

Nucleon structure study at RHIC and EIC

YKIS2018b Symposium

Kyoto, Japan

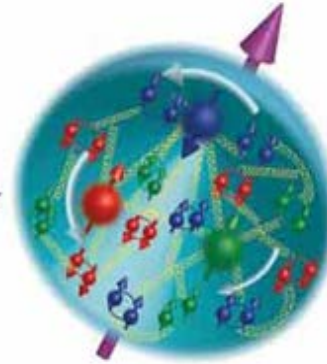
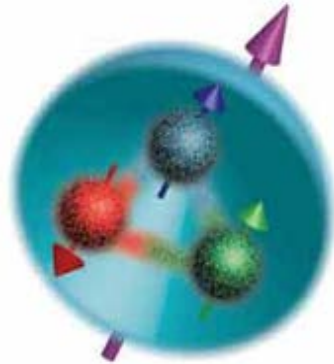
June 12, 2018

Yuji Goto (RIKEN)

Nucleon puzzles

- Two pictures

static picture
low energy
low resolution



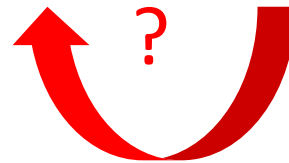
dynamic picture
high energy
high resolution

Constituent quark picture

explaining magnetic moment
of nucleon/hadron

Quark-gluon picture

Nucleon spin puzzle:
only 30% of the nucleon spin
is contributed by the quark spin



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

Orbital angular momentum

Quark spin

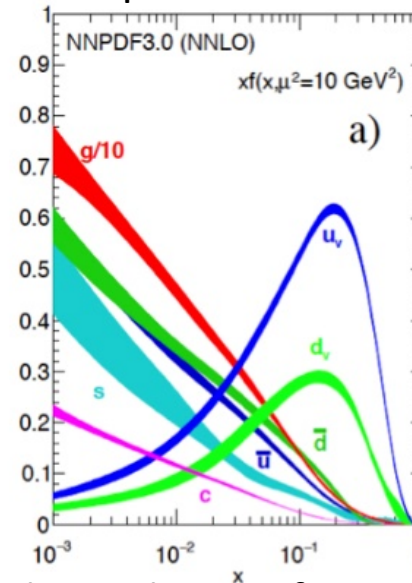
Gluon spin

How can the constituent quark be explained by the quark+gluon?
Impossible? No correspondence?

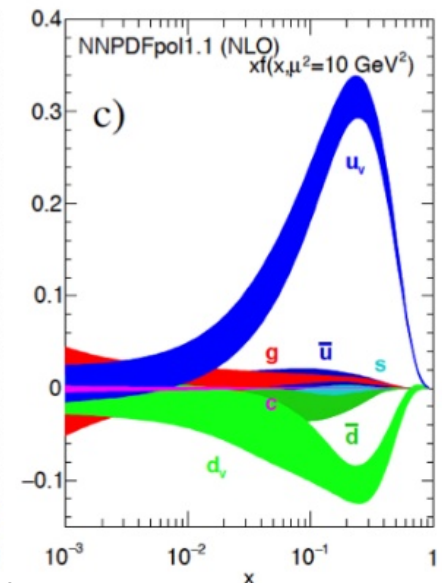
Quark-gluon structure

- 1-D picture
 - Parton distribution function (PDF) of quarks and gluons
 - x : momentum fraction of quarks and gluons
- 3-D picture
 - Generalized parton distribution (GPD) function
 - charge distribution
 - magnetic-moment distribution
 - mass distribution
 - and their radius (R)
 - orbital motion / orbital angular momentum

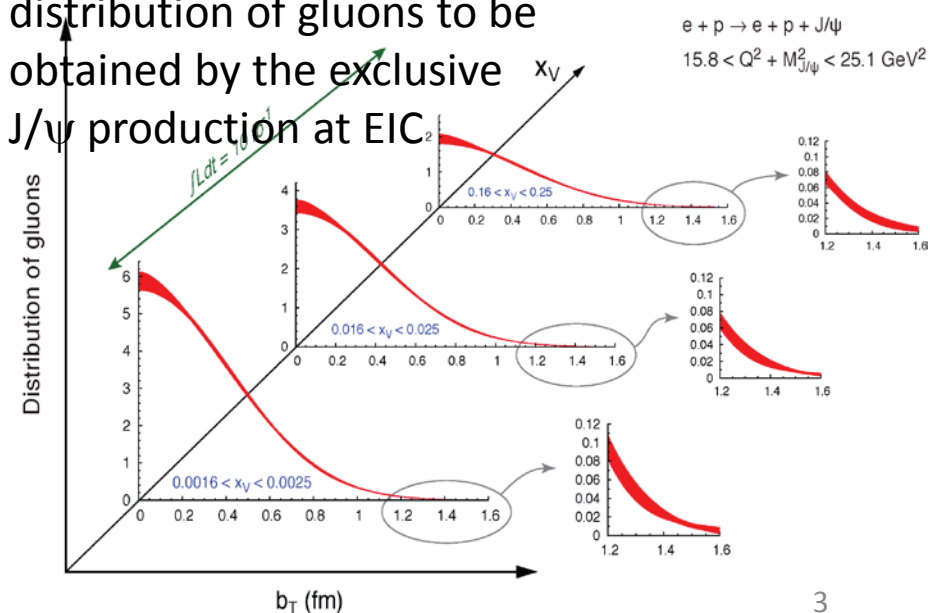
Unpolarized PDF



Polarized PDF

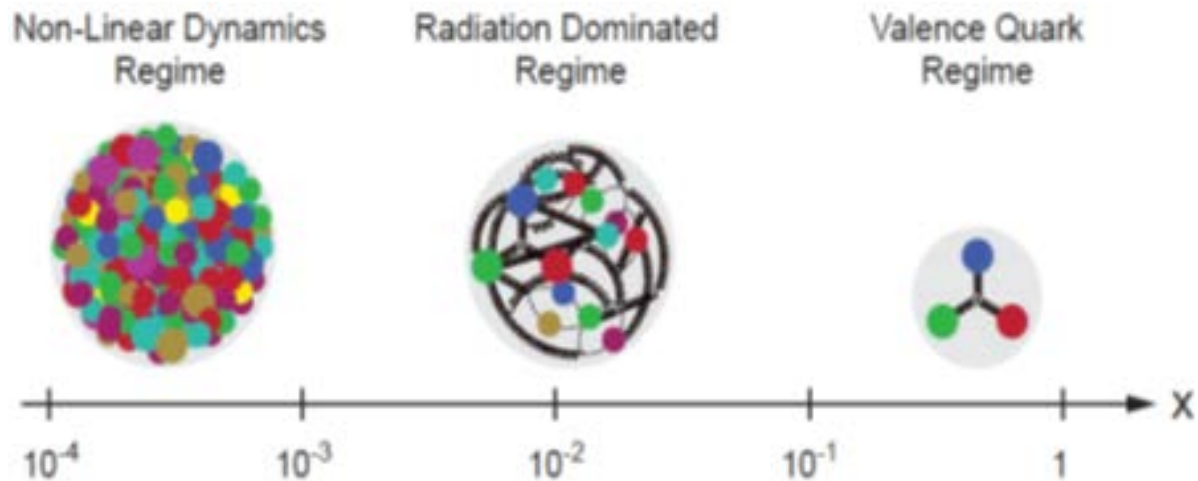


x -dependence of spatial distribution of gluons to be obtained by the exclusive J/ψ production at EIC



Quark-gluon structure

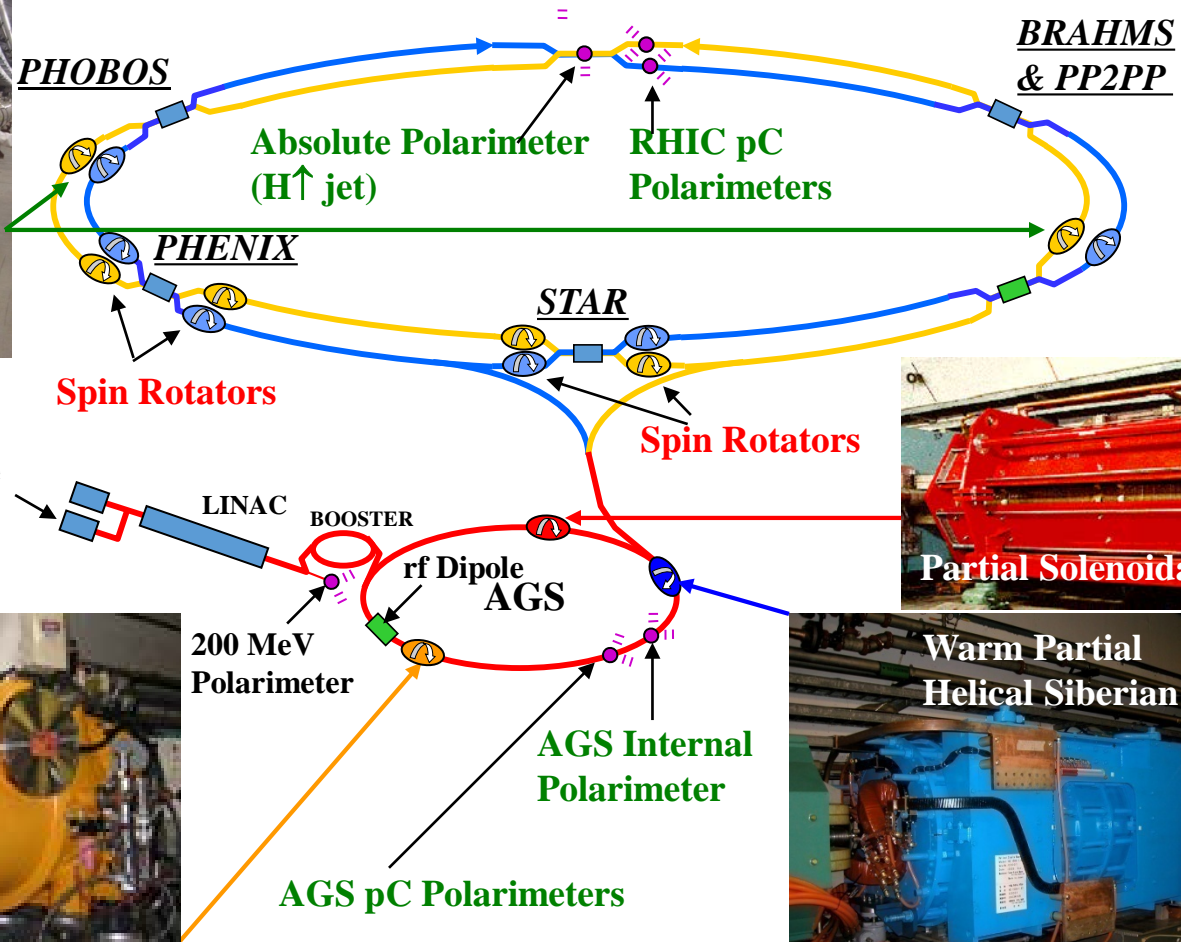
- Establishing new 3-D picture of the nucleon



- Gluon saturation at small-x
 - Color Glass Condensate (CGC) → Quark Gluon Plasma (QGP)
- Nucleon puzzles
 - Spin, radius, mass, pressure...
 - and more for standard model & beyond, stability of universe...
 - Neutron EDM, Neutron lifetime, Proton lifetime...
 - Importance of precise comparison with Lattice QCD

Polarized proton acceleration at RHIC

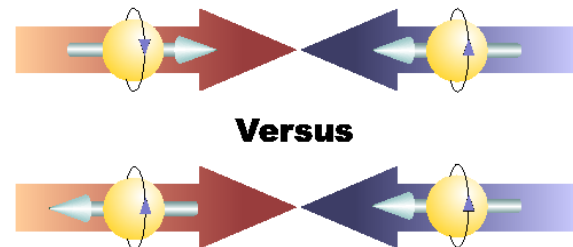
- Keeping and monitoring polarization from the polarized proton source



Longitudinal polarized proton collision

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

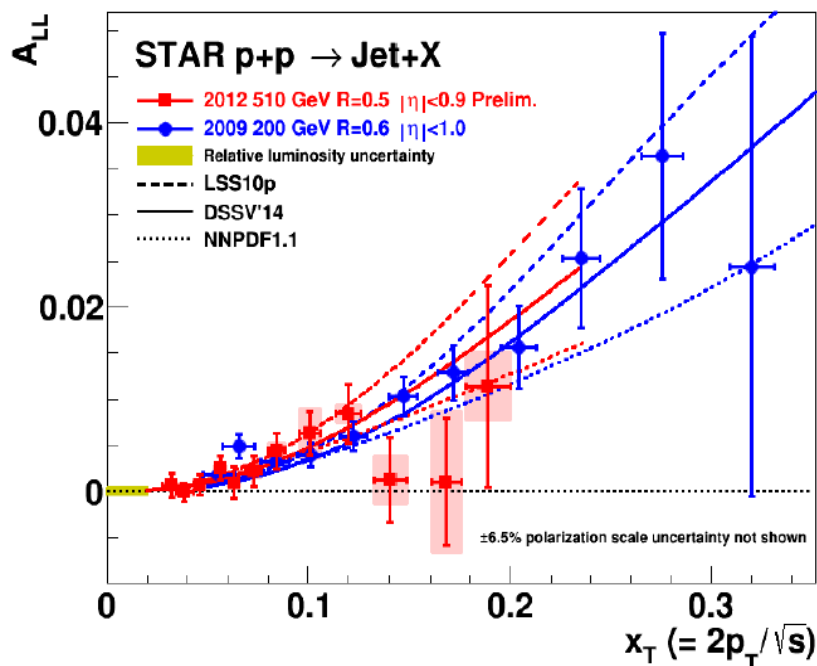
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$



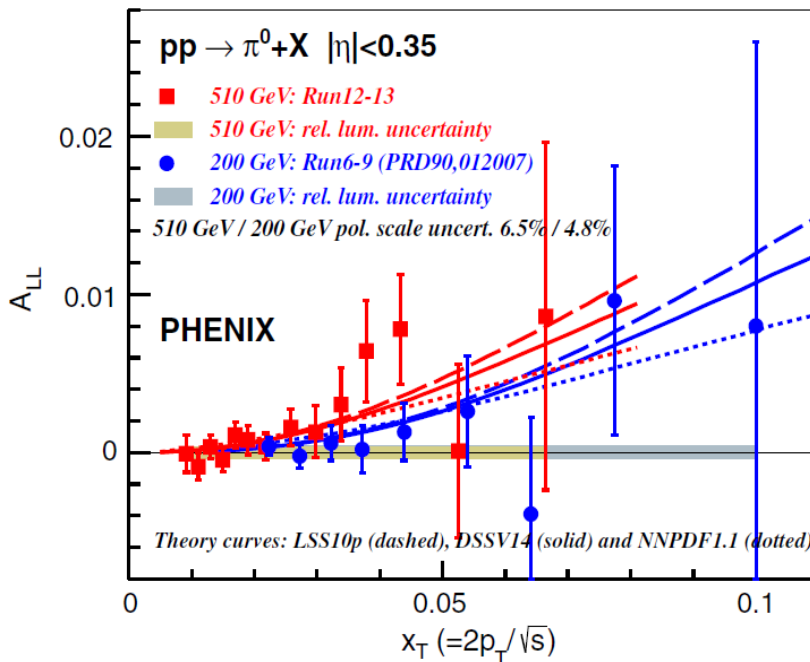
- Gluon polarization

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

Midrapidity jet at STAR



Midrapidity π^0 at PHENIX



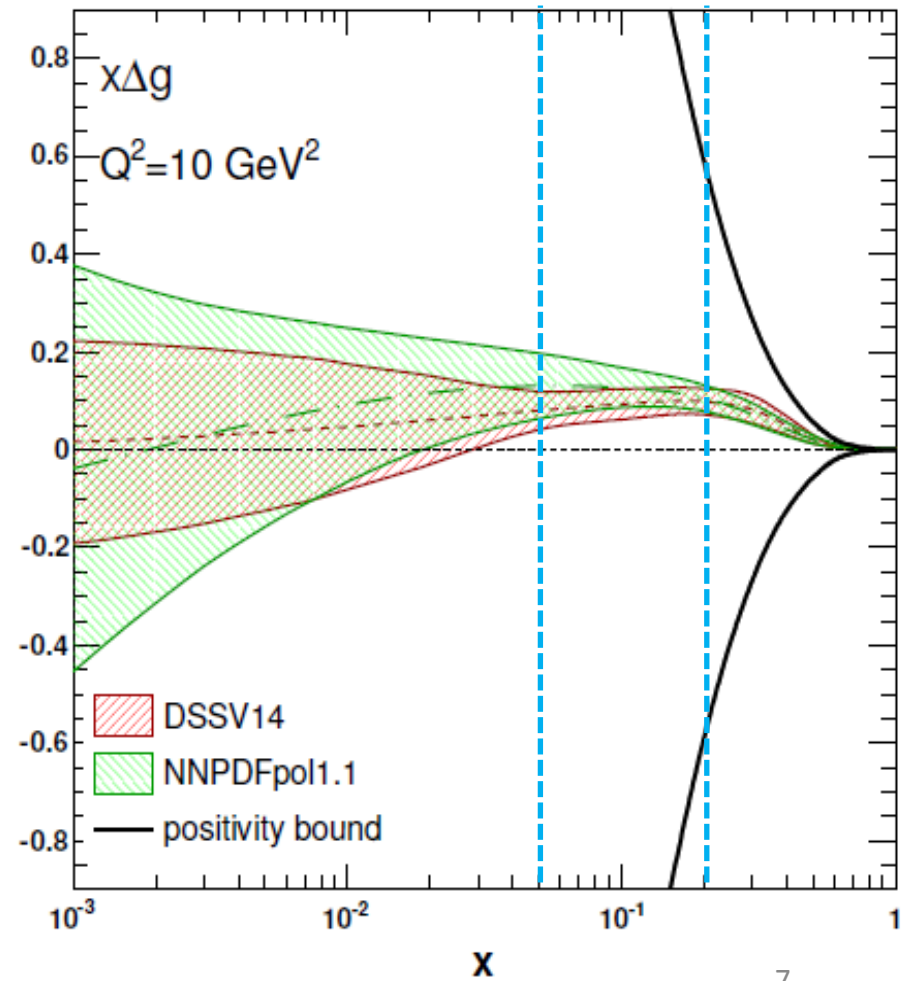
Gluon polarization

- Positive gluon polarization obtained by DSSV and NNPDF groups with the QCD global analysis including polarized proton collision data at RHIC

arXiv:1503.03518

- 2014 press releases
- Gluon polarization
 - 200 GeV collision data at RHIC
 - Jet asymmetry from STAR
 - π^0 asymmetry from PHENIX

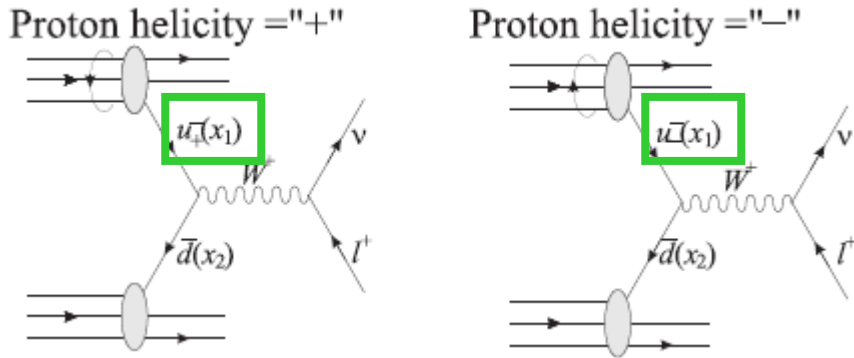
$Q^2 = 10 \text{ GeV}^2$	$\int_{0.05}^{0.2} dx \Delta g(x, Q^2)$
NNPDFpol1.1	$+0.15 \pm 0.06$
DSSV14	$0.10^{+0.06}_{-0.07}$



Anti-quark polarization

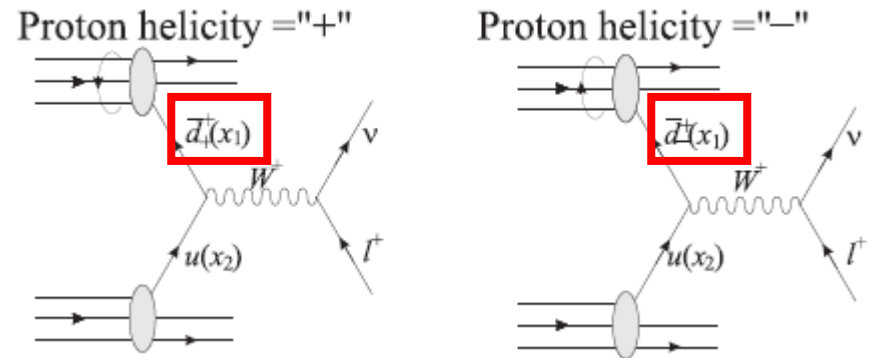
- Parity-violating A_L measurement with W-boson production

Forward rapidity



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

Backward rapidity



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

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

- W boson produced in the backward rapidity sensitive to the anti-quark polarization
- W boson data obtained by 2013 and data analysis to be finalized and published soon

Anti-quark polarization

- W boson data obtained by 2013 and data analysis to be finalized and published soon
- $\Delta\bar{u} > \Delta\bar{d}$ suggested by the QCD global analysis
 - $\bar{d} > \bar{u}$ in the unpolarized case

PHENIX

W→e 2011-13

W→μ 2012-2013

arXiv:1804.04181

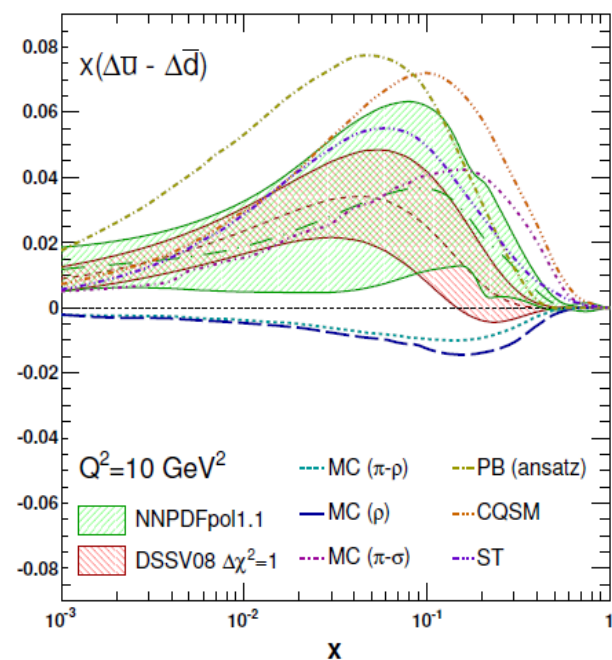
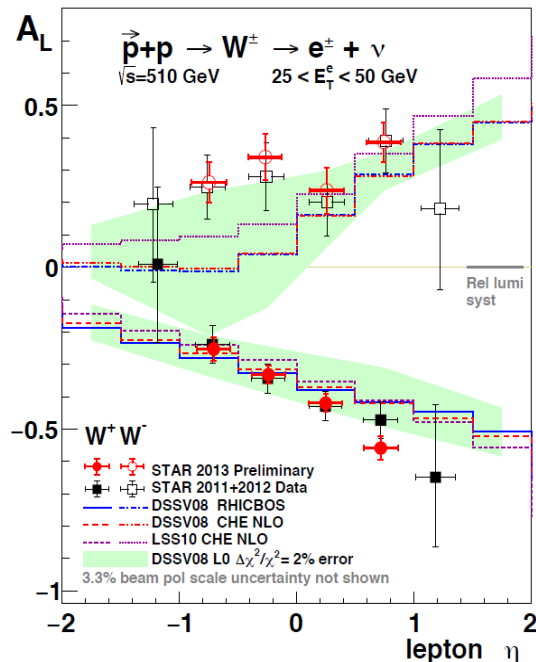
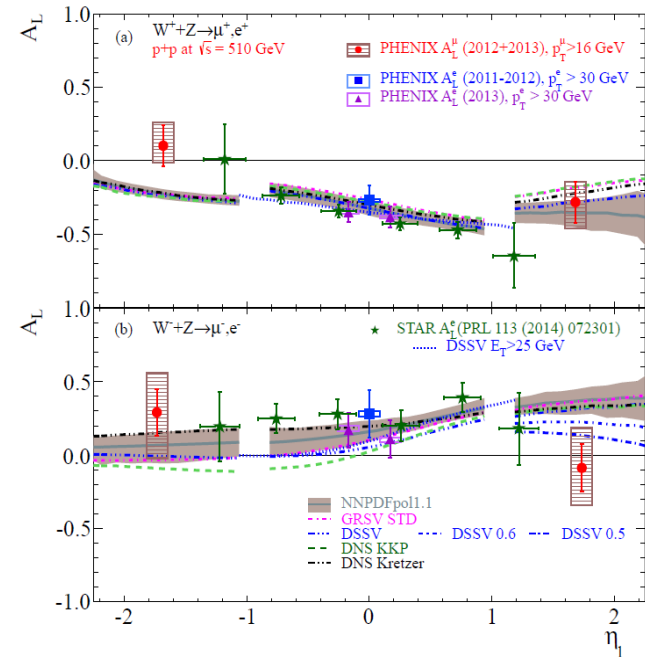
STAR

W→e 2011-12

PRL 113, 072301 (2014)

W→e 2013 preliminary

arXiv:1406.7122

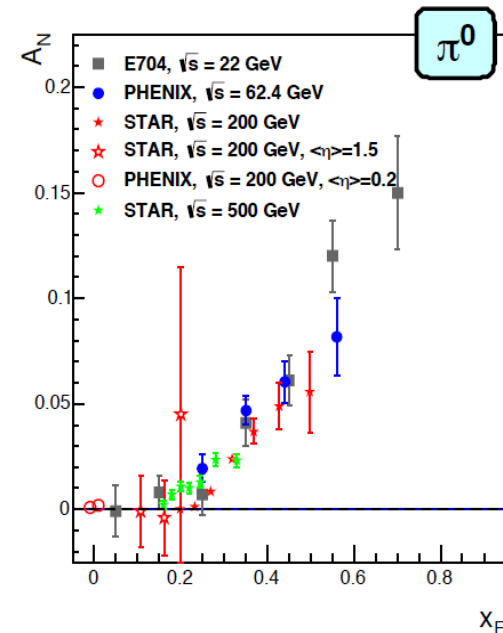
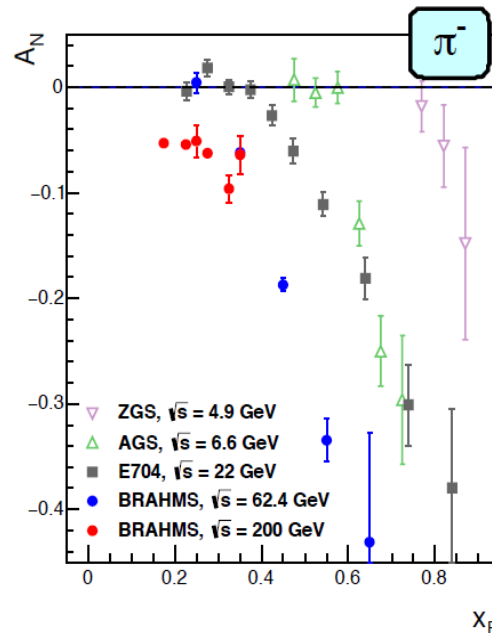
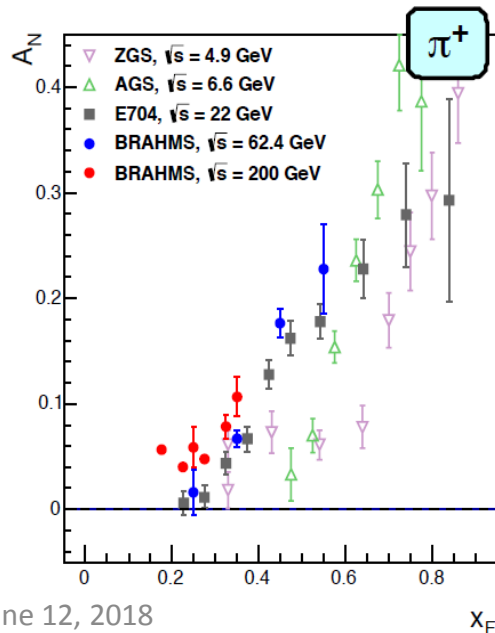
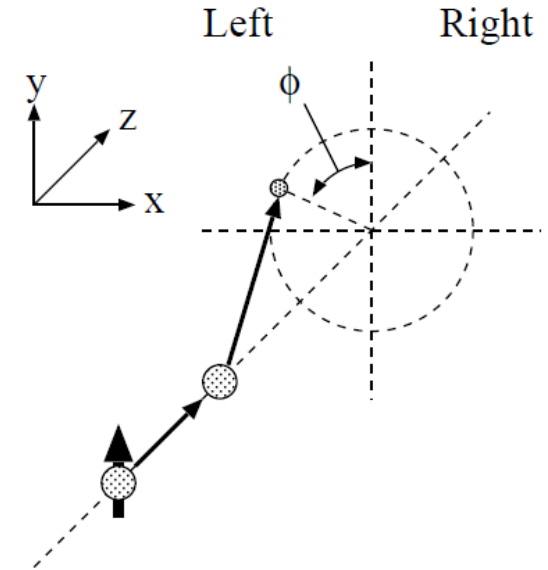


Transverse polarized proton collision

- A_N (transverse single-spin asymmetry) measurement

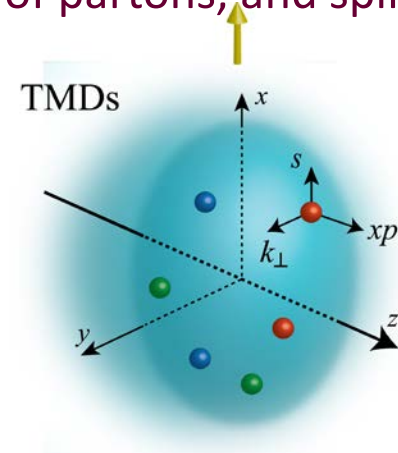
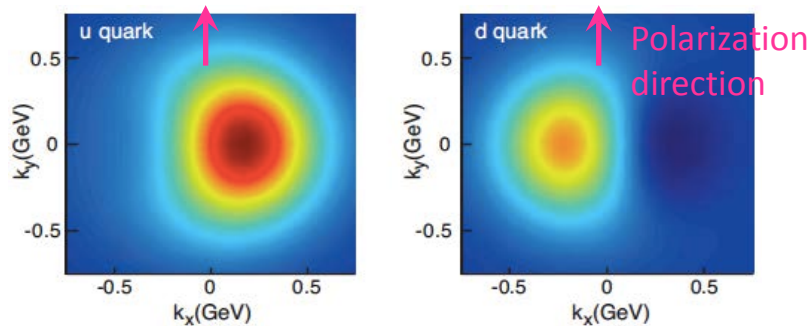
$$A_N = \frac{d\sigma_{Left} - d\sigma_{Right}}{d\sigma_{Left} + d\sigma_{Right}}$$

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

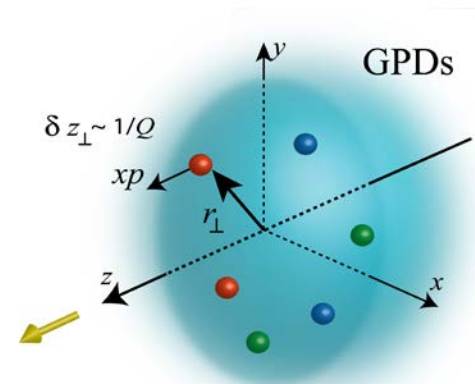
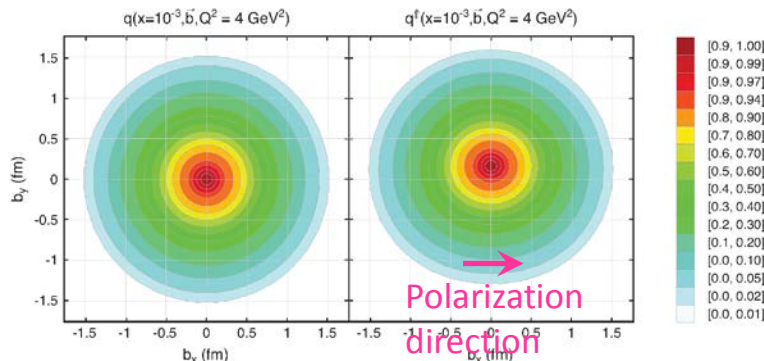


3D structure of the nucleon

- 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



Transverse polarization phenomena

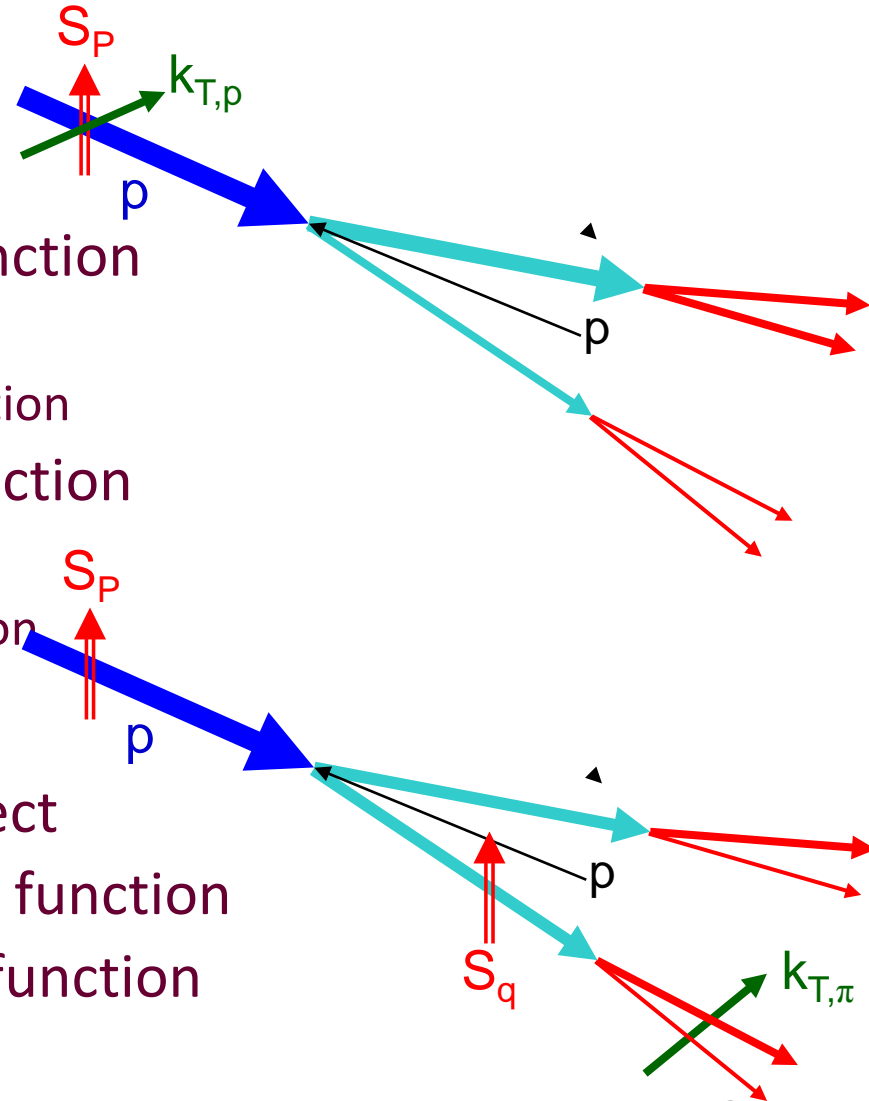
- TMD (Transverse Momentum Dependent) function and higher-twist function

- “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

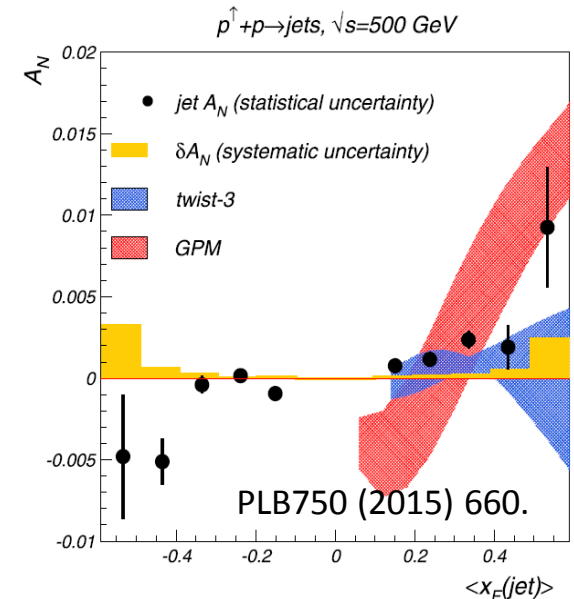
- “Collins” effect

- Transversity + final-state effect
- TMD (Collins) fragmentation function
- Higher-twist fragmentation function

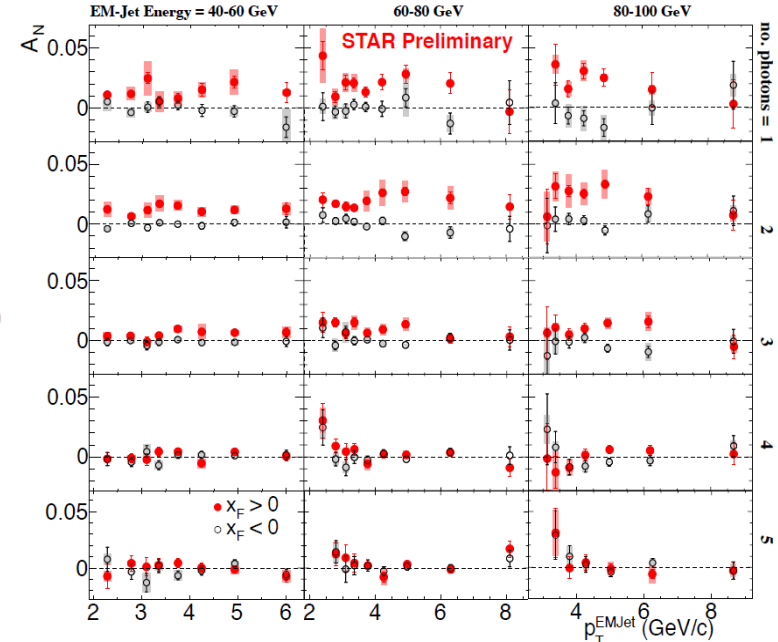


Forward jet / hadron production

- A_N DY experiment
 - Small A_N of forward jet production comparing with that of forward hadron production
 - Mixture of u-quark jet and d-quark jet?

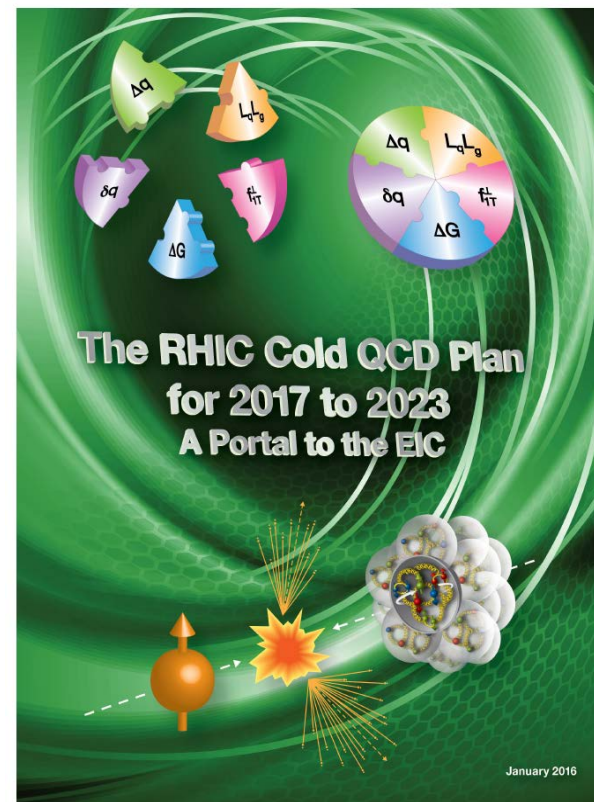


- Multiplicity dependence
 - A_N for different # of photons
 - A_N decreases as the event complexity increases (more jet-like)
 - How much of the large π^0 A_N comes from hard scattering? Or diffractive scattering?



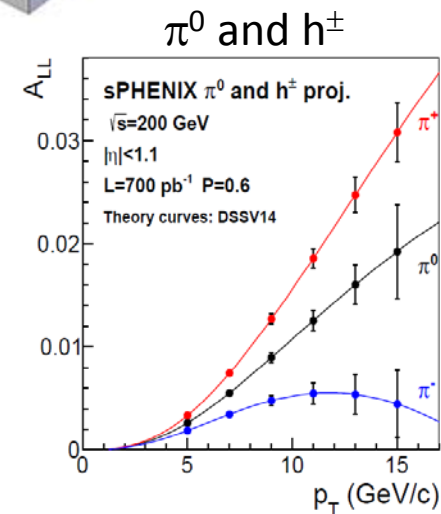
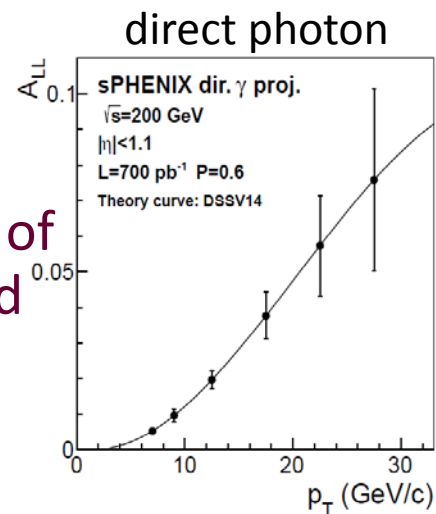
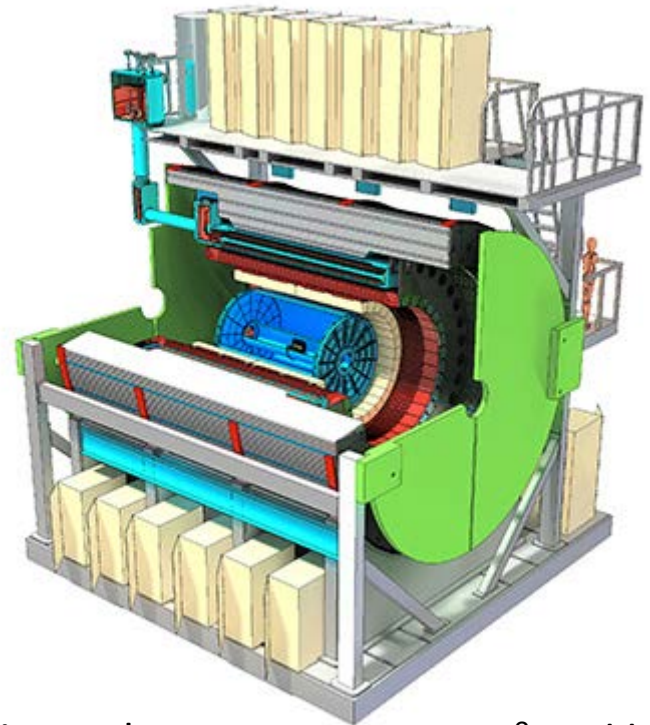
Future of nucleon spin physics at RHIC

- RHIC Cold QCD Plan for 2017–2023
 - arXiv:1602.03922
 - Completion of the RHIC spin program
- A portal to the EIC
 - “providing a comprehensive set of measurements in hadronic collisions that, when combined with data from the EIC, will establish the validity and limits of factorization and universality”
- Transverse-spin asymmetries
 - A_N for charged hadrons and flavor enhanced jets
 - Hadron asymmetries in jet modulations
 - A_N for Drell-Yan / photon
- Nuclear parton distribution and gluon saturation
- Gluon polarization at small Bjorken- x



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 2022-2023 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, ...



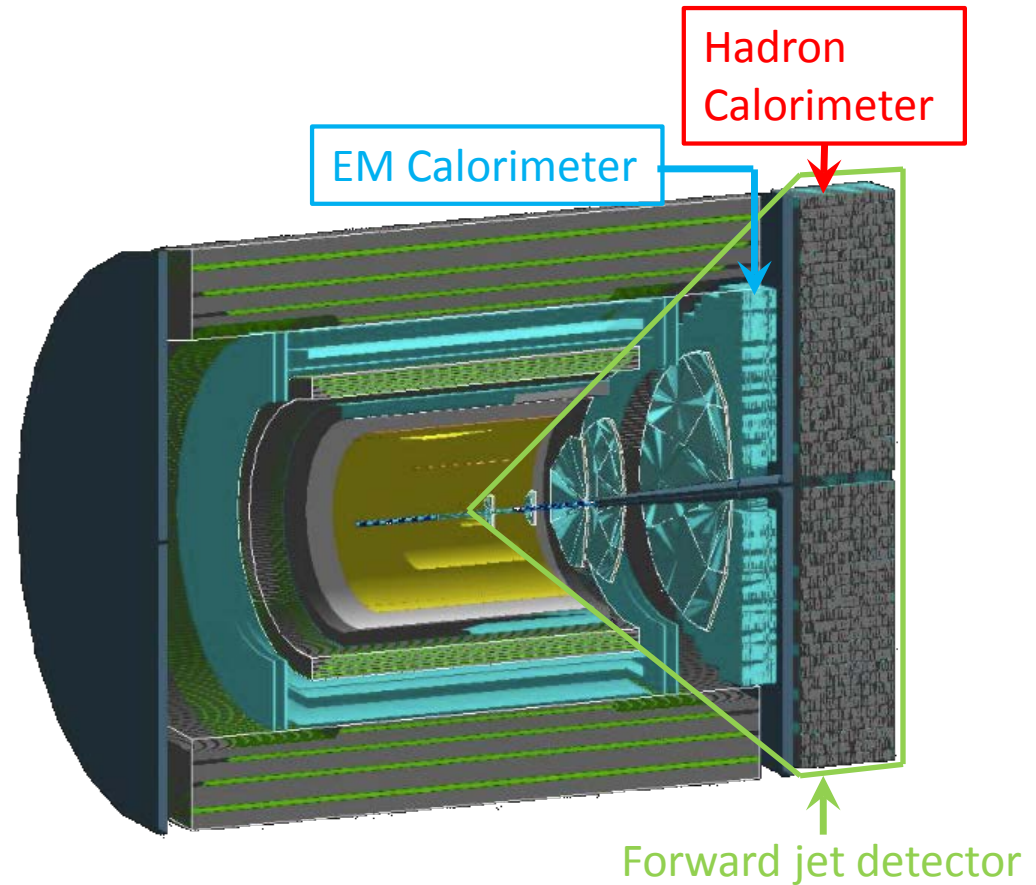
Forward sPHENIX (fsPHENIX)

- Lol 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



Spin physics at *fs*PHENIX

- Jet asymmetries tagging positive/negative hadrons
 - Separation of up-quark jet and down-quark jet
- EM + Hadron calorimeters & tracker are necessary
 - For jet + hadron measurement & triggering

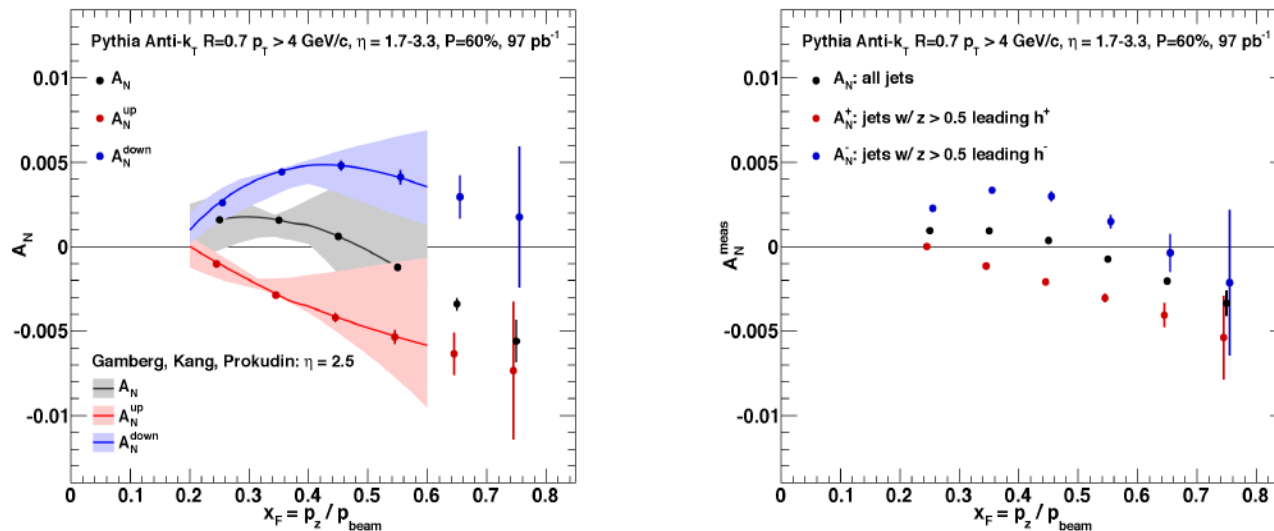


Figure 2-11: Left: up quark (red points), down quark (blue points) and all jet (black points) single spin asymmetries as a function of x_F as calculated by the ETQS based on the SIDIS Sivvers functions. Right: Expected experimental sensitivities for jet asymmetries tagging in addition a positive hadron 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

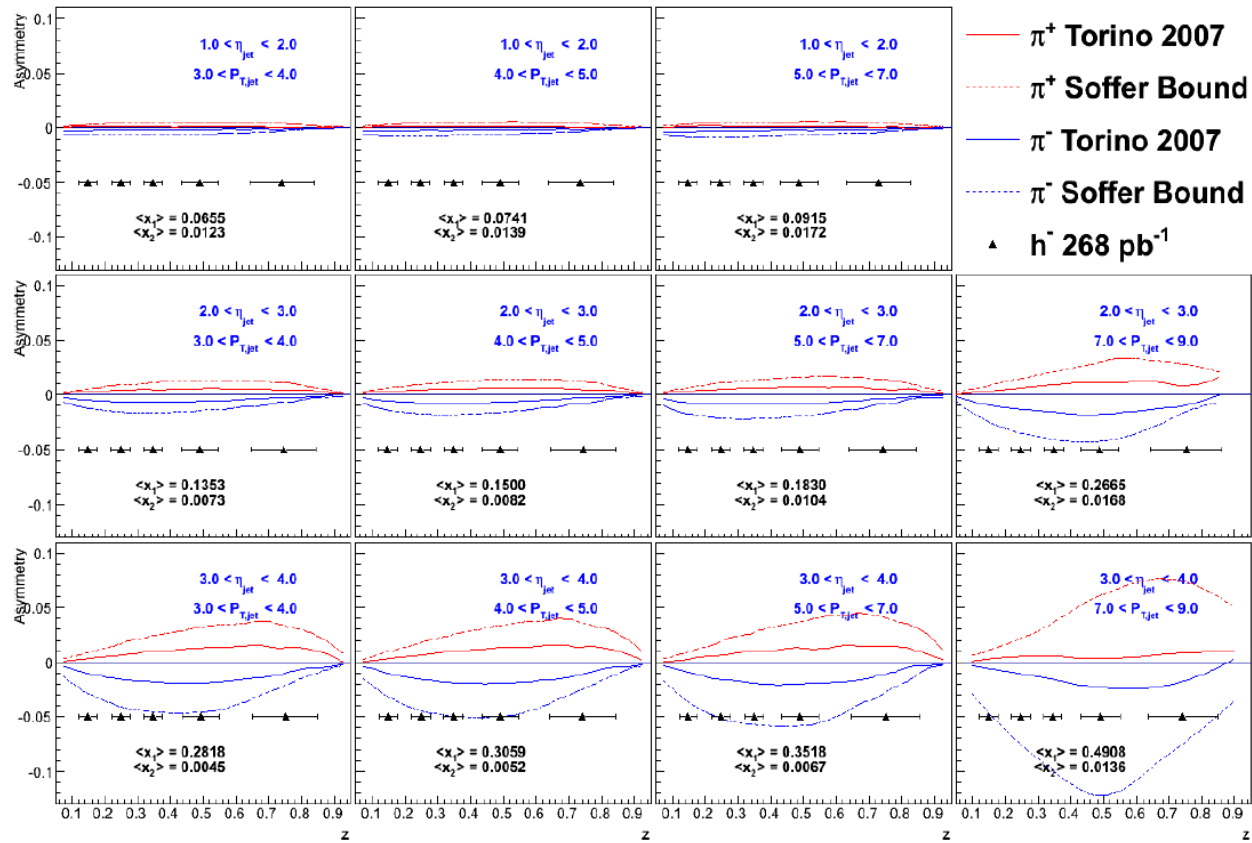


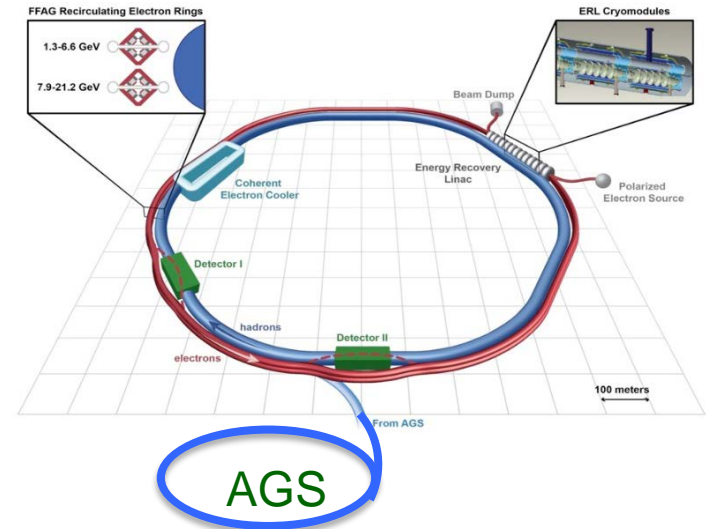
Figure 2-14: Expected h^- Collins asymmetry uncertainties (black points) compared to positive (red) and negative (blue) pion asymmetries based on the Torino extraction [45] (full lines) and the Soffer bound [83] (dashed lines) as a function of fractional energy z for various bins in jet rapidity and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

Expected h^- Collins asymmetry uncertainties

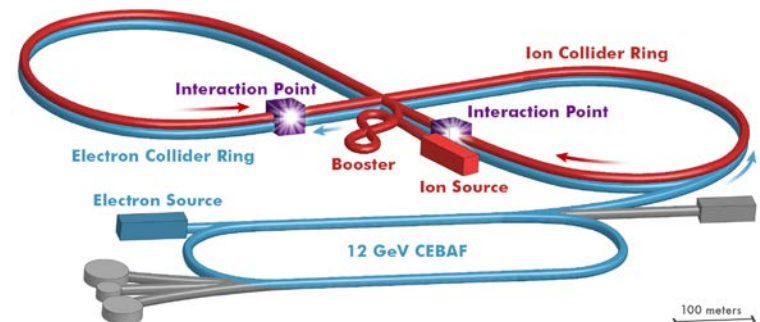
EIC (Electron Ion Collider) project

- World's first polarized electron + proton / light-ion / heavy-ion collider
 - Wide (Q^2, x) region
- Electron + proton / light-ion collision
 - Polarized beam
 - e, p, d/³He
 - High luminosity
 - $L_{ep} \sim 10^{33-34} \text{ cm}^{-2}\text{s}^{-1}$
 - 100-1000 times HERA
 - Collision energy
 - $\sqrt{s} = 20 - 100 (140) \text{ GeV}$
- Electron + heavy-ion collision
 - Wide range in nuclei

eRHIC at BNL

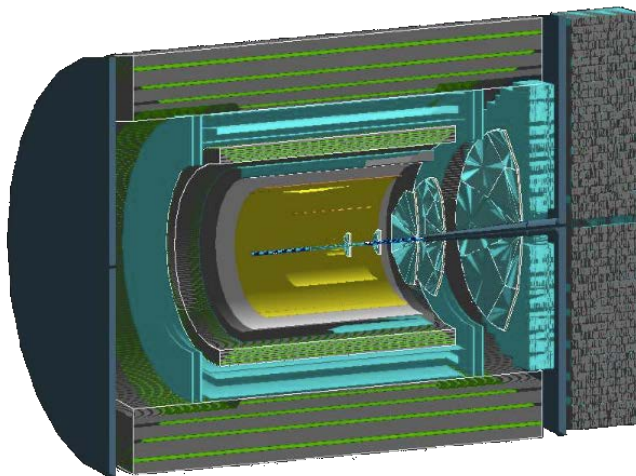


JLEIC at Jefferson Lab

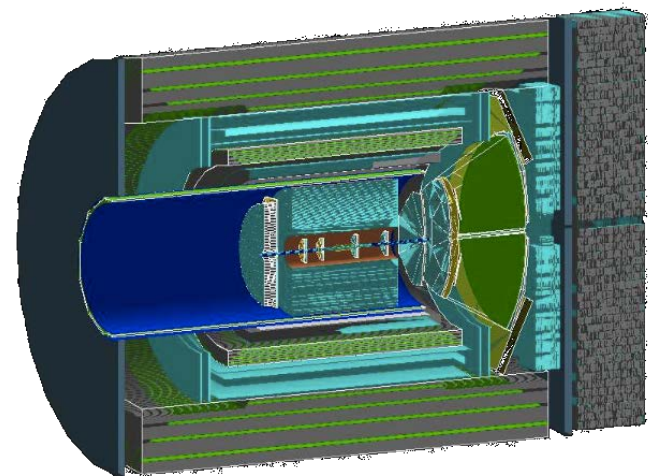
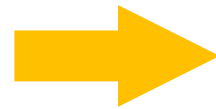


EIC project

- Recommendation for new facility construction in NSAC 2015 Long Range Plan
- Review by NAS (National Academy of Science)
 - Positive review done, report expected soon
- eRHIC detector
 - Lot of upgrade from sPHENIX to ePHENIX
 - ePHENIX hadron arm from fsPHENIX + new electron arm
- Operation in 2025 or later



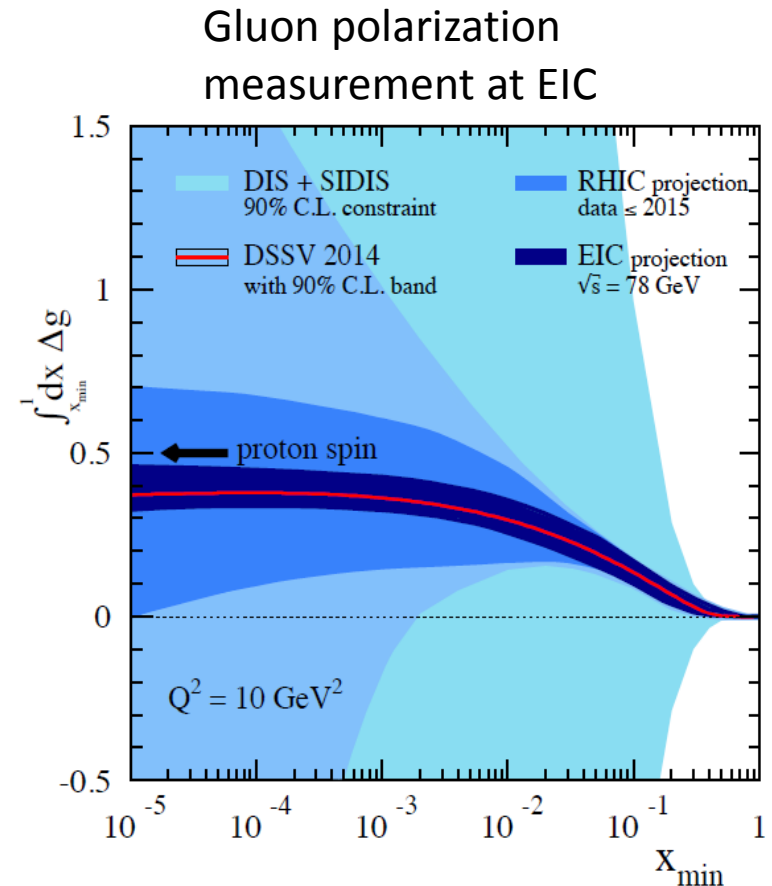
sPHENIX (+ fsPHENIX)



ePHENIX

Gluon physics at EIC

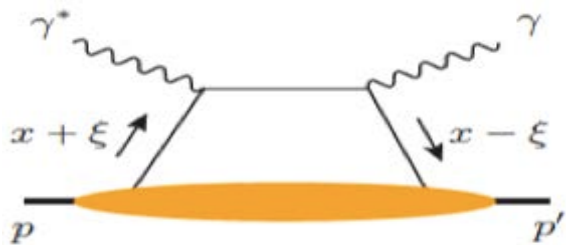
- 3D structure of nucleon and nuclei
 - TMD / GPD measurements
 - Gluon distribution (radius...)
- Nucleon spin
 - Small Broken- x region and evolution
 - GPD and orbital angular momentum
- Gluon saturation (discovery)
 - Collective gluon field
 - Initial state of Quark-Gluon Plasma
- Hadronization and jet production in nuclei



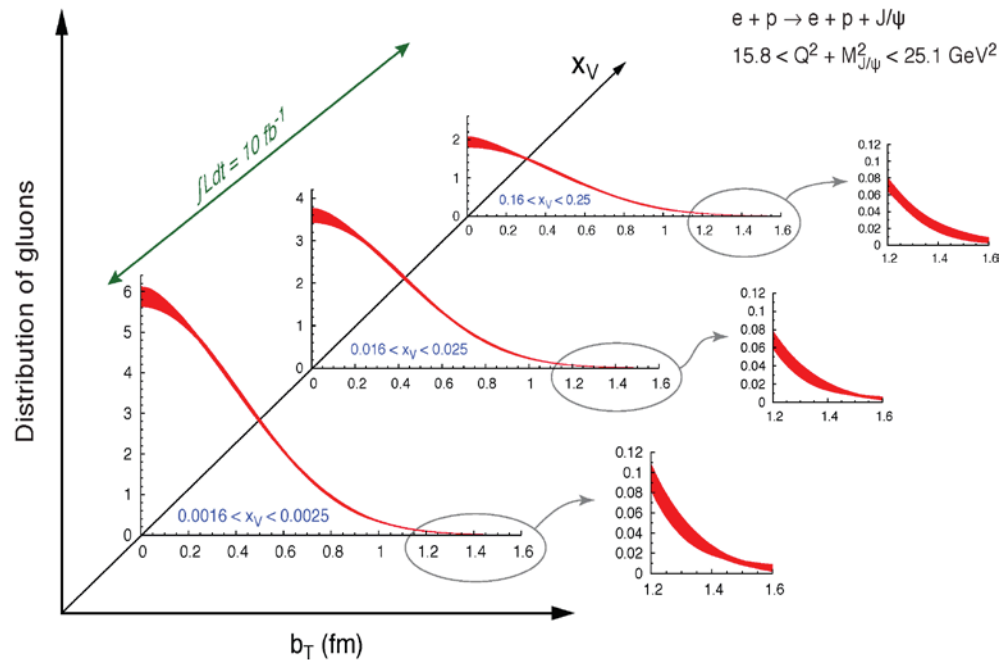
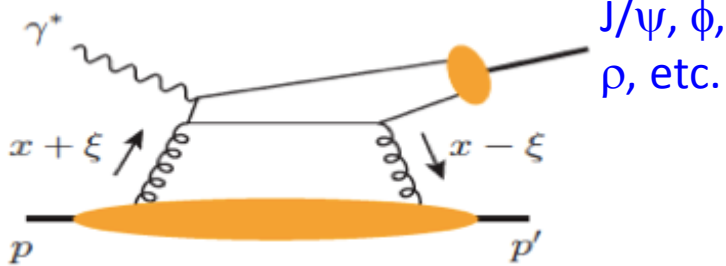
GPD (Generalized Parton Distribution)

- Tomography of the nucleon / nucleus
 - DVCS (Deeply Virtual Compton Scattering)
 - Meson production
- Spatial imaging of gluons and sea quarks
 - 2D (spatial) + 1D (longitudinal moment) coordinate space image
- Gluon GPDs from J/ψ production at EIC

DVCS (Deeply Virtual Compton Scattering)



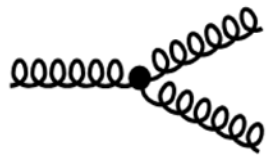
Meson Production



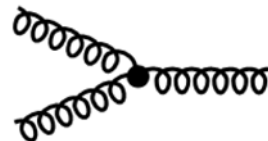
Gluon saturation

- Gluon density saturated where gluon emission and recombination comparable
 - Color glass condensate (CGC)
 - First observation of a collective gluonic system

gluon emission

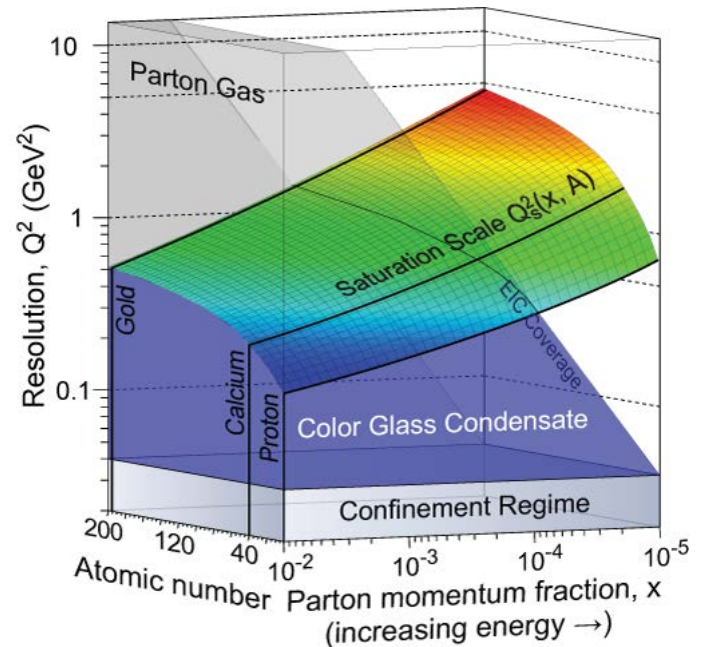
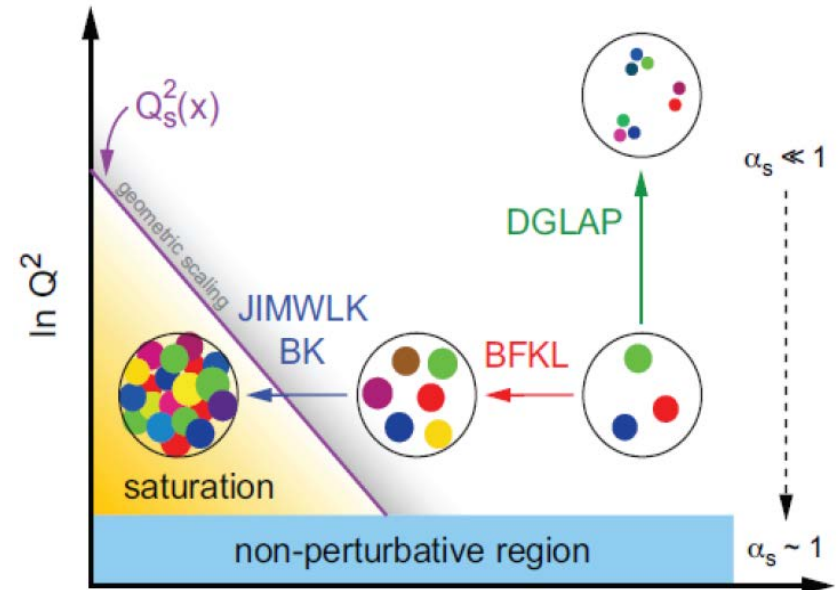


gluon recombination



At Q_s

- Enhancement with nucleus
 - Saturation at significantly lower energy in e+A collisions at EIC



Summary

- Nucleon puzzles
 - Correspondence between the constituent quark and quark+gluon
 - From 1-D picture to 3-D picture
- RHIC spin program
 - 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 (Transverse Momentum Dependent) functions
- Cold QCD plan to complete the RHIC spin program
 - Construction of the sPHENIX detector and proposal of the forward sPHENIX detector
- EIC (Electron Ion Collider) project
 - eRHIC at BNL or JLEIC at JLab
 - NAS review done positive, report expected soon
 - DOE's CD process will start
 - Proposal of upgrade from sPHENIX to ePHENIX