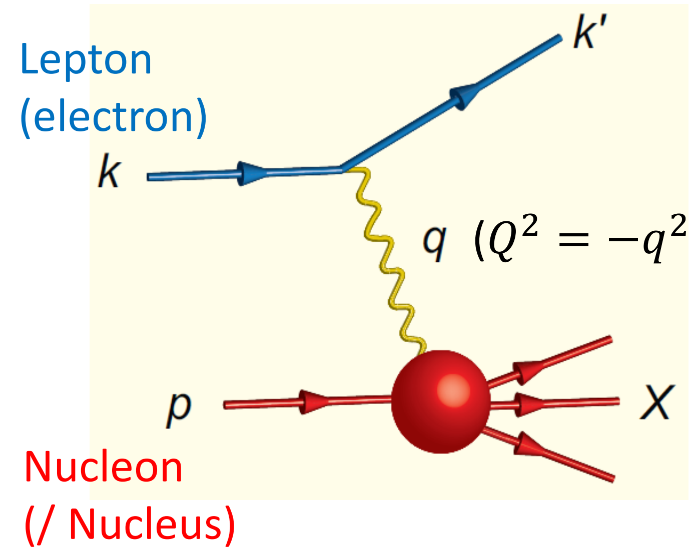
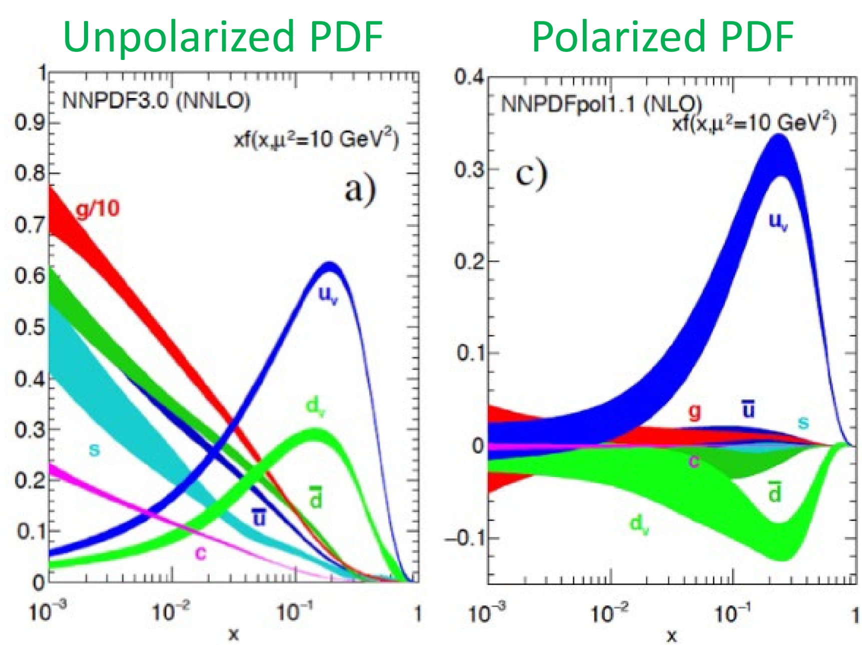
RHIC Spin and sPHENIX

Mini-workshop @ sPHENIX-INTT analysis workshop
In NCU, Taiwan
November 17, 2023
Yuji Goto (RIKEN)

Quark-gluon structure

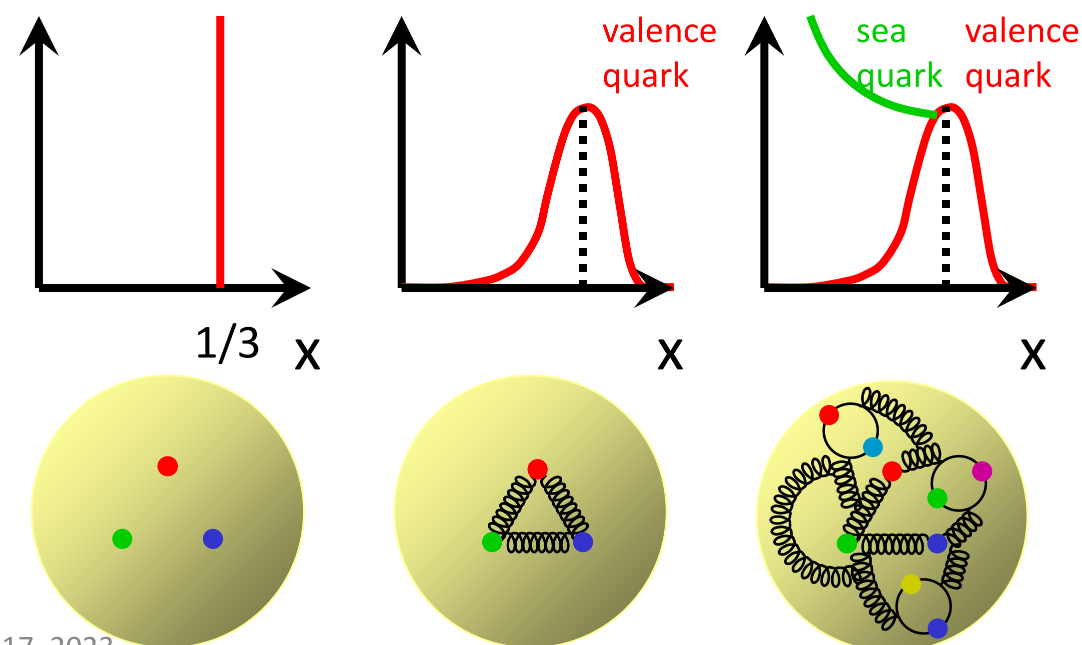
- Deep inelastic scattering (DIS) of lepton (electron)
  - Large Q^2 ($Q^2 = -q^2$) provides a hard scale to resolve quarks and gluons in the proton
- Parton distribution function (PDF) of quarks and gluons
  - 1D longitudinal motion of partons
  - x : momentum fraction of quarks and gluons
  - Significant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





Nucleon structure

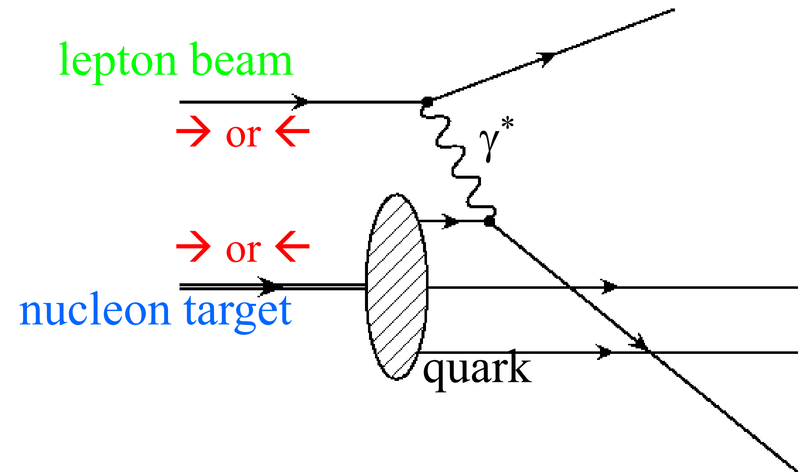
- Nucleon: the simplest multi-body system for studying dynamics of confined quarks and gluons
- Simple parton picture
  - 1-dimensional picture: in “longitudinal” direction
  - The nucleon consists of incoherent quarks and gluons
  - Described by the parton distribution functions (PDF)



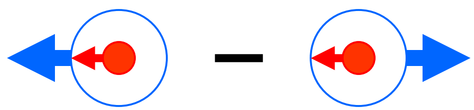
x: Bjorken’s x
“longitudinal” momentum fraction
(1-dimensional picture)

Origin of the nucleon spin 1/2 ?

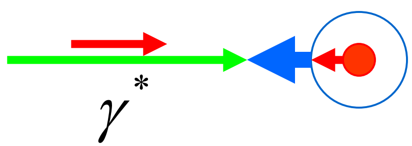
- polarized DIS
  - in quark parton model

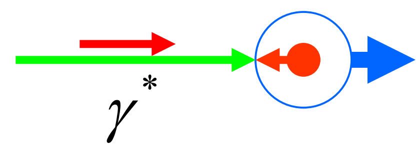


$$\Delta q(x) = q^+(x) - q^-(x)$$



$$S_\gamma + S_N = 1/2 \qquad\qquad S_\gamma + S_N = 3/2$$





$$\sigma^T_{1/2} \sim \sum_i e_i^2 q_i^+(x) \qquad\qquad \sigma^T_{3/2} \sim \sum_i e_i^2 q_i^-(x)$$

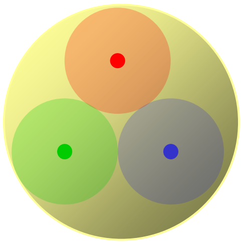
$$A_1 = \frac{\sigma^{\mathrm{T}}_{1/2} - \sigma^{\mathrm{T}}_{3/2}}{\sigma^{\mathrm{T}}_{1/2} + \sigma^{\mathrm{T}}_{3/2}} \sim \frac{\sum_i e_i^2 (q_i^+(x) - q_i^-(x))}{\sum_i e_i^2 (q_i^+(x) + q_i^-(x))} = \frac{\sum_i e_i^2 \Delta q_i(x)}{\sum_i e_i^2 q_i(x)} = \frac{g_1(x)}{F_1(x)}$$

polarized structure function

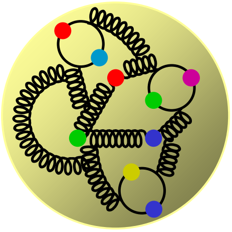
unpolarized structure function

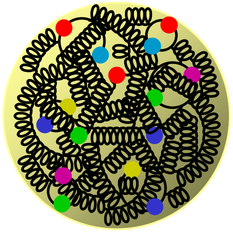
Nucleon structure

- 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")



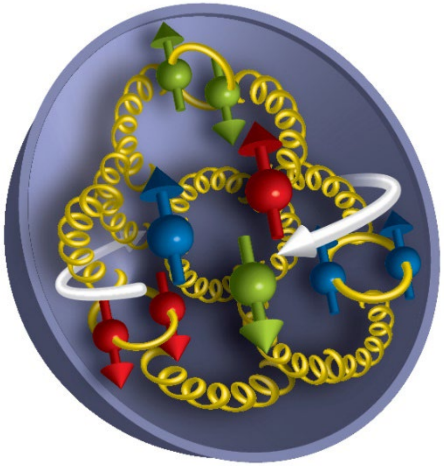
- Quark-gluon model
  - Current quarks and gluon interaction
  - Initial state of high-energy hadron colliders





- 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

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

Orbital angular momentum

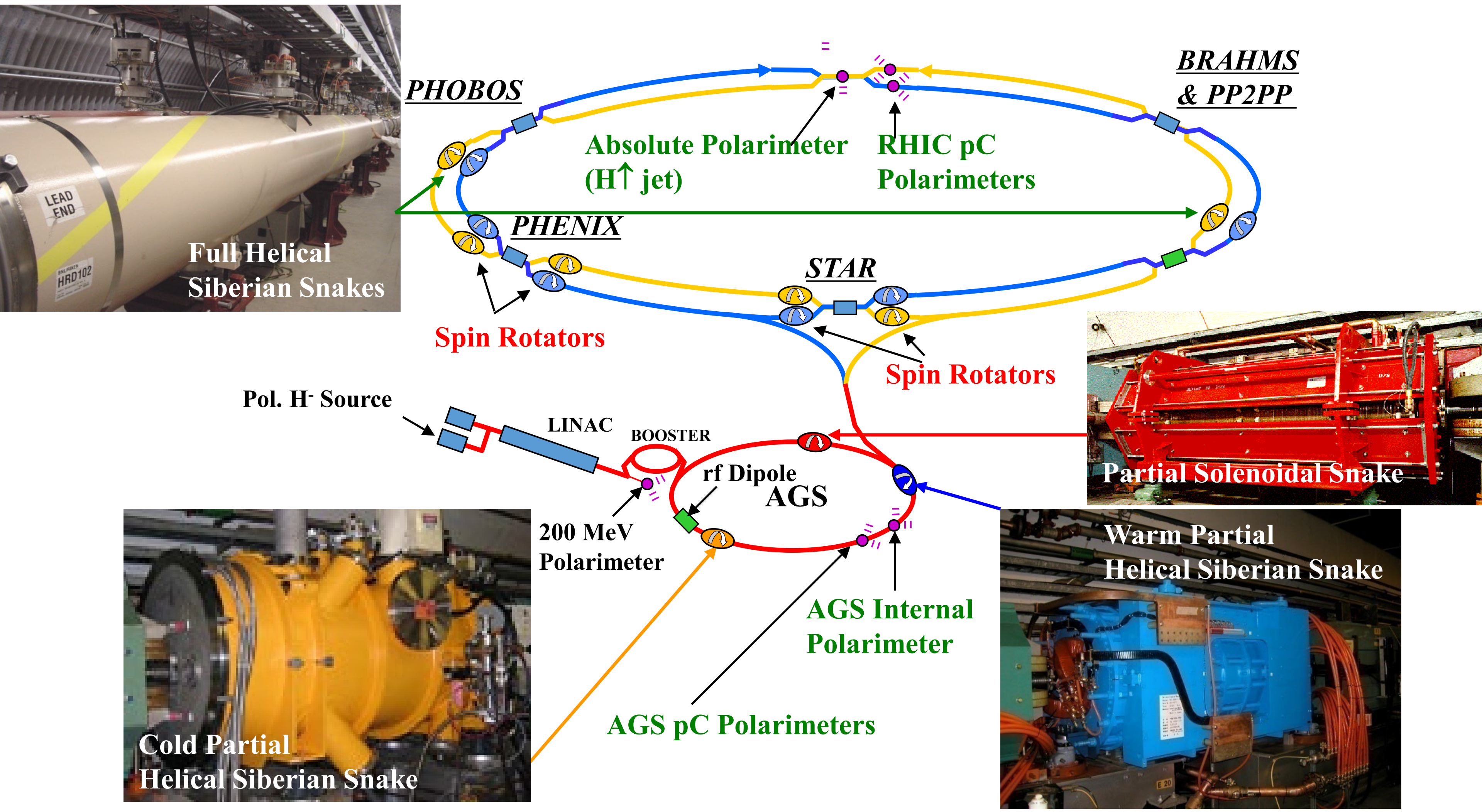
Gluon spin

Quark spin

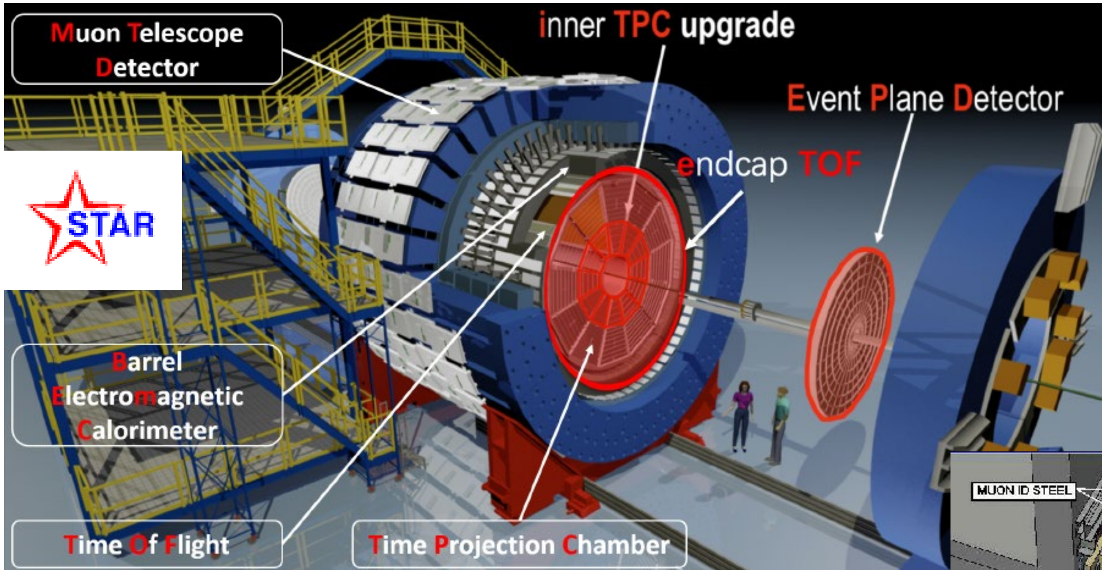
  - Quark-spin contribution is only about 30% of the nucleon spin
- Longitudinal-spin (beam axis direction) asymmetry measurement
  - Gluon polarization measurement
  - Anti-quark polarization measurement using W boson
- Transverse-spin asymmetry measurement
  - Understanding of orbital motion inside the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

Polarized proton acceleration at RHIC

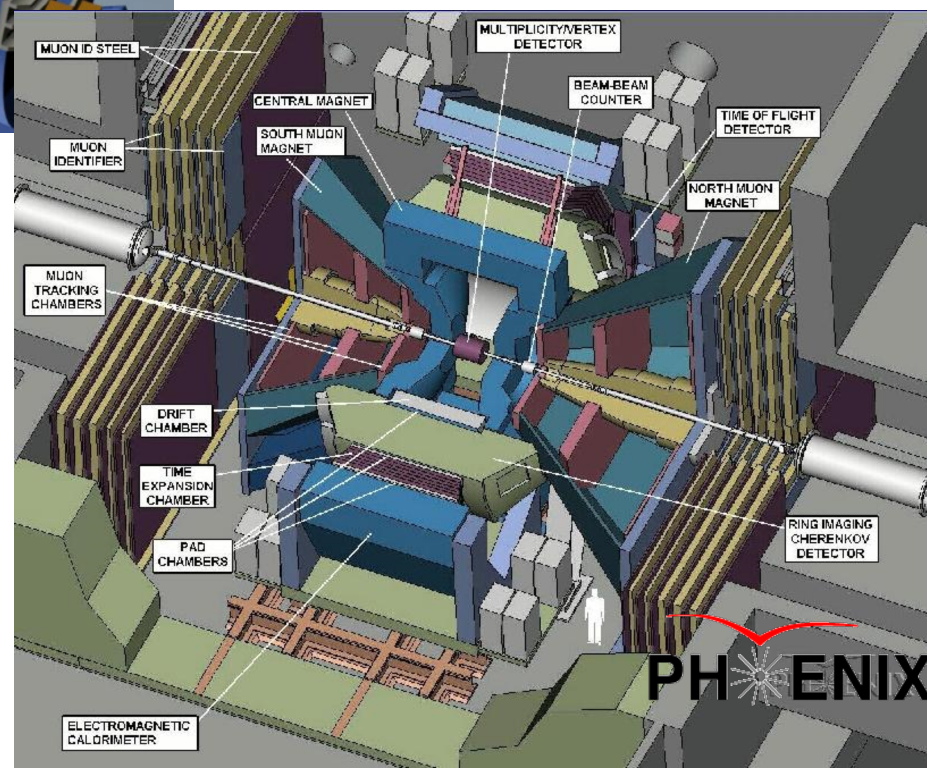
- Keeping and monitoring polarization from the polarized proton source



Polarized proton collision experiments



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

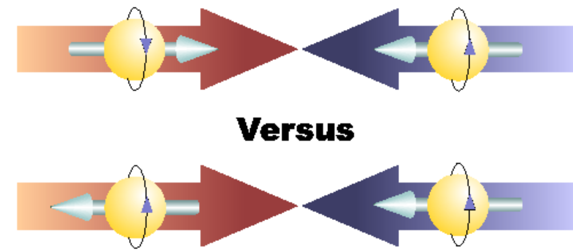


- PHENIX detector
  - limited acceptance
  - high resolution central EMCal
  - high-rate trigger and DAQ
  - forward muon detectors

Longitudinal polarized proton collision

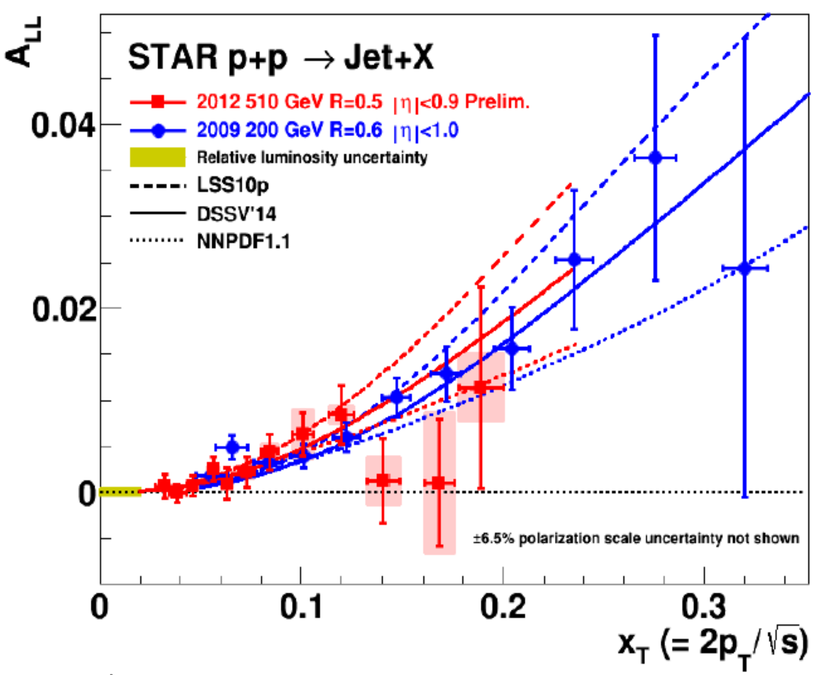
- A_{LL} (double-helicity asymmetry) measurement
  - Polarized in the beam axis direction

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

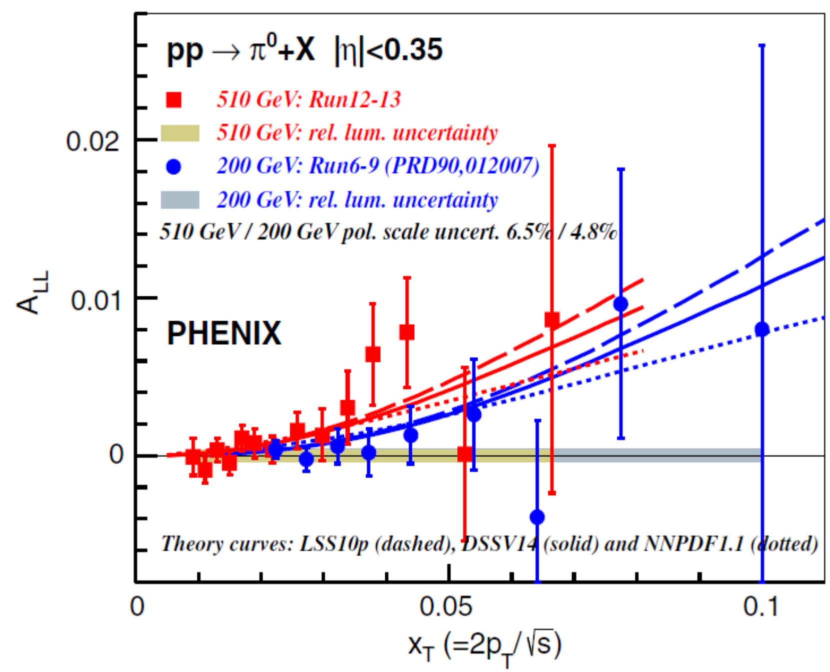


- Gluon polarization
  - A_{LL} measurement for gluon+gluon and gluon+quark reactions

Midrapidity jet at STAR

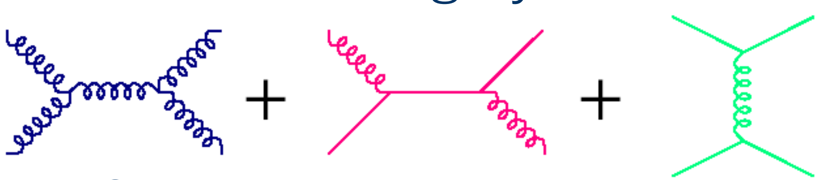


Midrapidity π^0 at PHENIX



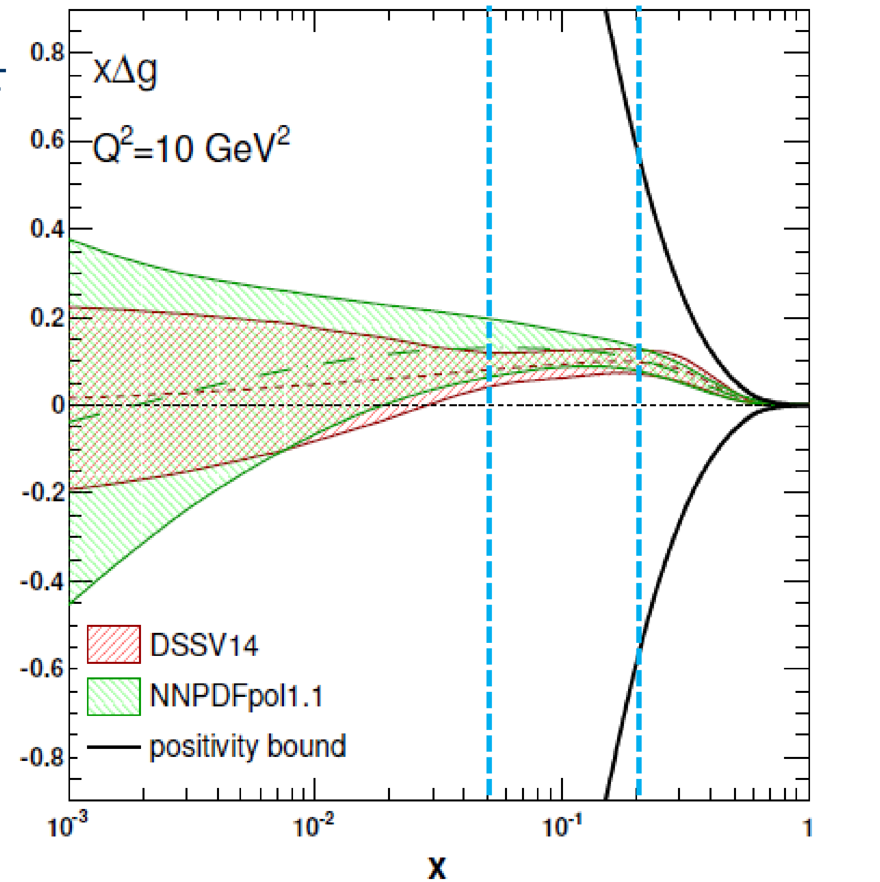
Gluon polarization Δg

- 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

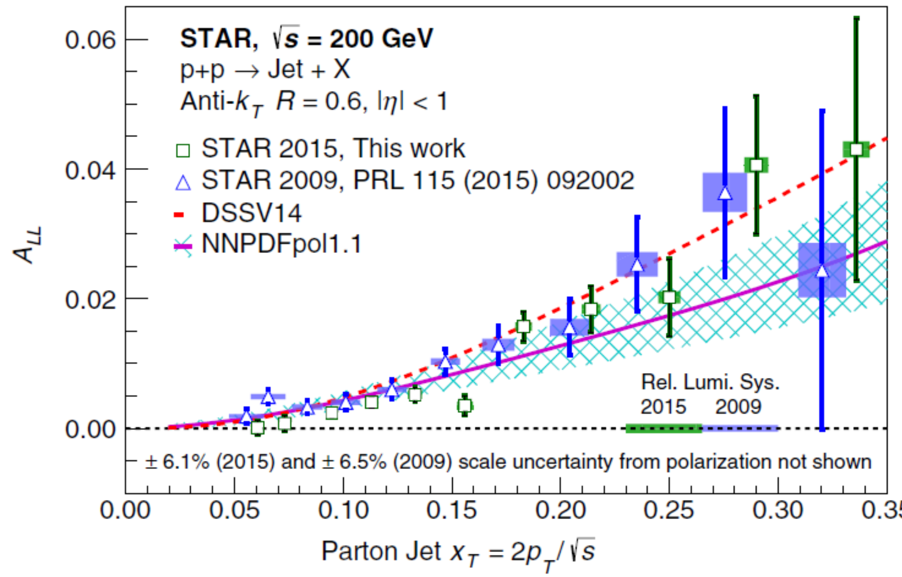


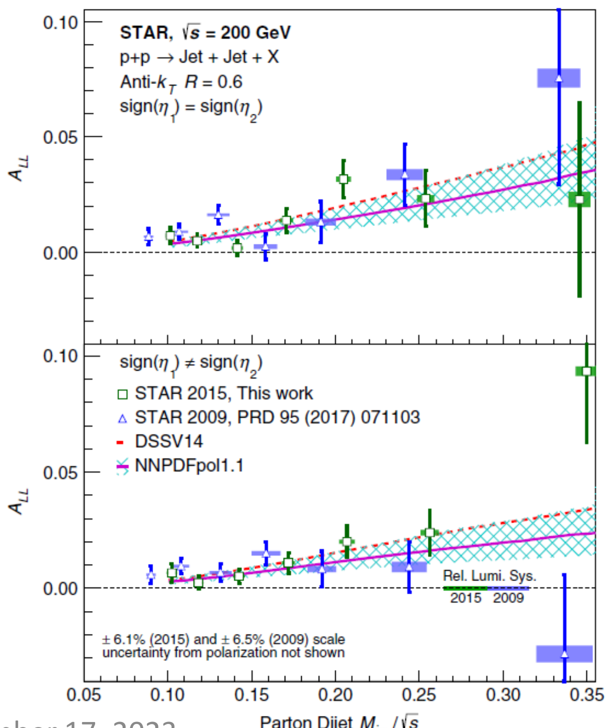
$Q^2 = 10\ \text{GeV}^2$	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

STAR jet & dijet

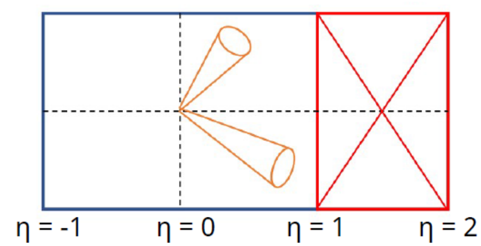
STAR $\sqrt{s}$ = 200 GeV

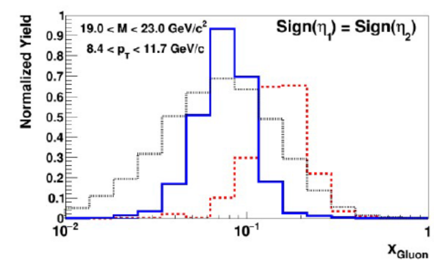
- Phys. Rev. D 100, 052005 (2019)
  - $\sqrt{s}$ = 510 GeV
- Phys. Rev. D 103, L091103 (2021)
  - $\sqrt{s}$ = 200 GeV
- Jet A_{LL}
  - the most precise dataset
- Dijet A_{LL}
  - constraints to underlying partonic kinematics



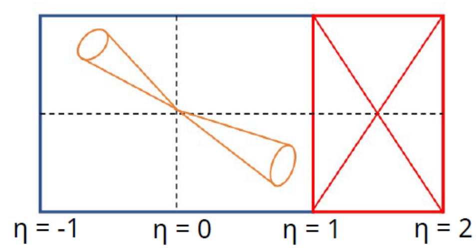


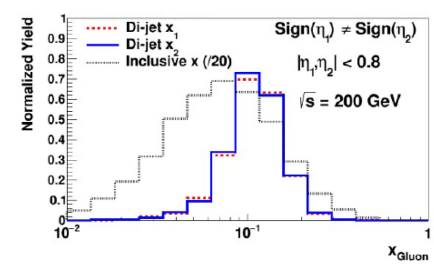
sign(η_1) = sign(η_2)





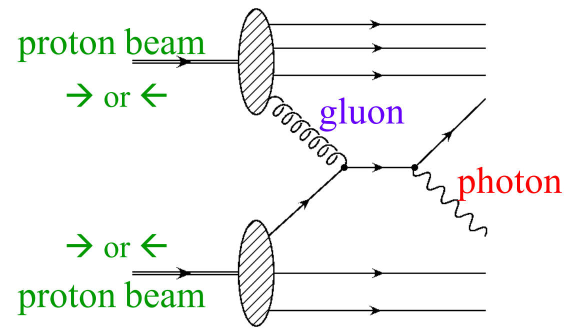
sign(η_1) ≠ sign(η_2)





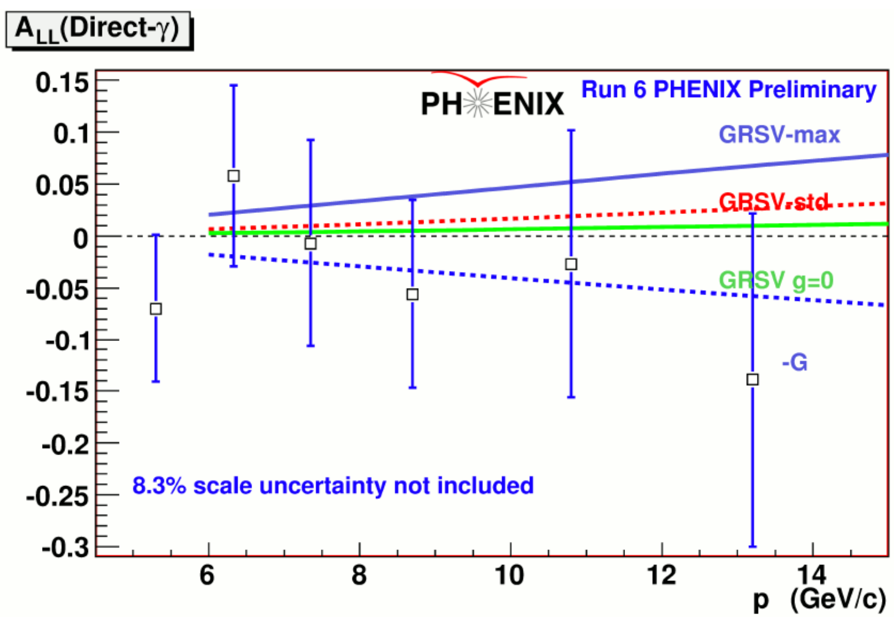
PHENIX direct photon

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



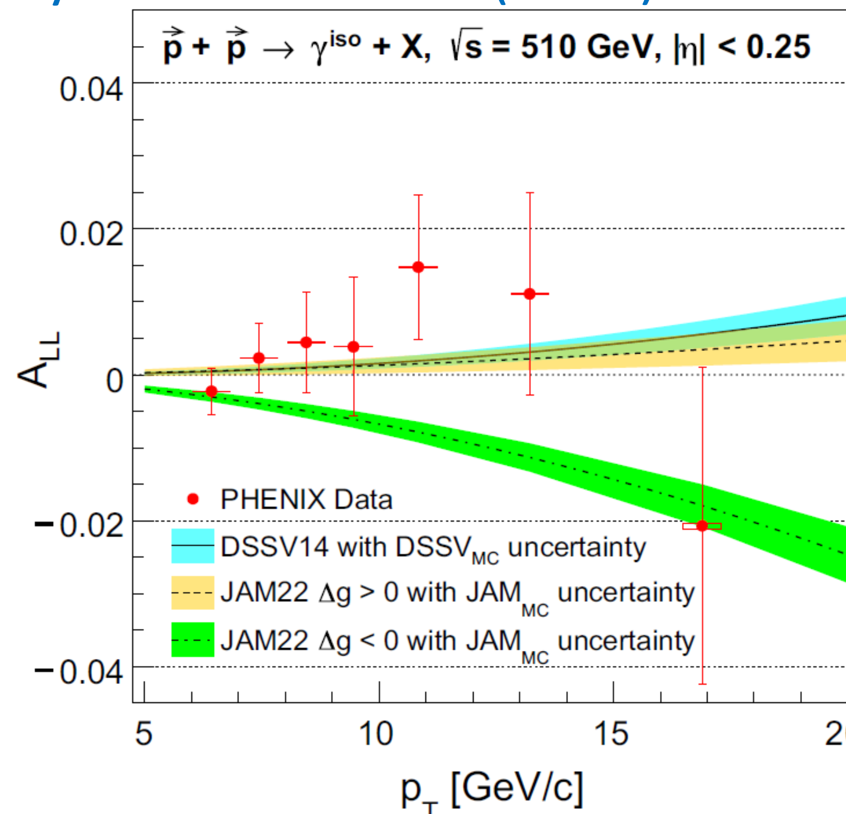
√s = 200 GeV

Preliminary result (unpublished)



√s = 510 GeV

Phys. Rev. Lett. 130 (2023) 251901

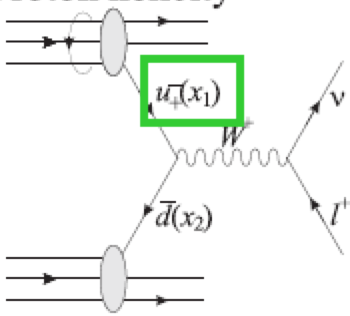


Anti-quark polarization

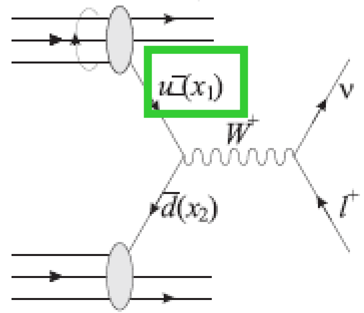
- Parity-violating A_L measurement with W-boson production

Forward rapidity

Proton helicity ="+"

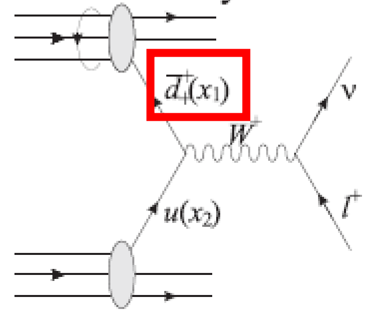


Proton helicity ="–"

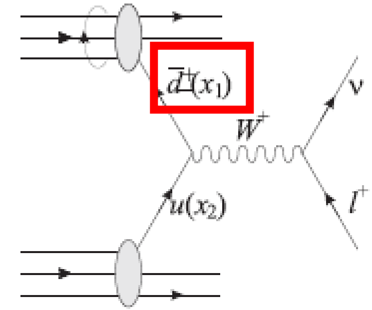


Backward rapidity

Proton helicity ="+"



Proton helicity ="–"



$$\frac{-\Delta u(x_a)}{u(x_a)}$$

$$\frac{\Delta \bar{d}(x_a)}{\bar{d}(x_a)}$$

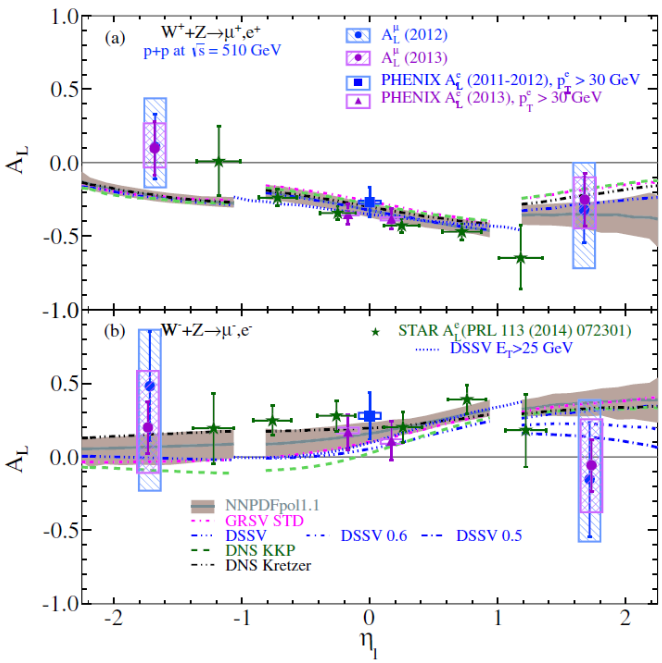
$$A_L^{W^+} = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

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

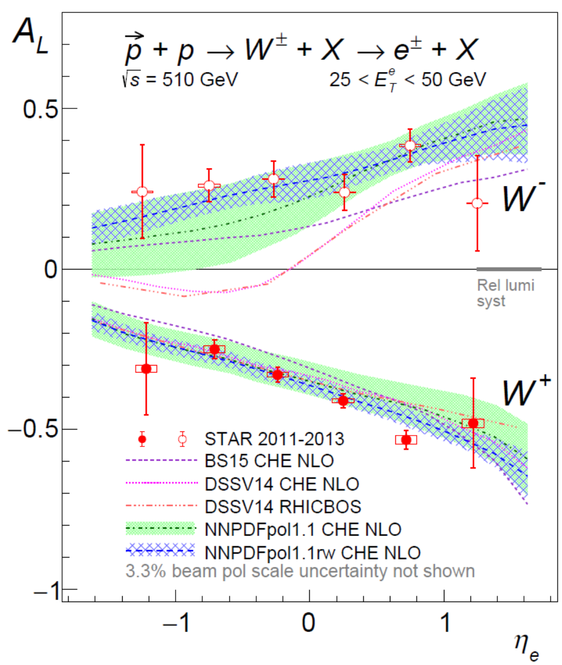
Anti-quark polarization

- 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

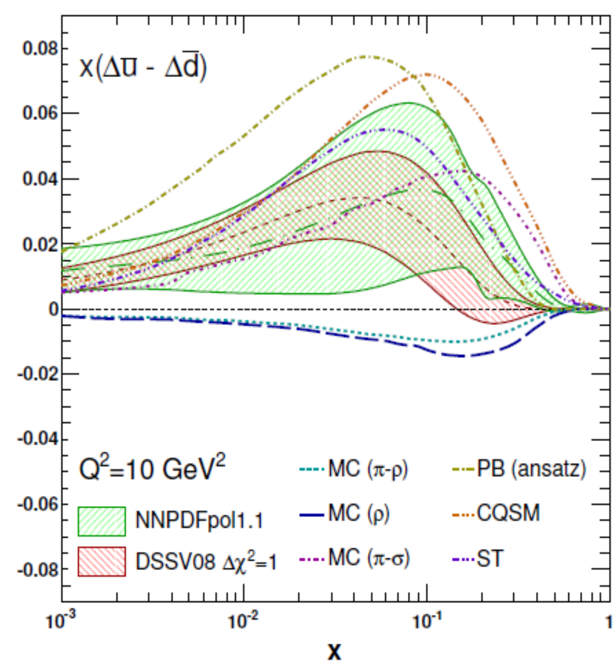
PHENIX: PRD98 (2018) 032007



STAR: PRD99 (2019) 051102



arXiv:1406.7122

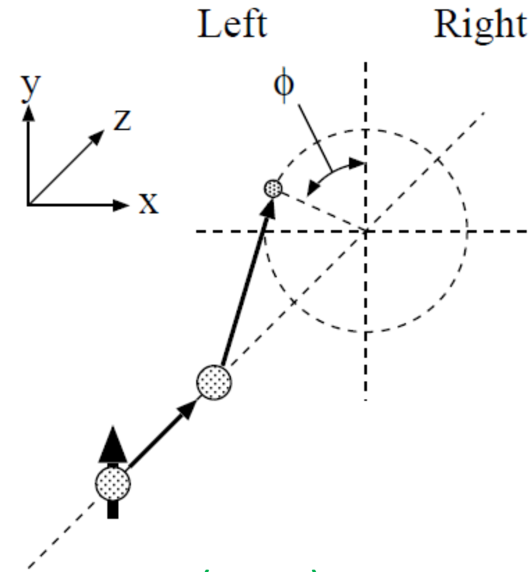


Transverse asymmetry measurement

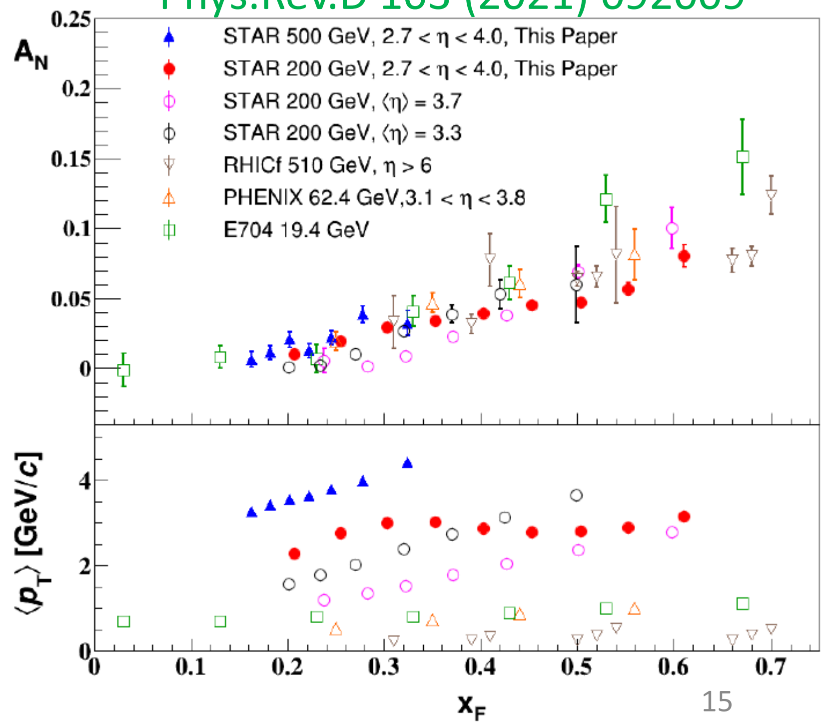
- A_N (transverse single-spin asymmetry) measurement

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

  - 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

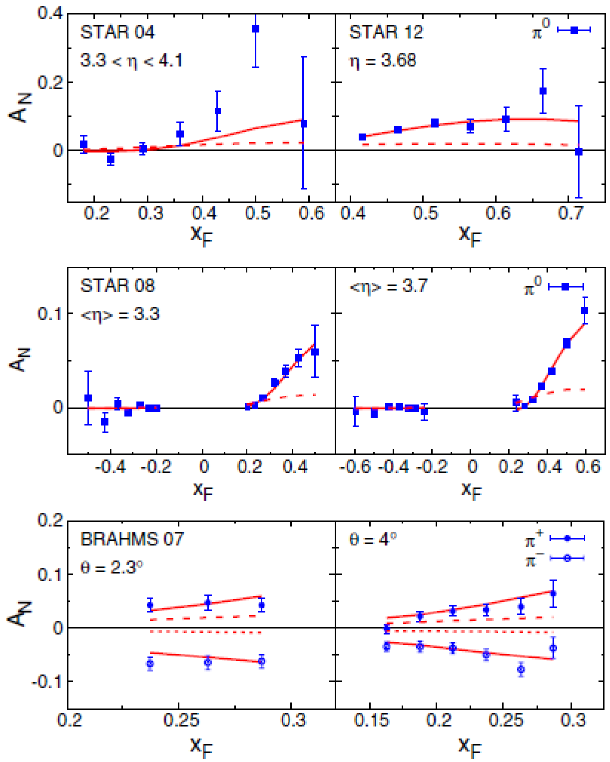


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

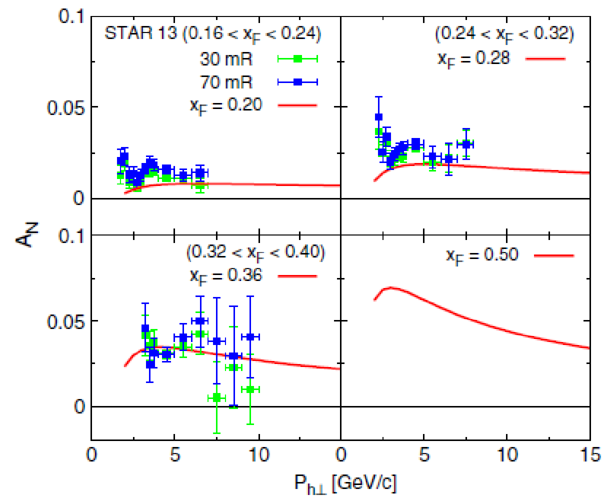
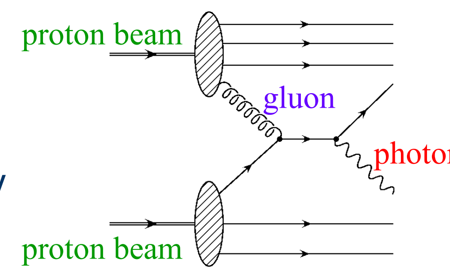


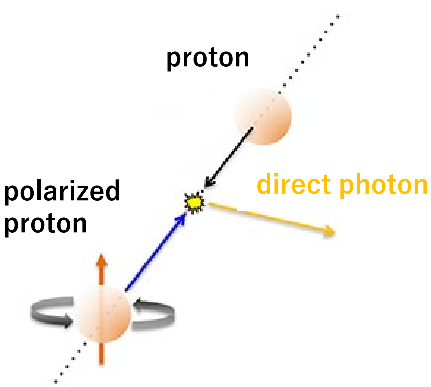
FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

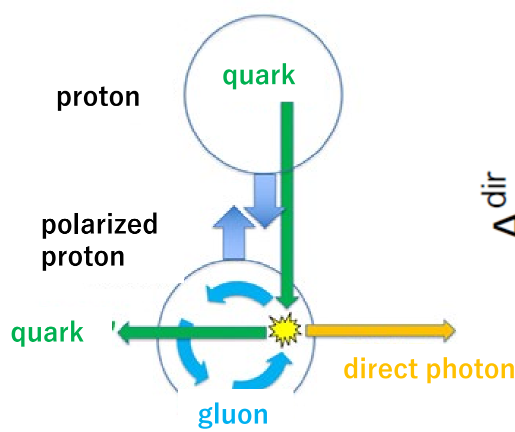
Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).

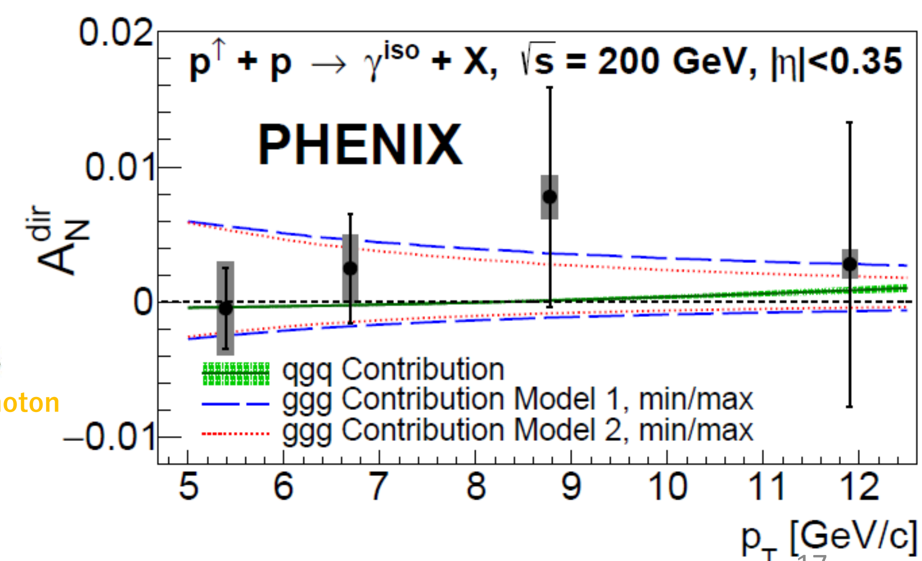
PHENIX direct photon

- 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



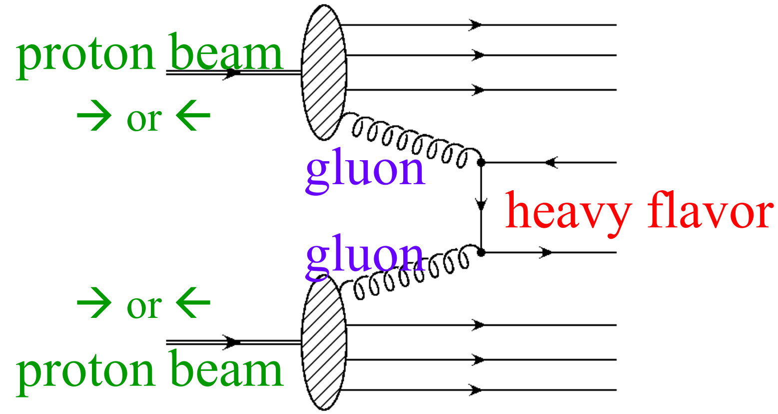


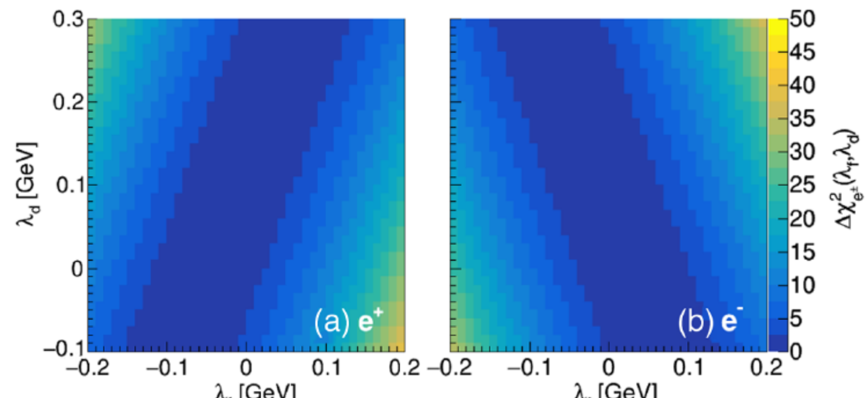


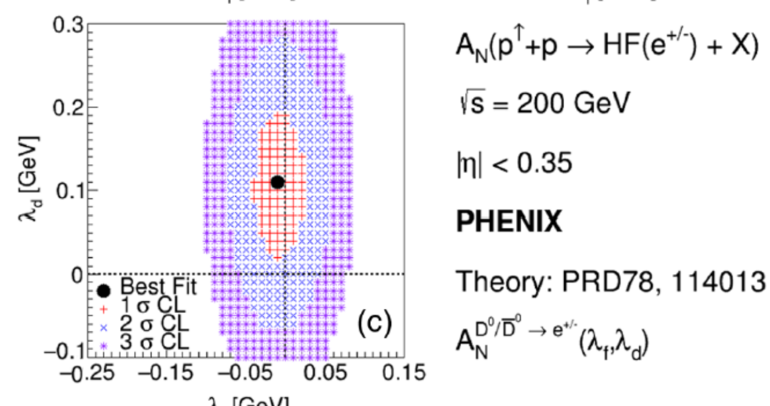


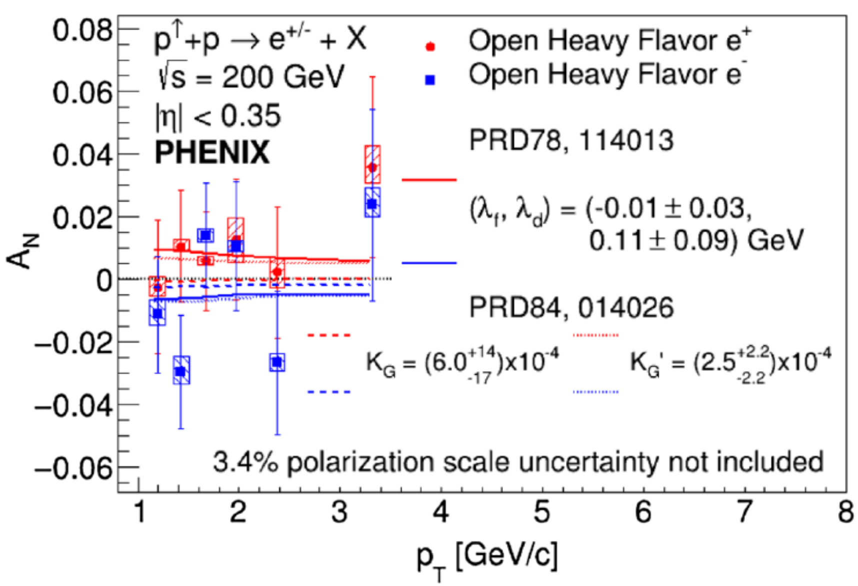
PHENIX heavy flavor

- 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





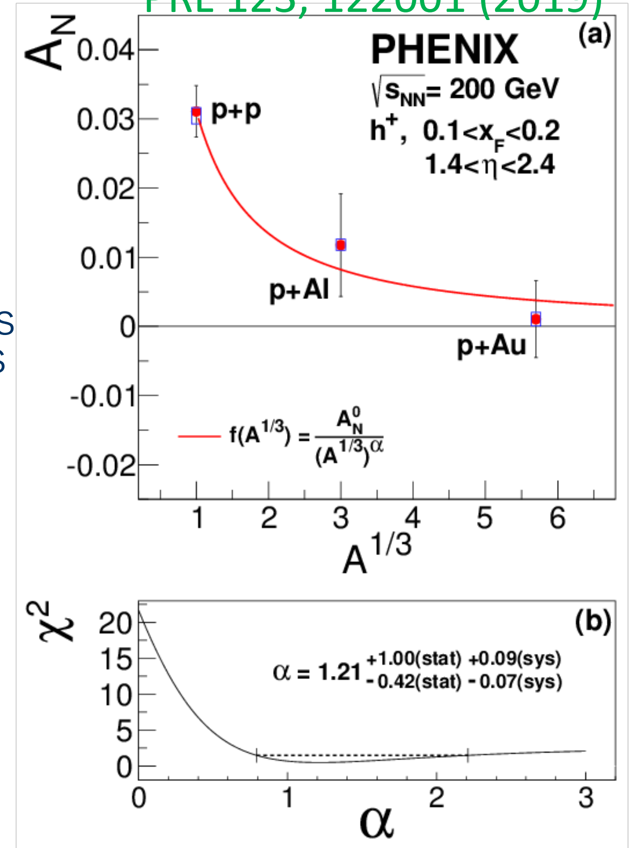




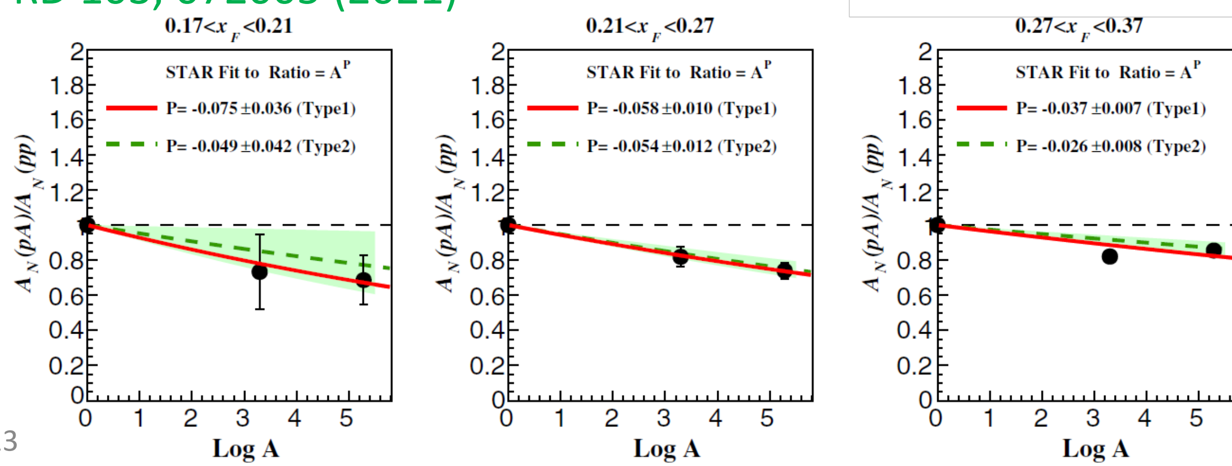
Polarized p+A collisions

- 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)

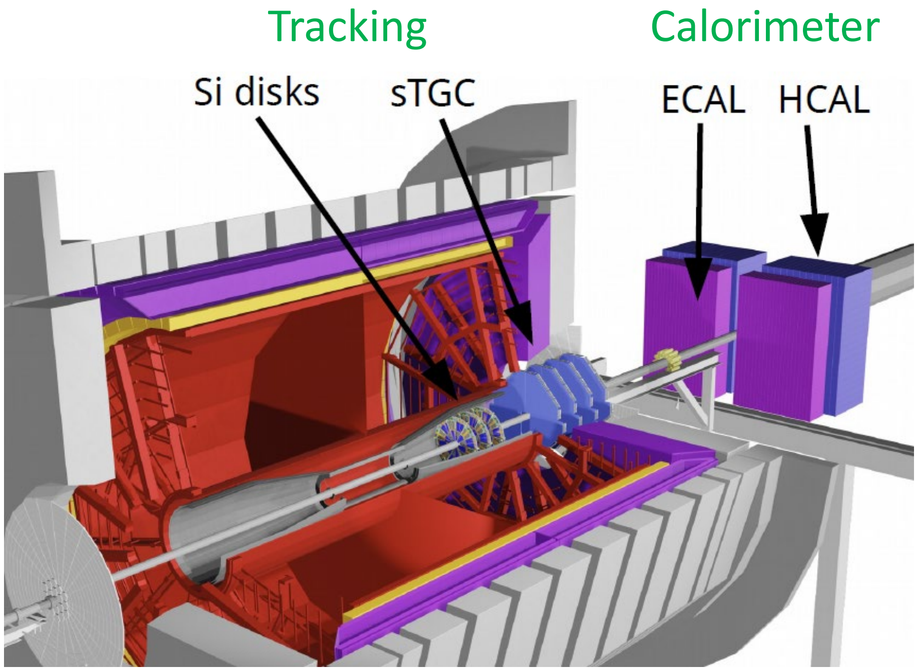


PRD 103, 072005 (2021)



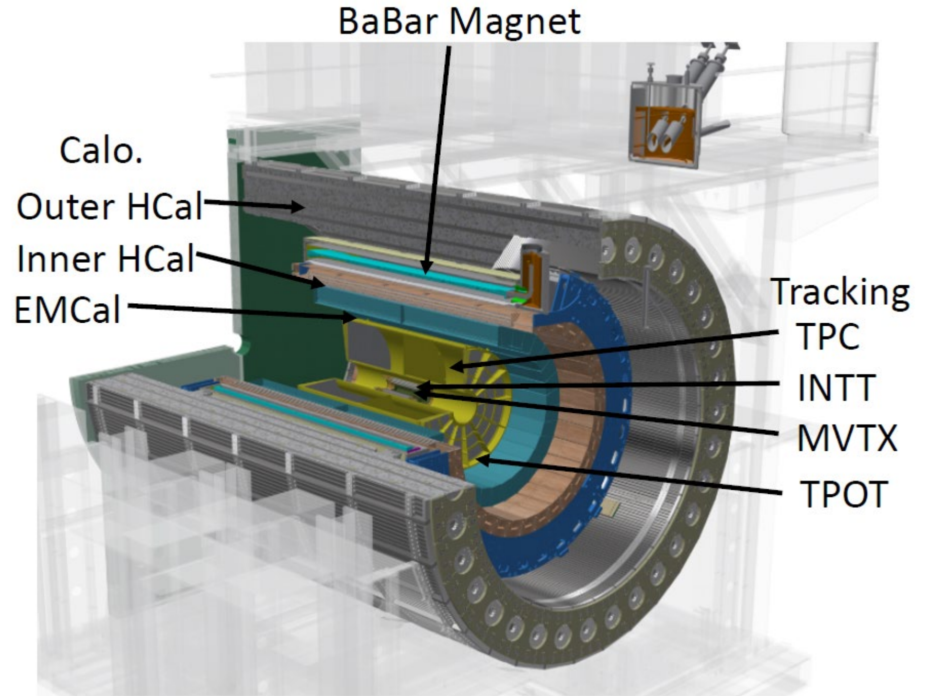
STAR upgrade

- Forward rapidity
  - $2.5 < \eta < 4$
    - Tracking + Calorimeter
  - TMD measurements at high *x*
    - Sivers with jet and photon
    - Transversity + Collins/IFF
    - Diffractive processes
- Midrapidity
  - $-1.5 < \eta < 1.5$
    - iTPC
  - Improved statistical precision and extended acceptance
    - Sivers with W/Z and dijet
    - Transversity + Collins/IFF
- Run 2022
  - Polarized p+p @ $\sqrt{s}$ = 510 GeV
- Run 2024
  - Polarized p+p & p+A @ $\sqrt{s}$ = 200 GeV



sPHENIX experiment

- 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
- Physics at sPHENIX
  - Jet correlation and jet structure
  - Parton energy loss
  - Upsilon spectroscopy
  - Cold QCD & spin physics



Not shown: sEPD and MBD

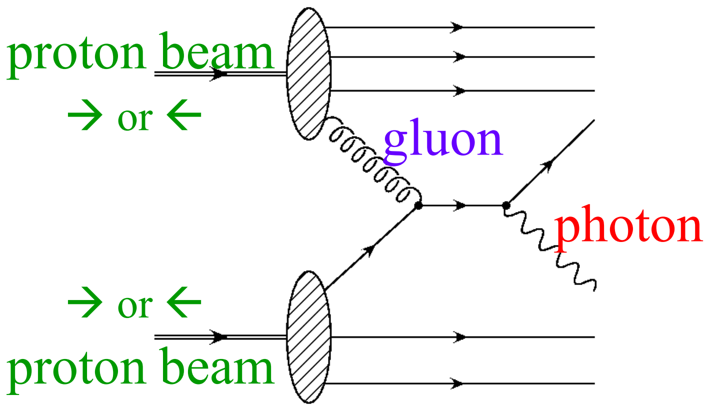
sPHENIX & STAR (2023-25)

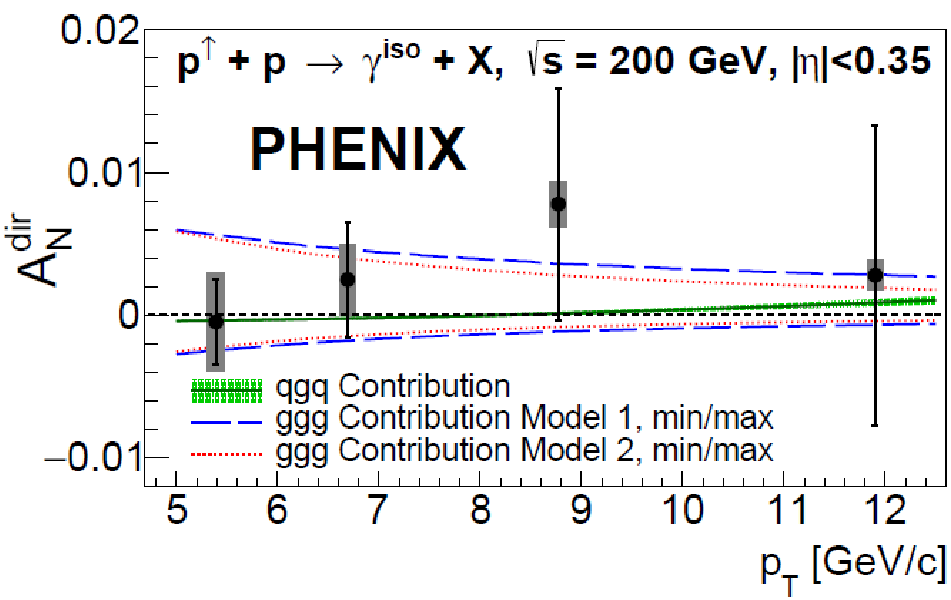
sPHENIX BUP 2022 [sPH-TRG-2022-001] 24 (28) cryo week scenarios

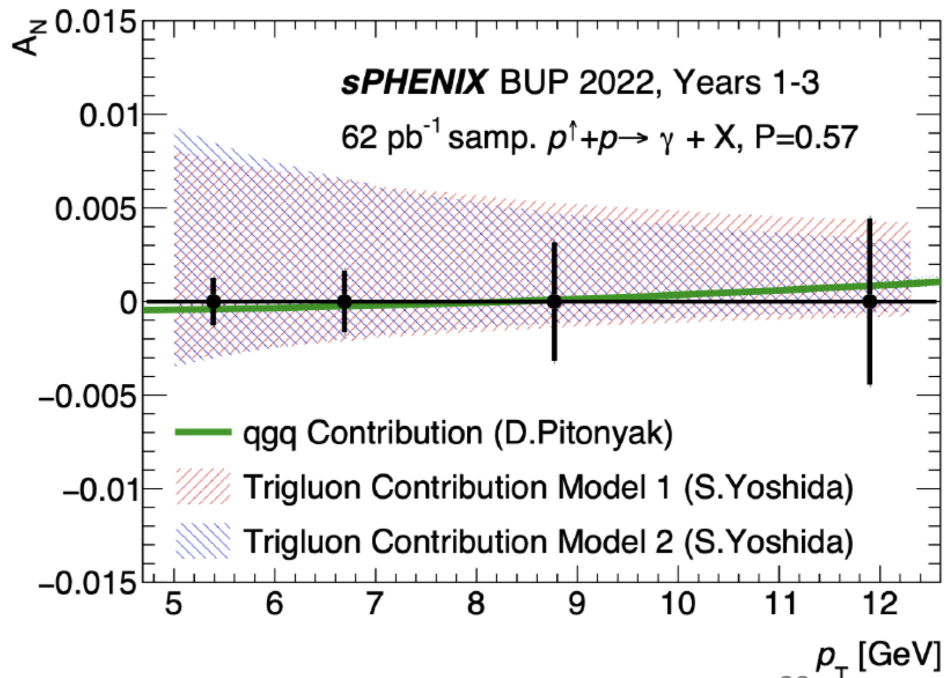
Year	Species	$\sqrt{s_{NN}}$ [GeV]	Cryo Weeks	Physics Weeks	Rec. Lum. $\|z\| < 10$ cm	Samp. Lum. $\|z\| < 10$ cm
2023	Au+Au	200	24 (28)	9 (13)	3.7 (5.7) nb^{-1}	4.5 (6.9) nb^{-1}
2024	$p^{\uparrow}p^{\uparrow}$	200	24 (28)	12 (16)	0.3 (0.4) pb^{-1} [5 kHz] 4.5 (6.2) pb^{-1} [10%-*str*]	45 (62) pb^{-1}
2024	$p^{\uparrow}$+Au	200	–	5	0.003 pb^{-1} [5 kHz] 0.01 pb^{-1} [10%-*str*]	0.11 pb^{-1}
2025	Au+Au	200	24 (28)	20.5 (24.5)	13 (15) nb^{-1}	21 (25) nb^{-1}

sPHENIX experiment

- Direct photon

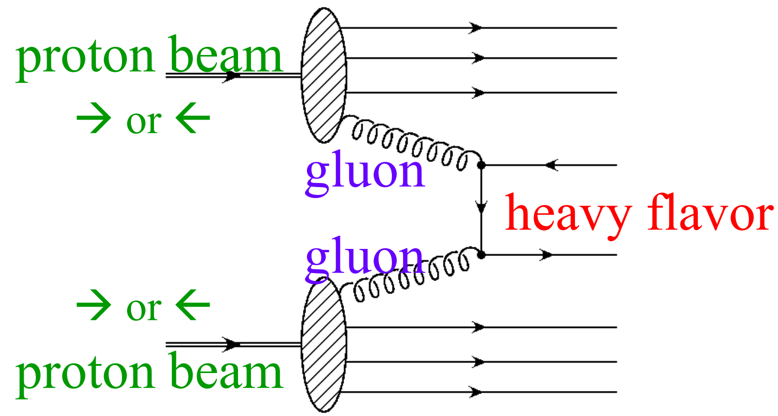


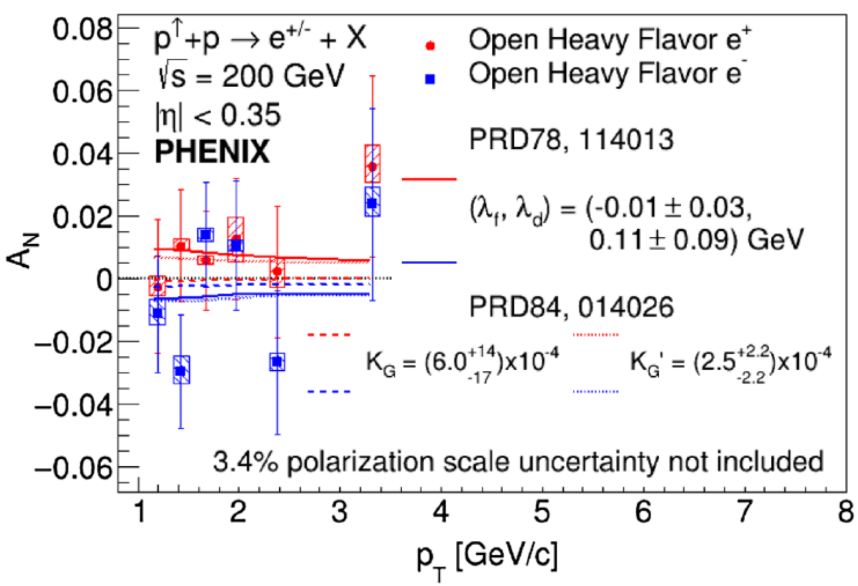


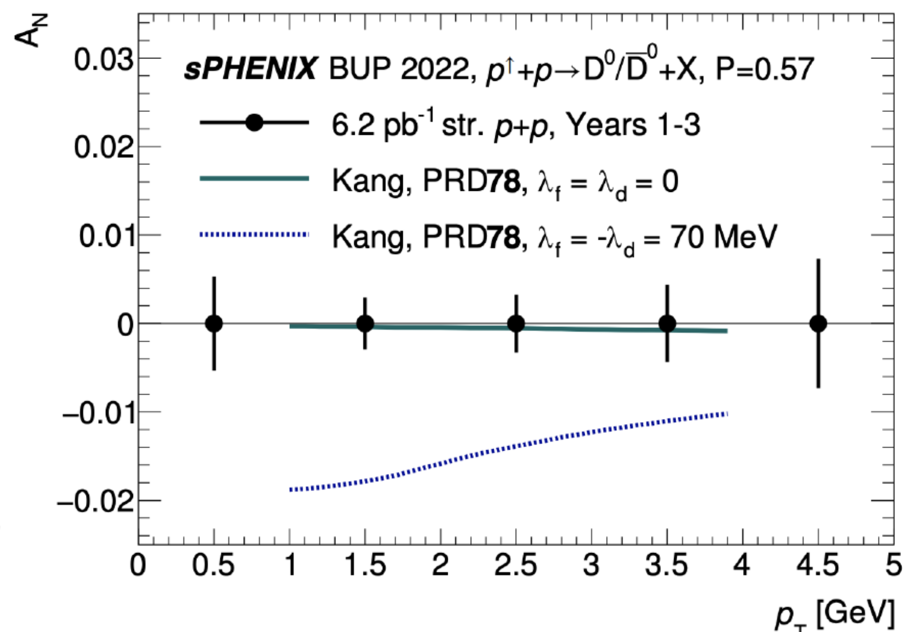


sPHENIX experiment

- 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



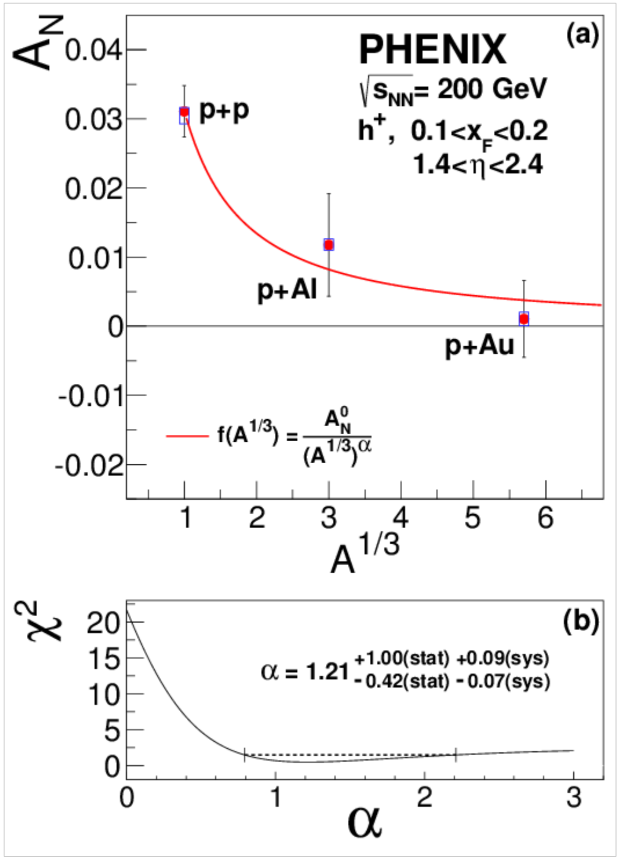


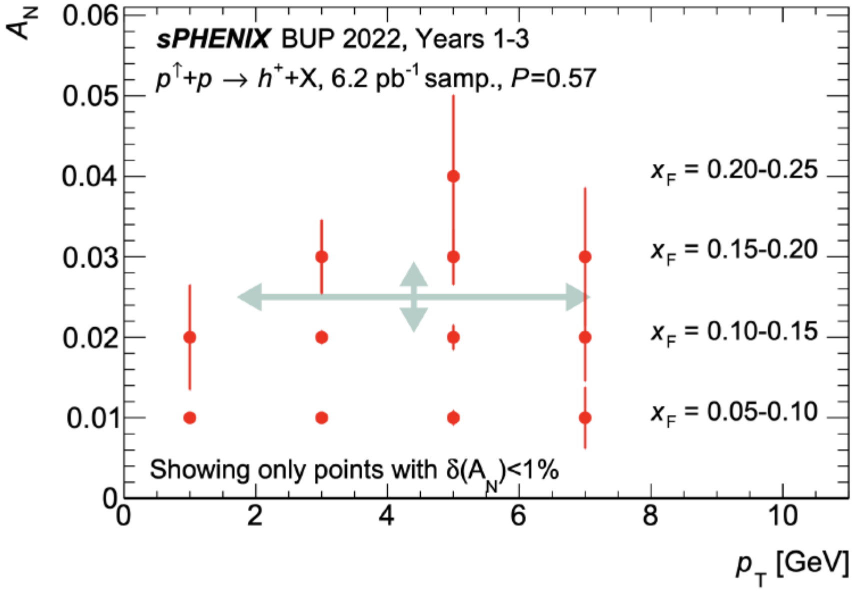


sPHENIX BUP 2022

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
  - Study of orbital motion of quarks and gluons inside the nucleon
    - Direct photon
    - Open heavy flavor
    - TMD Sivers effect
    - Transversity