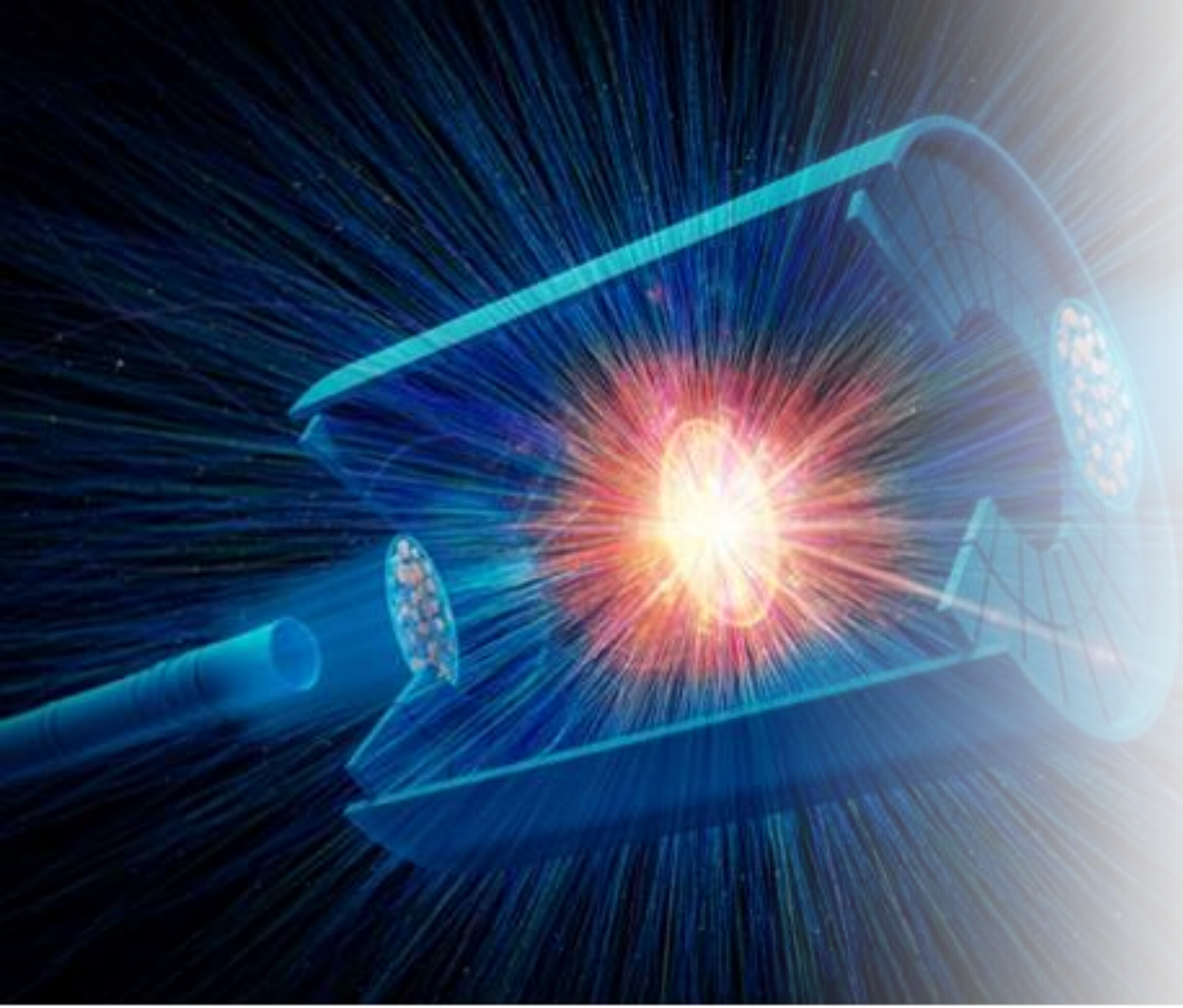


STAR Physics Highlights

Frank Geurts

for the STAR Collaboration

Outline

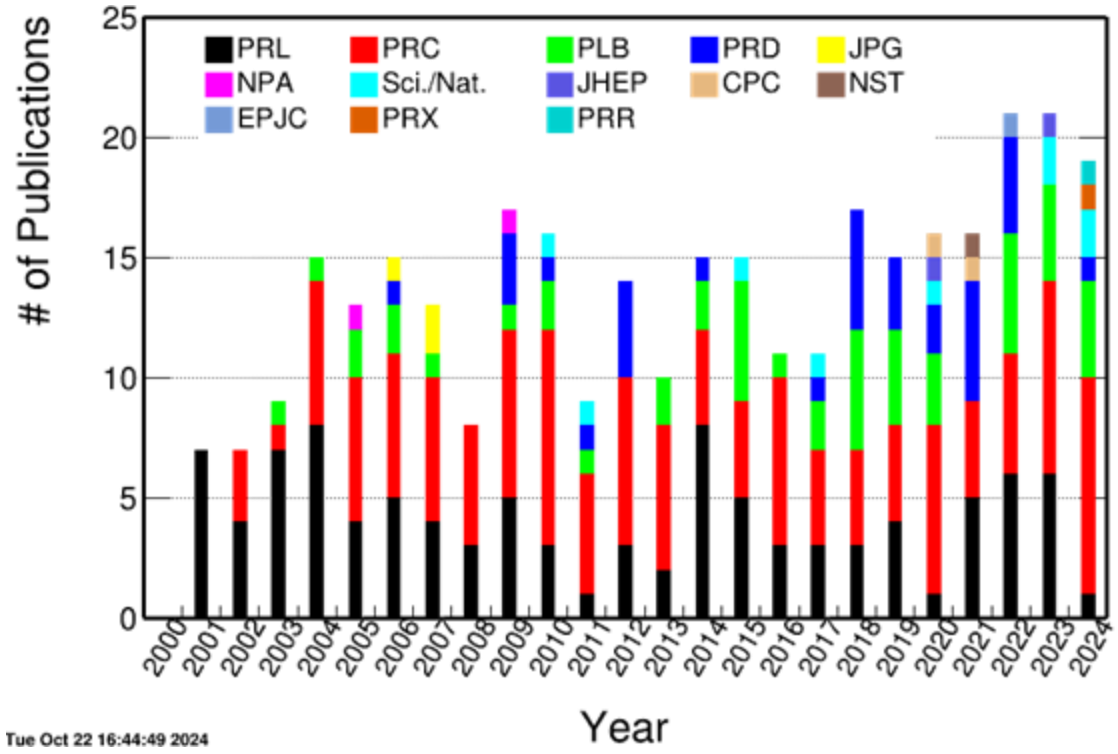
- General overview paper preparations, submissions, publications
- STAR Strategy for Data Preservation
- STAR Data Analysis Map
- Physics Highlights

- Summary

STAR recent publications

- 2023: 21 published and accepted
  - 6 PRL, 8 PRC, 4 PLB, 2 Sci/Nat, 1 JHEP
  - 100th STAR PRL published!
- 2024: 19 papers published and accepted
  - 1 PRL, 9 PRC, 4 PLB, 1 PRD, 2 Nat/Sci,1 PRX, 1 PRR
  - Well distributed across all PWGs:
    ColdQCD (2), CF (2), FCV (7), HP (2), LFSUPC (6)
- Papers in journal review: 8
  - in collaboration review: 3
  - in preparation for collaboration review: 20
- Active GPCs: 31
- steady flux of analyses requesting “preview” status
  - 26 since March 2024

- Awarded PhDs (2023-2024): 31
  - Totals: 321 PhD and 22 MS theses



STAR's Strategy for Data Preservation

Past Efforts

- All STAR analyses accompanied with a STAR Note, duly reviewed. All papers uploaded with comments and revisions; same for all presentations since early 2000s
- Web service virtualized/containerized to enable easy migration to facility-based support
- Database snapshots demonstrated to work off-site in lieu of servers
- Container-based workflows validated
  - Mustafa et al., JPCS **898** (2017) 082023

Recent Efforts

- integrate **HEPdata** submission in STAR's publication workflow
  - used STAR's shift-credit mechanism
- move STAR software repository to **GitHub**
  - use industry standards
  - keep documentation of developments/updates close to code
- automatic generation of **software containers**
  - virtualization of OS and STAR libraries: run anywhere, anytime
- **document** internal GPC discussions
  - next: enabling collaboration access to these dedicated and archived mailing lists

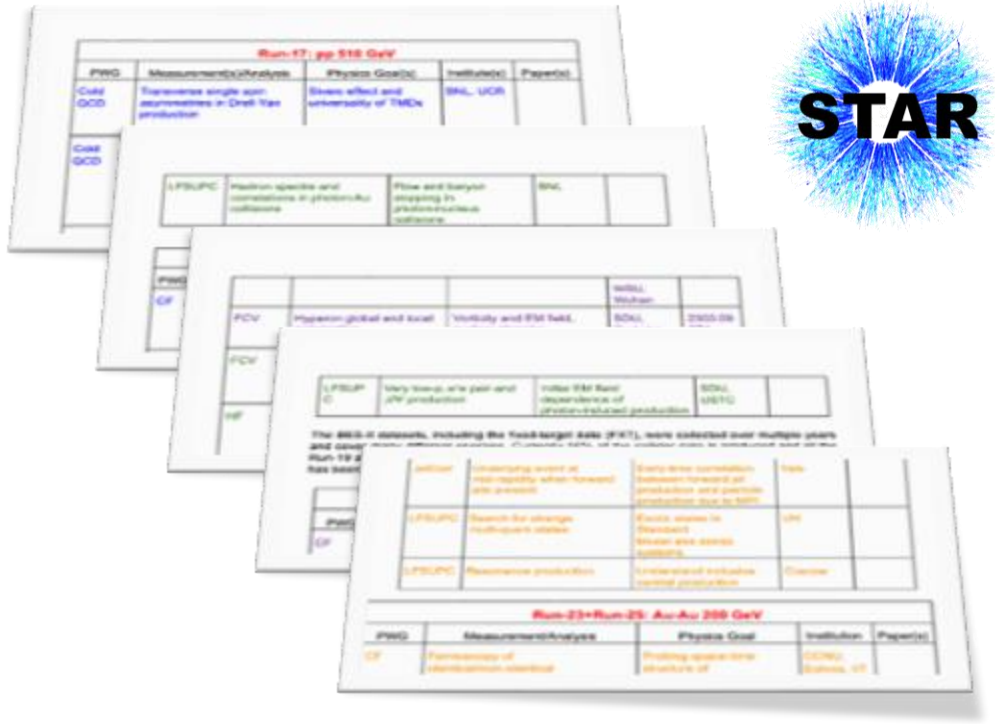
Efforts in preparation:

- **documentation preservation**:
  - transition STAR's old Drupal server (v6) to a newer version (v9+)
    - take advantage of BNL's resources for common preservation efforts
    - careful since STAR is still very active (e.g. detector operations)
- **software sustainability**:
  - transition STAR's ROOT 5.34 environment to ROOT6
    - allow STAR production & analyses to take advantage of latest libraries
    - allow incremental changes in software stack to easier integrate with common preservation efforts

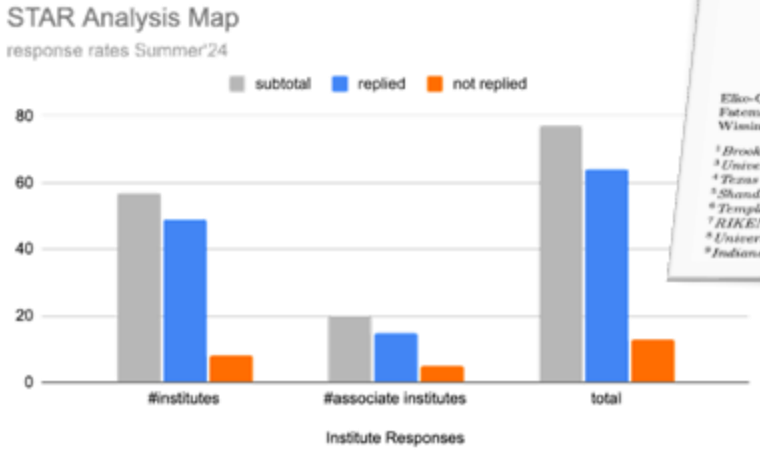
Next steps:

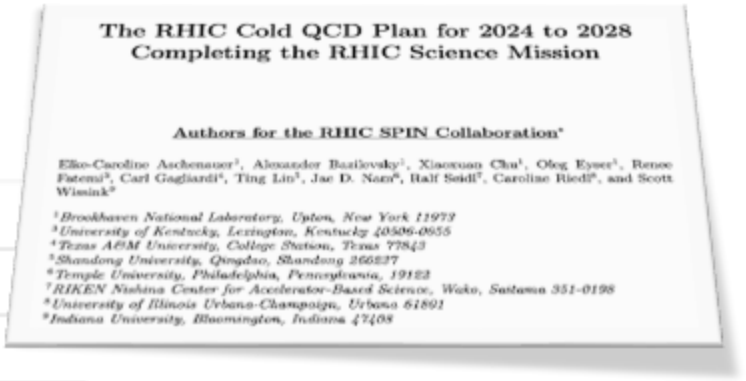
- create "buy-in": **engage whole collaboration**
  - use shift-credit mechanism
- improve **workflow documentation** (calibrations, analyses, etc)
- look for **commonalities** with other BNL collaborations
  - seeking strong support from BNL

STAR Data Analysis Map



- Existing Analysis Map has been regularly updated as institutes join and (preliminary) results are released
  - published/preliminary/underway/ production not started
- Comprehensive review of Analysis Map
  - Spring/Summer ’24
  - 83% positive response rate




The RHIC Cold QCD Plan for 2024 to 2028
Completing the RHIC Science Mission

Authors for the RHIC SPIN Collaboration*

- RHIC Cold QCD Plan
  - STAR Note 837

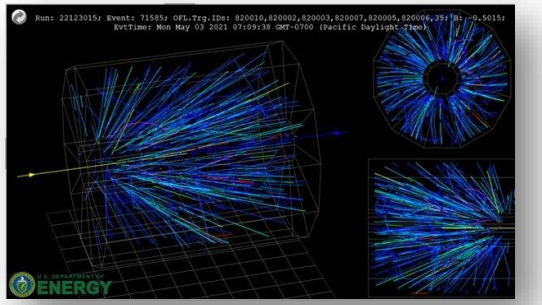
Physics Highlights

Focus on recently published papers

- DOE NP Highlights
- BES Phase-2 net-proton higher moments paper
- Selection of published papers from all five PWGs

DOE Office of Science NP Highlights == clickable ==

December 6, 2022

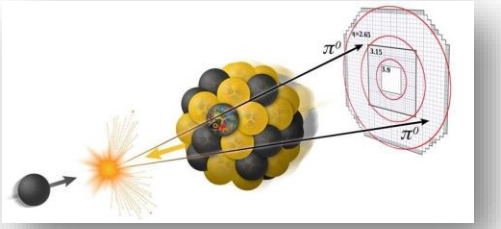


Scientists Narrow the Anchor Point in a Quantum Chromodynamics Critical Point Search

March 22, 2023

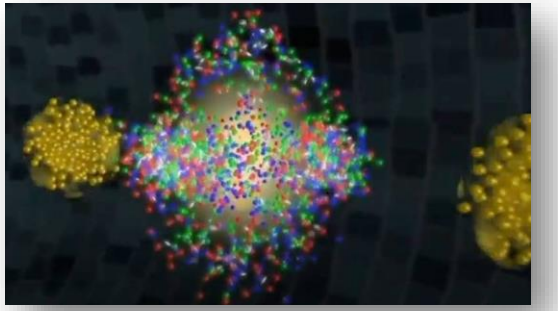
New Type of Entanglement Lets Scientists 'See' Inside Nuclei

March 24, 2023



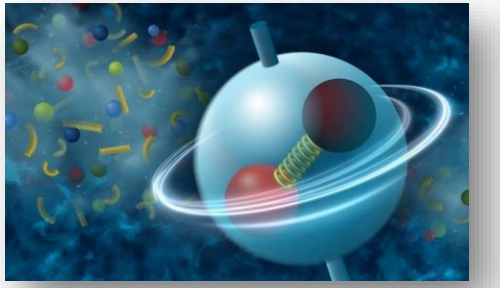
Signs of Gluon Saturation Emerge from Particle Collisions

April 7, 2023



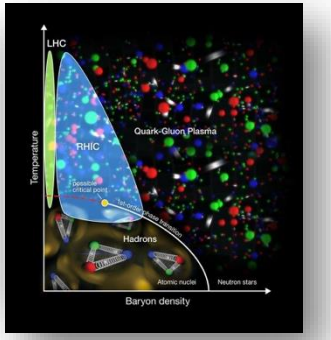
New Findings on the Flow of Particles in Heavy Ion Collisions

May 5, 2023



Surprising Preference in Particle Spin Alignment

June 5, 2023

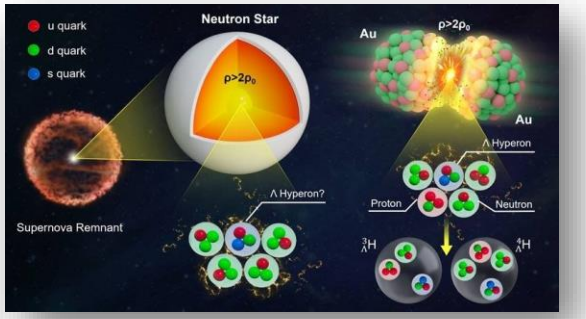


A Low-Energy 'Off Switch' for Quark-Gluon Plasma

June 15, 2023

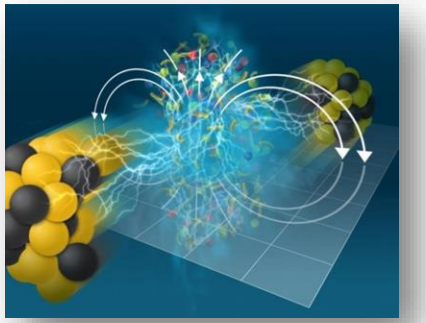
STAR Physicists Track Sequential 'Melting' of Upsilons

August 21, 2023



New Insights into How Strange Matter Interacts with Ordinary Matter

May 17, 2024



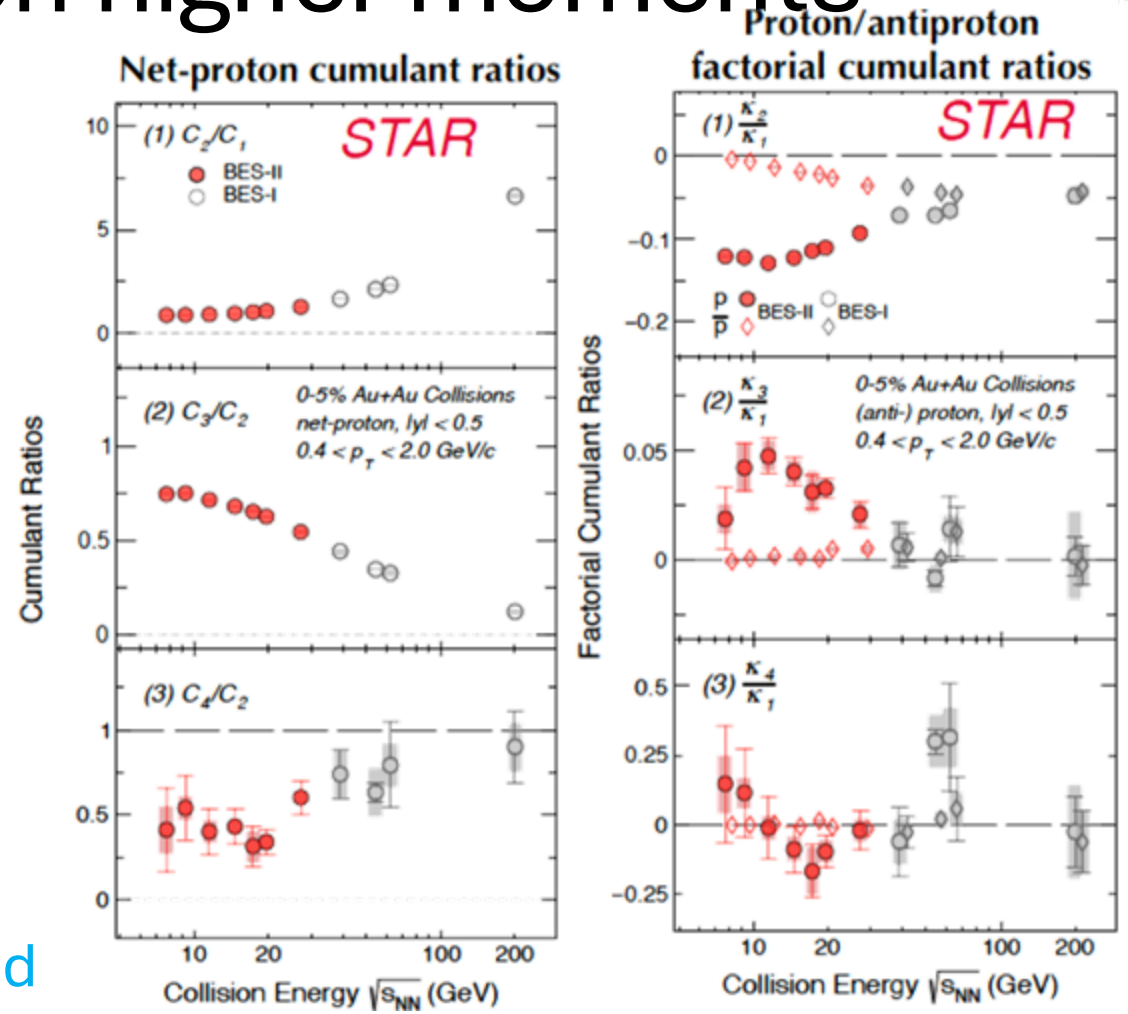
STAR Sees a Magnetic Imprint on Deconfined Nuclear Matter

BES Phase-2: net-proton higher moments

- Collider data from 7.7 – 27 GeV
  - $150 < \mu_B < 400$ MeV
- Precision results on proton cumulants and factorial cumulants
  - from BES-II with greatly improved statistical and systematic uncertainties
  - Reduction factors in uncertainties on 0-5% C_4/C_2 (BES 1 vs BES 2)

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

➢ Very interesting trends observed as a function of collision energy



STAR: CPOD'24, SQM'24
[paper in collaboration review]

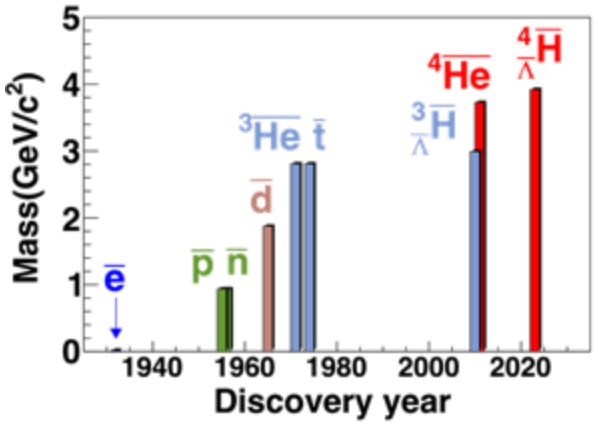
Light Flavor Spectra & UPC

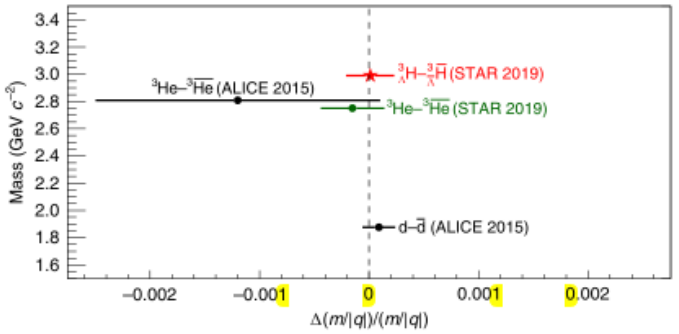
- Measurements of dielectron production in Au+Au Collisions at $\sqrt{s_{NN}}$= 27, 39, and 62.4 GeV, PRC **107** (2023) L061901
- Beam Energy Dependence of Triton Production and Yield Ratio ($N_t N_p/N_d^2$) in Au+Au Collisions at RHIC, PRL **130** (2023) 202301
- K^0 production in Au+Au collisions 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
- Pion, kaon, and (anti)proton production in U+U collisions $\sqrt{s_{NN}}$ = 193GeV measured with the STAR detector, PRC **107** (2023) 24901
- Observation of strong nuclear suppression in exclusive J/ψ photoproduction in Au+Au ultra-peripheral collisions at RHIC, PRL **133** (2024) 52301
- **Observation of the Antimatter Hypernucleus $^{4}_{\Lambda}\overline{\mathrm{H}}$, Nature 632 (2024) 1026**
- **Exclusive J/ψ, ψ(2S), and e^+e^- pair production in Au+Au ultra-peripheral collisions at RHIC, PRC 110 (2024) 14911**
- **Results on Elastic Cross Sections in Proton-Proton Collisions at $\sqrt{s}$ = 510 GeV with the STAR Detector at RHIC, PLB 852 (2024) 138601**

New Heaviest Exotic Antimatter Nucleus

Nature 632 (2024) 1026

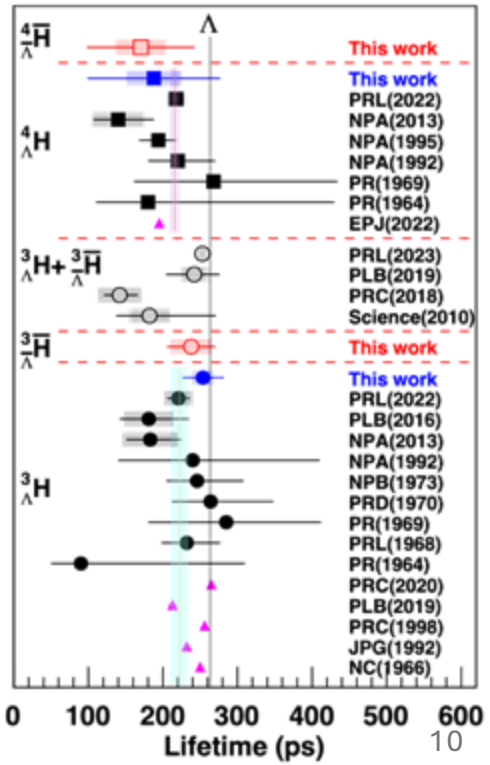
- STAR: a history of antimatter searches
- antimatter hypertriton $^{3}_{\Lambda}\overline{\mathrm{H}}$
  Science 328 (2010) 58
- antihelium-4 (anti-alpha) $^{4}\overline{\mathrm{He}}$
  Nature 473 (2011) 353



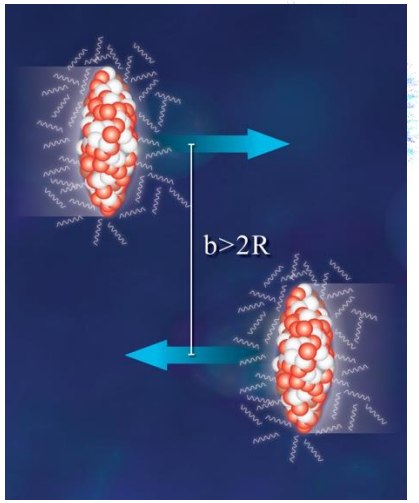


➢ Study matter-antimatter asymmetry through discovery of new antimatter particles; test CPT invariance

- mass difference between $^{3}_{\Lambda}\overline{\mathrm{H}}$ and $^{3}_{\Lambda}\mathrm{H}$, and between $^{3}\overline{\mathrm{He}}$ and $^{3}\mathrm{He}$
  - Nature Phys. 16 (2020) 409
- lifetime differences between $^{3}_{\Lambda}\overline{\mathrm{H}}$ and $^{3}_{\Lambda}\mathrm{H}$ and between $^{4}_{\Lambda}\overline{\mathrm{H}}$ and $^{4}_{\Lambda}\mathrm{H}$
  - ➢ **first observation of 15.6 $^{4}_{\Lambda}\overline{\mathrm{H}}$ candidates (estimate background count 6.4)**
  - ➢ **no significant difference between lifetimes**
- next step: study mass differences
  2022 SCGSR Award, Emily Duckworth (Kent)



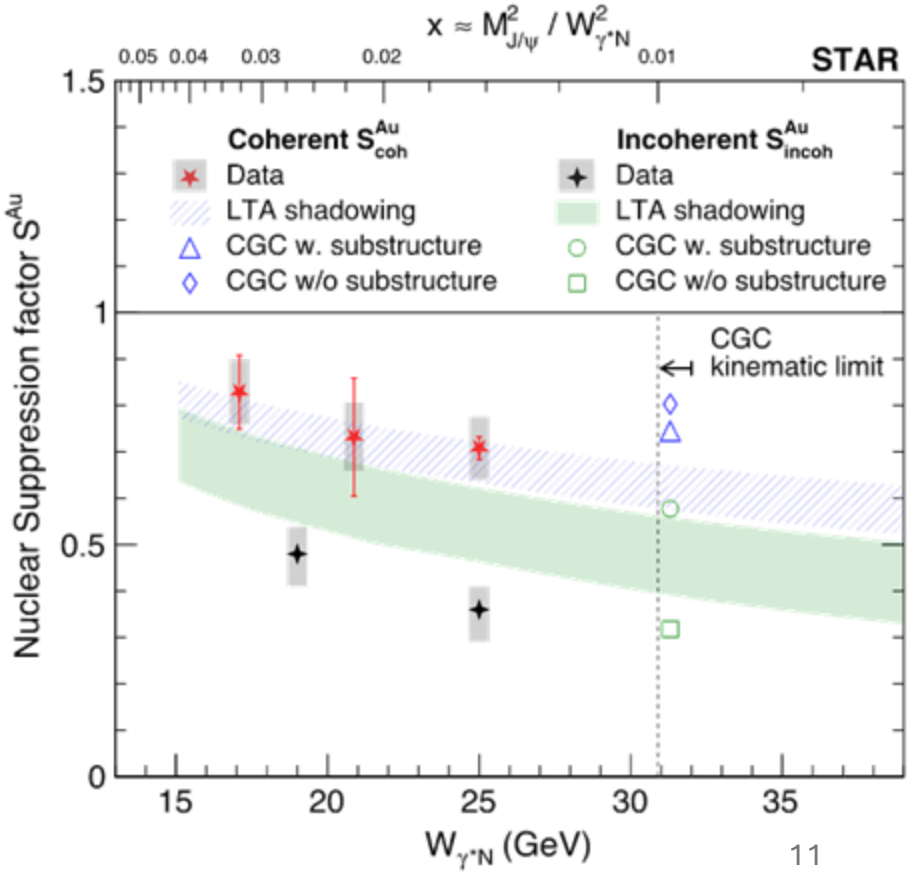
Observation of large nuclear suppression in J/ψ photoproduction in ultra-peripheral Au+Au



PRL 133 (2024) 052301
PRC 110 (2024) 014911

- Observed in both coherent and incoherent UPC collisions
- Incoherent nuclear suppression via J/ψ photoproduction
  measured by STAR for the first time
  ➢ indicates a stronger modification than its coherent counterpart

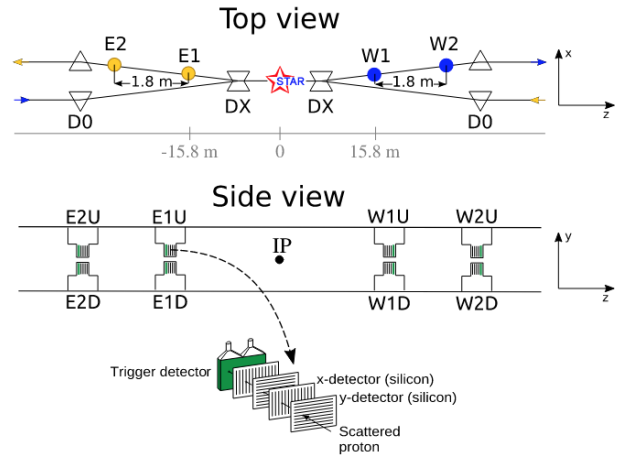
- sensitive experimental probe to bound vs free nucleon and its implication to the Cold Nuclear Matter effect.

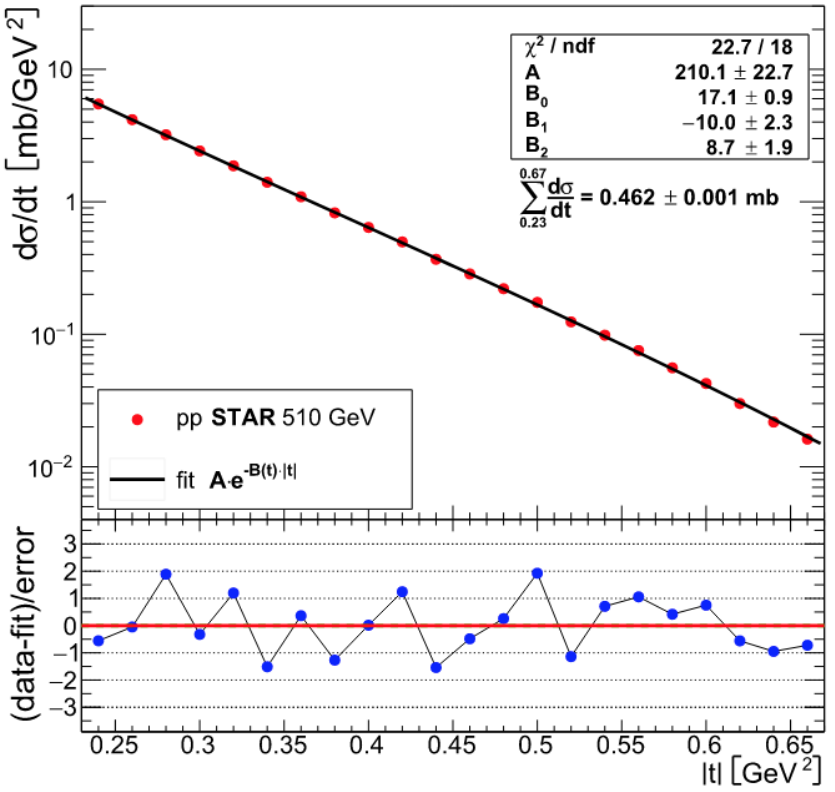


Elastic Cross Sections in pp collisions at 510 GeV

PLB 852 (2024) 138601

- Precise pp elastic differential cross section for in 510 GeV collisions
  - $0.23 < |t| < 0.67$ GeV^2 hadronic term can be described as $\frac{d\sigma}{dt} = Ae^{-B(t)|t|}$
  - STAR found B ~ constant in pp at 200GeV
    - PLB 808 (2020)135663
  - theory allows B to be non-constant
- First measurement in this range, below LHC energies for which a non-constant behavior of B(t) is observed
  - Only measurement between ISR and LHC showing non-constant behavior
- Comparison with phenomenological model predictions in good agreement, esp. $|t|<0.4$GeV^2
  - maximum Odderon amplitude (FMO), 2-channel eikonal model (KMR), and 3-component Pomeron/Odderon (PPP)





Flow, Chirality, and Vorticity (1)

- 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
- Hyperon polarization along the beam direction relative to the second and third harmonic event planes in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRL **131** (2023) 202301
- 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
- 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

Flow, Chirality, and Vorticity (2)

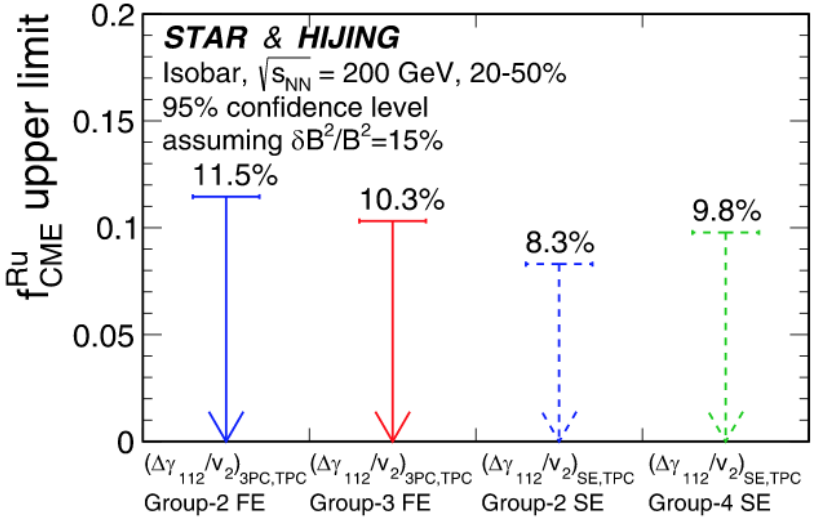
- Event-by-event correlations between Λ (anti-Λ) hyperon global polarization and handedness with charged hadron azimuthal separation in Au+Au collisions at $\sqrt{s_{NN}}$ = 27 GeV from STAR, PRC **108** (2023) 14909
- Global polarization of Λ and anti-Λ hyperons in Au+Au collisions at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV, PRC **108** (2023) 14910
- Estimate of Background Baseline and Upper Limit on the Chiral Magnetic Effect in Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV at the Relativistic Heavy-Ion Collider, PRC **110** (2024) 14905
- **Upper limit on the chiral magnetic effect in isobar collisions at the Relativistic Heavy-Ion Collider, PRR 6 (2024) 32005**
- Estimate of background baseline and upper limit on the chiral magnetic effect in isobar collisions at $\sqrt{s_{NN}}$ = 200 GeV at the BNL Relativistic Heavy Ion Collider, PRC **110** (2024) 014905
- **Observation of the electromagnetic field effect via charge-dependent directed flow in heavy-ion collisions at the Relativistic Heavy-Ion Collider, PRX 14 (2024) 11028**
- **Reaction plane correlated triangular flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV, PRC 109 (2024) 44914**
- **Imaging shapes of atomic nuclei in high-energy nuclear collisions, accepted by Nature (published online Nov.6)**

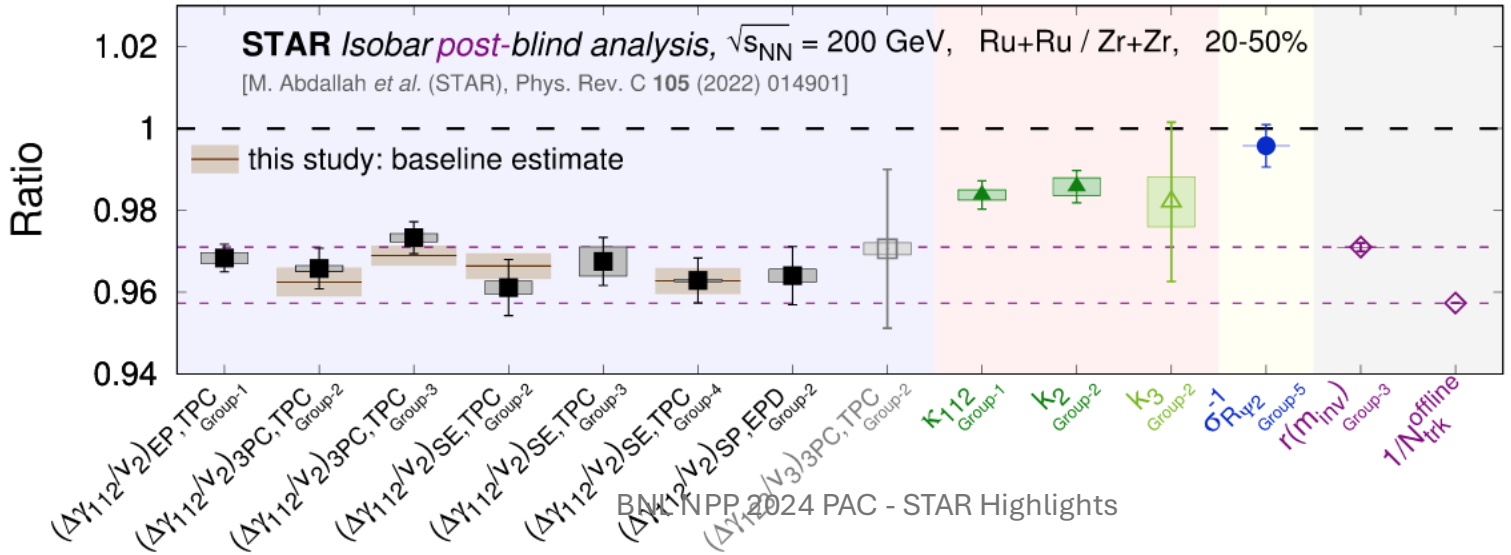
Background baseline estimates and upper limit on the chiral magnetic effect

PRR 6 (2024) 32005
PRC 110 (2024) 14905

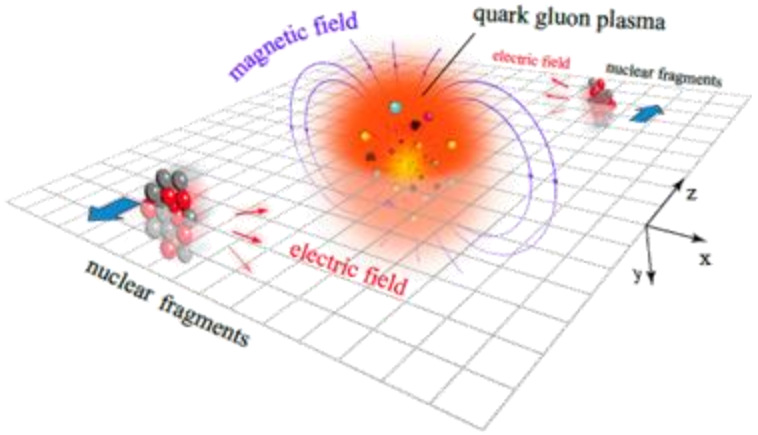
- Post-blind analysis of isobar data, estimating contributions from nonflow correlations to $Y = \frac{(\Delta\gamma/v_2)^{Ru}}{(\Delta\gamma/v_2)^{Zr}}$

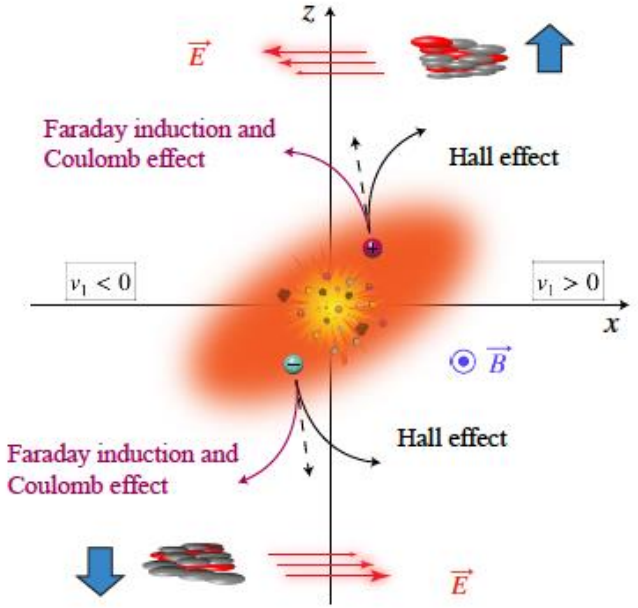
➢ Finds upper limit on the CME fraction of ~10% at 95% confidence level





Identified particle charge-dependent directed flow v_1

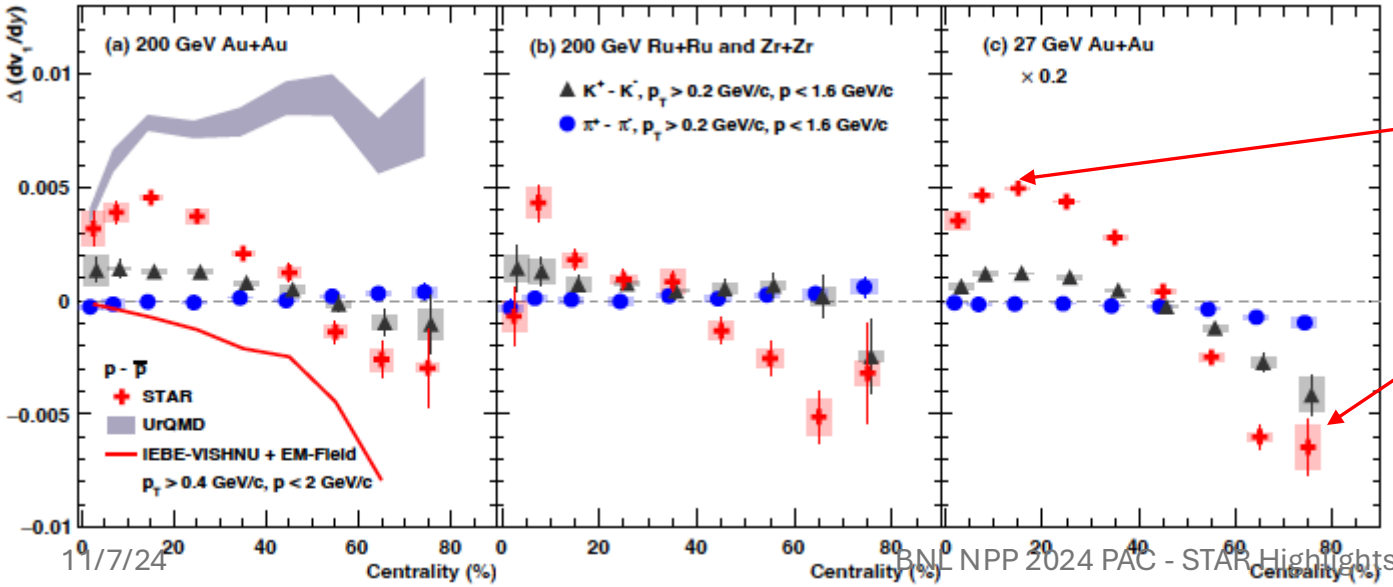




PRX 14 (2024) 11028

Transported-quark effect:
positive charge-dependent v_1 slope

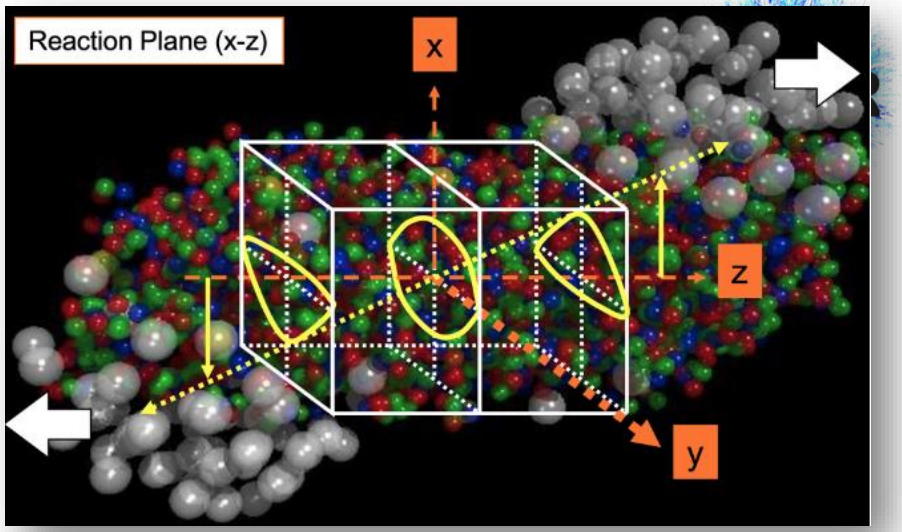
Faraday + Coulomb:
negative charge-dependent v_1 slope



Results in central collisions can be explained by transported quark effect.

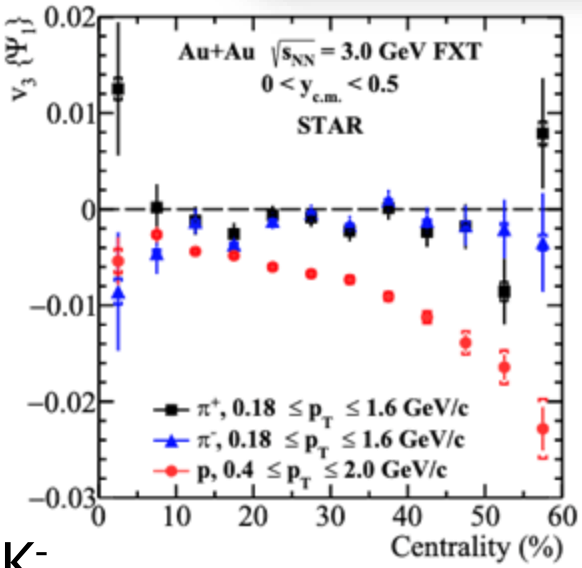
Results in peripheral collisions reveal the contributions from the Faraday induction and Coulomb effect for the first time in heavy-ion collisions.

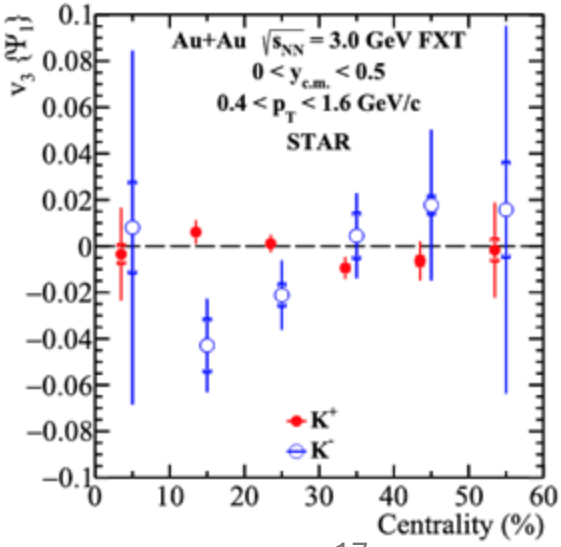
Triangular flow measurements in Au+Au at $\sqrt{s_{NN}}$ = 3 GeV



PRC 109 (2024) 44914

- Lowest energy in the STAR Beam Energy Scan
- $v_3\{\Psi_1\}$ for $\pi^{\pm}$,$K^{\pm}$, p vs. centrality, rapidity, and pT
  - $v_3\{\Psi_1\}$ correlated with reaction plane
- Comparison with HADES $\sqrt{s_{NN}}$ = 2.4 GeV
  - Considerable differences (5x) in slope
  - Further studies needed to better understand physical drivers of this discrepancy
- Extensive comparison with several models
  - AMPT, RQMD, SMASH, JAM
  - suggests medium is not in a partonic state
- Larger 3GeV data set (5x) will help improve K^- results
  - will also include forward PID (eTOF)

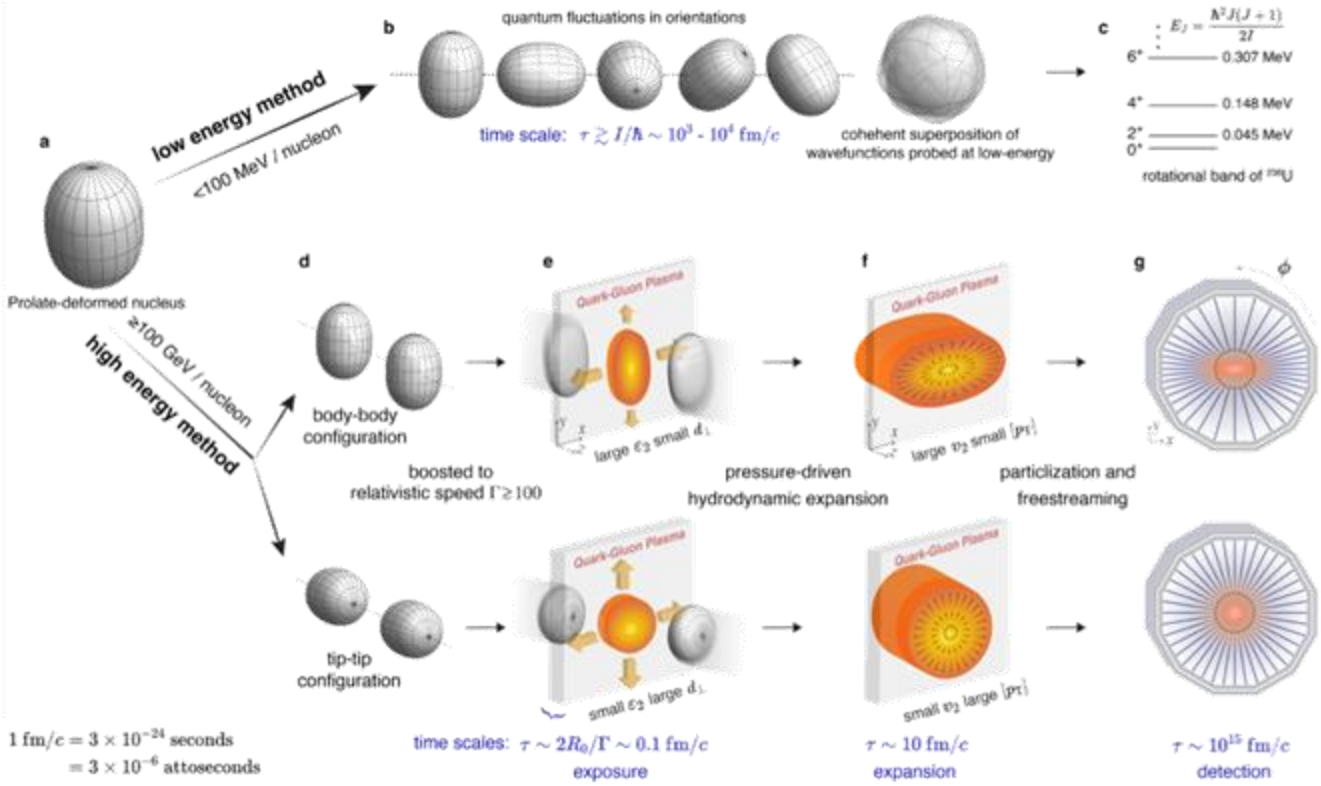




Imaging shapes of atomic nuclei

- Use collective flow to assist nuclear shape imaging at high energies
  - capture fast snapshot of nucleon spatial distributions
- ^{238}U measurements consistent with prior low-energy experiments
  - compare highly prolate shape of ^{238}U with mildly oblate ^{197}Au
  - ➢ First indication of a small rigid triaxial component in deformation of ^{238}U
    - Consistent with expectations from Otsuka, et al. (2303.11299)
- New tool that can be especially effective for discerning shape differences between isobar(-like) pairs
  - Odd-mass (N or Z) nuclei
    - when compared to neighboring even-even nuclei
  - Octupole and hexadecapole deformations
    - Through measurements of high-order flow

  etc. …
- But also, help explain mechanisms of QGP initial condition formation.



Accepted by Nature

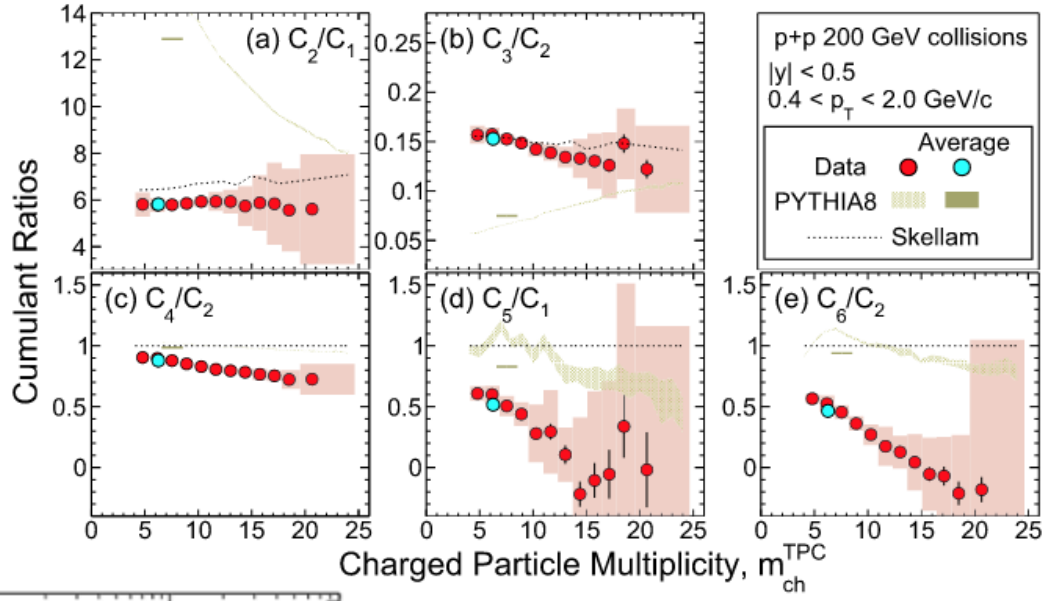
doi: 10.1038/s41586-024-08097-2

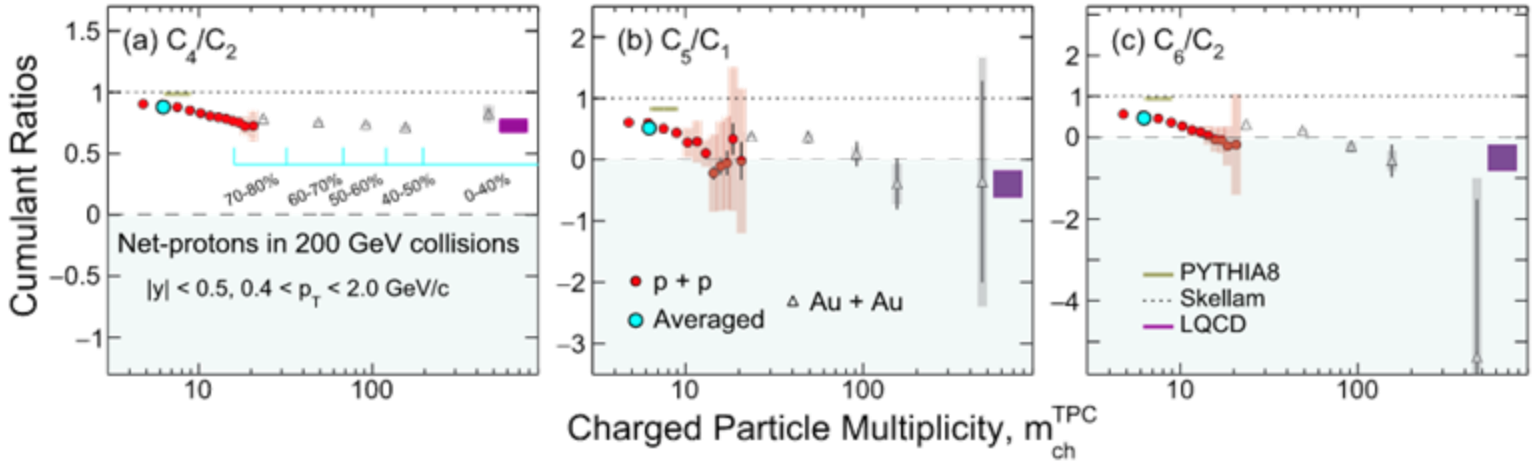
Correlations & Fluctuations

- 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 $\sqrt{s_{NN}}$ = 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, PLB **845** (2023) 138165
- **Measurements of charged-particle multiplicity dependence of higher-order net-proton cumulants in p+p collisions at $\sqrt{s}$ = 200 GeV from STAR at RHIC, PLB 857 (2024) 138966**
- **Collision-energy Dependence of Deuteron Cumulants and Proton-deuteron Correlations in Au+Au collisions at RHIC, PLB 855 (2024) 138560**

Net-proton Cumulants in pp at $\sqrt{s}$=200 GeV

- First measurement of higher-order cumulants
  - C_2/C_1, C_3/C_2, C_4/C_2, C_5/C_1, and C_6/C_2
  - C_4/C_2, C_5/C_1, C_6/C_2 decrease between pp and AuAu
    - PYTHIA fails to reproduce multiplicity dependence and hierarchy
- Lattice QCD predicts negative values for C_5/C_1, C_6/C_2 for themalized nuclear matter
  - but uncertainties too large at high multiplicities





PLB 857 (2024) 138966

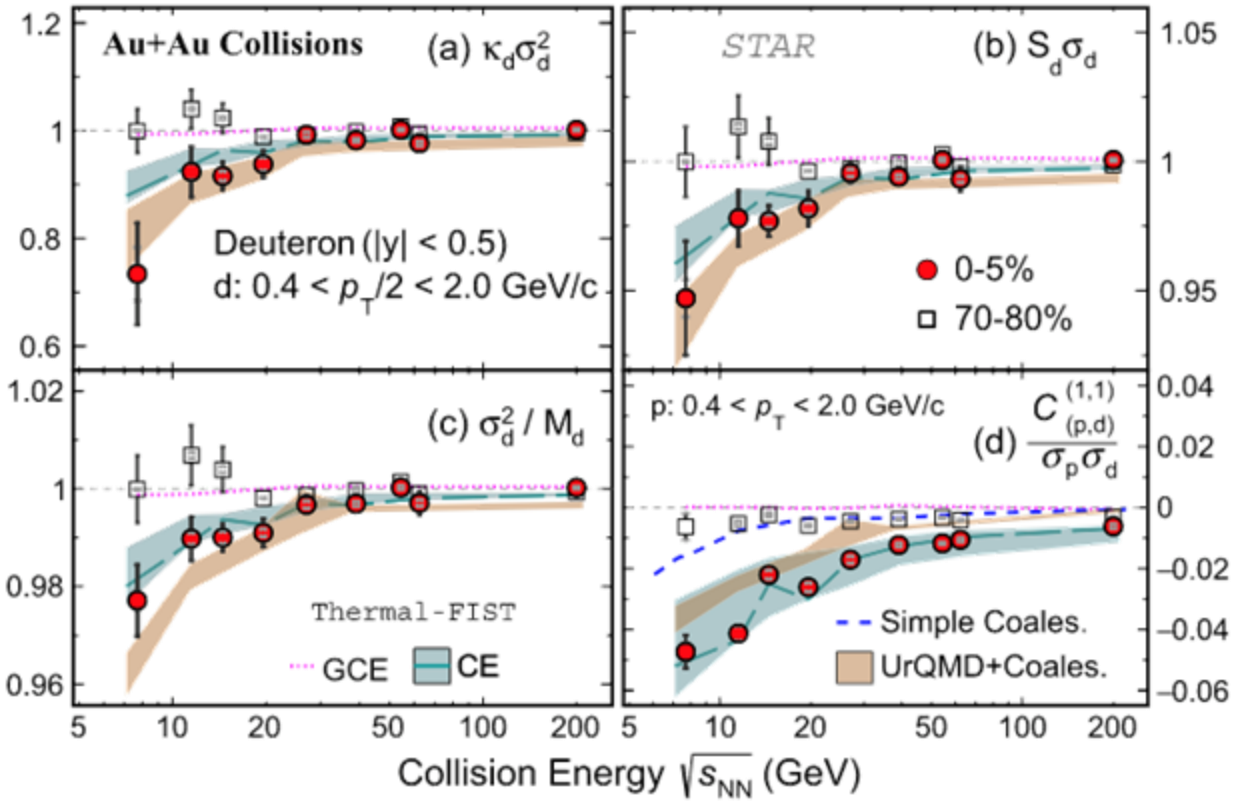
BES: deuteron cumulants

- First measurement of cumulants, up to 4th order
  - BES Phase-1 data

➢ Cumulant ratios favor CE over a GCE in thermal models
  - CE explicitly conserves B number

- Anti-correlation between p and d numbers (negative correlation coefficients)

❖ BES Phase-2 data (incl. FXT) will allow for more differential studies



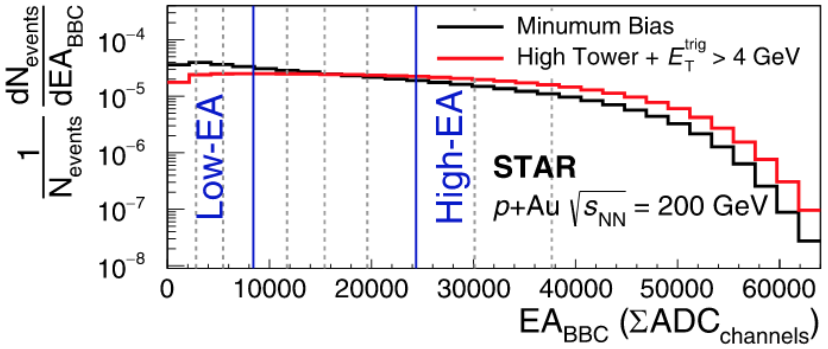
PLB 855 (2024) 138560

Hard Probes

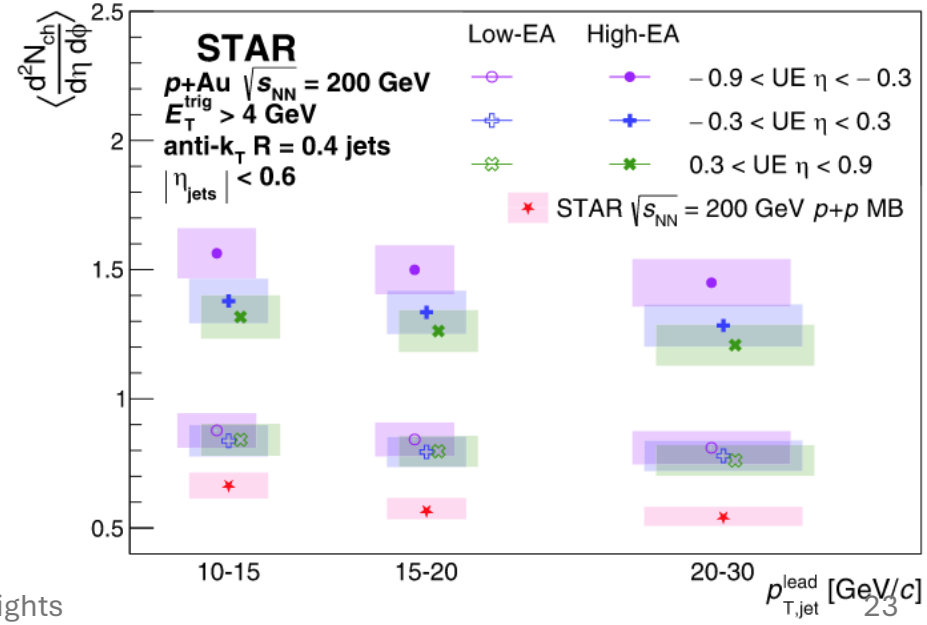
- Elliptic Flow of Heavy-Flavor Decay Electrons in Au+Au Collisions at $\sqrt{s_{NN}}$ = 27 and 54.4 GeV at RHIC, PLB **844** (2023) 138071
- Measurement of electrons from open heavy-flavor hadron decays in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, JHEP **176** (2023) 2023
- Measurement of sequential Upsilon suppression in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, PRL **130** (2023) 112301
- **Event activity correlations and jet measurements in p+Au collisions at at $\sqrt{s_{NN}}$ = 200 GeV, PRC 110 (2024) 44908**
- **Jet-hadron correlations with respect to the event plane in at $\sqrt{s_{NN}}$ = 200 GeV Au+Au collisions in STAR, PRC 109 (2024) 44909**

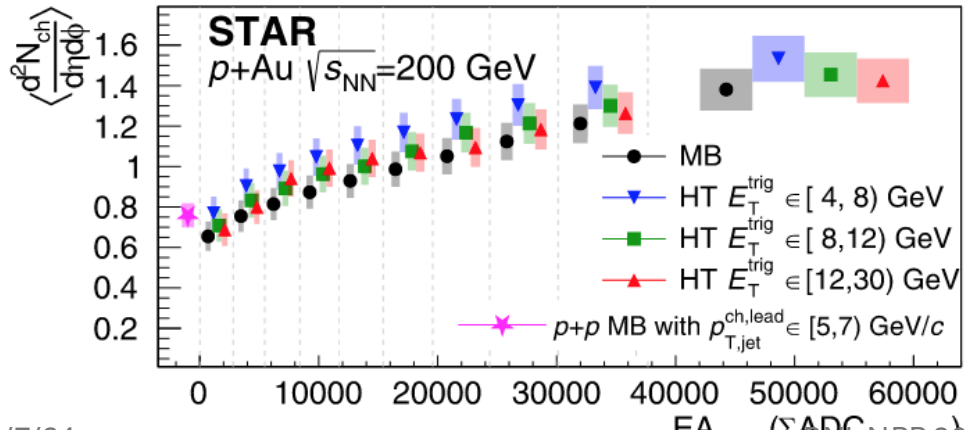
Event activity correlations in p+Au

- Event activity (EA) from -5 < η < -3.4 (Au-going direction)
- Correlations between EA and particles produced in |η|< 1
  - ➢ Study correlations with soft and hard-scale production
- Soft-scale:
  - at low-EA, n^{ch} comparable to pp
  - monotonic increase with increasing EA
- Hard-scale:
  - high-p_T particle production inversely related to EA
  - no presence of jet quenching in top-30% EA p+Au



PRC 110 (2024) 044908

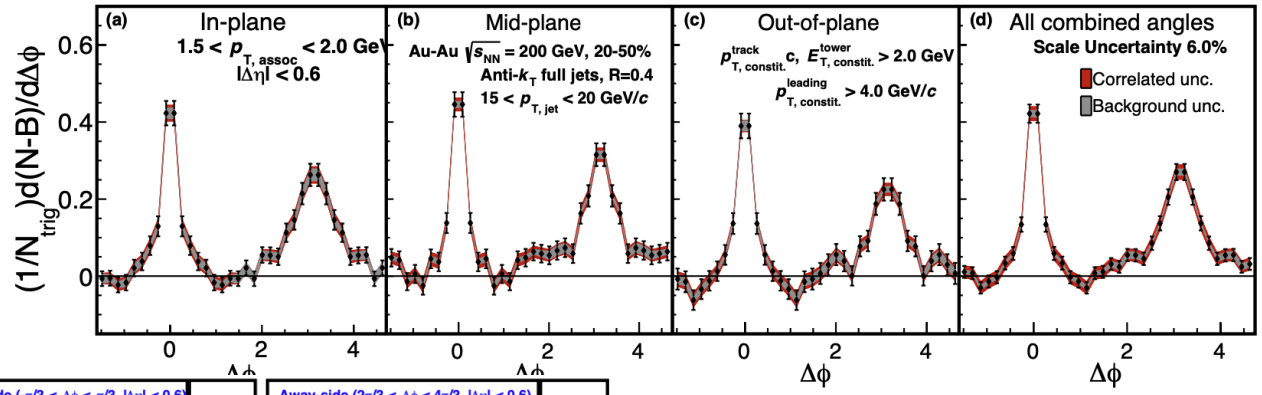


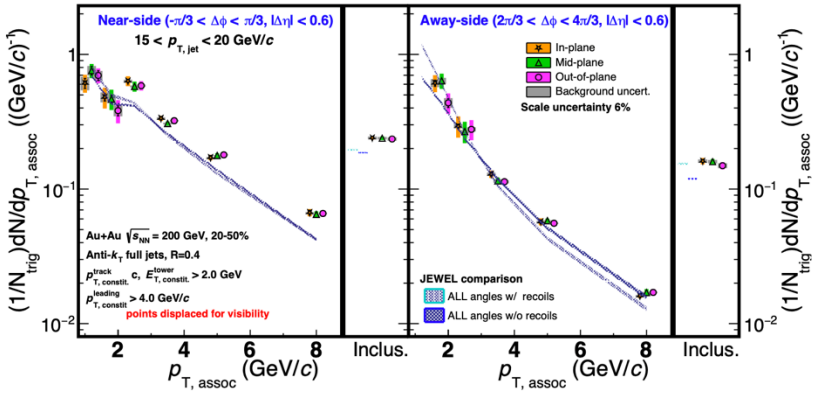


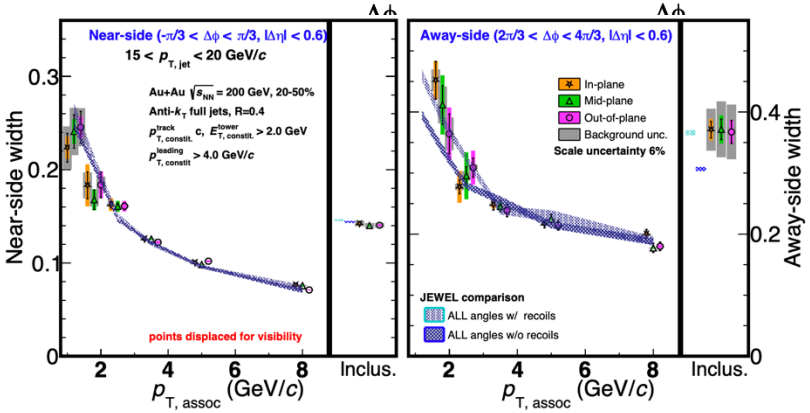
Jet-hadron correlation with respect to event plane

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

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







PRC 109 (2024) 44909

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

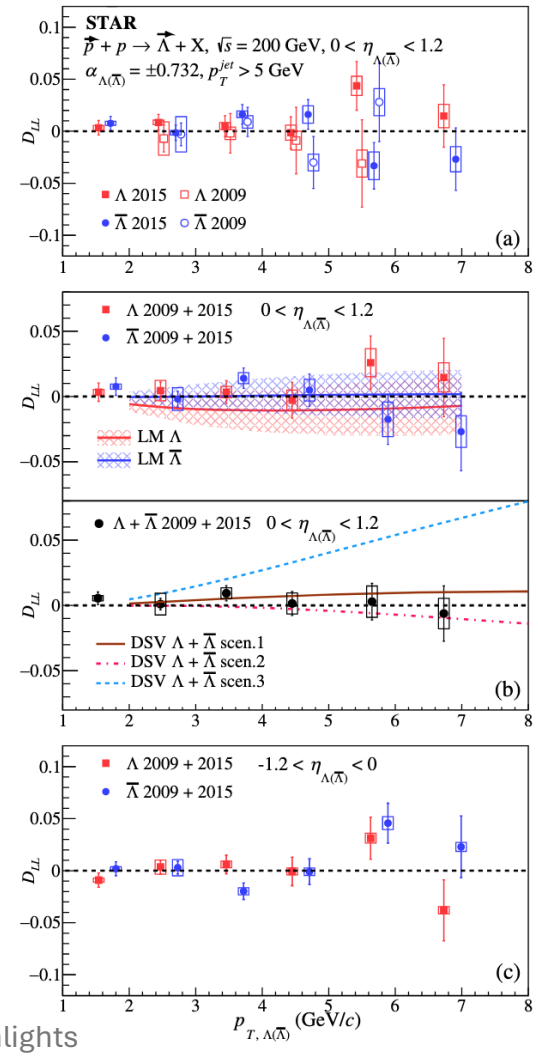
Cold QCD

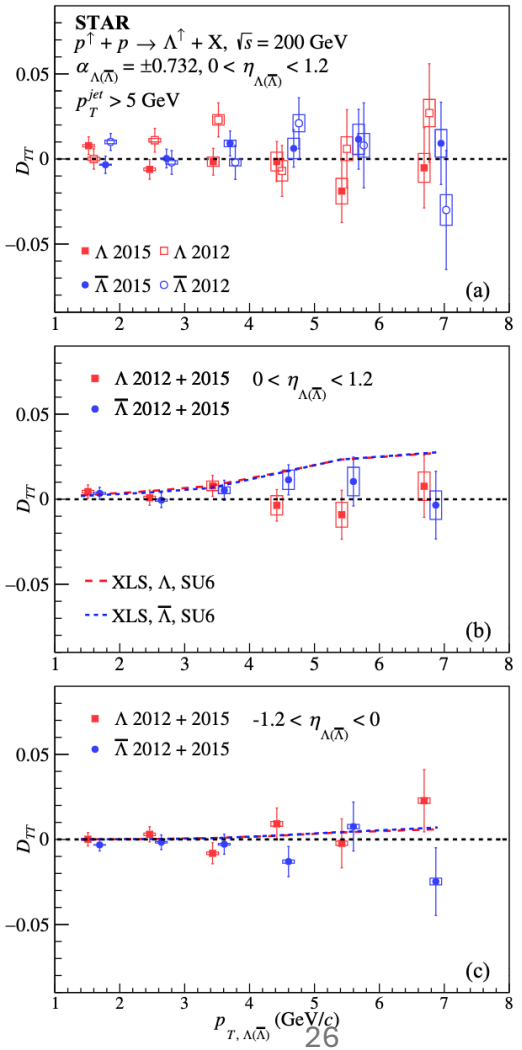
- **Longitudinal and transverse spin transfer to Lambda and anti-Lambda hyperons in polarized p+p collisions at $\sqrt{s}$ = 200 GeV, PRD 109 (2024) 12004**
- **Measurements of unpolarized cross section and transverse single spin asymmetry of Z^0 in 500/510 GeV p+p collisions, PLB 854 (2024) 138715**

Longitudinal and transverse spin transfer to Lambda and anti-Lambda hyperons

PRD 109 (2024) 12004

- Improved measurements with 2x more statistics
  - Run-15 pp at $\sqrt{s}$=200 GeV, 52 pb^{-1} sampled luminosity
  - past publications in 2009 and 2018
- Longitudinal transfer D_{LL}: sensitive to $s/\bar{s}$ helicity distribution through polarized fragmentation functions
  - ➢ Good agreement with theory predictions
  - Except for extreme assumption of quark flavor independent FFs (scenario 3)
- Transverse transfer D_{TT}: transversely polarized p beams provide a natural connection to transversity distributions
  - ➢ Consistency with theory predictions
  - Uncertainties at high pT still large
- First measurements of D_{LL} and D_{TT} vs z
  - z = fractional moment of jet carried by the $\Lambda/\bar{\Lambda}$ hyperons
  - direct probe of the polarized FFs





Transverse single spin asymmetry of Z^0

- Combined data sets of 2011, 2012, 2013, and 2017
  - P+p at $\sqrt{s}$ =500 and 510 GeV
  - 2017: 14x integrated luminosity 2011

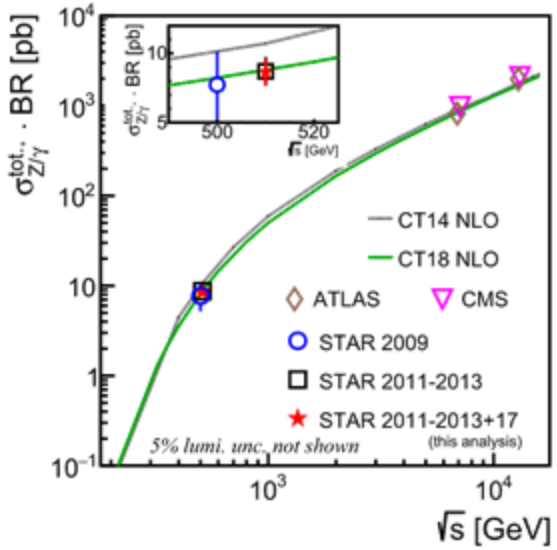
➢ (Total) Cross sections provide stringent test of the energy dependence of PDFs

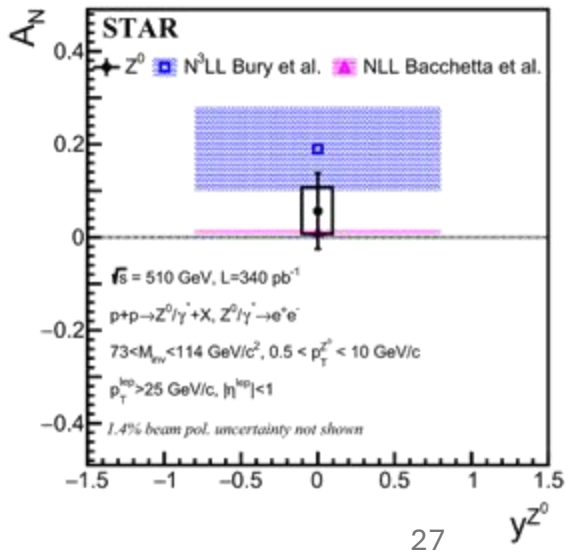
- Z^0 TSSA sensitive to one of the polarized TMDs
  - the Sivers function
- A_N predicted to have the opposite sign in $p + p \rightarrow W/Z + X$
  - based on the non-universality property of the Sivers function between DY/Z/W production and SIDIS

➢ Results can accommodate non-universality

- but no conclusive verification

- Inclusive based on 2017 data only (340 pb^{-1})
  - expect substantial improvements with 2022 data (400 pb^{-1})





PLB 854 (2024) 138715

Summary

- STAR continues to be very productive
  - expect 2024 to be the third year with 20+ publications
  - journal portfolio expanded to include Physical Review X, Physical Review Research, Science Advances
- Many more papers in the pipeline
  - record number of internal previews (precursor to GPC formation)
  - large number of active GPCs
    - substantial fraction of STAR collaborators are involved in the publication process
- Strategy developed for Data Preservation
  - must include efforts that include software and analysis workflows
  - must come with strong support from BNL