# STAR Beam Use Request for the Continuation of Run 25

Lijuan Ruan

BNL NPP 2025 PAC meeting, October 16, 2025

# Executive summary: what else we would like to do in addition to 200 GeV Au+Au

For 200 GeV Au+Au, we project reaching the minimum-bias goal on Dec. 31 and the high-$p_T$ goal on Dec. 25.

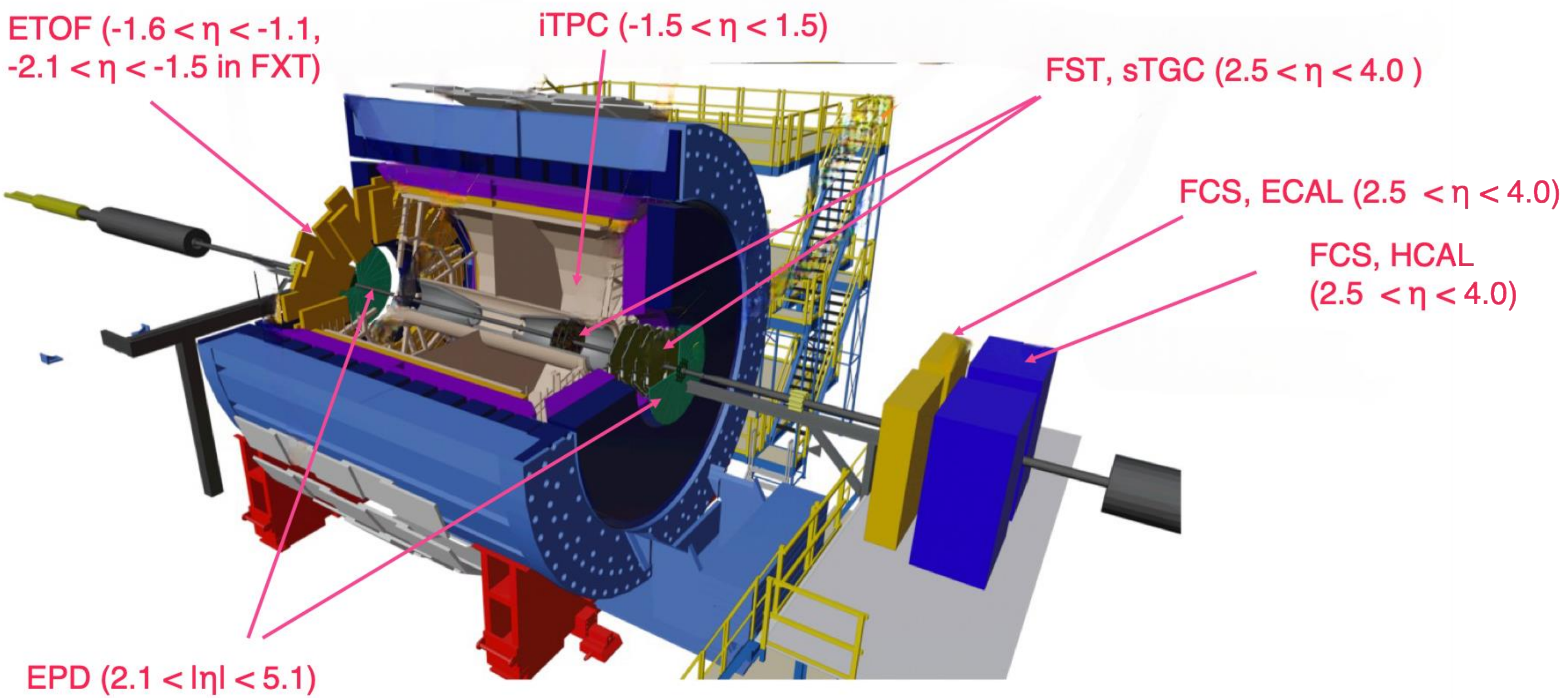
STAR's highest scientific priority: to **complete the must-do Cold QCD physics** with transversely polarized p+Au data at 200 GeV. We request at least 5-weeks of physics running to achieve a sampled luminosity of 0.22 $pb^{-1}$, assuming a proton beam polarization of 53%

Next priority: substantially large fixed-target dataset at 4.5 and 4.2 GeV to establish the energy dependence for the **QCD critical point search**

In addition, STAR requests 250 million isobar events (Zr+Zr and Ru+Ru combined) each at two energy points (27 and 62 GeV) to **measure charge transport**

# STAR experiment

STAR is composed of 77 institutes from 14 countries, with a total of 754 collaborators.




25 years of operation, major successful upgrades, vibrant physics programs

387 published papers, 343 PhD and 34 MS theses

# The pAu request

Table 1: Luminosity of $p$+Au collected during Run-15 and its 5-week projection provided by CAD

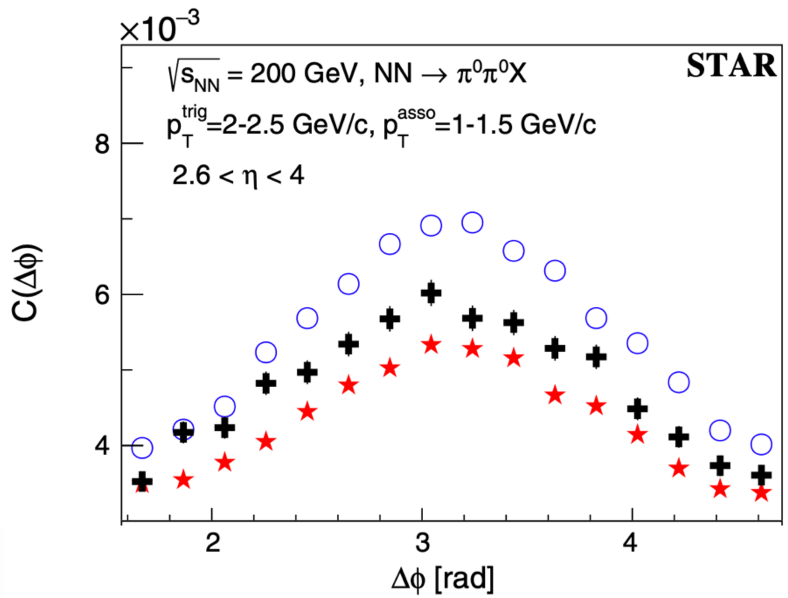
| Time | CAD $\frac{Lumi.}{week}$ | $Lumi.$ per PAC Req. (calc. from CAD number) | nPDF | Saturation | GPD | TMD |
|---|---|---|---|---|---|---|
| Run-15 | 0.233 $pb^{-1}$ | 0.45 $pb^{-1}$ (5w, collected) | ✓ | di-$\pi^0$ (✓) | ✓ | ✓ |
| June 2023 | 0.233 $pb^{-1}$ | 0.52 $pb^{-1}$ (5w) | ✓ | di-$\pi^0$ (✓)<br>di-$h^\pm$ (✓) | ✓ | ✓ |
| BUR23-24 | 0.120 $pb^{-1}$ | 0.27 $pb^{-1}$ (5w) | Limited | di-$\pi^0$ (×)<br>di-$h^\pm$ (✓) | Limited | Limited |
| BUR25 | 0.095 $pb^{-1}$ | 0.22 $pb^{-1}$ (5w) | Limited | di-$\pi^0$ (×)<br>di-$h^\pm$ (✓) | Limited | Limited |
| BUR25 Ext. | 0.095 $pb^{-1}$ | 0.07 $pb^{-1}$ (2.5w) | × | × | × | × |

STAR requested 10.5 weeks of physics data taking for p+Au in Run 24, as presented at the Sep. 2023 PAC meeting.

STAR was then asked to consider a 5-week p+Au scenario and to sharpen the corresponding physics case. We responded in both the 2024 and 2025 PAC meetings that 5 weeks would be the minimum required.

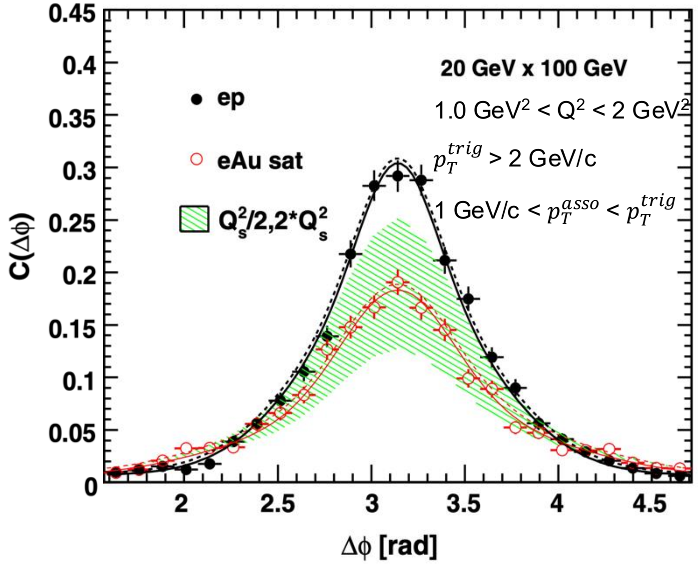
# QCD non-linear effects

## STAR pp/pA

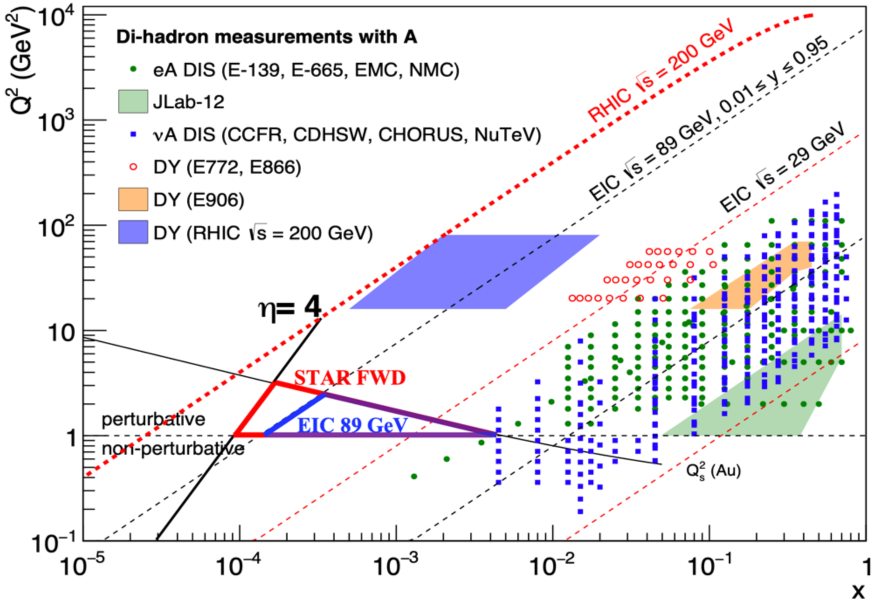



## EIC ep/eA

L. Zheng et al., PRD 89 (2014) 074037




EIC Yellow Report, arXiv:2103.05419

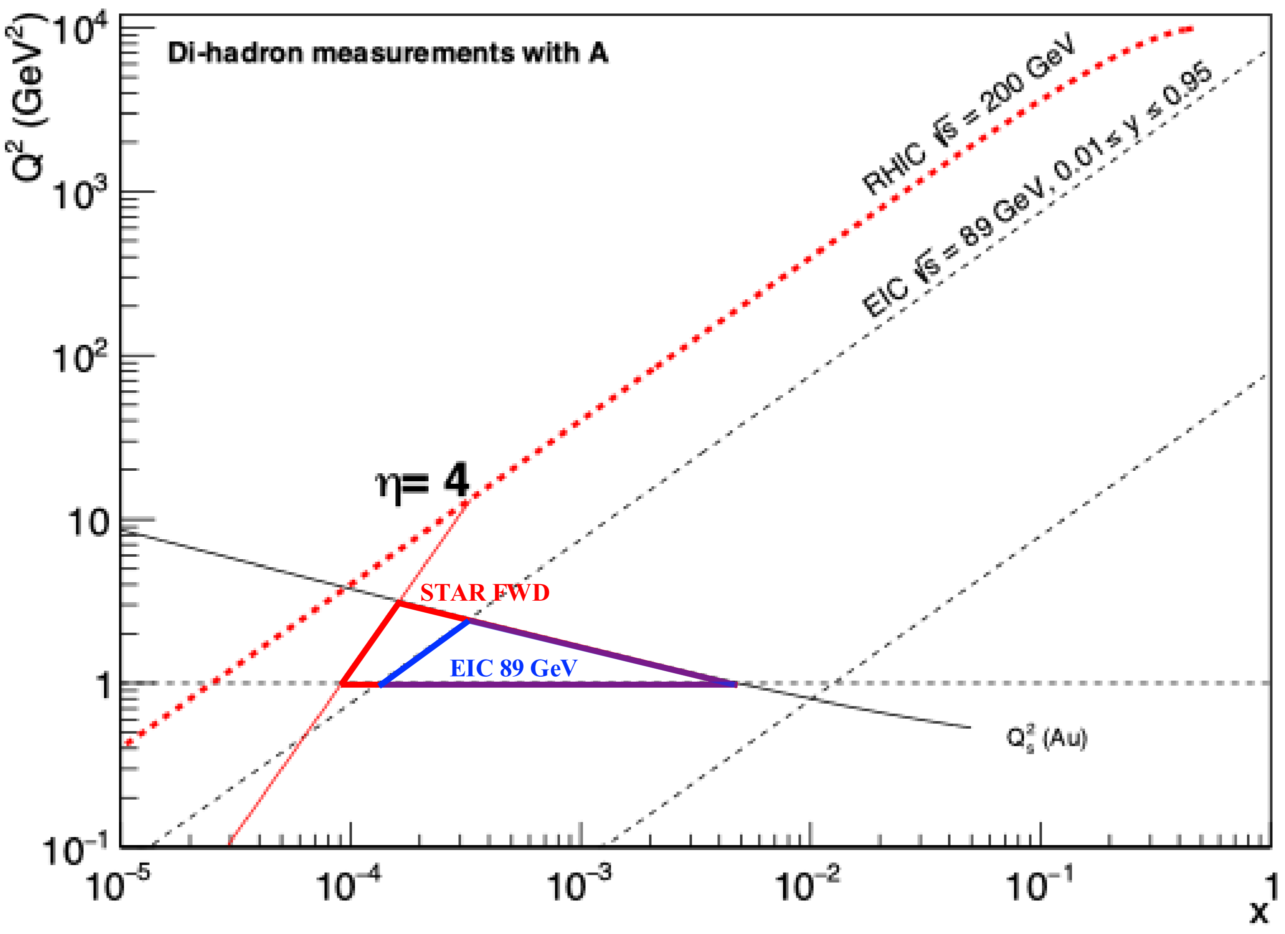



x range: $10^{-4}$ – 0.5
$Q^2$ range: 0.1 – 10 GeV$^2$
covers the entire region in red triangle

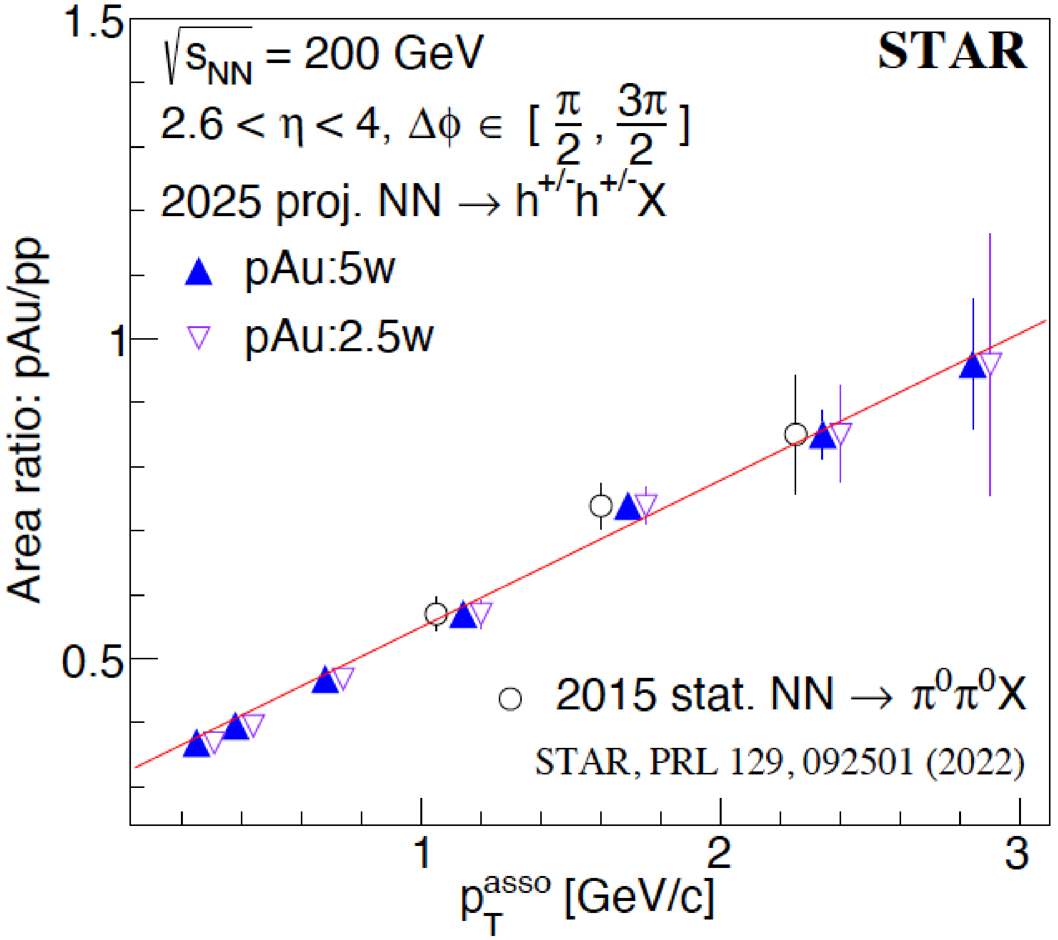
x range: ~$10^{-4}$ – ~1
$Q^2$ range: 1 – 2 GeV$^2$
covers the entire region in blue triangle

- Suppression was **observed in pA collisions** relative to pp collisions at STAR
- Suppression is **predicted in eA collisions** relative to ep collisions at the EIC
- Saturation in x-$Q^2$ region: STAR data with **Forward Upgrades overlap** with EIC 89 GeV data

# QCD non-linear effects

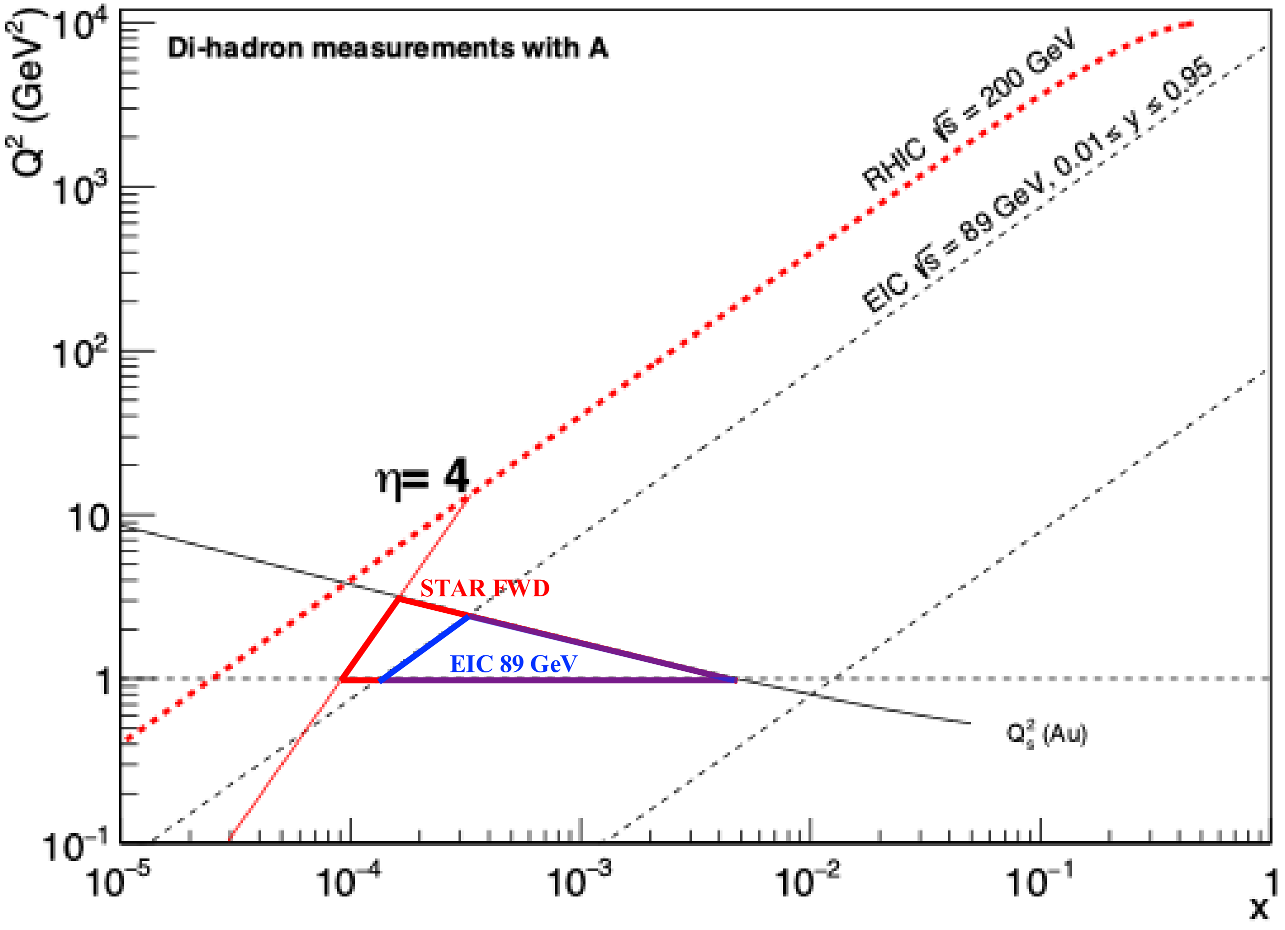



A cleaner version of x-$Q^2$ map



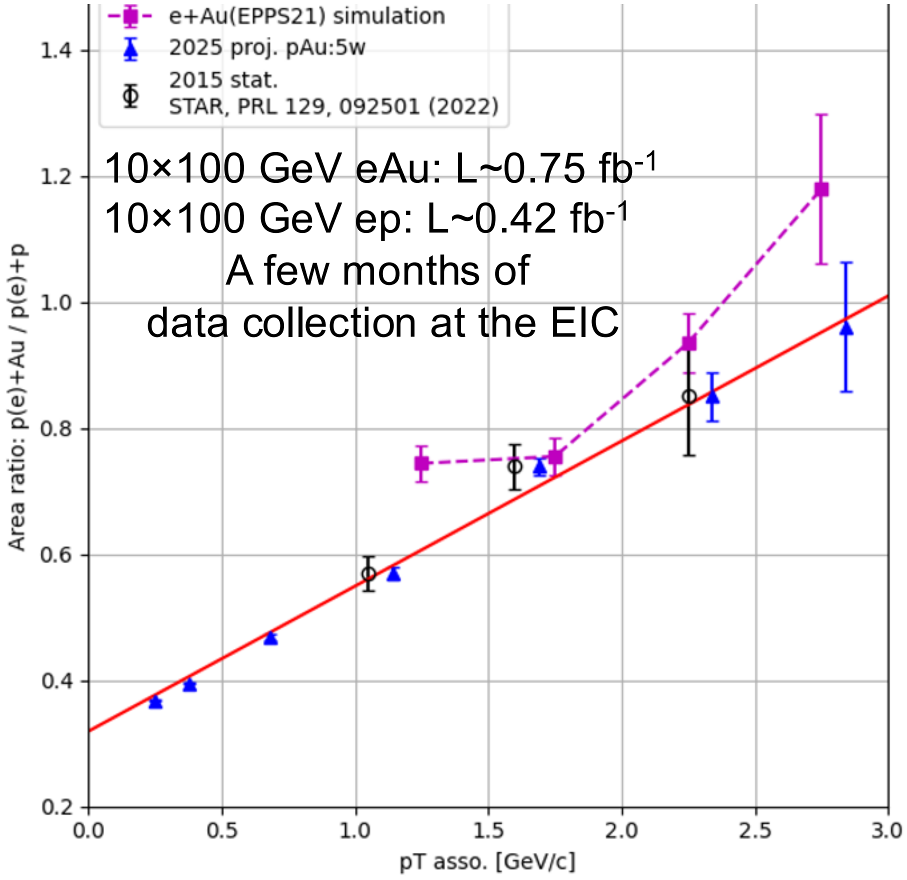

Di-charged hadron correlation projection plot

# QCD non-linear effects



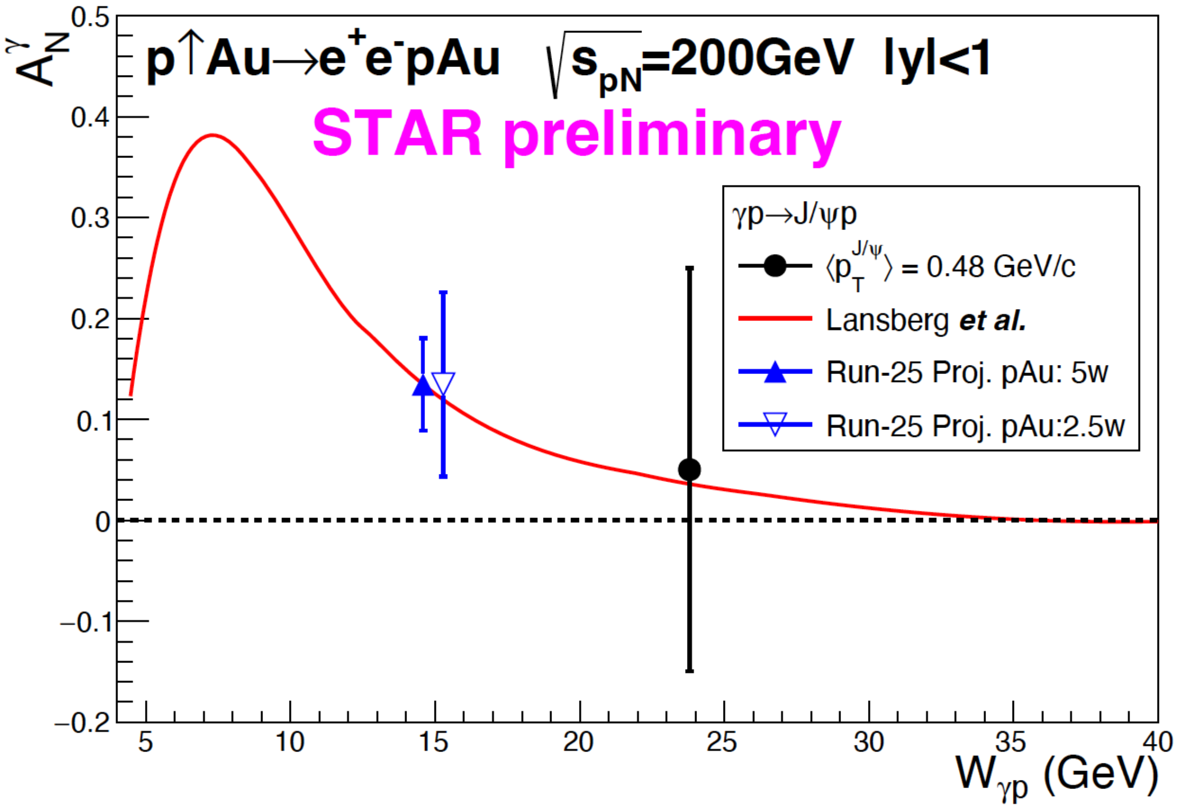

A cleaner version of x-$Q^2$ map

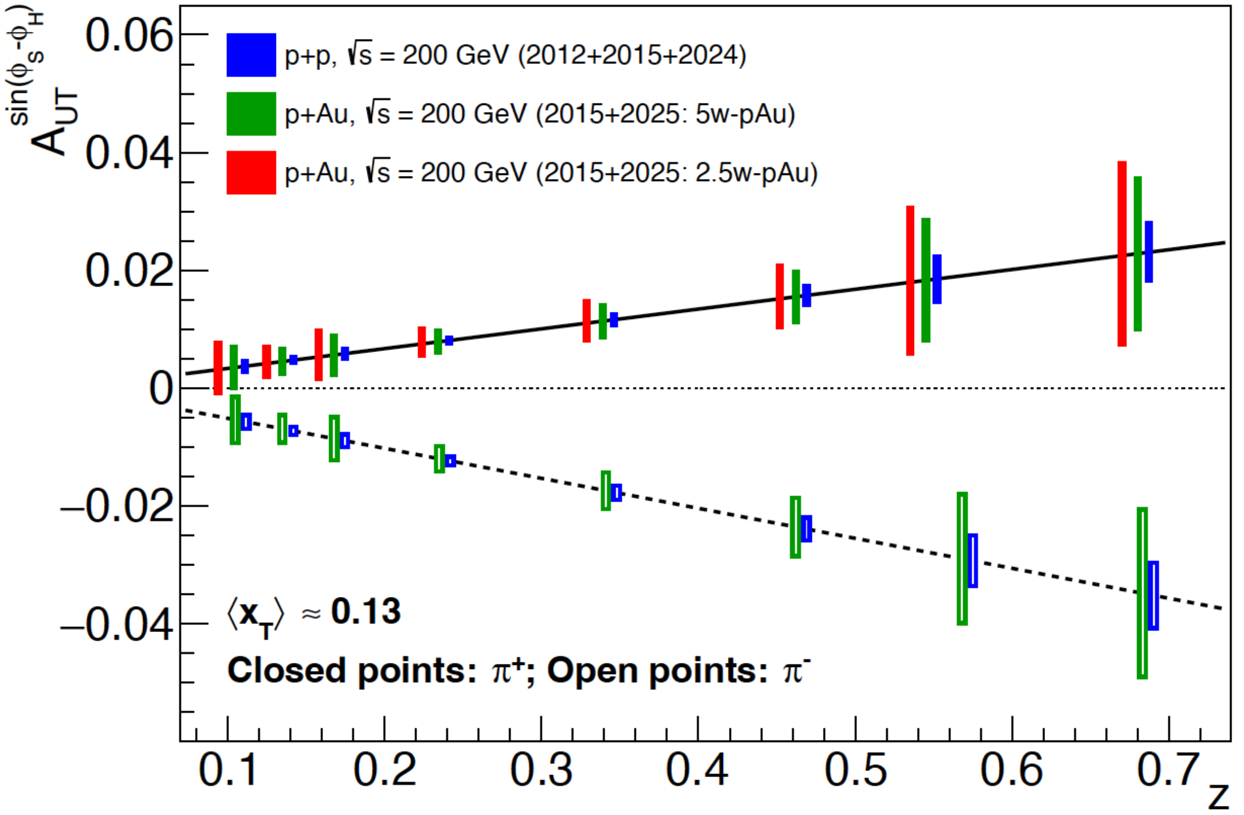
## STAR pp/pA vs. EIC ep/eA




Di-charged hadron correlation projection plot

# Generalized parton distribution and Collins effect




Exclusive J/ψ $A_N$ in UPC, $Q^2$~10 $GeV^2$, $10^{-4}<x<10^{-1}$

Access GPD $E_g$ for gluons, sensitive to spin-orbit correlation

$A_{UT}$ in p+Au: an alternative universality test and a unique look at spin-dependent hadronization

# Impact of STAR science goals without pA data

STAR

- ❑ Quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions for initial and final state TMDs
  Test of Sivers non-universality: $Sivers_{SIDIS}$ = -- $Sivers_{DY, W+/-, Z0}$; Full jet and dijet Sivers asymmetry
  Probe final state TMDs: Collins asymmetry for hadrons in jet
  - ❑ Requirement:
    - ➢ large data sets √s = 200 and 508 GeV p↑p
      → low to high x, highest and lowest x with fSTAR
    - ➢ $A_{UT}$ for $W^{+/-}$ $Z^0$, $A_{UT}$ for hadrons in jet
- ❑ ~~First look at gluon GPD → $E_g$~~
  - ❑ Requirement:
    - ➢ data sets √s = 508 GeV p↑p and √s = 200 GeV p↑A
    - ➢ $A_{UT}$ for J/ψ in UPC
- ❑ Physics driving the large $A_N$ at forward rapidities and high $x_F$
  - ➢ Requirement:
    - ➢ large data sets √s = 200 and 508 GeV p↑p
      → low to highest $x_F$ → fSTAR
    - ➢ charge hadron $A_N$ at forward rapidities
- ❑ ~~Nuclear dependence of PDFs, FF, and TMDs~~
  - ➢ Requirement:
    - ➢ large equal data set of √s = 200 p↑p and p↑Au
      → low to high x, highest and lowest x with fSTAR
    - ➢ $R_{pA}$ direct photons and DY, hadrons in jet $A_{UT}$
- ❑ ~~Non-linear effects in QCD~~
  - ➢ Requirement:
    - ➢ large equal data set of √s = 200 p↑p and p↑Au
      → lowest-x through fSTAR
    - ➢ correlations for $h^{+/-}$, γ-jet, di-jets

Full detector capability with forward upgrades and excellent PID over an extended η coverage

**Without pA data, STAR's forward upgrade will not be fully utilized for its discovery potential and RHIC will lose important physics opportunities on the following:**

- **First look at gluon GPD → $E_g$**
- **Probe nuclear dependence of PDFs, FF, and TMDs**
- **Study non-linear effects in QCD**
- **Discover a novel vortical configuration**

The RHIC cold QCD plan for 2024 to 2028:
https://drupal.star.bnl.gov/STAR/starnotes/public/SN0837

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# The pAu request

**Five weeks of physics data collection would be the minimum** to leverage recent detector investments, address fundamental questions in QCD, and serves as a vital bridge to the EIC era.

**Eight weeks would allow for a broader physics program.**

# Net-proton higher moments from BES-II

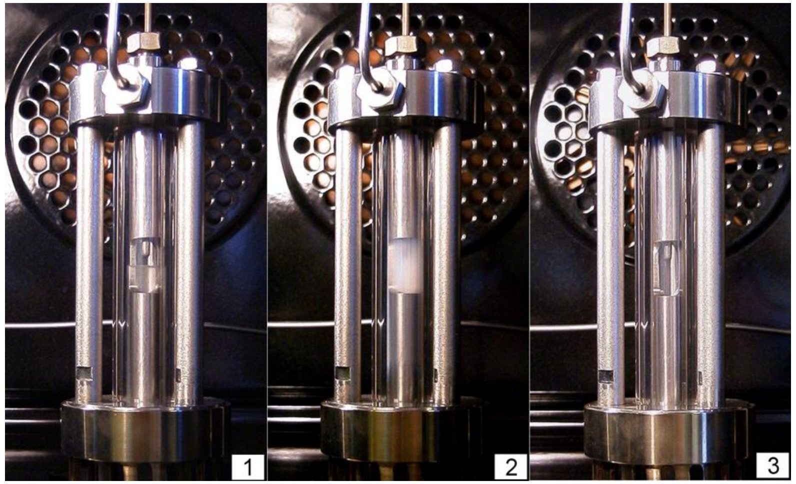
**How to infer the QCD critical point**

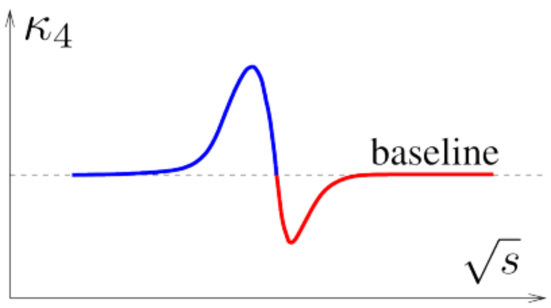
Divergence of the correlation length, dynamics slow down, Large density fluctuations

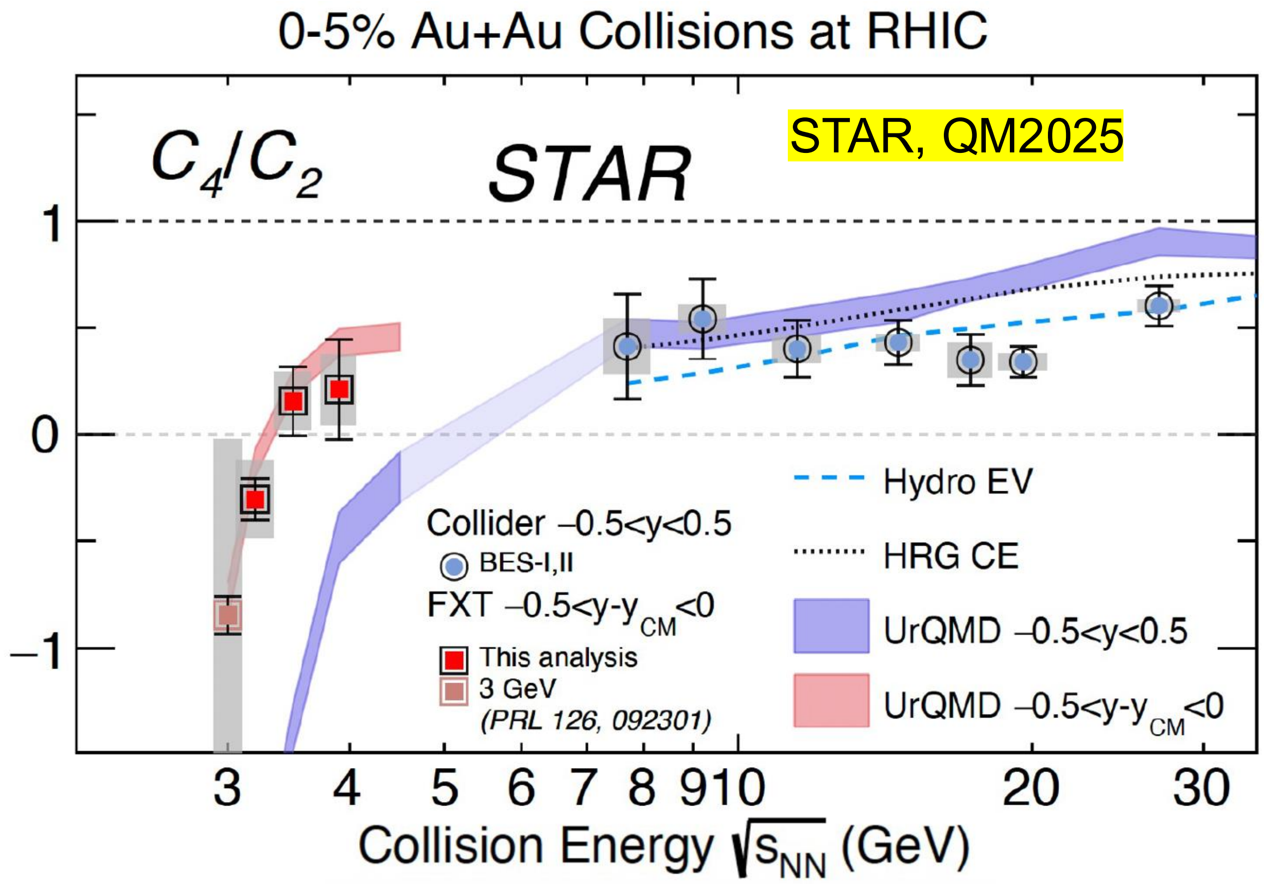
- Critical opalescence, magnetic susceptibility

Correlation length related to various moments of the distributions of conserved quantities such as net-baryon, net-charge, and net-strangeness.

Lattice calculations show that moments of the conserved charge (net-baryon, net-charge, net-strangeness) distributions are related to the susceptibilities

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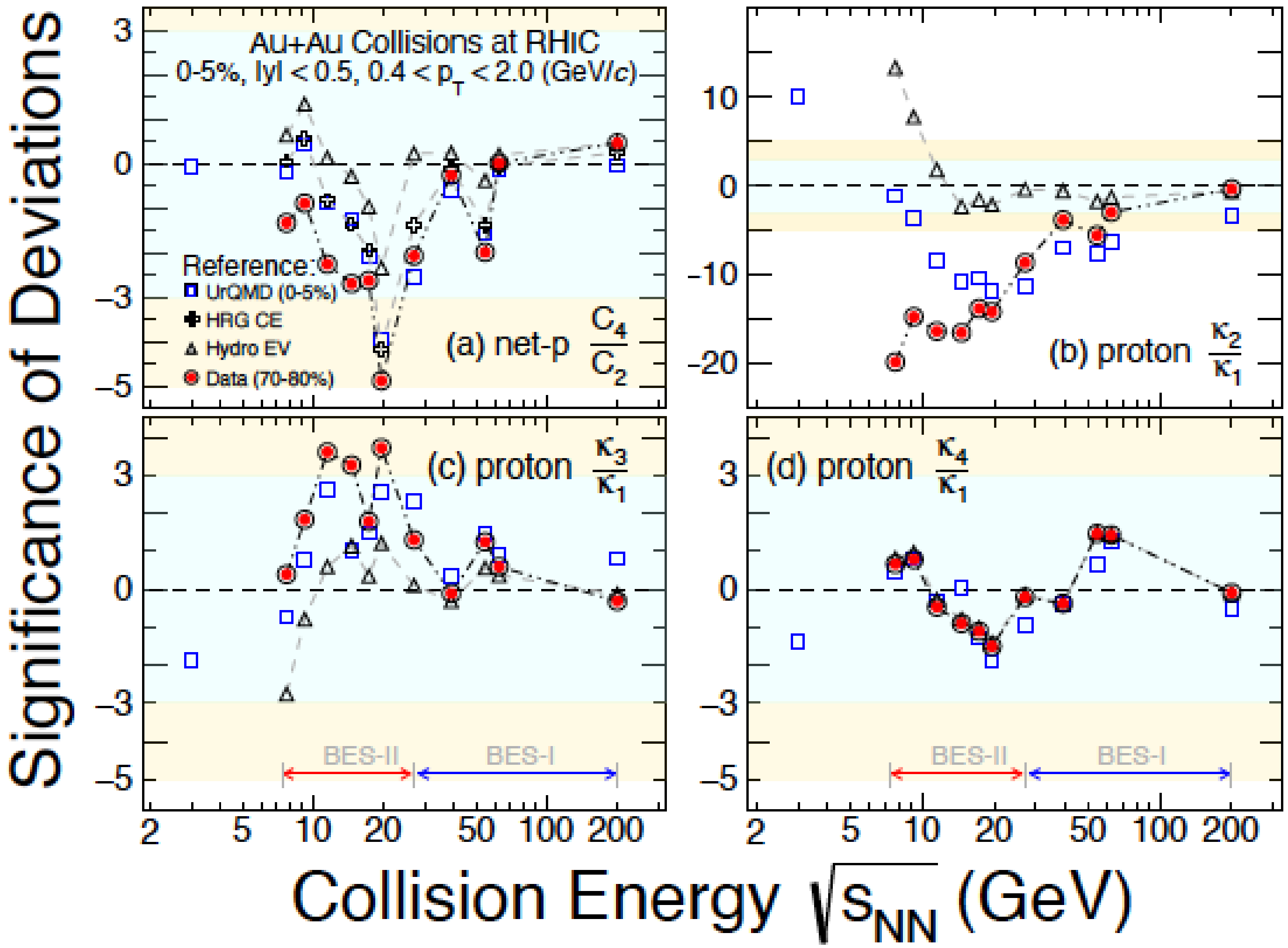
# Net-proton cumulants and proton factorial cumulants from 7.7 GeV to 27 GeV

**156 < $\mu_B$ < 420 MeV**

STAR, PRL**135**(2025)142301

Highlighted in APS, featured in Physics




Precision results on net-proton cumulants and proton factorial cumulants from BES-II with greatly improved statistical and systematic uncertainties

**Reduction factor in uncertainties on 0-5% $C_4/C_2$ : BES-II vs BES-I**

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

2 - 5σ deviation from peripheral data or calculations without critical point effects

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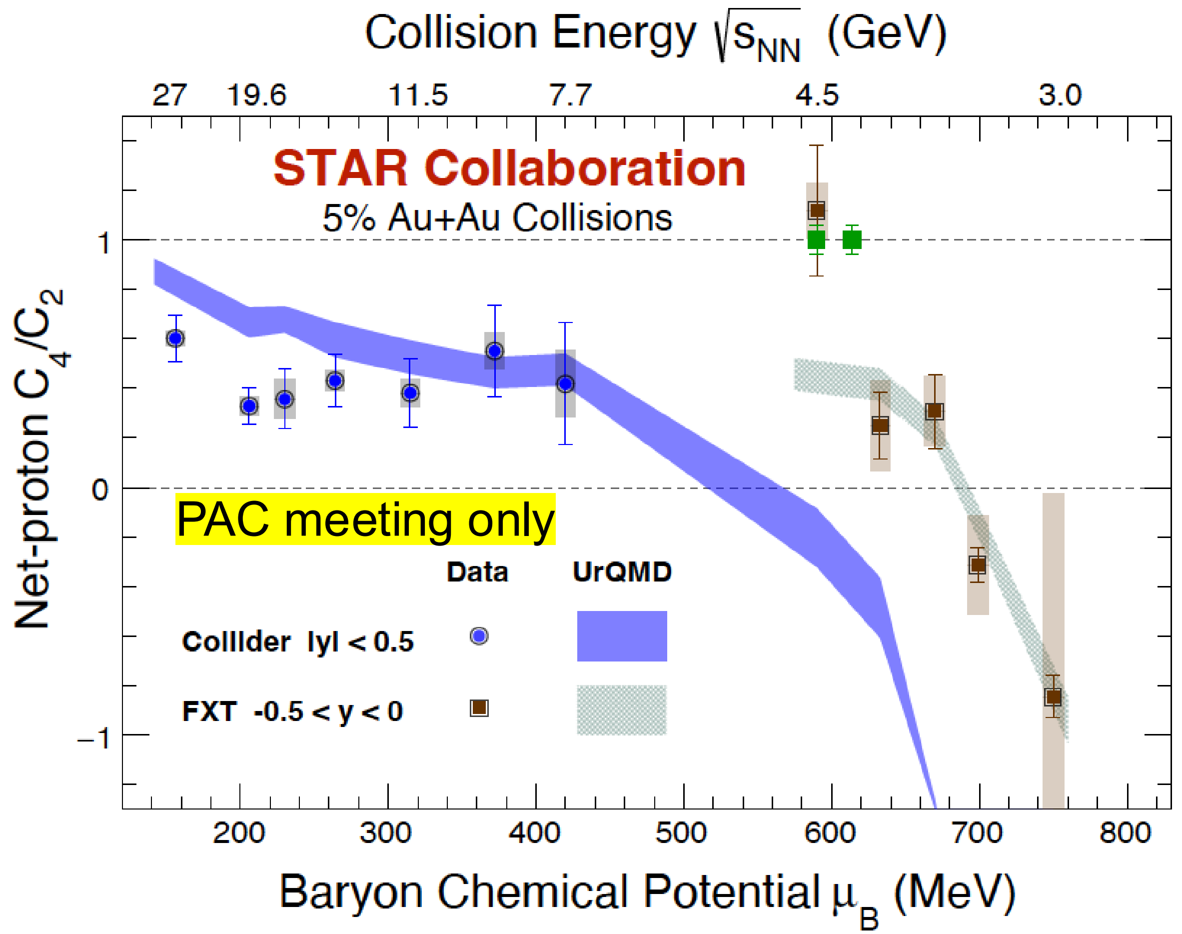
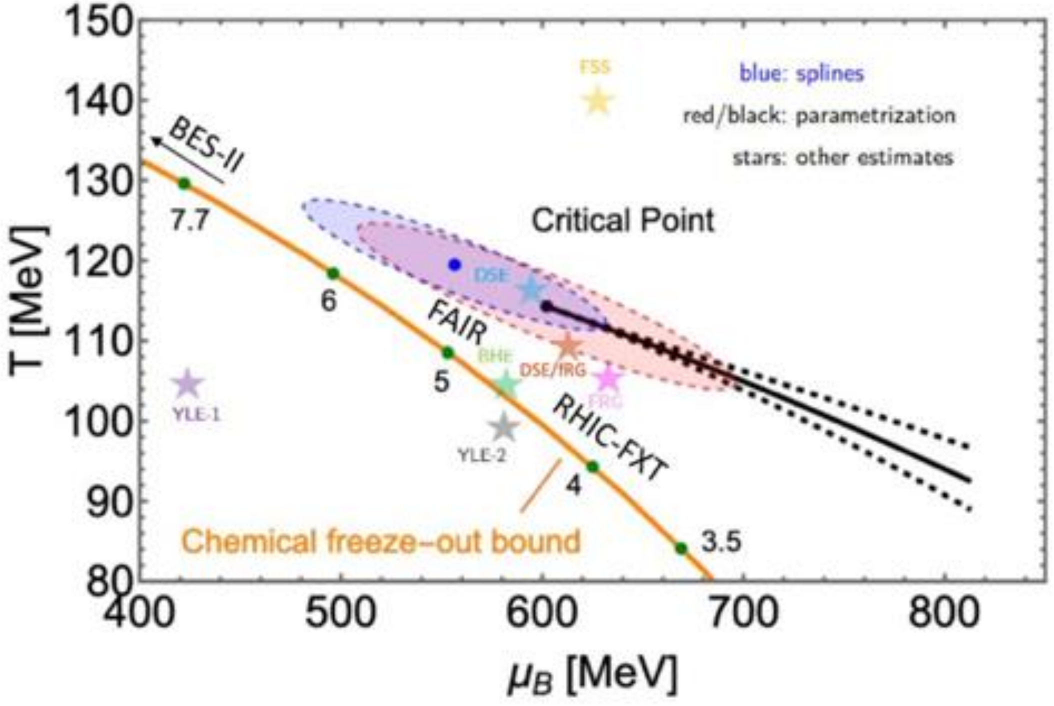
# Update at the June 2025 PAC meeting




PAC meeting, June 2025

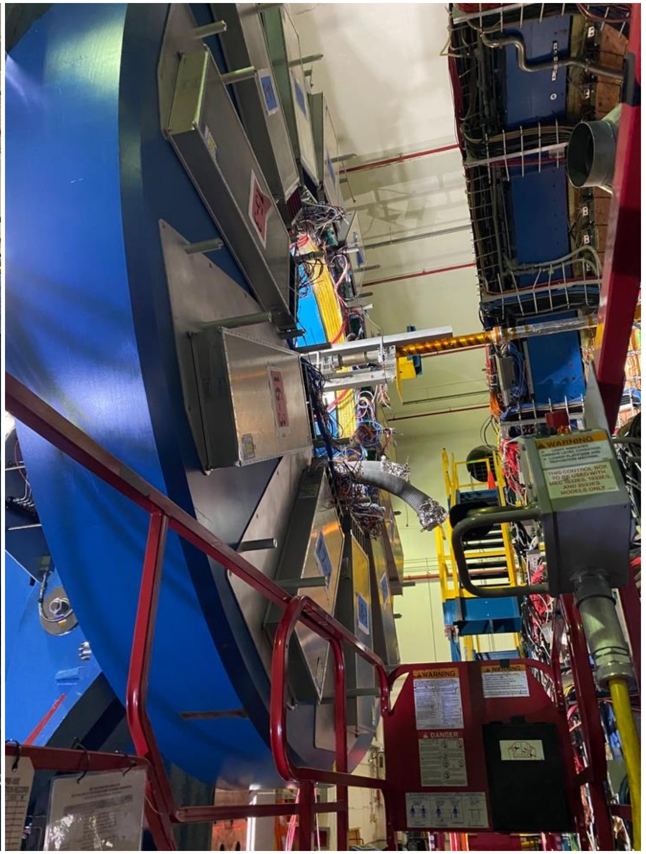



FXT 4.5 GeV: 2 sigma effect above the UrQMD baseline

Green data: precision projection with 2 B good events

# Update since the June 2025 PAC meeting: eTOF repair

- After the June 2025 PAC meeting, the eTOF experts purchased new electronic boards.
- During the 69 kV power downtime, we uninstalled the eTOF modules, and the electronic boards were shipped to BNL.
- During the yellow vacuum leak downtime, the eTOF experts came to BNL and repaired the eTOF electronics. eTOF is now installed at STAR and taking data smoothly.
- **Issue:** The HV for two sectors will need to be checked during the access day on October 29.
- To avoid possible damage, eTOF only takes data during the 2nd and 3rd runs of the low-luminosity data collection period.



**We thank everyone involved, including the CAD technicians, for their commitment and dedication!**

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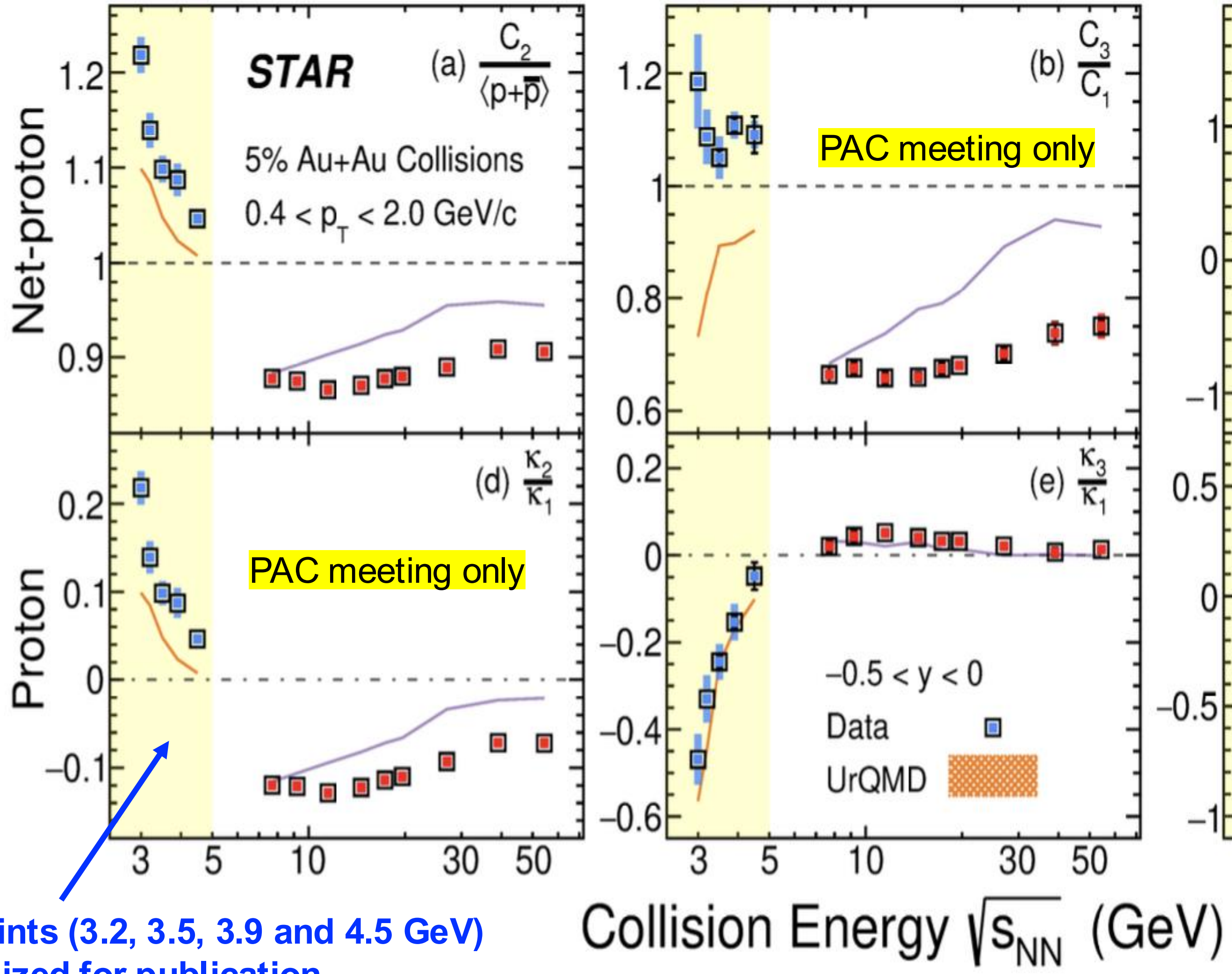
# Update: Energy dependence of cumulant and factorial cumulant ratios

7.7~54 GeV : Phys. Rev. Lett. **135** (2025) 142301
3.0 GeV : Phys. Rev. Lett. **128** (2022) 202303
Phys. Rev. C **107** (2023) 24908




**4 new data points (3.2, 3.5, 3.9 and 4.5 GeV) are being finalized for publication.**

The plots shown in this slides have larger statistical and systematic errors given by tighter event selections than the preliminary results and done by our standard CBWC approach.

UrQMD baselines for FXT energies are also updated in order to have similar centrality resolution to the experimental data.

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# The ask: more FXT data collection

Aim for **>5σ significance** over the baseline, assuming the data points remain unchanged.

- **3 weeks:** 2 + 2 billion events at 4.5 and 4.2 GeV
- **2 weeks:** 2 + 0.5 billion events at 4.5 and 4.2 GeV
- **1 week:** 1 billion events at 4.5 GeV

This should not present any issues for the machine to deliver a single beam at 9.8 and 8.65 GeV with the associated conditions.

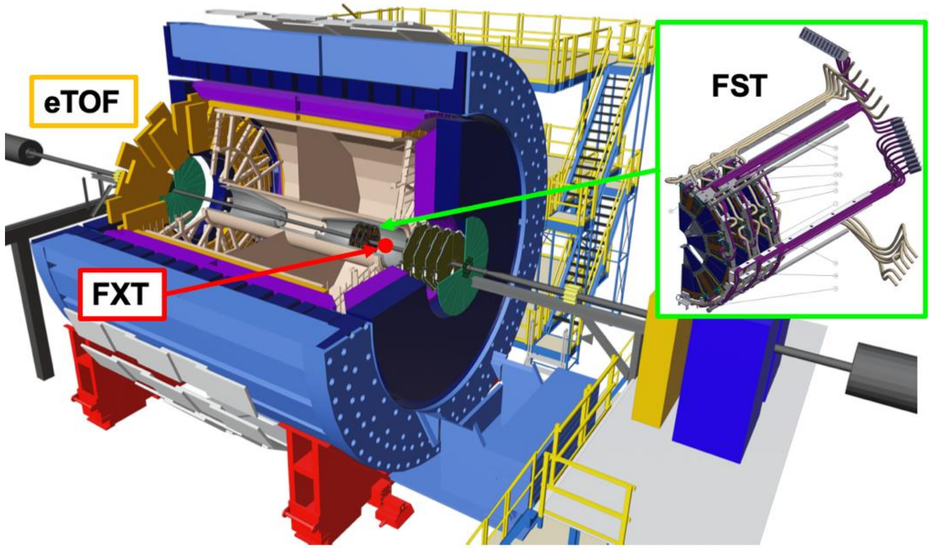
Note:

- DAQ rate has improved by a factor of 2 since Run 21
- Additional pile-up protection will be implemented at the trigger level
- Forward silicon tracker material effect

# Forward Silicon Tracker (FST) material

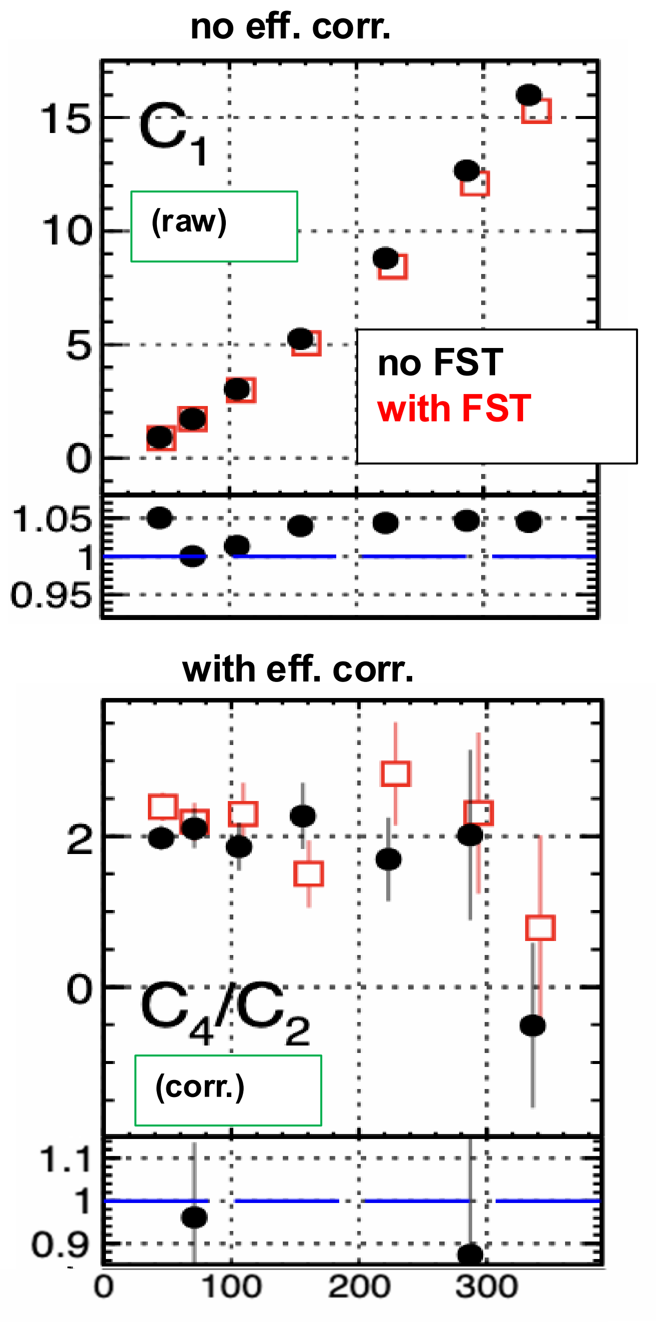
## FXT 4.5 GeV UrQMD full Geant simulation with/without FST

**with only active FST material in this Geant model**




The efficiency reduction of ~5% with the FST (only active silicon material) can be corrected; $C_4/C_2$ is consistent within statistical uncertainties using 5M UrQMD events with full GEANT simulation.

**Request:** One-hour FXT beam test to evaluate the impact of all passive materials (including detector service lines), as well as to measure data volume and DAQ rate.



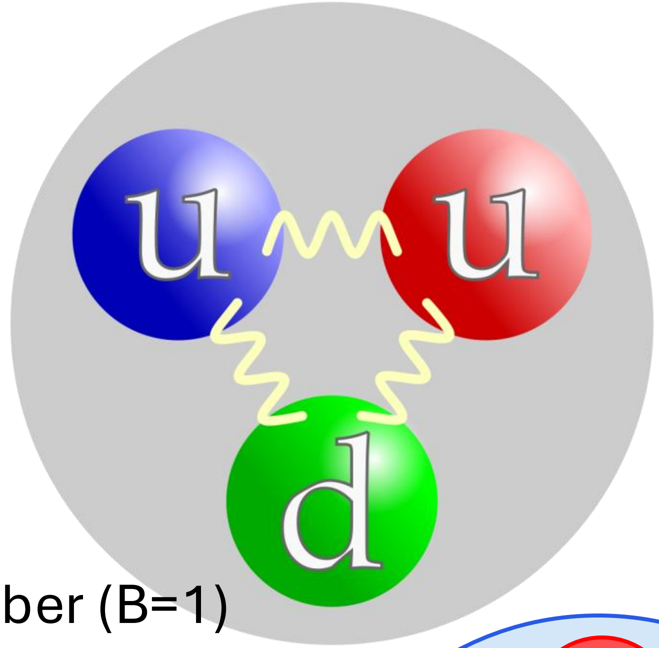
# The FXT request

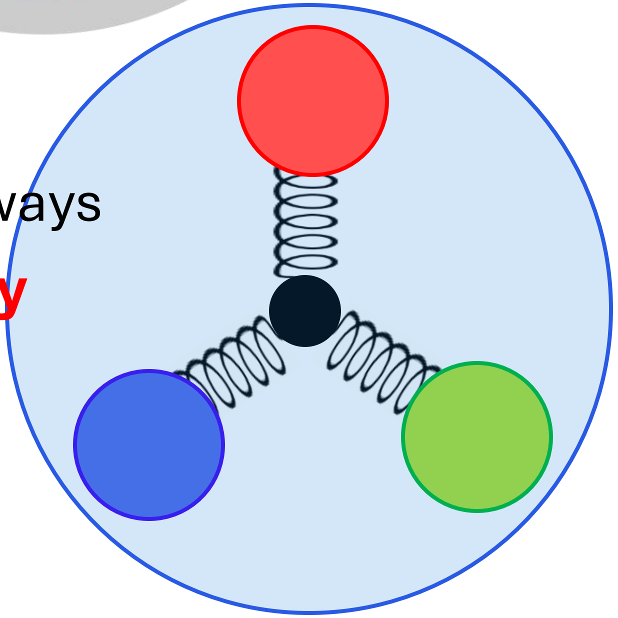
**1–3 weeks of FXT data collection at 4.5 and 4.2 GeV** are requested to establish the energy dependence for the critical point search.

One-hour FXT beam test to evaluate the impact of all passive materials (including detector service lines), as well as to measure data volume and DAQ rate.

# What carries baryon number?

- Textbook picture of a proton
  - Lightest baryon with strictly conserved baryon number
  - Each valence quark carries 1/3 of baryon number
  - Proton lifetime $>10^{34}$ years
  - Quarks are connected by gluons
- Alternative picture of a proton
  - Proposed at the Dawn of QCD in 1970s
  - A Y-shaped gluon junction topology carries baryon number (B=1)
  - The topology number is the strictly conserved number
  - Quarks do not carry baryon number
  - Valence quarks are connected to the end of the junction almost always
- **Neither of these postulations has been verified experimentally**

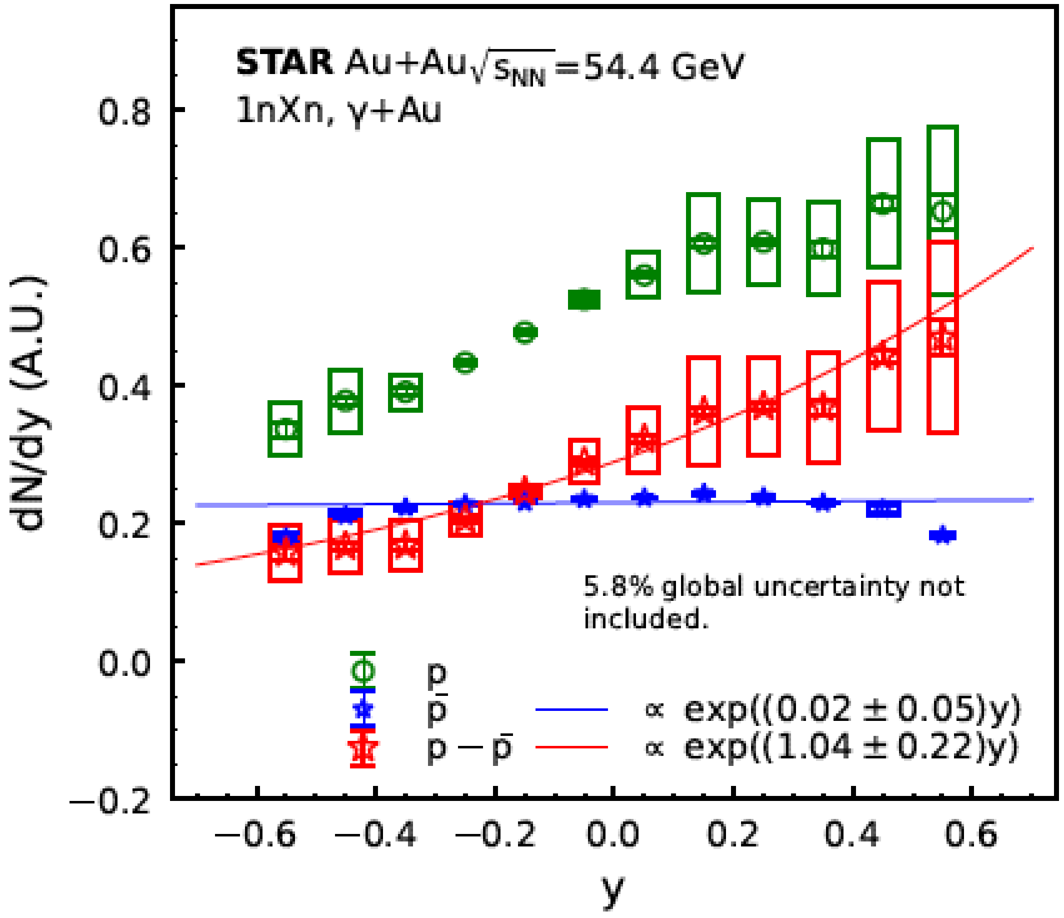


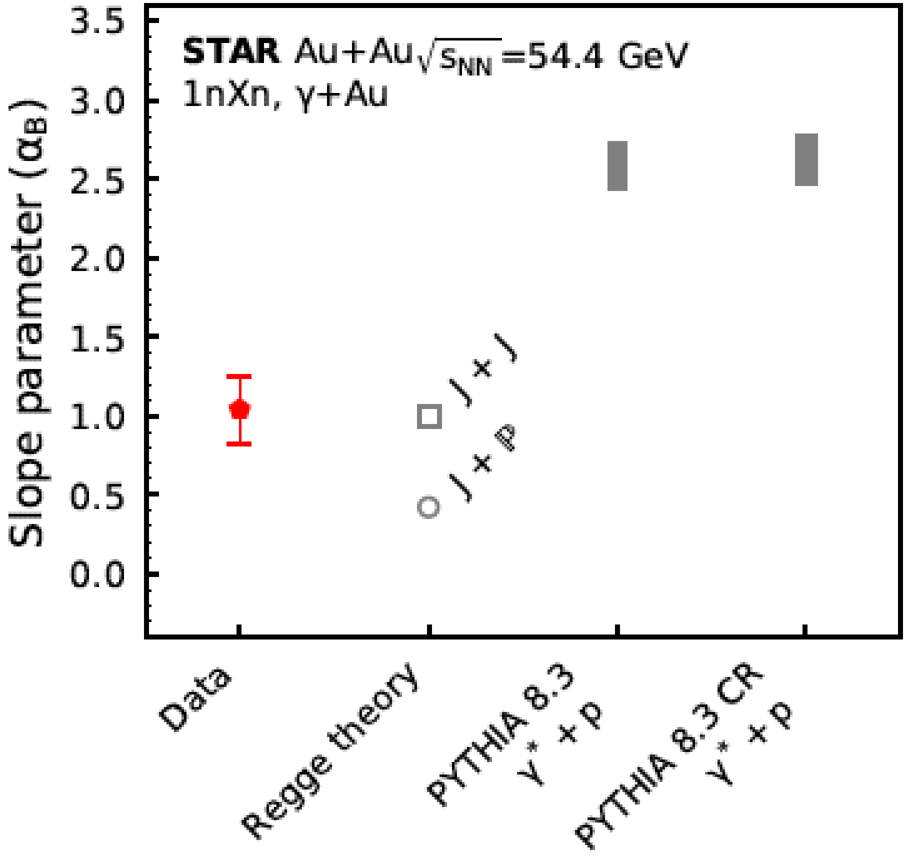




[1]: Artru, X.; String Model with Baryons: Topology, Classical Motion. Nucl. Phys. B 85, 442–460 (**1975**).
[2]: Rossi, G. C. & Veneziano, G. A; Possible Description of Baryon Dynamics in Dual and Gauge Theories. Nucl. Phys. B 123, 507–545 (**1977**)

# Baryon transport in gamma+Au collisions

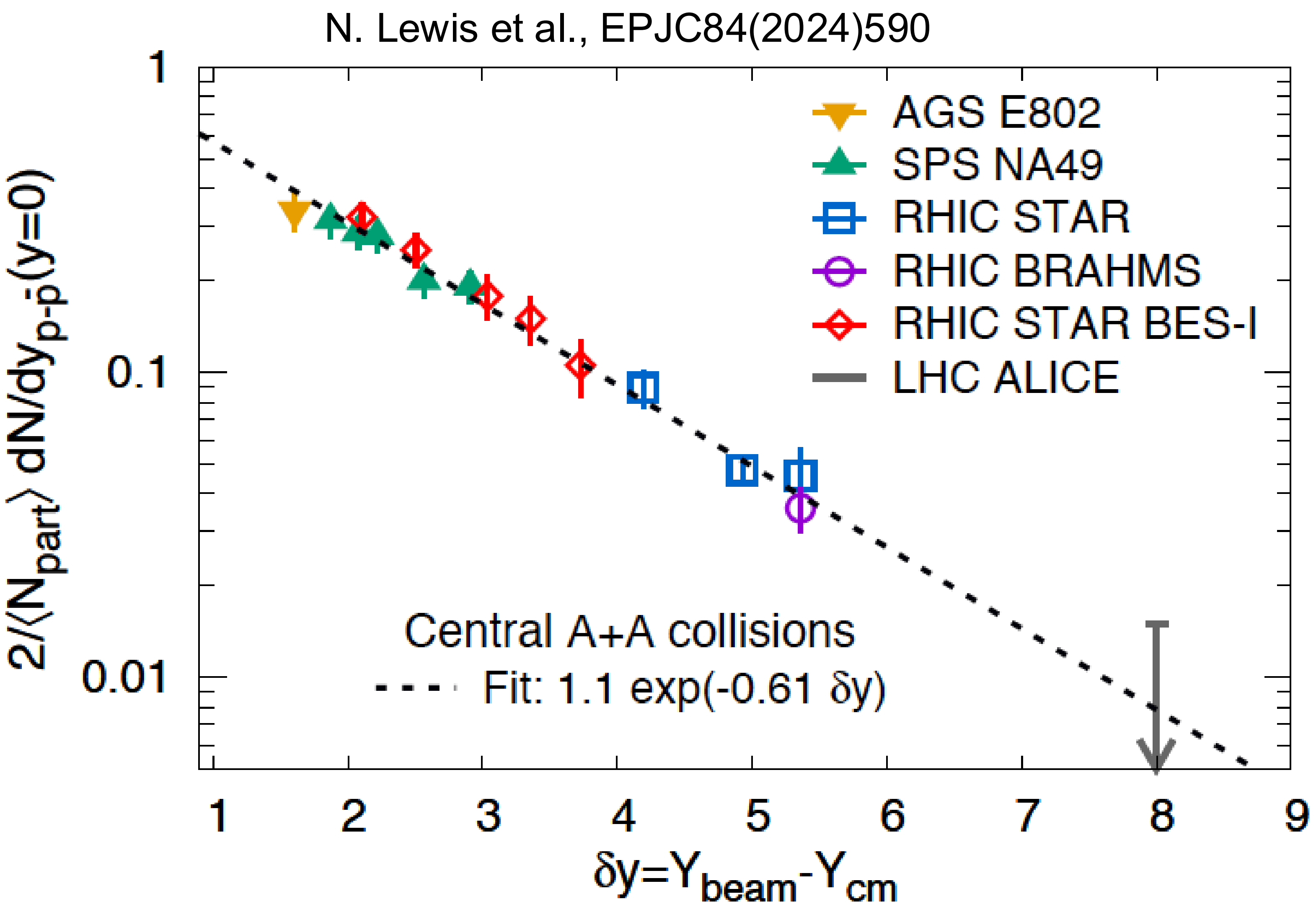
STAR, arXiv: 2408.15441, submitted to Science




The slope parameter is consistent with the Regge theory prediction incorporating the baryon junction.

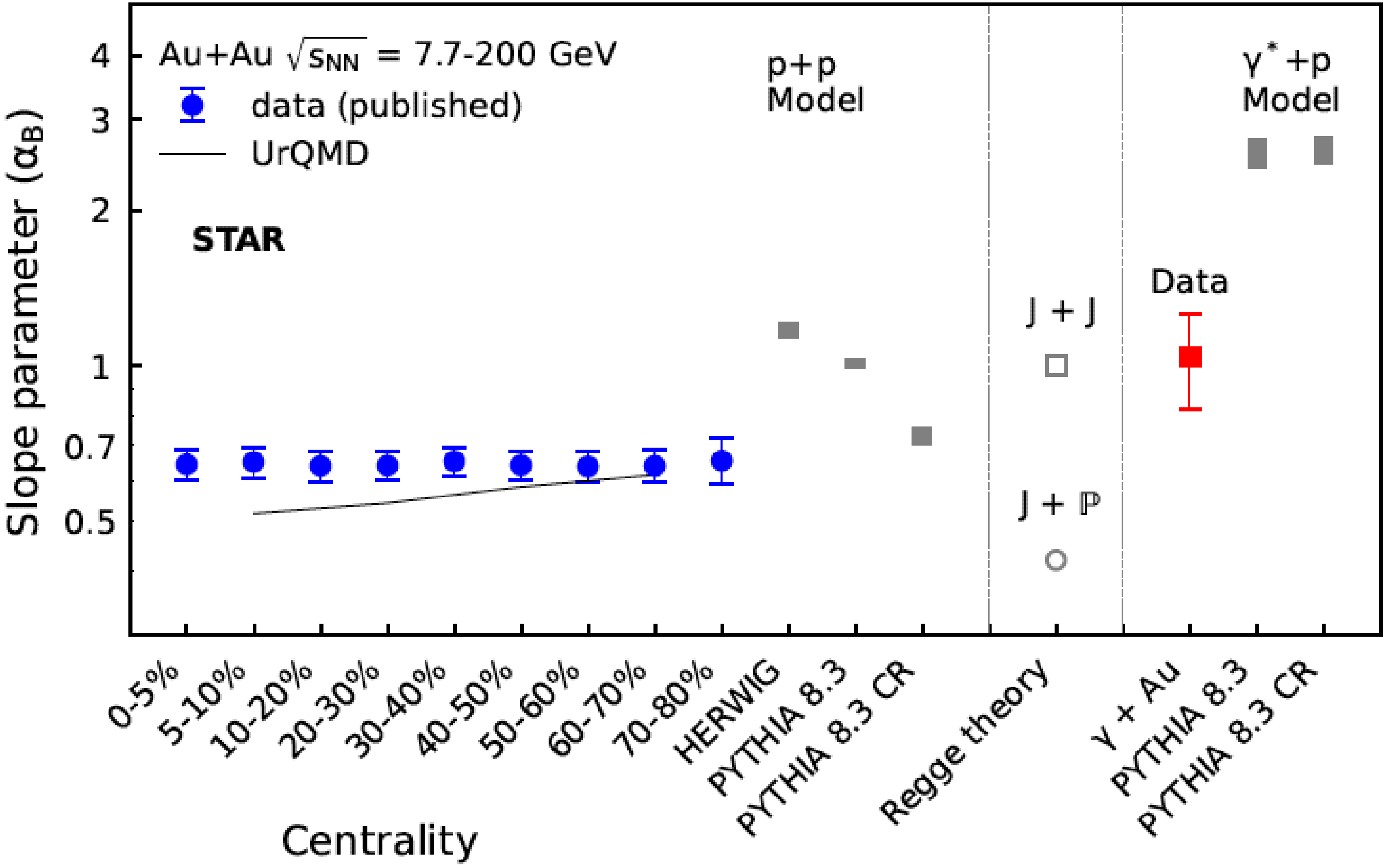
# Baryon transport in A+A collisions




The slope parameter is independent of collision centrality with an average value of 0.64 ± 0.05

# Rapidity slope of baryon transport

STAR, arXiv: 2408.15441, submitted to Science




Models that do not include the baryon junction fail to describe the data.

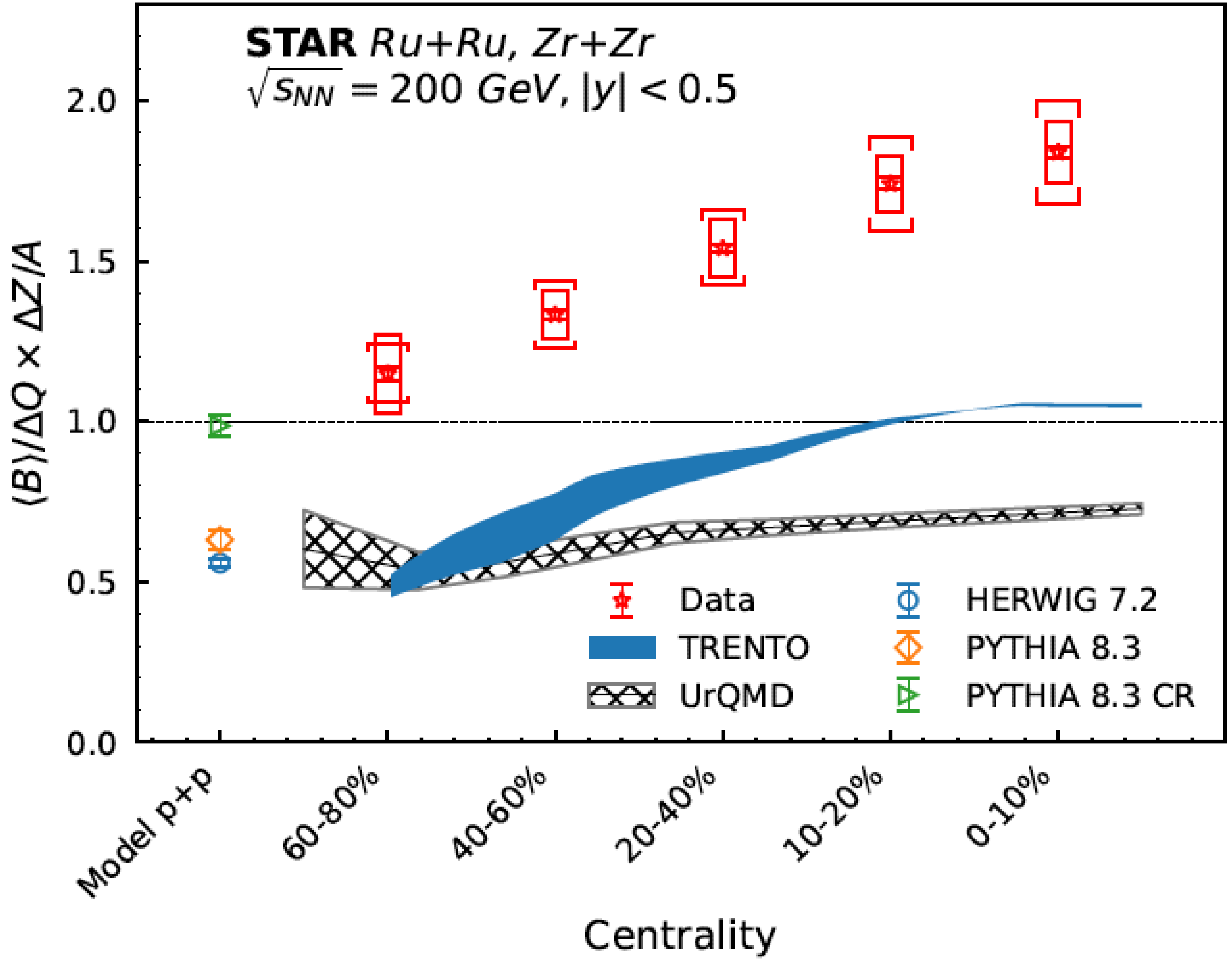
# Baryon to charge transport ratio

Naïve picture:

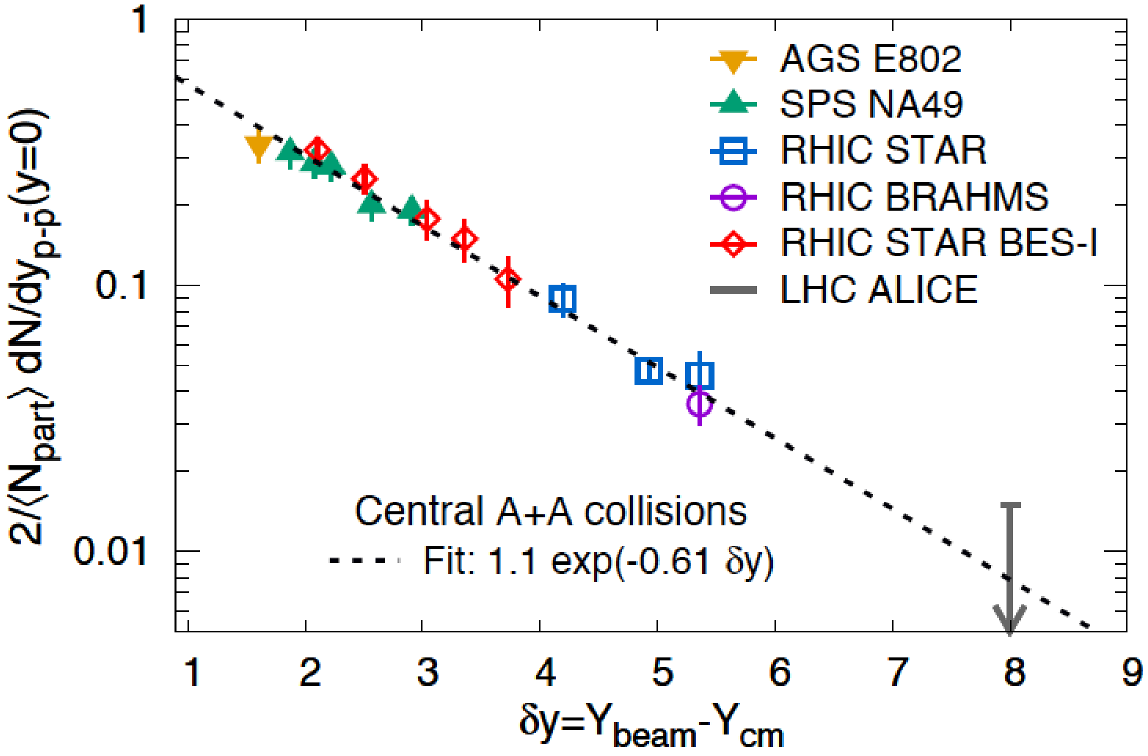
- Valence quark: B/Q = A/Z; ratio=1`
- Gluon junction: B/Q > A/Z; ratio > 1

Larger baryon transport compared to charge transport is consistent with the expectation of the baryon junction scenario

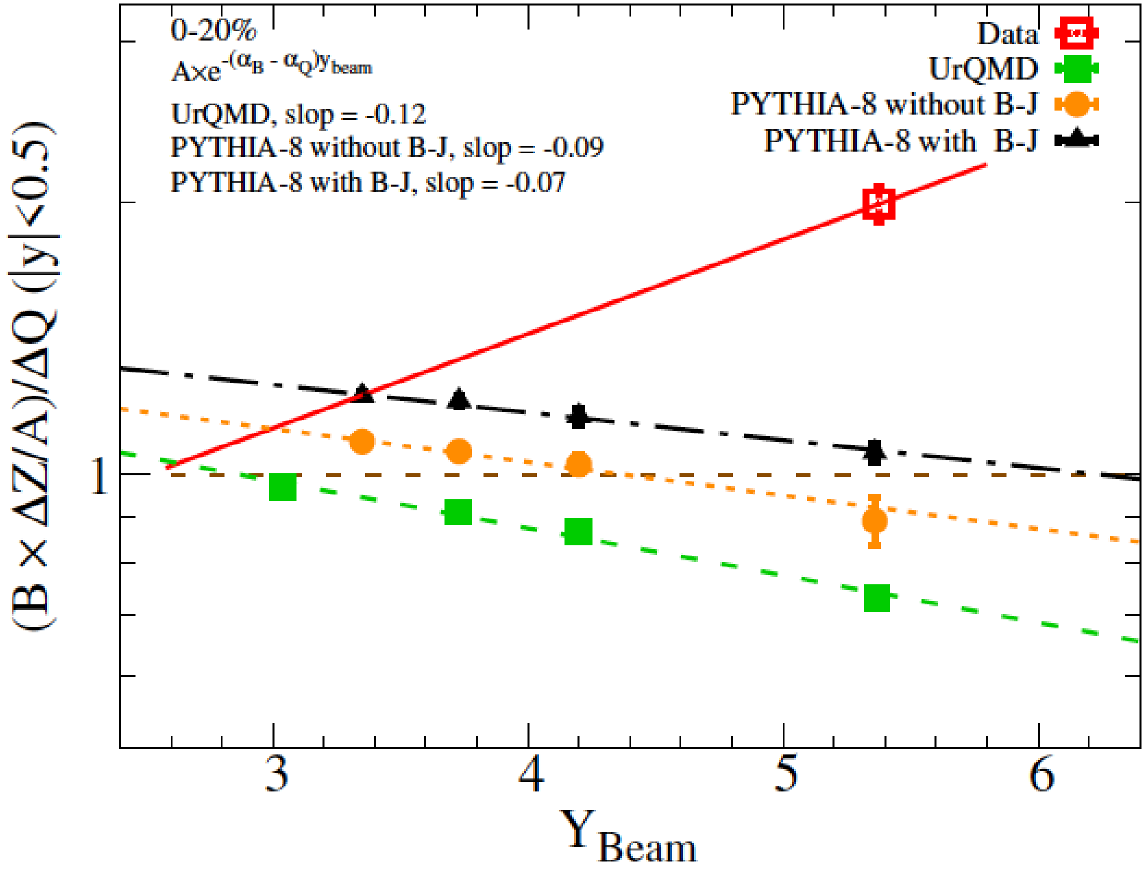
STAR, arXiv: 2408.15441, submitted to Science



# How to measure charge transport




Unlike baryon transport, directly measuring charge transport is challenging.




Measure baryon to charge transport ratio as a function of beam rapidity

# The isobar request

| isobar beam energy | stat | raw minbias | good minbias | DAQ hours |
|---|---|---|---|---|
| 200 | 1% | 6.2B | 3.2B | 895 |
| 62 | 5% | 250M | 128M | 14 |
| 27 | 5% | 250M | 128M | 20 |

**Table 2:** comparisons of requested isobar collision events and DAQ hours at 62 and 27 GeV to the existing 200GeV. DAQ could take minbias isobar data at 5KHz. This will allow us to extract a slope (-($\alpha_B - \alpha_Q$)) with 2% stat uncertainty to distinguish between +0.00 and -0.12 at $5\sigma$ level.

- **1 week of isobar collisions (Zr+Zr and Ru+Ru) at 62 and 27 GeV** to measure charge transport, largely dominated by machine setup time

# Summary

Priority order:

**Five weeks of physics data collection would be the minimum** to leverage recent detector investments, address fundamental questions in QCD, and serves as a vital bridge to the EIC era. **Eight weeks would allow for a broader physics program.**

**1–3 weeks of FXT data collection at 4.5 and 4.2 GeV** are requested to establish the energy dependence for the critical point search.

**1 week of isobar collisions (Zr+Zr and Ru+Ru) at 62 and 27 GeV** to measure charge transport, largely dominated by machine setup time

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# Backup

# Executive summary of plans for Run 25

Full detector capability with forward upgrades and excellent PID over an extended η coverage

**Table 1: Proposed Run-25** assuming 20 or 28 cryo-weeks of running in 2025 and 2 weeks of set-up time to achieve minimum-bias running conditions. For both scenarios, we request 200 GeV Au+Au collisions. We provide the requested event count for our minimum bias (MB) trigger, and the requested sampled luminosity from our a high-$p_T$ trigger that covers all $v_z$. During Runs 23 and 24, STAR collected 8 billion MB Au+Au events and achieved a sampled luminosity of 1.2 $nb^{-1}$.

| $\sqrt{s_{NN}}$ (GeV) | Species | Number Events/ Sampled Luminosity | Year |
|---|---|---|---|
| 200 | Au+Au | 8B+**5B** / 1.2 $nb^{-1}$+**20.8** $\mathbf{nb^{-1}}$ | 2023+2024+**2025 (20 cryo-weeks)** |
| 200 | Au+Au | 8B+**9B** / 1.2 $nb^{-1}$+**28.6** $\mathbf{nb^{-1}}$ | 2023+2024+**2025 (28 cryo-weeks)** |

Au+Au: probe the inner workings of the QGP;

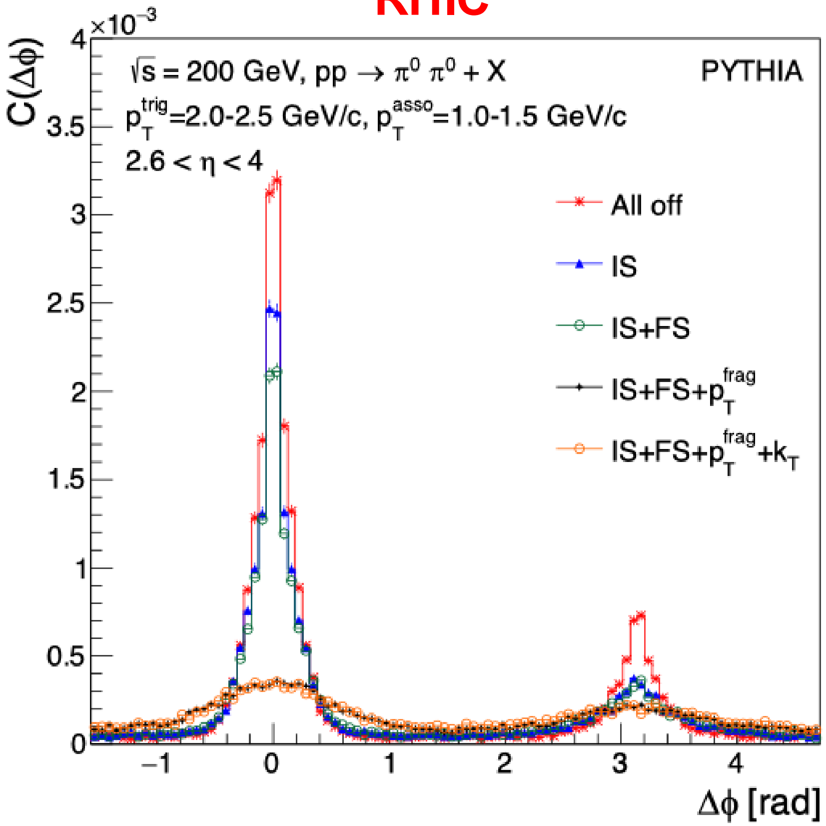
- original goals: 20 B MB events/40 $nb^{-1}$

STAR requests an extension of Run-25 beyond 28 cryo-weeks, allowing 5 weeks of p+Au physics data collection to achieve a sampled luminosity of 0.22 $pb^{-1}$

# QCD non-linear effects

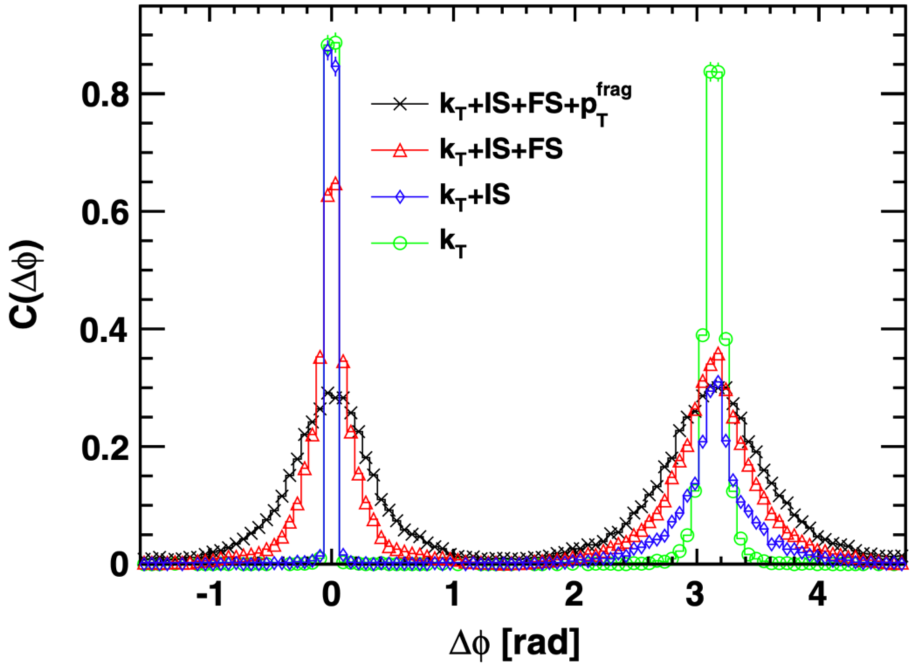
K. Cassar et al., arXiv:2503.08447

**RHIC**




L. Zheng et al., PRD 89 (2014) 074037

**EIC**



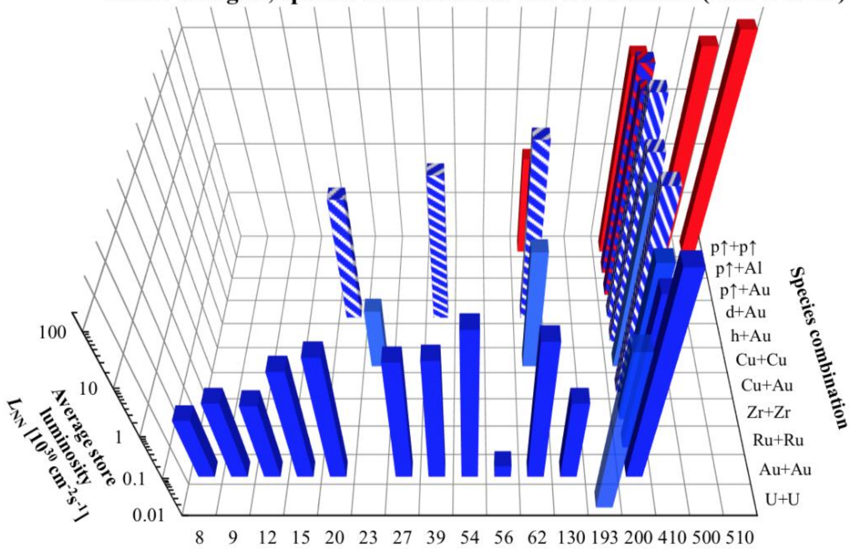

- Broadening effects caused by saturation are overshadowed by NLO contributions: Initial- and finial-state parton showers, and fragmentation $p_T$, which are independent of saturation.
- It will be challenging to observe broadening phenomena at both RHIC and the EIC.

## It has been an amazing journey

# Evolution of the STAR Detector

major upgrades over the last twenty years to improve particle identification and vertex reconstruction, and is still evolving with an extension to forward rapidity as of today. pioneered in using new technologies: MRPC, MAPS, GEM and siPM.
Estimate 35M(initial) +75M(upgrades)$.

RHIC energies, species combinations and luminosities (Run-1 to 19)




| Detector | primary functions | DOE+(in-kind) | year |
|---|---|---|---|
| TPC+Trigger | $\|\eta\|$ <1 Tracking | | 1999- |
| Barrel EMC | $\|\eta\|$ <1 jets/$\gamma$/$\pi^0$/e | | 2004- |
| FTPC | forward tracking | (Germany) | 2002-2012 |
| L3 | Online Display | (Germany) | 2000-2012 |
| SVT/SSD | V0/charm | (France) | 2004-2007 |
| PMD | forward photons | (India) | 2003-2011 |
| EEMC | 1< $\eta$ <2 jets/$\pi^0$/e | (NSF) | 2005- |
| Roman Pots | diffractive | | 2009- |
| TOF | PID | (China) | 2009- |
| FMS/Preshower | 2.5< $\eta$ <4.2 | (Russia) | 2008-2017 |
| DAQ1000 | x10 DAQ rate | | 2008- |
| HLT | Online Tracking | (China/Germany) | 2012- |
| FGT | 1< $\eta$ <2 $W^{\pm}$ | | 2012-2013 |
| GMT | TPC calibration | | 2012- |
| HFT/SSD | open charm | (France/UIC) | 2014-2016 |
| MTD | muon ID | (China/India) | 2014- |
| EPD | event plane | (China) | 2018- |
| RHICf | $\eta$ >5 $\pi^0$ | (Japan) | 2017 |
| iTPC | $\|\eta\|$ <1.5 Tracking | (China) | 2019- |
| eTOF | -2< $\eta$ <-1 PID | (Germany/China) | 2019- |
| FCS | 2.5< $\eta$ <4 calorimeter | (NSF) | 2021- |
| FTS | 2.5< $\eta$ <4 Tracking | (NCKU/SDU) | 2021- |

2

25 years of operation, major successful upgrades, vibrant physics programs

386 published papers, 343 PhD and 34 MS theses

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# Physics Opportunities for 2023+2024+2025

Time

## To address important questions about the inner workings of the QGP

- What is the nature of the 3-dimensional initial state at RHIC energies? $r_n$ over a wide rapidity, J/ψ $v_1$, photon Wigner distributions
- What is the precise temperature dependence of shear and bulk viscosity? $v_n$ as a function of η
- What can be learned about confinement from charmonium measurements? J/ψ $v_2$
- What is the temperature of the medium? Different ϒ states, ψ(2S), thermal dileptons
- What are the electrical, magnetic, and chiral properties of the medium? Λ, Ξ, Ω $P_H$ and K*, ϕ, J/ψ $\rho_{00}$, thermal dileptons, CME observables
- What are the underlying mechanisms of jet quenching at RHIC energies? What do jet probes tell us about the microscopic structure of the QGP as a function of resolution scale? $\gamma_{dir}$+jet $I_{AA}$, $\gamma_{dir}$+jet acoplanarity, jet substructure
- What is the precise nature of the transition near $\mu_B$=0? Net-proton $C_6/C_2$
- What can we learn about the strong interaction? Correlation functions

## To inform EIC physics with photon induced processes:

- Probe gluon distribution inside the nucleus: vector mesons (J/ψ), dijets (?)
- Search for collectivity and signatures of baryon junction: inclusive charge particles and cross sections, $v_n$ , identified particle spectra

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# Future opportunity I

**Nuclear data for space radiation protection**

Not part of STAR physics program in the final RHIC phase but represents an opportunity for RHIC to contribute with some important nuclear data

- The Space Radiation Protection community has identified 3-50 GeV/n region as an area of need. https://doi.org/10.3389/fphy.2020.565954
- STAR has excellent light fragment capabilities.
- RHIC can deliver the ion beam species (C, Al, Fe) and energies (3-50 GeV/n) of need to the Space Radiation Protection community. STAR installed the targets of interest (C, Al, Ni) and is ready to take FXT data when opportunities arise.

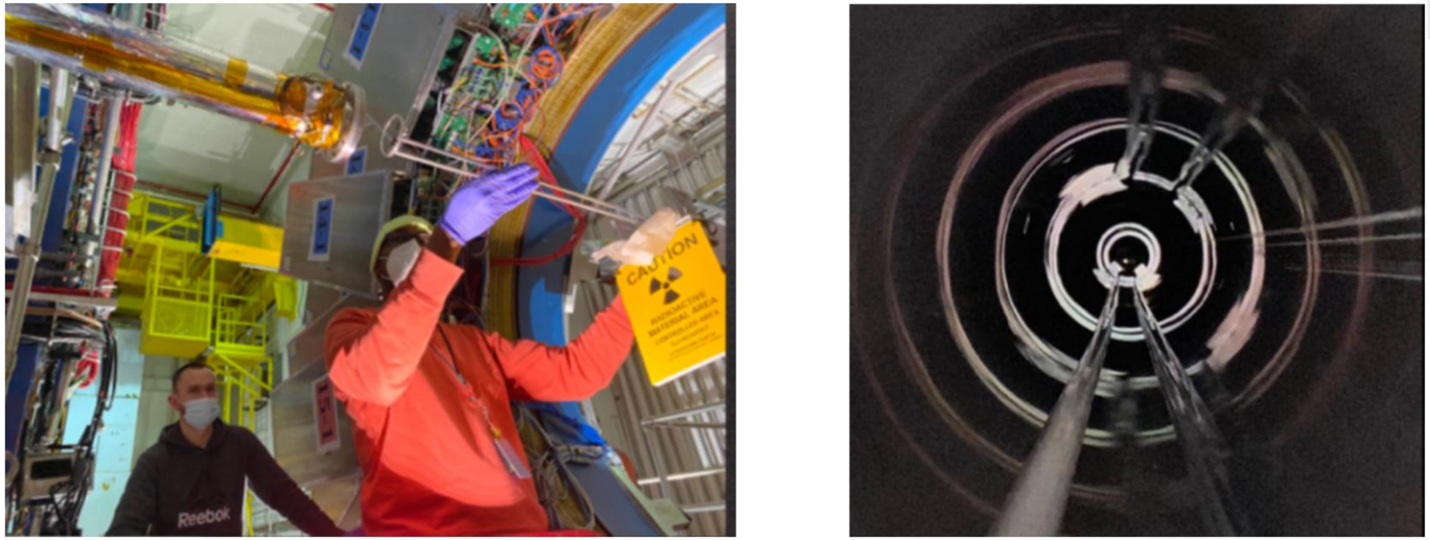



**Figure 112:** Left panel: Installation of the targets and holder on the East side of the STAR detector. Right Panel: A view down the beam pipe showing the three targets (C, Al, and Ni) installed at STAR.

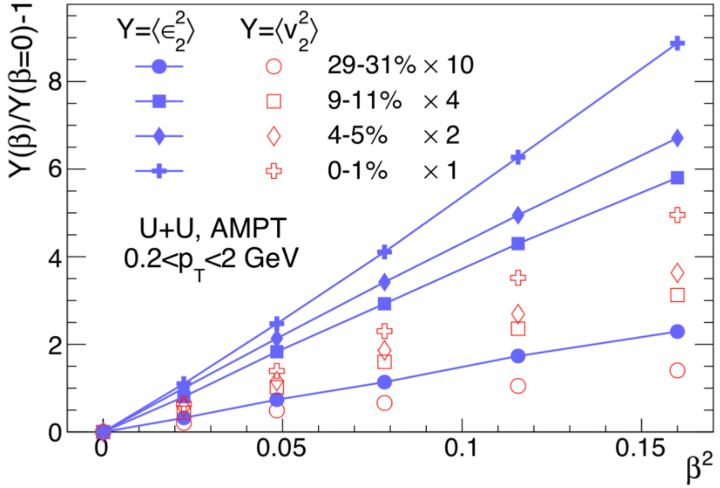
In total, two weeks of running including machine setup

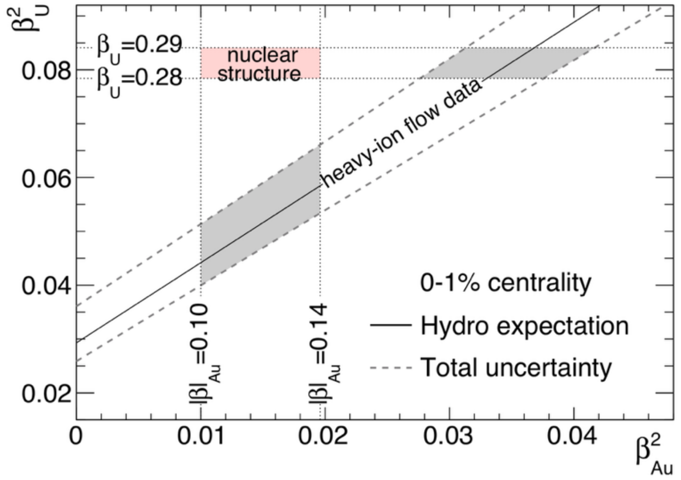
# Future opportunity II

## Imaging shape and radial profile of atomic nuclei

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi)/a}} \qquad R(\theta,\phi) = R_0\left(1+\beta_2[\cos\gamma Y_{2,0}+\sin\gamma Y_{2,2}]+\beta_3 Y_{3,0}+\beta_4 Y_{4,0}\right)$$

- **Collective flow measurements sensitive to nuclear deformation**
- **Understanding of the nuclear shape of current available systems not ideal: impact η/s extraction**




- Step1: calibrate systematics using $^{208}$Pb at 200 GeV

  Pb: control on effects of Au deformation; precision on initial state and pre-equilibrium dynamics (energy dependence) vs. LHC

  Constrain **η/s** with improved understanding of initial state.

- Step2: uncover the nuclear force: triaxiality in rare earths

  Run alternatively Pb+Pb, $^{154}$Sm ($\beta_2$=0.34) + Sm, $^{166}$Er ($\beta_2$=0.34) + Er

  - To discover experimentally the triaxiality of well-deformed rare-earth nuclei

  Use hydrodynamics and flow measurements to perform precision cross-check of low energy nuclear physics.

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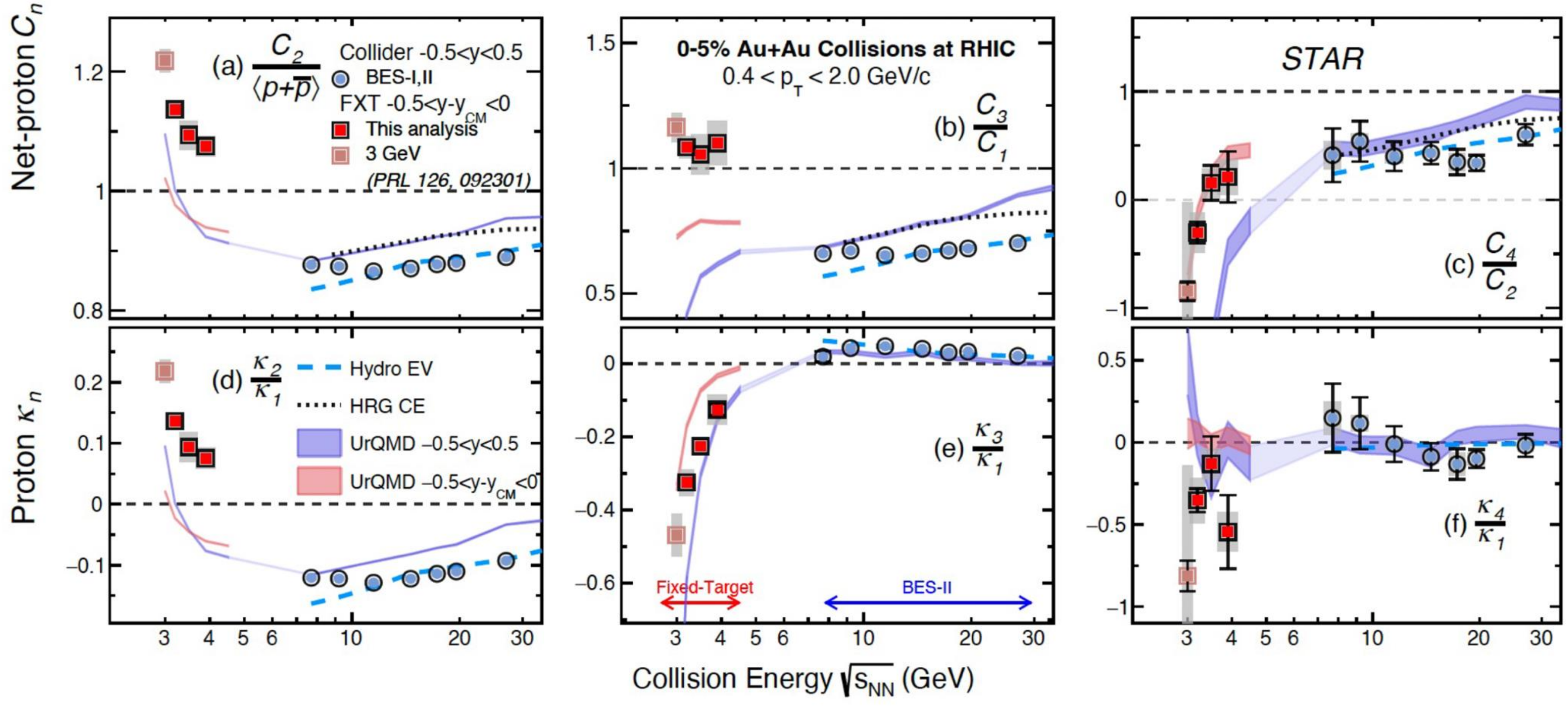
# Net-proton cumulants and proton factorial cumulants from FXT energies




Proton $C_4/C_2$, $\kappa_4/\kappa_1$ consistent with UrQMD

Proton (factorial) cumulants deviate from UrQMD at second and third order

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