

RHIC sPHENIX experiment

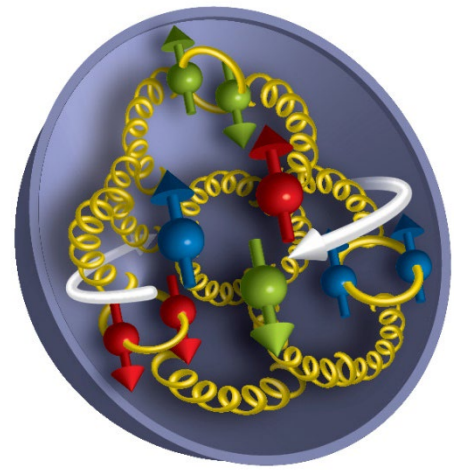
EIC-Asia Workshop

National Cheng Kung University, Tainan, Taiwan

January 29, 2024

Yuji Goto (RIKEN)

Nucleon spin physics



- Spin puzzle

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

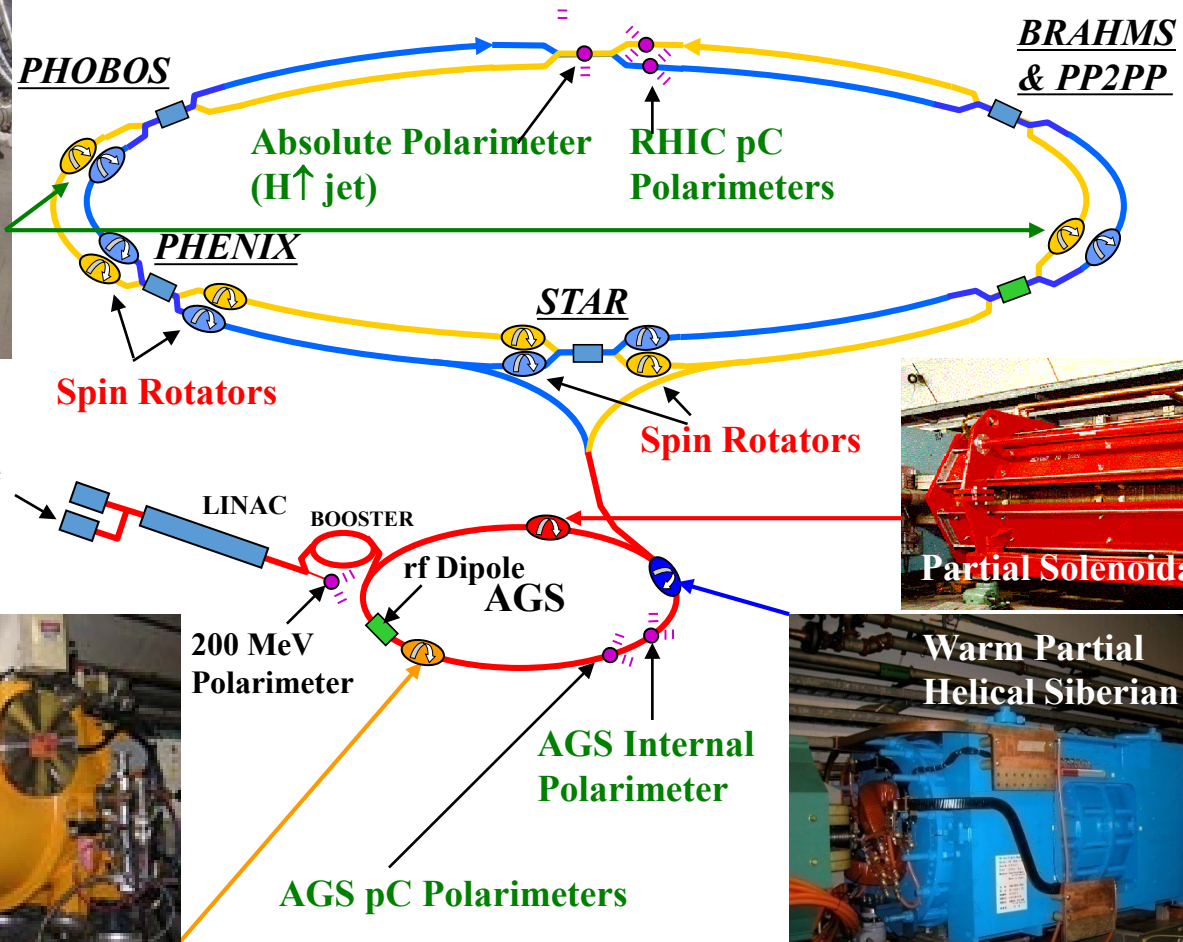
$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + \Delta g + L$$

Quark spin Gluon spin Orbital angular momentum

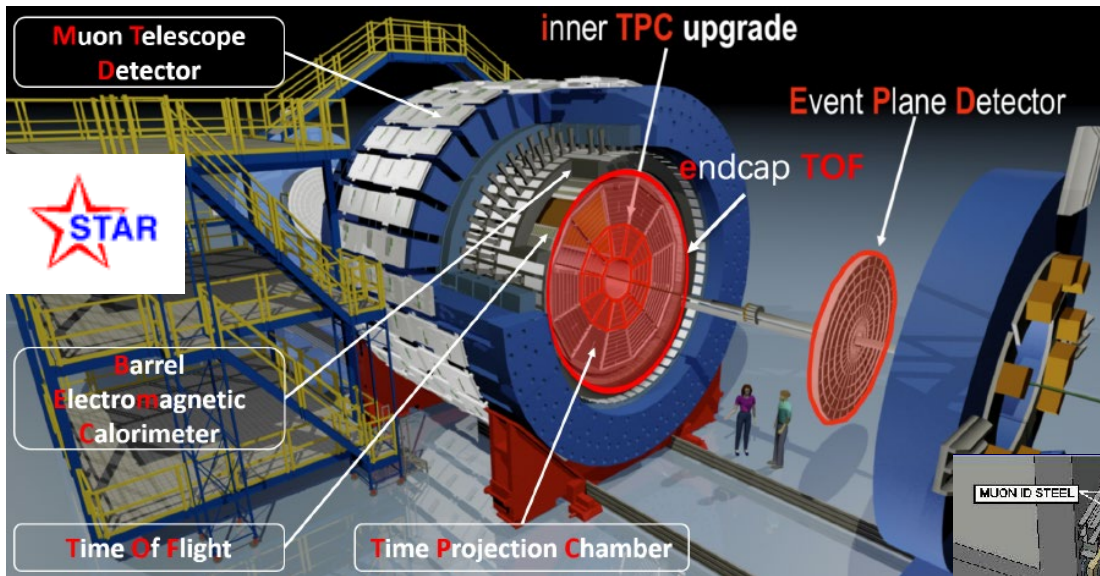
- Quark-spin contribution is only about 30% of the nucleon spin
- Longitudinal-spin (beam axis direction) asymmetry measurement
 - Gluon polarization measurement
 - Anti-quark polarization measurement using W boson
- Transverse-spin asymmetry measurement
 - Understanding of orbital motion inside the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

Polarized proton acceleration at RHIC

- Keeping and monitoring polarization from the polarized proton source

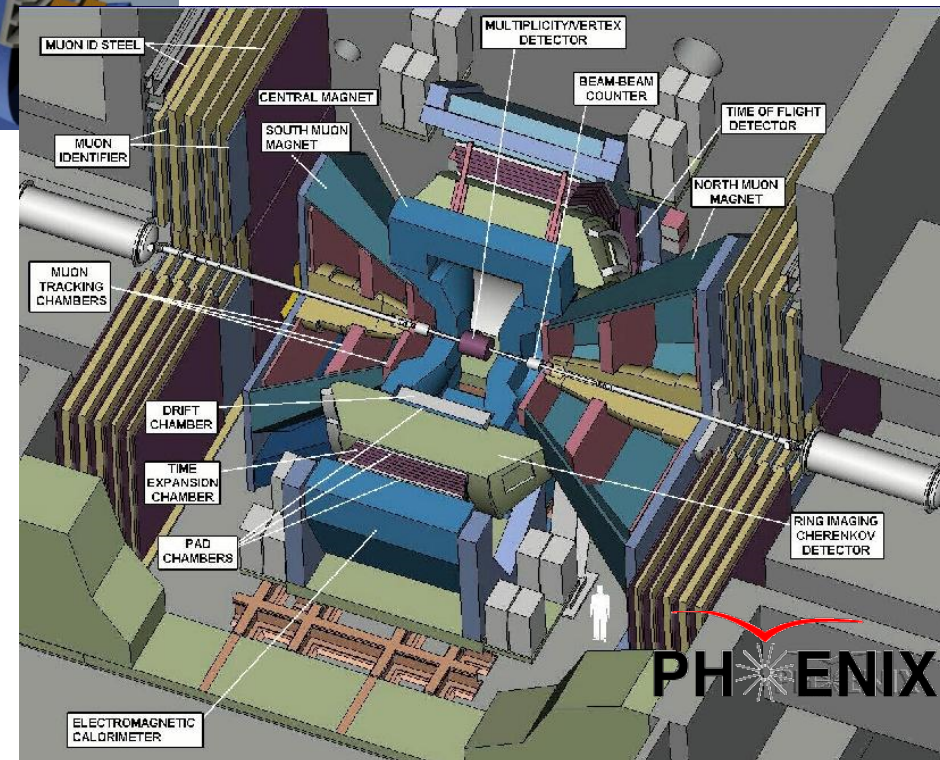


Polarized proton collision experiments



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

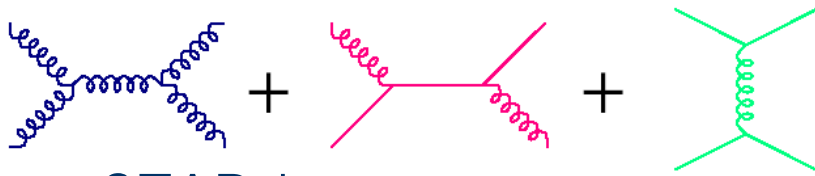
- PHENIX detector
 - limited acceptance
 - high resolution central EMCal
 - high-rate trigger and DAQ
 - forward muon detectors



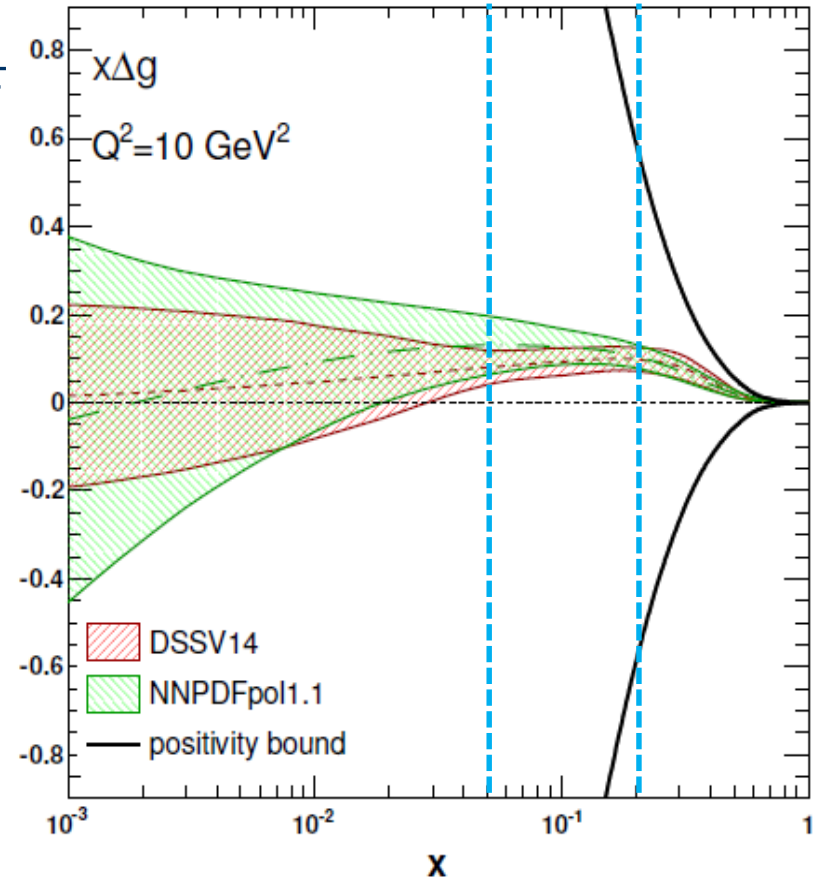
Gluon polarization Δg

arXiv:1503.03518

- 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

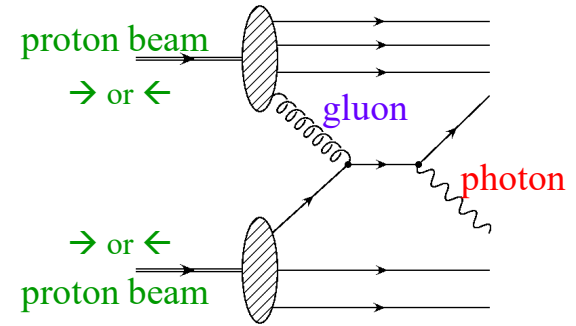


$$Q^2 = 10 \text{ GeV}^2 \quad \int_{0.05}^{0.2} dx \Delta g(x, Q^2)$$

NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

PHENIX direct photon

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

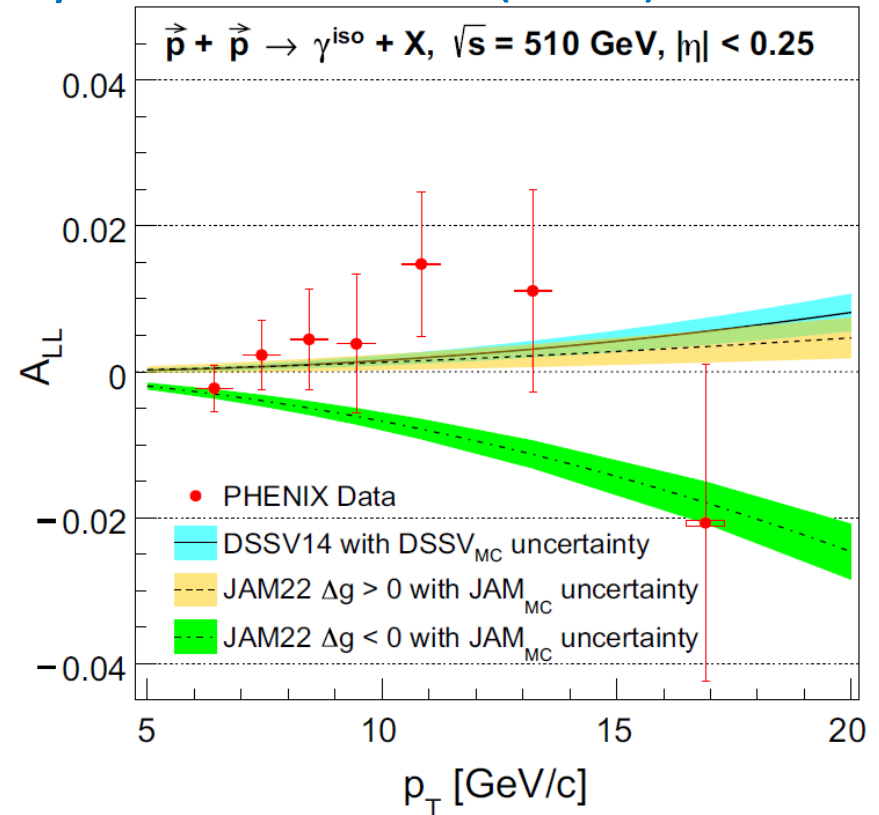
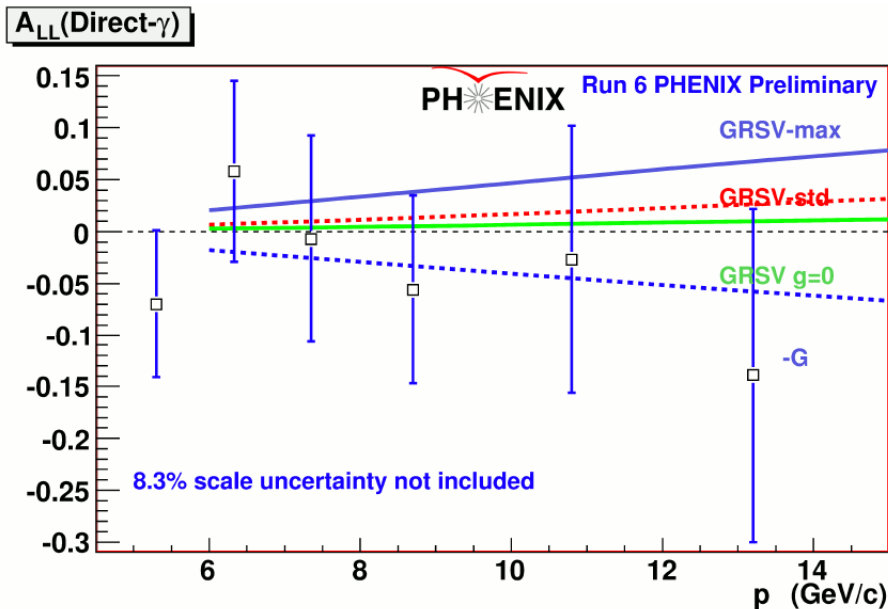


$\sqrt{s} = 200 \text{ GeV}$

Preliminary result (unpublished)

$\sqrt{s} = 510 \text{ GeV}$

Phys. Rev. Lett. 130 (2023) 251901

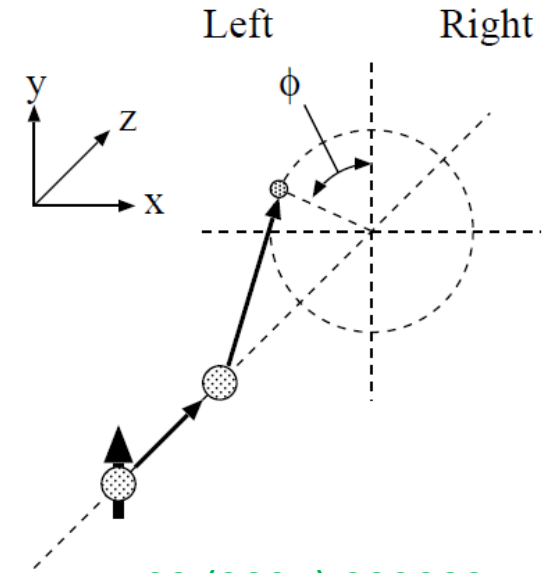


Transverse asymmetry measurement

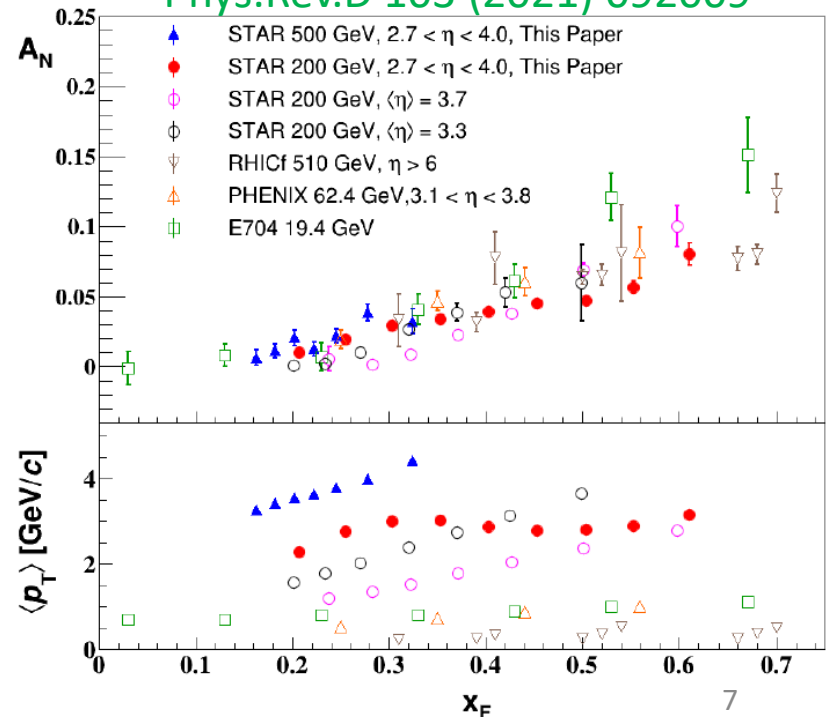
- A_N (transverse single-spin asymmetry) measurement

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

- 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?

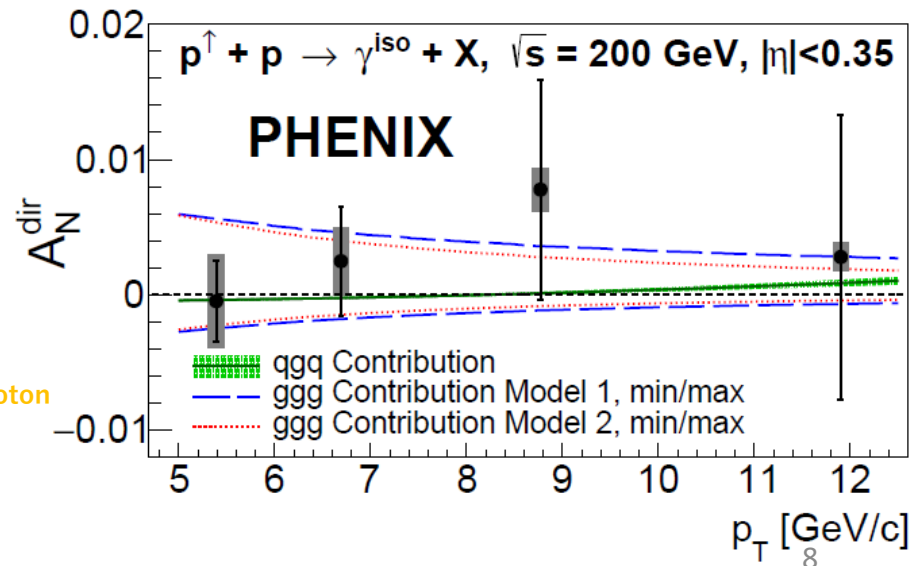
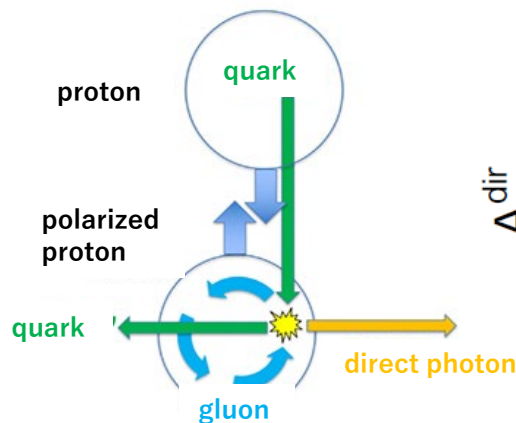
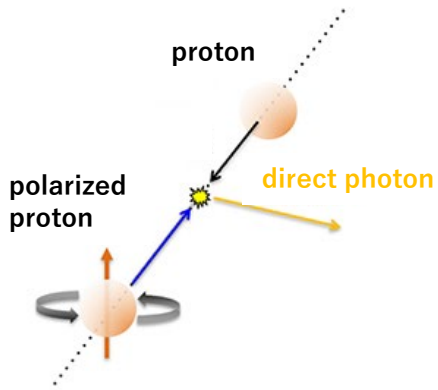
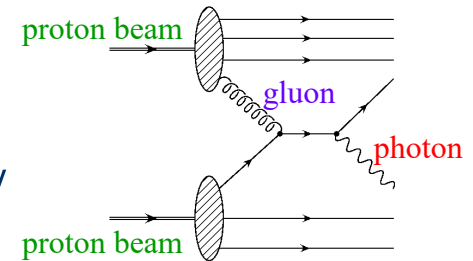


Phys.Rev.D 103 (2021) 092009



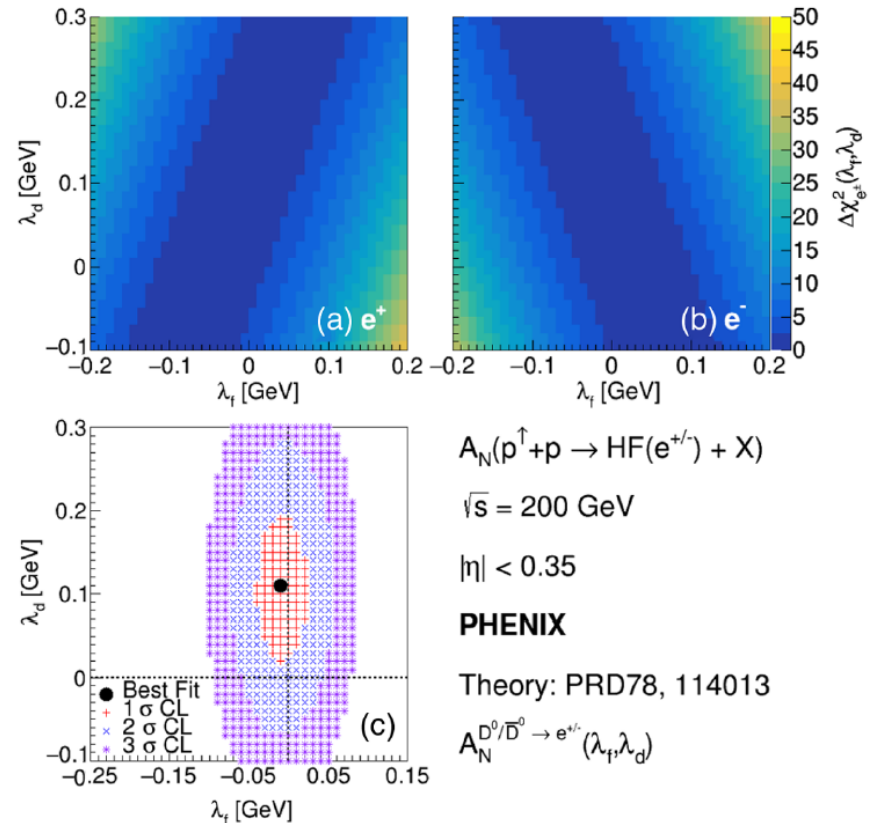
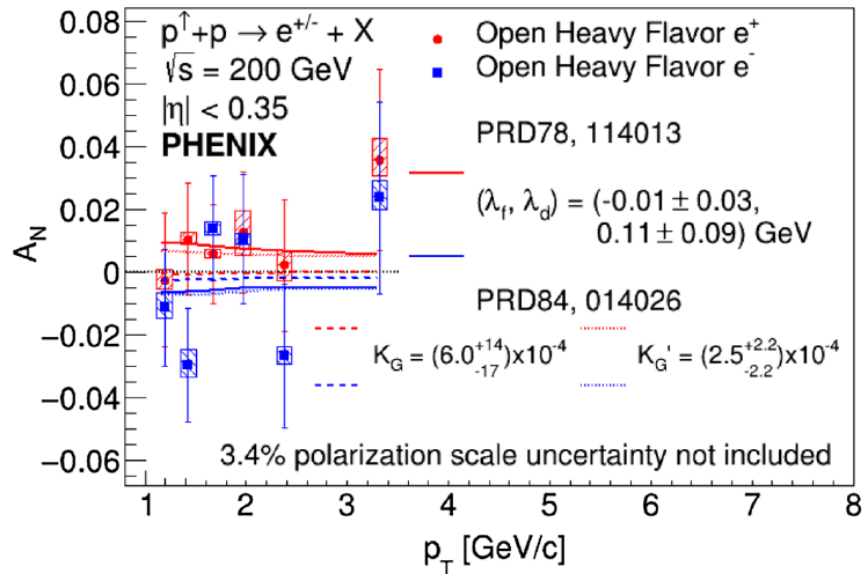
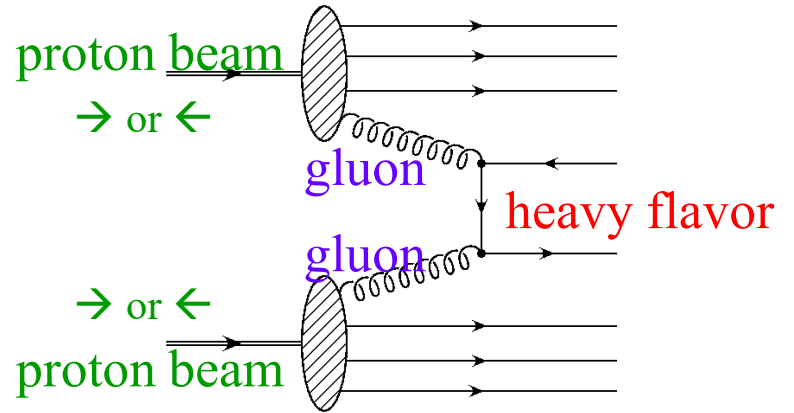
PHENIX direct photon

- 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

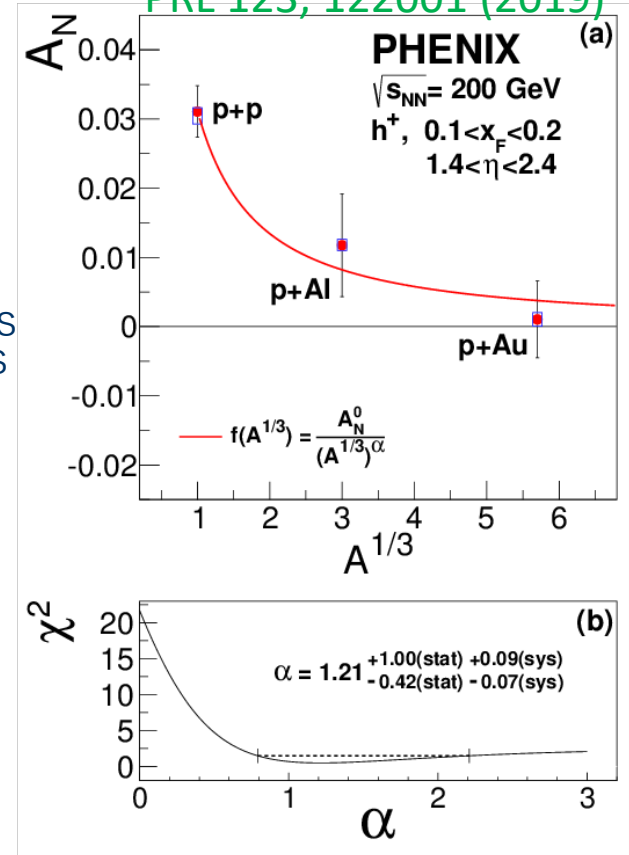
- PHENIX open heavy flavor at midrapidity
 - Phys. Rev. D 107 (2023) 052012.
 - Gluon fusion process
 - Sensitive to initial-state gluon
 - e^\pm asymmetry measurement
 - Lepton-decay channel
 - Restriction to the tri-gluon correlation function



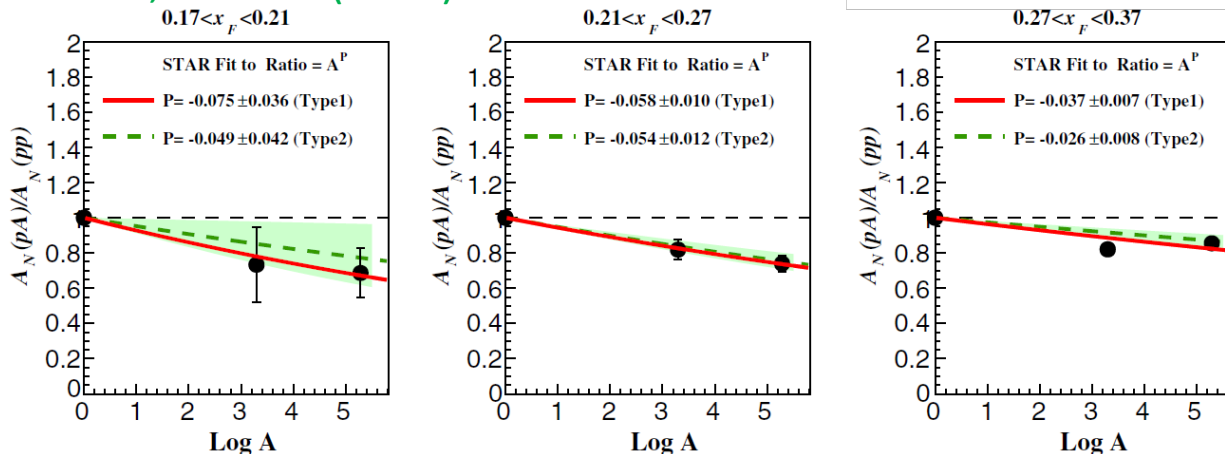
Polarized $p+A$ collisions

- 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)

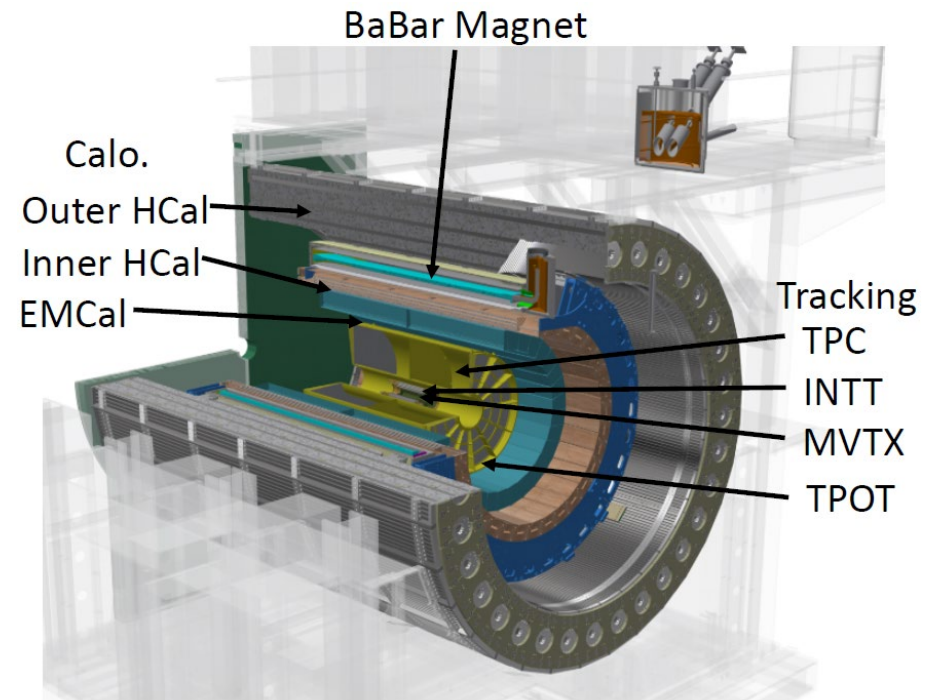


PRD 103, 072005 (2021)



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

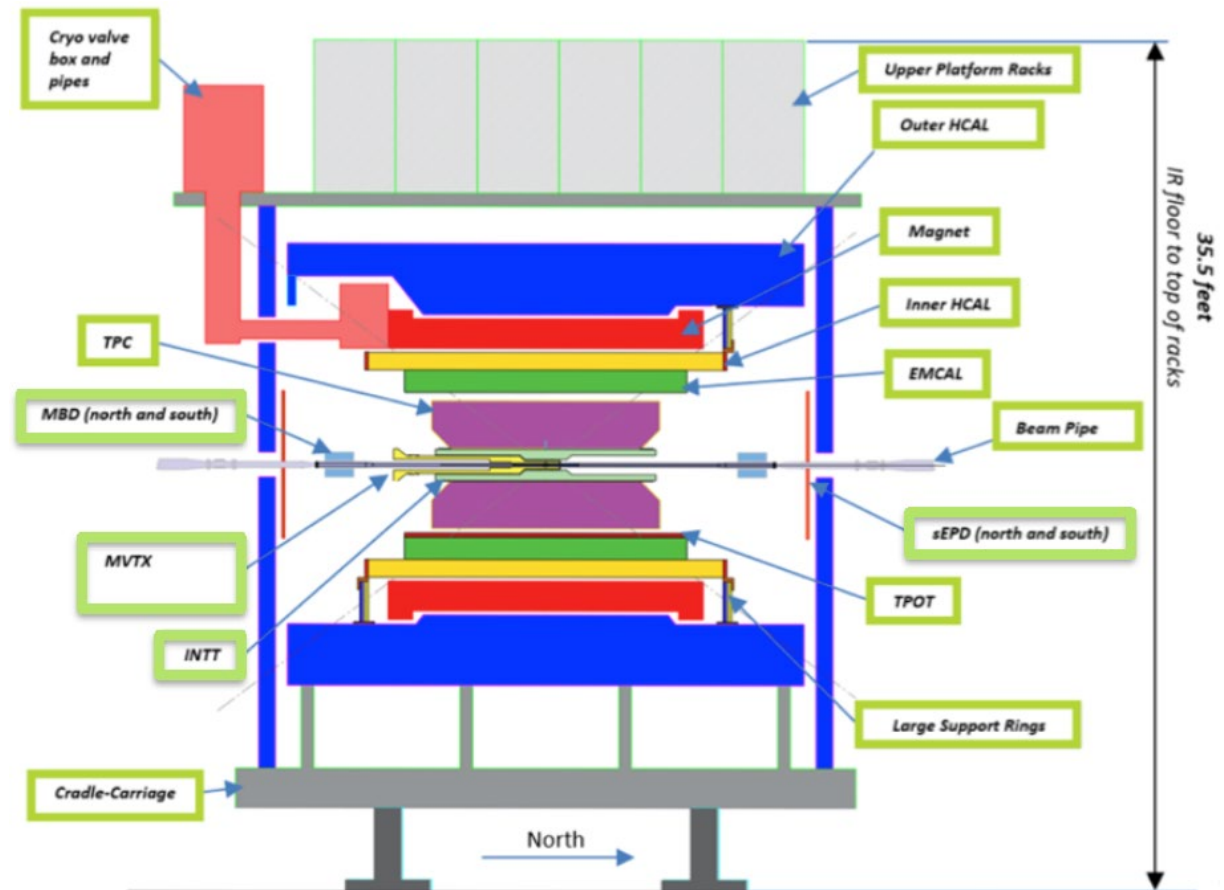


Not shown: sEPD and MBD



sPHENIX detector

- Large, uniform acceptance
 - 2π coverage in azimuth
 - $-1.1 < \eta < 1.1$ geometric coverage
- Full EM & hadronic calorimetry
- High precision tracking
- High precision vertexing, DCA
- Huge Au+Au samples w/ unbiased trigger



Physics at sPHENIX

- Study QCD phenomena discovered at RHIC with unprecedented precision
 - Jet correlation and jet substructure
 - Parton energy loss
 - Upsilon spectroscopy
 - Cold QCD & spin physics

Jet physics
vary momentum & angular scale of probe

Quarkonium spectroscopy
vary size of probe

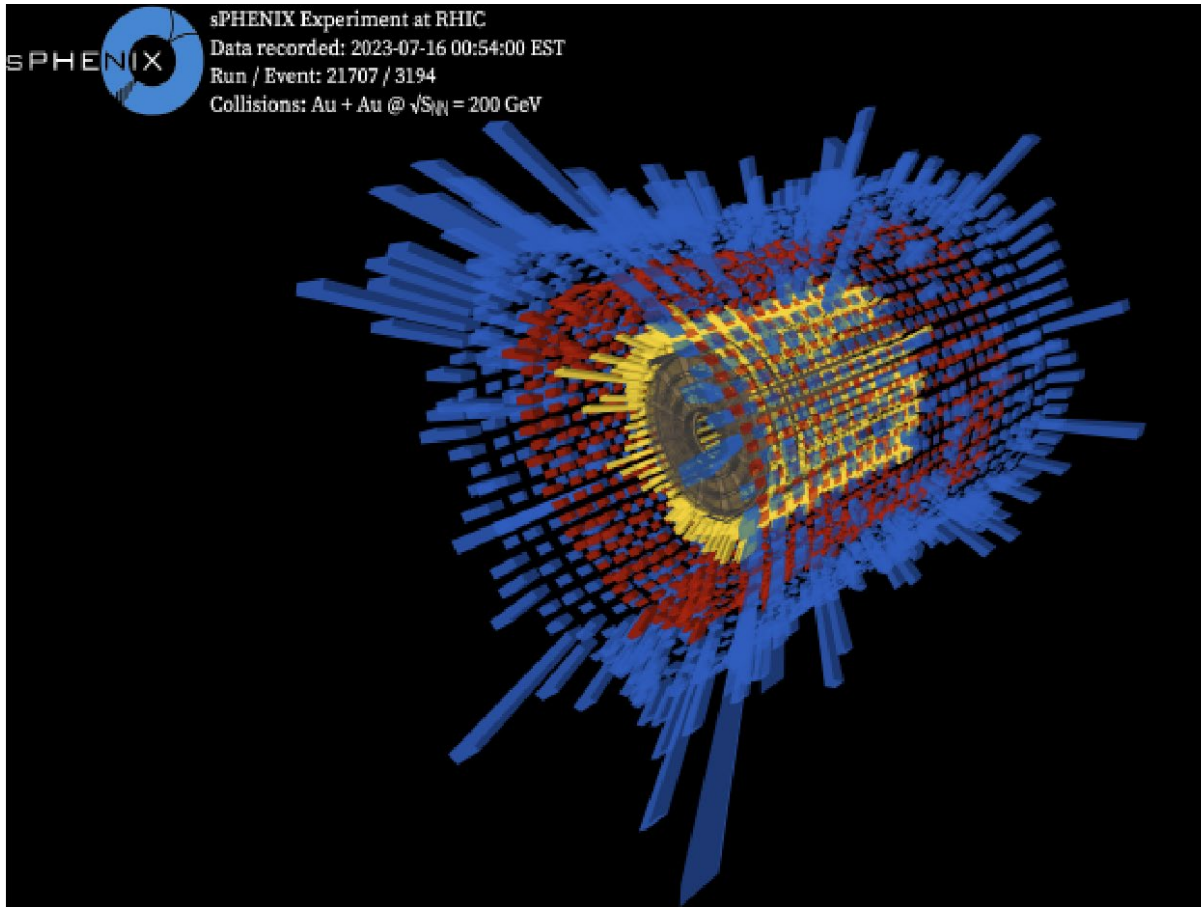
Cold QCD
vary temperature of QCD matter
study proton spin, transverse-momentum, and cold nuclear effects

Parton energy loss
vary mass & momentum of probe
photon
gluon

SPHENIX

Hadron and EM calorimeters

- sPHENIX have kinematic reach out to ~ 70 GeV for jets, kinematic overlap with LHC

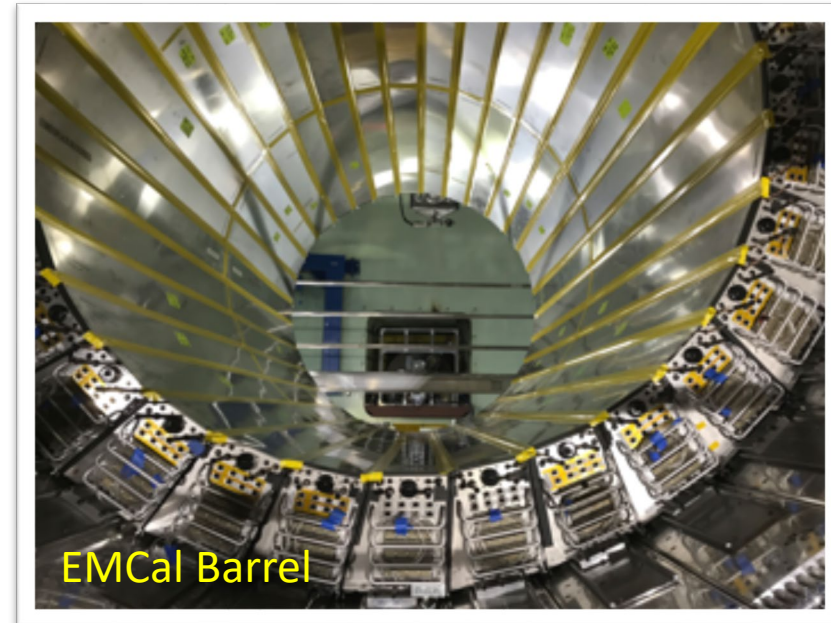
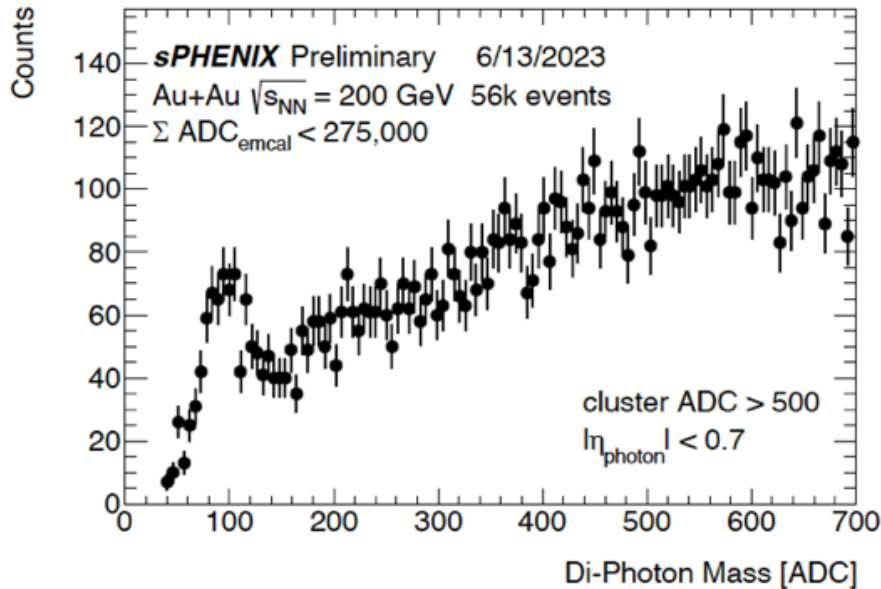
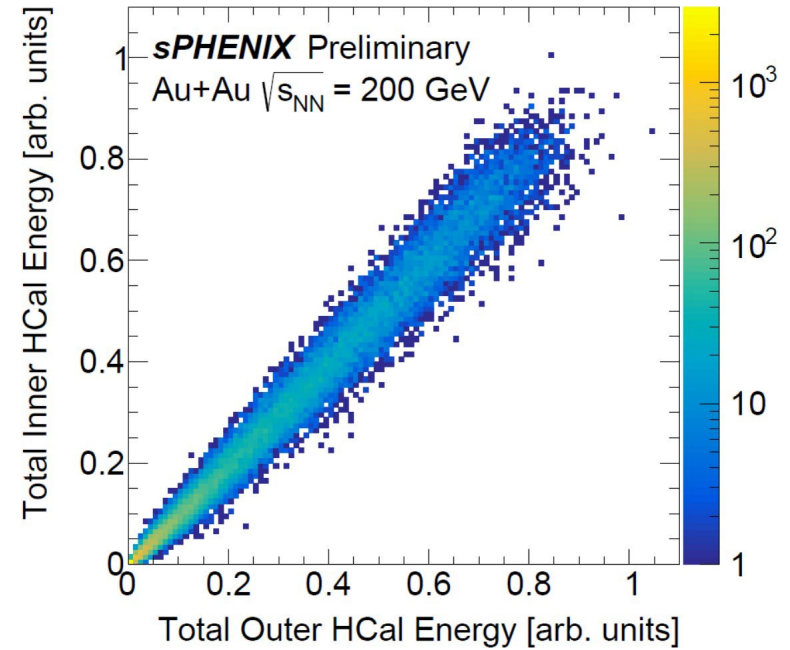


Central Au+Au collisions in calorimeters



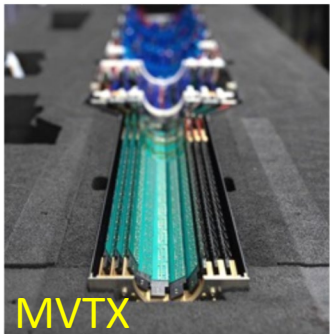
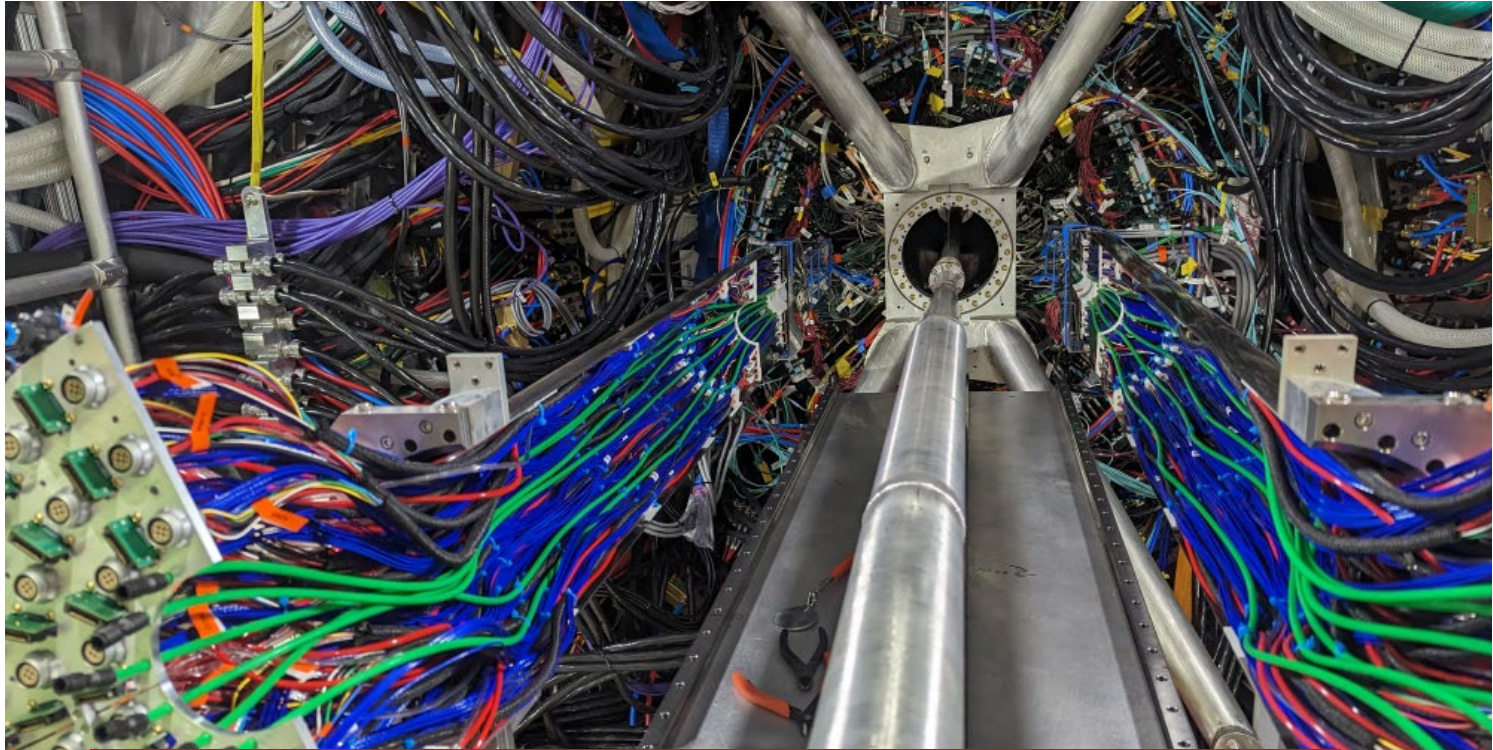
Hadron and EM calorimeters

- Energy correlation of Outer HCal and Inner HCal
- EMCal π^0 mass peak from $\gamma\gamma$

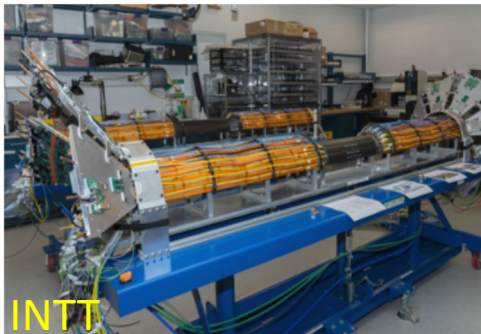


Tracking detectors

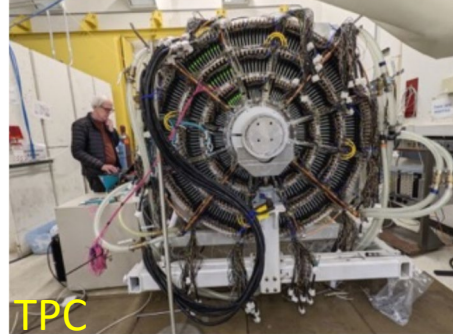
- All trackers installed in position (March 30th, 2023)



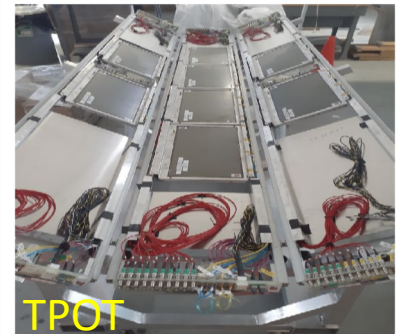
MVTX



INTT

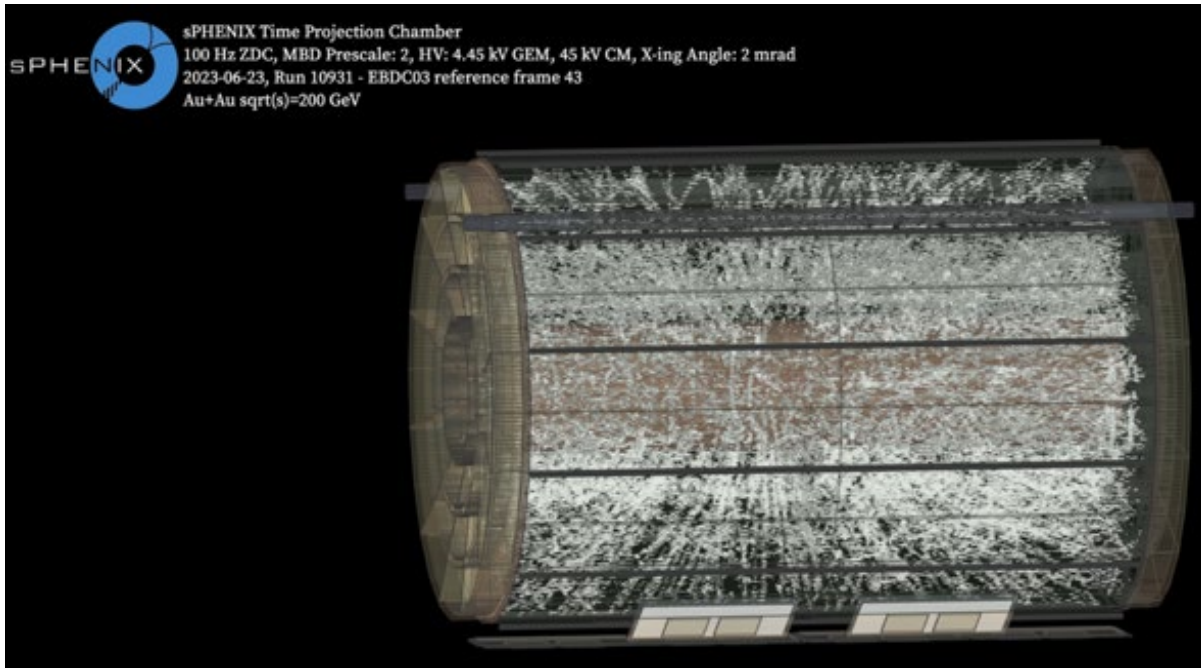


TPC

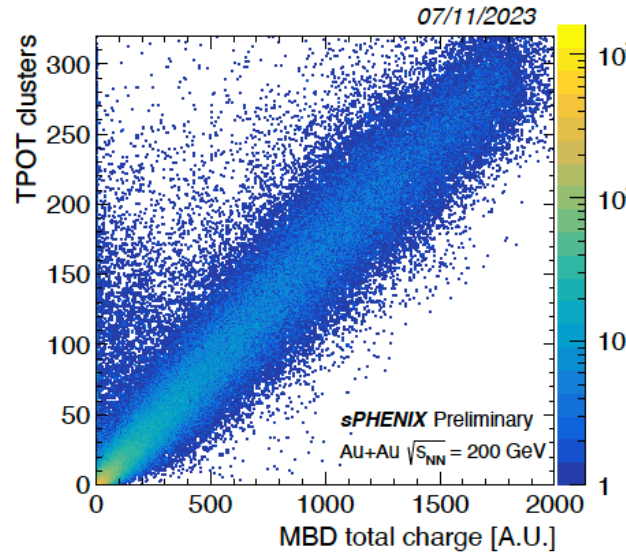
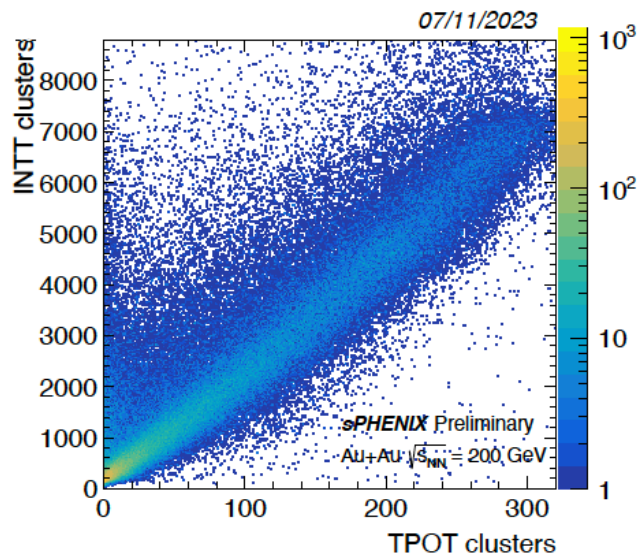


TPOT

Tracking detector commissioning



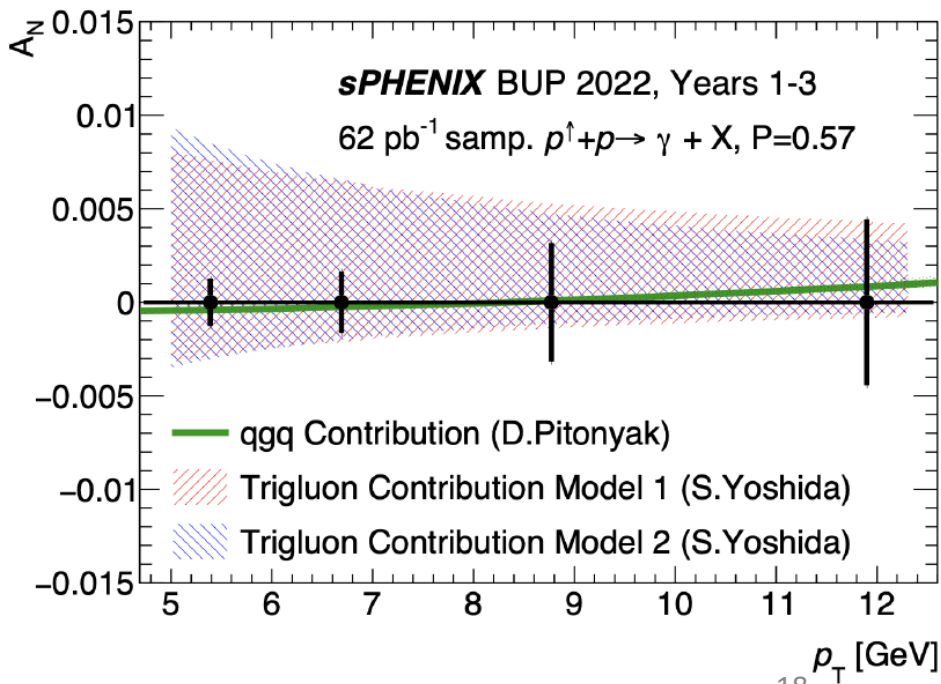
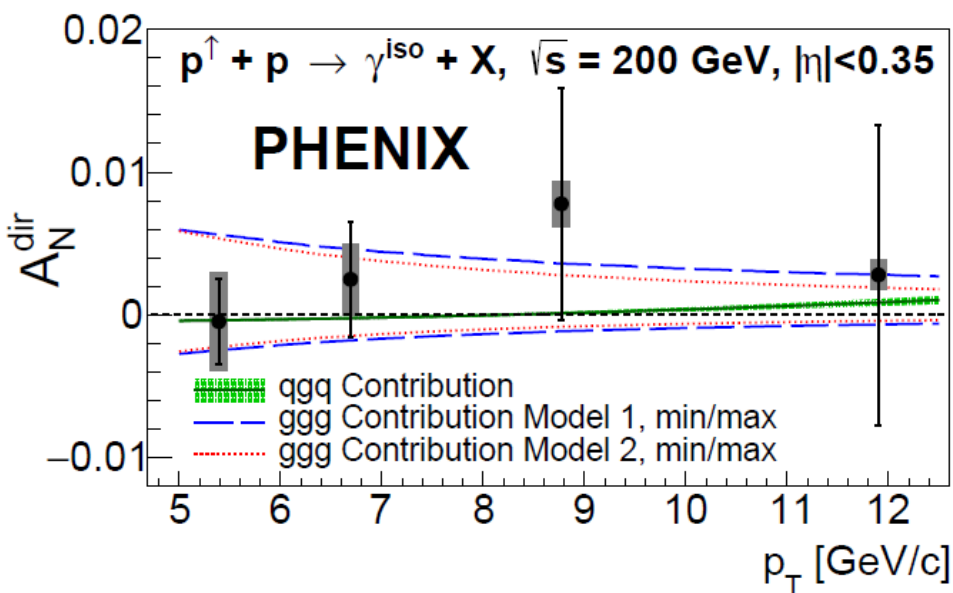
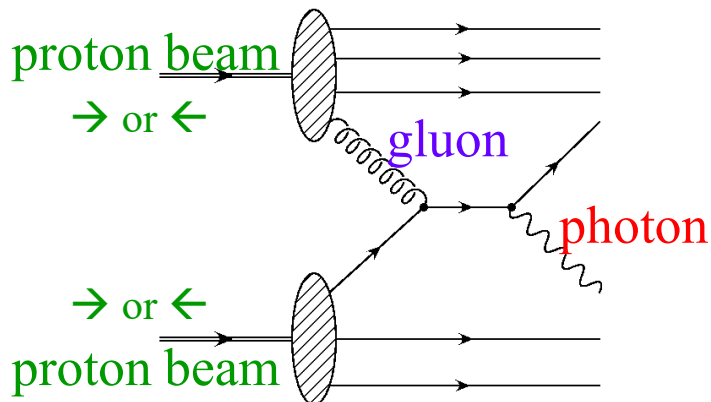
TPC event display in Au+Au at 200 GeV



Multiplicity correlations between MBD-INTT-TPOT

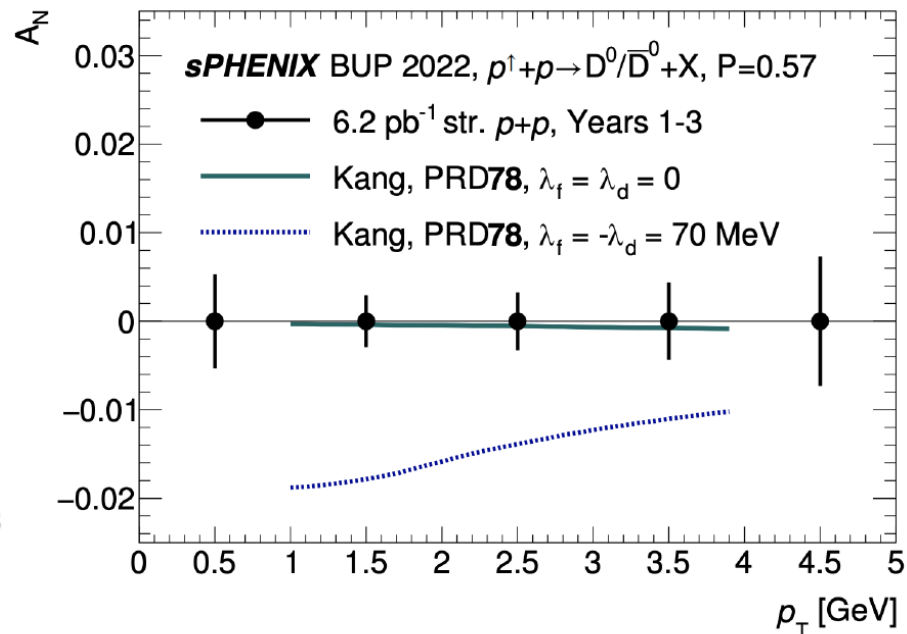
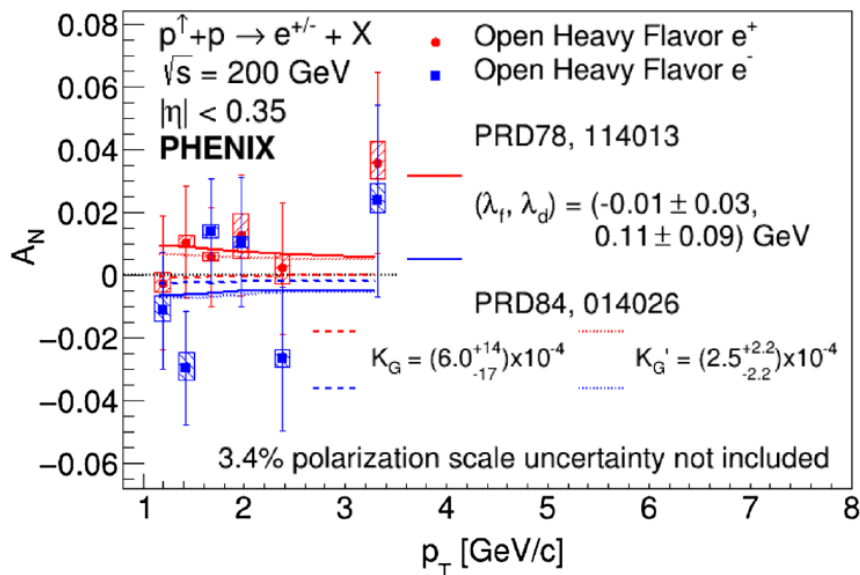
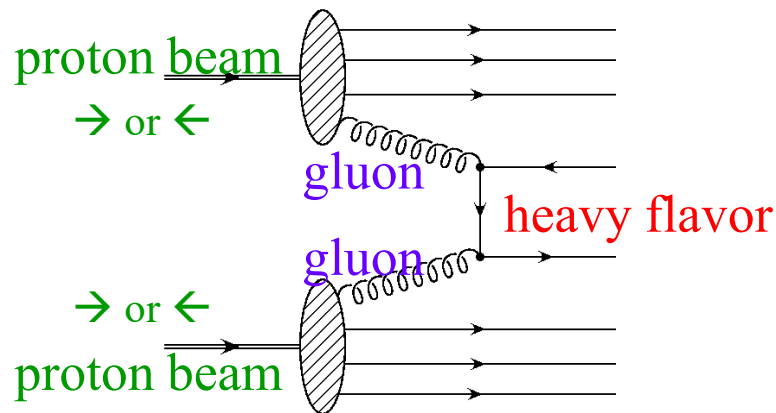
sPHENIX experiment

- Direct photon



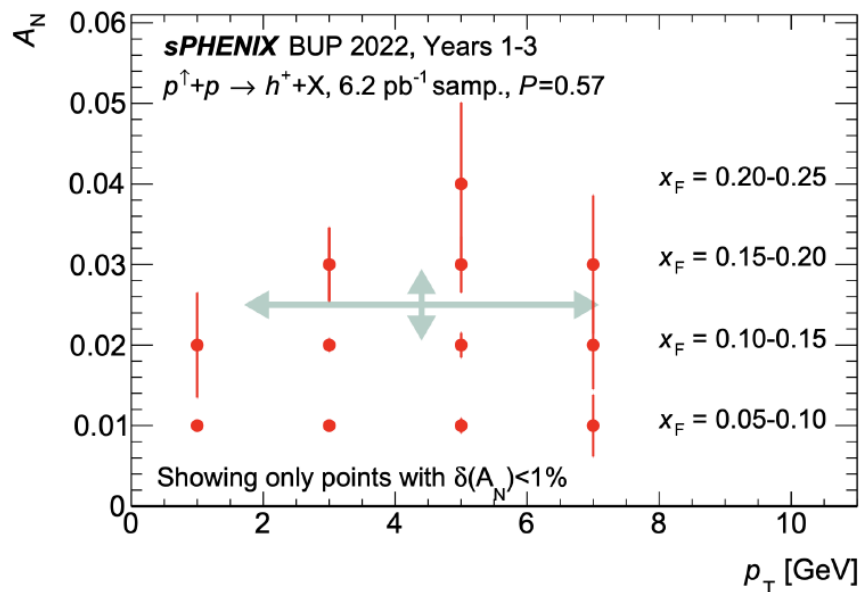
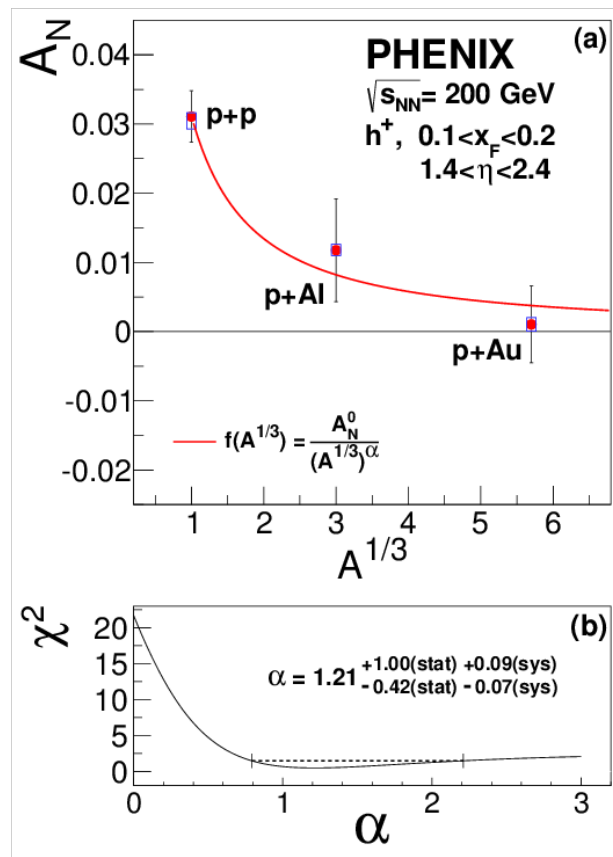
sPHENIX experiment

- 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 experiment

- Polarized-p + A collisions
- PHENIX charged hadron A_N : $1.4 < \eta < 2.4$
 - $0.1 < x_F < 0.2$, $1.8 < p_T < 7$ GeV/c
 - Asymmetry consistent with the $A^{1/3}$ dependence first predicted by the nuclear effect associated with CGC
- STAR π^0 A_N : $2.6 < \eta < 4.0$
 - $0.2 < x_F < 0.7$, $1.5 < p_T < 7$ GeV/c
 - 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 remaining
- sPHENIX experiment
 - Study of orbital motion of quarks and gluons inside the nucleon
 - Direct photon
 - Open heavy flavor
 - TMD Sivers effect
 - Transversity
- sPHENIX fully installed and operational in RHIC Run 2023
 - Detector subsystem performance consistent with expectations, though some debugging and commissioning work remaining