PHENIX Transverse-Spin Physics

Korea-Japan PHENIX Collaboration Workshop

November 27, 2012

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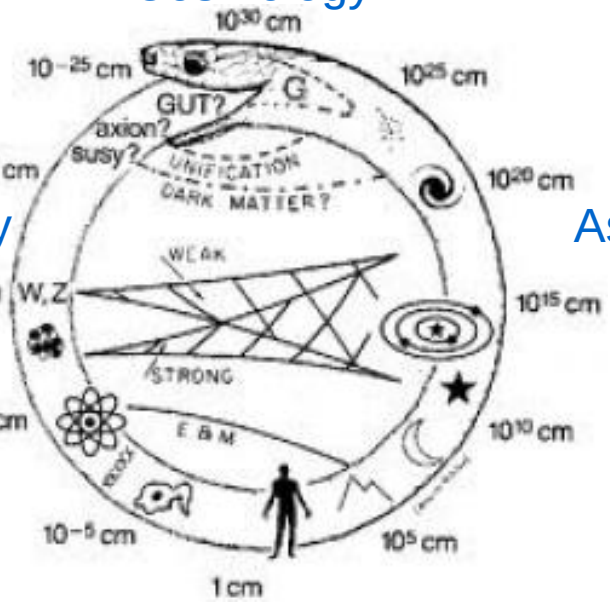
Hierarchy in Nature

- Glashow's ouroboros

Cosmology



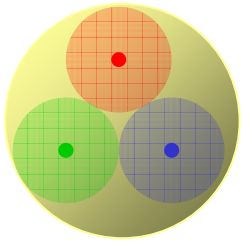
High-energy elementary particle physics
Quark-gluon physics
Hadron physics
Nuclear physics

Astrophysics

  - 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")



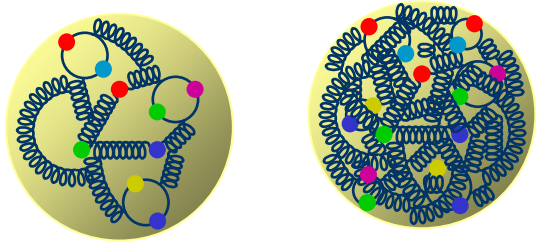
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L$$

Orbital angular momentum

Gluon spin contribution

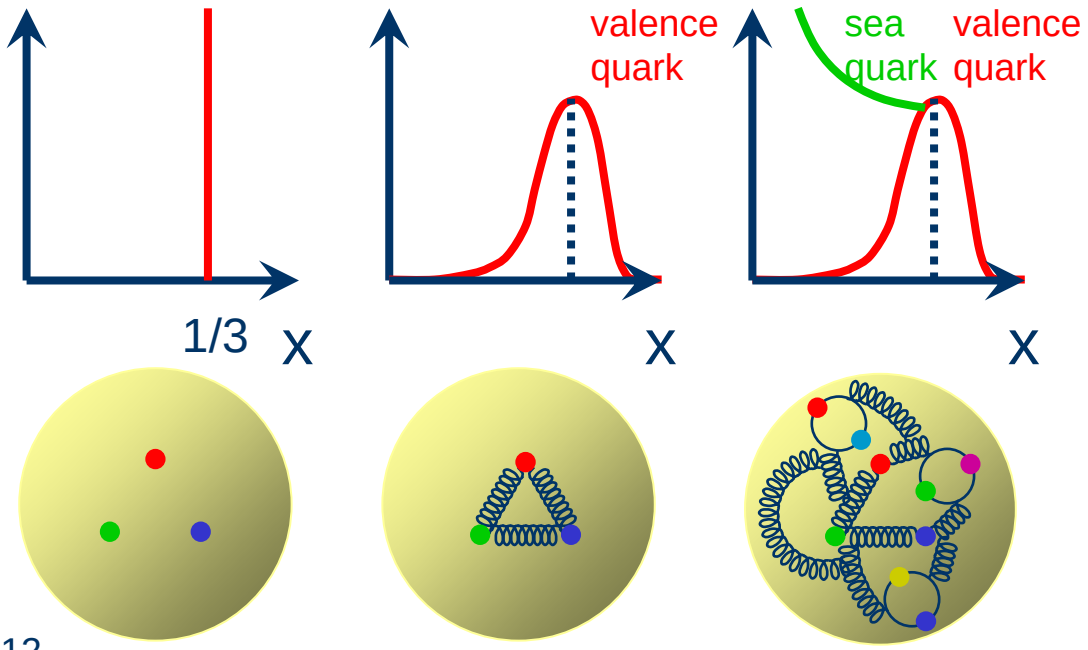
Quark spin contribution

- 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)



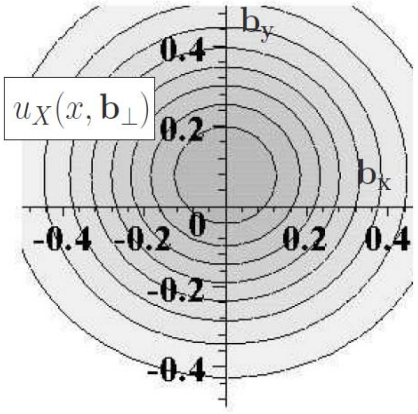
Spin Puzzle

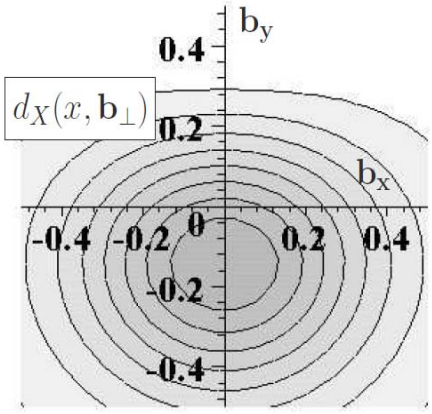
- Longitudinal-spin physics
  - Helicity structure of the nucleon
    - 1-dimensional
  - Collinear factorization
    - Incoherent scattering of partons
    - momentum fraction in longitudinal direction
      - *x*: Bjorken's *x* (x_{Bj})
  - Parton distribution in longitudinal direction



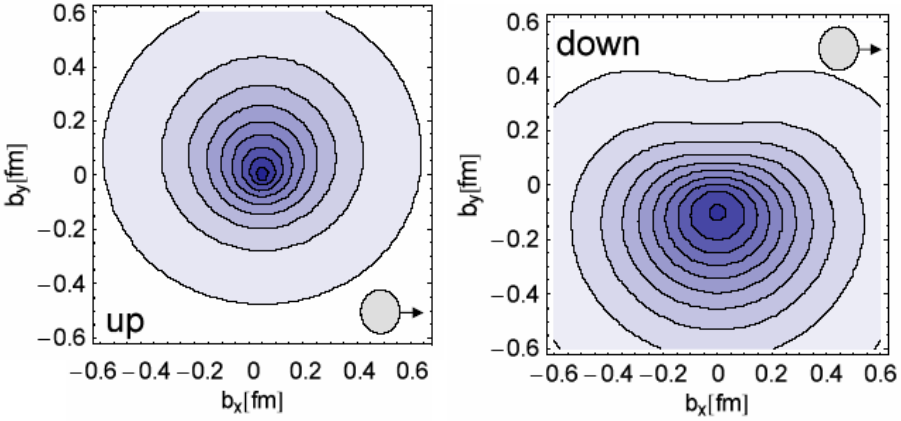
Spin Puzzle

- 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

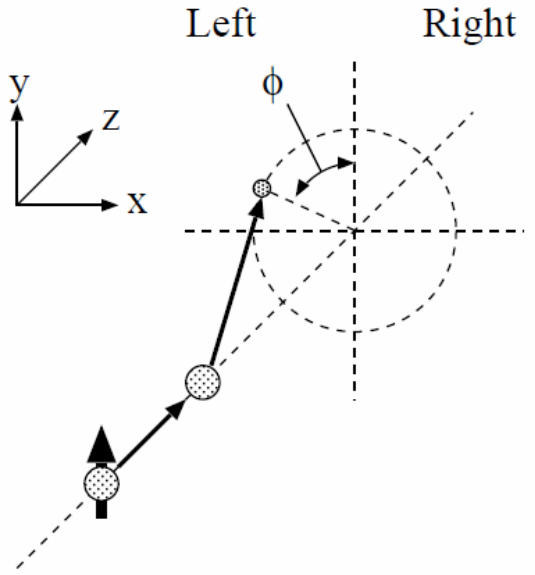
- Single transverse-spin asymmetry

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

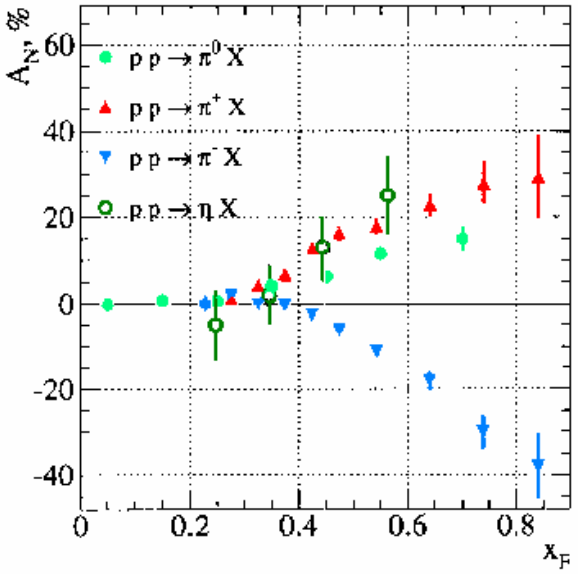
  - Expected to be small in hard scattering at high energies

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

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



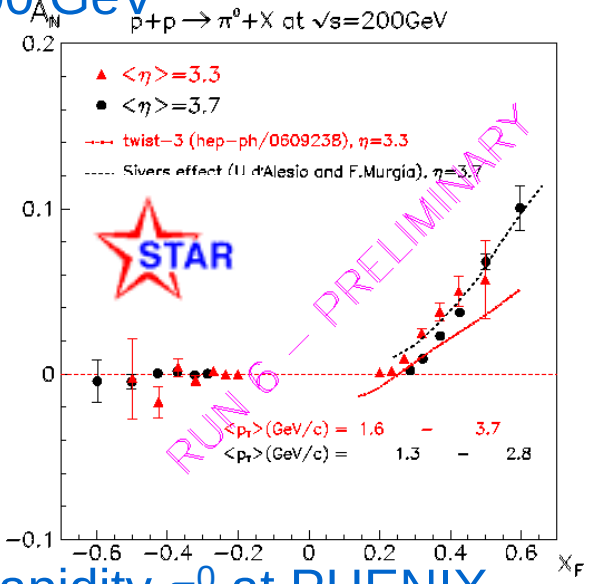
$x_F = 2p_L/\sqrt{s}$ (Feynman's x)

Transverse-polarization runs at RHIC

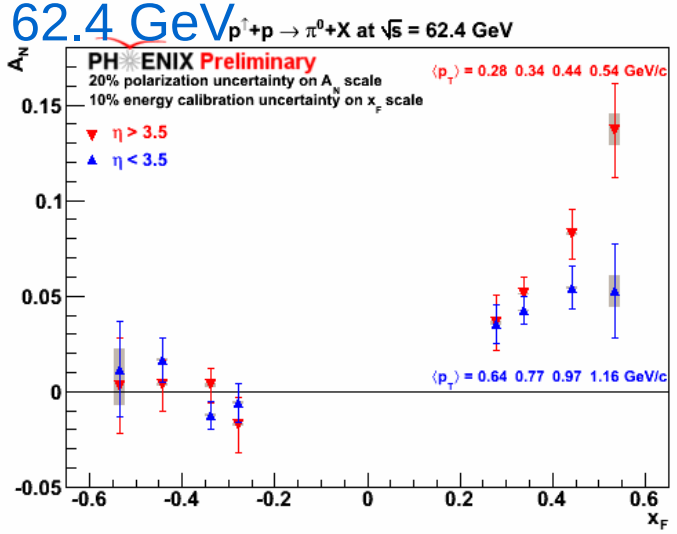
Year	√s [GeV]	Recorded PHENIX	Recorded STAR	Pol [%]
2001 (Run 2)	200	0.15 pb^{-1}	0.15 pb^{-1}	15
2003 (Run 3)	200	/	0.25 pb^{-1}	30
2005 (Run 5)	200	0.16 pb^{-1}	0.1 pb^{-1}	47
2006 (Run 6)	200	2.7 pb^{-1}	8.5 pb^{-1}	57
2006 (Run 6)	62.4	0.02 pb^{-1}		53
2008 (Run8)	200	5.2 pb^{-1}	7.8 pb^{-1}	45
2011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

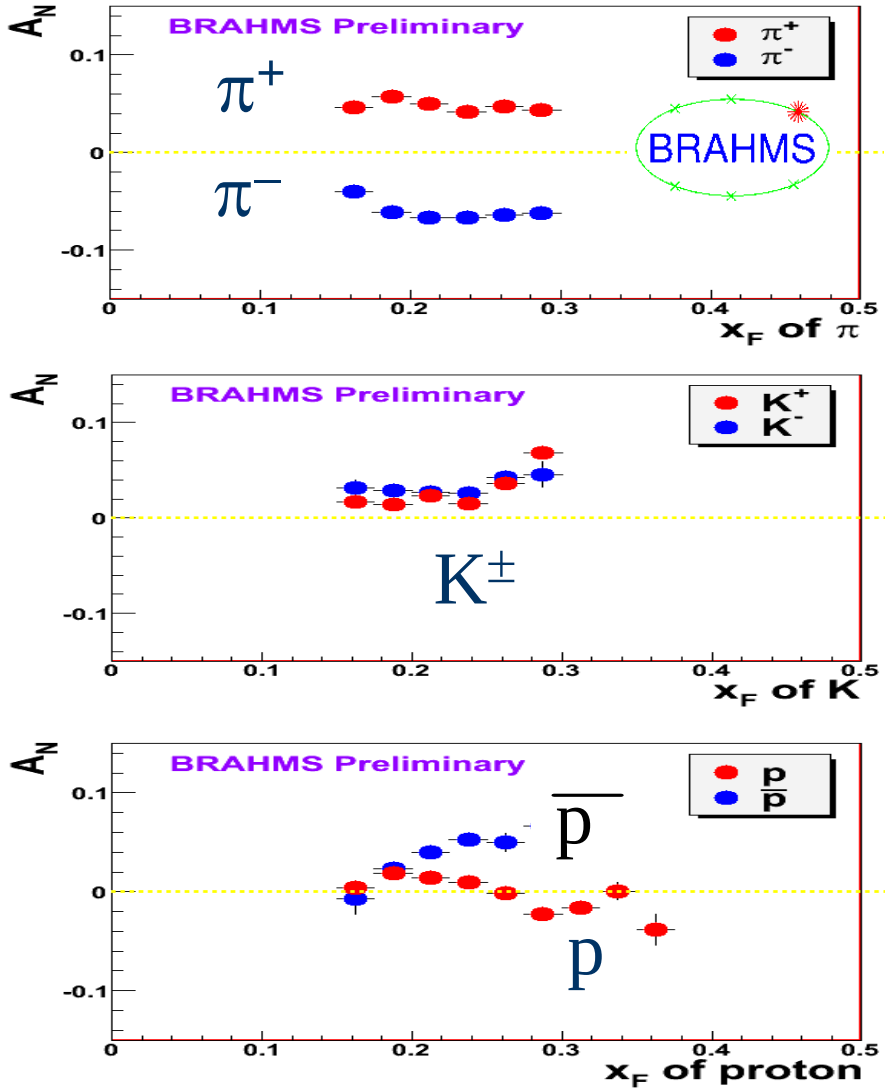
Forward rapidity π^0 at STAR
at $\sqrt{s}$ = 200 GeV



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

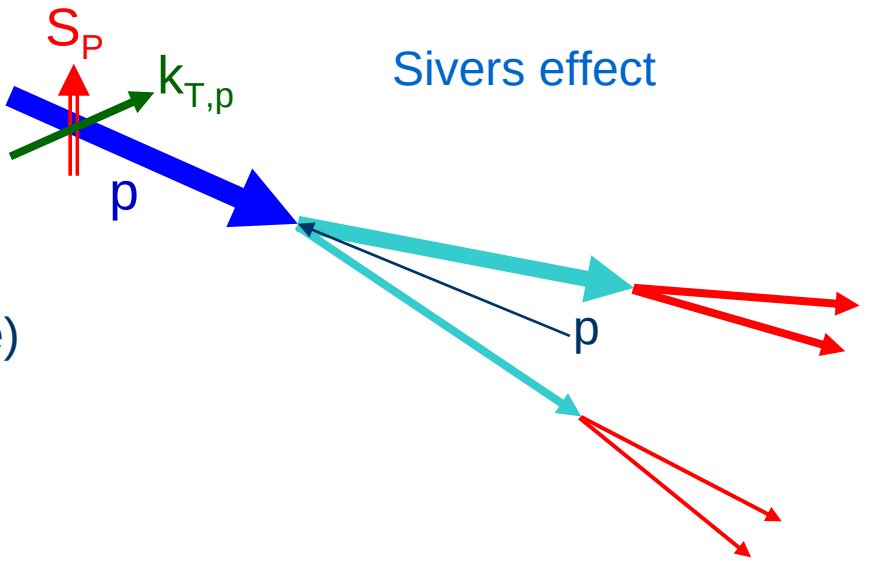


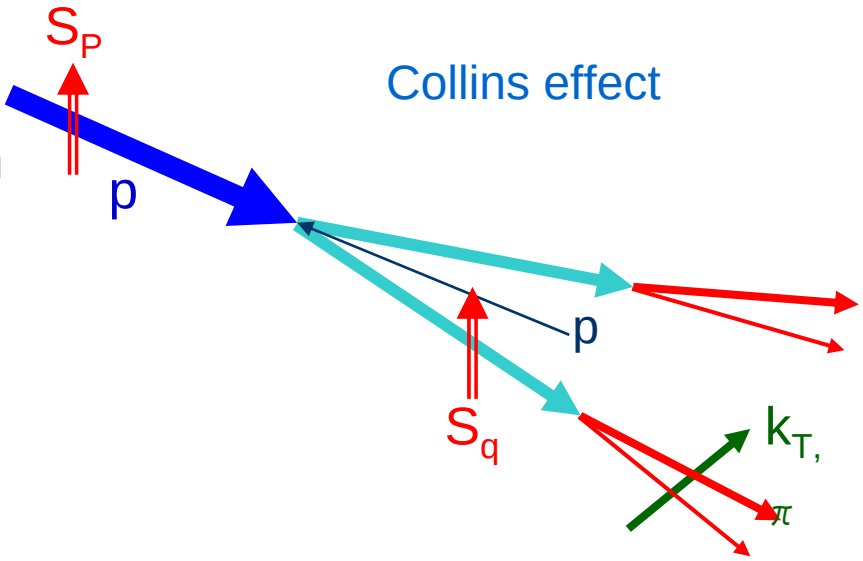
Forward identified particles
at BRAHMS



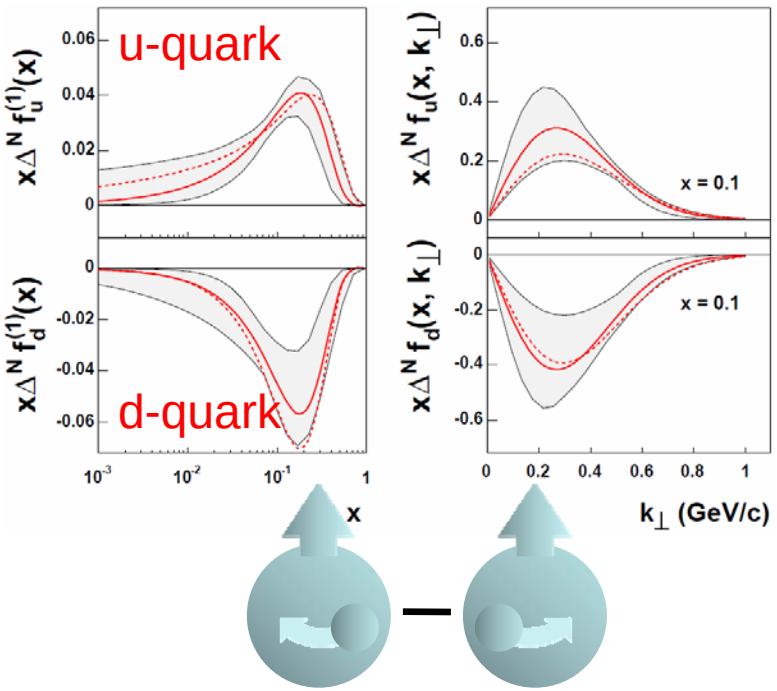
Transverse-spin physics

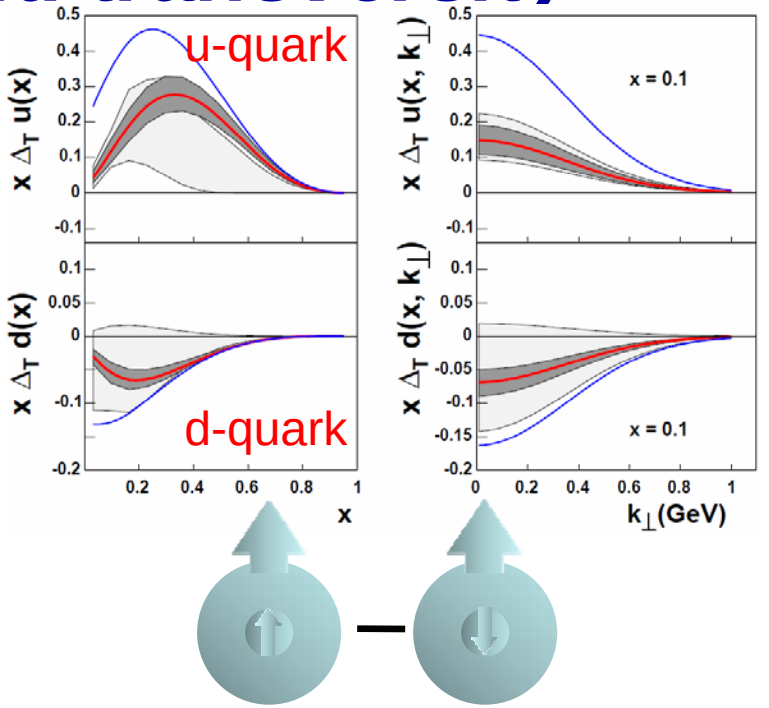
- Perturbative-QCD models
  - Sivers effect
    - Sivers distribution (initial state)
  - Collins effect
    - Transversity distribution (initial state) + Collins fragmentation (final state)
  - Higher-twist effect
- Many-body correlation of quarks and gluons
  - Sivers effect on TMD (transverse-momentum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





TMD distribution and transversity





Sivers function:

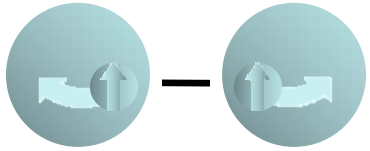
correlation between nucleon transverse spin and parton transverse momentum (k_T)

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

Transversity:

correlation between nucleon transverse spin and parton transverse spin

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



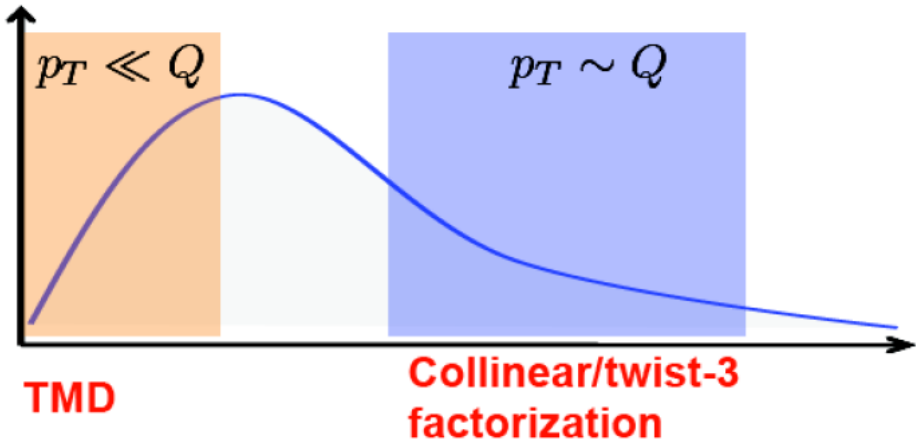
Boer-Mulders function:

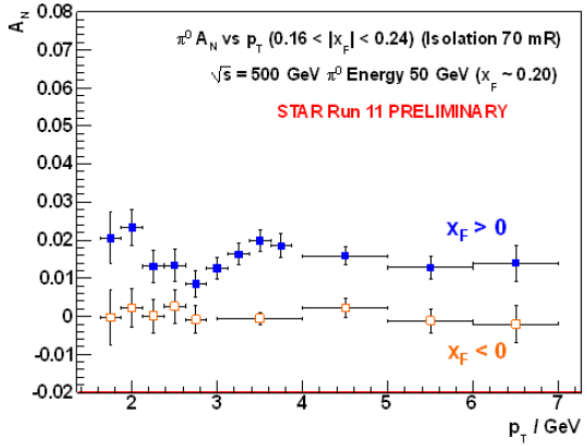
correlation between parton transverse spin and parton transverse momentum (k_T)

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

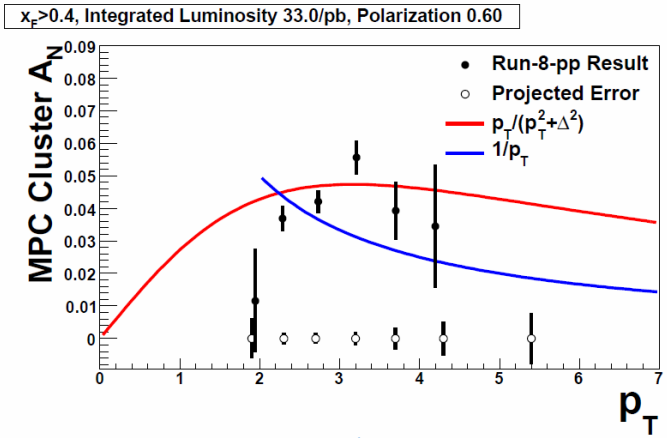
Transverse-spin physics

- 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





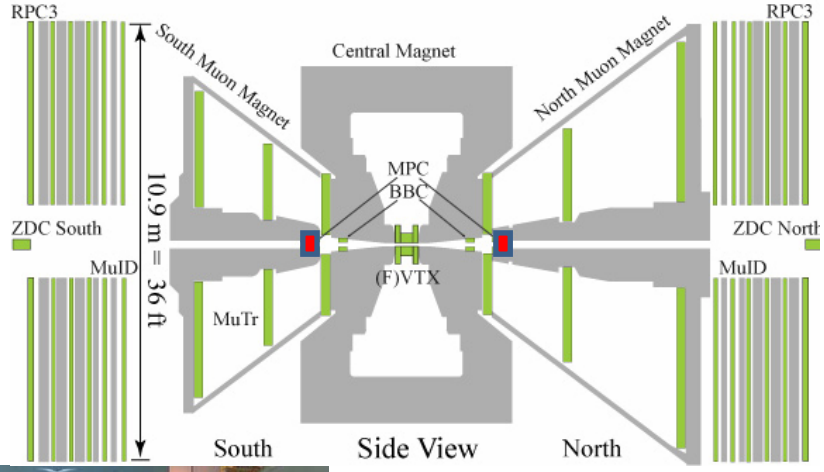
STAR $\sqrt{s}$ = 500 GeV

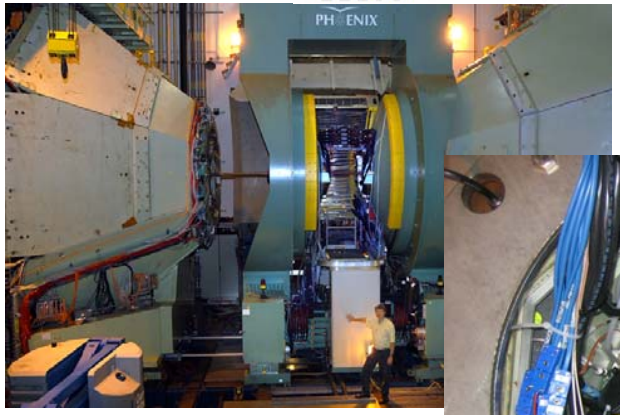


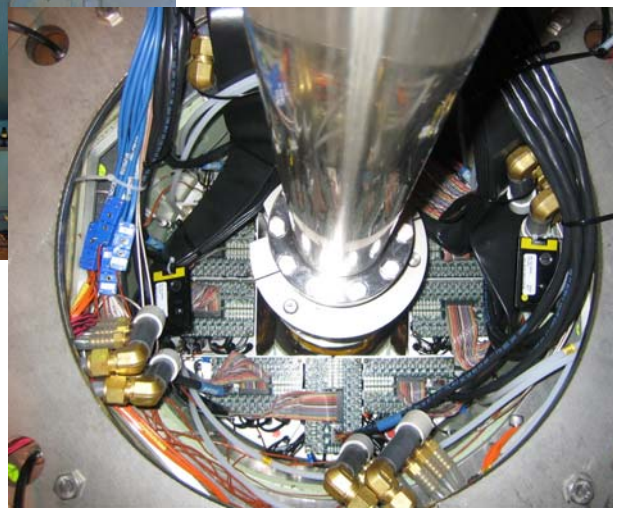
PHENIX $\sqrt{s}$ = 200 GeV

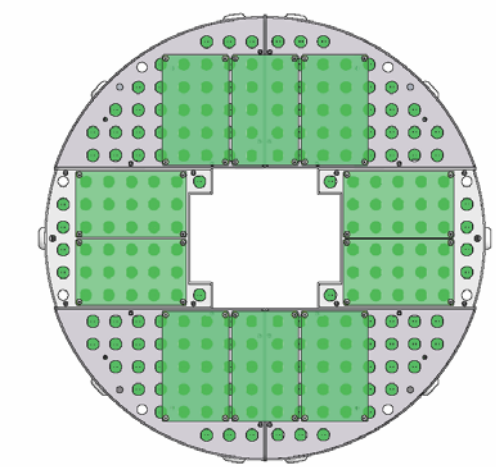
MPC at PHENIX

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



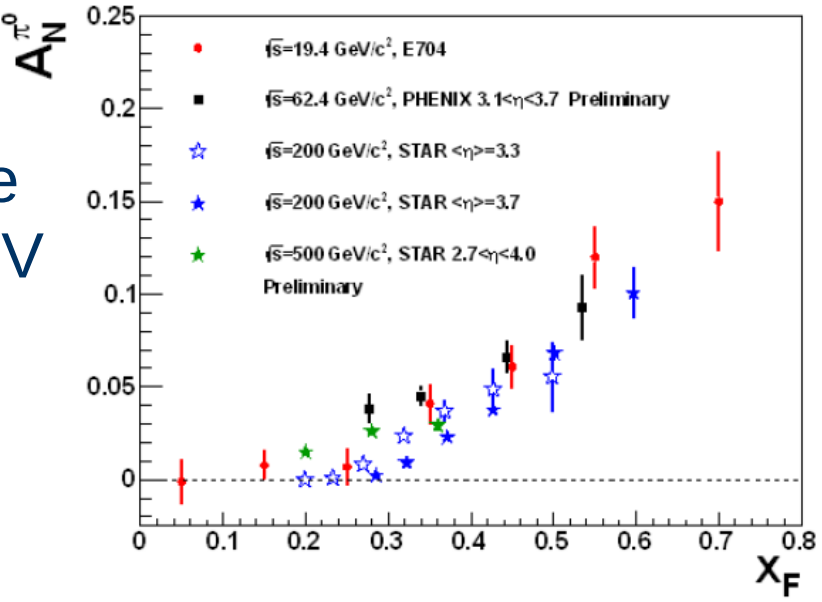




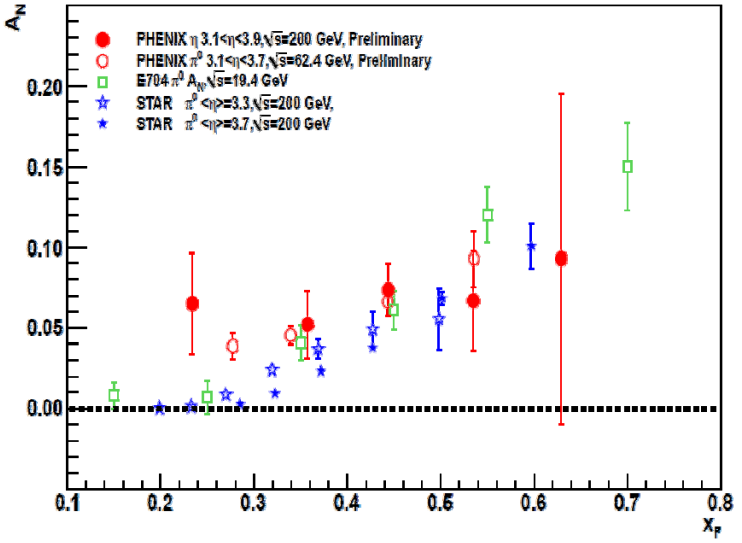


MPC at PHENIX

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

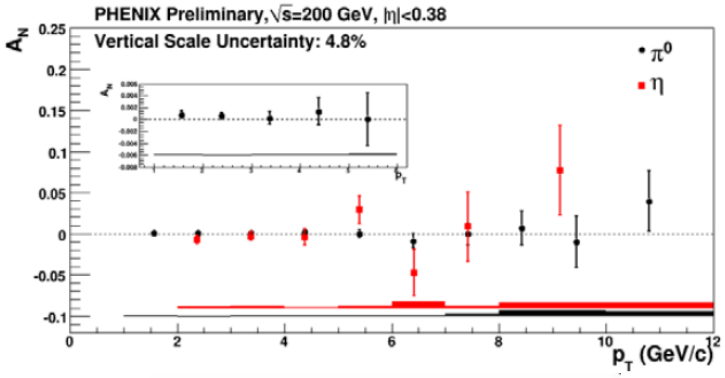


- η
  - Flavor-dependence information

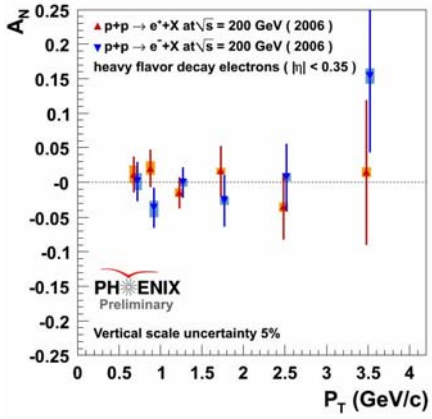


Midrapidity asymmetries

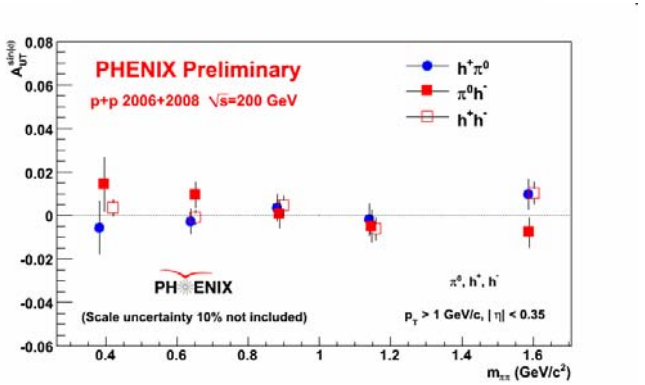
- π^0 and η
  - gluon+gluon & gluon+quark dominant at low p_T
  - Restriction to Gluon Sivers effect



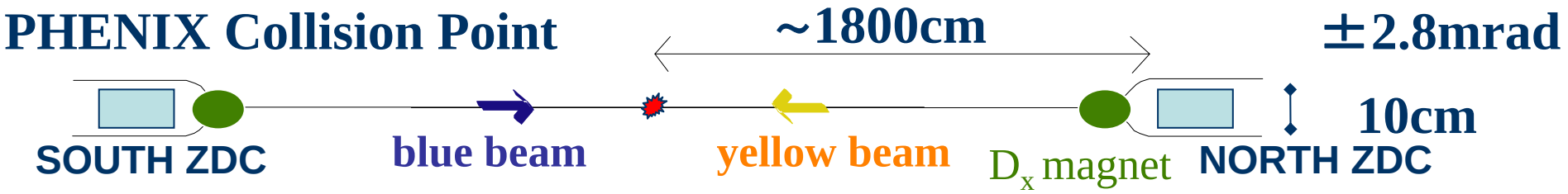
- Single electron
  - Open heavy-flavor decay to electron/positron
  - Restriction to tri-gluon correlation
  - To be improved with VTX



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

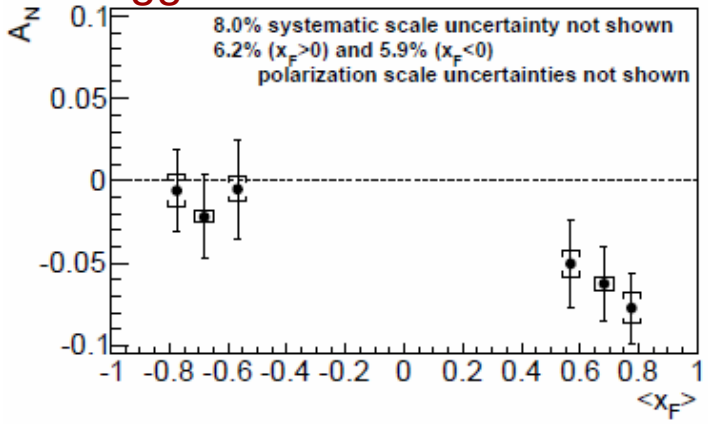


Forward neutron asymmetry

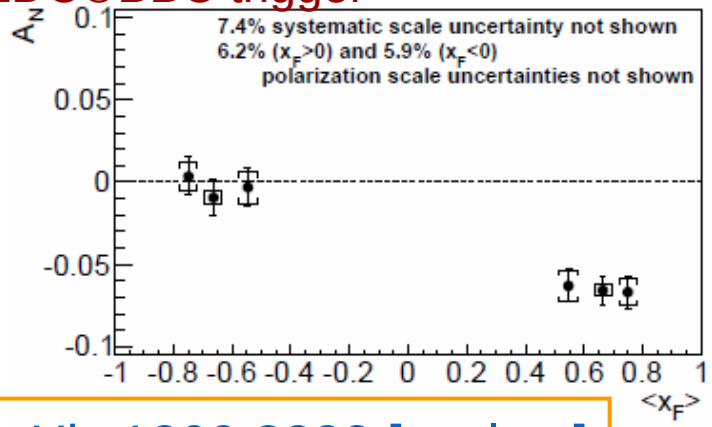


- ZDC + SMD
  - ZDC (Zero-Degree Calorimeter)
    - Hadron sampling calorimeter
  - SMD (Shower Maximum Detector)
    - Position measurement
- x_F distribution
  - Significant negative A_N in the forward region
    - No x_F dependence within the uncertainties
  - No significant backward asymmetry

ZDC trigger



ZDC⊗BBC trigger



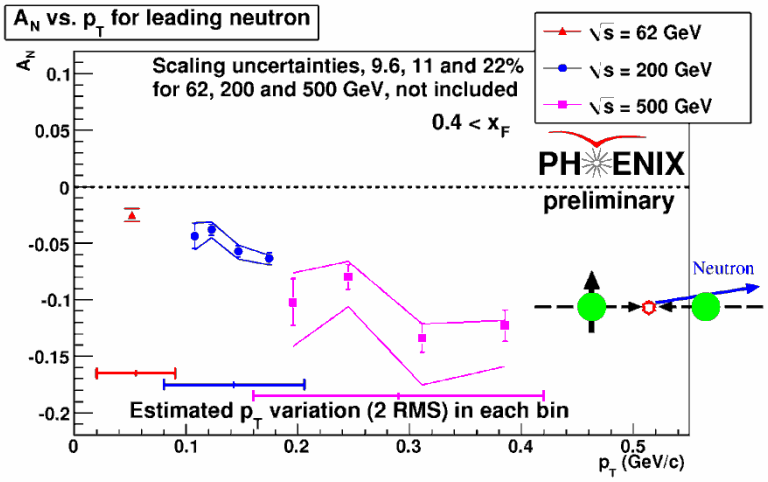
arXiv:1209.3283 [nucl-ex]

Forward neutron asymmetry

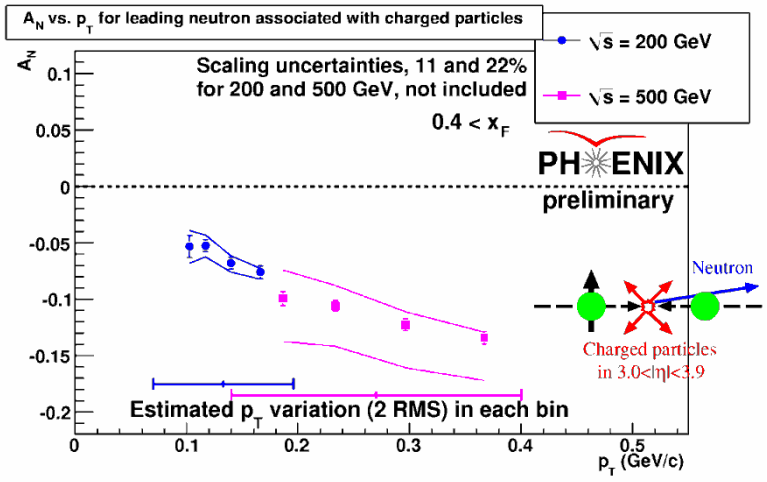
- √s dependence of p_T distribution
  - A_N(62 GeV) < A_N (200 GeV) < A_N (500 GeV)
  - √s dependence or p_T dependence?

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

Inclusive neutron



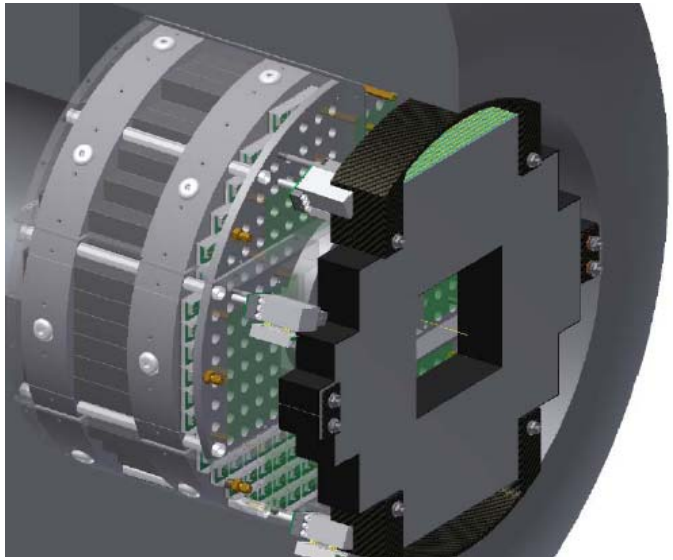
Neutron with charged particles

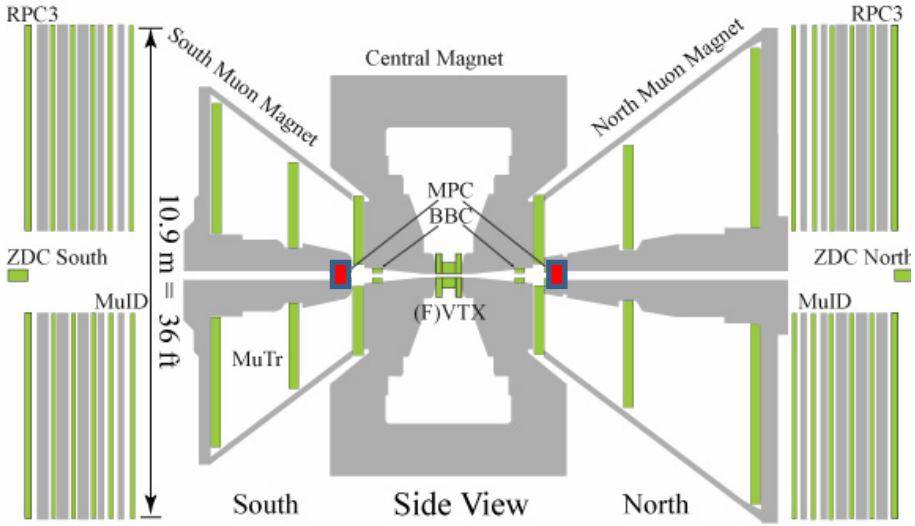


  - Sensitivity to presence of different mechanisms, e.g. Reggeon exchanges with spin-non-flip amplitude, even if they are small amplitudes

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

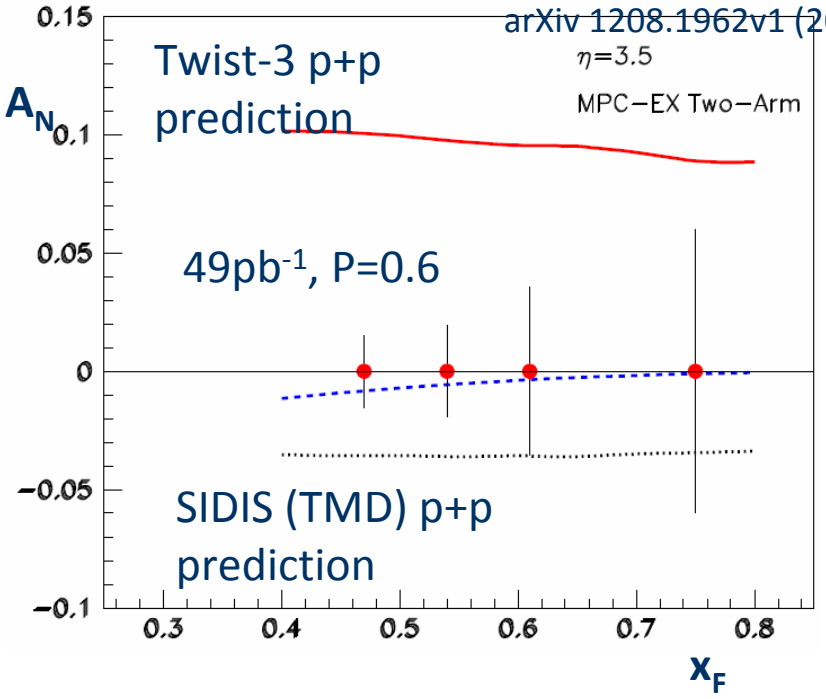


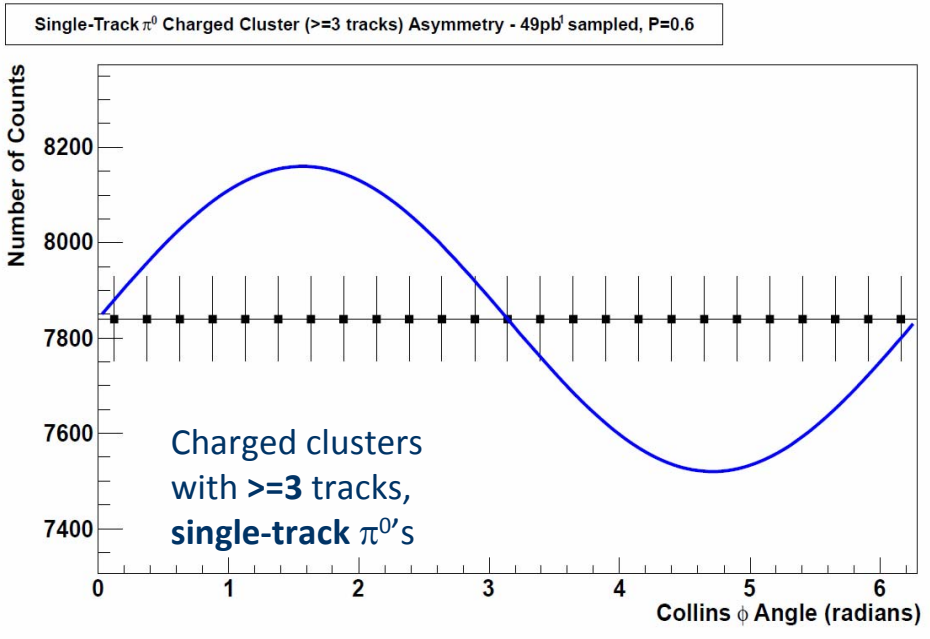


Spin physics in the future

- 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)

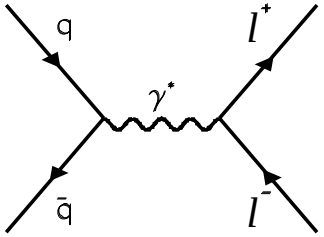




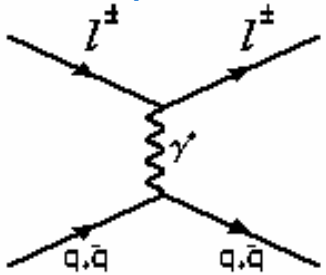
Spin physics in the future

- (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 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

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

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

Semi-Inclusive DIS asymmetry

- Measurement of Sivers asymmetry and Collins asymmetry

M. Anselmino, et al.
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