# STAR Foward Systems and Related Topics

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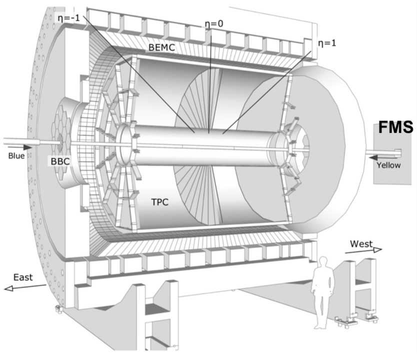
# STAR Forward Detectors

The STAR forward detectors during 2011 to 2017 (before STAR Forward Upgrade):

- Forward Meson Spectrometer (FMS): $2.6 < \eta < 4.2$, $\phi \in (0, 2\pi)$; Detect $\gamma$, $\pi^0$, $\eta$
- Roman Pot detector (RP): Not shown in the picture; Located about 15 m away from Interaction Point on both sides; Detect slightly scattered protons



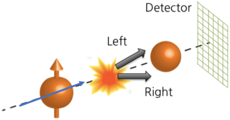

RP (not shown)

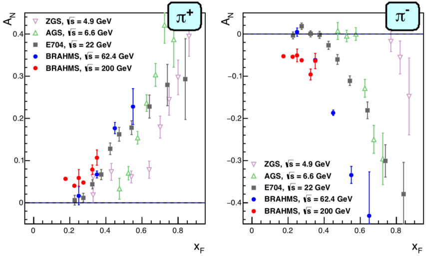
- Trigger detectors: Beam-Beam Counter (BBC); Zero Degree Calorimeter (ZDC); Vertex Position Detector (VPD)

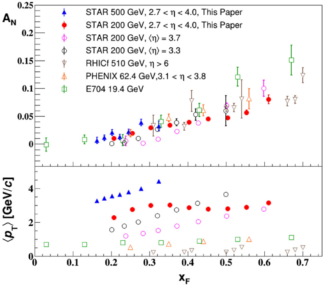
# Transverse Single-Spin Asymmetry (TSSA, $A_N$)

Highlight of STAR Forward Physics with Transversely Polarized Beam: TSSA

- $A_N$: $\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$
- pQCD predicts $A_N$ is small: $A_N \sim \frac{m_q \alpha_s}{p_T} \sim 0$
- Large $A_N$ at forward region is observed in proton-proton collisions
- Theories: TMD framework (Sivers effect, Collins effect), Twist-3 framework
- Indication from experiment: diffraction?



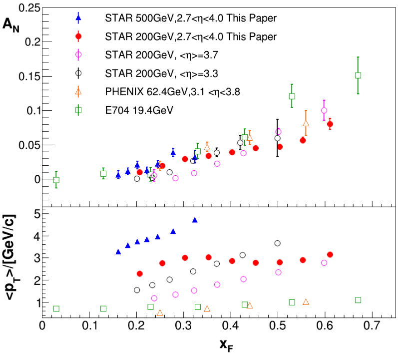




References:

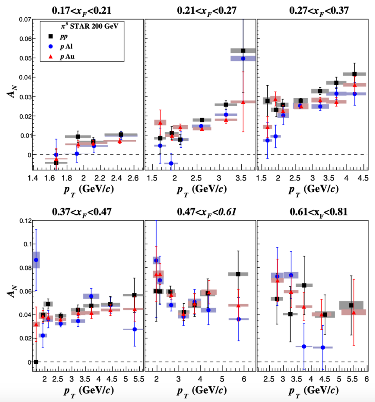
- E.C. Aschenauer *et al.*, arXiv:1602.03922
- (STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)

# Inclusive $\pi^0$ $A_N$

(STAR) J. Adam *et al.*,Phys. Rev. D 103, 092009 (2021)




(STAR) J. Adam *et al.*,Phys. Rev. D 103, 072005 (2021)

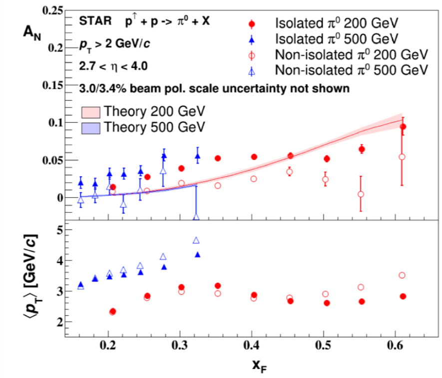



- $\pi^0$ $A_N$ depends on $x_F$ for 200 GeV and 500 GeV results, consistent with previous STAR results
- $\pi^0$ $A_N$ shows independence on $\sqrt{s}$

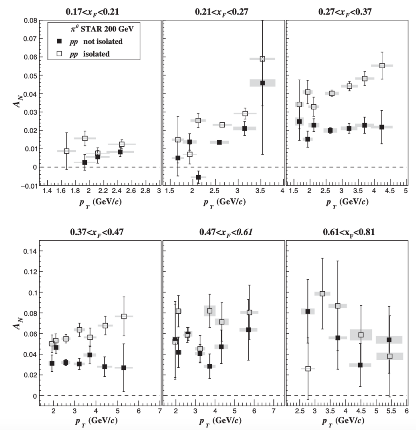
- $\pi^0$ $A_N$ for $p+p$, $p+Al$, and $p+Au$ increases with increasing $p_T$ at $0.17 < x_F < 0.47$, but flattens or falls with $p_T$ for larger $x_F$

# Isolated and Non-isolated $\pi^0$ $A_N$

(STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)



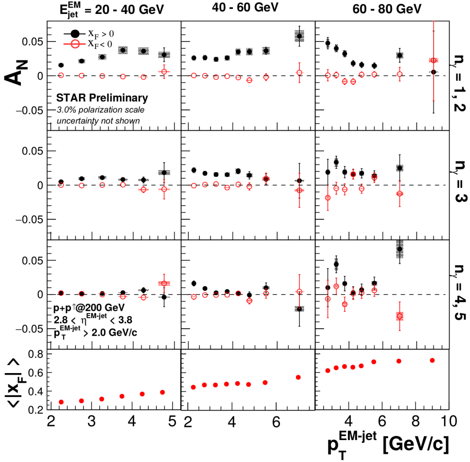

(STAR) J. Adam *et al.*, Phys. Rev. D 103, 072005 (2021)

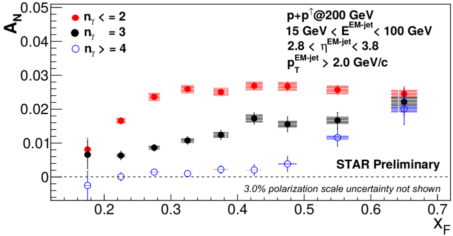



- $A_N$ for isolated $\pi^0$ is significantly larger than that for non-isolated $\pi^0$ regardless of $x_F$ and $p_T$
  - Isolated $\pi^0$: No other nearby photons
- Indication for large $A_N$ from diffraction?

# Multi-dimensional Studies for Inclusive EM-jet at 200 GeV

The Electromagnetic jets (EM-jets) are the jets reconstructed using only photons

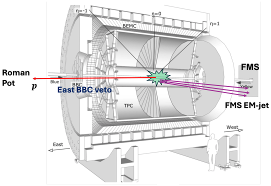


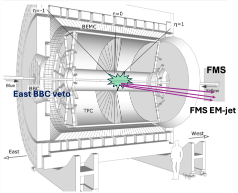

- The EM-jet $A_N$ decreases with increasing photon multiplicity for $x_F > 0$
  - $A_N$ is larger for the EM-jets consisting of 1 or 2 photons
- $A_N$ increases with $x_F$ for all the cases of photon multiplicity
- Is it an indication that large $A_N$ could come from diffractive processes?

# Diffractive Processes and Semi-exclusive Process

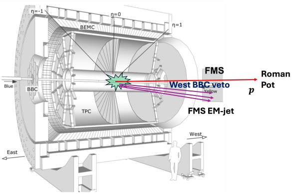
- **Single diffractive process**: $p + p \to p +$ EM-jet $+$ X
  - One proton track detected by east side RP
  - Determine Rapidity Gap: East side BBC veto ($-5 < \eta < -2.1$)
- These east RP tagged events are small fraction of real single diffractive events due to limited RP acceptance



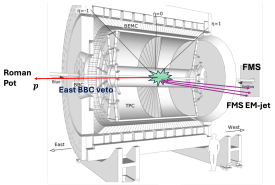

- The **Rapidity Gap event (RG)** requires: EM-jet at FMS and East side BBC veto
- No RP requirement for RG events
- At least 50% RG events are single diffractive events

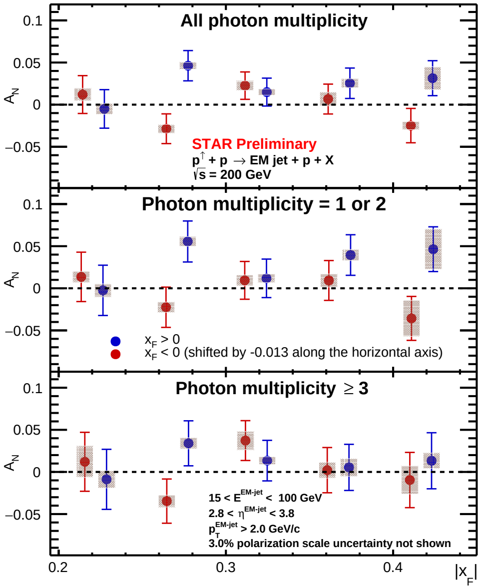



- **Semi-exclusive process** requires:
  1. FMS EM-jet
  2. One proton track detected by west side RP
  3. Zero or one proton track on east RP
  4. Veto on West BBC
- The rapidity gap is not large enough, so we do not classify this process as diffractive process



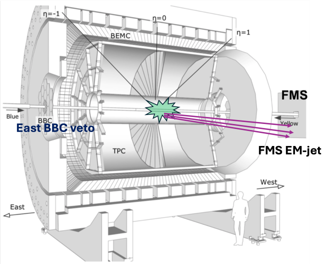
# Single Diffractive EM-jet $A_N$ at 200 GeV

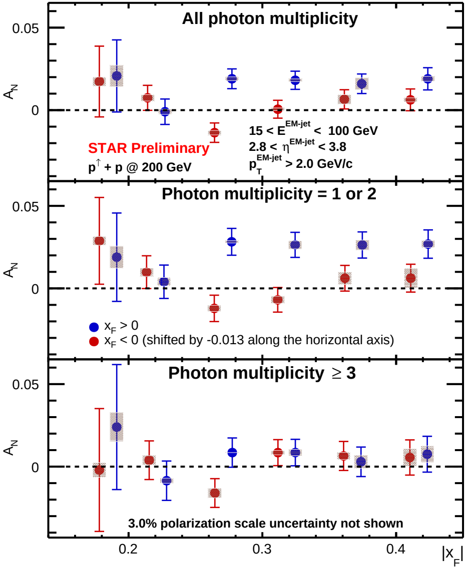



- The EM-jet $A_N$ for $x_F > 0$ ($> 2\ \sigma$ significance of non-zero) is observed for the case of all photon multiplicity and 1 or 2 photon multiplicity
- The EM-jet with 1 or 2 photon multiplicity has larger $A_N$ than with 3 or more photon multiplicity

# Rapidity Gap Event EM-jet $A_N$ at 200 GeV

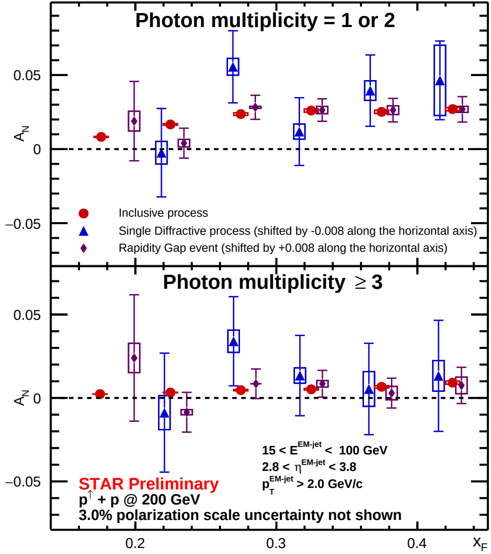


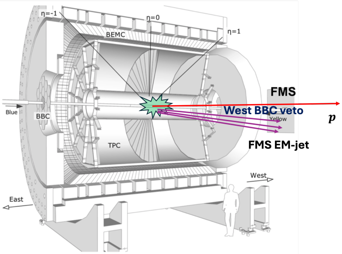

- The size of EM-jet $A_N$ for rapidity gap events is similar to that for inclusive process
- The $A_N$ for the EM-jet with 1 or 2 photon multiplicity is the largest

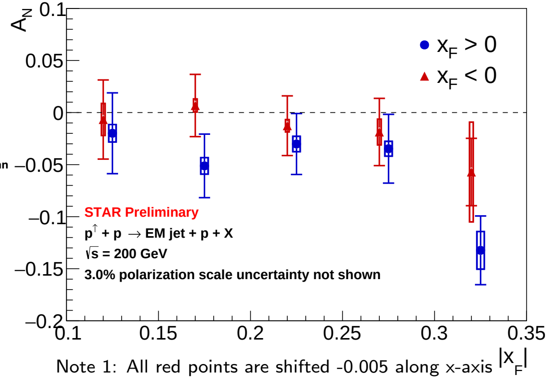
# Will Single Diffractive Process Contribute to Large $A_N$ in Inclusive Process?

- $A_N$ for the three processes consistent with each other within uncertainty
- Fraction of diffractive cross section in the total inclusive cross section at the forward region is about 20%. A large $A_N$ for the diffractive process is expected if it is the dominant contributor to the large $A_N$ in the inclusive process.
- The single diffractive processes fail to provide evidence for its significant contribution to large $A_N$ in the inclusive processes



# Semi-exclusive Process EM-jet $A_N$ at 200 GeV



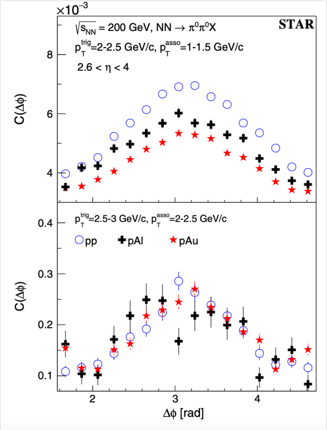




Note 1: All red points are shifted -0.005 along x-axis
Note 2: The rightmost point is for $0.3 < |x_F| < 0.45$

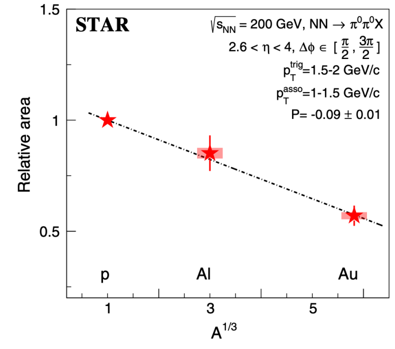
- A non-zero $A_N$ for $x_F > 0$ is observed with 3.3 $\sigma$ significance for semi-exclusive process
- Sign of $A_N$ is negative. Theoretical inputs are needed to understand the different sign

# Unpolarized Physics: Nonlinear Gluon Effects in QCD

(STAR) M.S. Abdallah *et al.*, Phys. Rev. Lett. 129, 092501




- First measurement of the A dependence of nonlinear gluon effects




- At low $p_T$ regime, a clear suppression is observed in p + A compared to the p + p data
- Such suppression scaling with $A^{1/3}$ matches gluon saturation models
- At high $p_T$ regime, the suppression is weaker

# STAR Forward Upgrade

**Coverage:** $2.5 < \eta < 4.0$

- Located on STAR west side
- Rapidity coverage is the same as the EIC hadron arm

**Requirement:**

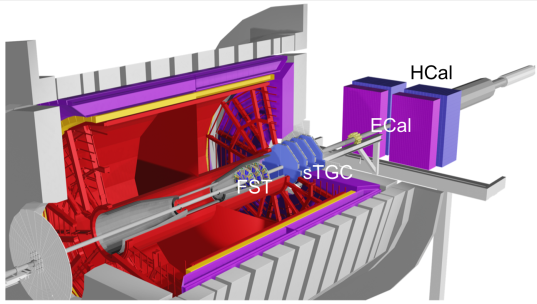
| Detector | pp and pA | AA |
|---|---|---|
| ECal | $\sim$10 % / $\sqrt{E}$ | $\sim$20 % / $\sqrt{E}$ |
| HCal | $\sim$50 % / $\sqrt{E}$ + 10% | - |
| Tracking | Charge separation<br>photon suppression | $\delta p_T/p_T$ $\sim$20 - 30%<br>for $0.2 < p_T < 2$ GeV/c |

**Combines:**

1. Forward Tracking System (FTS)
   - Forward Silicon Tracker (FST)
   - small-strip Thin Gap Chambers (sTGC)
2. Forward Colorimeter System (FCS)
   - Electromagnetic Calorimeter (ECal)
   - Hadronic Calorimeter (HCal)

**Measures:**

- $h^{+/-}$, $e^{+/-}$ (with good e/h separation)
- Photon, $\pi^0$, jets



# Status of the STAR Forward Upgrade

## STAR Forward Upgrade data taking works well:

Completed:

- Run-22: $p + p$ $\sqrt{s} = 508$ GeV
- Run-23: $Au + Au$ $\sqrt{s} = 200$ GeV

Plans:

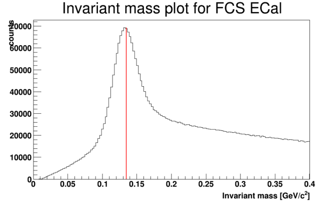
- Run-24: $p + p$ $\sqrt{s} = 200$ GeV & $Au + Au$ $\sqrt{s} = 200$ GeV
- Run-25: $Au + Au$ $\sqrt{s} = 200$ GeV & possible $p + Au$ $\sqrt{s} = 200$ GeV

## Data production, calibration, and analysis are in progress:

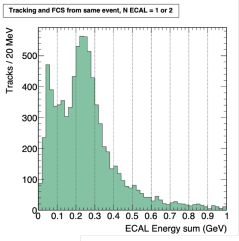
- (Pre-)productions for run 22 are ready for Forward Upgrade software developments, calibrations, and analyses
- $\pi^0$ reconstruction for FCS ECal calibration is developed
- MIP study is ongoing
- Jet reconstruction & energy calibration are in progress
- $J/\psi$ analysis is in progress
- Track matching studies between Forward Tracking and Calorimeters, as well as within calorimeters, are in progress

# Status of the STAR Forward Upgrade

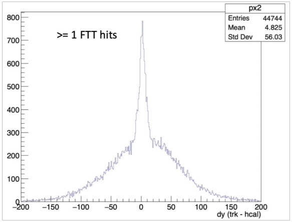
$\pi^0$ reconstruction for FCS ECal




ECal MIP at around 0.3 GeV




Y(track project to HCal) - Y(HCal cluster)

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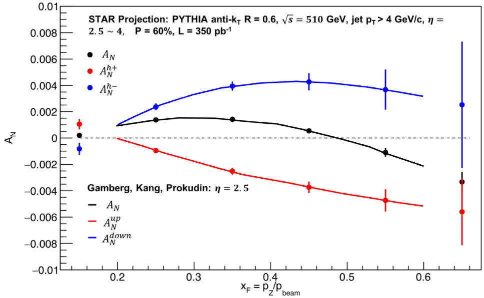
# TSSA with STAR Forward Upgrade

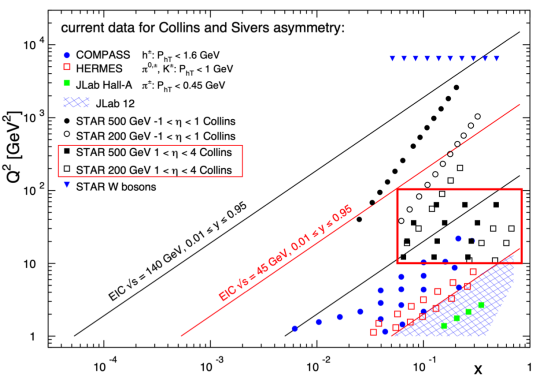



**What can be measured with STAR Forward Upgrade for $A_N$?**

- (isolated)$\pi^0$, EM-jets
- (isolated)$h^{+/-}$
- Full jets
- Diffractive process

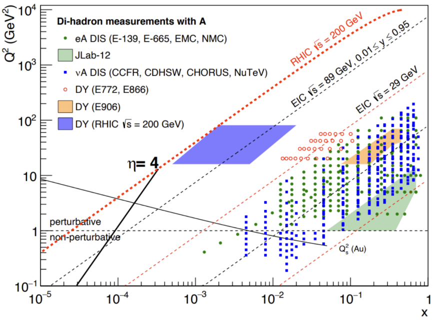
- $A_N$ for full jet reconstruction, combined with charge-sign tagging of a hadron fragment with $z > 0.5$
- Projected statistical uncertainties drawn on twist-3 predictions
- Access to higher $x_F$ with $p + p$ at $\sqrt{s} = 200$ GeV (Run-24); and access to higher $p_T$ with $p + p$ at $\sqrt{s} = 508$ GeV (Run-22)

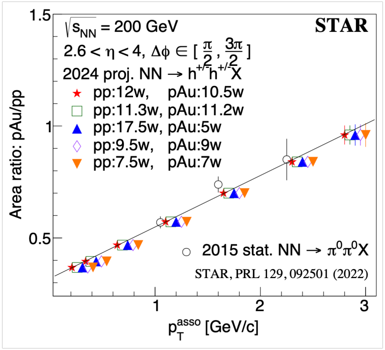
# Collins Asymmetry with STAR Forward Upgrade




- STAR has performed Collins asymmetry measurement at mid-rapidity
- Similar x range as existing SIDIS measurements
- $Q^2$ values are one to two orders of magnitude higher than SIDIS at the same x
- STAR forward upgrade will provide unique kinematics coverage for Collins asymmetry measurement
- x up to $\sim 0.5 \to$ sensitive to valence quark
- Spans in $Q^2$ by a factor of 6

# Non-linear QCD with the STAR Forward Upgrade




- Previous STAR measurements used di-$\pi^0$ ; STAR Forward Upgrade will enable studies with di-$h^{+/-}$ with $p + Au$ collisions (possibly in Run-25)
- The di-$h^{+/-}$ measurement can extend both lower and higher (x, $Q^2$) to map out the $Q^2$ boundary
- STAR hadro-production measurements are essential to explore the universality of non-linear effects along with the future EIC

# Conclusion and Outlook

Fruitful results in forward region at STAR with FMS:

- Large $A_N$ observed in forward $\pi^0$ and EM-jets
- First diffractive $A_N$ is studied, but diffractive $A_N$ can not have significant contribution to large $A_N$
- STAR di-$\pi^0$ correlation study shows strong suppression at low $p_T$ in $p + A$, following expected $A^{1/3}$ dependence

STAR Forward Upgrade will enable a wide range of high-impact measurements, shining light to the future EIC:

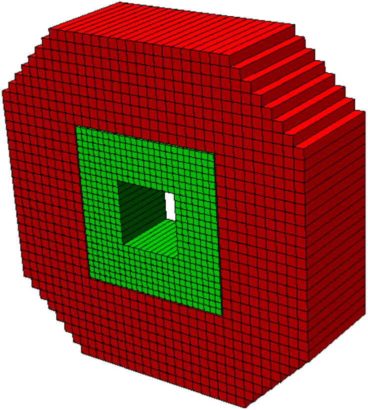
- The STAR Forward Upgrade was installed in 2021 and collected data successfully in Run-22 and Run-23
- The STAR Forward Upgrade will continue to collect data in Run-24 and Run-25
- With the forward tracking systems, it is allowed for studies with charged hadrons for lots of topics

# Back up

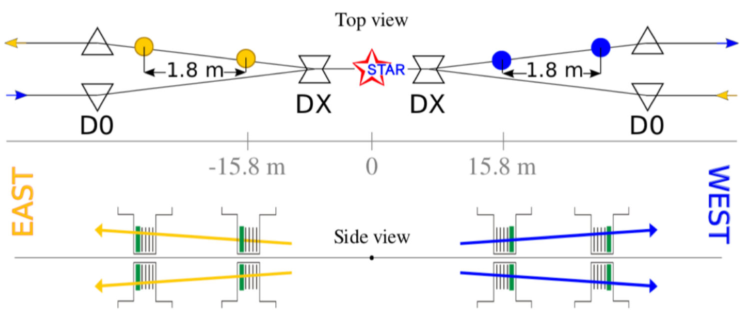
# Forward Meson Spectrometer (FMS)

- FMS can detect photons, neutral pions, and eta mesons in the forward direction
- $2.6 < \eta < 4.2$

- FMS consists of 1264 Lead-Glass cells with photomultiplier tubes (PMT) readout connected, separated into two regions
- Inner region (green) have smaller size cells than the outer region (red), which can provide better photon separation ability
- All cells have $\sim$18 radiation length



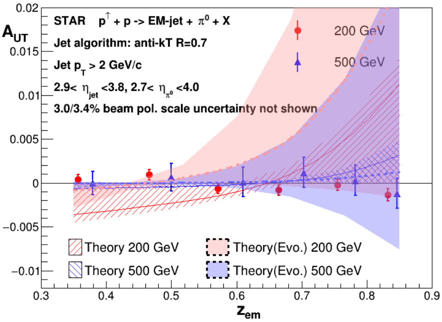
# Roman Pot (RP)

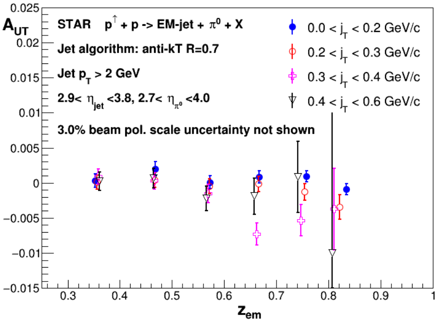



- Roman Pots (RP) are vessels which house the Silicon Strip Detector planes (SSDs). They are put close to the beam pipe
- RPs are able to detect and track slightly scattered protons close to beamline
- 2 sets of RP (inner and outer) on each side
- Each RP set contains a package above and below the beamline
- 4 SSDs per package (2 x-type and 2 y-type)

# Collins Asymmetry for $\pi^0$ in a jet at 200 GeV and 500 GeV

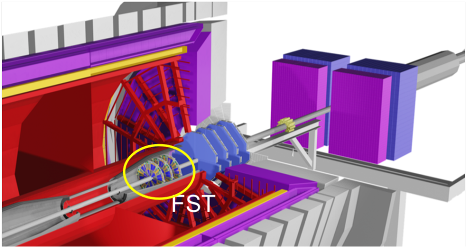
(STAR) J. Adam *et al.*, Phys. Rev. D 103, 092009 (2021)

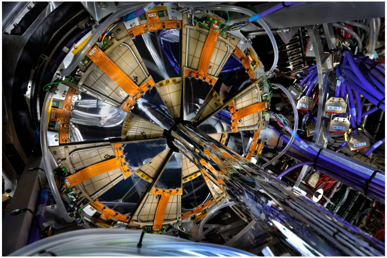


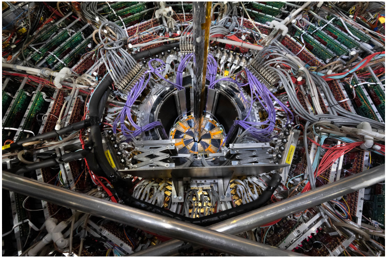




- The Collins asymmetries are very small at both energies
- The Collins asymmetries show weak $j_T$ dependency
  - $z_{em} = \frac{E_{\pi^0}}{E_{jet}}$
  - $j_T$ is the $E_{\pi^0}$ projection perpendicular to jet

# Forward Silicon Tracker (FST)

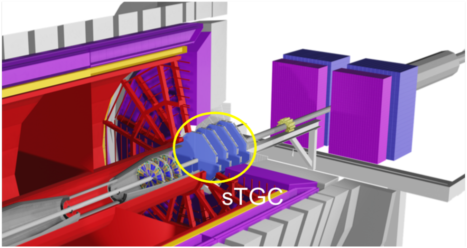


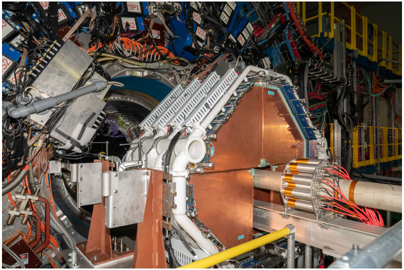





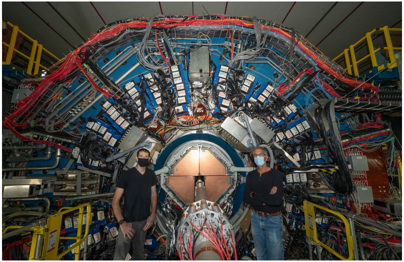
- 3 disks (at 152, 165, and 179 cm from the STAR IP), each with 12 modules
- Each module includes 3 single-sided double-metal mini-strip sensors (Si from Hamamatsu)
  - Fine granularity in $\phi$ and coarse in R
- Material budget $\sim 1.5\%\ X_0$ per disk
- Technology is similar to STAR Intermediate Silicon Tracker
  - Same APV25-S1 front-end chip
  - Reusing the IST data acquisition and cooling systems

# Small-strip Thin Gap Chambers (sTGC)

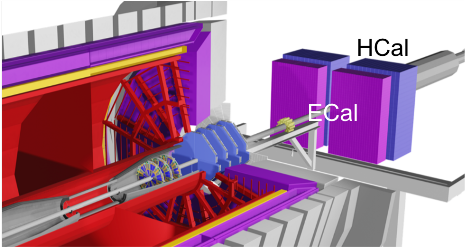


- 4 planes (at 307, 325, 343 and 361 cm from IP), each consisting of 4 pentagonal modules
  - Double-sided sTGC with diagonal strips give x, y, u in each layer
  - Position resolution $< 200\ \mu m$
- Material budget $\sim 0.5\%\ X_0$ per layer
- Readout based on VMM chips
  - Similar to the ATLAS sTGC system



# Forward Calorimeter System (FCS)




- FCS is located at $\sim$ 7 m from the STAR IP
- Split in 2 movable halves inside and outside of ring
- Slightly projective

**Preshower (not shown):**

- Split signals off from STAR EPD for triggering

**ECal:**

- Reuse PHENIX Pb-Scintillator calorimeter
  - 1496 channels: $5.52 \times 5.52 \times 33\ cm^3$
  - 66 sampling cells with 1.5 mm Pb / 4 mm Sc
  - 36 wavelength-shifting fibers per channel
  - 18 $X_0$; 0.85 nuclear interaction lengths
- Replaced PMTs with SiPM readout

**HCal:**

- Fe/Sc (20 mm/3 mm) sandwich
  - 520 channels: $10 \times 10 \times 84\ cm^3$
  - Approximately 4.5 nuclear interaction lengths
- Uses same SiPM readout as ECal
- Developed in collaboration with EIC R&D