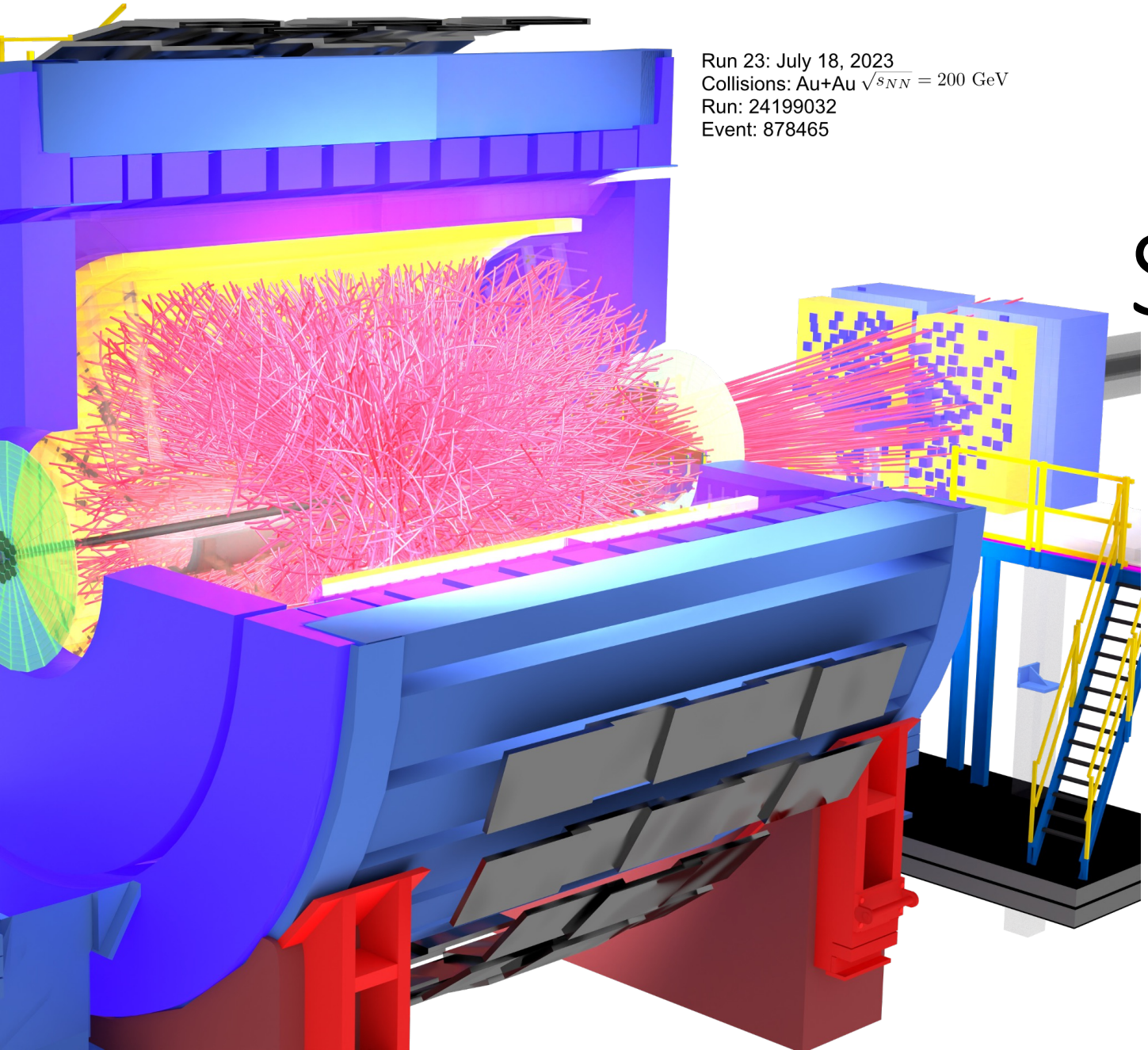


STAR Heavy-Ion Highlights

Frank Geurts

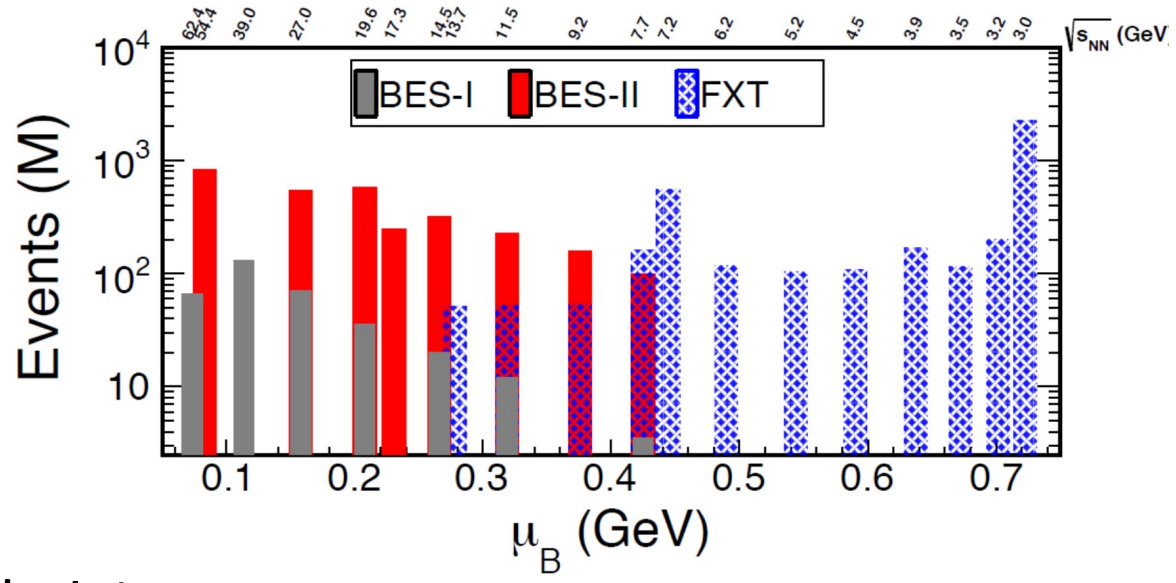
for the STAR Collaboration

Outline

- BES-2: statistics & production
- Recent papers: statistics and highlights
  - Light Flavor Spectra / UPC
  - Flow, Chirality, Vorticity
  - Correlations & Fluctuations
  - Hard Probes
- QuarkMatter ’23

BES-2 Statistics & Production

2018	Start	Stop	Good	Target	Calib/Prod	RbyR QA	Centrality	Analysis
27 GeV	May 10th	June 17th	555 M	700 M	Produced	Completed	Completed	Published 7
3.0 FXT	May 30th	June 4th	258 M	100 M	Produced	Completed	Completed	Published 9
7.2 FXT	June 11th	June 12th	155 M	none	Produced	Completed	Completed	Preliminary
2019	**Start**	**Stop**	**Good**	**Target**	**Calib/Prod**	**RbyR QA**	**Centrality**	**Analysis**
19.6 GeV	Feb 25th	April 3rd	582 M	400 M	Produced	Completed	Completed	Preliminary
14.6 GeV	April 4th	June 3rd	324 M	310 M	Produced	Completed	Completed	Preliminary
3.9 FXT	June 18th	June 18th	52.7 M	50 M	Produced	Completed	Completed	Preliminary
3.2 FXT	June 28th	July 2nd	200.6 M	200 M	Produced	Completed	Completed	Preliminary
7.7 FXT	July 8th	July 9th	50.6 M	50 M	Produced	Completed		Preliminary
200 GeV	July 11th	July 12th	138 M	140 M	Produced	Completed	Completed	
2020	**Start**	**Stop**	**Good**	**Target**	**Calib/Prod**	**RbyR QA**	**Centrality**	**Analysis**
11.5 GeV	Dec 10th	Feb 24th	235 M	230 M	Produced			Preliminary
7.7 FXT	Jan 28th	Jan 29th	112.5 M	100 M	Produced	Completed		Preliminary
4.5 FXT	Jan29th	Feb 1st	108 M	100 M	Produced	Completed		Preliminary
6.2 FXT	Feb 1st	Feb 2nd	118 M	100 M	Produced	Completed		
5.2 FXT	Feb 2nd	Feb 3rd	103 M	100 M	Produced	Completed		
3.9 FXT	Feb 4th	Feb 5th	117 M	100 M	Produced	Completed	In progress	Preliminary
3.5 FXT	Feb 13th	Feb 14th	115.6 M	100 M	Produced	Completed	In progress	Preliminary
9.2 GeV	Feb 24th	Sep 1st	161.8 M	160 M	Produced	Ready		Preliminary
7.2 FXT	Sep 12th	Sep 14th	317 M	None				
2021	**Start**	**Stop**	**Good**	**Target**	**Calib/Prod**	**RbyR QA**	**Centrality**	**Analysis**
7.7 GeV	Jan 31st	May 1st	100.9 M	100 M	Produced	Completed	In progress	Preliminary
3.0 FXT	May 1st	June 28th	2103 M	2.0 B				
9.2 FXT	May 6th	May 6th	53.9 M	50 M				
11.5 FXT	May 7th	May 7th	51.7 M	50 M				
13.7 FXT	May 8th	May 8th	50.7 M	50 M				
17.3 GeV	May 25th	June 7th	256.1 M	250 M				
7.2 FXT	June 3rd	July 3rd	88.6 M	None				



Updates:

- ✓ Run-21 Au+Au 17.3 GeV: production finished
- ✓ Run-21 Au+Au 7.7 GeV: centrality completed
- ✓ Run-20 Au+Au 3.5, 3.9 FXT: centrality completed
- Run-20 9.2GeV: run-by-run QA in progress
- Run-20 11.5 GeV: run-by-run QA in progress

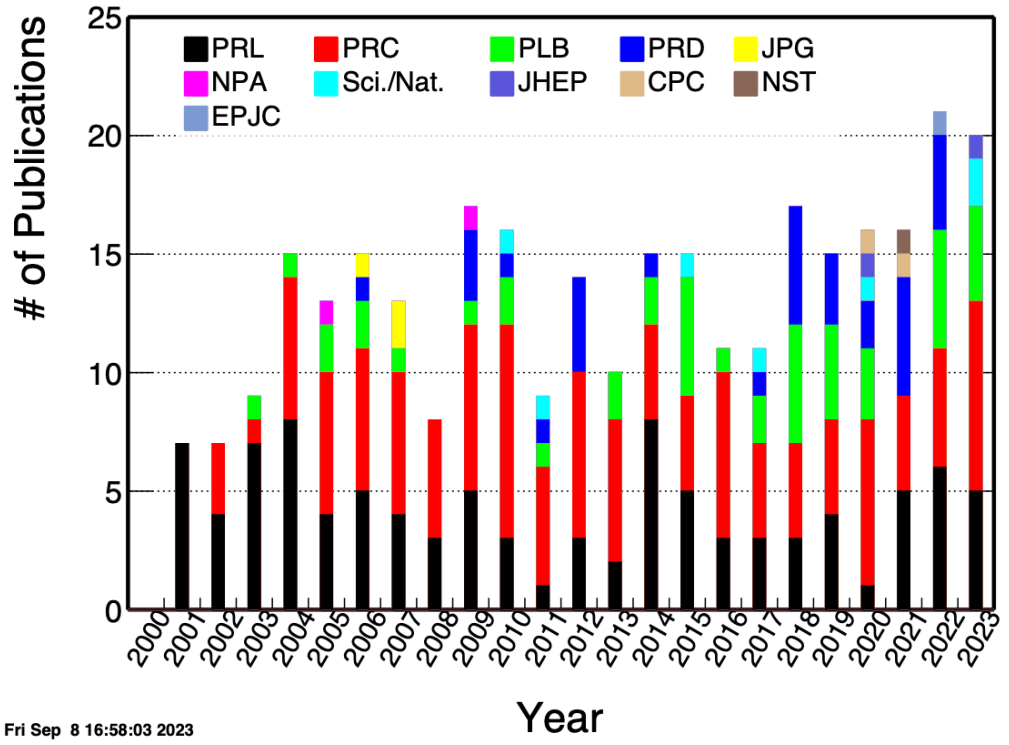
STAR Recent Publications

- 2022: 21 published papers
  - 6 PRL, 5 PRC, 5 PRD, 4 PLB, 1 EJPC
- 2023: 19+1 published and accepted
  - 5 PRL, 8 PRC, 3+1 PLB, 2 Sci/Nat, 1 JHEP
- Journal review: 10
  - collaboration review: 8; active GPCs: 31

❖3GeV FXT (Run-18): 10 papers

❖27GeV (Run-18): 8 papers

✓ 98% of STAR papers uploaded to HEPdata
  - integral part of the publication workflow



Tomography of ultra-relativistic nuclei with polarized photon-gluon collisions
- Sciences Advances 9 (2023) 3903

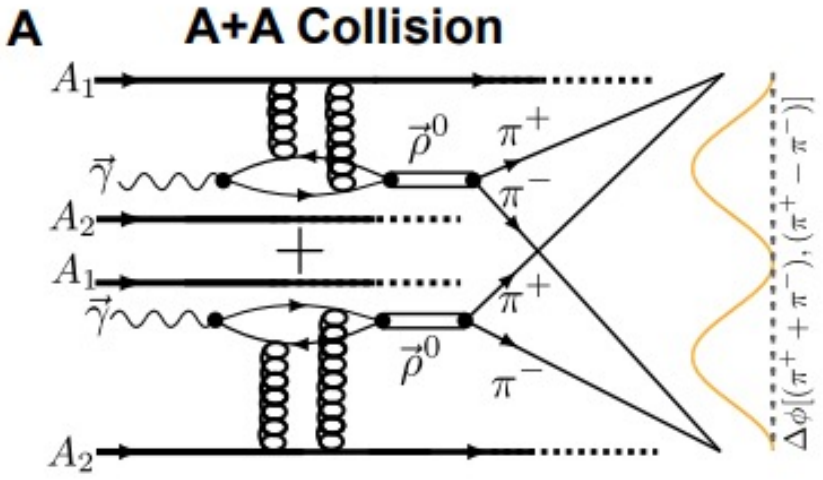
Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions
- Nature 614 (2023) 224

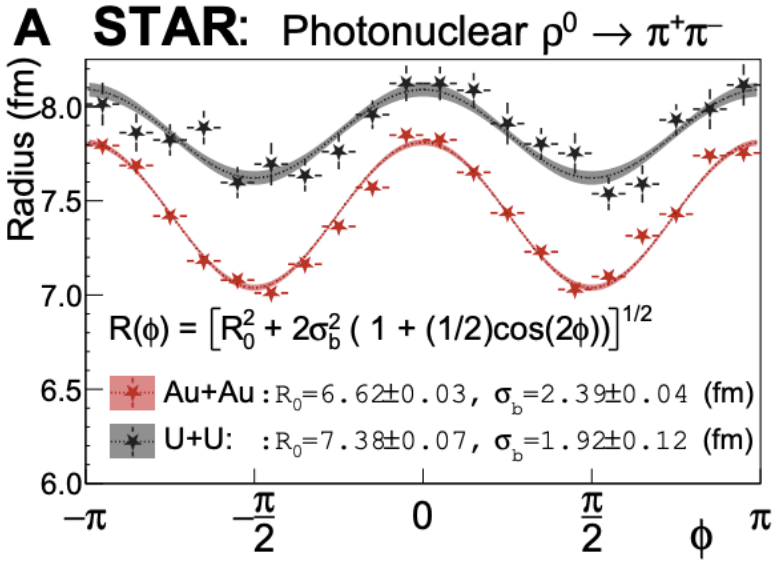
Light Flavor Spectra & UPC

- Measurements of dielectron production in Au+Au Collisions at $\sqrt{s_{NN}}$= 27, 39, and 62.4 GeV, PRC **107** (2023) L061901
- Beam Energy Dependence of Triton Production and Yield Ratio ($N_t N_p/N_d^2$) in Au+Au Collisions at RHIC, PRL **130** (2023) 202301
- K^0 production in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27 and 39 GeV from RHIC beam energy scan, PRC **107** (2023) 034907
- Tomography of Ultra-relativistic Nuclei with Polarized Photon-gluon Collisions, Sci. Adv. **9** (2023) 3903
- Measurement of $^4H4_\Lambda$ and $^4He4_\Lambda$ binding energy in Au+Au collisions at $\sqrt{s_{NN}}$ = 3GeV, PLB **834** (2022) 137449

Entangled enabled interference

Tomography of ultra-relativistic nuclei with polarized photon-gluon collisions





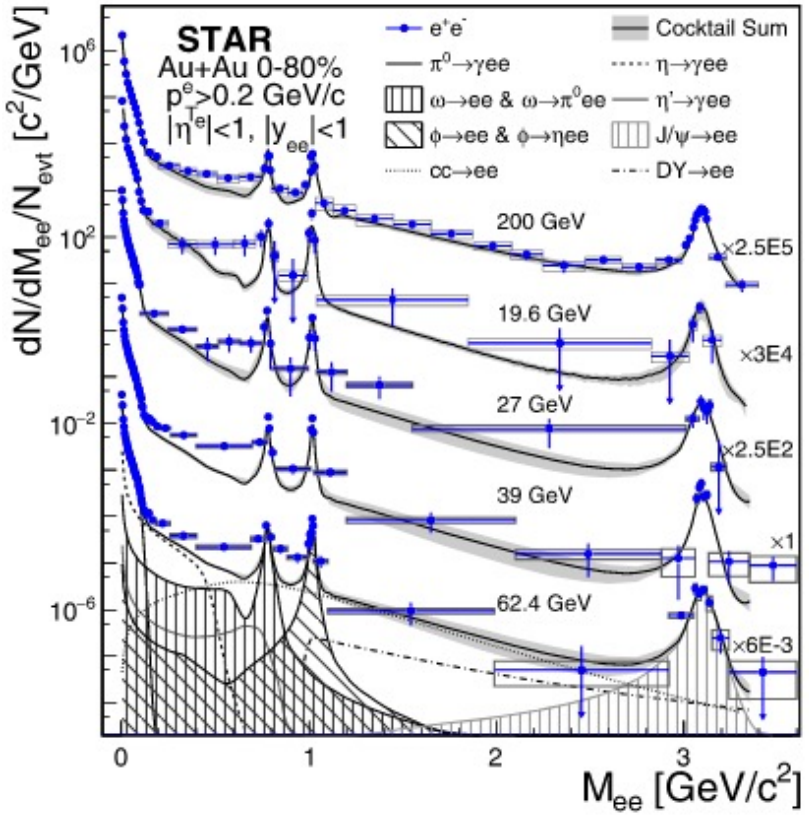
Science Advances 9 (2023) 3903

Quantum interference enabled nuclear tomography:

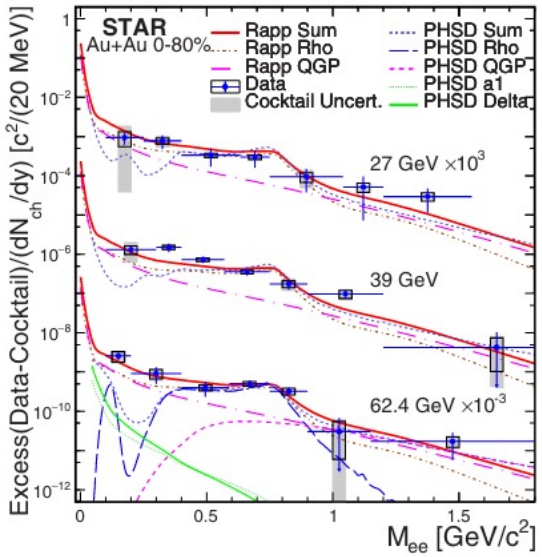
- a novel approach to extract the strong-interaction nuclear radii, which were found to be larger than the nuclear charge radii

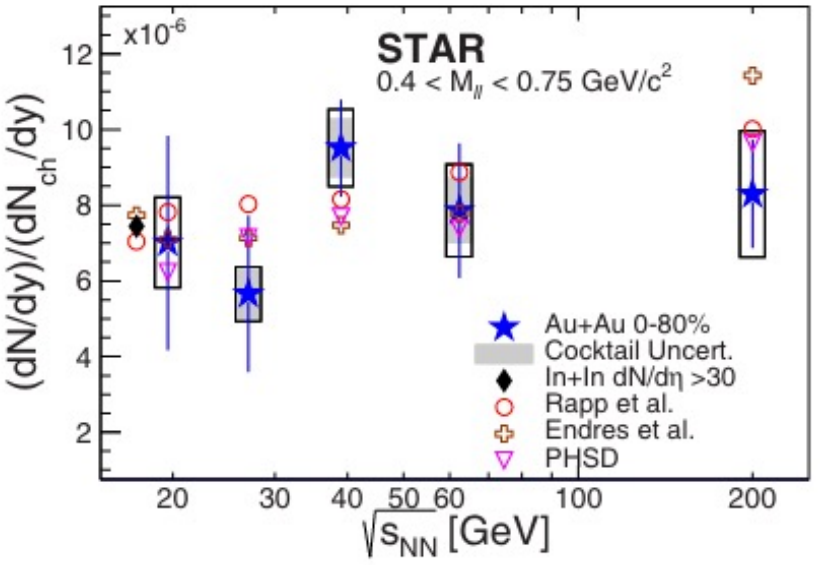
BES-1 dielectron measurements

PRC 107 (2023) L061901



- BES-1 LMR dielectron program completed
- Models consistently reproduce LMR excess
- No significant $\sqrt{s_{NN}}$ dependence of the dN_{ch}/dy-normalized integrated LMR excess



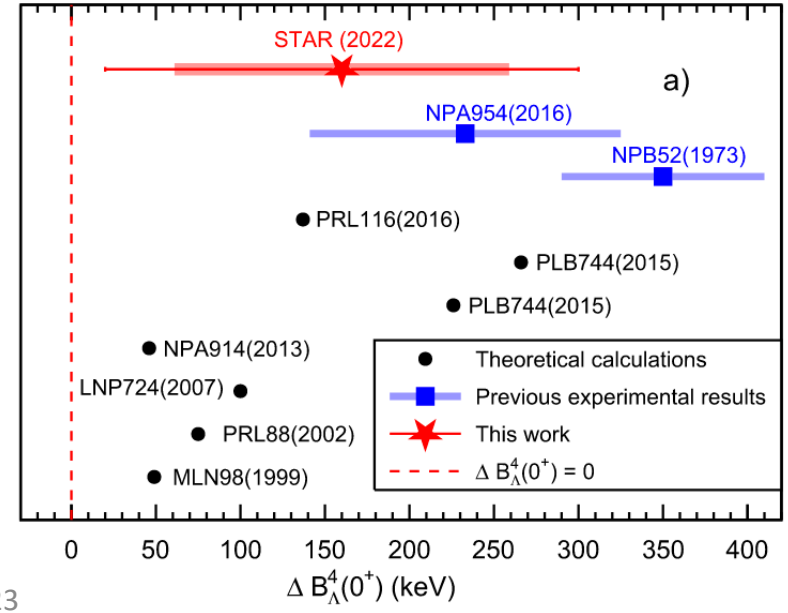


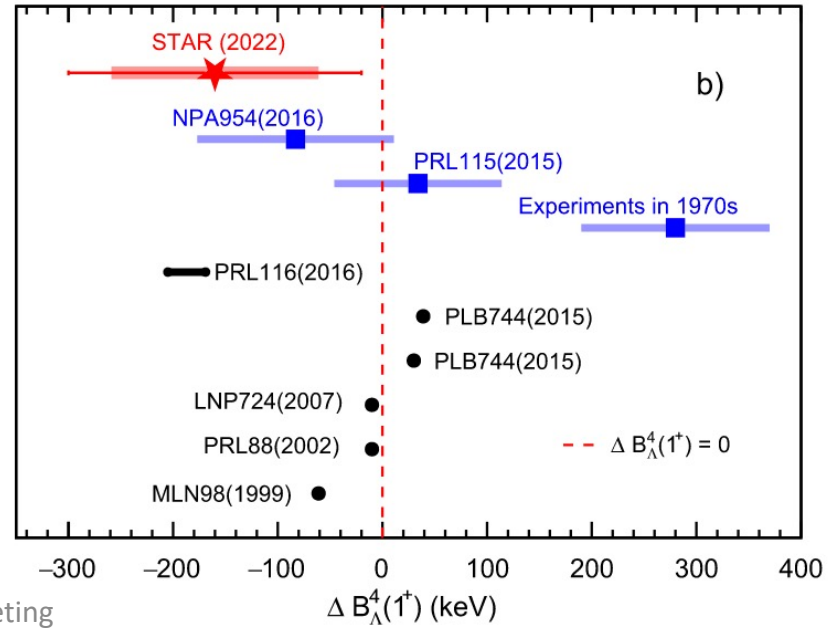
Binding energy of hypernuclei masses

PLB 834 (2022) 137449

- Charge symmetry breaking observed between triton and ^{3}He
- Study hyper-nucleon (YN) interactions:
  - Λ is neutral: expect Λ-p and Λ-n interactions to be similar
  - however, binding energy difference $\Delta B^4_\Lambda(0^+_{gs})$ between $^4H_\Lambda$ and $^4He_\Lambda$ much larger
- Ab initio chiral effective field calculations that include CSB effect claim $\Delta B^4_\Lambda(1^+_{exc}) \approx -\Delta B^4_\Lambda(0^+_{gs}) < 0$

➢ confirmed by STAR using Au+Au at $\sqrt{s_{NN}}$ =3GeV data set

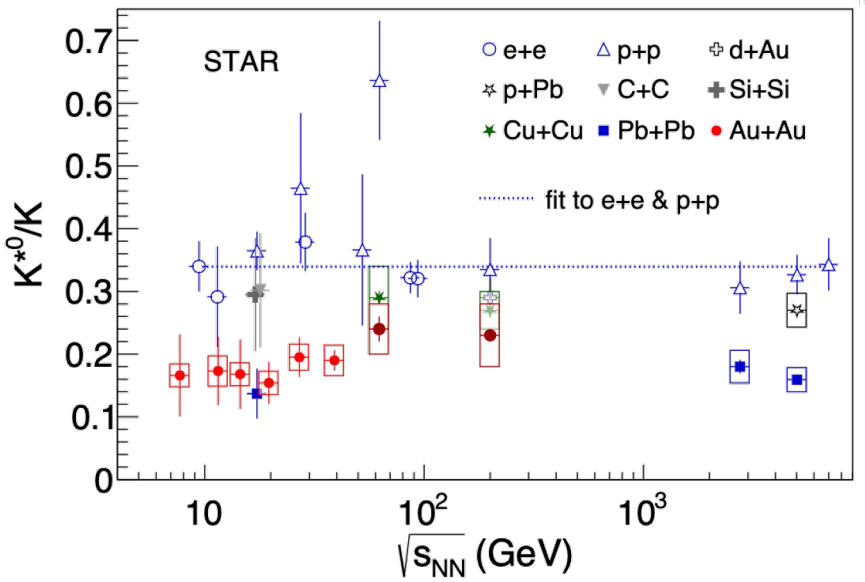


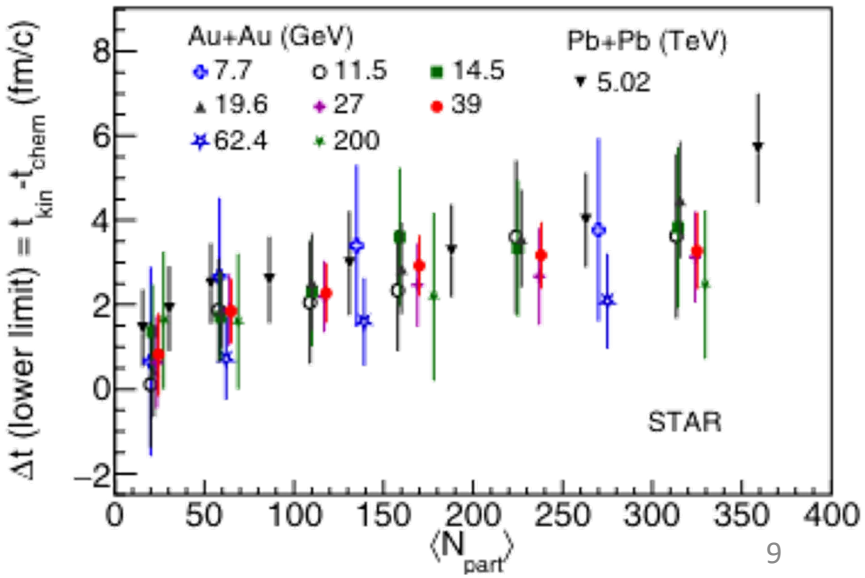


BES-1 :: K^{*0} measurements

PRC 107 (2023) 034907

- K^{*0} short-lived resonance (4.16 fm/c) → ideal candidate to probe hadronic phase between chemical and kinetic FO
  - competing rescattering and regeneration
  - measure the K^{*0}/K ratio in central Au+Au collisions
- K^{*0}/K observed to be smaller than in small systems (e.g., e+e, p+p)
- similar decreasing centrality dependence as in previous RHIC and LHC measurements
  - compare with ϕ/K ratio which is mostly independent from centrality

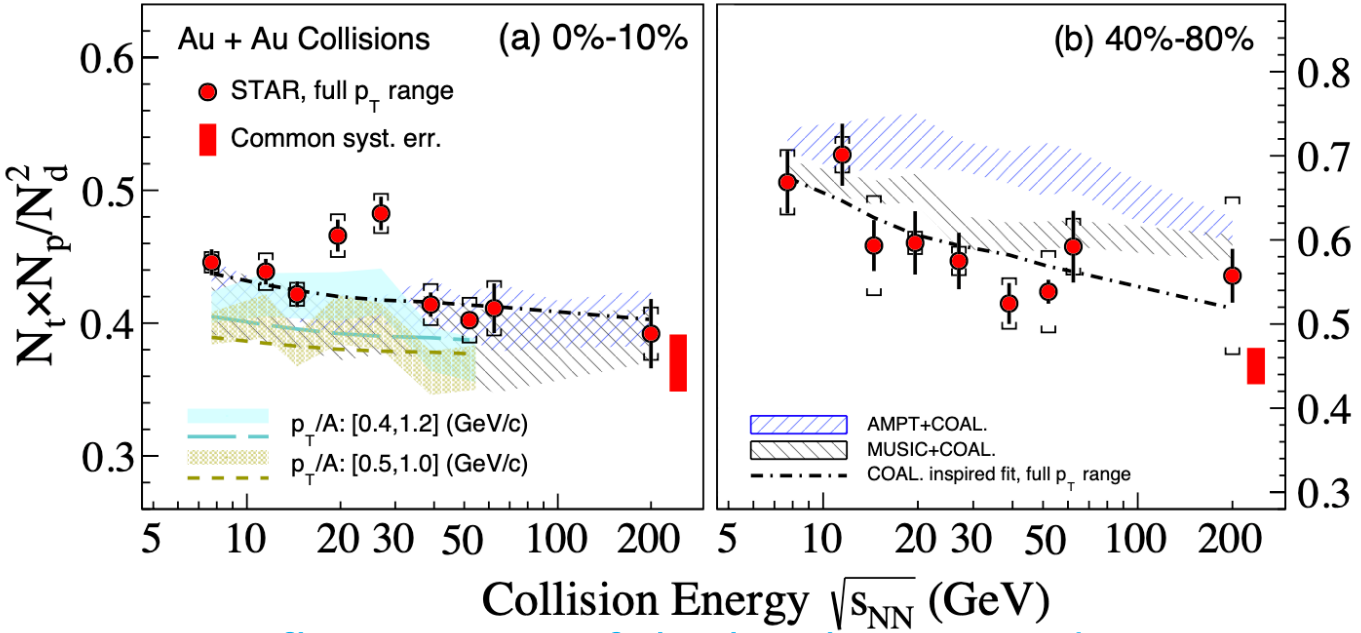




➢ in support of a dominance of K^{*0} hadron rescattering over regeneration

- estimate (lower limit) of lifetime between chemical and kinetic FO, assuming
  - all losses are due to hadronic rescattering
  - no regeneration

Light nuclei yield ratio



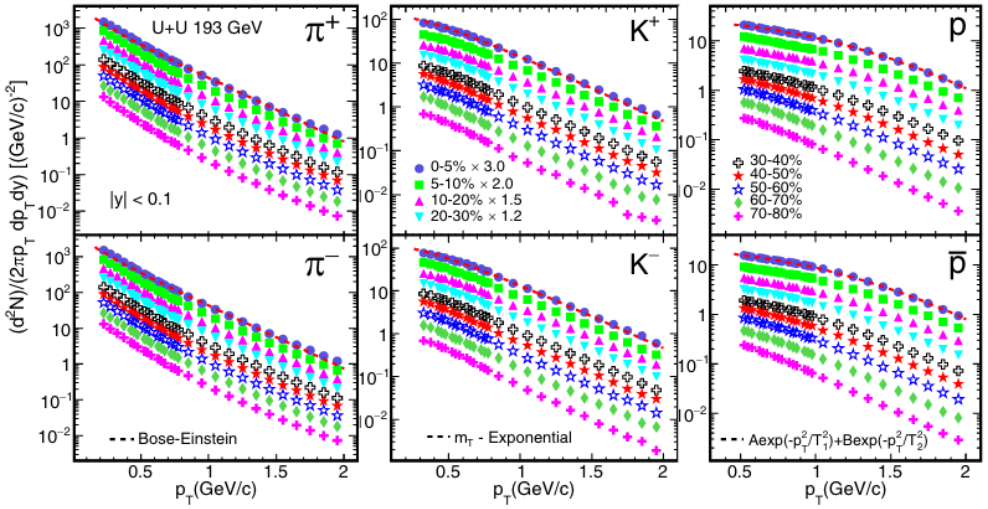
PRL 130 (2023) 202301

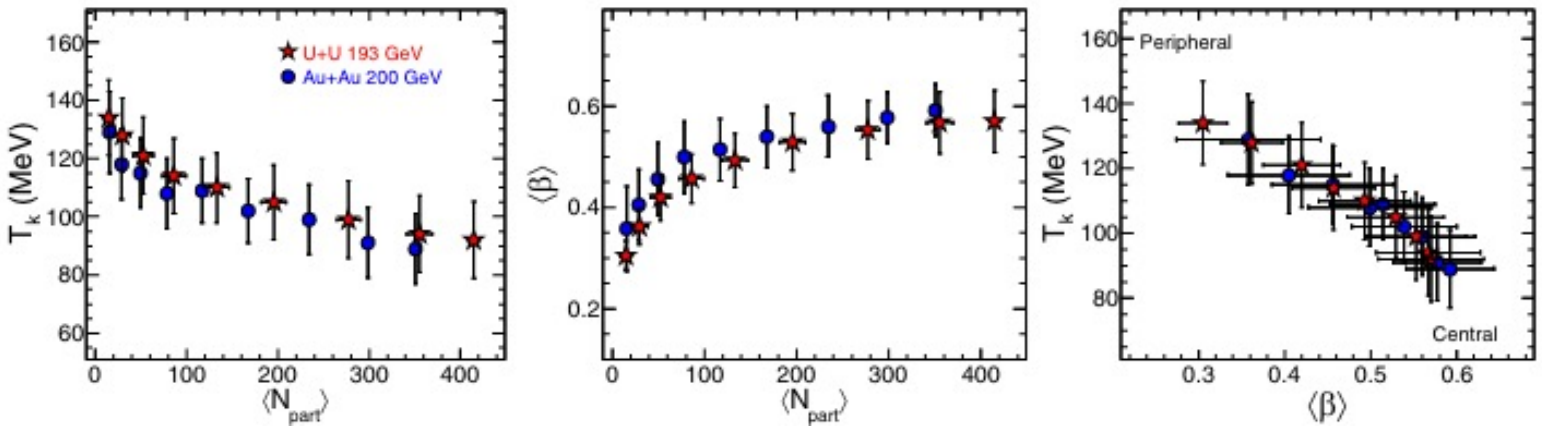
- ratio $N_t N_p / N_d^2$: sensitive to fluctuations of the local neutron density
  - enhancements relative to coalescence baseline
  - significance (0-10%)
    - 19.6 GeV → 2.3$\boldsymbol{\sigma}$
    - 27 GeV → 3.4$\boldsymbol{\sigma}$

➢ Constrain production dynamics of light nuclei and our understanding of QCD phase diagram

Light hadron production U+U @ $\sqrt{s_{NN}}$=193 GeV

PRC 107 (2023) 024901

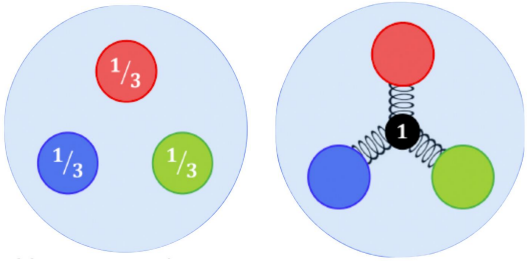




- Comprehensive paper releasing $\pi^{+/-}$, $K^{+/-}$, (anti)proton spectra
  - various bulk observables, e.g. particle yields, <pT>, particle ratios,
- compared with published Au+Au @ $\sqrt{s_{NN}}$=200 GeV and AMPT models
  - ➢ consistency with 200GeV measurements in similar $\langle N_{part} \rangle$ ranges
  - suggests that when combining all (different) initial state orientations of U+U collisions the resulting final state approximates what is observed in spherically symmetry nuclei, i.e. governed by $\langle N_{part} \rangle$

Search for evidence of the baryon junction

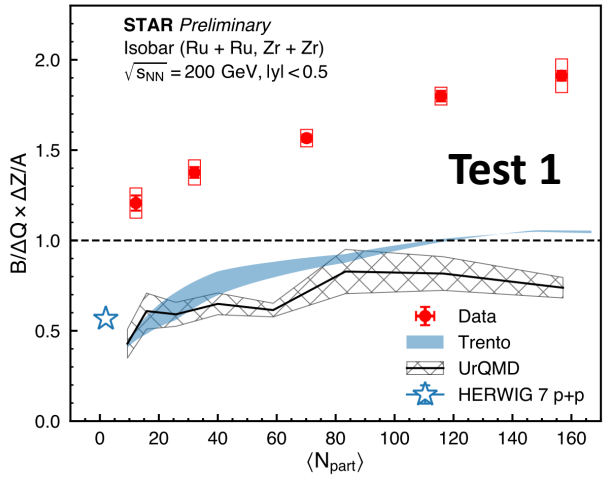
- What carries baryon number?
  - valence quark *vs* baryon junction?



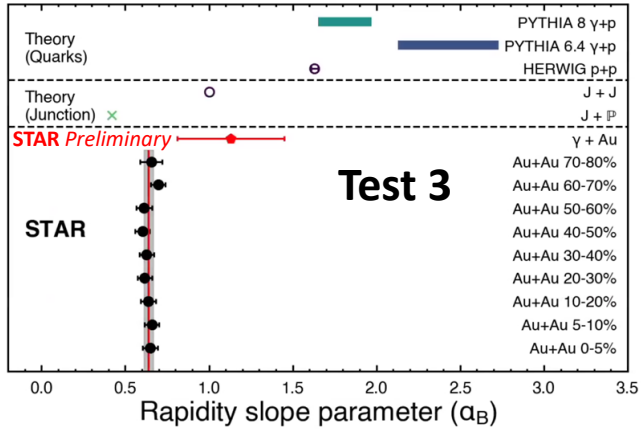
- Valence quark carry most of the momentum
- Junction carries lower momentum
  - enhanced baryon stopping ad midrapidit

Three tests:

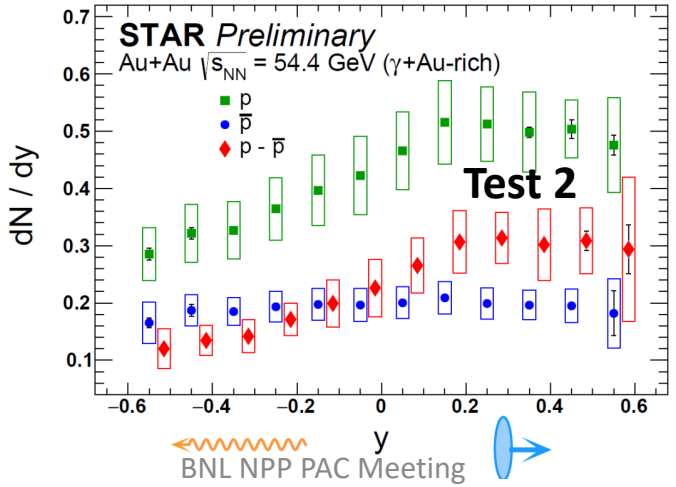
1. net-B *vs* net-Q in isobar collisions
2. net-B in photonuclear collisions
3. net-proton yield vs rapidity in hadronic Au+Au collisions



Model calculations cannot describe isobar data



slopes of net-p yields < PYTHIA/HERWIG



net-p yield described by $e^{-(1.32\pm0.32)\delta y}$
PYTHIA predicts $e^{-(2.43)\delta y}$

➢ Simple valance quark picture not compatible with data

Flow, Chirality, and Vorticity

- Observation of Global Spin Alignment of ϕ and K^{*0} Vector Mesons in Nuclear Collisions, Nature **614** (2023) 244
- Collision-system and beam-energy dependence of anisotropic flow fluctuations, PRL **129** (2022) 252301
- Observation of Directed Flow of Hypernuclei $^3H_\Lambda$ and $^4H_\Lambda$ in $\sqrt{s_{NN}}$ = 3 GeV Au+Au Collisions at RHIC, PRL **130** (2023) 212301
- Measurements of the elliptic and triangular azimuthal anisotropies in central ^{3}He+Au, d+Au and p+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRL **130** (2023) 242301
- Beam energy dependence of the linear and mode-coupled flow harmonics in Au+Au collisions, PLB **839** (2023) 137755
- Search for the Chiral Magnetic Effect in Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV with the STAR forward Event Plane Detectors, PLB **839** (2023) 137779
- Centrality and transverse momentum dependence of higher-order flow harmonics of identified hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRC **105** (2022) 64911
- Pair invariant mass to isolate background in the search for the chiral magnetic effect in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRC **106** (2022) 34908
- Azimuthal anisotropy measurement of (multi)strange hadrons in Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV, PRC **107** (2023) 24912
- Search for the chiral magnetic wave using anisotropic flow of identified particles at RHIC, PRC **108** (2023) 14908
- Event-by-event correlations between Λ (anti-Λ) hyperon global polarization and handedness with charged hadron azimuthal separation in Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV from STAR, PRC **108** (2023) 14909
- Global polarization of Λ and anti-Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV, PRC **108** (2023) 14910

Global spin alignment of vector mesons

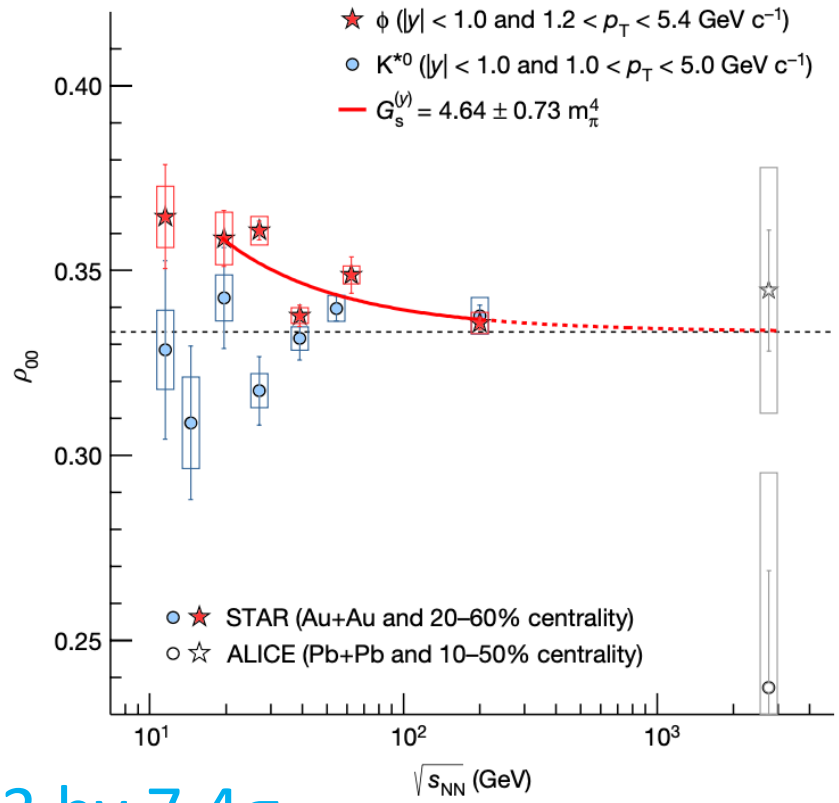
$$\rho_{00}(\phi) \approx \frac{1}{3} + c_\Lambda + c_\epsilon + c_E + c_\phi;$$

Λ-like (-10^{-5})

Electric field (10^{-5})

Vorticity tensor (-10^{-4})

Vector meson field



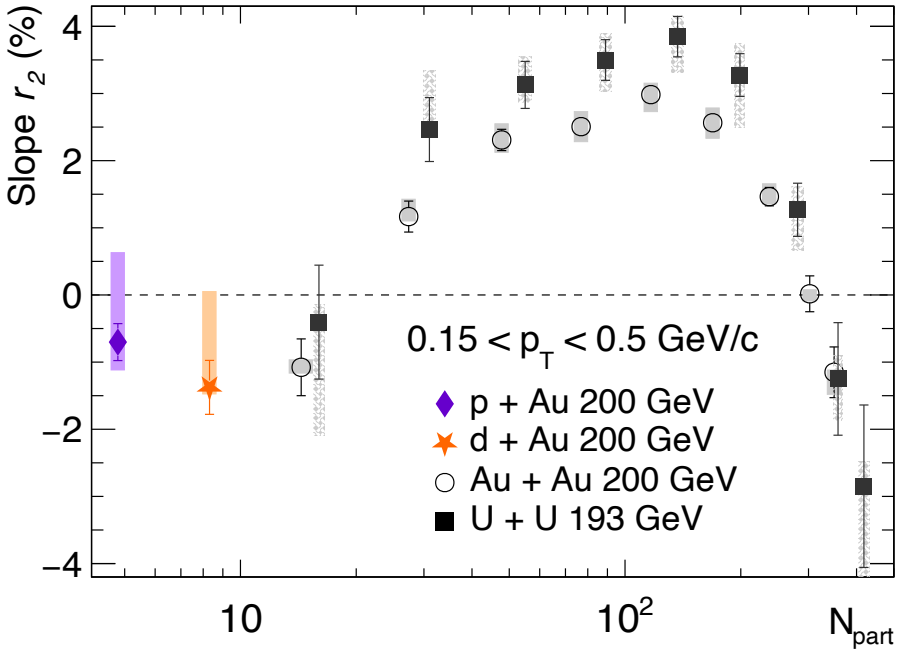
Nature 614 (2023) 224

- Surprising pattern observed: ϕ-meson $\rho_{00} > 1/3$ by 7.4σ
  - *possible explanation with a strong vector meson field;*
  - *provides a potential new avenue for understanding the strong interaction at work at the subnucleon level*

Search for the Chiral Magnetic Wave

- Look for differences in v_2 between positive and negatively charged particles
  - STAR comprehensive study; results include Au+Au $\sqrt{s_{NN}}$= 27 – 200GeV, UU at 193GeV, and p/d+Au 200GeV
- at LHC, $r_2=d\Delta v_2/dA_{ch}$ slopes similar in p+Pb and Pb+Pb at 5.02TeV
  - suggests r_2 slopes in Pb+Pb not arising from CMW
- Potential difference in physics mechanism at RHIC *vs* LHC
  - could magnetic field strength at LHC drop faster than at RHIC energies?
- Compare small systems, p/d+Au with Au+Au, U+U
  - ➢ r_2 measurements in small systems at RHIC compatible with 0
  - ▪ absence of CMW signal in small system -> supports decoupling B-field and 2nd order event plane

PRC 108 (2023) 014908

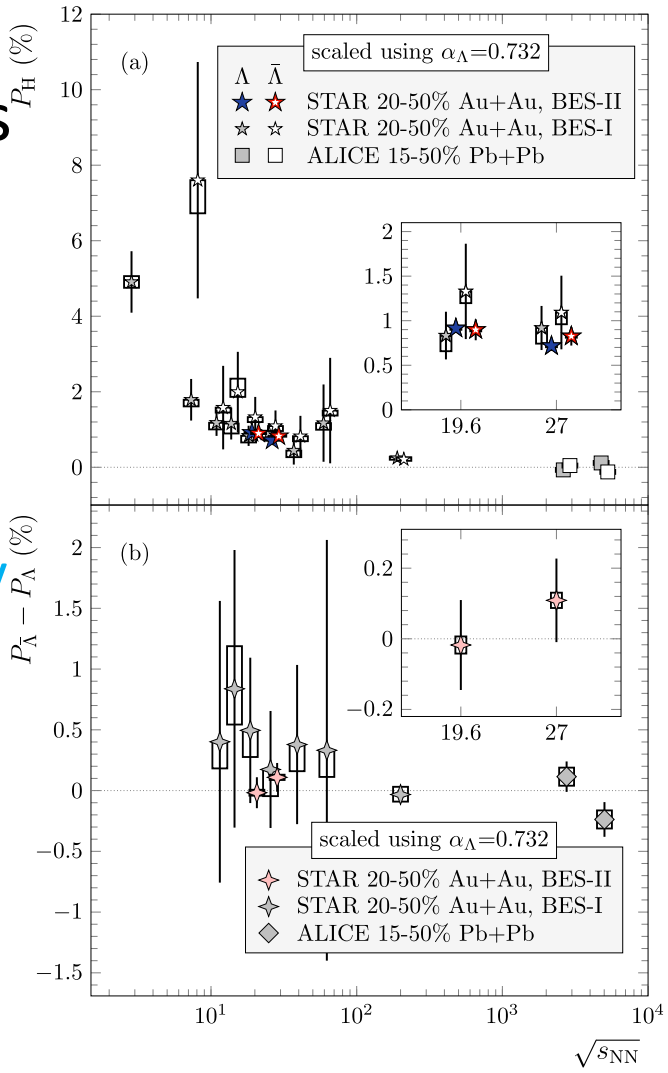


BES-2: Global hyperon polarization

PRC 108 (2023) 014910

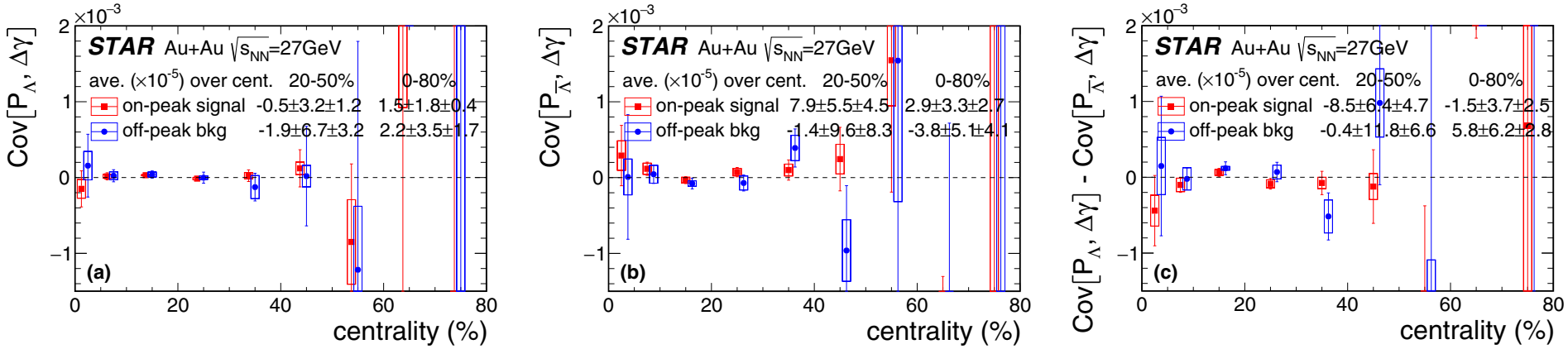
- Polarization measured across wide range of beam energies
  - is there splitting between P(Λ) and P(Λbar)?
    - suggested from late-stage B-field

- High-statistics samples for Au+Au for 19.6 and 27 GeV
  - ➢ upper limits for P(Λbar) - P(Λ) < 0.24% and < 0.35%, respectively
  - with (naïve) assumptions, B-field estimates B < 9.4×10^{12} T and $< 1.4 \times 10^{13}$ T, respectively
  - call for better theory understanding of late-stage B field, and higher statistics, and study of y-dependence



Global P(Λ) correlation measurements

PRC 108 (2023) 014909



- Use event-by-event correlations between global Λ polarization measurements and CME observables in Au+Au at 27 GeV

➢ Covariance of $P_{\Lambda(bar)}$ and parity-even azimuthal correlator $\Delta\gamma=\gamma_{OS}-\gamma_{SS}$ consistent with 0

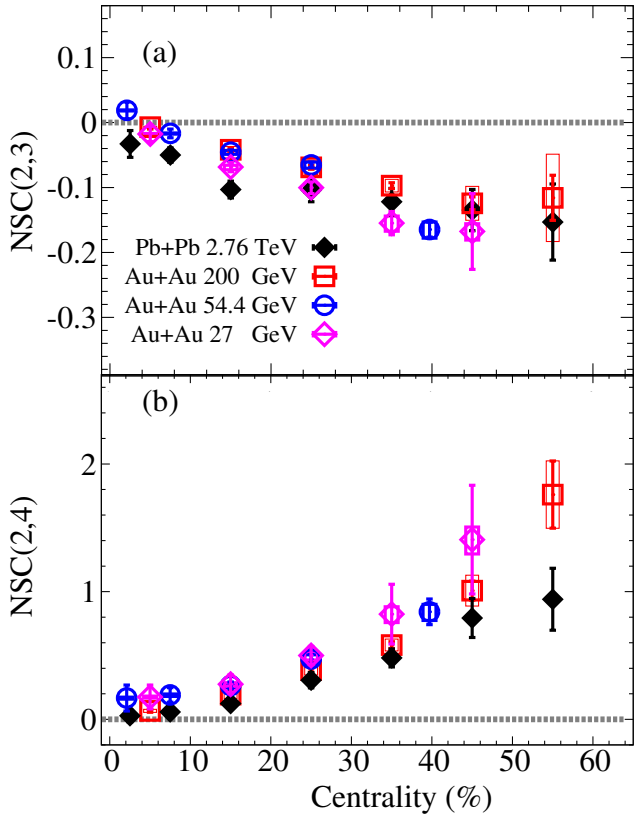
  - correlations less than 10^{-4} but needs theory input to appreciate the significance in terms of CME

BES-1/2: $\sqrt{s_{NN}}$ dependence flow correlations

†PRL 129 (2022) 252301
†† PLB 839 (2023) 137755

- BES-1 comprehensive measurement† of $v_2\{k\}$ k=2,4,6
  - comparison to model calculations and LHC suggest initial-state-driven fluctuations dominate the flow fluctuations
- BES-2 (27 and 54.4 GeV) Normalized Symmetric Cumulants††
  - distinguish between different IS models
  - pin down T, μ_B dependence of specific shear viscosity η/s

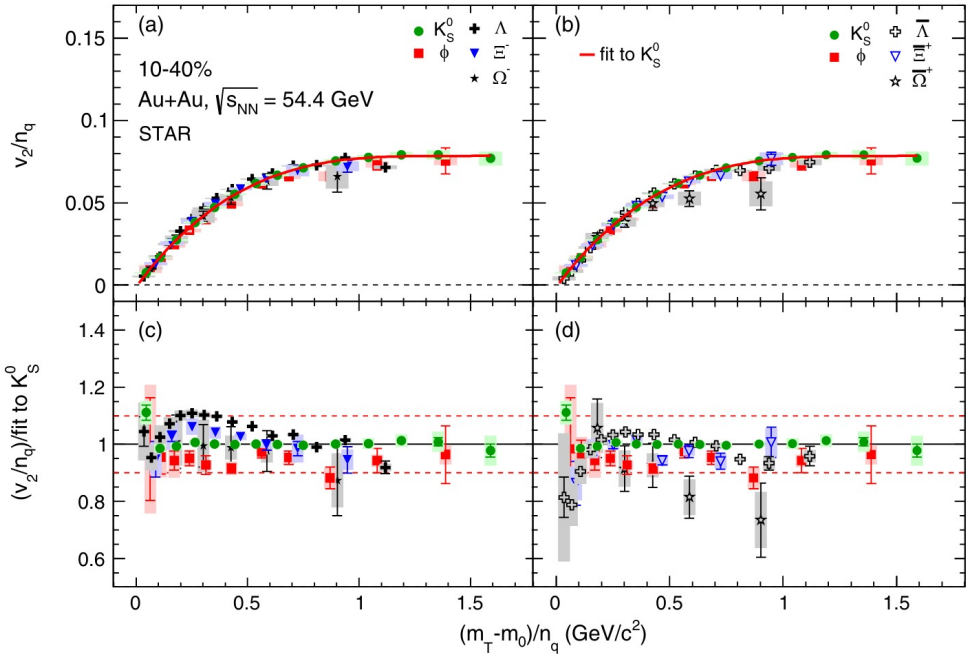
➢ NSC(2,4) and NSC(2,3) nearly beam independent
  - consistent with significant role from IS effects

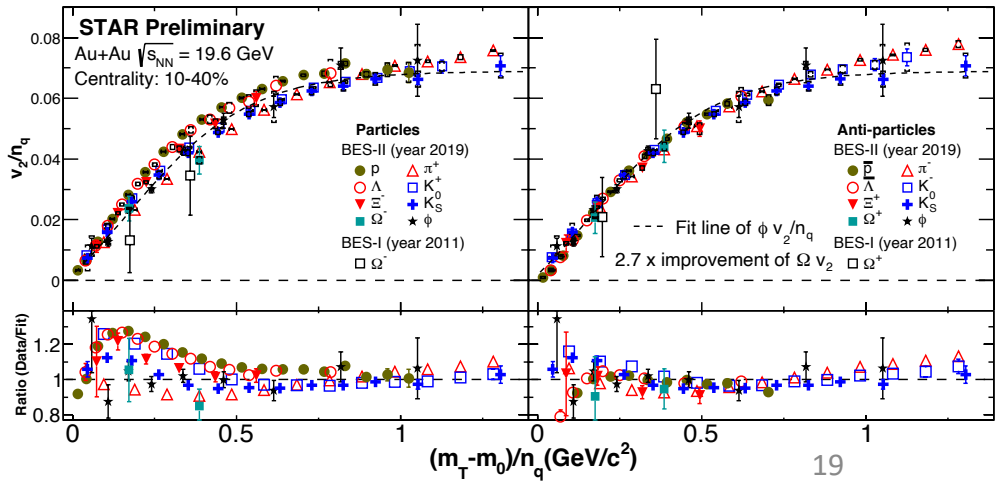


BES-2 v_2 of identified particles

PRC 107 (2023) 024912

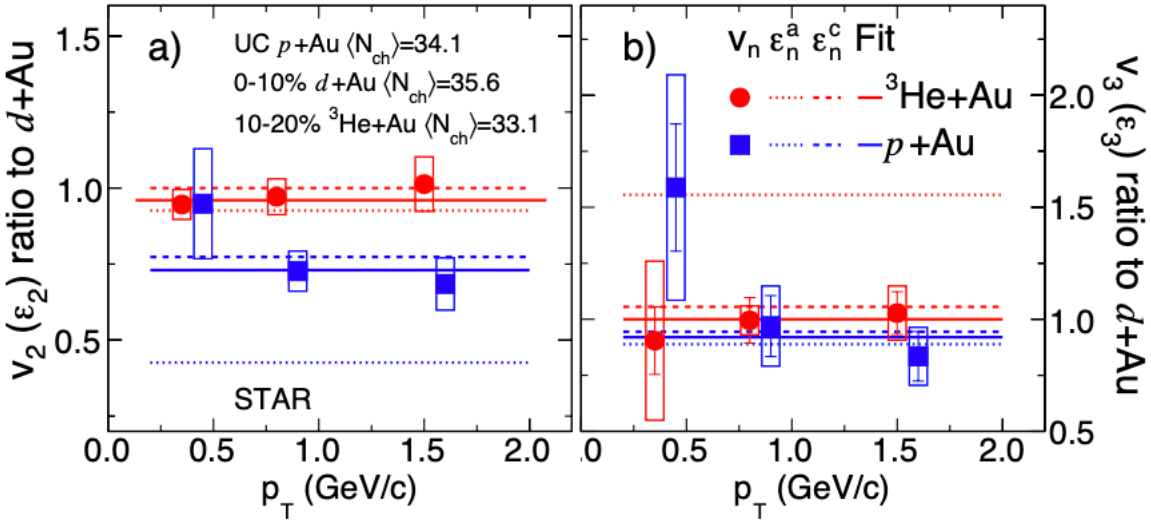
- azimuthal anisotropy of identified particles *vs* p_T and centrality
  - help put substantial constraints on transport and hydro models
- Run-17 54 GeV data for (multi)strange hadrons published
  - ➢ n_q scaling of v_2 holds within 10%
- Preliminary BES-2 results at 14.6 and 19.6 GeV
  - indicate n_q scaling for multi-strange particles is violated





Elliptic & triangular flow in small-sized systems

PRL 130 (2023) 242301



v_2 (^{3}He+Au) ~ v_2 (d+Au) > v_2 (p+Au)
v_3 (^{3}He+Au) ~ v_3 (d+Au) ~ v_3 (p+Au)

➢ Suggest an influence on eccentricity from sub-nucleonic fluctuations in small-sized systems

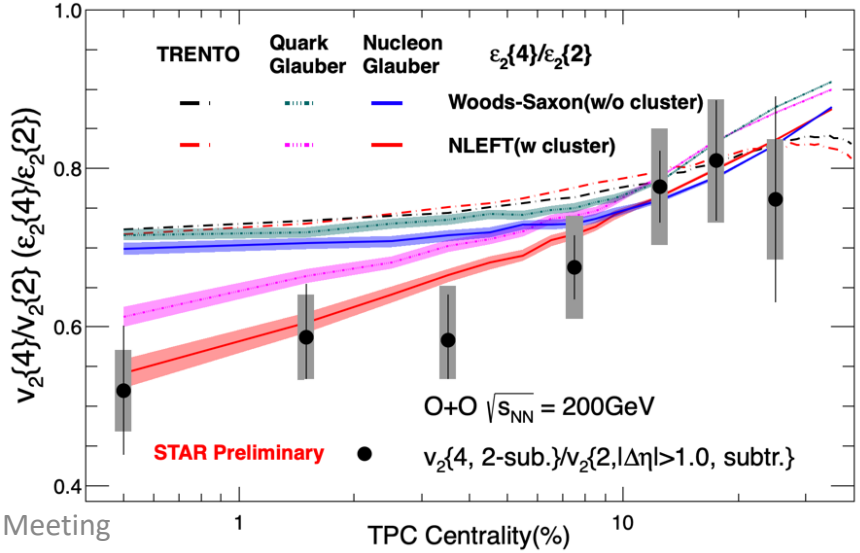
- provide stringent constraints on the hydrodynamic modeling

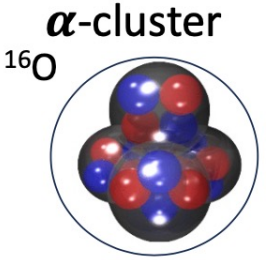
Next: Run-21 d+Au data with forward upgrades to explore mid-mid *vs* mid-forward correlations

Flow in O+O at 200GeV (preliminary, QM23)

- $v_2\{4\}$ drops faster than $v_2\{2\}$ in central O+O

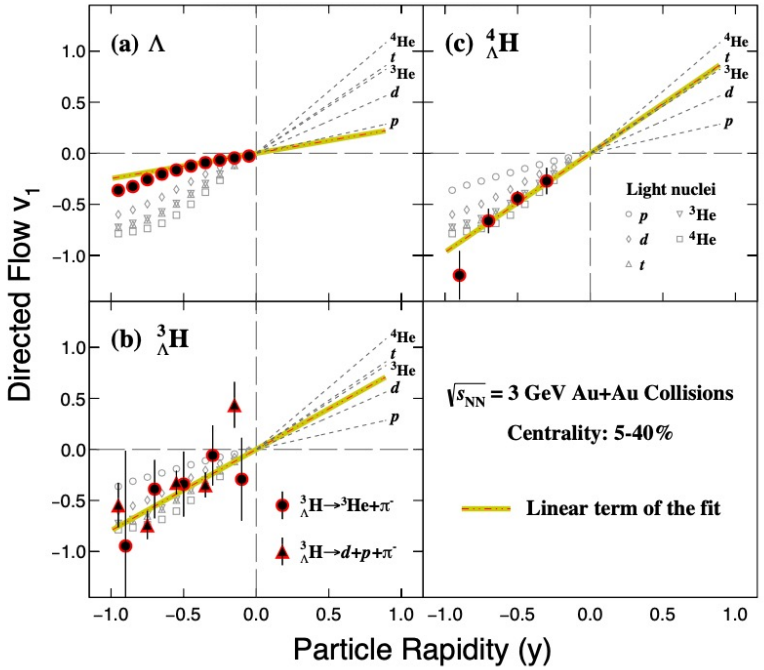
➢ $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from nucleon or quark Glauber model with clusters describe $v_2\{4\}/ v_2\{2\}$ better than without

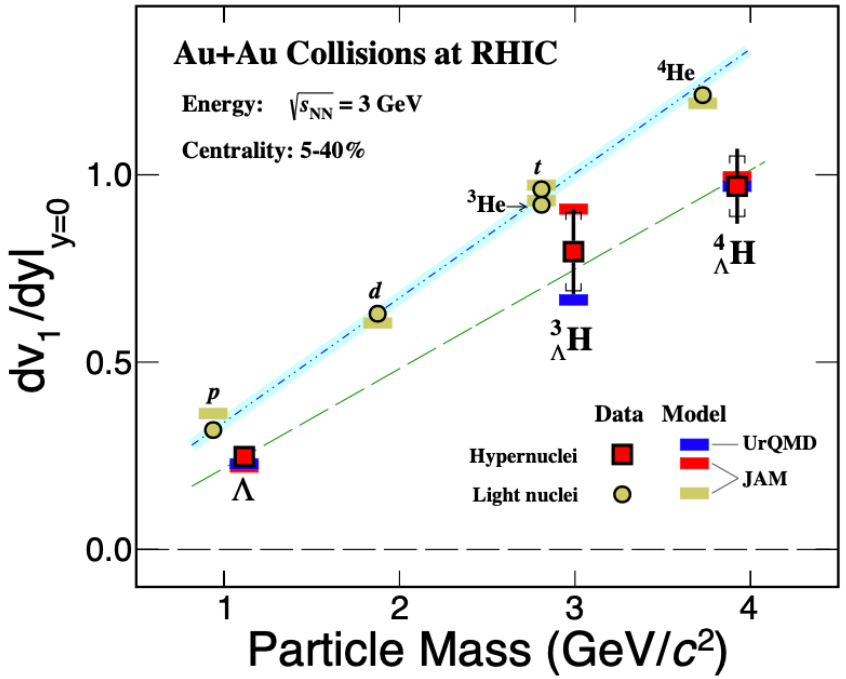




Directed Flow of Hyper-nuclei

PRL 130 (2023) 212301





- First observation of significant hypernuclei directed flow in high energy nuclear collisions
  - Fixed target program: Au+Au at 3GeV
- Midrapidity v_1 slopes follow baryon number scaling
  - implying that coalescence is the dominant production mechanism

➢ Constrain hyperon-nucleon interactions at high baryon density

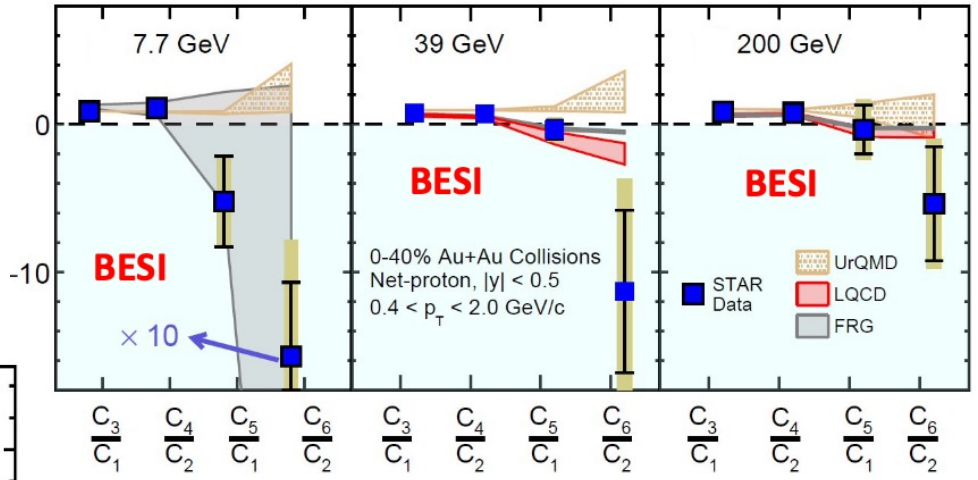
Correlations & Fluctuations

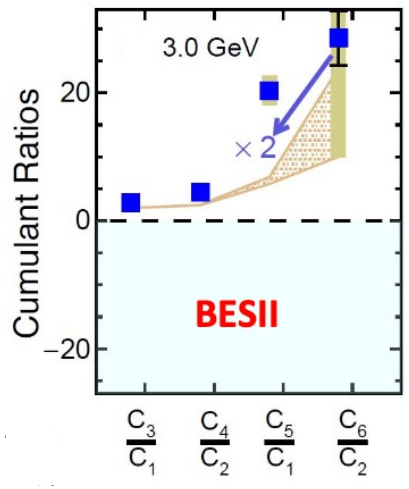
- Observation of Global Spin Alignment of phi and K^{*0} Vector Mesons in Nuclear Collisions, Nature **614** (2023) 244
- Beam Energy Dependence of Fifth and Sixth-Order Net-proton Number Fluctuations in Au+Au Collisions at RHIC, PRL **130** (2023) 82301
- Higher-order cumulants and correlation functions of proton multiplicity distributions in sqrt{sNN} = 3 GeV Au+Au collisions at the RHIC STAR experiment, PRC **107** (2023) 24908
- Energy Dependence of Intermittency for Charged Particle in Au+Au at RHIC, accepted by PLB

BES-1/2: Hyper-order Cumulant Ratios

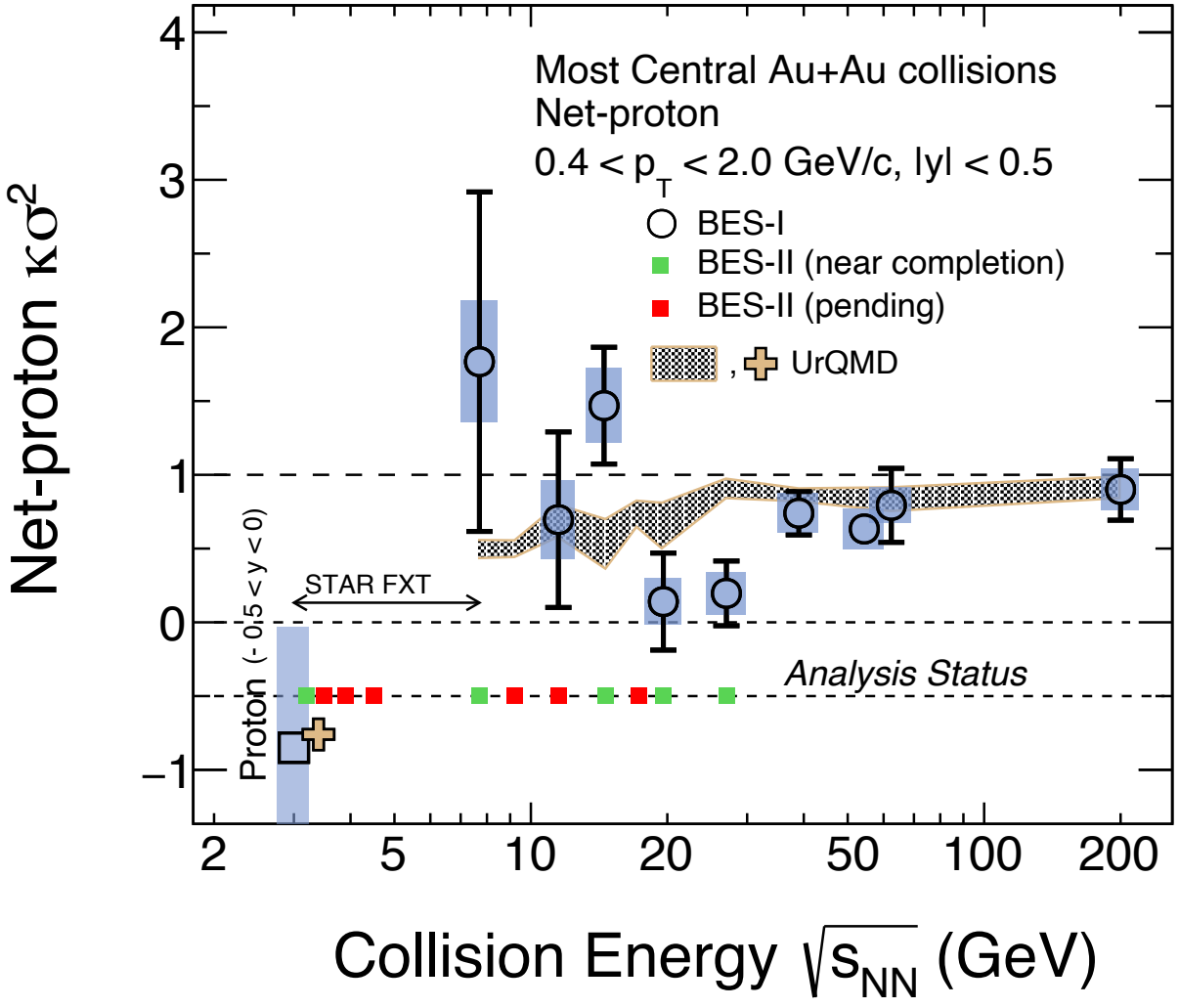
PRL 130 (2023) 082301

- Higher-order cumulants more sensitive to correlation length
- Cumulant ratios cancel volume dependence
  - directly related to susceptibilities
- 7 – 200GeV: falling trend of with rising order
  - ➢ $C_3/C_1 > C_4/C_2 > C_5/C_1 > C_6/C_2$
    - predicted by LQCD
- 3 GeV:
  - ➢ rising trend with rising order
    - in agreement with UrQMD
    - suggestive of hadronic matter



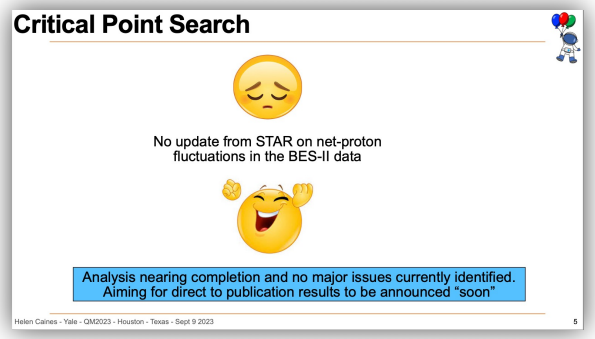


Net-proton analysis status at BES-II energies



Strategy:

- multiple analysis teams
- no preliminary releases
- collider energies and FXT each in single paper



Helen Caines @QM23

near completion*

$\sqrt{s_{NN}}$ = 3.2 (FXT),
7.7, 14.6, 19.6, 27 GeV

pending* = due to unavailability of embedding

$\sqrt{s_{NN}}$ = 3.5 (FXT), 3.9 (FXT), 4.5 (FXT),
9.2, 11.5, 17.3 GeV

Baseline calculations (UrQMD/CE) for all collision energies near completion

Hard Probes

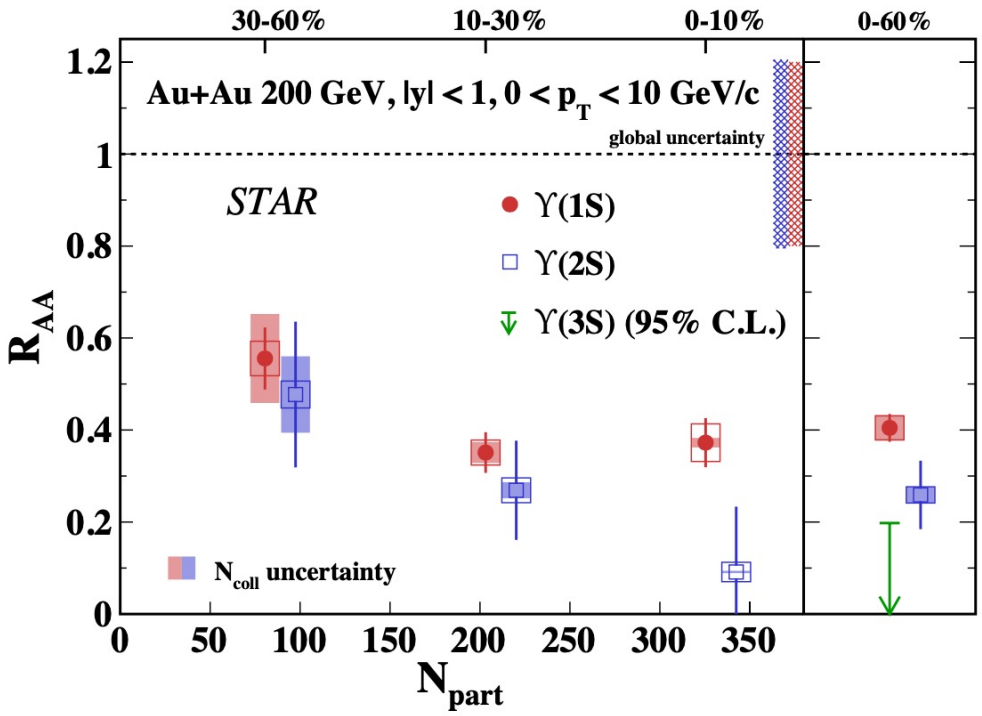
- Elliptic Flow of Heavy-Flavor Decay Electrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV at RHIC, PLB **844** (2023) 138071
- Measurement of electrons from open heavy-flavor hadron decays in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, JHEP **176** (2023) 2023
- Measurement of sequential Upsilon suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRL **130** (2023) 112301
- Evidence of Mass Ordering of Charm and Bottom Quark Energy Loss in Au+Au Collisions at RHIC, EPJC **82** (2022) 1150

Sequential Upsilon Suppression

PRL 130 (2023) 112301

- Υ(1S), Υ(2S), Υ(3S)
  - sizes: 0.28, 0.56, 0.78 fm
- Combined results from dimuon (Run-14-16) and dielectron channels (Run-10)
- At RHIC energies, negligible contributions from b and b-bar recombination
- Excellent probe to study color screening in QGP

➢ magnitude Υ(1S) suppression comparable to LHC energies
  - R_{AA} *vs* p_T and centrality for Υ(1S) and Υ(2S)
  - upper limit for Υ(3S) suppression

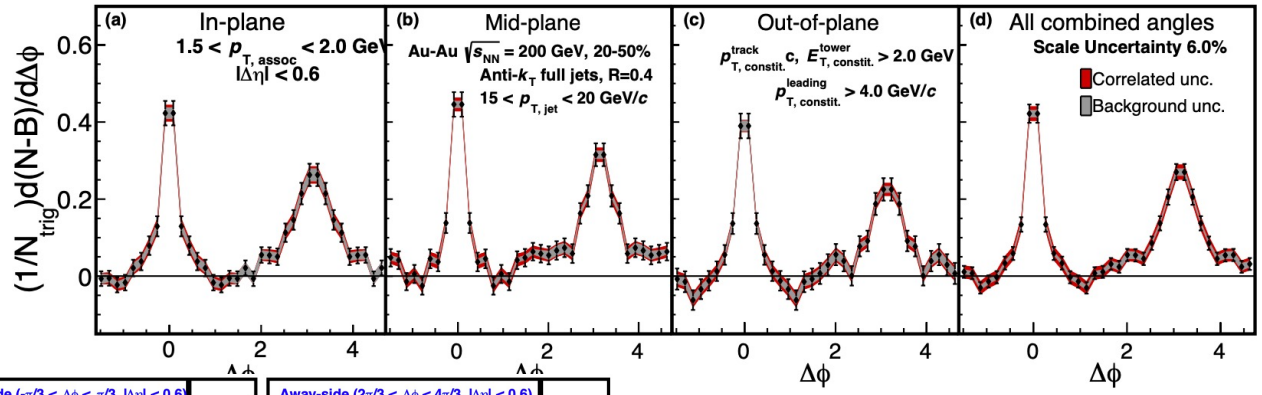


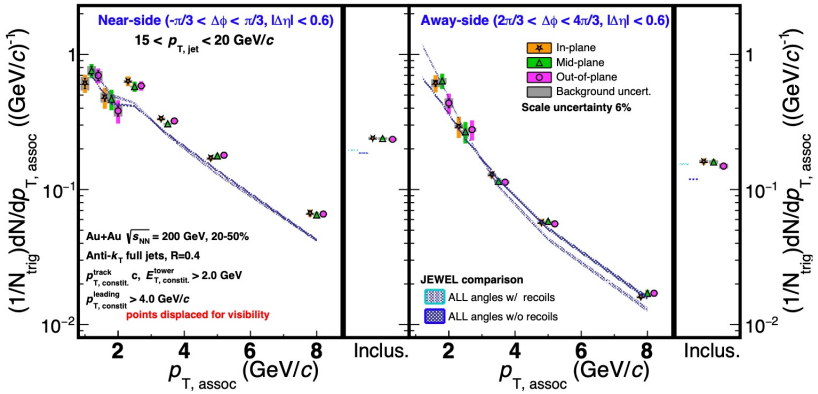
➢ Observe sequential Υ suppression at RHIC

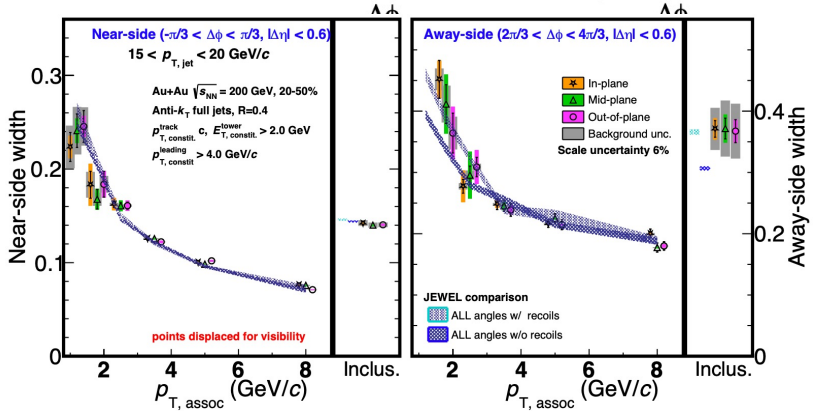
Jet-hadron correlation with respect to event plane

Measure yields and widths in three categories, based on the angle between the trigger jet and the event plane:

- Less than π/6 (in-plane)
- Between π/6 and π/3 (mid-plane)
- Greater than π/3 (out-of-plane)







submitted to PRC
2307.13891

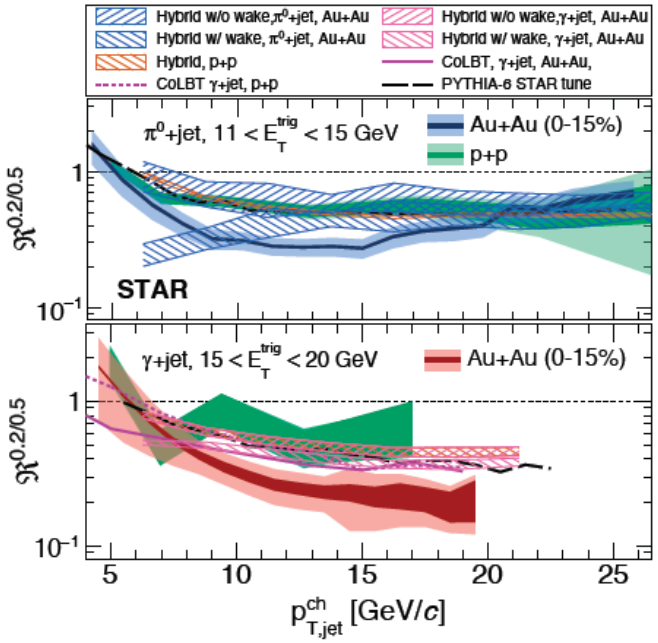
For near-side and away-side yields and widths:

➢ no dependence on orientation of the jet axis with respect to the event plane is seen within the uncertainties in the kinematic region studied

Measurement of in-medium jet modification using direct γ+jet and π^0+jet correlations

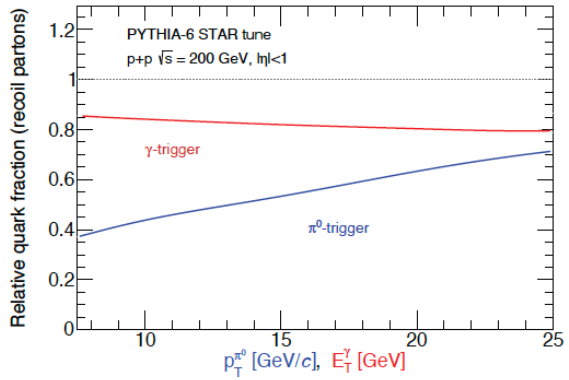
First measurement of jet quenching via γ+jet correlations in central Au+Au collisions at 200GeV

- based on previous STAR photon and jet measurements (mixed-events)



Comparison of γ and π^0 triggers:

- variation in q/g fraction of recoil population
- variation in geometric bias
- significant test of model calculations



submitted to PRL (2309.00156) and PRC (2309.00145)

Jet shape: R-dependence of recoil jet yield

- Jet shape in pp well-described by PYTHIA
- Jet shape broadened in central Au+Au for both triggers

I_{AA}: R=0.5 compatible with unity

➢ new measurements of angular distribution of quenching-induced radiation

➢ not well-described by models

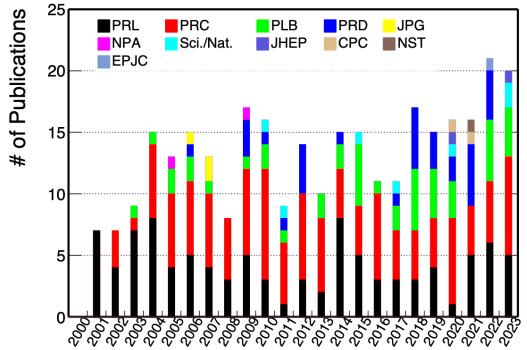
QuarkMatter ‘23 Conference

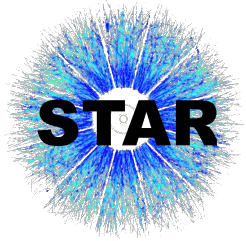
- Record number of STAR contributions
  - 24 parallel speakers
  - 45 contributed posters
  - 5 plenary speakers
    - incl. STAR highlights talk
  - 1 flash speaker (poster award)
  - 1 best presentation award

- Gender balance
  - internal abstract submission ~27% female
    - compared to STAR: 17 ± 5% (”juniors” 22 ± 6%)
  - STAR QM speakers (incl. plenary): 20%
    - compared to QM23 (parallel): 22%

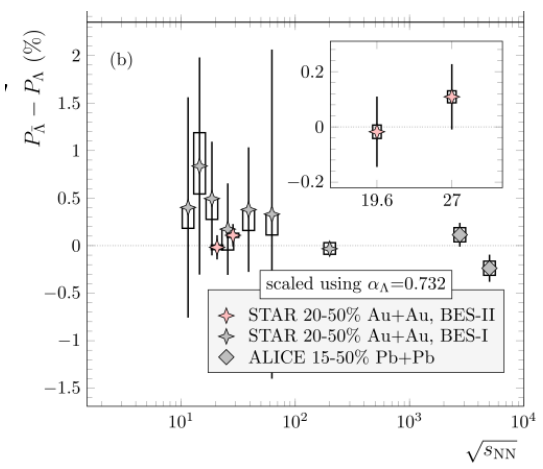
Many STAR results featured in various plenary overview talks, cf. Rosi Reed’s overview talk for the latest preliminary results: https://indico.cern.ch/event/1139644/contributions/5343956/

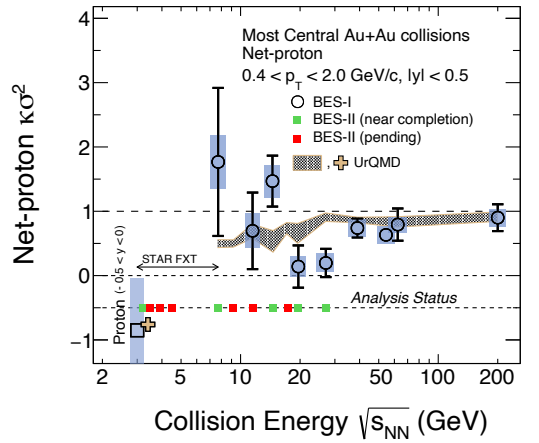
Summary





- STAR's publication record continues to be on a rise
  - large fraction of STAR collaborators is involved in the publication process
- First BES-2 publications from high-statistics 27, 19.6, and 3GeV
  - 10 papers that include results from 3 GeV (FXT, 2018)
  - 8 papers that include results from 27 GeV
  - 1 paper that includes results from 19.6 GeV
- Production of all BES-2 collider data finished
  - FXT production (2021) underway
- Net-proton analyses:
  - no release preliminary results
  - publications for collider energies in ~6 months
- Many preliminary results from all BES-2 collider energies at QM'23
  - next: prepare for publications
  - continue to rely on involvement of the full collaboration
  - continue to rely on the support from BNL





STAR at QuarkMatter 2023