Advances in Cold-QCD and Spin Physics at RHIC

Itaru Nakagawa | RIKEN / RBRC

Central theme

From evidence for gluon helicity to precision transverse-spin probes of multi-parton correlations.

Physics roadmap

PHENIX legacy

π^0 A_LL → gluon helicity
$W^{\pm}$ A_L → polarized sea
Forward η A_N → hadronization dynamics

Experimental transition

Higher luminosity
Full-azimuth tracking
EM + hadronic calorimetry
Streaming readout

sPHENIX opportunity

Neutral mesons
Inclusive jets
Isolated photons
Heavy flavor

Helicity structure → origin of transverse single-spin asymmetries

RHIC: polarized proton collisions

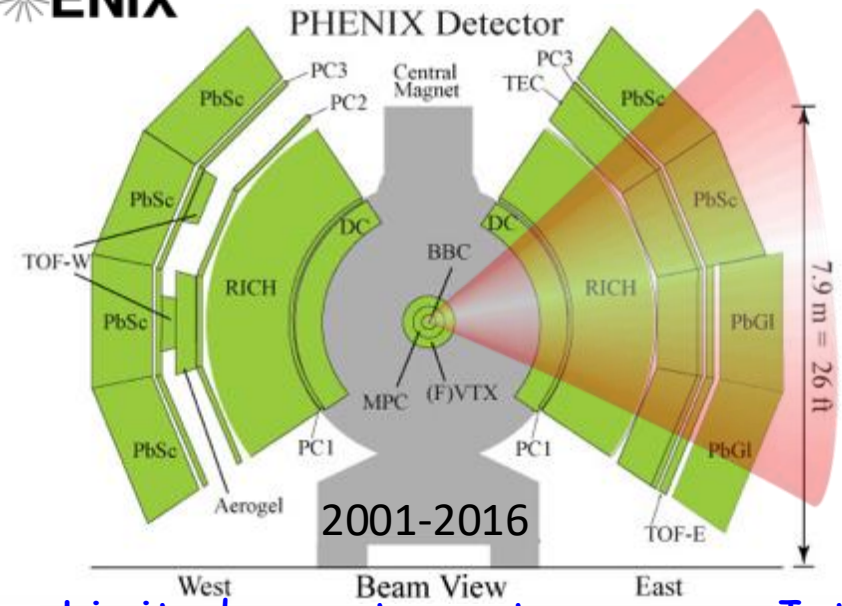
- Longitudinal polarization probes helicity PDFs and ΔG.
- Transverse polarization reveals spin–momentum correlations.
- Hard probes connect measured asymmetries to QCD factorization.

Key observables

A_LL = longitudinal double-spin asymmetry
A_L = parity-violating single-spin asymmetry
A_N = transverse single-spin asymmetry

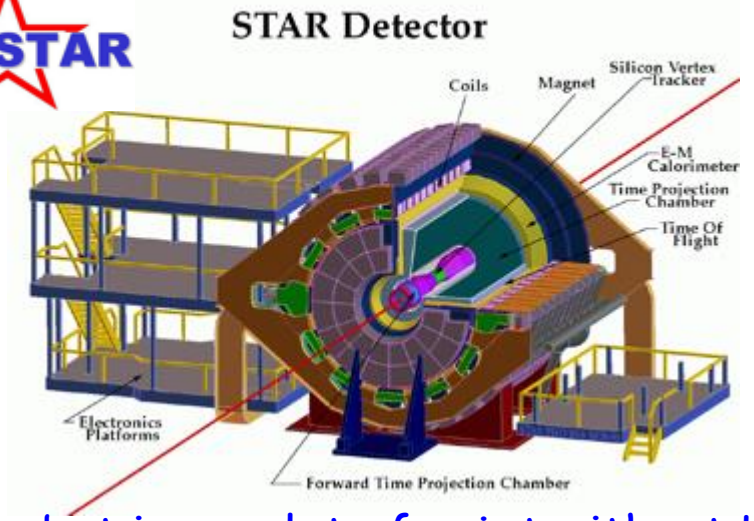
PHENIX and sPHENIX

PHENIX



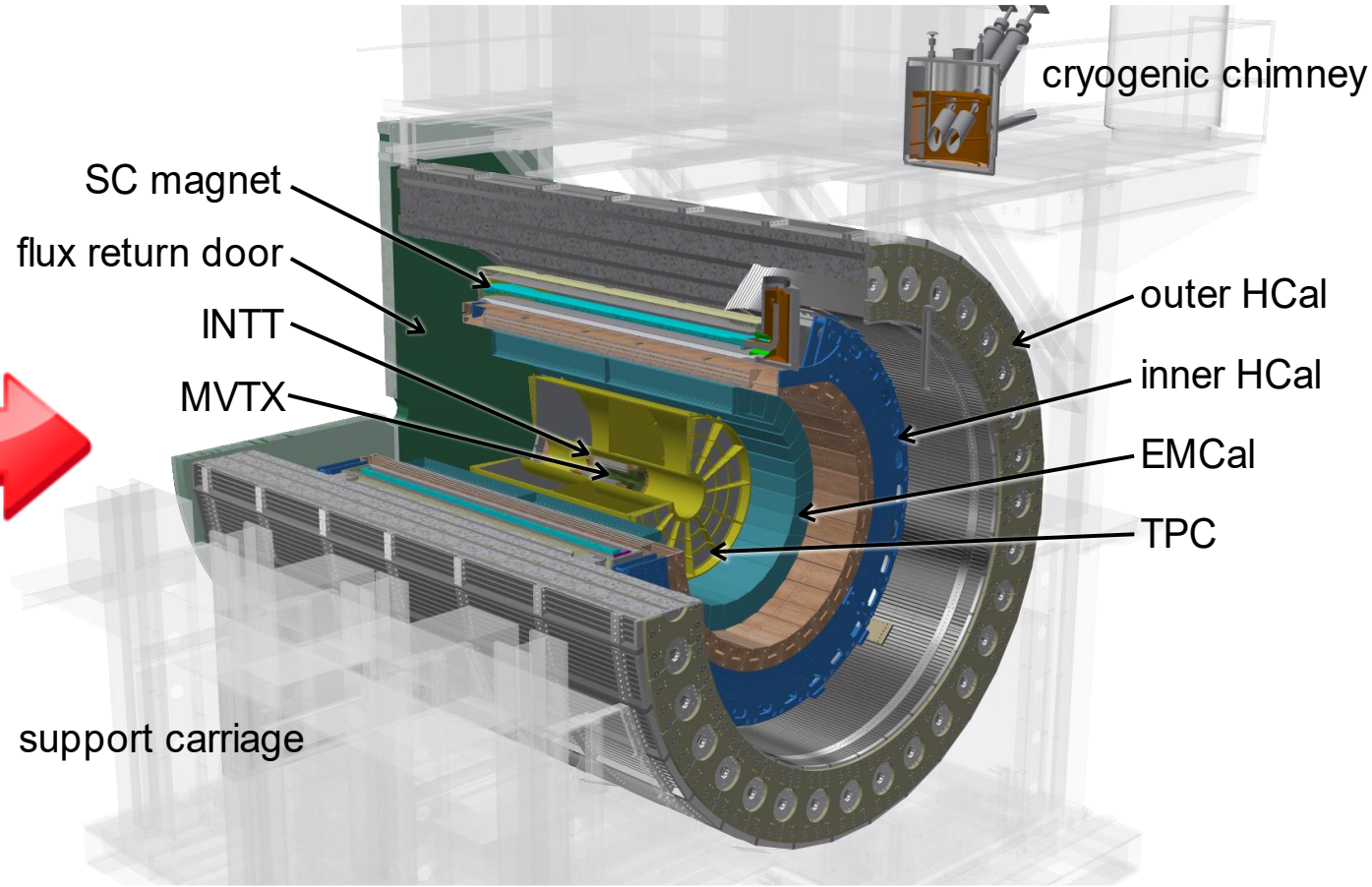
Limited acceptance to measure Jet.

STAR



4π, but incomplete for jet without HCAL

2023-2026



4π & -1<η<1 with HCAL
Designed to be ideal detector for Jet

PHENIX and sPHENIX

PHENIX Integrated Luminosity

Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2002	200	– / 0.15	15
2003	200	0.35 / –	27
2004	200	0.12 / –	40
2005	200	3.4 / 0.2	49
2006	200	7.5 / 2.7	57
2006	62.4	0.08 / 0.02	48
2008	200	– / 5.2	45
2009	200	16 / –	55
2009	500	14 / –	39
2011	500	18 / –	48
2012	200	– / 10	56
2012	510	32 / –	56
2013	510	155 / –	56
2015	200	– /60	58
2015	pAu@200	– /0.2	61
2015	pAl@200	– /0.5	58

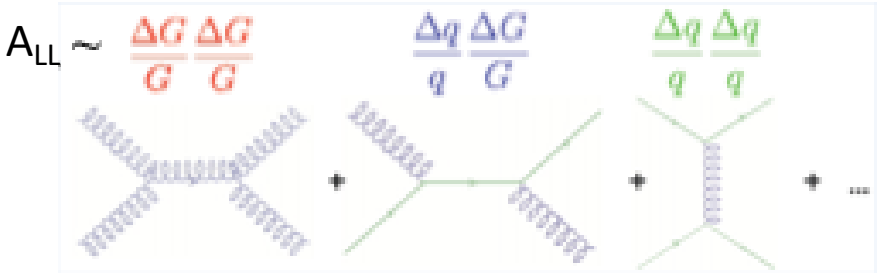
sPHENIX Integrated Luminosity

Sample	Run 2024	Run 2025	Total [pb^{-1}]	45pb^{-1} Goal
Calorimeter data	107	17	**124**	**256%**
Tracker streaming	2.9	9.7	**12.6**	**280%**
All detectors	13	17	**30**	**65%**

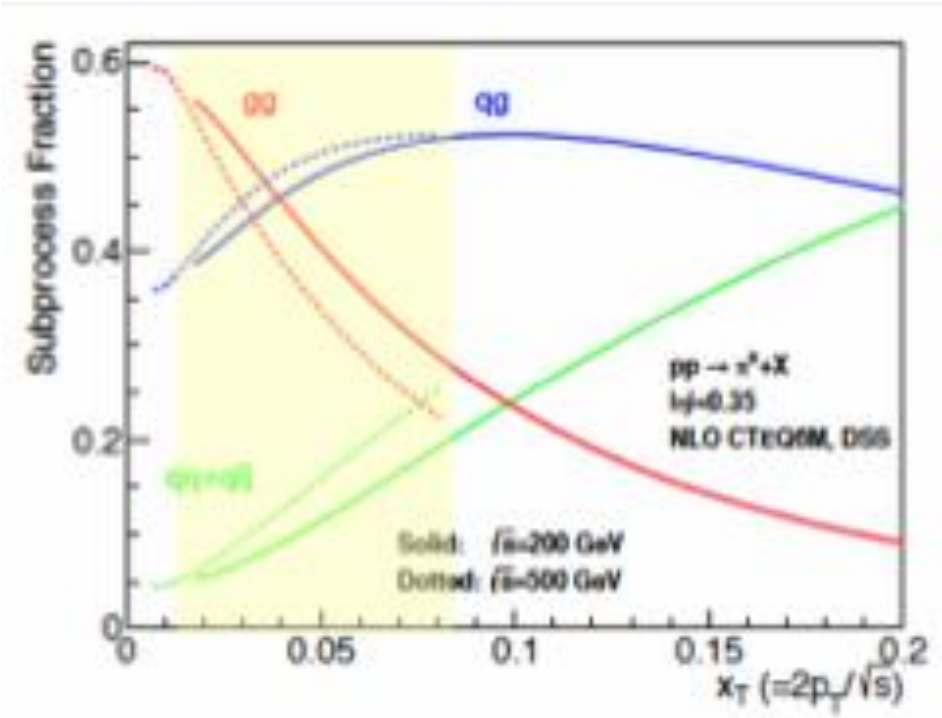
Feature	STAR	PHENIX	sPHENIX
Azimuth / η	≈2π, $\|\eta\| \lesssim 1$	2 × 90°, $\|\eta\| < 0.35$	2π, $\|\eta\| < 1.1$
Tracking	TPC + silicon (HFT era)	Drift chambers + VTX/FVTX	MVTX + INTT + TPC
PID	TPC dE/dx + TOF	RICH + TOF + EMCal	TPC dE/dx
Calorimetry	BEMC / EEMC	PbSc + PbGl EMCal	EMCal + HCal (inner & outer) Full jet-energy measurement
Best suited for	Wide-acceptance hadrons, flow, spin	e/γ, quarkonia, identified probes	Jets (HCal), γ, heavy flavor, high-rate probes

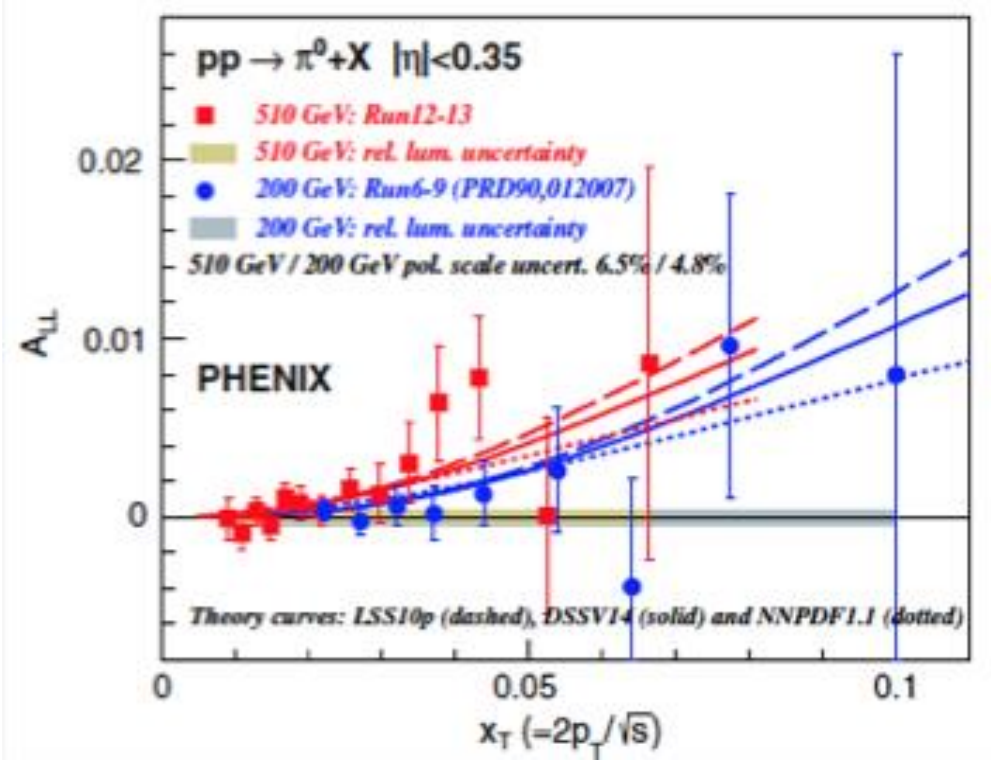
PHENIX: π^0 A_LL and gluon helicity

PRD93, 011501 (2016)



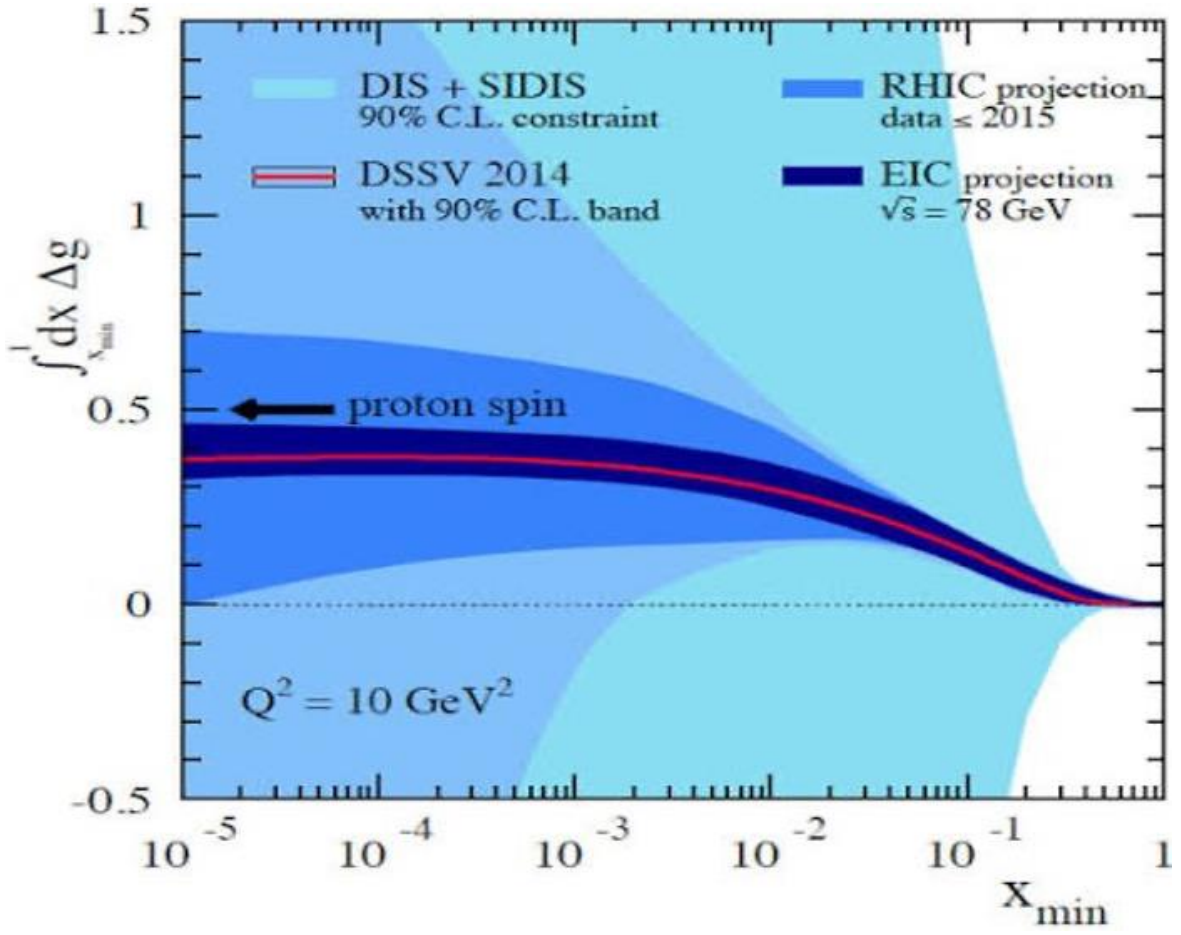
High energy p+p collision



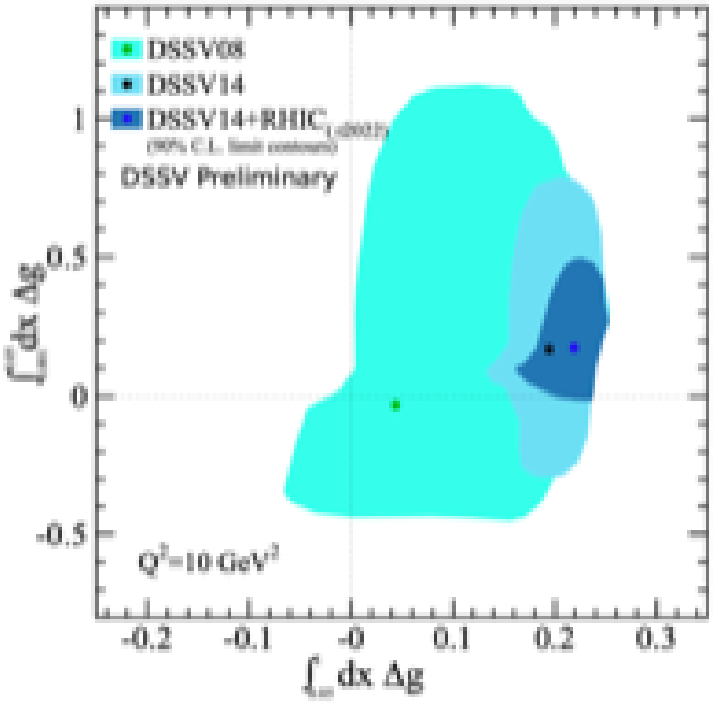


- Midrapidity π^0 production is sensitive to gluon-initiated scattering.
- Global QCD analyses support nonzero gluon polarization over measured x.
- The small-x contribution remains uncertain.

ΔG from global QCD analyses



Integrated gluon helicity: current constraints and EIC reach



$$\int_{0.05}^{1} dx\Delta(x) = 0.218 \pm 0.027$$

- Significant contribution from gluon spin (at x>0.05)

Similar conclusion from other global fits: NNPDF, JAM

- More ALL data are published: η, $\pi^{\pm}$, $h^{\pm}$, J/ψ, HF e
- Still large uncertainty in unmeasured region (x<0.05)

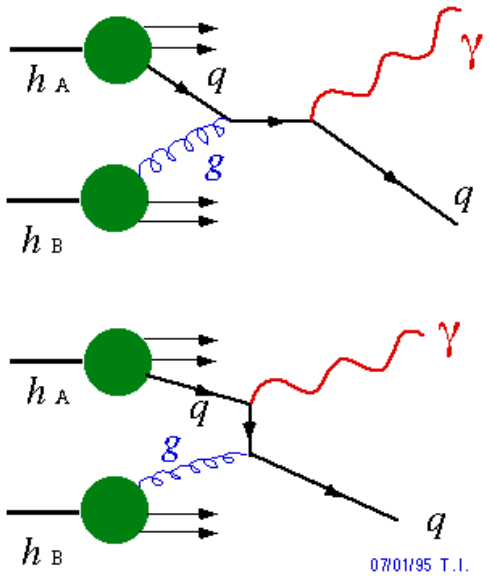
=> Will be fully resolved at EIC (no longitudinal in sPHENIX)

- Sign needs a confirmation (see next slide)

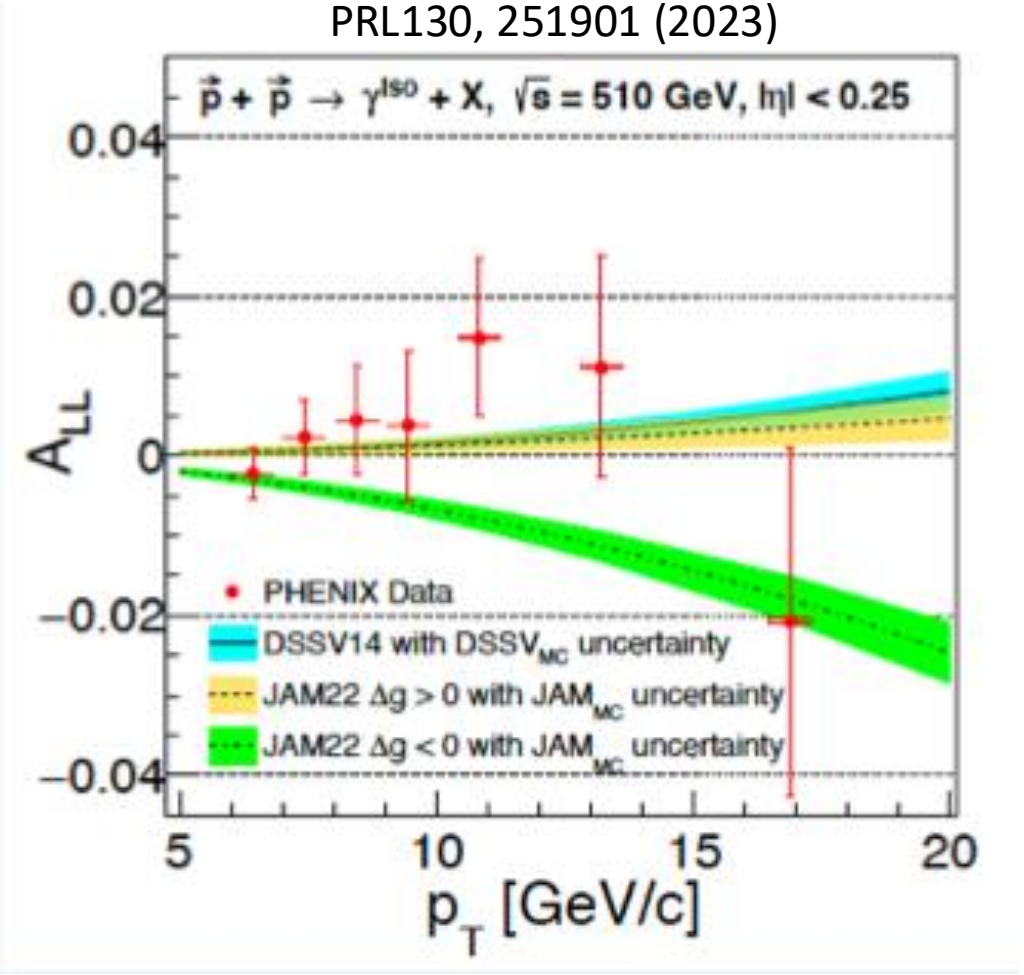
=> Need cleaner prob, e.g. direct photons

Direct photons help test the sign of ΔG

Gluon Compton Scattering



PRL130, 251901 (2023)

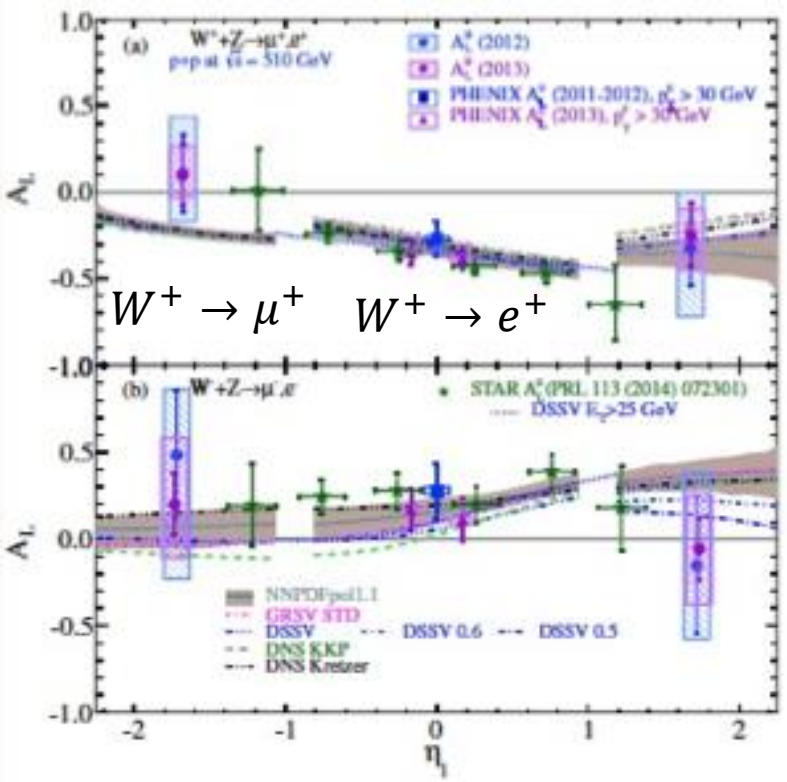


- Photon production reduces hadron-fragmentation dependence.
- PHENIX data favor positive ΔG in the measured region.
- Complementary to inclusive π^0 A_LL.

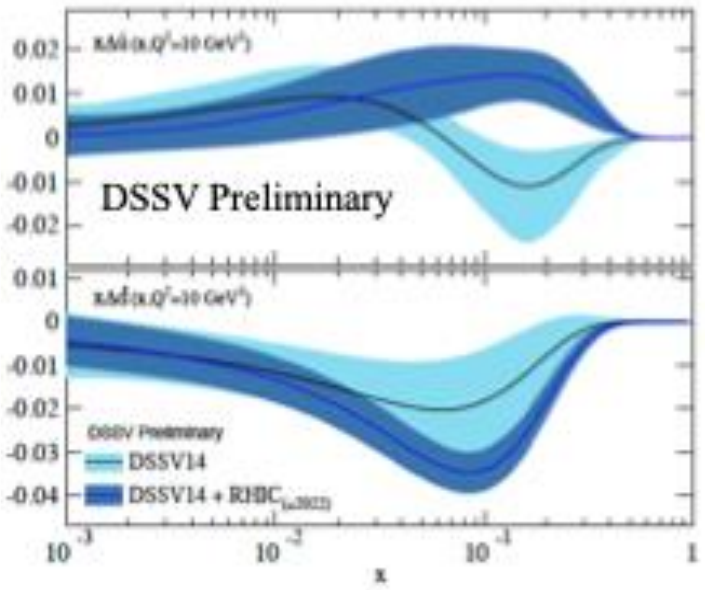
Source: Bazilevsky, DIS 2026, slide 6 (figure reproduced from review)

$W^{\pm}$ A_L: flavor-separated polarized sea

PRD 98, 032007 (2018)



$$d_L \bar{u}_R \to W^-$$
$$u_L \bar{d}_R \to W^+$$



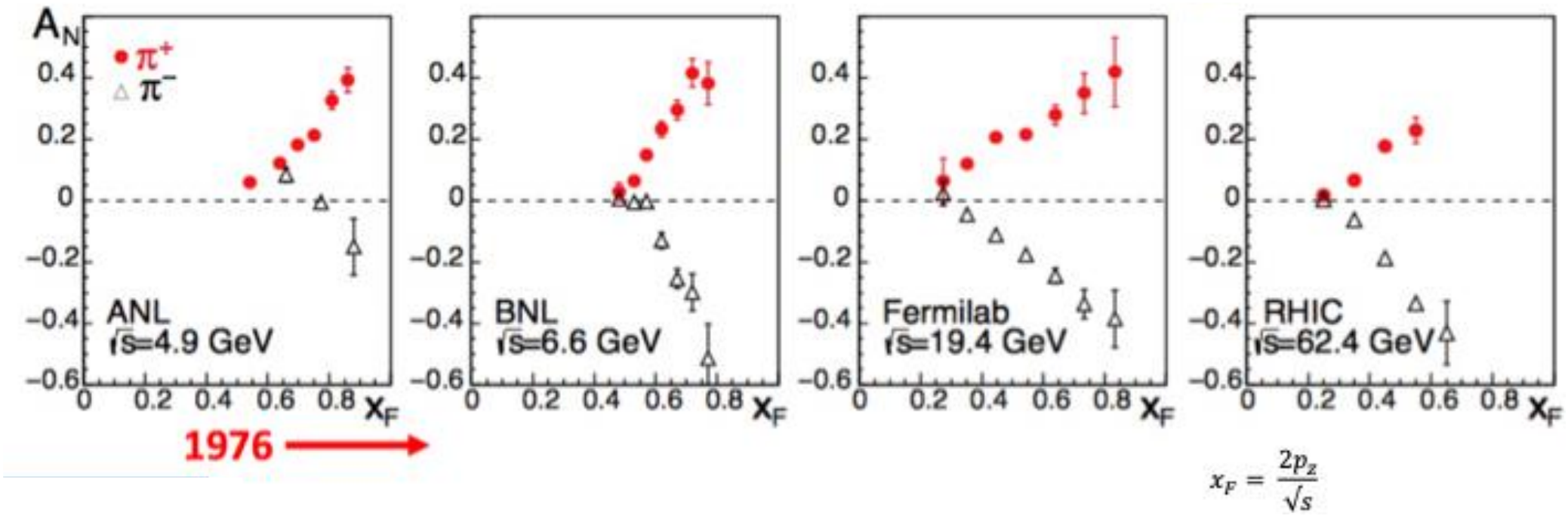
STAR+PHENIX included

- Parity-violating W production probes helicity at Q ~ M_W.
- No hadron fragmentation functions are needed.
- Data inform $\Delta\bar{u}$ and $\Delta\bar{d}$ in global analyses.

Source: Bazilevsky, DIS 2026, slide 7 (figure reproduced from review)

Transverse Single Spin Asymmetry in $p^{\uparrow}$+p Collision

Predicted to be small $\sim \frac{m_q \alpha_s}{Q}$



$$x_F = \frac{2p_z}{\sqrt{s}}$$

Transverse Spin Physics at RHIC

Initial State:

Ryotaro Koike's Talk

- A_N for jets, direct photons
- A_N for heavy flavor → gluon
- A_N for W, Z, DY

Sensitive to correlations
proton spin – parton **transverse motion**

Not universal between SIDIS & pp

- Parton dynamics
- 3D imaging

Final State:

- Hadron azimuthal asymmetry in jet
- Hadron pair azimuthal asymmetry (Interference fragmentation function)

Sensitive to
transversity x spin-dependent FF

Universal between SIDIS & pp & e+e-

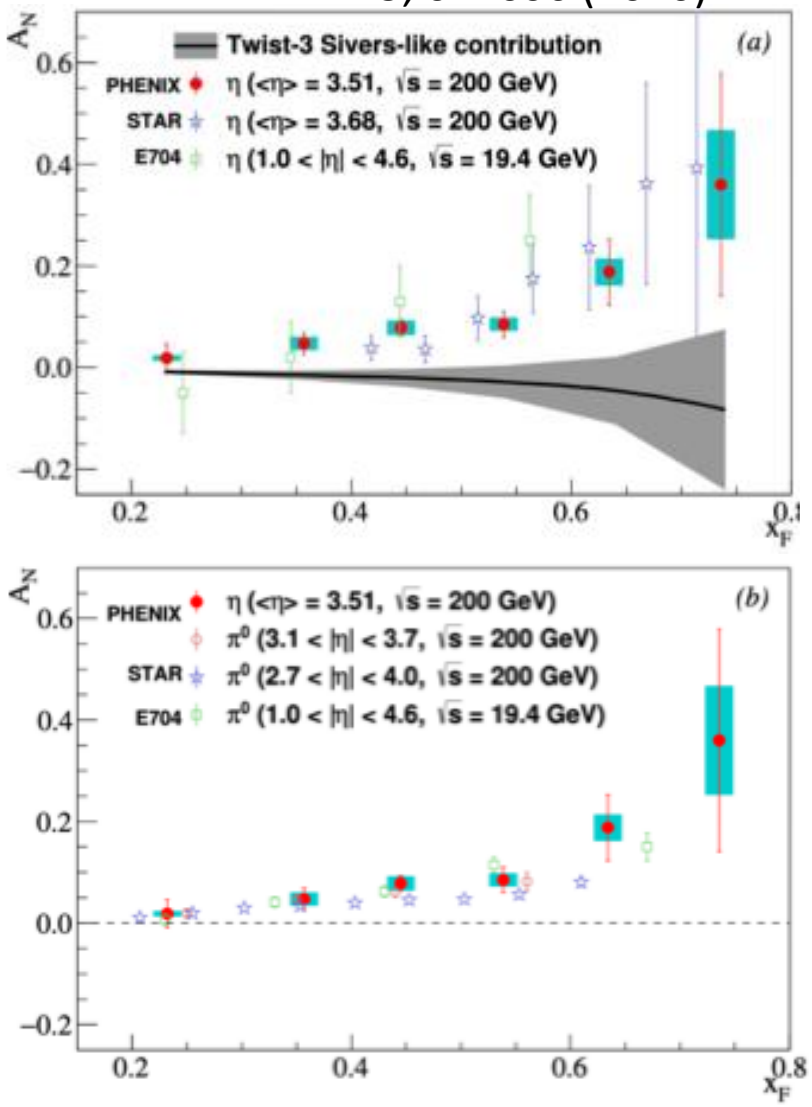
- Quark transversity
- Tensor charge

Other mechanisms

- Diffraction (Seughwan Lee's Talk)

Forward η A_N: a large transverse asymmetry

PRD 113, 071006 (2026)

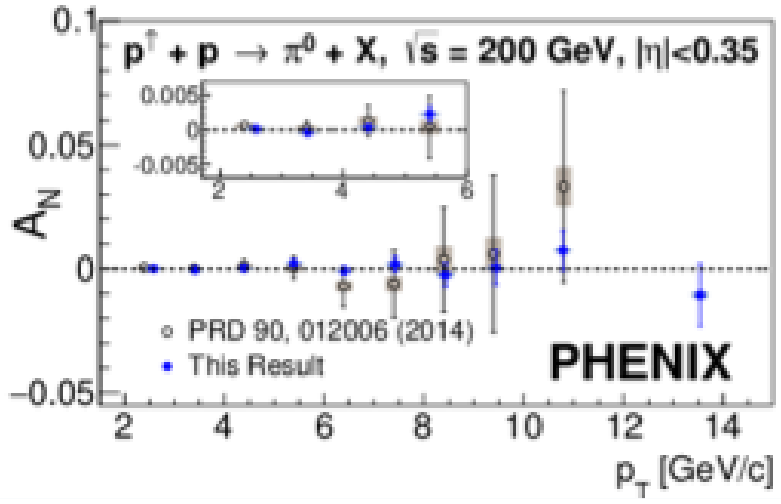


- Forward η A_N rises with x_F; backward A_N is near zero.
- Initial-state twist-3 calculations alone appear insufficient.
- η and π^0 asymmetries show broadly similar behavior. Suggests a limited impact from mass, isospin, strange quark content on spin-dependent hadronization

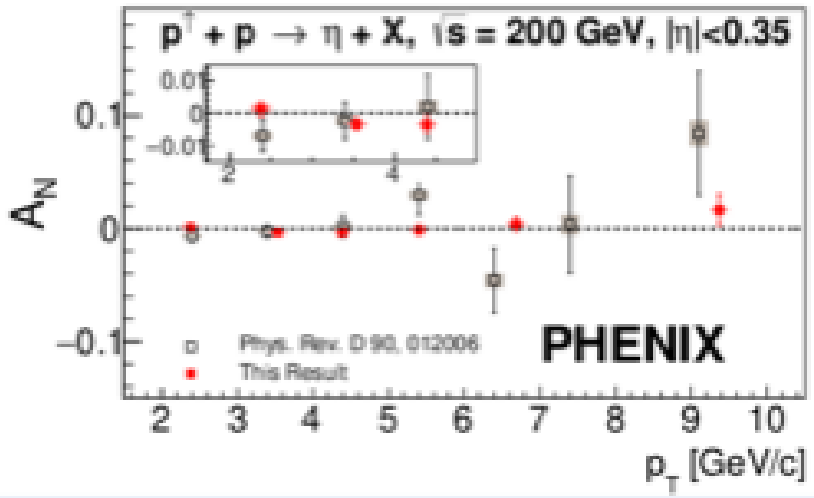
PHENIX → sPHENIX: midrapidity meson A_N

Sensitive to gluon dynamics
Used to constrain gluon Sivers
Anselmino et al, PRD 74 (2006), 094011
D'Alesio et al, JHEP 1509 (2015), 119

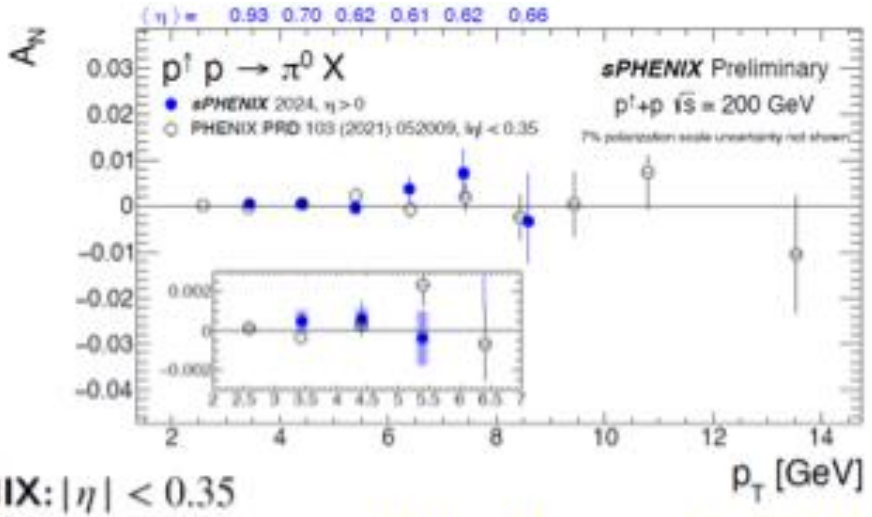
PHENIX: π^0, η

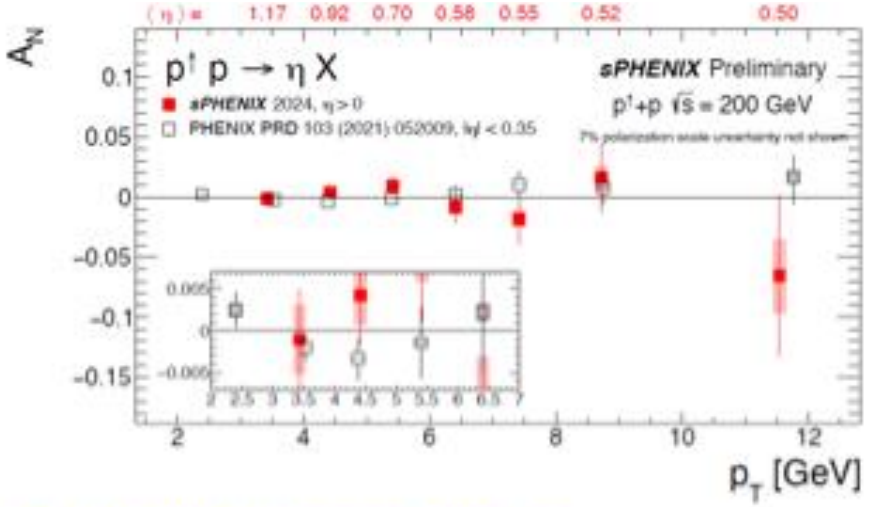


PRD103, 052009 (2021)



sPHENIX: π^0 and η (1/3 of total data)





PHENIX: $|\eta| < 0.35$
sPHENIX: $\eta > 0$

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

Advantages of Streaming readout

Calorimeter-triggered events

High-statistics jet and photon samples with calorimetric energy measurement.

Tracker streaming

Minimally trigger-biased tracking samples, enabling low-p_T charged particles and heavy-flavor reconstruction.

- Different readout modes target complementary spin observables.
- D^0 A_N is a promising future probe of gluon correlations.
- Streaming data do not provide the same calorimeter content as triggered samples.

Source: Seidl, DIS 2026, slide 7 (figure reproduced from review)

From hadrons to jets: cleaner initial-state access

Inclusive hadron A_N

Initial-state twist-3 correlations + fragmentation-related twist-3 contributions.

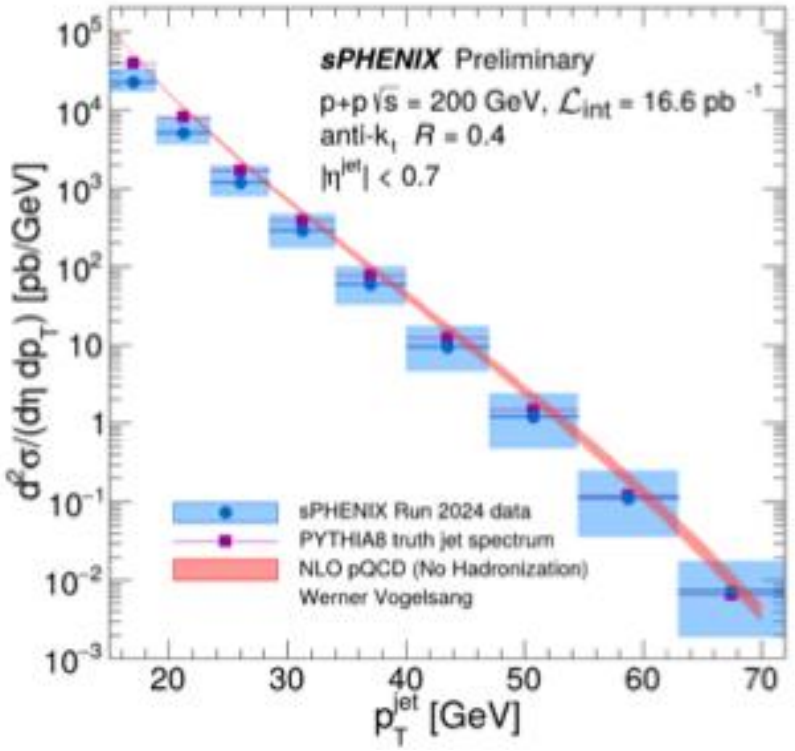
Inclusive jet A_N

Reduced sensitivity to hadron-specific fragmentation; direct reconstruction of outgoing partonic energy flow.

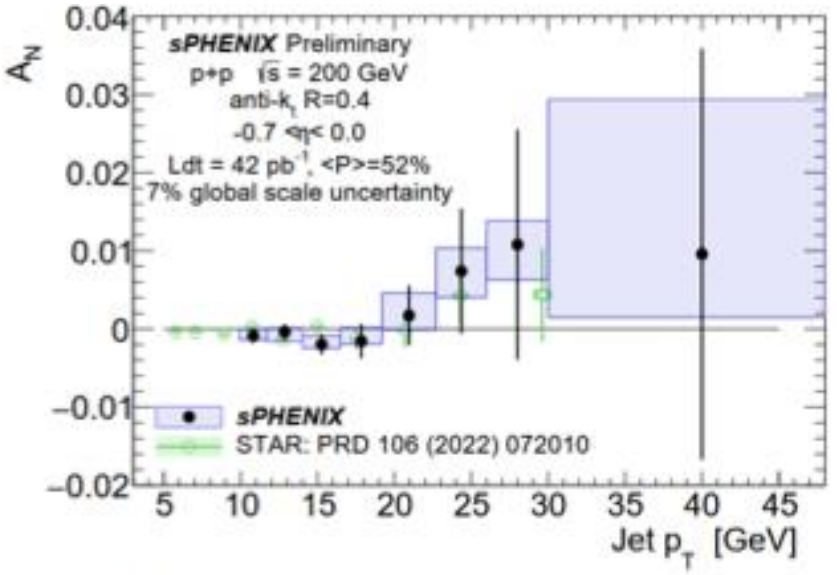
sPHENIX EMCal + HCal enable full calorimetric jet reconstruction at RHIC

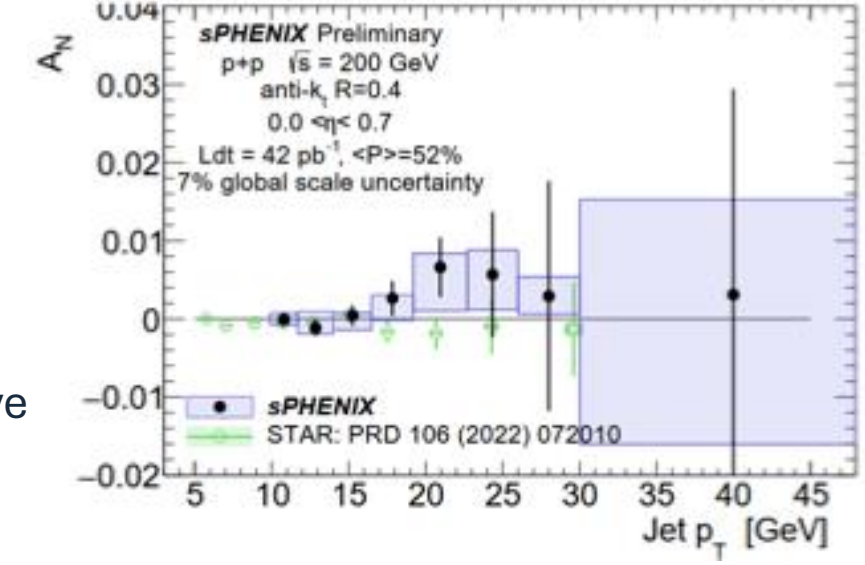
Jet A_N constrains combinations of quark–gluon and tri-gluon correlations; it does not isolate a single correlator.

sPHENIX: reconstructed jet performance



- Anti-kT R = 0.4 jets
- |η_jet| < 0.7
- Jet energy corrections and unfolding
- Precision calorimetry makes inclusive jet A_N feasible

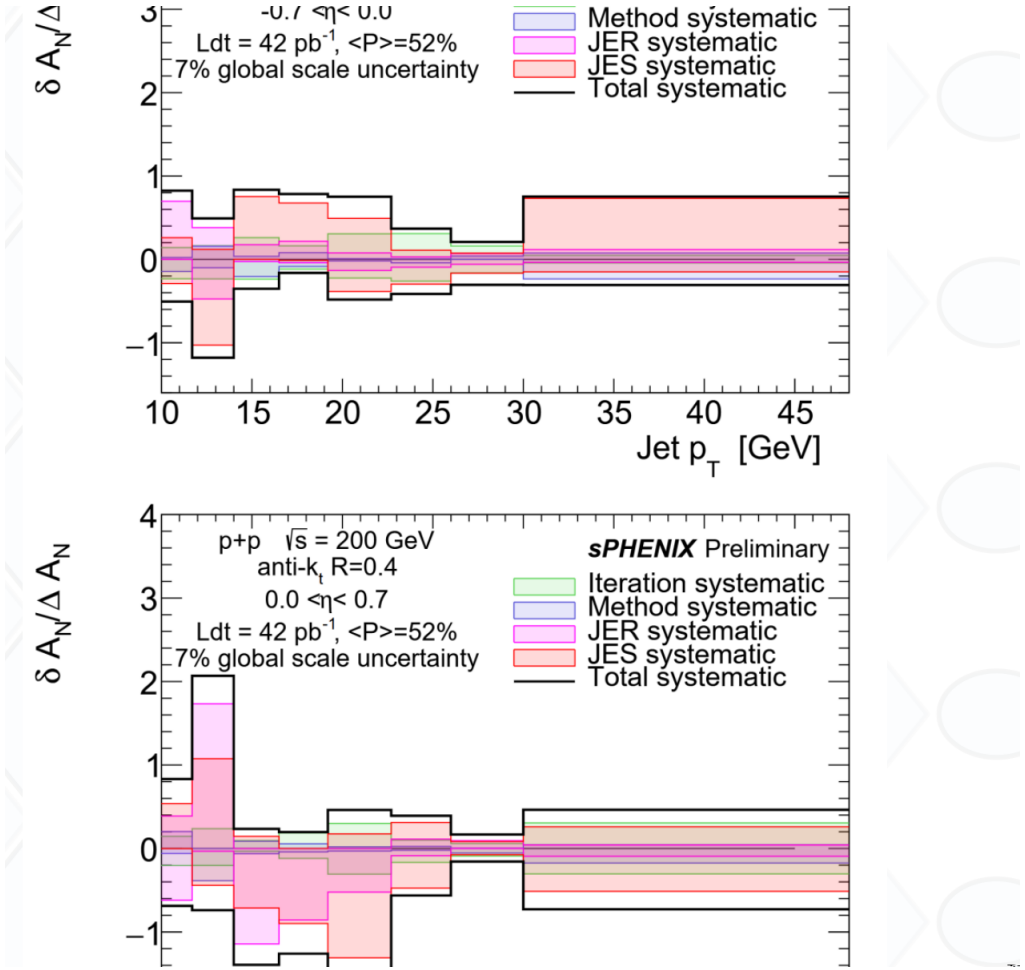




- Currently ~40% of data analyzed
- Asymmetries also fully unfolded
- Consistent with STAR results
- More details in:

sPH-CONF-COLDQCD-2025-02

Jet A_N: systematics and interpretation



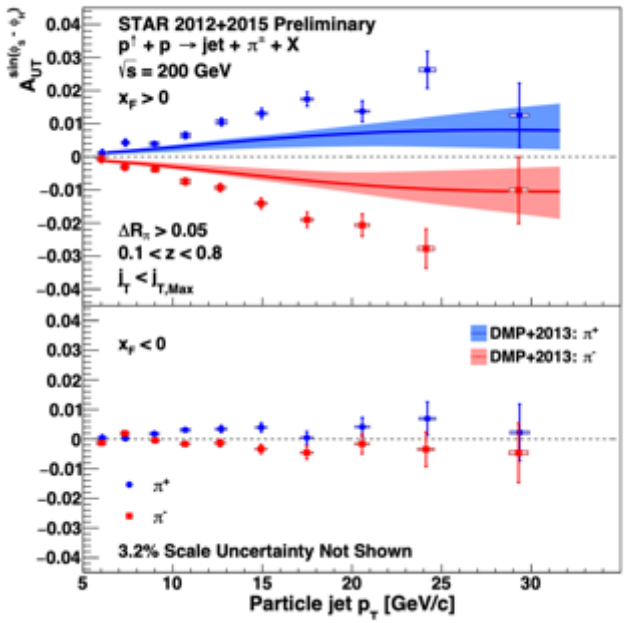
- Key systematics: JES, JER and unfolding iterations.
- Relative-luminosity and square-root methods agree.
- A_N constrains initial-state twist-3 dynamics, including gluonic correlations.

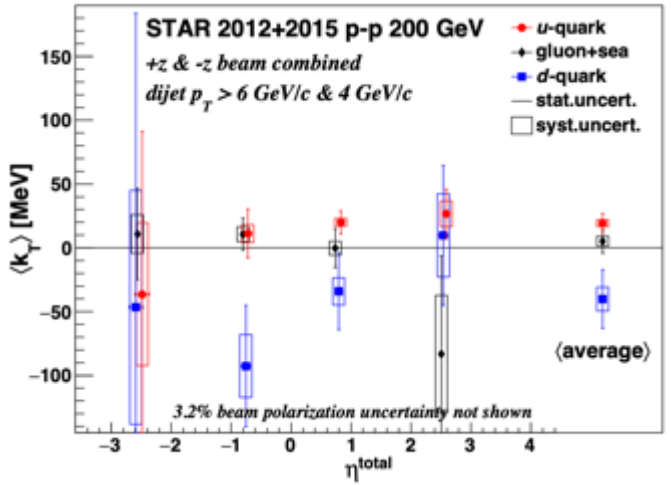
Source: Seidl, DIS 2026, slide 14 (figure reproduced from review)

TSSA Jet Channels

- **Inclusive jet** $(p^{\uparrow} + p \rightarrow \text{jet} + X)$
- **Jet + hadron in jet**
  - Both Transversity and Collins fragmentation function can be accessed.
  - Collins effect in pp→jet process: Azimuthal modulation depending on the proton spin relative to the jet axis
- **Dijet** $(p^{\uparrow} + p \rightarrow \text{jet} + \text{jet} + X)$
  - Direct access to parton intrinsic transverse momentum.
  - STAR preliminary results showed a nonzero effect for charge-tagged jets.
  - sPHENIX will significantly contribute to dijet measurement.
- **γ-Jet** $(p^{\uparrow} + p \rightarrow \gamma + \text{jet} + X)$
  - Both quark/gluon Sivers functions are accessible depending on the rapidity selection.

JPS Conf. Proc. **37**, 020118 (2022)

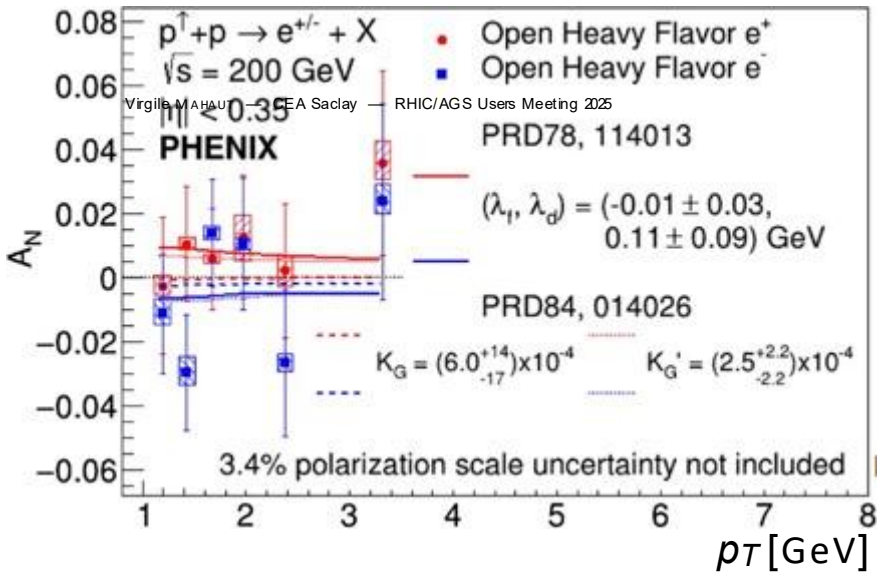




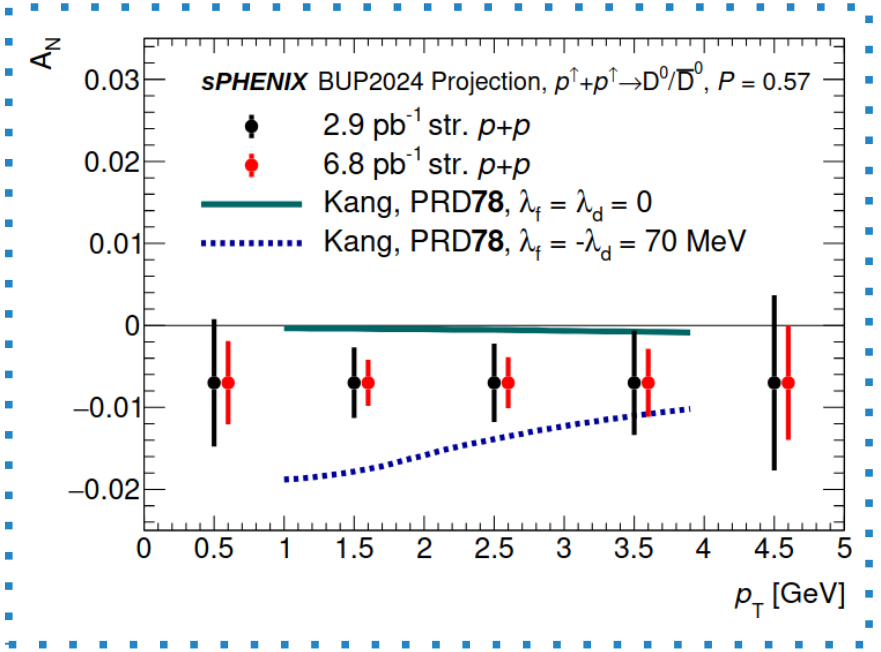
$\langle k_T \rangle$ **distribution by** $p^{\uparrow}p \rightarrow \text{jetjet}X$ **measurement by STAR (arXiv:2305.10359)**

Heavy Flavour TSSA

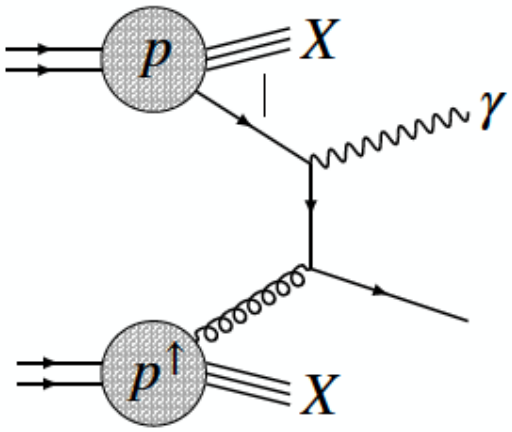
- As for direct photons, sensitive to twist-3 **tri-gluon correlators** and **gluon Sivers TMD**
- PHENIX: Open heavy flavour through leptonic decay: $p^{\uparrow}p \rightarrow e^{+/-}X$
- New with sPHENIX: Prompt D^0: $p^{\uparrow}p \rightarrow D^0/\bar{D}^0X$



Statistical projection for sPHENIX

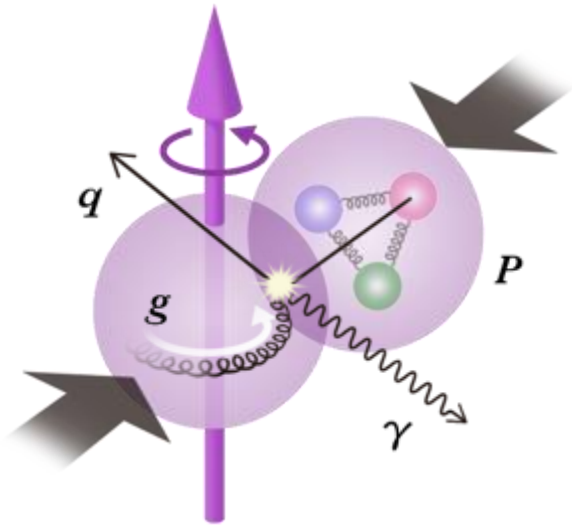


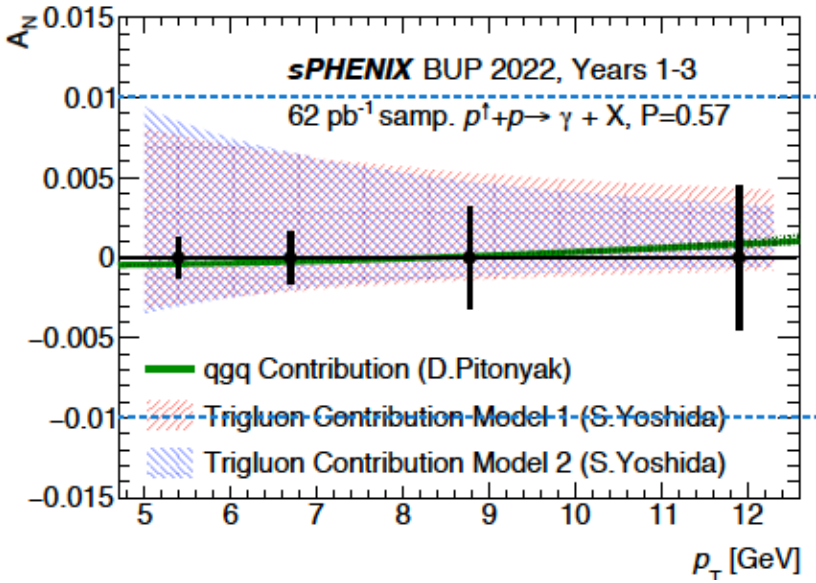
Gluon TMD by Direct-γ

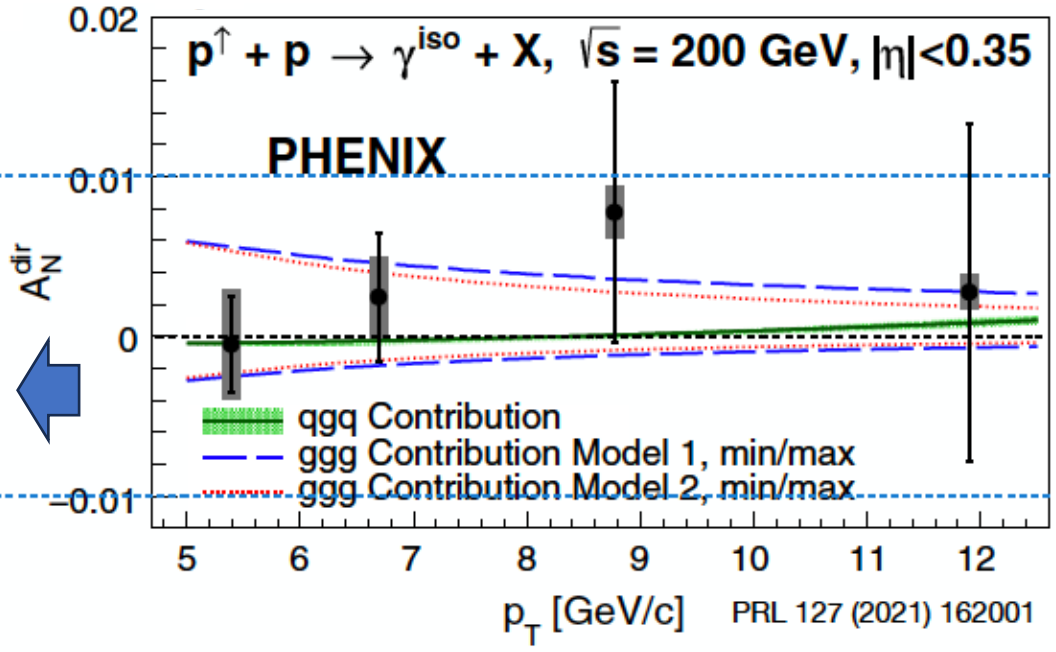


$$p^{\uparrow} + p \rightarrow \gamma + X$$

Hints on orbital motion of gluons thru Transverse Momentum Dependence measurement.







To be presented by Ryotaro Koike

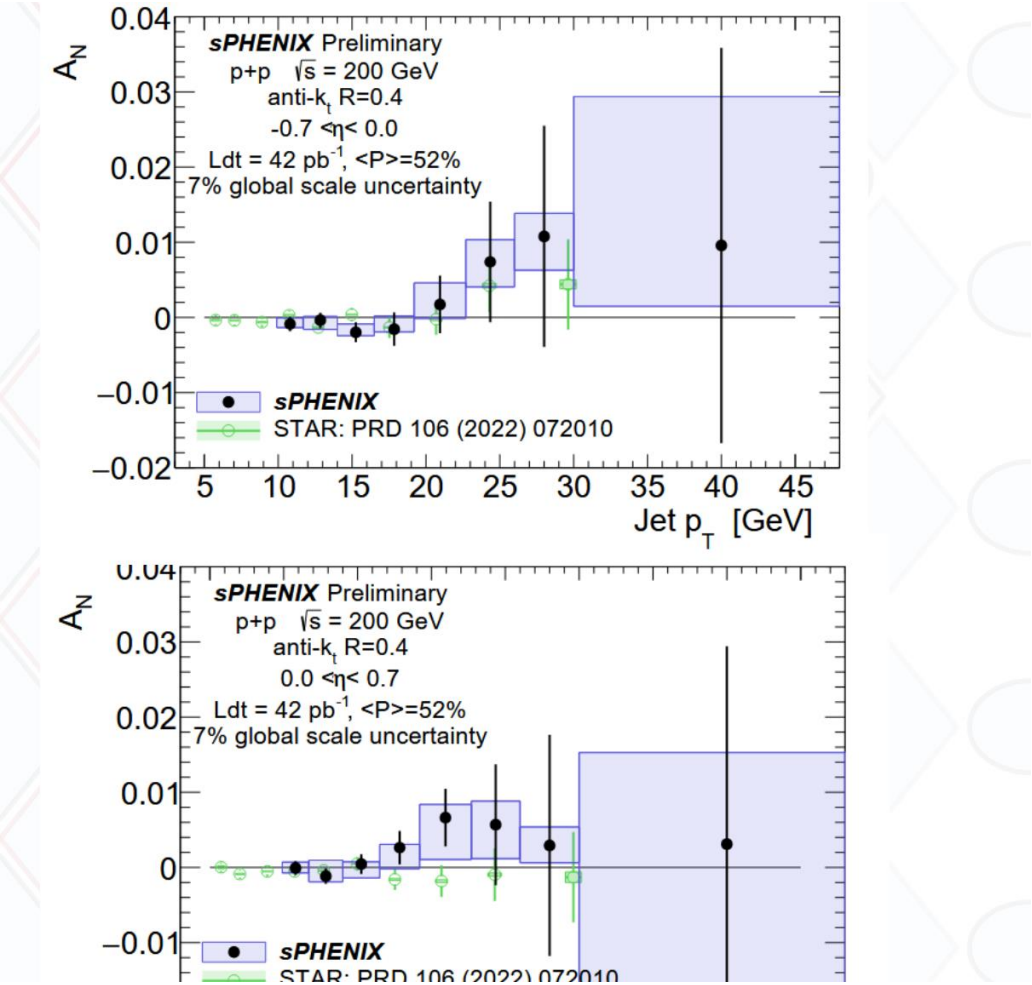
Summary and EIC outlook

- PHENIX established essential constraints on gluon helicity and polarized sea quarks.
- Forward hadron A_N demonstrates rich spin-dependent QCD dynamics.
- sPHENIX combines 124 pb^{-1} calorimeter data, full calorimetry and tracking/streaming capabilities.
- Inclusive jet A_N reduces hadron-fragmentation ambiguities and constrains initial-state correlations.
- The EIC will extend precision multidimensional imaging, especially at low x.

From spin asymmetries to the partonic mechanisms behind them

backup

Inclusive jet A_N: first sPHENIX results

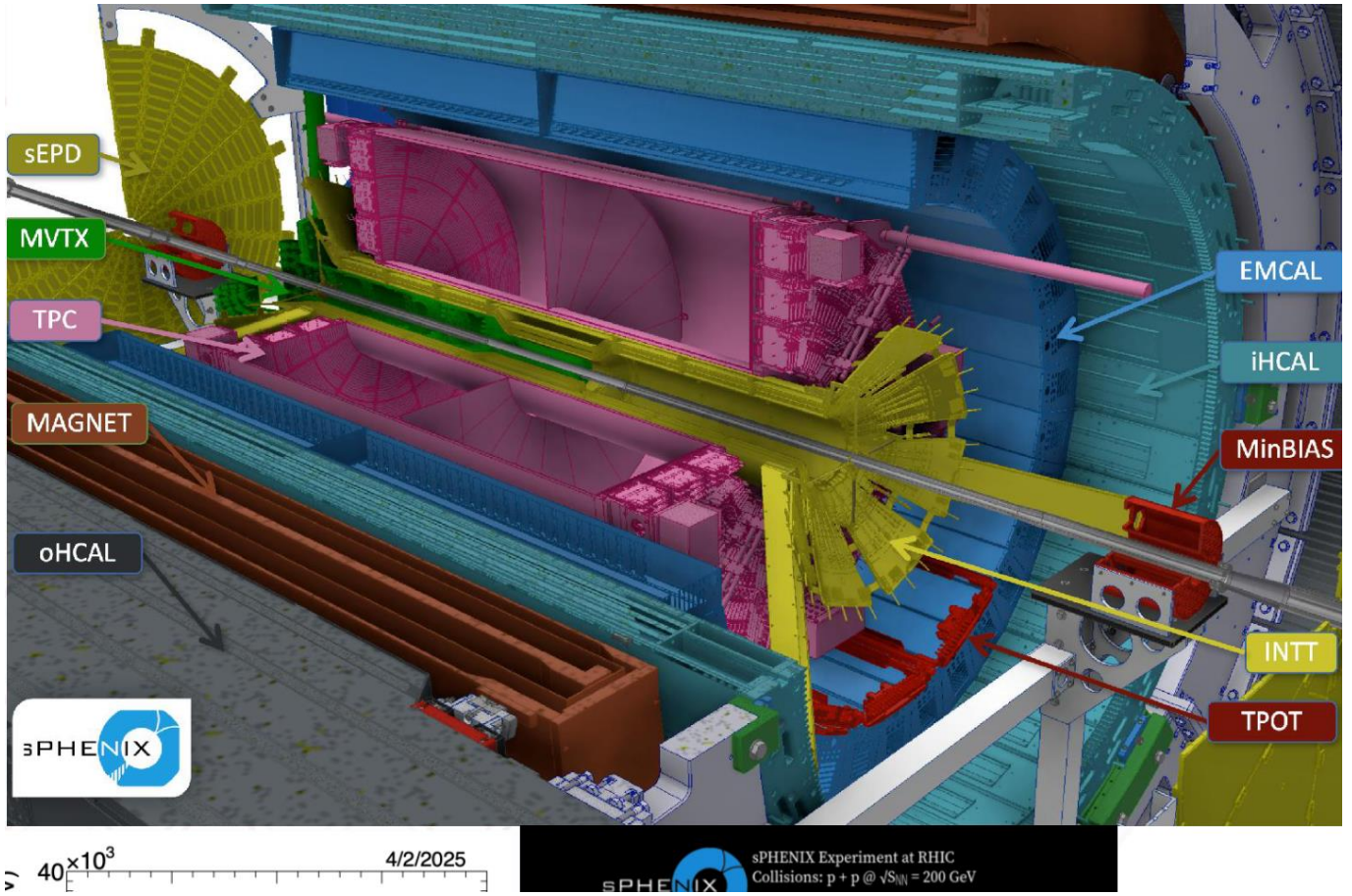


- Preliminary measurement using ~40% of the data set.
- Jet asymmetries unfolded to particle level.
- Consistent with STAR within uncertainties.
- Predominantly statistics limited.

Source: Seidl, DIS 2026, slide 15 (figure reproduced from review)

sPHENIX: full-azimuth jet detector

- $|\eta| < 1.1$ and full 2π azimuth
- MVTX + INTT silicon tracking
- TPC tracking and TPOT
- EMCal + inner/outer HCal
- BABAR solenoid
- Stream readout for trackers



Integrated luminosity: multiple data streams

Recorded integrated luminosity (pb^{-1})

Sample	Run 2024	Run 2025	Total
Calorimeter data	107	17	**124**
Tracker streaming	2.9	9.7	**12.6**
All detectors	13	17	**30**

These are distinct acquisition samples; totals must not be added together.

Source: Seidl, DIS 2026, slide 7 (figure reproduced from review)