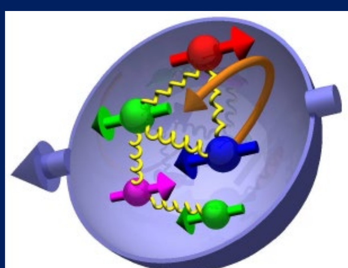
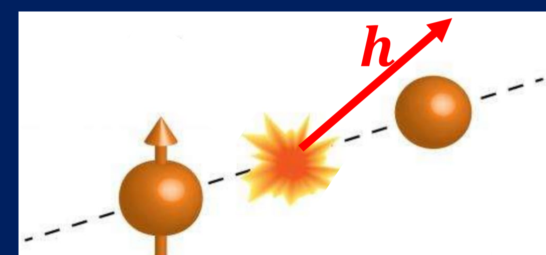
PHENIX Spin Program Accomplishments

And some first sPHENIX results!



Christine A. Aidala

University of Michigan



Spin Physics Ahead of NICA SPD

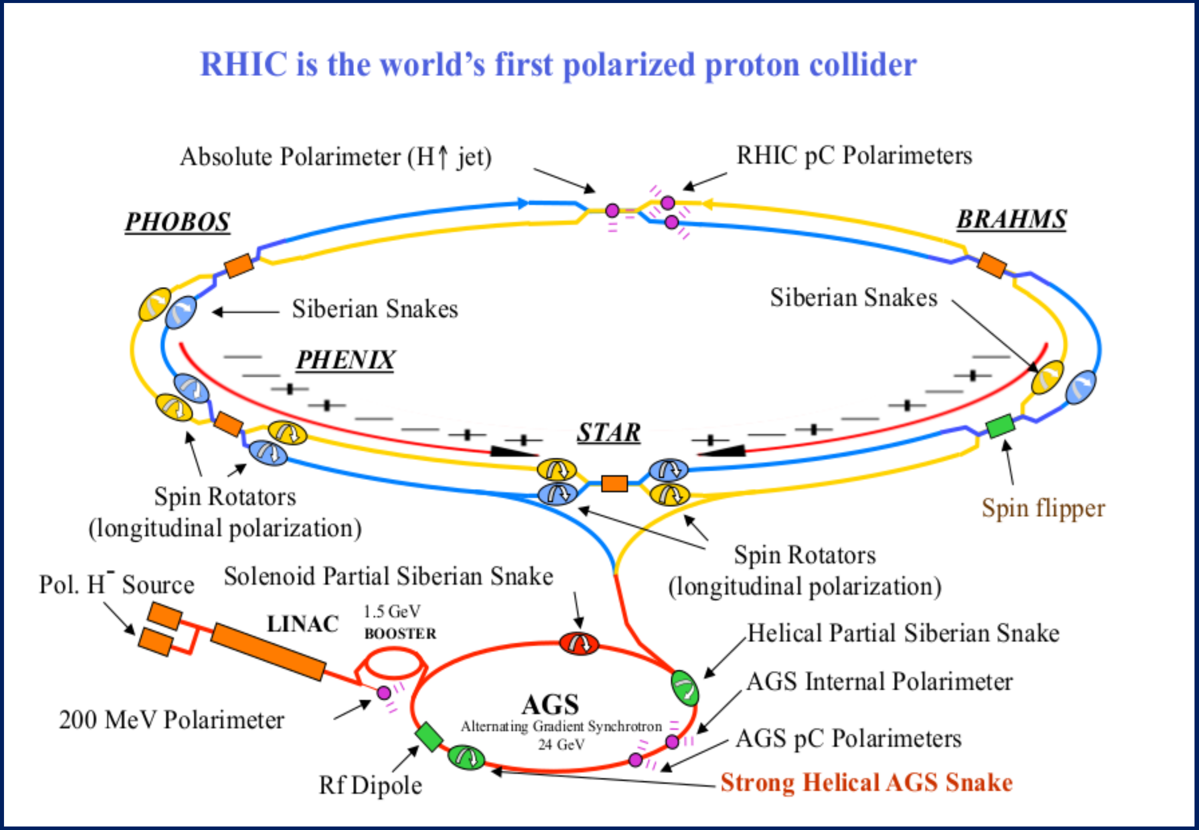
JINR

March 24, 2026

Polarized proton running at PHENIX

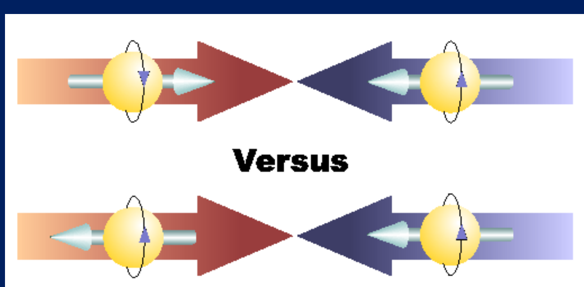
long./trans.

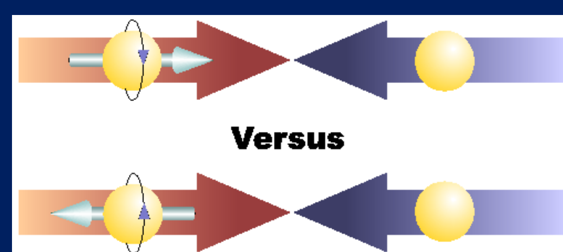
Year	√s [GeV]	L [pb^{-1}] (recorded)	Pol. [%]
2002	200	– / 0.15	15
2003	200	0.35 / –	27
2004	200	0.12 / –	40
2005	200	3.4 / 0.2	49
2006	200	7.5 / 2.7	57
2006	**62.4**	**0.08 / 0.02**	**48**
2008	200	– / 5.2	45
2009	200	16 / –	55
2009	**500**	**14 / –**	**39**
2011	**500**	**18 / –**	**48**
2012	200	– / 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

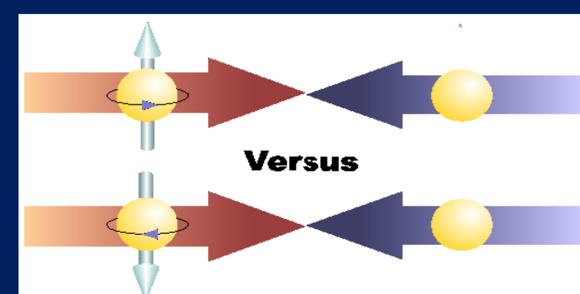


Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \rightarrow \pi + X)$ Prompt Photons $A_{LL}(gq \rightarrow \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow \ell^- + \bar{\nu}_l)$	Transversity Transverse-momentum-dependent distributions Single-Spin Asymmetries







The PHENIX Detector

Central Arms: π^0, $\pi^{\pm}$, η, $e^{\pm}$, γ, ...

- $|\eta| < 0.35$, $\Delta\phi = 0.5\pi$ per arm

Muon Arms: $\mu^{\pm}, h^{\pm}$

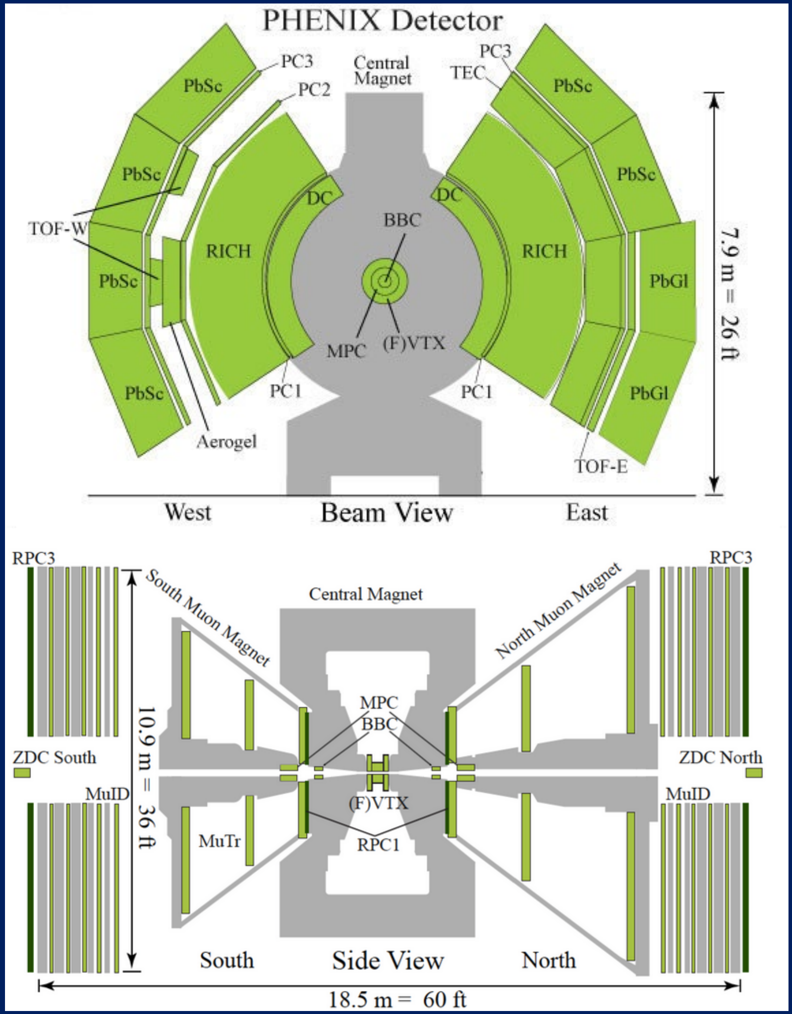
- $1.4 < |\eta| < 2.4$, $\Delta\phi = 2\pi$

Muon Piston Calorimeters: π^0, η

- $3.0 < |\eta| < 3.8$, $\Delta\phi = 2\pi$

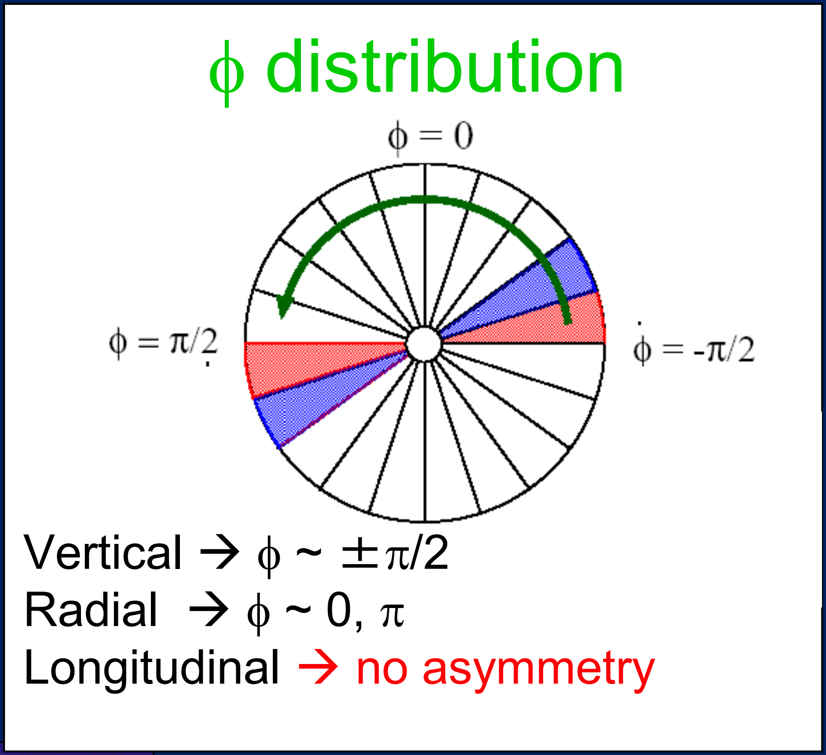
Zero Degree Calorimeters: Neutrons

- $|\eta| > 6.8$, $\Delta\phi = 2\pi$



PHENIX Local Polarimeter

- Take advantage of forward neutron TSSA discovered in first polarized RHIC run!
  - $A_N \sim -9\%$ (PLB 650, 325-330, 2007)
  - Allows measurement of any remaining component in an undesired direction
- Shower Max Detector (position) + Zero-Degree Cal. (energy)

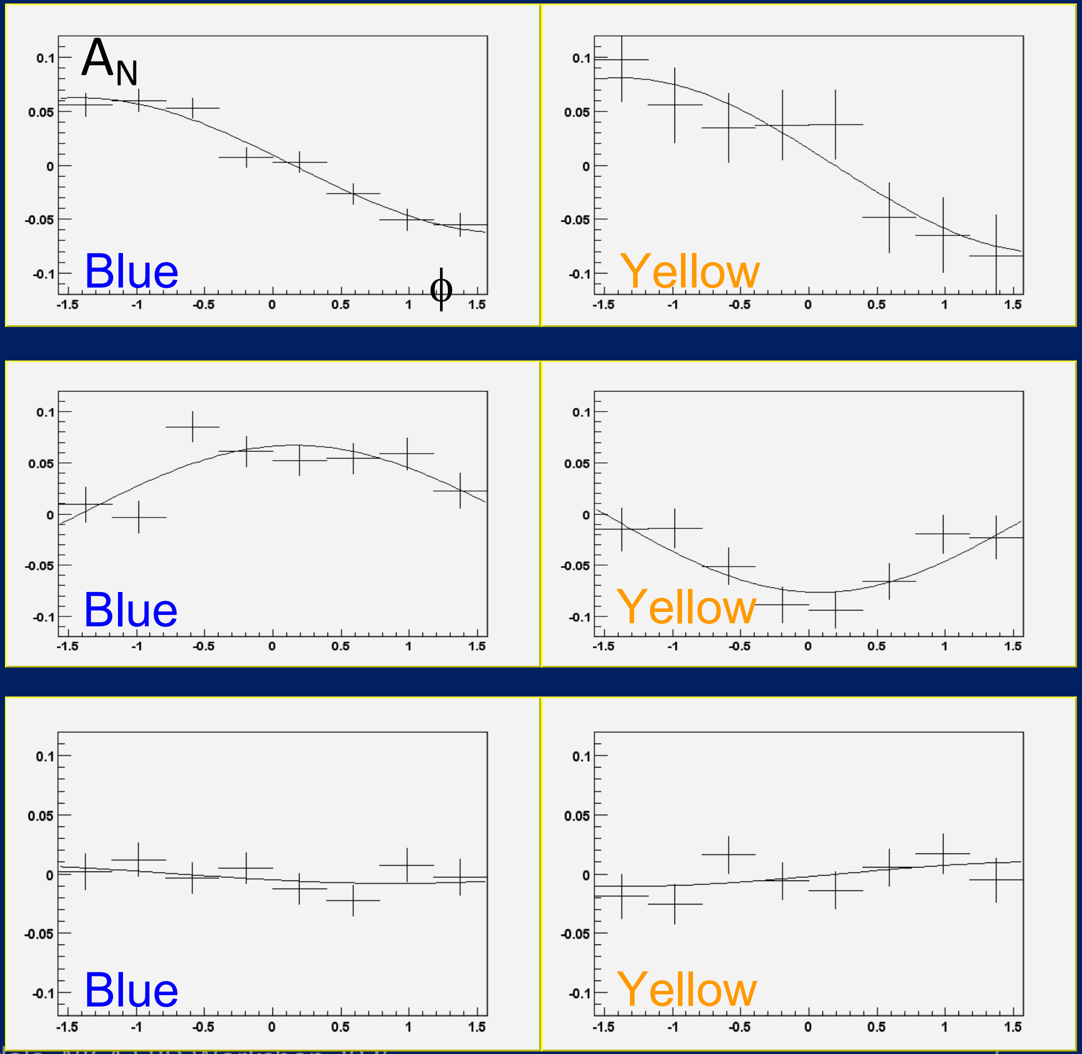


Neutron TSSA for Local Polarimetry

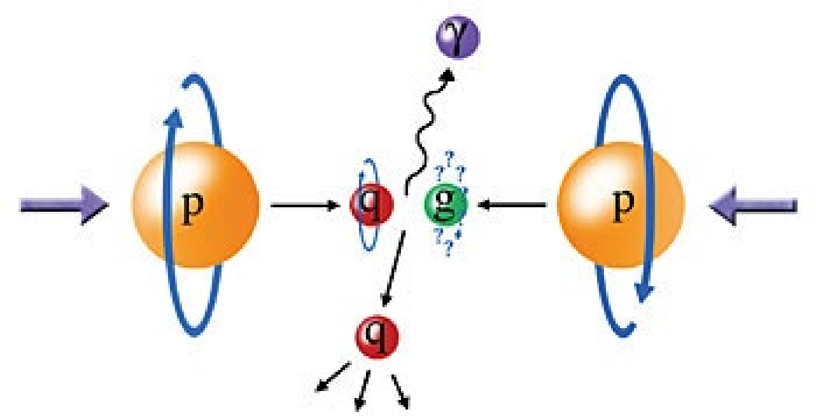
Spin Rotators OFF
Vertical polarization

Spin Rotators ON
Radial polarization

Spin Rotators ON
Longitudinal polarization



Probing the helicity structure of the nucleon with longitudinally polarized p+p collisions



$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$

Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

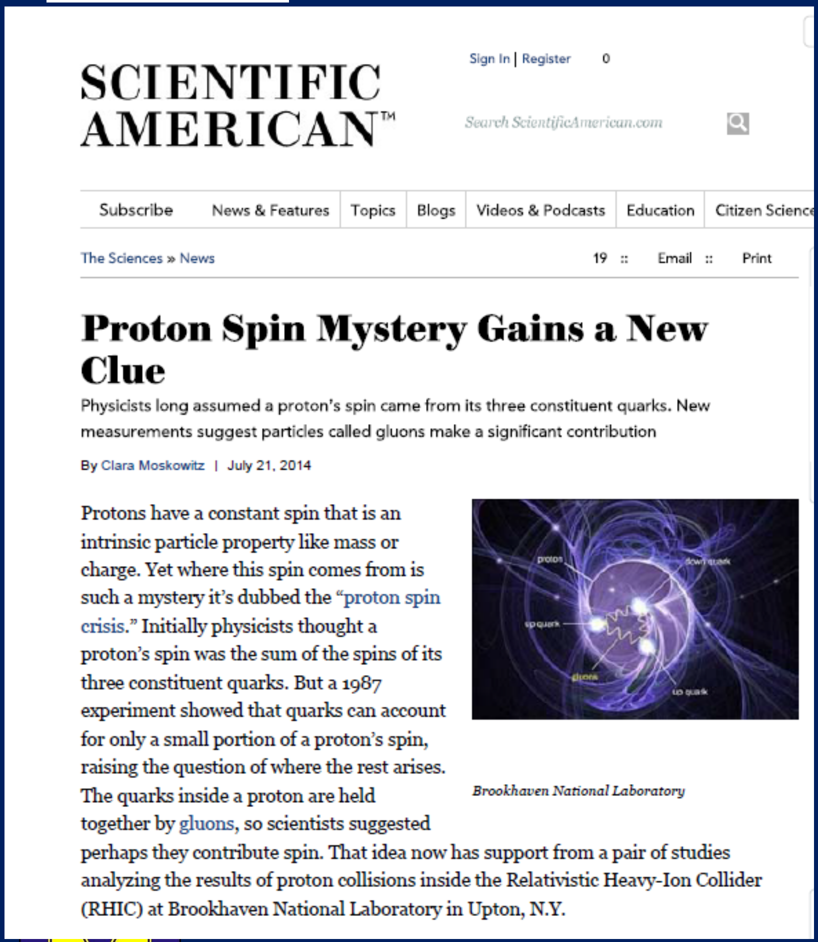
$$\Delta\sigma(pp \to \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg \to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

(SI)DIS, p+p | ? | pQCD | e+e-, SIDIS, p+p

Leading-order access to gluons → ΔG

Gluon helicity contribution to proton spin (ΔG)

July 2014


SCIENTIFIC AMERICAN™

Sign In | Register 0

Search ScientificAmerican.com

Subscribe | News & Features | Topics | Blogs | Videos & Podcasts | Education | Citizen Science

The Sciences » News 19 :: Email :: Print

Proton Spin Mystery Gains a New Clue

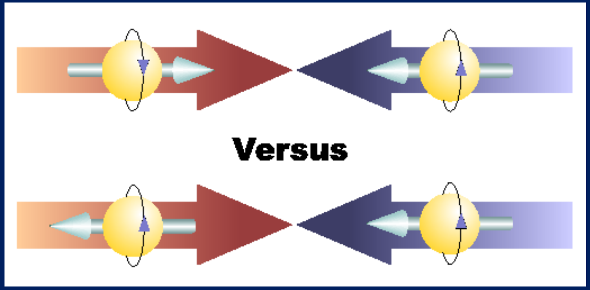
Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

By Clara Moskowitz | July 21, 2014

Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account for only a small portion of a proton's spin, raising the question of where the rest arises. The quarks inside a proton are held together by gluons, so scientists suggested perhaps they contribute spin. That idea now has support from a pair of studies analyzing the results of proton collisions inside the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, N.Y.

Brookhaven National Laboratory

$$\frac{1}{2} = \frac{1}{2}\cdot\Delta\Sigma + \Delta G + L_{G+q}$$



Gluon helicity contribution to proton spin (ΔG)

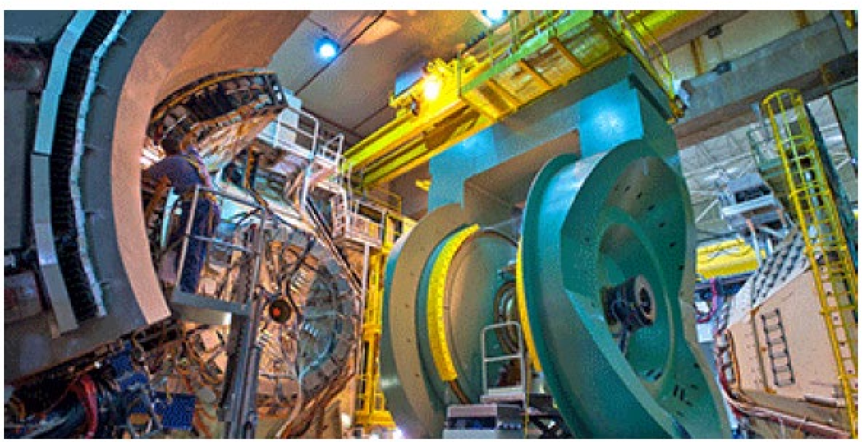
$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

APS physics | Physics

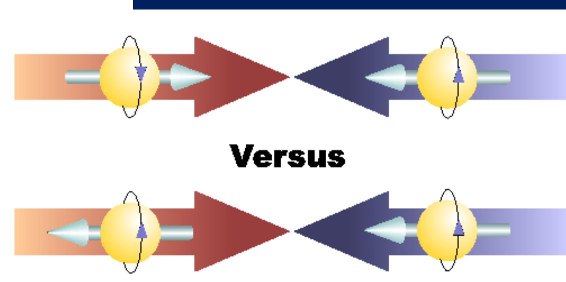
Synopsis: Gluons Chip in for Proton Spin

July 2, 2014

A new analysis of high-energy data shows that gluons may provide some of the proton's missing spin.

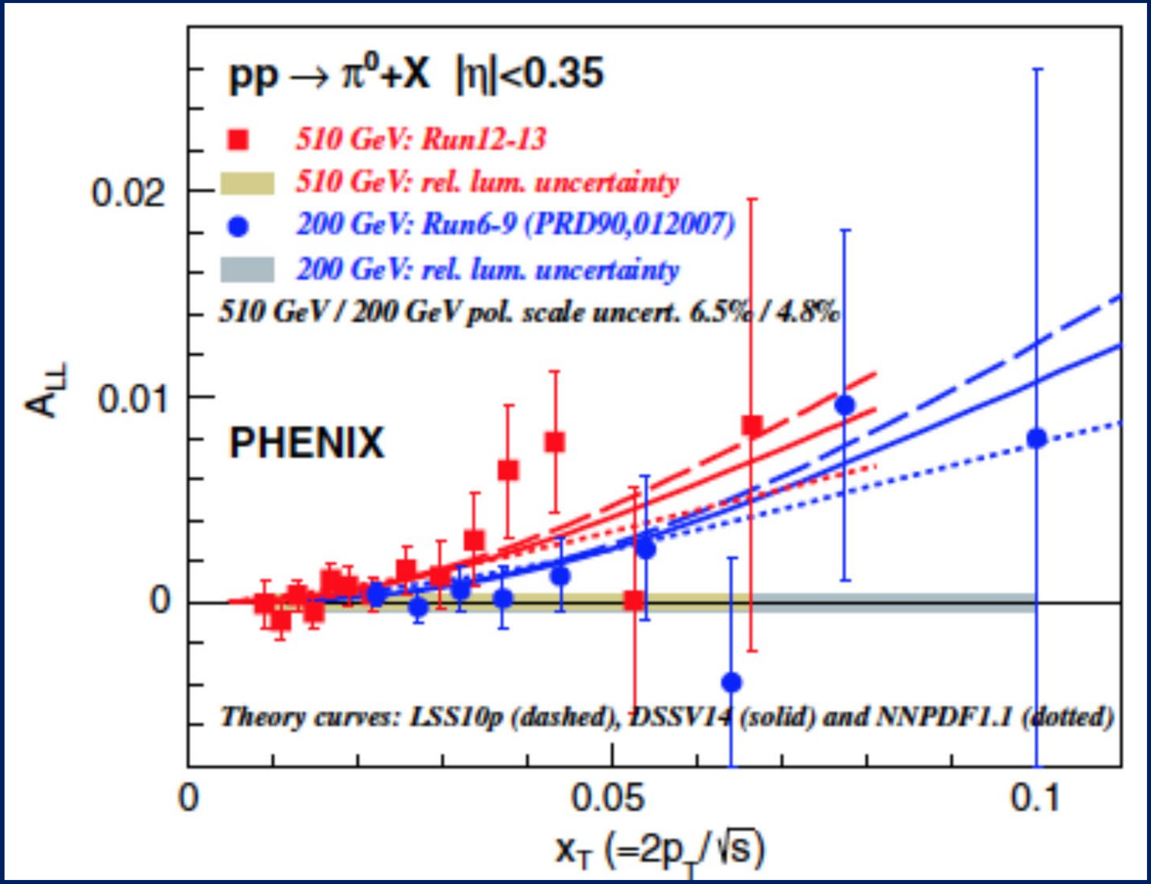


Brookhaven National Laboratory

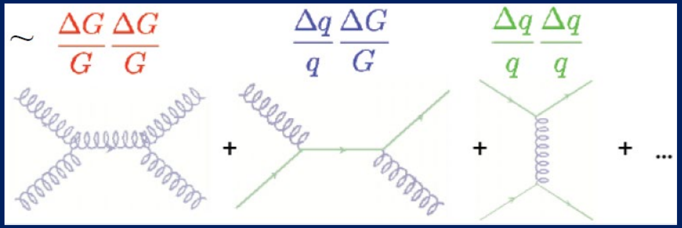


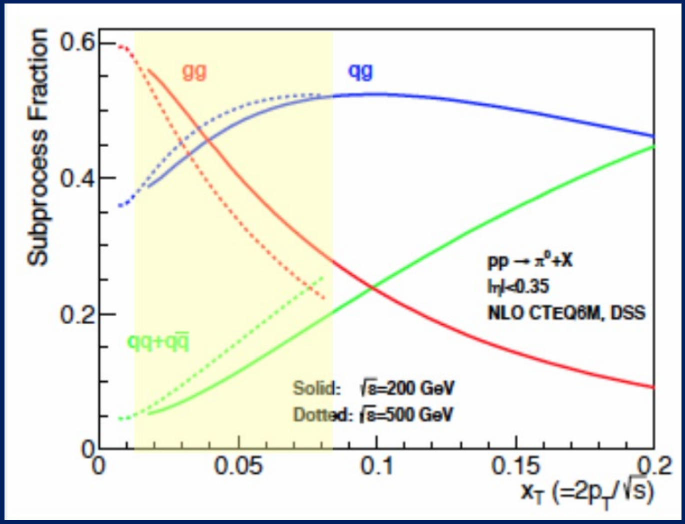
Gluon helicity contribution to proton spin (ΔG)

π^0 double-helicity asymmetry



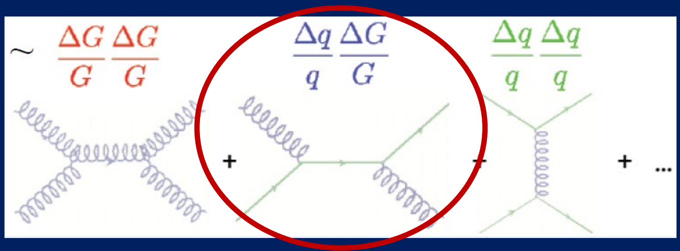
PRD93, 011501 (2016)



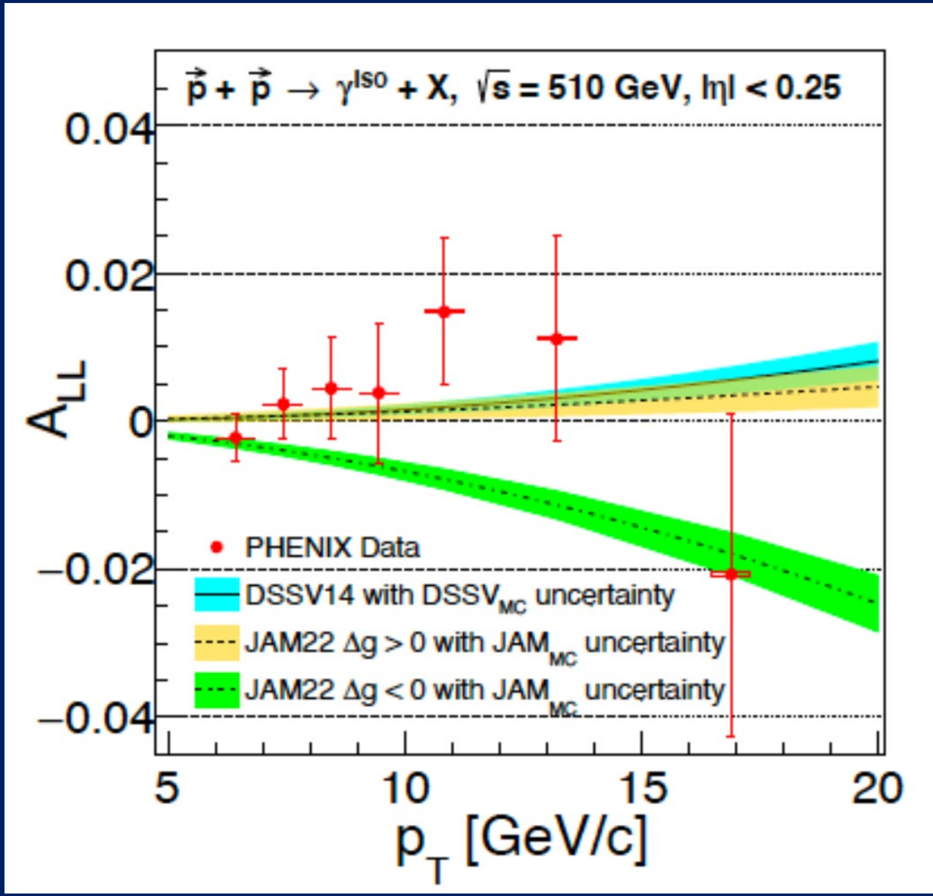


Nonzero A_{LL} associated with nonzero ΔG!

Gluon helicity contribution to proton spin (ΔG)



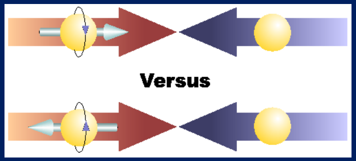
Direct photon double-helicity asymmetry



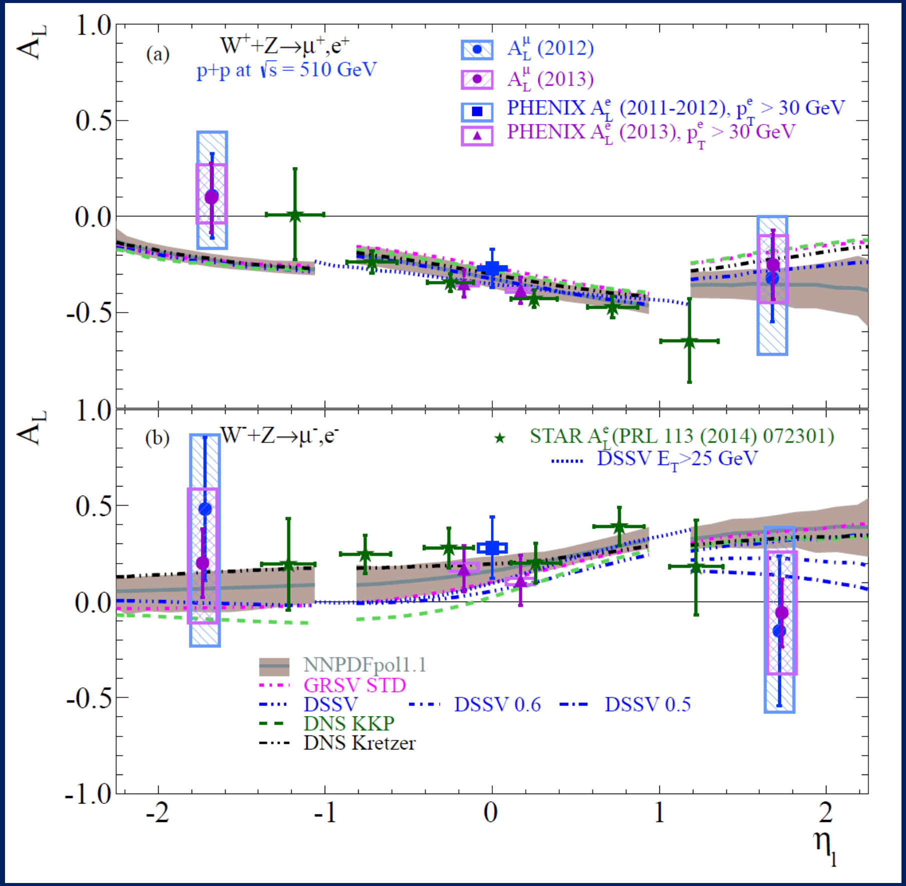
PRL130, 251901 (2023)

Direct photon production more sensitive to sign of ΔG

Flavor-separated sea quark helicity distributions



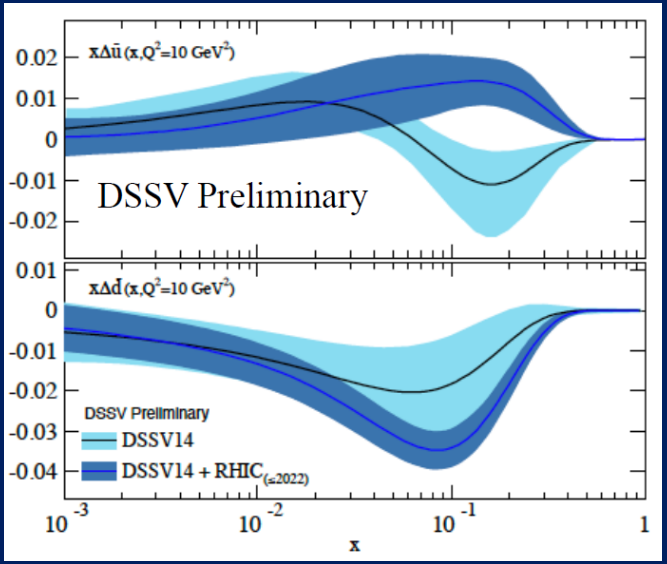
$W^{\pm}$ decay lepton single-helicity asymmetry



PRD98, 032007 (2018)

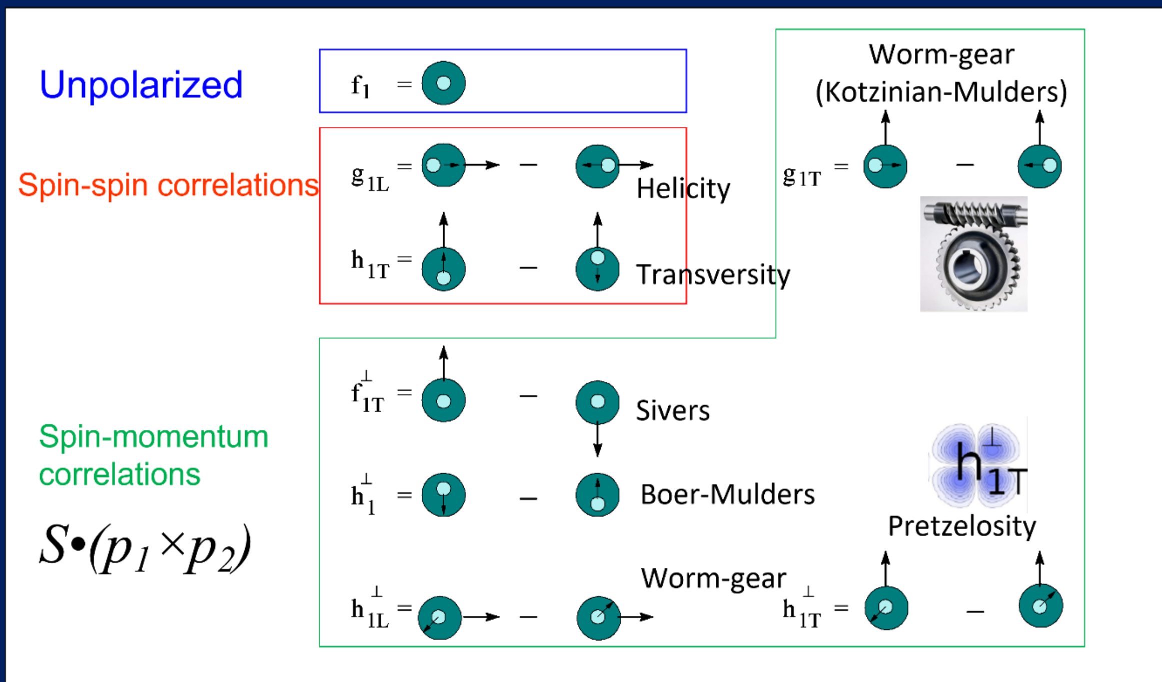
Access via parity-violating longitudinal single-spin asymmetry in $W^{\pm}$ production—no fragmentation functions necessary:

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



Preference for positive $\Delta\bar{u}$, negative $\Delta\bar{d}$

Spin-momentum correlations and parton ***dynamics***



In proton and/or in process of hadronization

Two formalisms:

- Transverse-momentum-dependent (TMD) distributions
- Collinear twist-3 multiparton correlators

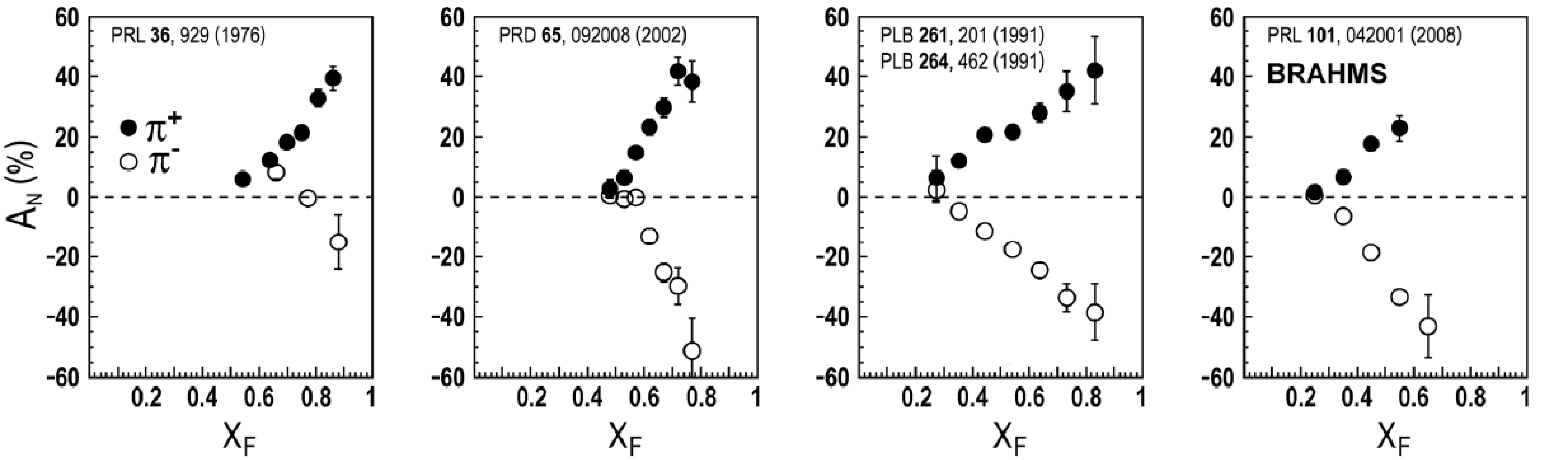
Large forward transverse single-spin asymmetries observed in p+p collisions

ANL
√s=4.9 GeV

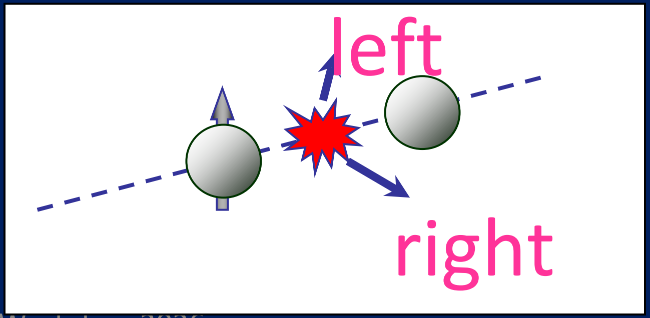
BNL
√s=6.6 GeV

FNAL
√s=19.4 GeV

RHIC
√s=62.4 GeV



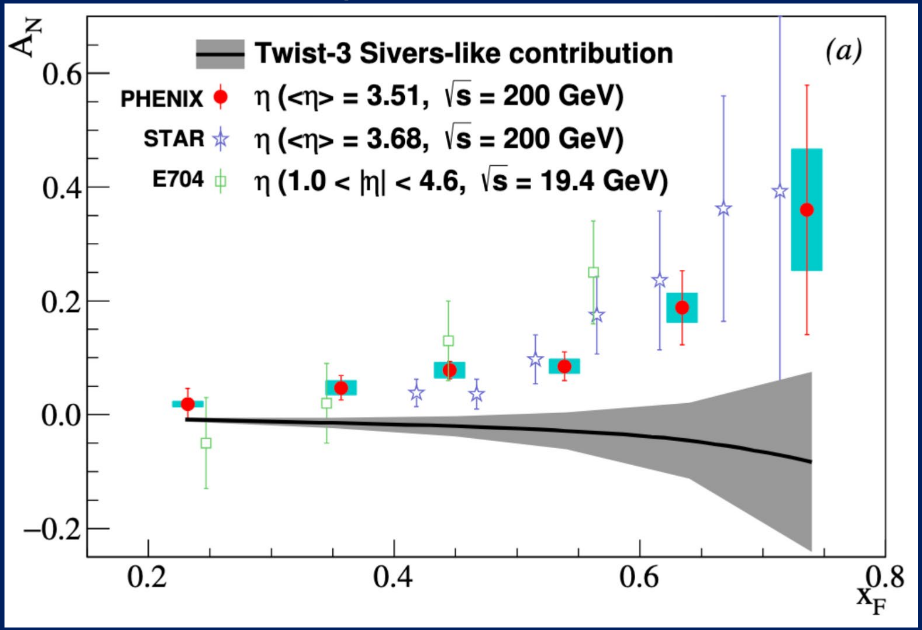
$$x_F = 2p_{long}/\sqrt{s}$$
$$= x_1 - x_2$$



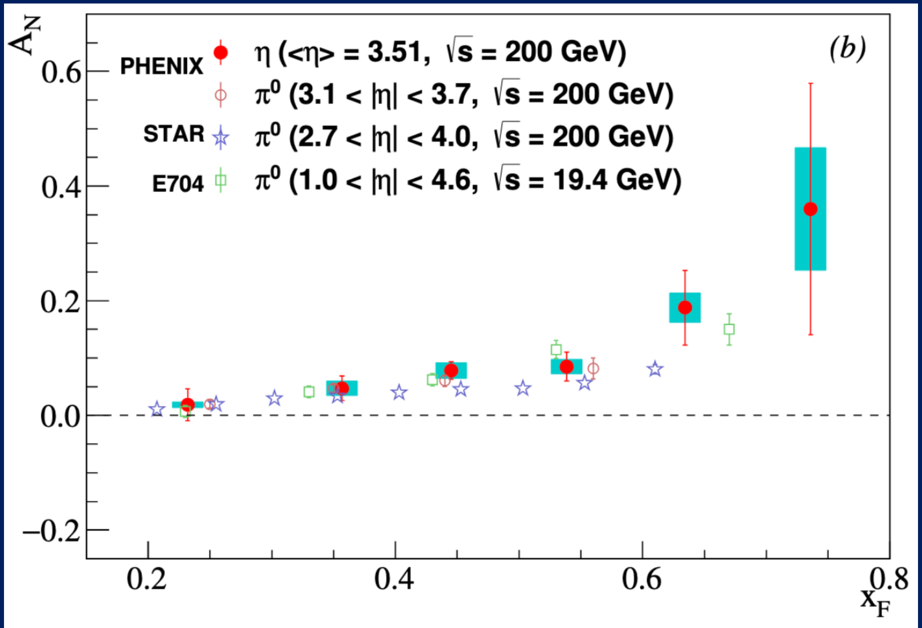
Forward η meson A_N

arXiv:2509.13497
Accepted by PRD

Compared to η TSSA at other energies



Compared to π^0 TSSA

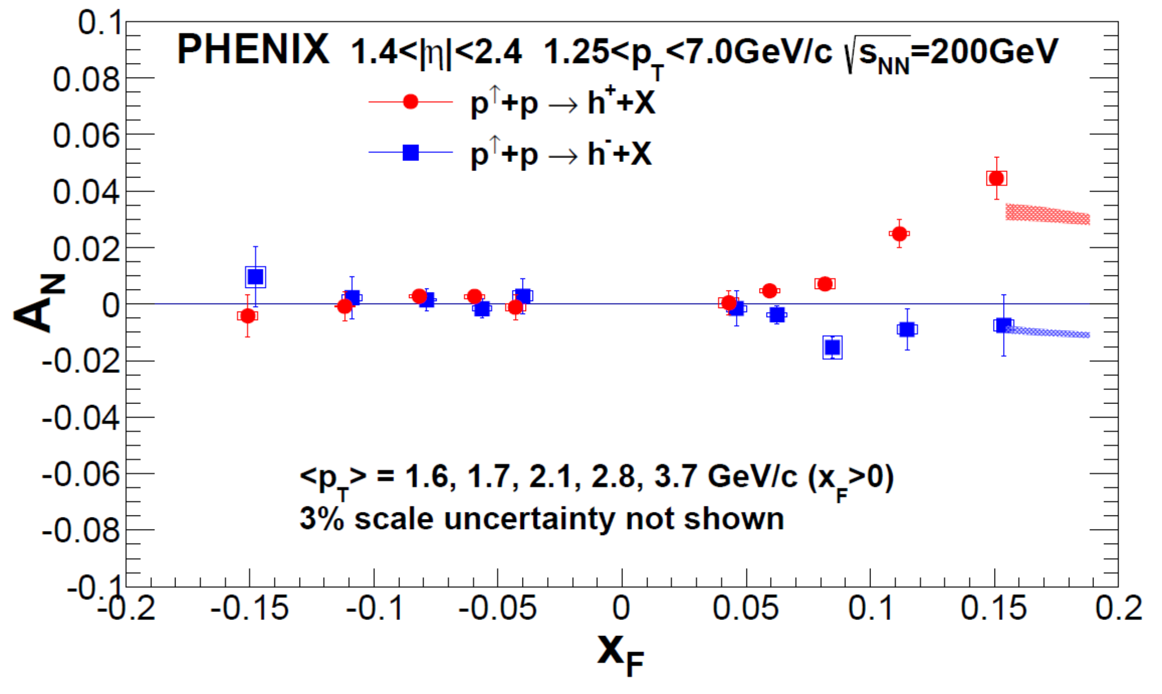


Twist-3 calculation for qgq correlator in proton (D. Pitonyak) insufficient to describe asymmetry → contributions from hadronization.

Similarity between η and π^0 suggests limited impact from mass, isospin, or strangeness

Forward and backward $h^{\pm}$ A_N

PRD108, 072016 (2023)

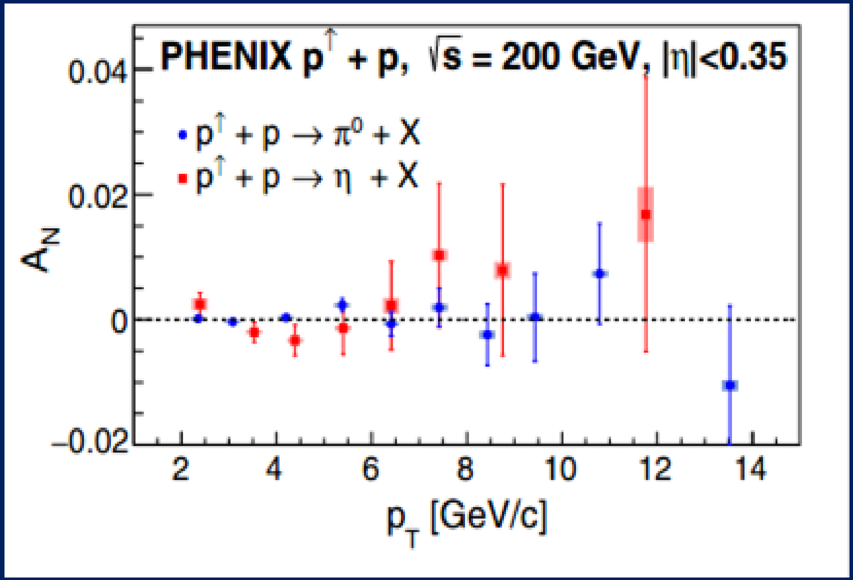


Inclusive positively charged hadrons measured in muon arms

$\pi^+/K^+/p$ fractions: 0.45/0.47/0.05

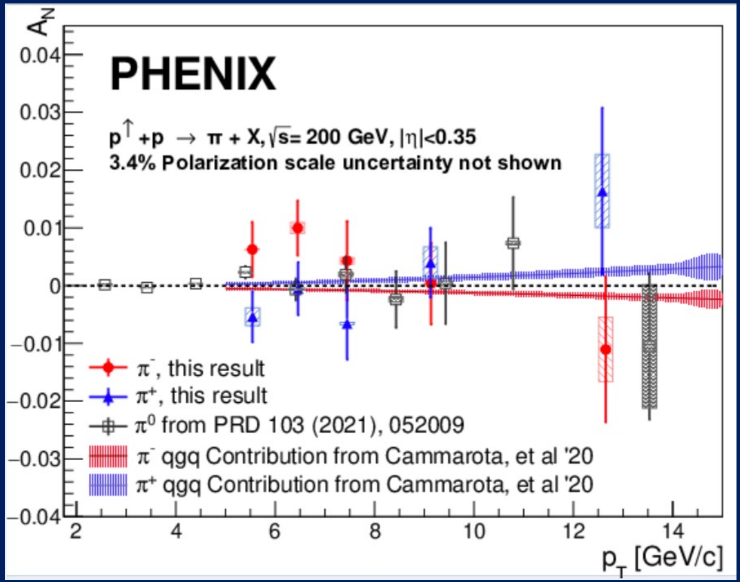
Midrapidity π^0, $\pi^{\pm}$, and η meson A_N

π^0 and η



PRD 103, 052009 (2021)

$\pi^{\pm}$



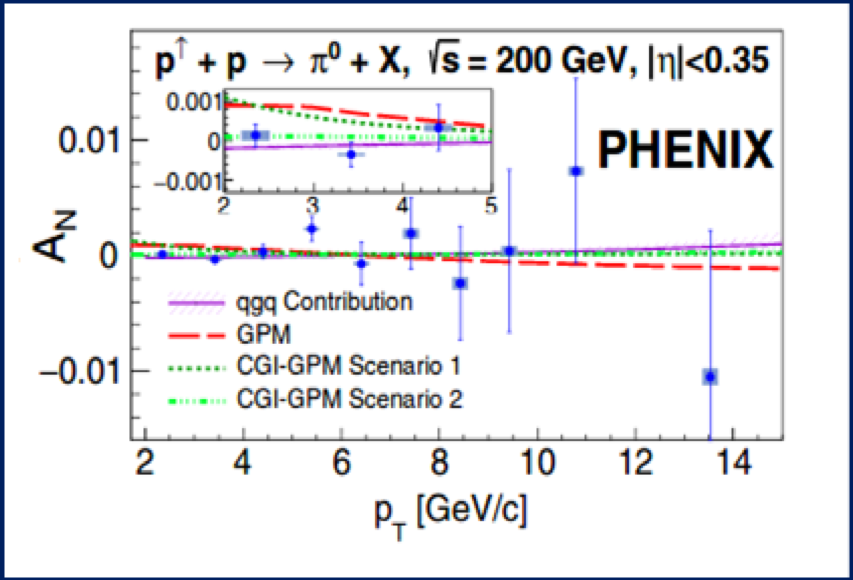
PRD 105, 032003 (2022)

Consistent with zero, within ~3× 10^{-4} for low-p_T π^0.

Help constrain twist-3 trigluon correlation functions (PRD 89, 034029 (2014)), or gluon Sivers TMD function in Generalized Parton Model (PRD 99, 036013 (2019))

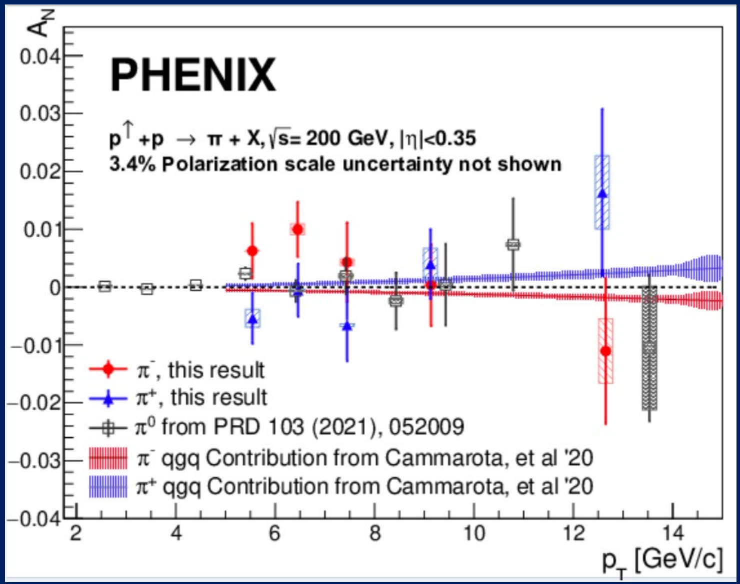
Midrapidity π^0, $\pi^\pm$, and η meson A_N

π^0 and η



PRD 103, 052009 (2021)

$\pi^\pm$



PRD 105, 032003 (2022)

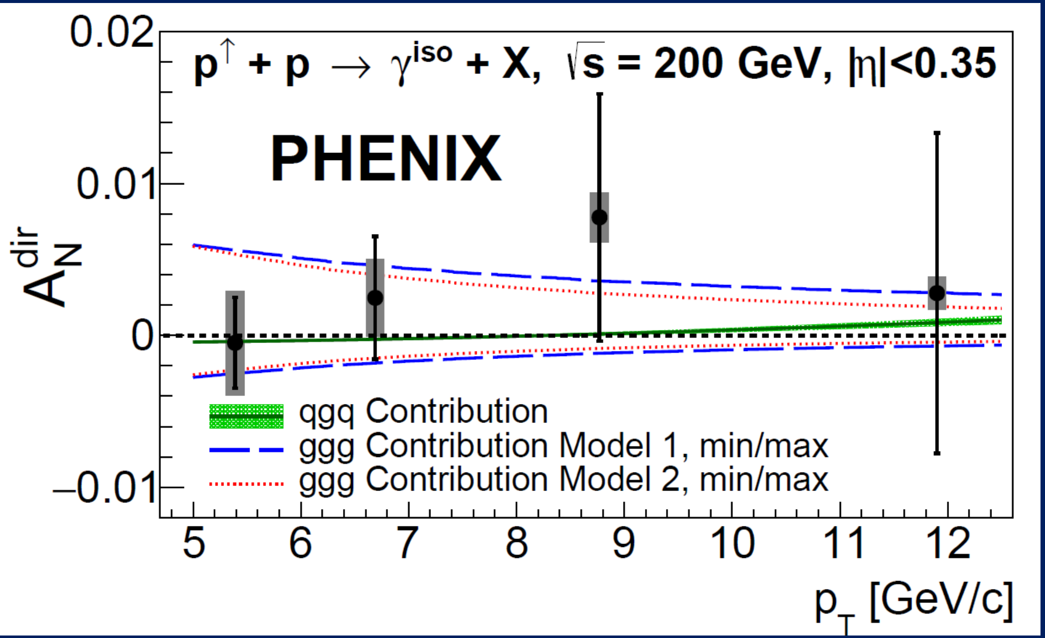
Consistent with zero, within ~3× 10^{-4} for low-p_T π^0.

Help constrain twist-3 trigluon correlation functions (PRD 89, 034029 (2014)), or gluon Sivers TMD function in Generalized Parton Model (PRD 99, 036013 (2019))

Midrapidity direct photon A_N

Consistent with zero

Quark-gluon Compton scattering – sensitive to trigluon correlators



PRL 127, 162001 (2021)

*qgq c*ontribution – Kanazawa, Koike, Metz, Pitonyak, PRD 91, 014013 (2015)

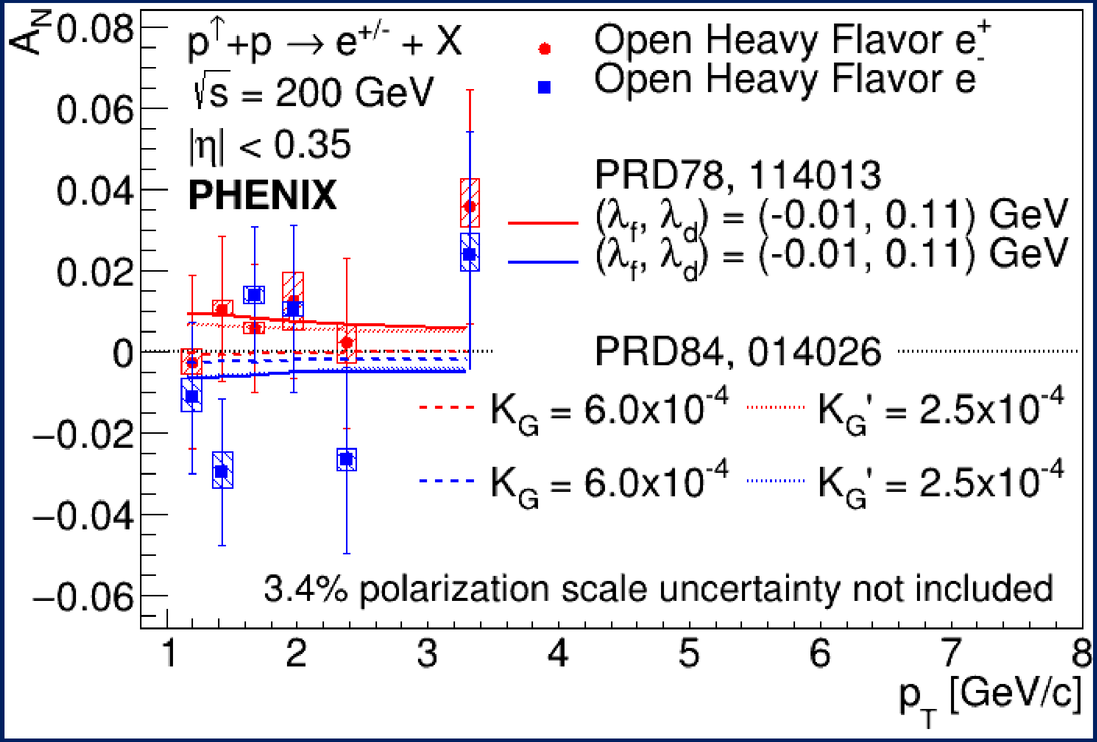
Already constrained by other measurements to be very small

ggg contribution – Koike and Yoshida, PRD 85, 034030 (2012)

Midrapidity open heavy flavor electron and positron A_N

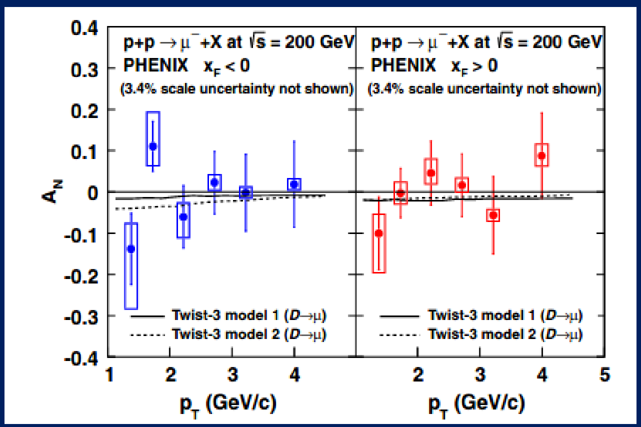
Gluon-gluon fusion – sensitive to trigluon correlators

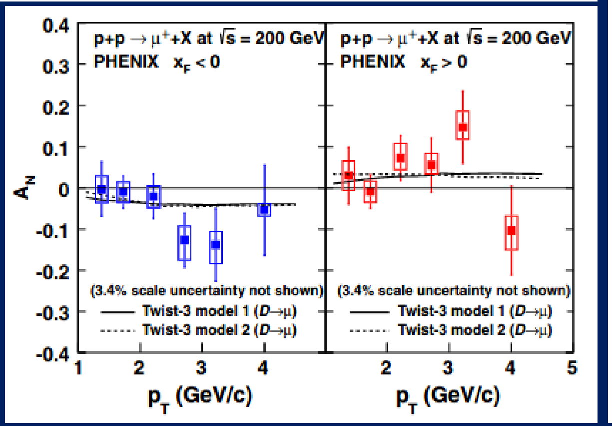
Theoretical calculations for trigluon correlation function parameters that best fit the data

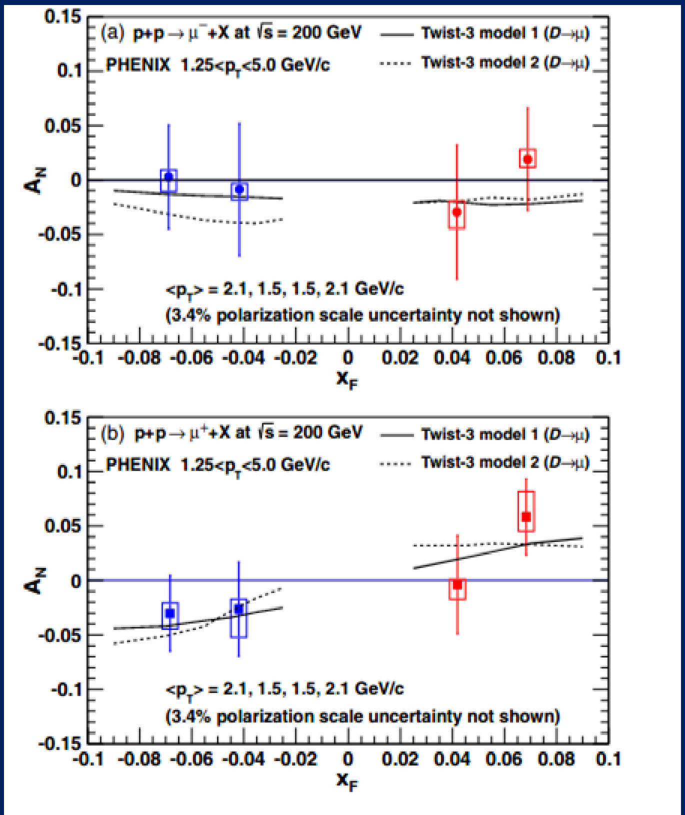


PRD 107, 052012 (2023)

Previous open heavy flavor results: Forward muon A_N



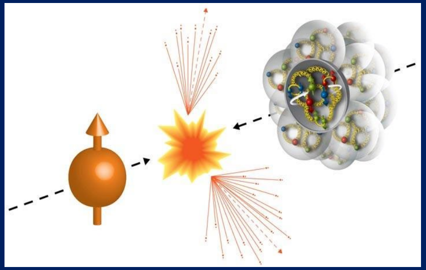


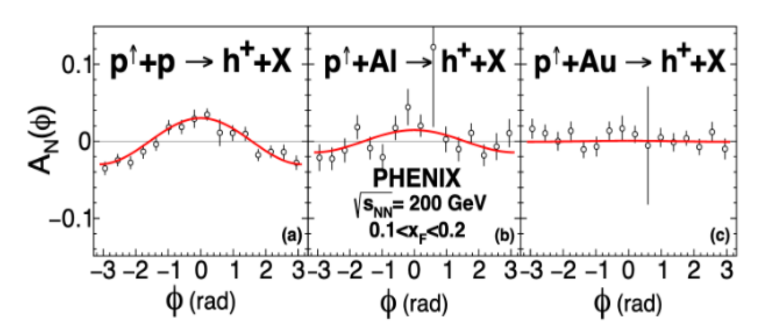


Asymmetries consistent with zero and theoretical predictions taking into account contributions from trigluon correlation functions from PRD 84, 014026 (2011)

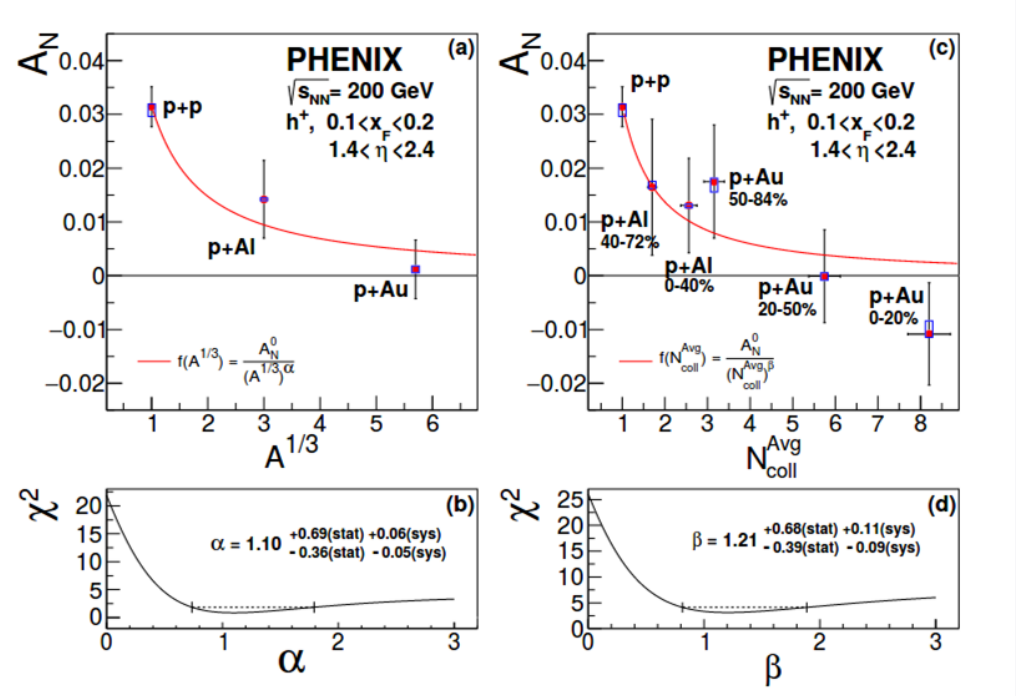
PRD 95, 112001 (2017)

Nuclear effects: Forward hadron A_N for $p^\uparrow+p$, $p^\uparrow+Al$, $p^\uparrow+Au$





- Inclusive positively charged forward hadron TSSAs
  - *$\pi^+/K^+/p$ fractions: 0.45/0.47/0.05*
- Clear suppression of A_N in p+A observed

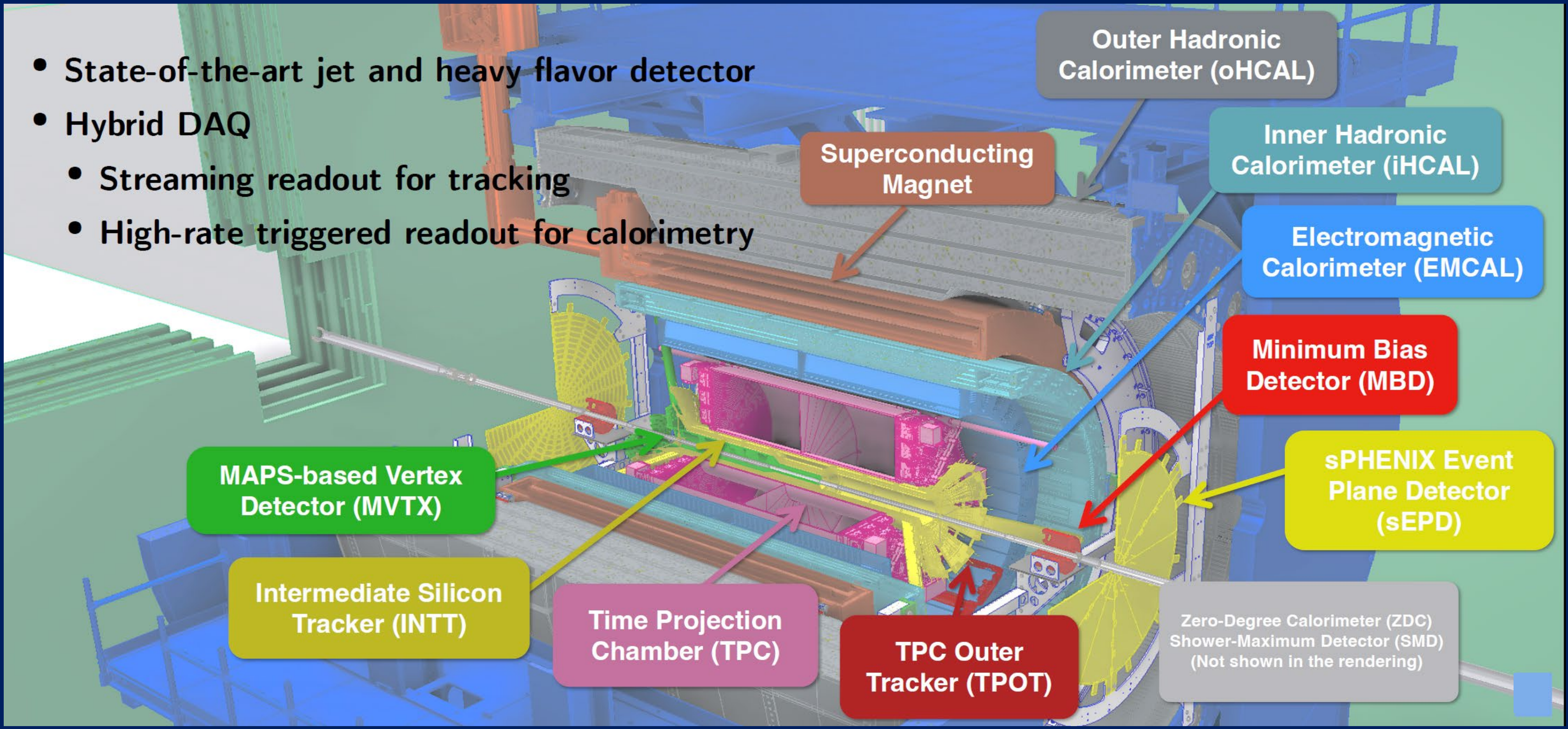


PRL 123, 122001 (2019)

sPHENIX

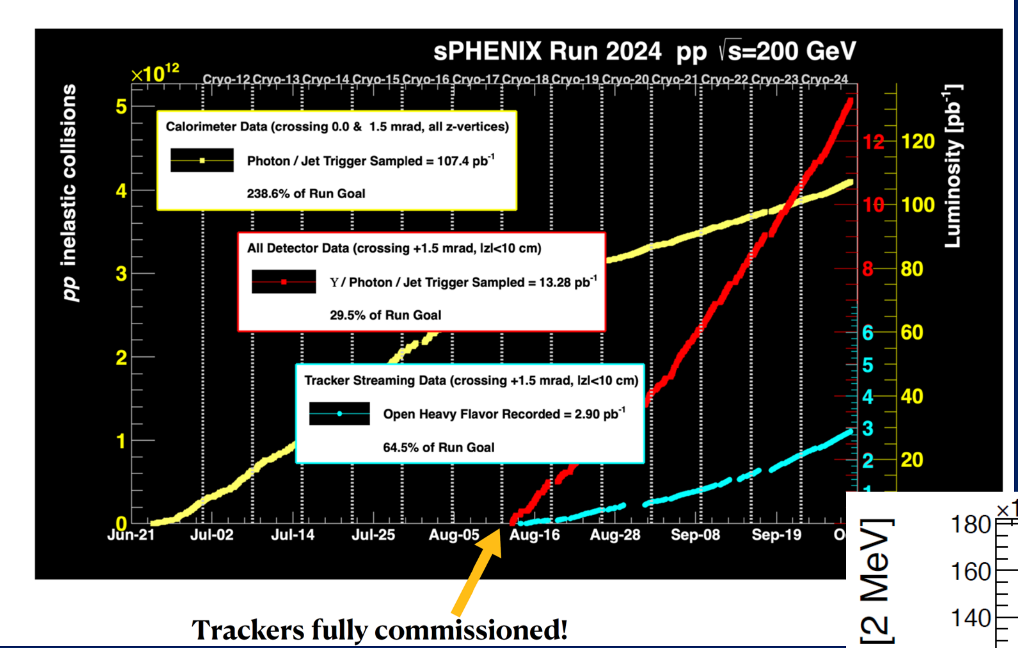
sPHENIX

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



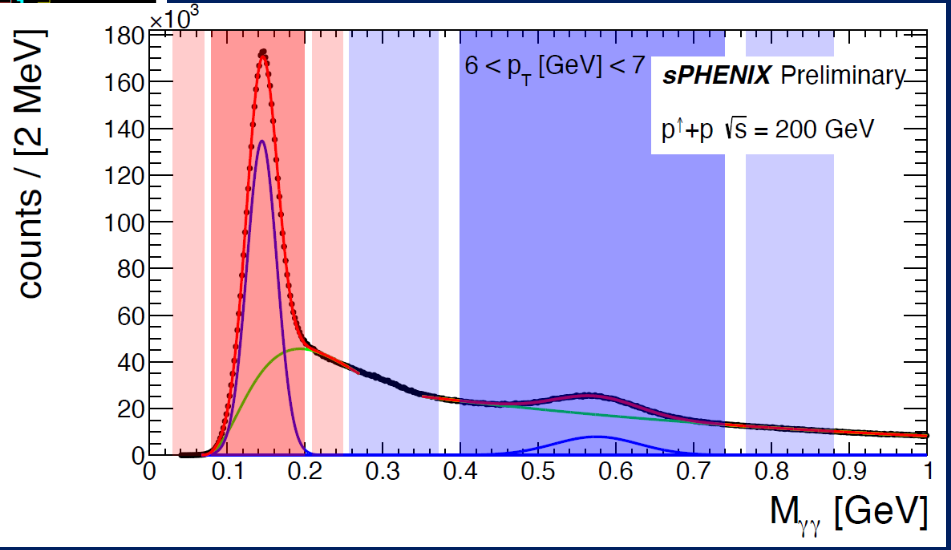
Au+Au, $p^{\uparrow} + p^{\uparrow}$, O+O data 2023-2026

sPHENIX 2024 p+p

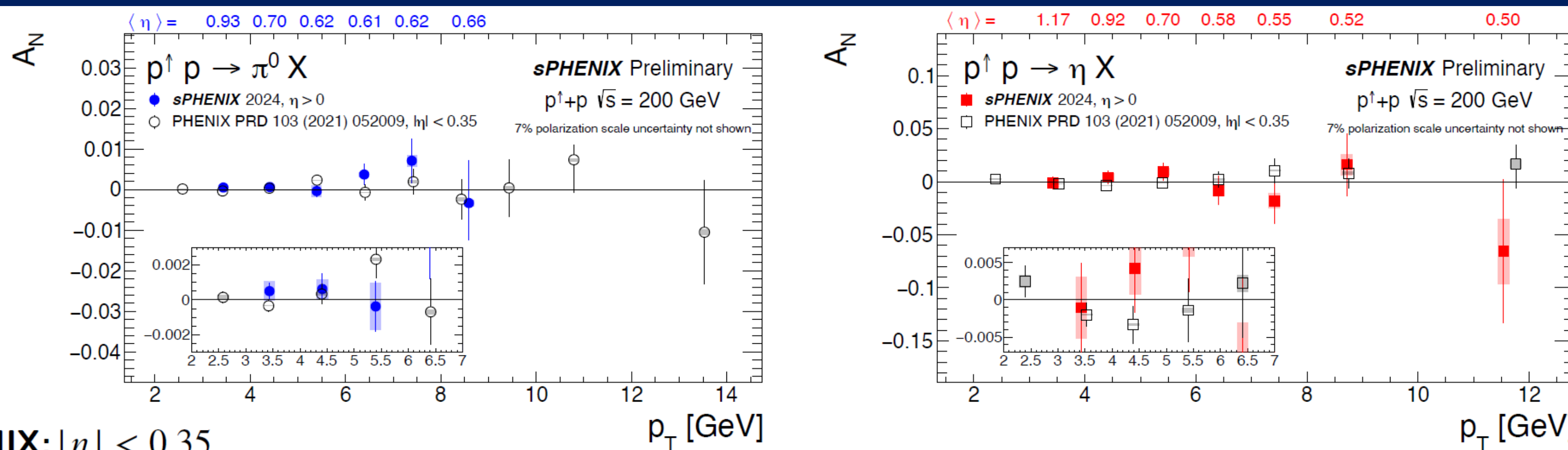


Integrated lumi with different subsystems commissioned

$\gamma\gamma$ invariant mass spectrum



Midrapidity π^0 and η meson A_N



PHENIX: $|\eta| < 0.35$

sPHENIX: $\eta > 0$

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

Only ~1/3 of data set.

Stay tuned for more spin results from sPHENIX!

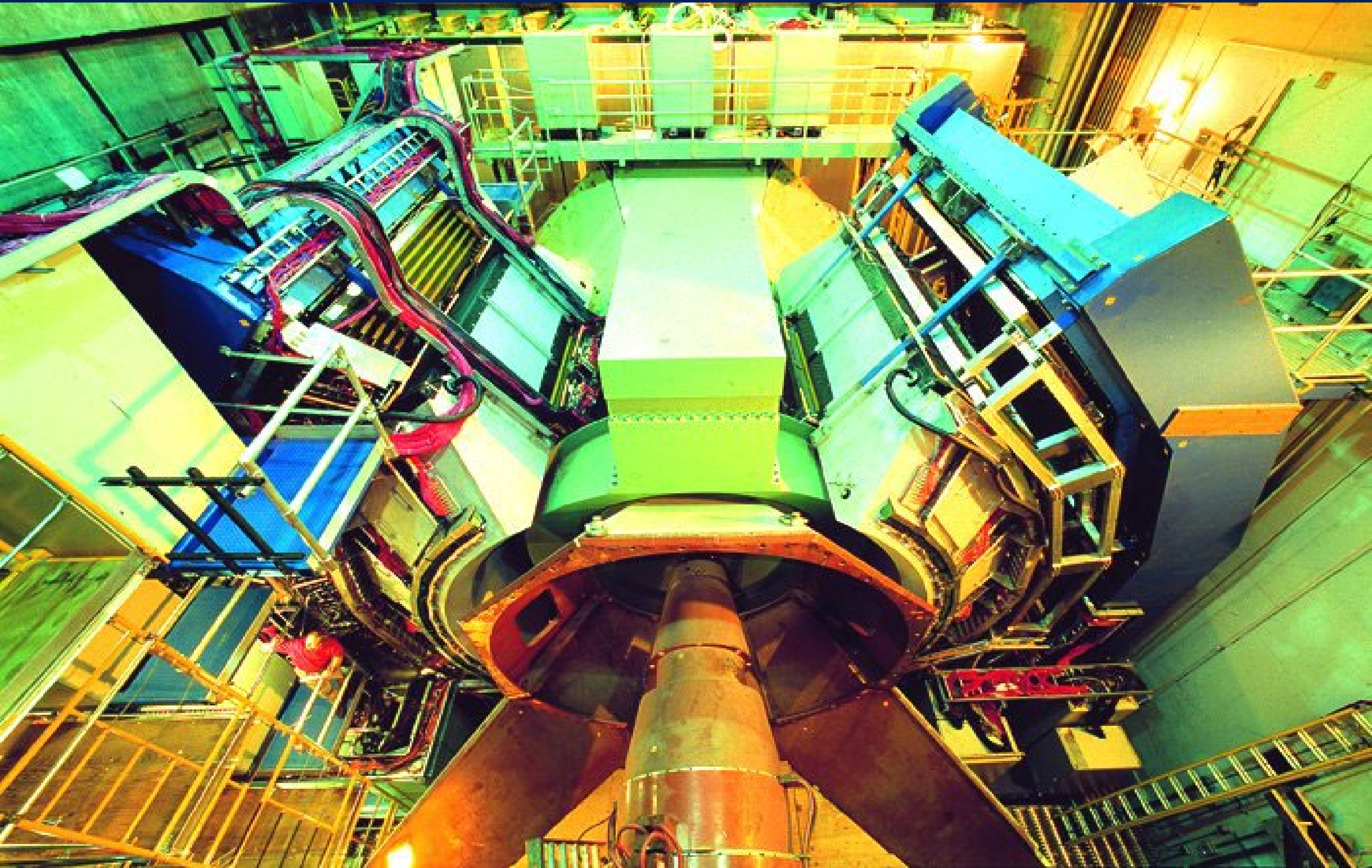
Conclusions

- Along with STAR, PHENIX pioneered a broad program studying spin physics in QCD at a proton collider
- An extensive legacy of measurements!

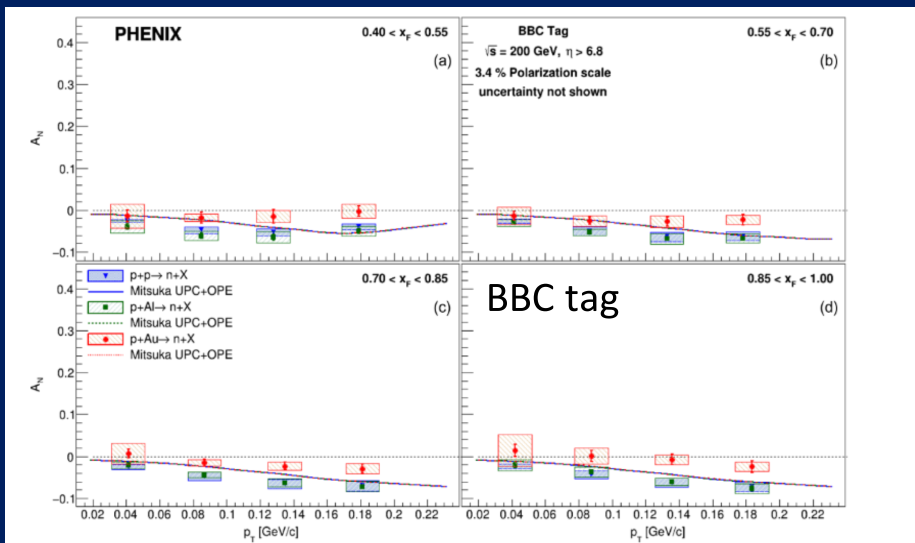
- Stay tuned for more results to come from sPHENIX!

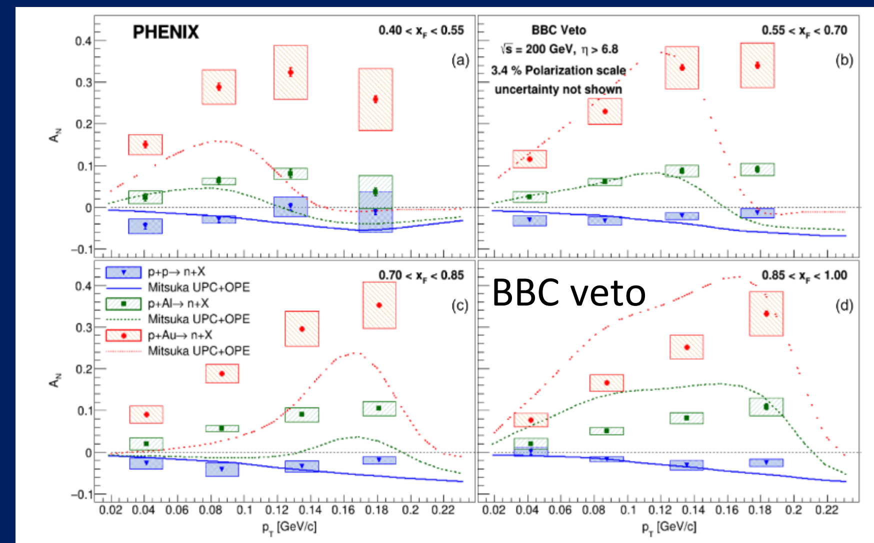
Extra

PHENIX Detector



Nuclear effects: Forward neutron A_N at $\sqrt{s_{NN}}$ = 200 GeV ($p^{\uparrow}$+p, $p^{\uparrow}$+Al, $p^{\uparrow}$+Au)



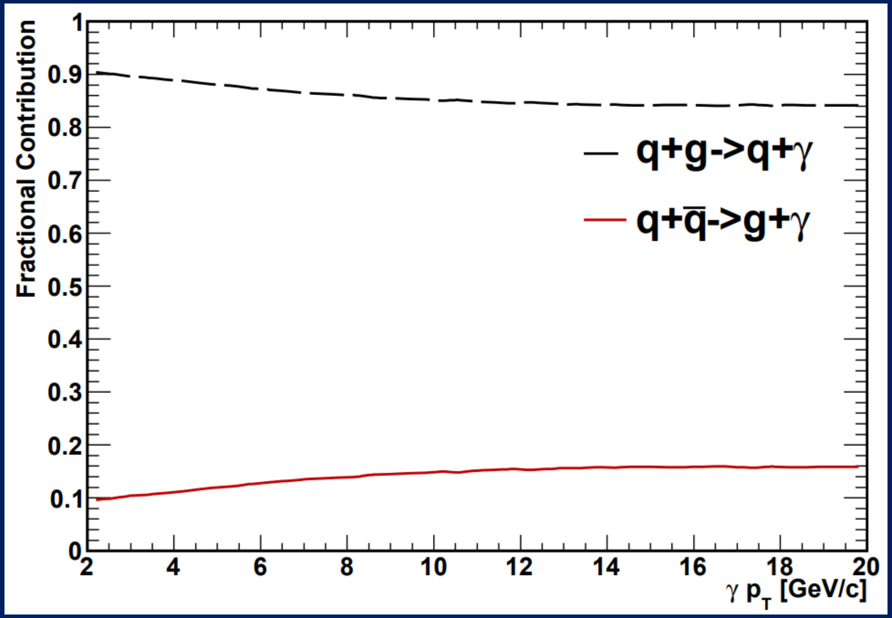


- Very forward neutron asymmetries are shown for *$p^{\uparrow}$+p, $p^{\uparrow}$+Al, $p^{\uparrow}$+Au* collision systems for both beam-beam-counter (BBC) tagged events, dominated by hadronic interactions (left), and BBC vetoed events (with little activity in the BBC) that show an enhancement of ultra peripheral collisions (UPC) (right)
- The asymmetries qualitatively agree with the UPC + one-pion-exchange (OPE) theory predictions

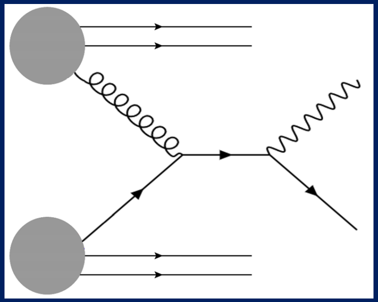
Phys. Rev. D 105, 032004 (2022)

See also detailed p_T-dependent p+p results in Phys. Rev. D 103, 032007 (2021)

Midrapidity direct photons



Fractional contribution of parton scattering to midrapidity inclusive direct photon production at leading order for p+p collisions at $\sqrt{s} = 200$ GeV. PHENIX PRD82, 072001 (2010)



- Only sensitive to initial-state proton structure
  - With isolation cut, NLO fragmentation photon contribution < 15% (PHENIX PRD 82, 072001 (2010))
- Strong sensitivity to gluons in the proton

Direct photon background:
Hadron decay photons with missing partner

Sometimes only one of the photons from a $h \rightarrow \gamma\gamma$ decay is measured and the second photon is missed

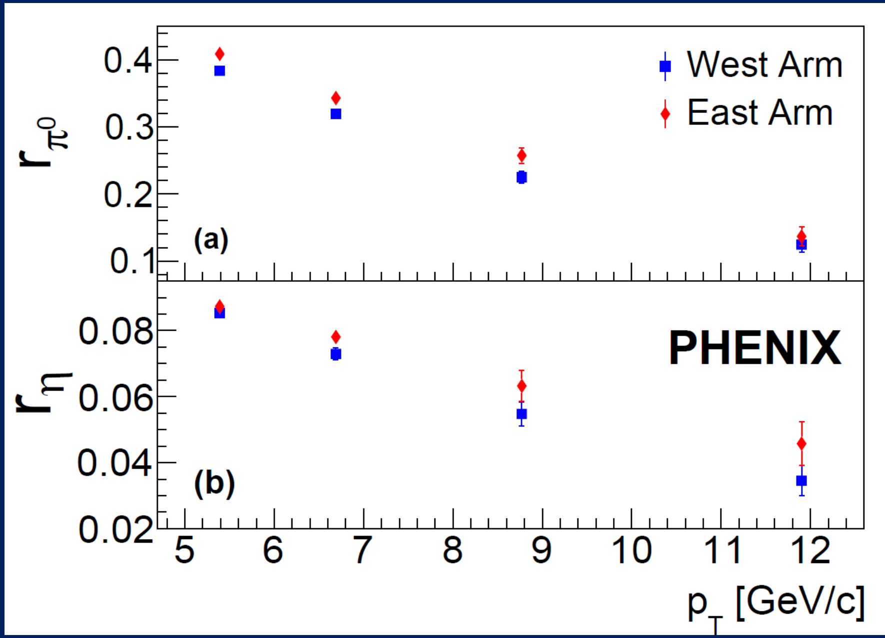
- η decays tend to be more asymmetric because they are ~4 times heavier than π^0s

Estimate number missed using ones that were tagged:

From data: Ratio of number isolated decay photons to direct photon candidate sample

$$r_{miss} = \frac{N_{bg}}{N_{sig} + N_{bg}} = R\,\frac{N_{tag}^{iso,h}}{N^{iso}}$$

From simulation: Converts between tagged decay photons to missed decay photons



PRL 127, 162001 (2021)

Direct photon selection

- Tagging cut - subtract out photons that are tagged as coming from $\pi^0 \rightarrow \gamma\gamma$ and $\eta \rightarrow \gamma\gamma$ decays
- Isolation cut – eliminate decay photons and next-to-leading-order fragmentation photons

$$E_\gamma * 10\% > E_{cone}$$

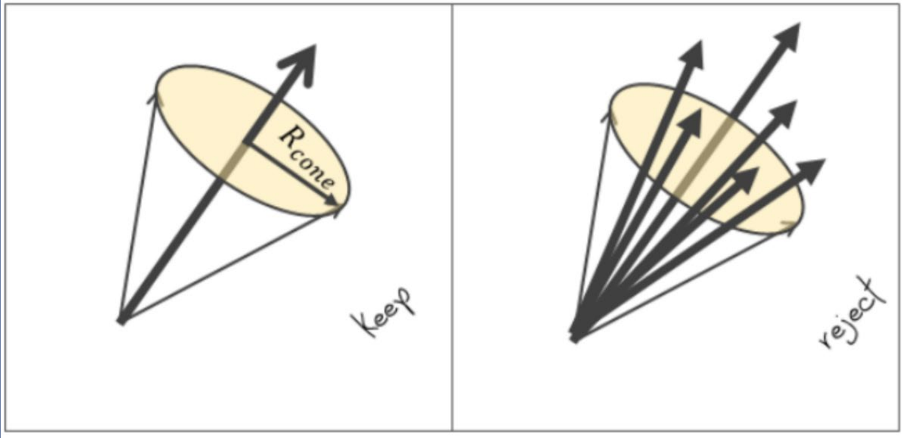


Figure from J.D. Osborn

Direct photon background:
Merging of π^0 decay photons

Photon merging - sometimes the two photons from a $\pi^0 \rightarrow \gamma\gamma$ decay are so close together that the EMCal cannot resolve them as separate photons

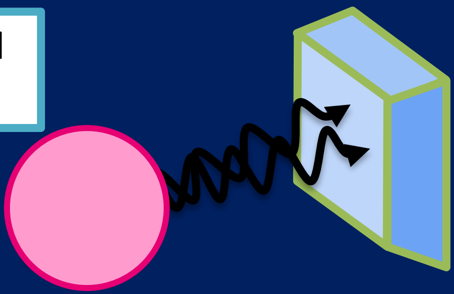
Similar to the background fraction due to missing one of the decay photons

Found to be negligible after a cluster shower shape cut

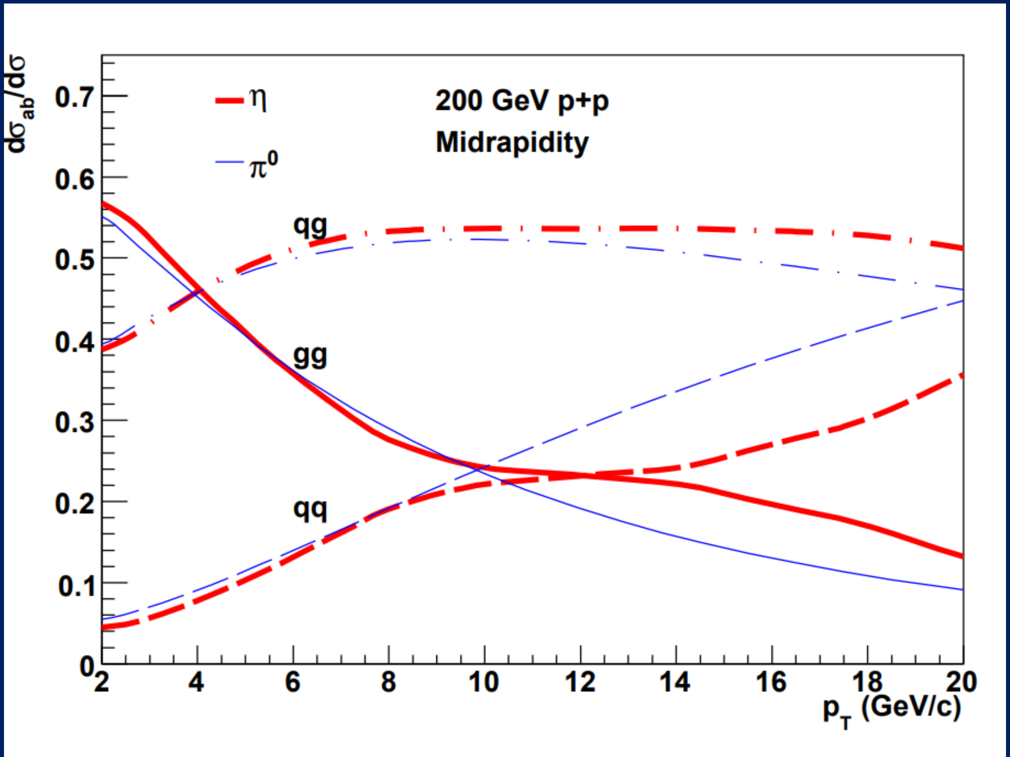
From Data: Ratio of number isolated decay photons to direct photon sample

$$r_{merge} = \frac{N_{bg}}{N_{sig} + N_{bg}} = \frac{N_{merge}}{N_{tag}} \frac{N_{tag}^{iso,h}}{N^{iso}}$$

From Simulation: Converts between tagged decay photons and merged π^0 photons



Partonic contributions for midrapidity π and η meson production



PRD 83, 032001 (2011)

- Midrapidity: Combination of quarks and gluons coming from the polarized proton
- (Forward rapidity: Primarily quarks coming from the polarized proton)

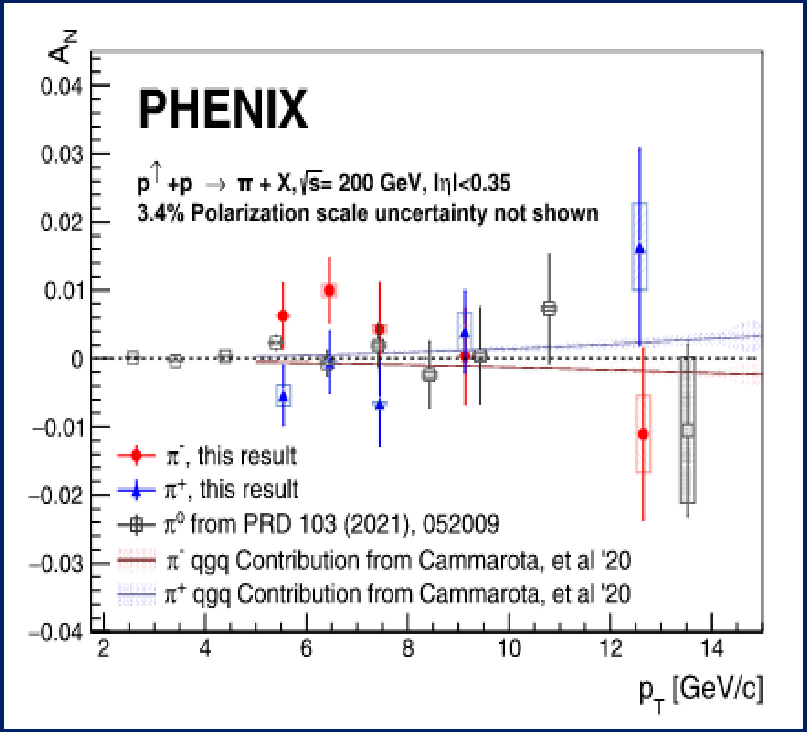
Midrapidity charged pion A_N at $\sqrt{s} = 200$ GeV

First results of midrapidity charged pion A_N from PHENIX

Compared with π^0 A_N from PRD 103, 052009 (2021)

$\pi^{+/-}$ A_N consistent with zero and theoretical predictions in measured range, but there is a hint that $\pi^{+/-}$ behave differently (potential flavor dependence)

- Flavor dependence can be seen in the *qgq* theory calculations at higher p_T



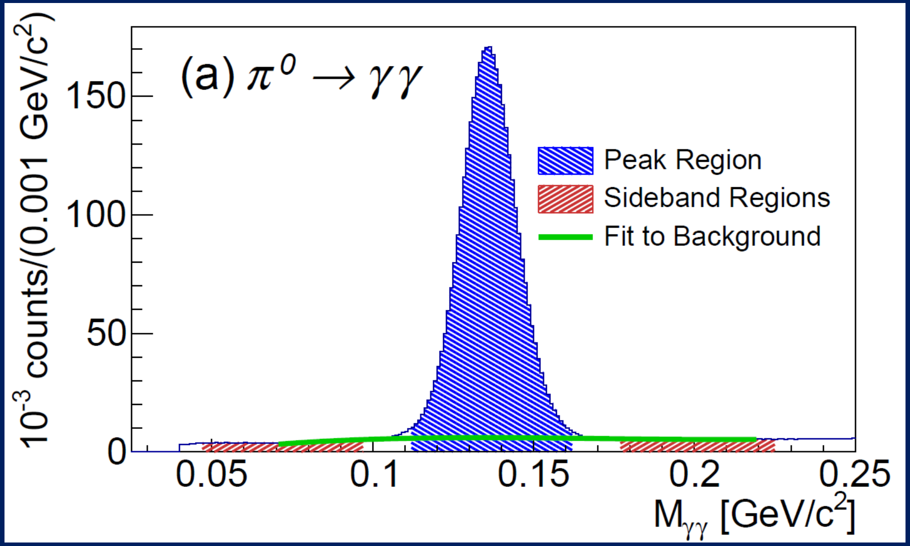
Phys. Rev. D 105, 032003 (2022)

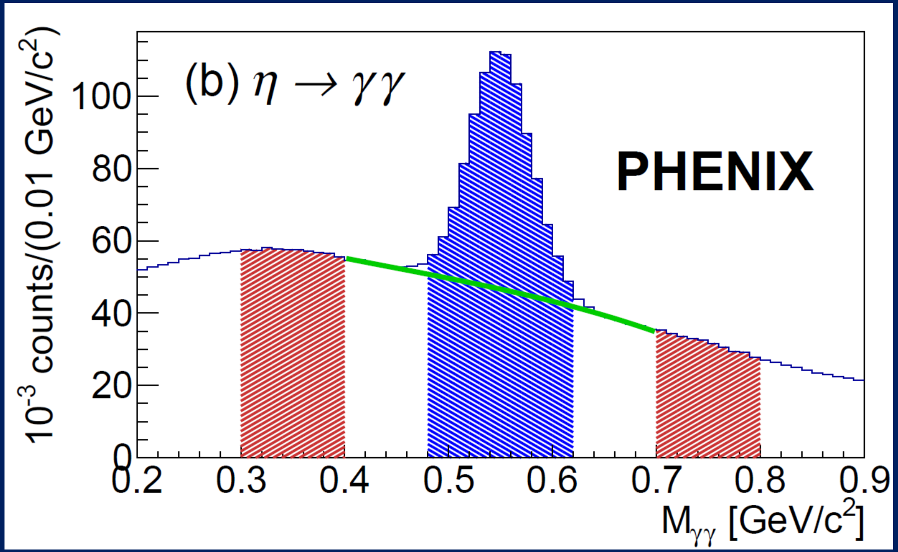
Asymmetry background subtraction

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

Where $r = \frac{N_{bg}}{N_{sig}+N_{bg}}$ is measured from a fit in the invariant mass peak region

Example invariant mass spectra for photon pairs in the West Arm with $4 < p_T < 5$ GeV/c





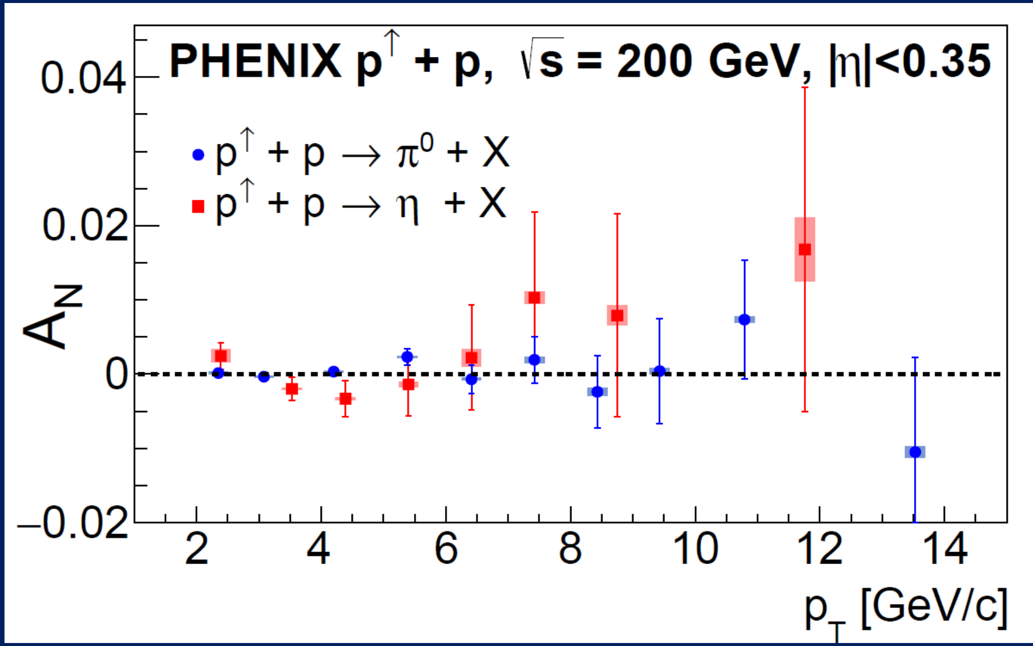
PRD103, 052009 (2021)

Comparing midrapidity π^0 and η results

- Any differences in π^0 and η A_N could be due to effects of strangeness or isospin in hadronization:

$$\pi^0 = \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right)$$

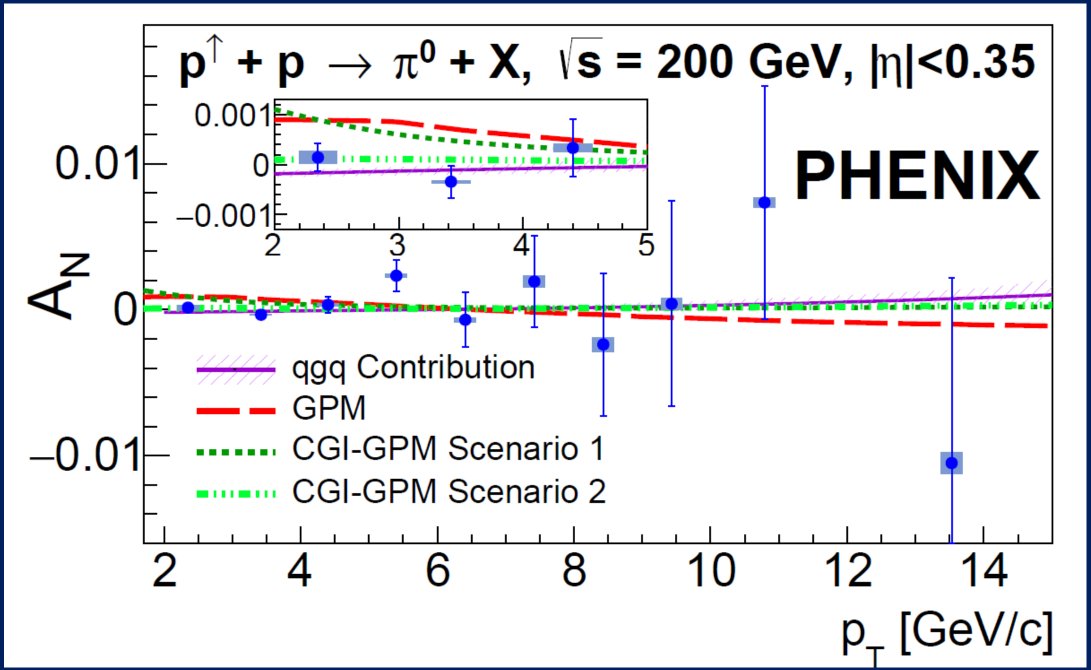
$$\eta = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$



PRD103, 052009 (2021)

- Or to mass effects in hadronization: $m_{\pi^0} \approx 135$ MeV/c^2 $m_\eta \approx 548$ MeV/c^2

Midrapidity $A_N^{\pi^0}$: Theoretical predictions



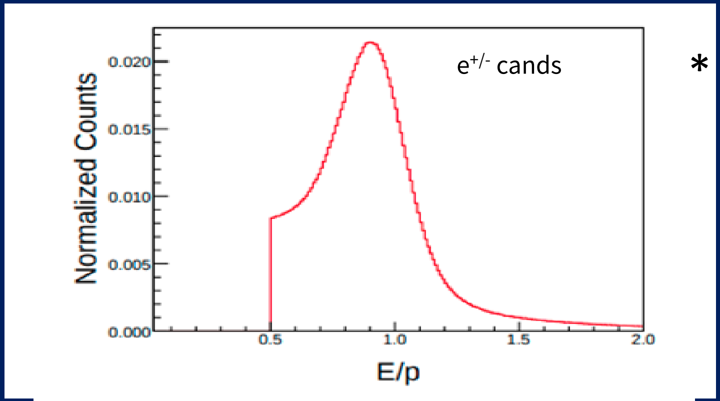
PRD103, 052009 (2021)

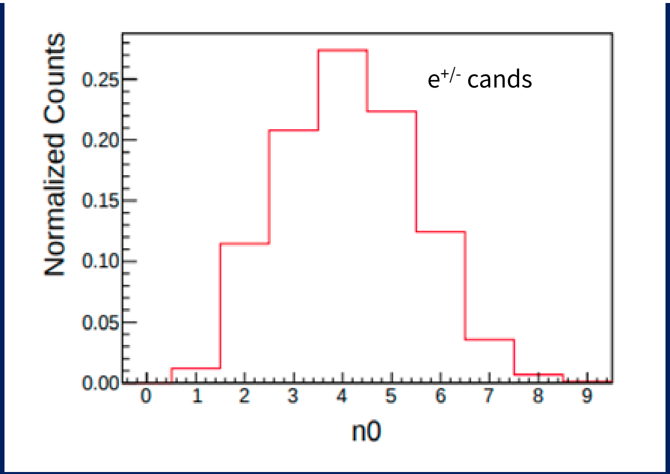
- Very small qgq correlator contribution predicted
  - JAM Collaboration, PRD 102, 054002 (2020)
- Results can help constrain gluon spin-momentum correlations
  - Twist-3 trigluon correlators (Beppu, Kanazawa, Koike, Yoshida, PRD 89, 034029 (2014))
  - Gluon Sivers function – in the Generalized Parton Model (GPM) (D'Alesio Flore, Murgia, Pisano, Taels, PRD 99, 036013 (2019))

Open heavy flavor electron analysis procedure 1

$e^{+/-}$ identification at PHENIX

- $|(E/p - \langle E/p \rangle)/\sigma_{E/p}| < 2$ -- ($\langle E/p \rangle \sim 1$)
- Track matching to EMCal energy deposits and RICH shower ring center
- >1 photomultiplier firing in RICH -- $p_e > 20$ MeV/c
- EM shower shape probability > 0.01
- Hit requirement in inner 2 layers of VTX
- Conversion veto cut on opening angle of nearby $e^{+/-}$ candidates





*Esha, Roli. (2020, September 15). Electron Identification in PHENIX

Open heavy flavor electron analysis procedure 2

TSSA Observable

A_N is calculated using the Relative Luminosity formula, integrating over the φ ranges of the east and west arms

$$A_N = \frac{1}{\langle|\cos\phi|\rangle}\frac{1}{P}\frac{N_L^{\uparrow} - R\cdot N_L^{\downarrow}}{N_L^{\uparrow} + R\cdot N_L^{\downarrow}} \text{ where } R = \frac{\mathcal{L}^{\uparrow}}{\mathcal{L}^{\downarrow}}$$

Background Sources (Heavy Flavor $e^{+/-}$)

- Photonic: π^0, η, γ: Asymmetries measured to be 0 ⟶ treated as dilution
  - π^0 and η (**PRD 103, 052009**)
  - γ (**PRL 127, 162001**)
- Nonphotonic: J/ψ, Ke3
  - Ke3 is a negligible fraction
  - J/ψ A_N taken from **PRD 82, 112008**, large source of statistical uncertainty
- Hadron contamination: $h^{+/-}$
  - $h^{+/-}$ A_N taken from **PRL 95, 202001**

Cross checks and systematic studies (Heavy Flavor $e^{+/-}$)

- Square Root formula: A_N^{sqrt} - A_N^{Lumi} taken as systematic
- cosφ modulation fit: 3 φ bins per arm

$$A_N \cdot \cos\phi_s = \frac{1}{P}\frac{N^{\uparrow}(\phi_s) - R\cdot N^{\downarrow}(\phi_s)}{N^{\uparrow}(\phi_s) + R\cdot N^{\downarrow}(\phi_s)}$$

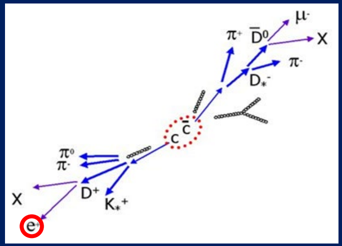
- Bunch shuffling: Randomize polarization direction, measure A_N/σ_{AN}
- Propagation of systematics on background fractions through background correction formula

$$A_N^{OHF\to e} = \frac{A_N^e - f_{h^\pm}A_N^{h^\pm} - f_{J/\psi\to e}A_N^{J/\psi\to e}}{1 - f_{h^\pm} - f_{J/\psi\to e} - f_{\pi^0\to e} - f_{\eta\to e} - f_{\gamma\to e}}$$

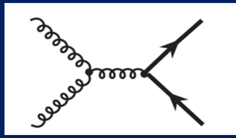
$$\sigma_{A_N^{OHF\to e}} = \frac{\sqrt{(\sigma_{A_N^e})^2 + (f_{h^\pm}\sigma_{A_N^{h^\pm}})^2 + (f_{J/\psi\to e}\sigma_{A_N^{J/\psi\to e}})^2}}{1 - f_{h^\pm} - f_{J/\psi\to e} - f_{\pi^0\to e} - f_{\eta\to e} - f_{\gamma\to e}}$$

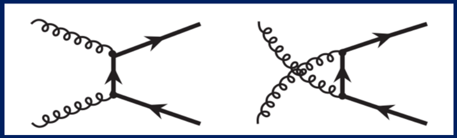
Open heavy flavor production

Primarily open charm production


**

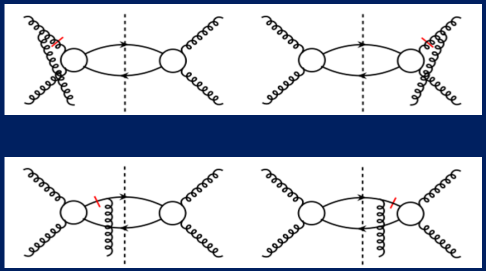
gg→QQ


*

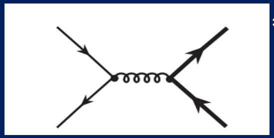


Dominant contribution @ 200 GeV midrapidity. ggg correlator **not** well constrained from previous measurements

ggg (trigluon) correlators *

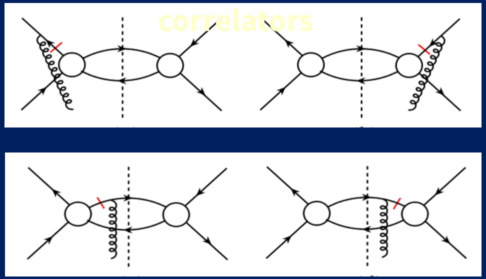


q$\bar{q}$→QQ


*

Small contribution @ 200 GeV midrapidity. qgq correlator somewhat constrained from previous measurements

qgq (Efremov-Teryaev-Qiu-Sterman) correlators *



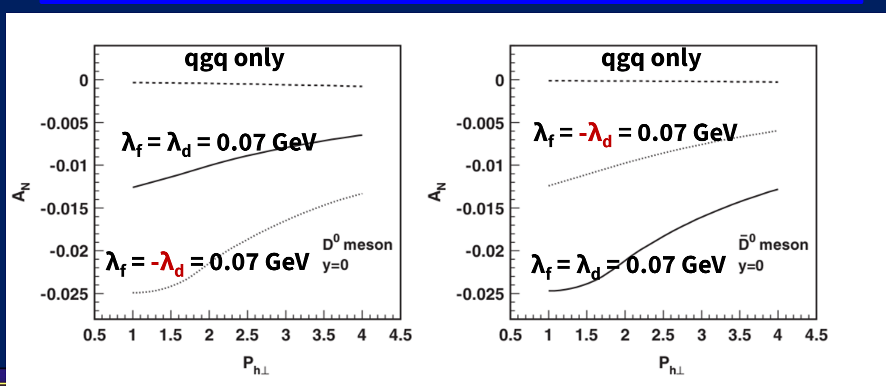
*Kang, Qiu, Vogelsang, Yuan, PRD78, 114013
**S. Sakai, The Azimuthal Anisotropy of Electrons from Heavy Flavor Decays in sqrt(s) = 200 GeV Au-Au Collisions at PHENIX, March 26, 2000

Open charm TSSA model calculations

PRD78, 114013 (Z. Kang, J. Qiu, W. Vogelsang, F. Yuan)

- Contributions from twist-3 qgq correlators as well as antisymmetric and symmetric ggg correlators considered
- Authors provided TSSA calculations for $A_N^{D0}(p_T)$, and $A_N^{\bar{D}0}(p_T)$
- Trigluon (ggg) correlators written as $T_G^{(f)}(x_1,x_2)$ (antisymmetric) and $T_G^{(d)}(x_1,x_2)$ (symmetric)
  - Model calculations rely on normalizing to the unpolarized gluon PDF

$$T_G^{(f)}(x,x) = \lambda_f G(x), \qquad T_G^{(d)}(x,x) = \lambda_d G(x)$$



PRD84, 014026 (Y. Koike, S. Yoshida)

- Contributions from twist-3 antisymmetric and symmetric ggg correlators considered
- Authors provided TSSA calculations for $A_N^{D0}(p_T)$, $A_N^{D+}(p_T)$, $A_N^{\bar{D}0}(p_T)$, and $A_N^{D-}(p_T)$
- Trigluon (ggg) correlators written as $N(x_1,x_2)$ (antisymmetric) and $O(x_1,x_2)$ (symmetric)
  - 4 independent contributions from these functions: {N(x,x), N(x,0), O(x,x), O(x,0)}
  - In $\sqrt{s} = 200$ GeV $p^\uparrow+p$ collisions, m_c is negligible, and TSSAs depend on effective trigluon correlators N(x,x) - N(x,0) and O(x,x) + O(x,0)
  - Model calculations rely on normalizing to the unpolarized gluon PDF

$$\begin{aligned} & O(x,x) = O(x,0) = N(x,x) = -N(x,0) \\ [\text{Model1}] \quad & O(x,x) = K_G x G(x) \\ [\text{Model2}] \quad & O(x,x) = K'_G \sqrt{x} G(x) \end{aligned}$$

Open charm TSSA model calculations

PRD78, 114013 (Z. Kang, J. Qiu, W. Vogelsang, F. Yuan)

$$T_G^{(f)}(x,x) = \lambda_f G(x), \qquad T_G^{(d)}(x,x) = \lambda_d G(x)$$

PRD84, 014026 (Y. Koike, S. Yoshida)

$$O(x,x) = O(x,0) = N(x,x) = -N(x,0)$$

$$[\text{Model1}] \quad O(x,x) = K_G x G(x)$$

$$[\text{Model2}] \quad O(x,x) = K'_G \sqrt{x} G(x)$$

Effective trigluon correlators N(x,x) - N(x,0) and O(x,x) + O(x,0) are explicitly related to $T_G^{(f,d)}(x,x) = T_G^{(+,-)}(x,x)$ in PRD82, 054005

$$\frac{xg}{2\pi} T_G^{(+)}(x,x) = -4M_N \left(N(x,x) - N(x,0)\right)$$

$$\frac{xg}{2\pi} T_G^{(-)}(x,x) = -4M_N \left(O(x,x) + O(x,0)\right)$$

The results presented here and in arXiv:2204.12899 [PHENIX] explicitly constrain parameters (λ_f,λ_d) from PRD78, 114013 as well as K_G and K_G' from PRD84, 014026

Open heavy flavor: Results from (λ_f,λ_d) scan

PRD 107, 052012 (2023)

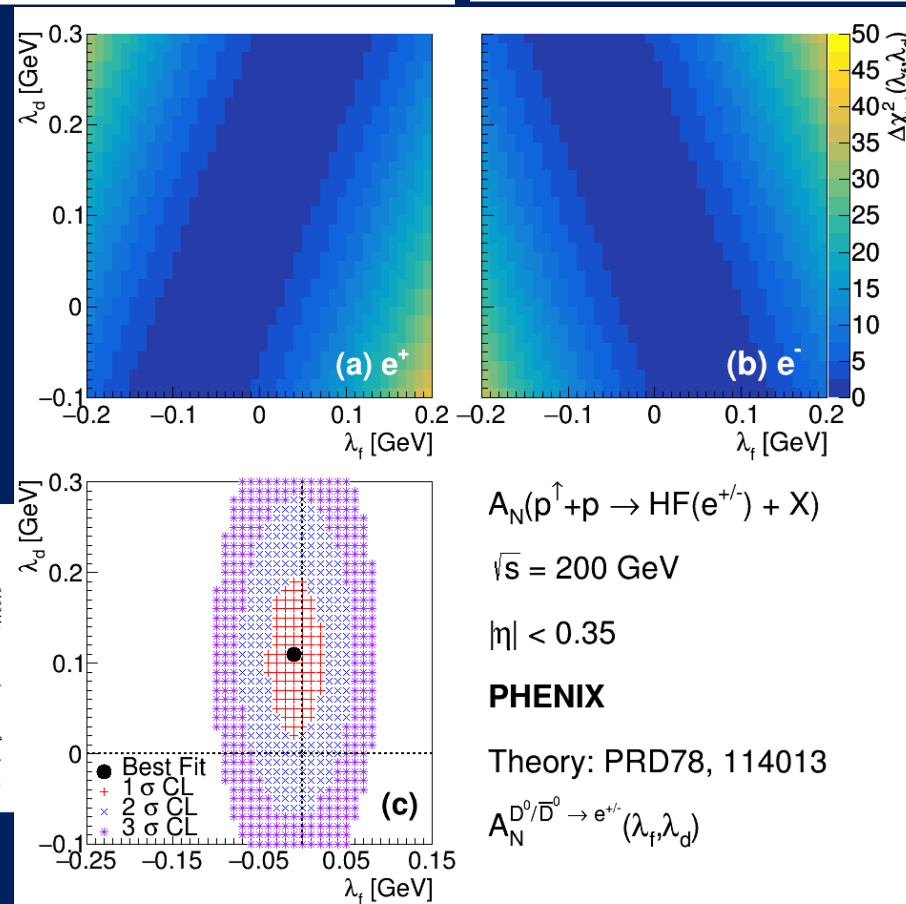
- -0.2 GeV < λ_f < 0.2 GeV
- -0.1 GeV < λ_d < 0.3 GeV
- 41 steps per parameter
- Calculate A_N for D^0 and $\bar{D}^0$
- Simulate $D^0 \rightarrow e^+$ and $\bar{D}^0 \rightarrow e^-$ decay with PYTHIA6
- Calculate $A_N^{D0\rightarrow e+}$ and $A_N^{\bar{D}0\rightarrow e-}$
- Calculate $\Delta\chi^2_{(+,-)}(\lambda_f,\lambda_d) = \chi^2_{(+,-)}(\lambda_f,\lambda_d) - \chi^2_{(+,-)min}$

a_0, b_0, a_1, a_2 parameterizations provided by Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan (**PRD78, 114013**)

- a_0 and b_0: contributions from qgq correlators
- a_1 and a_2: contributions from trigluon correlators

$$\chi^2_{(+)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(+)data} - A_N^{(+)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(+)data}}$$

$$\chi^2_{(-)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(-)data} - A_N^{(-)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(-)data}}$$



$$\chi^2(\lambda_f,\lambda_d) = \chi^2_{(+)}(\lambda_f,\lambda_d) + \chi^2_{(-)}(\lambda_f,\lambda_d)$$

$$\chi^2(\lambda_f,\lambda_d) - \chi^2_{min} < n^2$$

$$A_N^{D^0} = a_0 + \lambda_f a_1 + \lambda_d a_2$$

$$A_N^{\bar{D}^0} = b_0 + \lambda_f a_1 - \lambda_d a_2$$

Open heavy flavor: Results from (λ_f,λ_d) scan

PRD 107, 052012 (2023)

- -0.2 GeV < λ_f < 0.2 GeV
- -0.1 GeV < λ_d < 0.3 GeV
- 41 steps per parameter
- Calculate A_N for D^0 and $\bar{D}^0$
- Simulate $D^0 \to e^+$ and $\bar{D}^0 \to e^-$ decay with PYTHIA6
- Calculate $A_N^{D0\to e+}$ and $A_N^{\bar{D}0\to e-}$
- Calculate $\Delta\chi^2_{(+,-)}(\lambda_f,\lambda_d) = \chi^2_{(+,-)}(\lambda_f,\lambda_d) - \chi^2_{(+,-)min}$

a_0, b_0, a_1, a_2 parameterizations provided by Z.B. Kang, J.W. Qiu, W. Vogelsang, F. Yuan (**PRD78, 114013**)

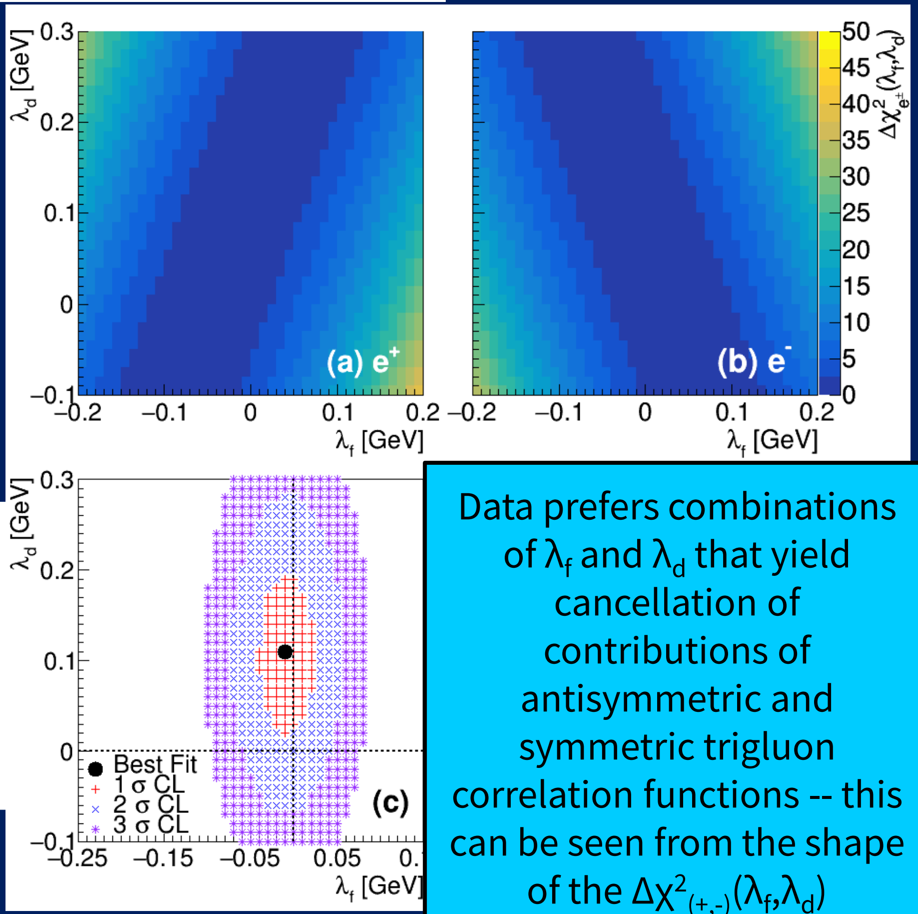
- a_0 and b_0: contributions from qgq correlators
- a_1 and a_2: contributions from trigluon correlators

$$\chi^2_{(+)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(+)data} - A_N^{(+)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(+)data}}$$

$$\chi^2_{(-)}(\lambda_f,\lambda_d) = \sum_i^{nbins} \frac{\left(A_N^{(-)data} - A_N^{(-)theory}(\lambda_f,\lambda_d)\right)^2}{\sigma^2_{(-)data}}$$

$$\chi^2(\lambda_f,\lambda_d) = \chi^2_{(+)}(\lambda_f,\lambda_d) + \chi^2_{(-)}(\lambda_f,\lambda_d)$$

$$\chi^2(\lambda_f,\lambda_d) - \chi^2_{min} < n^2$$



Data prefers combinations of λ_f and λ_d that yield cancellation of contributions of antisymmetric and symmetric trigluon correlation functions -- this can be seen from the shape of the $\Delta\chi^2_{(+,-)}(\lambda_f,\lambda_d)$ distributions

$$A_N^{D^0} = a_0 + \lambda_f a_1 + \lambda_d a_2$$

$$A_N^{\bar{D}^0} = b_0 + \lambda_f a_1 - \lambda_d a_2$$

Open heavy flavor: Results from K_G and K_G' scans

arXiv:2204.12899

- $-0.005 < K_G < 0.005$
- $-0.00025 < K_G' < 0.00075$
- 101 steps per parameter
- Calculate A_N for D^0, D^+, $\bar{D}^0$, and D^-
- Simulate $D^0 \to e^+$, $D^+ \to e^+$, $\bar{D}^0 \to e^-$, and $D^- \to e^-$ decay with PYTHIA6
- Calculate $A_N^{D0 \to e+}$, $A_N^{D+ \to e+}$, $A_N^{\bar{D}0 \to e-}$, and $A_N^{D- \to e-}$
- Calculate $\Delta\chi^2_{(+,-)}(K_G) = \chi^2_{(+,-)}(K_G) - \chi^2_{(+,-)min}$ and $\Delta\chi^2_{(+,-)}(K_G') = \chi^2_{(+,-)}(K_G') - \chi^2_{(+,-)min}$

1σ Confidence Intervals:

$K_G = 6.0 \times 10^{-4}$ (+0.0014 -0.0017)

$K_G' = 2.5 \times 10^{-4}$ (± 0.00025)

Consistent with modest upper bound on K_G and K_G' derived in PRD84, 014026 (2011)