Spin asymmetries of η mesons in polarized proton collisions at PHENIX

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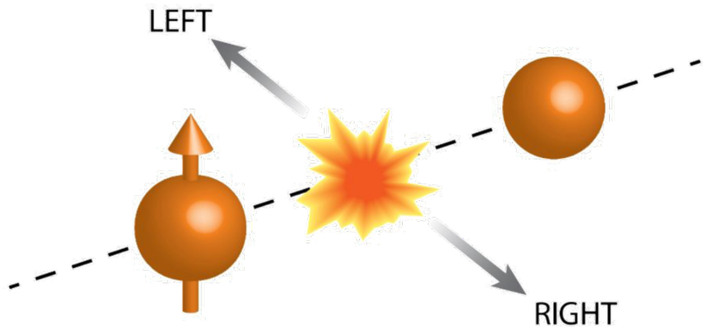
on behalf of the PHENIX collaboration

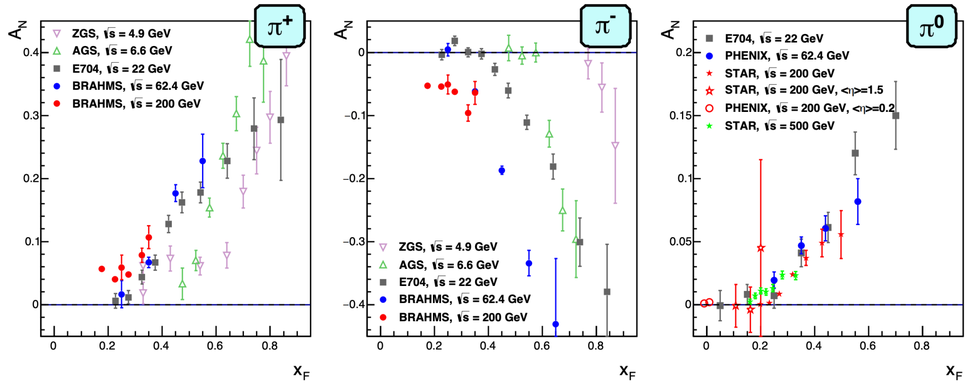
26th International
Symposium on Spin Physics
A Century of Spin

Transverse single spin asymmetries

- **Transverse single spin asymmetries** (TSSAs or A_N) are probes of spin-momentum correlations either within the proton or within the hadronization process
- Predictions from perturbative QCD with collinear, leading-twist PDFs/FFs give small $A_N \sim 10^{-4}$
- **TMD distributions**: can generate transverse spin asymmetries in observables like SIDIS or dihadron/dijet production in hadronic collisions
- In single inclusive production of particles from hadronic collisions, proper factorization framework is **collinear**



Large asymmetries up to 10's of percent have been observed!



Collinear higher-twist contributions to a spin asymmetry

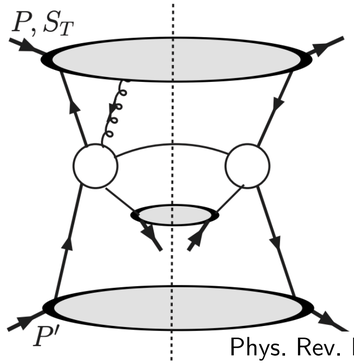
- In collinear factorization, the generation of the spin asymmetry comes from terms at sub-leading twist

$$\Delta(s_T) \propto T^{(3)}(x, x') \otimes \sigma \otimes D(z) + \delta q(x) \otimes \sigma' \otimes D^{(3)}(z, z')$$

- What are these higher-twist terms?
  - Multiparton correlators that encode the quantum interference between a parton and a composite state that includes the parton with an additional gluon

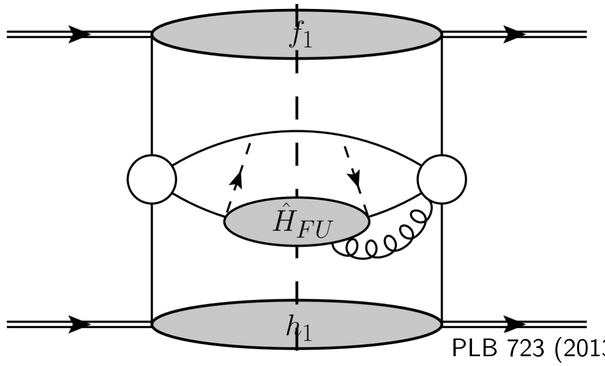
Forward η production dominated by valence quark interactions → sensitive to ETQS quark-gluon correlator

Initial-state correlator



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

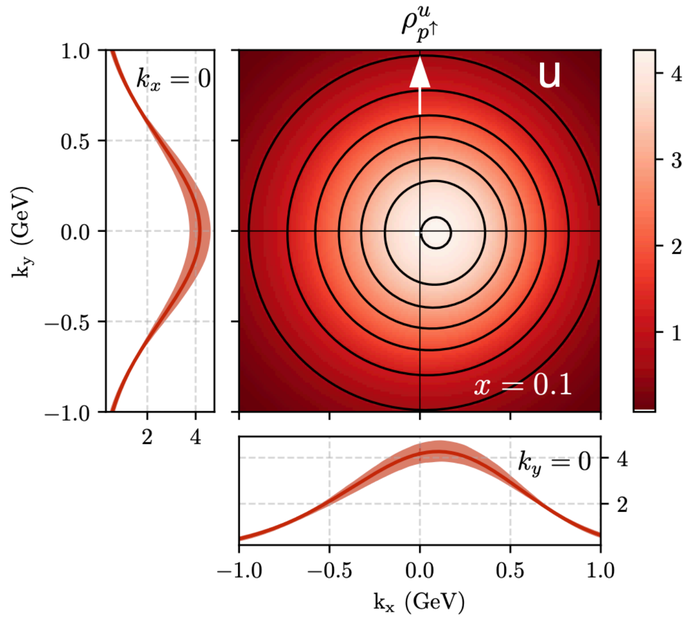
Final-state correlator

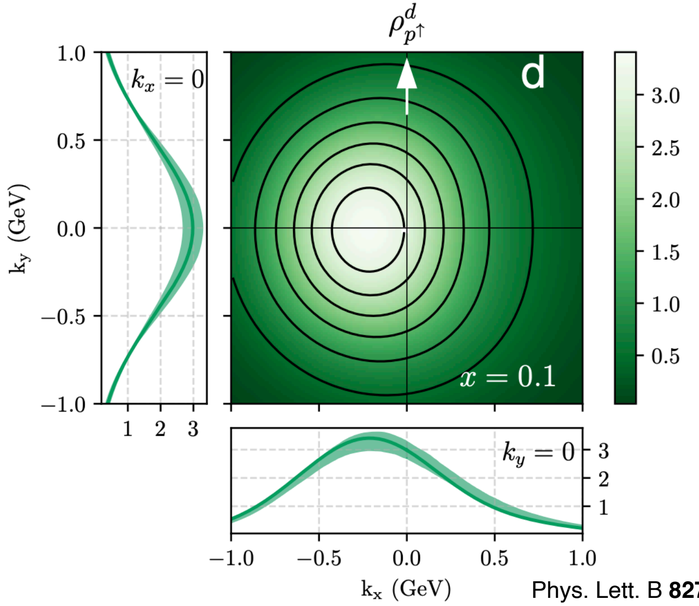


PLB 723 (2013) 365–370

A picture of an initial-state-induced spin asymmetry

- Transverse momentum imbalance of partons in the transversely polarized proton
- Encoded explicitly in the Sivers TMD PDF and related to the twist-3 correlators by k_T moment
- Sivers-like term couples with the collinear leading-twist fragmentation functions to produce the spin asymmetry

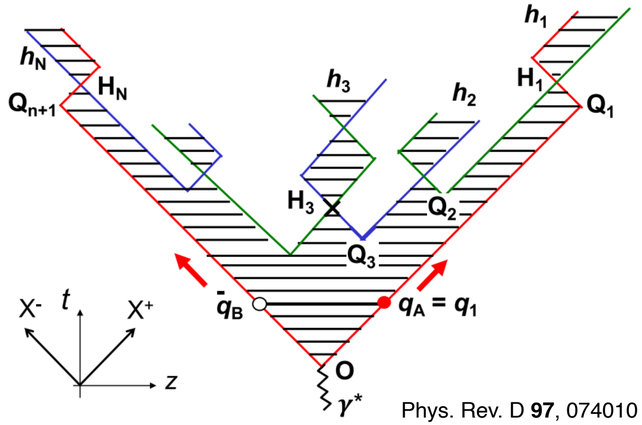




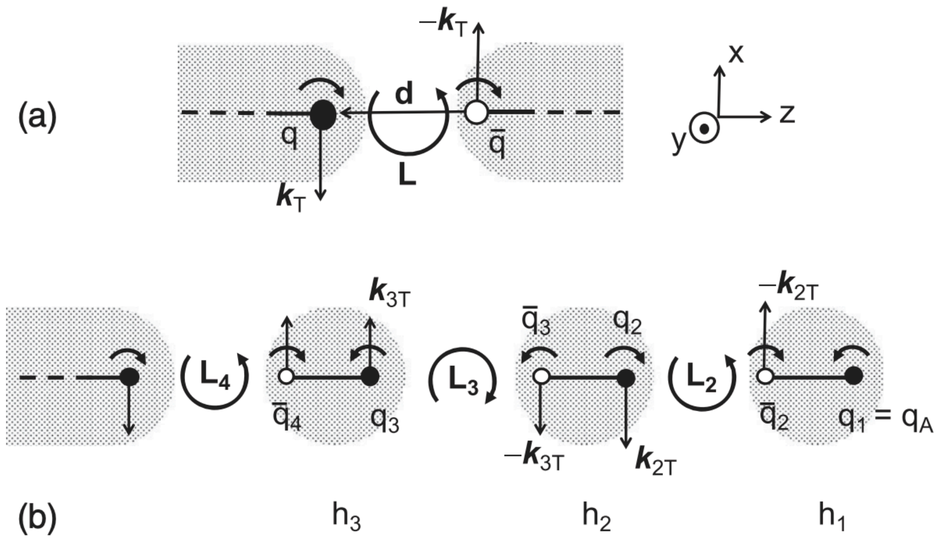
Phys. Lett. B **827**, 136961 (2022)

A picture of a final-state-induced asymmetry

- Quark-antiquark pairs in ${}^3P_0$ state created in the string breaking
  - $J^{PC} = 0^{++}$, spins are parallel with one unit of orbital angular momentum in opposite direction
- Fragmentation in preferred direction from the transfer of ${}^3P_0$ angular momentum to hadron transverse momentum - gives rise to Collins effect when coupled with initial-state transversity distribution

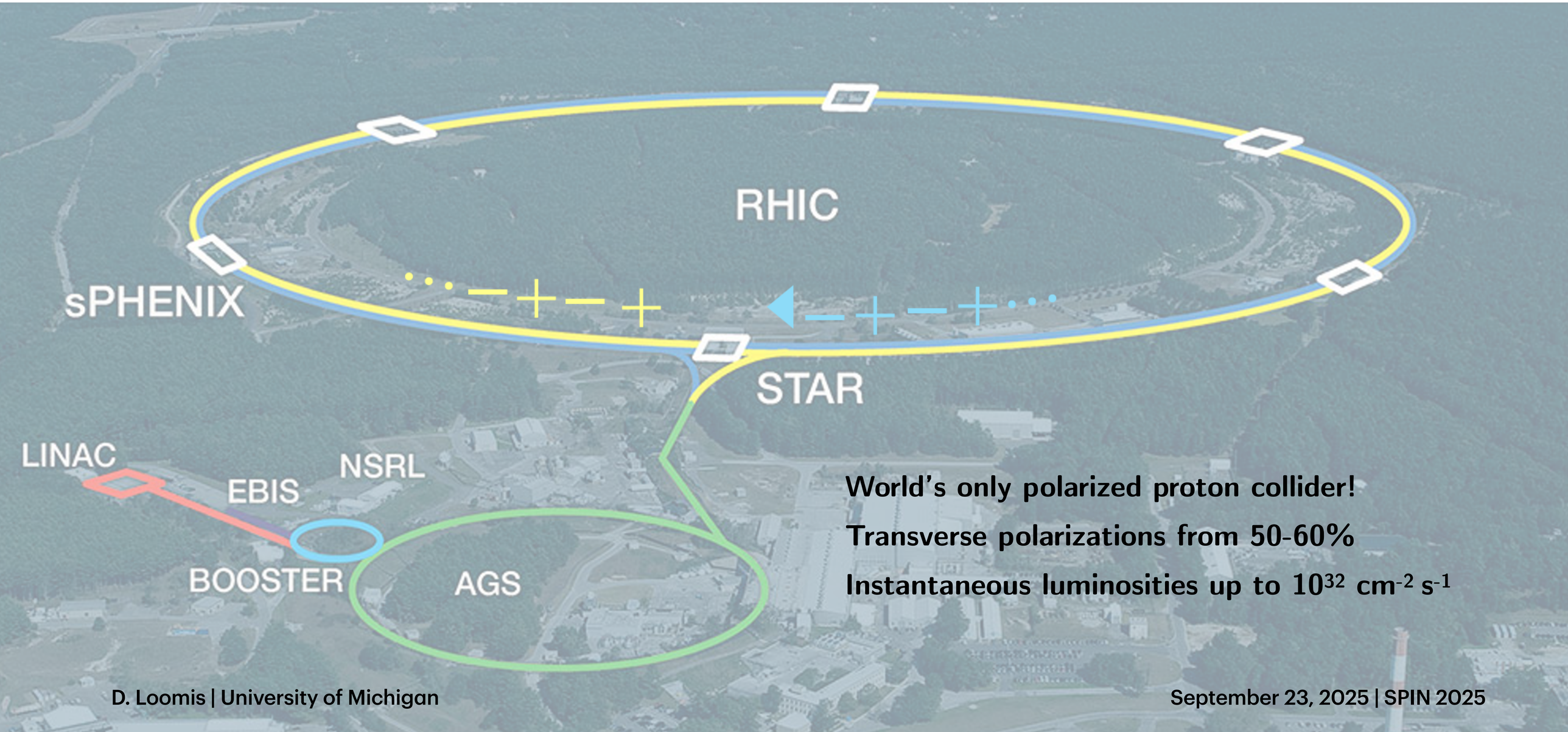


Phys. Rev. D **97**, 074010 (2018)



Phys. Rev. D **97**, 074010 (2018)

The Relativistic Heavy Ion Collider



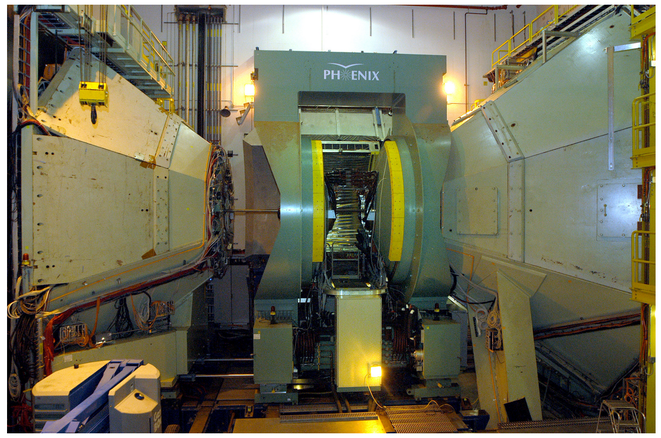
World's only polarized proton collider!

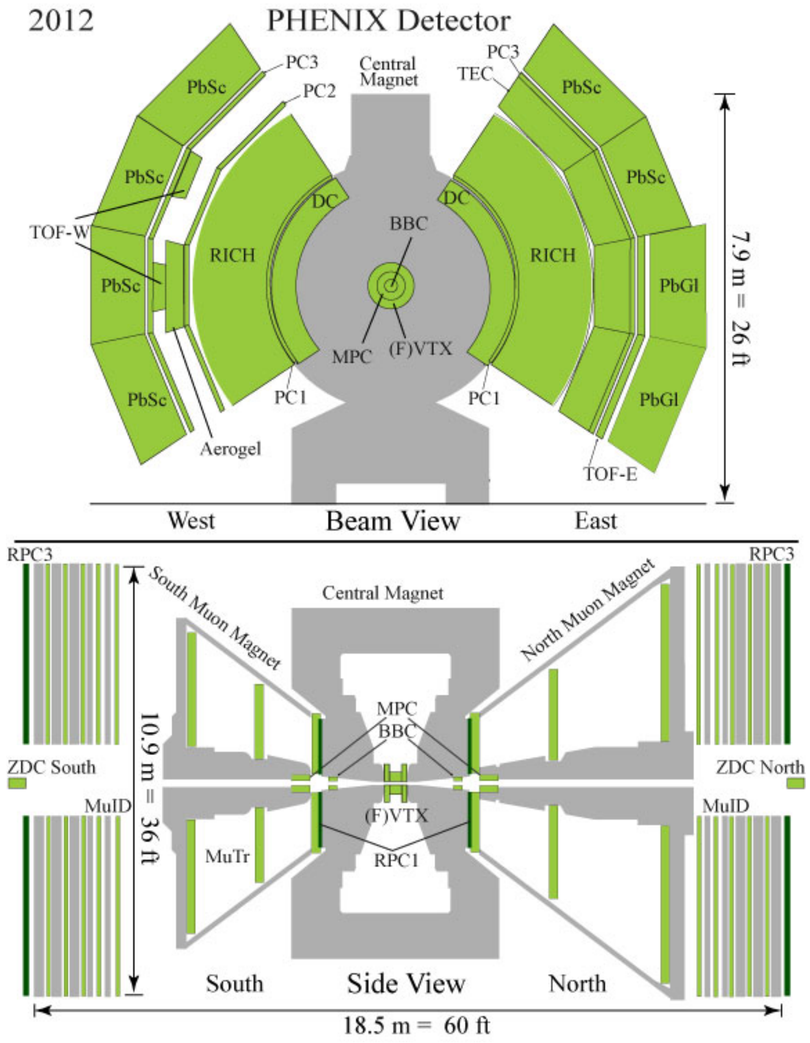
Transverse polarizations from 50-60%

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

The PHENIX experiment

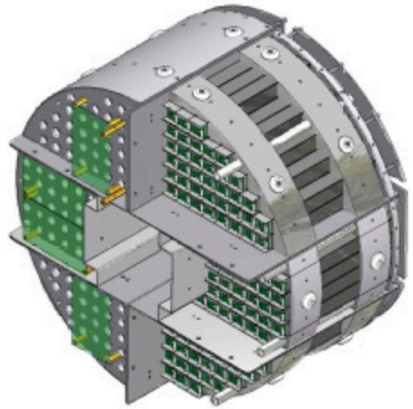
- Purpose built detector for high precision studies of photons/leptons
- Very modular: new subsystem/upgrade every year
- Central arms ($|\eta| < 0.35$)
  - high precision EMCal, PC/DC for track momentum, RICH PID
- Muon arms ($1.4 < |\eta| < 2.4$)
  - Charged track momentum, muon identification



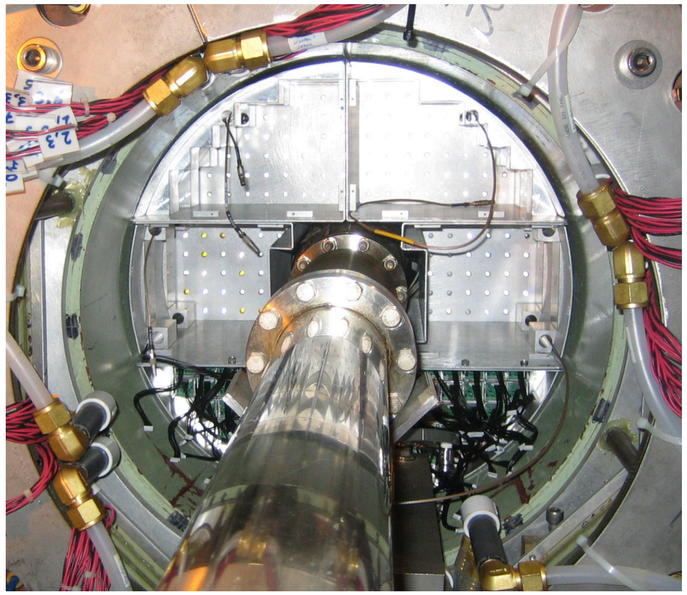


Forward detection at PHENIX

PHENIX Muon Piston Calorimeter



- Addition to PHENIX installed in 2006
- Forward scintillating PbWO4 electromagnetic calorimeter $(3.0 < |\eta| < 3.8)$
- $\sigma(E)/E = 13\,\%/\sqrt{E} \oplus 8\,\%$
- ~20 radiation lengths
- Moliere radius ~1 tower = 2.2 cm
- Avalanche photodiode+preamplifier used for light collection



Why η mesons at PHENIX?

- Practical: light neutral meson, still abundantly produced and reconstructible at high efficiency through $\eta \to \gamma\gamma$ (40% branching fraction)
- Higher mass than π^0 → resolve the diphoton separation to higher p_T and more **forward rapidities**
  - η mesons are then **essential** for **forward measurements at PHENIX** because the photons from π^0's in our forward calorimeter already merge into one cluster at transverse momenta ~1 GeV
  - Forward measurements are **crucial** for the PHENIX spin program
- η mesons are also interesting to explore and compare to the neutral pions to look for differences in the light pseudoscalar sector

Phenomenology of the η meson TSSA

- Goal: comparison of a high precision η meson TSSA measurement to a phenomenological prediction
- Let's look at what goes into a twist-3 TSSA calculation:

$$d\Delta\sigma(S_T) = \frac{2P_{hT}\alpha_S^2}{S}\sum_i\sum_{a,b,c}\int_{z_{\min}}^1\frac{dz}{z^3}\int_{x_{\min}}^1\frac{dx}{x}\frac{1}{x'}\frac{1}{xS+U/z}f_1^b(x')\left[M_h h_1^{a/p^\uparrow}(x)\mathcal{H}^{h/c,i}(x,x',z)+\frac{M}{\hat{u}}\mathcal{F}^{a/p^\uparrow,i}(x,x',z)D_1^{h/c}(z)\right]$$

Final-state Initial-state

- Two main issues with η mesons:
  - **Collinear η meson fragmentation functions** are more than a decade old and show disagreement with LHC data
  - No **η meson Collins TMD** available
- What does this mean practically?
  - We can get a prediction of the **initial-state Sivers-like contribution** to the asymmetry but it would be greatly improved with an updated global fit of the collinear fragmentation functions
  - We **cannot** get a prediction of **final-state Collins-like contribution** to the asymmetry

Phys. Rev. D **106**, 034014

Motivating the forward η meson cross section

- To address issue 1: we make two η meson cross section measurements at PHENIX as part of a new global FF fit
- Unique to forward rapidity PHENIX measurement: sample from high-z valence quarks

experiment	$\sqrt{s}$
PHENIX mid y	200 GeV
	510 GeV
PHENIX fwd y	200 GeV
	500 GeV
ALICE	2.76 TeV
	7 TeV
	8 TeV
	13 TeV
LHCb	5.02 TeV
	13 TeV

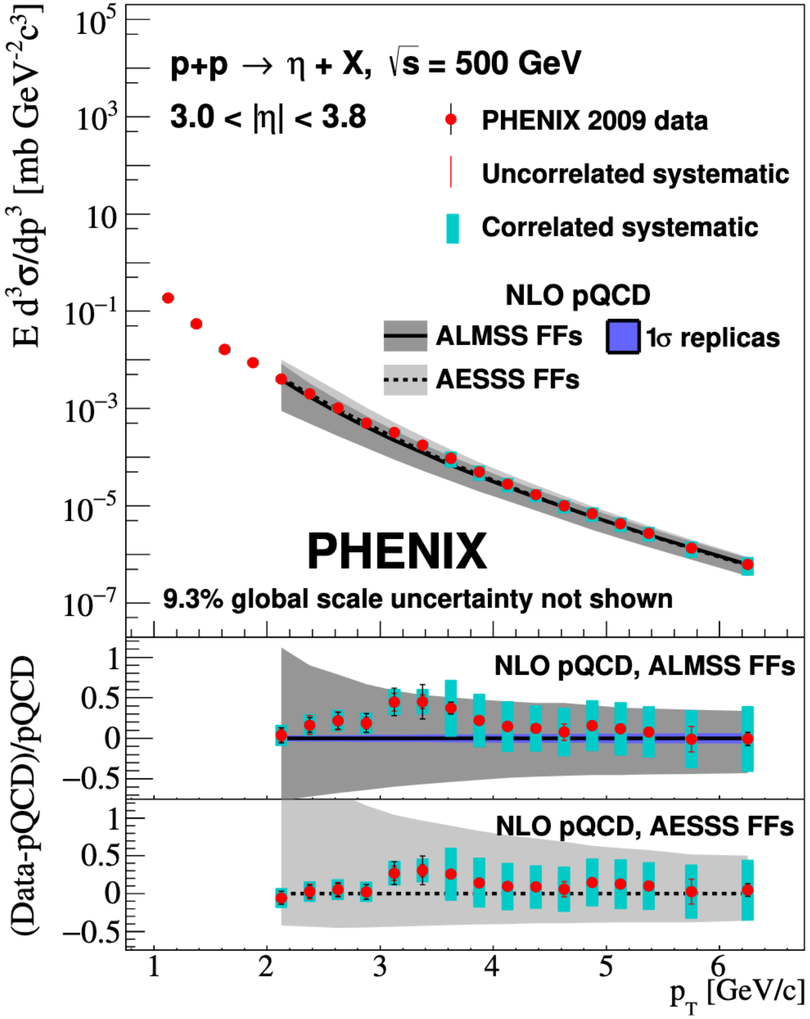
New pp datasets included in the updated FFs

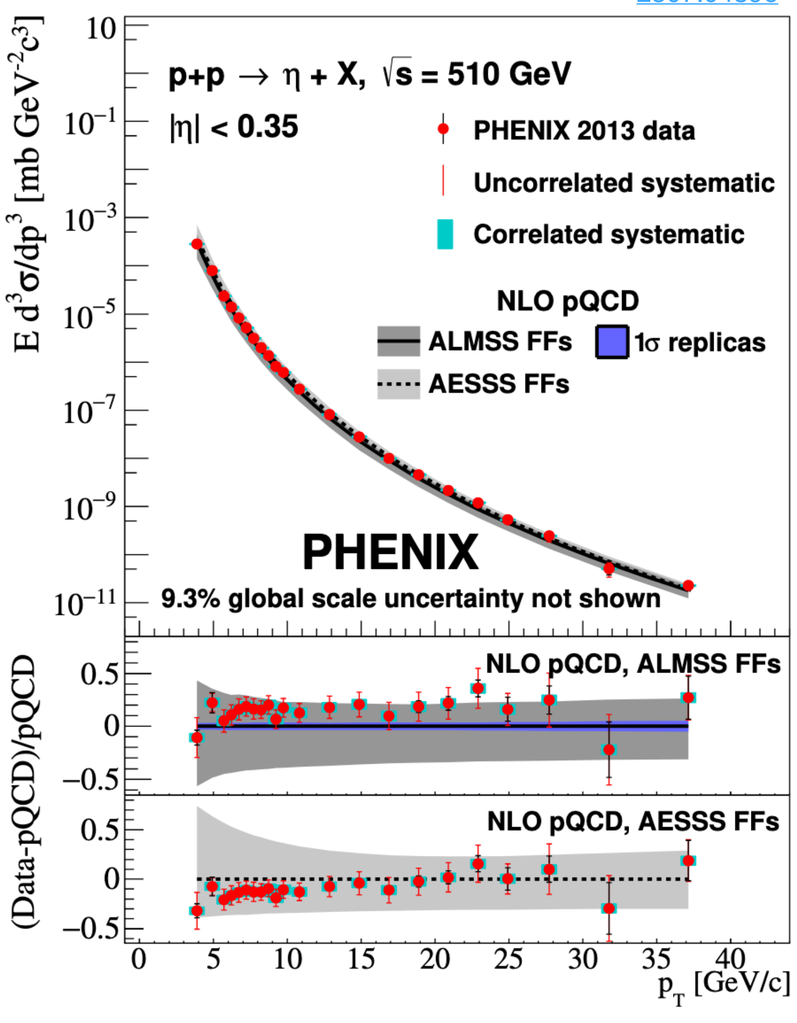
PHENIX η meson cross sections

Additional inputs to new η FFs

New!

2507.04896



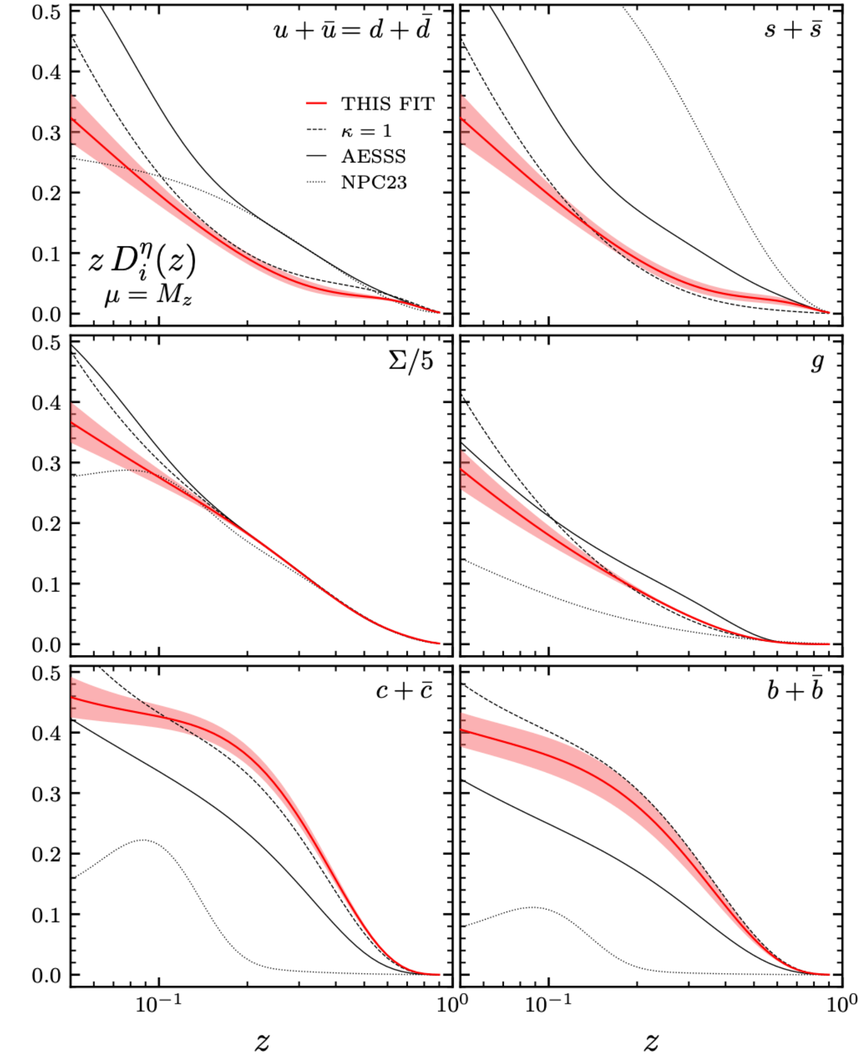


ALMSS η meson fragmentation functions

New!

- With new PHENIX cross sections and other recent cross sections from LHC/RHIC/Belle, an updated global fit of the η meson fragmentation functions was performed - ALMSS FF's

Aidala, Loomis, Martinez, Sassot, Stratmann (ALMSS) 2507.04887



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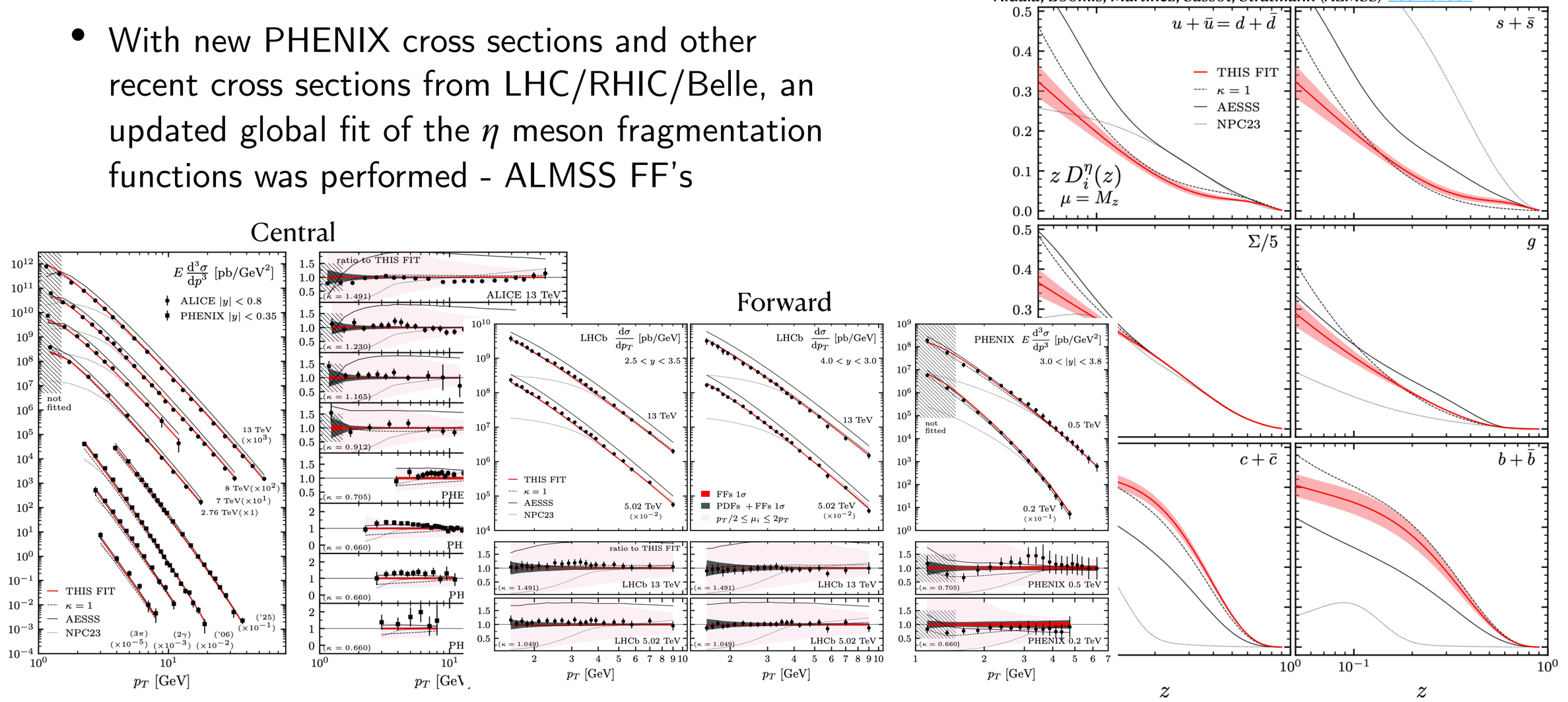
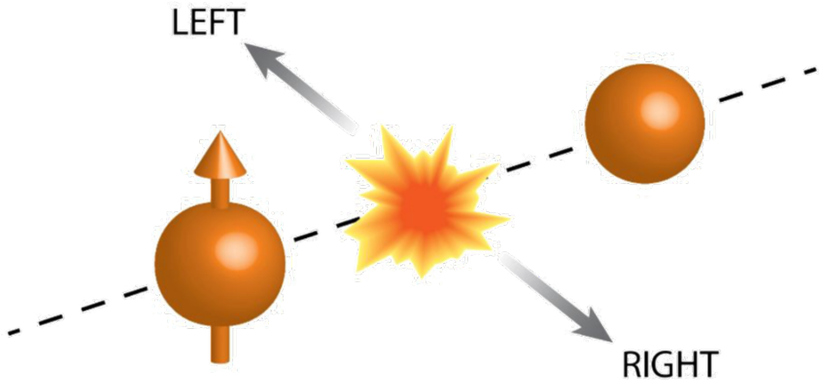




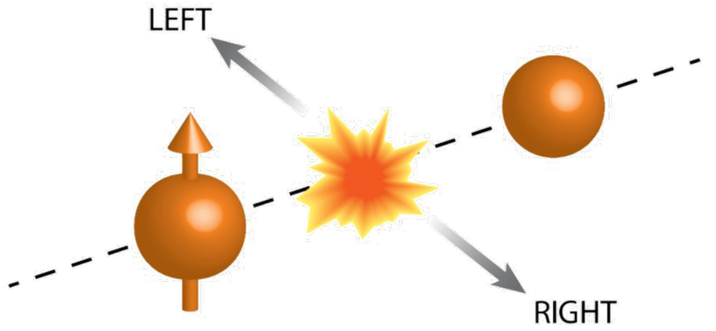
The forward η meson TSSA at PHENIX

The forward η meson TSSA

- 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**

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

- Procedure: Measure raw azimuthal asymmetry $\epsilon(\phi) = A_N P \cos\phi$ as a function of x_F and p_T, then apply purity and beam polarization correction



The forward η meson TSSA

Raw asymmetry

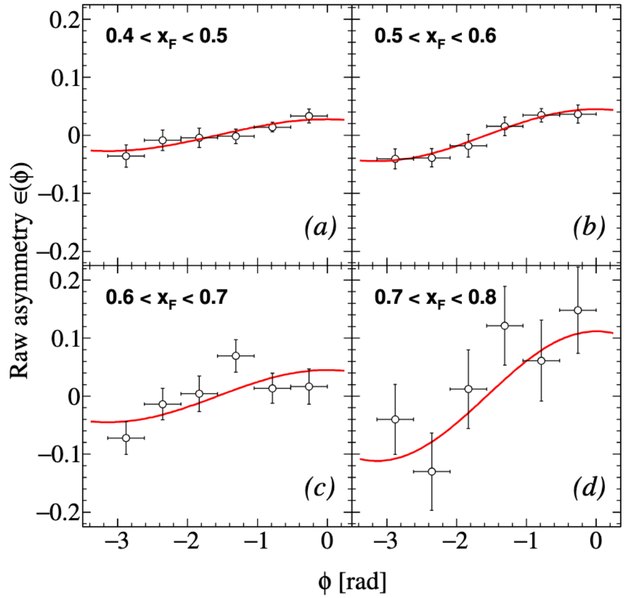
- Raw asymmetry: geometric mean of spin up vs. down counts

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

- Cross-check: difference in counts in same azimuthal bin for spin up vs. down (relies on relative luminosity, $\mathscr{R}$)

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

$$\boxed{\epsilon(\phi) = \epsilon\cos\phi \qquad A_N = \epsilon/P}$$



The forward η meson TSSA

Background fraction correction

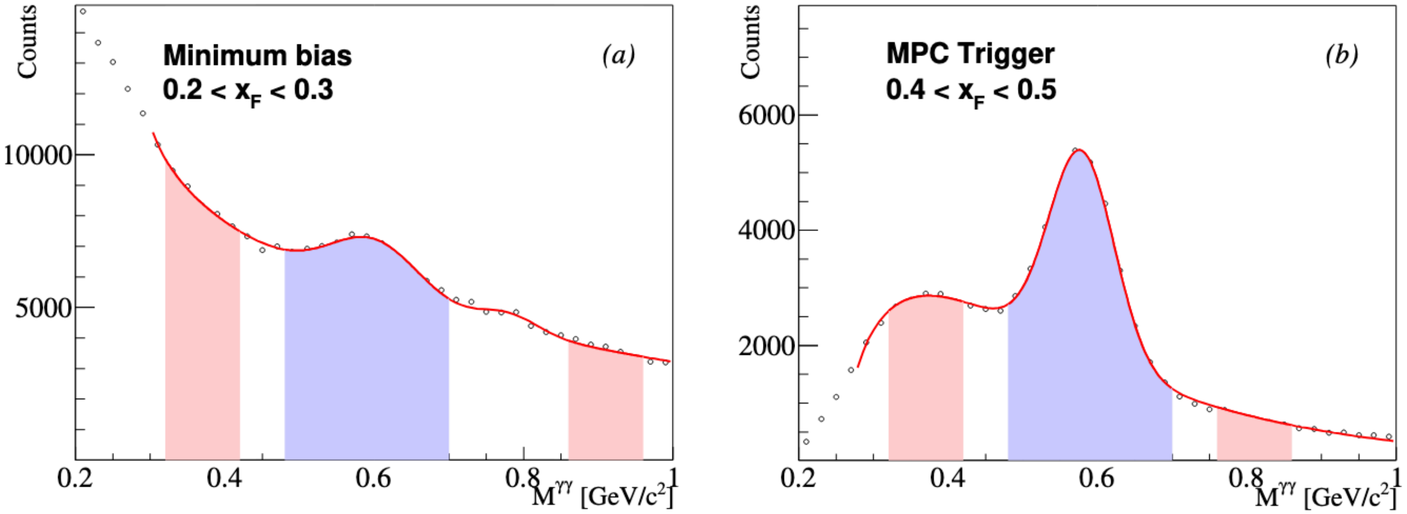
- η meson purity is ~30% for MB data and ~45% for high-p_T triggered data
- Sideband correction applied for background underneath the signal that can dilute the asymmetry

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

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

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

$r = 1 -$ purity



Final forward η meson TSSA

New!

- Most precise measurement to date of the forward η meson TSSA (combination of 2008+2012 PHENIX data)
- Calculations of the initial-state twist-3 contribution to the asymmetry appear insufficient to describe the large observed asymmetry
- Suggests a significant component of the asymmetry is carried by spin-dependent hadronization

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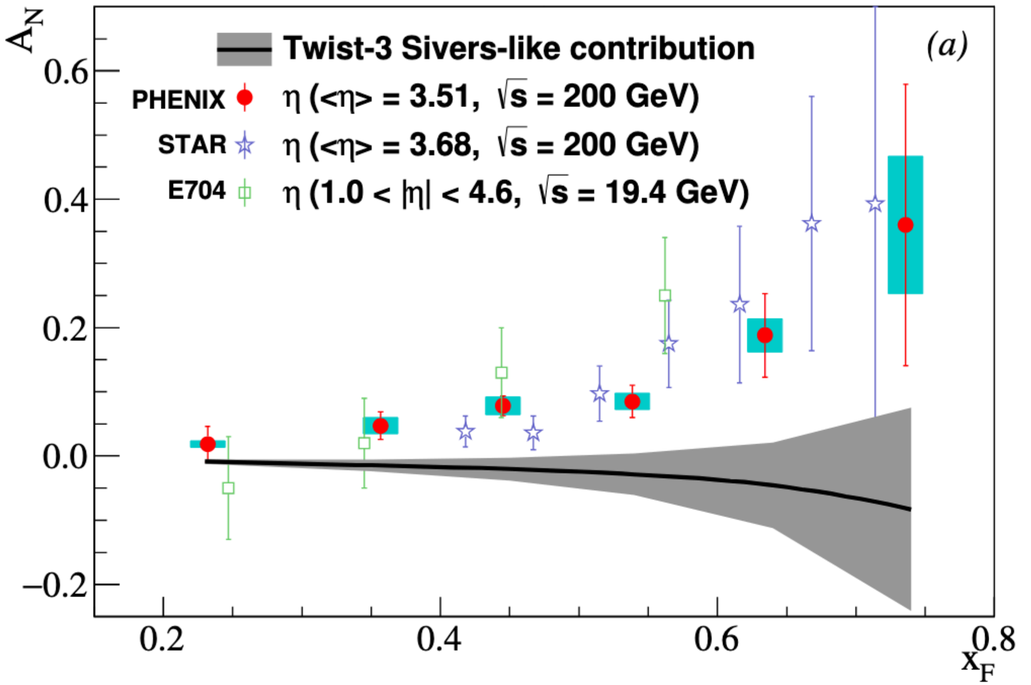

Twist-3 prediction here uses ALMSS eta FFs!

D. Pitonyak, Phys. Rev. D **106**, 034014 (2022)

Final forward η meson TSSA

New!

- The TSSA appears to be largely from the final-state: how does the asymmetry compare to the π^0?
- New high precision η meson measurement allows for a powerful comparison
- Similarity between η meson and π^0 suggests a limited impact from mass, isospin, strange quark content on spin-dependent hadronization

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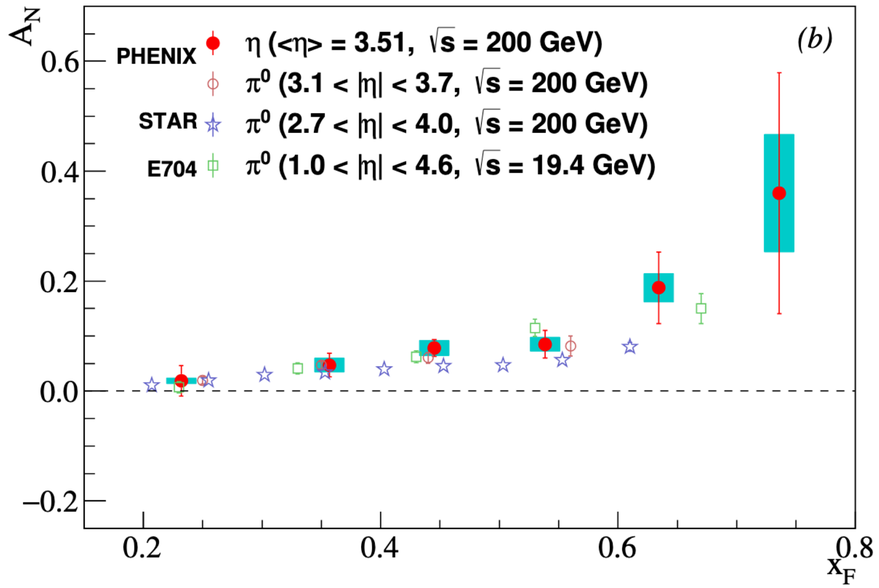
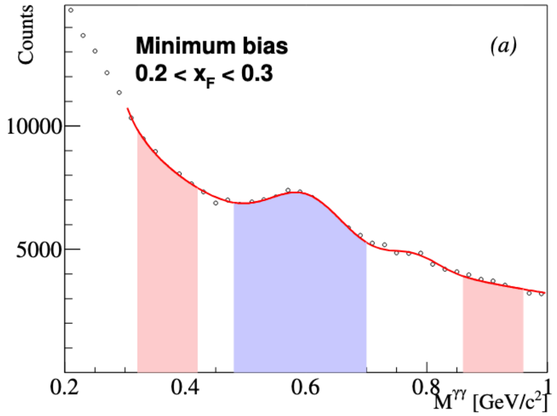
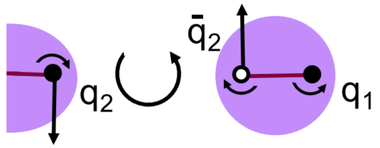


The forward ω meson TSSA

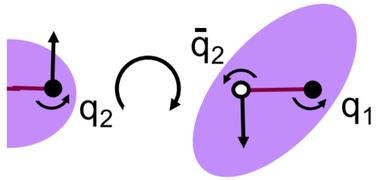
Vector vs. pseudoscalar meson spin-dependent fragmentation



- The small resonance around 782 MeV in the high-mass background of the η meson diphoton spectrum comes from $\omega(782) \rightarrow \pi^0 + \gamma$ where the boosted pion decays to photons that have merged into one cluster
- Now that we have the suggestion that the forward η asymmetry relies strongly on spin-momentum correlations in the final-state, it would be interesting to explore the **vector** omega meson
- Potential difference between how the spin is carried through hadronization into a vector meson and a pseudoscalar?



Pseudoscalar or vector with linear polarization in perpendicular plane



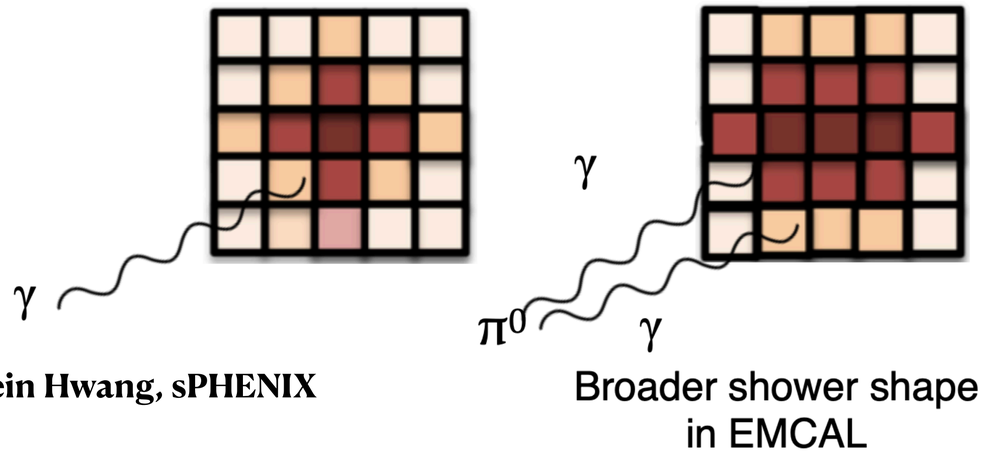
Phys. Rev. D **104**, 114038 (2021)

Vector with linear polarization in this plane

The forward ω meson TSSA

Cluster classification

- Signal purity is a major limiting factor to the analysis
- A reliable classification of merged pion clusters from photon clusters would help reduce background
- In general, merged pion clusters should have a larger spread, be less spherical, and have less energy deposited in the central tower of the cluster relative to the surrounding towers

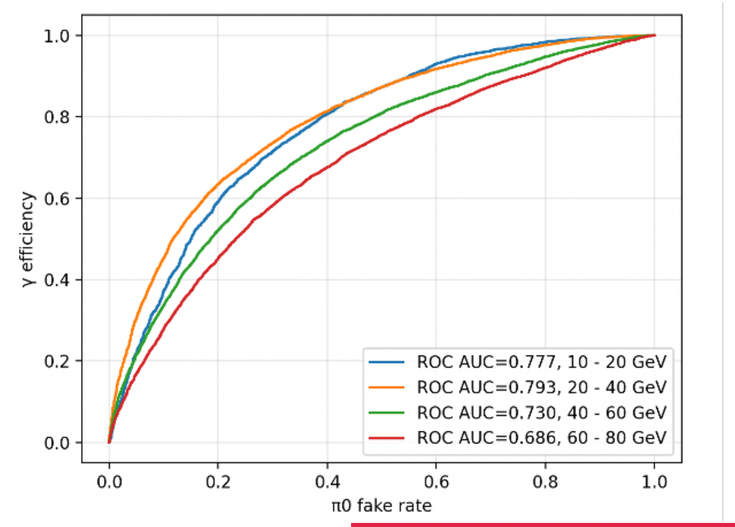


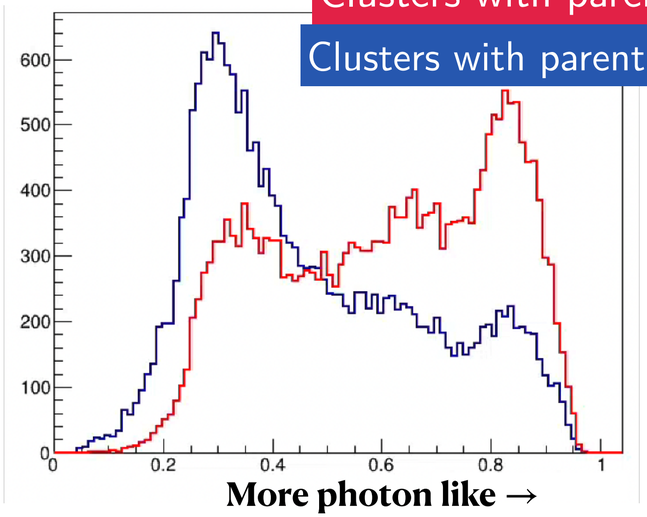
Training features
Principal axis eigenvalues of cluster dispersions
Cluster eccentricity
Cluster lateral spread
Cluster sphericity
Total energy / E_3x3 towers
Central tower energy / E_3x3 towers

The forward ω meson TSSA

Cluster classification

- Simple BDT classifier performs well on simulation, 30% improvement on TSSA uncertainty if requirement of classifying both merged pion and photon
- Early tests of the classifier on data look promising and have a realistic opportunity to make this measurement a reality!





Summary

- PHENIX has updated and improved the measurement of forward η meson TSSA
- The final PHENIX result combined across runs shows a substantial asymmetry increasing with x_F
- Predictions that use only the Sivers-like twist-3 quark-gluon correlator underestimate the magnitude of the asymmetry, suggesting a significant contribution from the final-state
- Comparison of the η meson TSSA to neutral pions in the same kinematic regime suggest minimal impacts on the spin-dependent fragmentation from hadron mass, isospin, strange quark content
- Stay tuned for the the ω meson TSSA to test the impact of polarization in the final state!