Neutral meson transverse single spin asymmetries and prospects for the D^0 transverse single spin asymmetry in polarized proton collisions with sPHENIX

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on behalf of the sPHENIX collaboration

26th International Symposium on Spin Physics

A Century of Spin

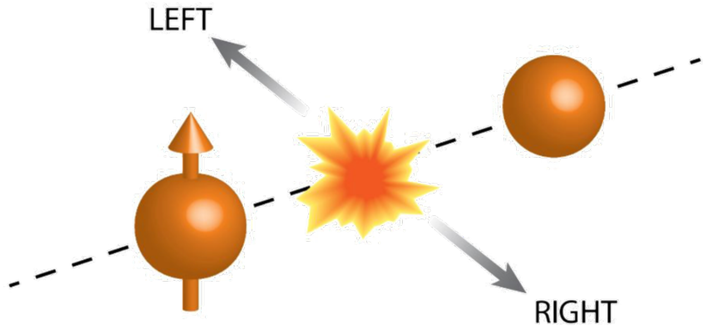
Transverse spin asymmetries in hadronic collisions

- Transversely polarizing one of the protons in a hadronic collision modifies the production of single inclusive particles by an **azimuthal modulation**, or equivalently a **left-right asymmetry**

$$d\sigma = (d\sigma)_0(1 + A_N P \cos\phi)$$

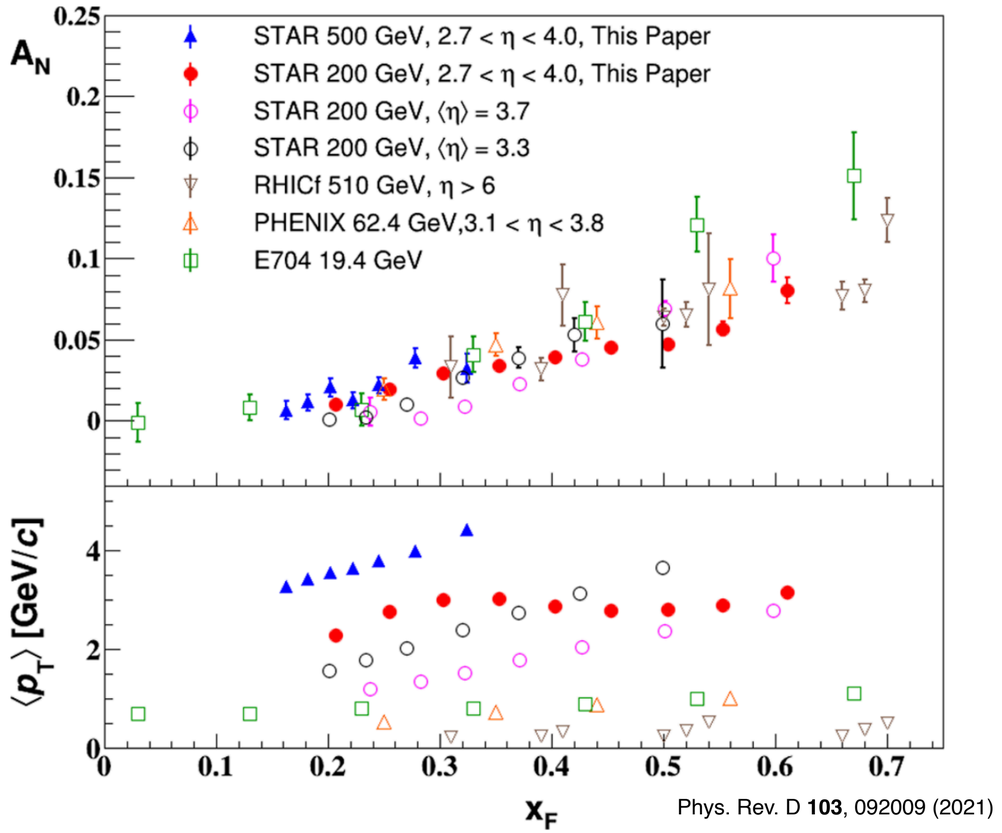
- Standard perturbative QCD predicts small A_N on the order of $\alpha_S m_q/\sqrt{s} \sim 10^{-4}$

A_N: transverse single spin asymmetry (TSSA)

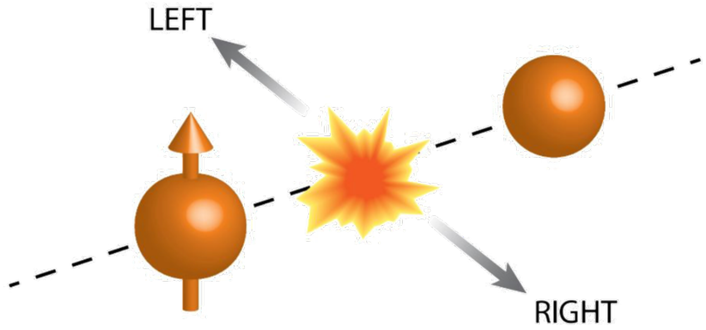


Transverse spin asymmetries in hadronic collisions

- Large asymmetries up to $\sim 10^{-1}$ have been observed!



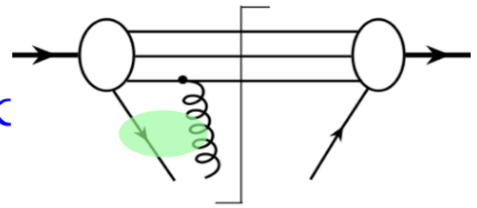
Phys. Rev. D **103**, 092009 (2021)



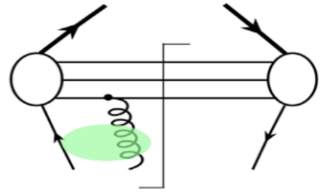
A factorization framework for TSSAs

- TMDs provide intuitive explanation for spin asymmetries **but** $p + p \to h + X$ is properly described within **collinear QCD factorization**
- TSSAs are attributed to multiparton correlations that appear in sub-leading terms of the (1/Q) "twist" expansion of the collinearly-factorized polarized cross section
- At twist-3, correlations described through nonperturbative **quark-gluon** and **trigluon correlators**

$$\Delta\sigma(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D(z) + \delta q(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z) + \ldots$$

$T^{(3)}(x,x) \propto$ 

Qiu, Sterman, 1991, ...

$D^{(3)}(z,z) \propto$ 

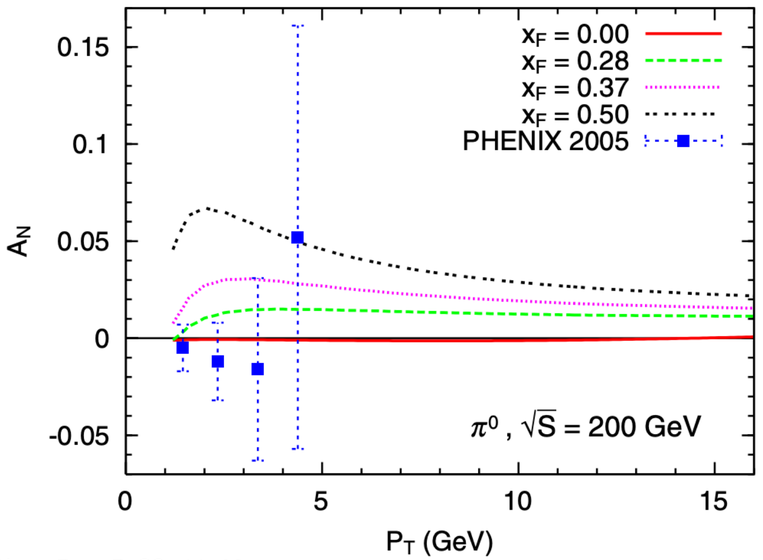
Kang, Yuan, Zhou, 2010

J. Qiu, NNPSS24

TSSAs at central vs. forward rapidity

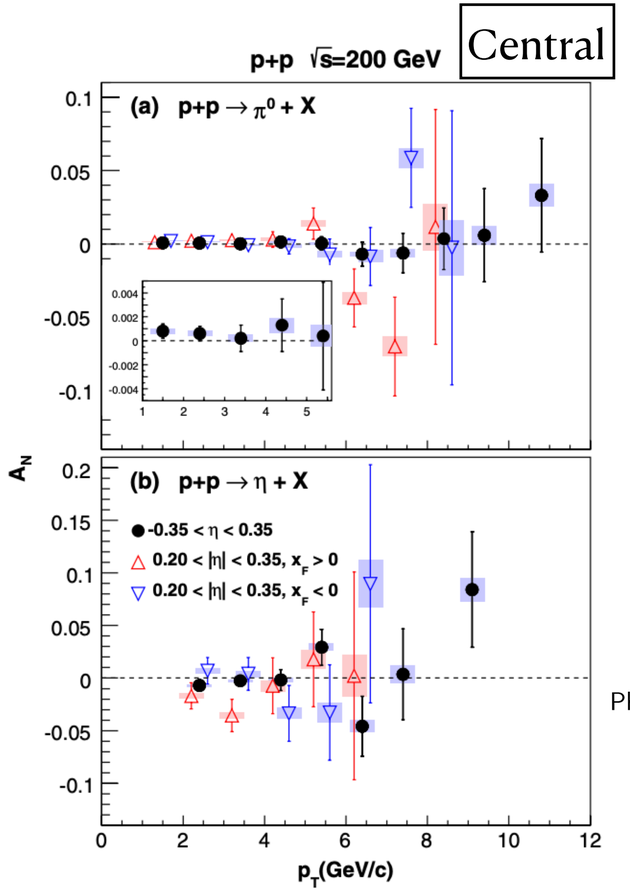
Unlike the large asymmetries seen in the forward region at high x_F, TSSAs of inclusive particles at central rapidities are predicted and observed to be quite small

Kanazawa and Koike



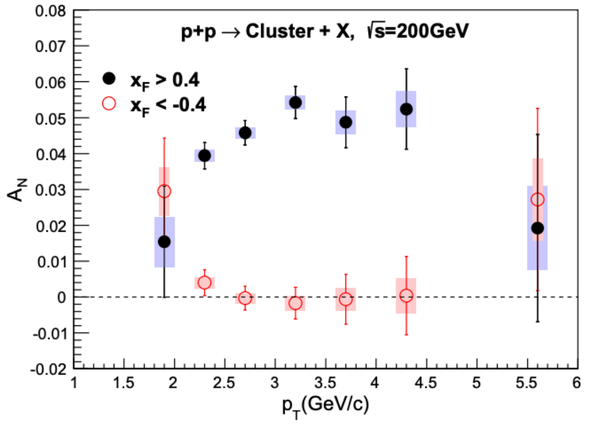
Phys. Rev. D **83**, 114024

Central



PHENIX

Forward



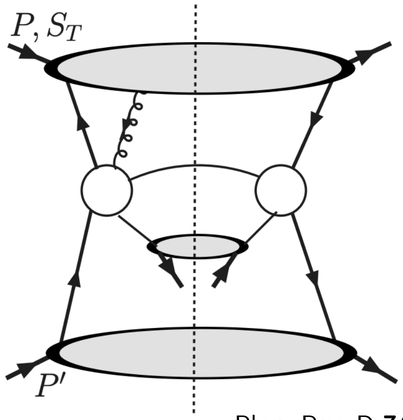
Phys. Rev. D **90**, 012006

The high precision neutral meson TSSA

Unlike the large asymmetries seen in the forward region at high x_F, TSSAs of inclusive particles at central rapidities are predicted and observed to be quite small

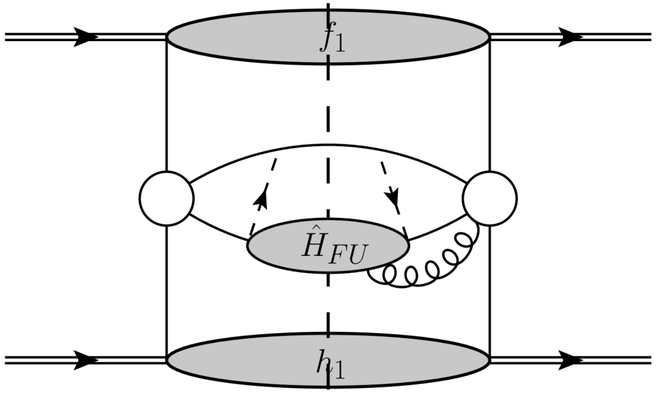
- One approach: beat down statistical uncertainties as much as possible with the abundantly produced and well-reconstructed **light neutral mesons**
- Many competing twist-3 contributions complicates the interpretation of an asymmetry

Initial state: quark-gluon, trigluon correlators



Phys. Rev. D **74**, 114013

Final state: quark-gluon correlators



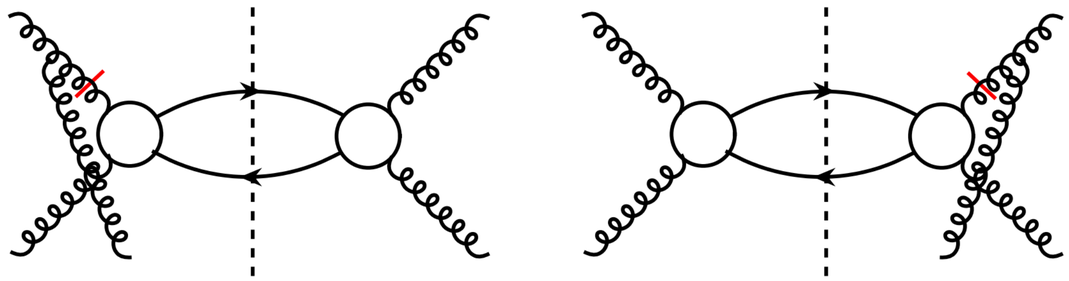
PLB 723 (2013) 365–370

The pioneering D^0 TSSA

Unlike the large asymmetries seen in the forward region at high x_F, TSSAs of inclusive particles at central rapidities are predicted and observed to be quite small

- Another approach is to choose a final state with a clean interpretation: **open heavy flavor**
  - Dominated by gg scattering → reduced contribution from quark-gluon correlator
  - No gluon transversity → no final state effects

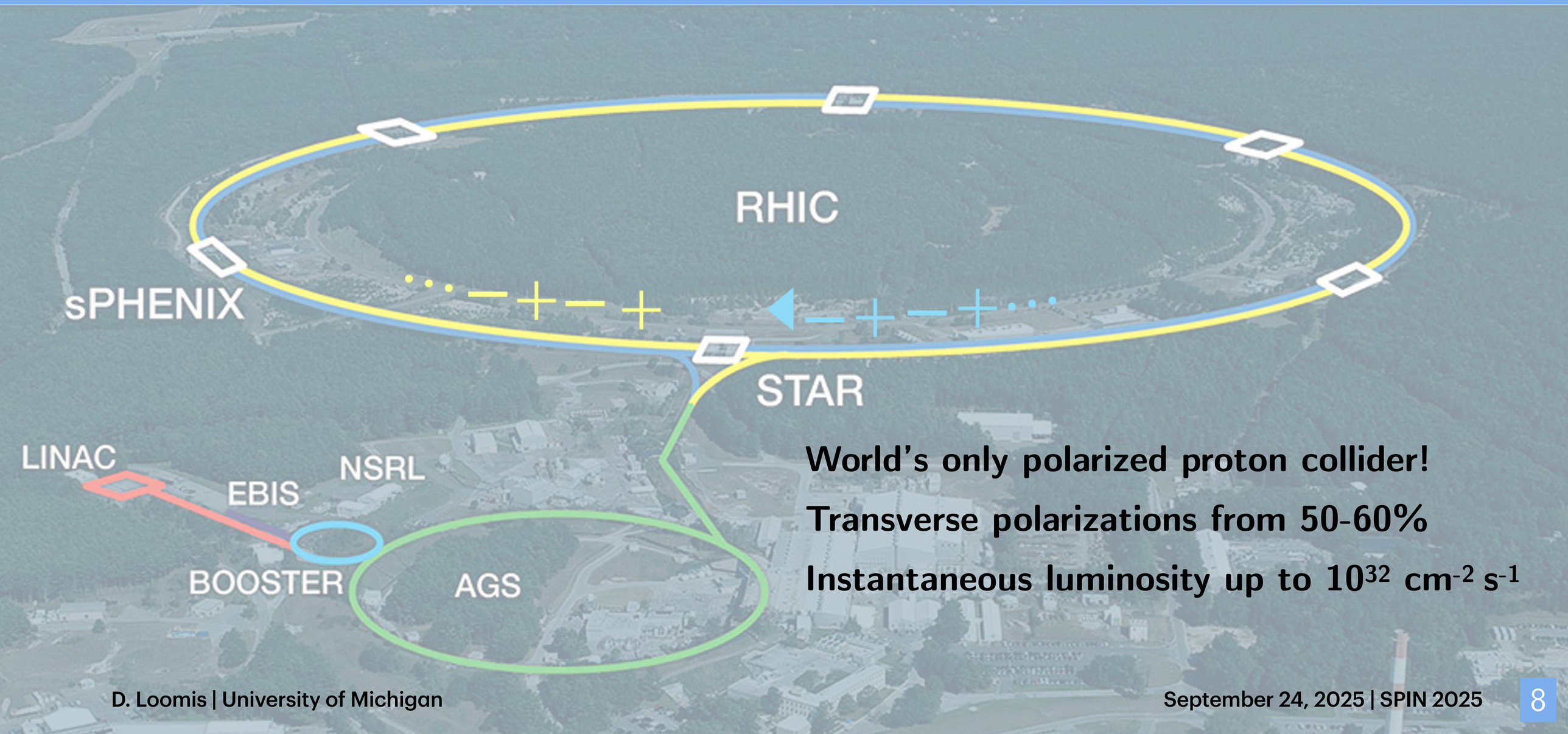
Initial-state trigluon correlator



Phys. Rev. D **78**, 114013

sPHENIX has the unique capability to measure the open heavy flavor TSSA on the actual D^0 resonance!

The Relativistic Heavy Ion Collider



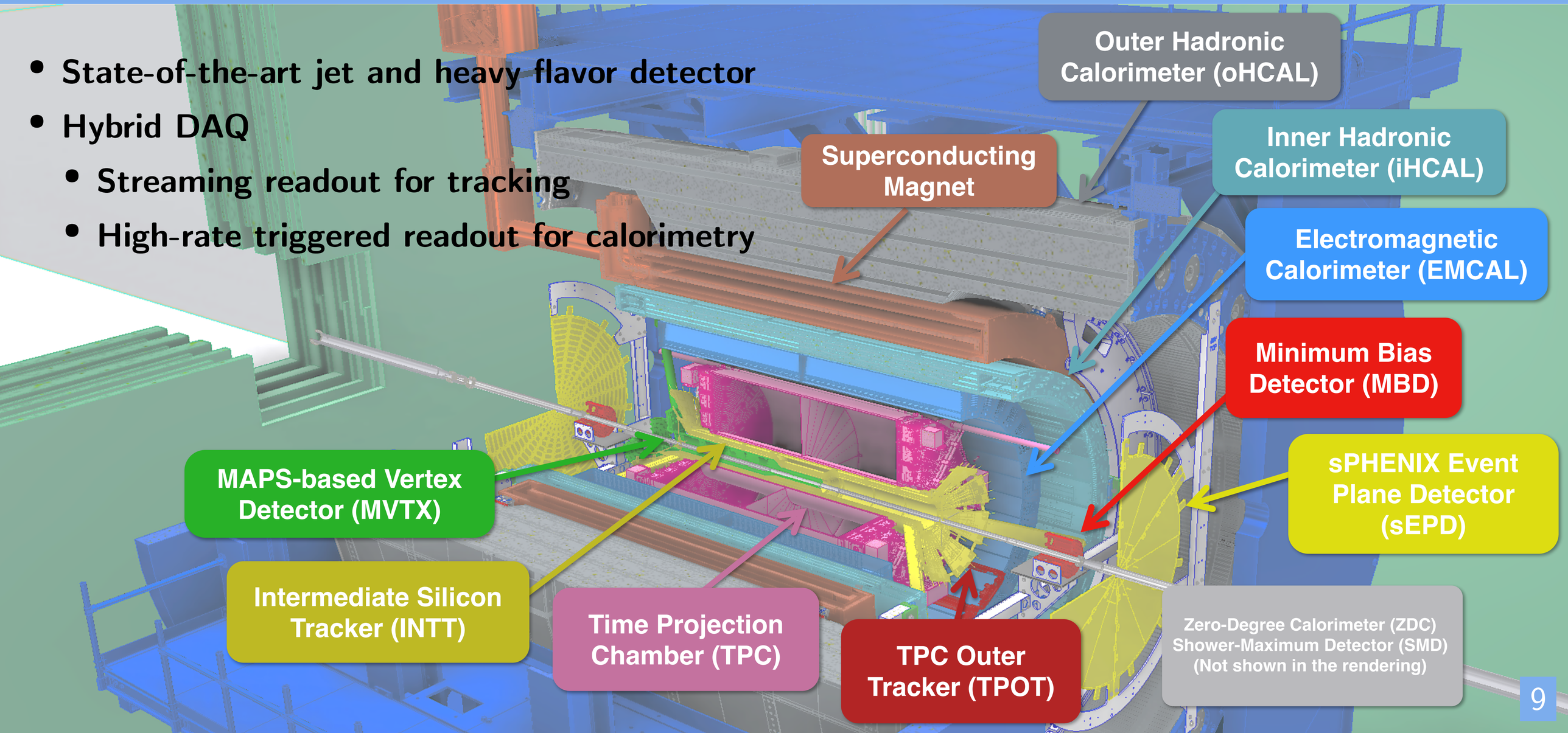
World's only polarized proton collider!

Transverse polarizations from 50-60%

Instantaneous luminosity up to 10^{32} cm^{-2} s^{-1}

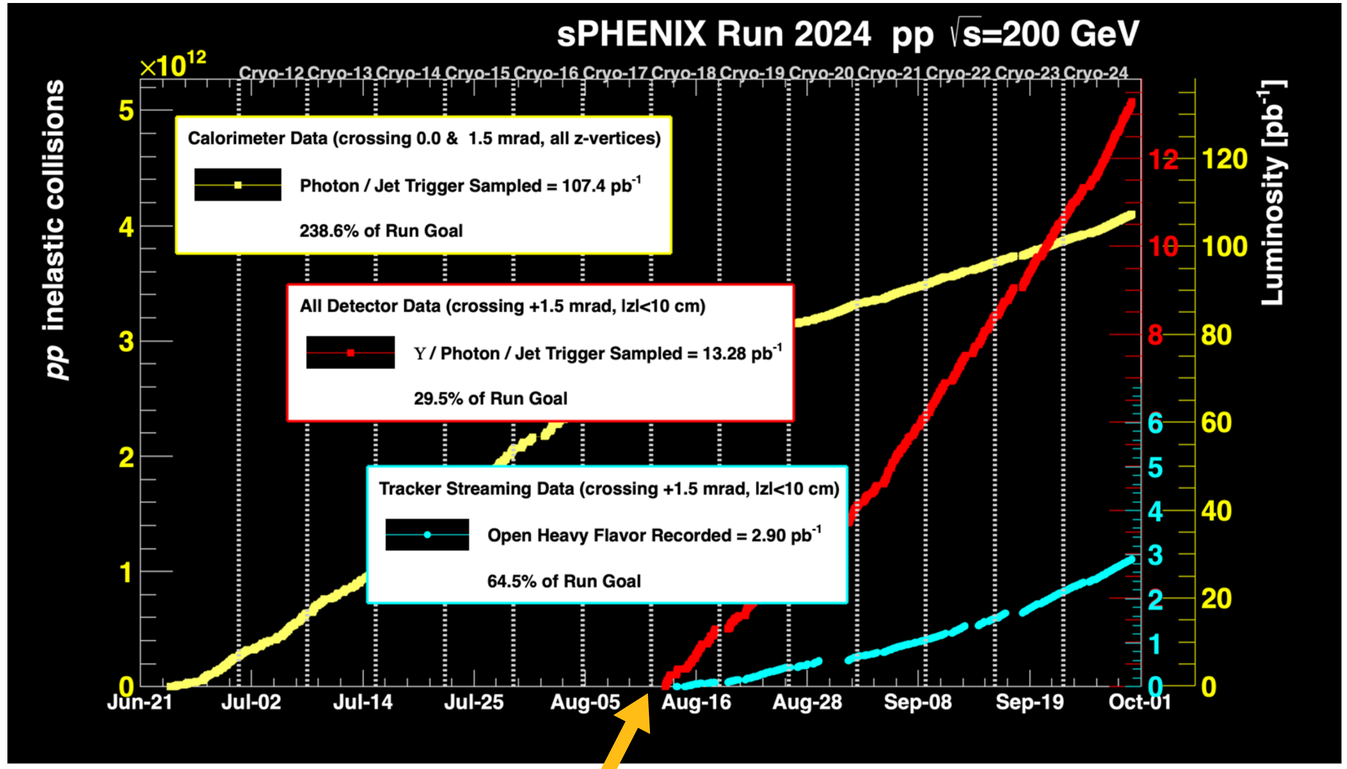
The sPHENIX experiment

- State-of-the-art jet and heavy flavor detector
- Hybrid DAQ
  - Streaming readout for tracking
  - High-rate triggered readout for calorimetry



Transversely polarized proton running in 2024

- Large calorimeter dataset suitable for high precision measurement of π^0, η
- **Streaming readout** of tracking detectors proved essential to maximize our performance in the physics data-taking period



Trackers fully commissioned!

Reconstructing light neutral mesons

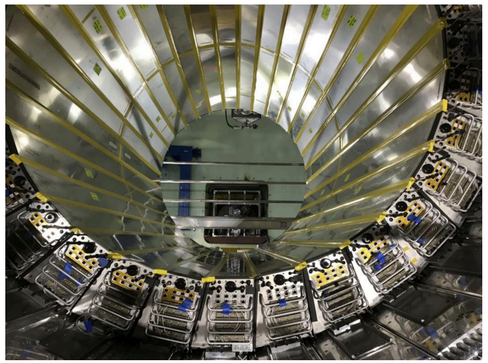
- Neutral mesons measured in the EMCAL through pairs of clusters corresponding to $\pi \to \gamma\gamma$, $\eta \to \gamma\gamma$
- Selections:
  - MBD North+South coincidence and EMCAL "photon" trigger for high-p_T reach
  - 1 GeV minimum cluster energy
  - Maximum cluster pair energy asymmetry $|E_1 - E_2|/(E_1 + E_2) < 0.7$

EMCAL

Tungsten SciFi sampling calorimeter

Moliere radius: ~2.3 cm ~1 tower

$\Delta\phi \times \Delta\eta = 0.024 \times 0.024$

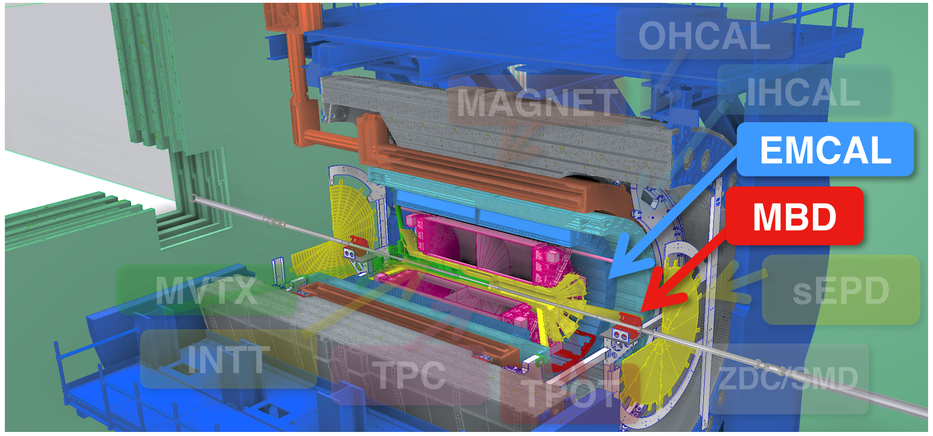


MBD

Reuse of PHENIX BBC

Array of Cherenkov quartz radiators

Minimum bias trigger on hard collision z-vertex determination



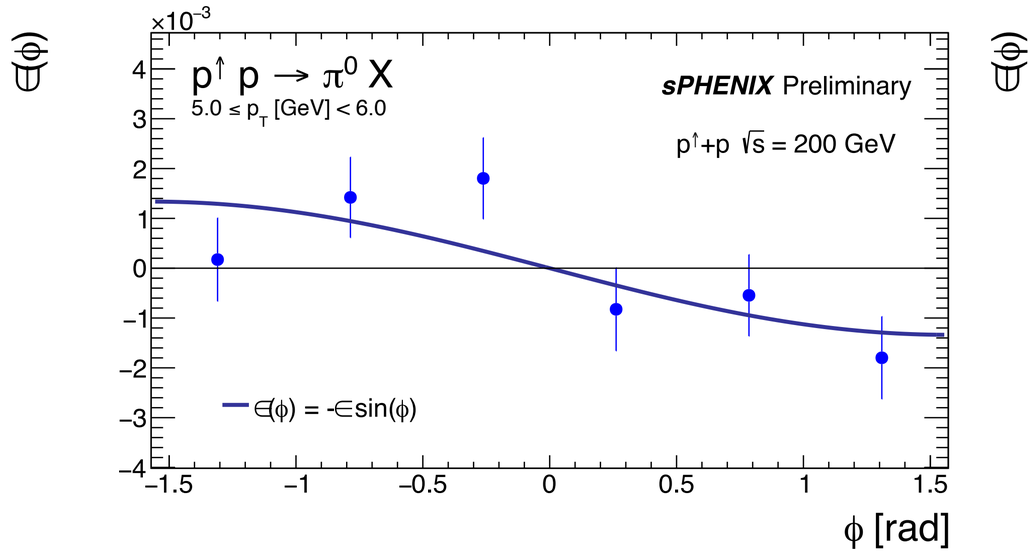
Raw azimuthal asymmetries of neutral mesons

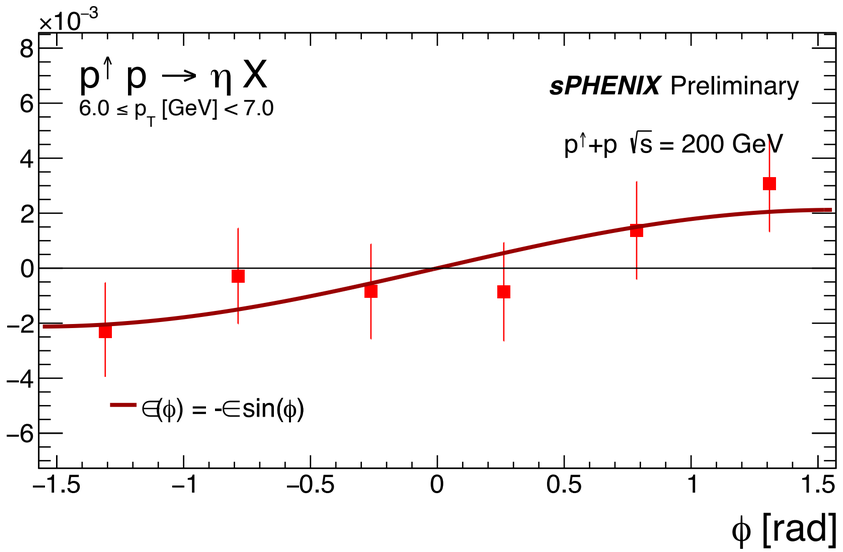
- Raw asymmetry: difference in counts when beam is transversely polarized up vs. down

$$\epsilon(\phi) = \frac{N^{\uparrow}(\phi) - \mathscr{R} N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + \mathscr{R} N^{\downarrow}(\phi)} \qquad \mathscr{R} = \frac{\mathscr{L}^{\uparrow}}{\mathscr{L}^{\downarrow}}$$

- Cross-check: geometric mean of spin up vs. down counts (independent of relative luminosity, $\mathscr{R}$)

$$\epsilon(\phi) = \frac{\sqrt{N^{\uparrow}(\phi) N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi) N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi) N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi) N^{\uparrow}(\phi+\pi)}}$$





$$\epsilon(\phi) = -\epsilon \sin\phi$$
$$A_N = \epsilon / P$$

Background fraction correction

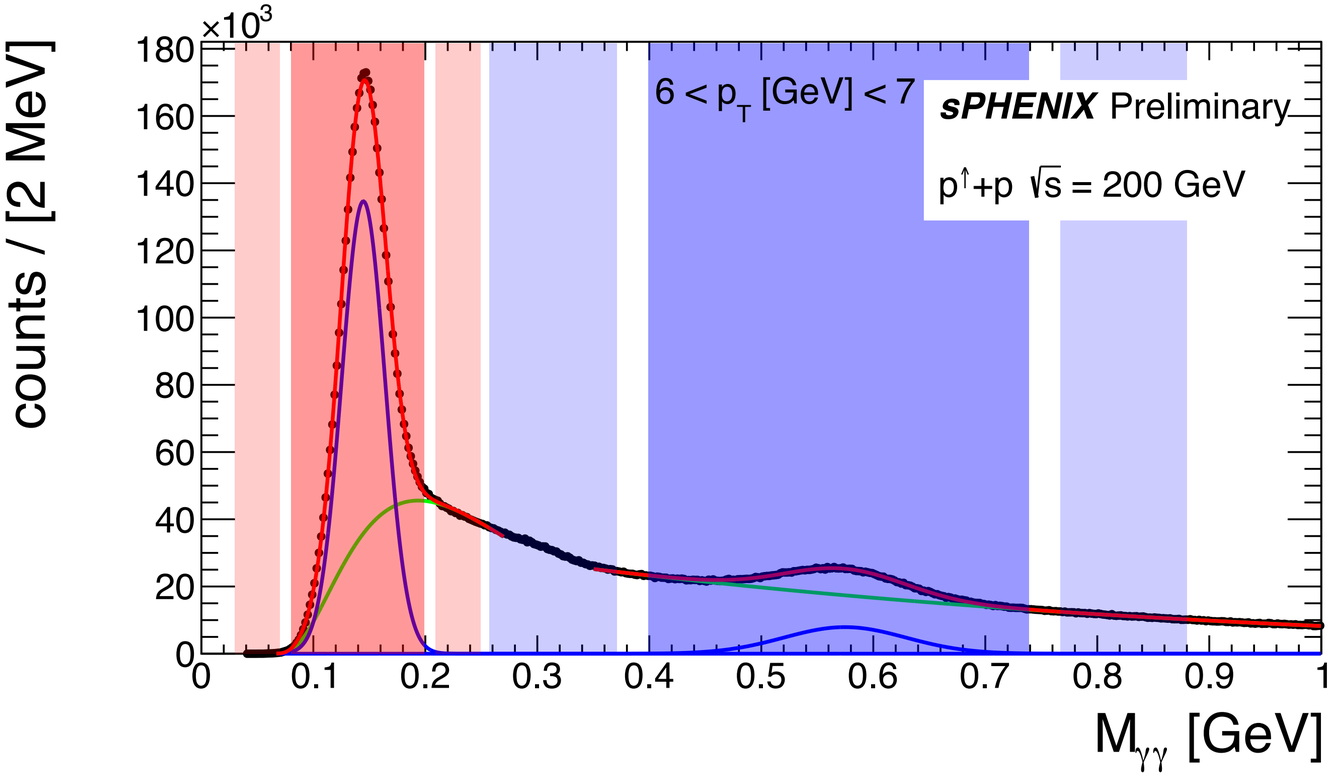
- Signal purity is ~60% for π^0 and ~15% for η mesons
- Sideband correction applied for background underneath the signal that can dilute the asymmetry

$$A_N = \frac{A_N^{peak} - rA_N^{bkg}}{1 - r}$$

$$\sigma_{A_N} = \frac{\sqrt{\sigma^2_{A_N^{peak}} + r^2\sigma^2_{A_N^{bkg}}}}{1 - r}$$

A_N^{bkg}: weighted average of asymmetries measured in low and high-mass sidebands

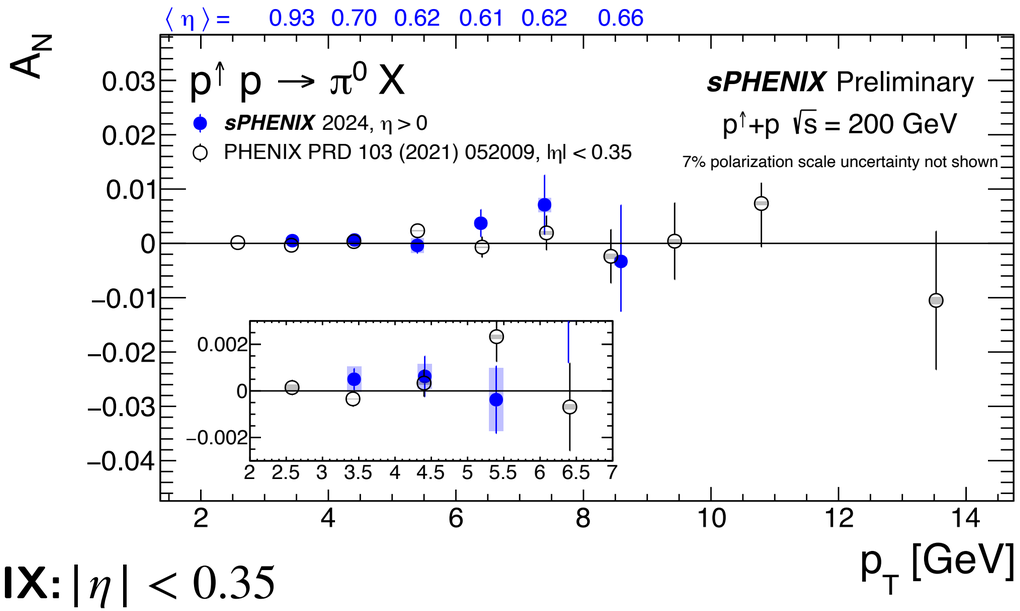
$r = 1 -$ purity

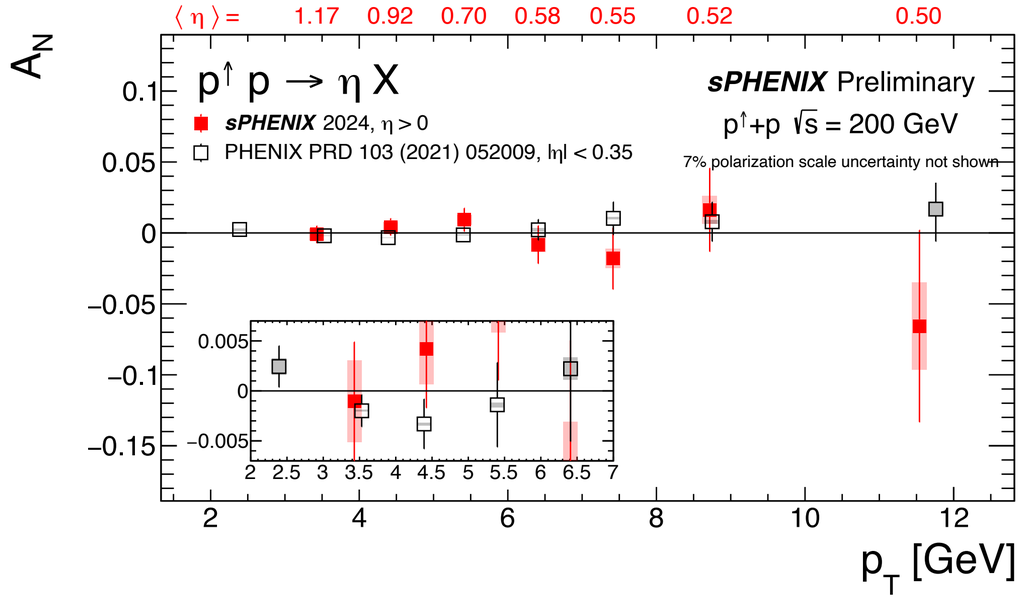


The neutral meson TSSA

- Forward-going asymmetries **consistent with zero** with **sub-percent precision**
- Systematics: raw asymmetry extraction, purity determination, bunch shuffling
- Still to come: more data push to lower p_T bins, x_F-dependent asymmetry

Only ~1/3 of total dataset!





PHENIX: $|\eta| < 0.35$

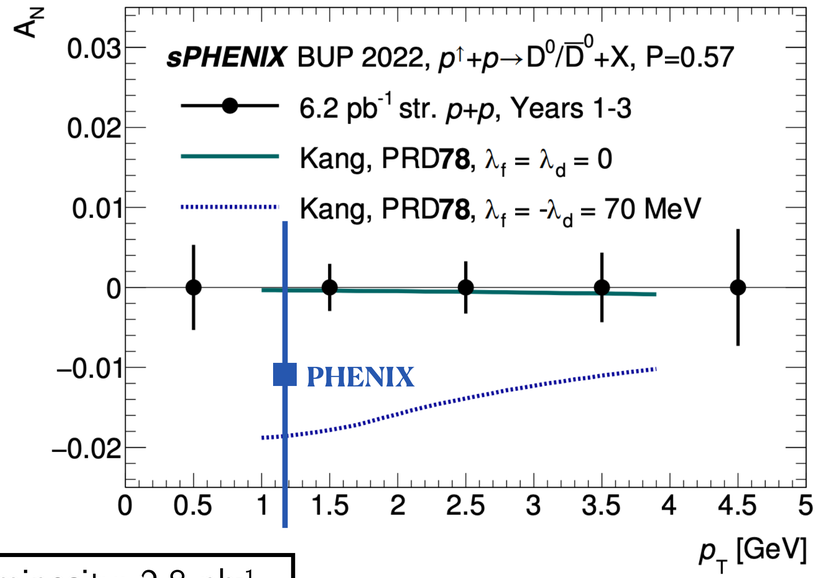
sPHENIX: $\eta > 0$

https://www.sphenix.bnl.gov/sPH-CONF-COLDQCD-2025-01

D^0 TSSA projections

- A **first of its kind** D^0 TSSA measurement at sPHENIX will give unprecedented access to the initial-state trigluon correlators
  - Potential sensitivity to where some models predict the asymmetry to be

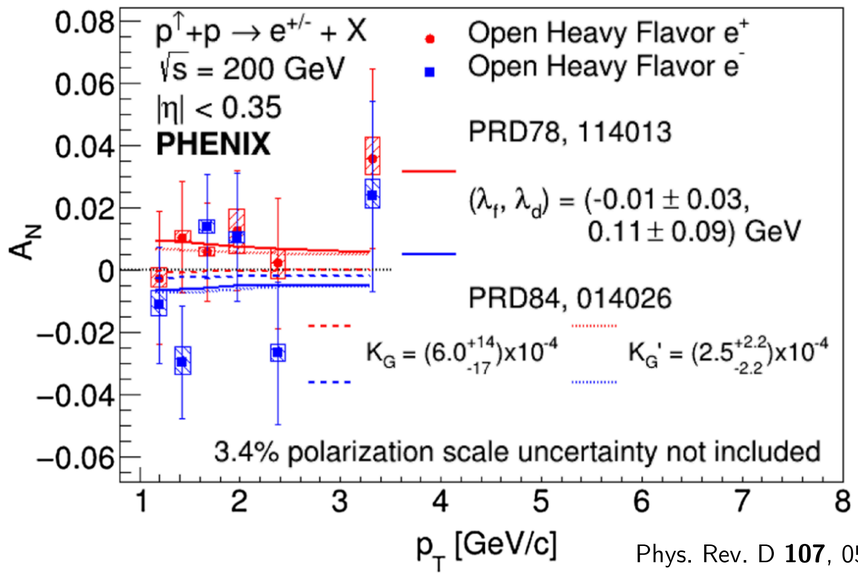
sPHENIX D^0 TSSA



*Actual 2024 luminosity: 2.8 pb^{-1}

sPHENIX 2023 BUP

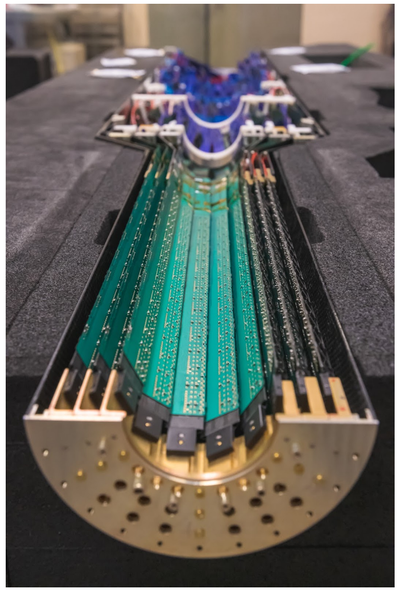
PHENIX open heavy flavor electron TSSA



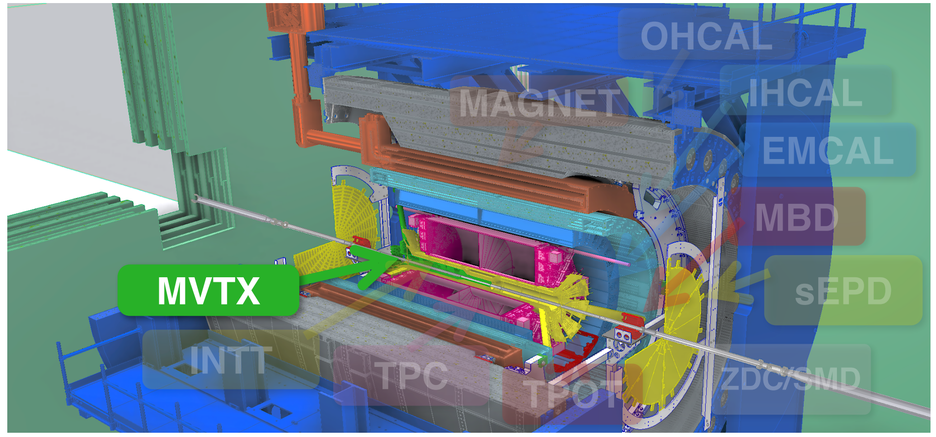
Phys. Rev. D **107**, 052012

Tracking at sPHENIX

- MVTX
  - MAPS-based precision vertexing

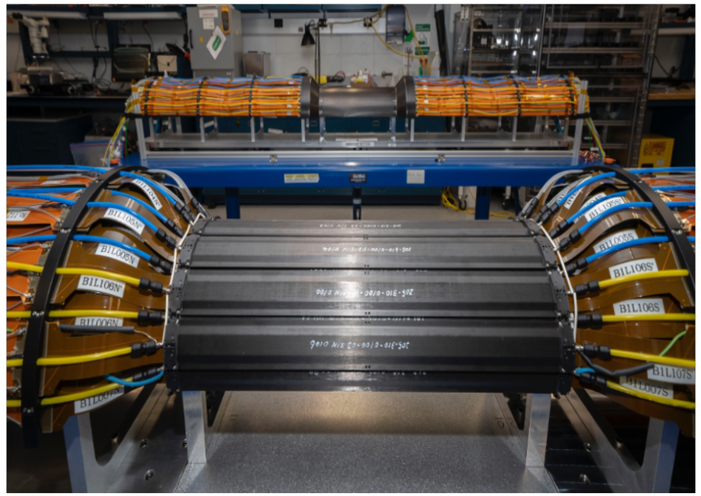


ALICE ITS2 staves
ALPIDE chip
5 μm position resolution
low material budget ~0.3% X_0

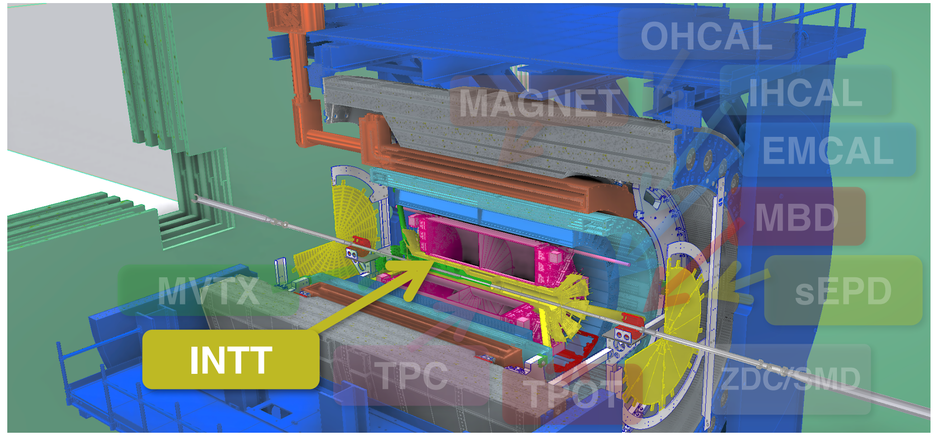


Tracking at sPHENIX

- MVTX
  - MAPS-based precision vertexing
- INTT
  - Bunch crossing identification
  - Pattern recognition/track seeding

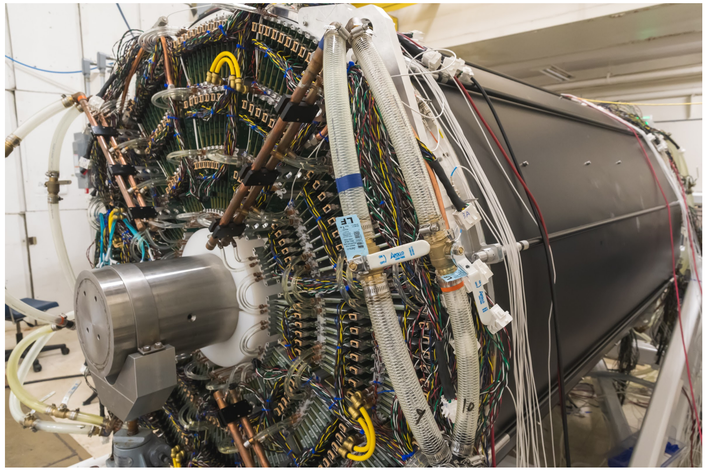


Silicon strip barrel-type tracker
PHENIX FPHX readout chip
10 μm resolution in Rϕ
106 ns timing resolution
low material budget ~1.1% X_0

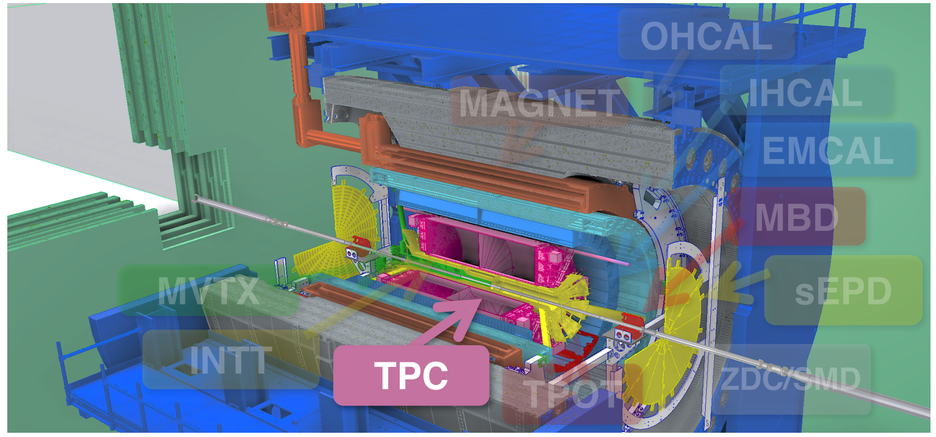


Tracking at sPHENIX

- MVTX
  - MAPS-based precision vertexing
- INTT
  - Bunch crossing identification
  - Pattern recognition/track seeding
- TPC
  - Track momentum resolution
  - dE/dx p-K-π PID

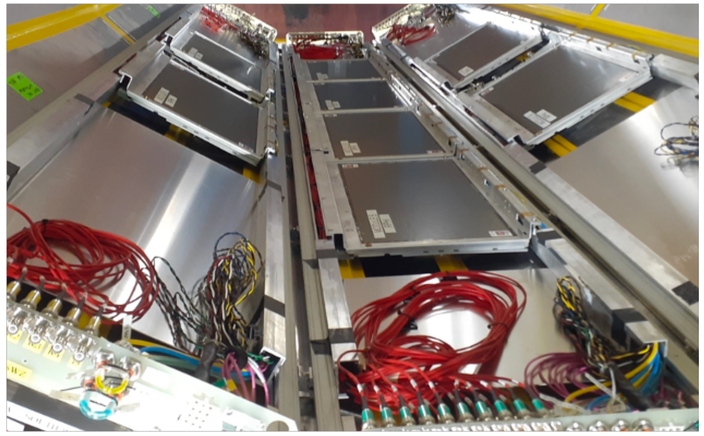


Compact Time Projection Chamber
Ar/CF4/C4H10 (75:20:5) mixture
Quad-GEM gain stage
ALICE SAMPA readout chip

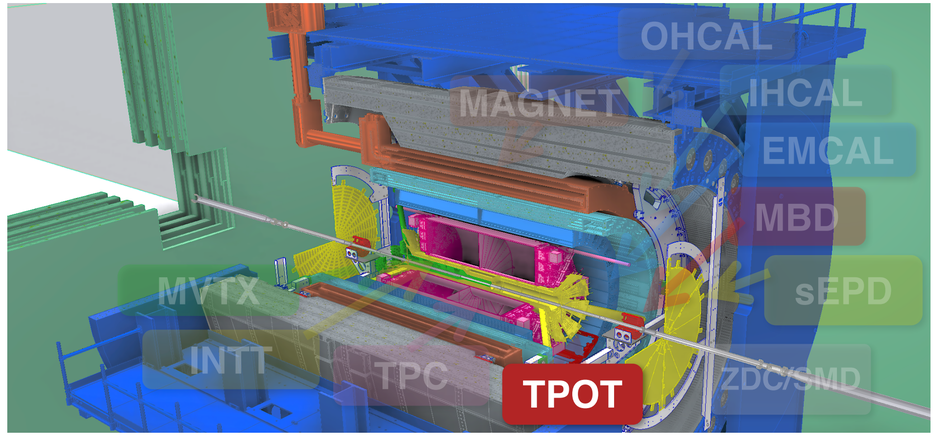


Tracking at sPHENIX

- MVTX
  - MAPS-based precision vertexing
- INTT
  - Bunch crossing identification
  - Pattern recognition/track seeding
- TPC
  - Track momentum resolution
  - dE/dx p-K-π PID
- TPOT
  - TPC distortion correction

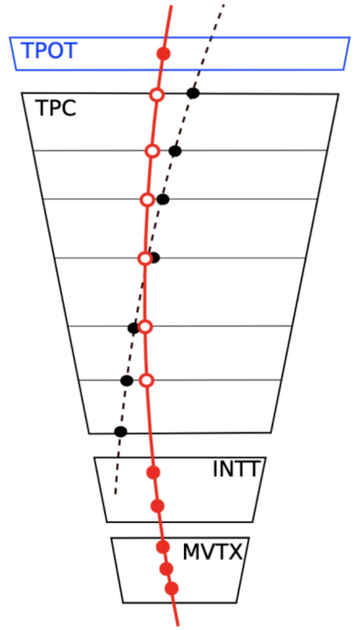


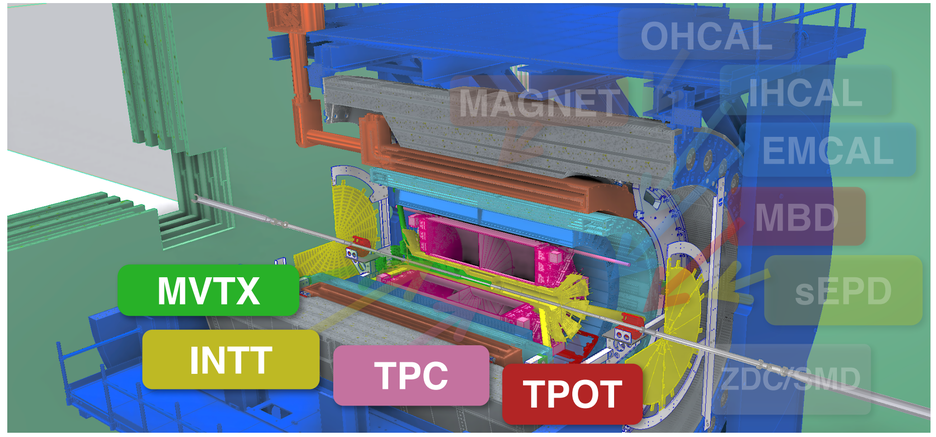
Micromegas detector
Partial coverage outside of TPC
100 μm position resolution



Track reconstruction

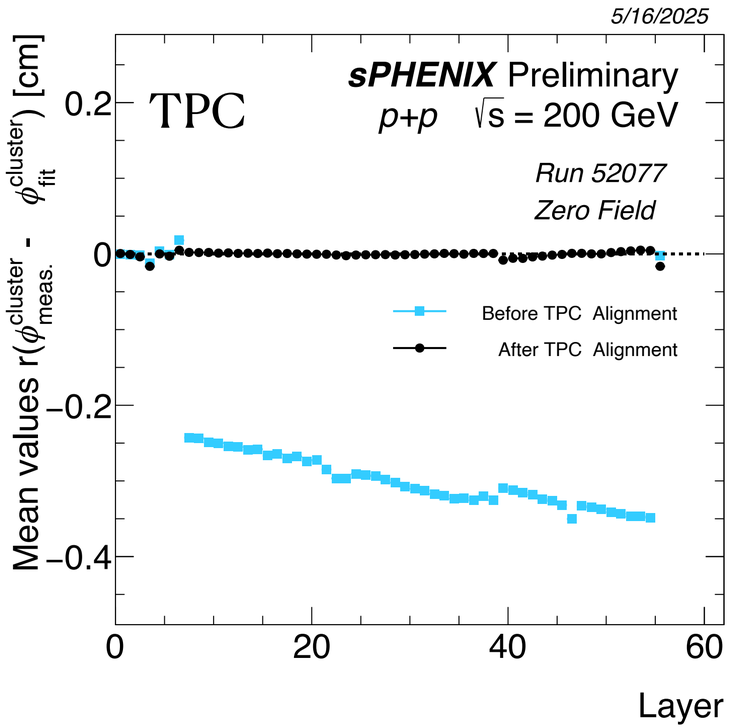
- 55 total layers of tracking sensors
- Independent seeding of tracks in silicon and TPC
- Seeds that are matched between silicon and TPC are then fit with A Common Tracking Software (ACTS) Kalman filter
- A separate Kalman filter takes reconstructed tracks as inputs and finds secondary vertices and parent candidates for specified decay channels

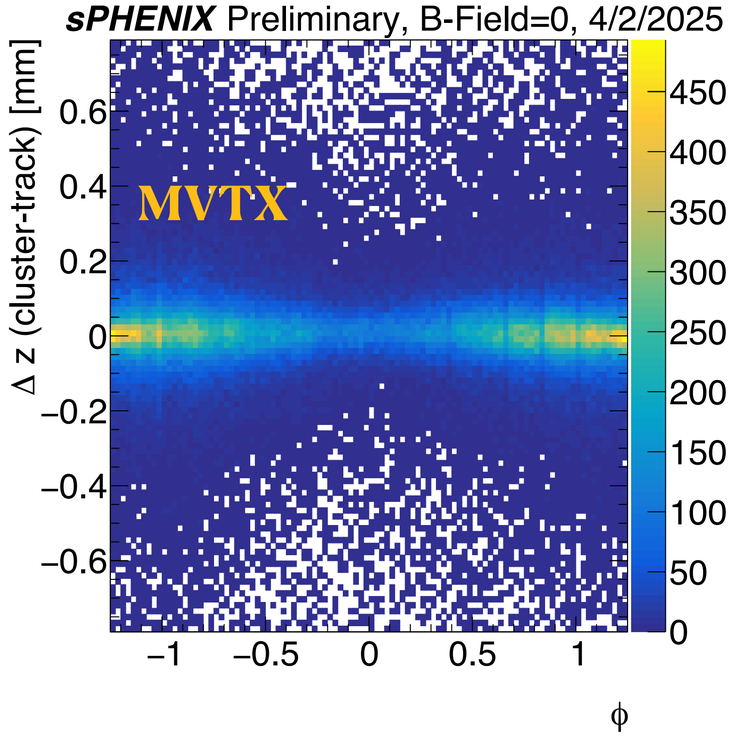




Tracking performance status

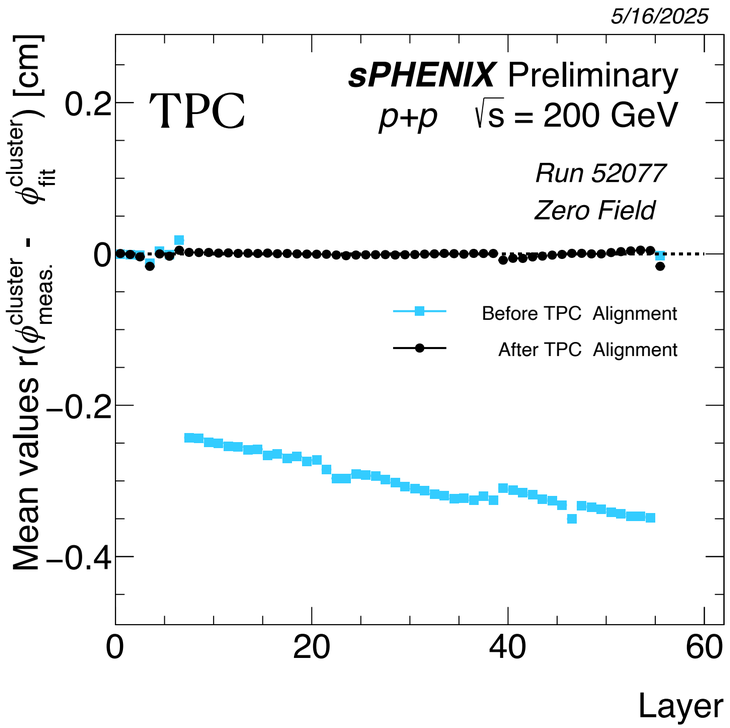
- Significant progress made since the run in understanding the **alignment** of the trackers

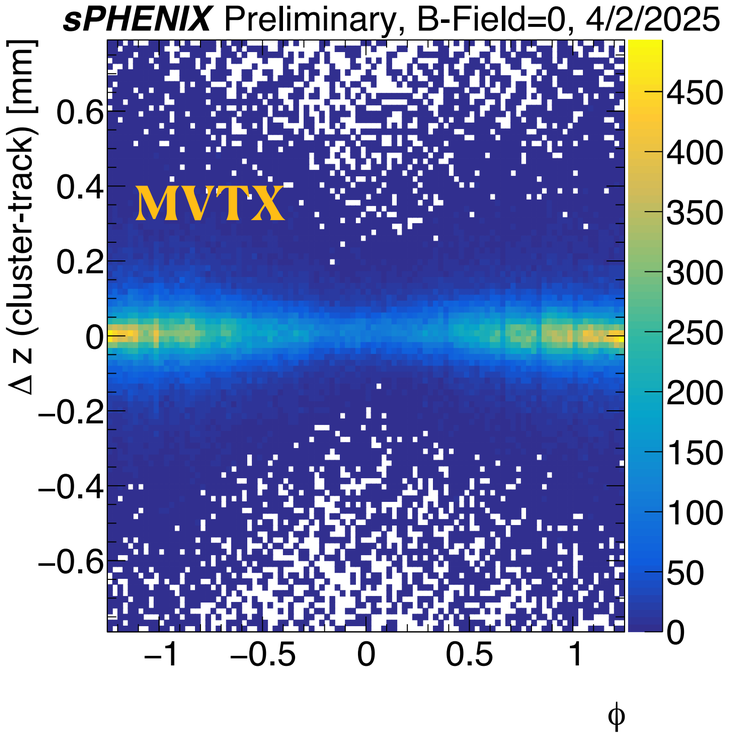


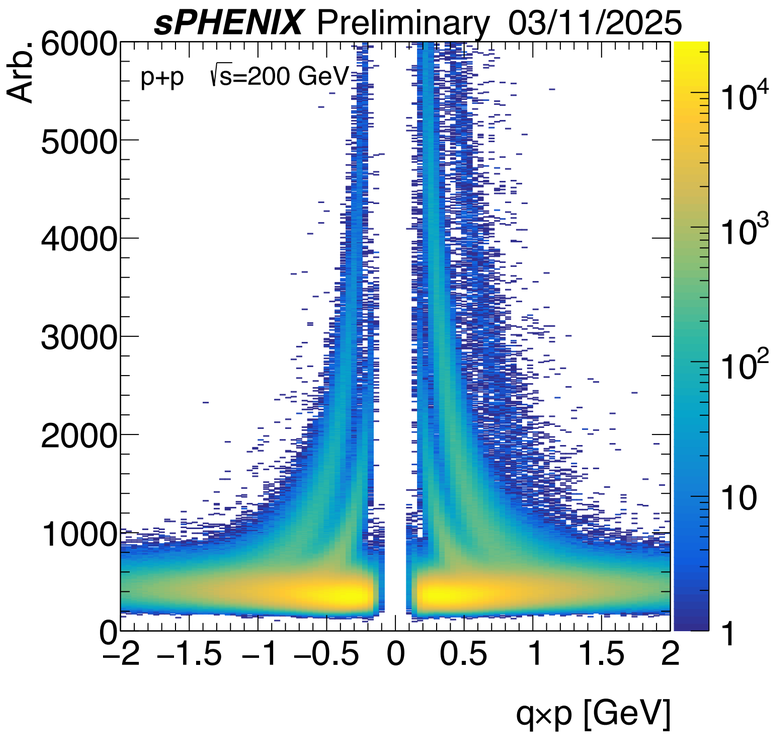


Tracking performance status

- Significant progress made since the run in understanding the **alignment** of the trackers
- Additional performance boost: **low momentum p-K-π PID** available through dE/dx in TPC

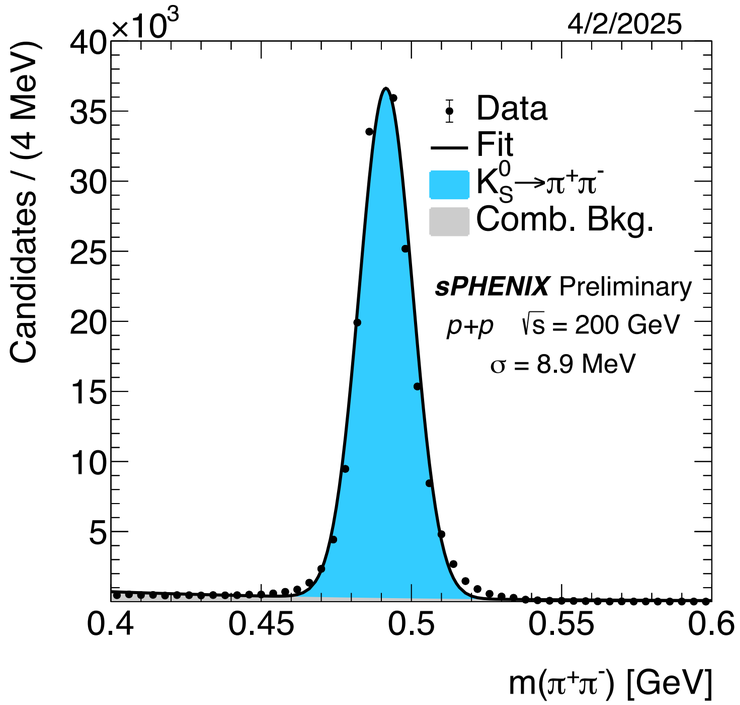


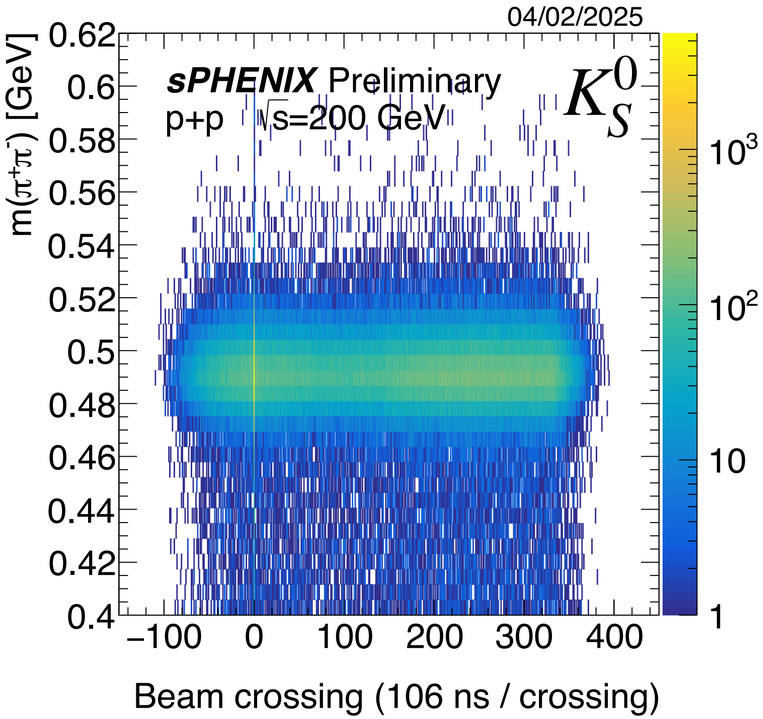




Tracking performance status

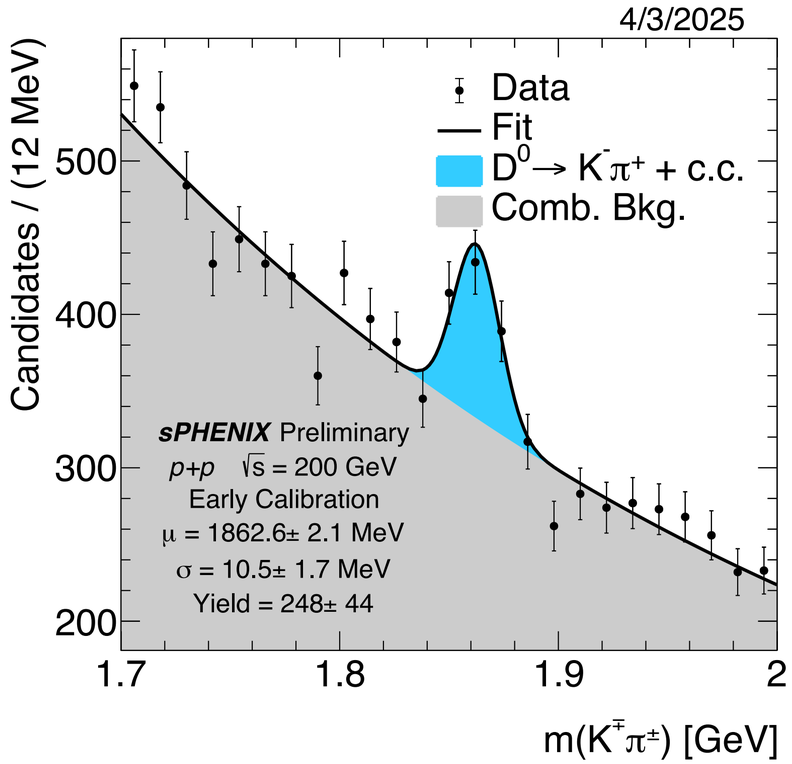
- Clean K_S^0 signal found across streaming readout window
- $\sim 10\times$ more K_S^0 than triggered crossing only
- **Streaming readout** proven successful!

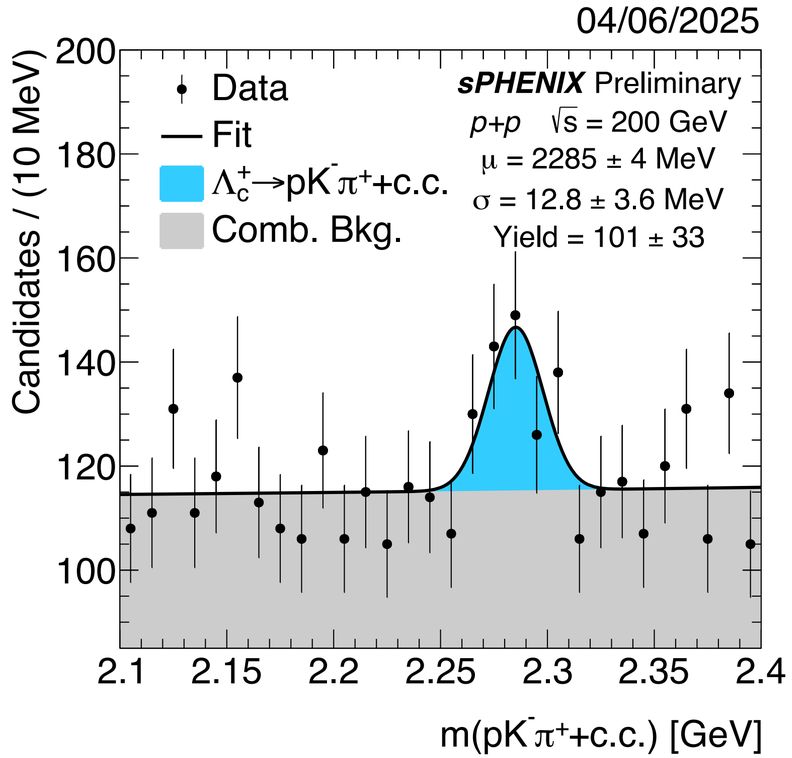




Heavy flavor reconstruction status

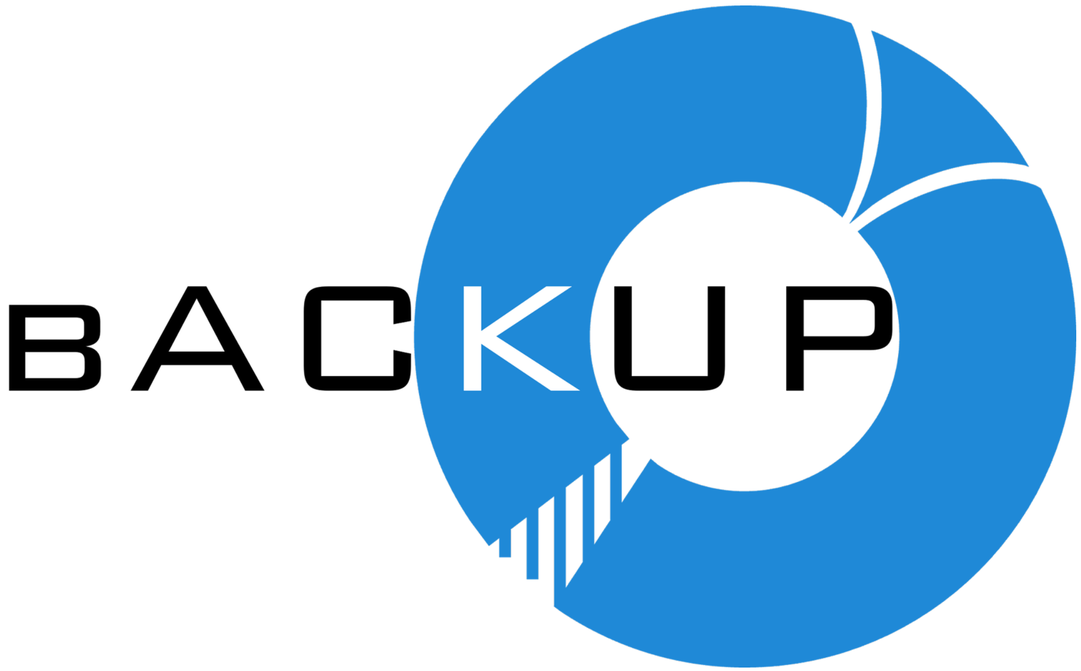
- Early calibrations already show reconstructable heavy flavor in just **1 hour of data-taking**
- D^0 TSSA to come after more thorough understanding of tracking calibrations/characterizations



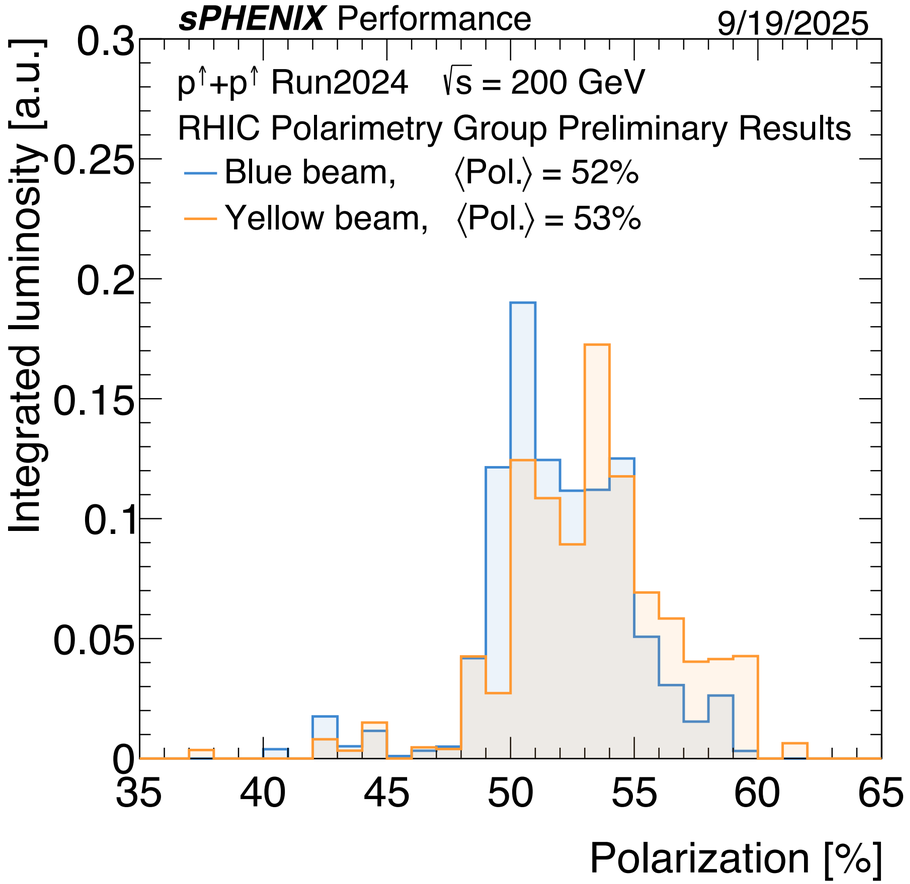


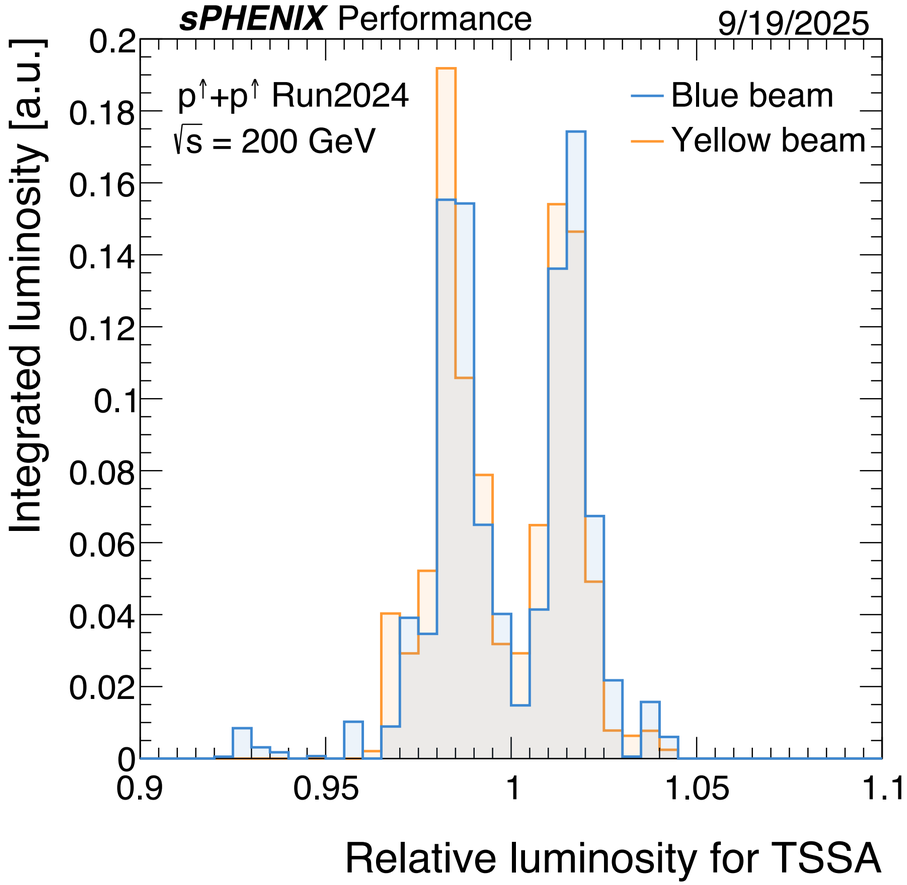
Summary

- The sPHENIX spin program is underway!
- First spin measurement of the light neutral meson TSSAs are already testing the sub-percent precision level with much more data to come
- D^0 meson TSSA will be a unique measurement to sPHENIX that should play an important role in our understanding of the role of gluons in the spin structure of the proton
- More spin talks from sPHENIX
  - Inclusive jet TSSA from Genki Nukazuka, 9:00 AM Wednesday
  - Direct photon TSSA from Jaein Hwang, 9:40 AM Wednesday


BACKUP

RHIC 2024 polarized proton performance





sPHENIX 2024 local polarimeter

- Zero-degree calorimeter + Shower Maximum Detector fully commissioned for sPHENIX local polarimetry during 2024 data-taking
- Part of official spin quality assurance workflow