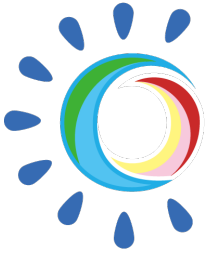


SQM2022

The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Recent results from STAR

Barbara Trzeciak, for the STAR Collaboration
Czech Technical University in Prague

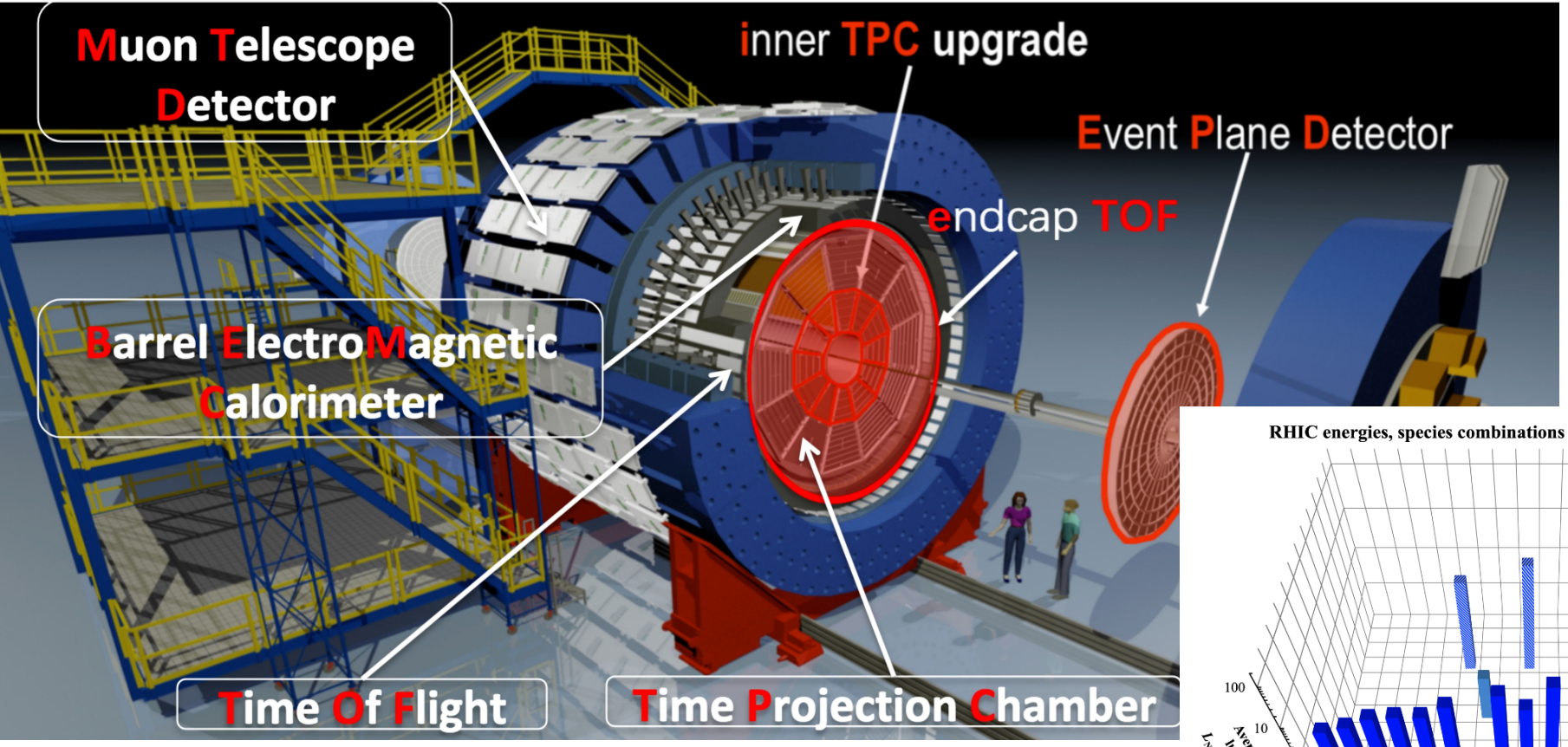
Supported in part by

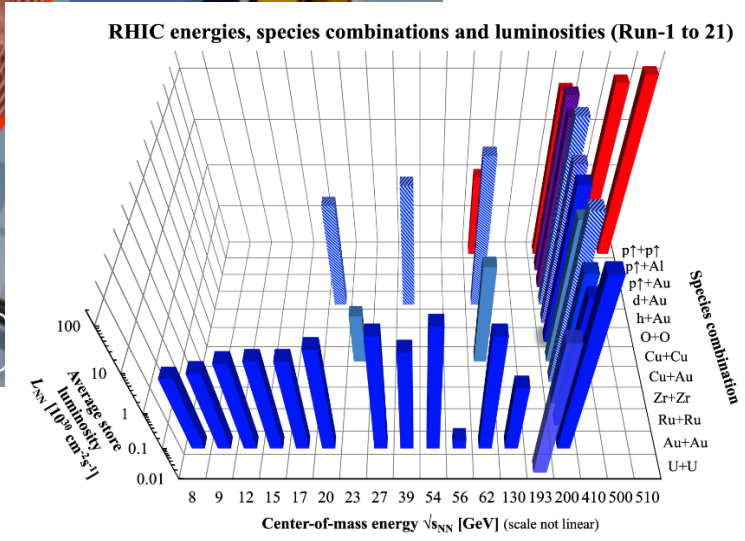
U.S. DEPARTMENT OF ENERGY | Office of Science

CTU CZECH TECHNICAL UNIVERSITY IN PRAGUE

GAČR CZECH SCIENCE FOUNDATION

STAR detector at RHIC





Outline

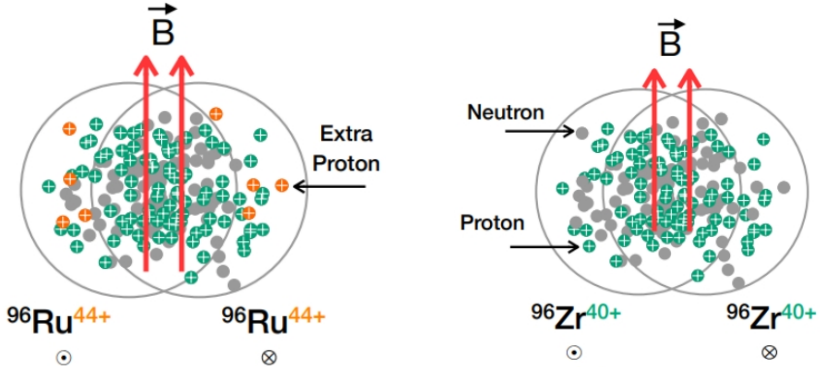
1. Isobar and Au+Au at 200 GeV
   - CME: non-flow background
   - Initial geometry and EM field
   - Global and local hyperon polarization
   - Kaon femtoscopy
   - J/ψ suppression and elliptic flow
   - Higher order cumulants

2. BES-II collider results
   - Particle production
   - Global spin alignment of vector mesons
   - Anisotropic flow of strange hadrons and light nuclei
   - K* resonance production
   - Production of (anti-)light hypernuclei

3. BES-II fixed-target, 3 GeV results
   - Hypernuclei production
   - Strange hadron production
   - Elliptic and directed flow

4. Upgrades and future program

Isobar collisions

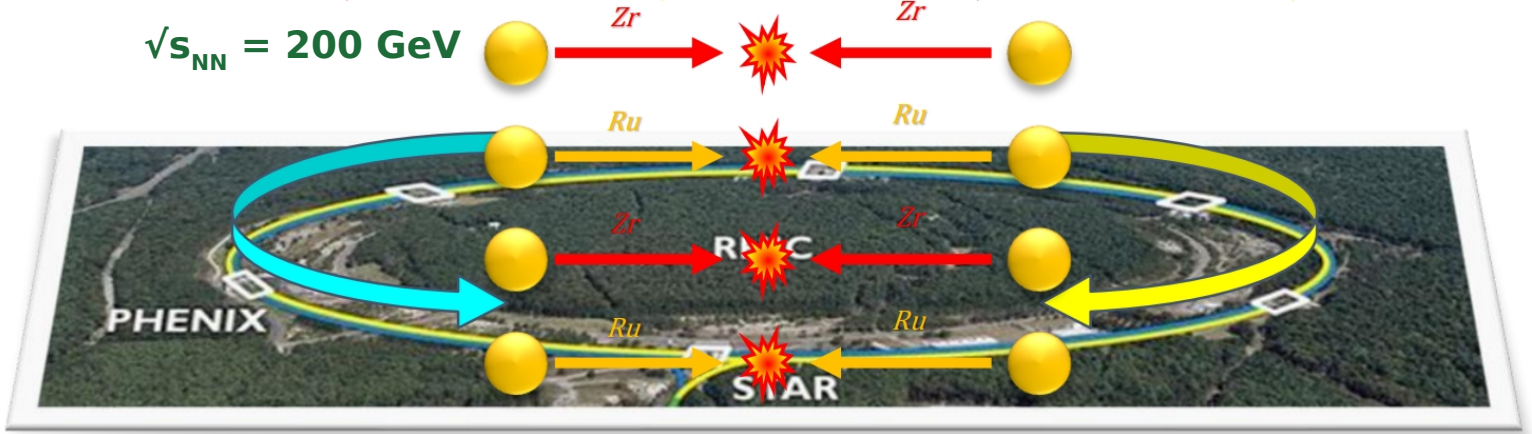


B-field² in Ru+Ru ~15% larger than in Zr+Zr

Special run to minimize systematics:

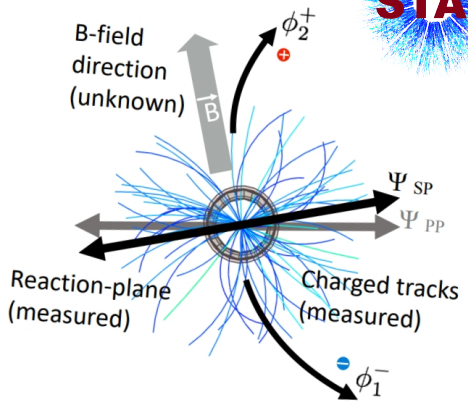
- Fill-by-fill switching
- Level luminosity

$\sqrt{s_{NN}}$ = 200 GeV



CME: non-flow background

- Non-flow correlations → deviation of CME baseline from unity

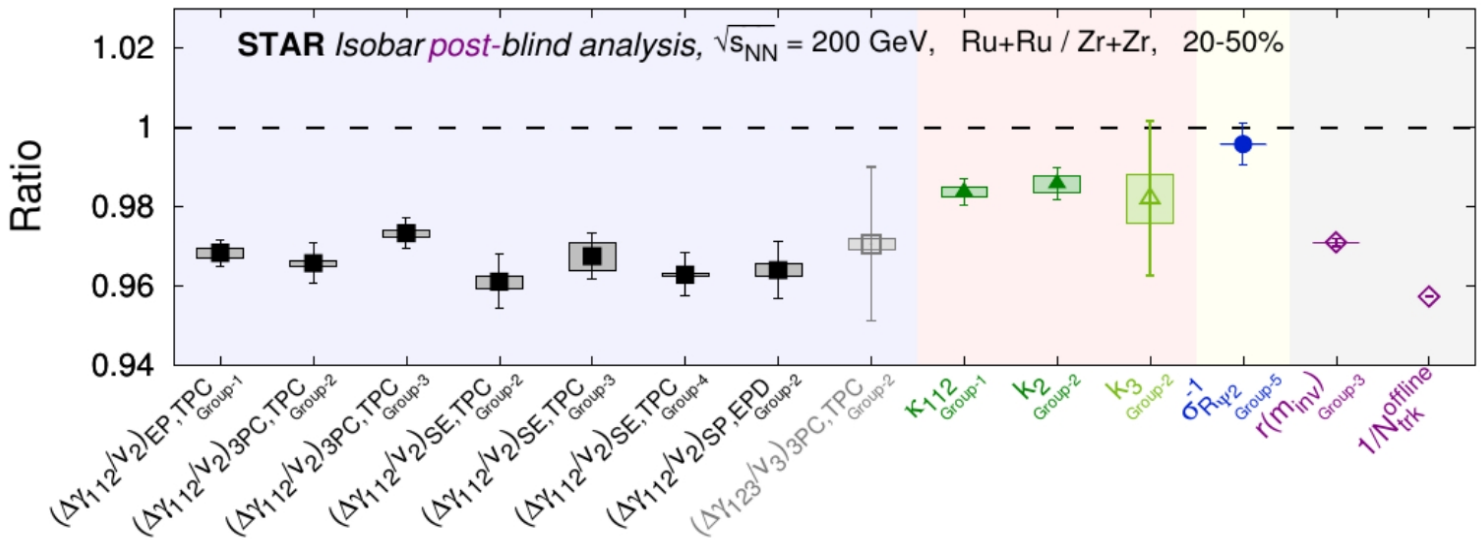


CME sensitive observable

$$\Delta\gamma \equiv C_3/v_2^* \qquad C_{3,\mathrm{OS}} = \langle \cos(\phi_\alpha^\pm + \phi_\beta^\mp - 2\phi_c) \rangle,$$

$$C_3 = C_{3,\mathrm{OS}} - C_{3,\mathrm{SS}} \qquad C_{3,\mathrm{SS}} = \langle \cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\phi_c) \rangle,$$

Pre-defined criteria: $(\Delta\gamma/v_2)_{\mathrm{Ru+Ru}} > (\Delta\gamma/v_2)_{\mathrm{Zr+Zr}}$



STAR, Phys. Rev. C, 105 (2022) 014901

Yicheng Feng
14.6 2:20pm

CME: non-flow background

- Non-flow correlations → deviation of CME baseline from unity

CME sensitive observable

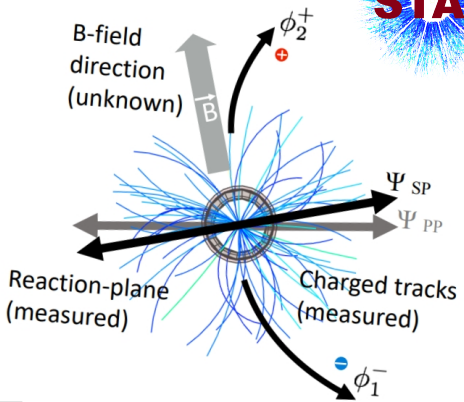
$$\Delta\gamma \equiv C_3/v_2^* \qquad C_{3,\mathrm{os}} = \langle\cos(\phi_\alpha^\pm + \phi_\beta^\mp - 2\phi_c)\rangle,$$

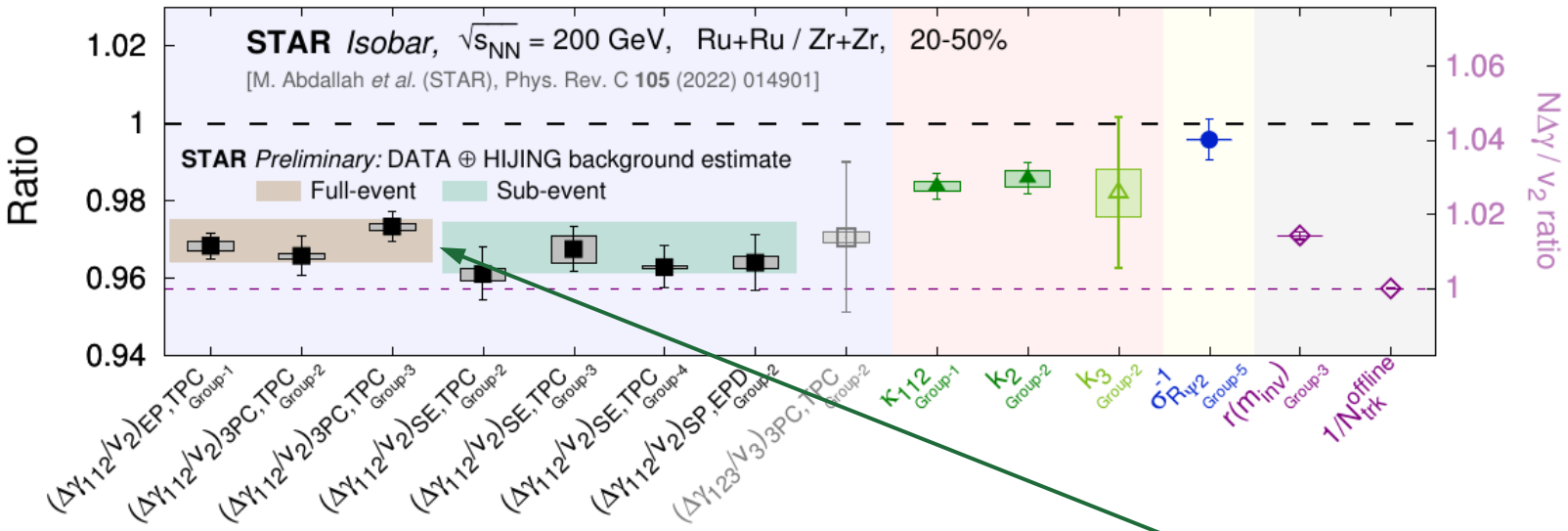
$$C_3 = C_{3,\mathrm{os}} - C_{3,\mathrm{ss}} \qquad C_{3,\mathrm{ss}} = \langle\cos(\phi_\alpha^\pm + \phi_\beta^\pm - 2\phi_c)\rangle,$$

$$\Delta\gamma = \Delta\gamma^{CME} + k\frac{v_2}{N} + \Delta\gamma^{non-flow}$$

Measurement: $\Delta\gamma$ | Signal: $\Delta\gamma^{CME}$ | Bkg 1: $k\frac{v_2}{N}$ | Bkg 2: $\Delta\gamma^{non-flow}$

Pre-defined criteria: $(\Delta\gamma/v_2)_{Ru+Ru} > (\Delta\gamma/v_2)_{Zr+Zr}$



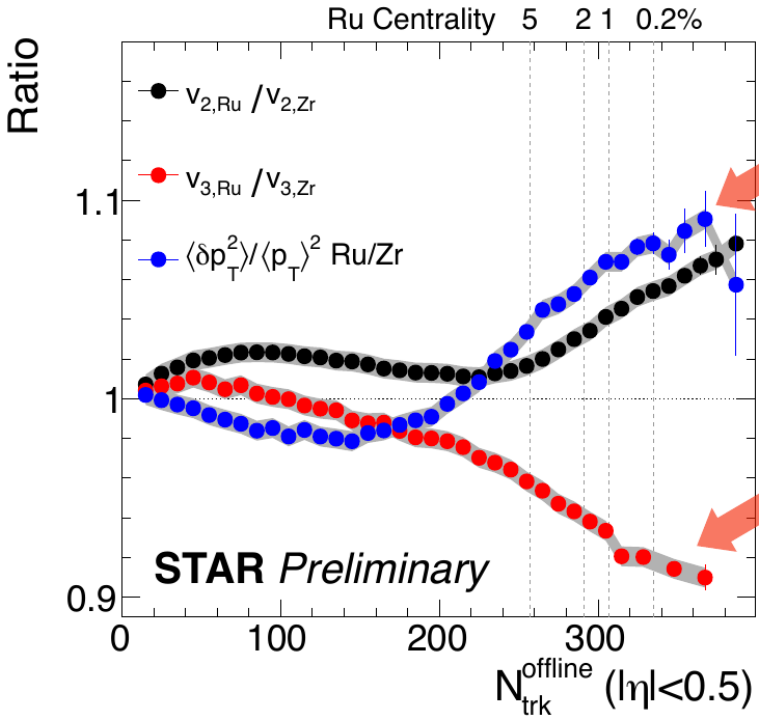


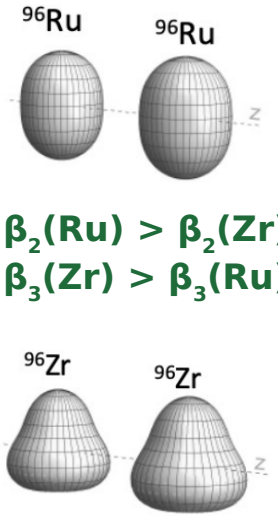
STAR, Phys. Rev. C, 105 (2022) 014901

Yicheng Feng
14.6 2:20pm

➔ Isobar data consistent with the current estimate of non-flow background within error

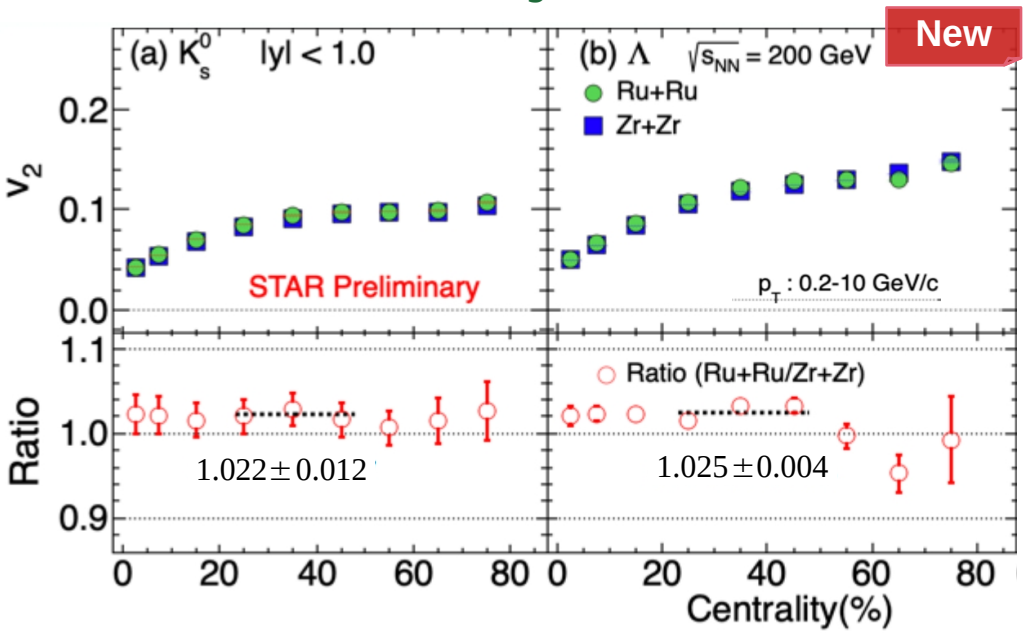
Nuclear deformation





$\beta_2(Ru) > \beta_2(Zr)$
$\beta_3(Zr) > \beta_3(Ru)$

Strange hadrons

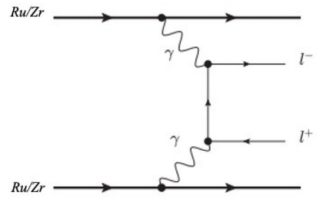


Priyanshi Sinha
14.6 4:10pm

➔ New ways to constrain nuclear deformation with heavy ion collisions

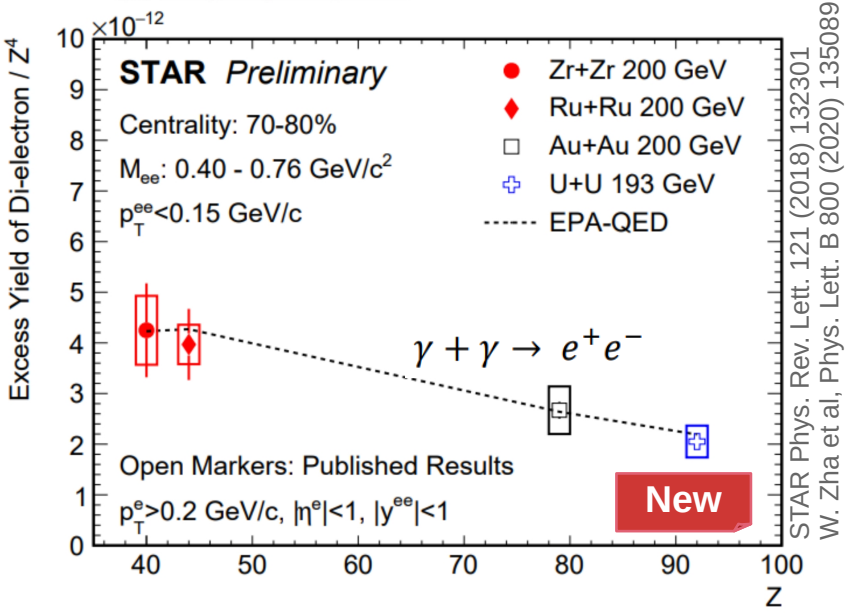
Initial electromagnetic field

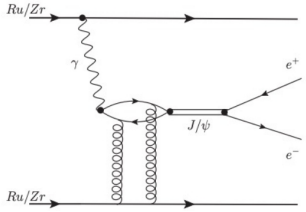
- Excess of very low p_T J/ψ and e^+e^- productions in peripheral heavy-ion collisions



Low p_T dileptons

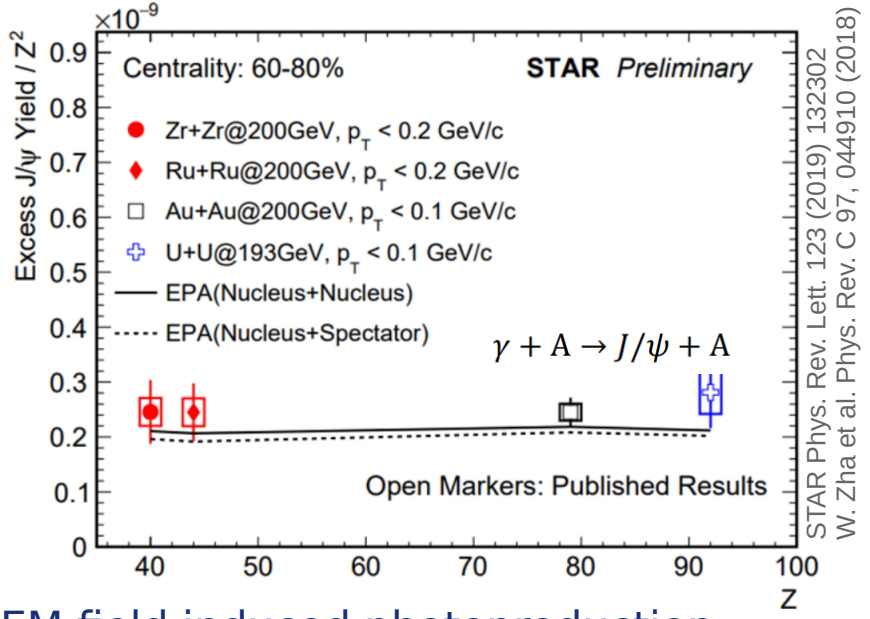
$\sigma(\gamma\gamma \to ee) \sim Z^4$





Low p_T J/ψ

$\sigma(\gamma A \to J/\psi) \sim Z^2$



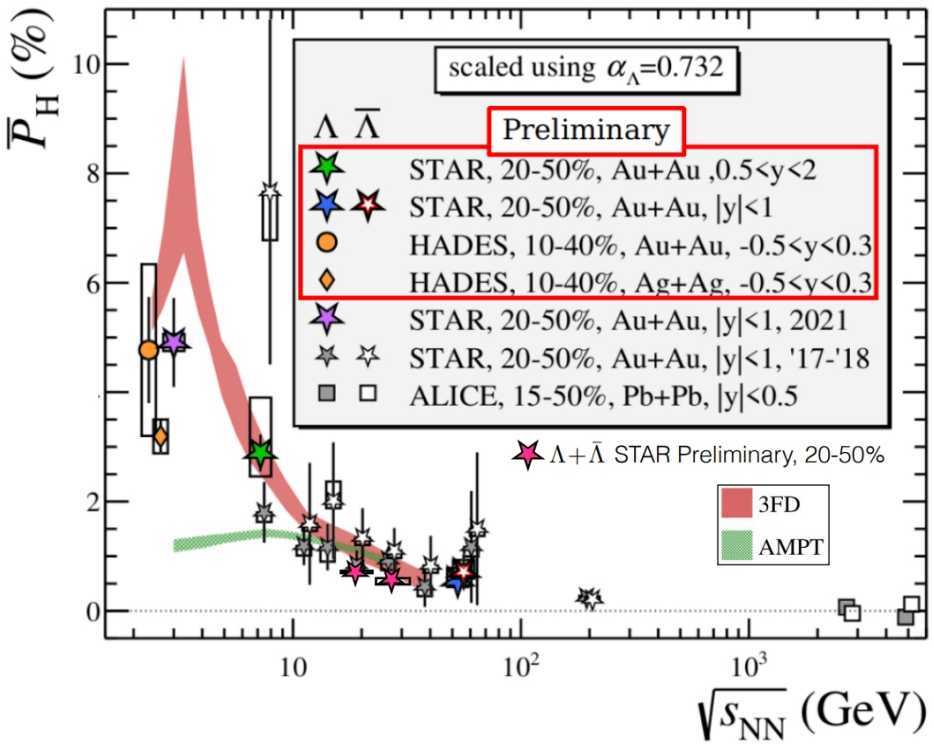
➔ Low p_T production consistent with QED → EM field induced photoproduction

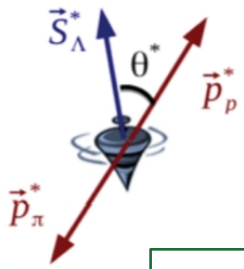
➔ $\gamma+\gamma \to e^+e^-$: collision system dependence

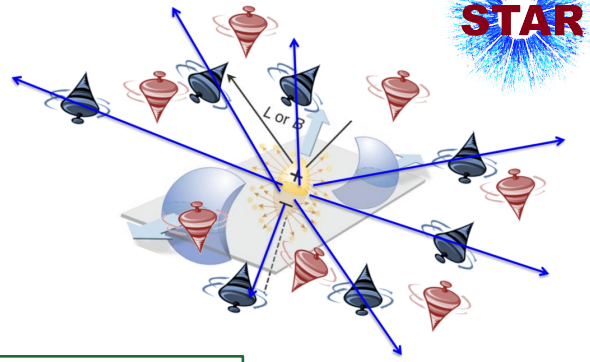
Kaifeng Shen
15.6 9:40am

Global hyperon polarization

- Vorticity of the medium and magnetic field







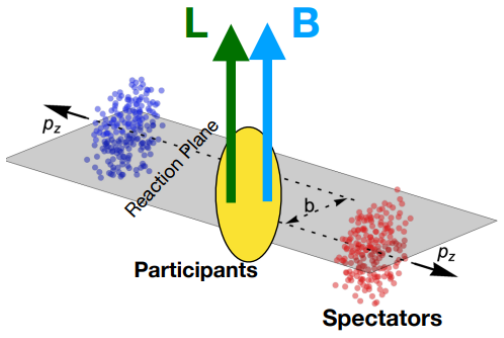
$$P_H = \frac{8}{\pi\alpha_H}\frac{\langle \sin(\Psi_1 - \phi^*_d)\rangle}{\mathrm{Res}(\Psi_1)}$$

Fluid vorticity → Λ, anti-Λ in same direction

$$\omega = k_B T(P_\Lambda + P_{\bar{\Lambda}})/\hbar$$

Magnetic field → Λ, anti-Λ in opposite direction

$$B = \frac{T}{2\mu_\Lambda}(P_\Lambda - P_{\bar{\Lambda}})$$

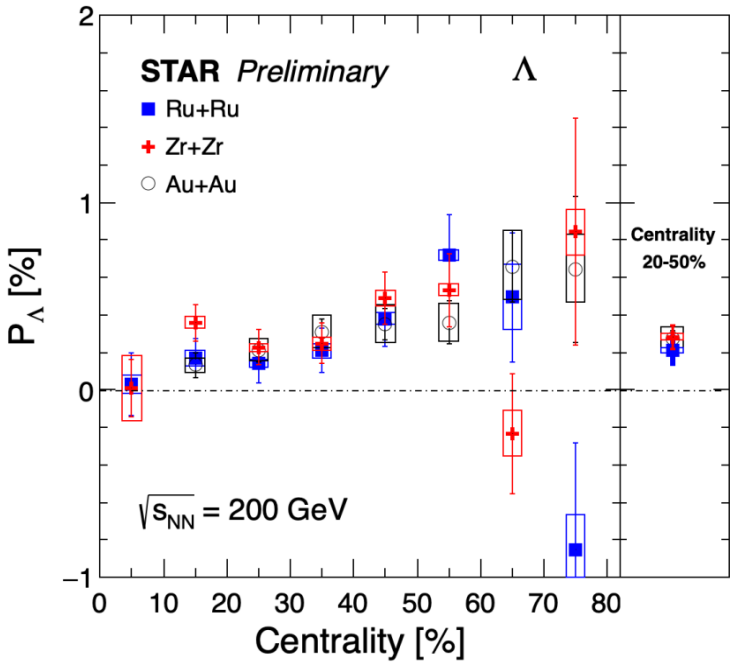


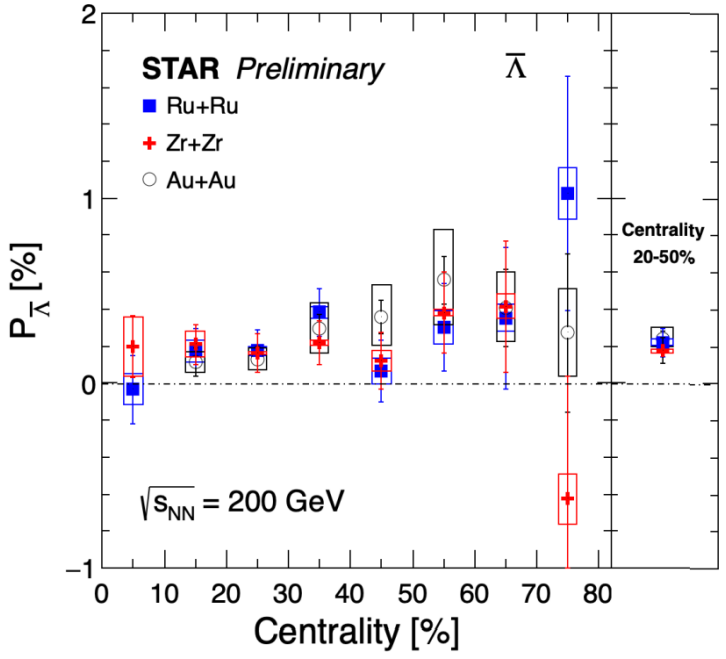
➔ Increasing global polarization, P_H, trend down to $\sqrt{s_{NN}}$ = 3 GeV

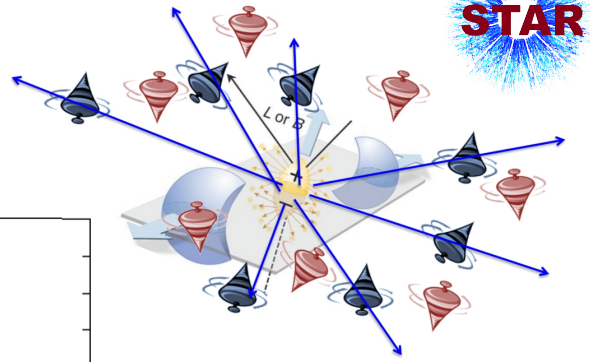
➔ Results from STAR BES-II: $\sqrt{s_{NN}}$ = 3, 7.2, 19.6, 27, 54.4 GeV

Global hyperon polarization

- Au+Au, Ru+Ru vs Zr+Zr at 200 GeV → system size and magnetic field driven effects







$$P_H = \frac{8}{\pi \alpha_H} \frac{\langle \sin(\Psi_1 - \phi_d^*) \rangle}{\mathrm{Res}(\Psi_1)}$$

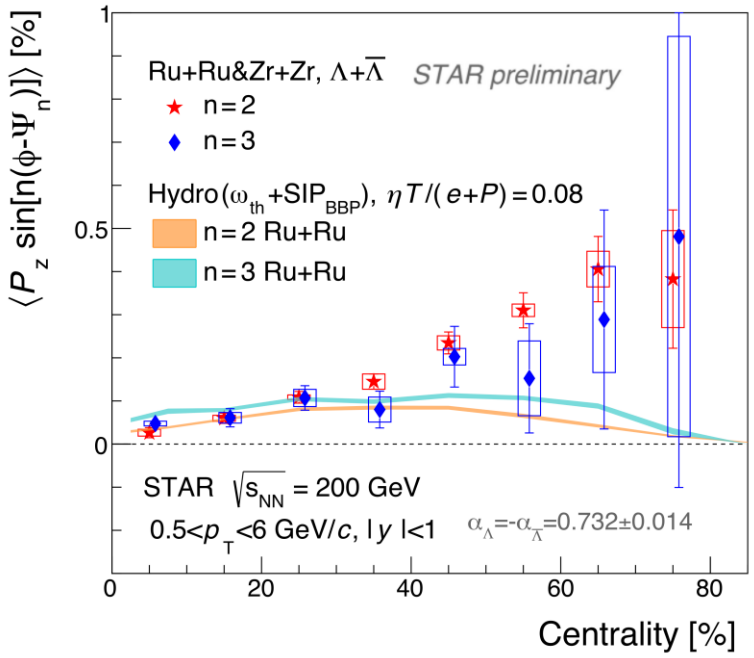
➔ Increasing P_H with centrality, no collision system dependence

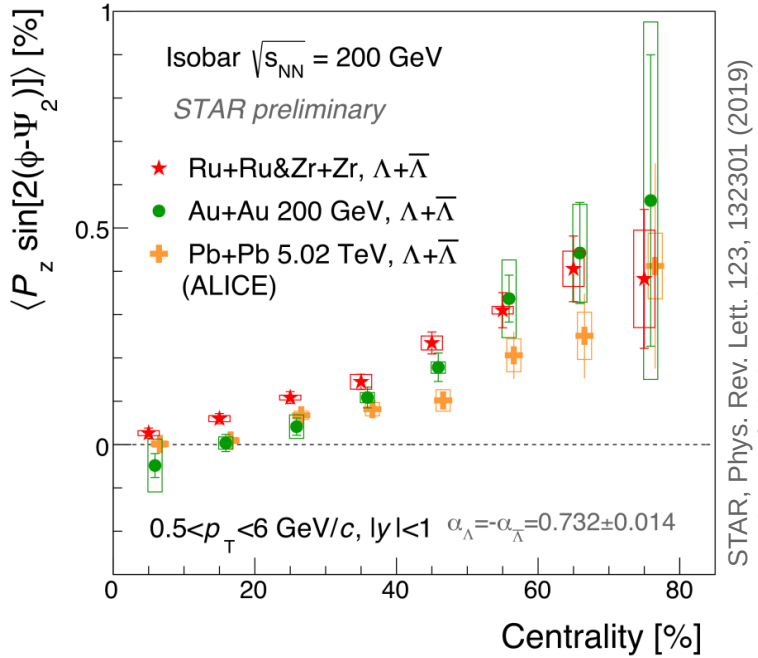
➔ No B-field driven splitting between P_Λ and $P_{\text{anti-}\Lambda}$ observed

Xingrui Gou
14.6 2:20pm

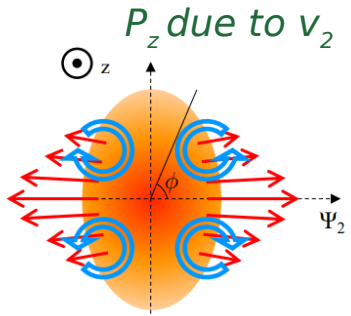
Local hyperon polarization

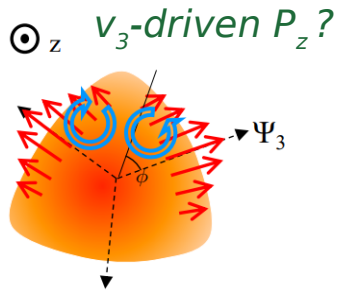
- Anisotropic flow → Longitudinal polarization P_z (thermal vorticity + shear term)





STAR, Phys. Rev. Lett. 123, 132301 (2019)
ALICE, arXiv:2107.11183





➔ 2nd and **3rd order** P_z increase with centrality and have comparable magnitude

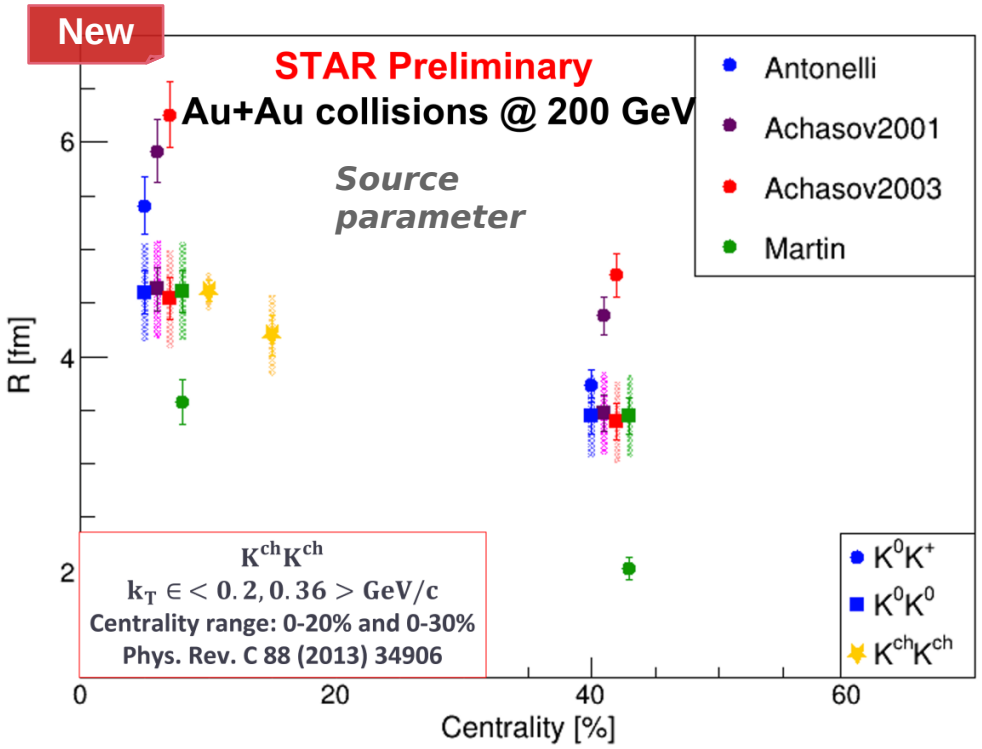
➔ Additional constraint on shear viscosity

➔ Similar P_z in isobar, Au+Au and Pb+Pb → hint of system size dependence rather than energy dependence ?

Xingrui Gou
14.6 2:20pm

Femtoscopy of two-kaon combinations

- Spatial and temporal extent of the emission source

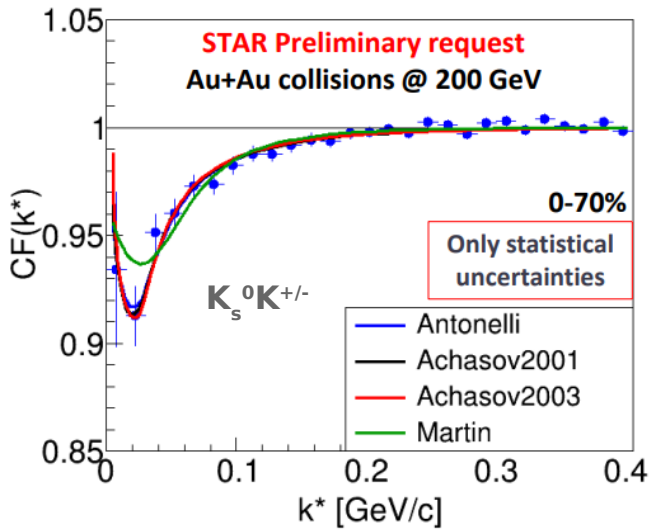


Kaon correlation function sensitive to:

$K_s^0K_s^0$ — Quantum Statistical effects (QS)
Final State Interactions (FSI)
- Strong Interaction (SI) → $f_0(980)$ and $a_0(980)$

$K_s^0K^{+/-}$ — Final State Interactions (FSI)
- Strong Interaction (SI) → **$a_0(980)$**

$K^{ch}K^{ch}$ — Quantum Statistical effects (QS)
Final State Interactions (FSI)
- Coulomb (COUL)

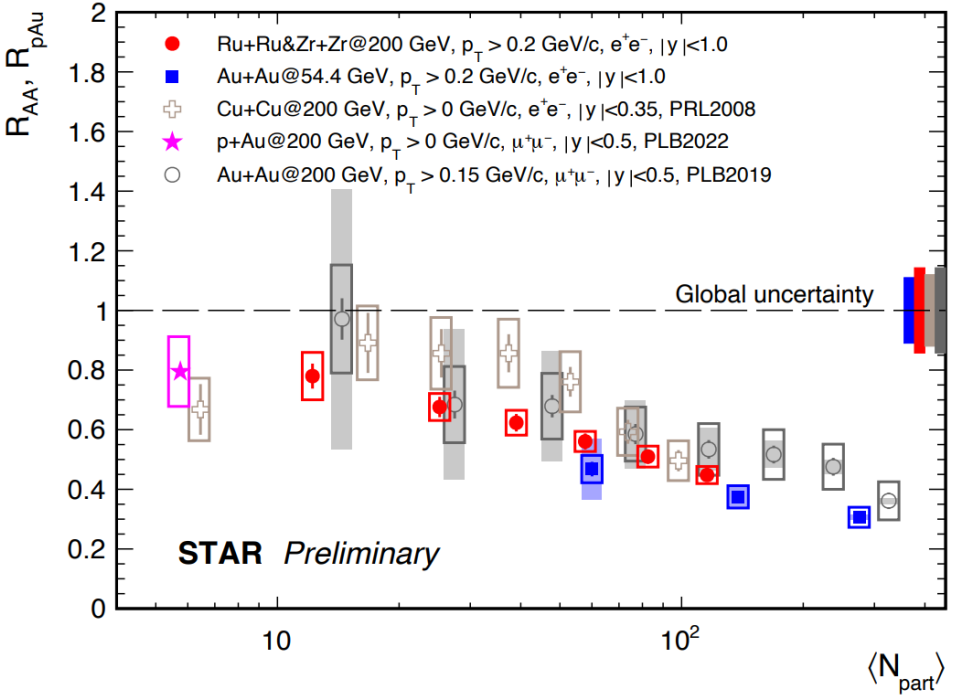


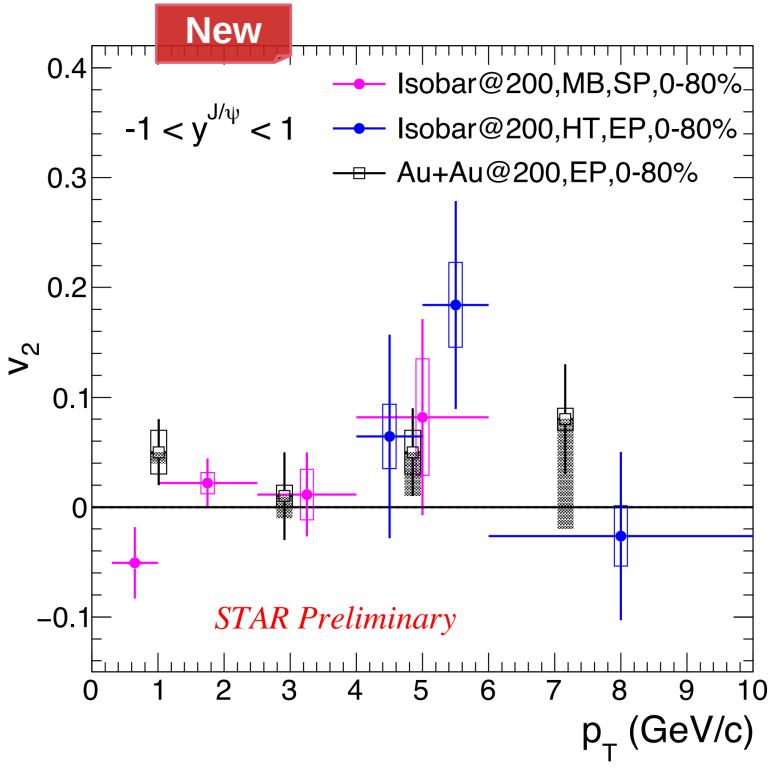
Diana Pawłowska
14.6 12:10pm

➔ The radius of the source depends on centrality

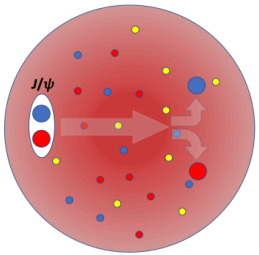
J/ψ suppression and elliptic flow

- Dissociation vs regeneration effects

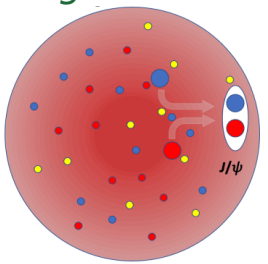




Dissociation



Regeneration



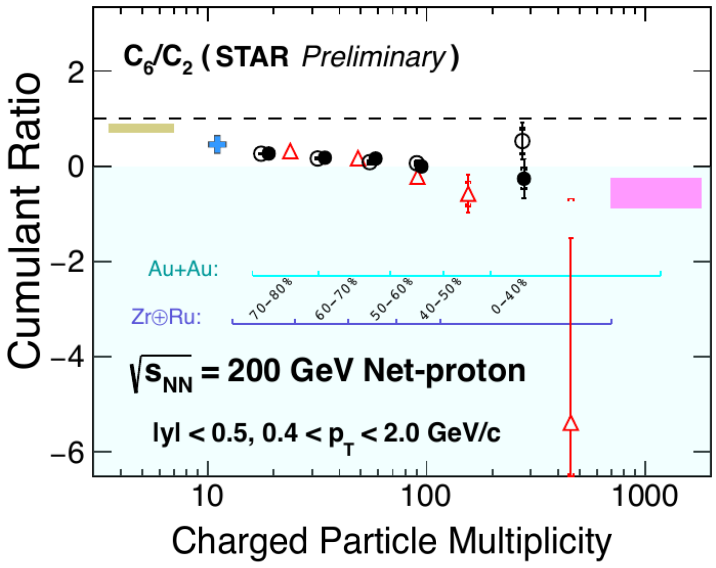
➔ No significant colliding system and energy dependence of the J/ψ suppression at RHIC at similar N_{part}

➔ v_2 consistent with zero in isobar and Au+Au at $\sqrt{s_{NN}}$ = 200 GeV

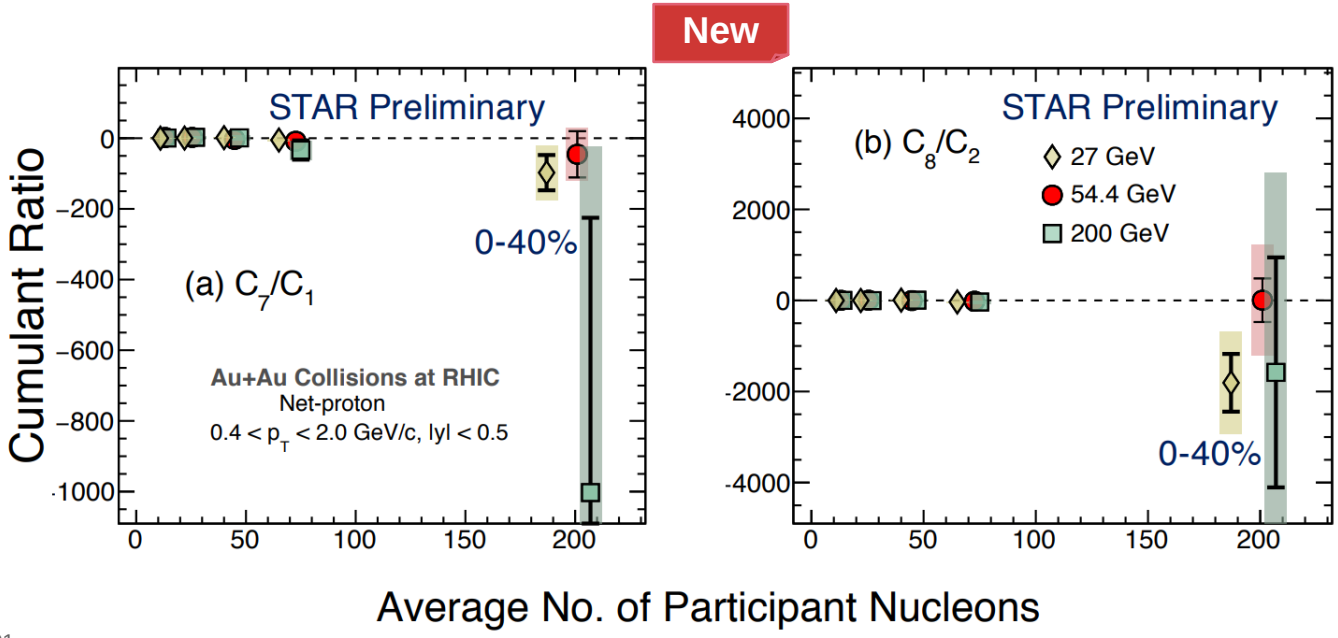
Qian Yang
14.6 2:40pm

Higher-order net-proton cumulants

- Cumulants of conserved quantities (Q, B, S) sensitive to the correlation length



New



STAR: Phys. Rev. C 104 (2021) 024902; Phys. Rev. Lett 127 (2021) 262301

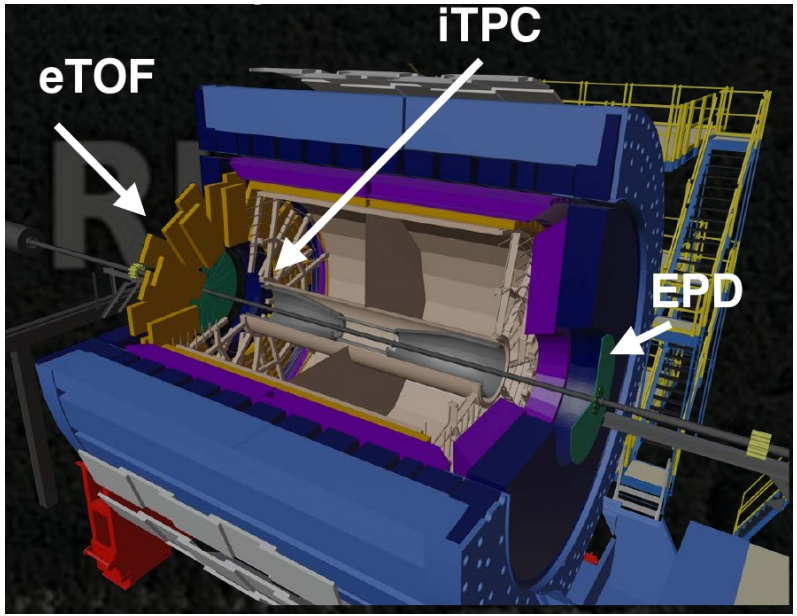
➔ **200 GeV $C_6/C_2 < 0$**: systematic decreasing trend with multiplicity, consistent with lattice QCD results that predict **crossover** at $\mu_B = 0$

➔ C_7/C_1 and C_8/C_2: hint of < 0 at high multiplicity, but with large uncertainties

Ashish Pandav
14.6 2:00pm

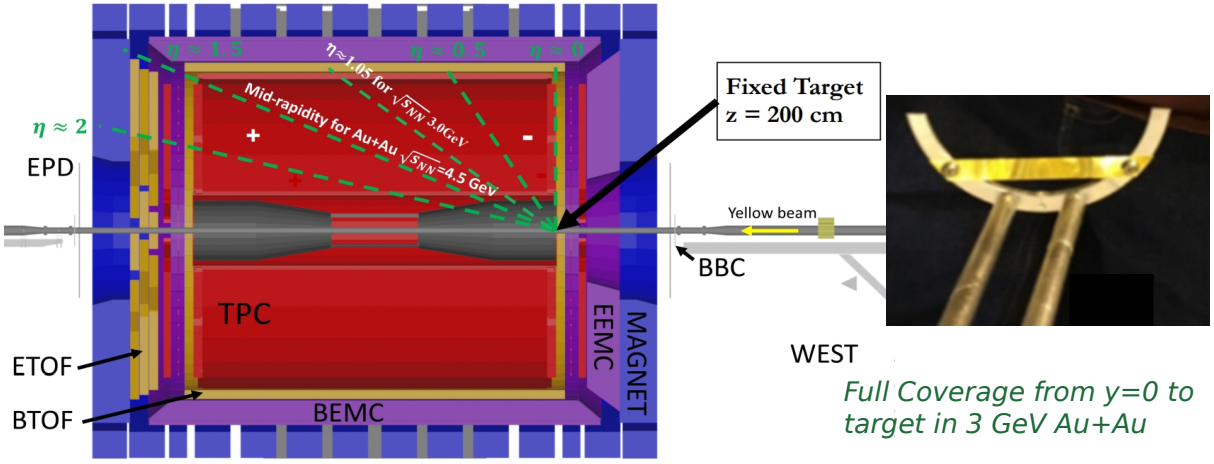
BES-II and Fixed-Target setup

BES-II Upgrades



- **iTPC (2019+)**
  - Extended η acceptance and improved tracking and dE/dx resolution
- **eTOF (2019+)**
  - Extended PID coverage
- **EPD (2018+)**
  - Improved EP resolution

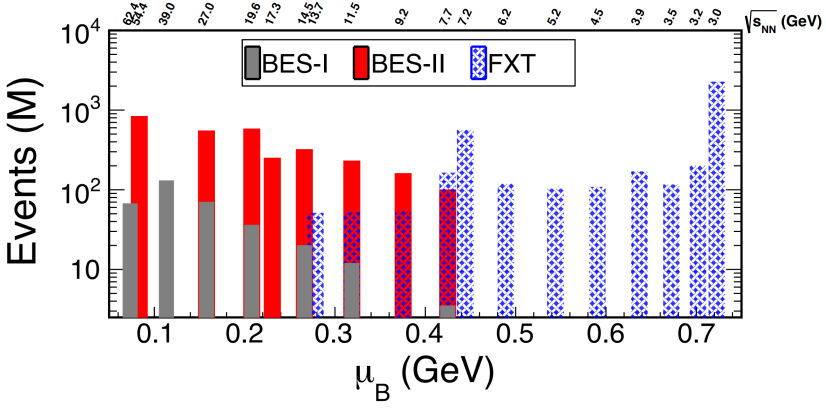
Fixed Target

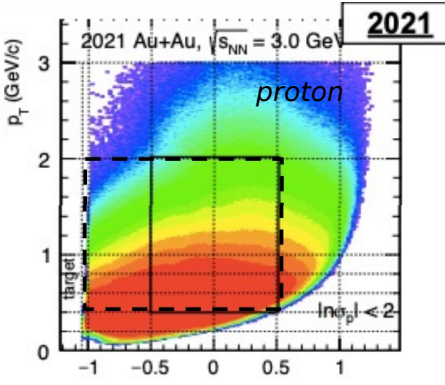


In C.M. frame, $y_{target} = -1.045$ for the 3GeV collisions

Full Coverage from y=0 to target in 3 GeV Au+Au

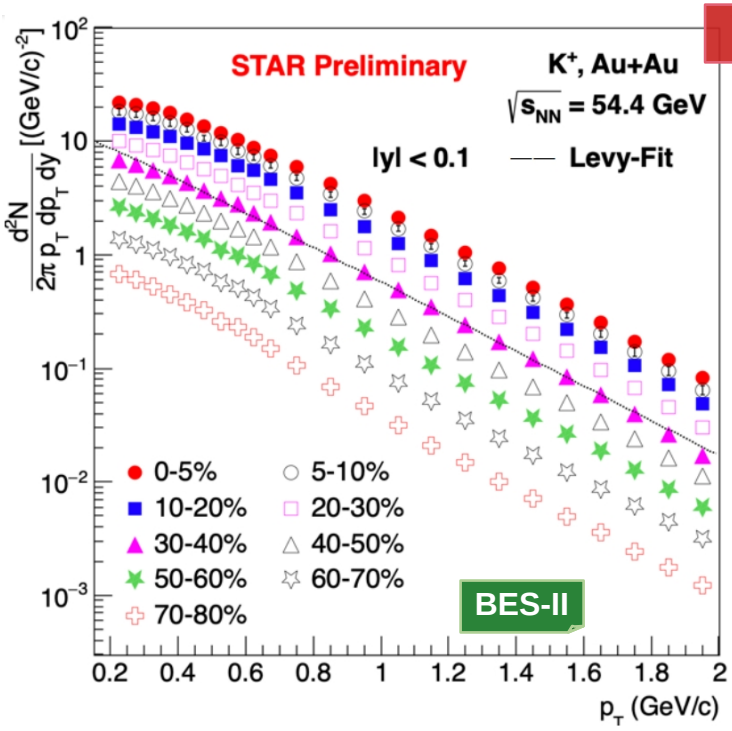
Beam Energy Scan II completed



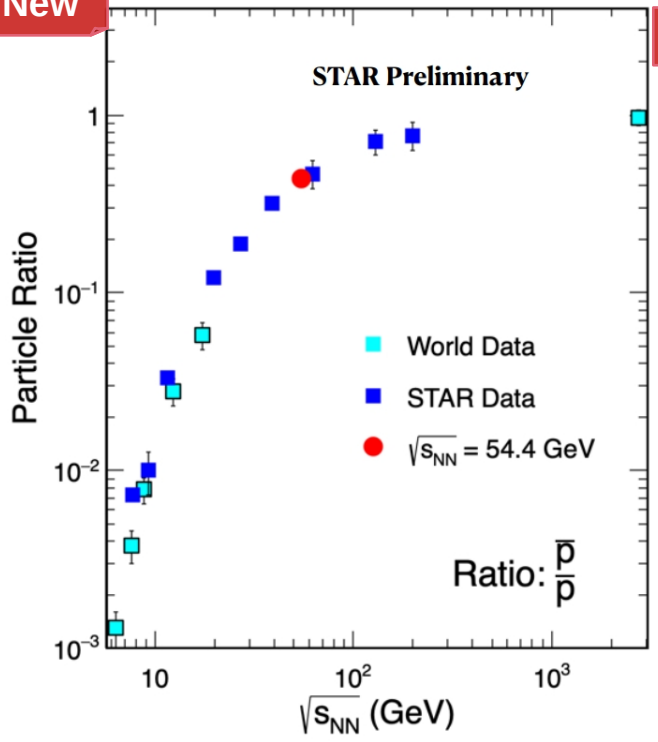


Particle production at 54.4 GeV

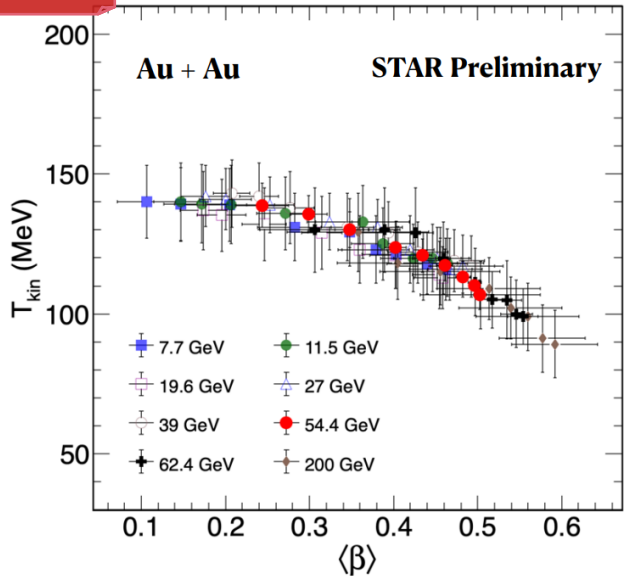
- p_T spectra and ratios of $\pi^{+/-}$, $K^{+/-}$, p and anti-p



New



New



Krishan Gopal
14.6 12:10pm

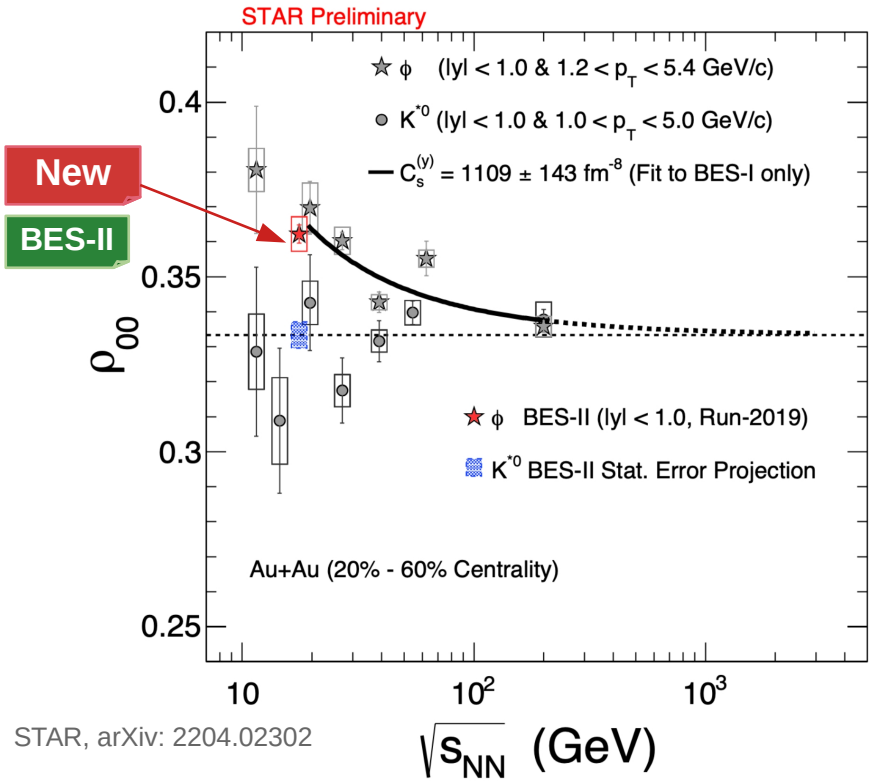
➔ Particle ratios follow global energy dependence trend

➔ anti-p/p decreases with decreasing with $\sqrt{s_{NN}}$ → baryon stopping

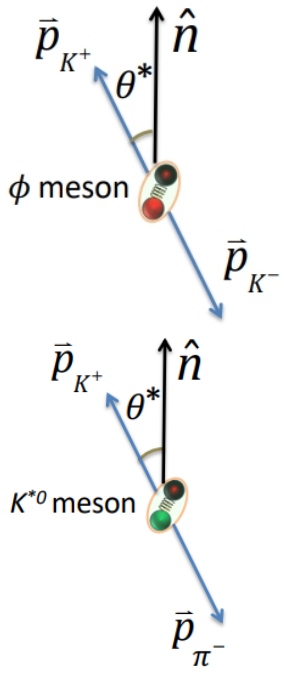
➔ Kinetic freeze-out parameters extracted from fits to p_T spectra

Global spin alignment of vector mesons

- Sensitivity to vorticity and hadronization mechanism



STAR, arXiv: 2204.02302



Vorticity tensor ~10^{-4} | Vector meson strong force field

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

Quark coalescence vorticity & magnetic field ~10^{-5} | Electric field ~10^{-5}

$$c_\phi \equiv \frac{g_\phi^4}{27 m_s^4 m_\phi^4 T_{eff}^2} \langle \boldsymbol{p}^2 \rangle_\phi \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle;$$

$$C_s(y) \equiv g_\phi^4 \langle \tilde{E}_{\phi,z}^2 + \tilde{E}_{\phi,x}^2 \rangle$$

Sheng el. al., Phys. Rev. D 101, 096005 (2020)
Sheng el. al., Phys. Rev. D 102, 056013 (2020)

$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

$\rho_{00} \neq 1/3$ → spin alignment

Gavin Wilks
14.6 3:20pm

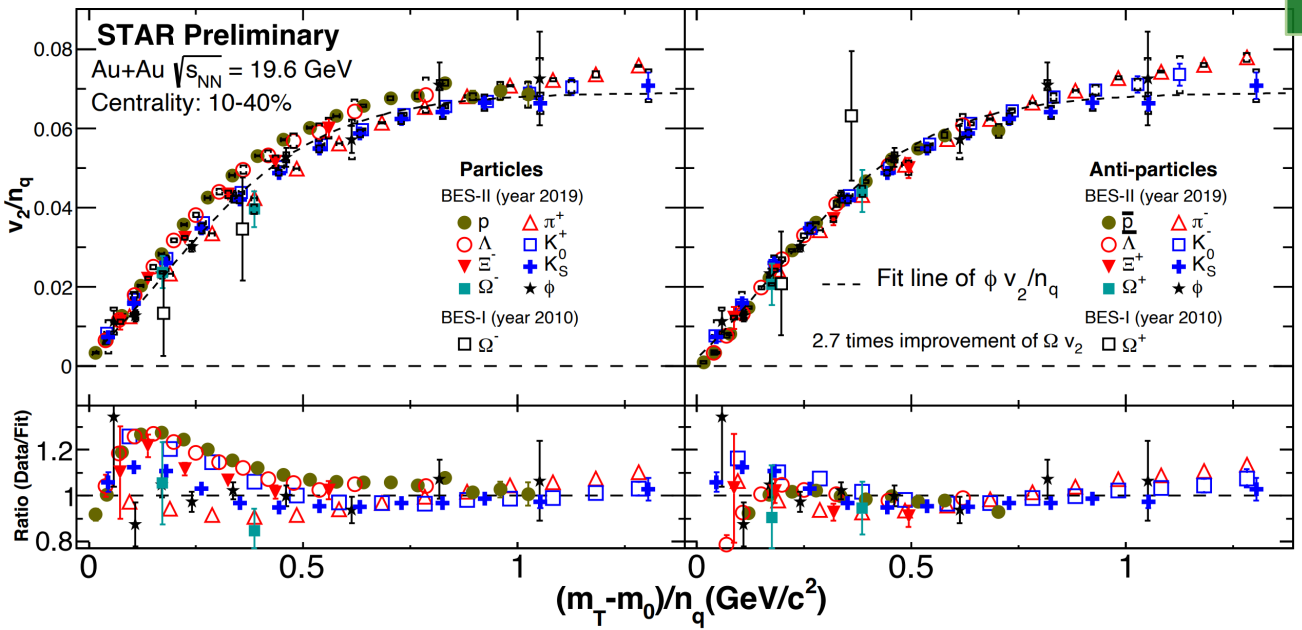
➔ 19.6 GeV Au+Au BES-II: ρ_{00} for φ meson > 1/3 with 5.3σ

➔ Polarization by vector meson strong force field ? More input from theory needed

Sheng et al., arXiv:2205.15689

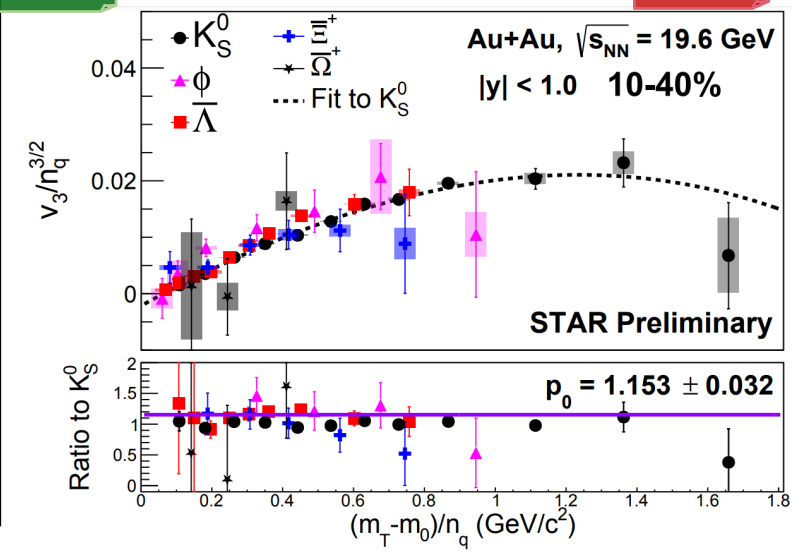
Anisotropic flow of strange hadrons

- Strange hadrons less affected by hadronic phase → information primarily from the early stages of the high energy collisions



BES-II

New



- ➔ Mass scaling at low $(m_T-m_0)/n_q$. NCQ scaling at higher $(m_T-m_0)/n_q$
  - ➔ holds better for anti-particles (within 15%) → transport vs produced quarks
  - ➔ partonic collectivity
- ➔ v_3 possible to measure with BES-II statistics

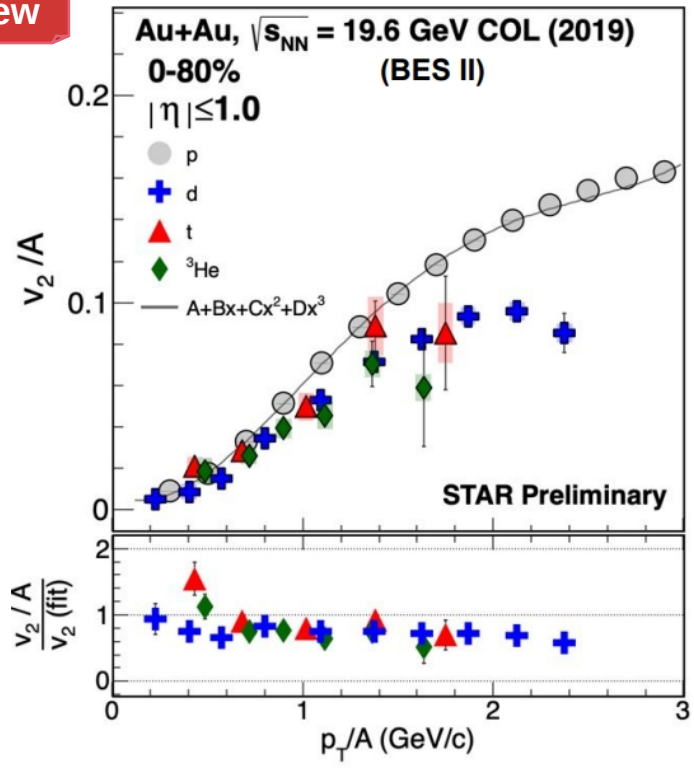
Li-Ke Liu
14.6 3:00pm

Prabhupada Dixit
Poster BLK-10

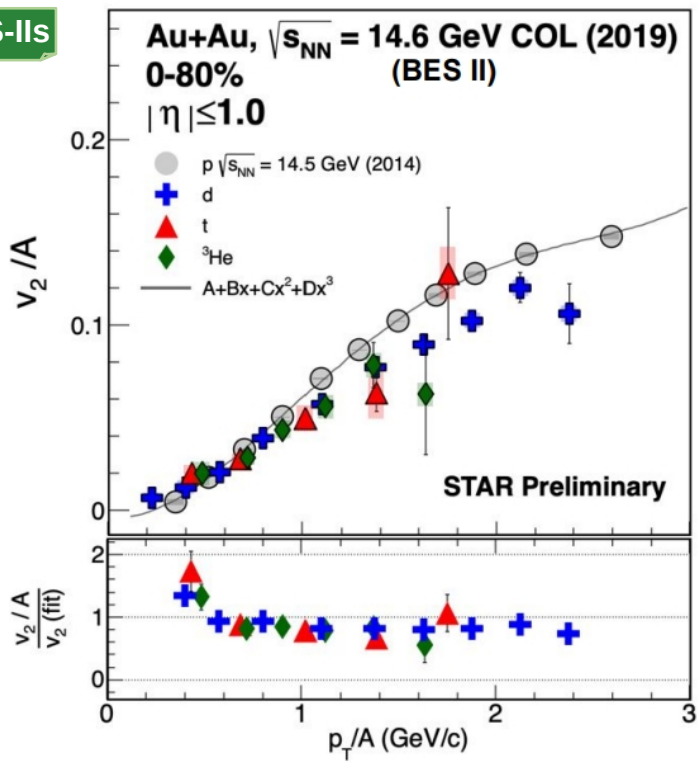
Elliptic flow of light nuclei

- Thermal production vs final-state coalescence of nucleons

New



BES-IIs



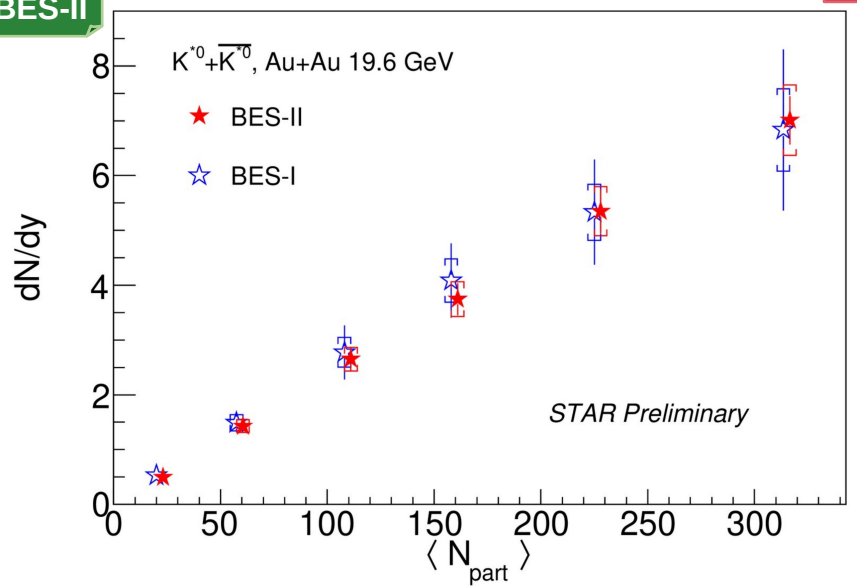
Rishabh Sharma
14.6 12:10pm

➔ Consistent with the mass number scaling within 20-30%

K*⁰ resonance production

- Resonance/non-resonance ratio → probing hadronic phase

K* BES-II



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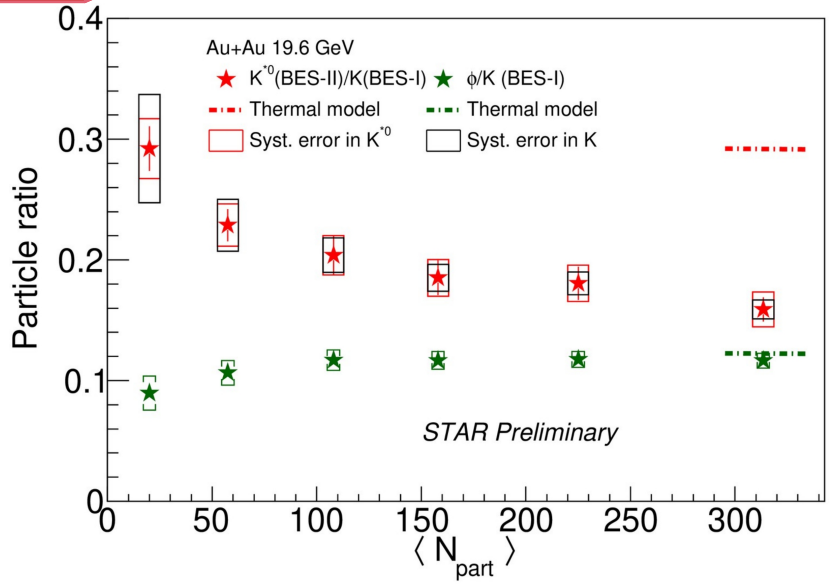
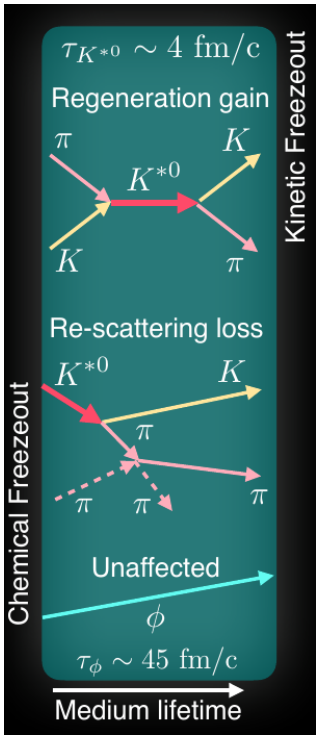




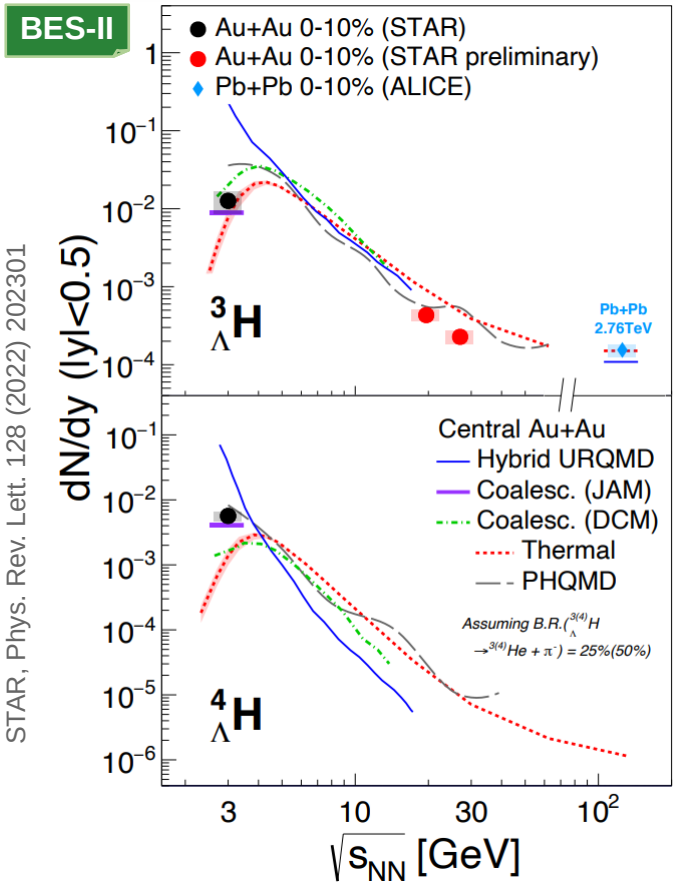
➔ Significant re-scattering in hadronic phase in central collisions at $\sqrt{s_{NN}}$ = 19.6 GeV

➔ Constraints on the hadronic phase lifetime

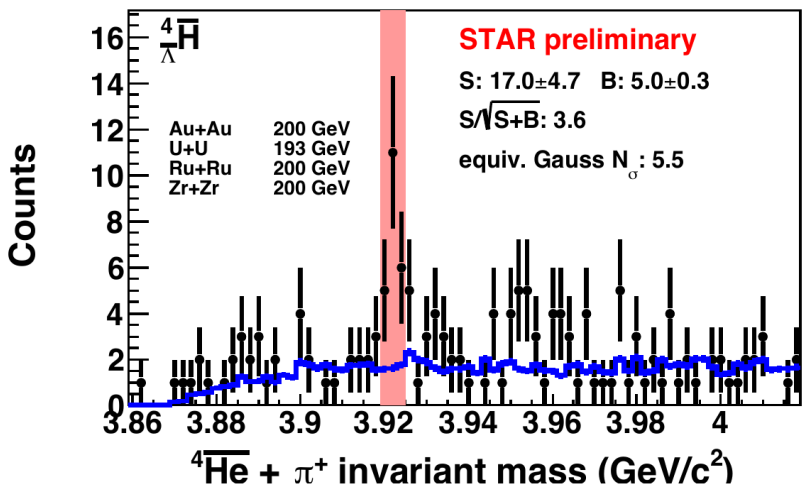
Aswini Sahoo
14.6 11:50am

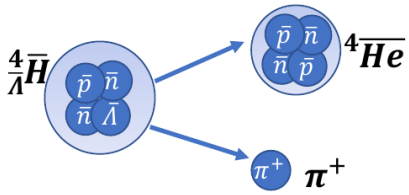
Production of (anti-)light hypernuclei

- Hyperon-Nucleon (Y-N) interactions → EOS of neutron stars and the hadronic phase of heavy-ion collisions



STAR, Phys. Rev. Lett. 128 (2022) 202301





➔ Precision measurements of production yields of hypernuclei at 3, **19.6 and 27 GeV** → constraints on hypernuclei production models at high μ_B

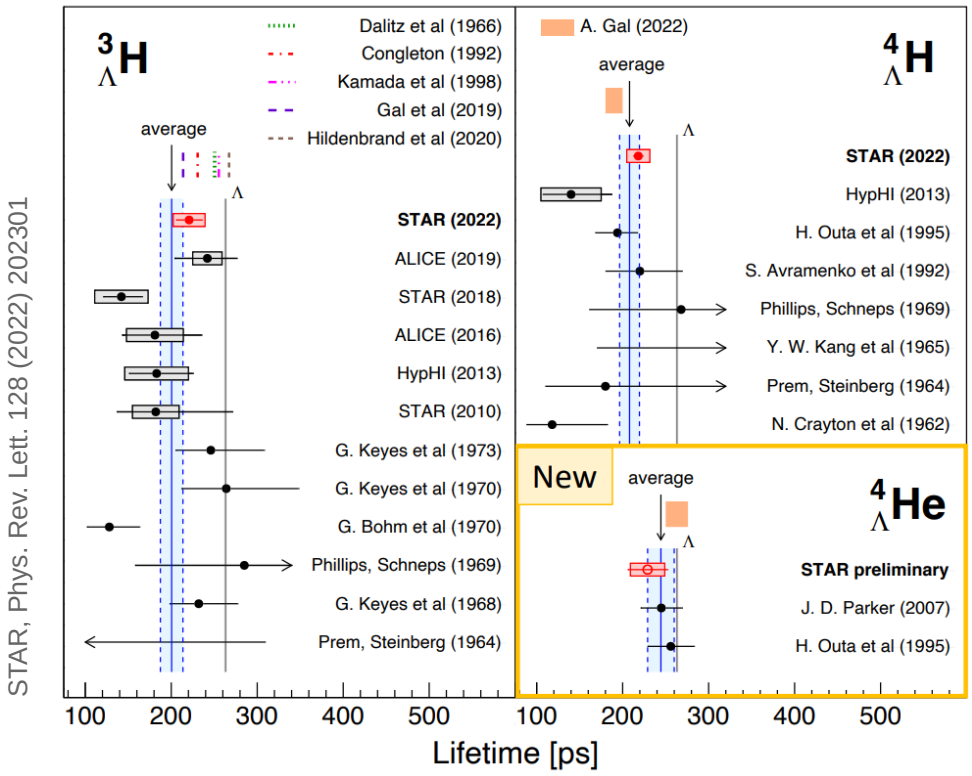
➔ The first observation of **Anti-Hyper-Hydrogen-4**

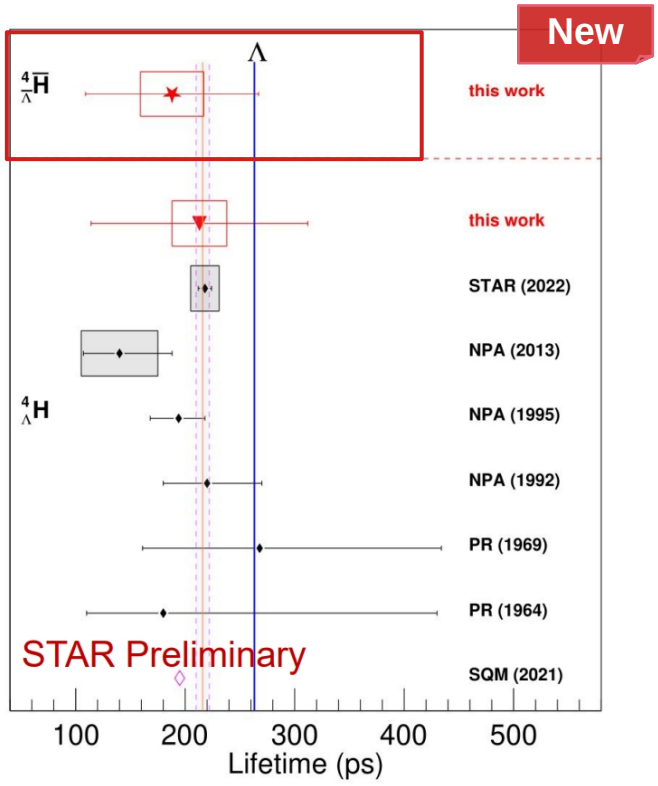
Yuanjing Ji 14.6 11:30am

Junlin Wu 15.6 11:50am

Lifetime of light hypernuclei

BES-II





- The first **Hyper-Helium-4 and Anti-Hyper-Hydrogen-4 lifetimes** measurements in heavy ion collisions
- Towards quantitative understanding of Y-N interaction

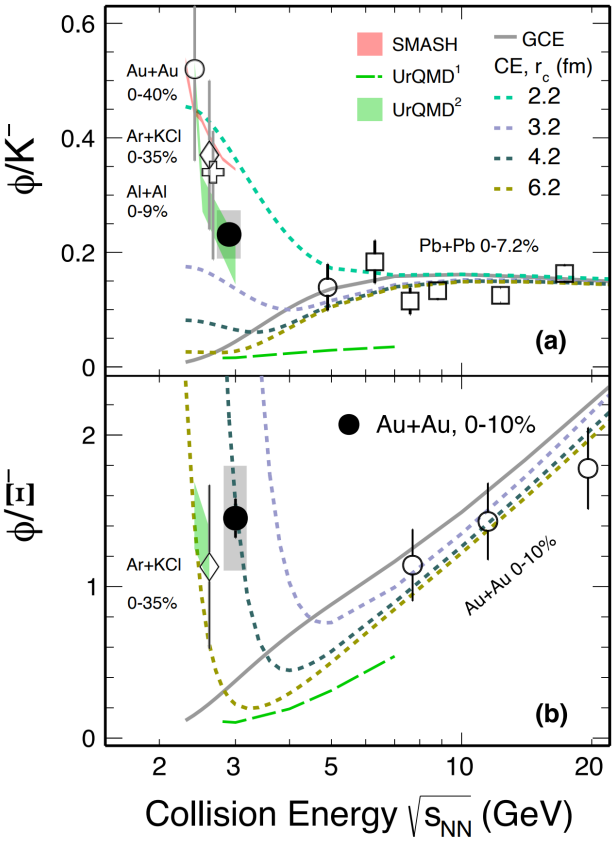
Xiujun Li
Poster RES-02

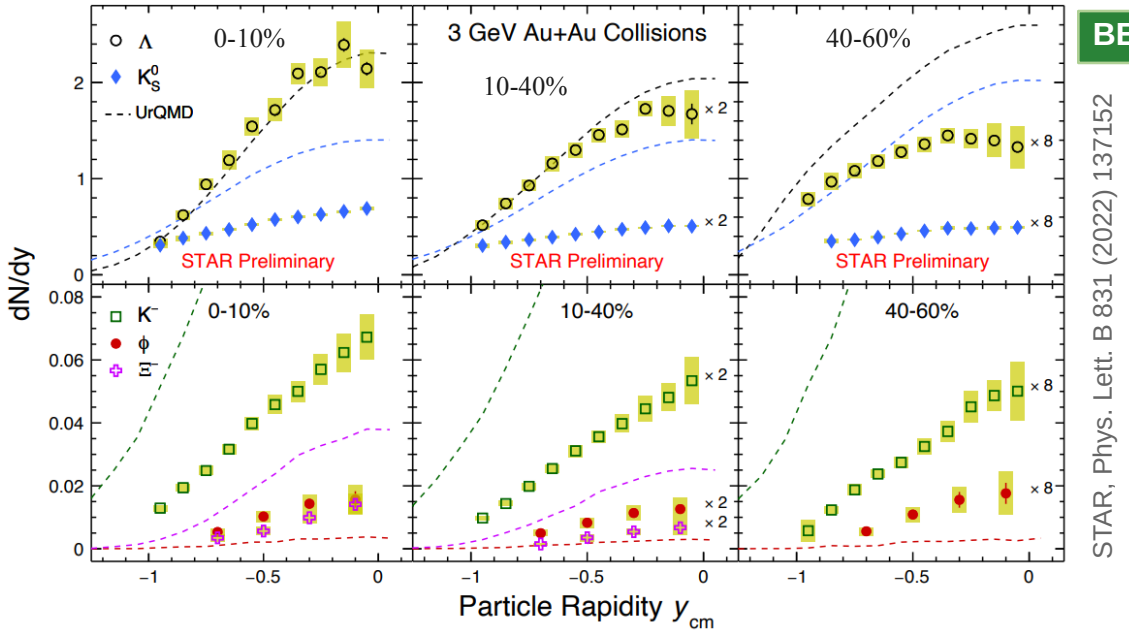
Yuanjing Ji
14.6 11:30am

Junlin Wu
15.6 11:50am

Strange hadron production at 3 GeV

- Φ to strange hadrons ratio: sensitive to the interaction length in the Canonical Ensemble





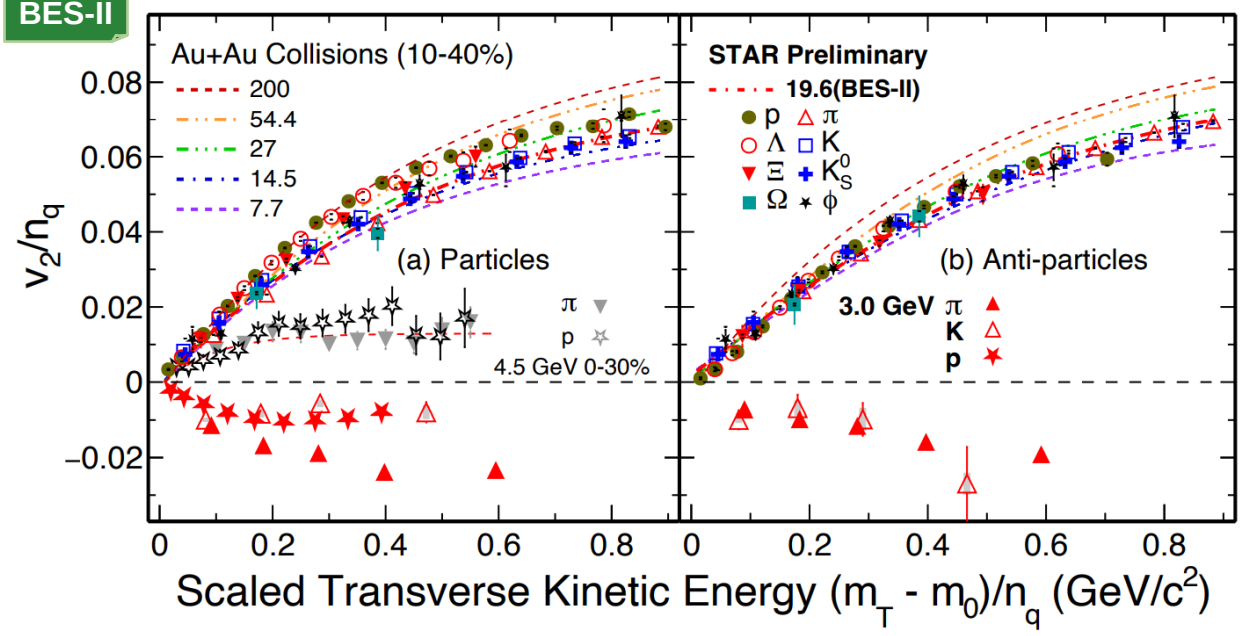
- ➔ Precise measurement of rapidity dependence of strange hadron production
- ➔ Local strangeness conservation required - **Canonical Ensemble favored**

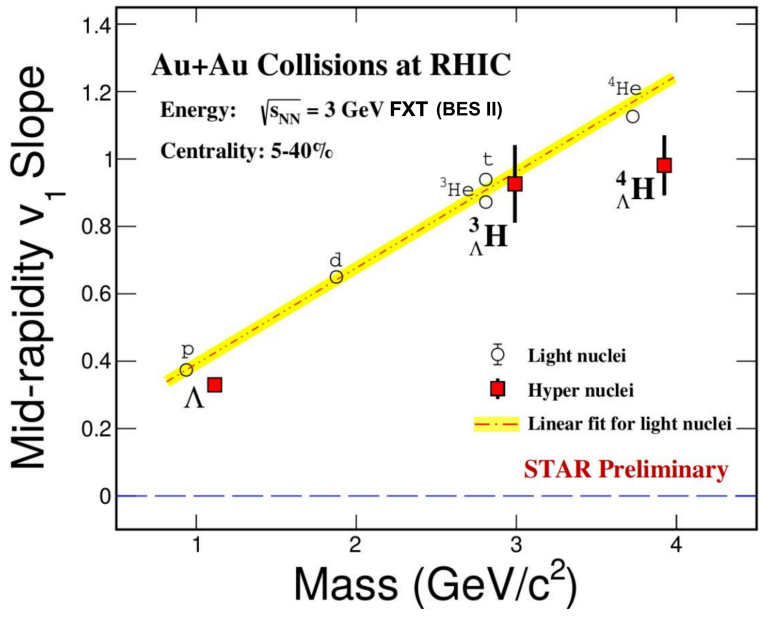
STAR: Phys. Lett. B 831 (2022) 137152,
Phys. Rev. C 102 (2020) 34909

Yingjie Zhou
15.6 2:00pm

Elliptic and directed flow at 3 GeV

BES-II





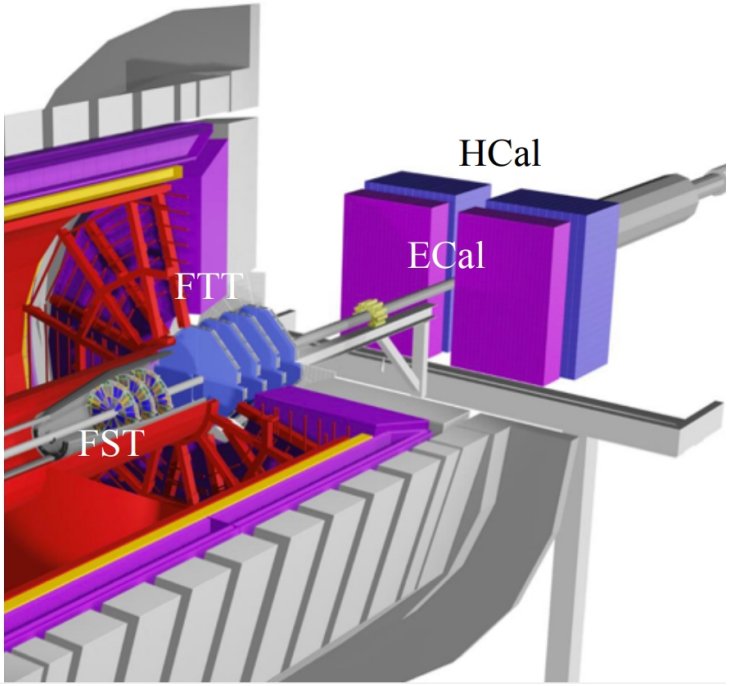
- Unlike at higher energies, absence of v_2 NCQ scaling and positive v_1 slope
  - transport models with baryonic mean-field potential qualitatively consistent with data

    Equation-of-State dominated by baryonic interactions at 3 GeV
- (Hyper-)nuclei likely formed via coalescence process

Li-Ke Liu 14.6 3:00pm

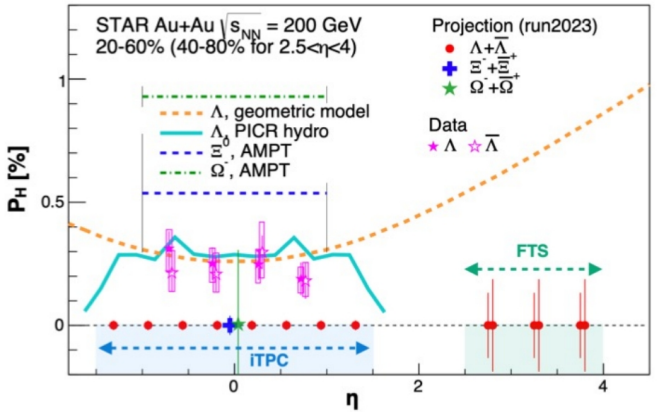
Rishabh Sharma 14.6 12:10pm

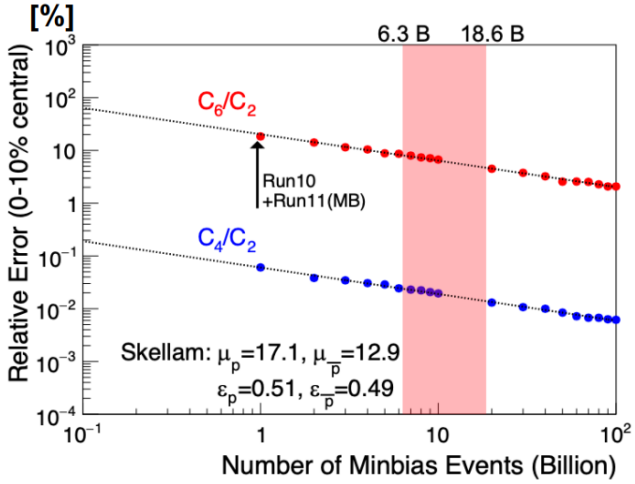
Forward Upgrade and 2023-25 Runs



- **Forward Tracking System (FTS)**
  - Forward Silicon Tracker (FST)
  - Forward Small-strip Thin Gap Chambers Tracker (FTT)
- **Forward Colorimeter System (FCS)**
  - Electromagnetic Calorimeter
  - Hadronic Calorimeter

- **Hot QCD – study of microstructure of QGP**
  Au+Au @200 GeV (2023 & 25)
  - What is the nature of the 3-dimensional initial state at RHIC energies?
  - What can be learned about confinement from charmonia measurements?
  - What are the electrical, magnetic and chiral properties of the medium?
  - What is the precise nature of the transition near μ_B=0?
  - …





- **Cold QCD: Equal N-N luminosities in pp and pAu in 2024 essential to optimize several critical measurements**
  - First look gluon GPD → Eg
  - Nuclear dependence of PDFs, FF, and TMDs
  - Non-linear effects in QCD

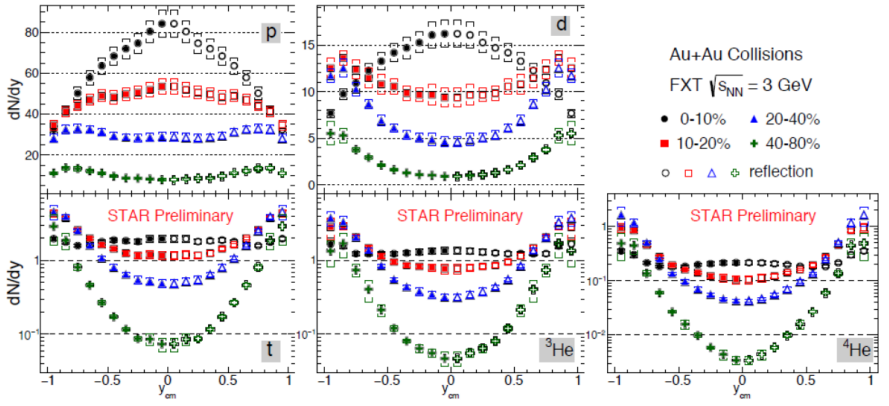
Future opportunities

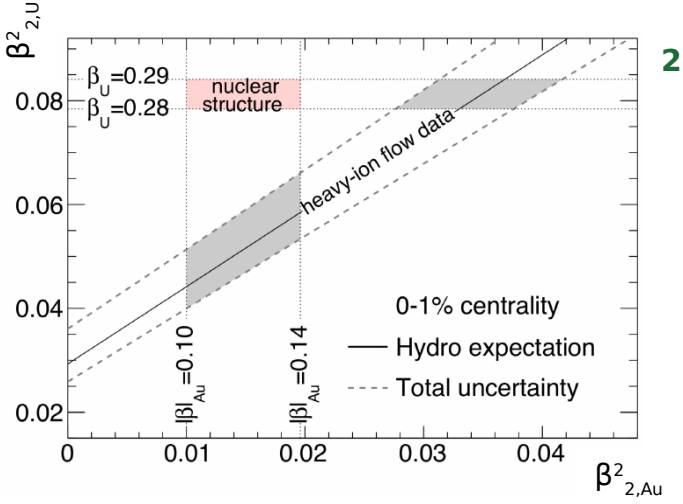
1 **Space Radiation Protection** community need

- **Light fragment yields** from C, Al, and Fe on C, Al, and Fe targets with beam energies from **3 to 50 GeV/n**
- STAR: excellent light fragments capabilities, can install targets of interest
- RHIC: can deliver required ion species in 3 to 50 GeV/n
- Short run required

https://doi.org/10.3389/fphy.2020.565954

Production of light nuclei at 3 GeV





2 **Shape tomography of atomic nuclei** using collective flow measurements

- Collective flow measurements sensitive to nuclear deformation
- Calibrate systematics using two species around 197Au: 208Pb & 198Hg (β_2 = -0.11) at 200 GeV: **Constrain η/s with improved understanding of initial state**
- Explore more exotic regions for triaxiality and octuple: **use hydrodynamics and flow measurements to perform precision cross-check of low energy nuclear physics**

Summary

- Stay tuned for more BES-II results
- More cold and hot QCD studies with p+p, p+Au and Au+Au @ 200 GeV in 2023-2025

SQM22 STAR talks:

1. CME: non-flow background: Yicheng Feng, 6/14/22, 2:20 PM
2. Elliptic flow of strange hadrons in isobar: Priyanshi Sinha, Jun 14, 2022, 4:10 PM
3. Photon-induced production: Kaifeng Shen, Jun 15, 2022, 9:40 AM
4. Global and local hyperon polarization: Xingrui Gou, Jun 14, 2022, 2:20 PM
5. Global spin alignment of vector mesons: Gavin Wilks, Jun 14, 2022, 3:20 PM
6. Kaon femtoscopy in Au+Au: Diana Pawlowska, Jun 14, 2022, 12:10 PM
7. J/ψ production and elliptic flow in isobar: Qian Yang, Jun 14, 2022, 2:40 PM
8. Higher order cumulants: Ashish Pandav, Jun 14, 2022, 2:00 PM
9. Particle production at 54.4 GeV: Krishan Gopal, Jun 14, 2022, 12:10 PM
10. K* resonance production in BES-II: Aswini Sahoo, Jun 14, 2022, 11:50 AM
11. Strange hadron production in BES-II: Yingjie Zhou, Jun 14, 2022, 2:00 PM
12. Anisotropic flow of strange hadrons in BES-II: Li-Ke Li, Jun 14, 2022, 3:00 PM
13. Collective flow of (hyper-)nuclei in BES-II: Rishabh Sharma, Jun 14, 2022, 12:10 PM
14. Production and lifetime of light hypernuclei: Yuanjing Ji, Jun 14, 2022, 11:30 AM
15. Observation of anti-hypernuclei: Junlin Wu, Jun 15, 2022, 11:50 AM

Summary

SQM22 STAR posters:

1. Probing novel baryonic spin Hall effect using Λ spin polarization at STAR: Qiang Hu, BLK-07
2. Directed flow of identified particles in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 and 19.6 GeV: Zuowen Liu, BLK-09
3. Triangular flow of strange and multi-strange hadrons in BES-II energies at RHIC: Prabhupada Dixit, BLK-10
4. Deuteron number fluctuations and proton-deuteron correlations in high-energy heavy-ion collisions in STAR experiment at RHIC: Debasish Mallick, BLK-12
5. Fluctuations in Lambda multiplicity distribution in Au+Au collisions at $\sqrt{s_{NN}}$ =3 GeV at STAR: Jonathan Gonzalo Ball Cap, LF-02
6. Strangeness production in Au+Au collisions at $\sqrt{s_{NN}}$ = 27, 19.6, and 14.5 GeV from STAR: Sameer Aslam, LF-06
7. Lifetime measurements of light hypernuclei in Au+Au collisions from STAR experiment: Xiujun Li, RES-02

Thank you !

Backup

Directed and elliptic flow at 3 GeV