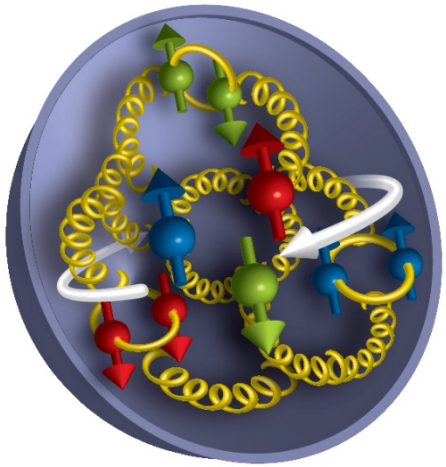
Forward Spin Physics at PHENIX and sPHENIX

International Workshop on Forward Physics
and Forward Calorimeter Upgrade in ALICE
March 7, 2019 at Tsukuba Univ.

Yuji Goto (RIKEN Nishina Center)

Nucleon spin physics



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

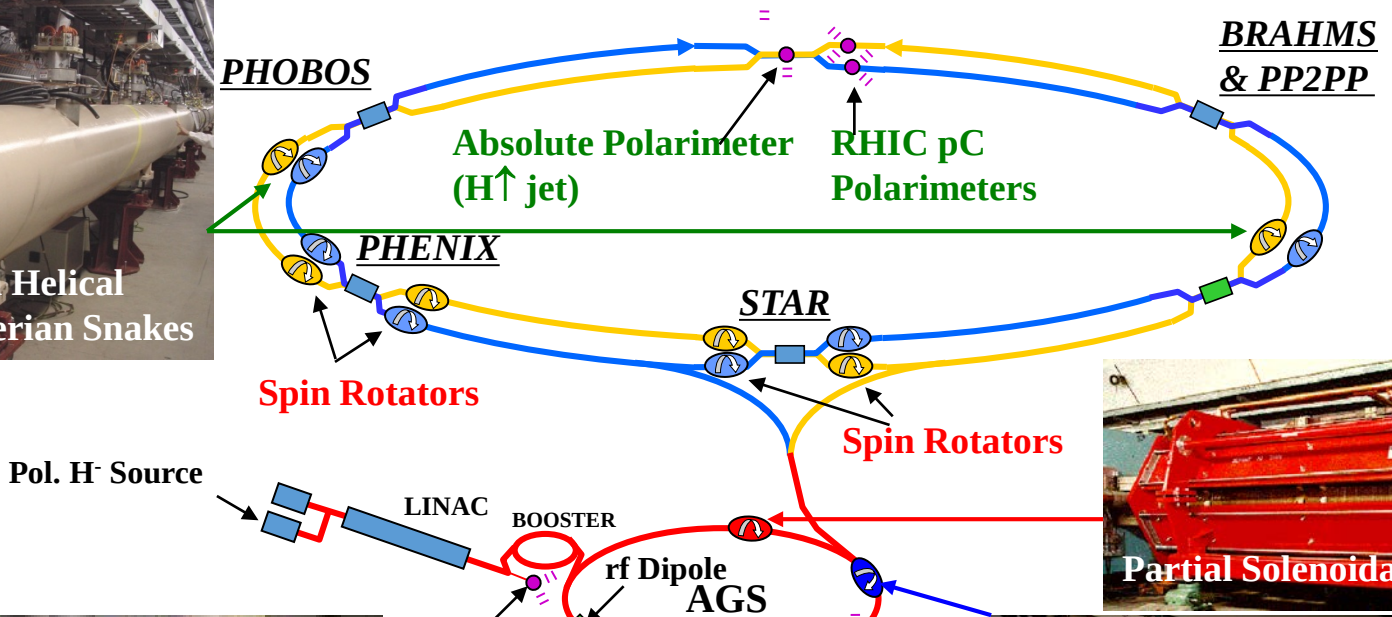
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

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

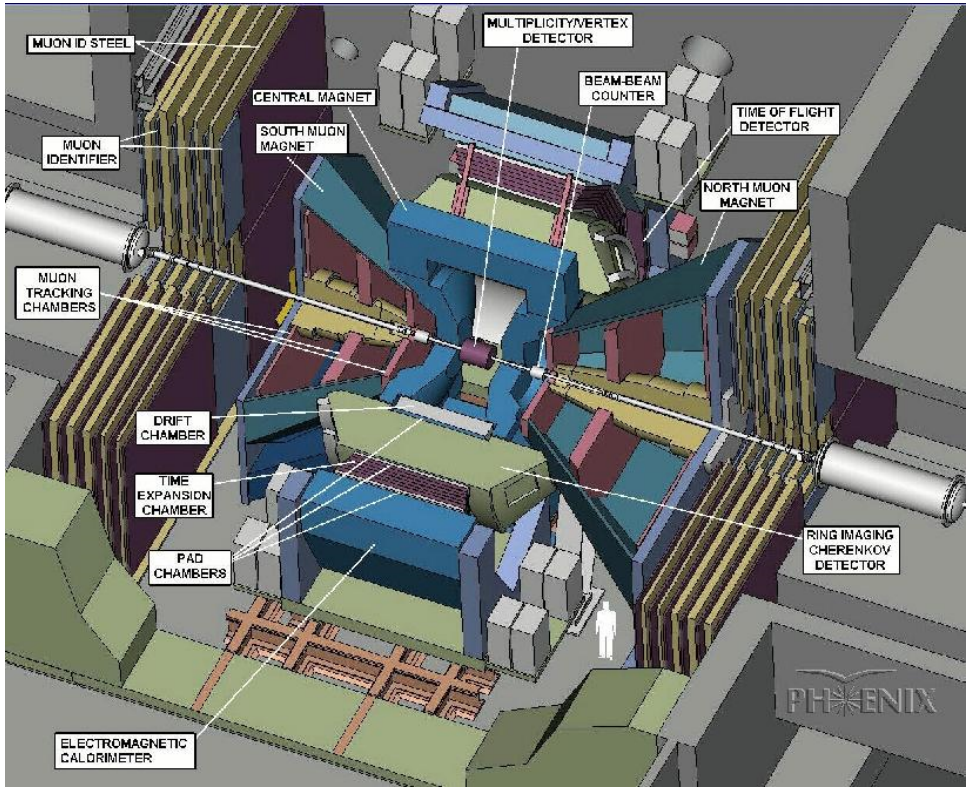
  - Quark-spin contribution is only about 30% of the nucleon spin
- Longitudinal-spin (beam axis direction) asymmetry measurement
  - Gluon polarization measurement
  - Anti-quark polarization measurement using W boson
- Transverse-spin asymmetry measurement
  - Understanding of orbital motion inside the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

Polarized proton acceleration at RHIC

- Keeping and monitoring polarization from the polarized proton source



PHENIX detector



- Philosophy
  - high resolution at the cost of acceptance
  - high rate capable DAQ
  - excellent trigger capability for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi = \pi/2 \times 2$
  - Momentum and energy measurement, particle-ID
  - Detecting electron, photon, hadron
  - Small amount of material to reduce conversion background
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum measurement and muon-ID
  - Hadron absorber (muon piston)

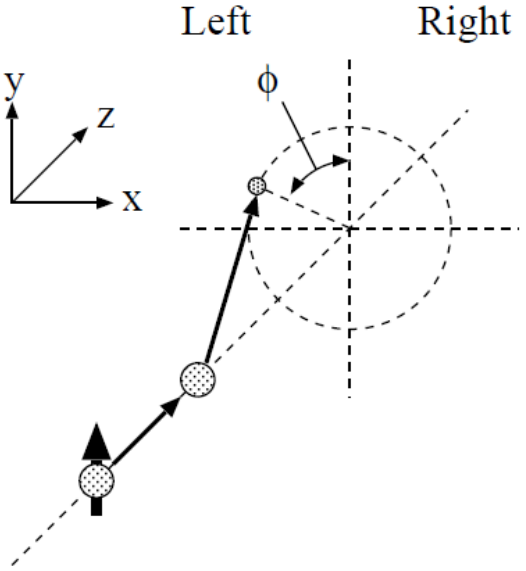
- Global detectors
  - beam-beam counter (BBC), zero-degree calorimeter (ZDC)
    - Minimum-bias trigger
    - Luminosity measurement
    - Local polarimeter

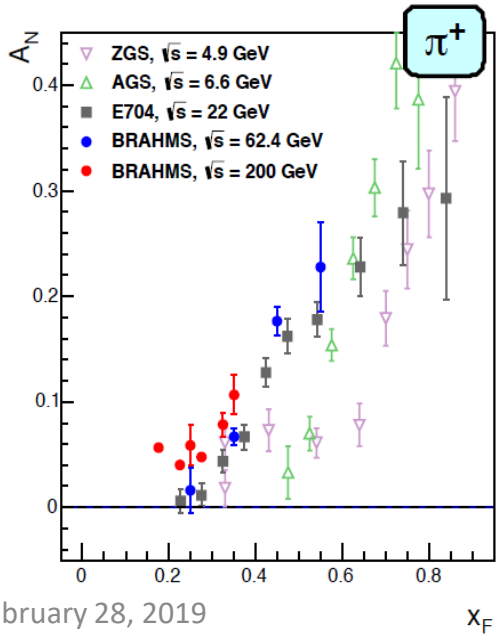
Transverse polarized proton collision

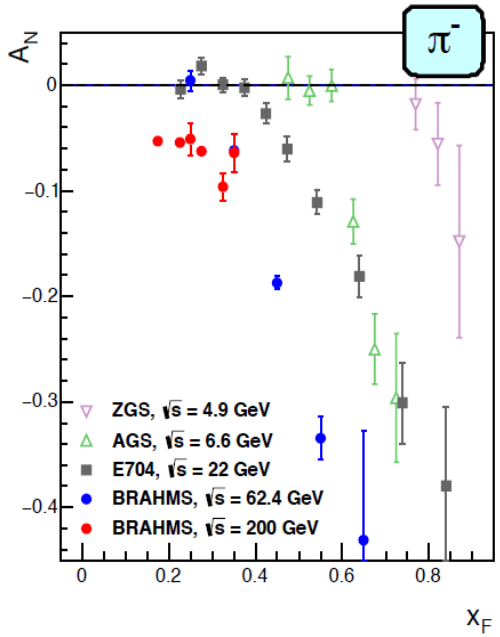
- A_N (transverse single-spin asymmetry) measurement

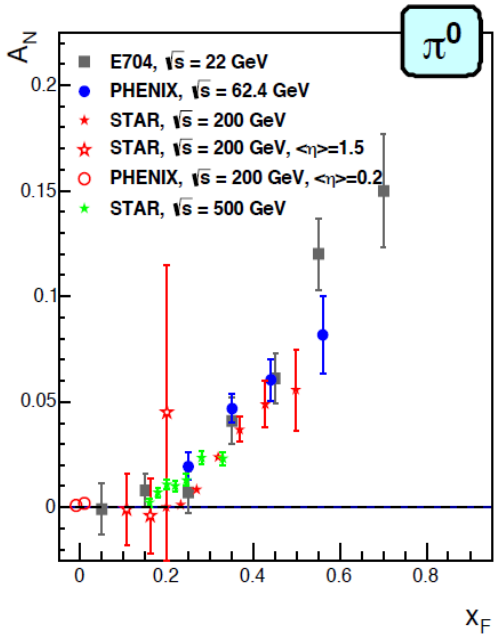
$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

  - Azimuthal angle modulation (or dependence)
- Large A_N for forward hadron production
  - Similar results in wide $\sqrt{s}$



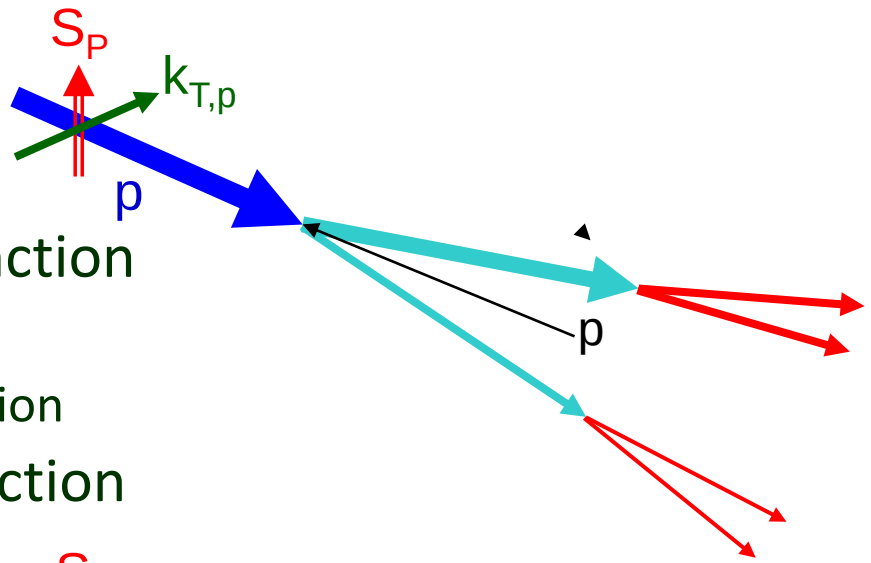


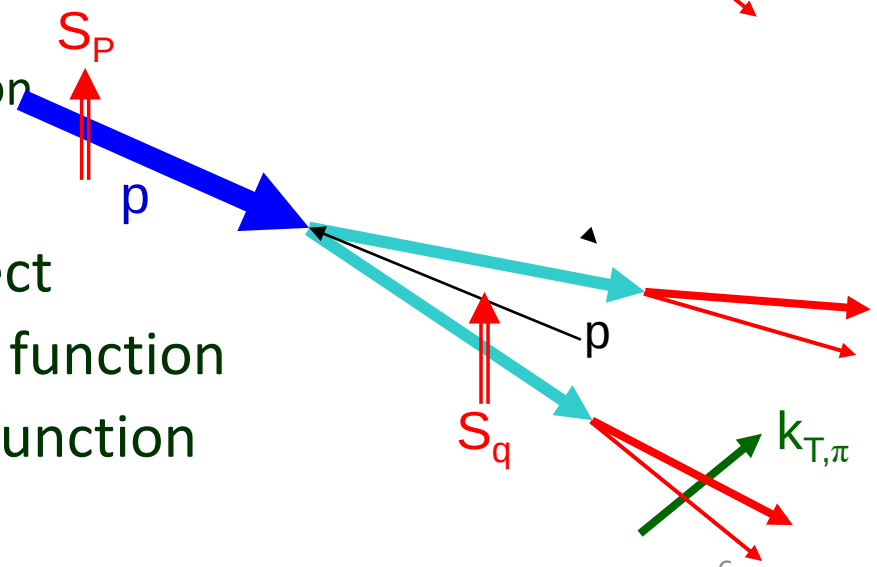




Transverse polarization phenomena

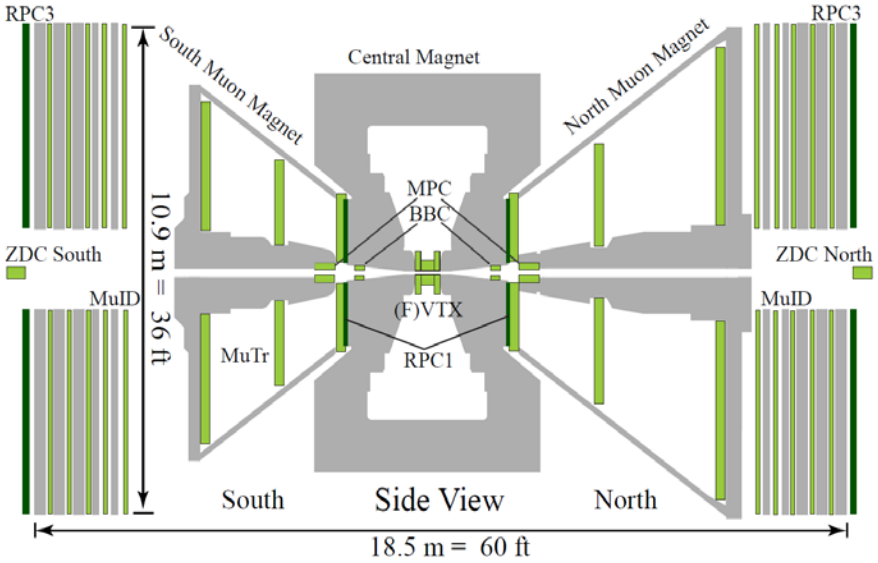
- TMD (Transverse Momentum Dependent) function and higher-twist function
- "Sivers" effect
  - Initial-state effect
  - TMD (Sivers) distribution function
    - Need 2 scales (p_T and Q^2)
    - Drell-Yan, W/Z boson production
  - Higher-twist distribution function
    - Need 1 scale (p_T)
    - Hadron, photon, jet production
- "Collins" effect
  - Transversity + final-state effect
  - TMD (Collins) fragmentation function
  - Higher-twist fragmentation function





Transverse-polarization runs

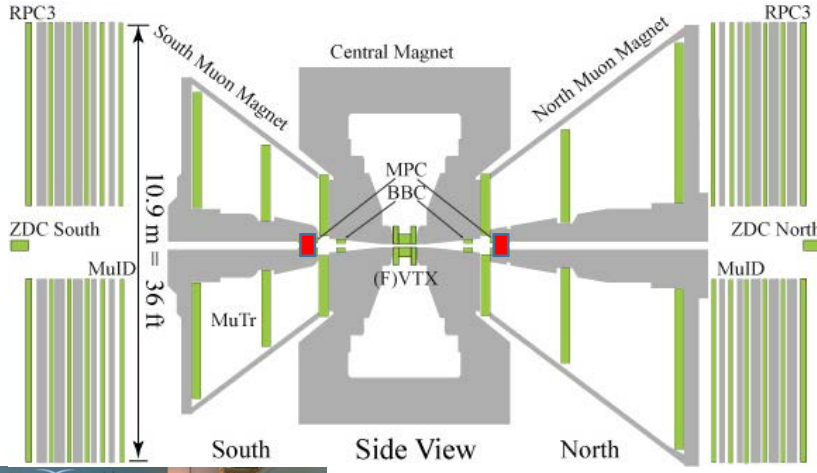
- Muon arm 2001-
- MPC 2006-
  - EM calorimeter
- FVTX 2012-
  - Silicon detector
- MPC-EX 2015-
  - Preshower detector

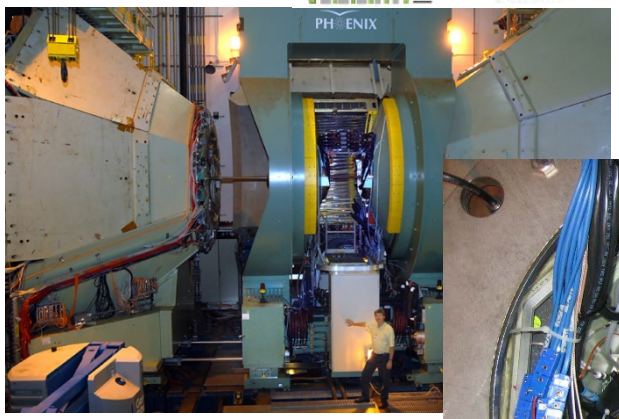


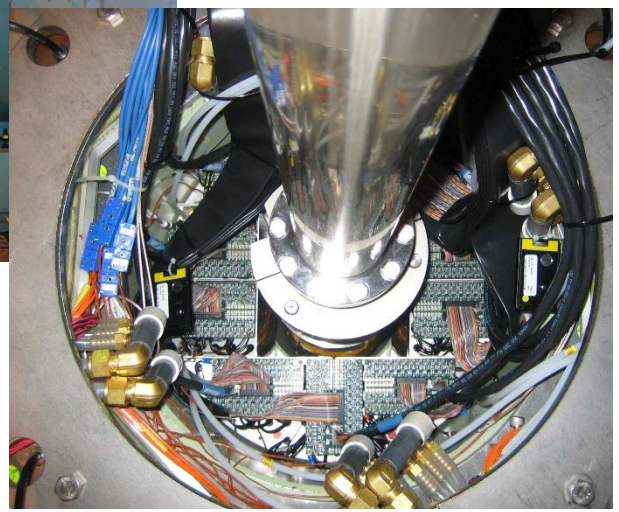
Year	Energy	Recorded Luminosity	Polarization	FoM (P^2L)
2001-2	200 GeV	0.15 pb^{-1}	15%	0.0034 pb^{-1}
2005	200 GeV	0.16 pb^{-1}	47%	0.035 pb^{-1}
2006	200 GeV	2.7 pb^{-1}	57%	0.88 pb^{-1}
2006	62.4 GeV	0.02 pb^{-1}	53%	0.0056 pb^{-1}
2008	200 GeV	5.2 pb^{-1}	45%	1.1 pb^{-1}
2012	200 GeV	9.2 pb^{-1}	59%	3.3 pb^{-1}
2015	200 GeV	110 pb^{-1}	57%	35 pb^{-1}

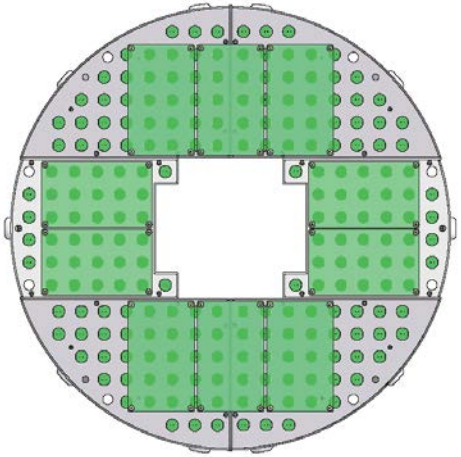
MPC @ PHENIX

- Muon Piston Calorimeter
- EM calorimeter installed in the small cylindrical hole in muon magnet piston
  - $PbWO_4$ crystals
    - $2.2 \times 2.2 \times 18\ cm^3$
  - 22.5 cm radius
  - 43.1 cm depth
  - $3.1 < |\eta| < 3.9$





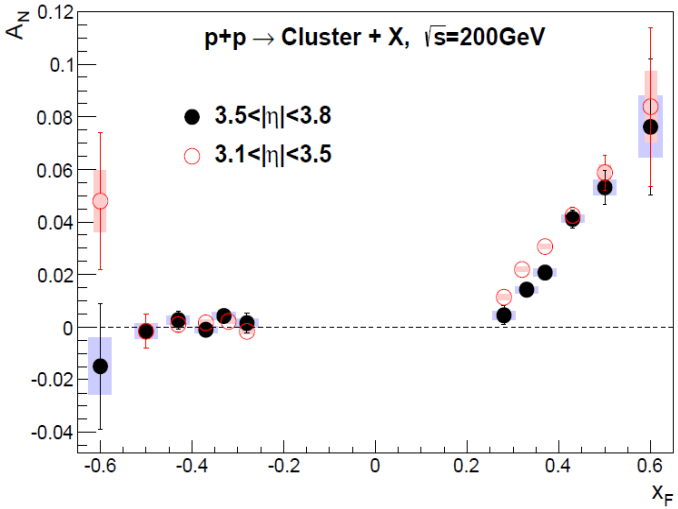


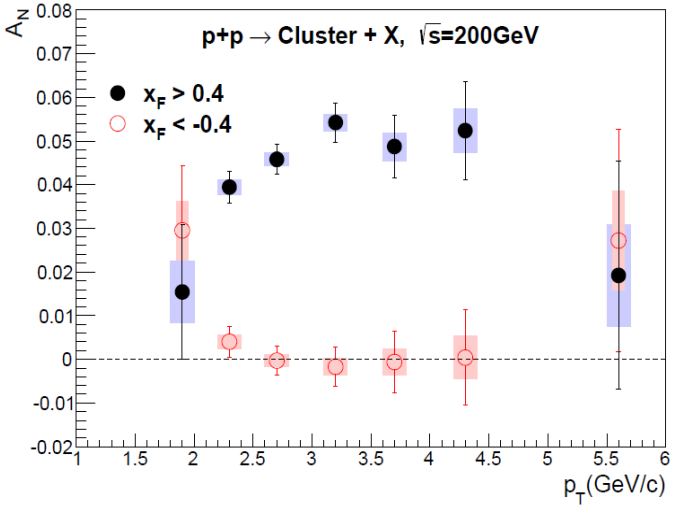


A_N measurements by MPC

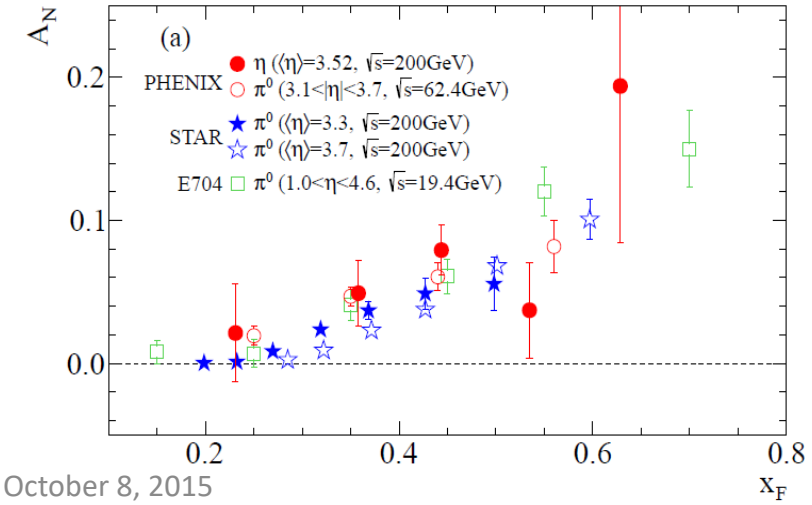
- Forward EM cluster by MPC at $\sqrt{s}$ = 200 GeV

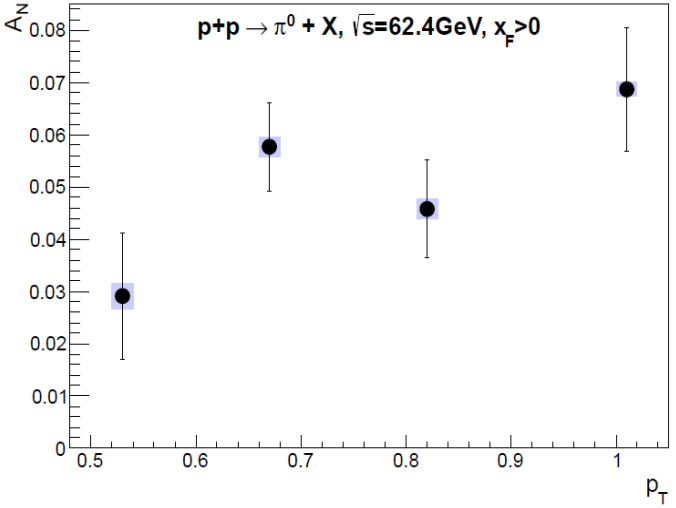
PRD90 (2014) 012006





- π^0 and η PRD90 (2014) 072008





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

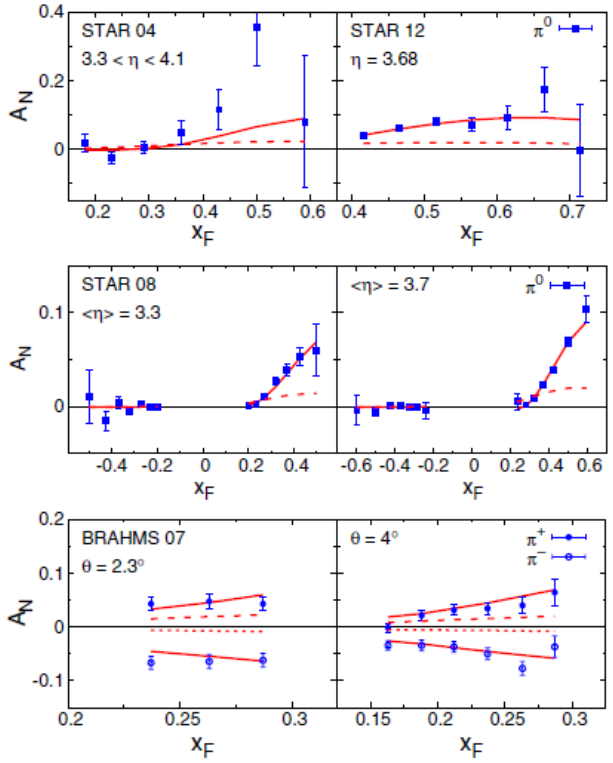


FIG. 1 (color online). Fit results for $A_N^{\pi^0}$ (data from [35–37]) and $A_N^{\pi^\pm}$ (data from [38]) for the SV1 input. The dashed line (dotted line in the case of π^-) means $\hat{H}_{FU}^{\Im}$ switched off.

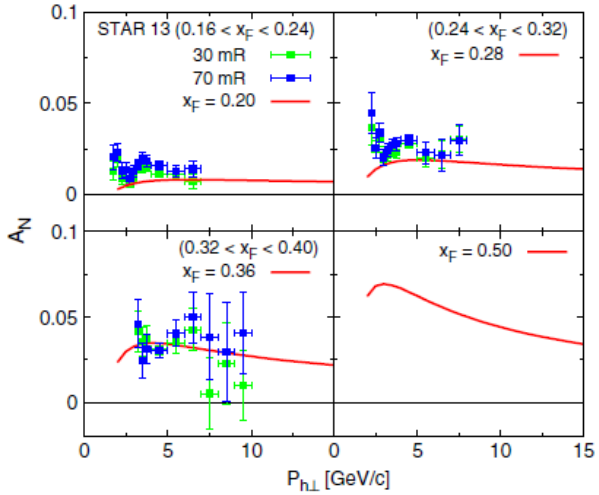


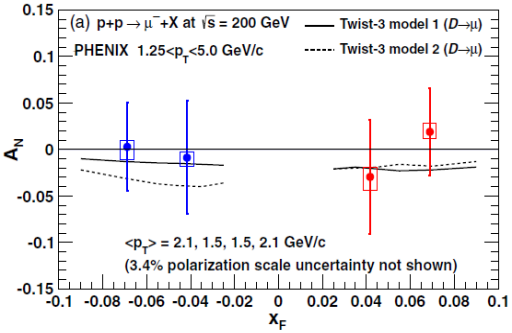
FIG. 4 (color online). A_N as function of $P_{h\perp}$ for SV1 input at $\sqrt{S} = 500$ GeV (data from [48]).

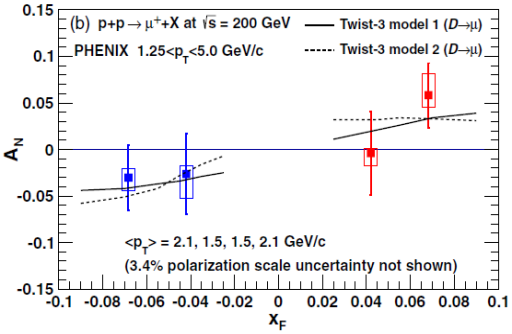
Kanazawa, Koike, Metz, Pitonyak
PRD 89, 111501 (2014).

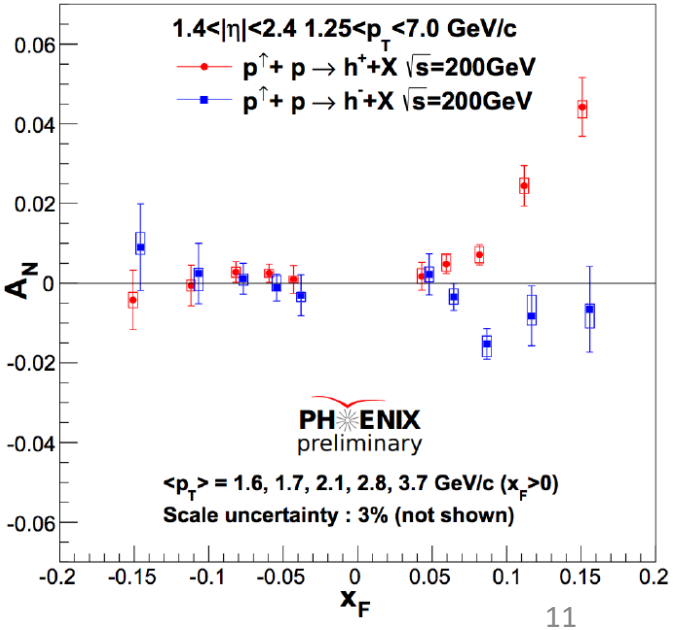
A_N measurements by muon arm

- Single muon
  - PRD95 (2017) 112001
  - Heavy flavor production
    - No final state effect from gluon-gluon process
    - Twist-3 tri-gluon correlation
- Single hadron
  - Preliminary result
- More studies with polarized-p + A collisions
  - Single hadron
  - J/ψ

PRD95 (2017) 112001

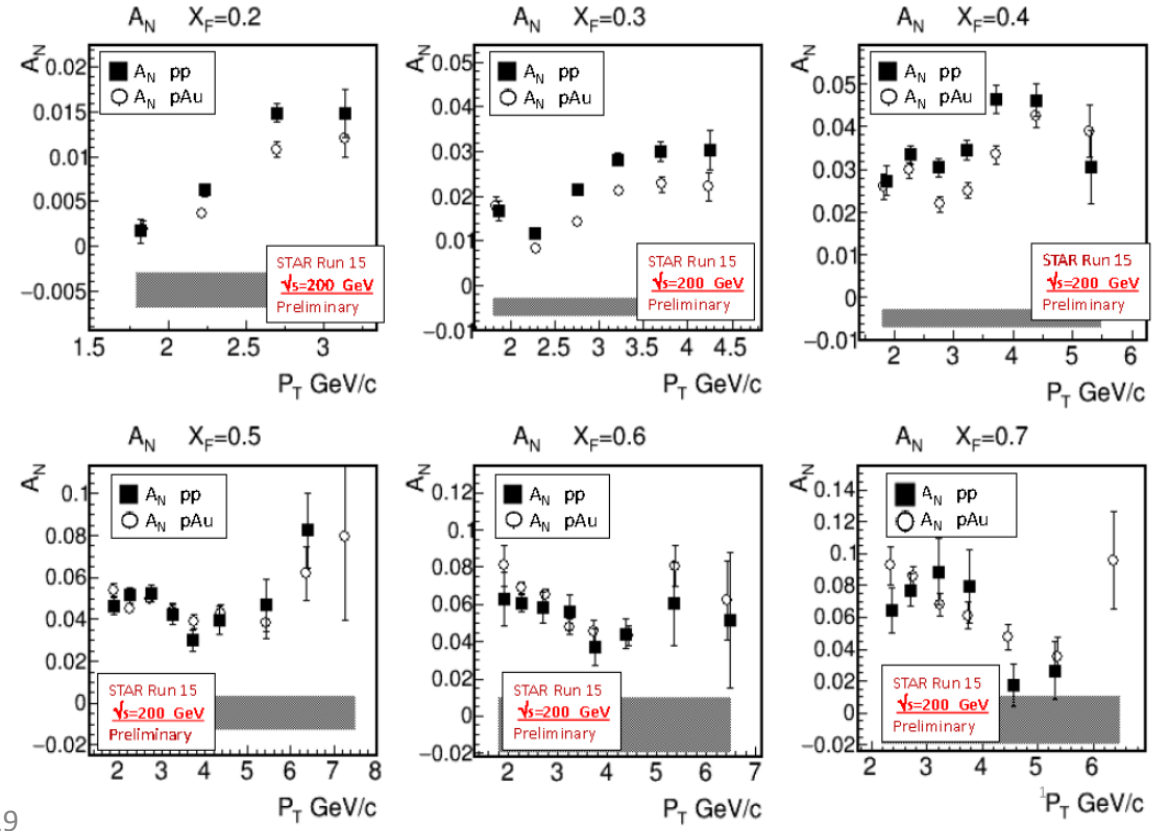






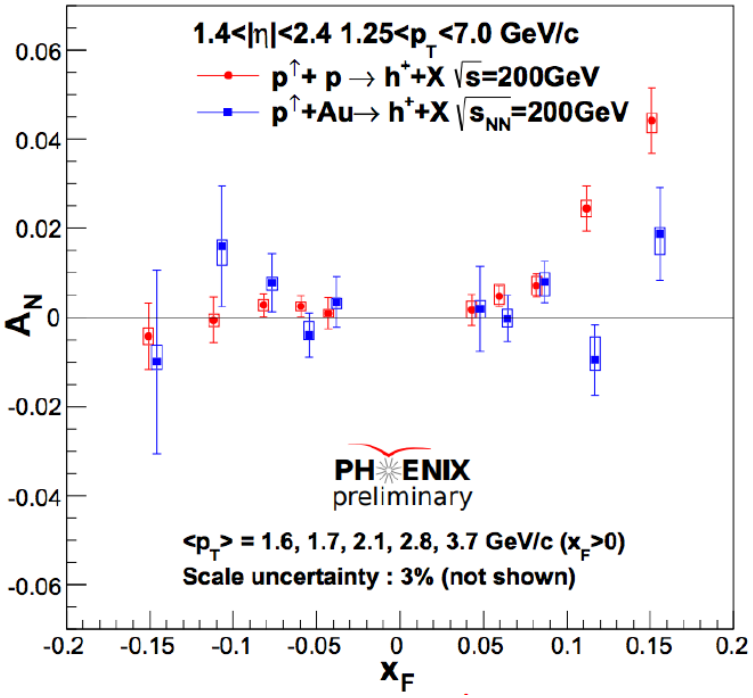
Polarized p+A collisions

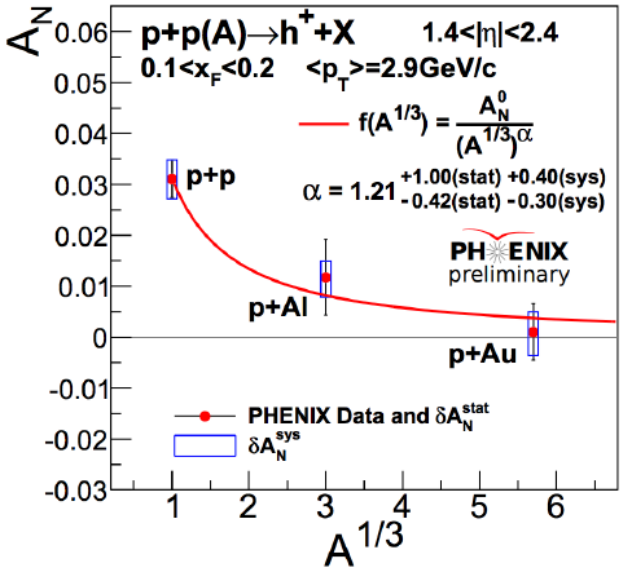
- STAR π^0 A_N at forward rapidities
  - $2.6 < \eta < 4$, $p_T > 1.5$ GeV/c, $0.2 < x_F < 0.7$
  - Prediction of reduced A_N in polarized p+A collisions due to the gluon saturation
  - No substantial reduction in 2015 STAR data
  - Origin of A_N unclear

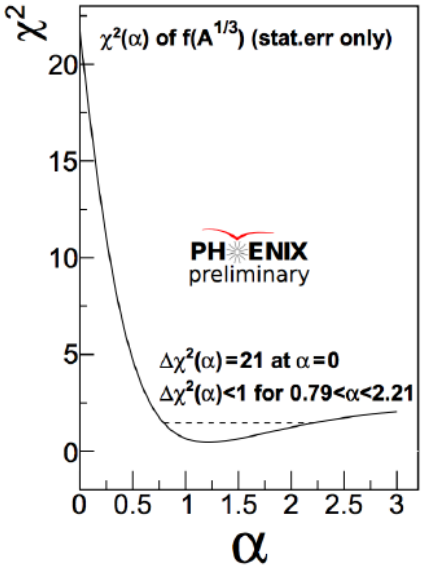


Polarized p+A collisions

- PHENIX forward hadron by muon arm
  - $1.4 < \eta < 2.4$, $1.8 < p_T < 7.0$ GeV/c, $0.1 < x_F < 0.2$
  - A dependence of the form $1/(A^{\frac{1}{3}})^{\alpha}$
  - Probe of underlying mechanisms of A_N
    - Gluon saturation, twist-3, hybrid, …
  - Importance of more detailed studies of A_N for various particle species in wide kinematic ranges



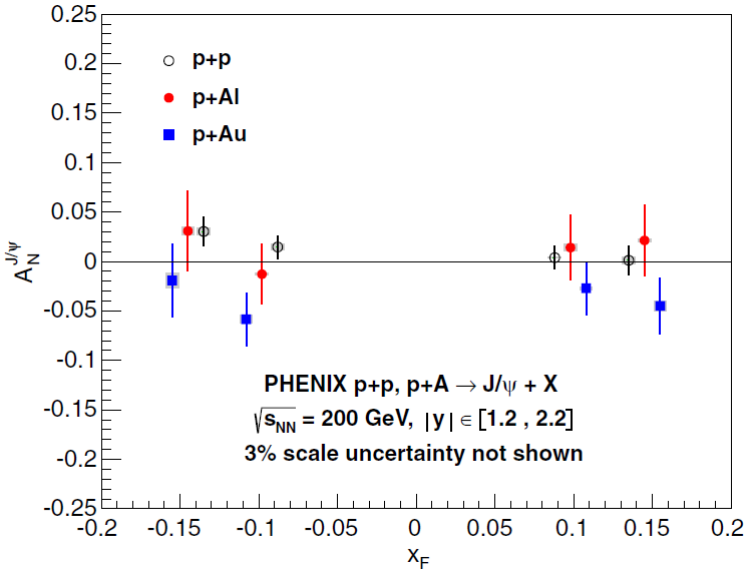


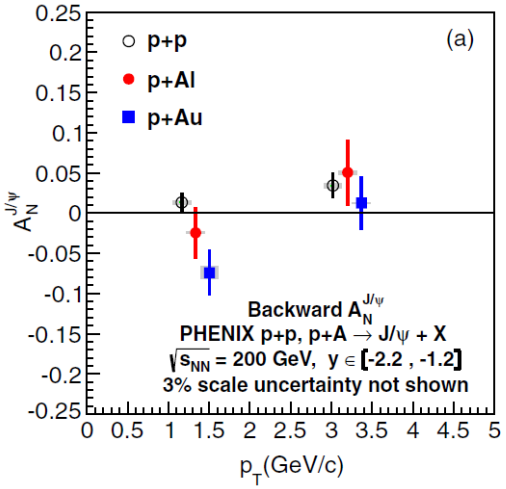


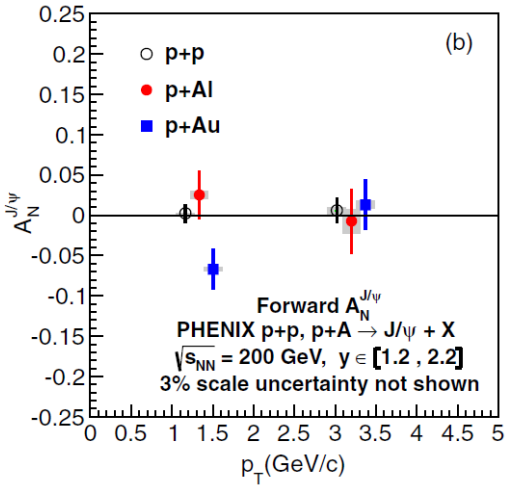
Polarized p+A collisions

- PHENIX forward J/ψ
  - PRD98 (2018) 012006
  - Negative A_N in p+Au at small p_T for both forward and backward rapidity
  - Nuclear environment creating non-zero asymmetries

PRD98 (2018) 112006



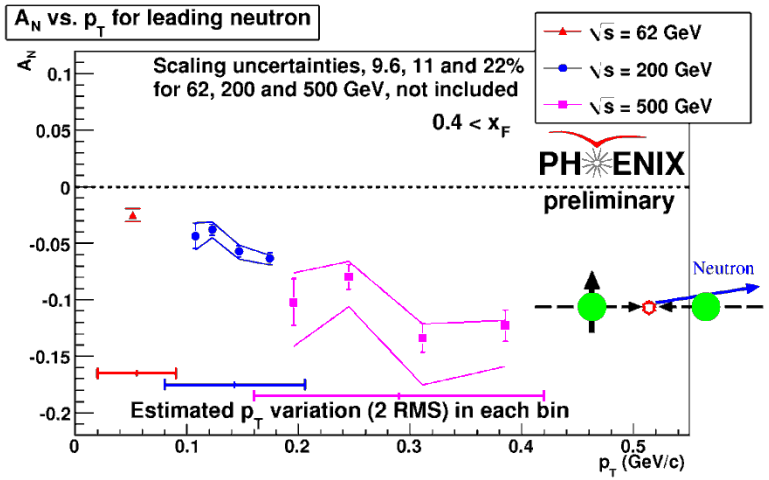




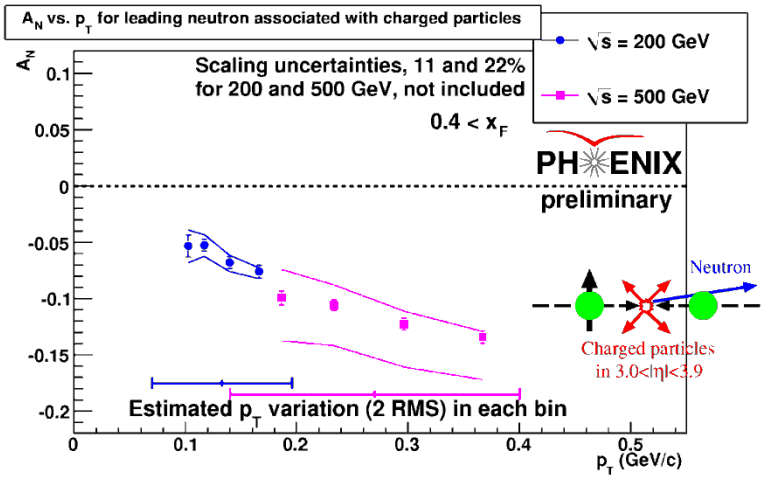
Very forward neutron asymmetry

- Very large left-right asymmetry (A_N) of very forward neutron discovered at RHIC
  - A_N(62 GeV) < A_N(200 GeV) < A_N(500 GeV)
  - $\sqrt{s}$ dependence or p_T dependence?
- Interference of pion exchange and other Reggeon exchange?
  - Kopeliovich, Potashnikova, Schmidt, Soffer: PRD84, 114012 (2011)

Inclusive neutron



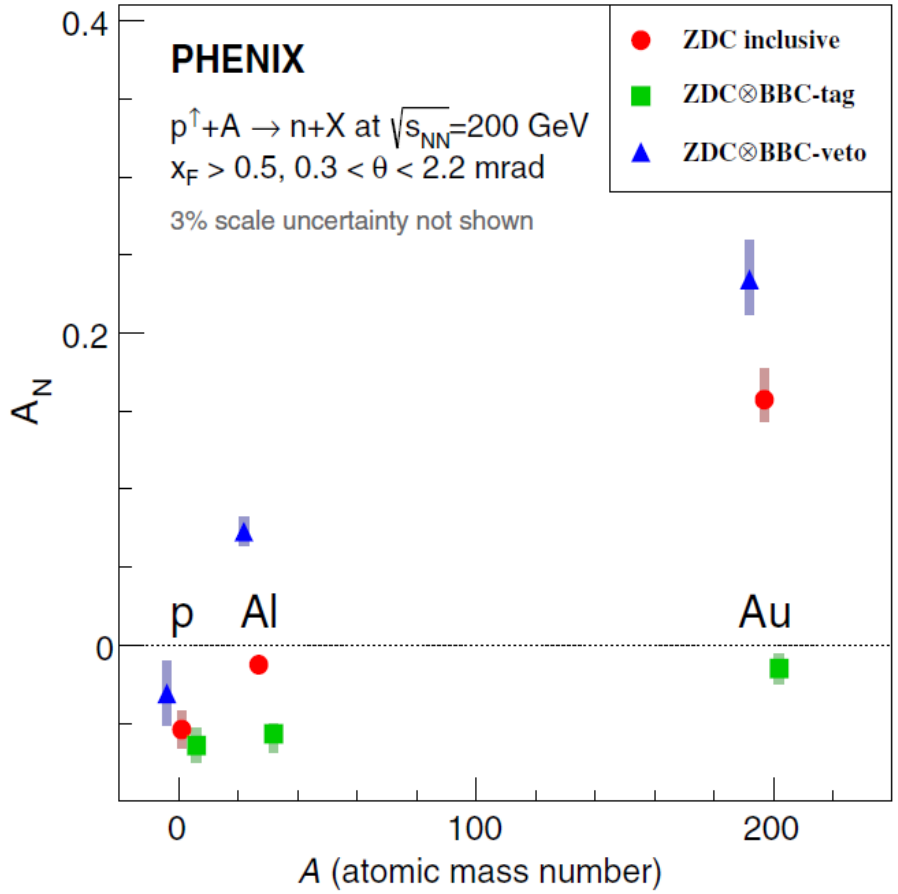
Neutron with charged particles



Polarized p+A collisions

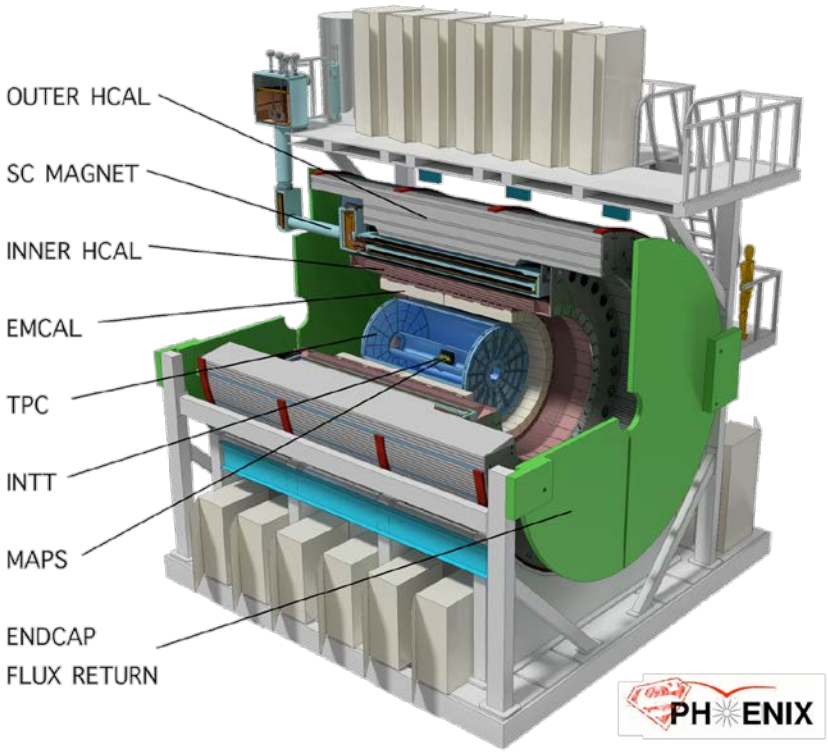
- Very forward neutron A_N
  - Unexpectedly large A dependence and sign change
  - Possible explanation with ultra-peripheral collisions (UPC)

PRL120 (2018) 022001

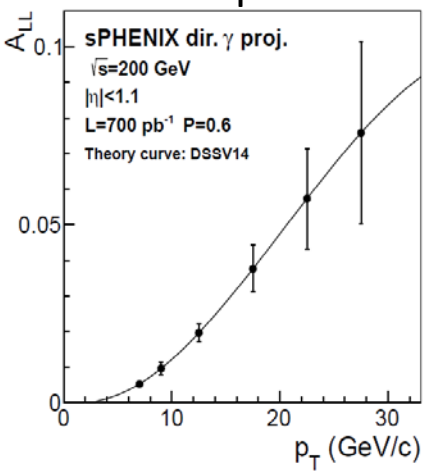


sPHENIX experiment

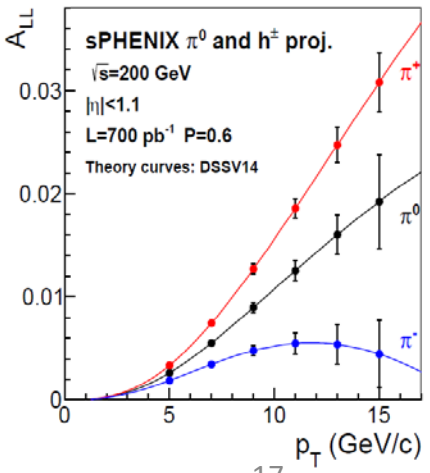
- Large-acceptance jet and upsilon detector around the BaBar superconducting solenoid
  - $|\eta| < 1.1$ and $0 < \phi < 2\pi$
  - EM & hadron calorimeters
  - TPC
  - Silicon detectors (MAPS)
- Construction schedule for 2023 sPHENIX run
- Gluon polarization measurement
  - > 100 times of the final statistics of PHENIX at $\sqrt{s}$ = 200 GeV polarized p+p
  - π^0, hadron, photon, jet, dijet, …



direct photon



π^0 and $h^{\pm}$



sPHENIX schedule

- 2024 $\sqrt{s}$ = 200 GeV polarized p+p & p+A collisions

Baseline 2023

2024

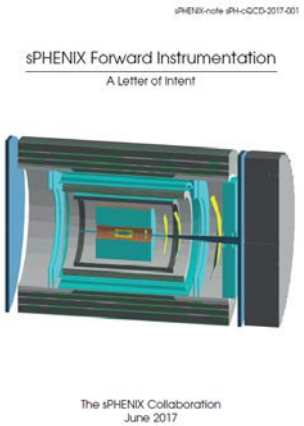
2025

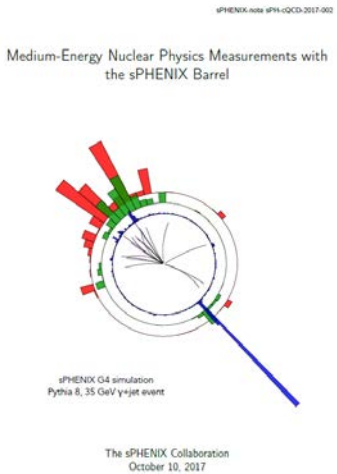
Extension depending on EIC construction

Year	Species	Energy [GeV]	Wks	Rec. L	Samp. L	Samp. L (all-z)
Year-1	Au+Au	200	16.0	7 nb^{-1}	8.7 nb^{-1}	34 nb^{-1}
Year-2	p+p	200	11.5	—	48 pb^{-1}	267 pb^{-1}
	p+Au	200	11.5	—	0.33 pb^{-1}	1.46 pb^{-1}
Year-3	Au+Au	200	23.5	14 nb^{-1}	26 nb^{-1}	88 nb^{-1}
Year-4	p+p	200	23.5	—	149 pb^{-1}	783 pb^{-1}
Year-5	Au+Au	200	23.5	14 nb^{-1}	48 nb^{-1}	92 nb^{-1}

Spin physics at sPHENIX

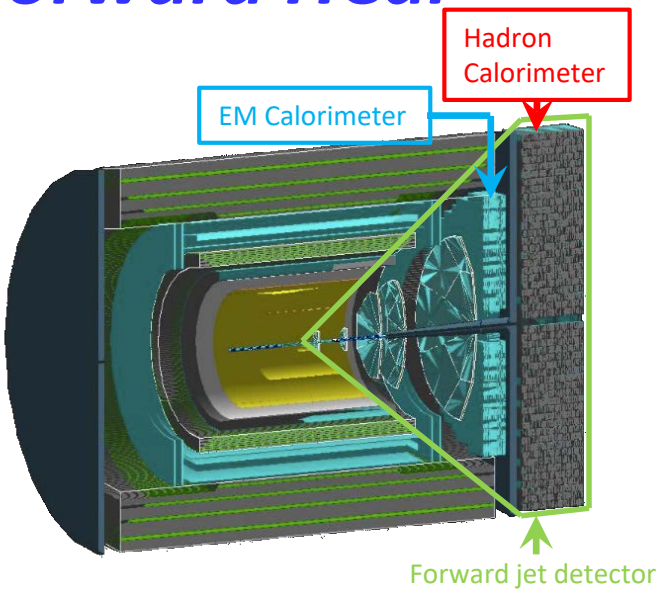
- sPHENIX Notes
- sPH-cQCD-2017-001
  - sPHENIX Forward Instrumentation, A Letter of Intent
  - Presented at BNL NPP 2017 PAC Meeting, June 2017
  - https://indico.bnl.gov/conferenceDisplay.py?confId=3125
  - Transverse polarization phenomena with jet + hadrons
- sPH-cQCD-2017-002
  - Medium-Energy Nuclear Physics Measurements Utilizing the sPHENIX Barrel Detector
  - Submitted to ALD in August, 2017
  - Presented at DOE site visit, September 2017
  - https://indico.bnl.gov/conferenceDisplay.py?confId=3403
  - ΔG & transversity measurements
- No output / progress yet

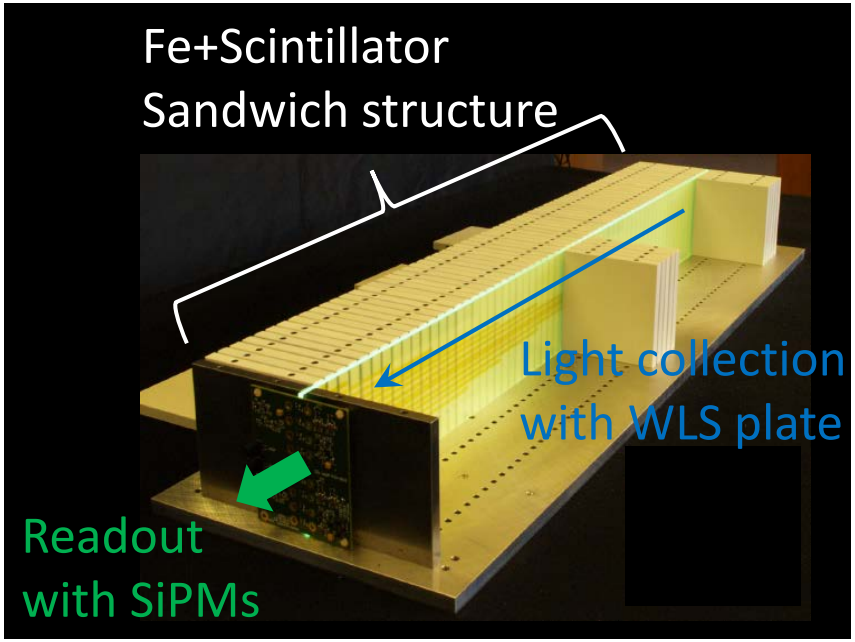




Forward sPHENIX & forward HCal

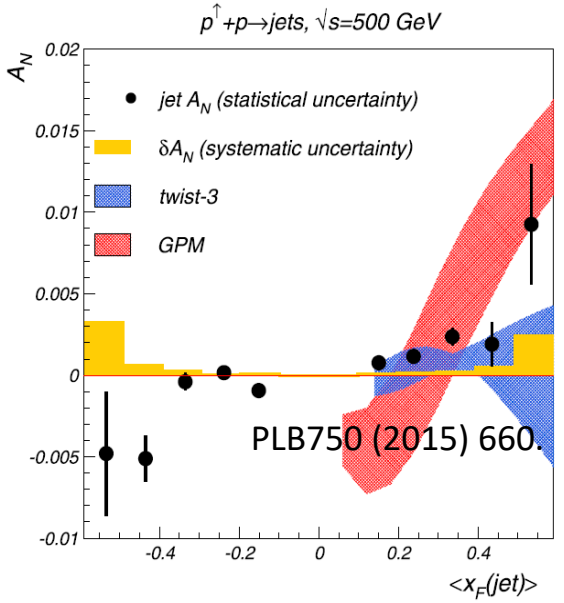
- fsPHENIX
  - $1.4 < \eta < 4$
  - EM calorimeter
  - Hadron calorimeter (fHCal)
  - Trackers
    - GEM / sTGC
    - Silicon detector
  - Magnetic field shaper
  - Within 4.5 m eRHIC IR constraint
- fHCal
  - Collaboration with Oleg Tsai and STAR/UCLA group
  - 10cm x 10cm x 81cm tower
  - 4 interaction length
  - Fe + scintillator sandwich
  - WLS light collection
  - SiPM readout

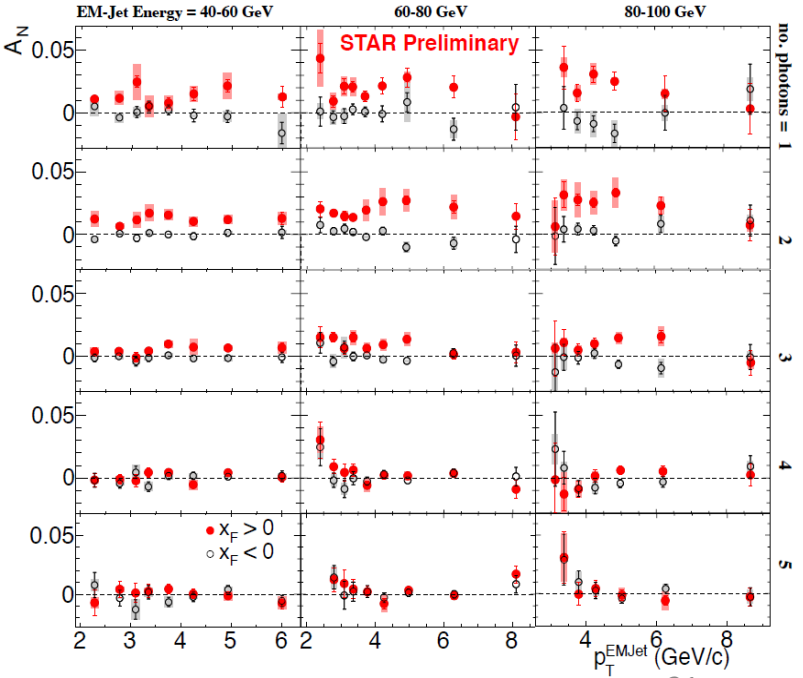




Transverse polarization phenomena

- New questions
- A_NDY jet asymmetry
  - Small A_N of forward jet production comparing with that of forward hadron production
  - Mixture (cancellation) of u-quark jet and d-quark jet, or other non-perturbative effects?
- STAR multiplicity dependence
  - A_N for different number of photons
  - A_N decreases as the event complexity increases (more jet-like)
  - How much of the large π^0 A_N comes from hard scattering?





Spin physics at fsPHENIX

- Transverse polarization phenomena with jet + hadrons
- Jet asymmetries tagging positive/negative hadrons
  - Flavor dependence of the twist-3 distribution
  - Evolution of the twist-3 distribution function
- EM + Hadron calorimeters & tracker are necessary
  - For jet + hadron measurement & triggering

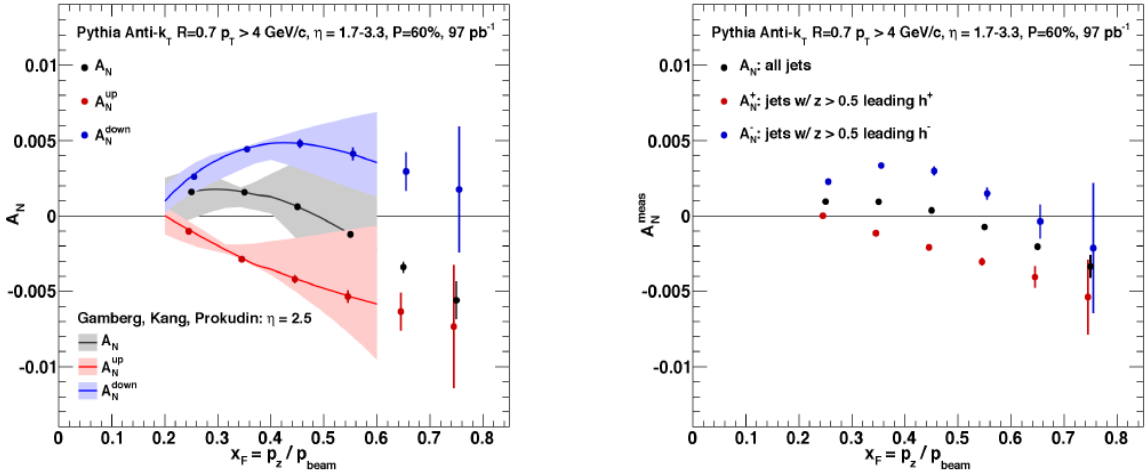


Figure 2-11: Left: up quark (red points), down quark (blue points) and all jet (black points) single spin asymmetries as a function of x_f as calculated by the ETQS based on the SIDIS Sivers functions. Right: Expected experimental sensitivities for jet asymmetries tagging in addition a positive hadron with z above 0.5 (red points), a negative hadron with z above 0.5 (blue points) or all jets (black) as a function of x_f. Note: these figures are currently for 200 GeV center-of-mass energy proton collisions – the 500 GeV results are expected to be qualitatively similar but with reduced uncertainties due to the larger luminosities expected.

Spin physics at fsPHENIX

- Hadron angular distribution in jets
  - Transversity & Collins function

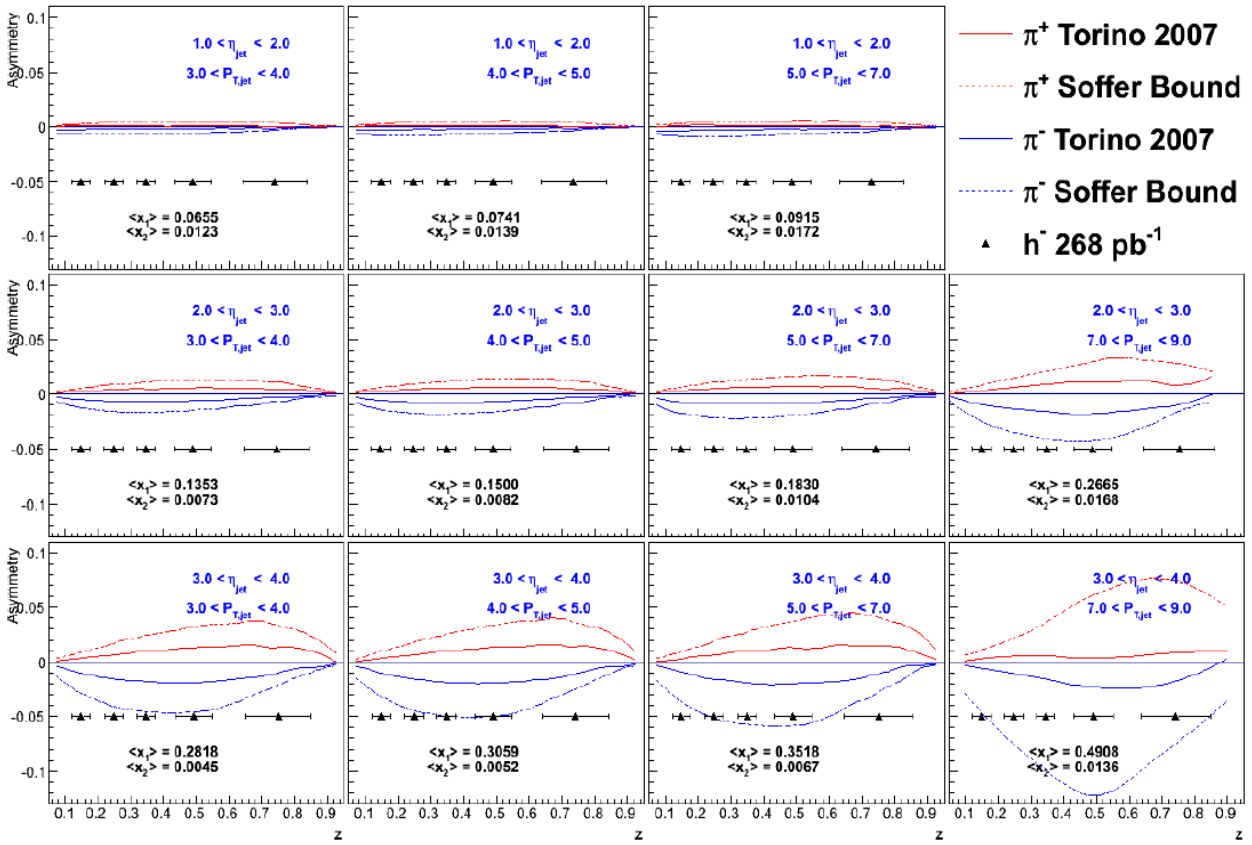


Figure 2-14: Expected h^- Collins asymmetry uncertainties (black points) compared to positive (red) and negative (blue) pion asymmetries based on the Torino extraction [45] (full lines) and the Soffer bound [83] (dashed lines) as a function of fractional energy z for various bins in jet rapidity and transverse momentum.

Expected h^- Collins asymmetry uncertainties

Forward HCal R&D

- Prototype & test bench at RIKEN
  - Still under consideration…
  - SiPM readout development & test
    - SiPM $\rightarrow$ preamp $\rightarrow$ digitizer $\rightarrow$ DAQ
    - Understanding dark noise, cross talk, after pulse
  - Non-uniformity
    - With LED, source, cosmic
  - Radiation damage
    - With neutron source?
    - SiPM performance, leakage current
  - Development of calibration system
    - LED, temperature
- More MC work
  - Light collection & compensation
- Test beam with STAR in April

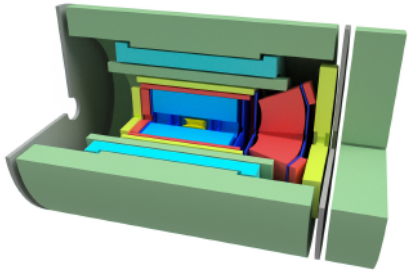
EIC-sPHENIX detector

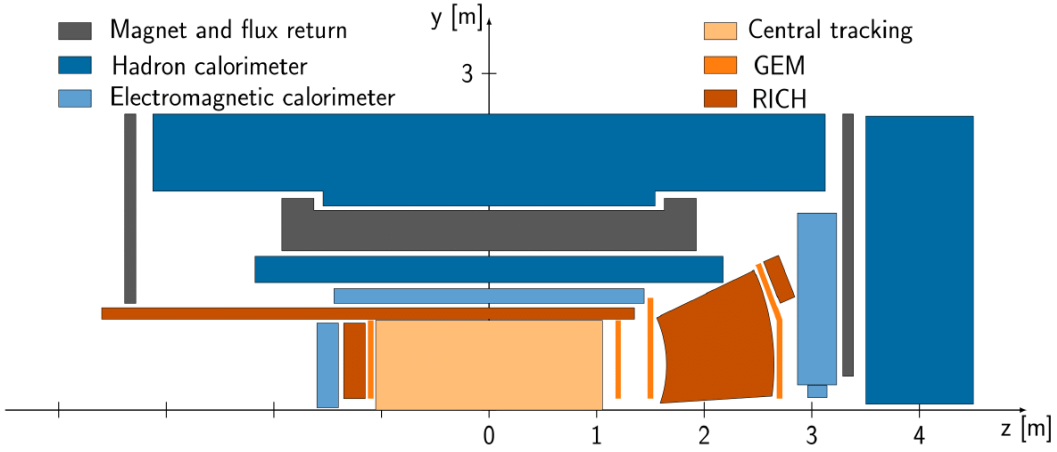
- sPH-cQCD-2018-001
  - An EIC Detector Built Around the sPHENIX Solenoid
  - https://indico.bnl.gov/event/5283
- EIC-sPHENIX detector
  - Design study ongoing

sPHENIX-note sPH-cQCD-2018-001

An EIC Detector Built Around The sPHENIX Solenoid

A Detector Design Study





Christine Aidala, Alexander Bazilevsky, Giorgian Borca-Tasciuc, Nils Feege, Enrique Gamez, Yuji Goto, Xiaochun He, Jin Huang, Athira K V, John Lajoie, Gregory Matousek, Kara Mattioli, Pawel Nadel-Turonski, Cynthia Nunez, Joseph Osborn, Carlos Perez, Ralf Seidl, Desmond Shangase, Paul Stankus, Xu Sun, Jinlong Zhang

For the EIC Detector Study Group and the sPHENIX Collaboration

October 2018

Detector development

- Collaboration with people having common interest in position-sensitive calorimeter
  - Tsukuba Univ. ALICE FoCal
  - Kobe Univ. LHeC (/EIC) ZDC
    - Radiation-hard scintillator
  - Nagoya Univ. RHICf / LHCf
- Possible proposal for EIC R&D program for very forward measurements
  - “Generic Detector R&D for an Electron Ion Collider” operated by BNL
  - Radiation tolerance / position-sensitive calorimeter / EIC IR design (ZDC + spectrometer)

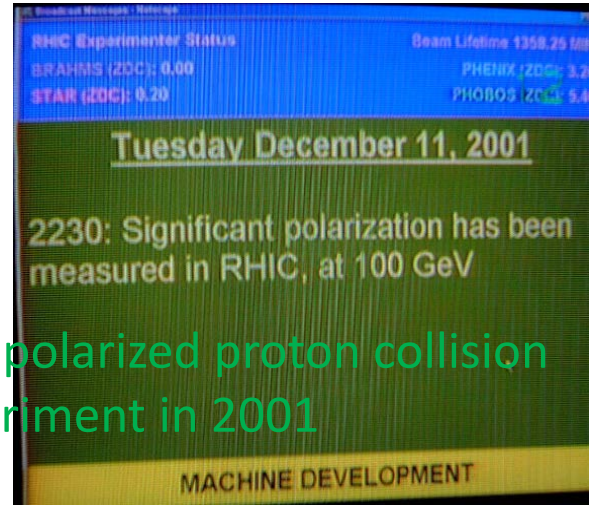
Summary

- Forward spin physics
  - Transverse polarization phenomena
  - Orbital motion inside the nucleon
- Forward spin physics at PHENIX
  - EM cluster, π^0 and η by MPC
  - Heavy flavors and hadrons by muon arm
  - More studies with polarized p+A collisions
- Forward spin physics at sPHENIX
  - Jet + hadrons
  - Jet asymmetries tagging hadrons
  - Hadron angular asymmetries in jets
- Forward calorimeter R&D
  - Forward HCal for sPHENIX & EIC-sPHENIX
  - Forward position-sensitive calorimeter

Backup Slides

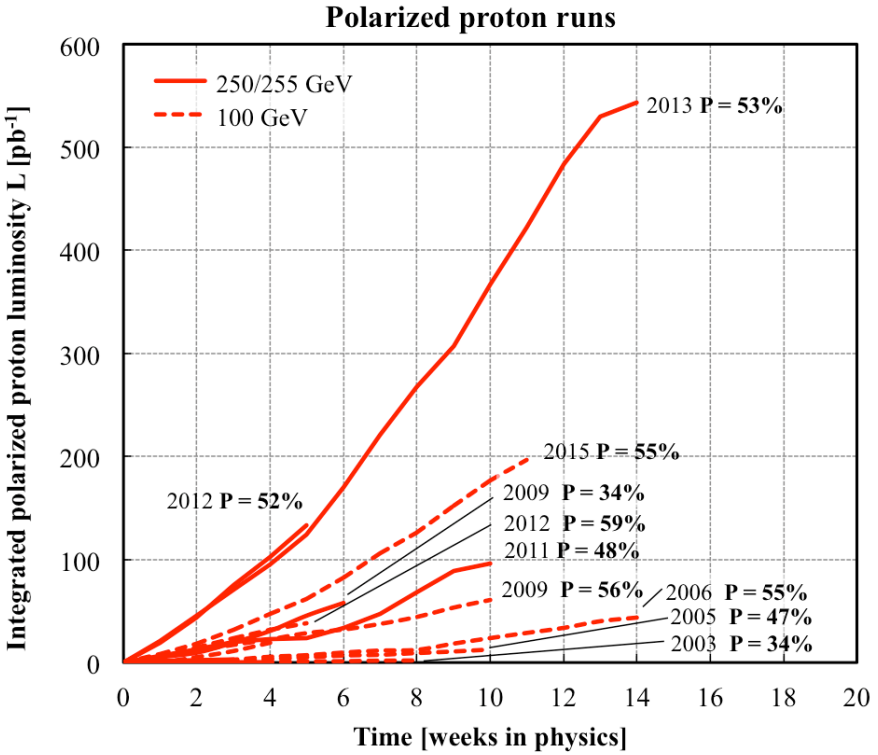
Polarized proton collision

- $\sqrt{s}$ = 200 GeV
  - Average luminosity 6.3×10^{31} $cm^{-2}s^{-1}$
  - Polarization 55%
- $\sqrt{s}$ = 510 GeV
  - Average luminosity 1.6×10^{32} $cm^{-2}s^{-1}$
  - Polarization 52%

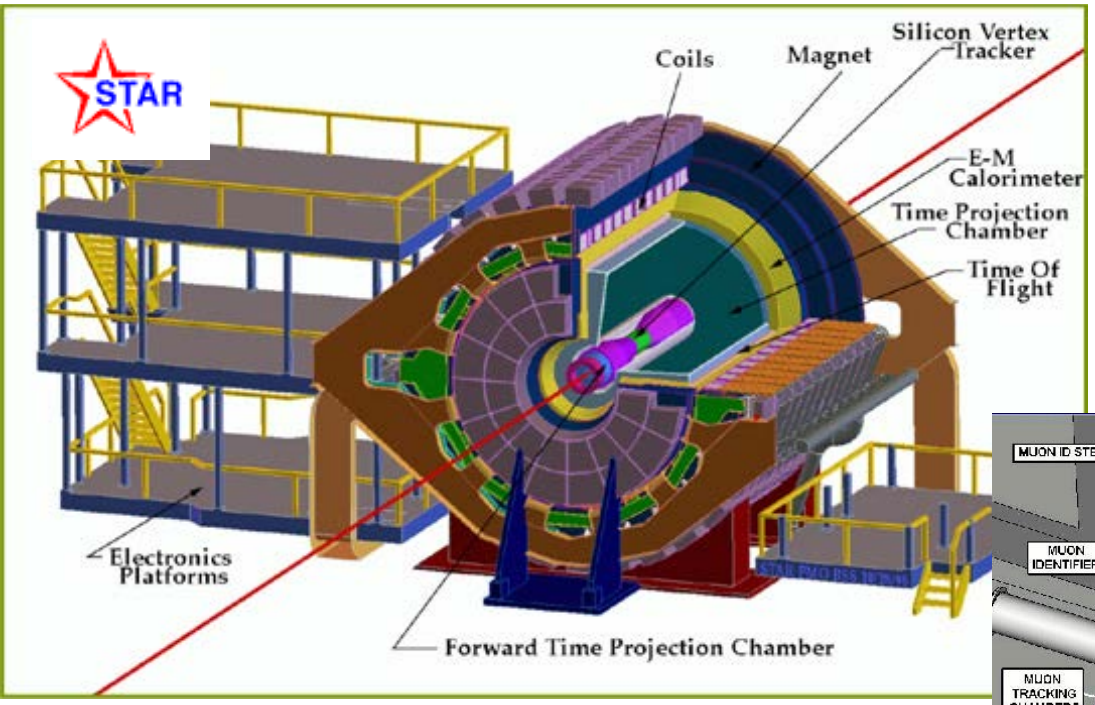


First polarized proton collision experiment in 2001

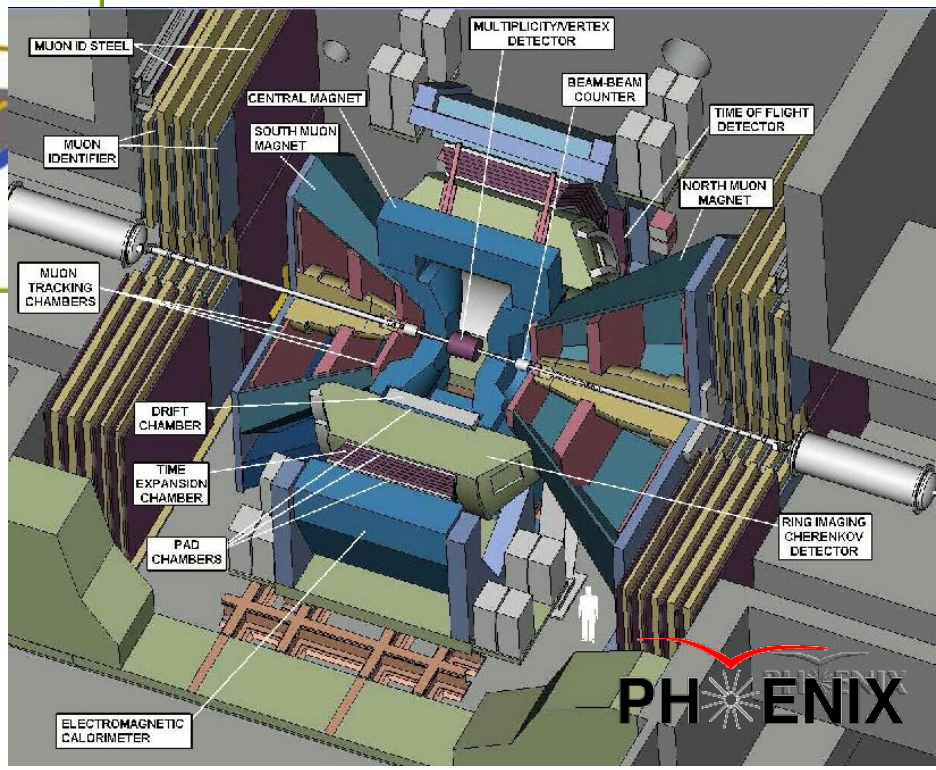
Year	$\sqrt{s}$ (GeV)	Recorded Luminosity for longitudinally / transverse polarized p+p STAR	Recorded Luminosity for longitudinally / transverse polarized p+p PHENIX	<P> in %
2006	62.4	-- pb^{-1} / 0.2 pb^{-1}	0.08 pb^{-1} / 0.02 pb^{-1}	48
	200	6.8 pb^{-1} / 8.5 pb^{-1}	7.5 pb^{-1} / 2.7 pb^{-1}	57
2008	200	-- pb^{-1} / 7.8 pb^{-1}	-- pb^{-1} / 5.2 pb^{-1}	45
2009	200	25 pb^{-1} / -- pb^{-1}	16 pb^{-1} / -- pb^{-1}	55
	500	10 pb^{-1} / -- pb^{-1}	14 pb^{-1} / -- pb^{-1}	39
2011	500	12 pb^{-1} / 25 pb^{-1}	18 pb^{-1} / -- pb^{-1}	48
2012	200	-- pb^{-1} / 22 pb^{-1}	-- pb^{-1} / 9.7 pb^{-1}	61/56
	510	82 pb^{-1} / -- pb^{-1}	32 pb^{-1} / -- pb^{-1}	50/53
2013	510	300 pb^{-1} / -- pb^{-1}	155 pb^{-1}/ -- pb^{-1}	51/52
2015	200	52 pb^{-1} / 52 pb^{-1}	-- pb^{-1}/ 60 pb^{-1}	53/57



Polarized proton collision experiments



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

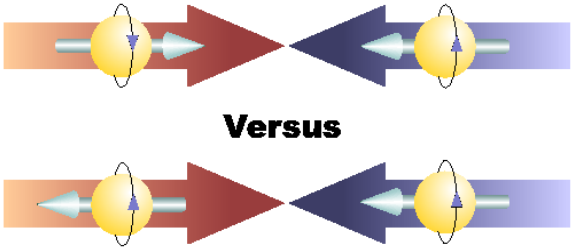


- PHENIX detector
  - limited acceptance
  - high resolution central EMCal
  - high-rate trigger and DAQ
  - forward muon detectors

Longitudinal polarized proton collision

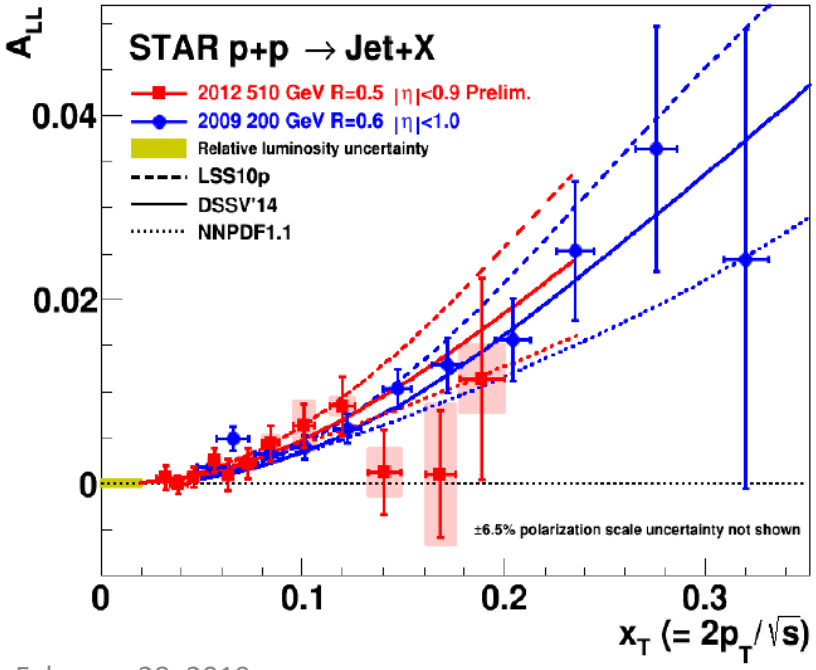
- A_{LL} (double-helicity asymmetry) measurement
  - Polarized in the beam axis direction

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

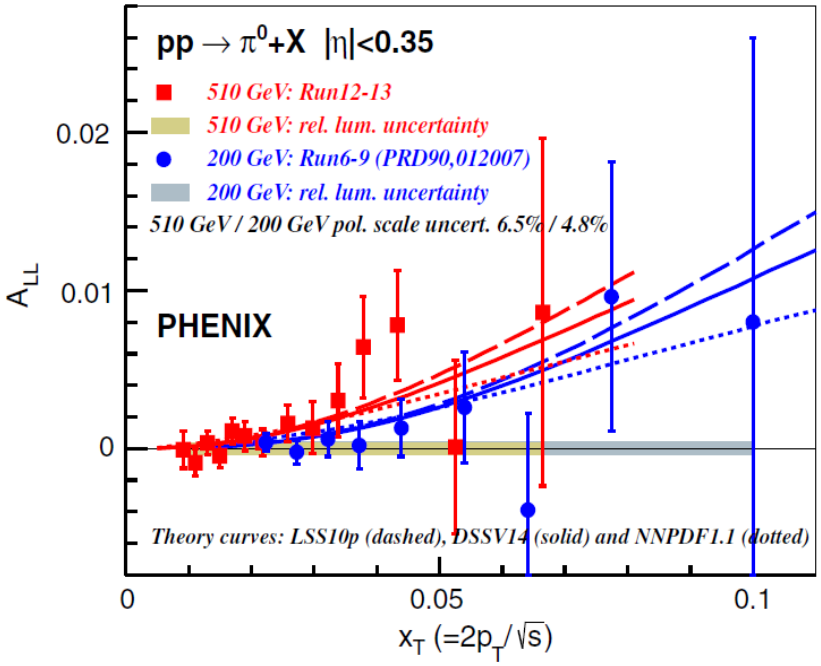


- Gluon polarization
  - A_{LL} measurement for gluon+gluon and gluon+quark reactions

Midrapidity jet at STAR



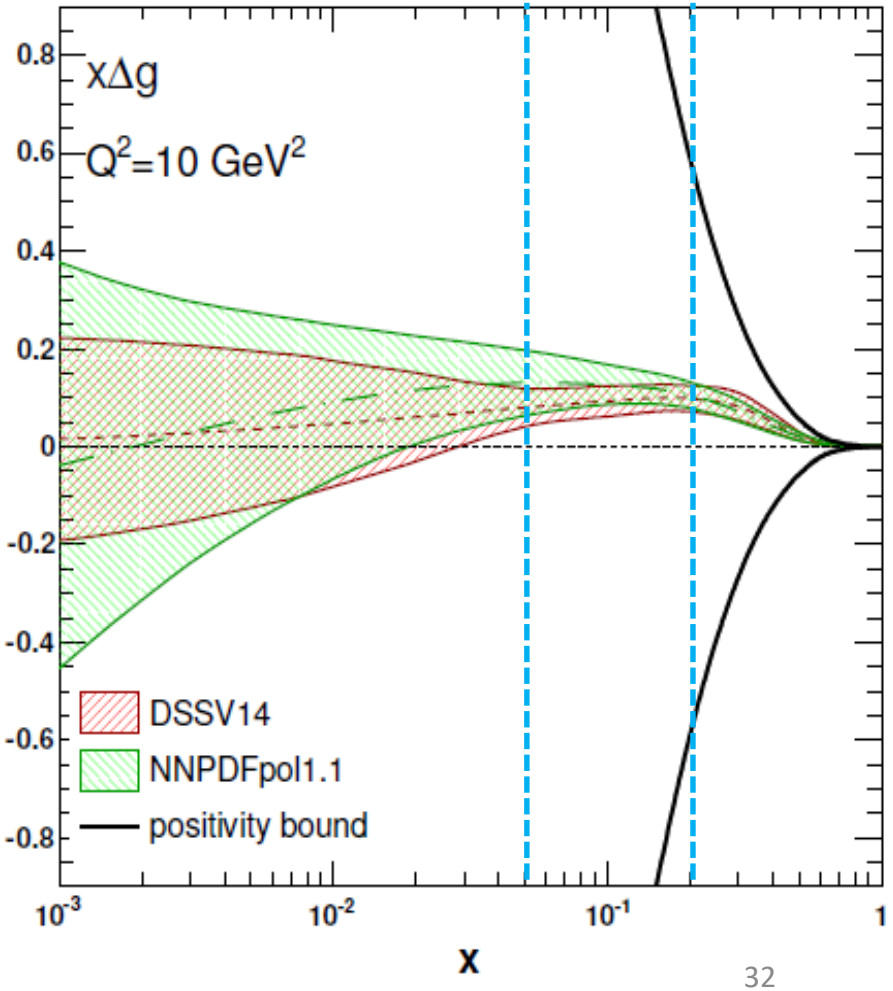
Midrapidity π^0 at PHENIX



Gluon polarization

- Positive gluon polarization obtained by DSSV and NNPDF groups with the QCD global analysis including polarized proton collision data at RHIC
  - 2014 press releases
  - 200 GeV collision data at RHIC
  - Jet asymmetry from STAR
  - π^0 asymmetry from PHENIX

arXiv:1503.03518

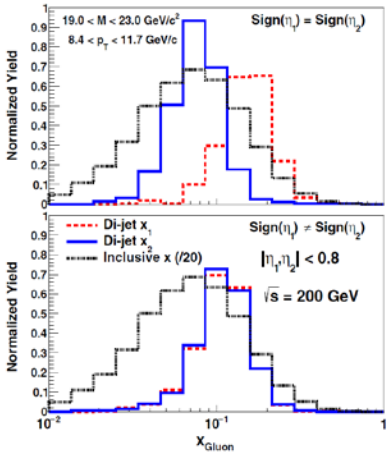


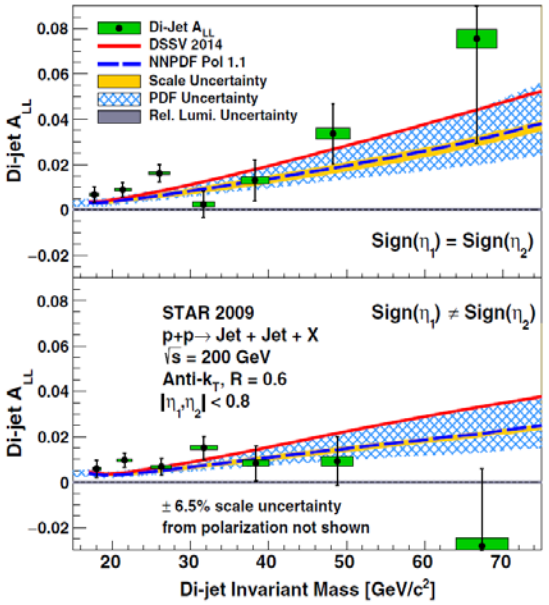
$Q^2 = 10$ GeV^2	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$

STAR dijet at $\sqrt{s}$ = 200 GeV

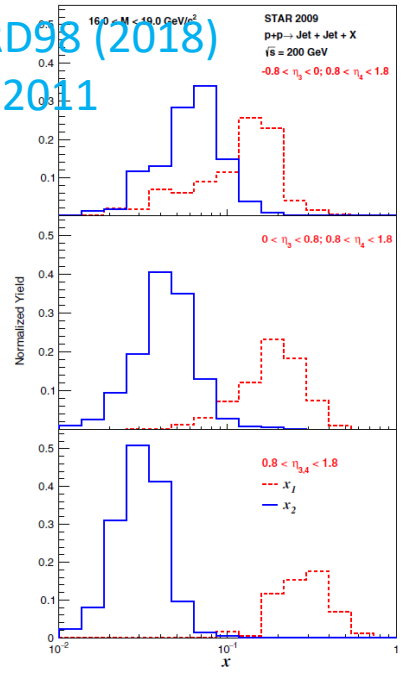
- Dijet
  - Information about x_1 and x_2
  - x-dependence (shape) of the gluon polarization
- Midrapidity dijet
  - PRD95 (2017) 071103(R)
- Forward-rapidity dijet
  - PRD98 (2018) 032011
- More forward access to lower x, down to 0.01

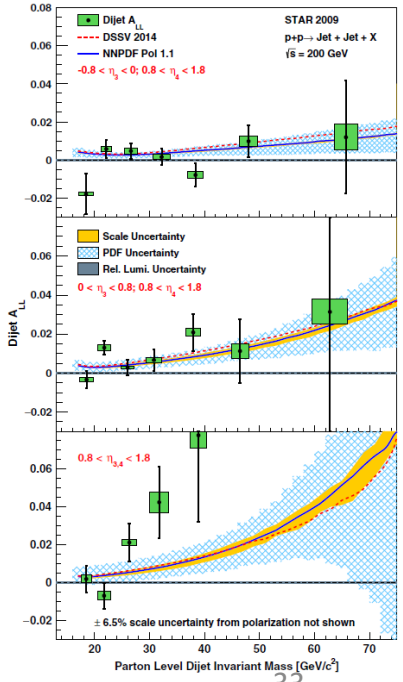
PRD95 (2017) 071103(R)





PRD98 (2018) 032011

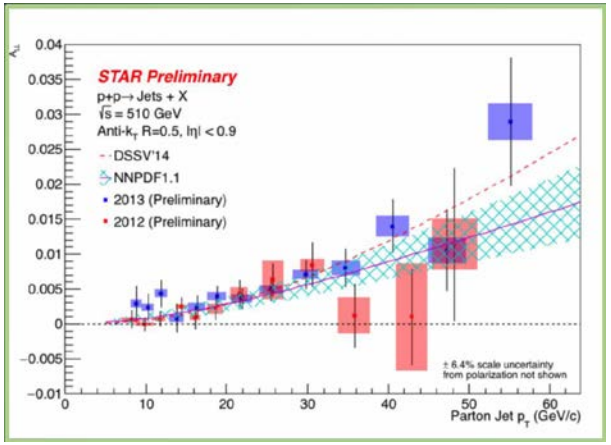


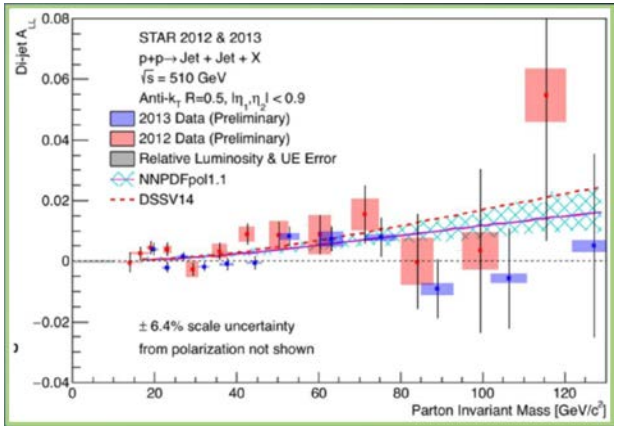


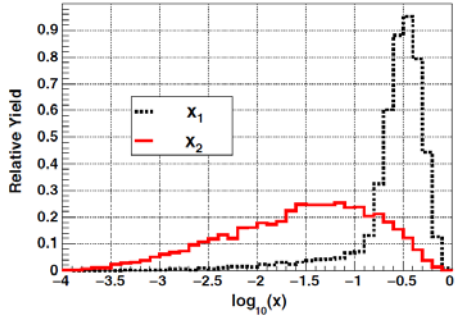
STAR at $\sqrt{s}$ = 510 GeV

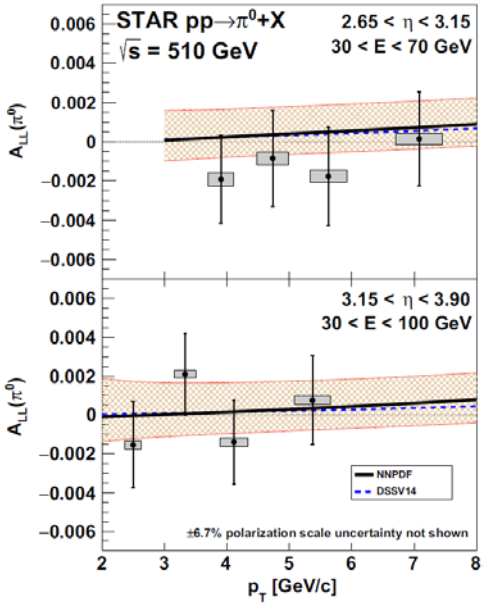
- Higher center of mass energy access lower *x*
- Midrapidity inclusive & dijet
  - Preliminary
- Forward-rapidity π^0
  - PRD98 (2018) 032013

PRD98 (2018) 032013





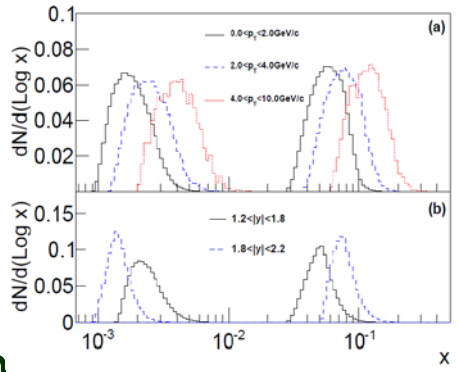


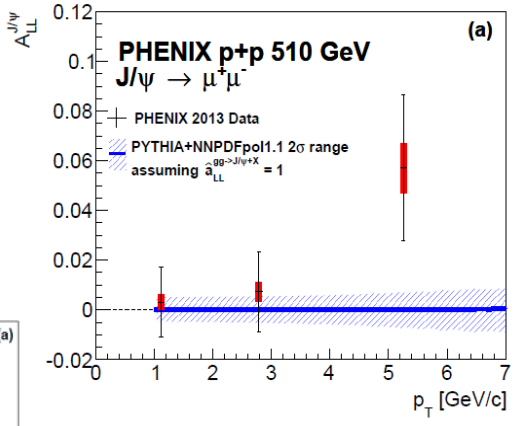


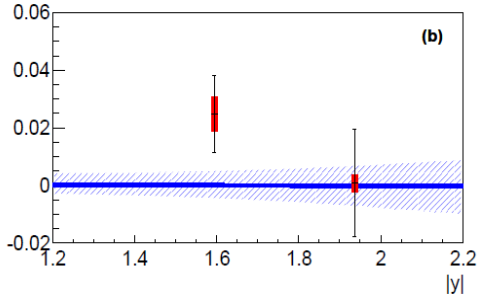
PHENIX at $\sqrt{s}$ = 510 GeV

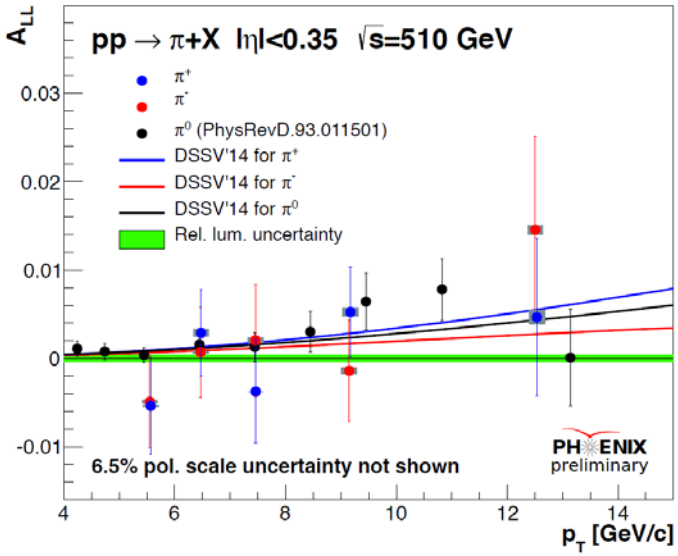
- Forward J/ψ
  - PRD94 (2016) 112008
  - Gluons from two distinct ranges of *x*
    - *x*~0.05 & *x*~0.002
- Midrapidity $\pi^{\pm}$
  - Preliminary
  - Check the sign of the gluon polarization

PRD94 (2016) 112008





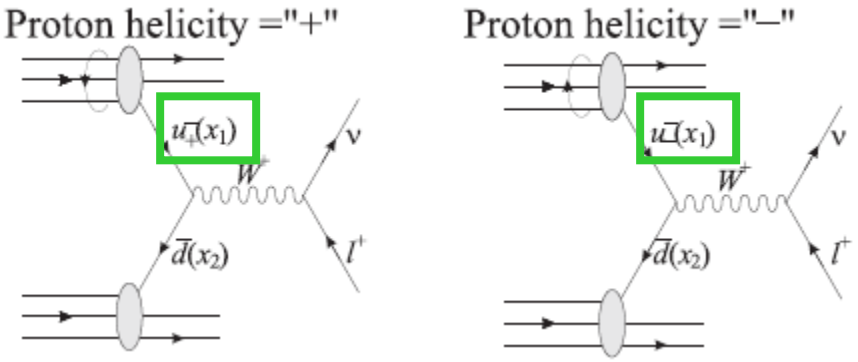




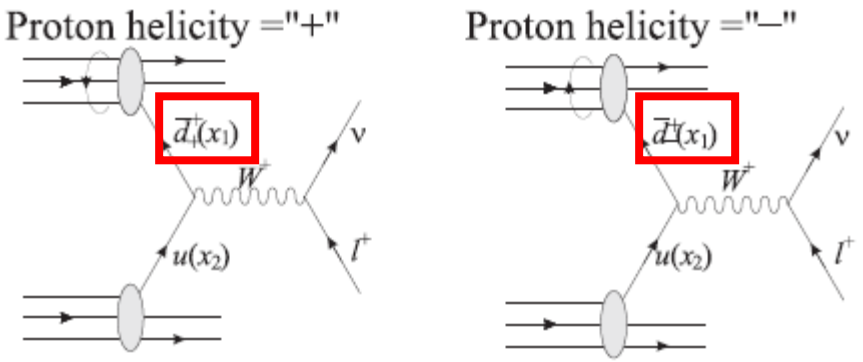
Anti-quark polarization

- Parity-violating A_L measurement with W-boson production

Forward rapidity



Backward rapidity



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

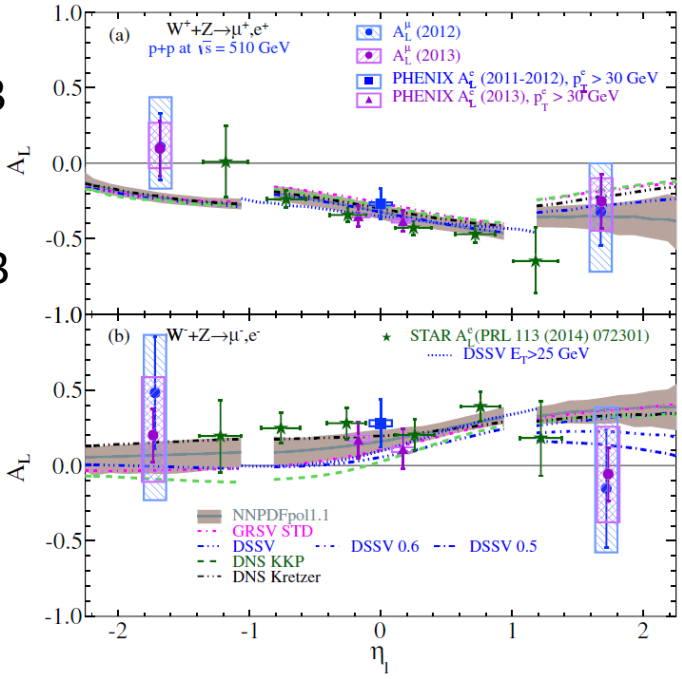
$$A_L^{W^+} = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta \bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)}$$

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

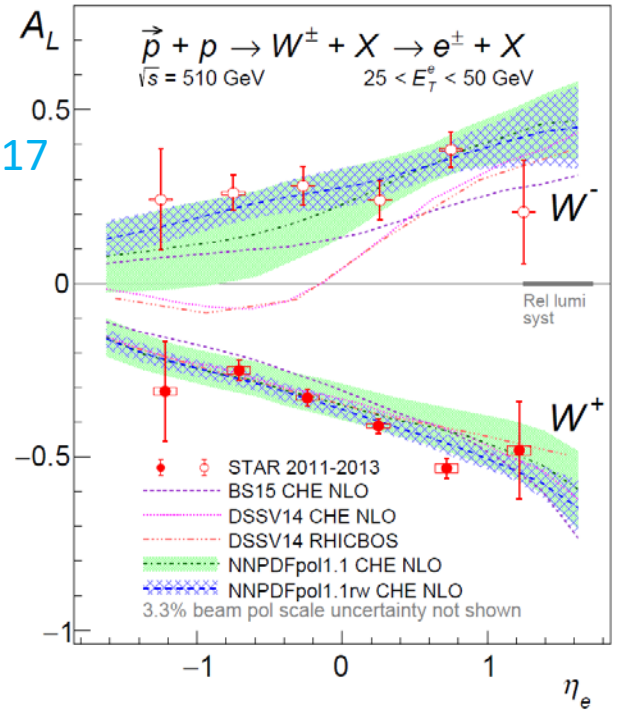
Anti-quark polarization

- 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
W→e 2011-13
PRD93 (2016) 051103
W→μ 2012-13
PRD98 (2018) 032007

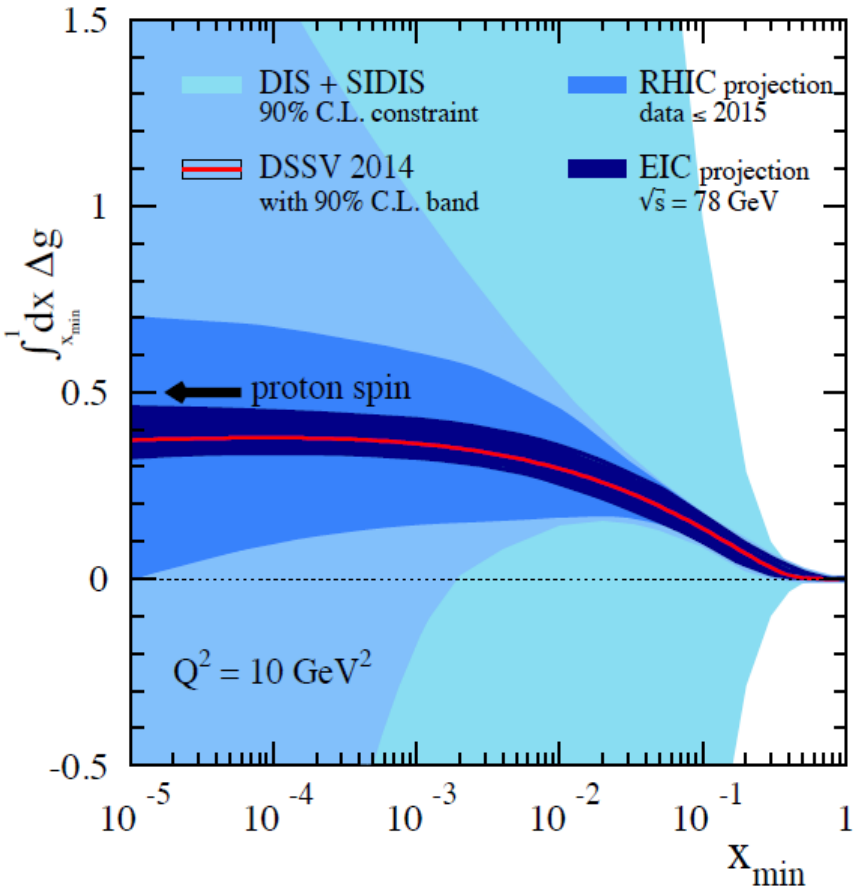


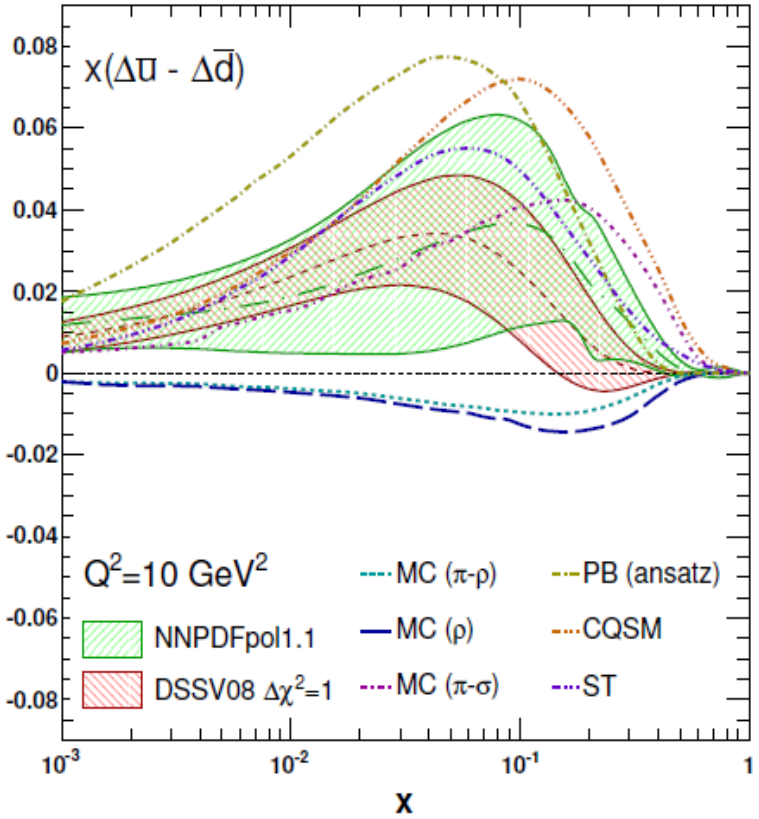
STAR
W→e 2011-13
arXiv:1812.04817



Impact of RHIC data

- Gluon & anti-quark polarization

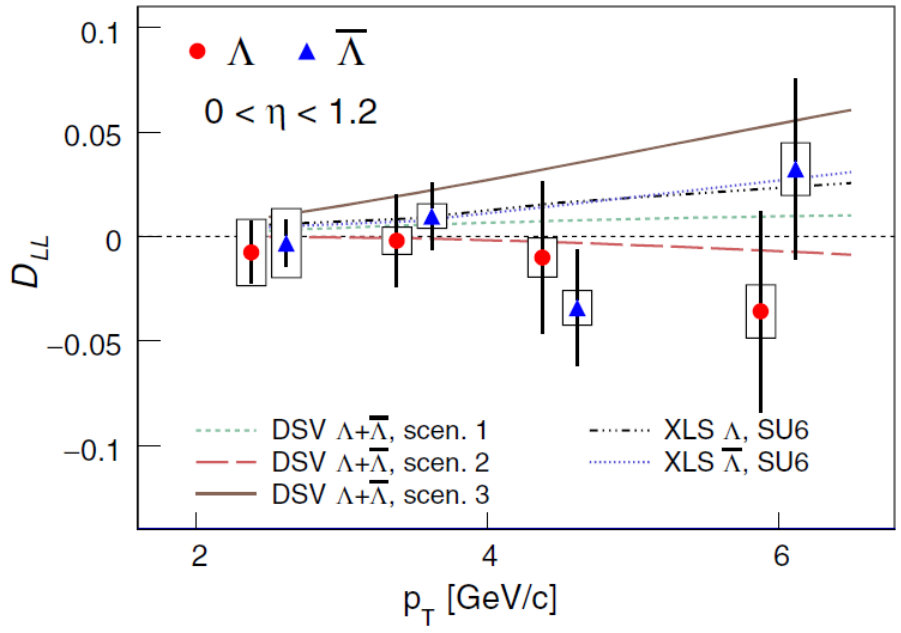




STAR $\Lambda/\bar{\Lambda}$ D_{LL}

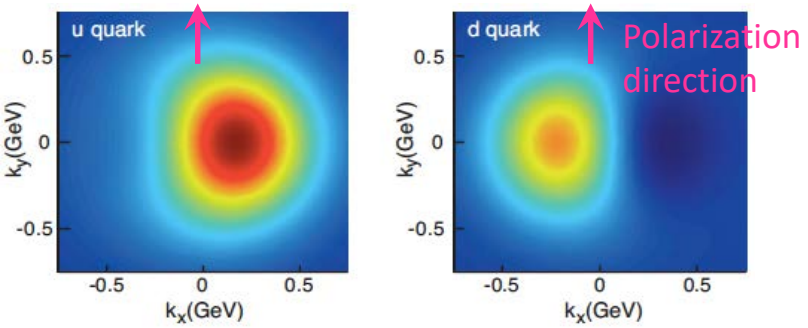
- Longitudinal spin transfer D_{LL}
  - Sensitive to helicity distributions and polarized fragmentation function
  - D_{LL} of $\bar{\Lambda}$ is naïvely connected to $\Delta\bar{s}$
  - Consistent with zero
  - More precision is needed to rule out various models

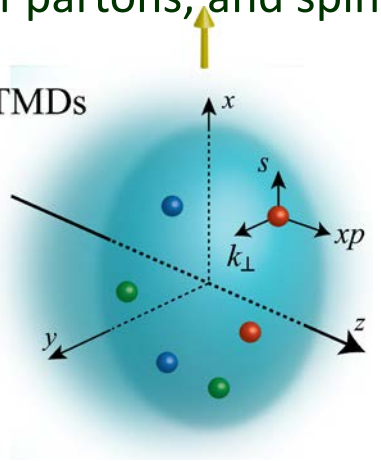
PRD98 (2018) 112009



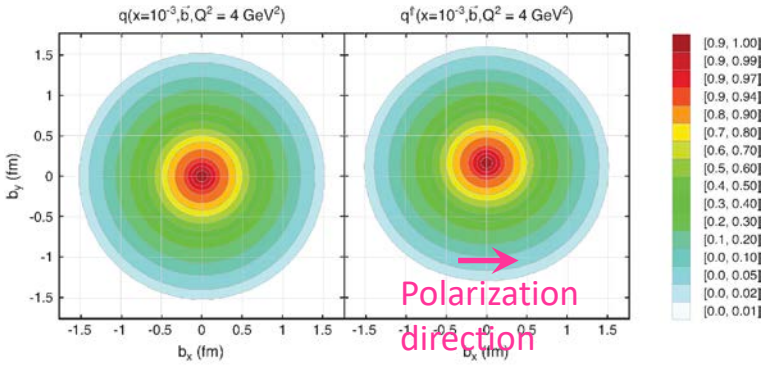
3D structure of the nucleon

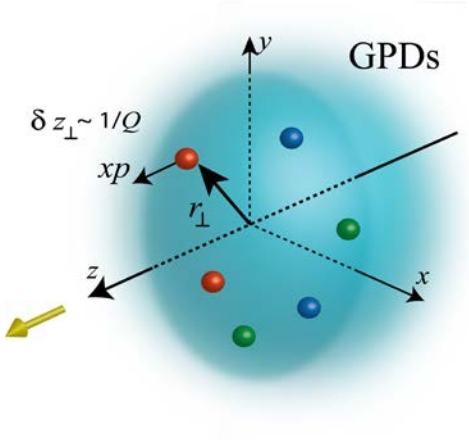
- Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between the (orbital) motion, spin of partons, and spin of the nucleon





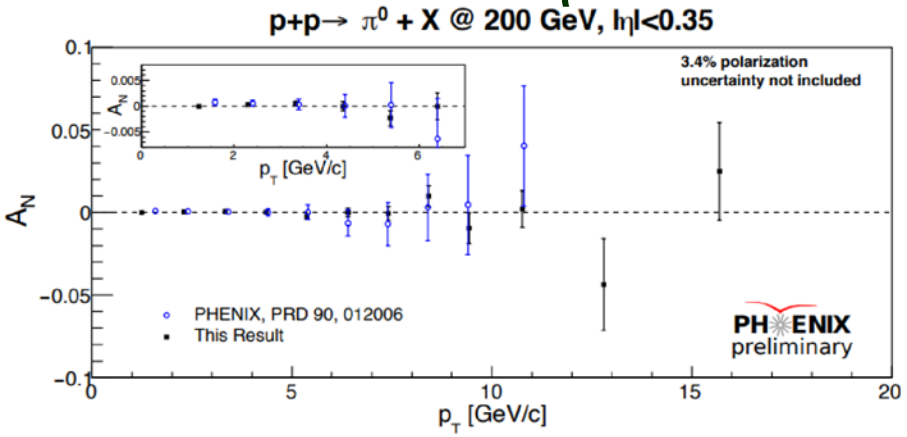
- GPD (Generalized Parton Distribution)
  - Spatial distribution or tomography

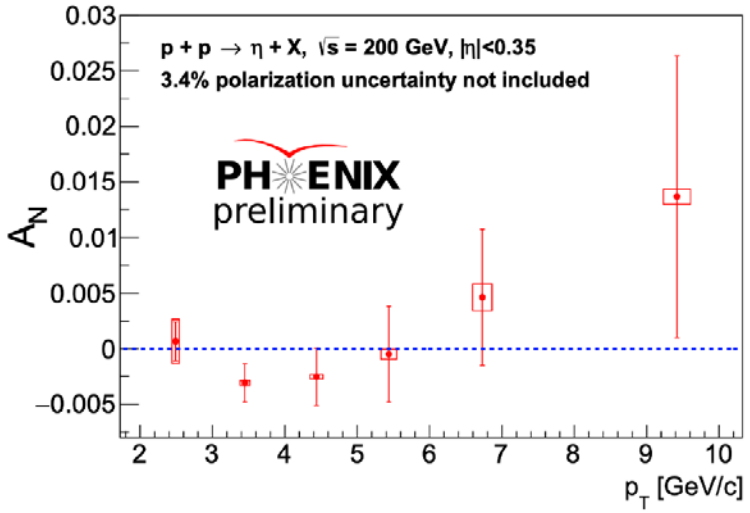




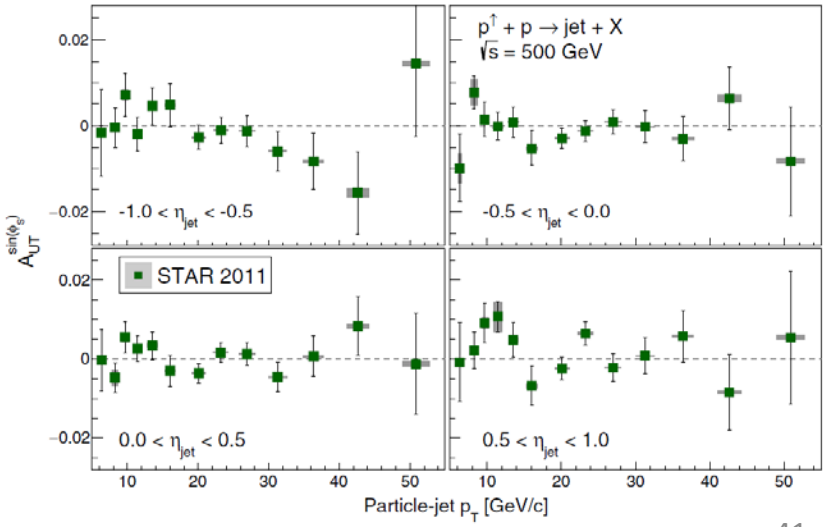
Midrapidity

- Asymmetries constrain twist-3 PDF for gluonic interactions connected to the gluon Sivers function
- PHENIX π^0 and η



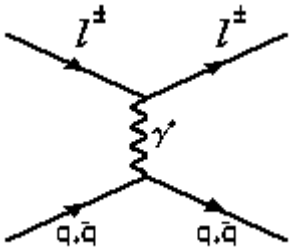


- STAR jet
  - PRD97 (2018) 032004

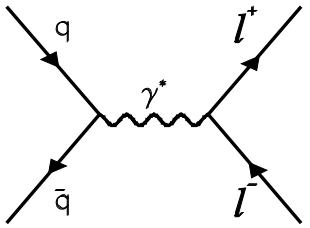


TMD function

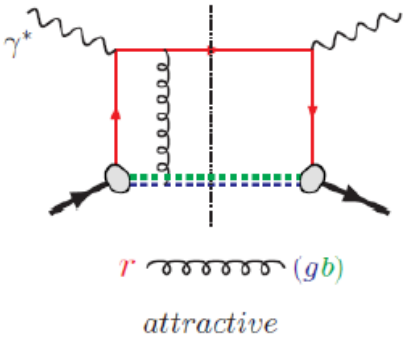
- Comparison between polarized semi-inclusive DIS and polarized Drell-Yan reaction
  - Important test to establish TMD (Transverse Momentum Dependent) function
    - Sign change of TMD (Sivers) distribution function
    - Initial- or final-state interaction effect
- W-boson production
  - 2011 data at STAR
  - PRL 116 (2016) 132301
  - Higher statistics in 2017

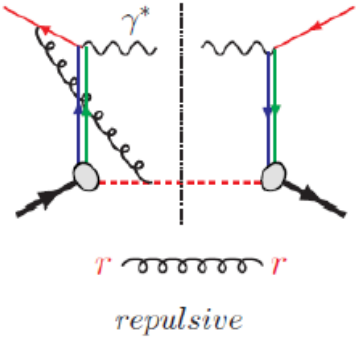


SIDIS

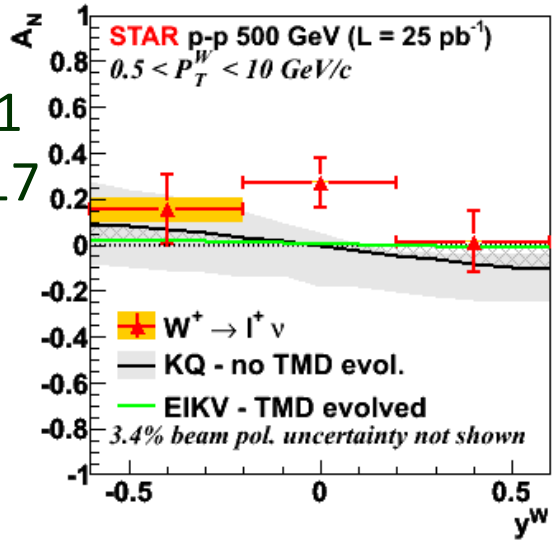


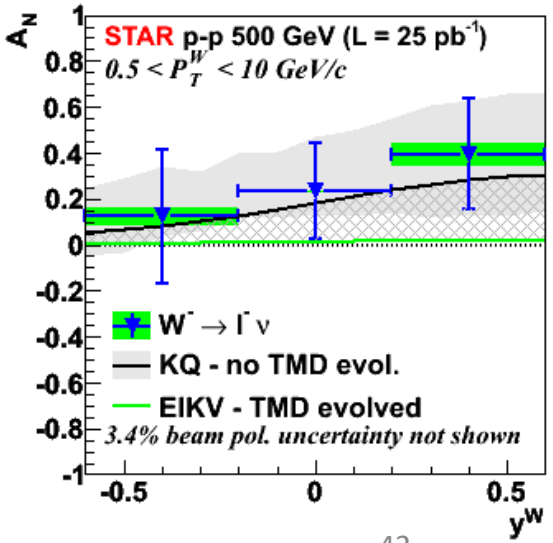
Drell-Yan





$$f_{1T}^{\perp}(x,k_{\perp})|_{SIDIS} = -f_{1T}^{\perp}(x,k_{\perp})|_{Drell-Yan}$$

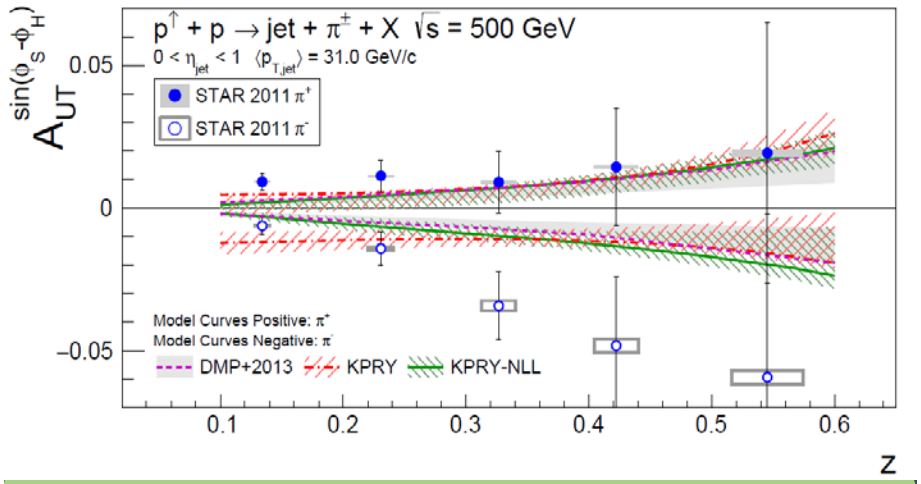


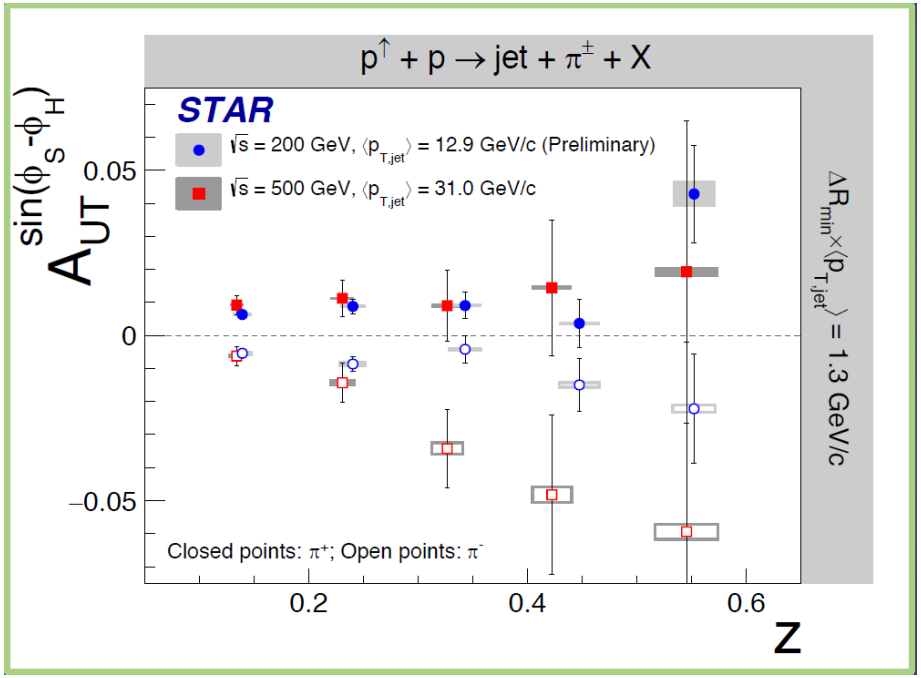


STAR transversity

- Quark transverse-spin contribution to the transversely polarized nucleon
  - Related to the tensor charge of the nucleon
- Collins asymmetry
  - SIDIS + B-factory based transversity fits
- Midrapidity
  - PRD97 (2018) 032004
  - Jet + $\pi^{\pm}$
  - 500 GeV (vs 200 GeV)

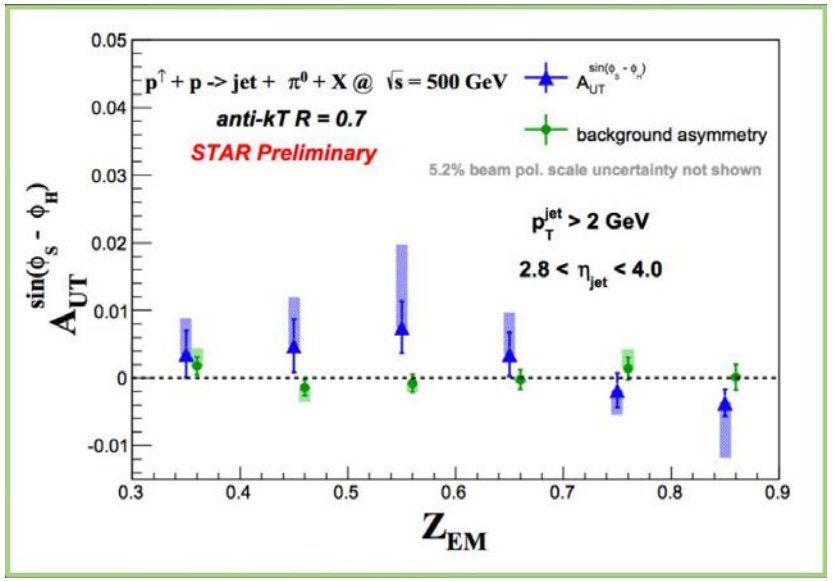
PRD97 (2018) 032004



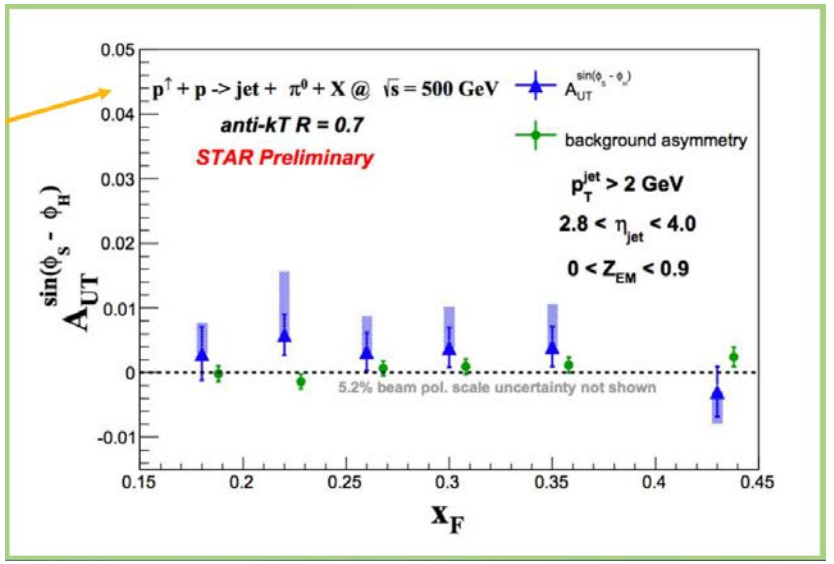


STAR transversity

- Forward-rapidity Collins asymmetry
  - Preliminary
  - Jet + π^0
  - Size and shape of asymmetries similar to midrapidity

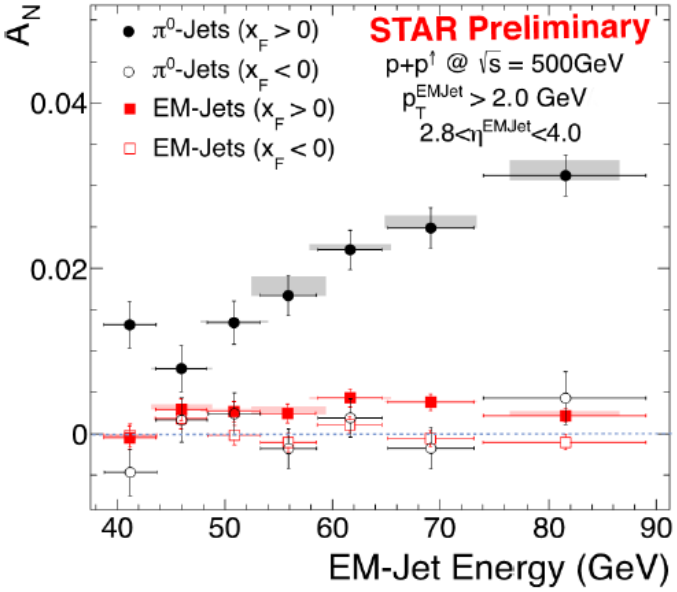


- Not explaining large forward SSA

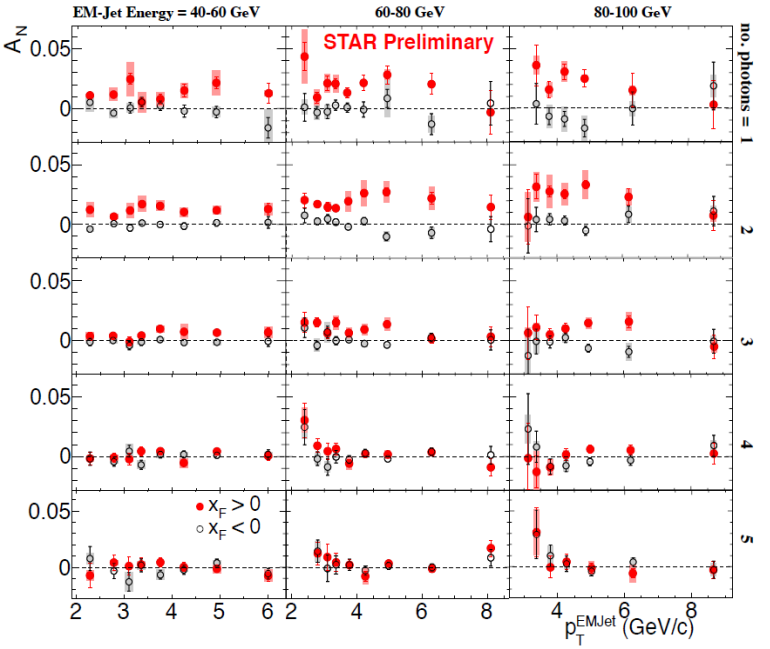


Forward SSA

- Recovering asymmetries if jet is composed largely of a single pion



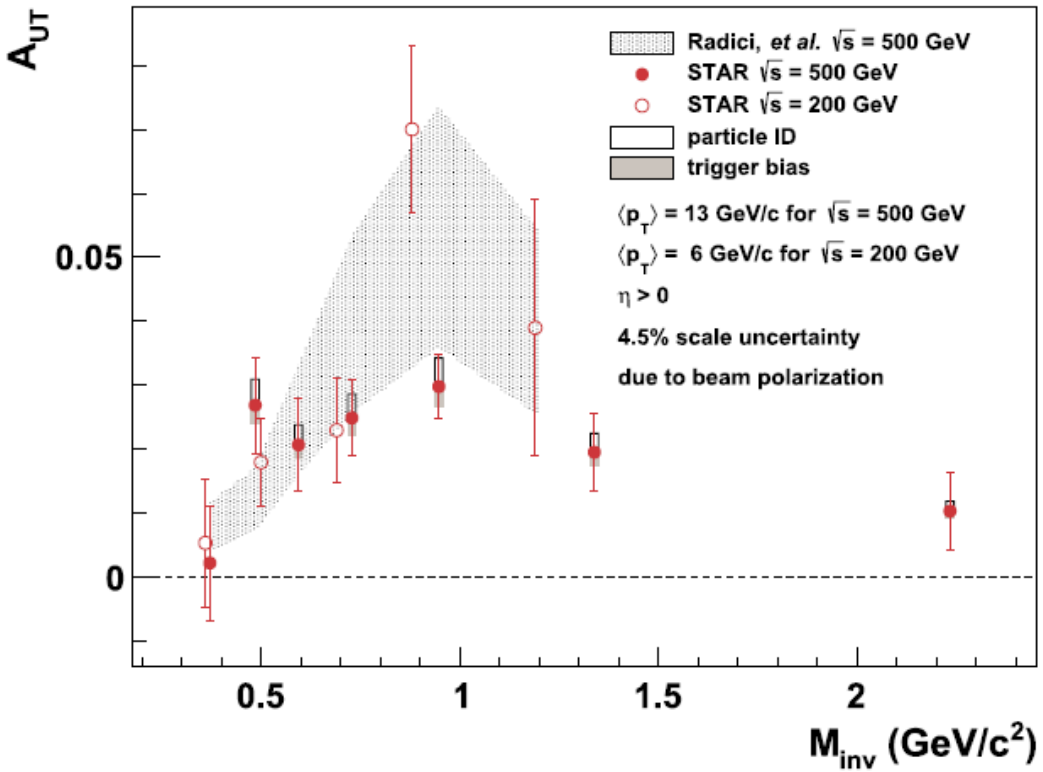
- Multiplicity dependence
  - A_N for different # of photons
  - A_N decreases as the event complexity increases (more jet-like)
  - How much of the large π^0 A_N comes from 2→2 parton scattering? Or diffractive events?



STAR transversity

- $\pi^+\pi^-$ interference fragmentation function (IFF)
  - Correlating quark polarization to azimuthal distribution of final state hadron pairs
  - Enhancement around the ρ-mass region
  - PLB780 (2018) 332-339

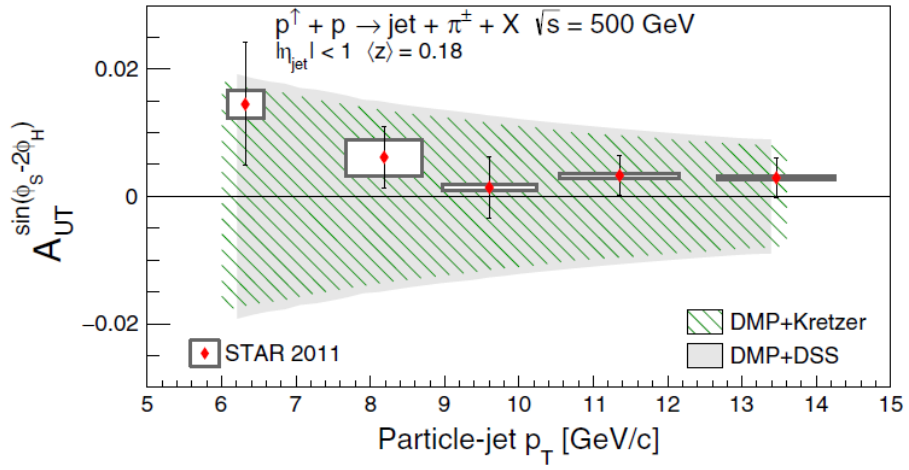
PLB780 (2018) 332-339

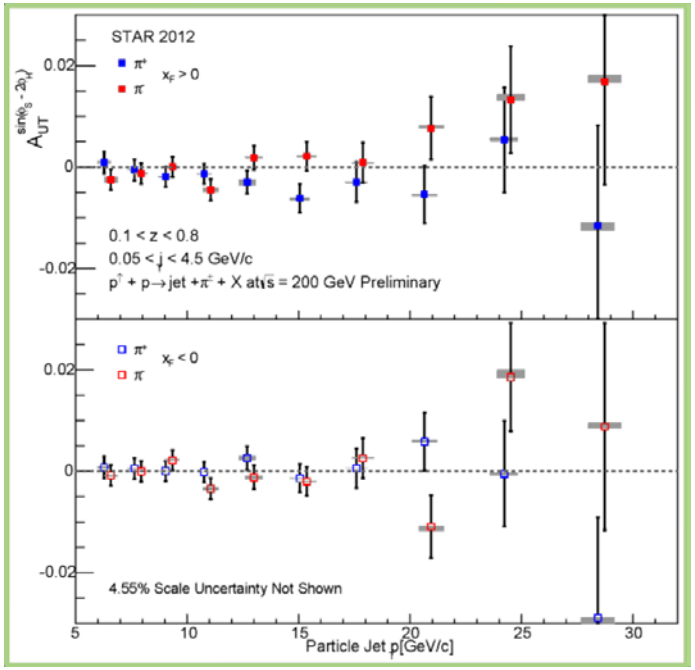


STAR gluon linear polarization

- Gluon TMDs
  - $\sin(\phi_S - 2\phi_H)$ moment
  - Gluon linear polarization ⊗ Collins-like FF
  - First limit on linearly polarized gluon in a polarized proton
  - 500 GeV result: PRD97 (2018) 32004
  - 200 GeV preliminary results will provide stronger constraints

PRD97 (2018) 32004

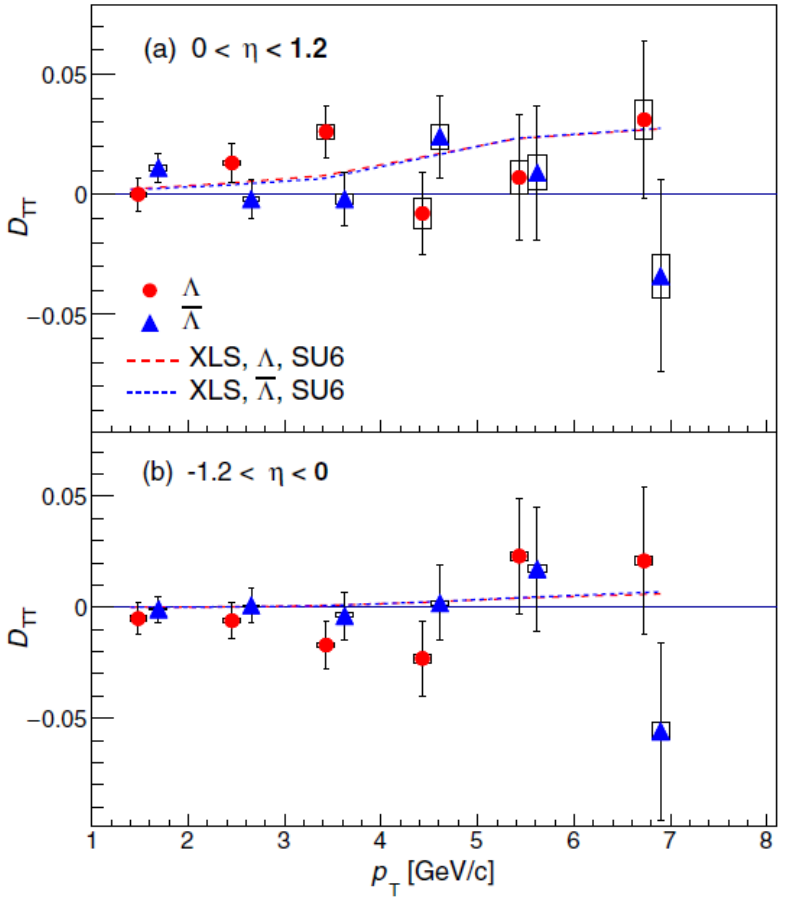




STAR transversity

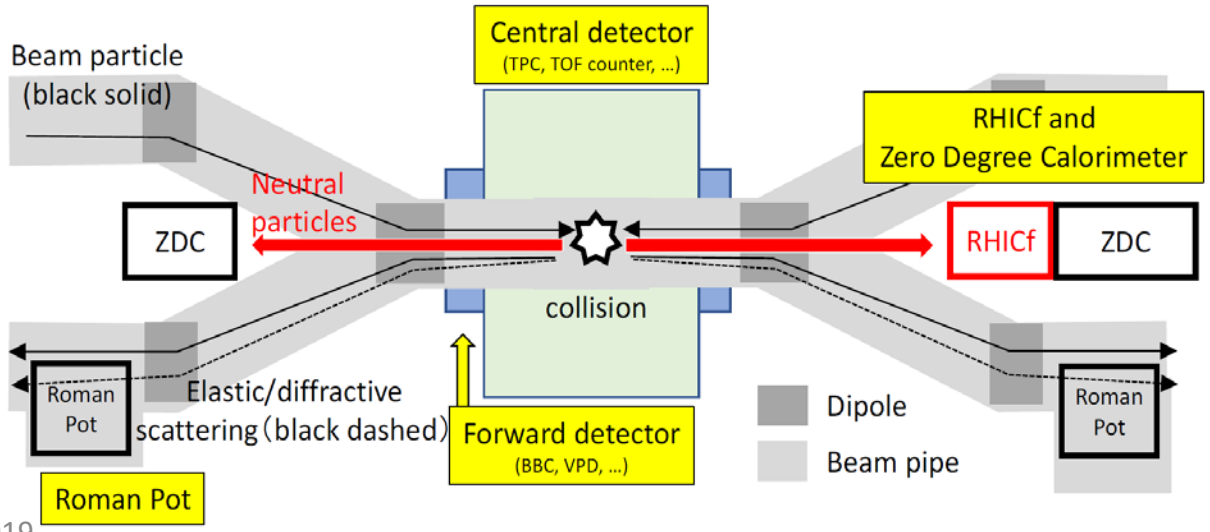
- Spin transfer
  - $\Lambda/\overline{\Lambda}$ D_{TT}
  - PRD98 (2018) 091103
  - Asymmetryies consistent with model calculation (consistent with zero)

PRD98 (2018) 091103



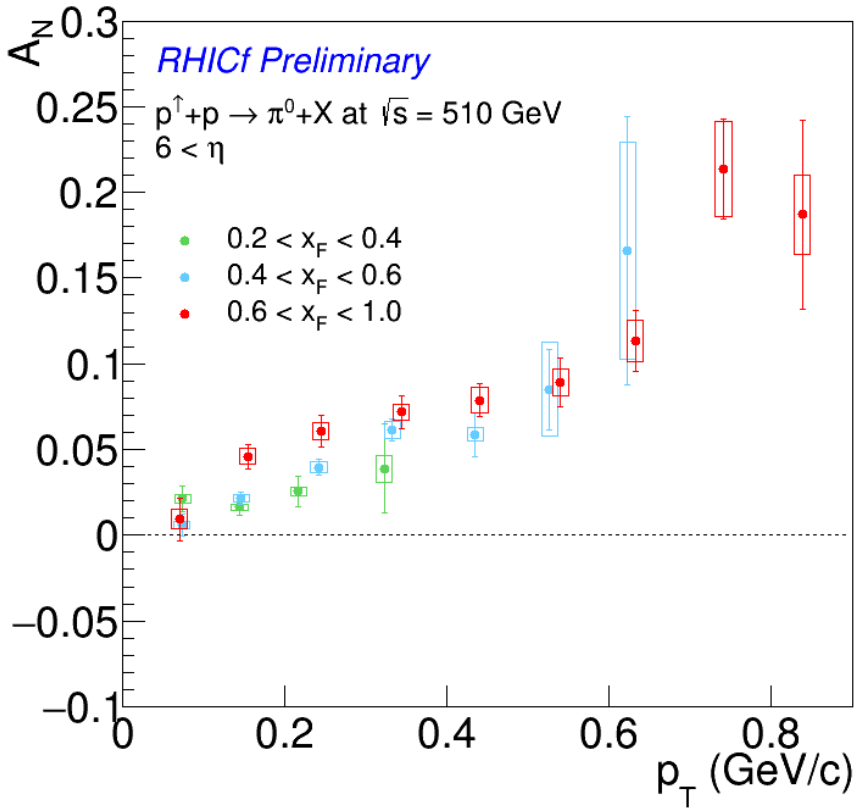
RHICf experiment

- EM calorimeter (RHICf detector) installed in front of the ZDC+SMD of the STAR experiment
  - Cross section and asymmetry measurement of neutral particle production (neutron, photon, π^0) with $\sqrt{s}$ = 510 GeV polarized proton collisions
  - Wide p_T region covered by changing the position of the RHICf detector vertically (up to 1.4 GeV/c)
  - Much higher position resolution than ZDC+SMD so that enable us higher resolution of p_T measurement



A_N of very forward π^0

- Large asymmetry (up to 0.1) even at low p_T (p_T < 0.6 GeV/c)
  - Production mechanism?
- Becoming larger (more than 0.1) at high p_T (0.6 GeV/c < p_T)
  - Contribution from hard scattering?



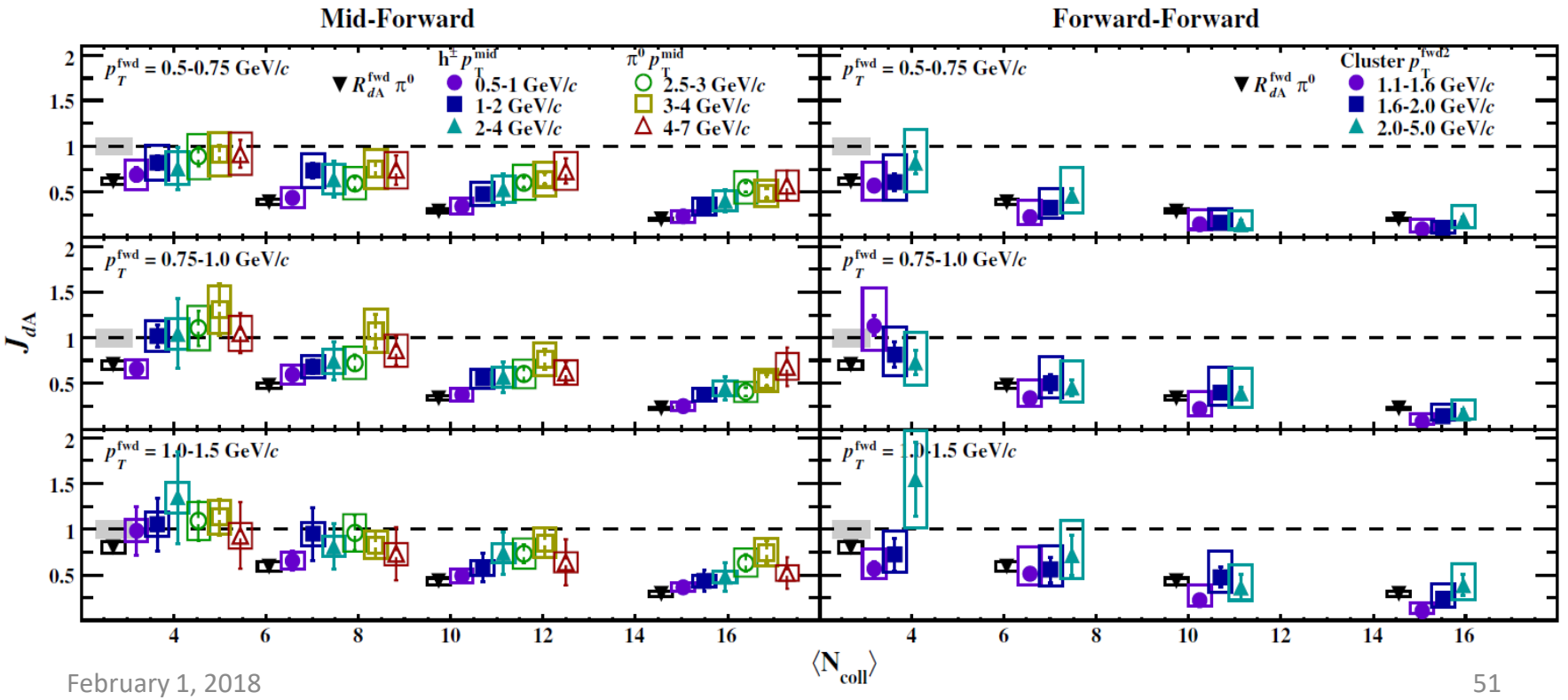
Background asymmetry (measured, zero consistent) subtracted

Bar: statistical error
Box: systematic uncertainties including beam center correction, acceptance correction, polarization, and background asymmetry subtraction

Cold nuclear matter effects

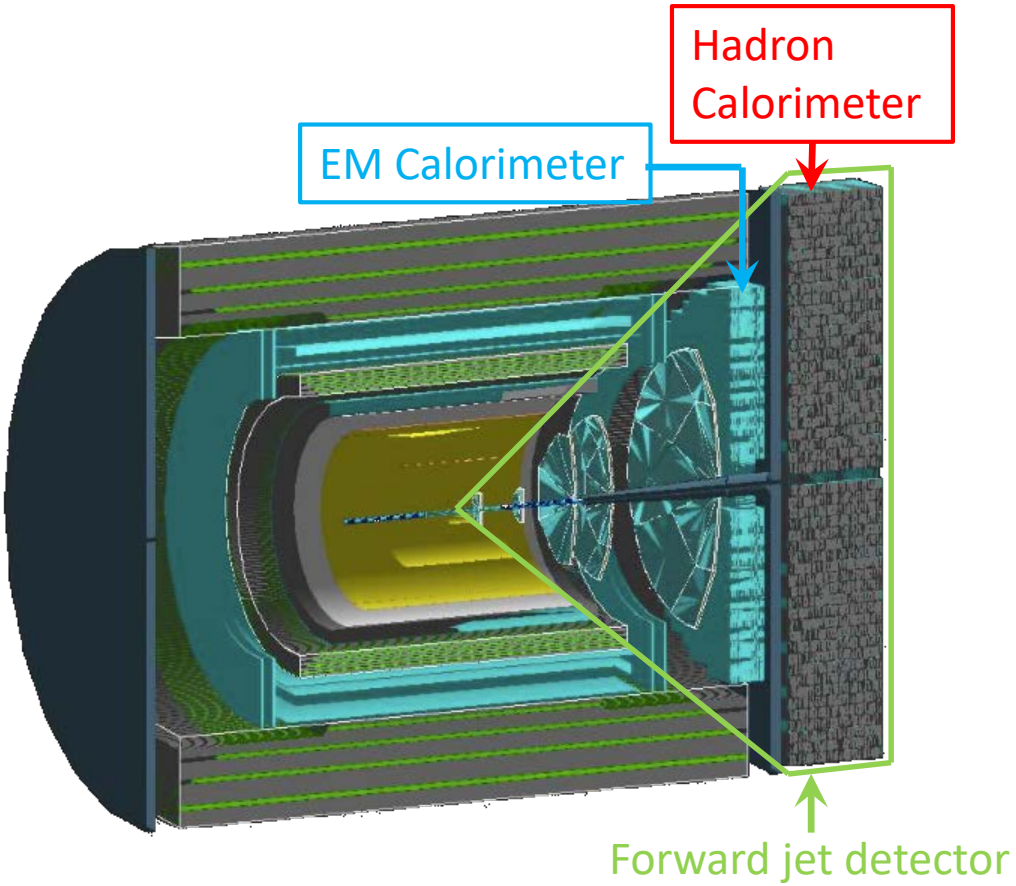
- Di-jet suppression at forward rapidities
  - d+Au vs p+p collisions
  - Suppression increasing with increasing N_{coll}
  - Decreasing with increasing p_T (related to increasing x)
    - Strong suppression at lowest x
    - Gluon saturation at low x?

PRL107 (2011) 172301



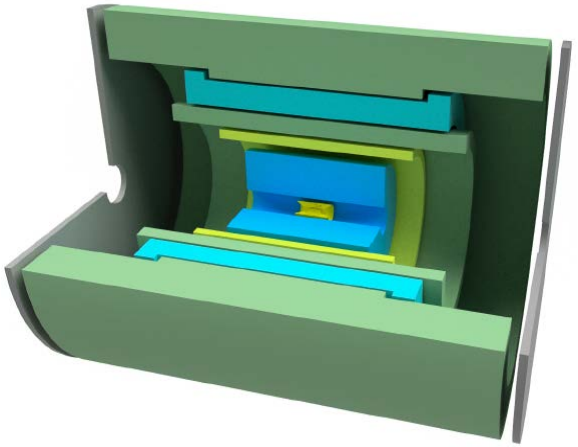
Forward sPHENIX (fsPHENIX)

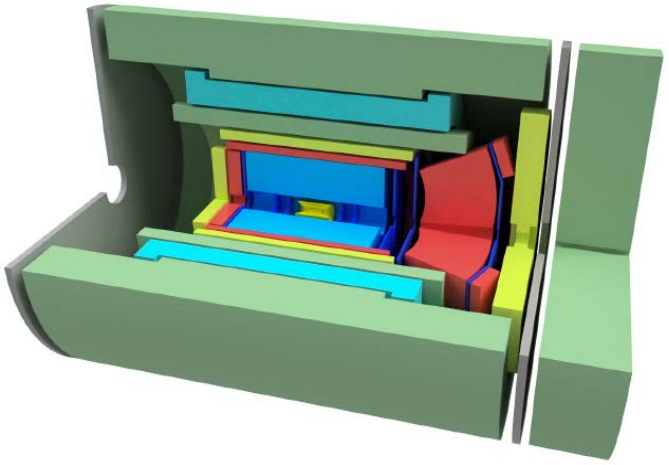
- LoI for fsPHENIX
  - $1.2 < \eta < 4$
  - EM calorimeter
  - Hadron calorimeter
  - Trackers
    - GEM / sTGC
    - Silicon detector
  - Magnetic field shaper
  - Within 4.5 m eRHIC IR constraint
- Physics at fsPHENIX
  - Transverse-spin asymmetries
    - Jet + hadron
  - Gluon polarization at small-*x*

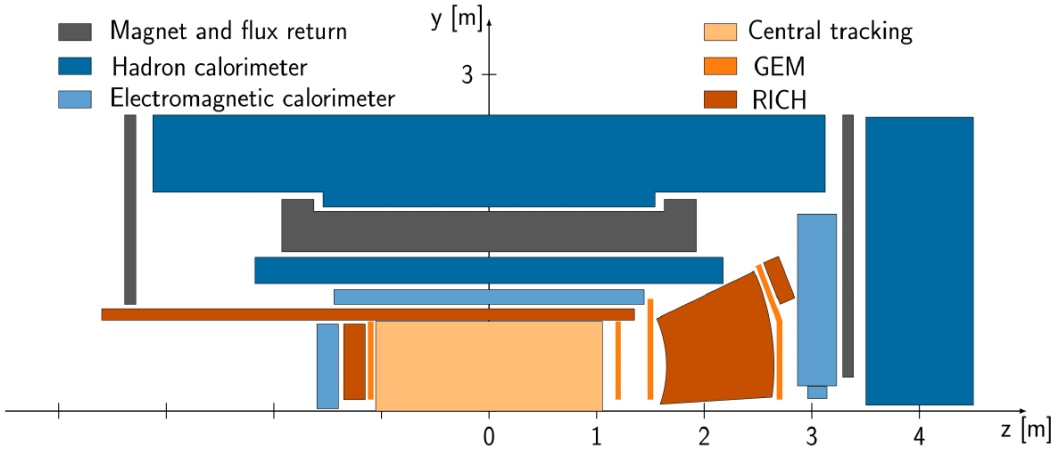


EIC-sPHENIX detector

- sPHENIX detector
  - 4π detector with BaBar superconducting solenoidal magnet
  - $|\eta| < 1.1$ and $0 < \phi < 2\pi$
    - EM and hadron calorimeters
    - TPC
    - Silicon detector
  - Under construction to operate from 2022-2023
- EIC-sPHENIX detector
  - Design study ongoing







Summary

- RHIC spin program
  - Origin of the nucleon spin 1/2 (spin puzzle)
    - Positive gluon spin contribution to the nucleon spin (gluon polarization) measured similar to the quark spin contribution
    - $\Delta\bar{u} > \Delta\bar{d}$ suggested for the anti-quark polarization
  - Understanding of the transverse polarization phenomena with higher-twist and TMD (Tranvserse Momentum Dependent) functions
    - Measurement of the 3D structure of the nucleon and orbital motion inside the nucleon
- Cold QCD plan to complete the RHIC spin program
  - STAR forward upgrades with forward calorimeter and tracking detectors
  - Construction of the sPHENIX detector and upgrades leading to capable EIC detectors