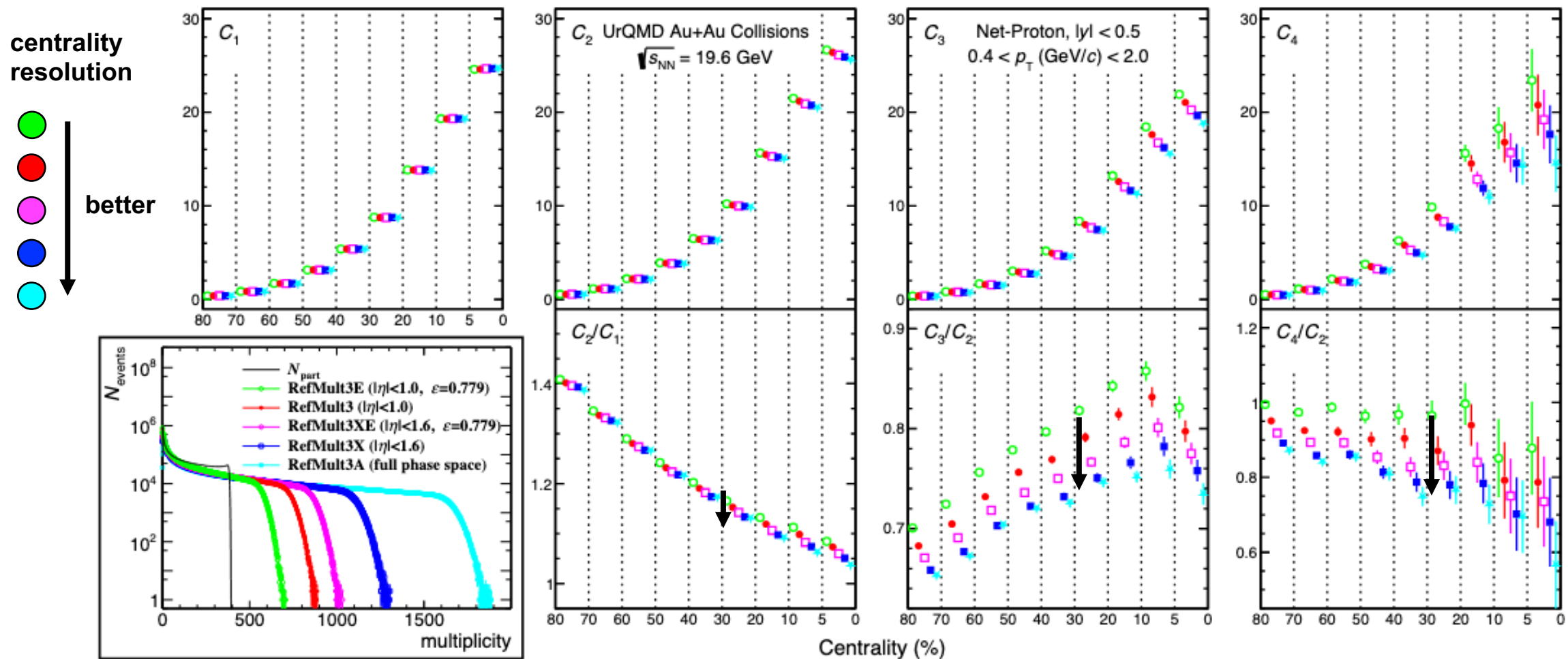


CPOD2024
SQM2024

$|\eta| < 1.0$ (1.6) excluding protons for RefMult3 (3X)

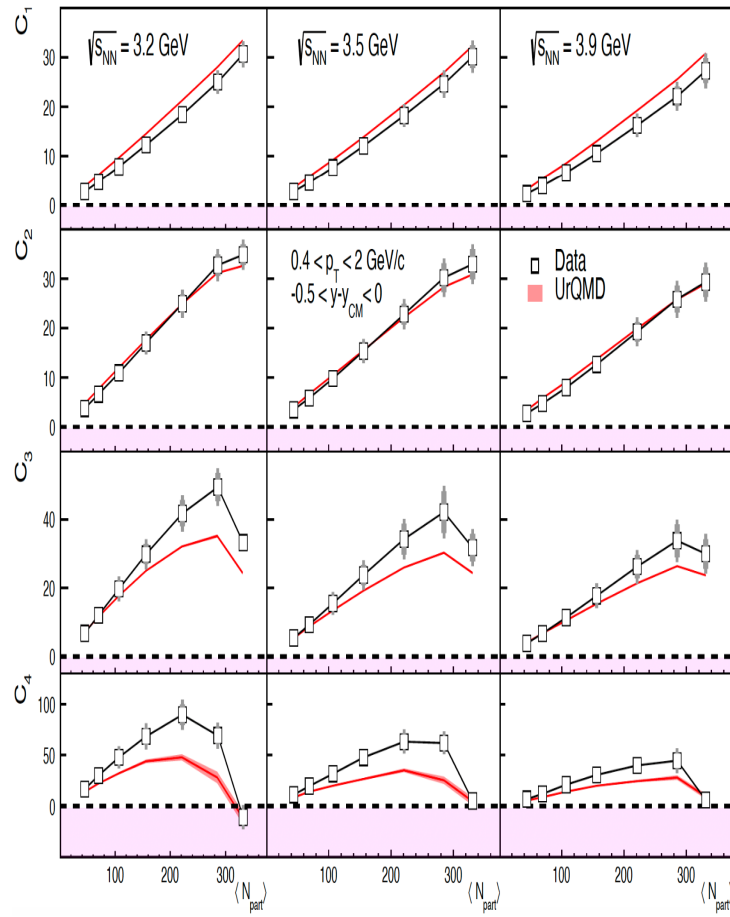


Improvement on centrality resolution (volume fluctuation), UrQMD test at Au+Au 19.6 GeV

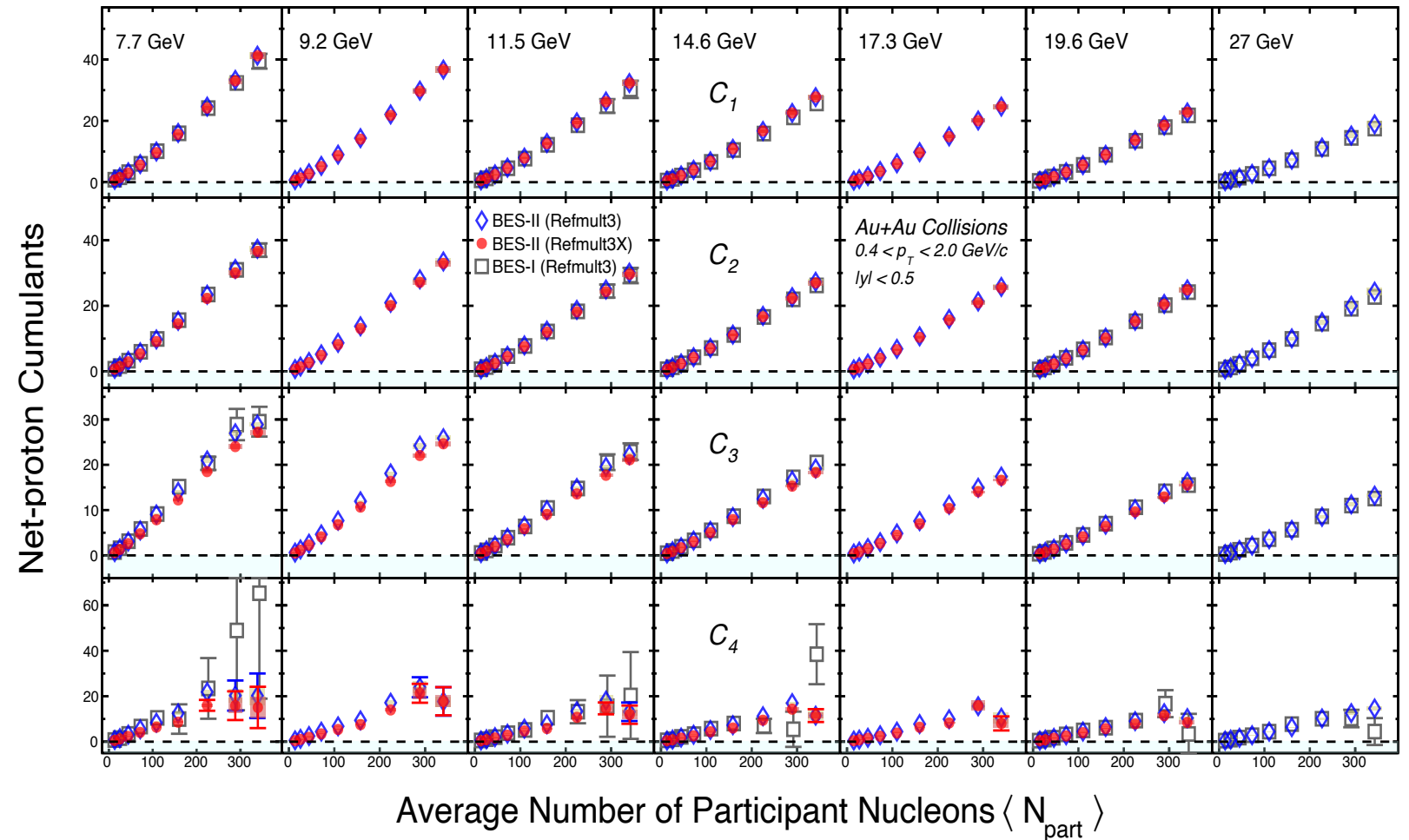


Beam energy and centrality dependence of cumulant $C_1 \sim C_4$

FXT : 3.2 ~ 3.9 GeV

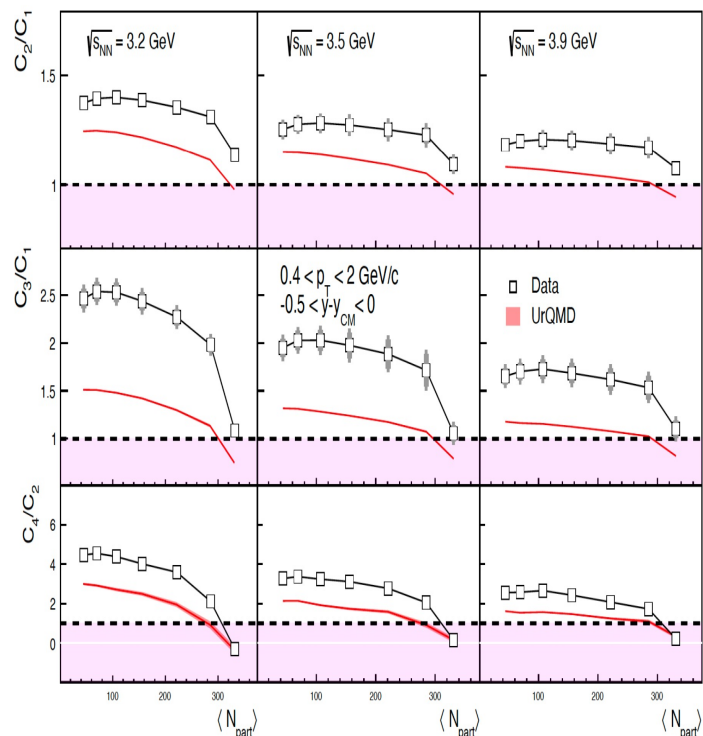


COL : 7.7 ~ 27 GeV

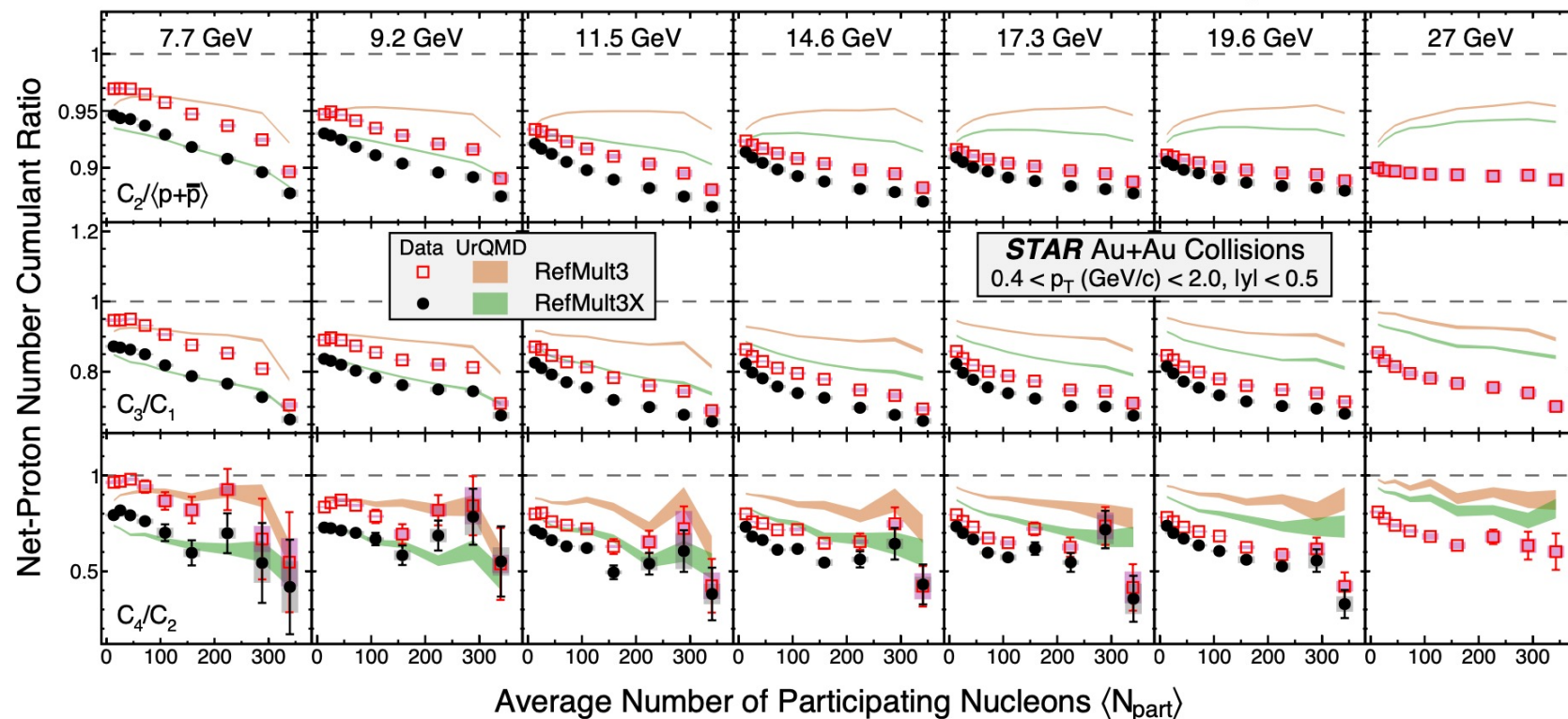


Beam energy and centrality dependence of cumulant ratios

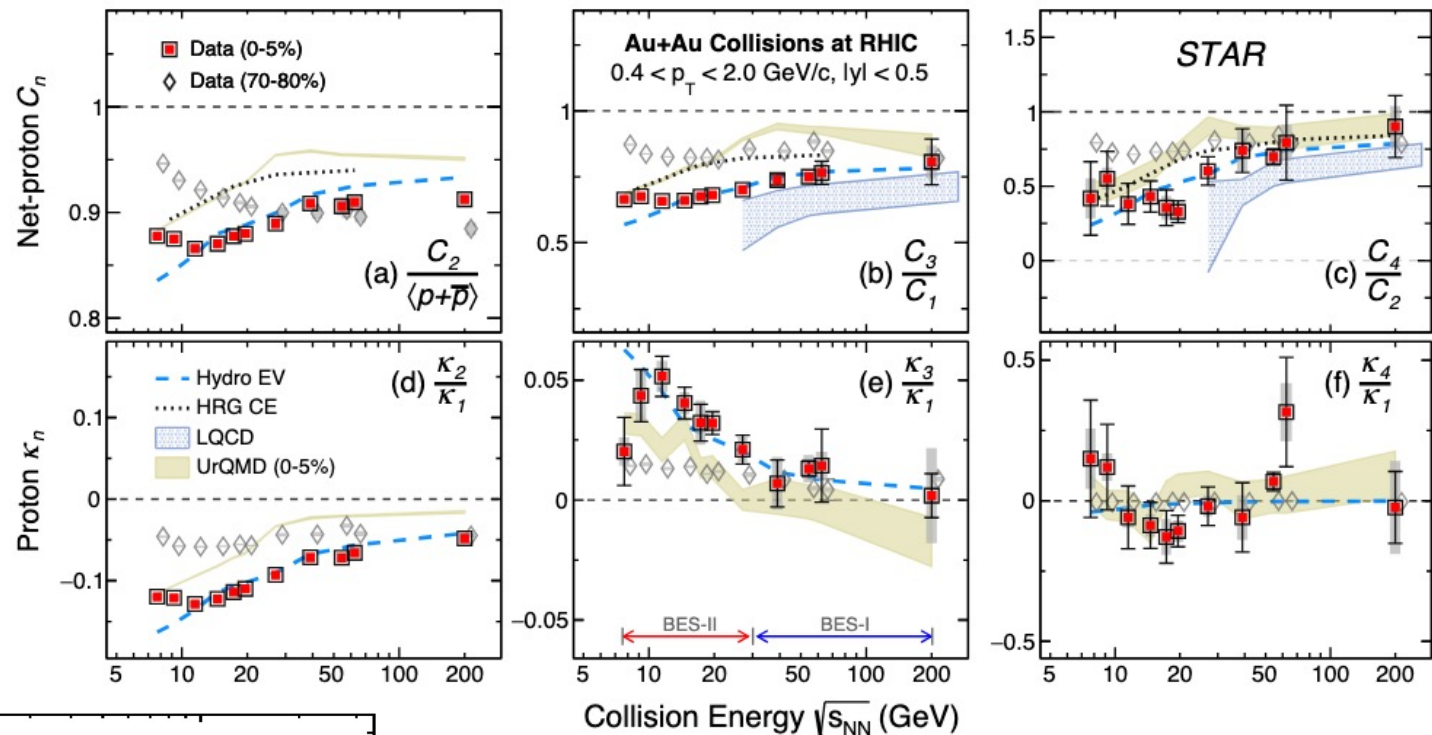
FXT : 3.2 ~ 3.9 GeV



COL : 7.7 ~ 27 GeV

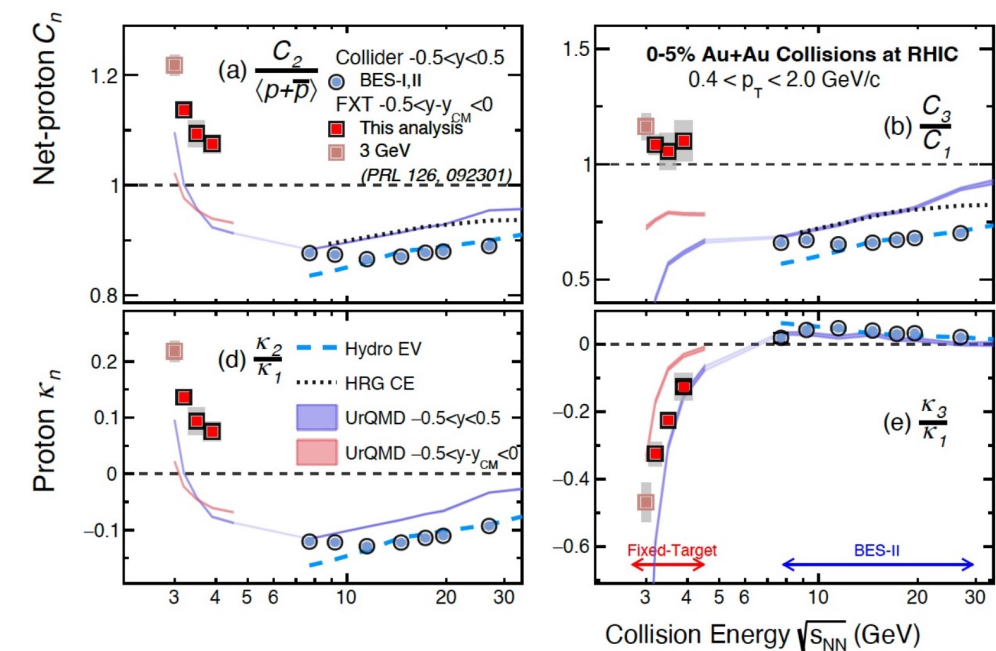


Beam energy dependence of (factorial) cumulant ratios

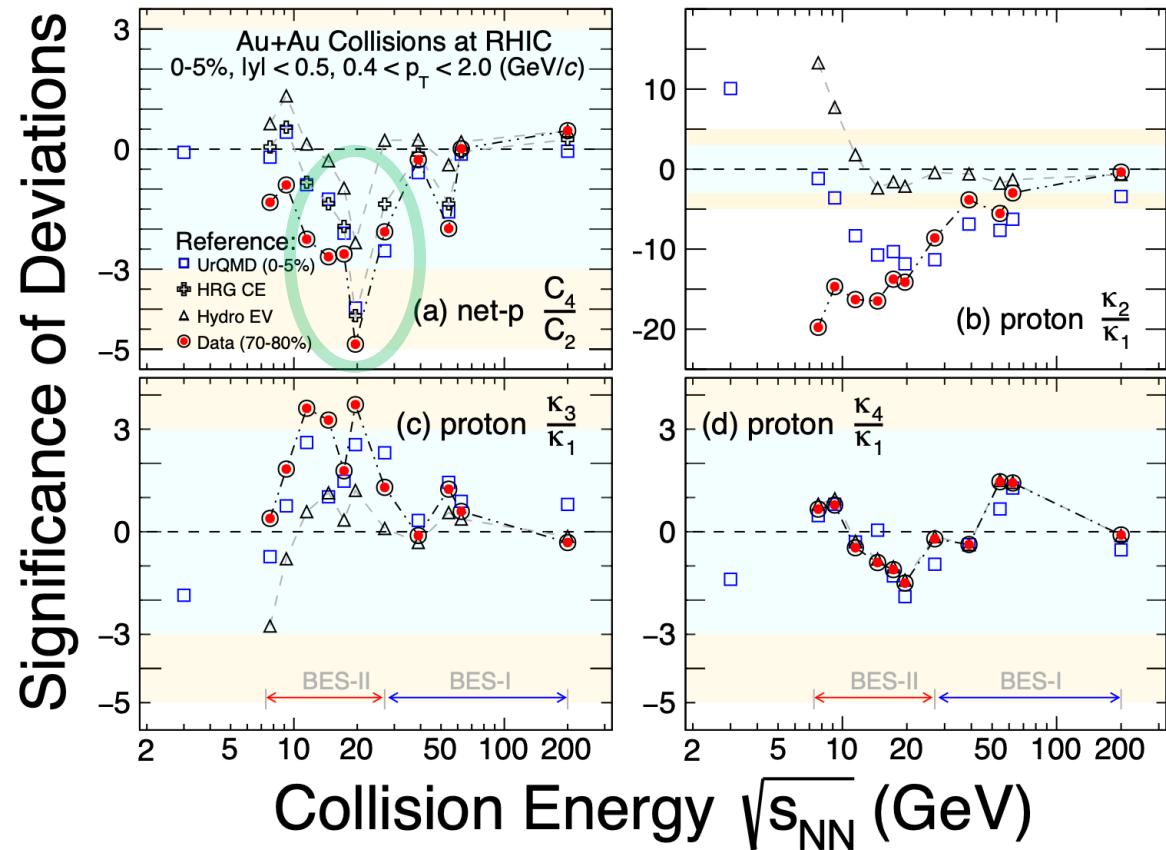


arXiv : 2504.00817, STAR

QM25, STAR

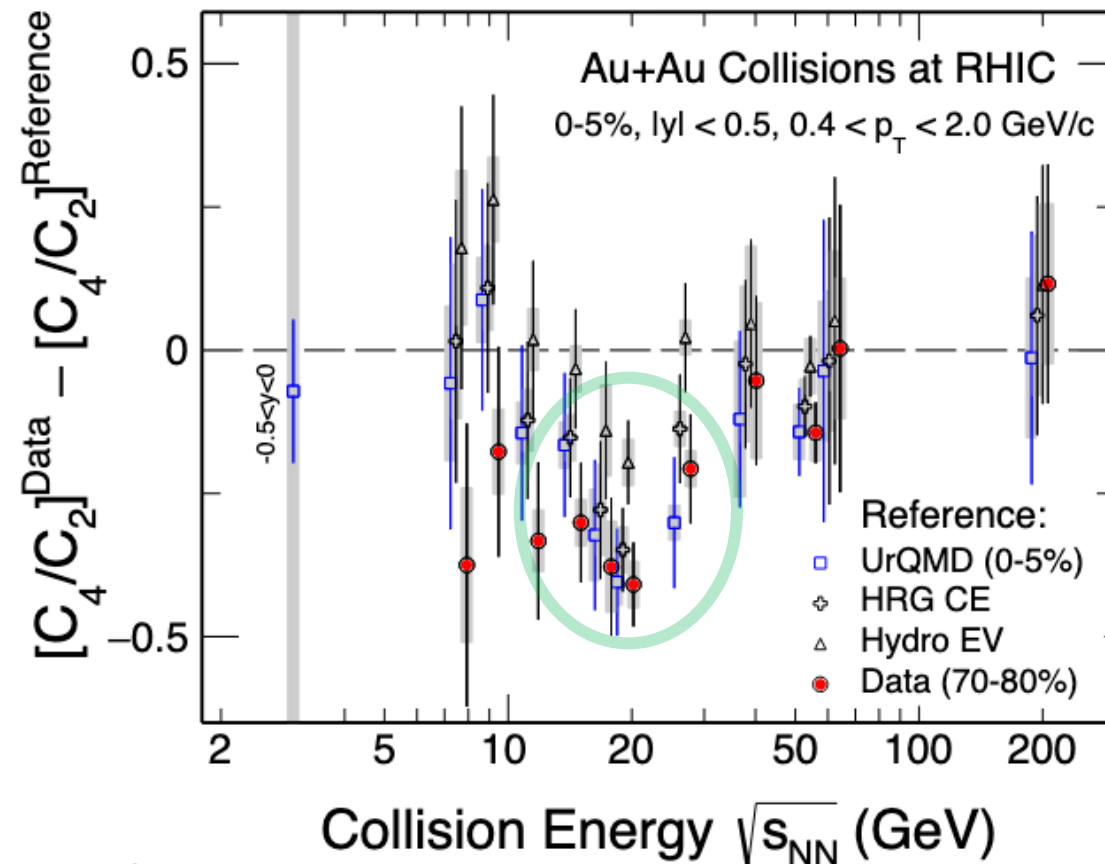


Significances of deviation

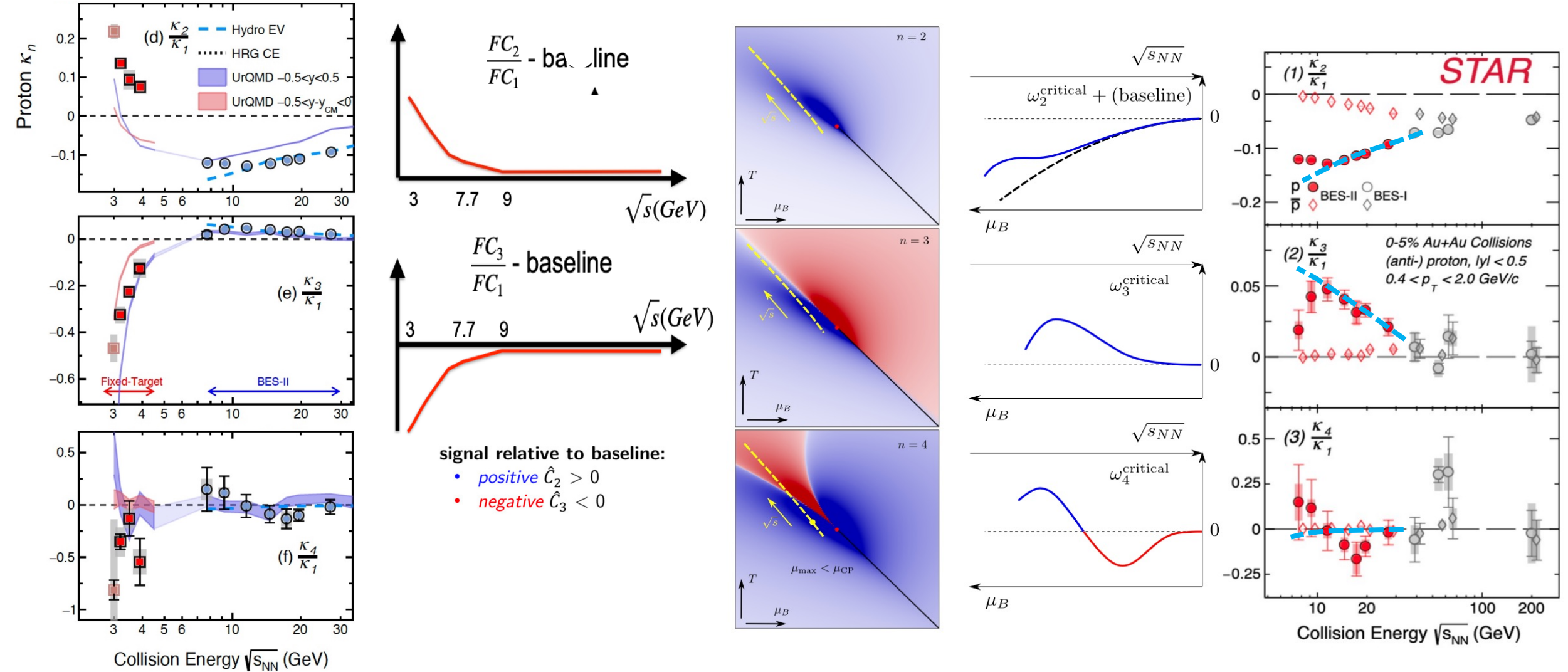


arXiv : 2504.00817, STAR

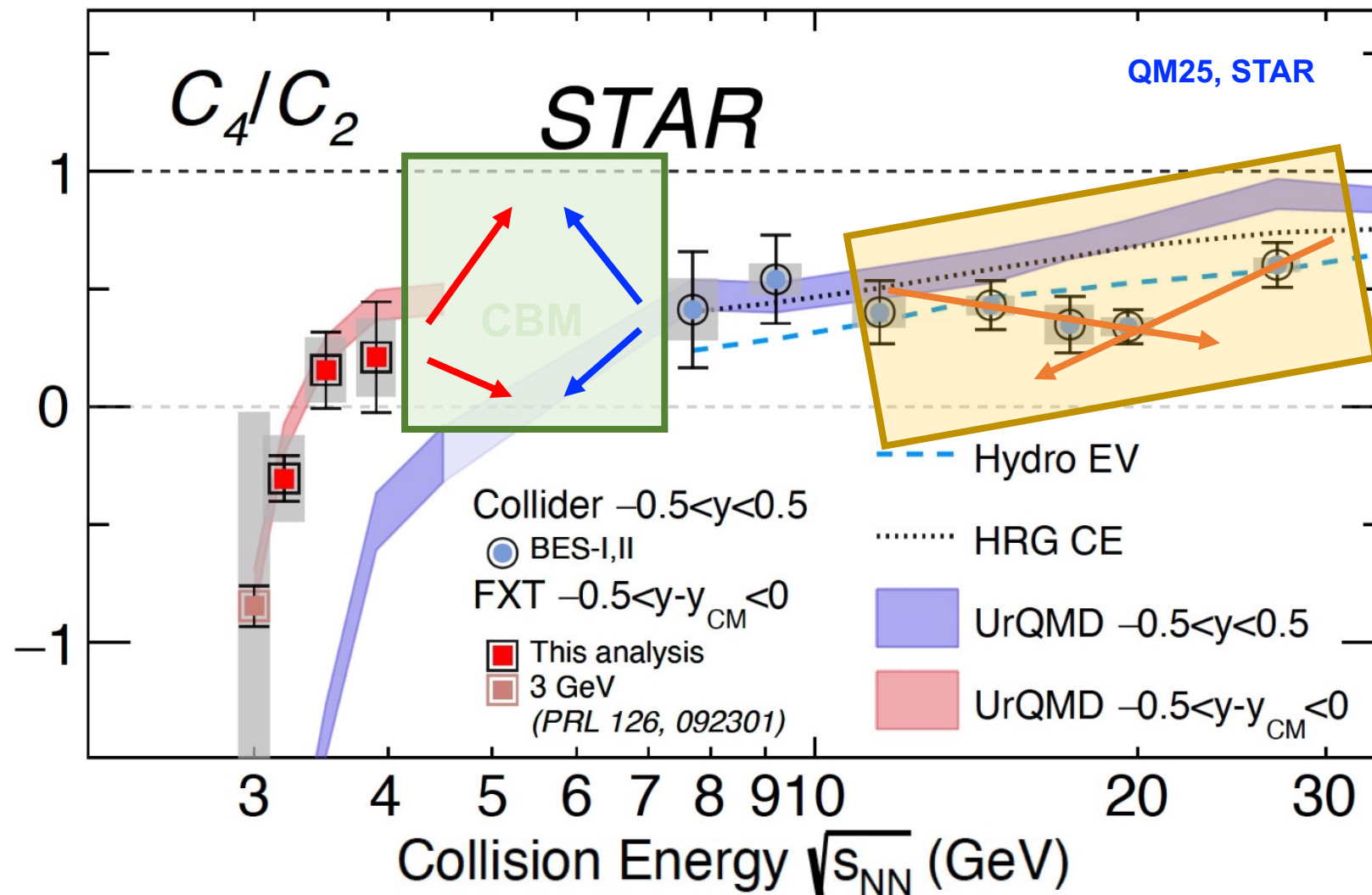
Differences with errors



Possible explanation with critical point



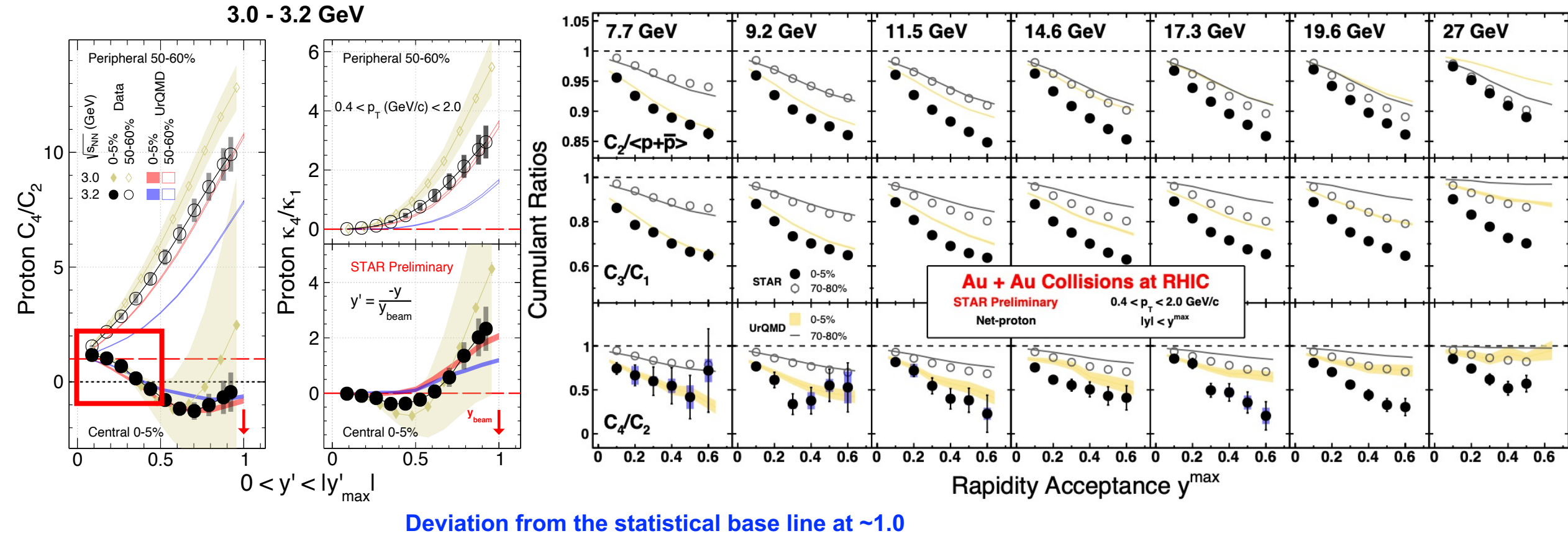
Beam energy dependence of (net-) proton C_4/C_2



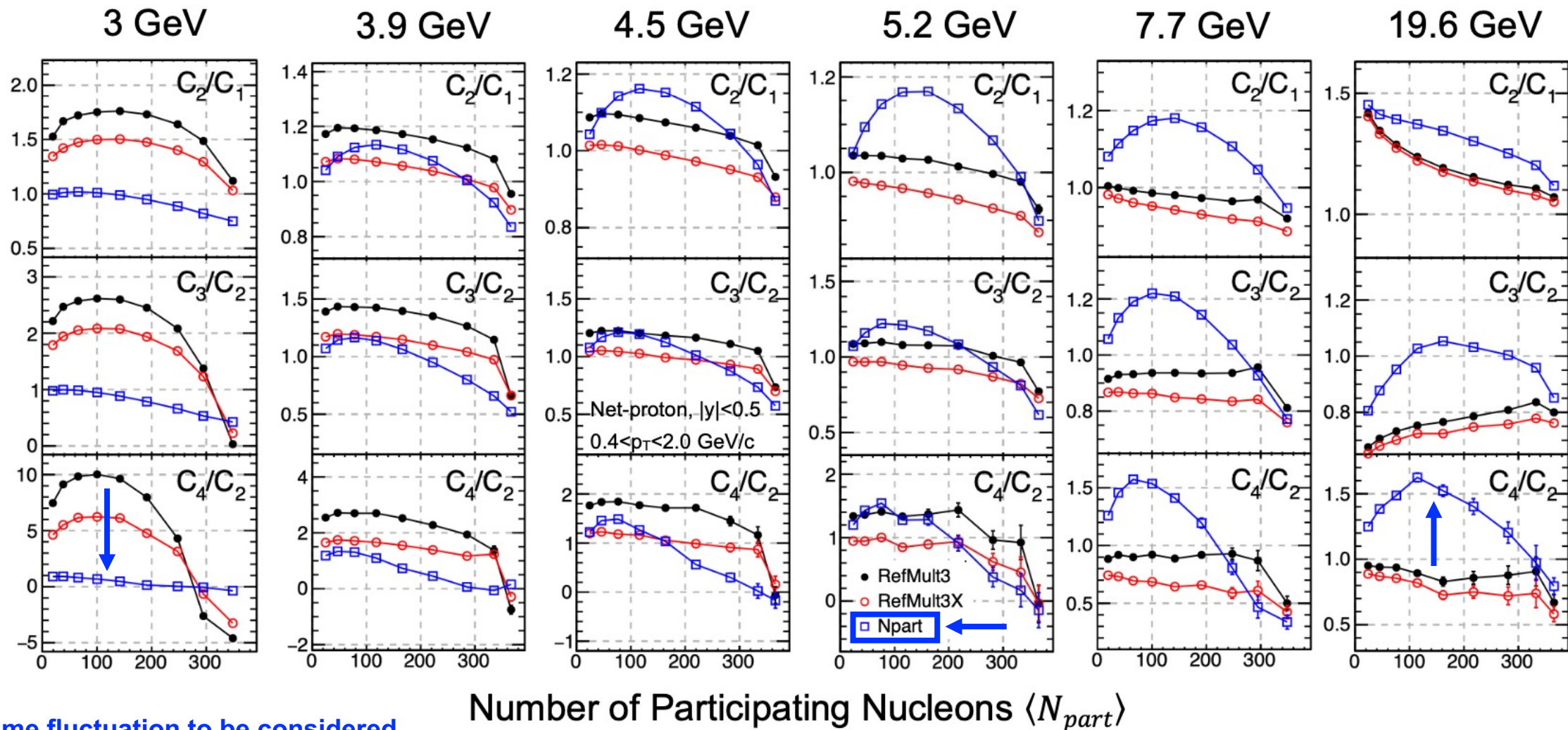
**FXT datasets
up to about $\sim 5\text{GeV}$
for mid-rapidity**

**more differential studies
more measurements
more experiments
CBM and more ...**

Rapidity window scan of net-proton cumulant ratios



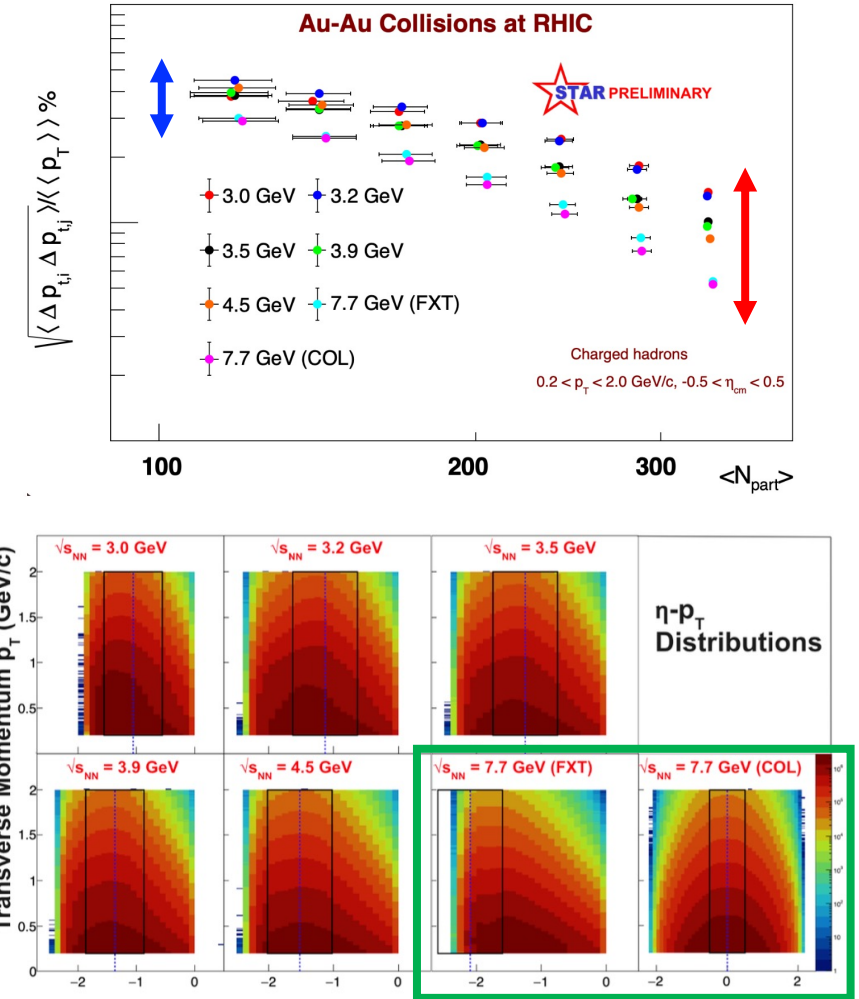
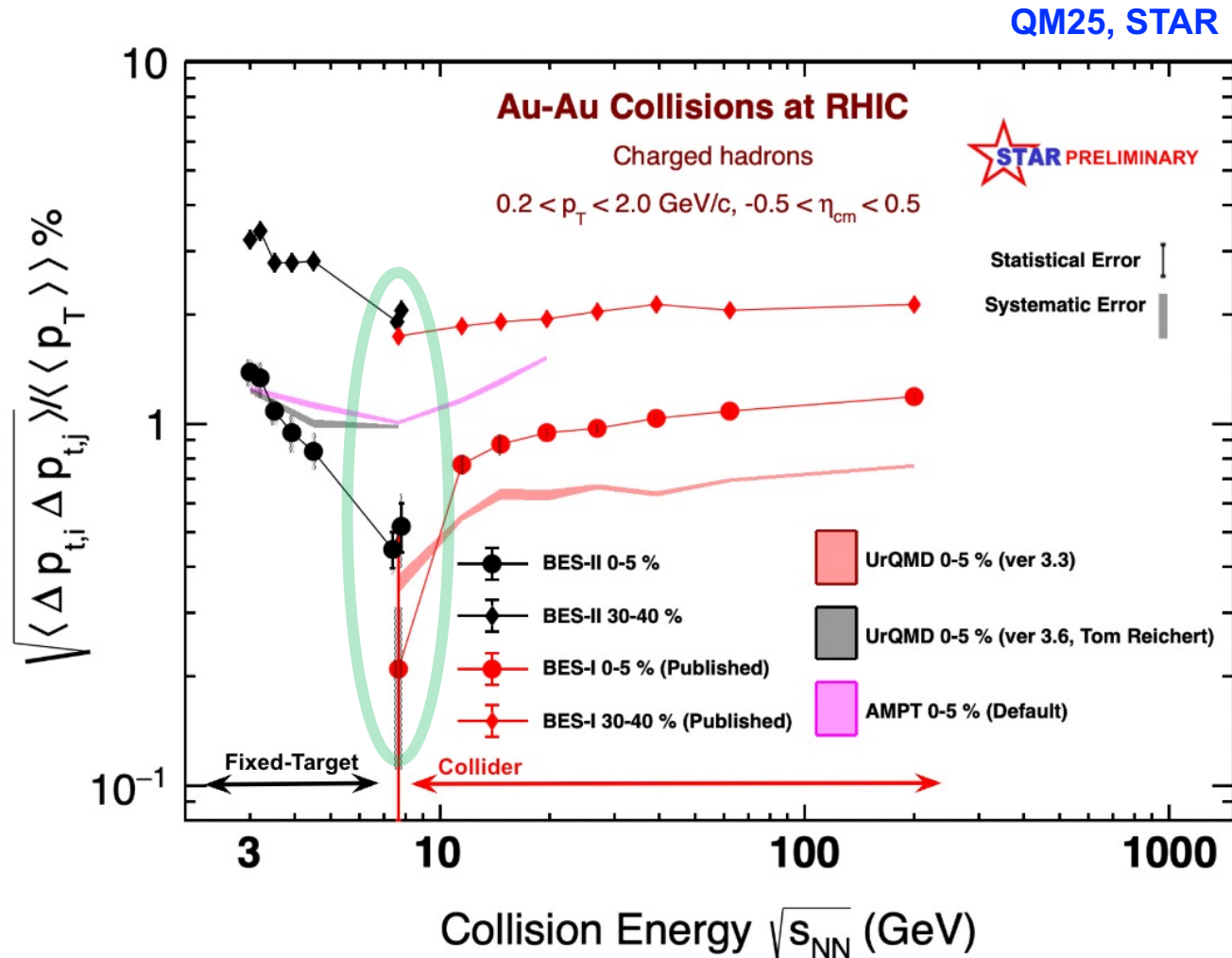
Some more UrQMD tests at different energies



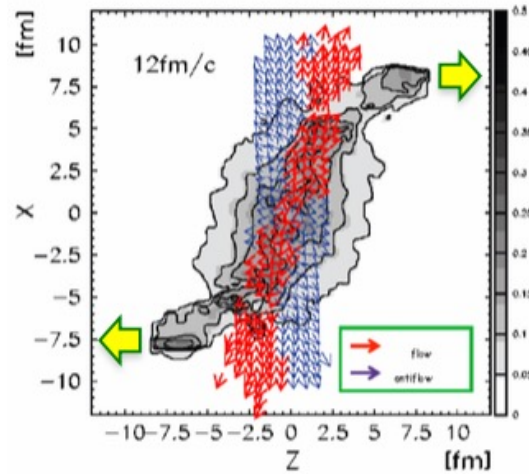
Volume fluctuation to be considered...

2nd order p_T correlation mean p_T fluctuation

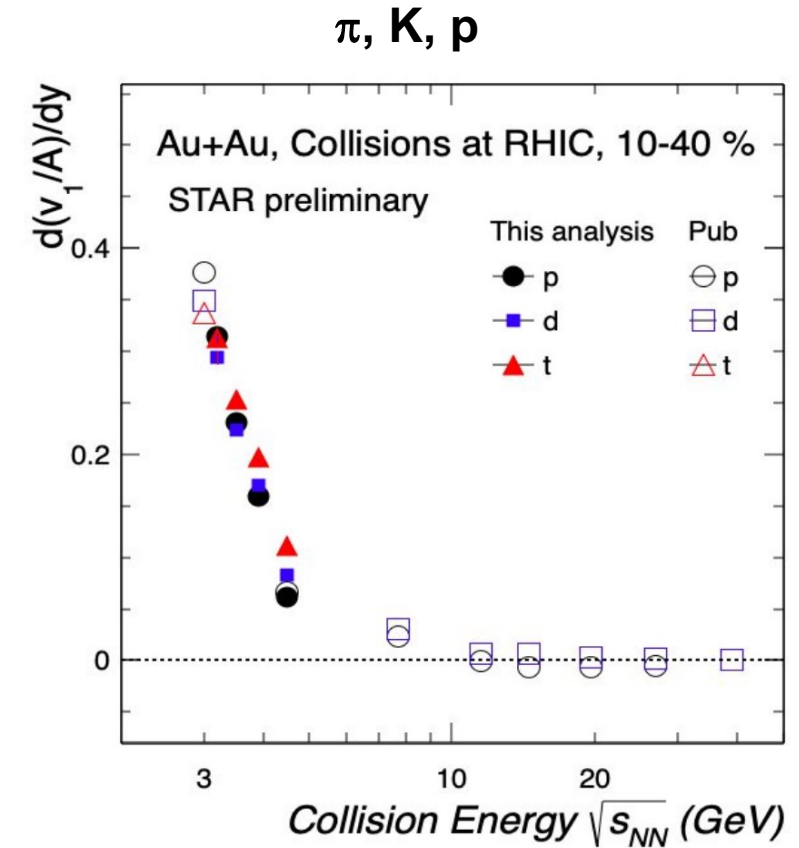
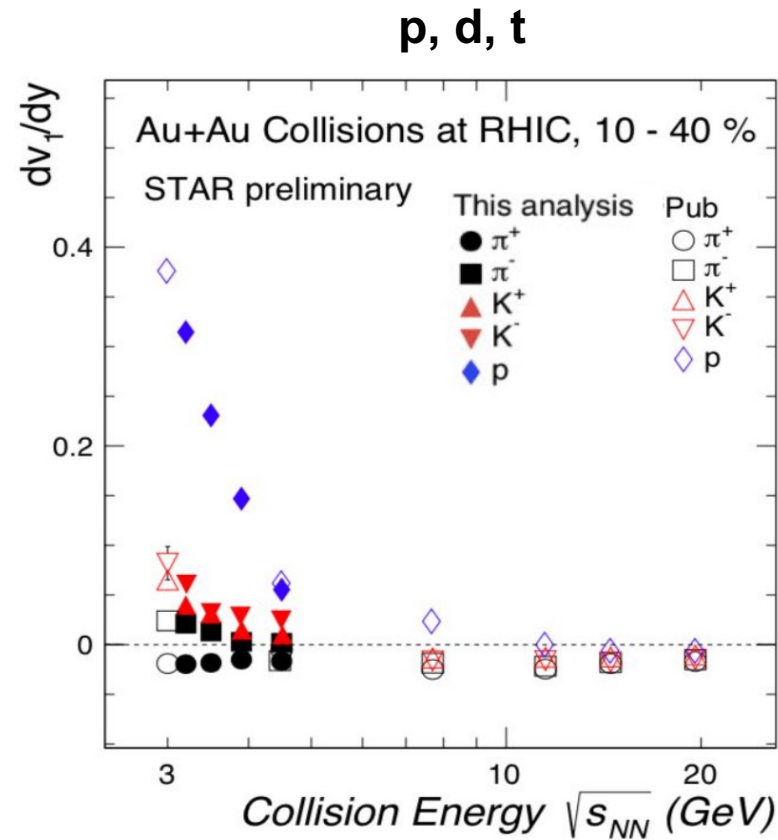
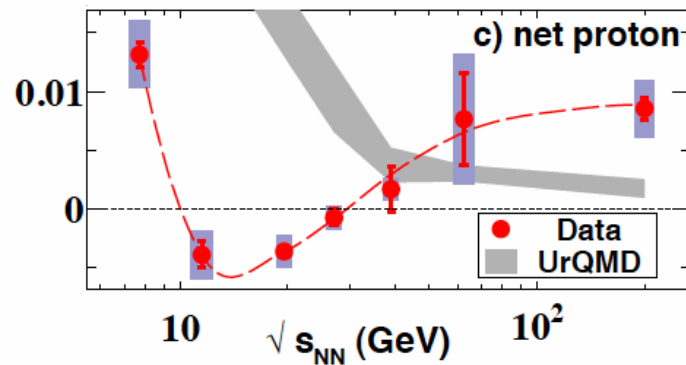
$$\langle \Delta p_{t,i} \Delta p_{t,j} \rangle = \langle (p_{t,i} - \langle p_t \rangle)(p_{t,j} - \langle p_t \rangle) \rangle_{i \neq j}$$

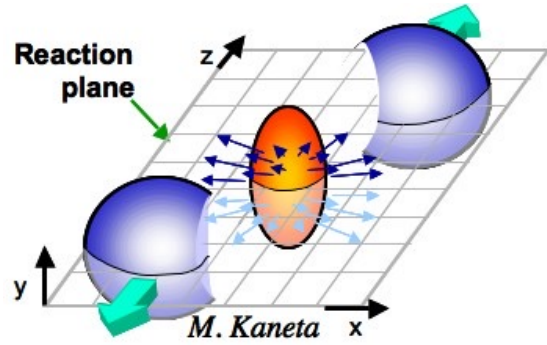


Directed flow (v_1 -slope) as a function of energy



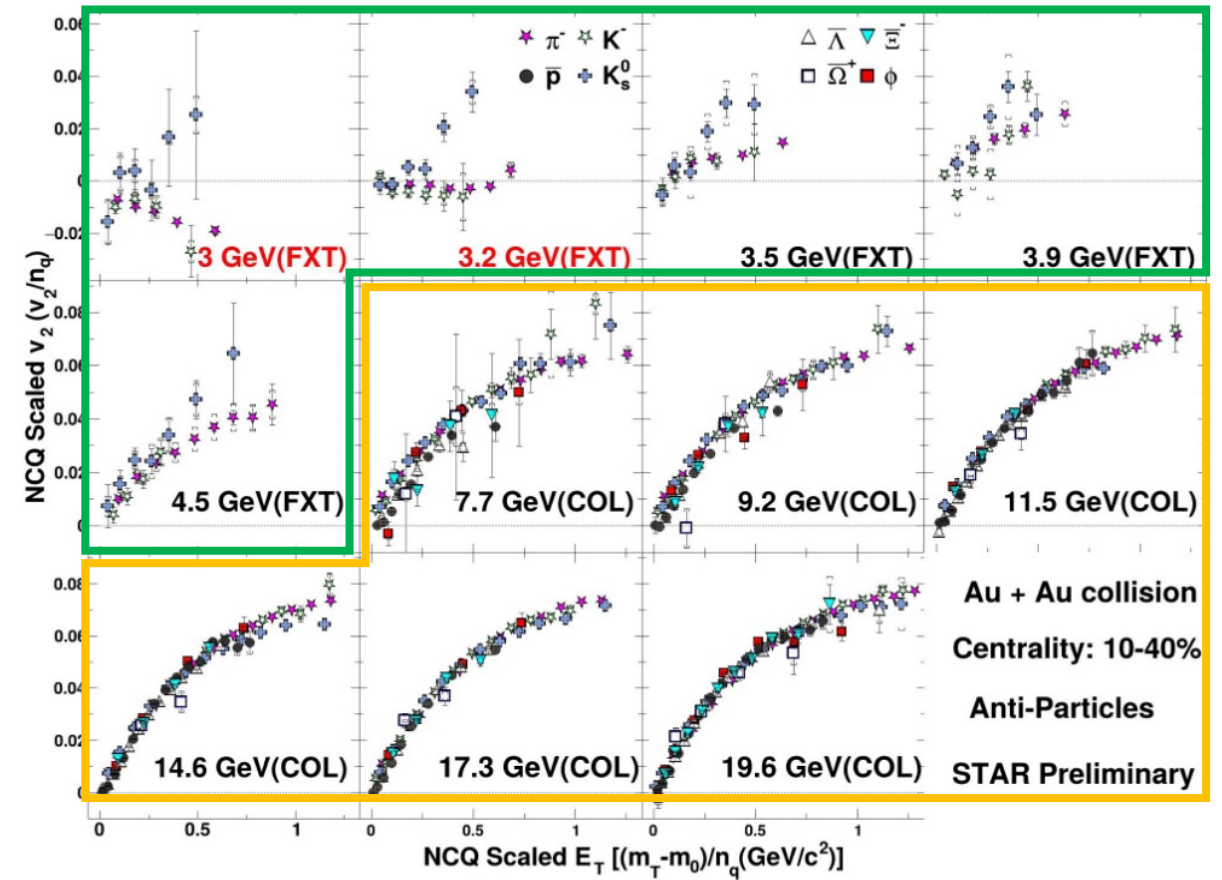
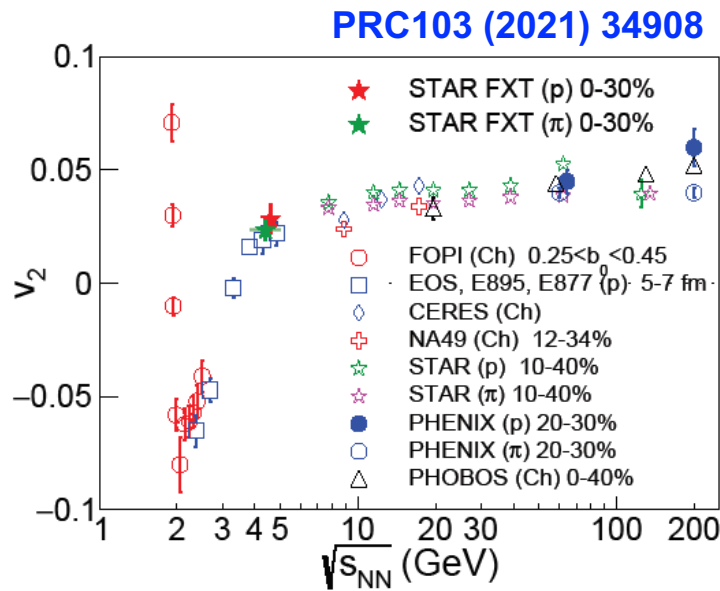
PRL112 (2014) 162301





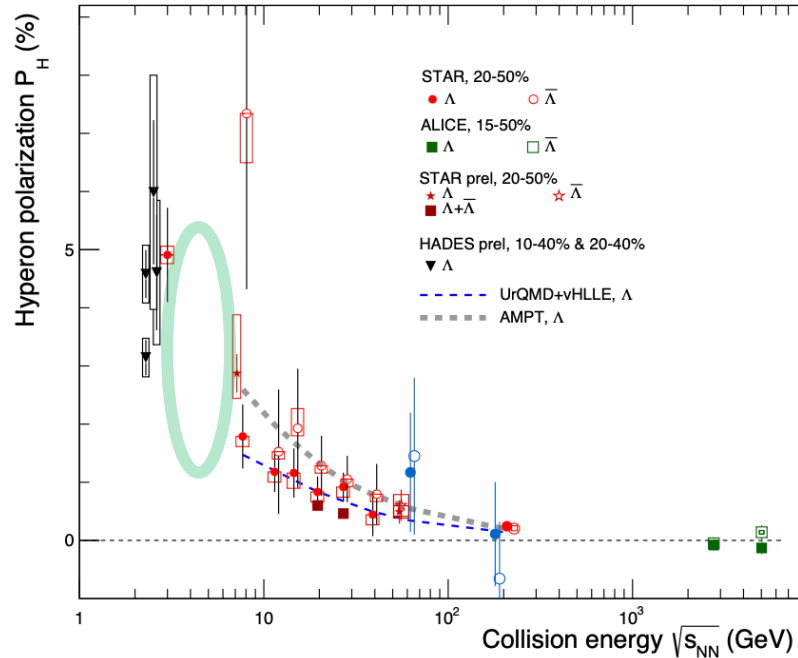
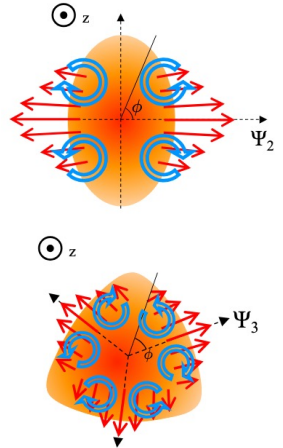
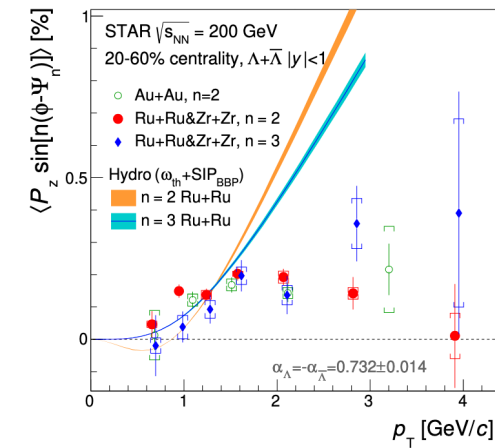
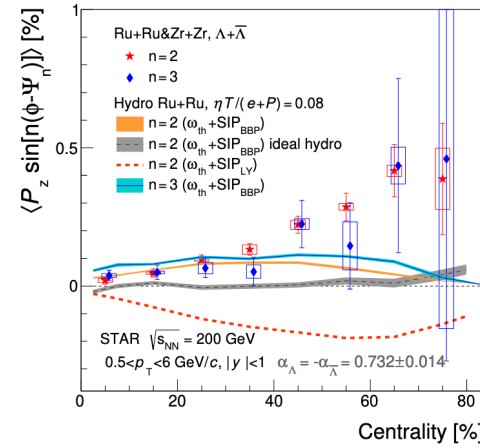
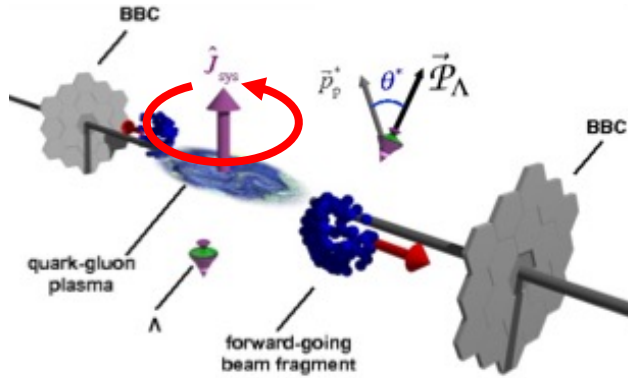
N_{CQ}-scaled elliptic flow v₂ measurements

QM25, STAR

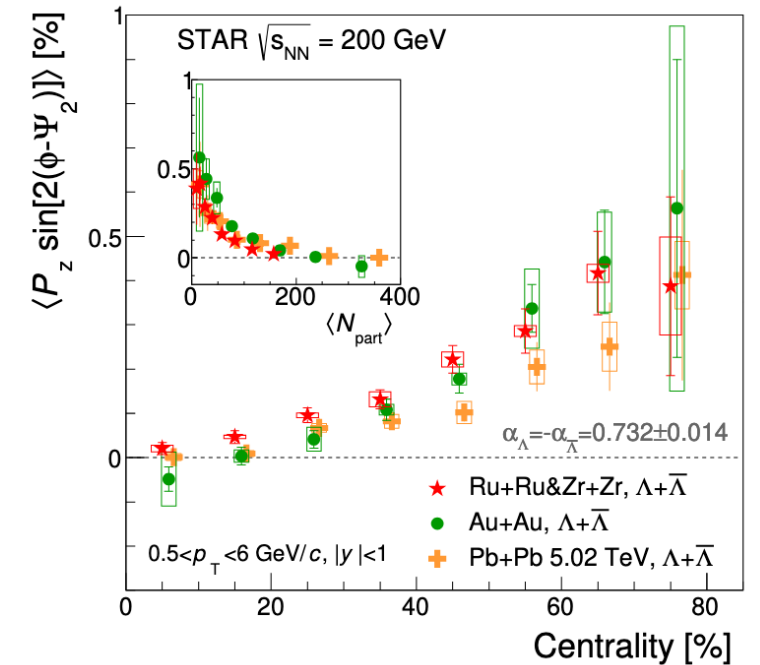
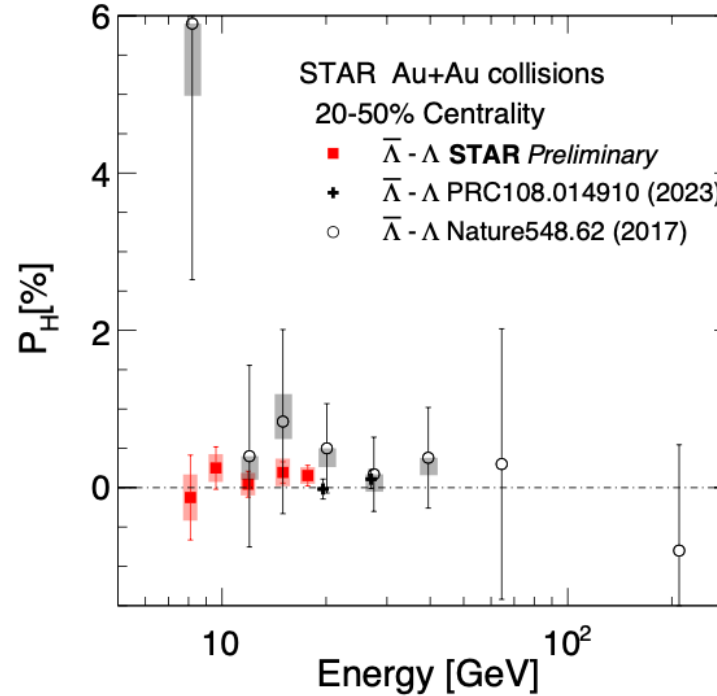


v₂ - N_{CQ} scaling breaks around 3-7 GeV

Global and Local polarization via vorticity, B-field and v_2 , v_3 expansion



STAR BES-II



Summary

- **BES-I and BES-II at RHIC**
- **Temperature measurements**
- **Net-proton fluctuation and Volume fluctuation**
- **Mean p_T fluctuation**
- **Directed and Elliptic Flow measurements**
- **Vorticity and Polarization**

