Introduction of Spin Physics at PHENIX

4th Korea-Japan
PHENIX Collaboration Meeting
at Hanyang University in Seoul, Korea
October 19, 2015

Yuji Goto (RIKEN/RBRC)

Hierarchy in Nature

- Glashow's ouroboros

Cosmology

microscopic

High-energy elementary particle physics

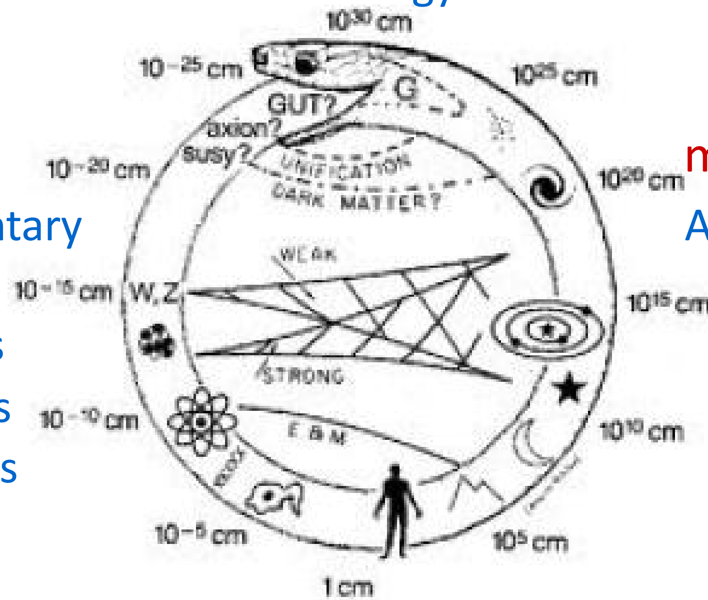
Quark-gluon physics

Hadron physics

Nuclear physics

macroscopic

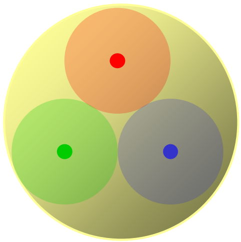
Astrophysics



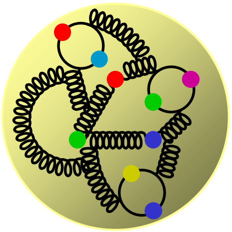
- Quark-gluon physics
  - State and structure of matter
  - Interaction and symmetry (breaking)
- Gap between "quark-gluon" and "hadron"

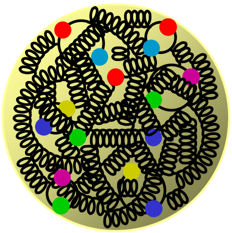
Nucleon structure

- 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

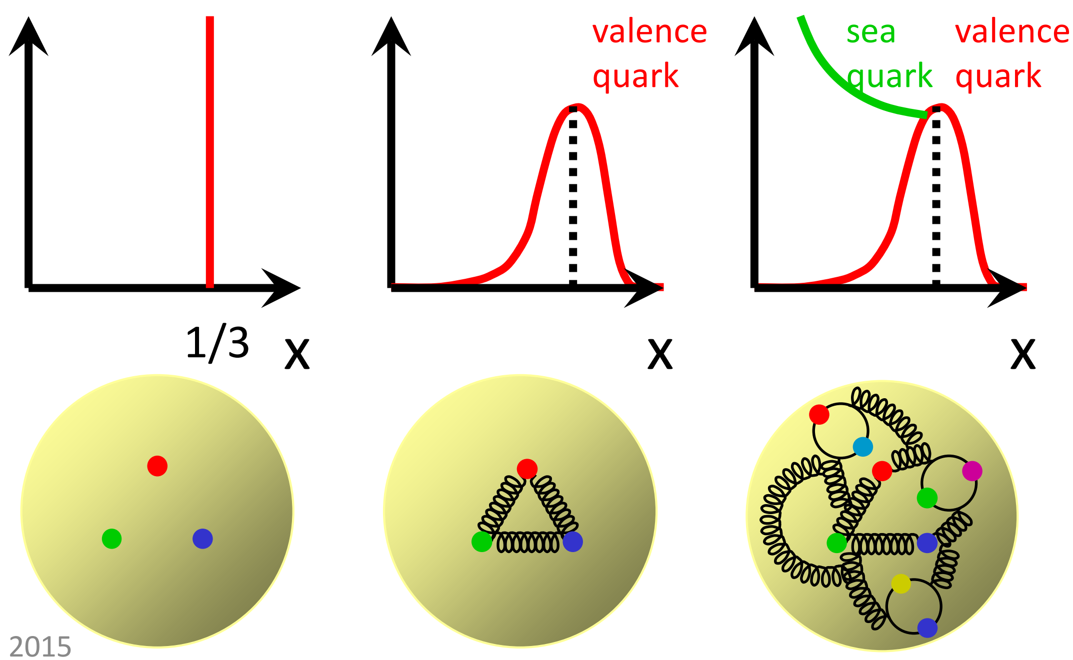




- Understanding the differences (or gap) of these models
  - Chiral symmetry (breaking)
  - Confinement

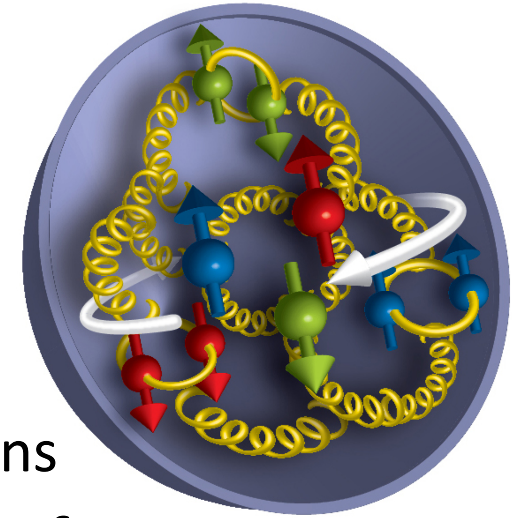
Nucleon structure

- 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)



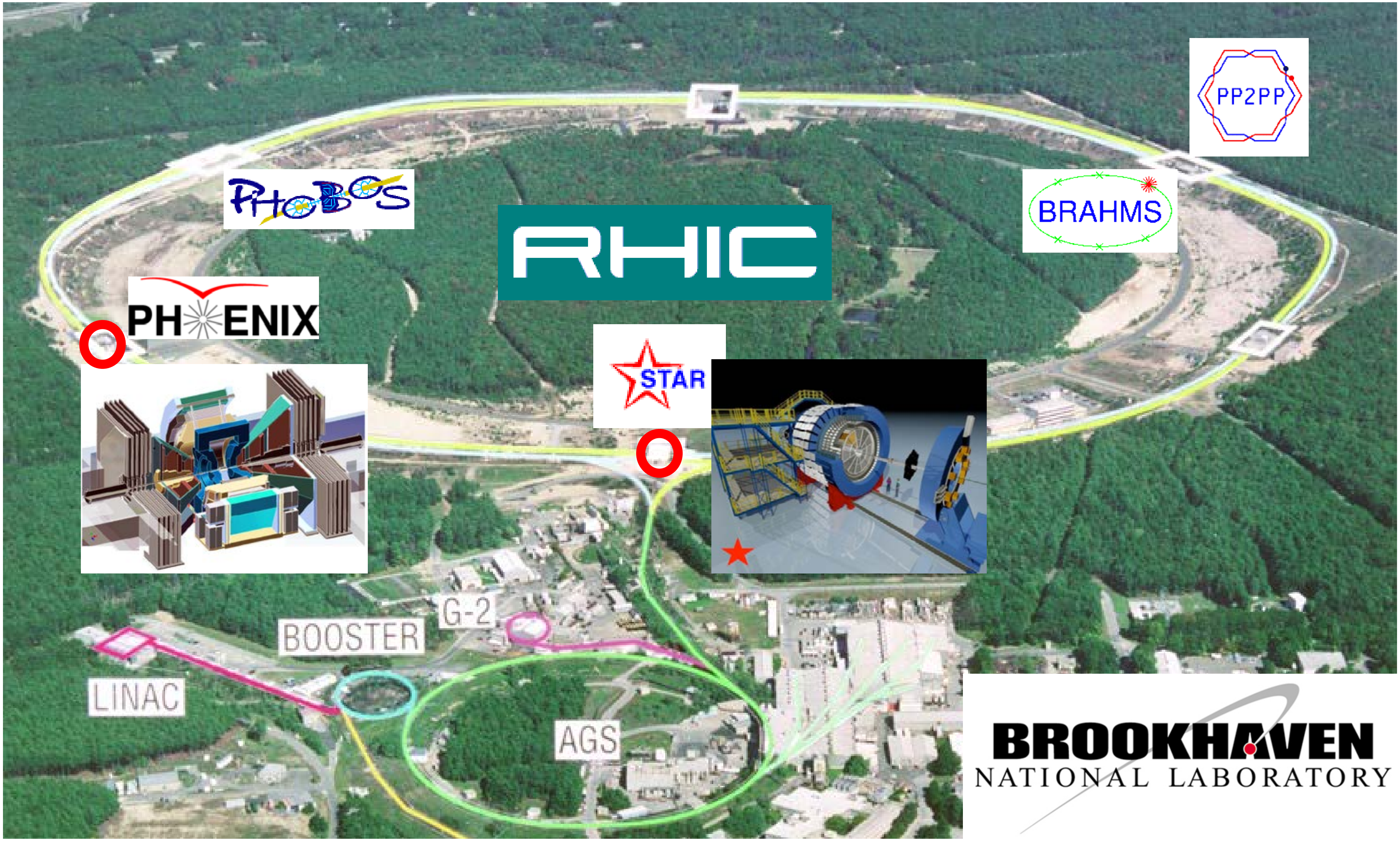
x: Bjorken’s x
“longitudinal” momentum fraction
(1-dimensional picture)

RHIC-Spin physics

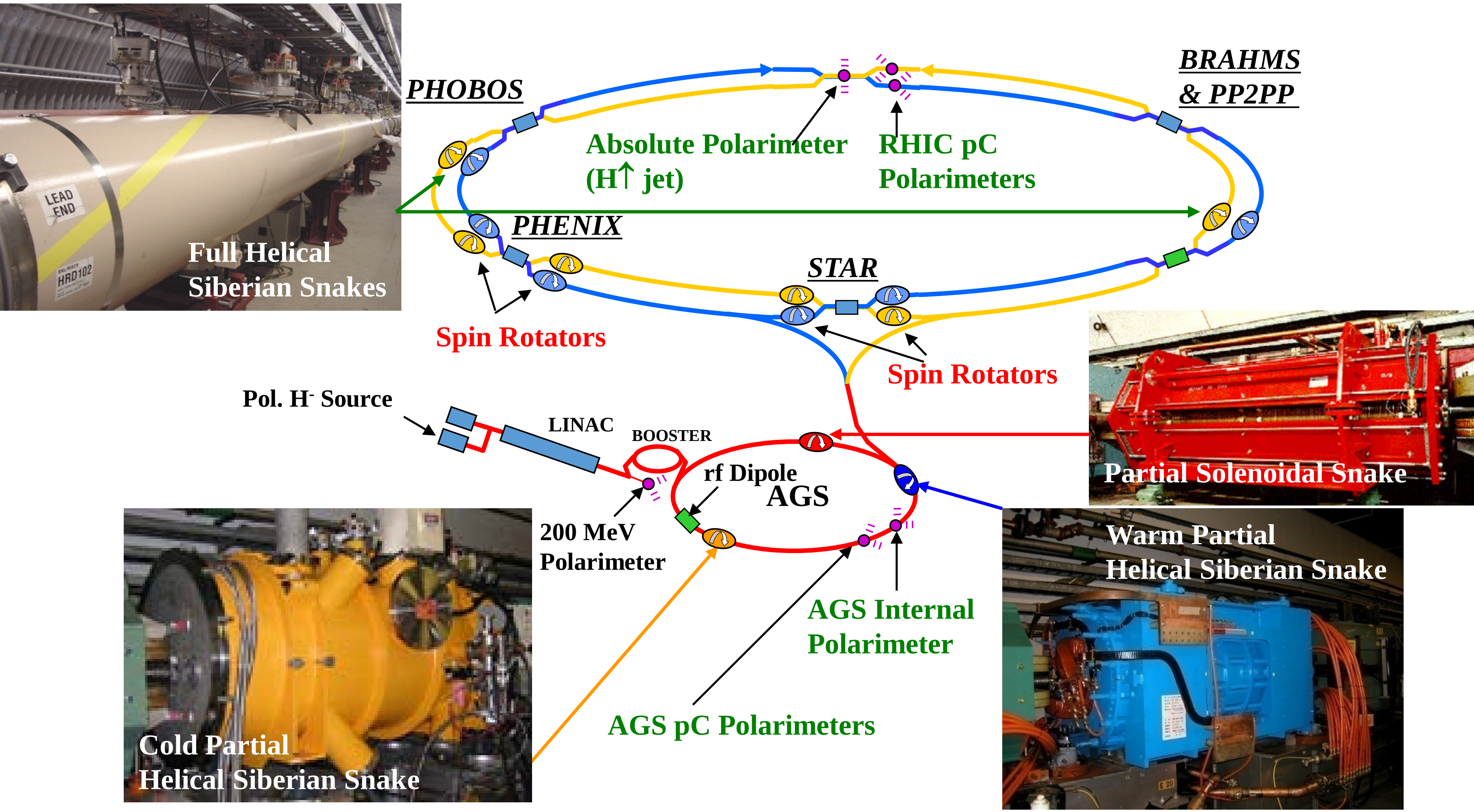


- Origin of the nucleon spin in quark-gluon picture
  - Quark spin
  - Gluon spin
  - Orbital angular momenta of quarks and gluons
- Quark-spin contribution is only 20%-30% of the nucleon spin
- Longitudinal-spin asymmetry measurement
  - Gluon polarization
  - Anti-quark polarization with W boson
- 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

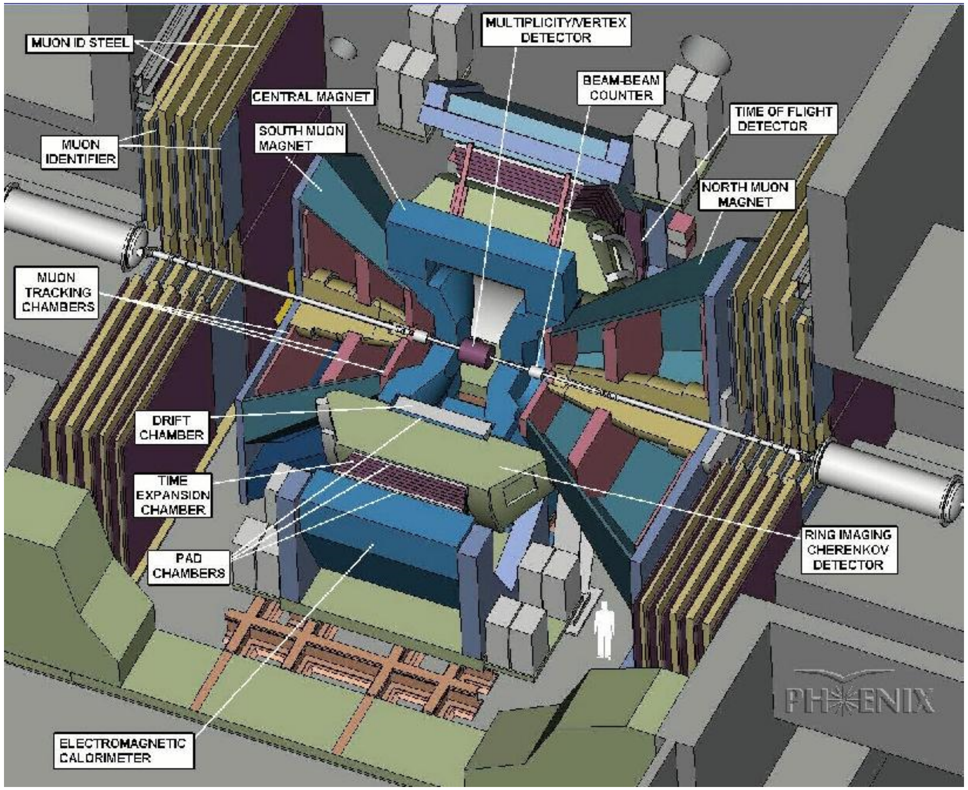
RHIC (Relativistic Heavy-Ion Collider)



RHIC polarized proton collider



PHENIX detector



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

- 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)

Gluon polarization

- Positive gluon polarization has been finally obtained at RHIC

2014. 7. 21

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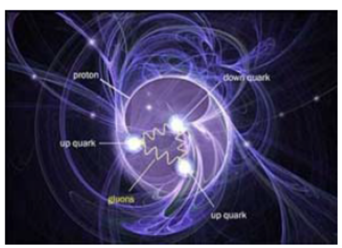
Proton Spin Mystery Gains a New Clue

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

July 21, 2014 | By Clara Moskowitz



Brookhaven National Laboratory

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

2014. 7. 11

IOP Physics World - the member magazine of the Institute of Physics

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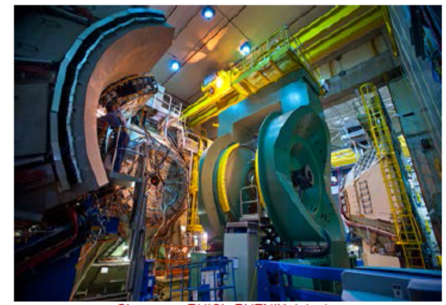
Gluons get in on proton spin

Jul 11, 2014 — 14 comments



Gluon gun: RHIC's PHENIX detector

For a quarter of a century, physicists have faced a paradox regarding the net spin of protons and neutrons – the spin of their constituent quarks accounts for only a small fraction of their overall spin. Now, new research carried out by physicists in Argentina and Germany who have analysed data produced by the Relativistic Heavy Ion Collider (RHIC), suggests that the missing spin might come from gluons that hold quarks together.

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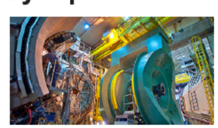
Synopsis: Gluons Chip in for Proton Spin



Brookhaven National Laboratory

Evidence for Polarization of Gluons in the Proton
Daniel de Florian, Rodolfo Sassot, Marco Stratmann, and Werner Vogelsang
Phys. Rev. Lett. **113**, 012001 (2014)
Published July 2, 2014

The proton has a spin that comes from its constituent quarks and gluons. Experiments in the 1980s found—unexpectedly—that the contribution from the intrinsic spins of the quarks was small. This so-called "proton spin crisis" remains unresolved, but a new comprehensive analysis of proton scattering data, reported in *Physical Review Letters*, finds the first clear evidence that the gluon spin polarization is not zero, suggesting that gluons may have a significant role in the spin of the proton.

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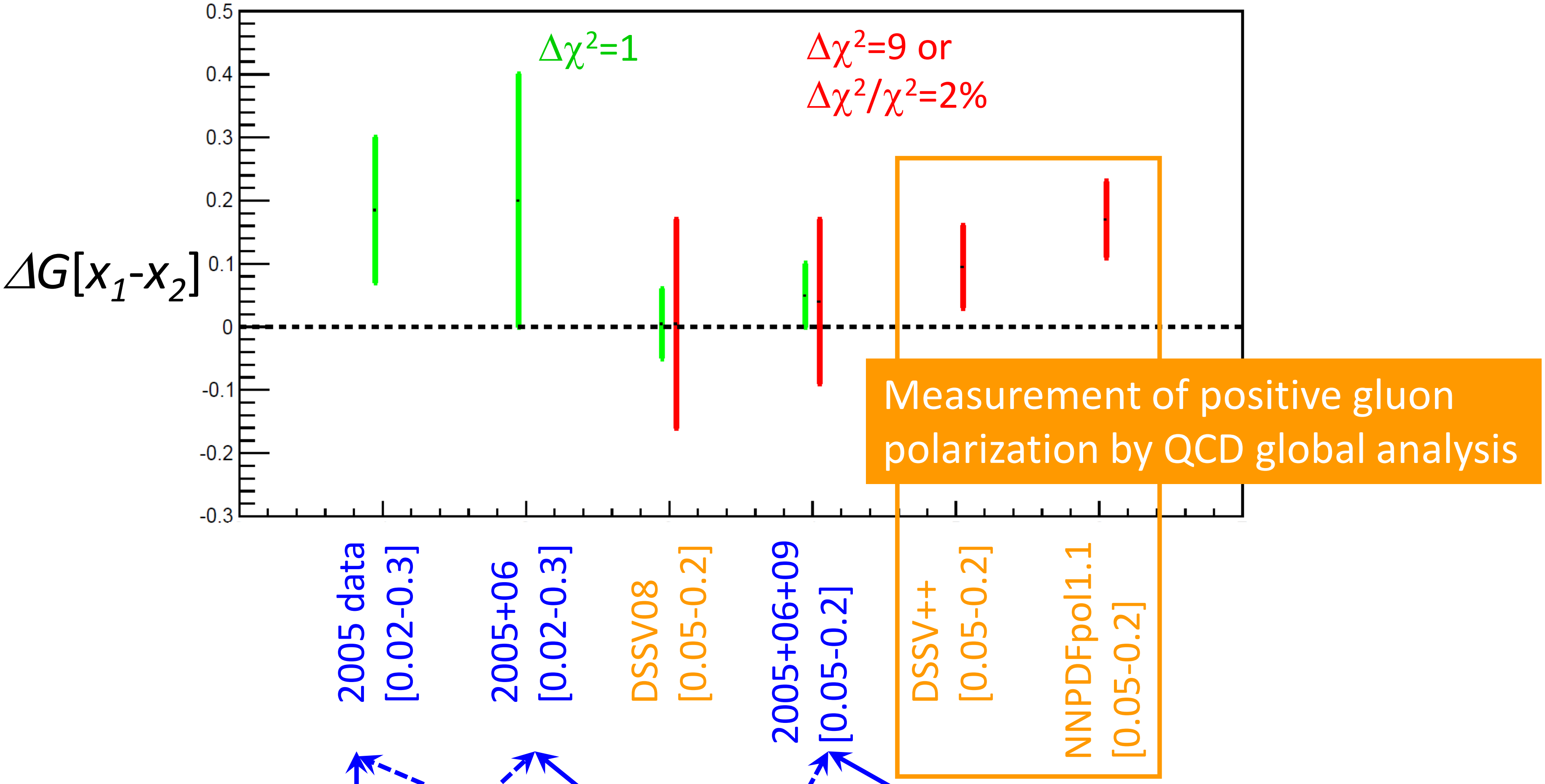
Gluon polarization: π^0 asymmetry measurement



PRD76 (2007) 051106 PRL103 (2009) 012003 PRD90 (2014) 012007

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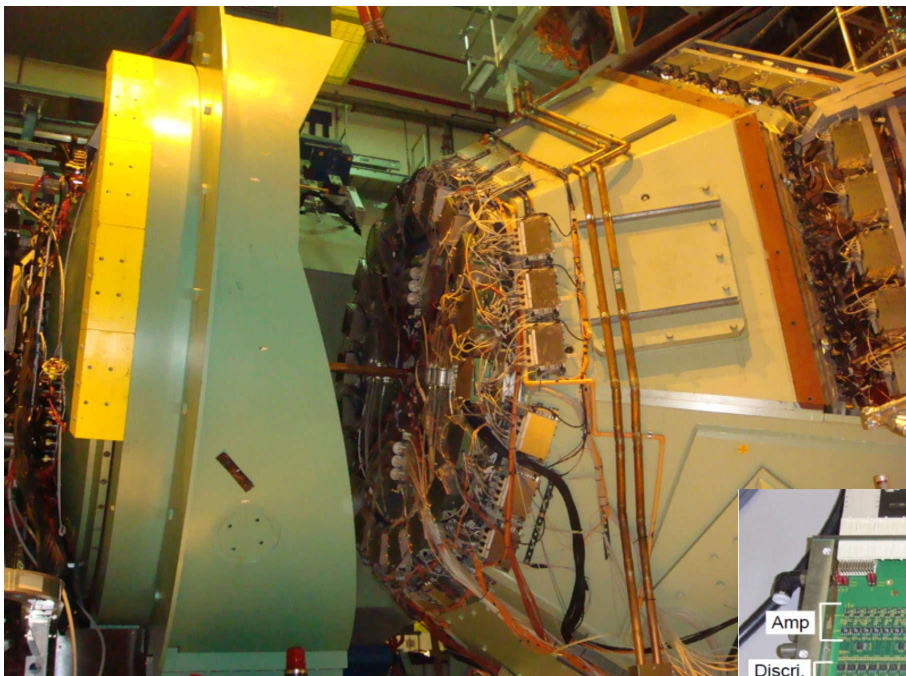
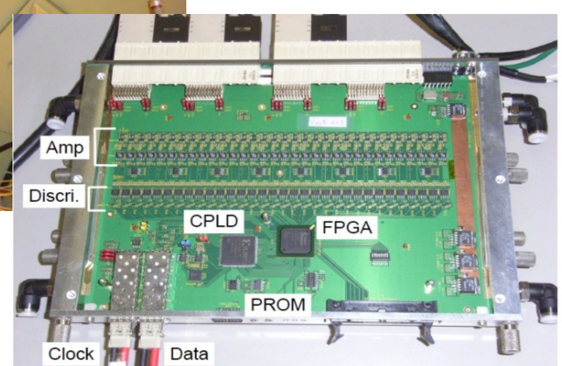
Anti-quark polarization with W boson

- Muon trigger upgrade for W boson measurement
  - Trigger FEE of Muon Tracker
  - RPC (Resistive Plate Chamber)



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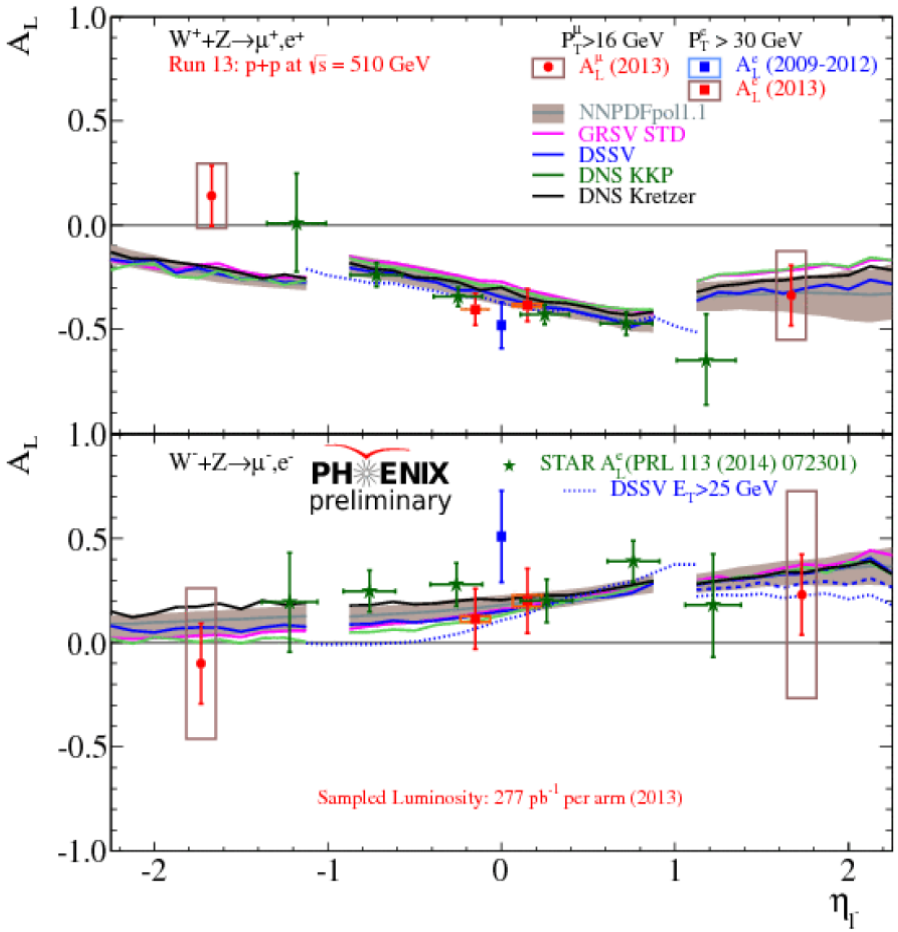
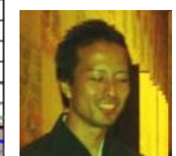
Anti-quark polarization with W boson

- RHIC W-boson run performed until 2013

STAR 2012 Results
PHENIX 2013 (Preliminary) Results





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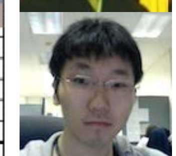

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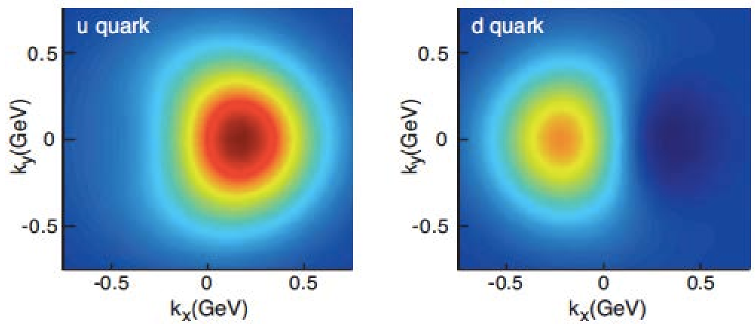
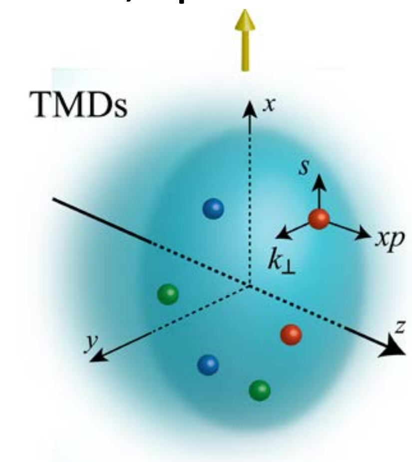
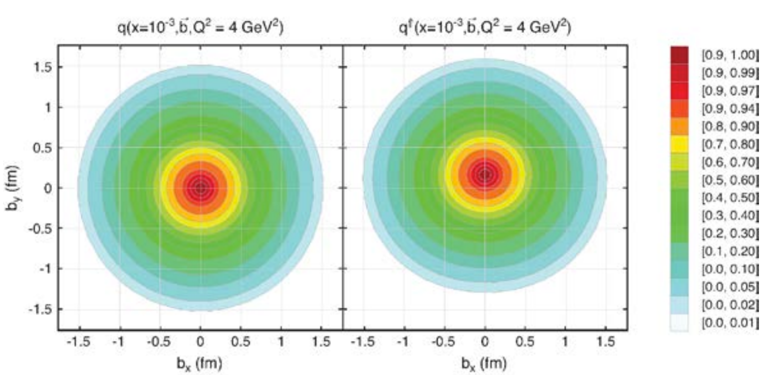
3D structure of the nucleon

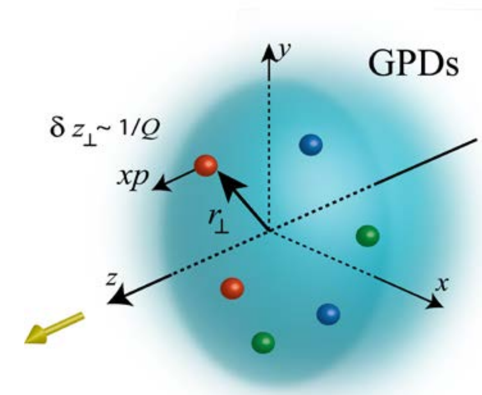
- Conclusive understanding of the nucleon spin
  - orbital motion inside the nucleon and orbital angular momenta of quarks and gluons
- TMD (Transverse-Momentum Dependent) distribution function
  - Correlation between transverse-momentum distribution, spin and orbital motion





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

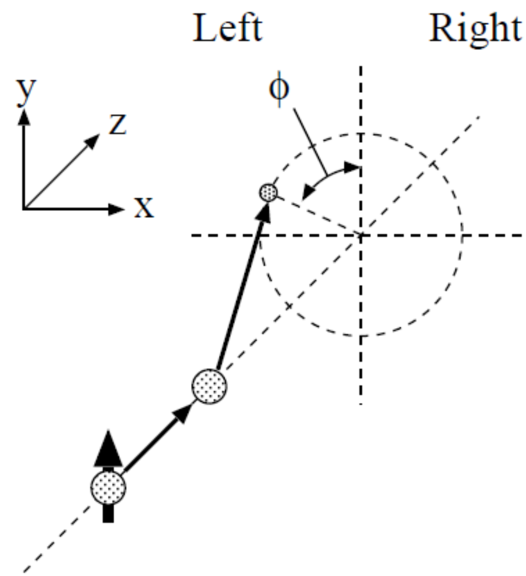




Transverse-spin asymmetry measurement

- Transverse single spin asymmetry (SSA)

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

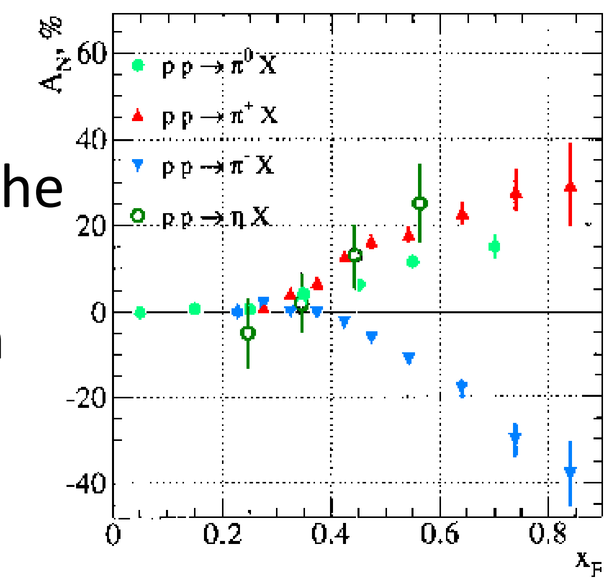


  - Expected to be small in hard scattering at high energies

$$A_N \approx \frac{m_q \alpha_S}{p_T} \approx 0.001$$

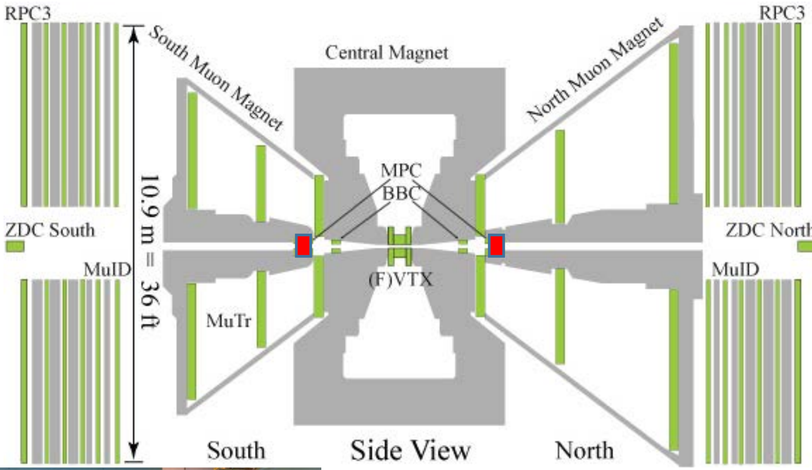
Kane, Pumplin, Repko
PRL 41 1689 (1978)

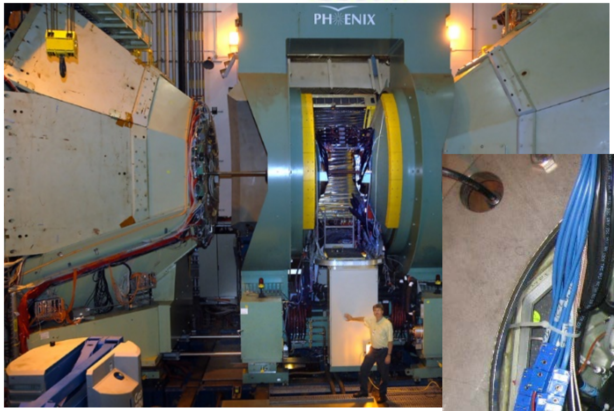
- FNAL-E704
  - Unexpected large asymmetry found in the forward-rapidity region
  - Development of many models based on perturbative QCD

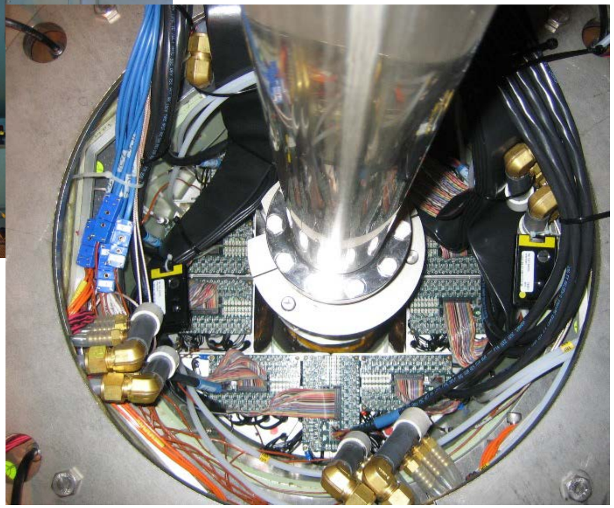


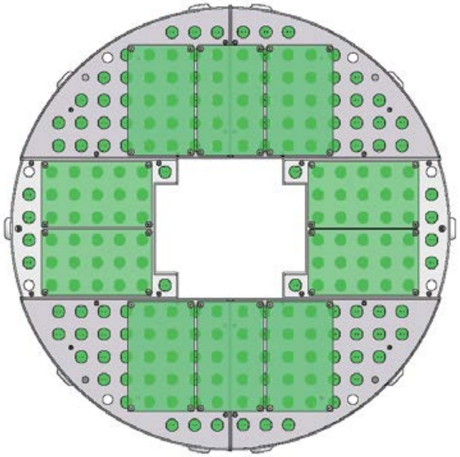
MPC

- 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
    - $3.1 < |\eta| < 3.9$



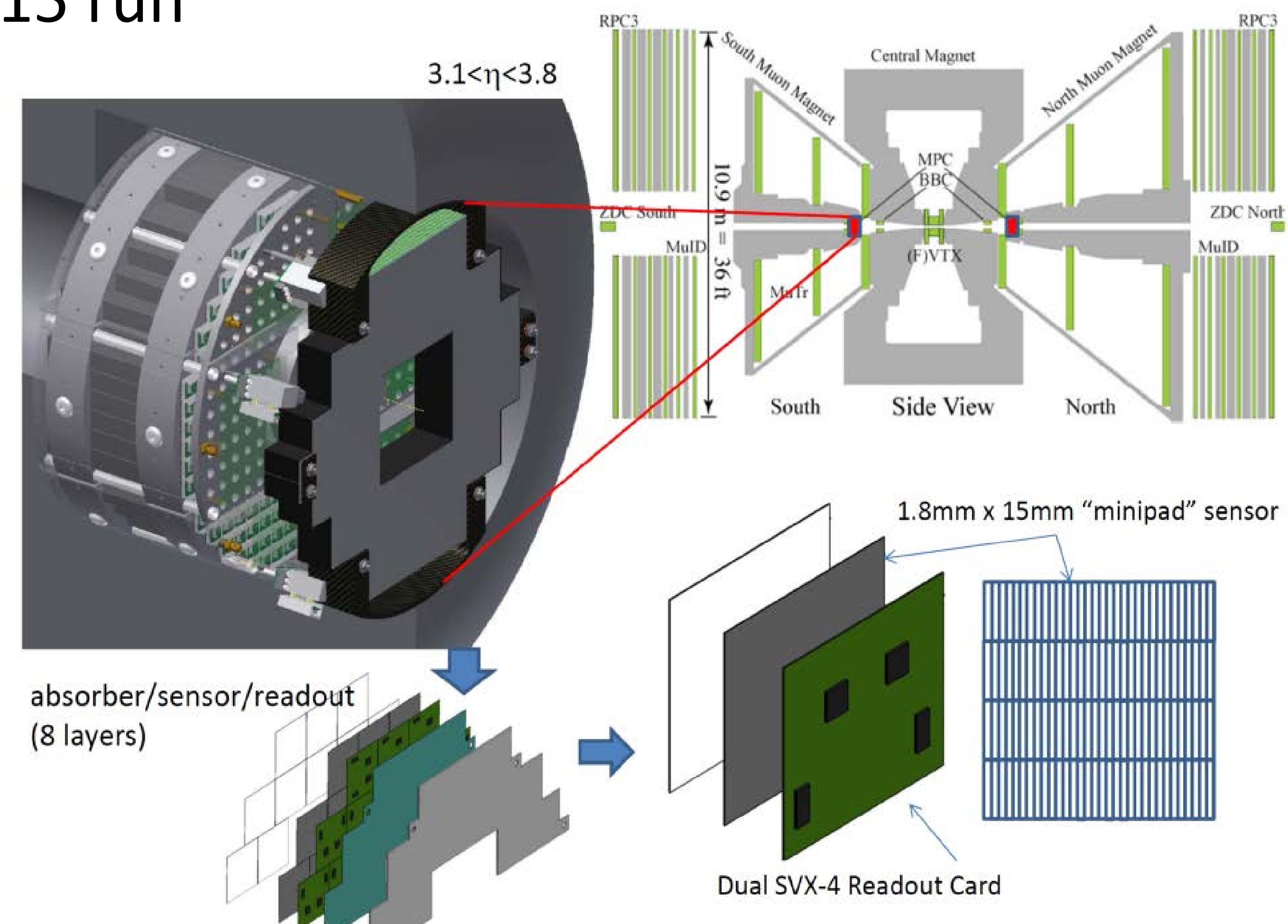






MPC-EX

- Pre-shower detector in front of MPC
  - Silicon mini-pad detectors with tungsten plates
- 2015 run



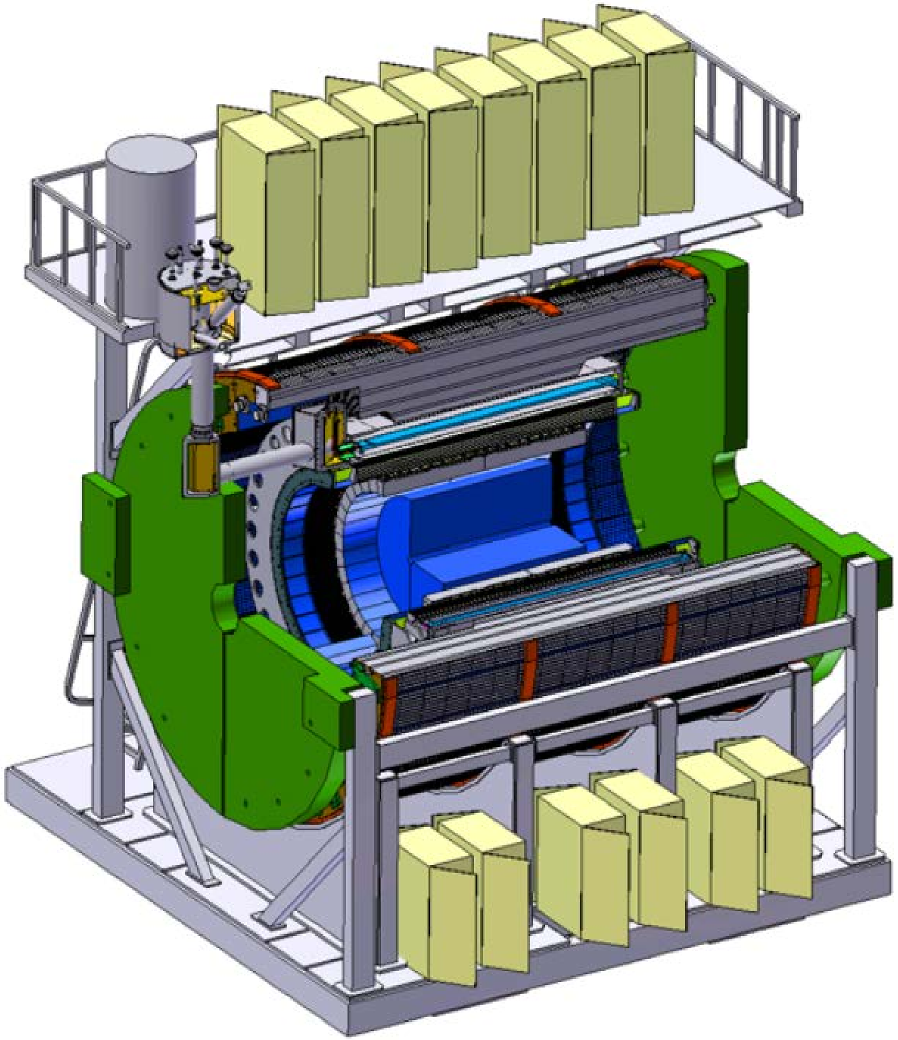
RHIC schedule

- PHENIX will end data taking after 2016 run
  - Polarized proton runs have already ended in 2015
- "sPHENIX" in 2021-22
  - Starting as a new collaboration
  - There will be polarized proton runs

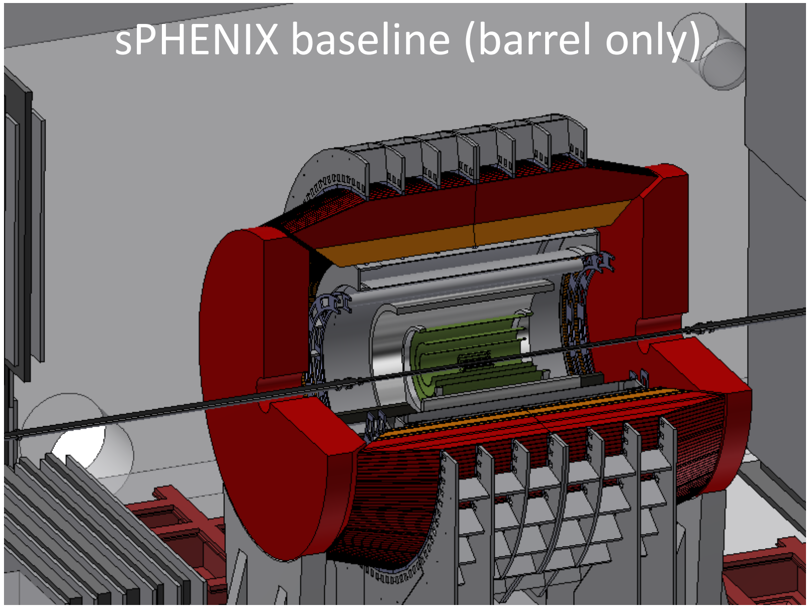
Years	Beam Species and	Science Goals	New Systems
2014	Au+Au at 15 GeV Au+Au at 200 GeV ^{3}He+Au at 200 GeV	Heavy flavor flow, energy loss, thermalization, etc. Quarkonium studies QCD critical point search	Electron lenses 56 MHz SRF STAR HFT STAR MTD
2015-16	p↑+p↑ at 200 GeV p↑+Au, p↑+Al at 200 GeV High statistics Au+Au Au+Au at 62 GeV ?	Extract $\eta/s(T)$ + constrain initial quantum fluctuations Complete heavy flavor studies Sphaleron tests Parton saturation tests	PHENIX MPC-EX STAR FMS preshower Roman Pots Coherent e-cooling test
2017	p↑+p↑ at 510 GeV	Transverse spin physics Sign change in Sivers function	
2018	No Run		Low energy e-cooling install. STAR iTPC upgrade
2019-20	Au+Au at 5-20 GeV (BES-2)	Search for QCD critical point and onset of deconfinement	Low energy e-cooling
2021-22	Au+Au at 200 GeV p↑+p↑, p↑+Au at 200 GeV	Jet, di-jet, γ-jet probes of parton transport and energy loss mechanism Color screening for different quarkonia Forward spin & initial state physics	sPHENIX Forward upgrades ?
≥ 2023 ?	No Runs		Transition to eRHIC

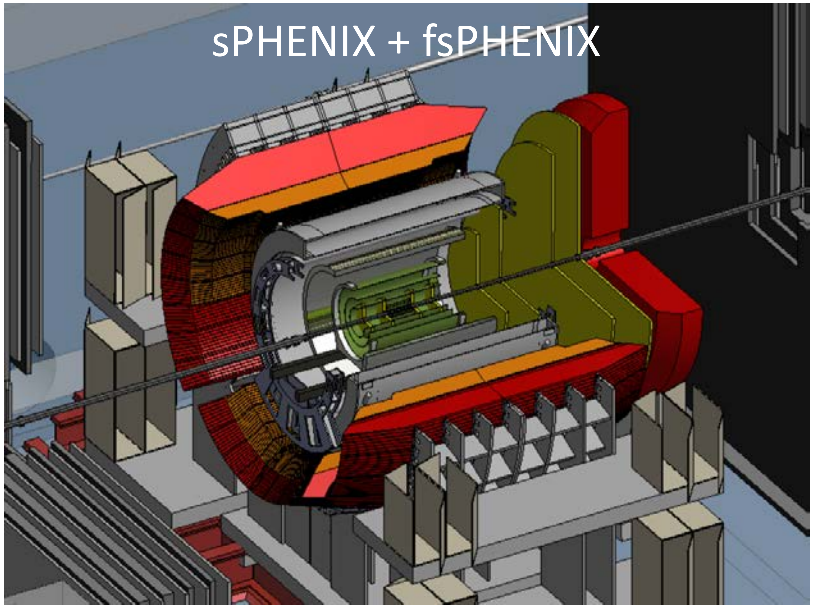
"sPHENIX"

- A new large-acceptance jet and Upsilon detector around the BaBar megnet
- Probe QGP with precision measurements of jet quenching and Upsilon suppression
- Spin physics and initial conditions at forward rapidities with p+p and p+A collisions



Forward "sPHENIX"





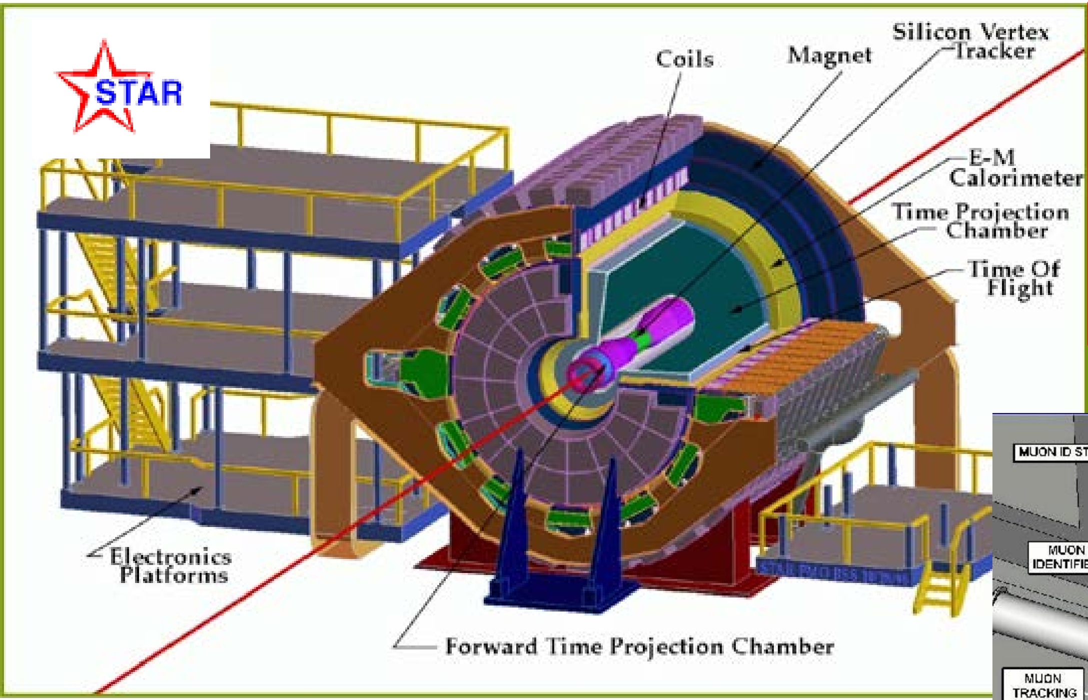
- Transverse spin physics
  - Transverse spin "puzzle"
  - Large single spin asymmetry (SSA) in the forward region
  - Understanding of the orbital motion
- p+A and p↑+A physics
  - Cold Nuclear Matter (CNM) effects
  - Polarization for probe to the gluon saturation

Summary

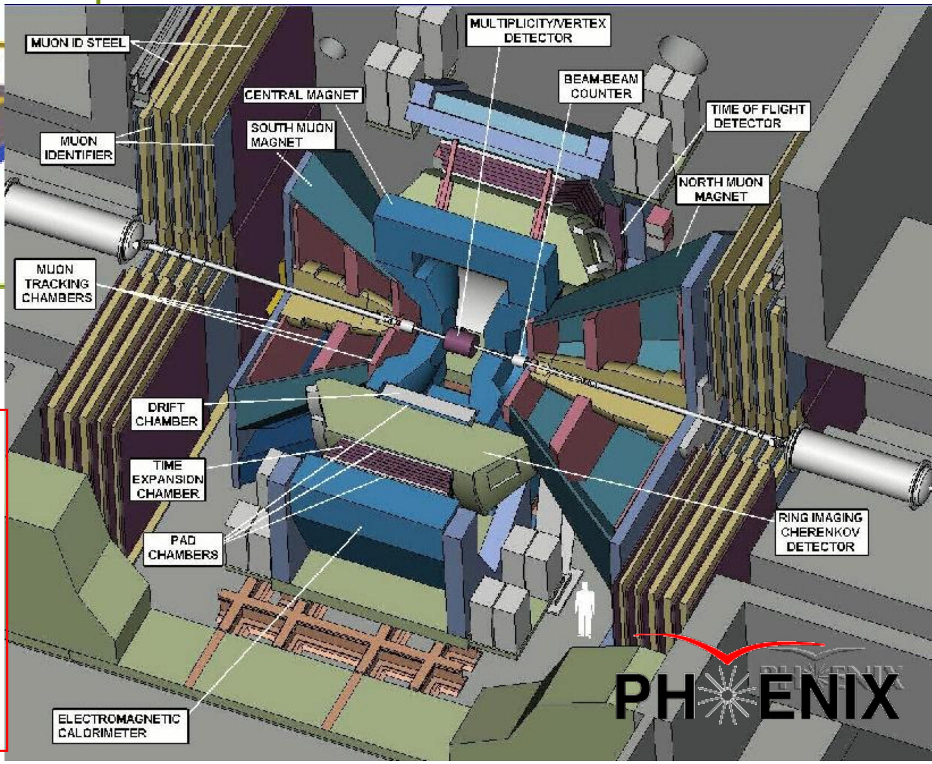
- Origin of the nucleon spin in quark-gluon picture
- Longitudinal-spin asymmetry measurements
  - Positive gluon polarization has been finally obtained
  - Anti-quark polarization with W boson
- Transverse-spin asymmetry measurements
  - Orbital motion inside the nucleon
  - 3D structure of the nucleon
- PHENIX polarized proton runs have already ended in 2015
- “sPHENIX“ in 2021-22
  - Transverse-spin physics with forward “sPHENIX”

Backup slides

PHENIX and STAR



- 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

Origin of the nucleon spin 1/2

- Expected to be explained by the quark spin (from the constituent quark model)
- Experiments
  - CERN-EMC experiment (polarized DIS experiment)
    - Quark-spin contribution
      $\Delta\Sigma = \Delta u + \Delta d + \Delta s = 12 \pm 9(\text{stat}) \pm 14(\text{syst})\%$
    - Combining with neutron and hyperon decay data
    - Total quark spin constitutes a small fraction of the nucleon spin
    - Integration in x = 0 ~ 1 makes uncertainty
  - SLAC/CERN/DESY/JLAB experiments
    - More data to cover wider x region with more precision
- Based on the quark-gluon model

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

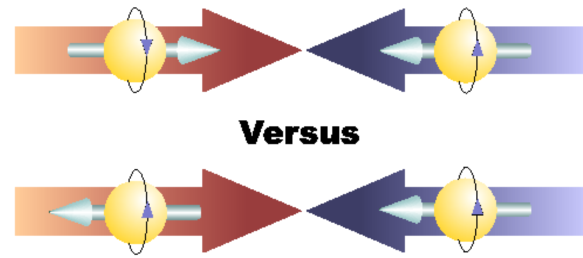
Orbital angular momentum

Gluon spin contribution

Quark spin contribution

Helicity structure of the nucleon

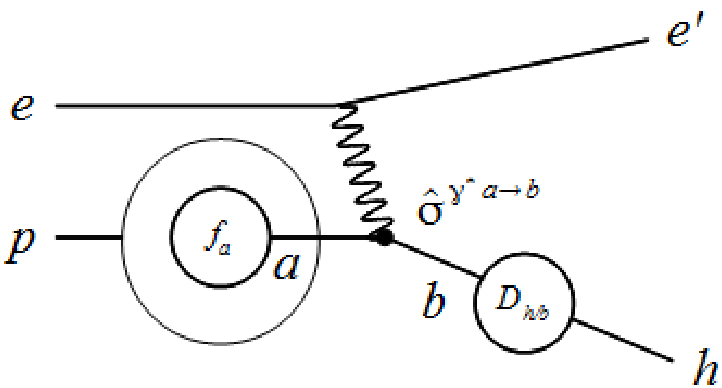
- Longitudinally polarized experiment
  - Polarized in beam or collision direction



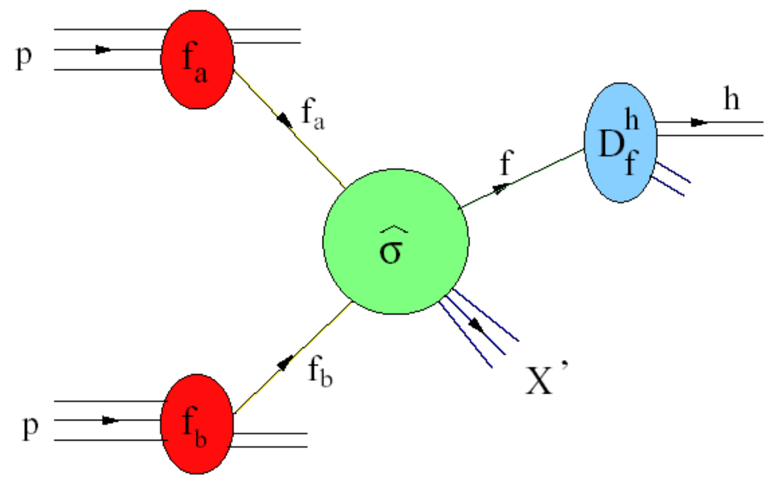
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

  - $f_a(x)$ or $q(x)$: parton distribution function (PDF)
    - "universal" property of the nucleon – same in all reactions

Deep Inelastic Scattering (DIS)



p+p Collision



unpolarized structure function

$$F_2(x) = x \sum_a e_a^2 f_a(x)$$

polarized structure function

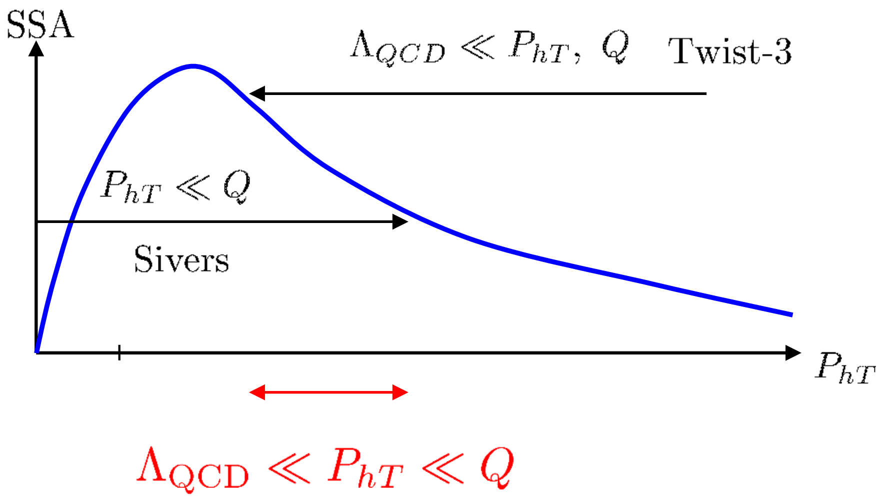
$$g_1(x) = \sum_a e_a^2 \Delta f_a(x)$$

$\Delta f_a(x)$ or $\Delta q(x)$: polarized PDF

TMD and higher-twist

- Theoretical description of SSA
  - TMD at low p_T and high Q^2
  - Higher twist at high p_T
  - Common description at medium p_T
- SSA description with initial state effect

$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

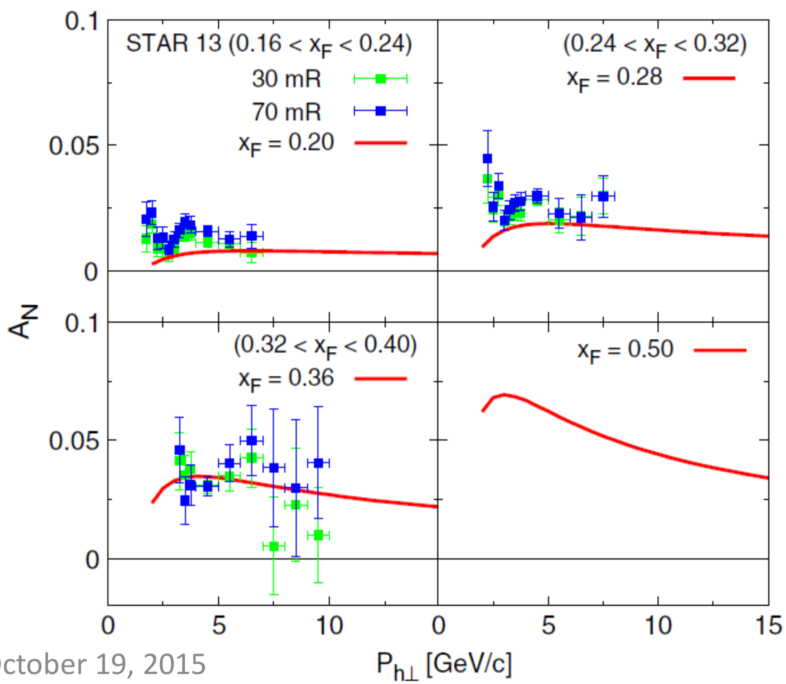


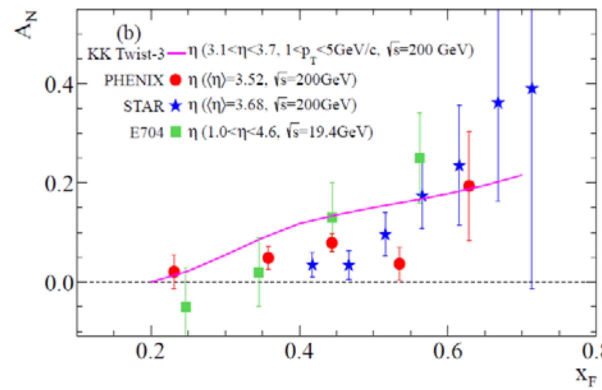
Twist-τ =
Suppressed by $\left(\frac{\Lambda_{\text{QCD}}}{Q}\right)^{\tau-2}$

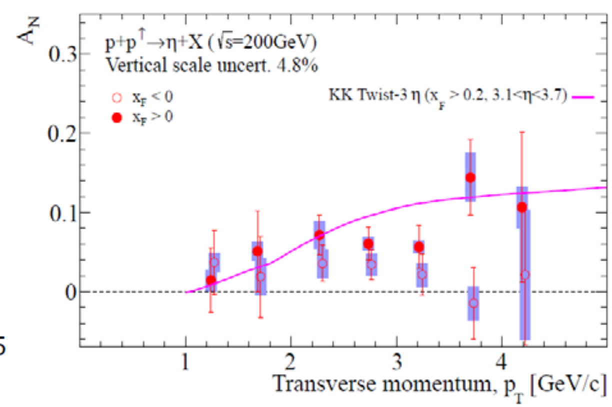
High-p_T measurements

- Measured SSA
  - No significant drop at high p_T
  - Not only initial state but also final state effect necessary
- Higher twist calculation of initial state and final state
  - Good fit with a new twist-3 fragmentation function

Kanazawa, Koike, Metz, Pitonyac: PRD89, 111501 (2014)

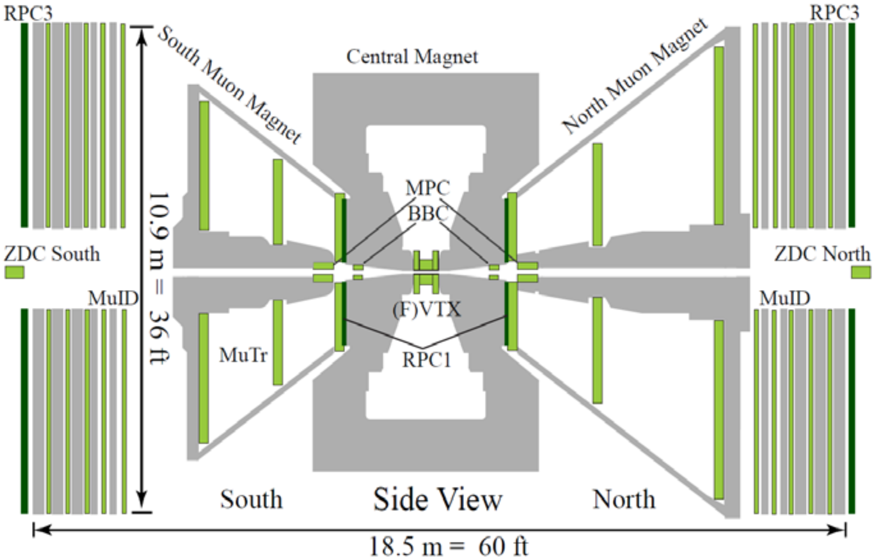






Transverse-polarization runs

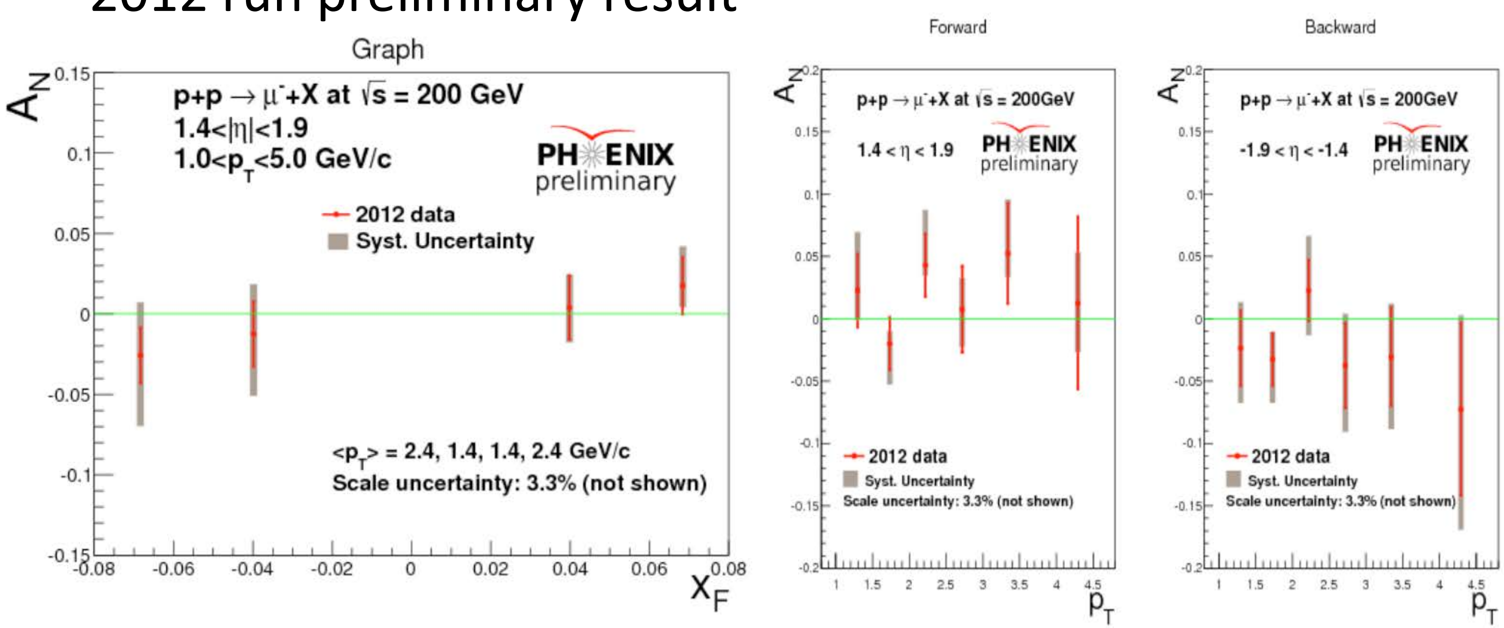
- Muon arm 2001-
- MPC 2006-
  - EM calorimeter
- FVTX 2012-
  - Silicon detector
- MPC-EX 2015-
  - Preshower detector



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}

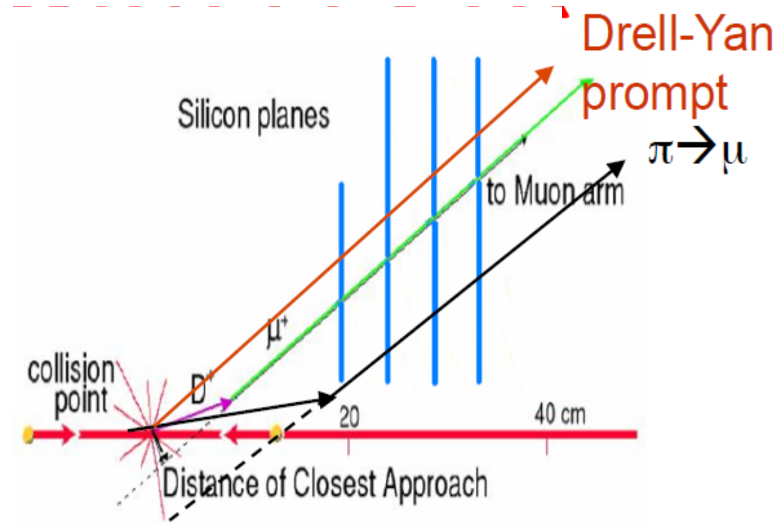
Heavy-flavor measurements

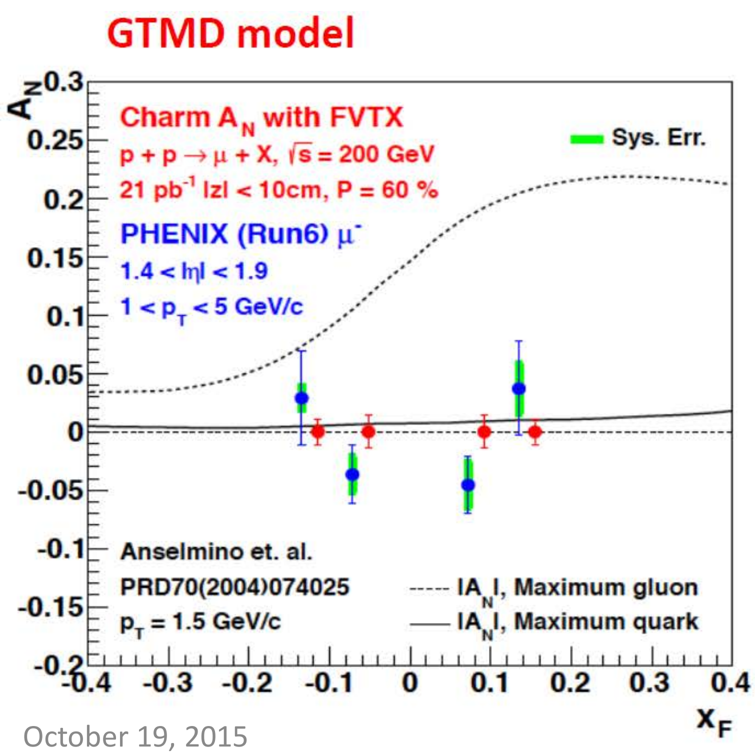
- Gluon contribution
  - Quark sector good knowledge
    - Twist-3 quark-gluon correlation functions
  - Gluon sector largely unknown
    - Twist-3 tri-gluon correlation functions
- Heavy-flavor from gluon-gluon process
  - No final state effect
- Single muon SSA
  - 2012 run preliminary result

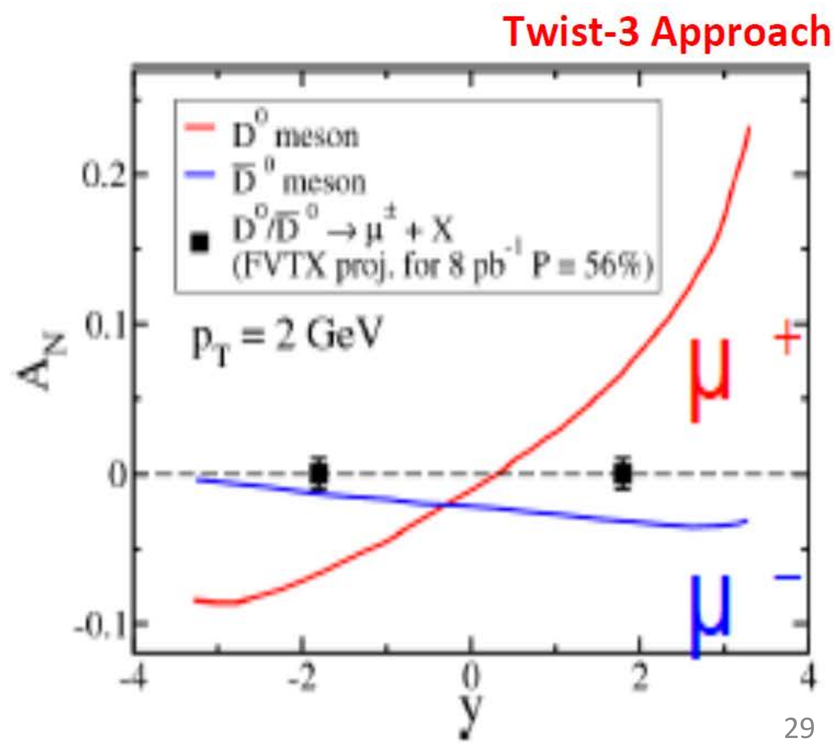


Single muon SSA

- Much improved results expected from 2015 run with VTX and FVTX

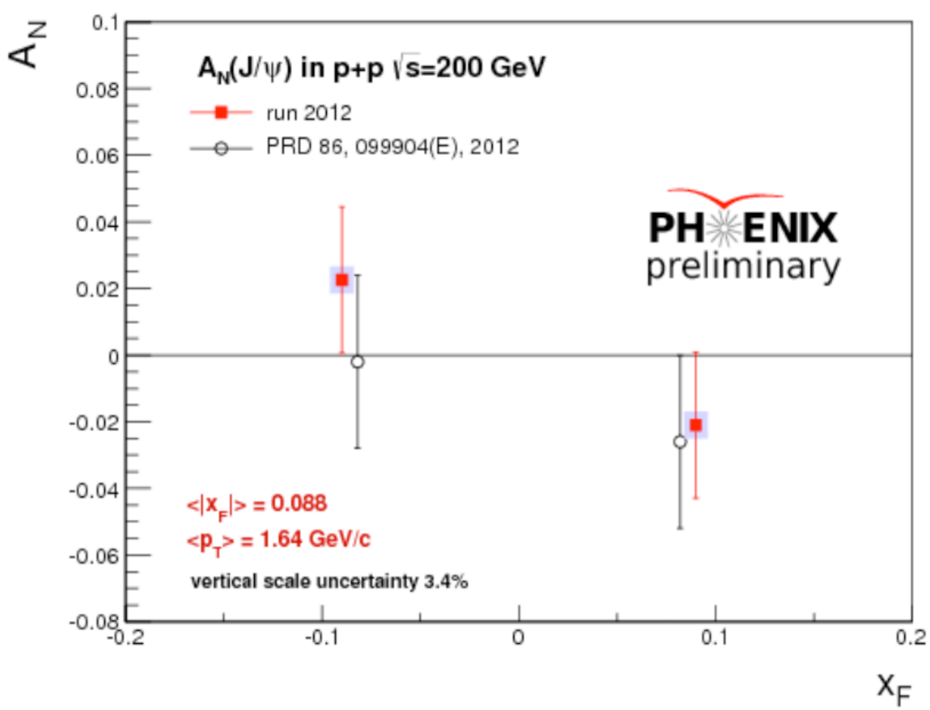


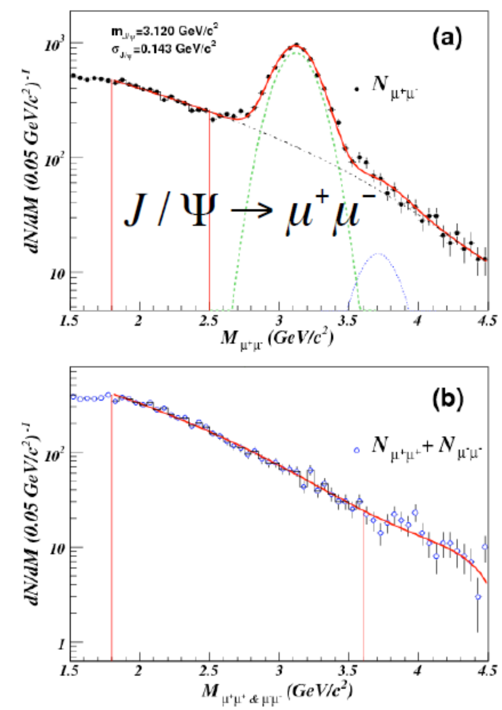




Forward J/ψ SSA

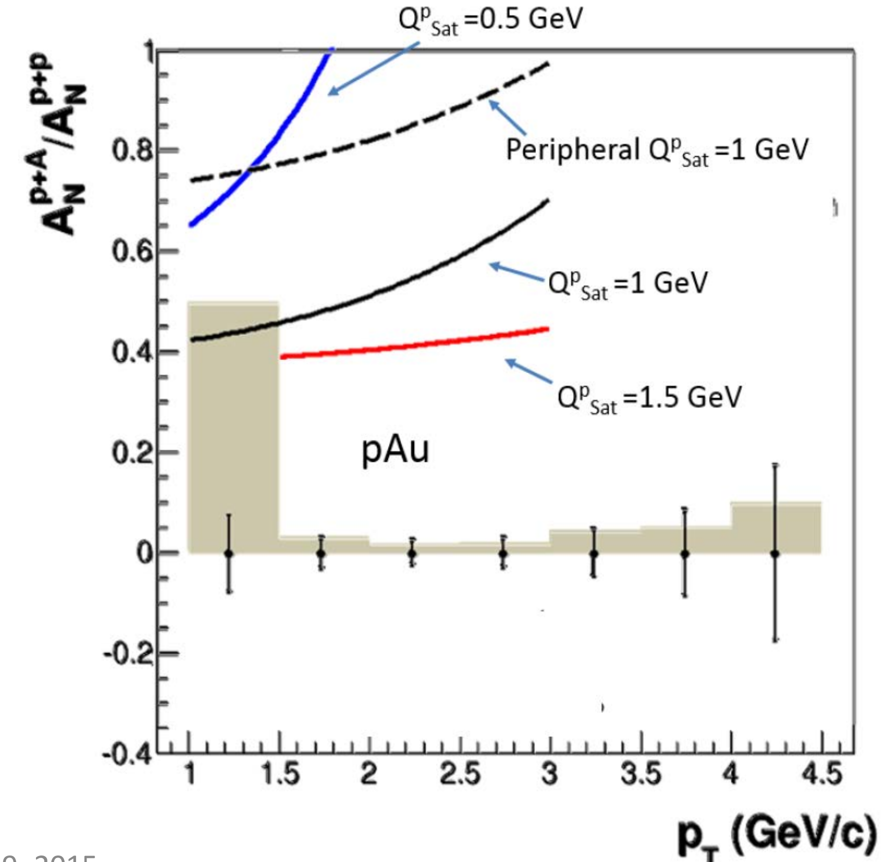
- 2012 run preliminary result
  - Asymmetry consistent with zero
  - More from 2015 run





$p\uparrow + A$

- Unique capability of RHIC
- Polarization for probe to the gluon saturation (CGC)
  - Measurement of Q_s
- Projection for 2015 run



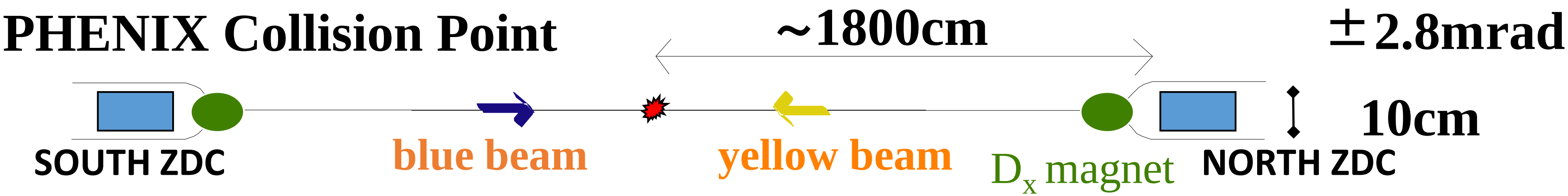
Z.-B.Kan and F.Yuan
PRD84, 034019 (2011)

$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h << Q_s^2}{\approx} \frac{Q_{s,p}^2}{Q_{s,A}^2} f(p_T^h)$$

$$\frac{A_N^{pA\to hX}}{A_N^{pp\to hX}} \underset{p_T^h >> Q_s^2}{\approx} 1$$

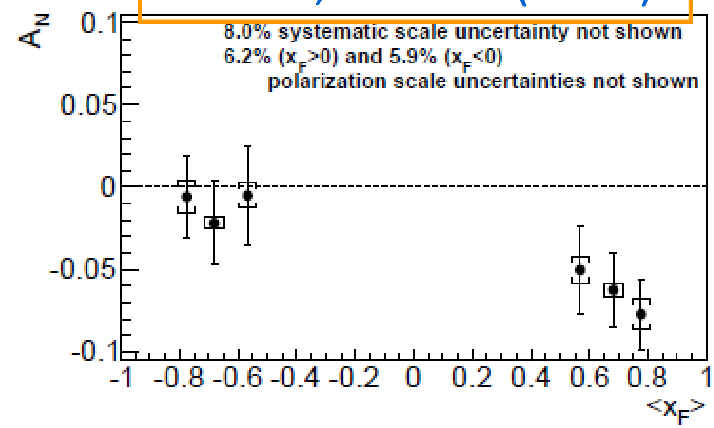
Odderon mechanism
(Kovchegov and Sievert)
predicts $\to 0$

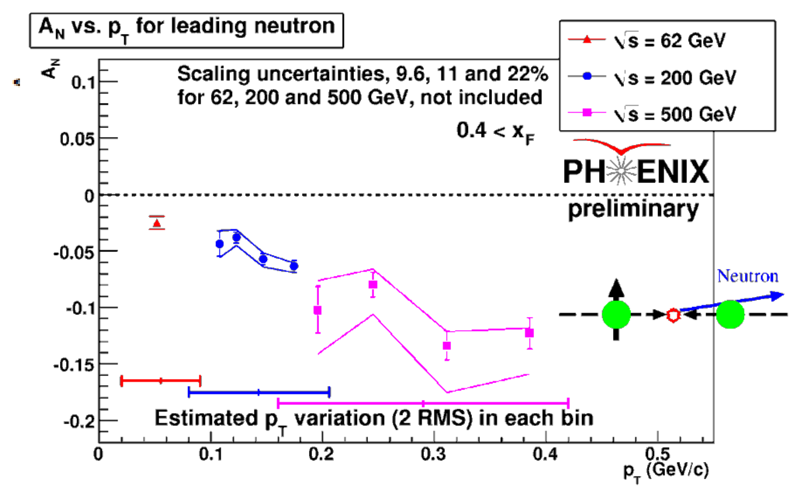
Forward neutron asymmetry



- ZDC + SMD
  - ZDC (Zero-Degree Calorimeter)
    - Hadron sampling calorimeter
  - SMD (Shower Maximum Detector)
    - Position measurement
- x_F distribution
  - Significant negative A_N in the forward region
    - No x_F dependence within the uncertainties
  - No significant backward asymmetry
- $\sqrt{s}$ dependence or p_T dependence

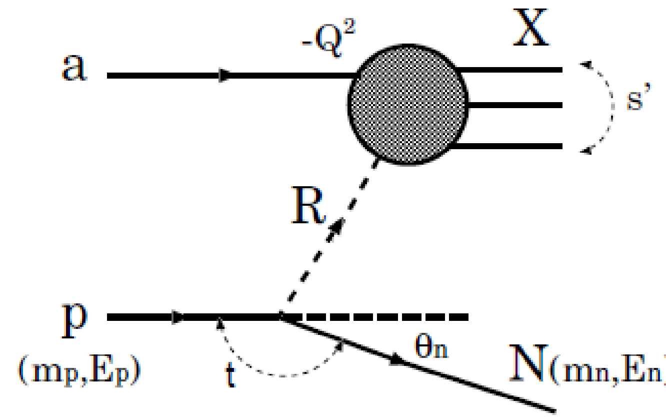
PRD 88, 032006 (2013)





Forward neutron production

- Cross section measurement
  - Forward peak in the x_F distribution around x_F~0.8
- OPE (one-pion exchange) model gives a reasonable description
- Asymmetry measurement
  - Interference between spin-flip and non-flip with a relative phase
  - Kopeliovich, Potashnikova, Schmidt, Soffer: Phys. Rev. D 84 (2011) 114012
  - Pion-a_1 interference: the data agree well with independence of energy
  - The asymmetry has a sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes



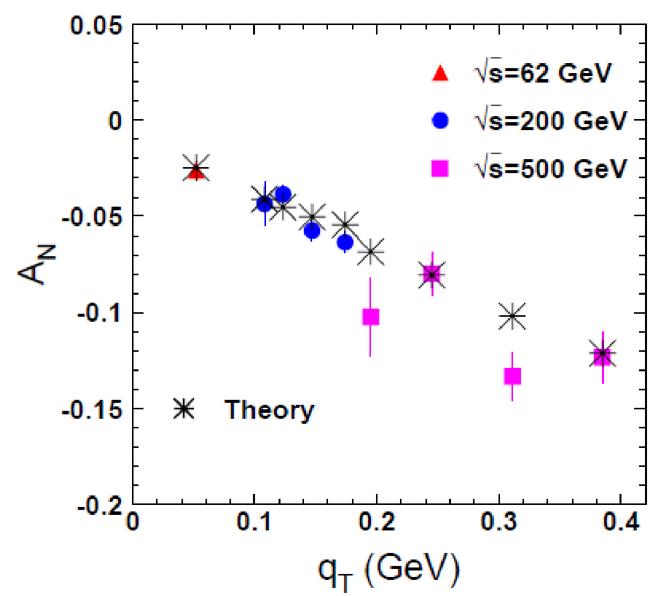
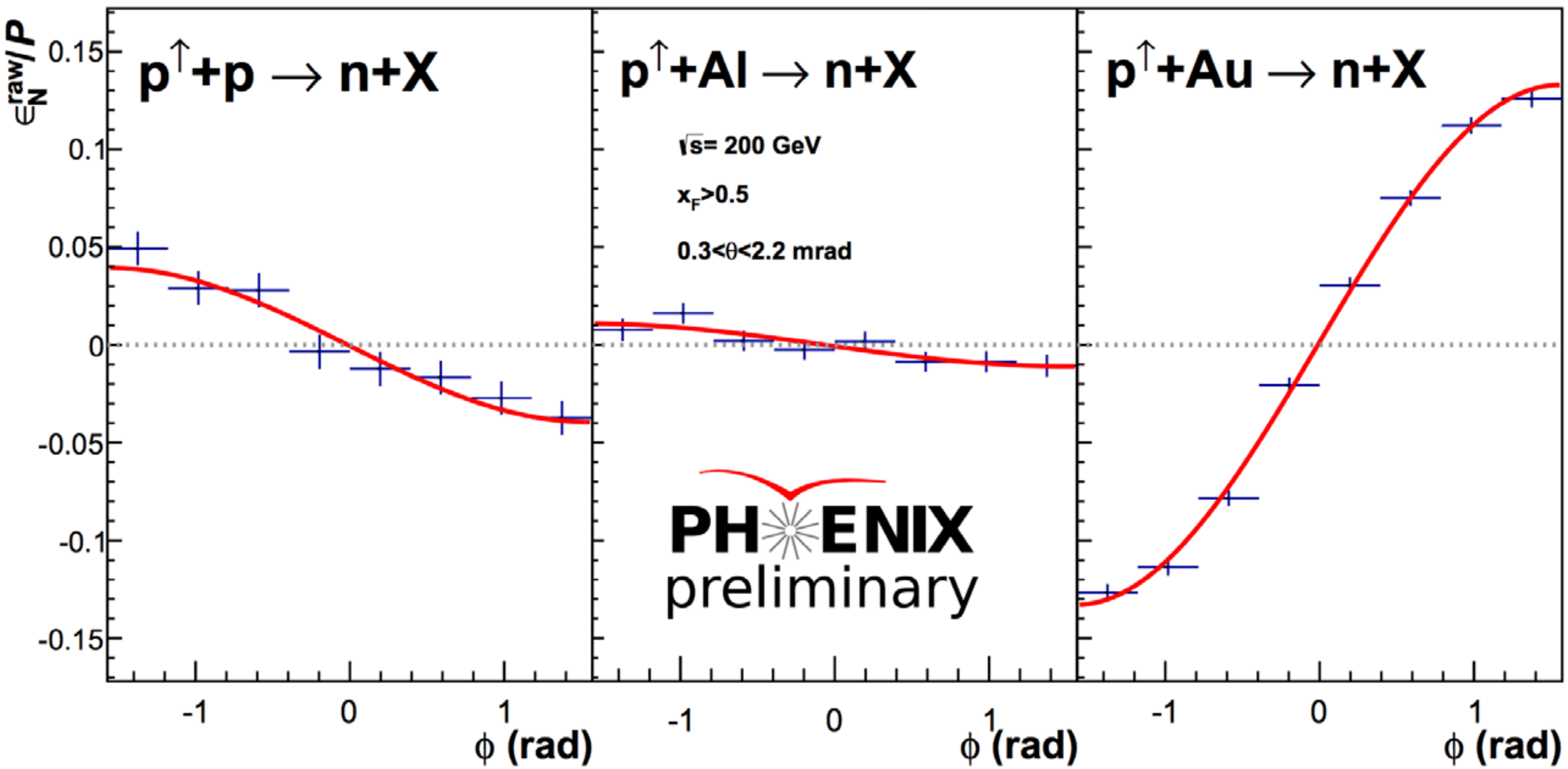


FIG. 1: (Color online) Single transverse spin asymmetry A_N in the reaction $pp \to nX$, measured at $\sqrt{s} = 62,\ 200,\ 500$ GeV [1] (preliminary data). The asterisks show the result of our calculation, Eq. (38), which was done point by point, since each experimental point has a specific value of z (see Table I).

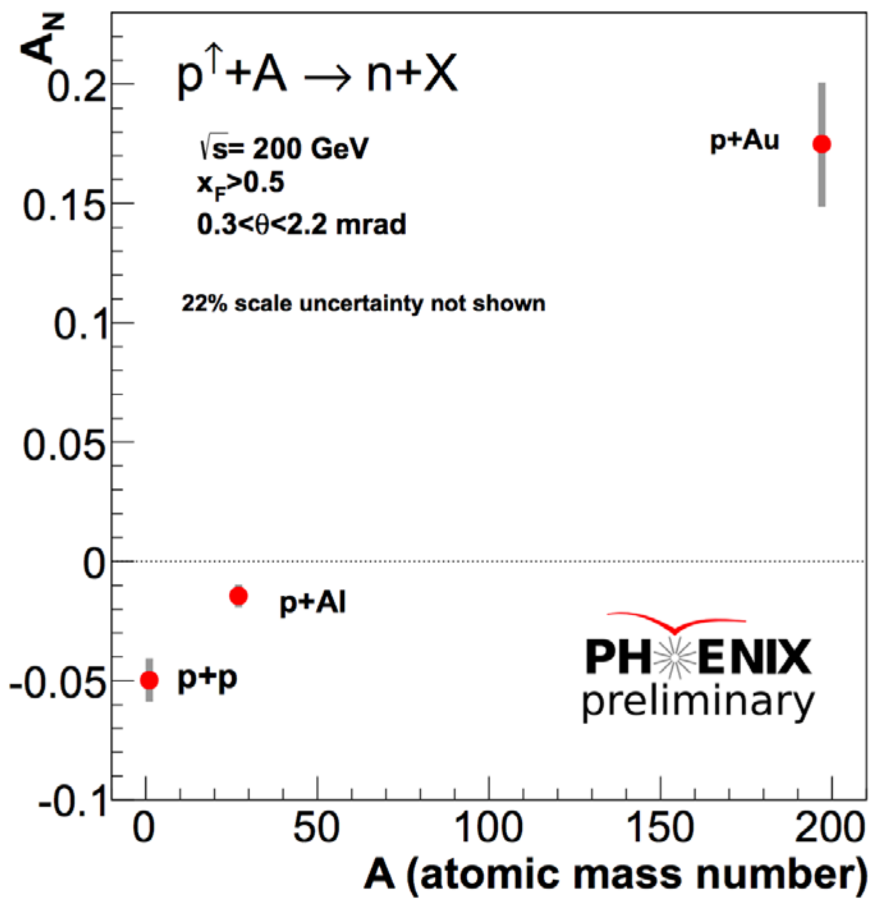
$p\uparrow + A$

- 2015 run preliminary result
  - ZDC trigger



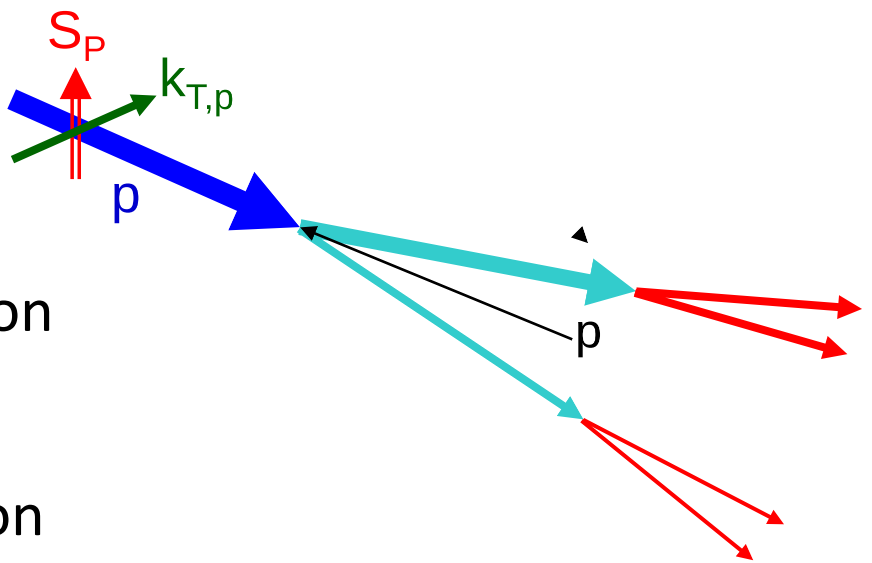
A-dependence of neutron A_N

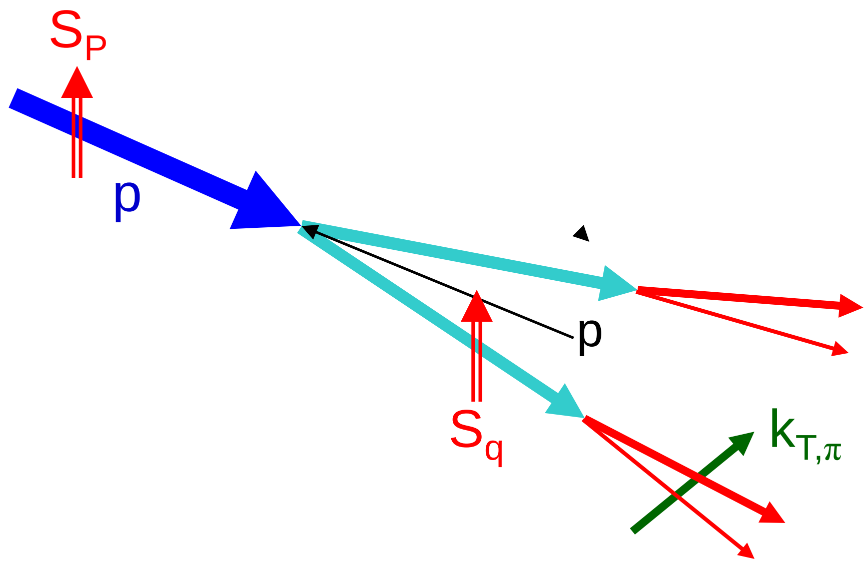
- Isospin effect?
- Nuclear effect?
  - Nucleus size
  - Neutron skin
  - Coherent effect
- Other trigger or offline event selection results to be obtained
- Inputs from theorists necessary



TMD and higher-twist

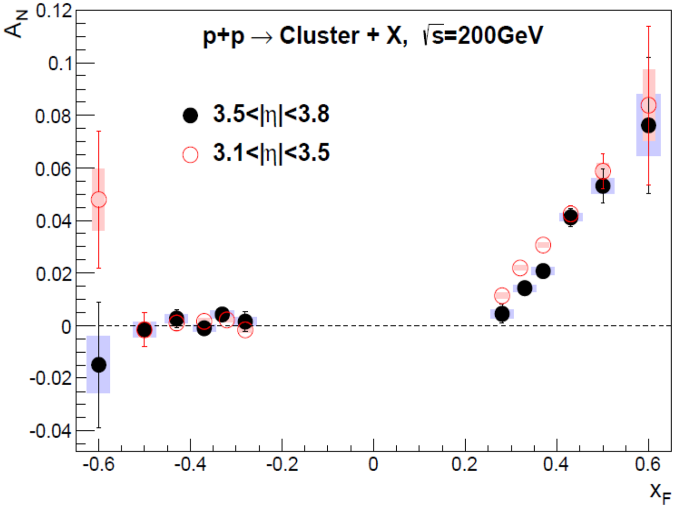
- Two theory frameworks
- "Sivers effect"
  - Initial-state effect
  - TMD (Sivers) distribution function
    - Need 2 scales (p_T and Q^2)
    - Drell-Yan, W/Z bosons
  - Higher-twist distribution function
    - Need 1 scale (p_T)
    - Hadron, photon, jet production
- "Collins effect"
  - Final-state effect
  - Transversity with TMD (Collins) fragmentation function
  - Transversity with higher-twist fragmentation function

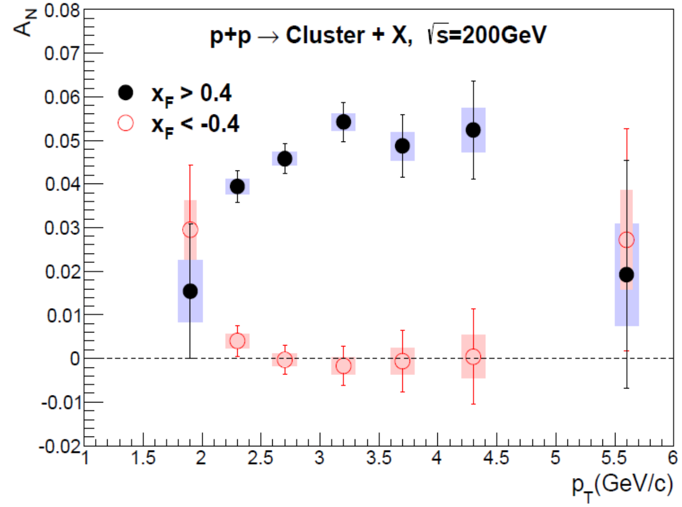




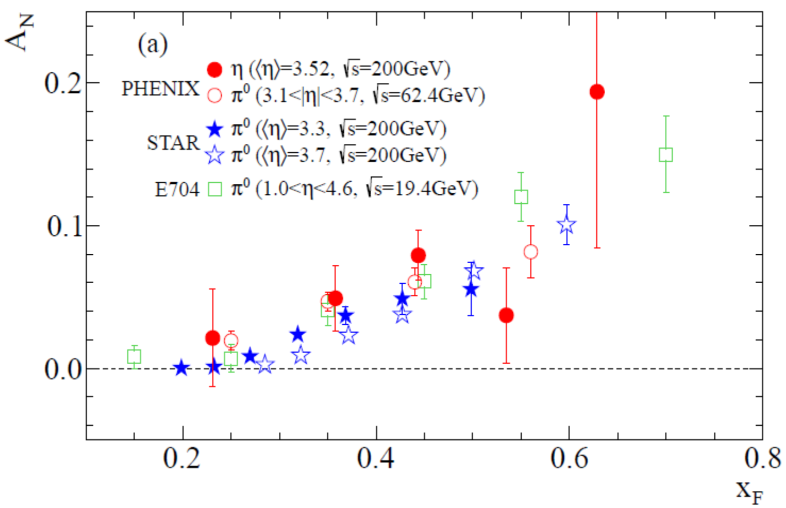
High-p_T measurements

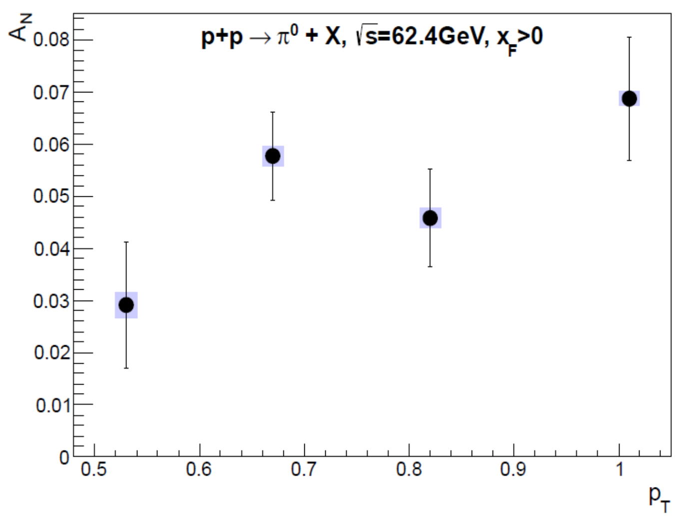
- Forward EM cluster at $\sqrt{s}$ = 200 GeV





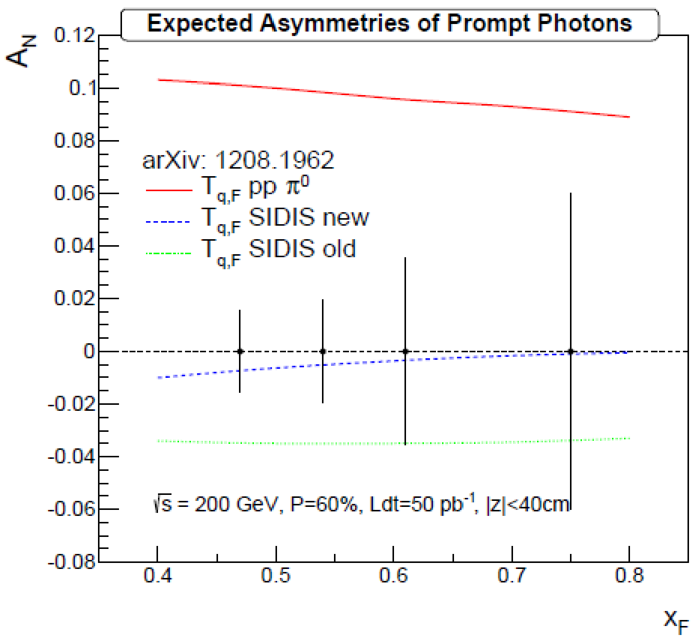
- π^0 and η



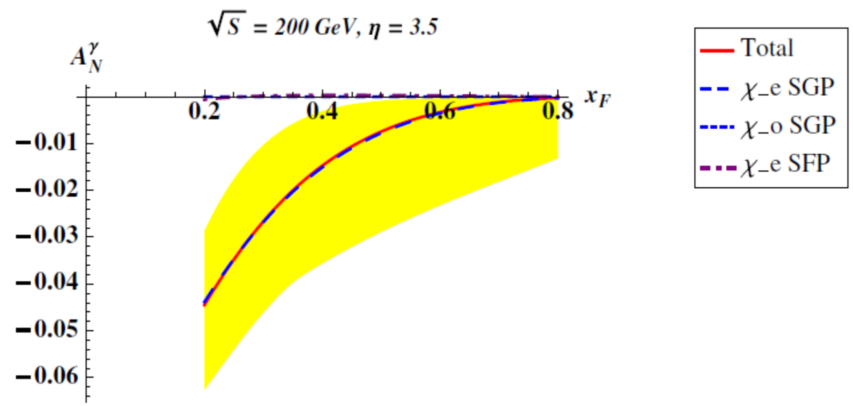


Direct photon

- Distinguish predicted higher-twist quark-gluon correlation functions
  - No final state effect



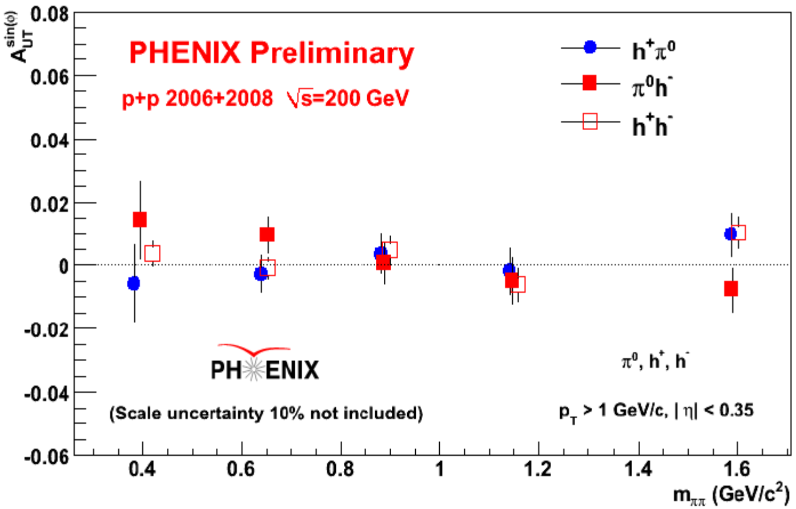
Kang, Qiu, Vogelsang and Yuan, PRD 83 094001 (2011)
Gamberg and Kang, arXiv 1208.1962v1 (2012)



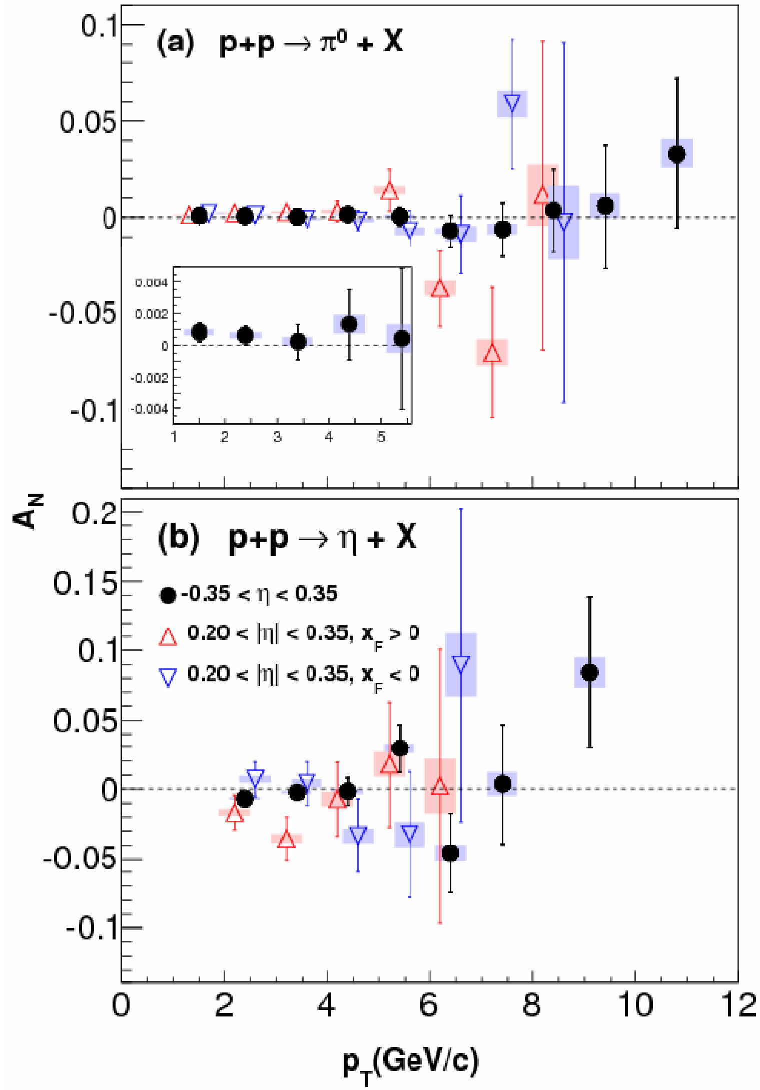
Kanazawa, Koike, Metz and Pitonyak, PRD 83 094001 (2015)

SSA at midrapidity

- Hadron pairs

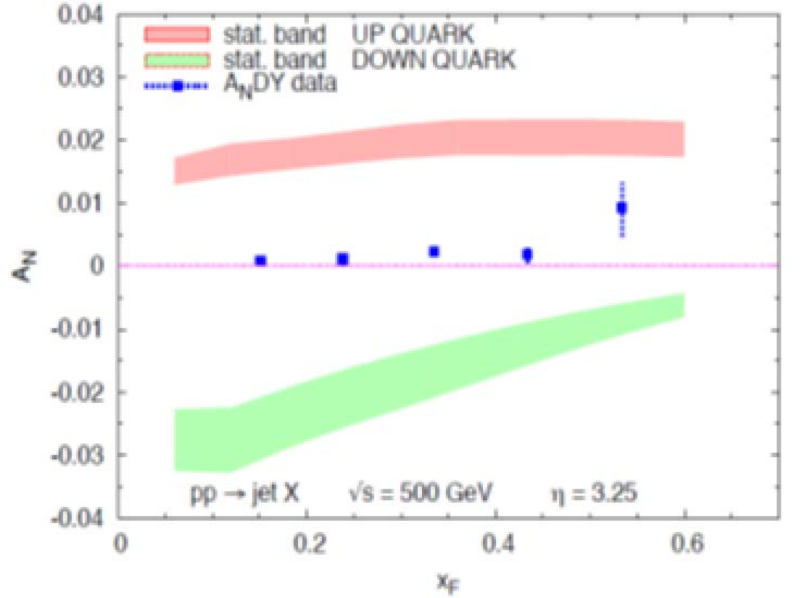


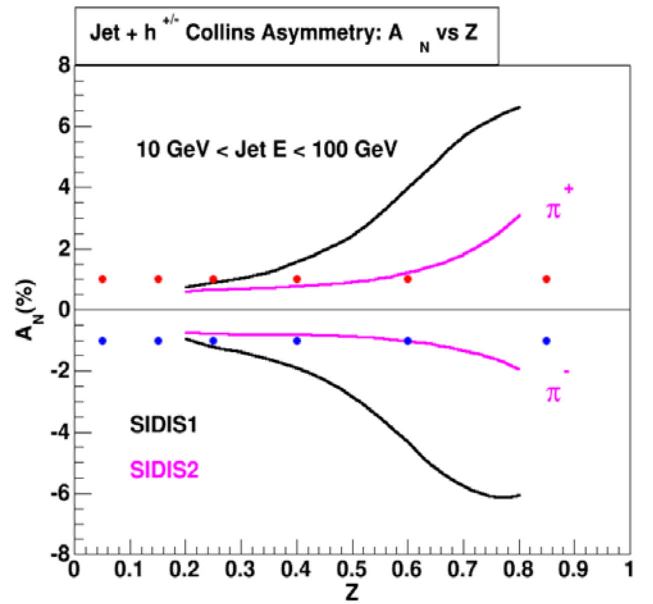
- π^0 and η



Jet measurements

- Small jet asymmetry measured by AnDY
  - Cancellation between u- and d-quarks
  - A cut on the charge of the leading hadron changes the composition of the jet sample
- Asymmetry measurement inside of jets
  - Transversity (initial state) + polarized fragmentation function (final state)





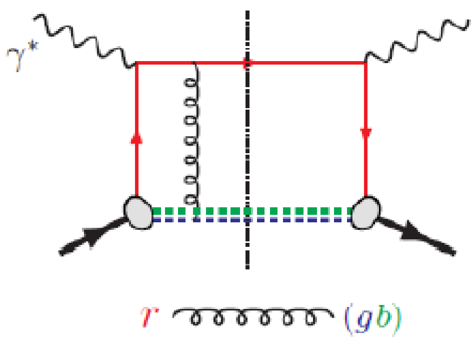
Drell-Yan measurement

- Establishment of non-universality of TMD distribution function
  - Opposite-sign contribution of TMD distribution function to SSA in SIDIS process and Drell-Yan process

$$f_{1T}^{\perp q}|_{\mathrm{SIDIS}} = -f_{1T}^{\perp q}|_{\mathrm{DY}}$$

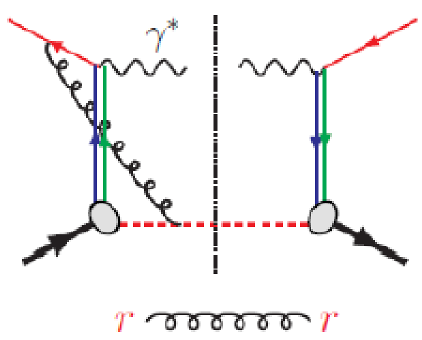
  - Fundamental property based on gauge invariance of QCD
  - Experimental verification required

SIDIS



attractive

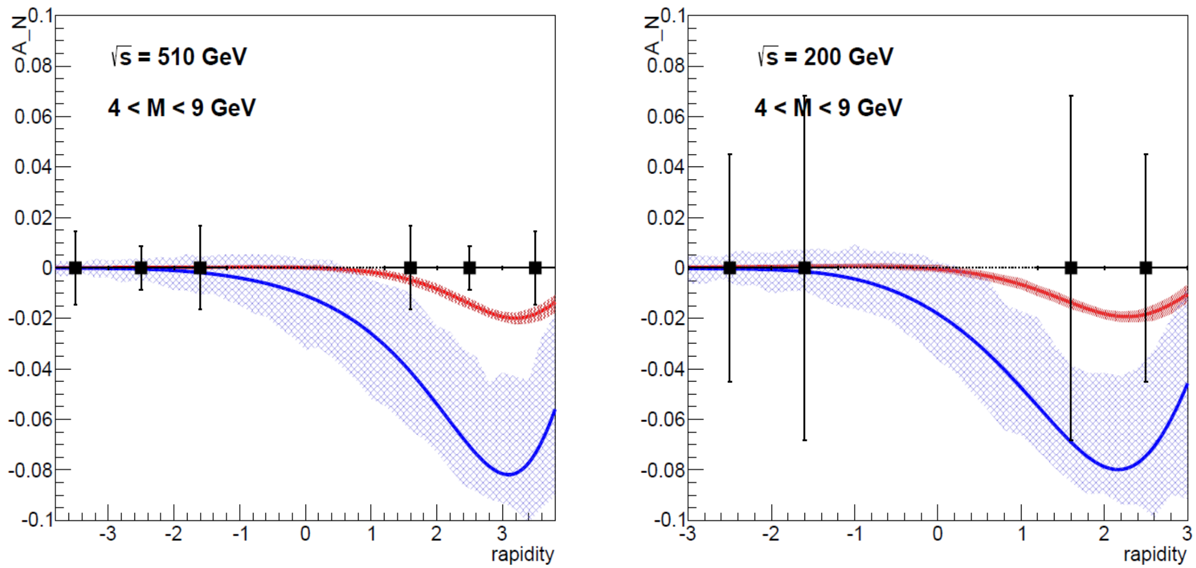
Drell-Yan



repulsive

Drell-Yan measurement

- Statistical sensitivities
  - With and without Sivers function evolution
- Better S/B (lower heavy-flavor cross section) but reduced luminosity at √s = 200 GeV
- Higher luminosity (higher statistics) but higher background at √s = 510 GeV



Drell-Yan measurement

	COMPASS-II	fsPHENIX 200 GeV	fsPHENIX 510 GeV
$L_{avg}(\text{cm}^{-2}\text{s}^{-1})$	1.18×10^{32}	0.76×10^{32}	6.48×10^{32}
Average L /week	14.3 pb^{-1}/week	18.7 pb^{-1}/week	128 pb^{-1}/week
Accelerator eff.	0.8	(included above)	(included above)
Detector up-time	0.85	0.6	0.6
Vertex cut	n/a	0.62	0.62
Sampled L /week	9.7 pb^{-1}/week	6.9 pb^{-1}/week	47.6 pb^{-1}/week
week/year	20	10	15
Sampled L /year	194 pb^{-1}/year	69 pb^{-1}/year	714 pb^{-1}/year
Dimuon trigger eff.	0.81	0.81	0.81

High mass: $4\,\text{GeV}/c^2 < M < 9\,\text{GeV}/c^2$

	COMPASS-II	fsPHENIX 200 GeV	fsPHENIX 510 GeV
Reconstruction eff.	0.8	0.312	0.305
Offline L /year	126 pb^{-1}/year	17.5 pb^{-1}/year	177 pb^{-1}/year
Cross section σ	1291 pb	1199 pb	2542 pb
Acceptance Ω	0.35	0.14	0.19
$\sigma\cdot\Omega$	452 pb	171 pb	478 pb
K factor (assumption)	2	1.38	1.38
Dimuon/year $L\cdot\sigma\cdot\Omega\cdot K$	115000/year	4150/year	117000/year
FoM/year	2230/year	747/year	14600/year
$\delta A_T^{\sin\phi_S} = 1/\sqrt{FoM}$	0.021	0.037	0.0083

Low mass: $2\,\text{GeV}/c^2 < M < 2.5\,\text{GeV}/c^2$

	COMPASS-II	fsPHENIX 200 GeV	fsPHENIX 510 GeV
Reconstruction eff.	0.8	0.285	0.272
Offline L /year	126 pb^{-1}/year	16.0 pb^{-1}/year	157 pb^{-1}/year
Cross section σ	6231 pb	2811 pb	4630pb
Acceptance Ω	0.43	0.22	0.21
$\sigma\cdot\Omega$	2679 pb	610 pb	955 pb
K factor (assumption)	2	1.38	1.38
Dimuon/year $L\cdot\sigma\cdot\Omega\cdot K$	674000/year	13500/year	207000/year
FoM/year	13200/year	2430/year	25900/year
$\delta A_T^{\sin\phi_S} = 1/\sqrt{FoM}$	0.0087	0.020	0.0062

Summary

- Transverse-spin properties of the nucleon
  - Conclusive understanding of the nucleon spin
  - Orbital motion inside the nucleon
  - Description with TMD and higher twist effect
  - Distinguish between initial state and final state effect
  - Forward measurements with MPC and MPC-EX
- p↑+A asymmetry measurement
  - Unique capability of RHIC
  - MPC-EX result to be obtained
  - Neutron asymmetry
- sPHENIX forward measurement
  - Jet and Drell-Yan asymmetry measurements
  - Support from the spin community important and necessary