Workshop on physics performance studies at NICA (NICA-2024)

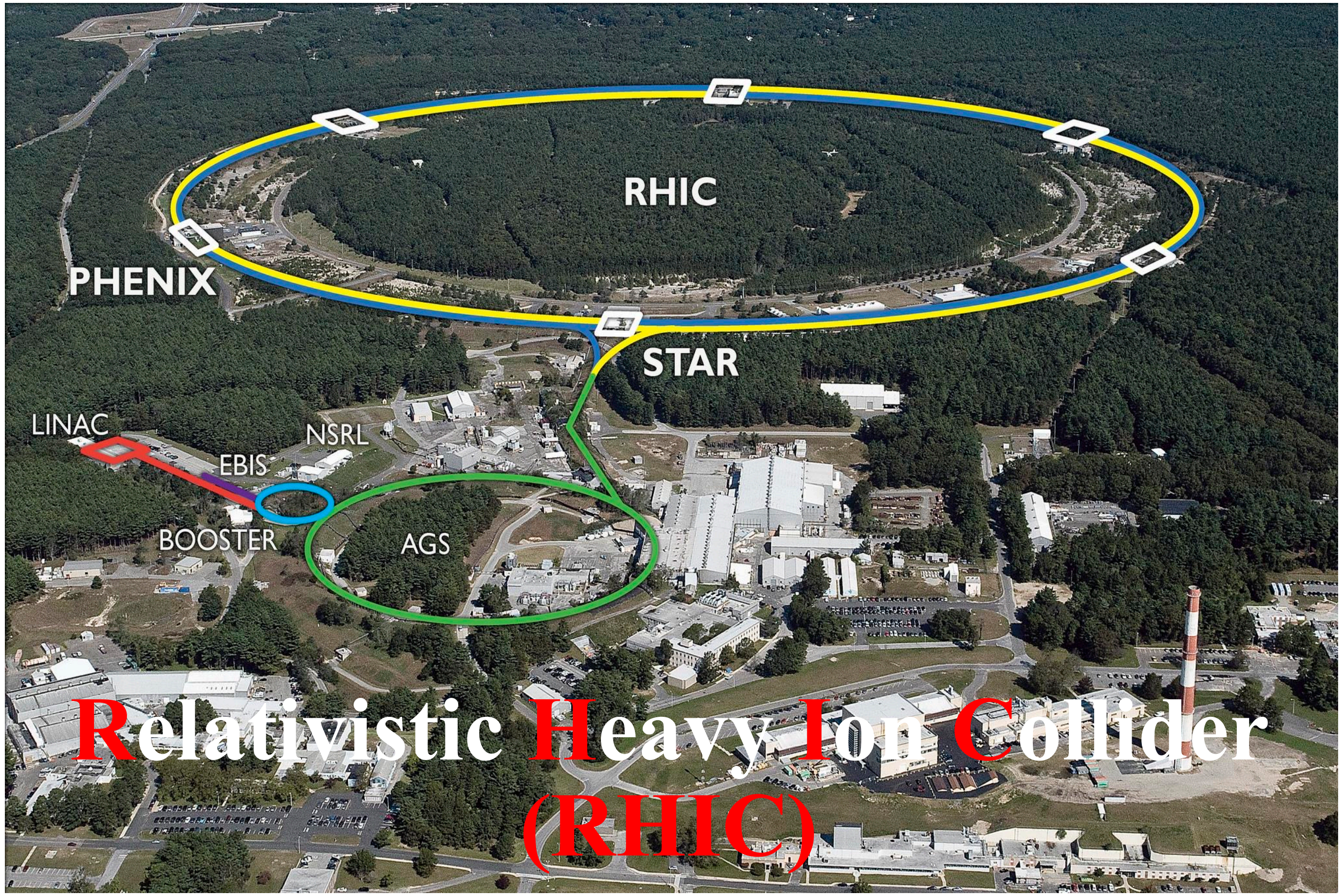
Forward Upgrade at STAR

Ting Lin (林挺)
Shandong University (山东大学)

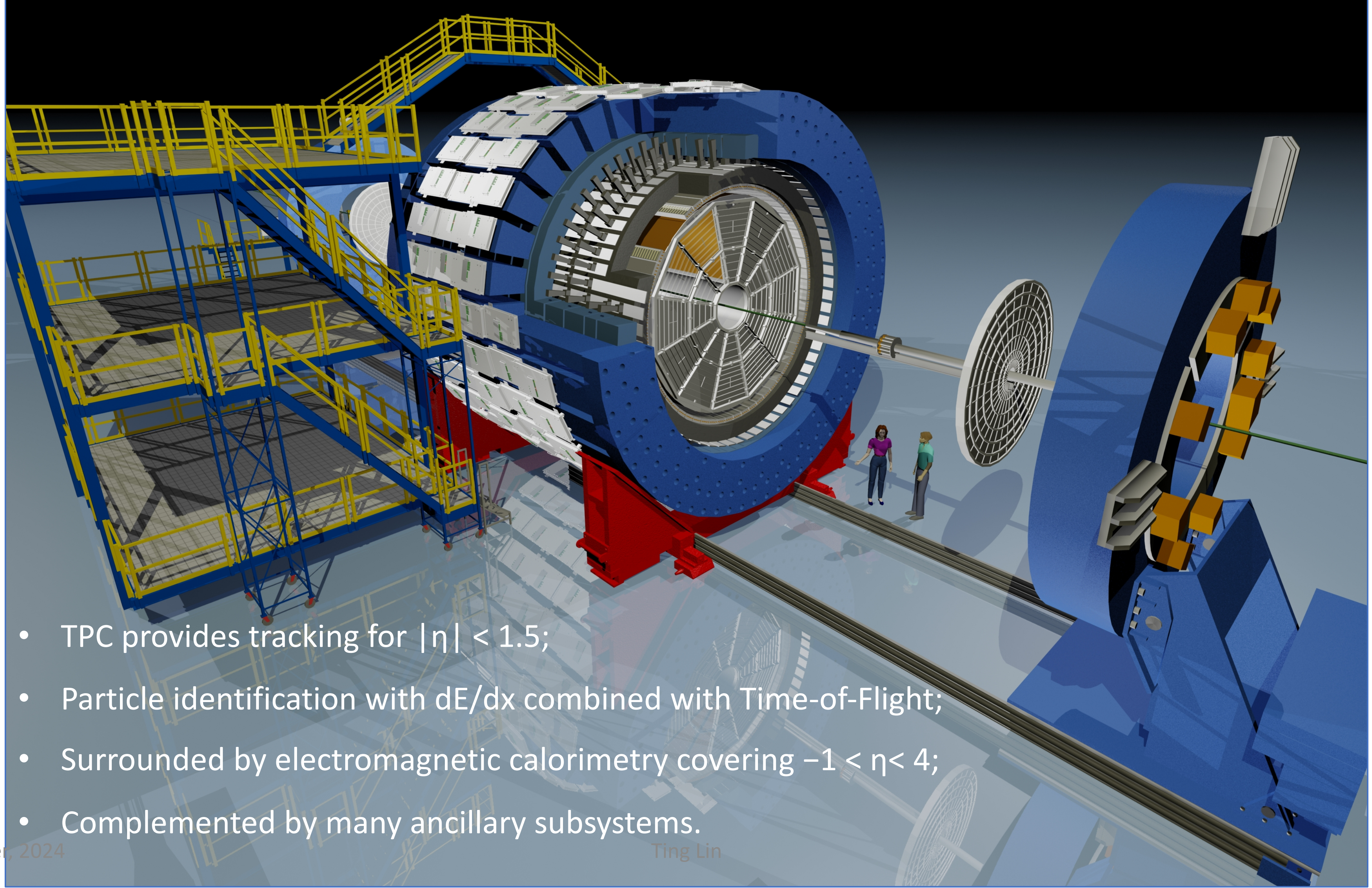
山东大学
SHANDONG UNIVERSITY

Outline:

- STAR Forward Upgrades
  - Forward Silicon Tracker
  - Forward sTGC Tracker
  - Forward Calorimeter System
- Physics Program
  - Cold QCD/Spin Physics
  - Heavy Ion Physics
- Summary

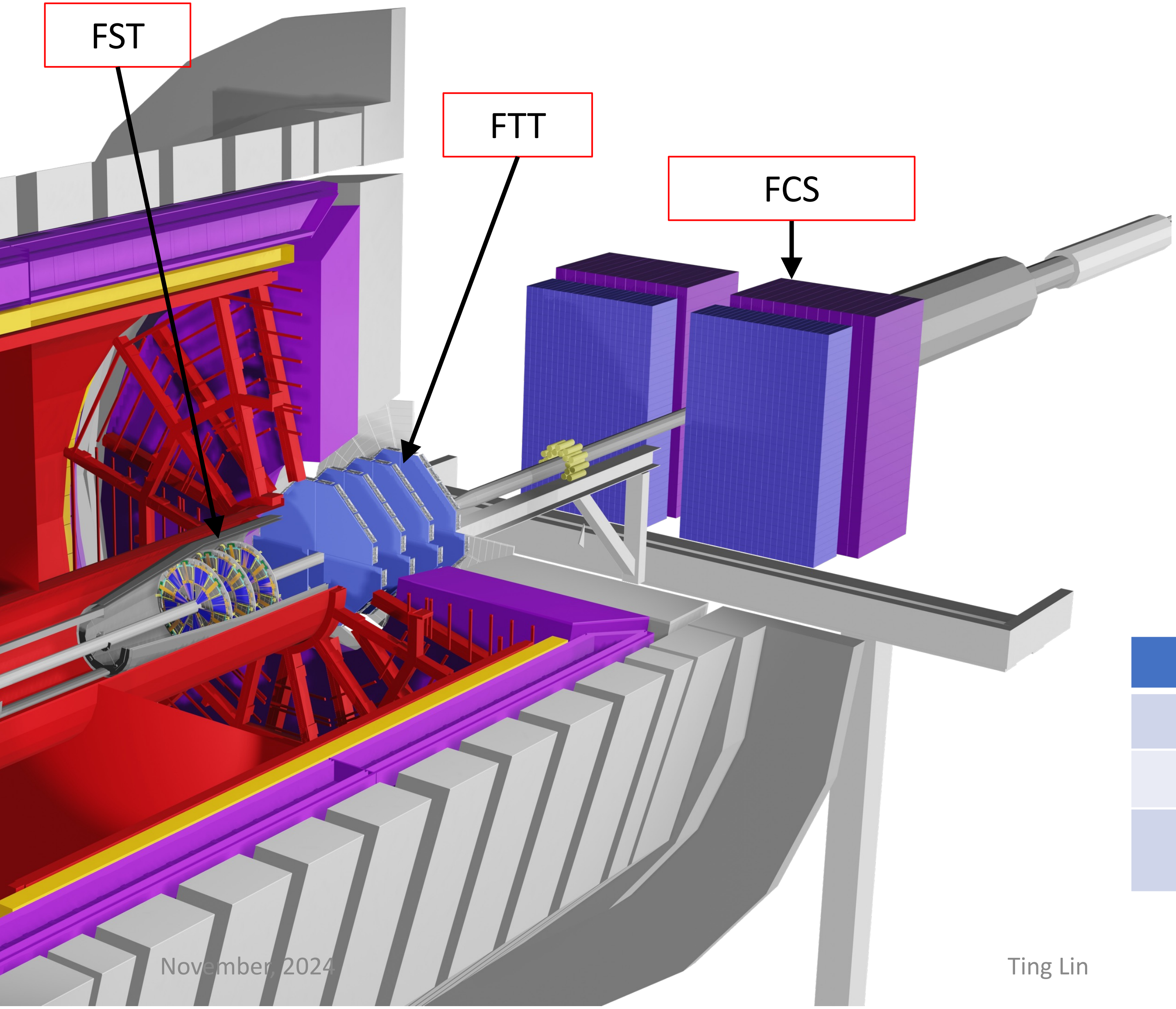


The STAR Detector



- TPC provides tracking for $|\eta| < 1.5$;
- Particle identification with dE/dx combined with Time-of-Flight;
- Surrounded by electromagnetic calorimetry covering $-1 < \eta < 4$;
- Complemented by many ancillary subsystems.

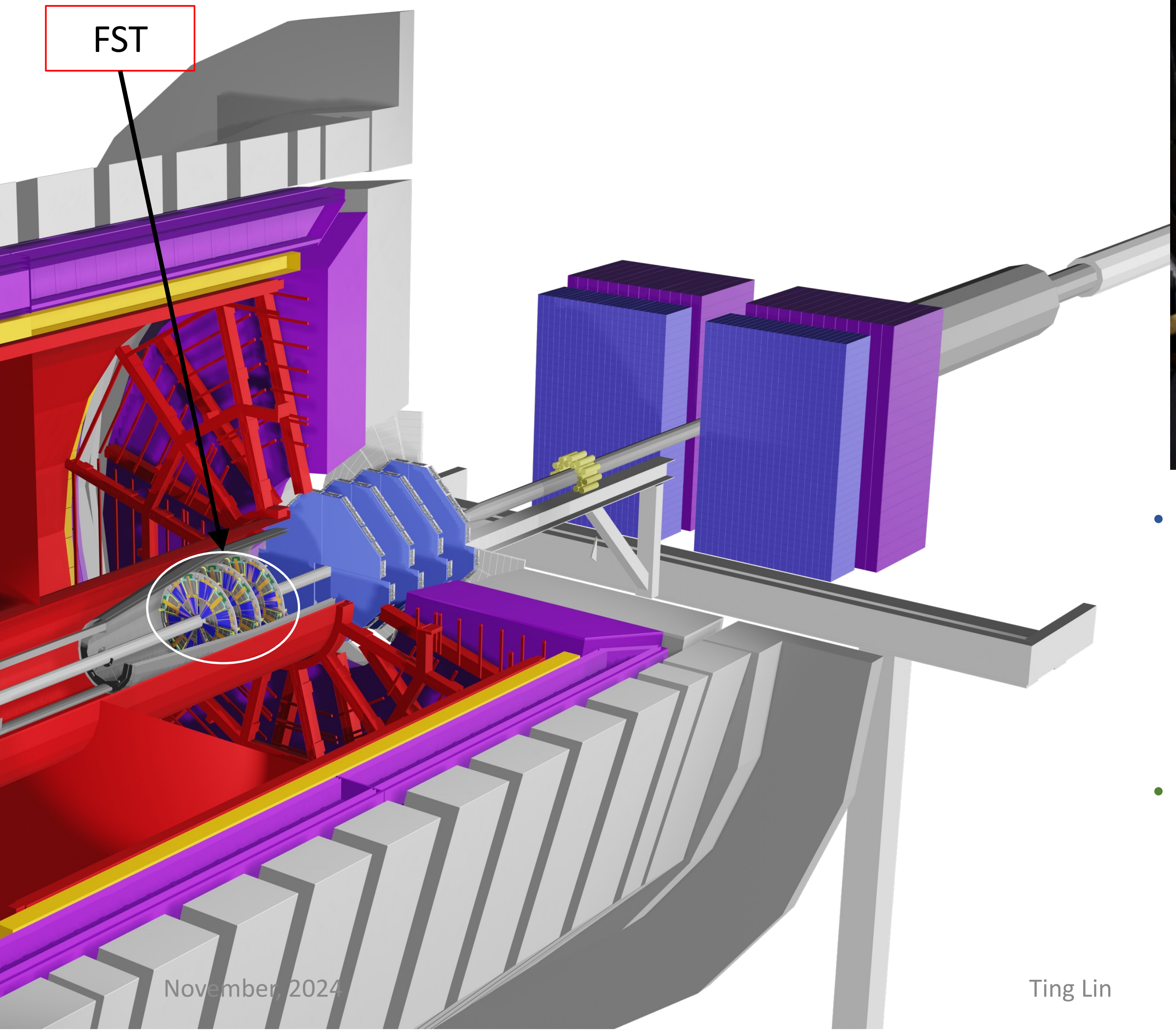
The STAR Forward Upgrade:

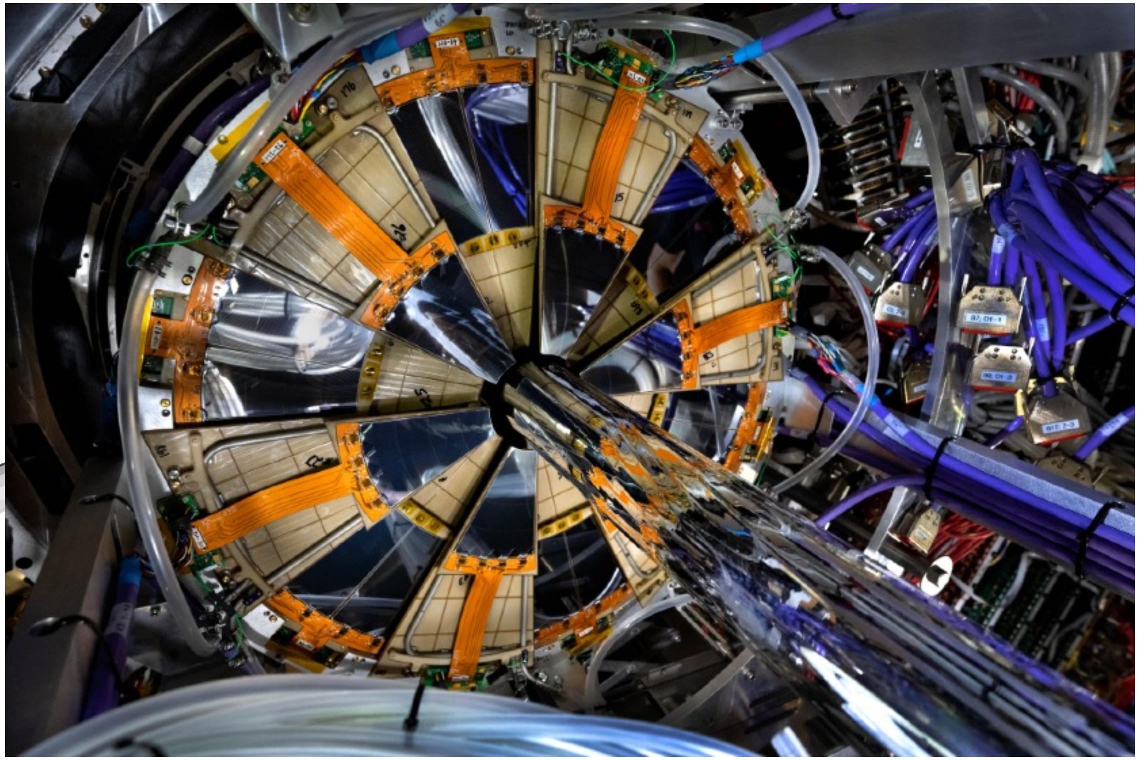


- Covering $2.5 < \eta < 4$, where STAR only had Pb-glass electromagnetic calorimetry before:
  - Si disks + small-strip Thin Gap Chamber (sTGC) for tracking;
  - Electromagnetic and hadronic calorimetry with SiPM readout and new ADC+trigger electronics

Detector	p+p and p+A	A+A
ECal	~10%/$\sqrt{E}$	~20%/$\sqrt{E}$
HCal	~50%/$\sqrt{E}$ + 10%	---
Tracking	Charge separation Photon suppression	0.2< p_T < 2 GeV/c, with 20-30% $1/p_T$

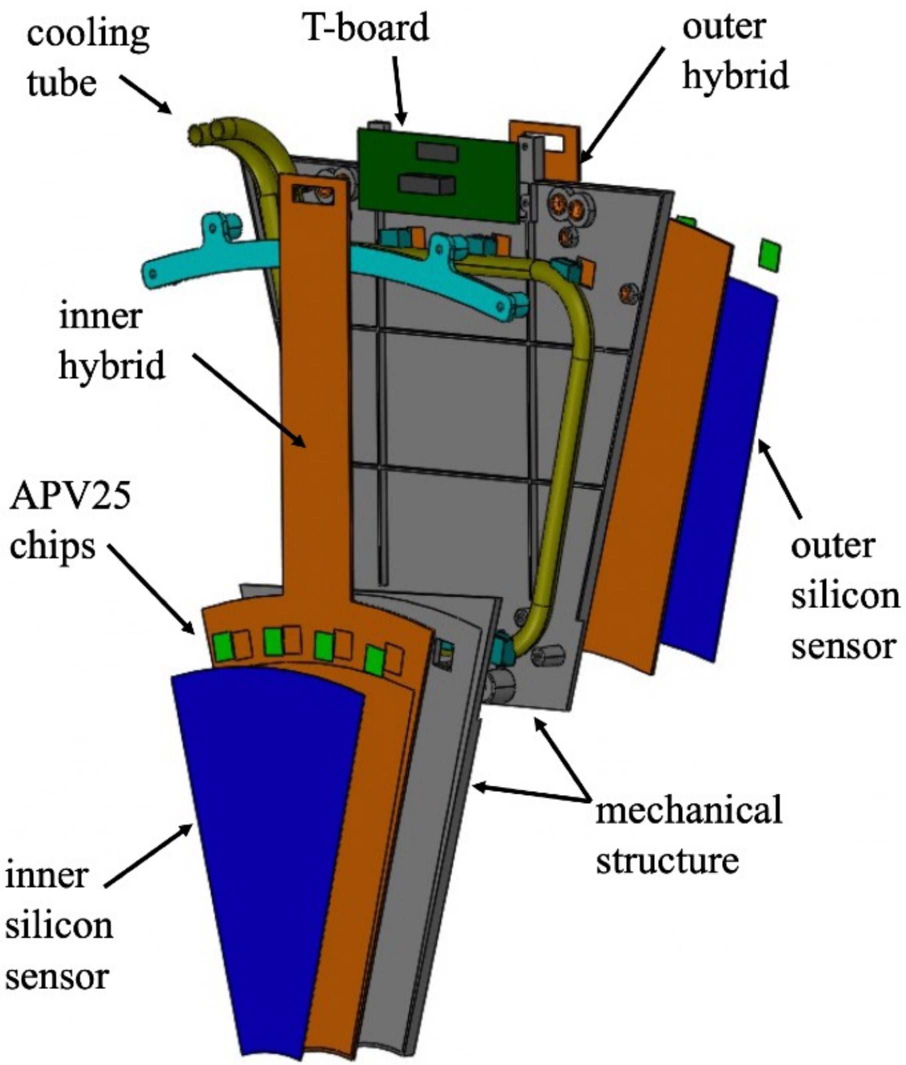
Forward Silicon Tracker (FST)

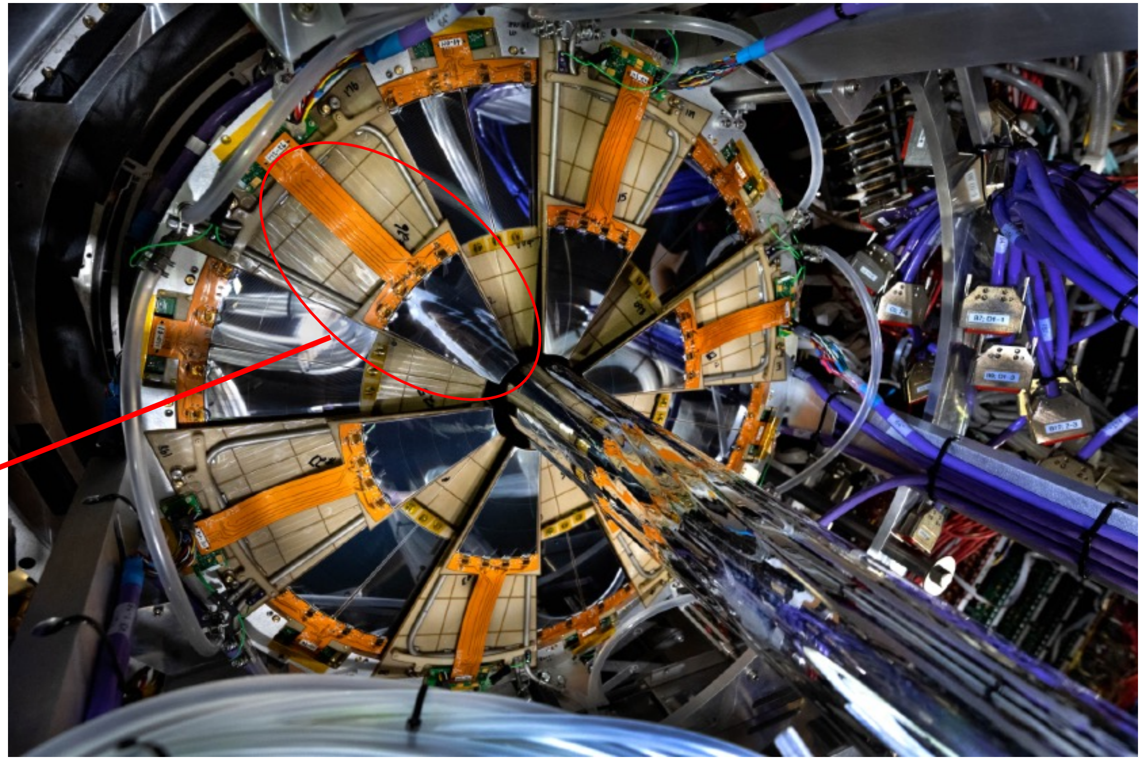




- 3 disks, each with 12 modules, fine granularity in ϕ and coarse in R
  - Each module includes 3 single-sided double-metal mini-strip sensors;
  - Material budget ~1.5% X_0 per disk;
  - Si from Hamamatsu;
- Technology is similar to STAR Intermediate Silicon Tracker (IST)
  - Same APV25-S1 front-end chip;
  - Reuses the IST data acquisition and cooling systems.

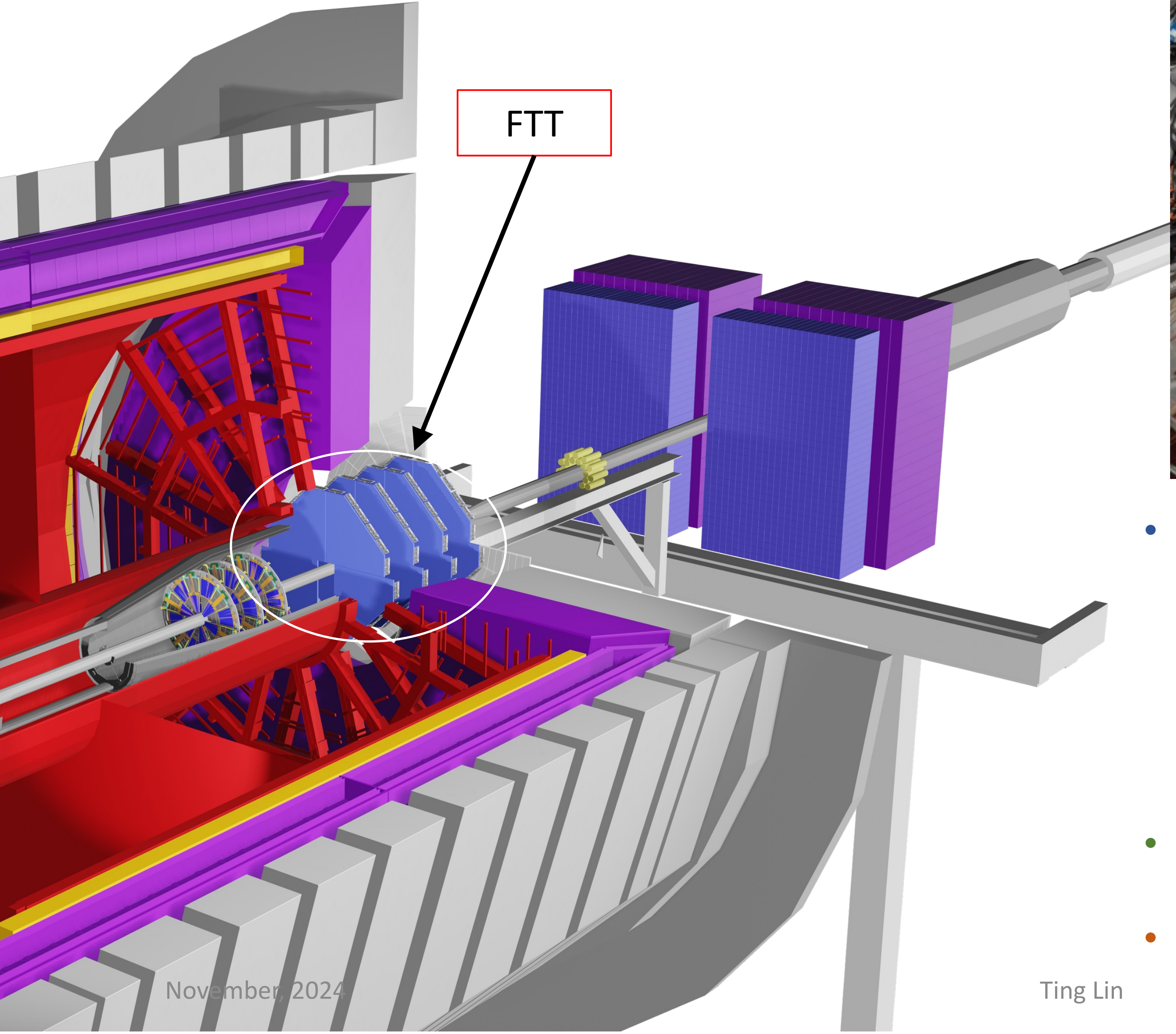
Forward Silicon Tracker (FST)

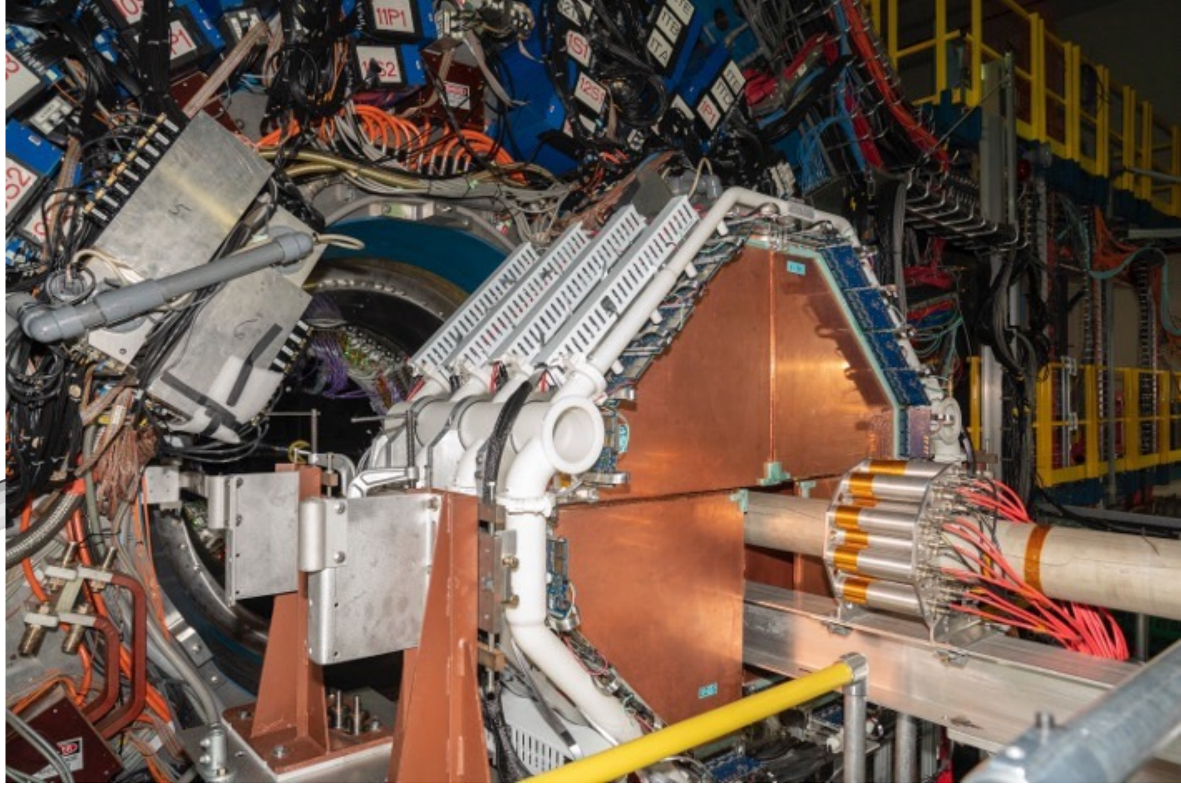




- Two regions, inner: 5 < R < 16.5 cm; outer: 16.5 < R < 28 cm;
  - Kapton flexible hybrid
  - Si sensors: 128 × 4 ($\phi \times$R) strips
  - APV chips;
- Mechanical Structure
  - PEEK (main structure + tube holder)
  - Stainless steel (cooling tubes)
  - Aluminum (heat sinks)
- Module Assembly
  - Gluing inner/outer hybrids and mechanical structures together
  - Mount/wire-bond APVs and Silicon sensors on hybrids

Forward sTGC Tracker (FTT)





- 4 planes, each consisting of 4 pentagonal modules
  - Double-sided sTGC with diagonal strips give x, y, u in each layer
  - Position resolution < 200 μm
  - Material budget ~0.5% X_0 per layer
- Readout based on VMM chips
- Similar to the LHC-ATLAS sTGC system

FTT Gas System

Gas cabinet

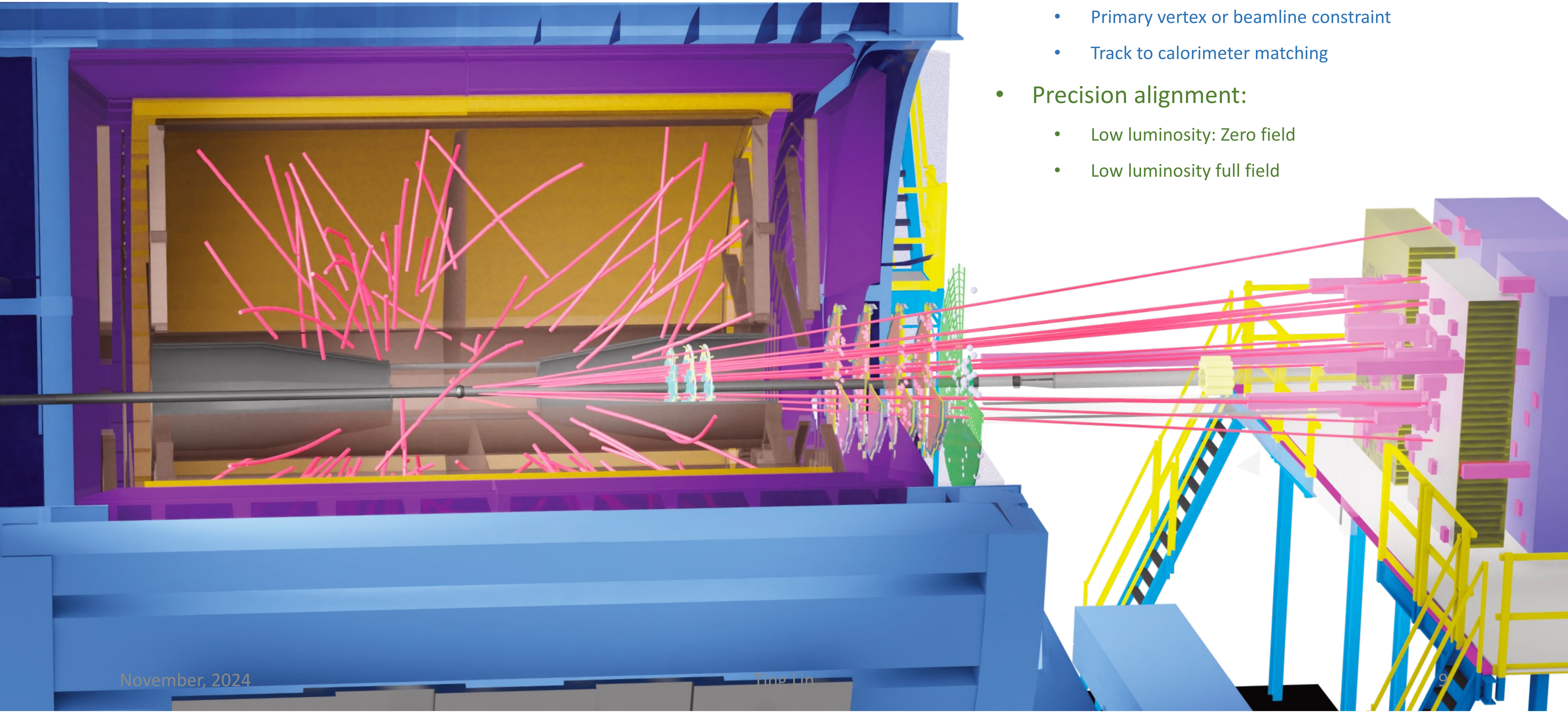
Front of the controls cabinet

Gas distribution panel

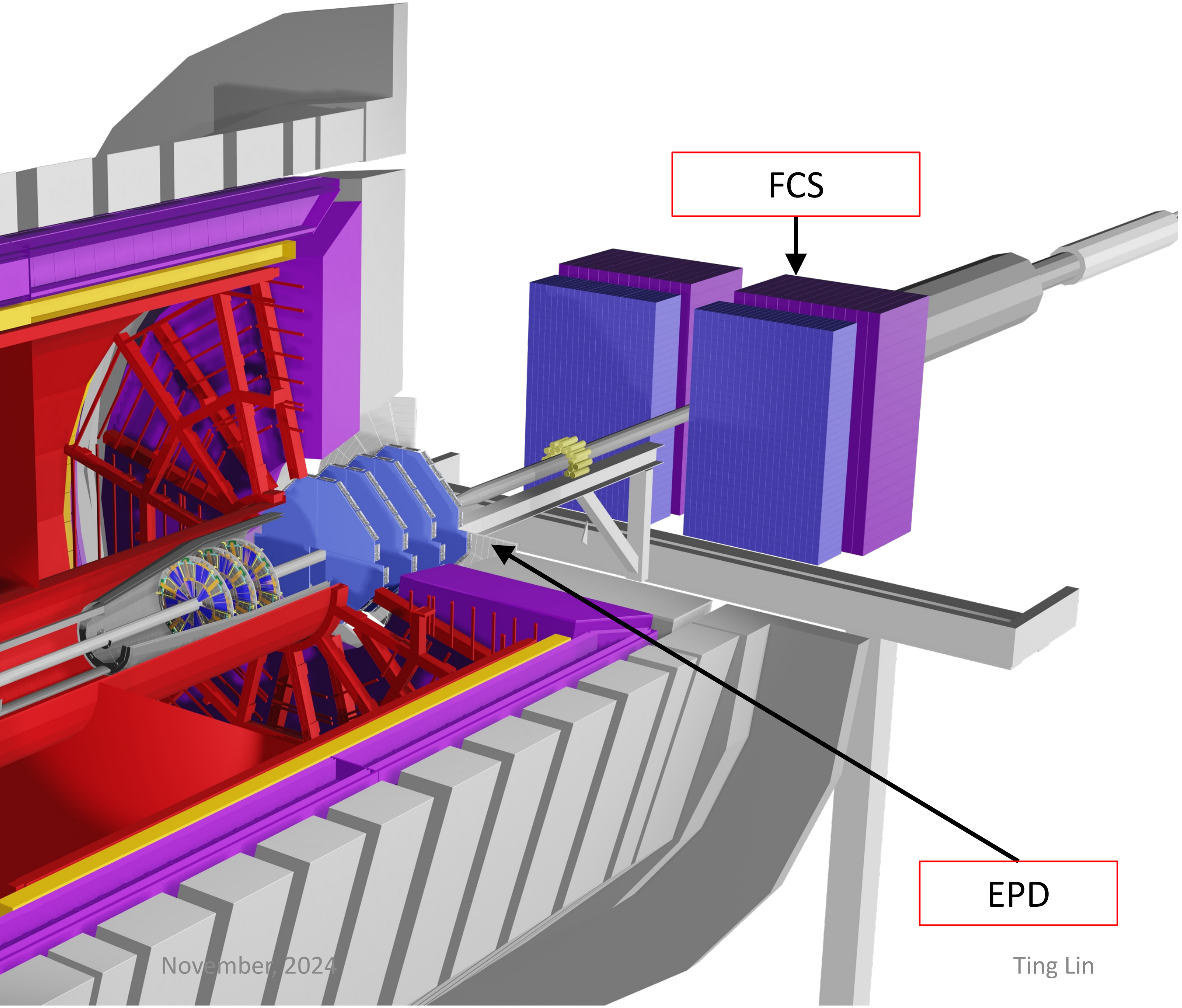
- sTGCs use 45% n-pentane + 55% CO_2, extreme care needed for the highly flammable gas;
  - Flash point 14 °C; explosive limits 1.5 – 7.8%;
  - Boiling point of 36 °C further complicates things;
- Has operated extremely well through major power failures and big storms.

Forward Tracking Performance

- Tracking with FST + FTT
  - Primary vertex or beamline constraint
  - Track to calorimeter matching
- Precision alignment:
  - Low luminosity: Zero field
  - Low luminosity full field

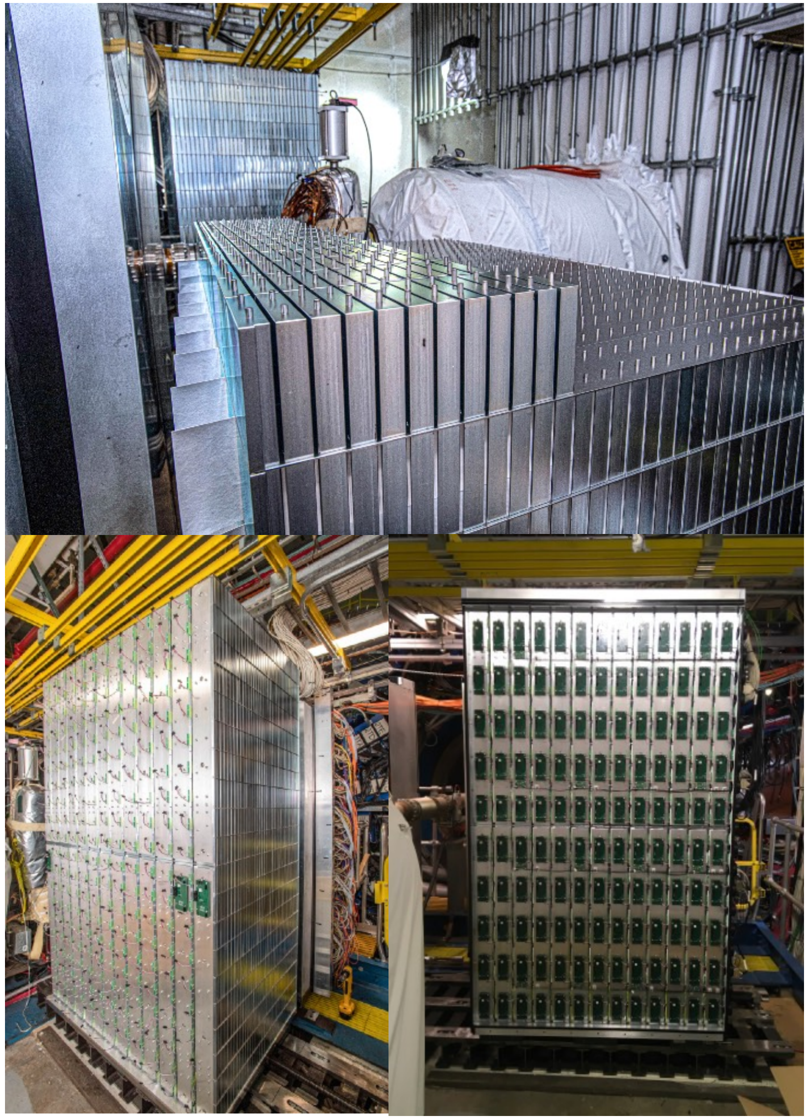


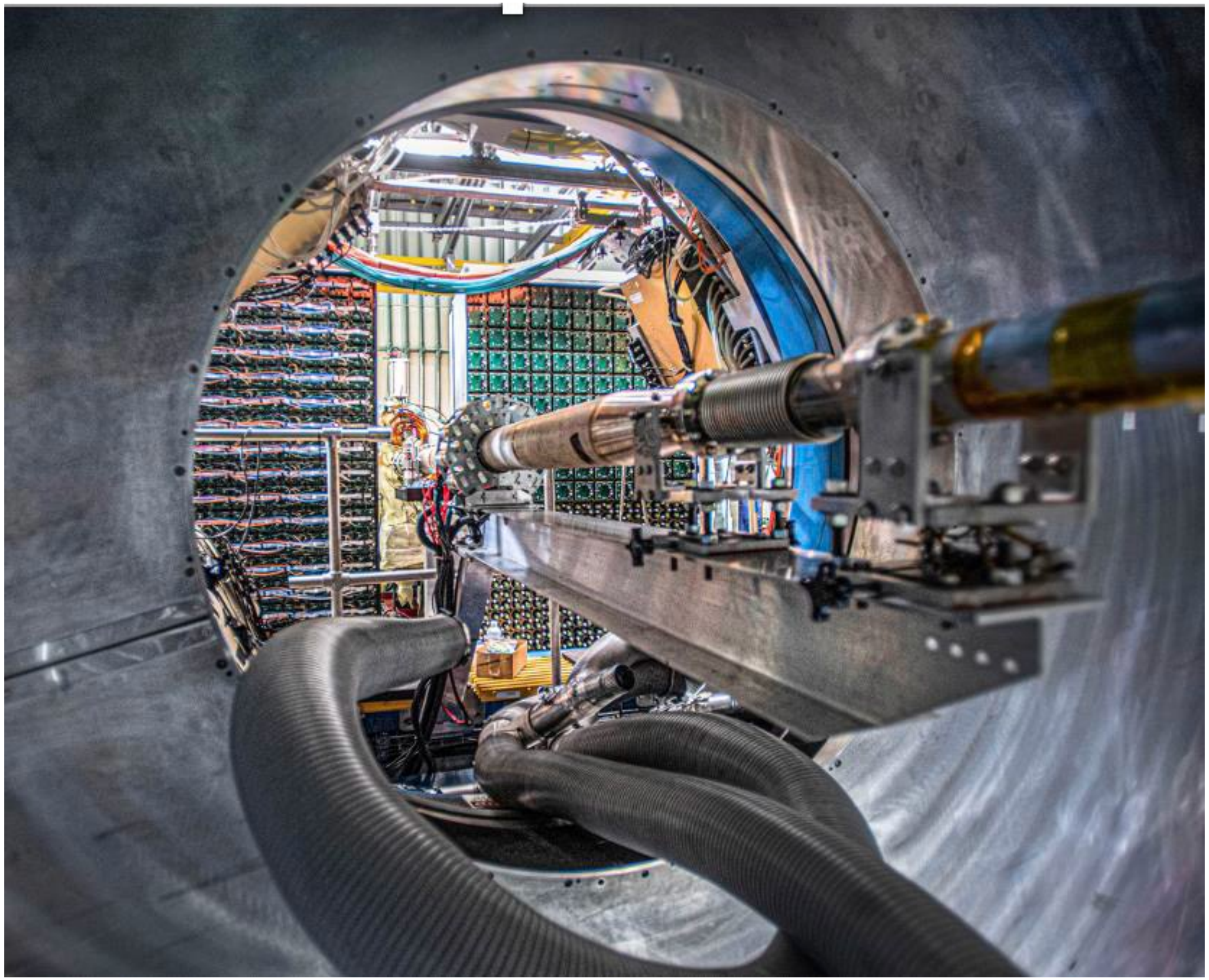
Forward Calorimeter System (FCS)



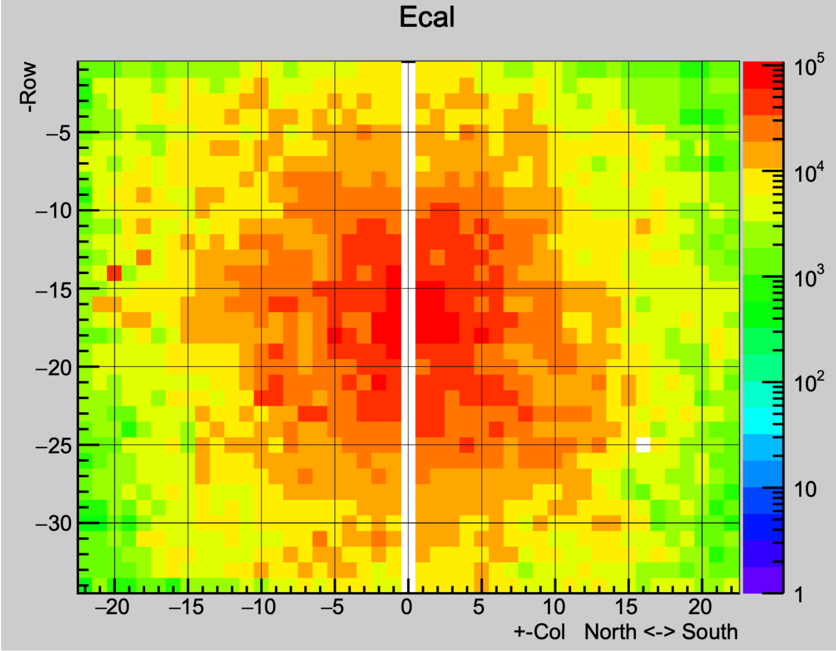
- Ecal, reuse PHENIX Pb-Scintillator calorimeter
  - 1496 channels: 5.52 x 5.52 x 33 cm3
  - 66 sampling cells with 1.5 mm Pb / 4 mm Sc
  - 36 wavelength-shifting fibers per cell
  - 18 X_0; 0.85 nuclear interaction lengths
  - Replaced PMTs with SiPM readout
- Hcal, developed in collaboration with EIC R&D
  - Fe/Sc (20 mm/3 mm) sandwich
    - 520 channels: 10 x 10 x 84 cm3
    - Approximately 4.5 nuclear interaction lengths
  - Uses same SiPM readout as ECal
- Pre-shower:
  - Split signals off from STAR EPD for triggering

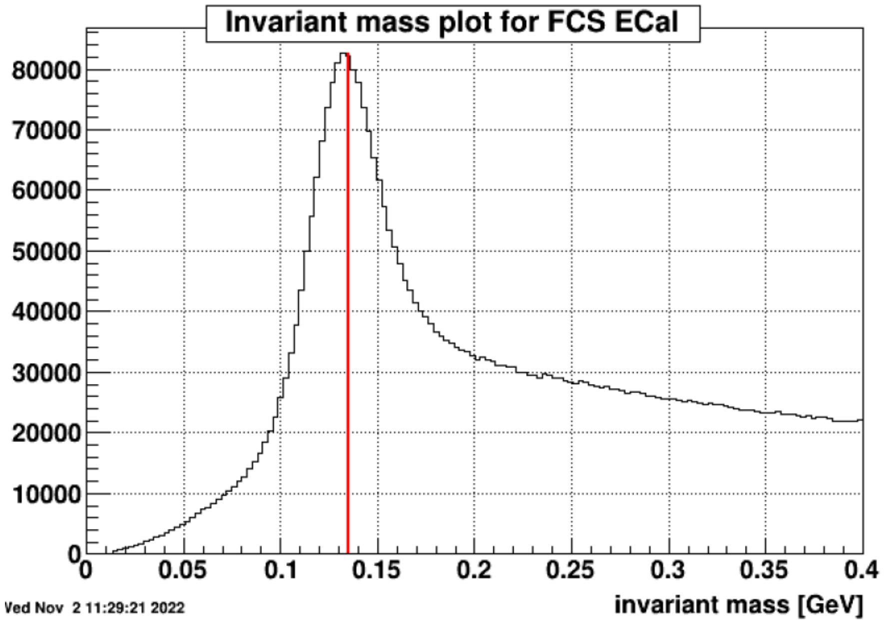
Forward Calorimeter System (FCS)

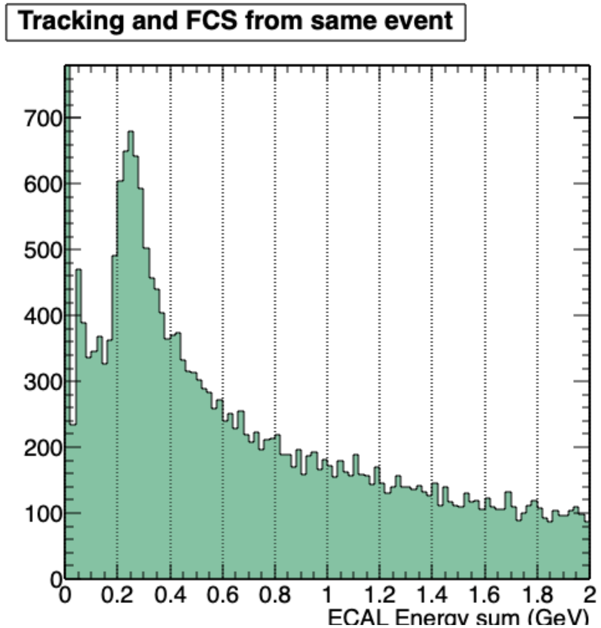




Forward Calorimeter System Performance







- Calibration based on MIP and π^0 reconstruction;
- Find nice correlations between reconstructed tracks and FCS hits;
- Working toward HCal MIP and J/ ψ reconstruction.

Forward Upgrade Timeline

- Summer, 2019: final funding was secured
- Fall, 2020: FCS and associated electronics installed
- Spring, 2021: FCS commissioned with beam
- August, 2021: FST installed
- October, 2021: sTGC installed
- November, 2021: FST and sTGC commissioned with cosmic rays
- November 29, 2021: cool down began for the 2022 RHIC run with 508 GeV pp collisions
- December 21, 2021: commissioning with beam completed, physics data taking began
- The STAR Forward Upgrade was completed on time and on budget. It has operated very smoothly and taken excellent data throughout the 2022-2024 RHIC runs.

Forward Physics Program

Forward Rapidity: 2.5 < η < 4

A+A

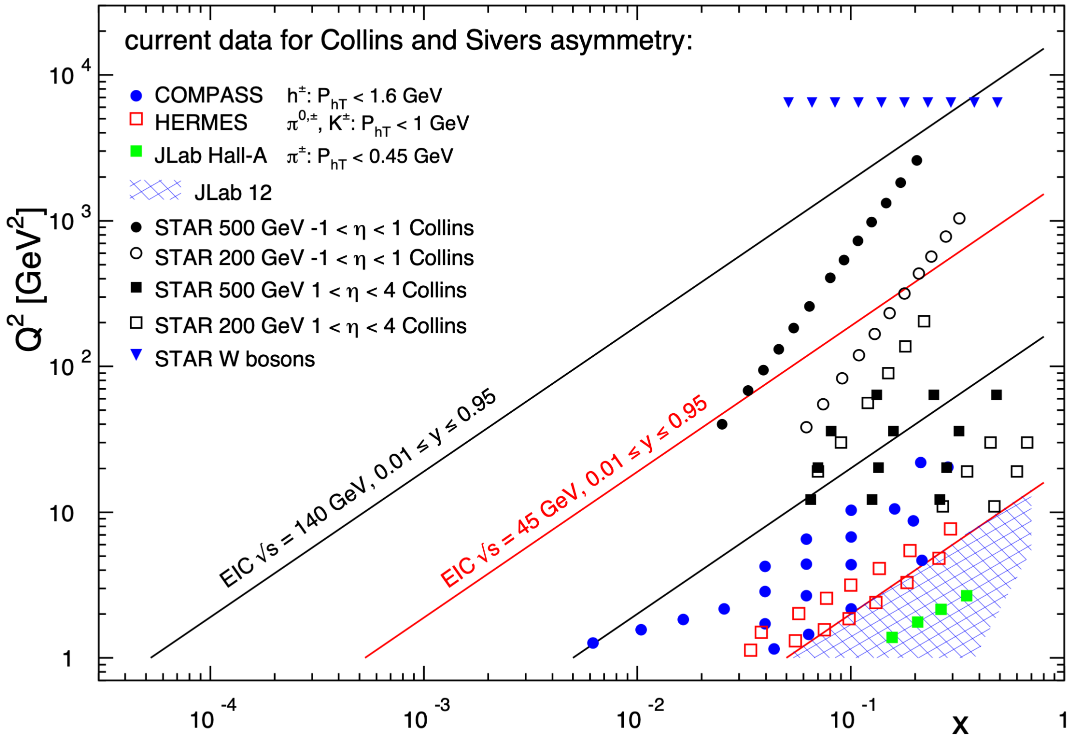
Beam:
200 GeV: Au+Au

Physics Topics:
- Temperature dependence of viscosity through flow harmonics up to η~4;
- Longitudinal decorrelation up to η~4;
- Global Lambda Polarization strong rapidity dependence;
- Collectivity in Photo-nuclear Processes.

p+p & p+A

Beam:
508 GeV: p+p
200 GeV: p+p and p+Au

Physics Topics:
- TMD measurements at high x
  - Transversity, Collins;
  - Sivers by DY and jets;
- UPC J/Ψ GPD at forward rapidity;
- Nuclear PDFs and FF;
- Gluon Saturation through di-hadrons, γ-Jets, di-jets.



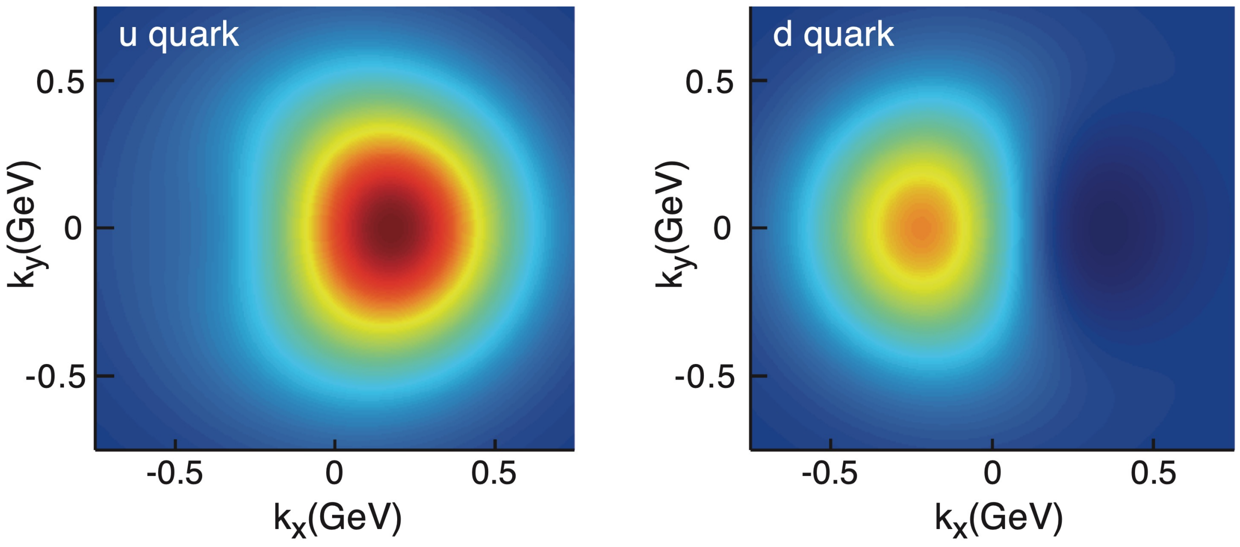
$\sqrt{s}$ (GeV)	Species	Events	Year
508	$p^{\uparrow}+p^{\uparrow}$	400 pb^{-1}	2022
200	Au +Au	1.5 Billion	2023
	$p^{\uparrow}+p^{\uparrow}$	235 pb^{-1}	2024
	Au +Au	6.5 Billion	
		9 Billion	2025
	$p^{\uparrow}$+ Au	0.22 pb^{-1}	

TMD Parton Distribution Functions

TMD Handbook, arXiv:2304.03302 [hep-ph]

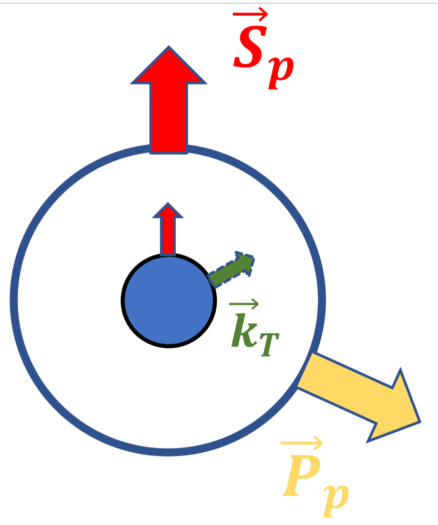
EIC White Paper arXiv:1212.1701

$x\, f_1(x, k_T, S_T)$



Leading Quark TMDPDFs — Nucleon Spin — Quark Spin

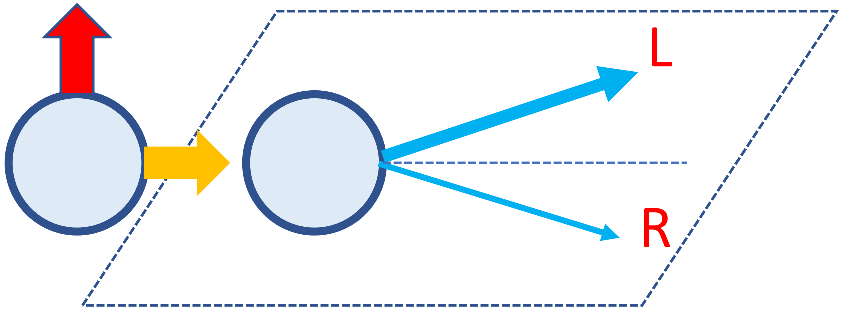
Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity $h_{1T}^\perp$ = Pretzelosity



- Image the transverse and longitudinal (2+1d) structure of the nucleon and nuclei;
  - Tomography of the nucleon;
- Access to transverse momenta at non-perturbative scales;
  - Probe at the confinement scale;
- Exhibit correlations arising from spin-orbit effects.

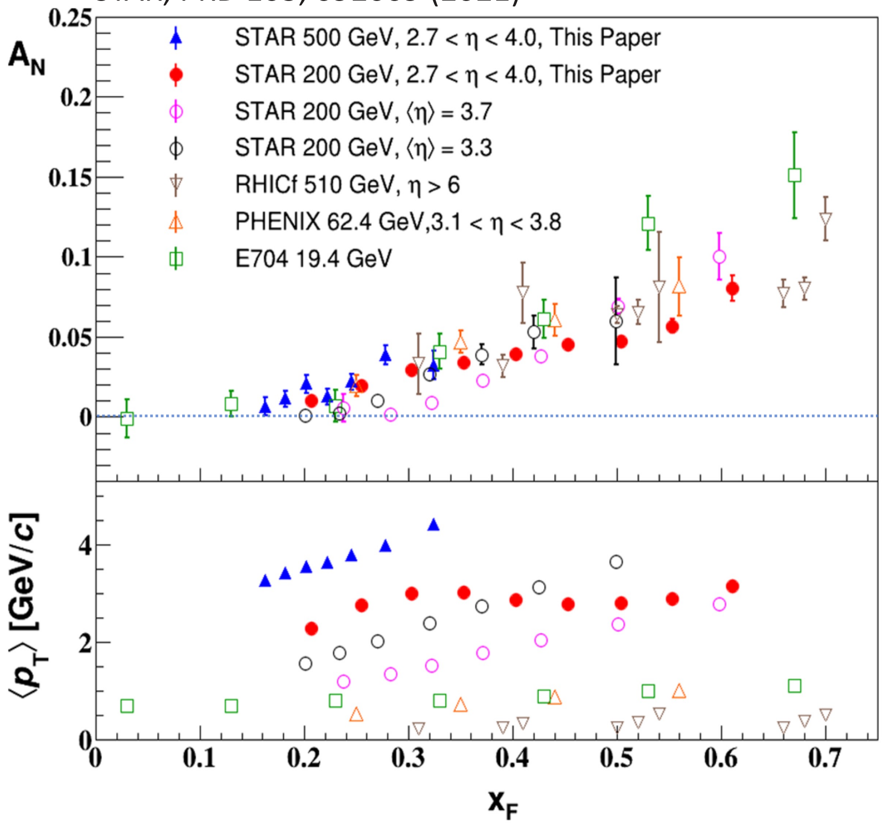
Transverse Single-Spin Asymmetry

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$



$p^{\uparrow} + p \to \pi^0 + X$

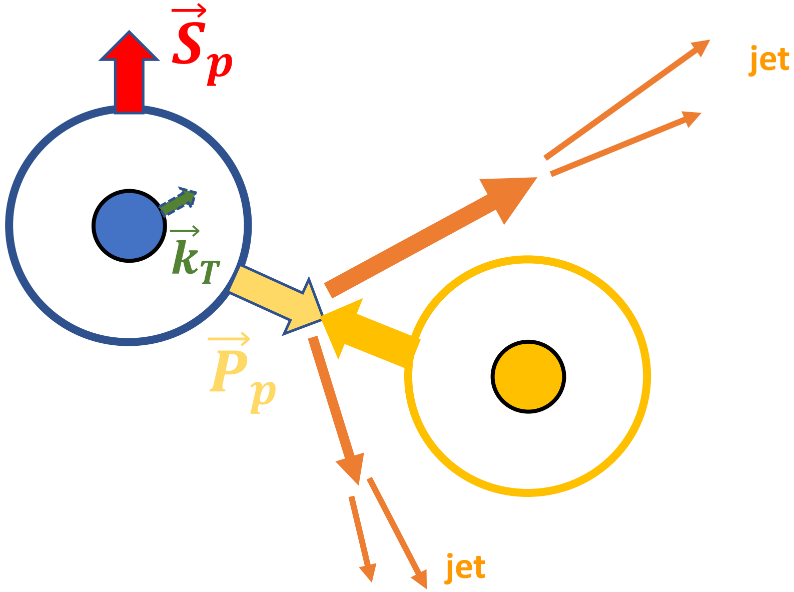
STAR, PRD 103, 092009 (2021)



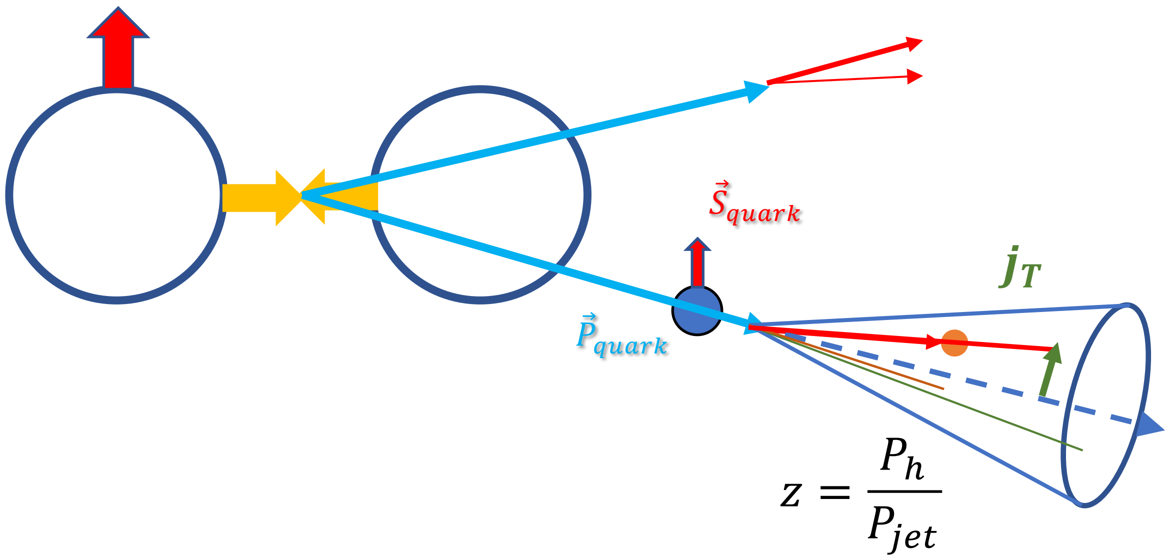
- Large transverse single-spin asymmetry (A_N) has been observed in transversely polarized pp collisions;
- Possible contributions: twist-3 correlators associated with the Sivers functions, Collins FF, diffractive Processes.

Initial and Final State Effect

Sivers Effect



Collins Effect

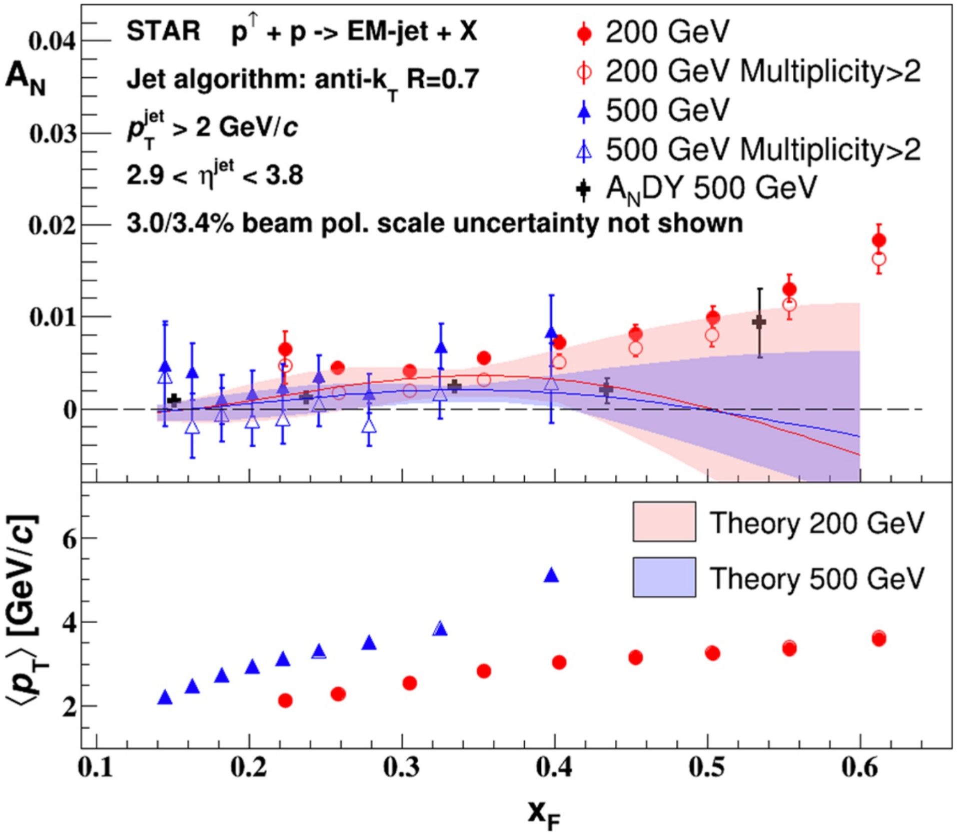


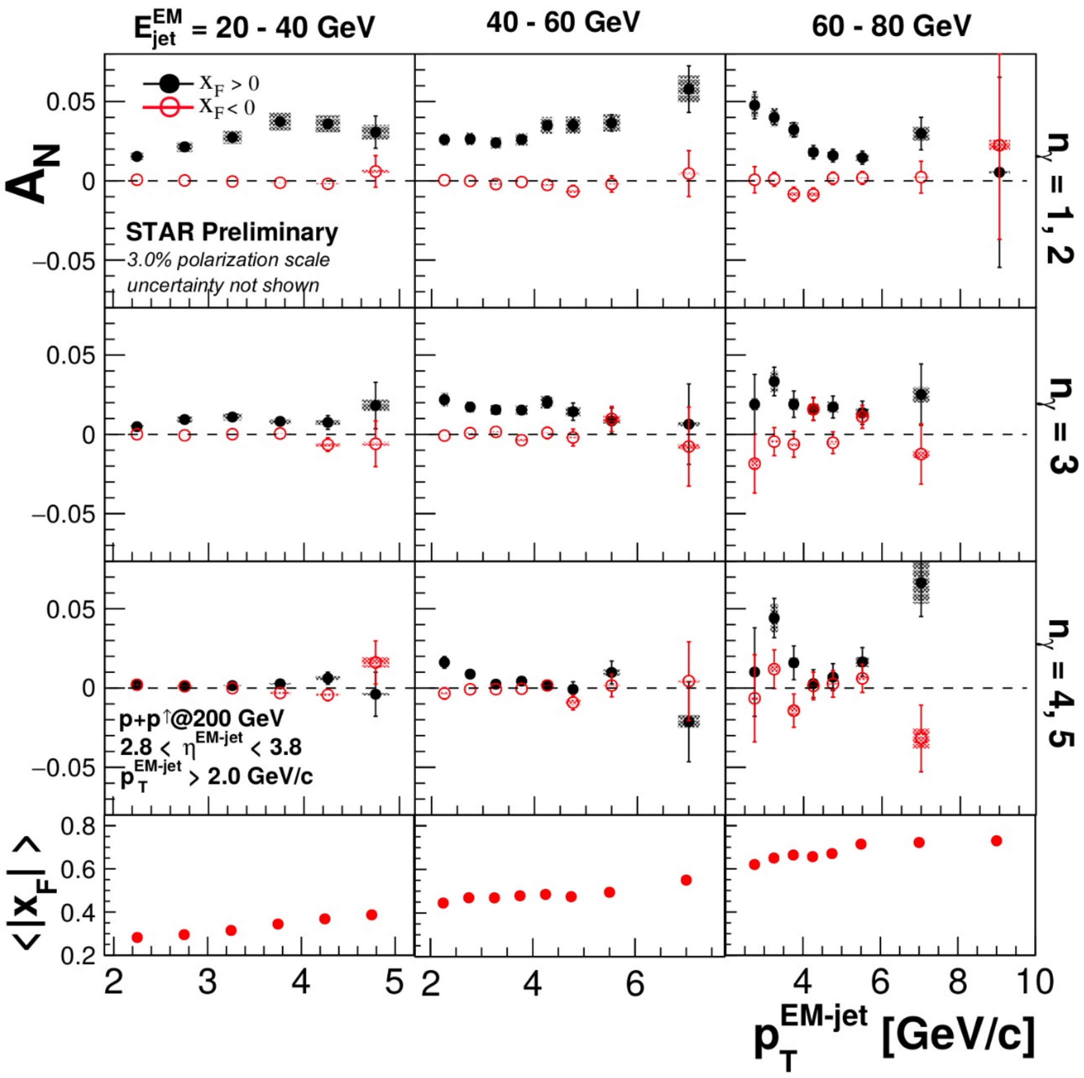
- Correlations of initial-state parton transverse momentum with proton's spin and momentum: $\sim \vec{S}_{proton} \cdot (\vec{P}_{proton} \times \vec{k}_T)$
- Non-universality exhibits the process dependence.

- Correlation between the polarization of a scattered quark and the momentum of hadron fragment transverse to the scattered quark direction: $\sim \vec{S}_q \cdot (\hat{p}_q \times \vec{j}_T)$;
- Chiral-odd, should couple with another chiral-odd distributions.

A_N for Forward Jet

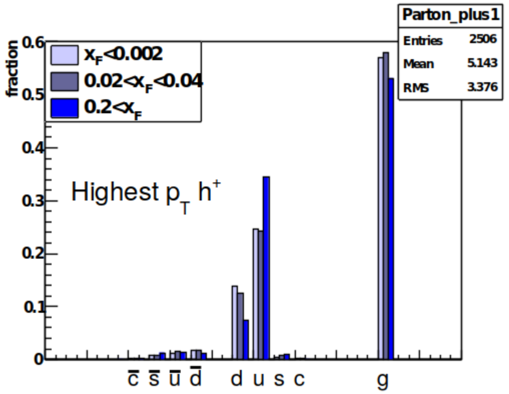
STAR, Phys. Rev. D 103, 092009 (2021)

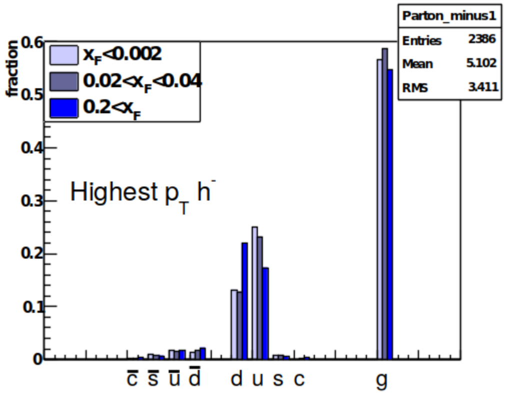


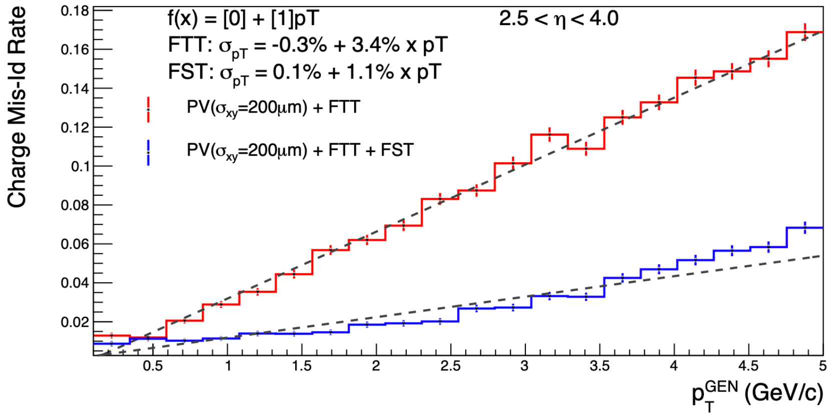


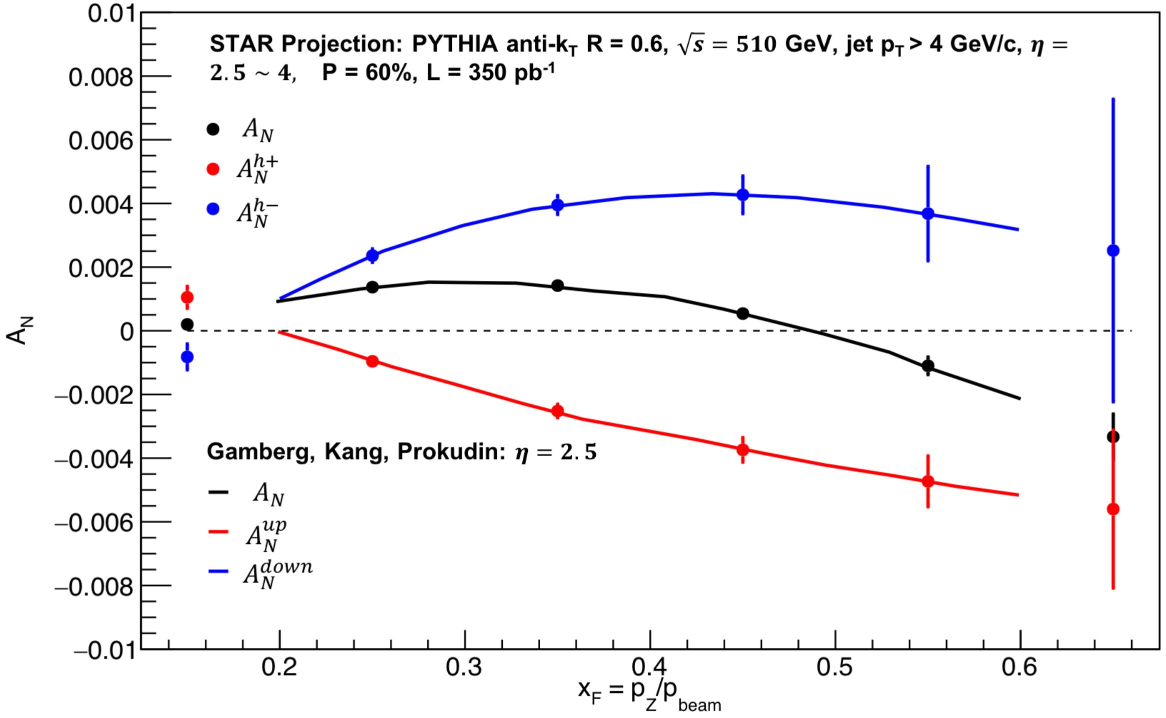
- The published STAR forward inclusive EM-jet result shows small TSSA;
- The EM-jet A_N decreases with increasing photon multiplicity for x_F >0; A_N is larger for the EM-jets consisting of 1 or 2 photons;
- These results provide substantial constraints on the Sivers effect at high x.

A_N for Forward Jet





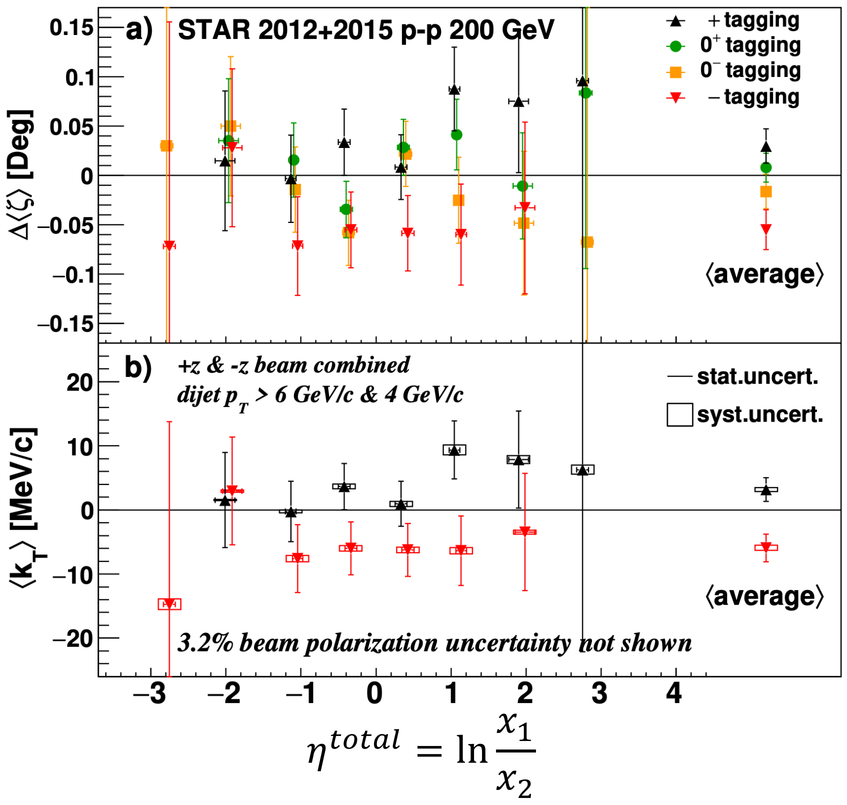


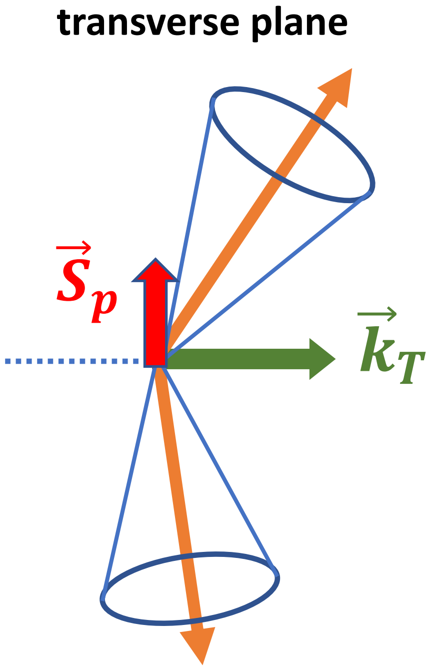


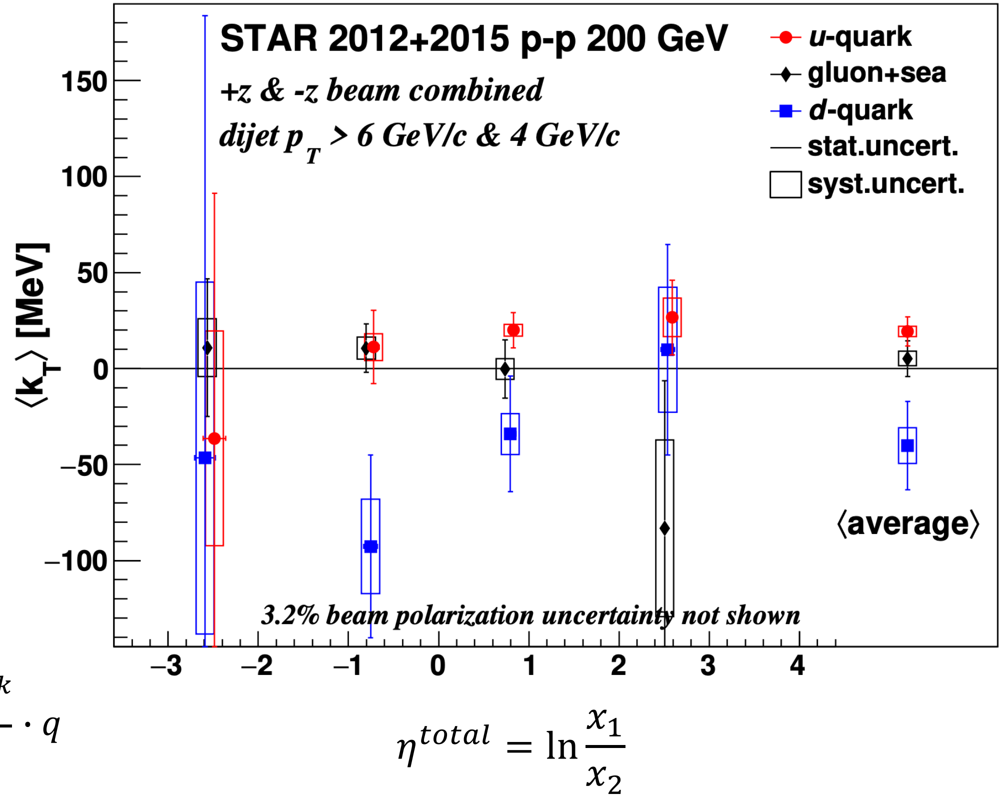
- Enhancement of the u/d quarks for positively/negatively charged leading hadrons at forward rapidity;
- FST+FTT provide very good charge identification capability, precise measurement can be made with the Forward Upgrades;
- Projected statistical uncertainties drawn on twist 3 predictions from Gamberg et. al.

Transverse Single-Spin Asymmetries for Dijet

STAR, arXiv:2305.10359



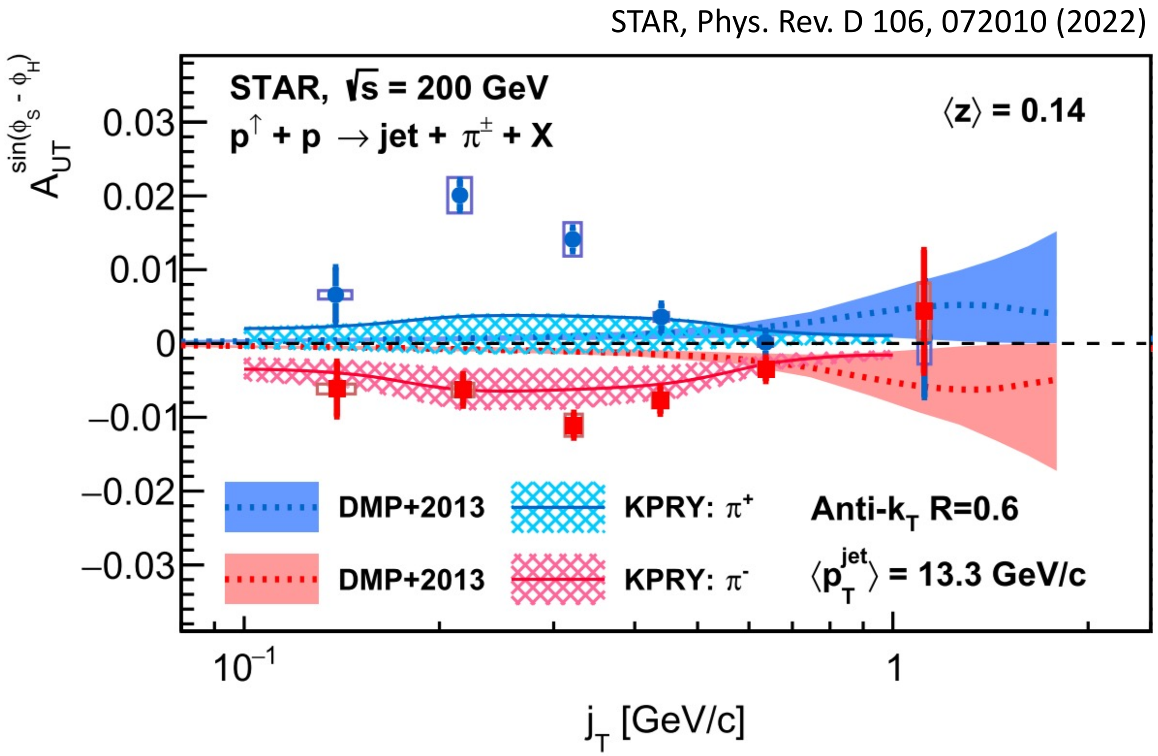


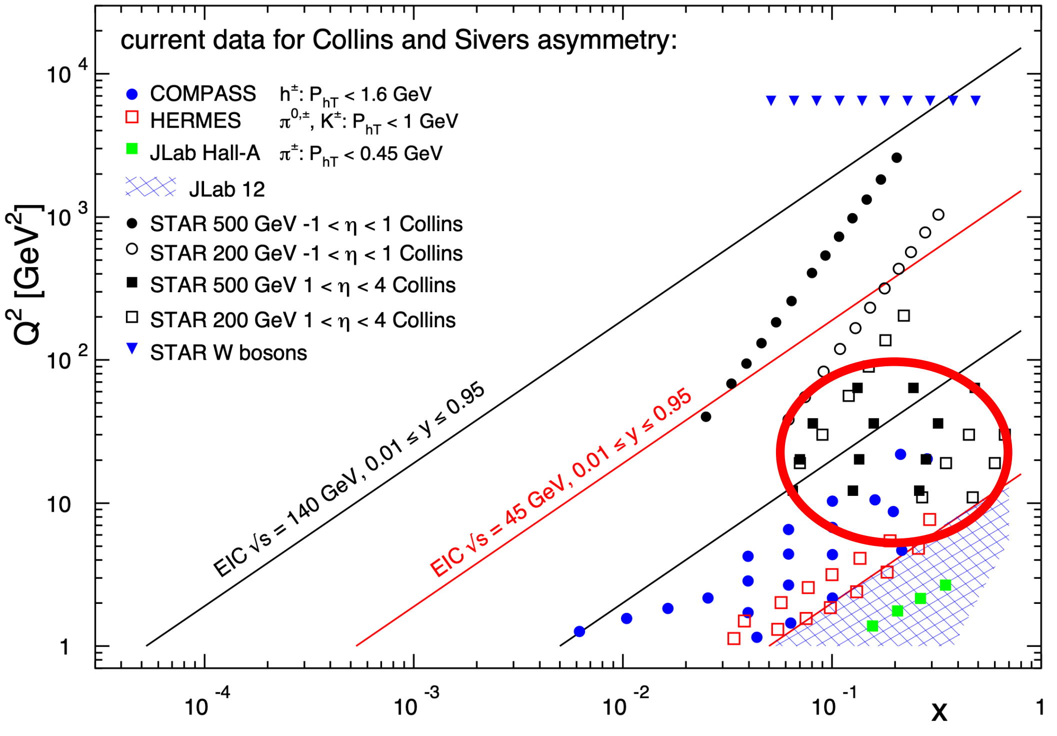


Jet Charge tagging: $Q = \sum_{p>0.8\mathrm{GeV}/c} \frac{p^{track}}{p^{jet}} \cdot q$

- First observation of non-zero Sivers asymmetries in dijet production in polarized p+p collisions;
- $\langle k_T^u \rangle = 19.3 \pm 7.6 \pm 2.6$ MeV/c, $\langle k_T^d \rangle = -40.2 \pm 23.0 \pm 9.3$ MeV/c, $\langle k_T^{g+sea} \rangle = 5.2 \pm 9.3 \pm 3.8$ MeV/c;
- With Forward Upgrades, measurement can be extended to larger pseudo-rapidity (for η^{total} from 1.5 ~ 7).

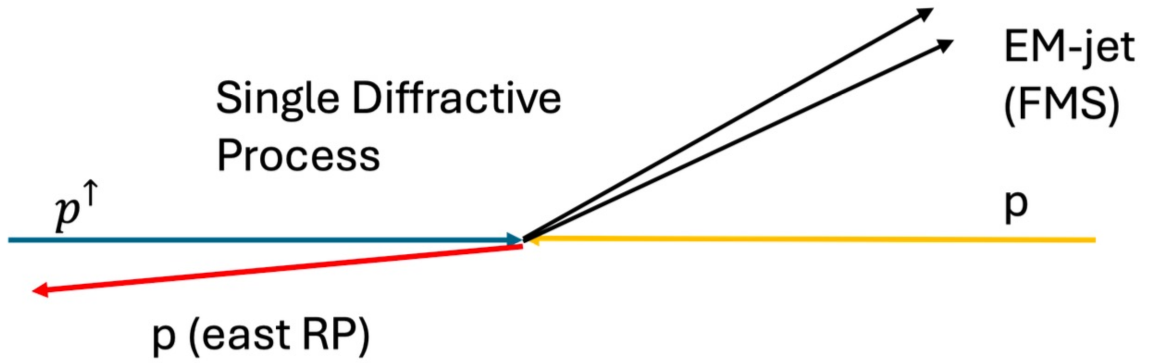
Collins Asymmetry at Forward Rapidity



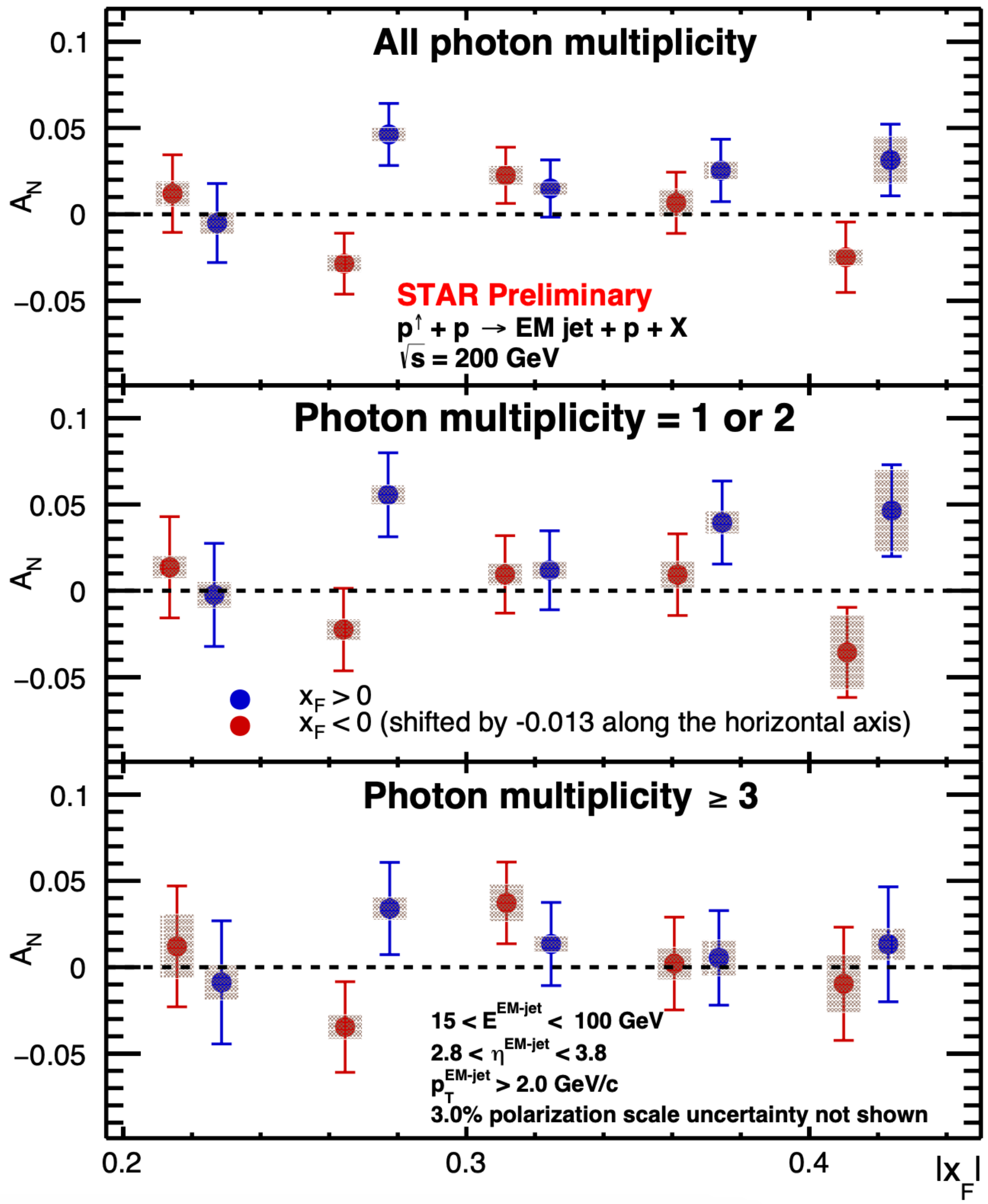


- STAR has performed detailed measurements of the Collins asymmetry at mid rapidity in both 200 and 510 GeV pp collisions;
- The Forward Upgrade will extend the x range to above 0.5 , while filling in the Q^2 region between SIDIS and mid rapidity STAR;
- Essential input for future universality studies at the EIC.

Diffractive Processes

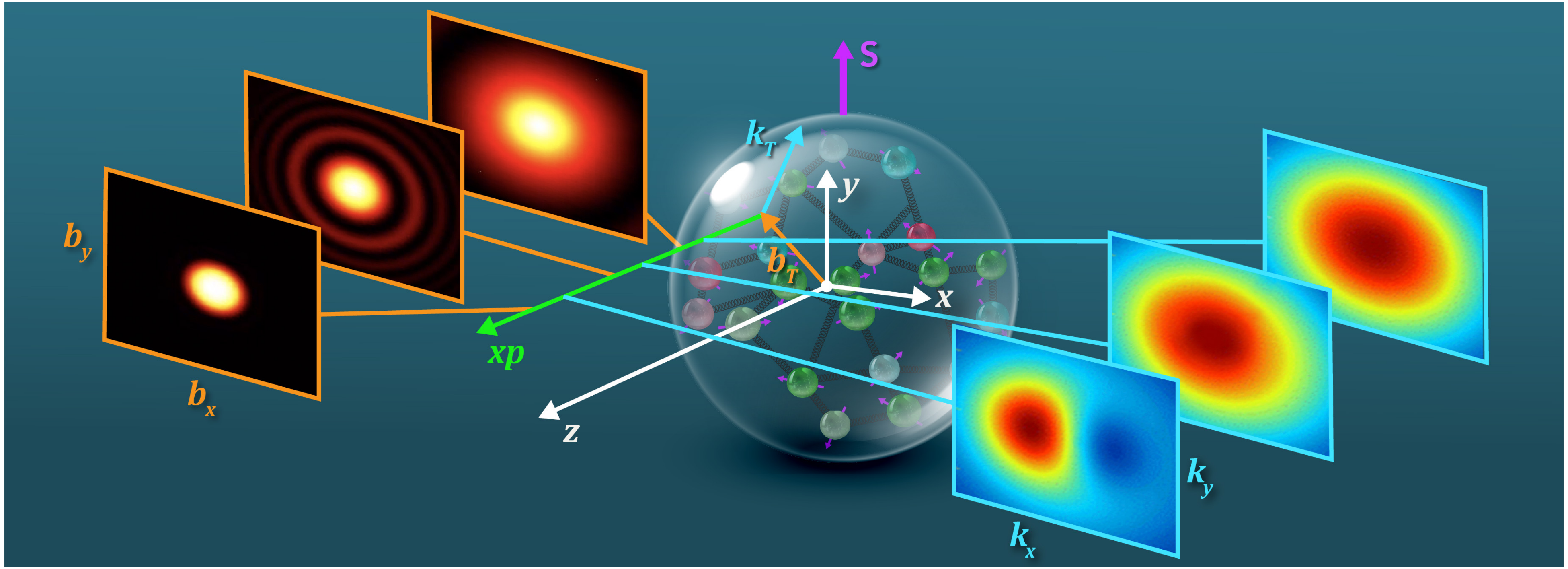


- Single diffractive process: Unpolarized proton intact, with the rapidity gap on the east side (−5 < η < −2.1);
- The EM-jet A_N for $x_F > 0$ is observed for the case of all photon multiplicity and 1 or 2 photon multiplicity with > 2σ significance of non-zero;
- With Forward Upgrades, full jets will be reconstructed (with rapidity gap) to study this process.



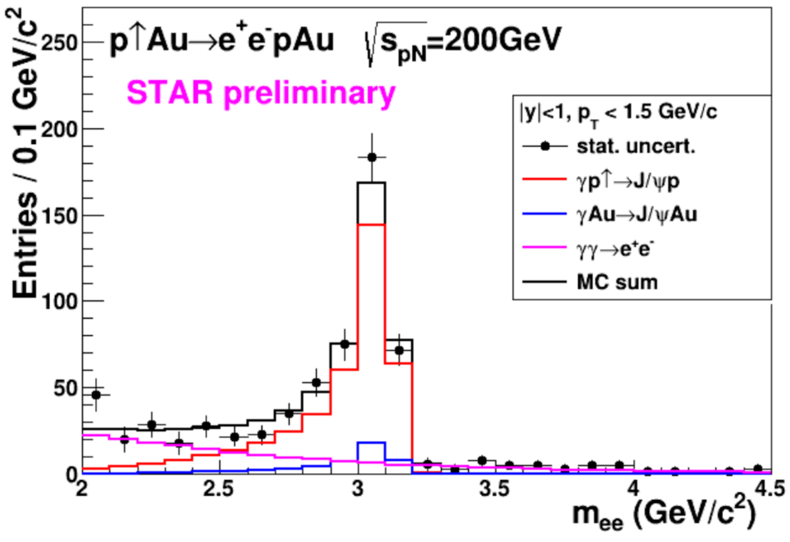
Three-Dimensional Imaging of The Proton

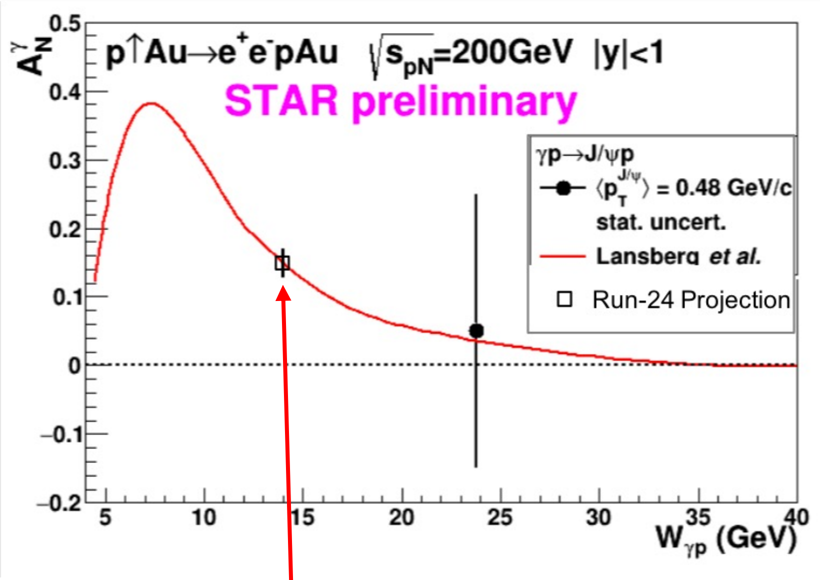
2023 NSAC Long Range Plan, arXiv 2303.02579

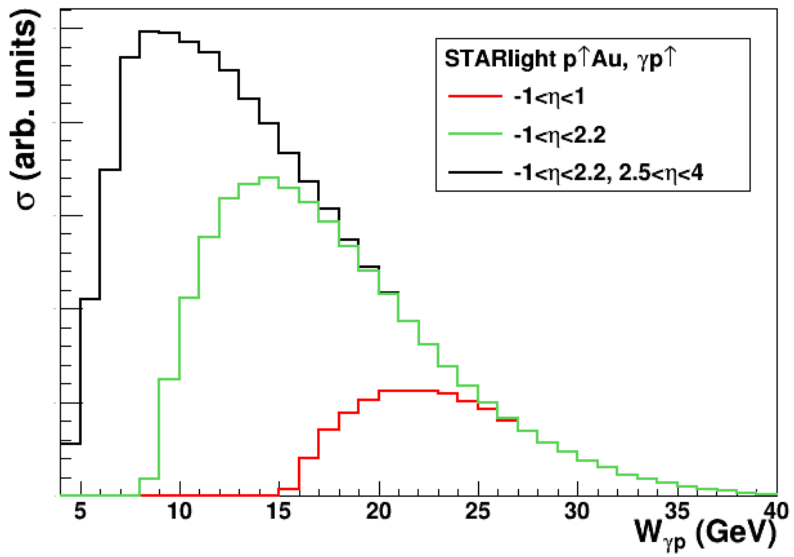


- Generalized Parton Distribution functions (GPDs) reveal the correlation of the partons' transverse spatial distribution and longitudinal momentum density;
- Transverse-Momentum-Dependent parton distribution functions (TMDs) encode information on how the momentum of quarks and gluons are correlated with the parent hadron properties;
- GPDs and TMDs are intimately connected to each other and are unified under the concept of Wigner distributions.

Generalized Parton Distribution Function

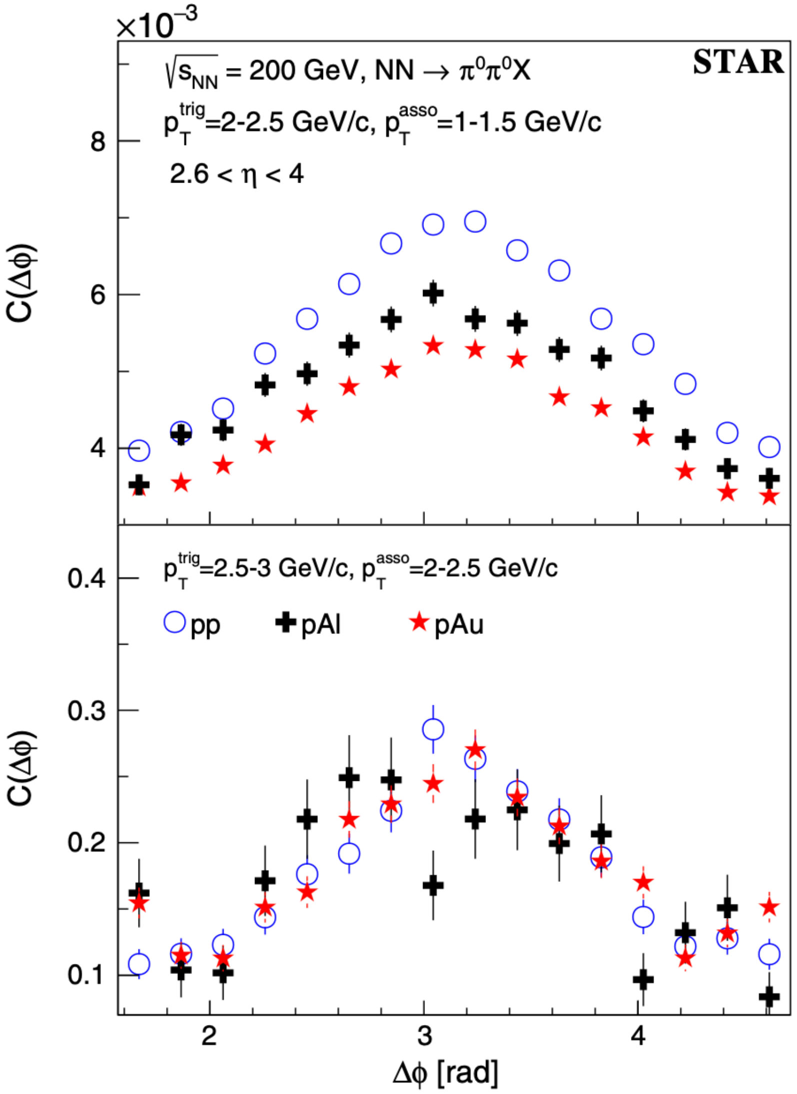




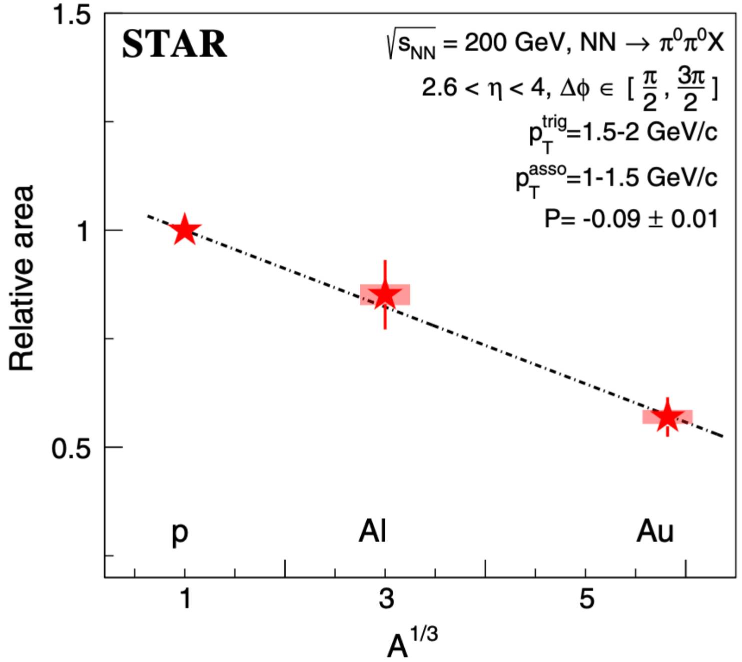


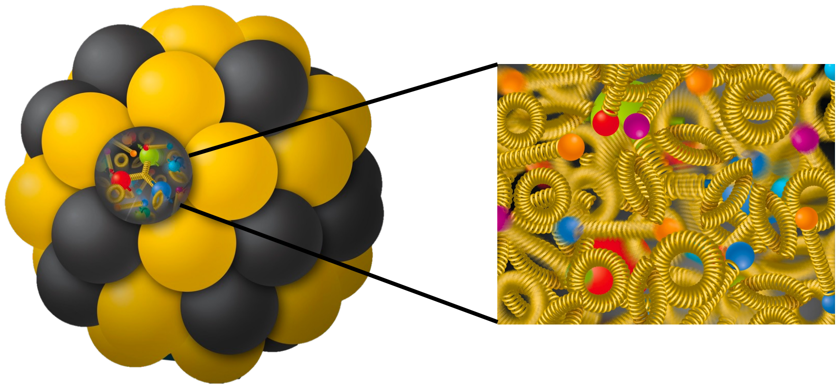
- Exclusive J/ψ TSSA measurement in Ultra Peripheral Collision (UPC);
- Access GPD E_g for gluons, sensitive to spin-orbit correlation;
- iTPC and forward detectors will enable high-impact measurements
  - A factor of 9-10 more data combined with iTPC and forward upgrades, expected statistical error 0.02 for $\langle W_{\gamma p}\rangle$ = 14 GeV.

Gluon Saturation



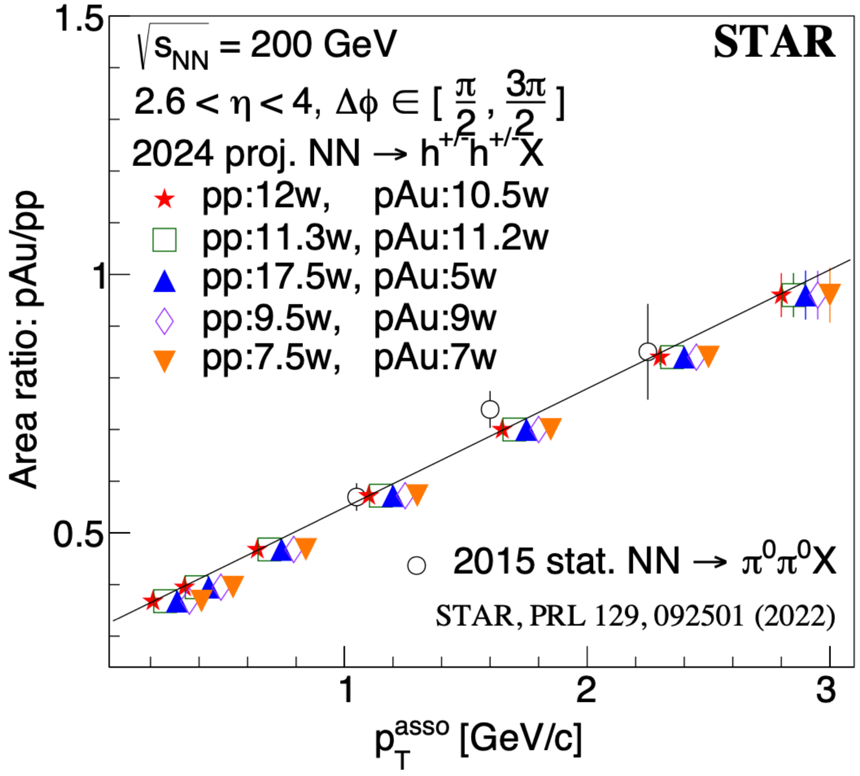
STAR, Phys. Rev. Lett.129, 092501(2022)

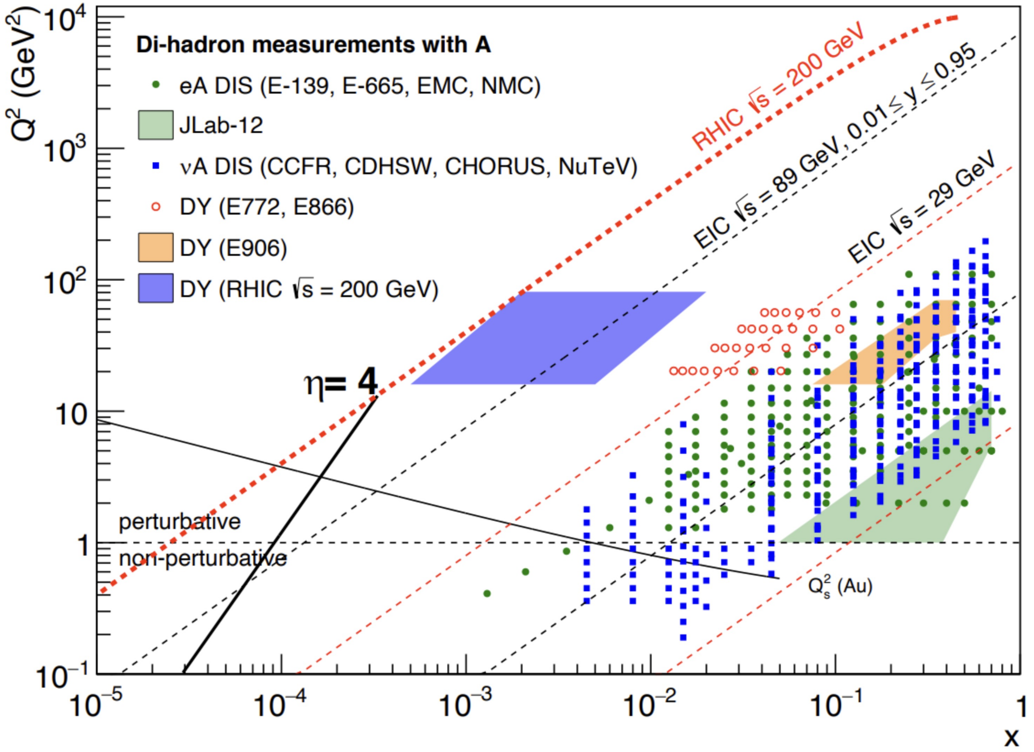




- Forward rapidity at STAR provide the unique opportunity to investigate very high gluon densities with an unambiguous probe through the disappearance of the backward jet in p + A
- STAR $\pi^0 - \pi^0$ correlations find strong suppression at low p_T where gluon saturation is expected;
  - The suppression follows the expected $A^{1/3}$ dependence
  - No suppression at high p_T (larger x) outside the non linear domain
- Such measurements are essential to explore the fundamental universality of non linear effects at EIC;

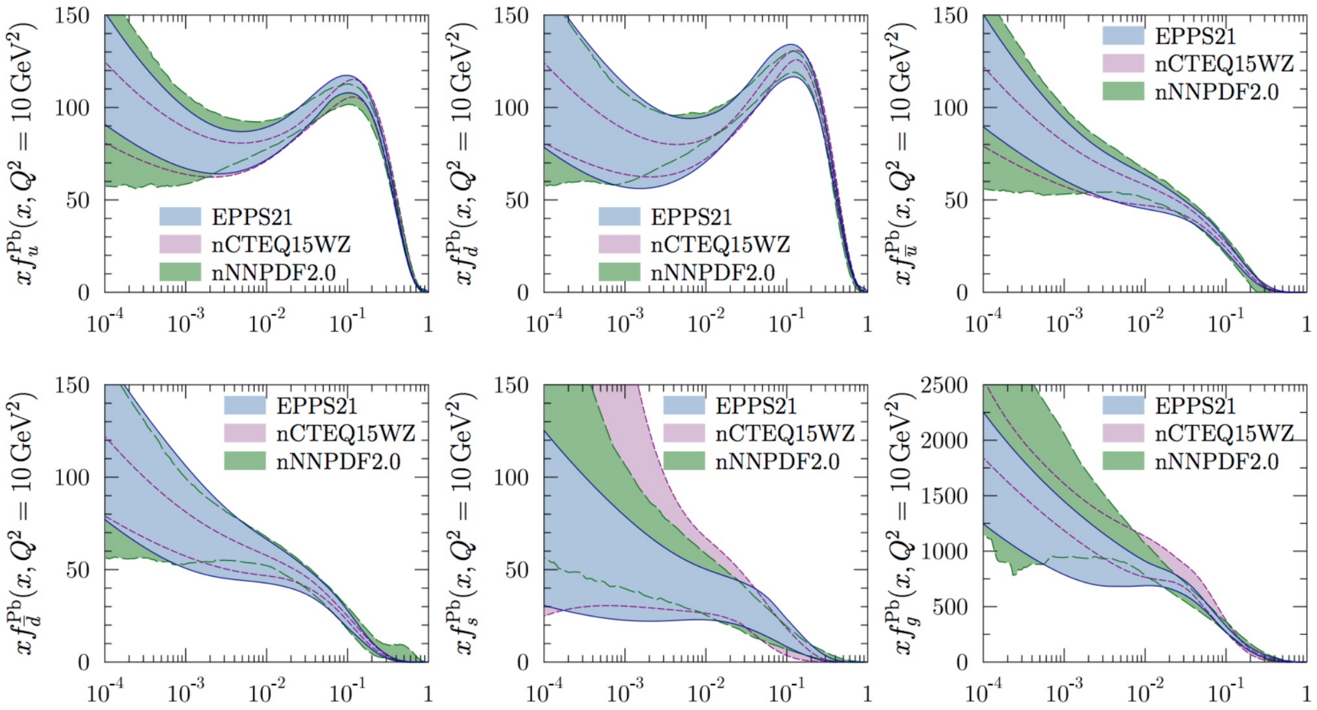
Non-linear QCD with the Forward Upgrade

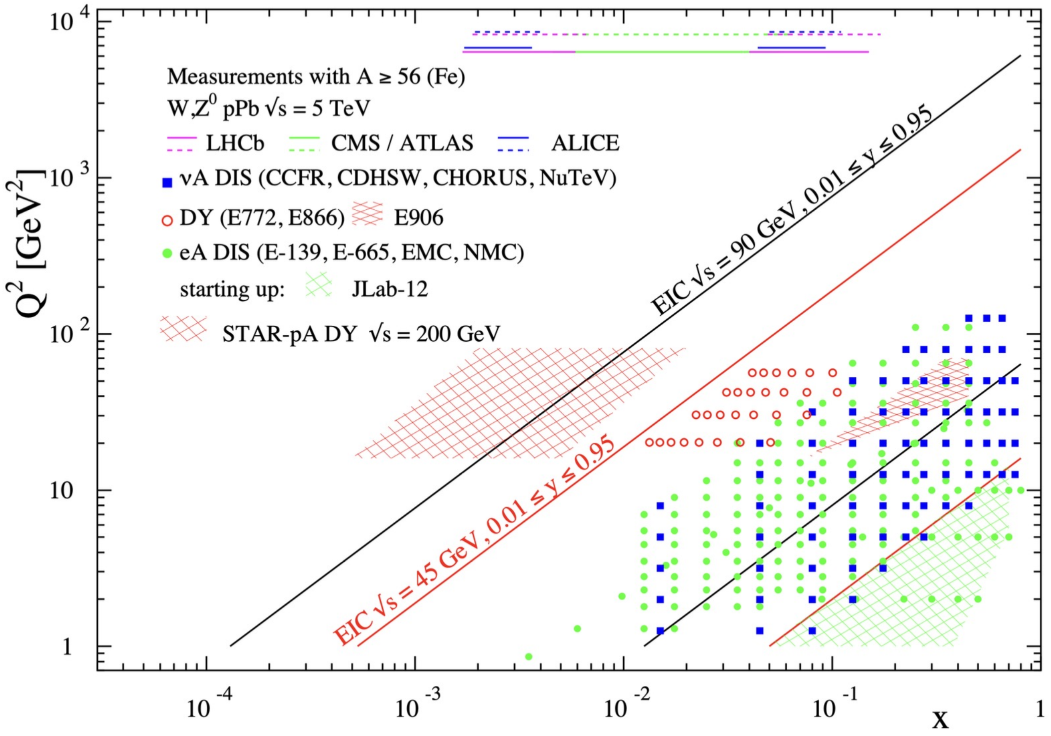




- STAR Forward Upgrades enable characterization of non-linear gluon effects through charged di-hadrons, γ-jet, di-jets;
- Charged di-hadrons can extend measurements to both lower and higher (x, Q^2) to map out the Q_s^2 boundary;
- γ-jet and di-jets are important complements: sample different mixes of WW and dipole gluon distributions.

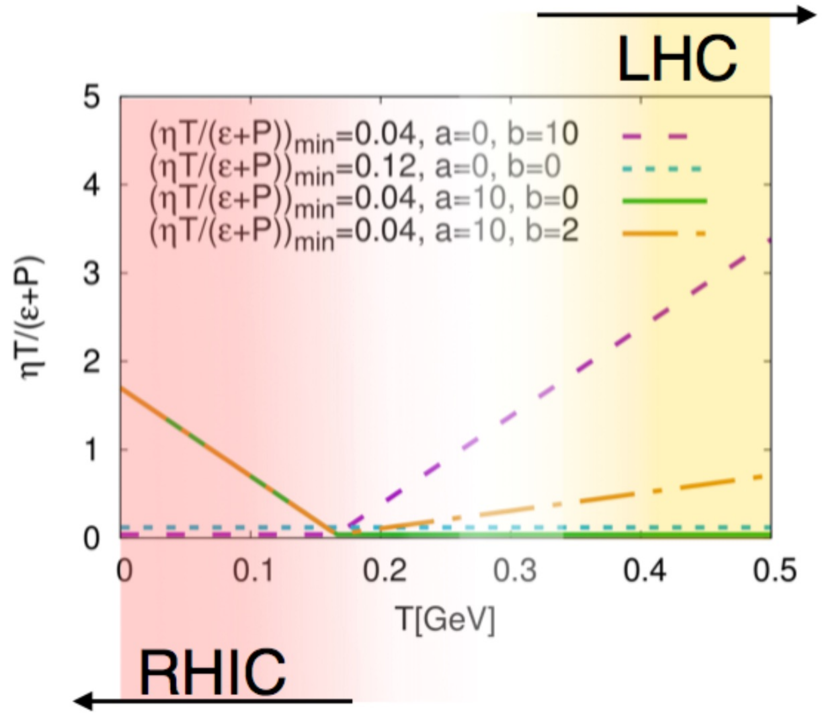
Nuclear Parton Distribution Functions

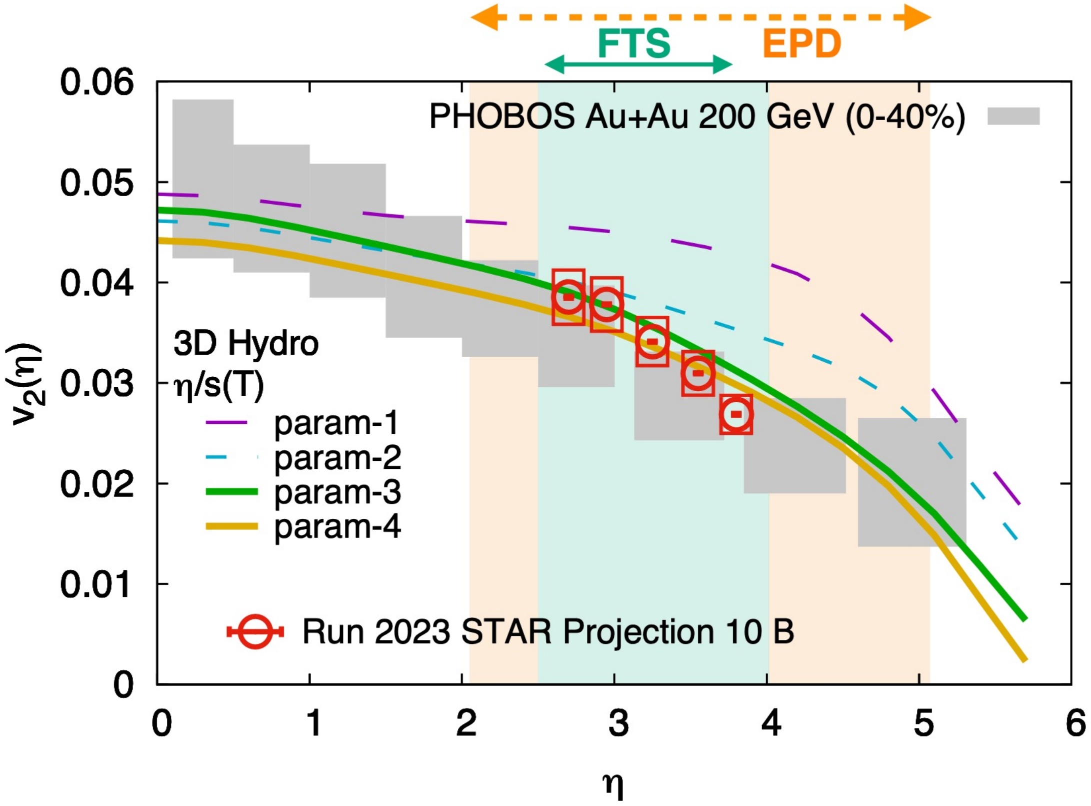




- The Forward Upgrade will enable measurements of $\mathrm{R_{pAu}}$ for direct photon and Drell-Yan production at $\sqrt{s_{NN}}$ = 200 GeV
  - Direct photons will constrain the nuclear gluon distribution over 0.0025 < x < 0.025;
  - Drell-Yan di-electrons will constrain the nuclear sea quark distribution over 0.001 < x < 0.01.

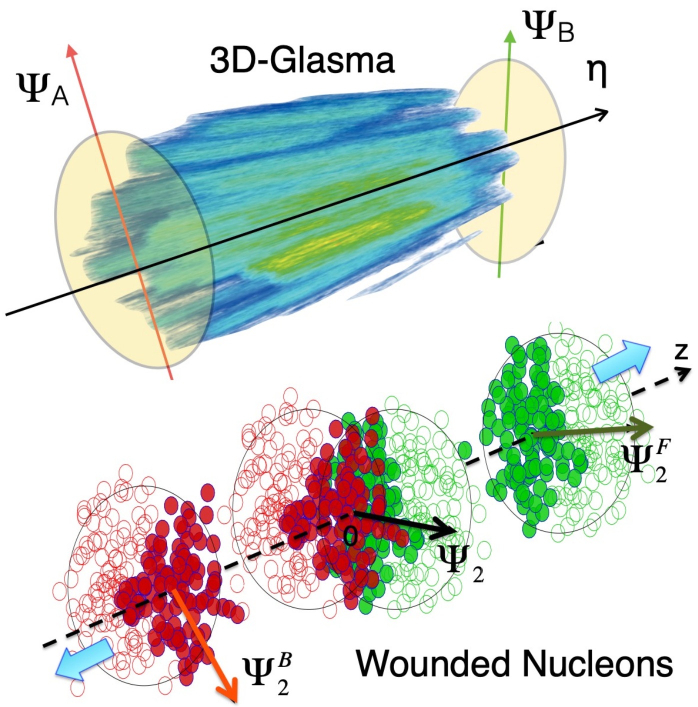
Flow Measurements to constrain η/s

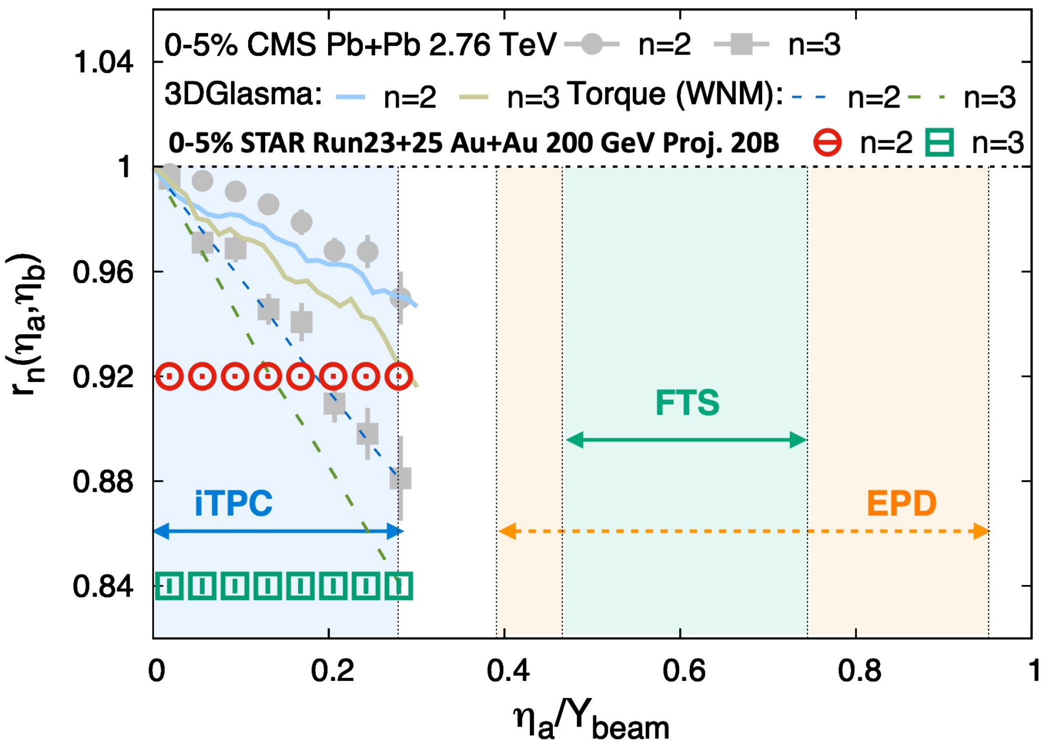




- η/s is expected to be smallest in the RHIC energy regime;
- Flow measurements at forward rapidity are sensitive to the temperature dependence of η/s;
- STAR Forward Upgrade measurements will be far more precise than previous PHOBOS measurements.

Constrain Longitudinal Structure of Initial State



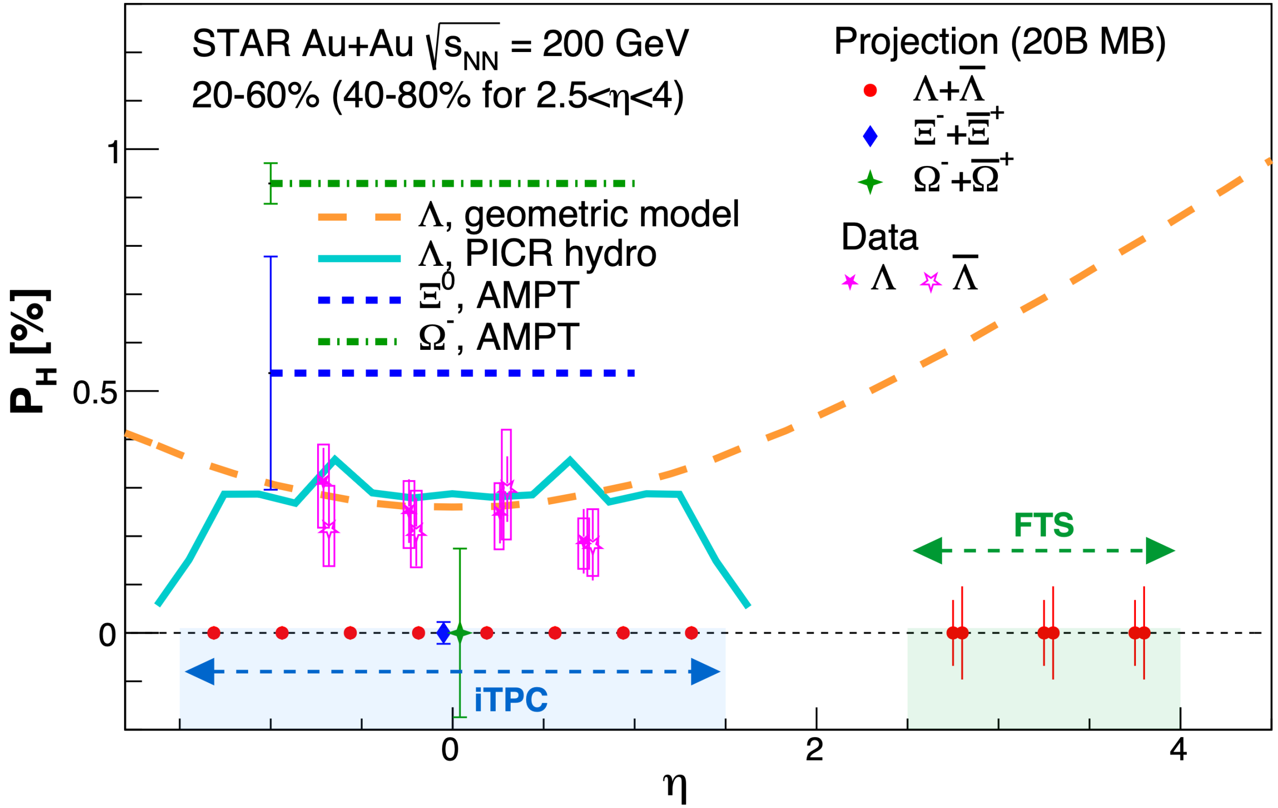


$$r_n(\eta_a,\eta_b) = V_{n\Delta}(-\eta_a,\eta_b)/V_{n\Delta}(\eta_a,\eta_b)$$

$V_{n\Delta}(\eta_a,\eta_b)$ is the Fourier coefficient calculated with pairs of particles in different η regions;

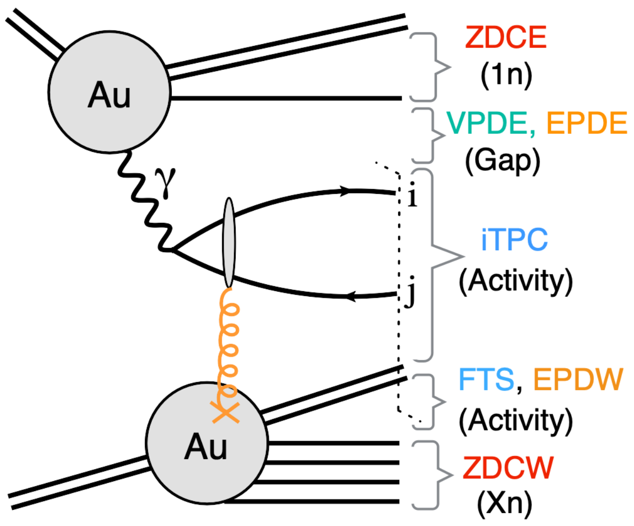
- $r_n(\eta_a,\eta_b)$ sensitive to different initial state inputs:
  - 3D-Glasma model: weaker decorrelation, describes CMS r_2 but not r_3
  - Wounded nucleon model: stronger decorrelation than data
- Precise measurement of r_n over a wide rapidity window will provide a stringent constraint.

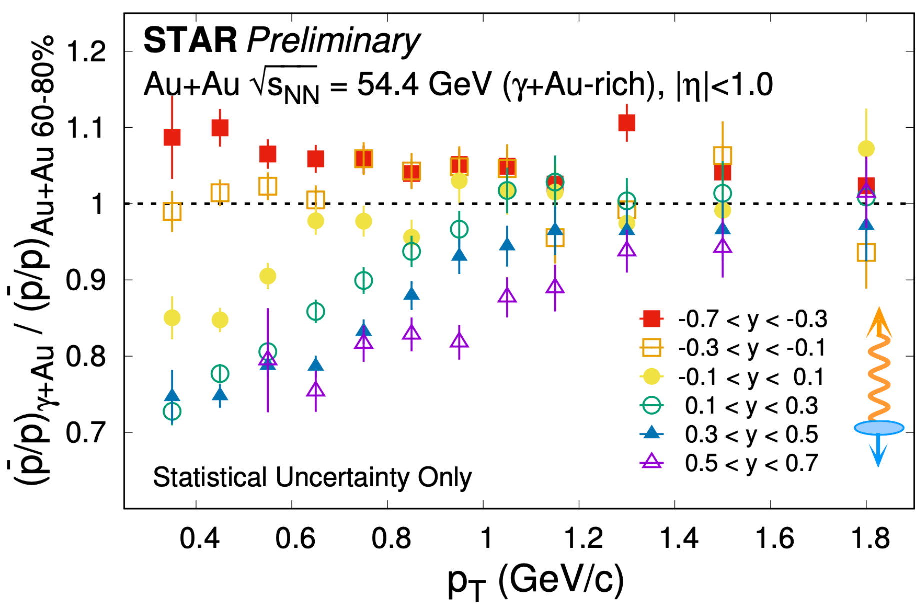
Global Vorticity Transfer

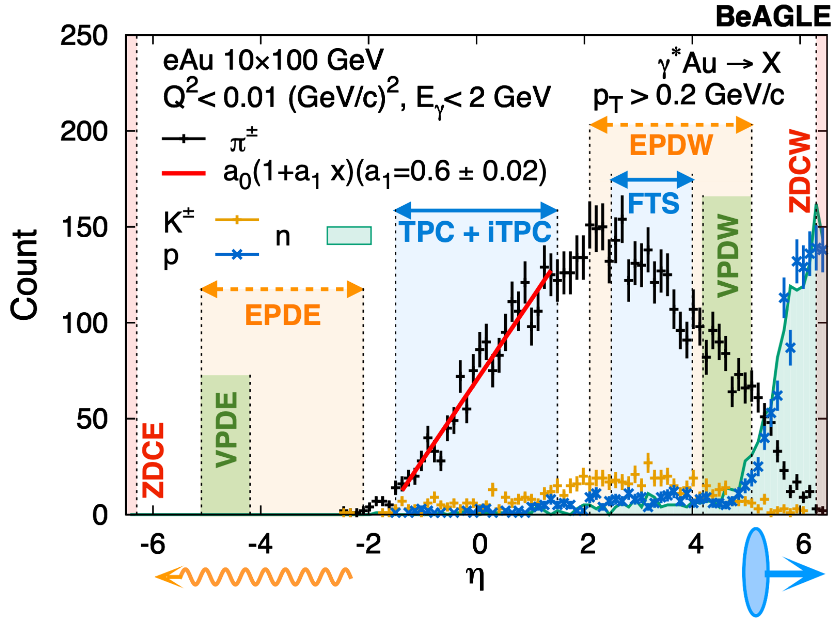


- How exactly is the global vorticity dynamically transferred to the fluid?
- How does the local thermal vorticity of the fluid transferred to the spin angular momentum?
- Rapidity dependence of Λ global polarization will probe the nature of the global vorticity transfer
  - Initial geometry and local thermal vorticity + hydro predict opposite trends.

Collectivity in Photo-Nuclear Processes







- The double ratio of antiprotons to protons in γ+Au-rich events compared to peripheral Au+Au indicating significant enhancement of protons at low p_T at mid-rapidity;
- This will be extend with high statistics γ+Au-rich event samples; the combination of the iTPC, EPD, FTS and ZDC can be used to isolate γ+Au events from peripheral Au+Au events (symmetric in η with no gaps).

Summary

- The Forward Upgrades has been running very successfully since 2022;
- The STAR Forward Upgrade enables a wide range of high impact measurements in polarized pp, p+Au and Au+Au collisions;
- Essential to fully realize the scientific promise of Electron Ion Collider;
  - Overlap kinematic coverage with EIC;
  - Establish the validity and limits of factorization and universality;
- Stay tuned!