Spin physics at PHENIX/sPHENIX

Workshop on parton distribution functions in the EIC era

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June 16, 2025

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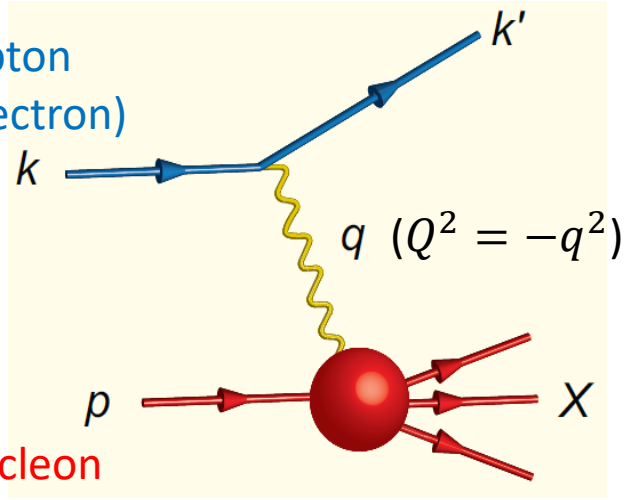
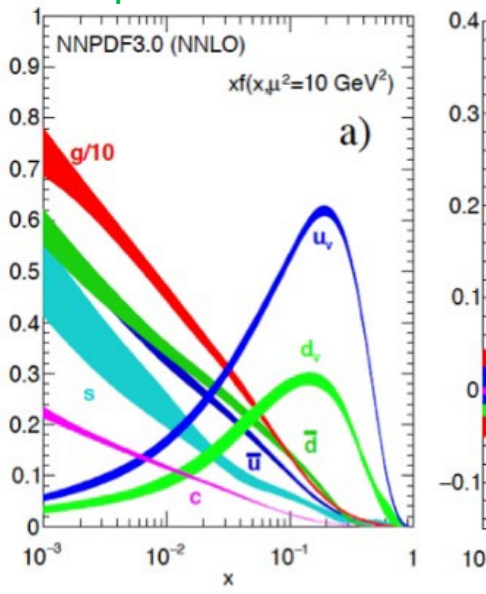
Quark-gluon structure

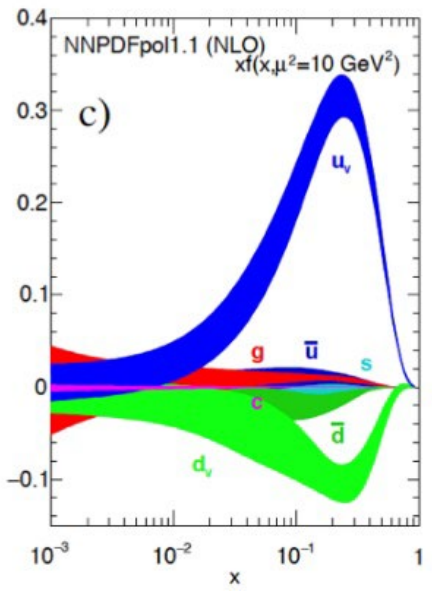
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant improvement of precision of the polarized PDF at EIC



Unpolarized PDF

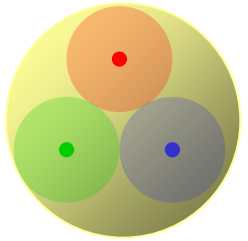


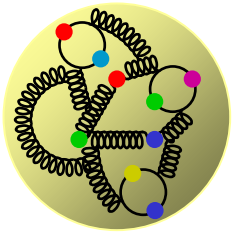
Polarized PDF

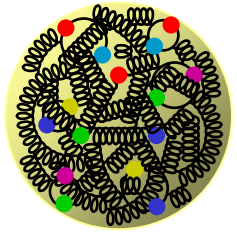


Nucleon structure

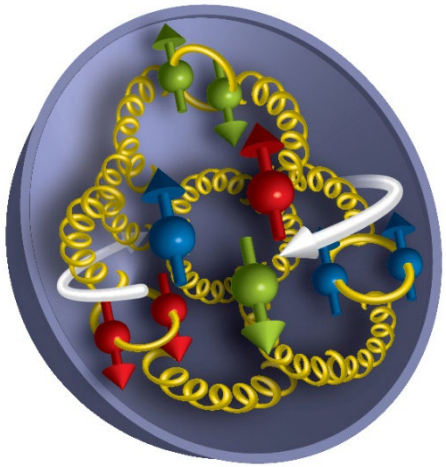
- Constituent-quark model
  - Quarks with the effective mass (caused by the gluon)
  - Explains the magnetic moment of the nucleons
  - But, the quark spin cannot explain the nucleon spin (“spin puzzle”)
- Quark-gluon model
  - Current quarks and gluon interaction
  - Initial state of high-energy hadron colliders
- Understanding the differences (or gap) of these models
  - Chiral symmetry (breaking)
  - Confinement







Nucleon spin physics



- Spin puzzle
  - Origin of the nucleon spin in the quark-gluon picture

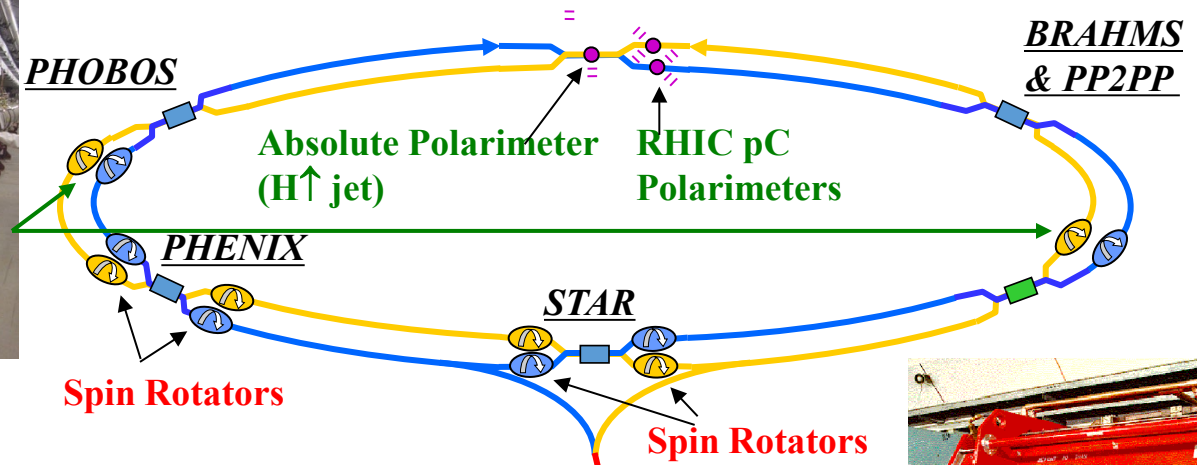
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Quark spin: $\frac{1}{2}\Delta\Sigma$ — Gluon spin: Δg — Orbital angular momentum: L

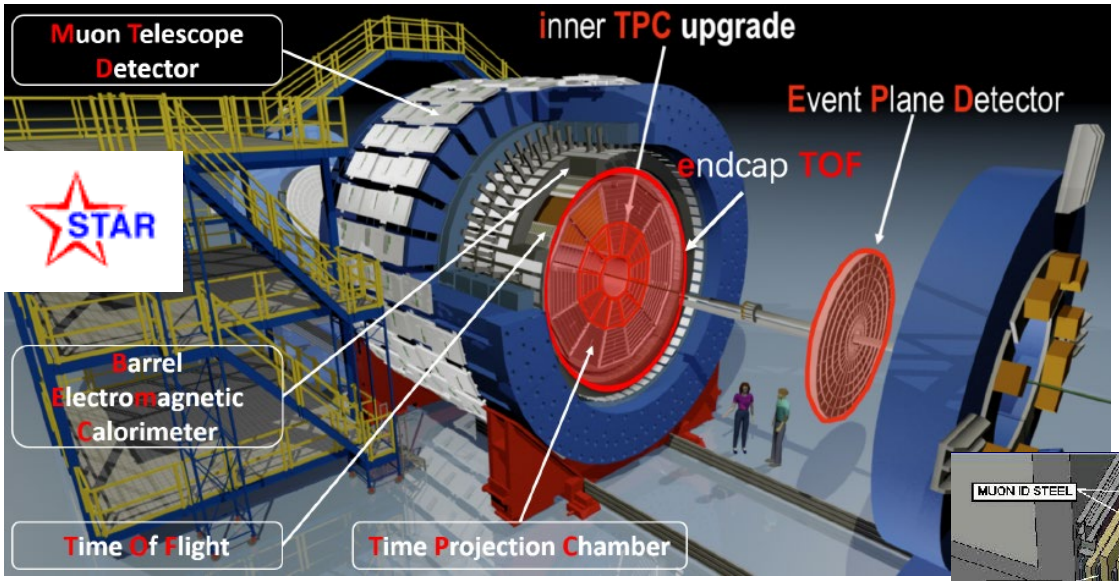
  - Quark-spin contribution is only about 30% of the nucleon spin
- Longitudinal-spin (beam axis direction) asymmetry measurement
  - Gluon polarization measurement
  - Anti-quark polarization measurement using W boson
- Transverse-spin asymmetry measurement
  - Understanding of orbital motion inside the nucleon and orbital angular momenta of quarks and gluons

Polarized proton acceleration at RHIC

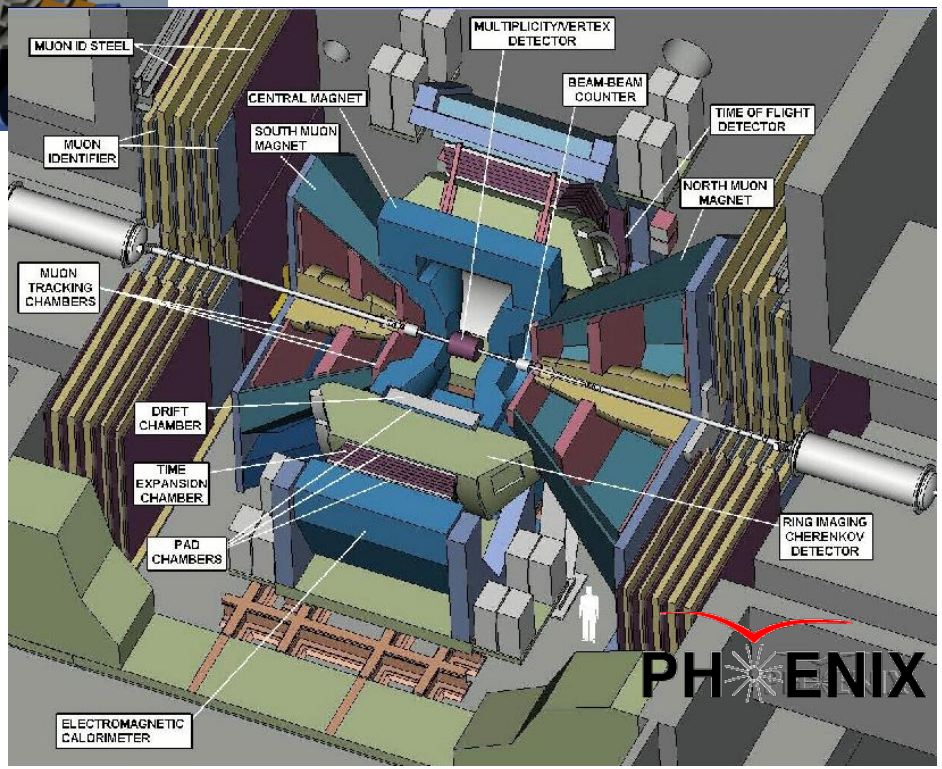
- Keeping and monitoring polarization from the polarized proton source



Polarized proton collision experiments



- STAR detector
  - 2π coverage for jet measurement
  - barrel TPC and EMC
  - endcap EMC

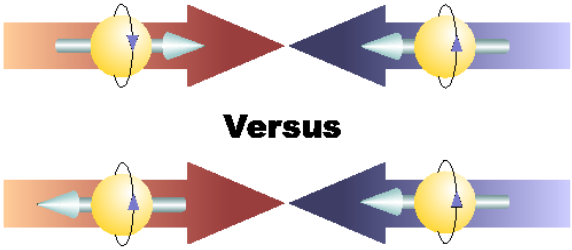


- PHENIX detector
  - limited acceptance
  - high resolution central EMCal
  - high-rate trigger and DAQ
  - forward muon detectors

Longitudinal polarized proton collision

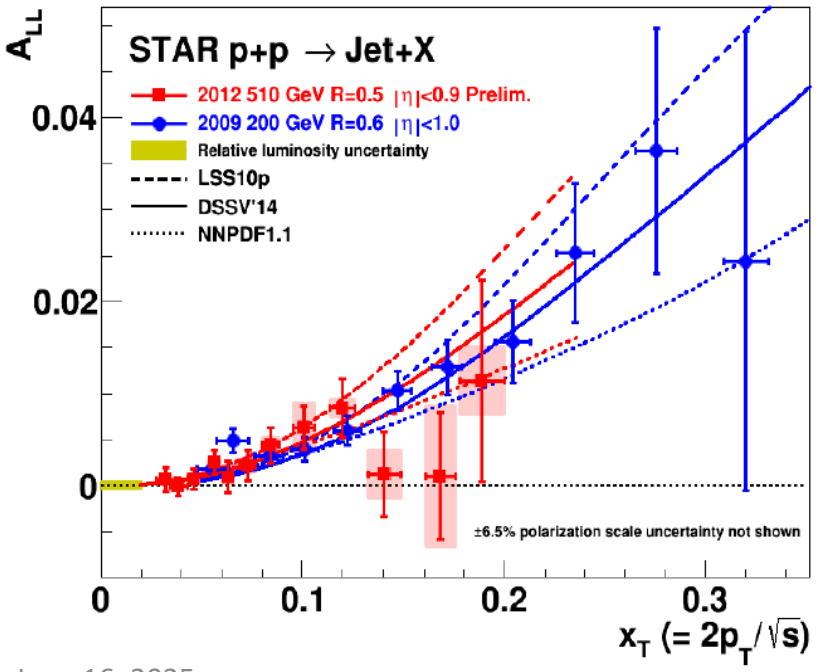
- A_{LL} (double-helicity asymmetry) measurement
  - Polarized in the beam axis direction

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

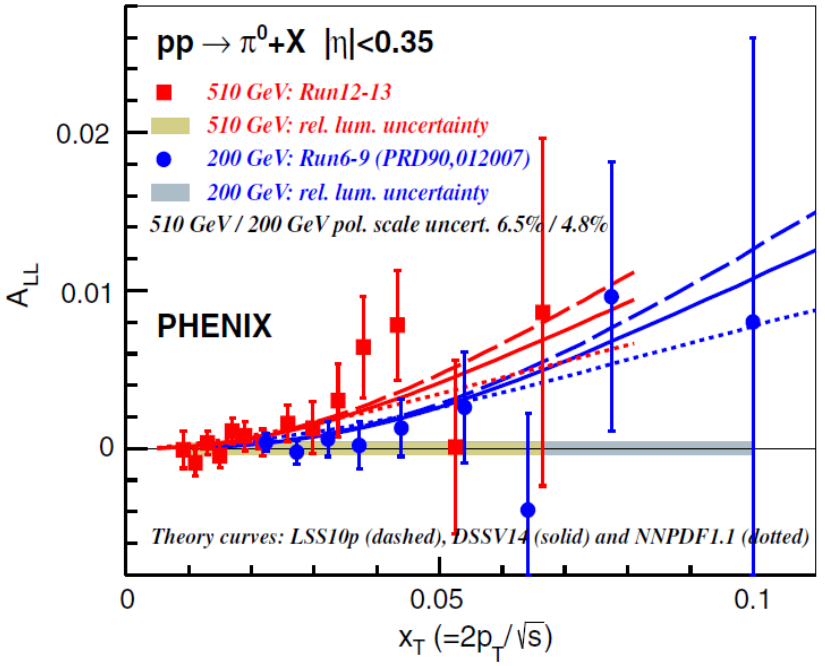


- Gluon polarization
  - A_{LL} measurement for gluon+gluon and gluon+quark reactions

Midrapidity jet at STAR

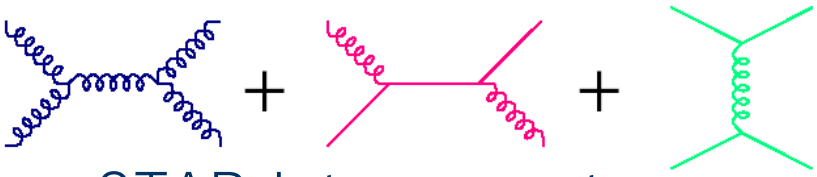


Midrapidity π^0 at PHENIX



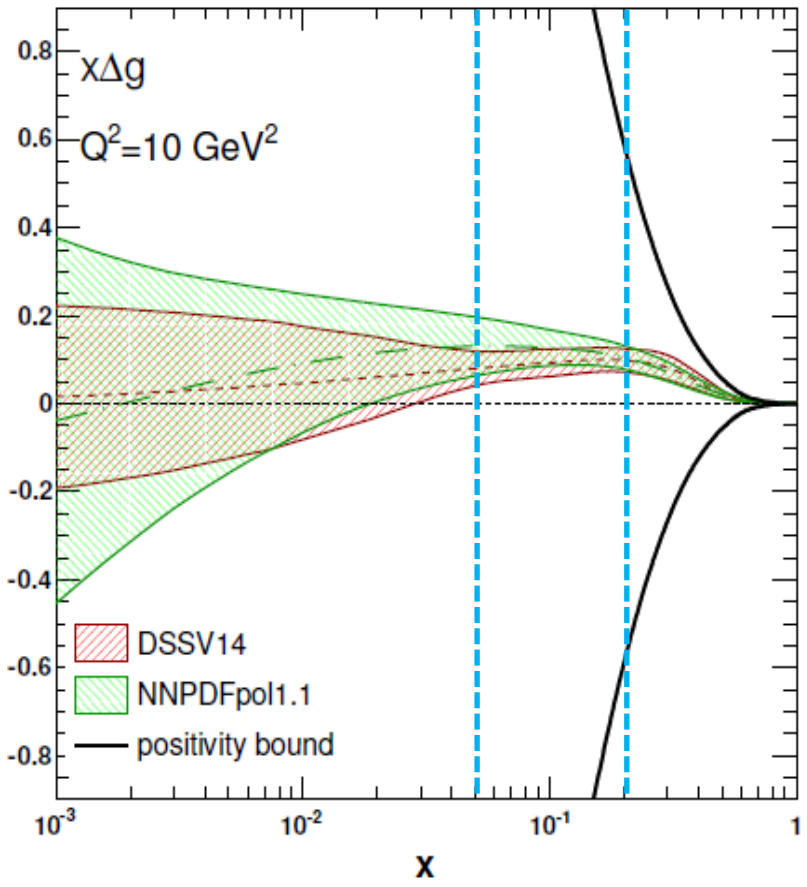
Gluon polarization Δg

- Positive gluon polarization
  - Obtained by DSSV and NNPDF groups with the QCD global analysis
  - including 200 GeV polarized proton collision data at RHIC
  - 2014 press releases
- gluon+gluon & quark+gluon reactions for large yield



  - STAR Jet asymmetry
    - Large acceptance
  - PHENIX π^0 asymmetry
    - Limited acceptance with high-performance EM calorimeter

arXiv:1503.03518

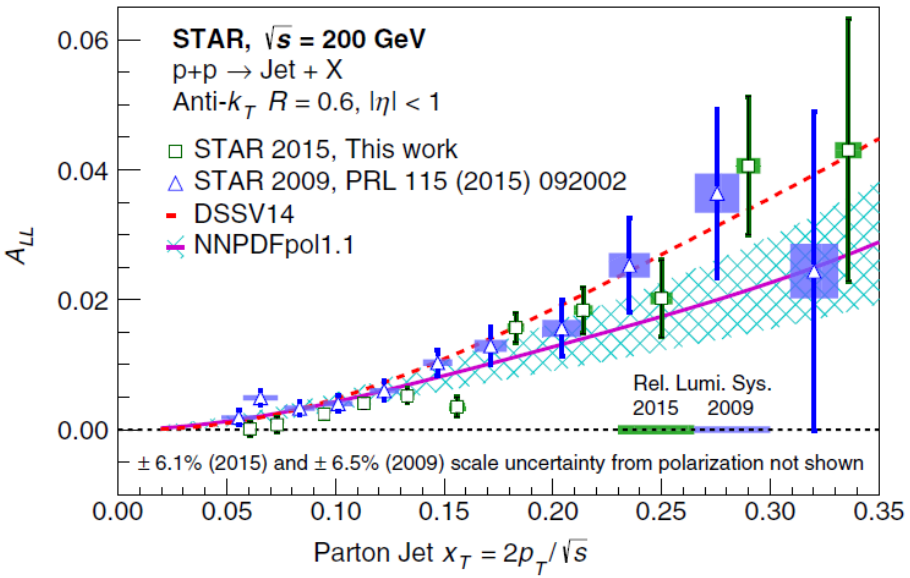


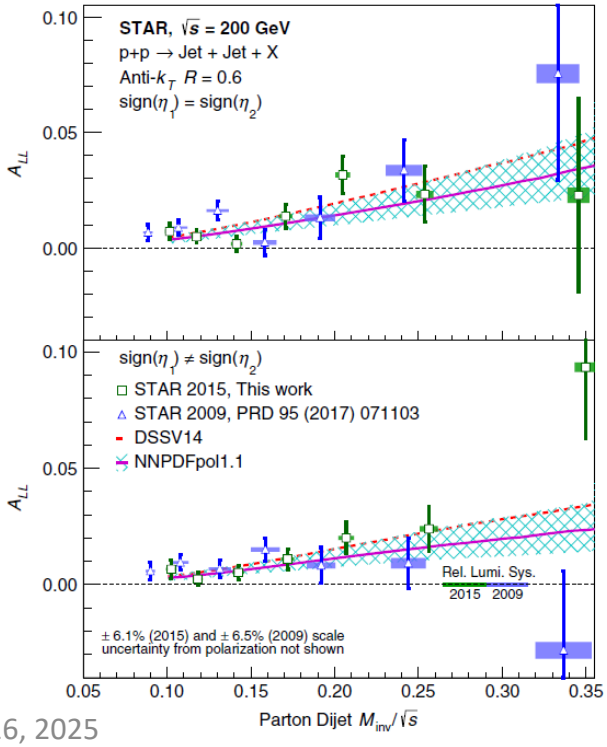
$Q^2 = 10$ GeV^2	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

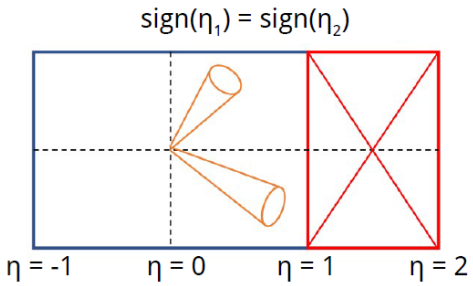
STAR jet & dijet

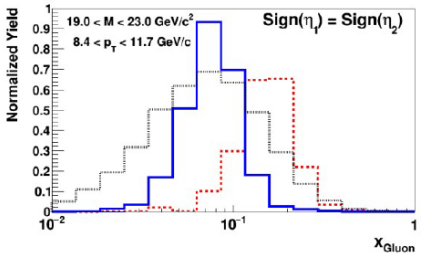
- Phys. Rev. D 100, 052005 (2019)
  - √s = 510 GeV
- Phys. Rev. D 103, L091103 (2021)
  - √s = 200 GeV
- Jet A_{LL}
  - the most precise dataset
- Dijet A_{LL}
  - constraints to underlying partonic kinematics

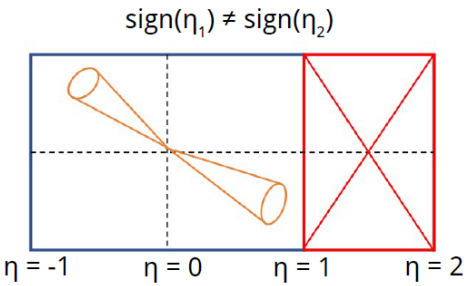
STAR √s = 200 GeV

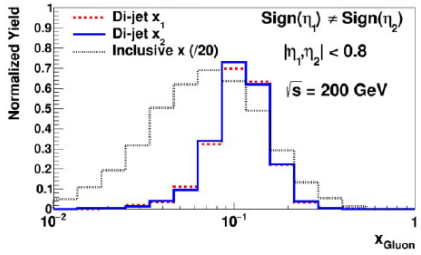






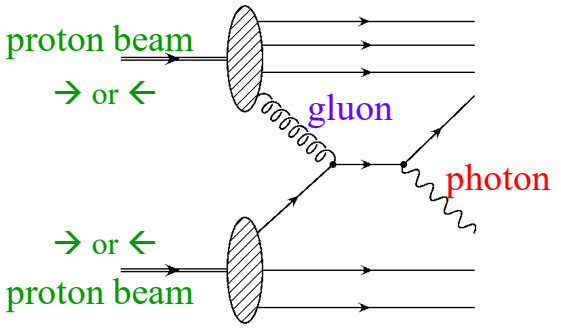






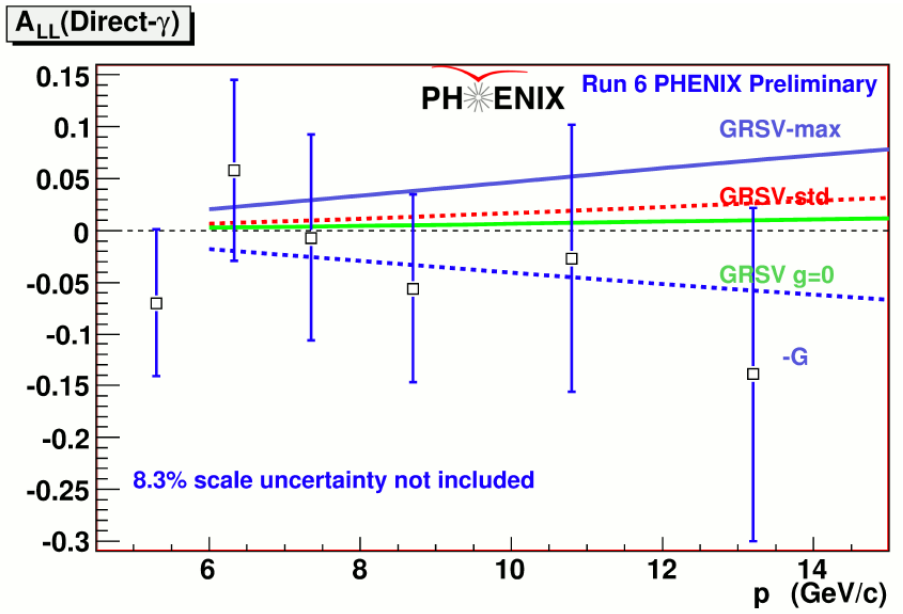
PHENIX direct photon

- A_{LL} measurement
  - Golden channel to access gluon polarization as hard interaction mostly quark-gluon reaction



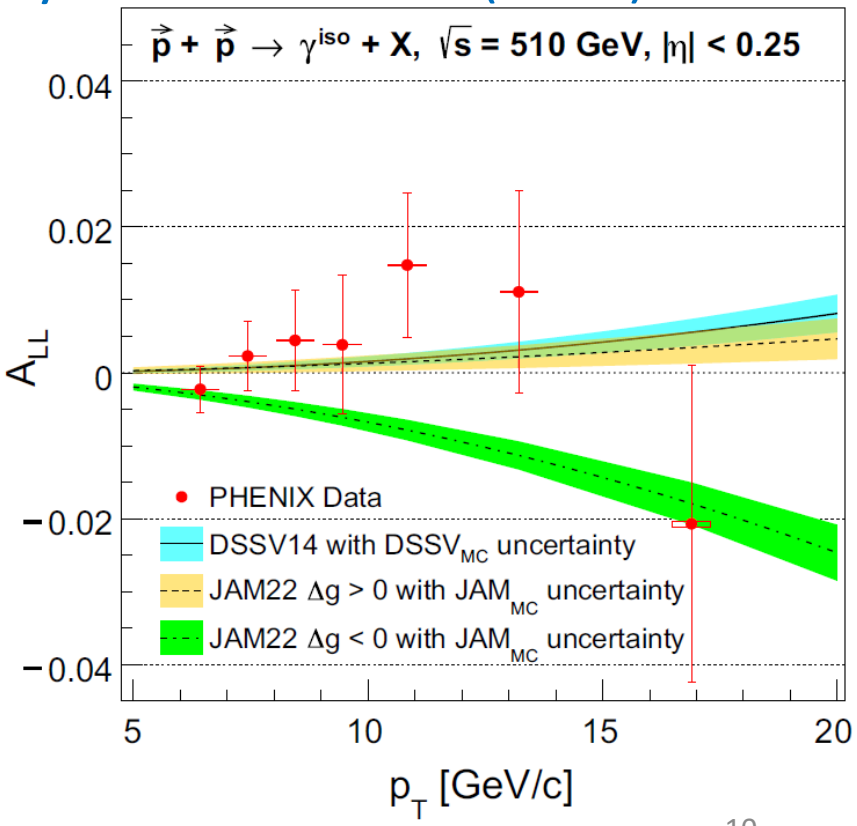
$\sqrt{s}$ = 200 GeV

Preliminary result (unpublished)



$\sqrt{s}$ = 510 GeV

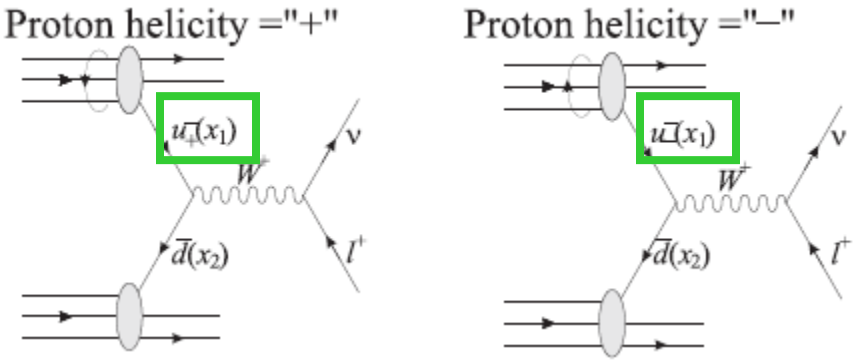
Phys. Rev. Lett. 130 (2023) 251901



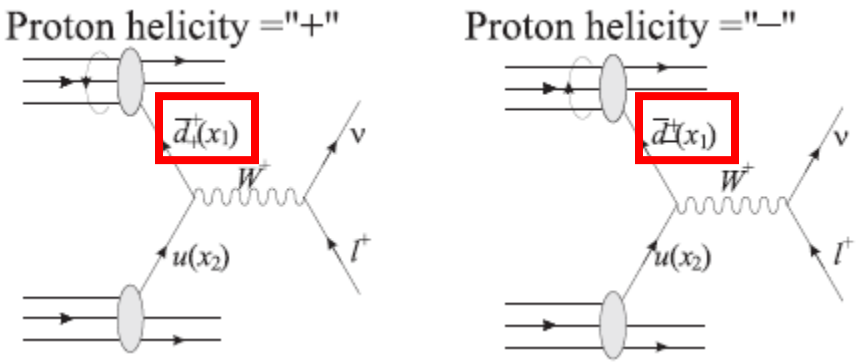
Anti-quark polarization

- Parity-violating A_L measurement with W-boson production

Forward rapidity



Backward rapidity



$$\frac{-\Delta u(x_a)}{u(x_a)} \qquad \frac{\Delta \bar{d}(x_a)}{\bar{d}(x_a)}$$

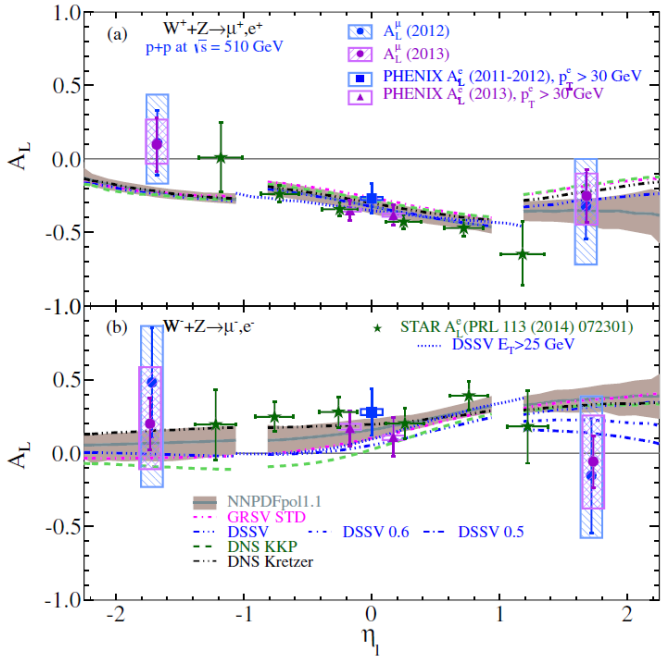
$$A_L^{W^+} = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

- W boson produced in the backward rapidity sensitive to the anti-quark polarization

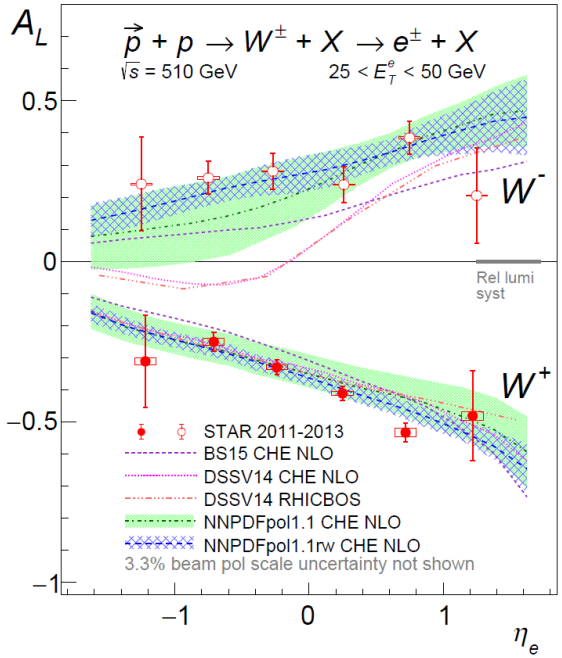
Anti-quark polarization

- Final results of W boson data obtained by 2013 has been released
- $\Delta\bar{u} > \Delta\bar{d}$ suggested by the QCD global analysis
  - $\bar{d} > \bar{u}$ in the unpolarized case

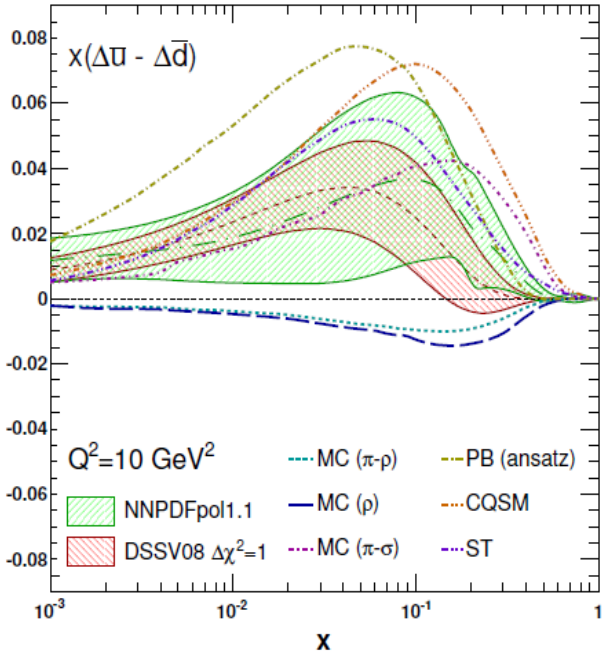
PHENIX: PRD98 (2018) 032007



STAR: PRD99 (2019) 051102



arXiv:1406.7122

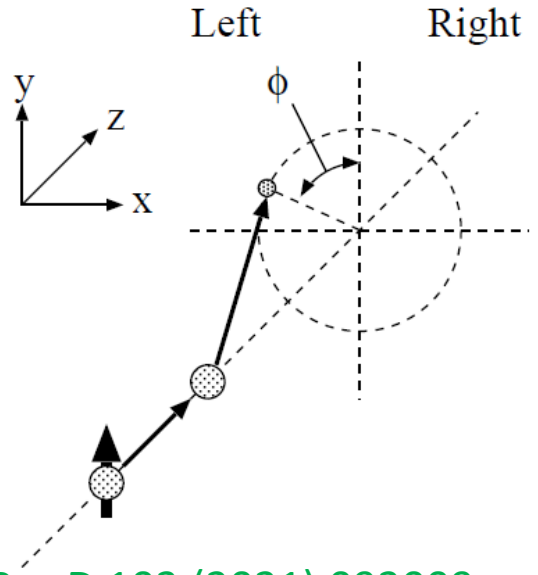


Transverse asymmetry measurement

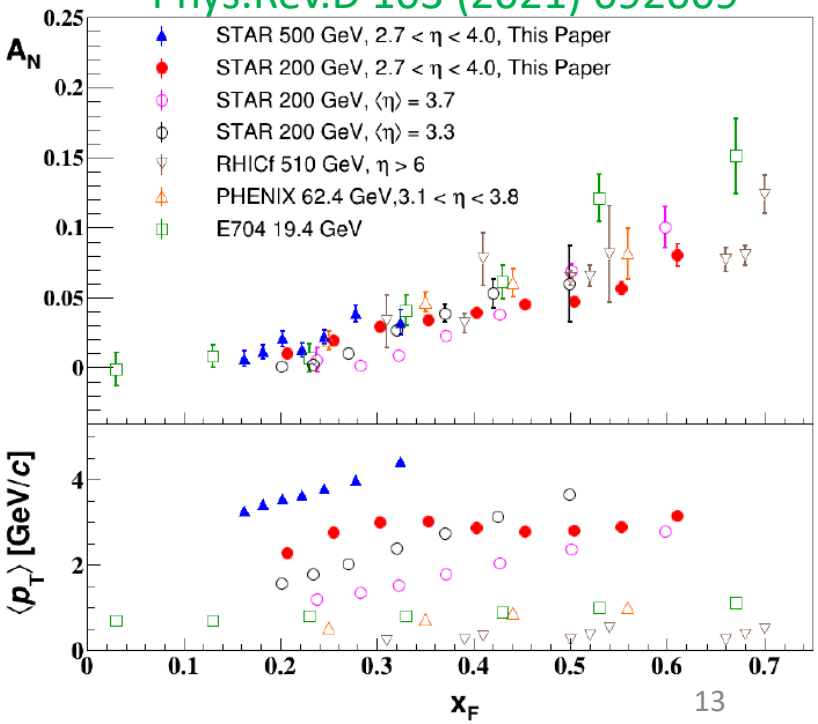
- A_N (transverse single-spin asymmetry) measurement

$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

  - Azimuthal angle modulation
- Large A_N for forward hadron production
  - similar results in wide $\sqrt{s}$
- TMD (Transverse Momentum Dependent) function and higher-twist function in pQCD regime
  - Initial-state effect or "Sivers" effect
  - Final-state effect or "Collins" effect
- Hard scattering and/or non-perturbative effect?



Phys.Rev.D 103 (2021) 092009



Higher-twist effect

- Quantum many-body correlation among quarks and gluons
  - Based on collinear factorization
  - quark-gluon correlation, tri-gluon correlation, twist-3 fragmentation
- Reproducing experimental data with precision calculation of twist-3 fragmentation function

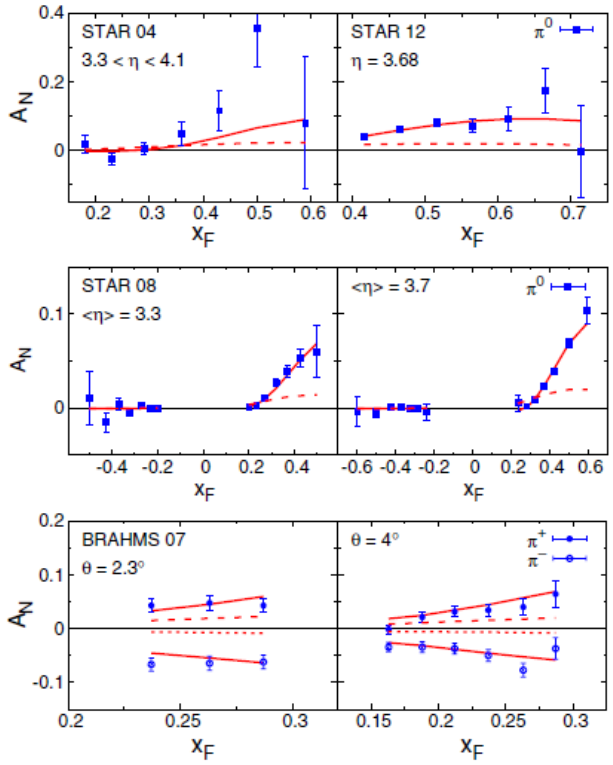


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

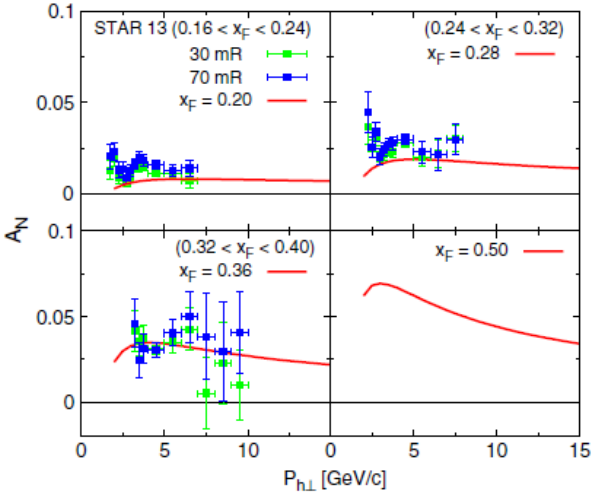
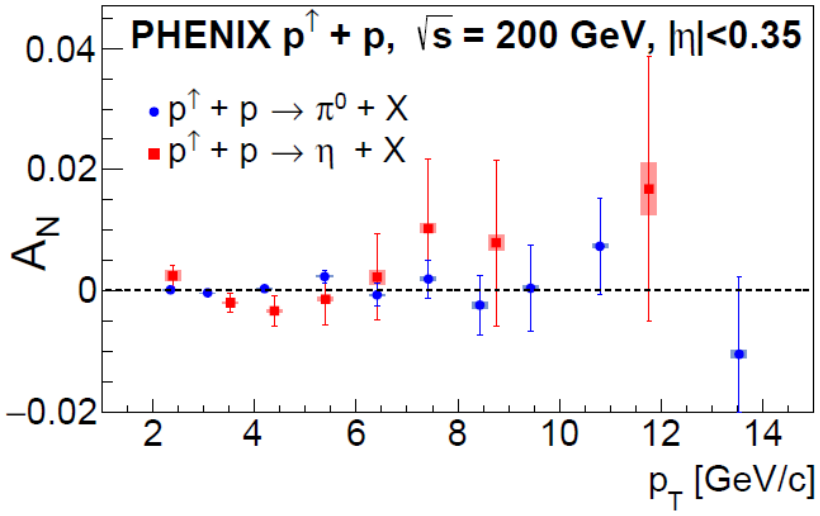


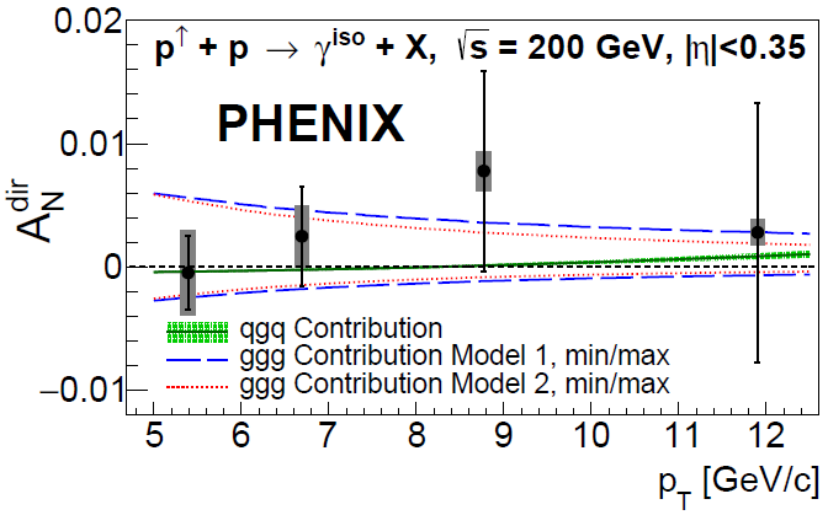
FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).

PHENIX π^0 & photon

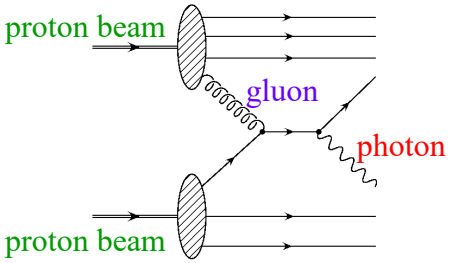
- π^0 & η
  - Phys. Rev. D 103, 052009 (2021)
  - Consistent with zero, significantly improved precision
  - Sensitive both initial and final state effects
  - Midrapidity measurement sensitive to gluons
- Direct photon
  - Phys. Rev. Lett. 127, 162001 (2021)
  - Sensitive to initial gluon dynamics at midrapidity
  - Constrain trigluon correlation function

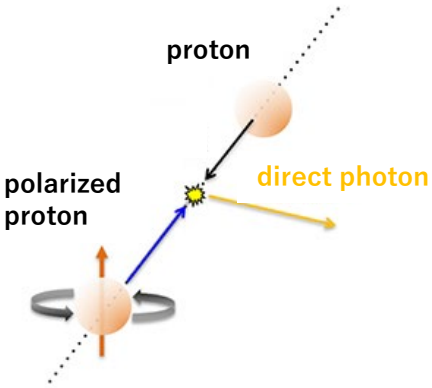


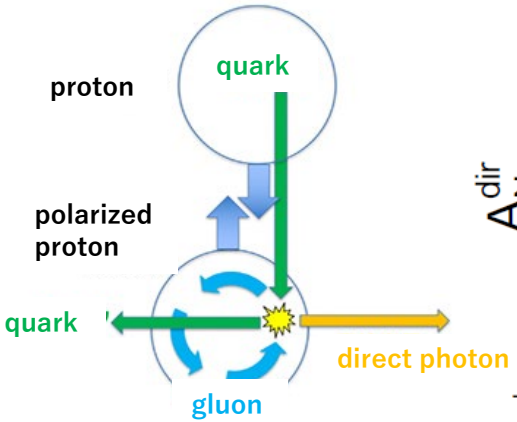


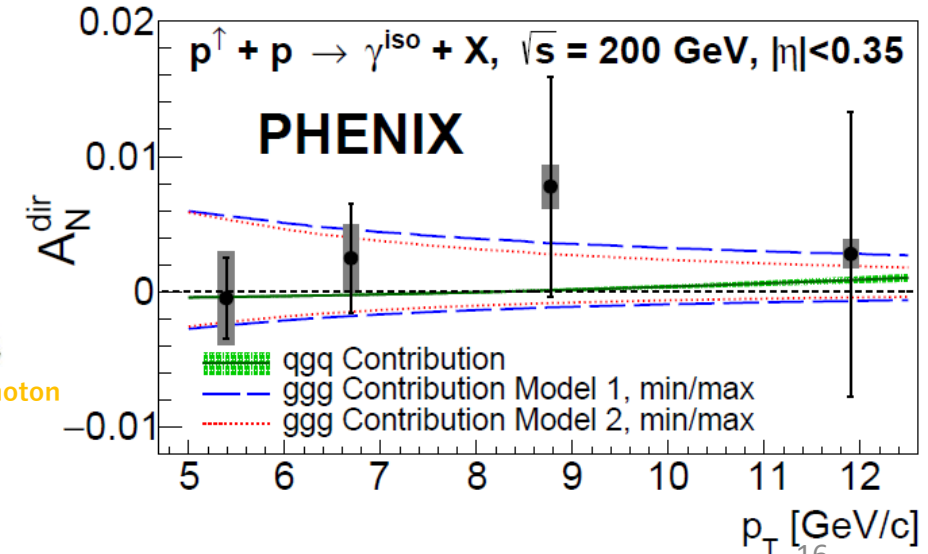
PHENIX direct photon

- Study of orbital motion of quarks and gluons inside the nucleon
- PHENIX experiment
  - π meson, η meson, J/ψ, charged hadron, muon & electron (heavy flavor), direct photon
- Direct photon
  - Phys.Rev.Lett. 127 (2021) 162001
  - Sensitive to initial gluon dynamics at midrapidity
  - Successful measurement of gluon motion inside the proton
  - Restriction to the tri-gluon correlation function



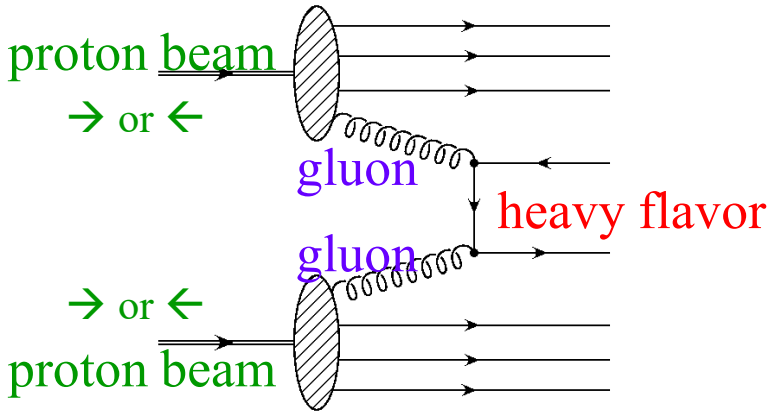


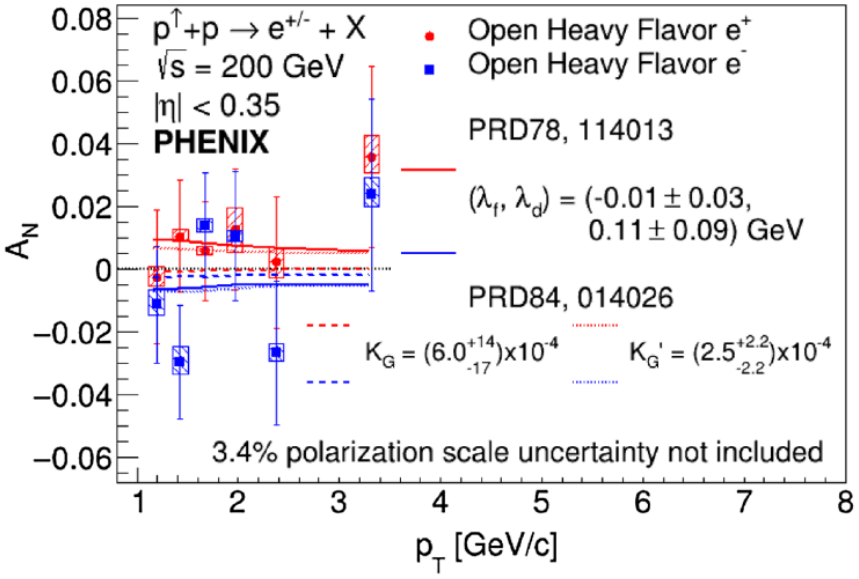


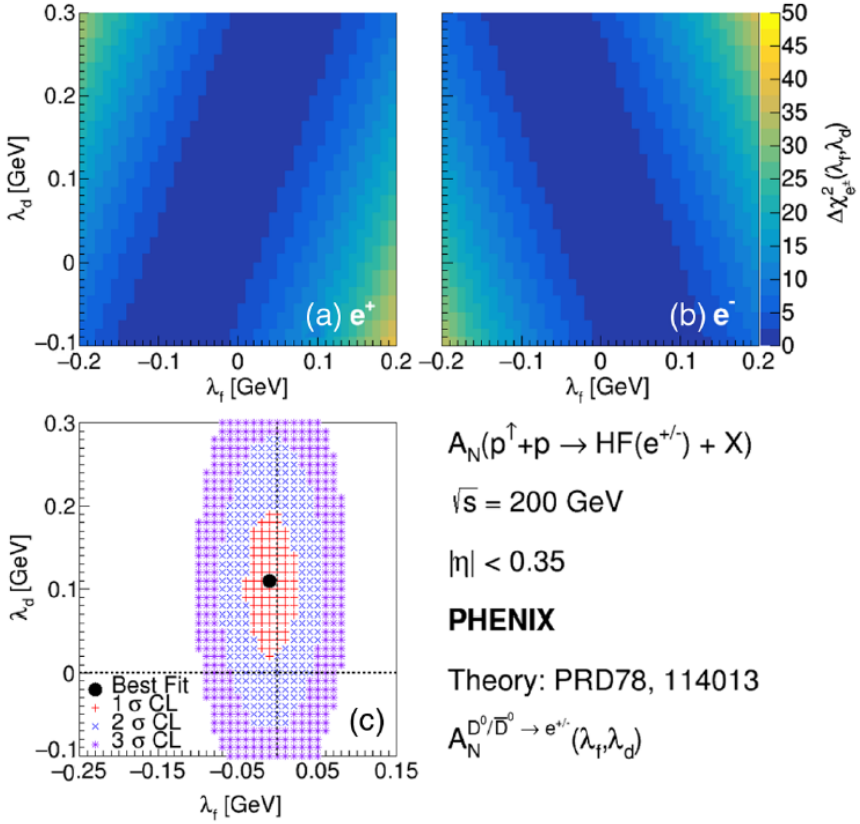


PHENIX heavy flavor

- PHENIX open heavy flavor at midrapidity
  - Phys. Rev. D 107 (2023) 052012.
  - Gluon fusion process
    - Sensitive to initial-state gluon
  - $e^{\pm}$ asymmetry measurement
    - Lepton-decay channel
  - Restriction to the tri-gluon correlation function

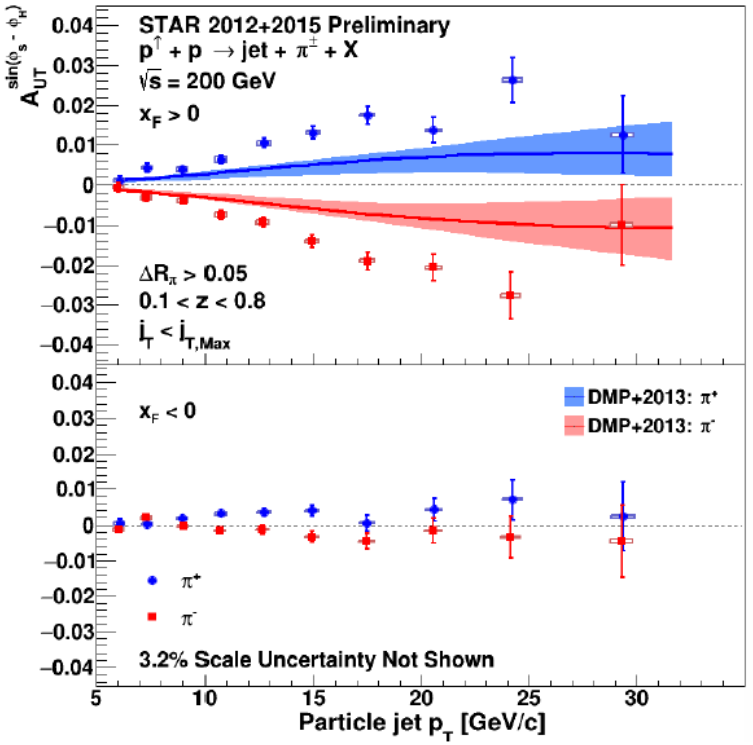


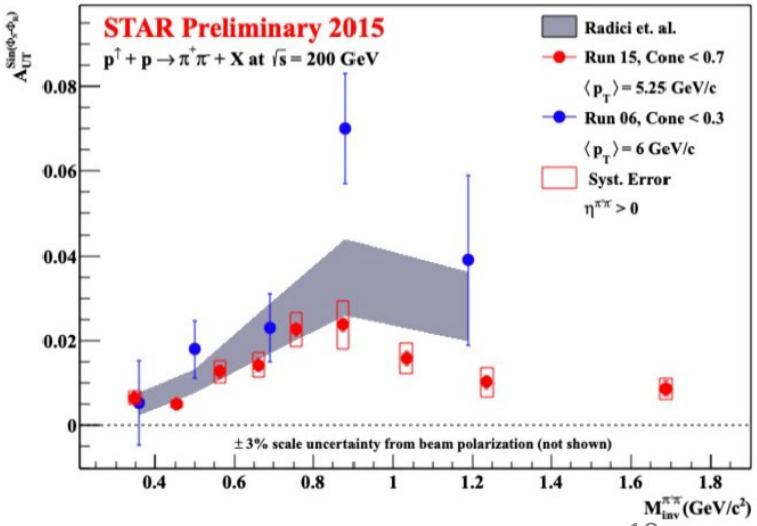




Transversity

- Quark transverse-spin contribution to the transversely polarized nucleon
  - Related to the tensor charge of the nucleon
- Spin-dependent modulation of hadrons in jets
  - Collins fragmentation function
- Di-hadron correlation measurements
  - Interference fragmentation function

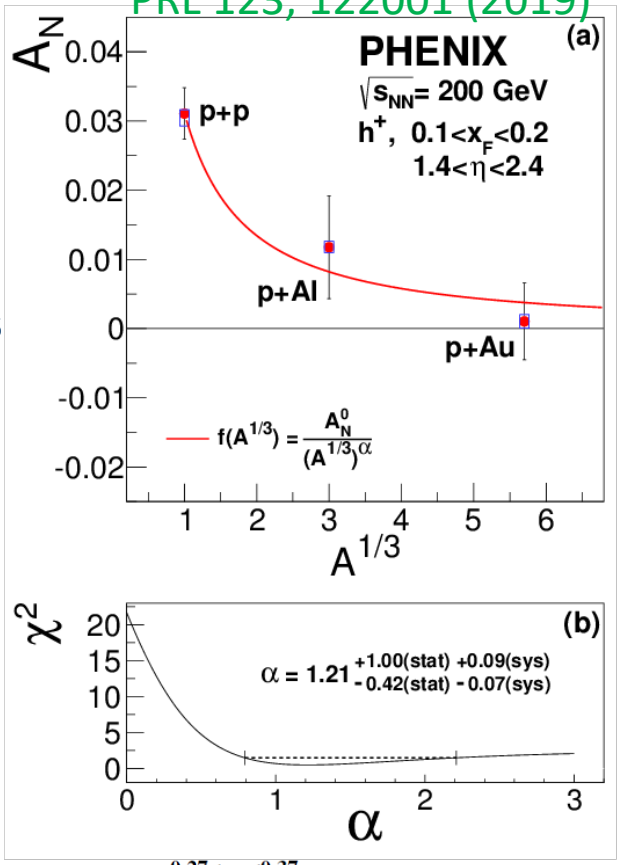




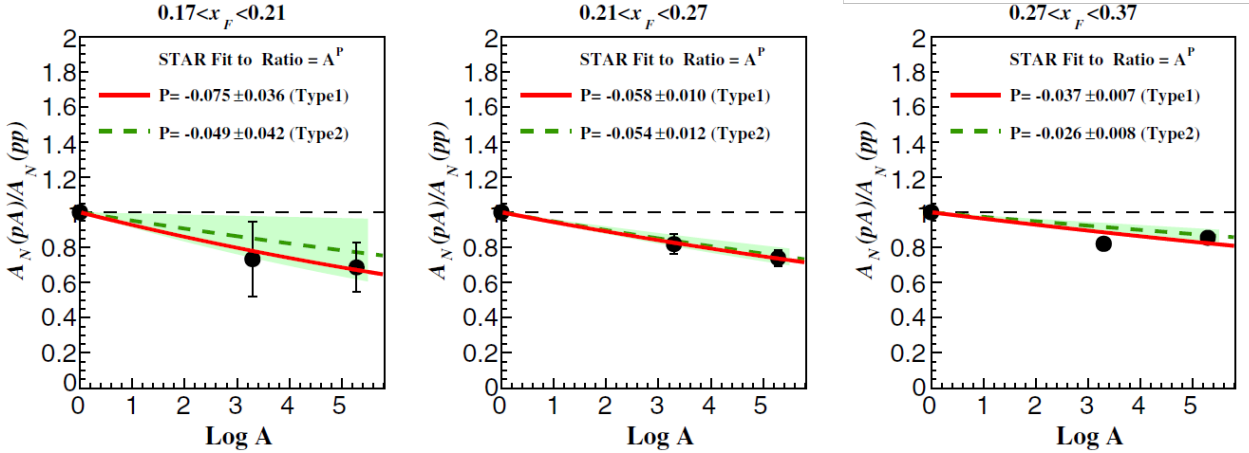
Polarized p+A collisions

- Prediction of reduced A_N in polarized p+A collisions due to the gluon saturation
  - Color Glass Condensate (CGC) calculation
- PHENIX charged hadron A_N : $1.4 < \eta < 2.4$
  - $0.1 < x_F < 0.2$, $1.8 < p_T < 7$ GeV/c
  - Asymmetries consistent with $A^{1/3}$ dependence as initially predicted by CGC related nuclear effects
  - However, probed x and scale too large for expected CGC effects
    - S. Benic and Y. Hatta, PRD99, 094012 (2019)
    - Twist-3 fragmentation + gluon saturation
- STAR π^0 A_N : $2.6 < \eta < 4.0$
  - $0.2 < x_F < 0.7$, $1.5 < p_T < 7$ GeV/c
  - No strong A dependence

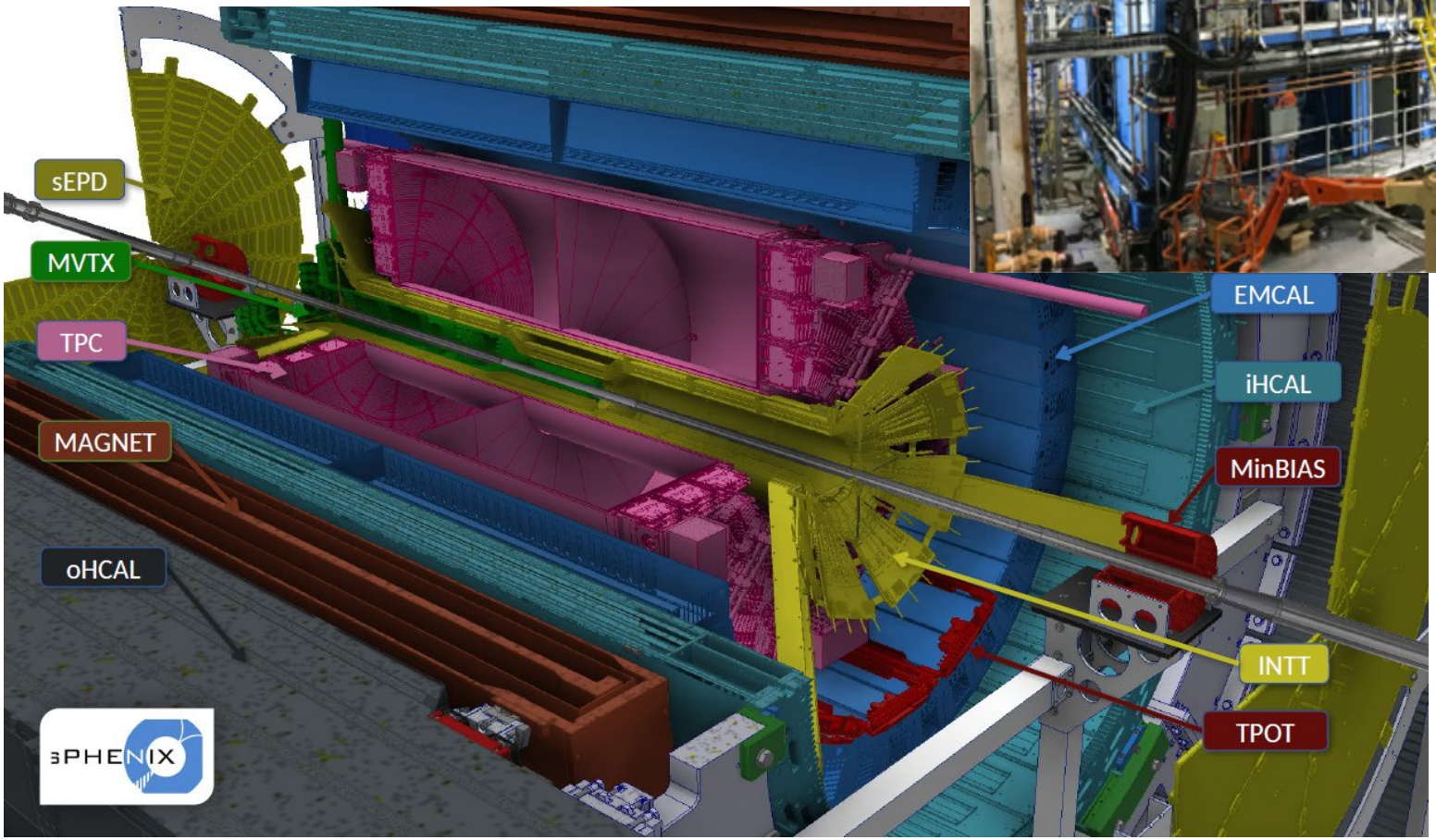
PRL 123, 122001 (2019)



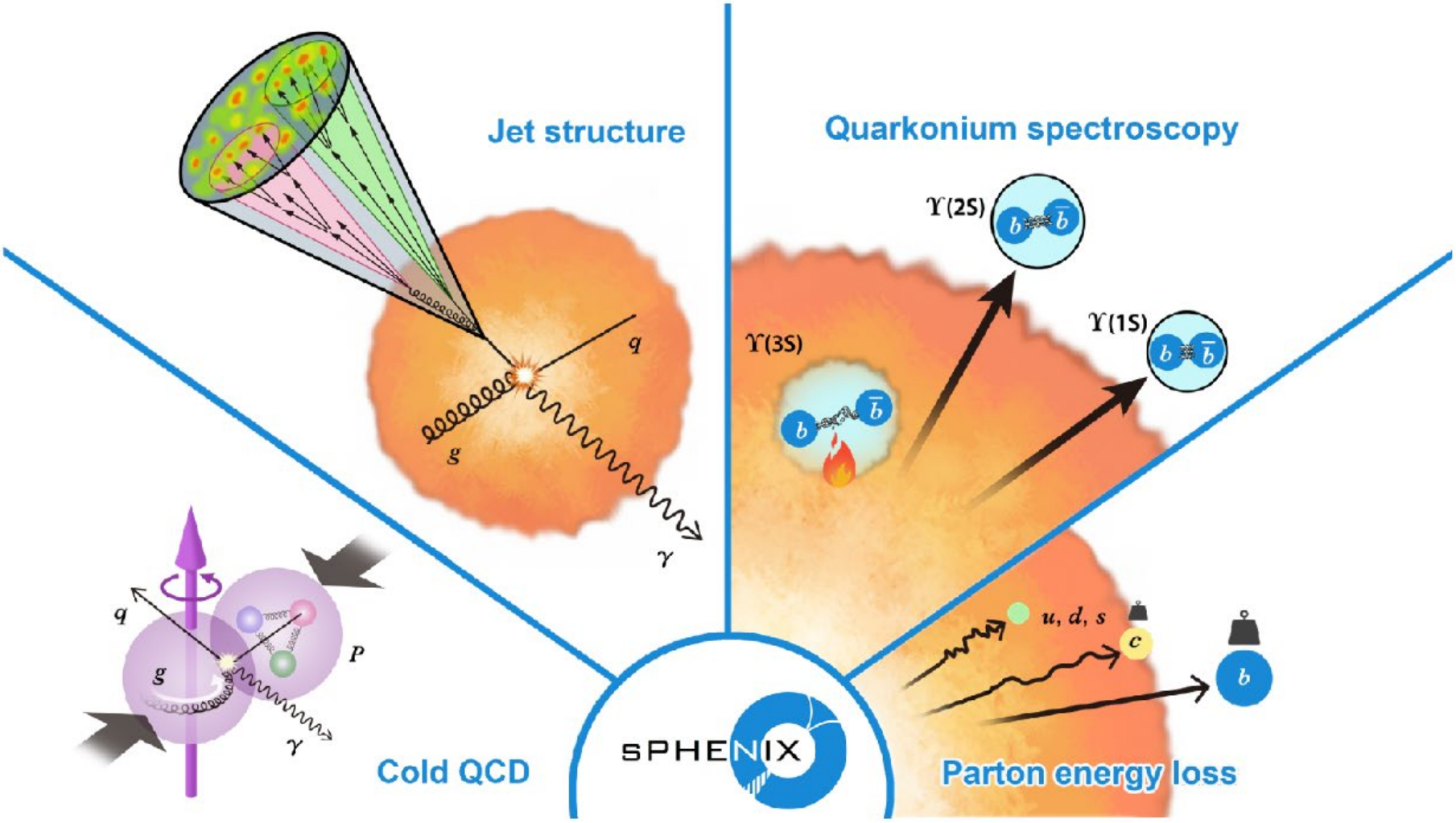
PRD 103, 072005 (2021)



sPHENIX detector

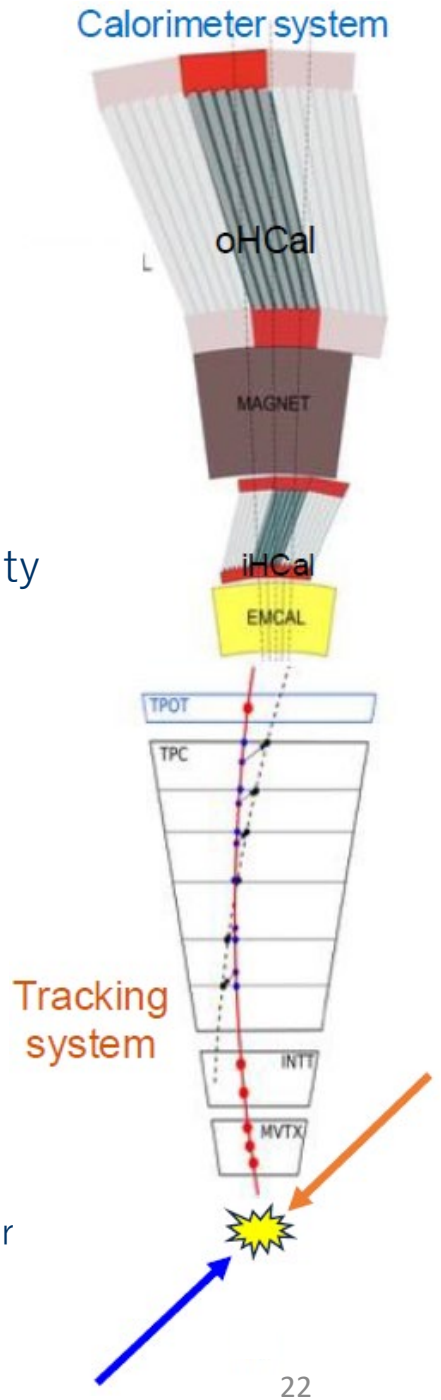


sPHENIX physics programs



sPHENIX detector

- Optimized for jet reconstruction and heavy-flavor reconstruction
  - Hermetic coverage
    - $|\eta|<1.1$ and 2π in ϕ
  - 1.4T solenoid from BaBar
  - High rate DAQ
    - 15 kHz for all subdetectors
- Calorimeters
  - EMCal and HCal coverage with first RHIC HCal at midrapidity
    - Full jet reconstruction and b-jet tagging
- Central Tracking Detectors
  - MVTX (MAPS-based) (r < 5 cm),
  - INTT (intermediate tracker) (r < 10 cm),
  - TPC (r < 80 cm), TPOT (TPC outer trackers)
  - Precise tracking with tracking system in stream readout
- General detectors
  - Forward MinBias detectors
  - sEPD (event-plane detector)
  - ZDC (zero-degree calorimeter) and SMD (shower-max detector)
    - Local polarimetry to monitor vertical polarization by measuring transverse single-spin asymmetries of neutrons produced in the far forward region



sPHENIX detector

Hadron and EM Calorimeters

Outer HCal Installation

Inner HCal Installation

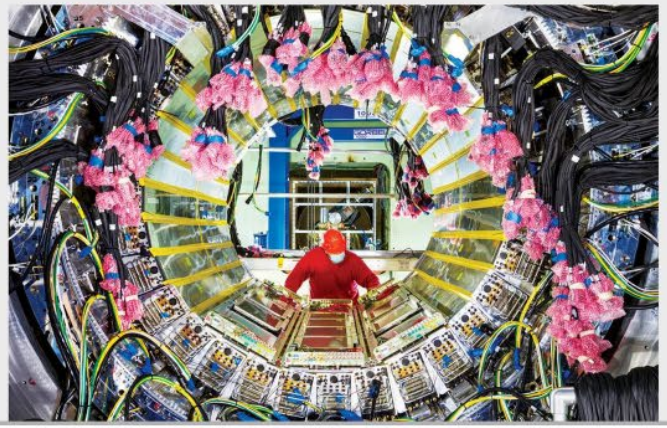
Tiny Bubbles of Primordial Soup Re-create Early Universe

MARCH 1, 2023 | 11 MIN READ

Tiny Bubbles of Primordial Soup Re-create Early Universe

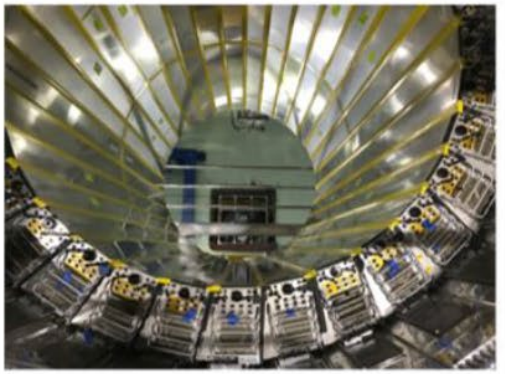
New experiments can re-create the young cosmos, when it was a mash of fundamental particles, more precisely than ever before

BY CLARA MOSKOWITZ

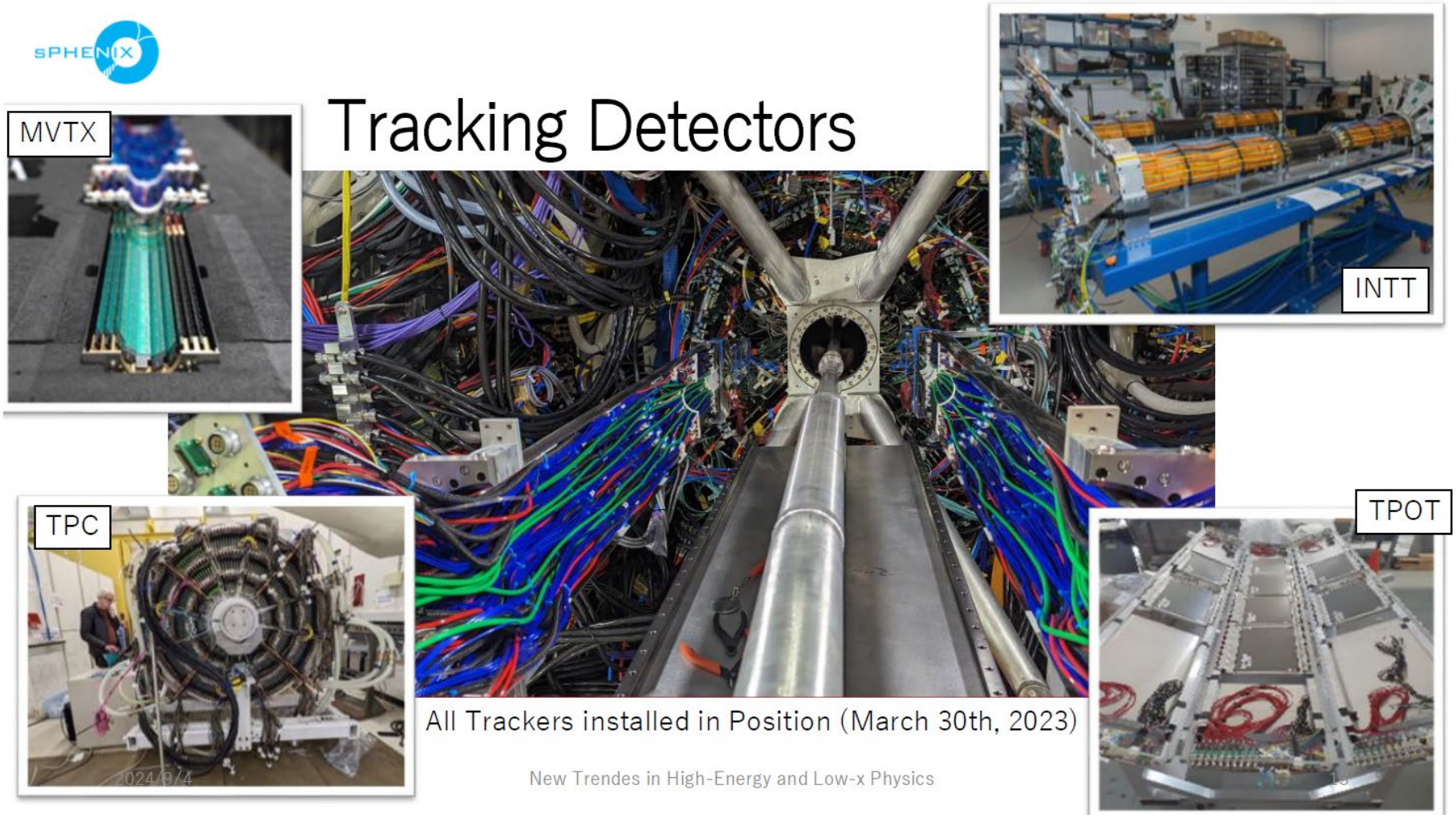


Scientific America, March 2023

EMCal in position



sPHENIX detector



Run 2024 & 2025

- Run 2024
  - Transversely polarized proton $p^{\uparrow} + p^{\uparrow}$ (~60% polarization) collision at $\sqrt{s} = 200$ GeV
  - Commissioning with Au + Au for 6 weeks, which was planned for 2023, is carried over
- Run 2025
  - The PAC recommends a Au+Au run in which sPHENIX collects at least 7 nb^{-1} of data as the highest priority for Run 25
  - The PAC has received beam use requests for running p+p, p+Au, and O+O collision systems, and sees all three of these proposed runs as fully aligned with RHIC's core scientific mission, and in fact as key elements of completing that mission

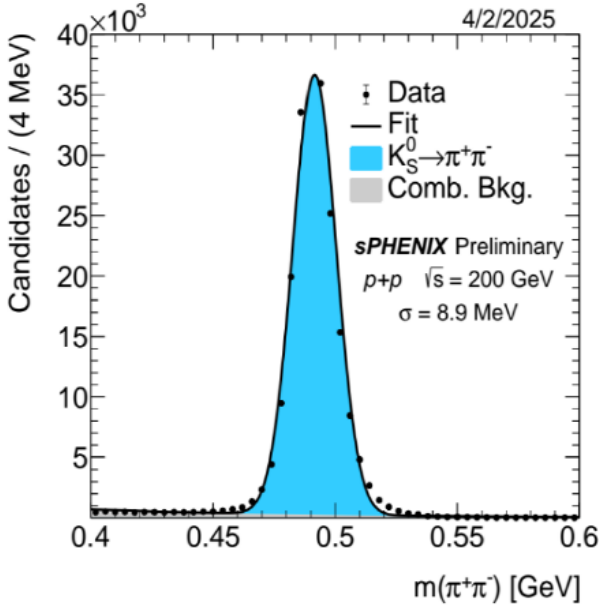
Physics program	Luminosity	% BUP23 Goal	Detector and Beam Conditions
Photons, jets, neutral mesons (HCal unique at RHIC)	107 pb^{-1} Sampled	240%	Calo+Global, Triggered, 0mrad + 1.5mrad, wide vertex
Jet+track structure, quarkonia, *b*-jets	13 pb^{-1} Sampled	30%	All sub-systems, Triggered, 1.5mrad, $\|z\| < 10$ cm
Open heavy flavor (RHIC-unique dataset)	2.9 pb^{-1} Recorded	65%	Trackers, Streaming, 1.5mrad, $\|z\| < 10$ cm

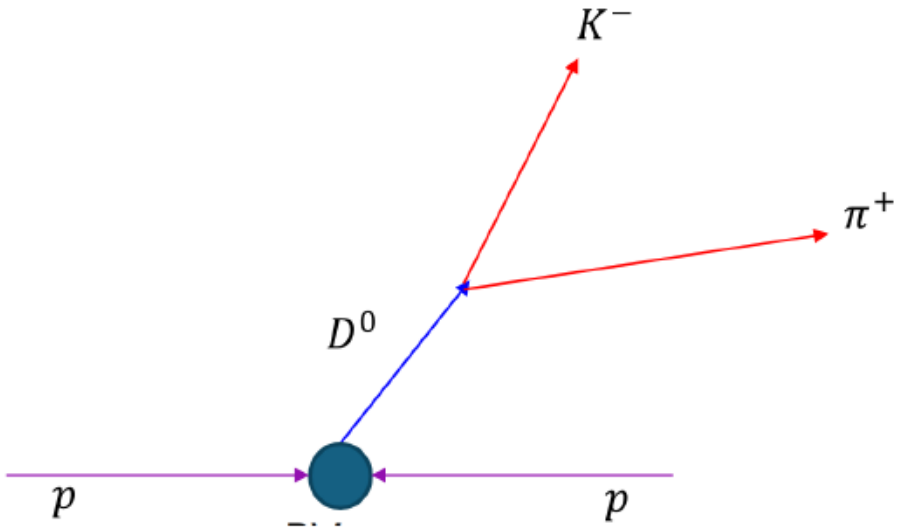
sPHENIX Physics Target in Run-25: **7 nb^{-1} (50B events)**		
Collision Species	Cryoweeks	Projected luminosity, $\|z\| < 10$ cm
Au+Au 200 GeV	20	2.4 – 4.2 nb^{-1} recorded
Au+Au 200 GeV	28	3.6 – 6.4 nb^{-1} recorded

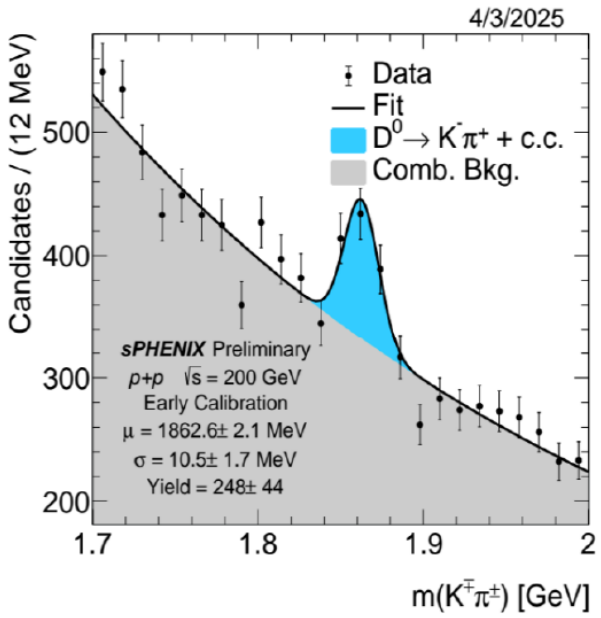
If Au+Au luminosity target is met, ordered priority list for additional running:		
Collision Species	Physics weeks	Projected luminosity, $\|z\| < 10$ cm
1. *p*+*p* 200 GeV	8	13 pb^{-1} sampled + 3.9 pb^{-1} streaming
2. *p*+Au 200 GeV	5	80 nb^{-1} sampled + 24 nb^{-1} streaming
3. O+O 200 GeV	2	13 nb^{-1} sampled + 3.9 nb^{-1} streaming

Streaming DAQ

- Trig. rate ~ 15 kHz < eff. streaming rate ~ 300 kHz < coll. rate ~ 1MHz
- INTT timing resolution: 106 ns (sync with RHIC clock)
- Uniform detection of K^0_s peak at all beam crossings
- Clear D^0 peak observed after only one hour of data
- Results with early tracking calibrations

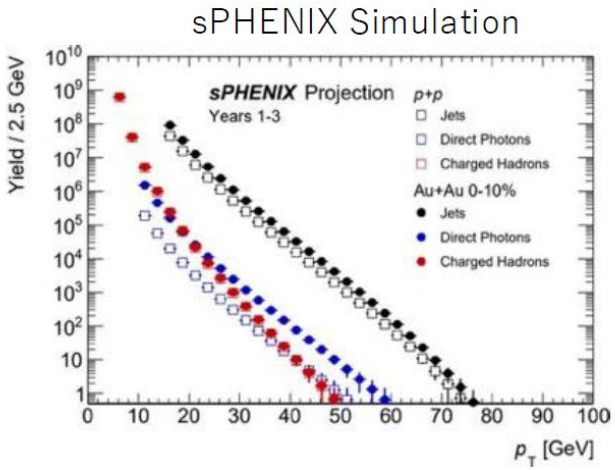


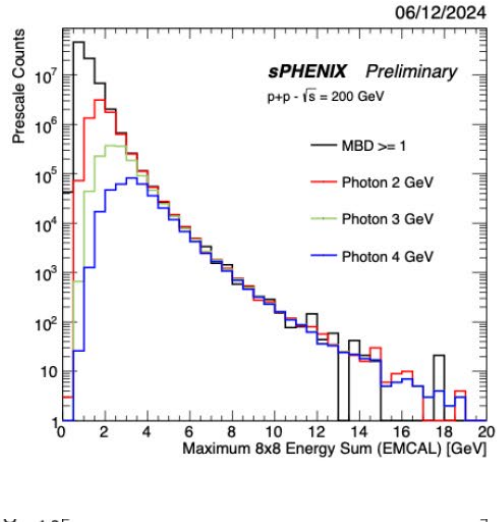


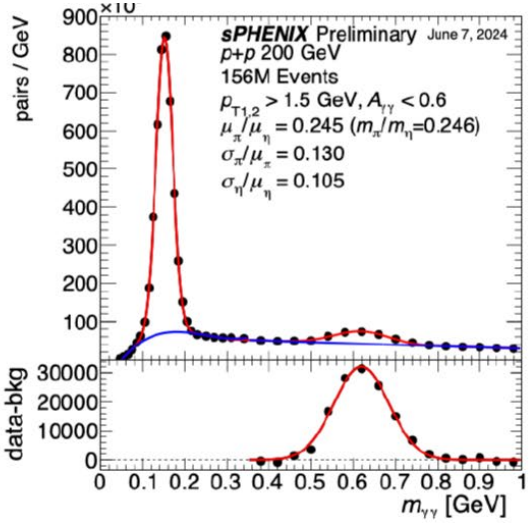


Photon and jet data in Run 2024 p+p

- sPHENIX will have kinematic reach out to ~ 70 GeV for jets, kinematic overlap with the LHC
- Sampled 107 pb^{-1} with γ/jet trigger so far

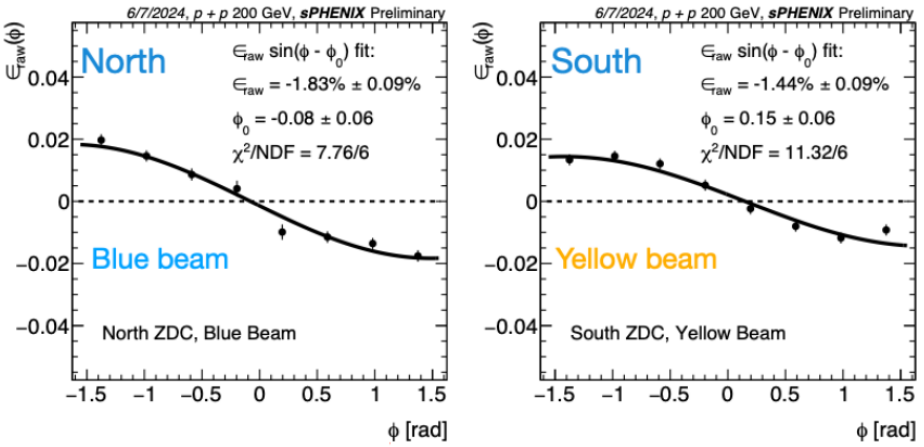


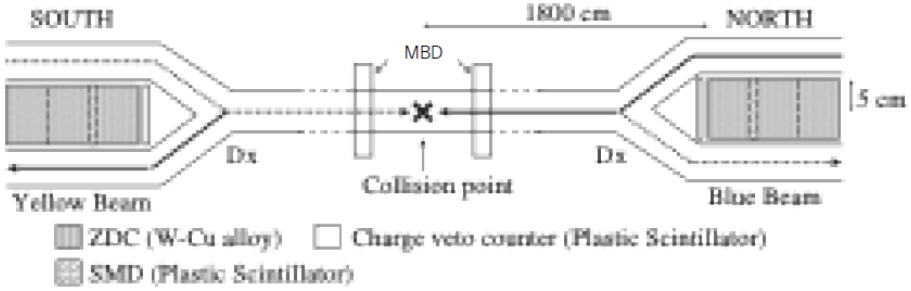




Zero-degree forward neutron asymmetries

- Confirmed the spin vector is pointing vertical and observed asymmetries are consistent with published data





$$A_N = \frac{e_N(\phi)}{\sin(\phi - \phi_0)} \frac{1}{P}$$

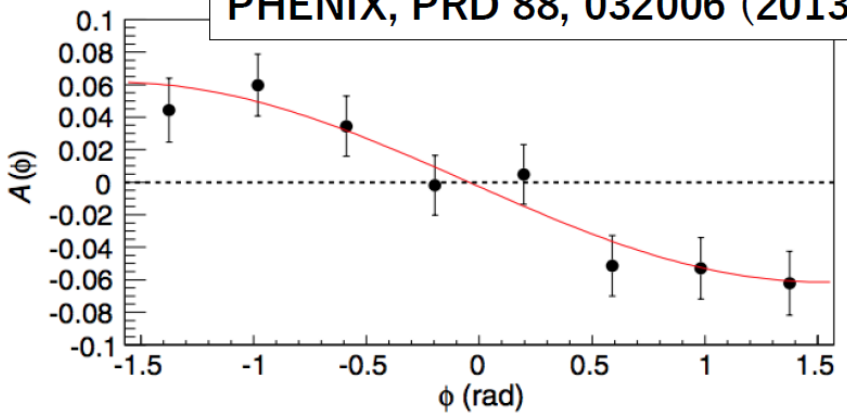
0 rad.

~33%

$$A_N = \frac{1.83}{0.33} \sim 0.054$$

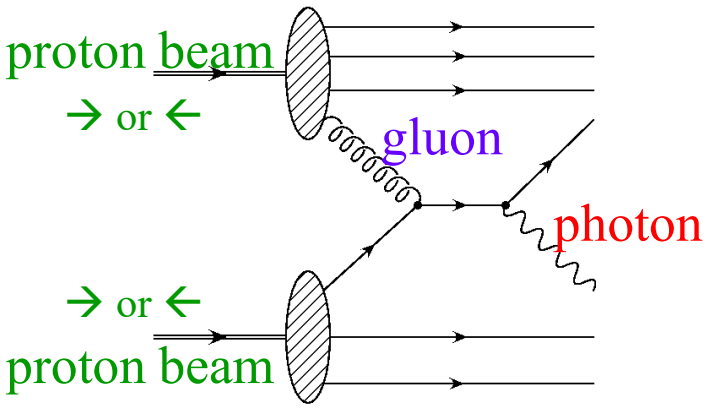
Consistent!

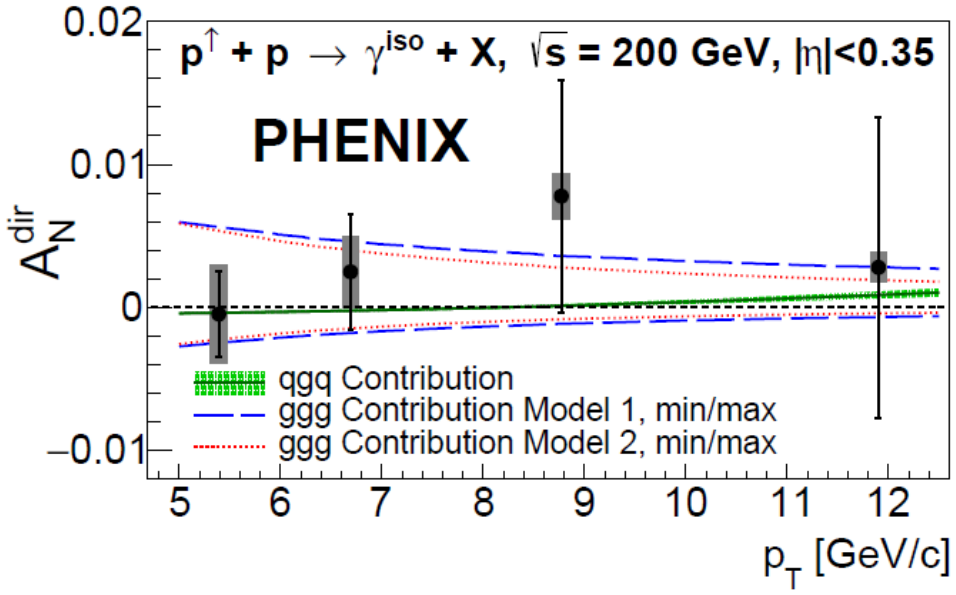
PHENIX, PRD 88, 032006 (2013)

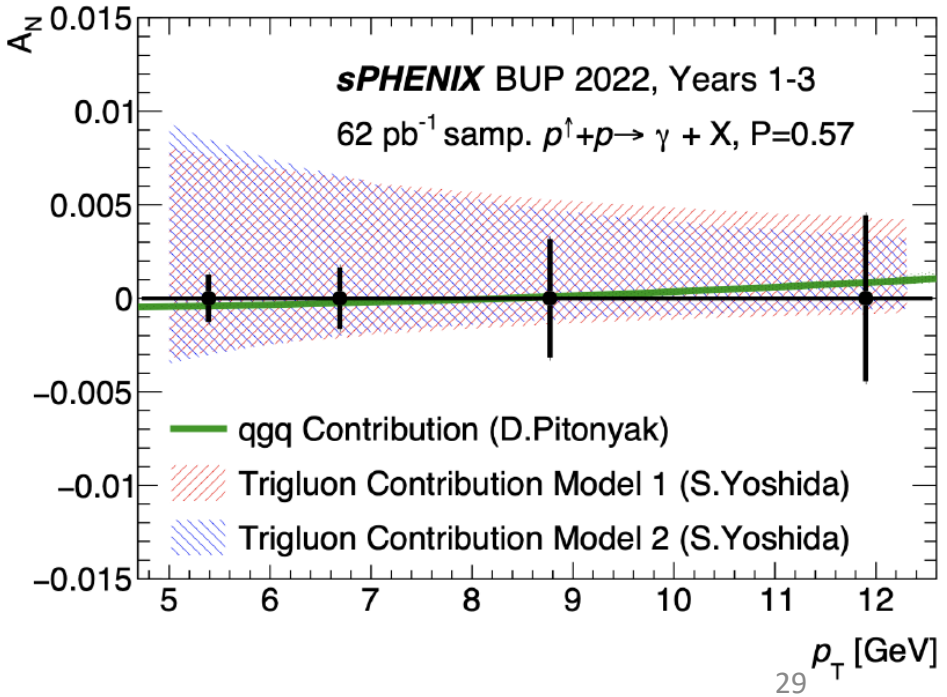


sPHENIX experiment

- Direct photon
  - Sensitive to initial gluon dynamics at midrapidity
  - Successful measurement of gluon motion inside the proton
  - Restriction to the tri-gluon correlation function

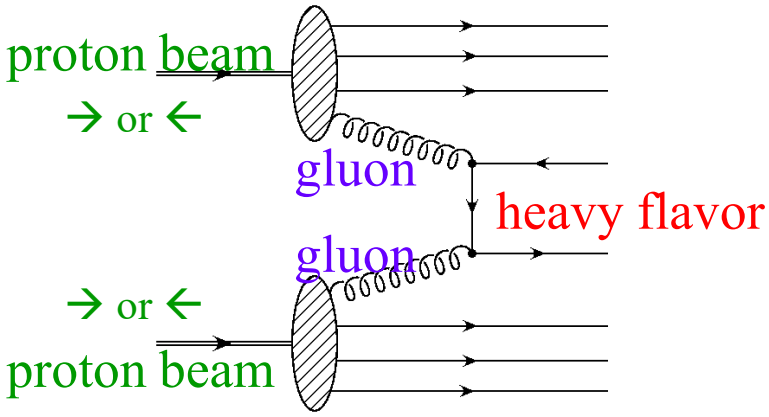


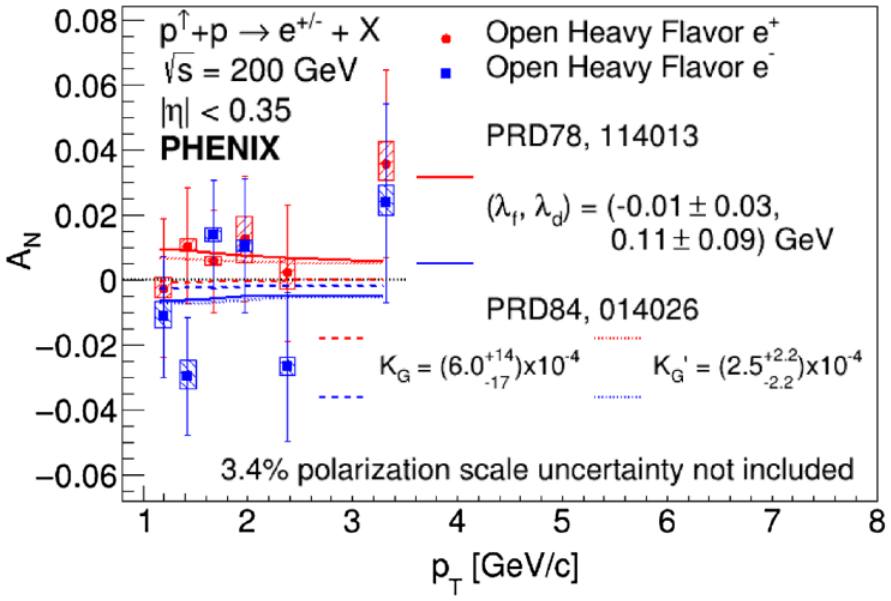


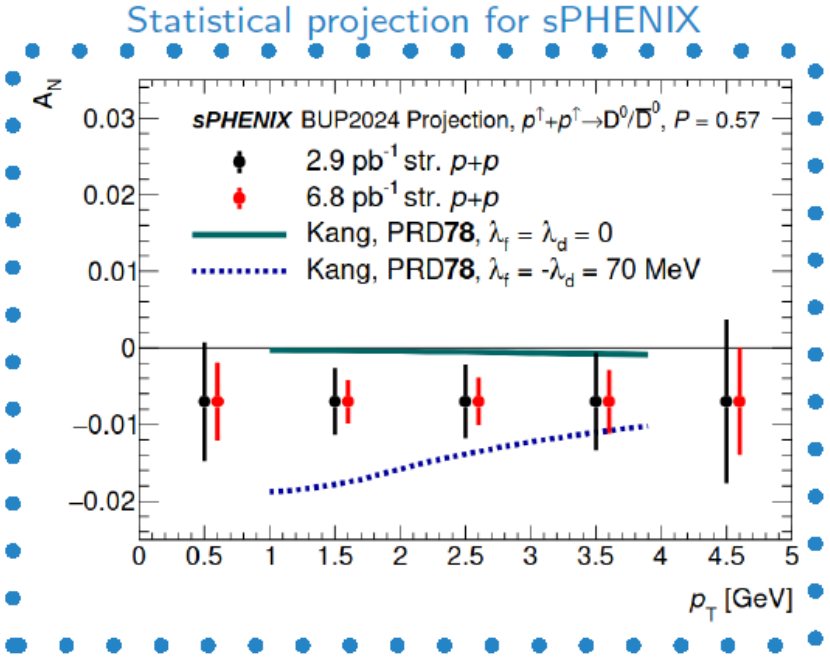


sPHENIX experiment

- Open heavy flavor
  - Gluon fusion process
    - Sensitive to initial-state gluon
    - Restriction to the tri-gluon correlation function
  - $e^{\pm}$ asymmetry measurement
    - Lepton-decay channel
  - D-meson asymmetry measurement



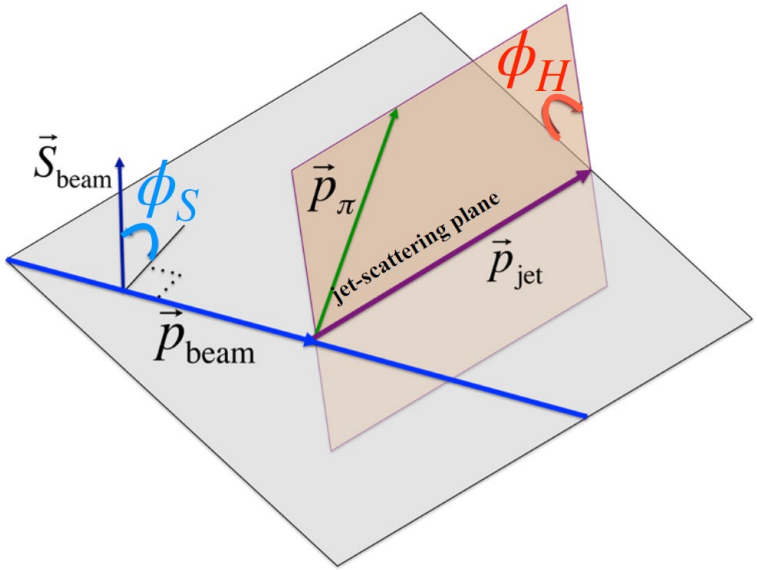


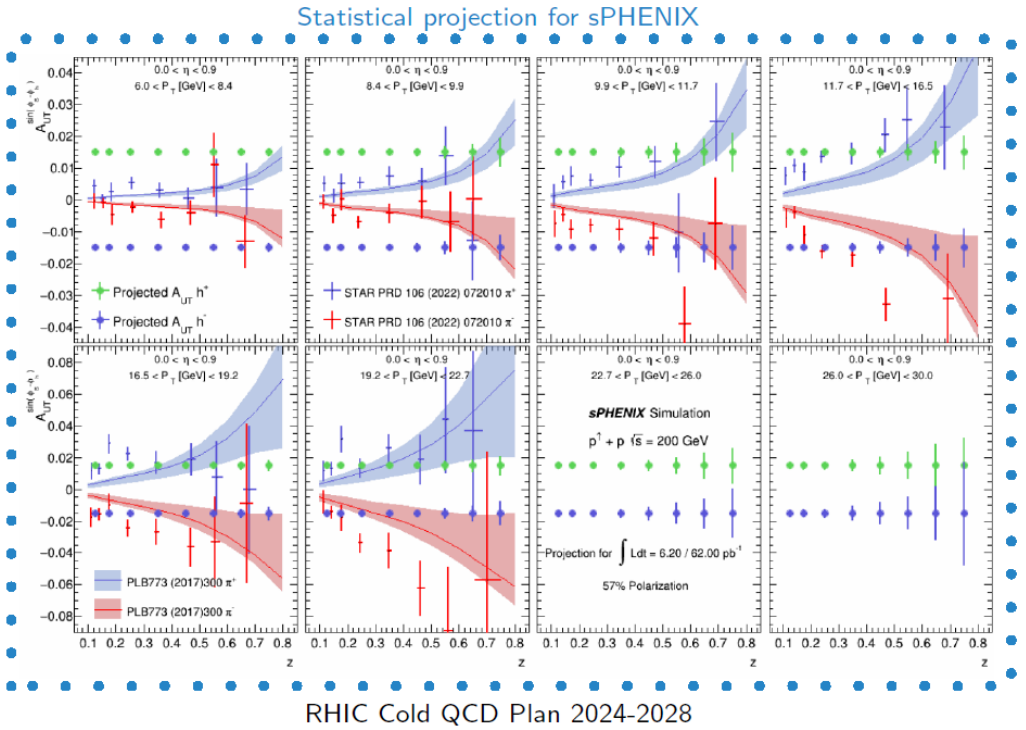


sPHENIX experiment

- Hadron in jets $p^{\uparrow} p \rightarrow$ jet h X
  - Access to Collins fragmentation function and transversity PDF

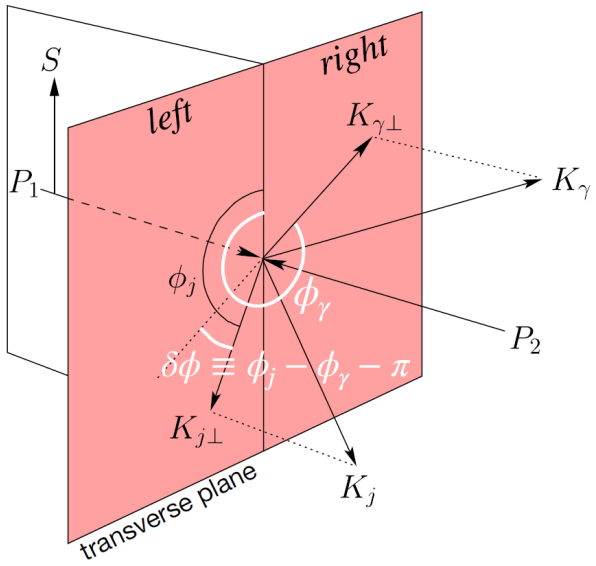
- Collins effect: the correlation of **transverse spin of a quark** and **the momentum of a hadron fragment** transverse to the scattered quark direction
- Collins asymmetry $A_{UT}^{\sin(\phi_S - \phi_H)}$ is related to Transversity PDF and Collins FF.





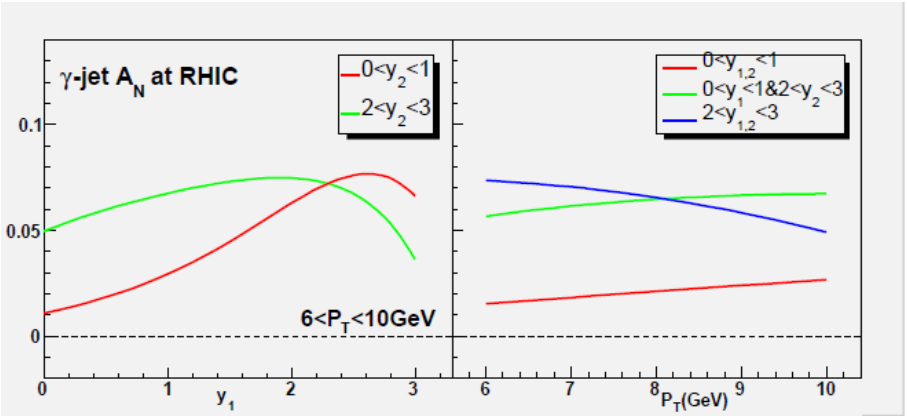
sPHENIX experiment

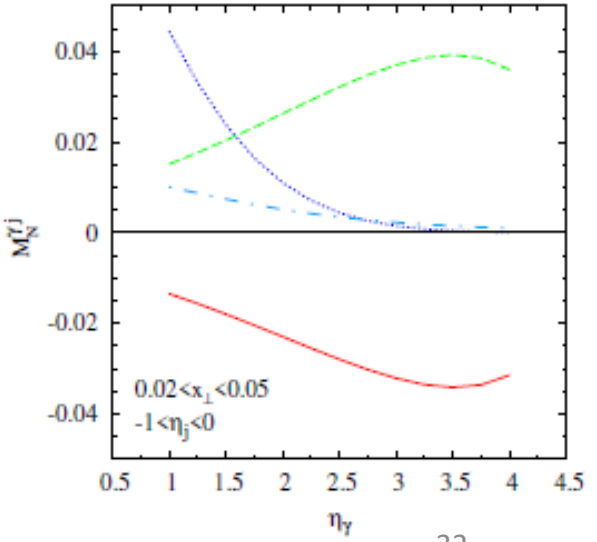
- Angular correlations in di-jet and jet+photon production
  - Sivers contributions to the asymmetries
  - Vogelsang and Yuan, PRD 72 (2005) 054028
- Jet+photon
  - Bacchetta et al., PRL 99 (2007) 212002
  - Quark-gluon scattering process isolated at leading order
  - Gluon Sivers effect can be accessed



PRL 99 (2007) 212002

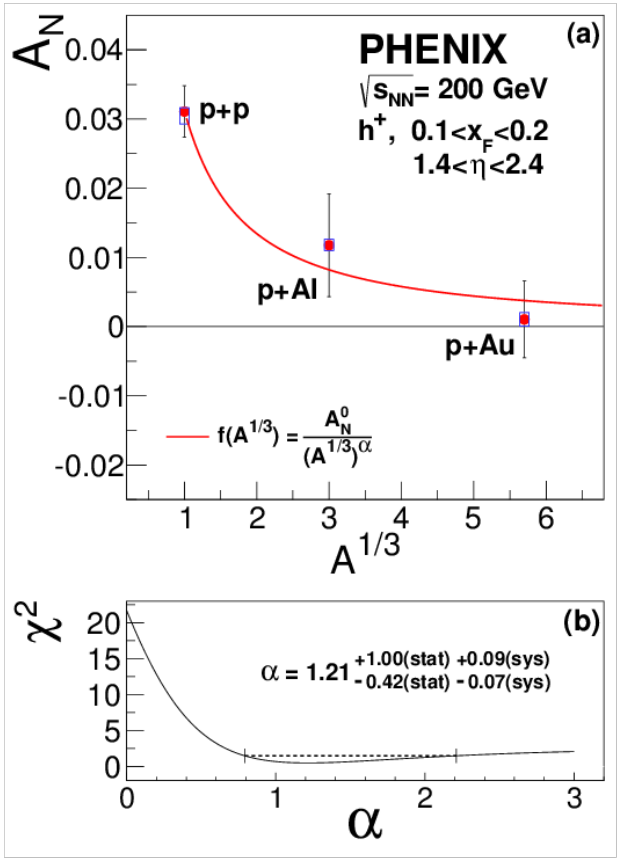
PRD 72 (2005) 054028

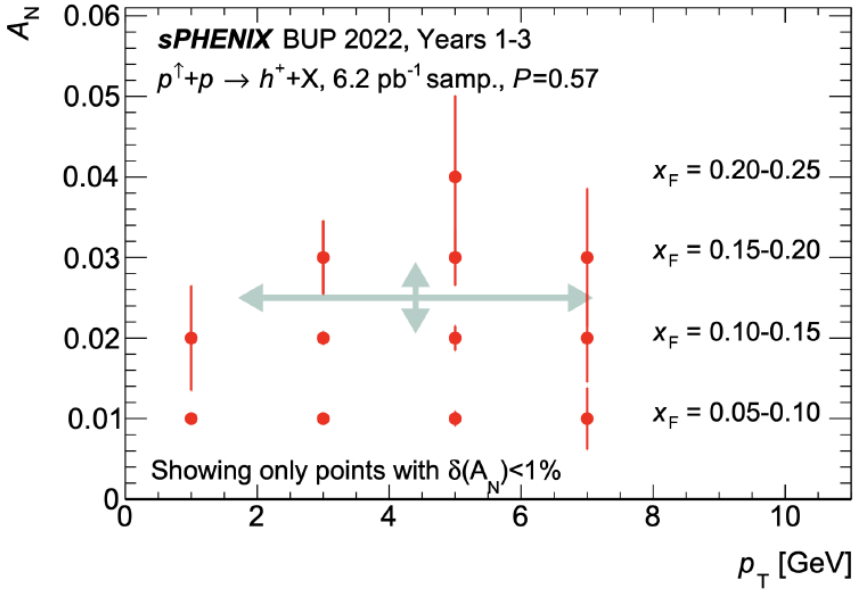




sPHENIX experiment

- Polarized-p + A collisions
- PHENIX charged hadron A_N
  - Asymmetry consistent with the $A^{1/3}$ dependence first predicted by the nuclear effect associated with CGC
- STAR π^0 A_N
  - No significant A-dependence





Summary

- Completion of the RHIC spin program
  - Data collection for the PHENIX experiment completed in 2016
  - Physics from longitudinally polarized proton collisions almost completed
  - Physics from transversely polarized proton collisions still remains
- sPHENIX experiment
  - A state-of-the-art jet detector at RHIC
    - Studying QGP and cold QCD
    - Fast DAQ rate, hermetic EM and hadron calorimetry, tracking streaming readout
  - Study of orbital motion of quarks and gluons inside the nucleon
    - Direct photon
    - Open heavy flavor
    - TMD Sivers effect
    - Transversity
    - Collins FF