RHIC-Spin Results

Hadron-Structure Physics at J-PARC
and Related Topics @ Tokai
March 18, 2013

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Origin of the nucleon spin 1/2

- Nucleon structure
  - Quark model
    - Magnetic moment of hadrons was explained from the spin of constituent quarks in the static quark model
  - Quark Parton Model ➔ QCD
    - Established by DIS (deep inelastic scattering) experiments
    - Basis of high-energy hadron collision (e.g. at LHC) as the initial state
    - Do we understand the nucleon with QCD?
    - Are there any phenomena not understood with QCD?
- Spin puzzle
  - Polarized DIS experiments found that nucleon's spin was not explained by the quark spin
    - (as expected by the most simple quark picture…)

Origin of the nucleon spin 1/2

- Spin puzzle

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

Orbital angular momentum

Gluon spin contribution

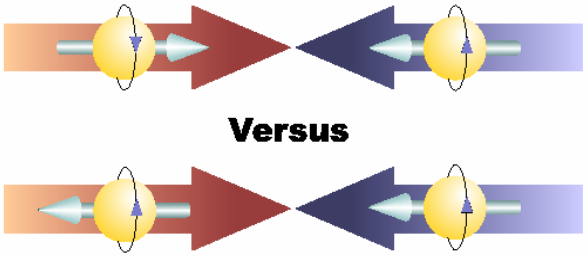
Quark spin contribution

- RHIC spin project
  - First goal: measurement of the gluon spin contribution
  - Still based on simple parton picture with coherent partons inside the nucleon
- Towards the complete picture
  - Many-body correlation of partons
    - Orbital motion of partons
  - 3D structure of the nucleon
    - Generalization of PDF (parton distribution function)

Nucleon structure and parton reaction

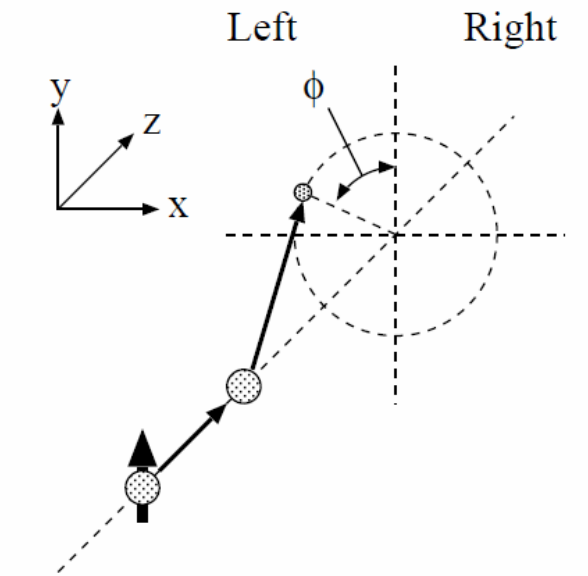
- Precision measurement of PDFs
  - Helicity structure of the nucleon

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



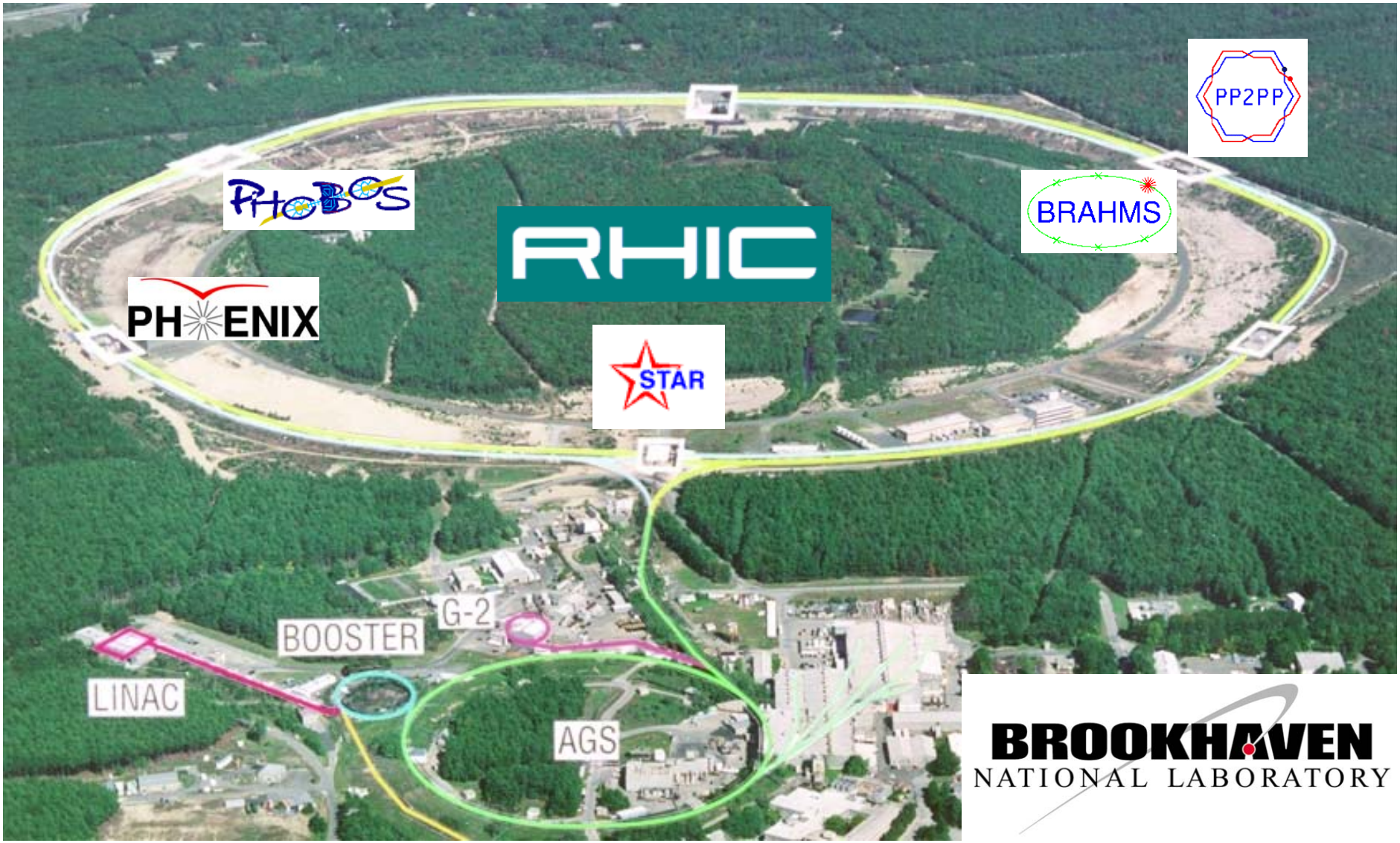
- Transverse-spin phenomena

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



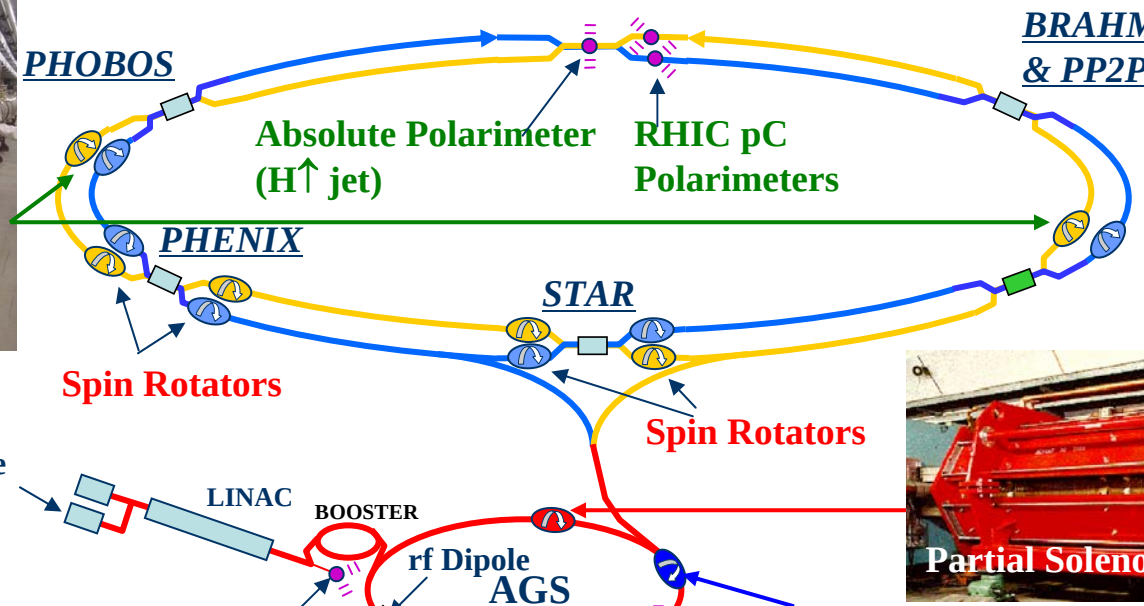
  - Many-body correlation of partons
  - TMD (transverse-momentum dependent) factorization
    - Transverse structure of the nucleon
  - Higher-twist effect on collinear factorization
    - Parton reaction

RHIC


PP2PP
PHOBOS
BRAHMS
RHIC
PHENIX
STAR
G-2
BOOSTER
LINAC
AGS
BROOKHAVEN
NATIONAL LABORATORY

RHIC polarized proton collider

Full Helical
Siberian Snakes



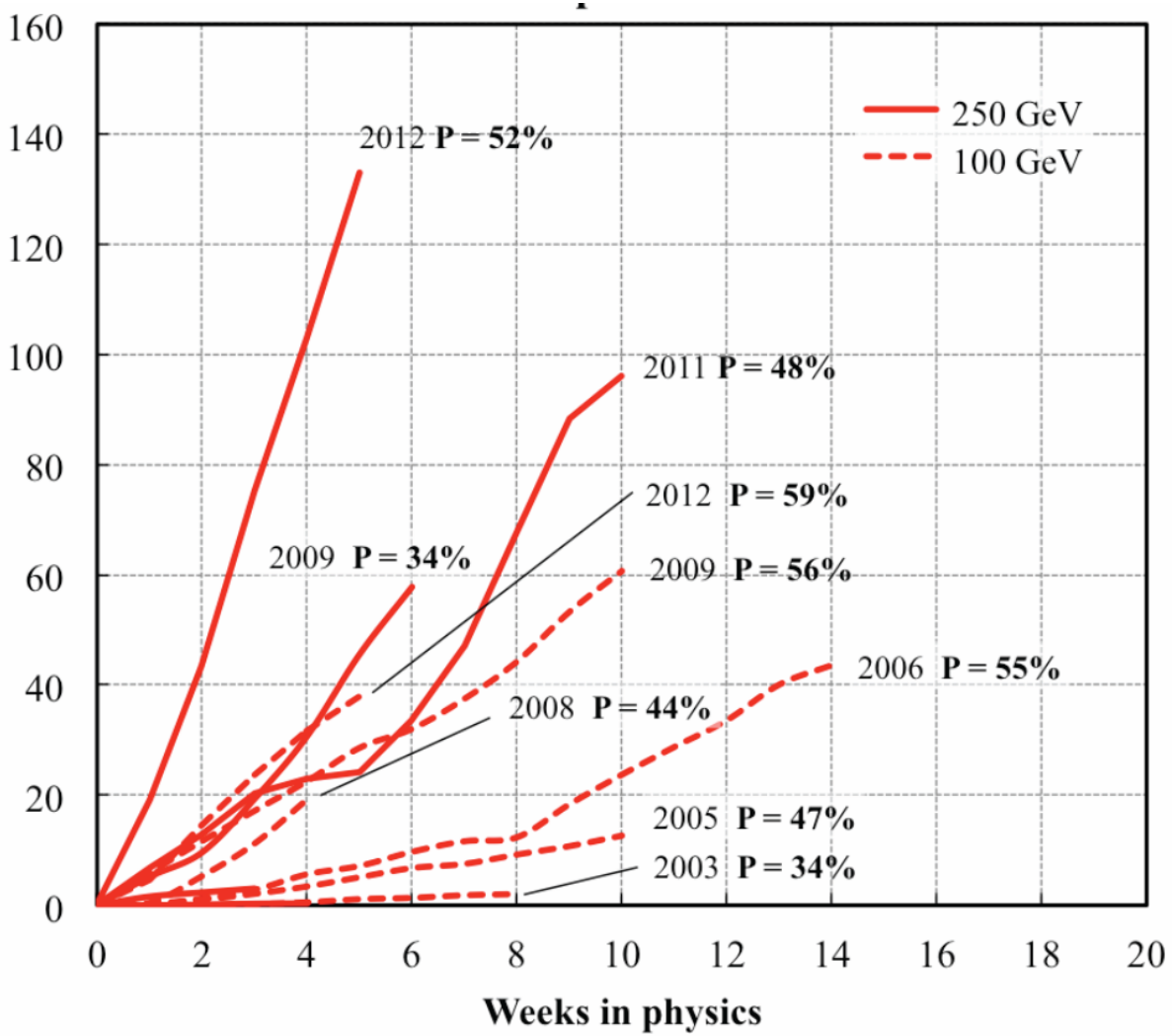

Partial Solenoidal Snake


Cold Partial
Helical Siberian Snake

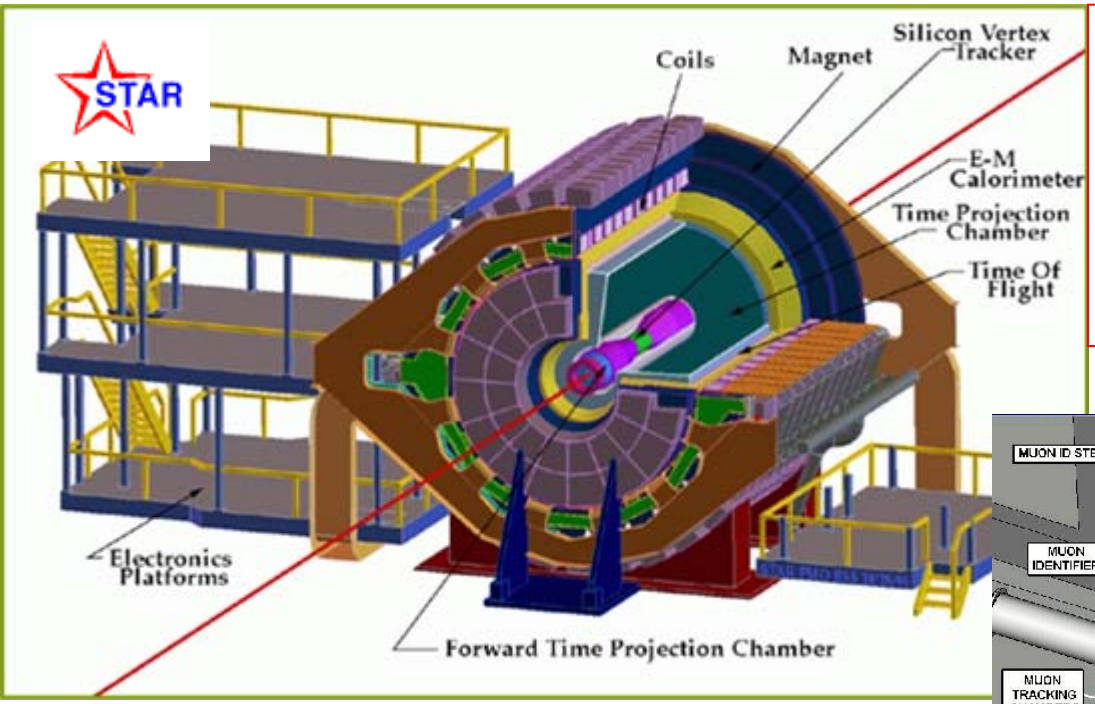

Warm Partial
Helical Siberian Snake

RHIC polarized proton collider

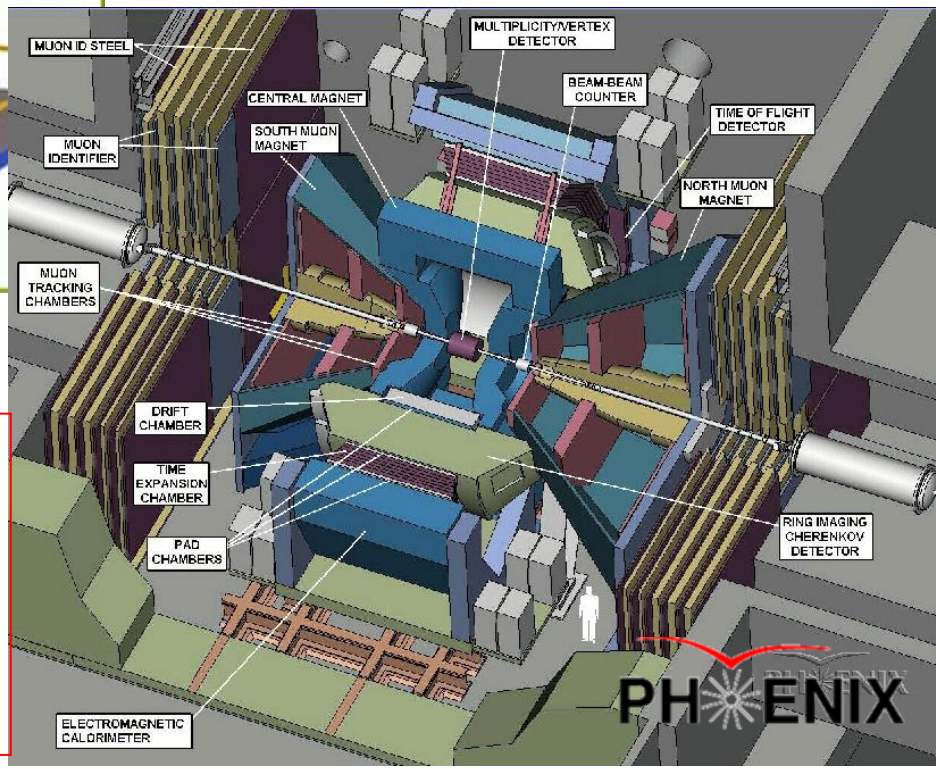
- Luminosity accumulation



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

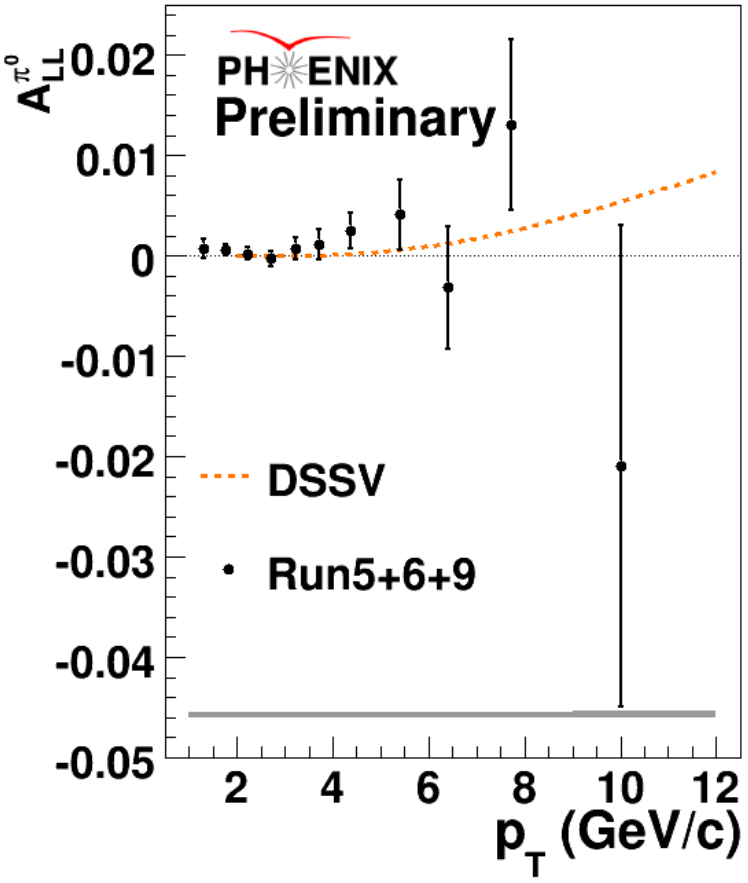
Longitudinal-polarization runs at RHIC

Year	√s [GeV]	Recorded PHENIX	Recorded STAR	Pol [%]
2002 (Run 2)	200	/	0.3 pb^{-1}	15
2003 (Run 3)	200	0.35 pb^{-1}	0.3 pb^{-1}	27
2004 (Run 4)	200	0.12 pb^{-1}	0.4 pb^{-1}	40
2005 (Run 5)	200	3.4 pb^{-1}	3.1 pb^{-1}	49
2006 (Run 6)	200	7.5 pb^{-1}	6.8 pb^{-1}	57
2006 (Run 6)	62.4	0.08 pb^{-1}		48
2009 (Run9)	500	10 pb^{-1}	10 pb^{-1}	39
2009 (Run9)	200	14 pb^{-1}	25 pb^{-1}	55
2011 (Run11)	500	27.5 / 9.5pb^{-1}	12 pb^{-1}	48
2012 (Run12)	500	30 / 15 pb^{-1}	82 pb^{-1}	50/54

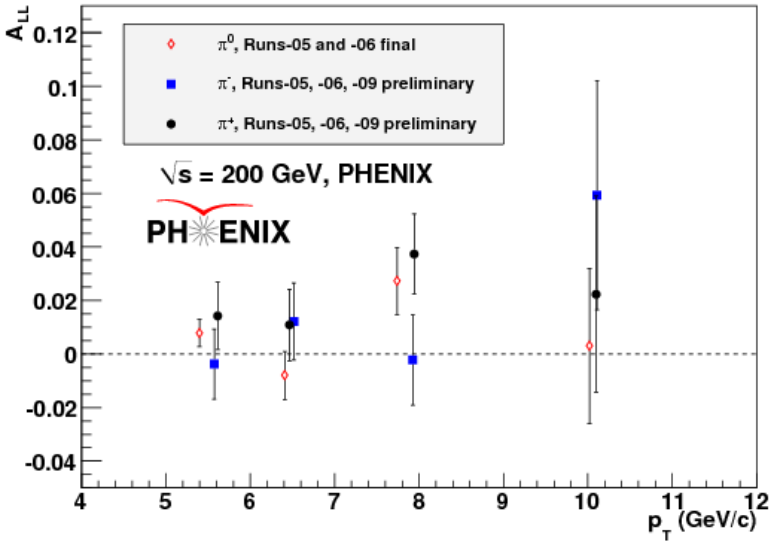
Polarized gluon distribution

- PHENIX A_{LL}

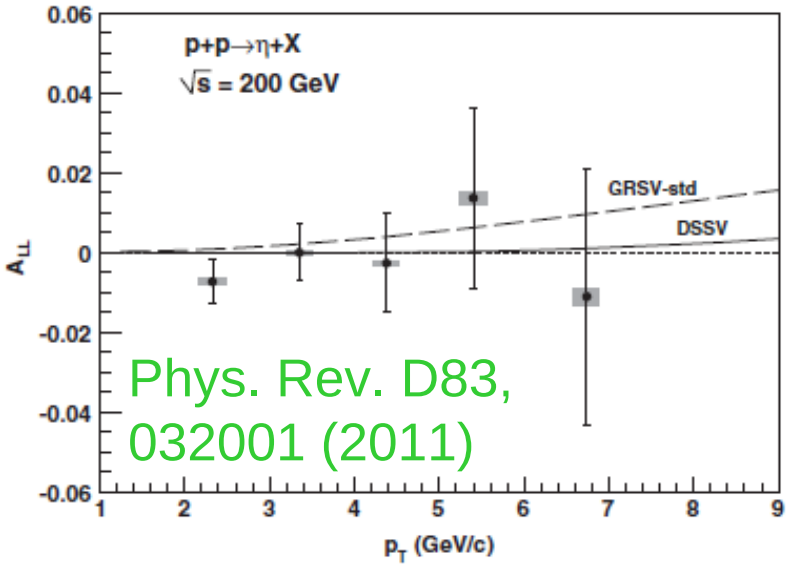
Neutral pion



Neutral and charged pion



η meson

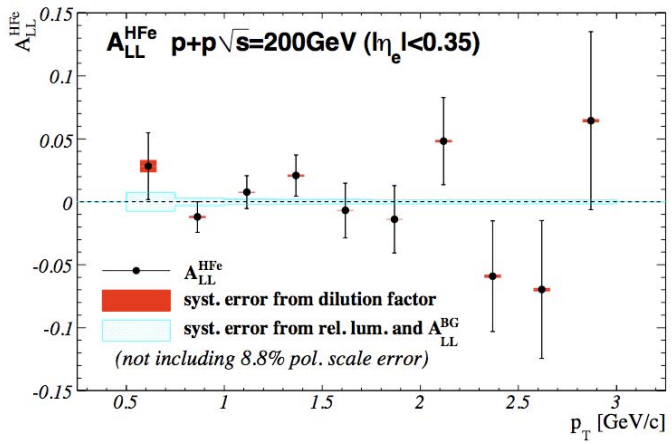


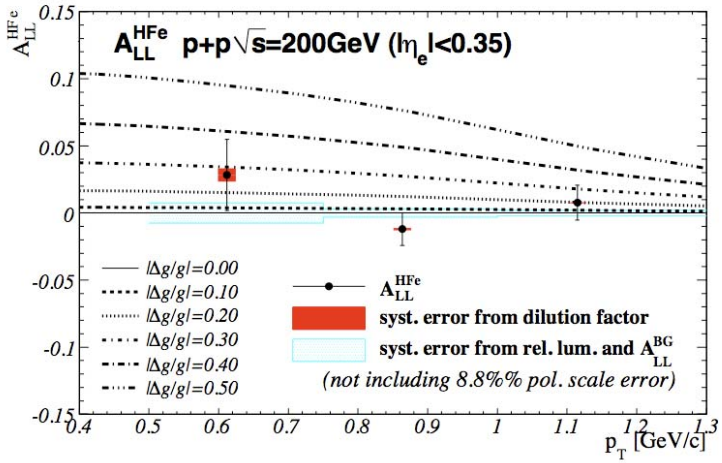
Phys. Rev. D83, 032001 (2011)

Polarized gluon distribution

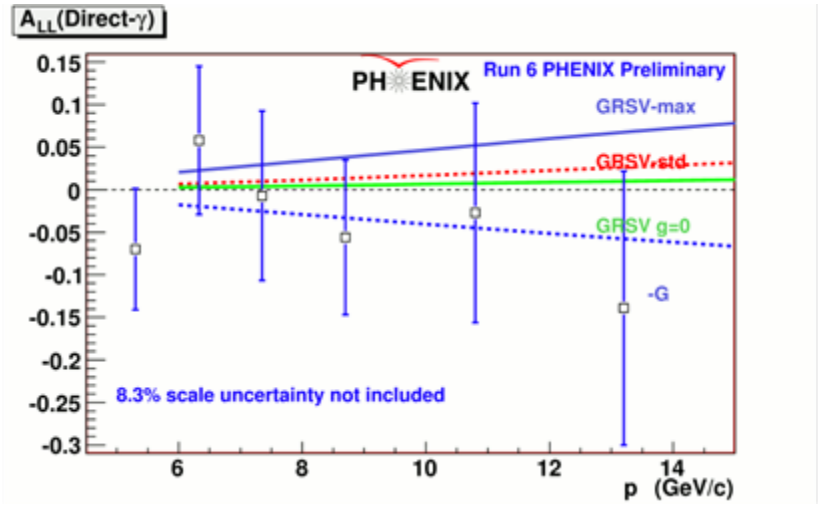
- PHENIX A_{LL}
  - Single electron

Phys. Rev. D87, 012011 (2013)



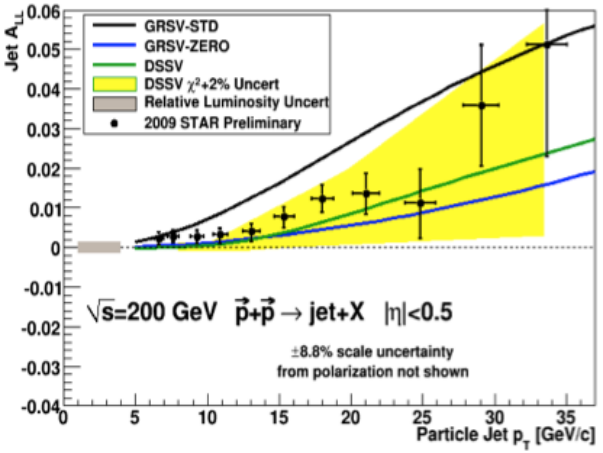


  - Direct photon

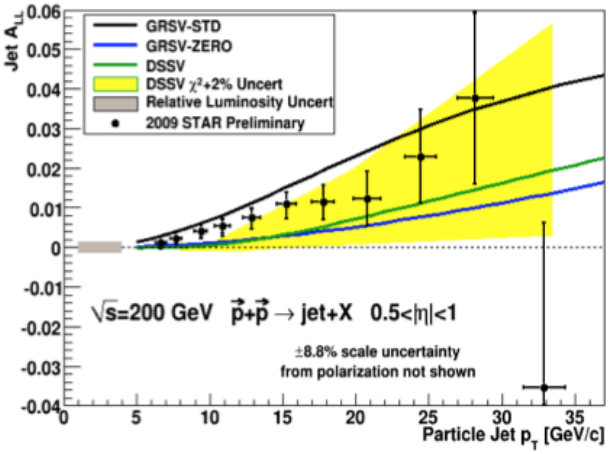


Polarized gluon distribution

- STAR A_{LL}
  - Jet production

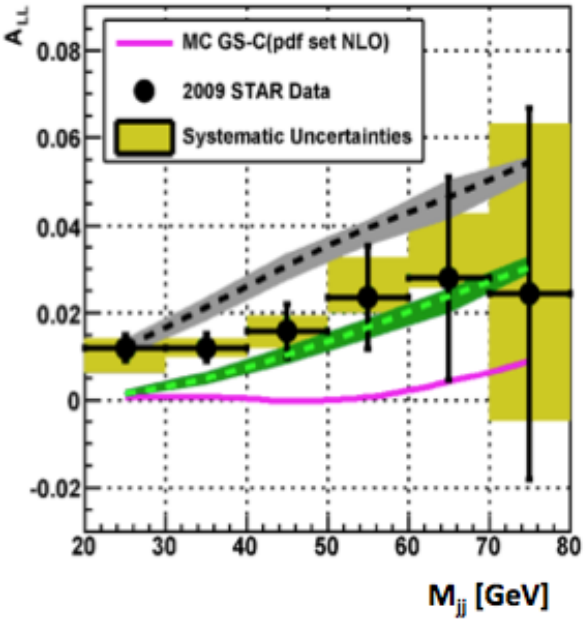


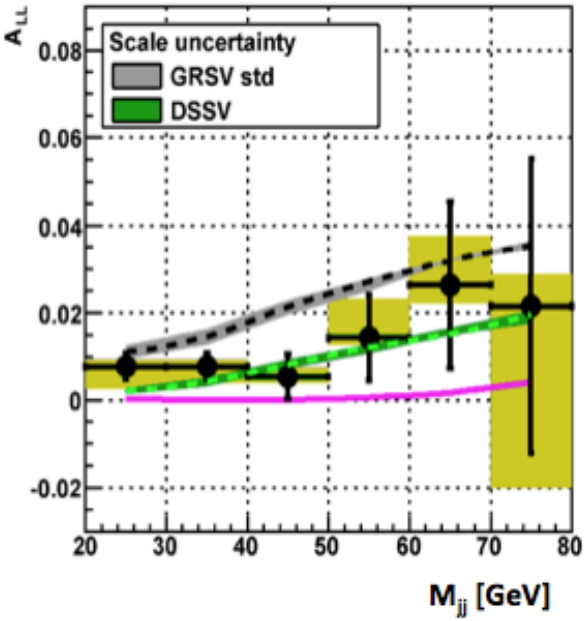
East - East and West - West Barrel



East Barrel - West Barrel

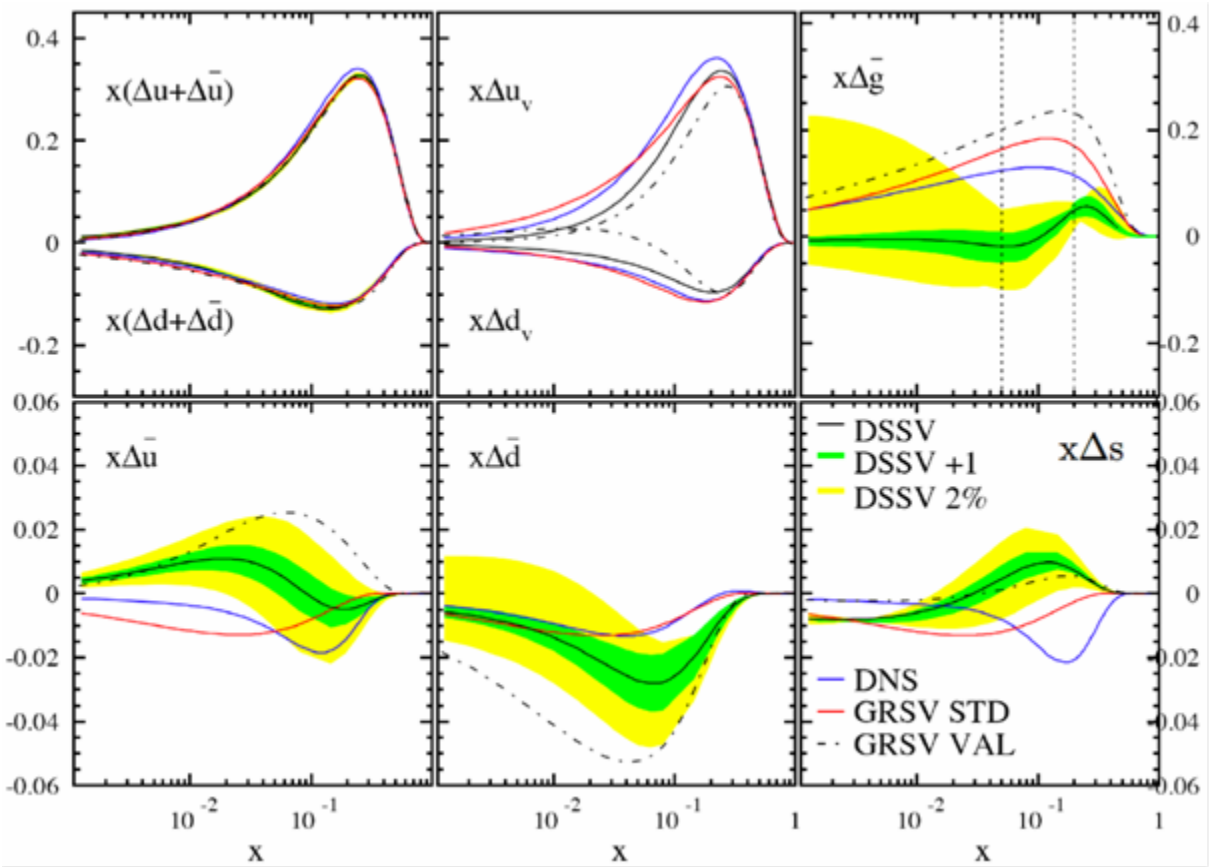
  - Jet pair





QCD global analysis

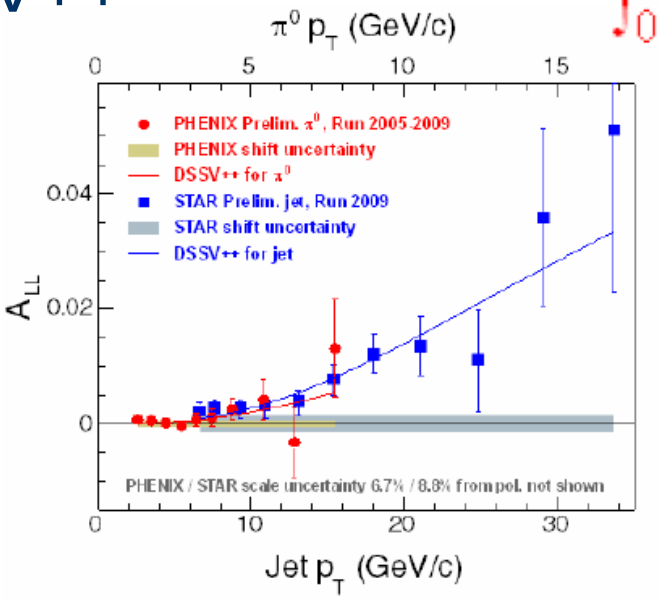
- DSSV group analyzed world data of polarized DIS, SIDIS and *p*+*p* collision
- RHIC *p*+*p* collision data significantly constrained gluon helicity distribution at $0.05 < x < 0.2$

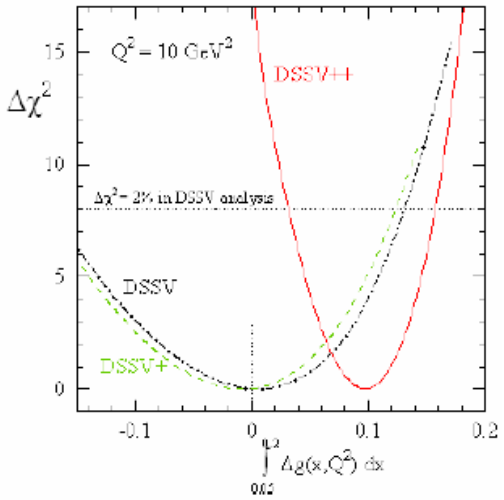


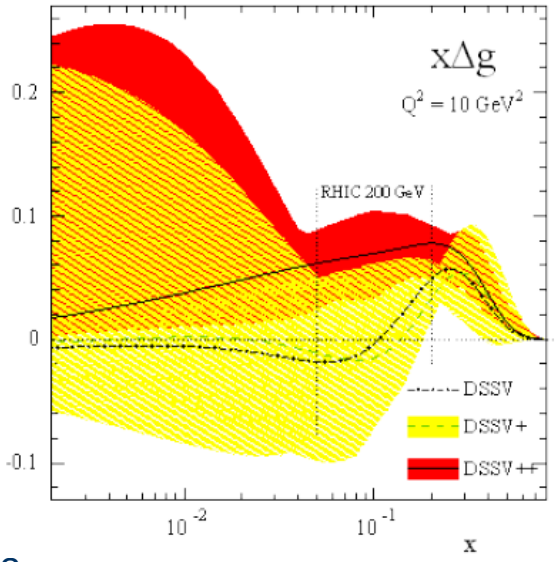
QCD global analysis

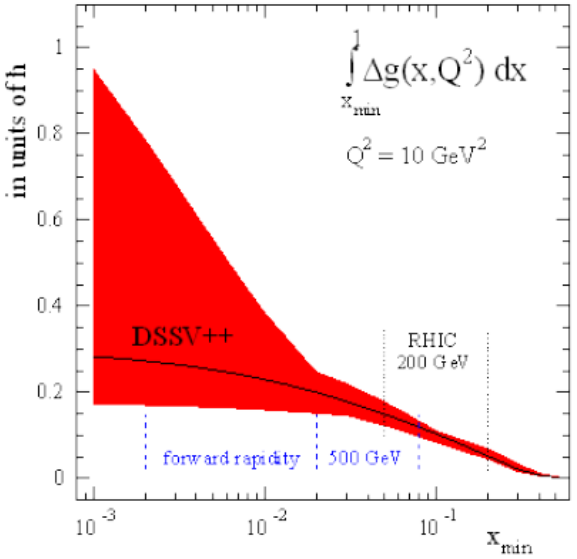
- DSSV++

$$\int_{0.05}^{0.2} \Delta g(x)\,dx = 0.1 \pm^{0.06}_{0.07}$$



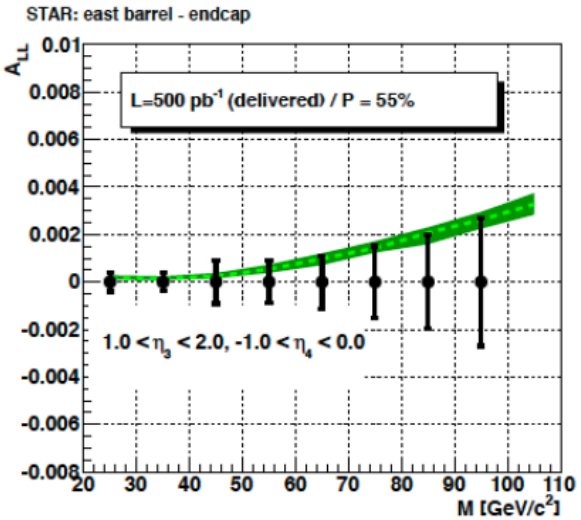


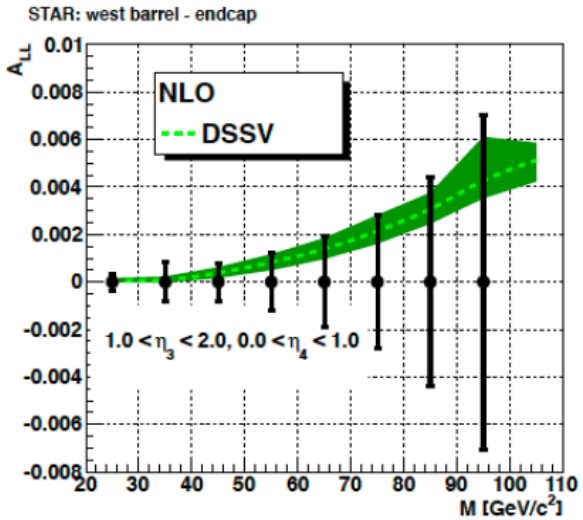




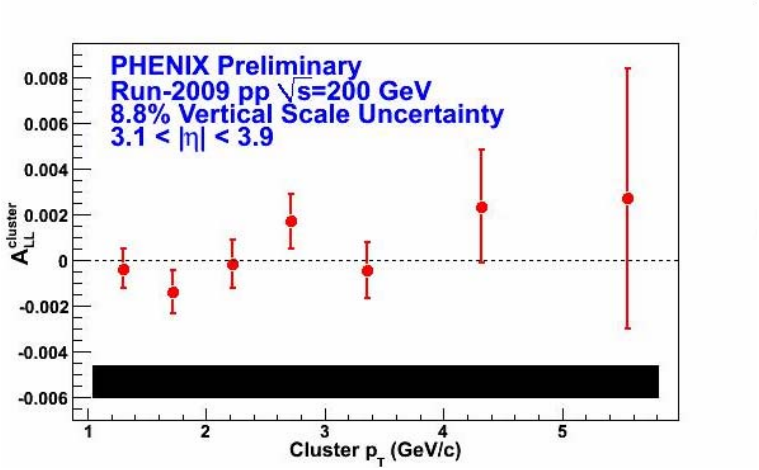
Polarized gluon distribution

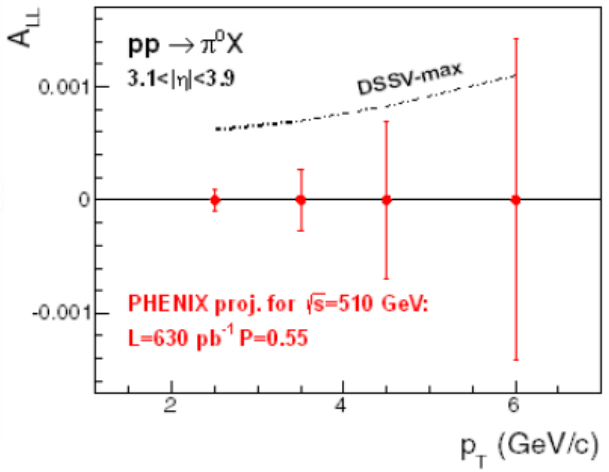
- STAR jet pair A_{LL}





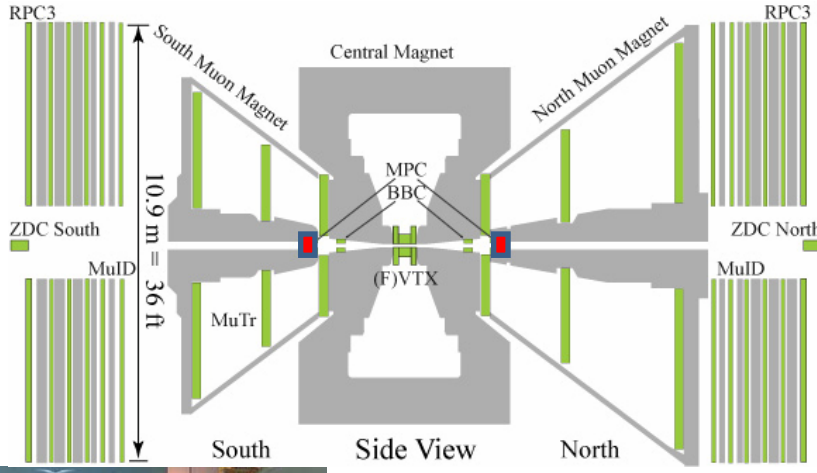
- PHENIX MPC cluster A_{LL}

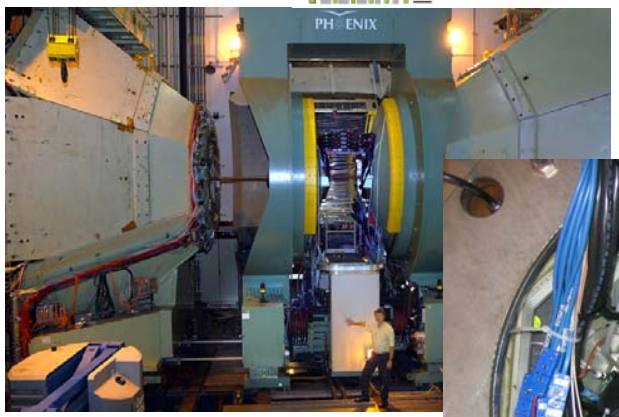


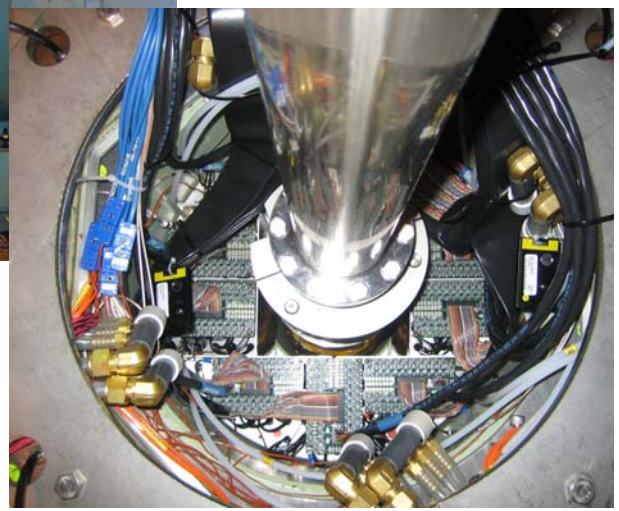


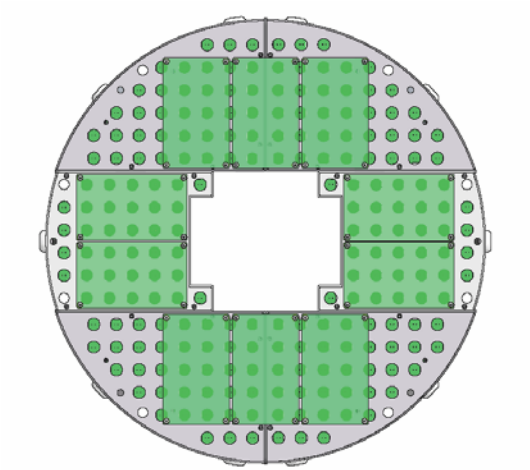
MPC at PHENIX

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



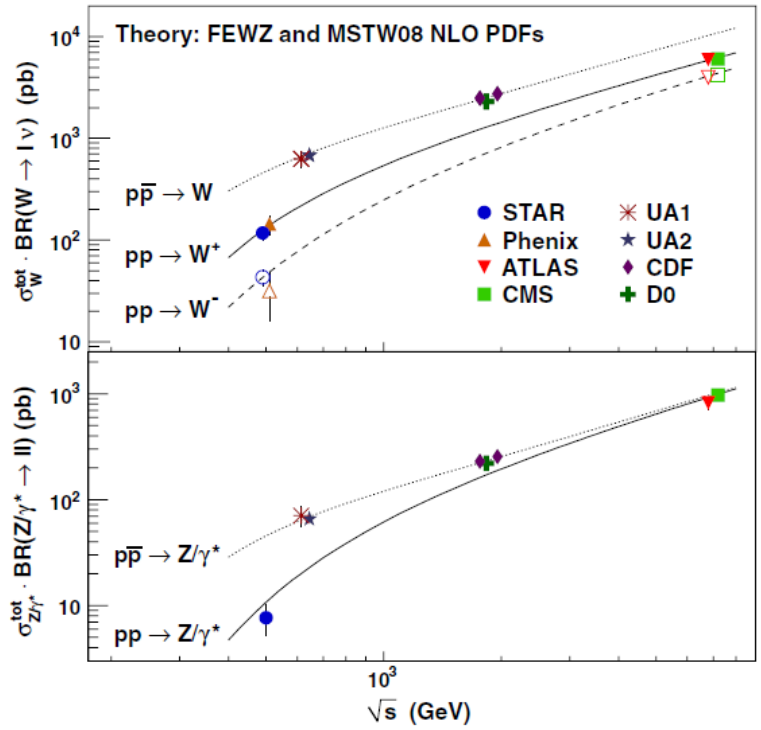




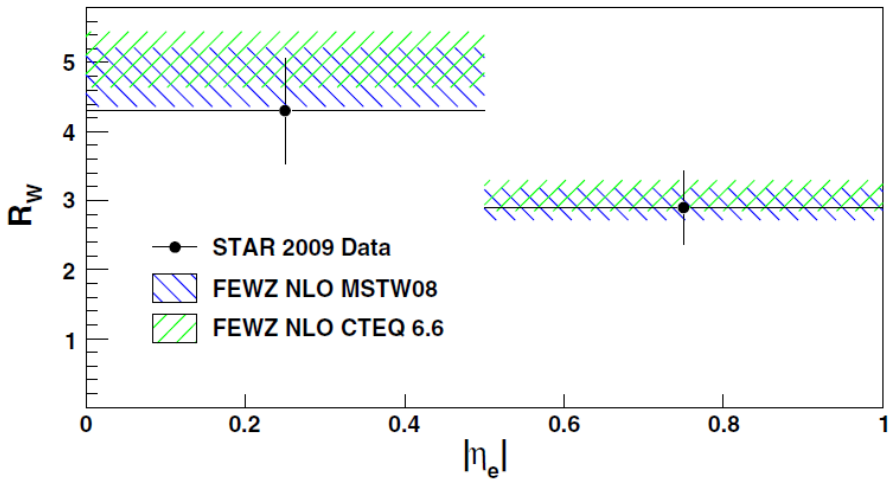


Polarized sea-quark distribution

- Flavor-sorted helicity distribution
  - Weak-boson production at $\sqrt{s}$ = 500-510 GeV
  - Parity-violating single-spin asymmetry measurement
- Weak-boson cross sections at midrapidity

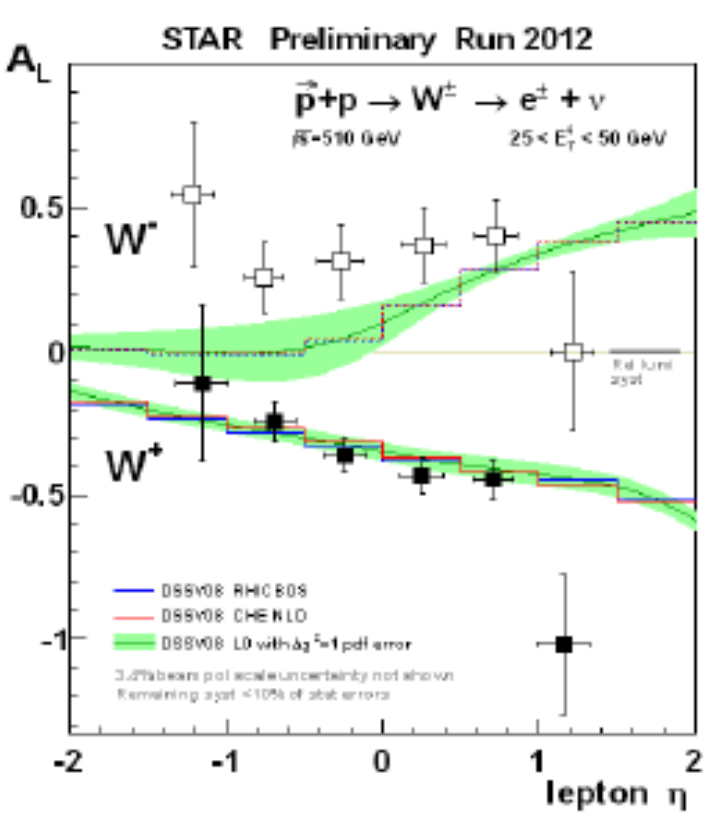


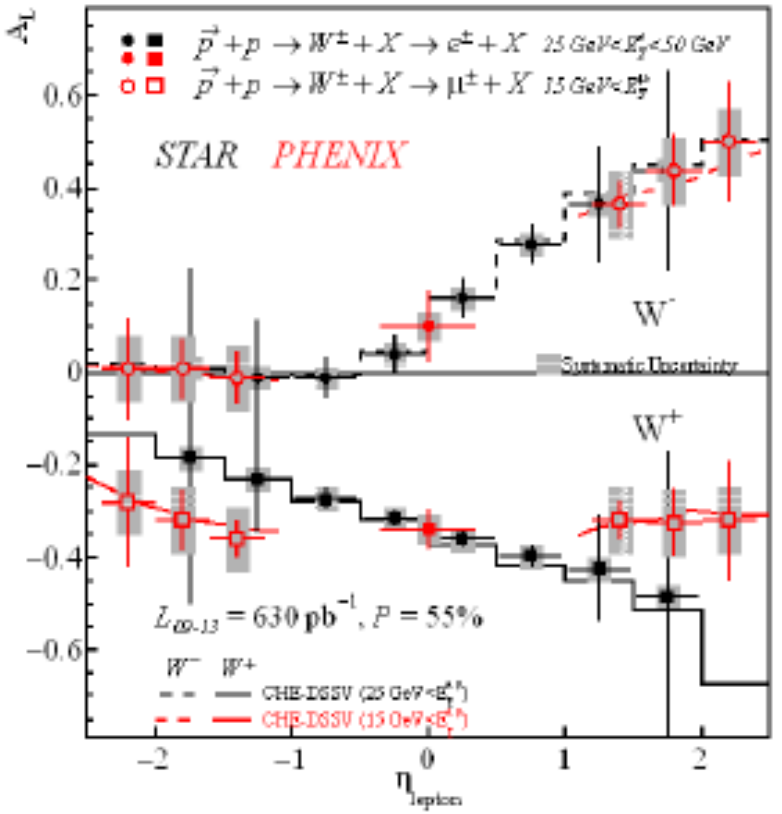
Phys. Rev. D85, 92010 (2012)



Polarized sea-quark distribution

- W-boson A_L^{PV}



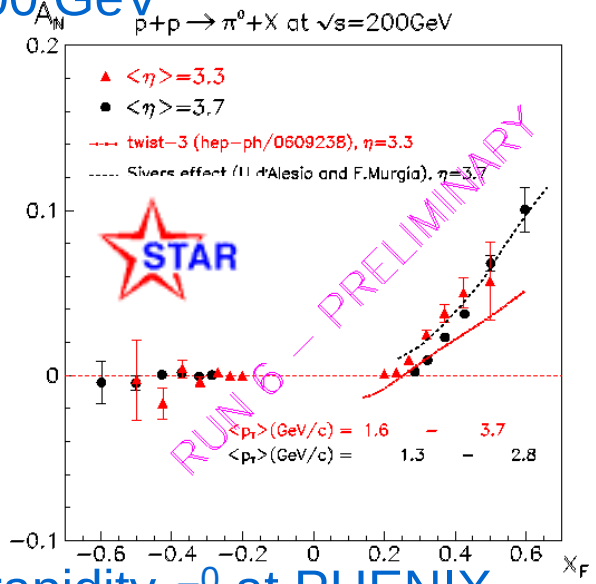


Transverse-polarization runs at RHIC

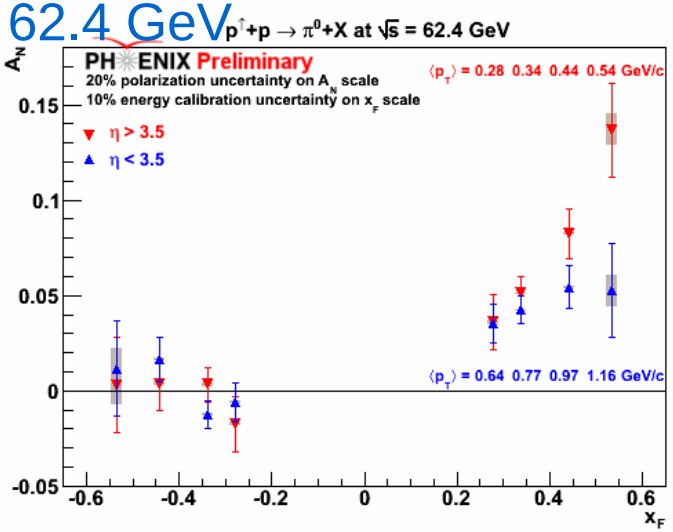
Year	√s [GeV]	Recorded PHENIX	Recorded STAR	Pol [%]
2001 (Run 2)	200	0.15 pb^{-1}	0.15 pb^{-1}	15
2003 (Run 3)	200	/	0.25 pb^{-1}	30
2005 (Run 5)	200	0.16 pb^{-1}	0.1 pb^{-1}	47
2006 (Run 6)	200	2.7 pb^{-1}	8.5 pb^{-1}	57
2006 (Run 6)	62.4	0.02 pb^{-1}		53
2008 (Run8)	200	5.2 pb^{-1}	7.8 pb^{-1}	45
2011 (Run11)	500	/	25 pb^{-1}	48
2012 (Run12)	200	9.2/4.3 pb^{-1}	22 pb^{-1}	61/58

Single transverse-spin asymmetries at RHIC

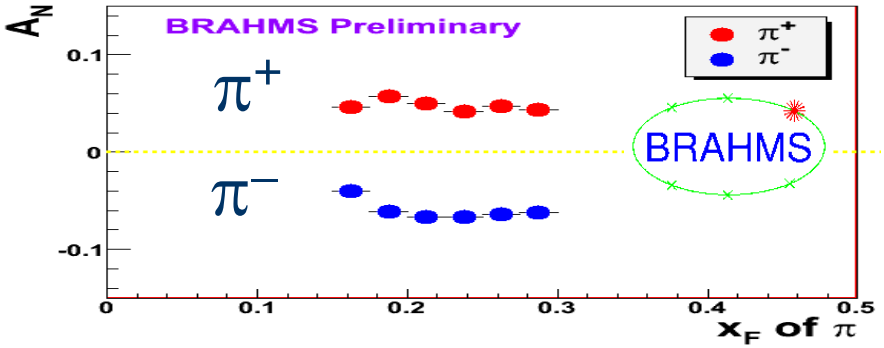
Forward rapidity π^0 at STAR
at $\sqrt{s}$ = 200 GeV

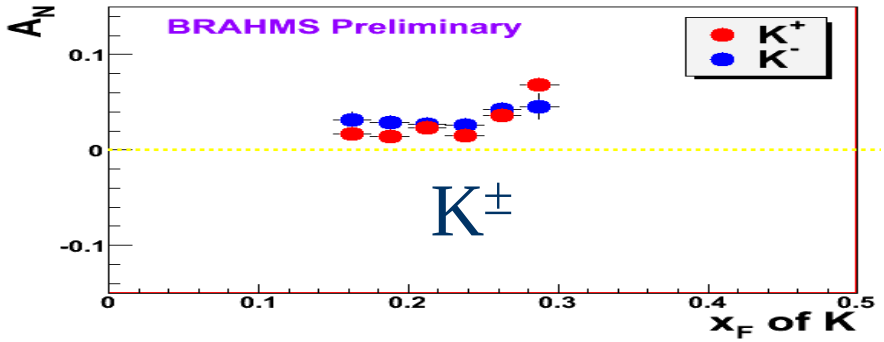


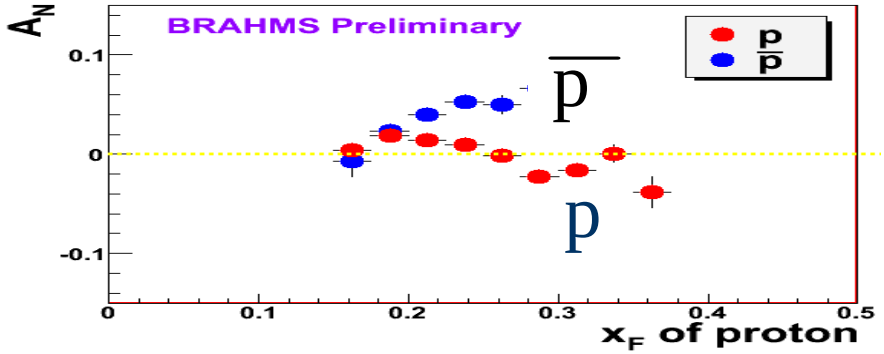
Forward rapidity π^0 at PHENIX
at $\sqrt{s}$ = 62.4 GeV



Forward identified particles
at BRAHMS

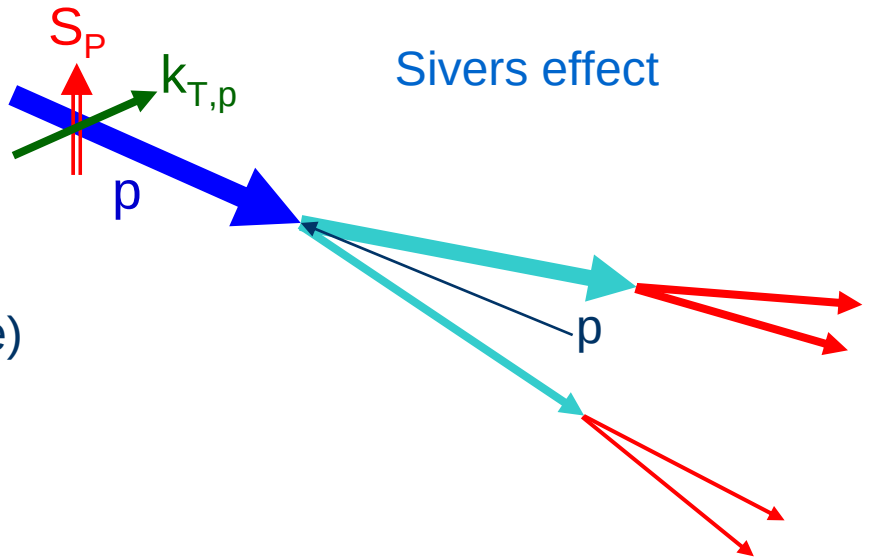




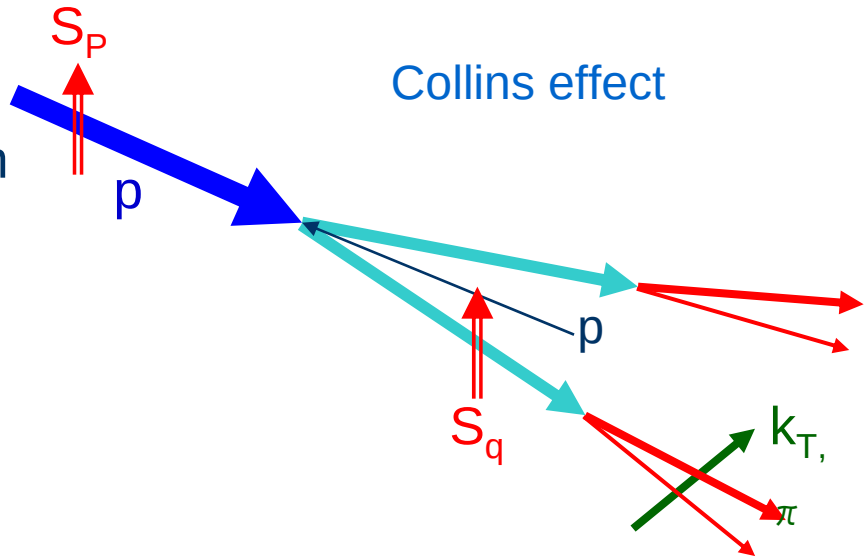


Transverse-spin physics

- Perturbative-QCD models
  - Sivers effect
    - Sivers distribution (initial state)
  - Collins effect
    - Transversity distribution (initial state) + Collins fragmentation (final state)
  - Higher-twist effect
- Many-body correlation of quarks and gluons
  - Sivers effect on TMD (transverse-momentum dependent) factorization
    - Transverse structure of the nucleon
    - Spin-orbit correlation
      - LS force inside the nucleon
  - Higher-twist effect on collinear factorization
    - Parton reaction



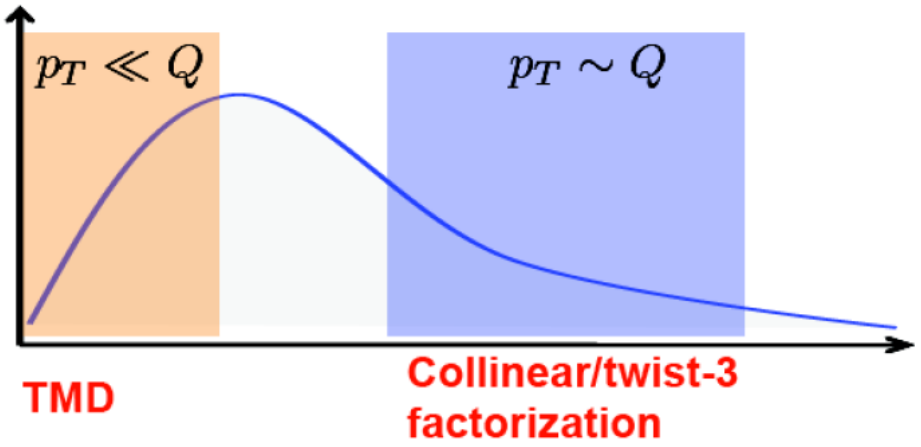
Sivers effect

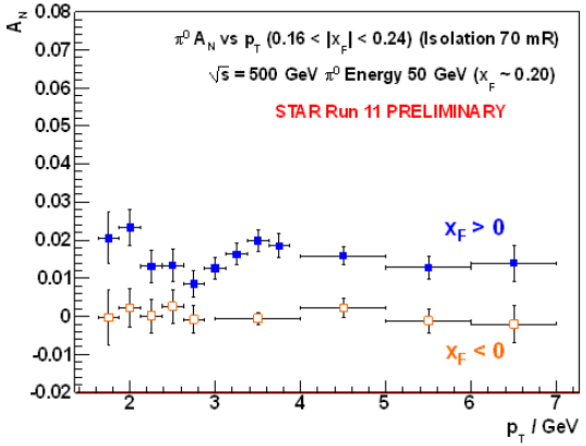


Collins effect

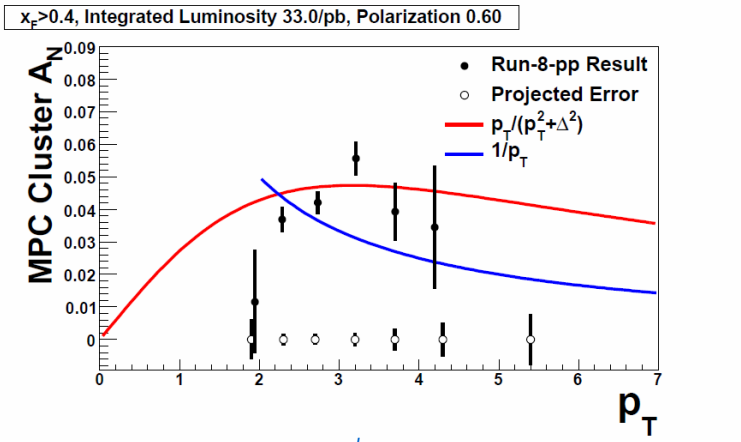
Transverse-spin physics

- How to distinguish
  - Sivers effect
  - Collins effect
  - Higher-twist effect
- p_T distribution
  - Need more statistics
    - To find $1/p_T$ at high p_T





STAR $\sqrt{s}$ = 500 GeV



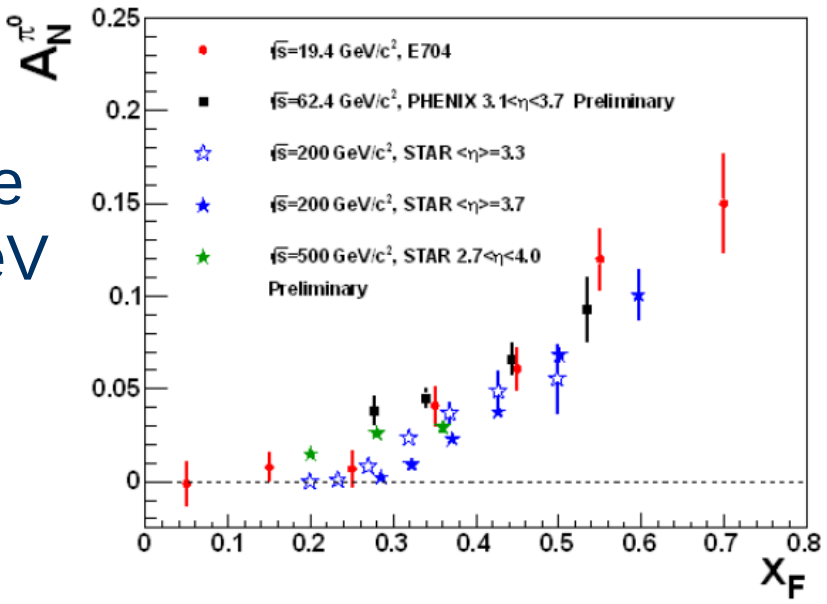
PHENIX $\sqrt{s}$ = 200 GeV

Transverse-spin asymmetry

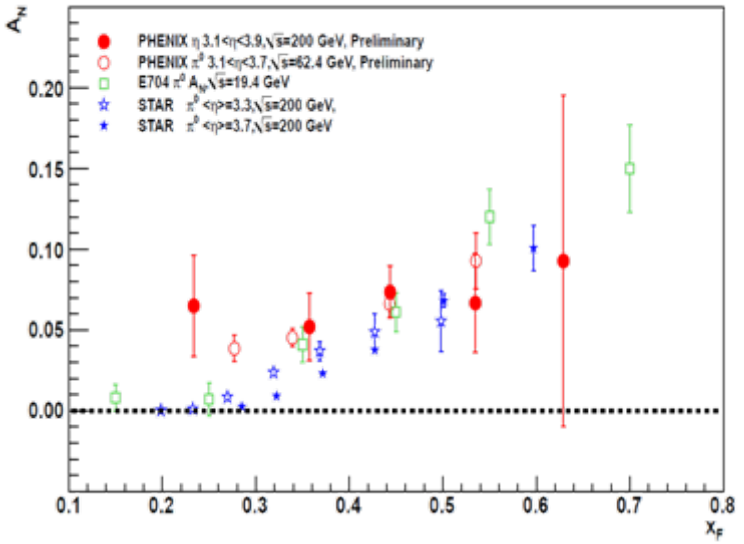
- TMD distributions and transversity distribution
  - Correlations of nucleon's transverse-spin, parton's transverse-spin, and parton's transverse momentum
    - "spin-orbit interaction" inside the nucleon
  - Sivers function
    - Transverse-momentum dependence of partons inside the transversely-polarized nucleon
  - Boer-Mulders function
    - Transverse-momentum dependence of transversely-polarized partons inside the (unpolarized) nucleon
  - Transversity
    - Correlation between transversely-polarized nucleon and transversely-polarized partons inside

MPC at PHENIX

- π^0
  - No strong $\sqrt{s}$ dependence from 19.4 GeV to 500 GeV

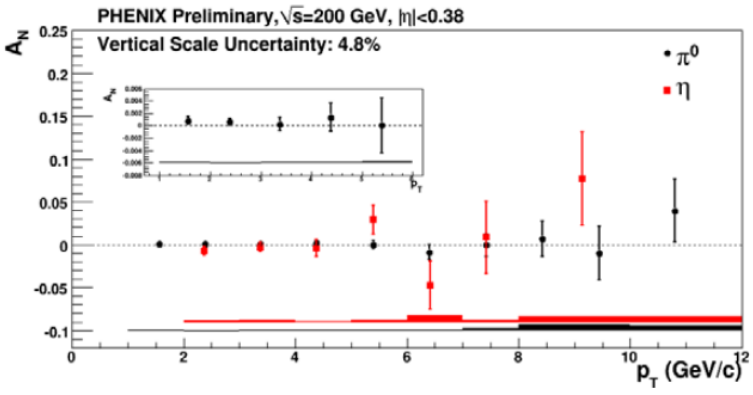


- η
  - Flavor-dependence information

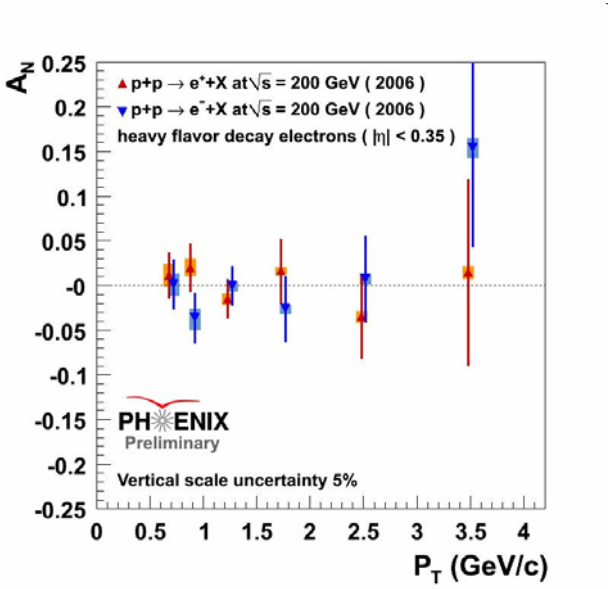


Midrapidity asymmetries

- π^0 and η
  - gluon+gluon & gluon+quark dominant at low p_T
  - Restriction to Gluon Sivers effect

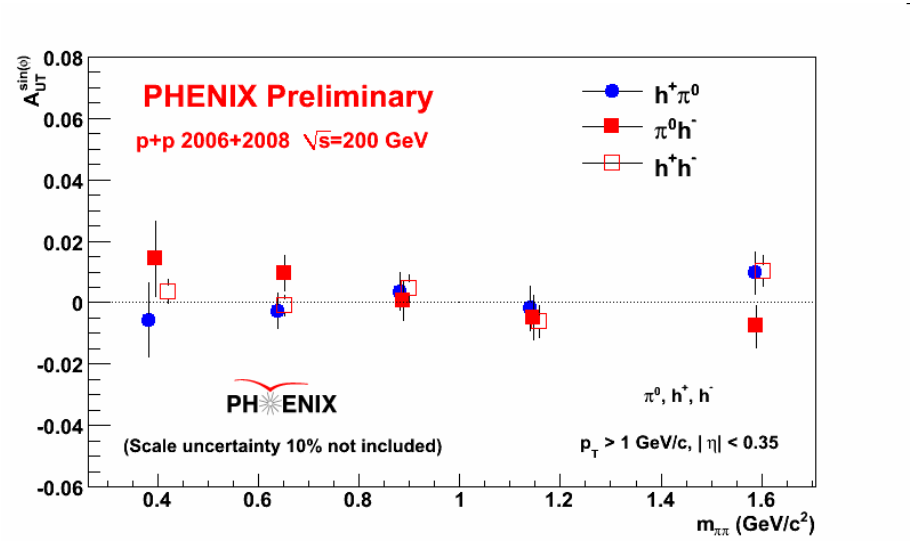


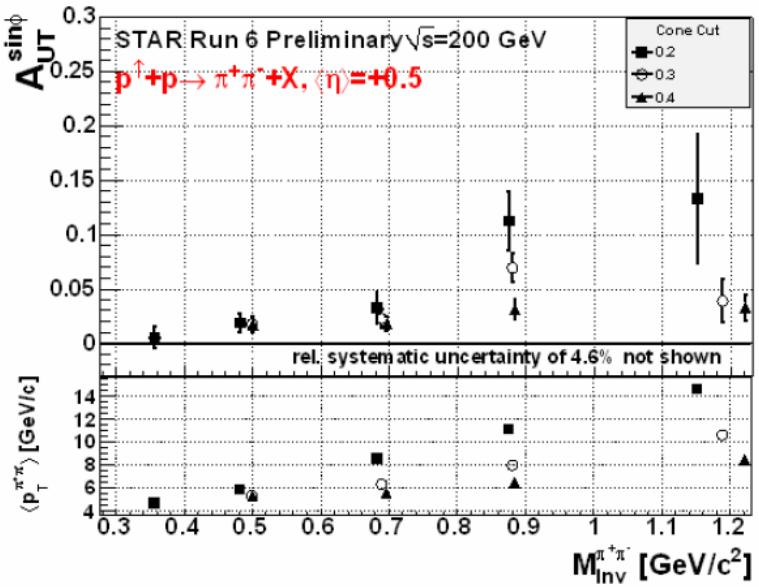
- Single electron
  - Open heavy-flavor decay to electron/positron
  - Restriction to tri-gluon correlation
  - To be improved with VTX



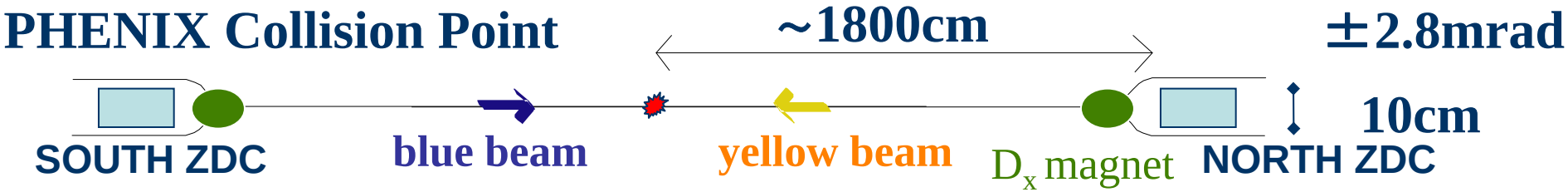
Midrapidity asymmetries

- Transversity measurement
  - with IFF (interference fragmentation function)
  - Pion (or hadron) pair as an analyzer



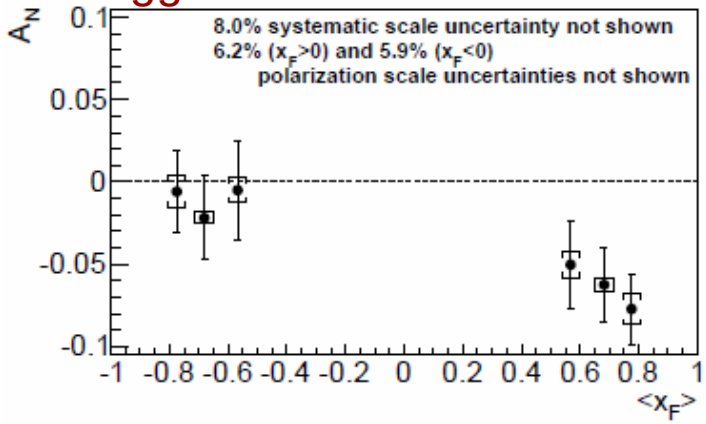


Forward neutron asymmetry

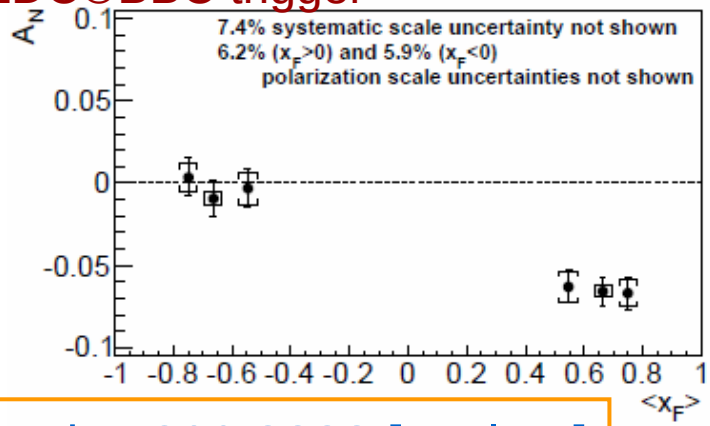


- ZDC + SMD
  - ZDC (Zero-Degree Calorimeter)
    - Hadron sampling calorimeter
  - SMD (Shower Maximum Detector)
    - Position measurement
- x_F distribution
  - Significant negative A_N in the forward region
    - No x_F dependence within the uncertainties
  - No significant backward asymmetry

ZDC trigger



ZDC⊗BBC trigger



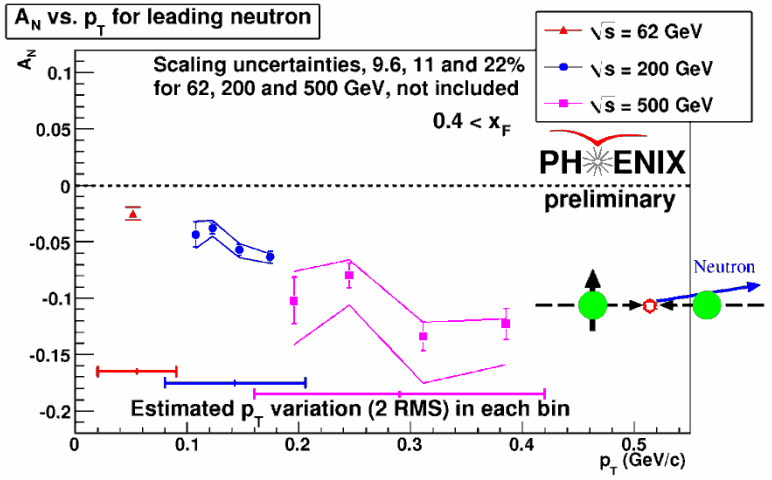
arXiv:1209.3283 [nucl-ex]

Forward neutron asymmetry

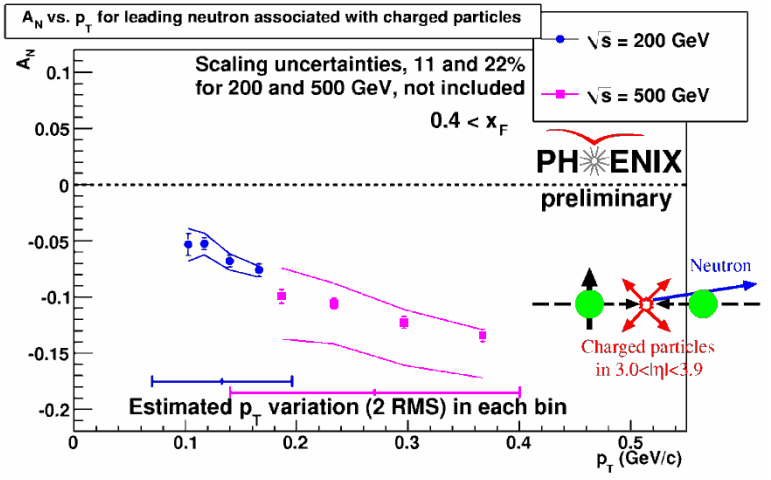
- √s dependence of p_T distribution
  - A_N(62 GeV) < A_N (200 GeV) < A_N (500 GeV)
  - √s dependence or p_T dependence?

PHENIX preliminary data
J. Phys. Conf. Ser. 295, 012097 (2011).

Inclusive neutron



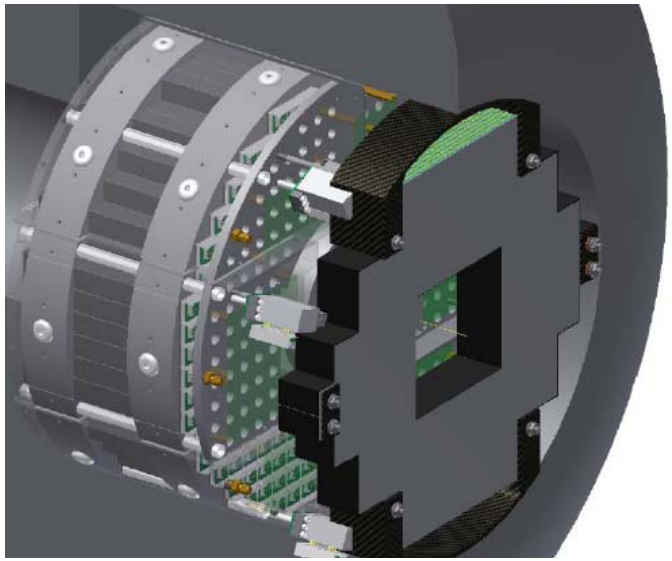
Neutron with charged particles

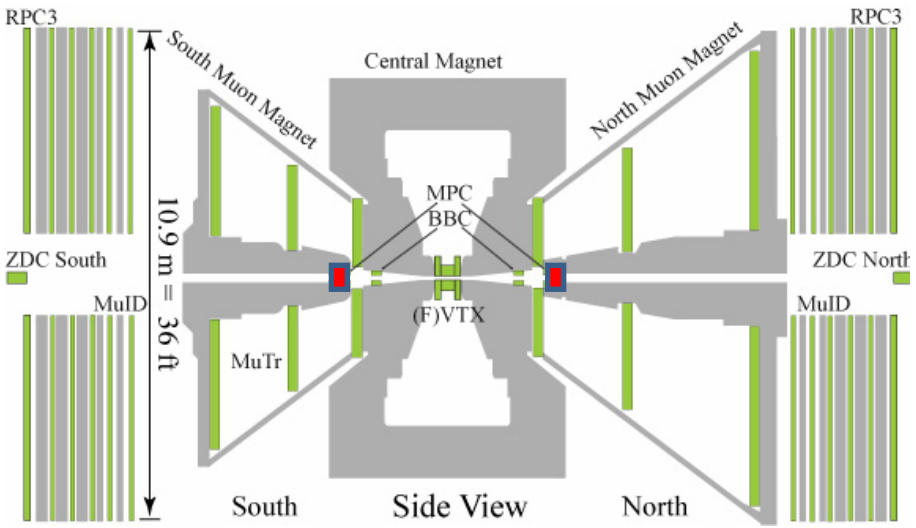


  - Sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

Spin physics in the future

- MPC-EX
  - Pre-shower detector in front of MPC
    - Silicon mini-pad detectors with tungsten plates
  - Approved by BNL and DOE
    - to be ready for 2015 run

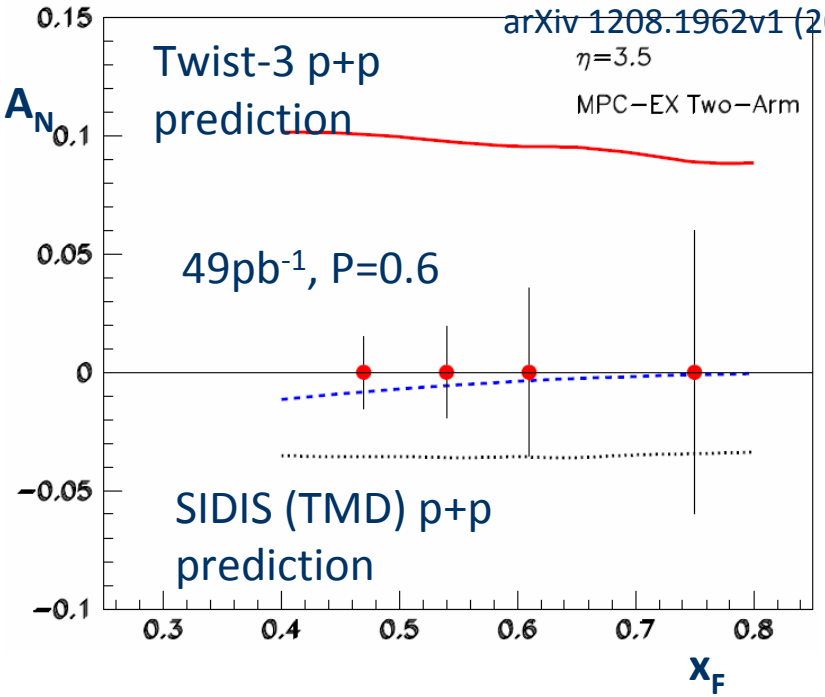


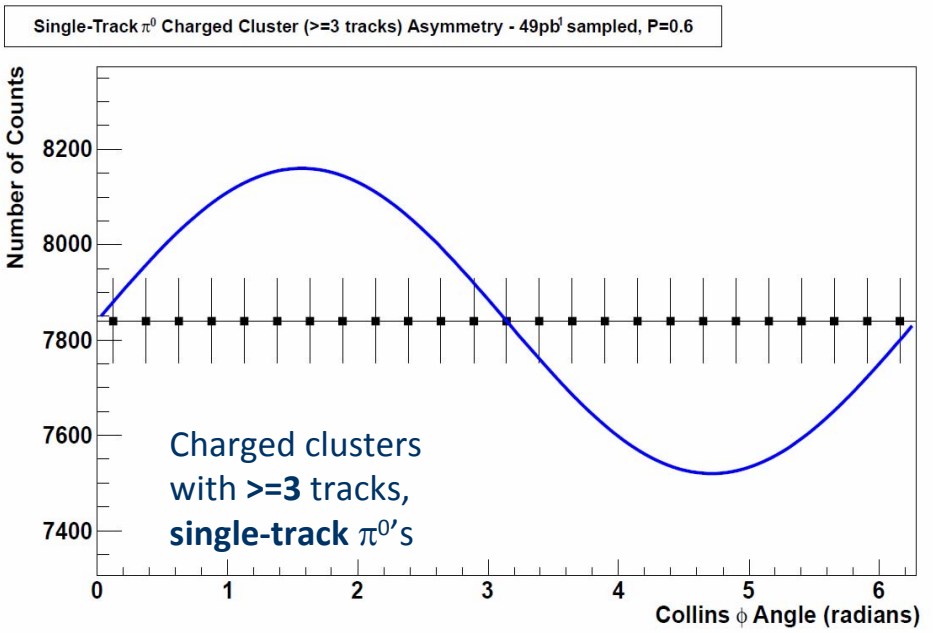


Spin physics in the future

- MPC-EX
  - Prompt photon asymmetry
    - To distinguish Sivers effect and higher-twist effect
  - Collins asymmetry in jet
    - π^0 correlations with jet-like clusters

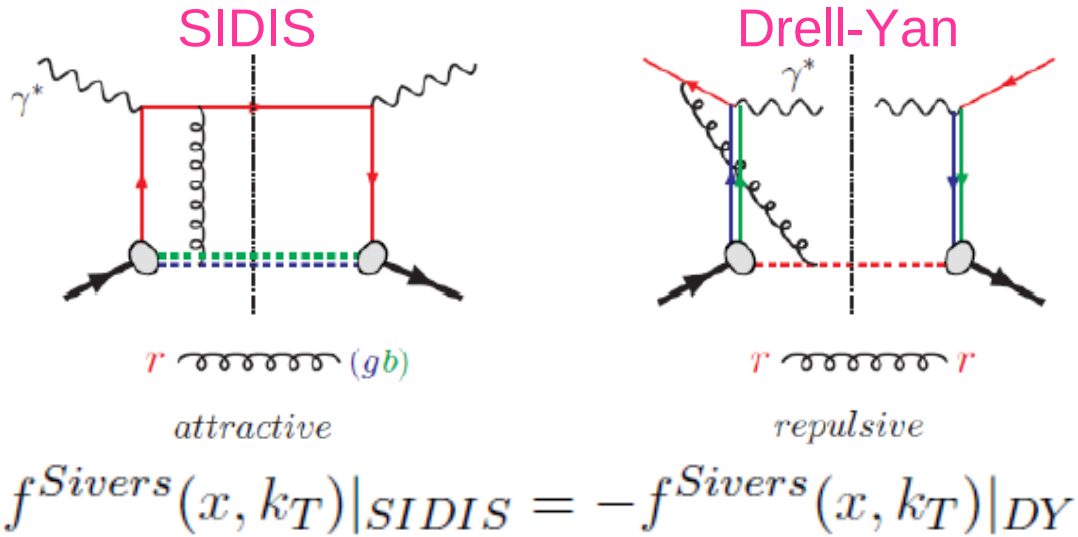
Phys Rev. D 83 094001 (2011)
arXiv 1208.1962v1 (2012)





Spin physics in the future

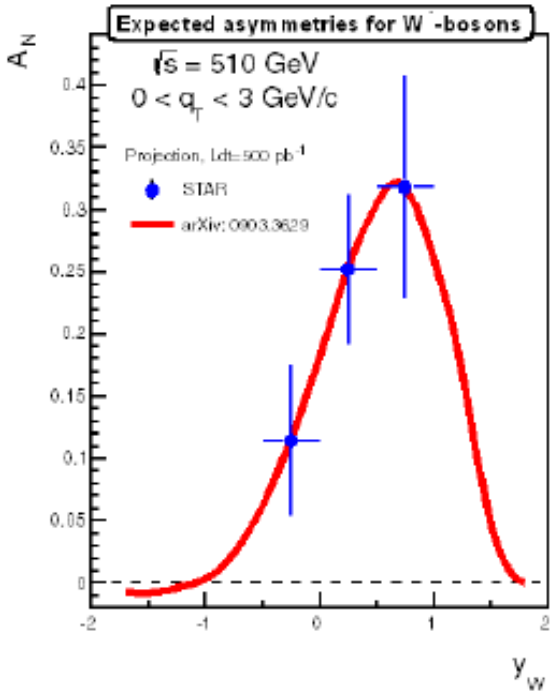
- 3-dimensional structure of the nucleon
  - Many-body correlation of partons
  - Parton distribution in transverse direction
    - Extended/generalized picture of parton distribution
    - Transverse-momentum dependence (TMD)
    - Space distribution (tomography)
- Drell-Yan in the future
  - Comparison of Sivers function measured by polarized SIDIS process and polarized DY process
  - For establishment of the TMD framework

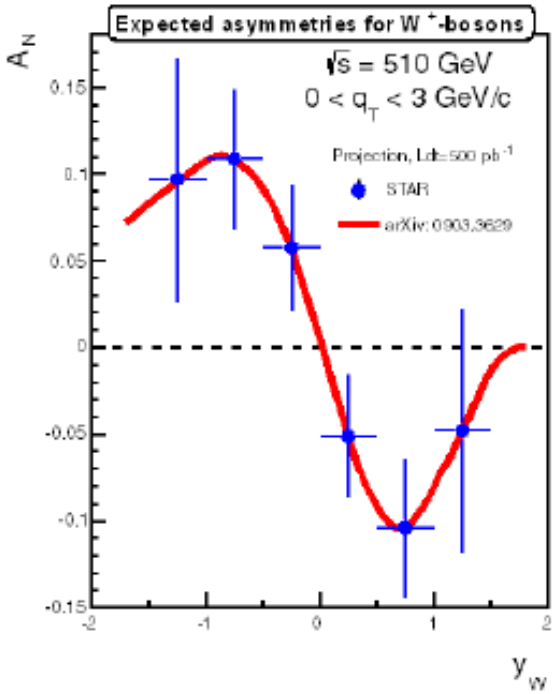


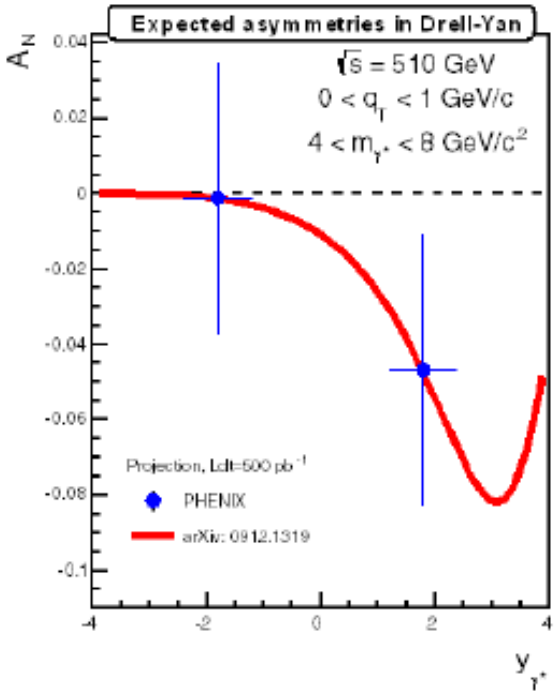
$$f^{Sivers}(x,k_T)|_{SIDIS} = -f^{Sivers}(x,k_T)|_{DY}$$

Spin physics in the future

- Weak bosons and Drell-Yan







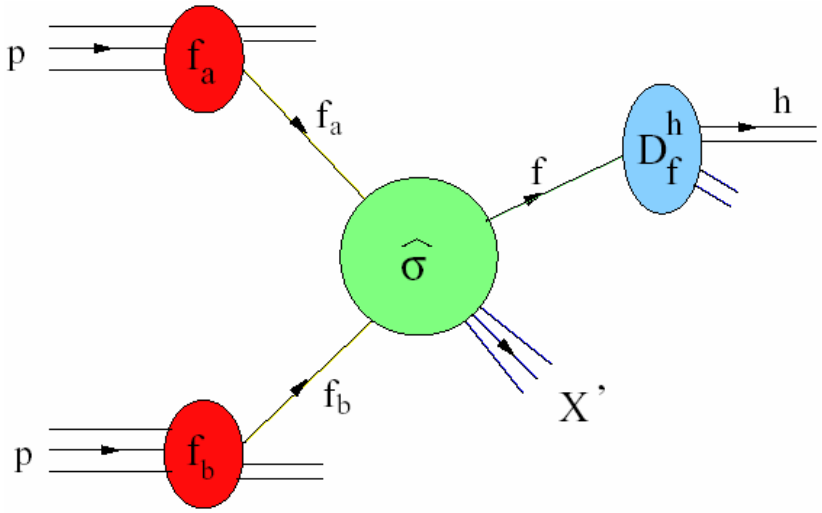
Spin physics in the future

Years	Beam Species and Energies	Science Goals	New Systems Commissioned/Required
2013	500 GeV $\vec{p}+\vec{p}$	Sea antiquark and gluon polarization	Electron lenses upgraded pol'd source
2014	200 GeV $p^{\uparrow}+p$ 200 GeV $\vec{p}+\vec{p}$	Unravel underlying sub-processes for A_N Improve precision on $\Delta g(x)$	PHENIX Muon Piston Calorimeter Extension
2015-2017	200 GeV $p^{\uparrow}+A$ 500 GeV $p^{\uparrow}+p$ 500 GeV $\vec{p}+\vec{p}$	Unravel underlying sub-processes for A_N, A_{UT} for excl. $J/\Psi \rightarrow$GPD E First measurement of PHENIX: $A_N(DY)$, STAR: $A_N(W/Z)$ Unravel underlying sub-processes for A_N $\Delta g(x)$ at low-x, sea antiquark polarizations	STAR inner TPC pad row upgrade
>2018	200 GeV $p^{\uparrow}+A$ 160 GeV $p^{\uparrow}+{}^3He^{\uparrow}$ 500 GeV $p^{\uparrow}+p$	Unravel underlying sub-processes for A_N, A_{UT} for excl. $J/\Psi \rightarrow$GPD E Quark flavor separation for TMDs Precision measurements of transversity, Sivers, IFF, and $A_N(DY)$	Forward upgrade to sPHENIX STAR forward physics upgrade Polarized He^3 beams

Backup Slides

How to describe the nucleon structure

- Factorization
  - Collinear factorization
  - Hadron production in proton collisions
    - pp→hX



$$d\sigma = \sum_{a,b,c} \int dx_a \int dx_b \int dz_c \; f_a(x_a,\mu)\, f_b(x_b,\mu)\, D_c^h(z_c,\mu)\, d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$$

$f_a(x_a,\mu)$, $f_b(x_b,\mu)$ parton distribution function (PDF)

$D_c^h(z_c,\mu)$ fragmentation function (FF)

} long distance term

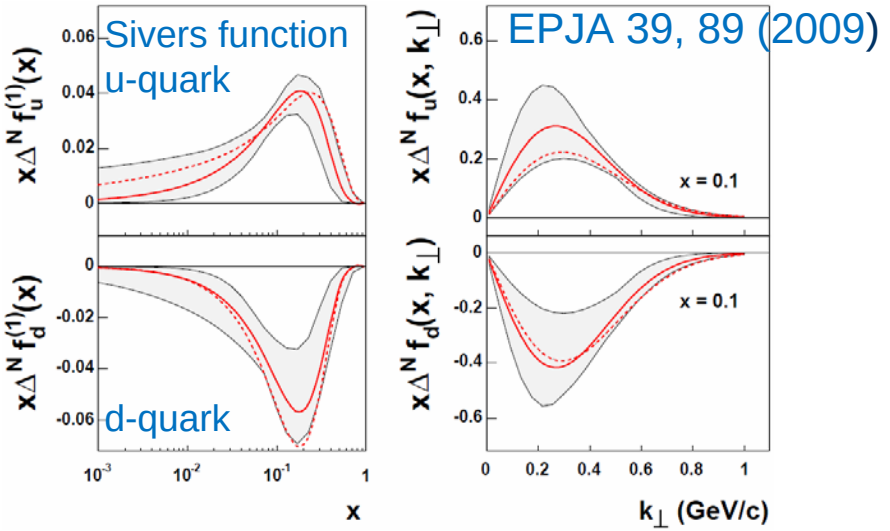
$d\hat{\sigma}_{ab}^c(x_a P_A, x_b P_B, P_h / z_c, \mu)$ partonic cross section — short distance term

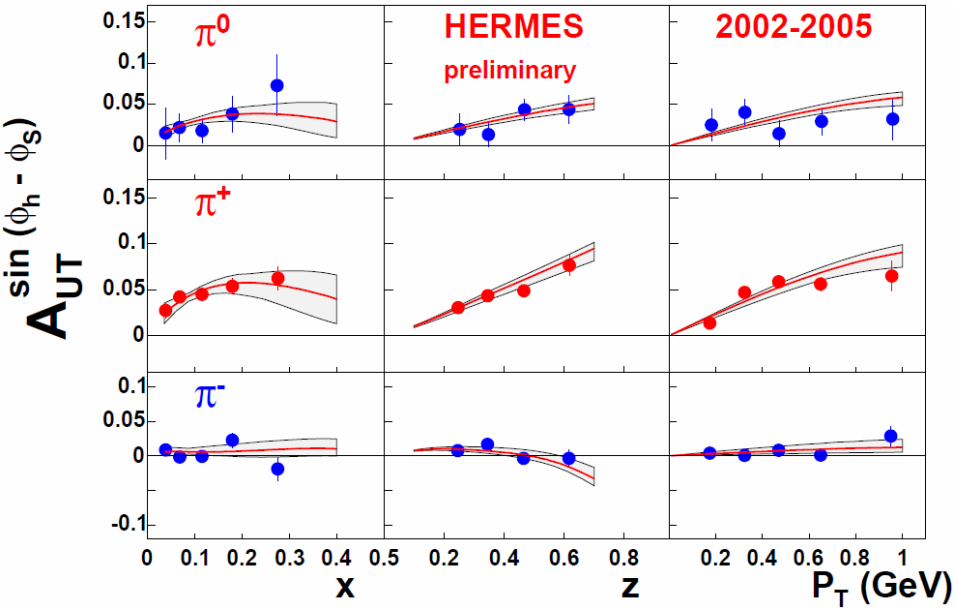
μ factorization scale – boundary between short and long distance

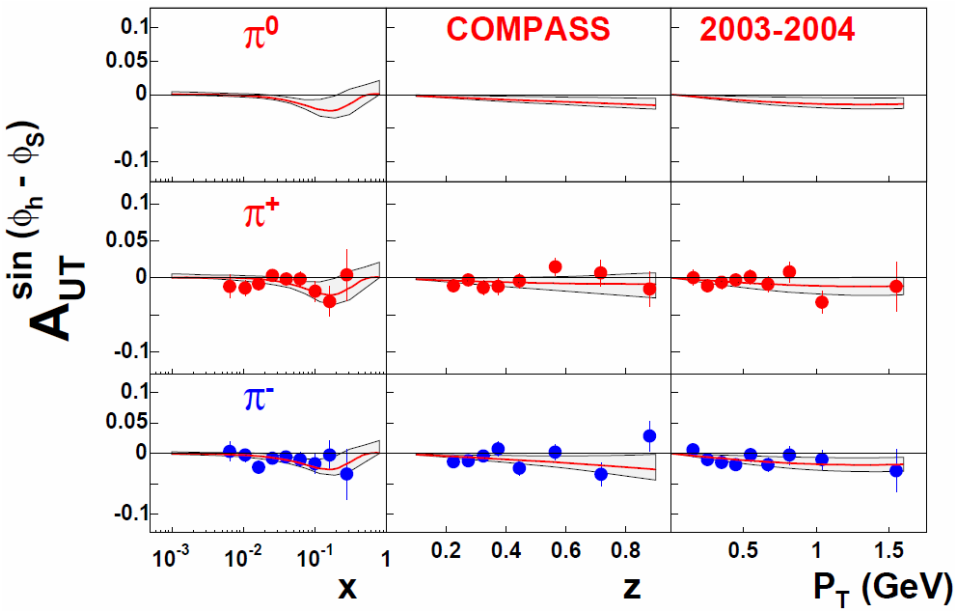
Semi-Inclusive DIS asymmetry

- Measurement of Sivers asymmetry and Collins asymmetry

M. Anselmino, et al. EPJA 39, 89 (2009)

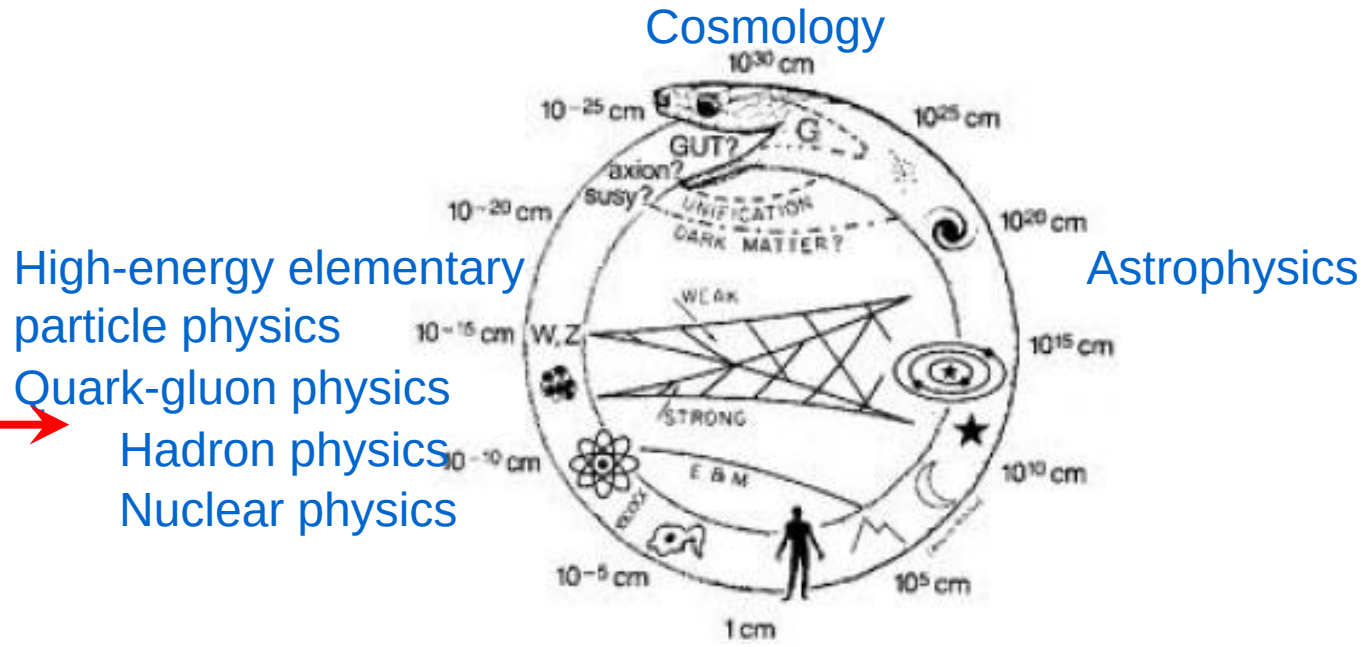






Hierarchy in Nature

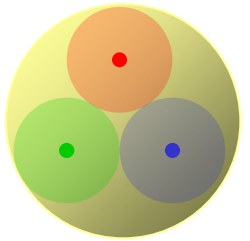
- Glashow's ouroboros



  - Interaction and (breaking of) symmetry
  - Status and structure of the material
- Gap between "quark & gluon" and "constituent quark"
  - Chiral-symmetry
  - Confinement

Quark-Gluon Physics

- Constituent-quark model
  - Explains the magnetic moment of the nucleon
  - But, the quark spin cannot explain the nucleon spin
  - "Spin Puzzle" (or "Spin Crisis")



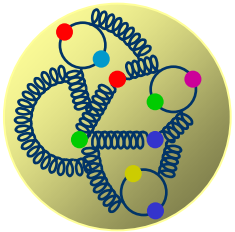
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

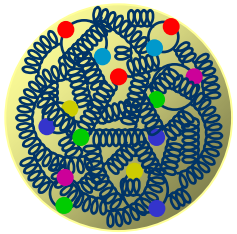
Quark spin contribution

Gluon spin contribution

Orbital angular momentum

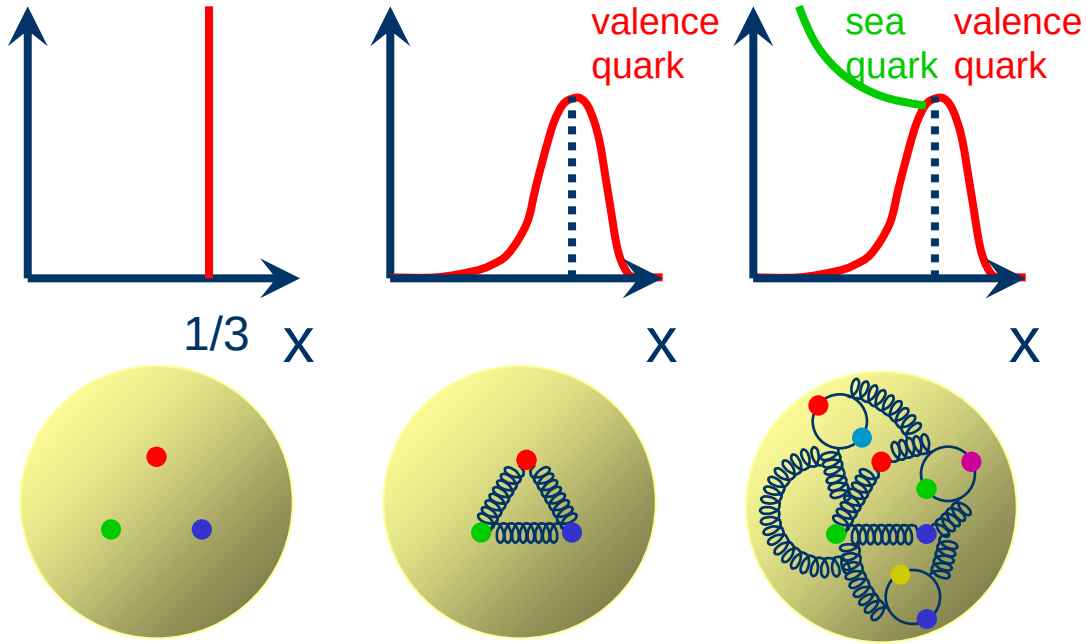
- Quark-gluon model (and QCD)
  - Understanding of gluon interaction
    - Chiral-symmetry
    - Confinement
  - Understanding of the nucleon structure
    - Initial state of high-energy hadron collider (i.e. LHC)





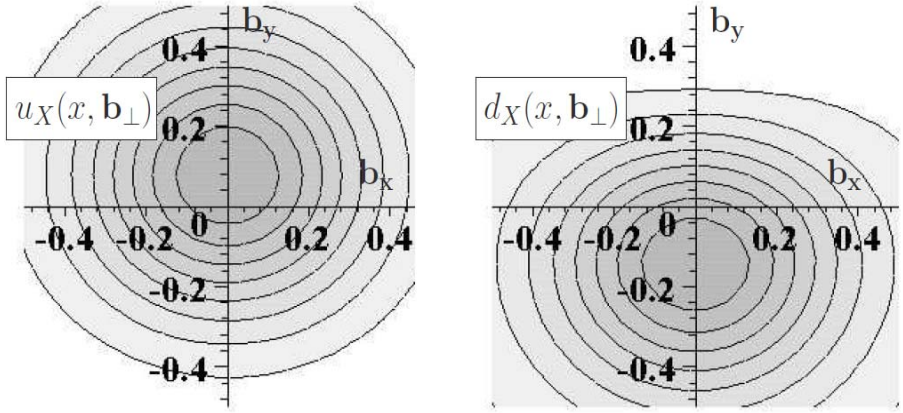
Spin Puzzle

- Longitudinal-spin physics
  - Helicity structure of the nucleon
    - 1-dimensional
  - Collinear factorization
    - Incoherent scattering of partons
    - momentum fraction in longitudinal direction
      - *x*: Bjorken's *x* (x_{Bj})
  - Parton distribution in longitudinal direction

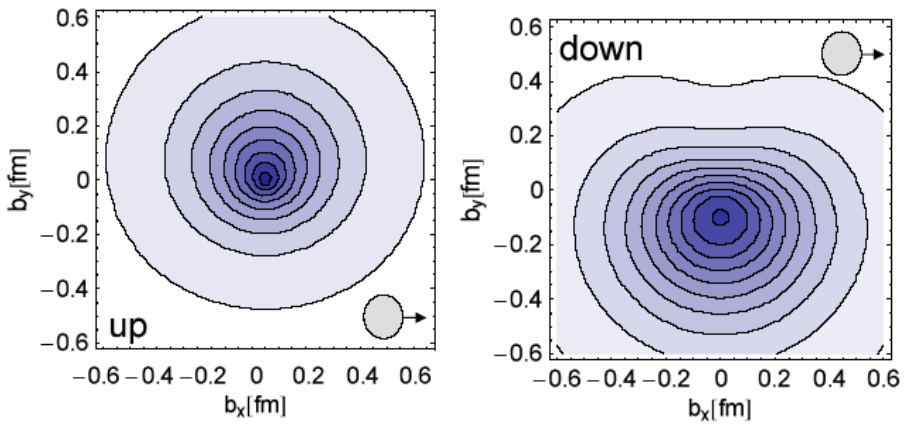


Spin Puzzle

- Transverse-spin physics
  - Transverse structure of the nucleon
    - 3-dimensional
  - Many-body correlation of partons
  - Parton distribution in transverse direction
    - Extended/generalized picture of parton distribution
    - Transverse-momentum dependence (TMD)
    - Space distribution (tomography)



Phenomenological model with GPD data

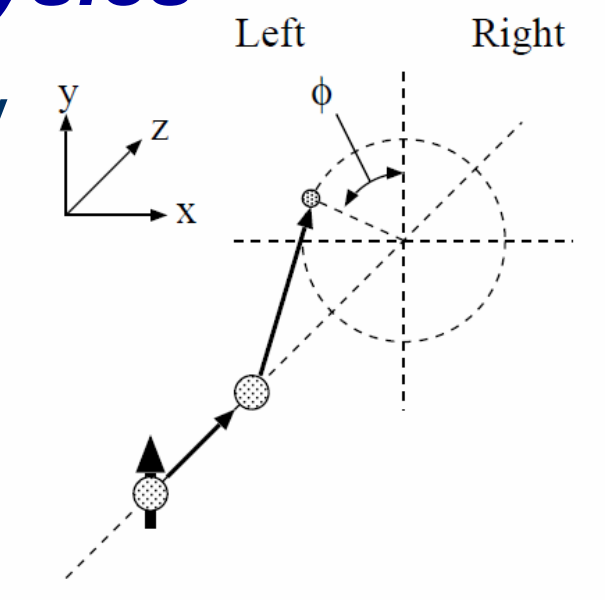


Lattice QCD calculation

Transverse-spin physics

- Single transverse-spin asymmetry

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

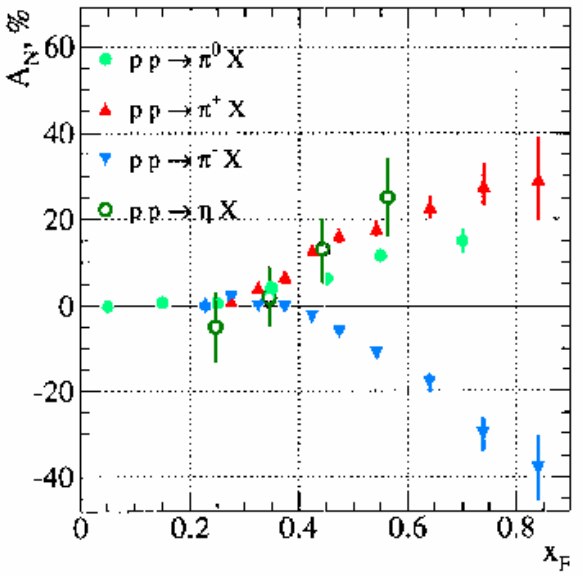


  - Expected to be small in hard scattering at high energies

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

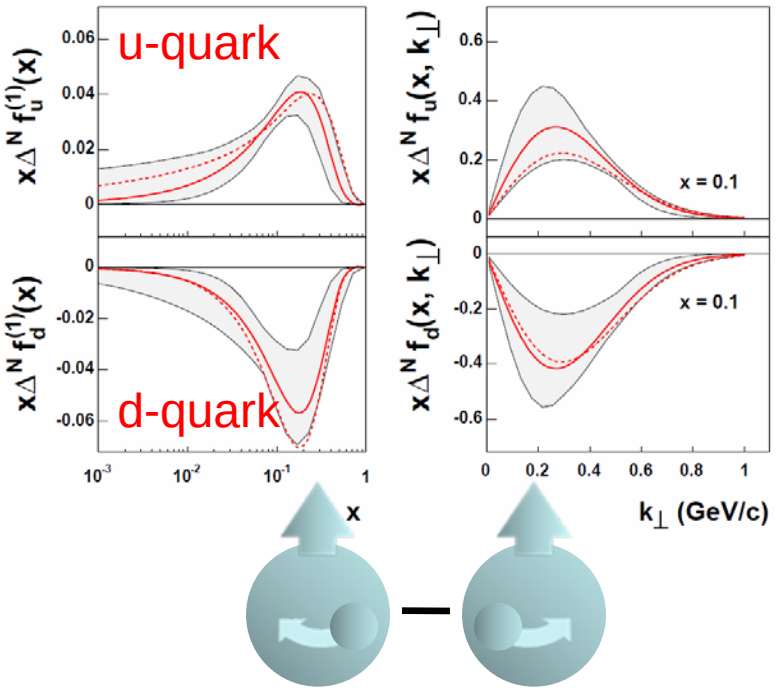
Kane, Pumplin, Repko
PRL 41 1689 (1978)

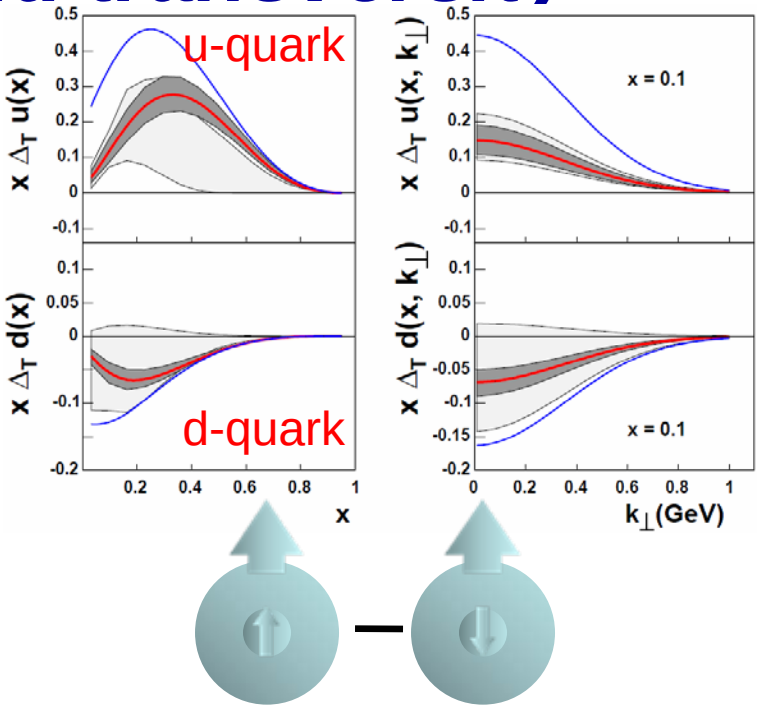
- FNAL-E704
  - Unexpected large asymmetry found in the forward-rapidity region
  - Development of many models based on perturbative QCD



$x_F = 2p_L/\sqrt{s}$ (Feynman's x)

TMD distribution and transversity





Sivers function:

correlation between nucleon transverse spin and parton transverse momentum (k_T)

$$f_{1T}^{\perp}(u) > 0 \quad f_{1T}^{\perp}(d) < 0 \text{ or opposite sign...}$$

Transversity:

correlation between nucleon transverse spin and parton transverse spin

$$h_1(u) > 0 \quad h_1(d) < 0$$

Boer-Mulders function:

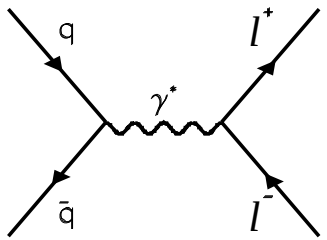
correlation between parton transverse spin and parton transverse momentum (k_T)

$h_1^{\perp}(u)$ and $h_1^{\perp}(d)$ expected to have the same sign...

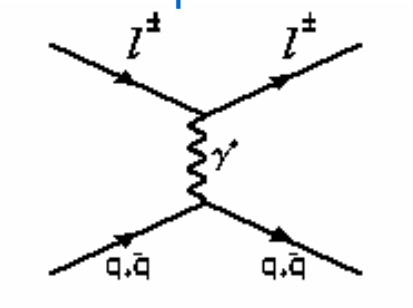
Spin physics in the future

- (Forward) sPHENIX
  - Sivers asymmetry in Drell-Yan process
    - Competitive program in the world
    - Comparison with Semi-Inclusive DIS measurement

Drell-Yan process



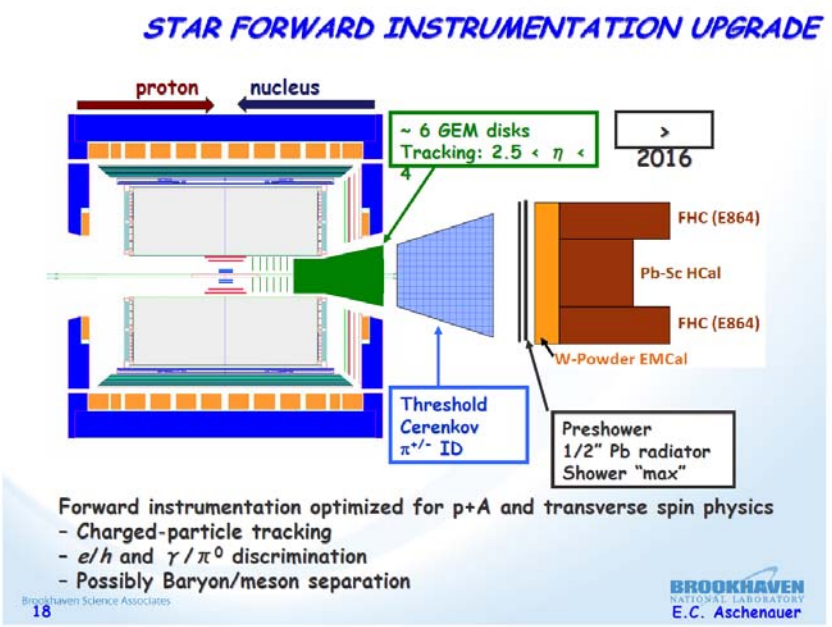
DIS process

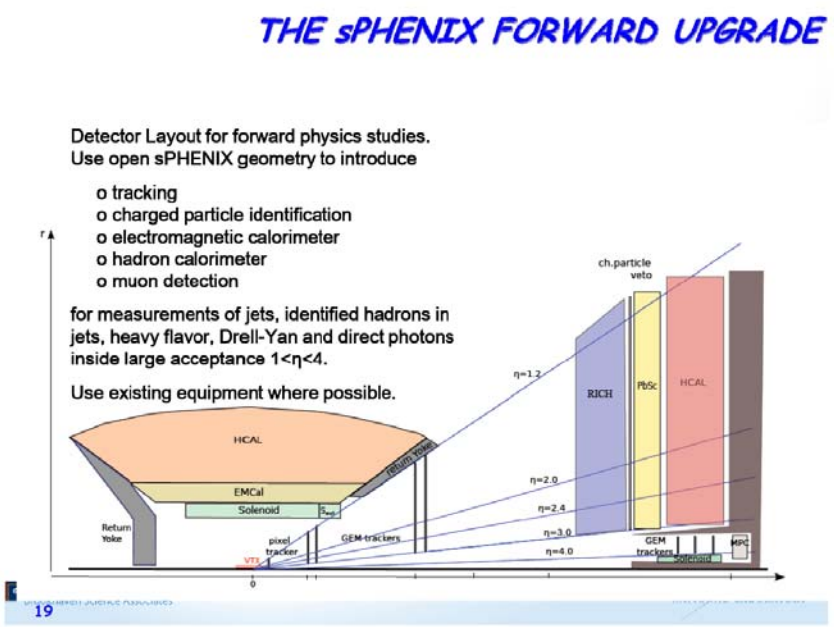


- ePHENIX at eRHIC
  - Polarized electron+proton collision
  - 3-dimensional space distribution measurement (tomography) inside the proton with deeply-virtual measurements of Compton scattering (DVCS) and meson production

Spin phyics in the future

- Detector upgrades

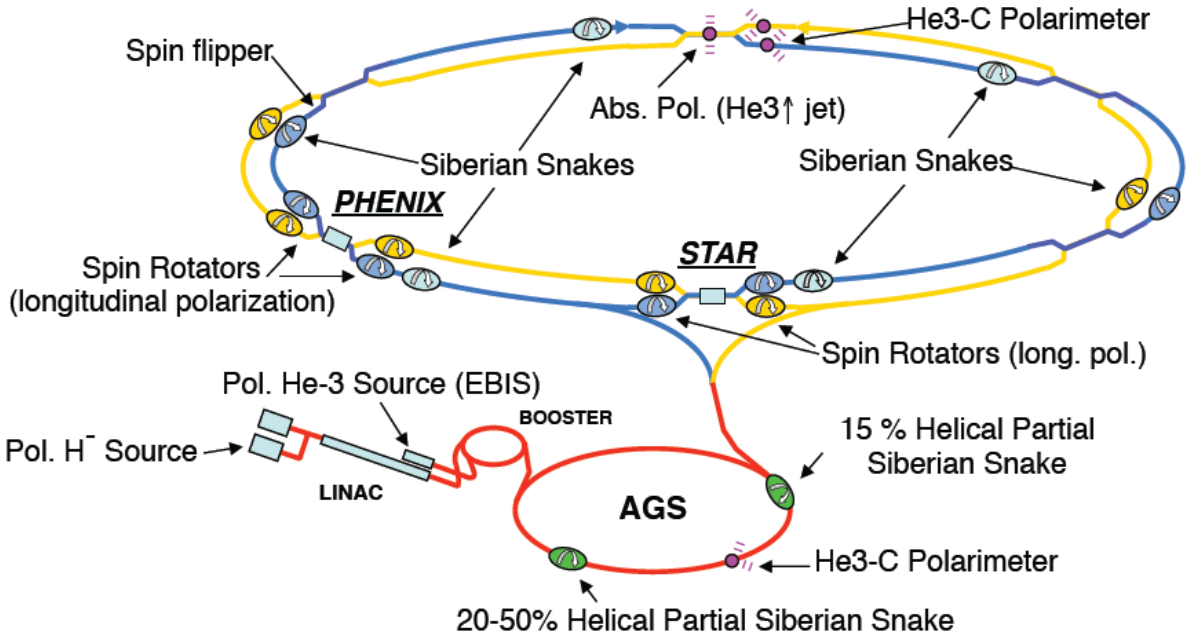




Spin physics in the future

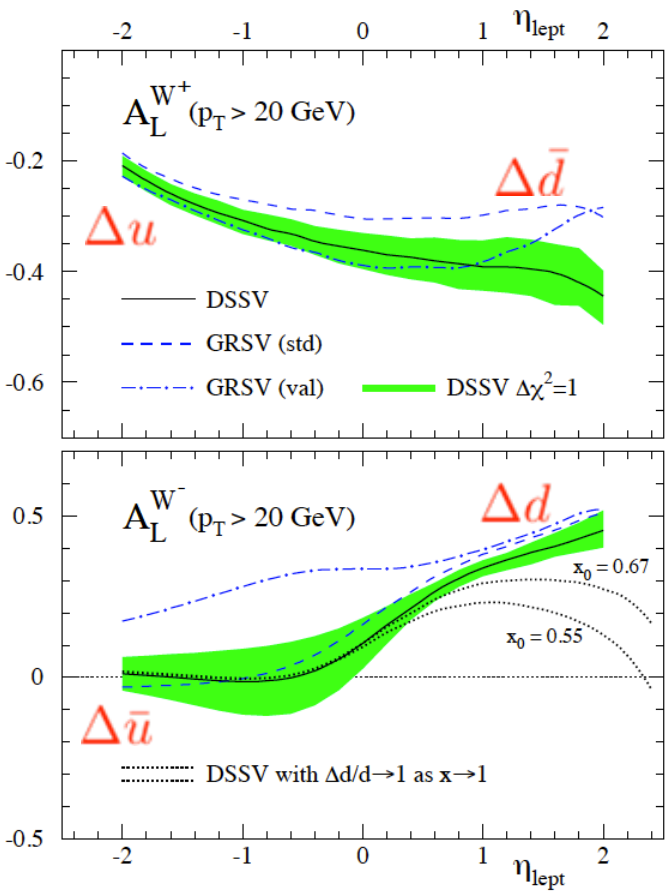
Polarized ^{3}He in RHIC

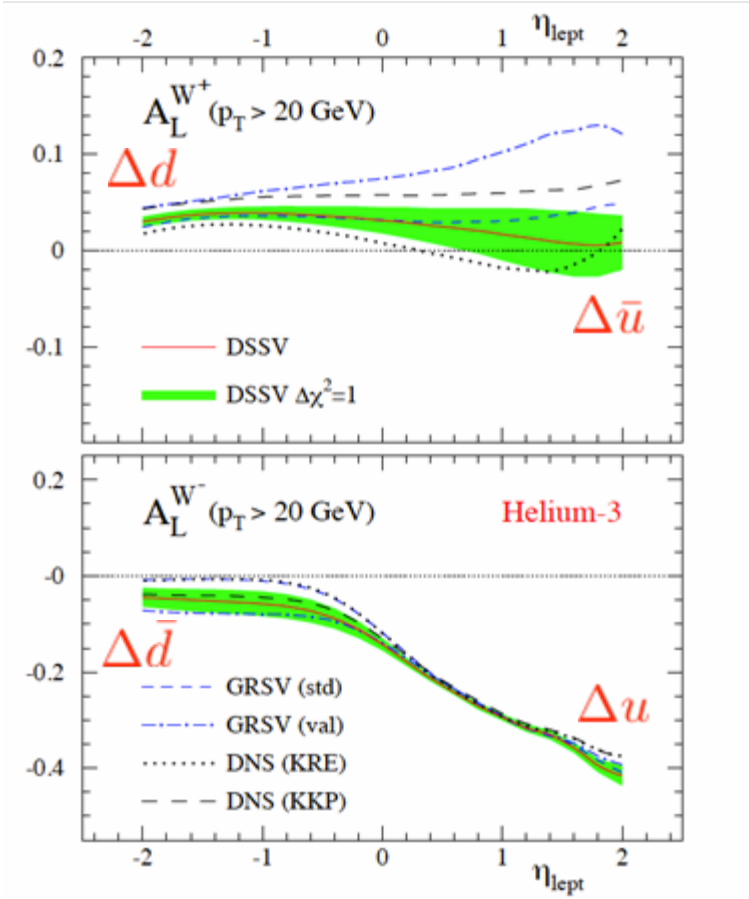
- Polarized ^{3}He possible from new EBIS (J. Maxwell, Tue., 3:30 pm)
- Max. energy in RHIC: 170 GeV/n
- Depolarizing res. are stronger, however no depolarization expected with six snakes in RHIC
- Accelerated unpolarized ^{3}He from EBIS in AGS
- Relative pol.: ^{3}He-C CNI polarimeter; successfully tested with unpolarized ^{3}He
- Absolute pol.: ^{3}He-^{3}He CNI polarimeter using polarized ^{3}He jet?



Spin physics in the future

- Polarized ^{3}He = polarized neutron





Summary

- Transverse-spin physics
  - To understand 3-dimensional parton structure of the nucleon
    - Many-body correlation of quarks and gluons
  - To solve the “spin puzzle”
    - origin of the nucleon spin: orbital angular momentum
  - Sivers effect / Collins effect / Higher-twist effect
    - p_T distribution measurement
- Single transverse-spin asymmetries at PHENIX
  - Forward asymmetry with MPC and MPC-EX (2015-)
  - Midrapidity asymmetry
  - Forward neutron asymmetry
- Transverse-spin physics will have a high priority as a goal of the RHIC-Spin project