Polarized nucleon-structure physics at RHIC-PHENIX

HADRON 2013 in Nara

November 7, 2013

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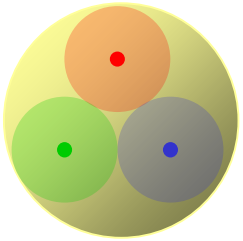
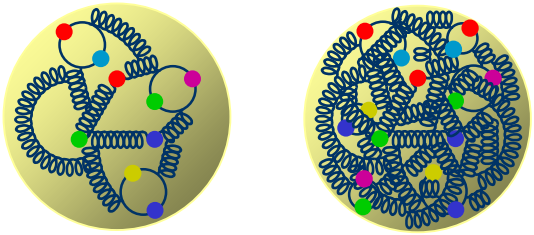
for the PHENIX Collaboration

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

Origin of the nucleon spin 1/2

PHENIX

- 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

x: Bjorken's x "longitudinal" momentum fraction

- Based on the quark-gluon model

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

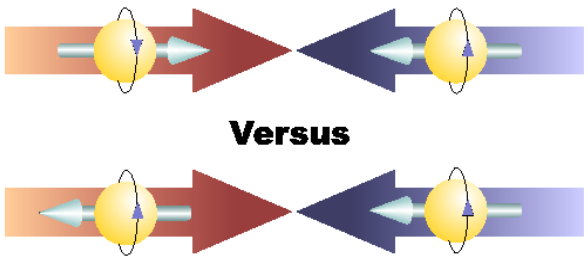
Orbital angular momentum

Gluon spin contribution

Quark spin contribution

Helicity structure of the nucleon

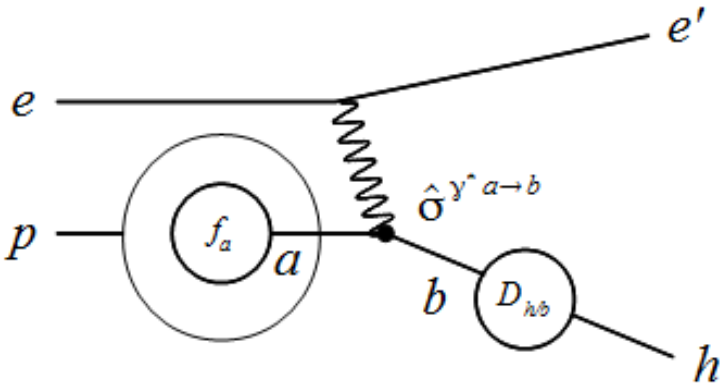
- Longitudinally polarized experiment
  - Polarized in beam or collision direction



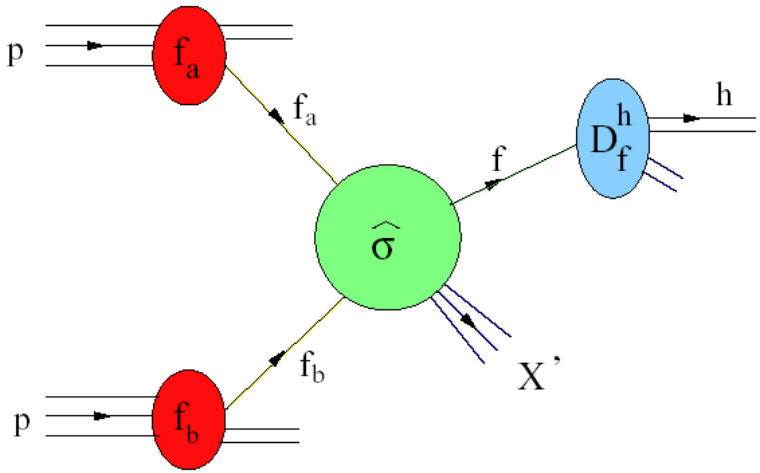
$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}}$$

  - $f_a(x)$ 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

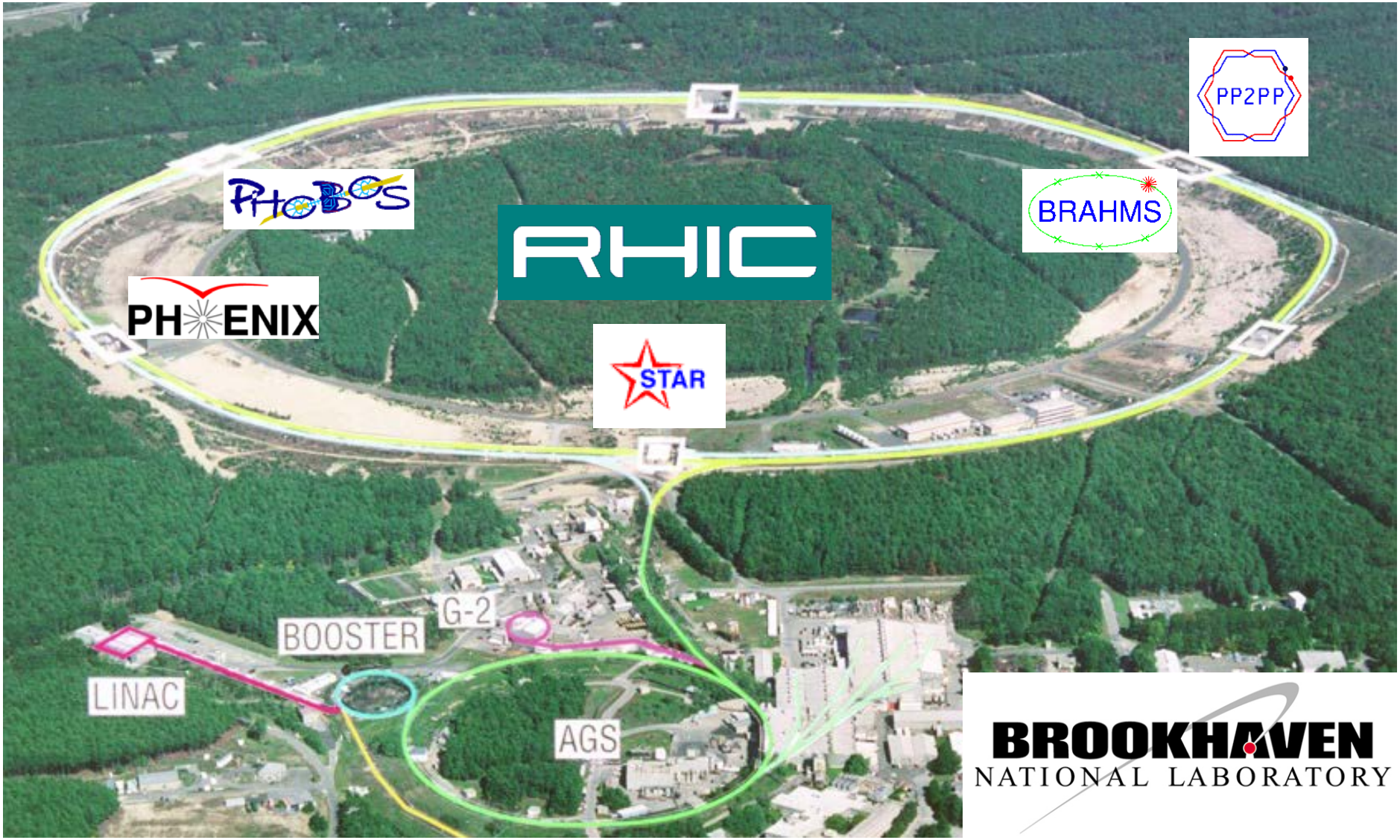
$$F_2(x) = x \sum_a e_a^2 f_a(x)$$

polarized structure function

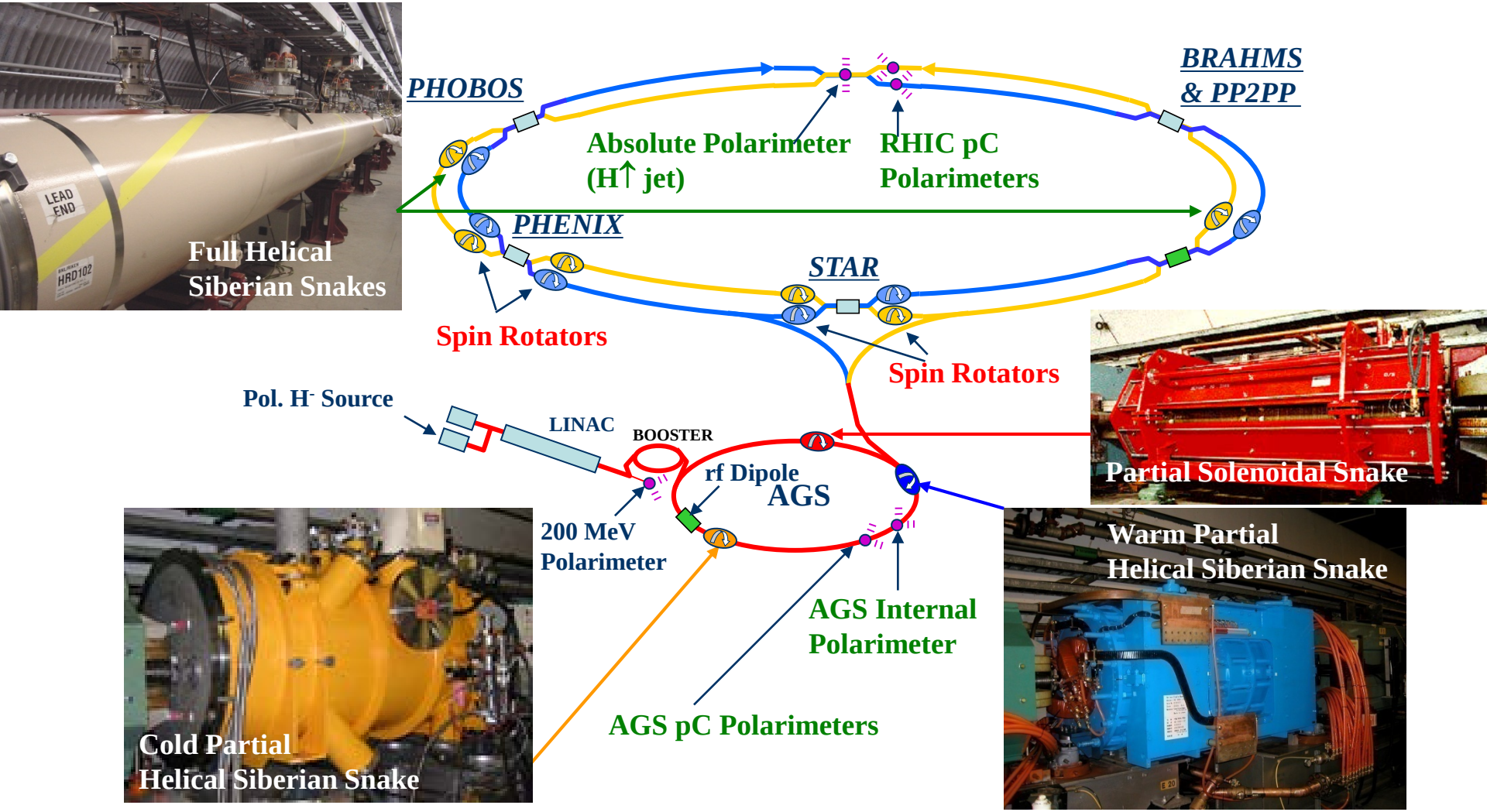
$$g_1(x) = \sum_a e_a^2 \Delta f_a(x)$$

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

RHIC (Relativistic Heavy-Ion Collider)

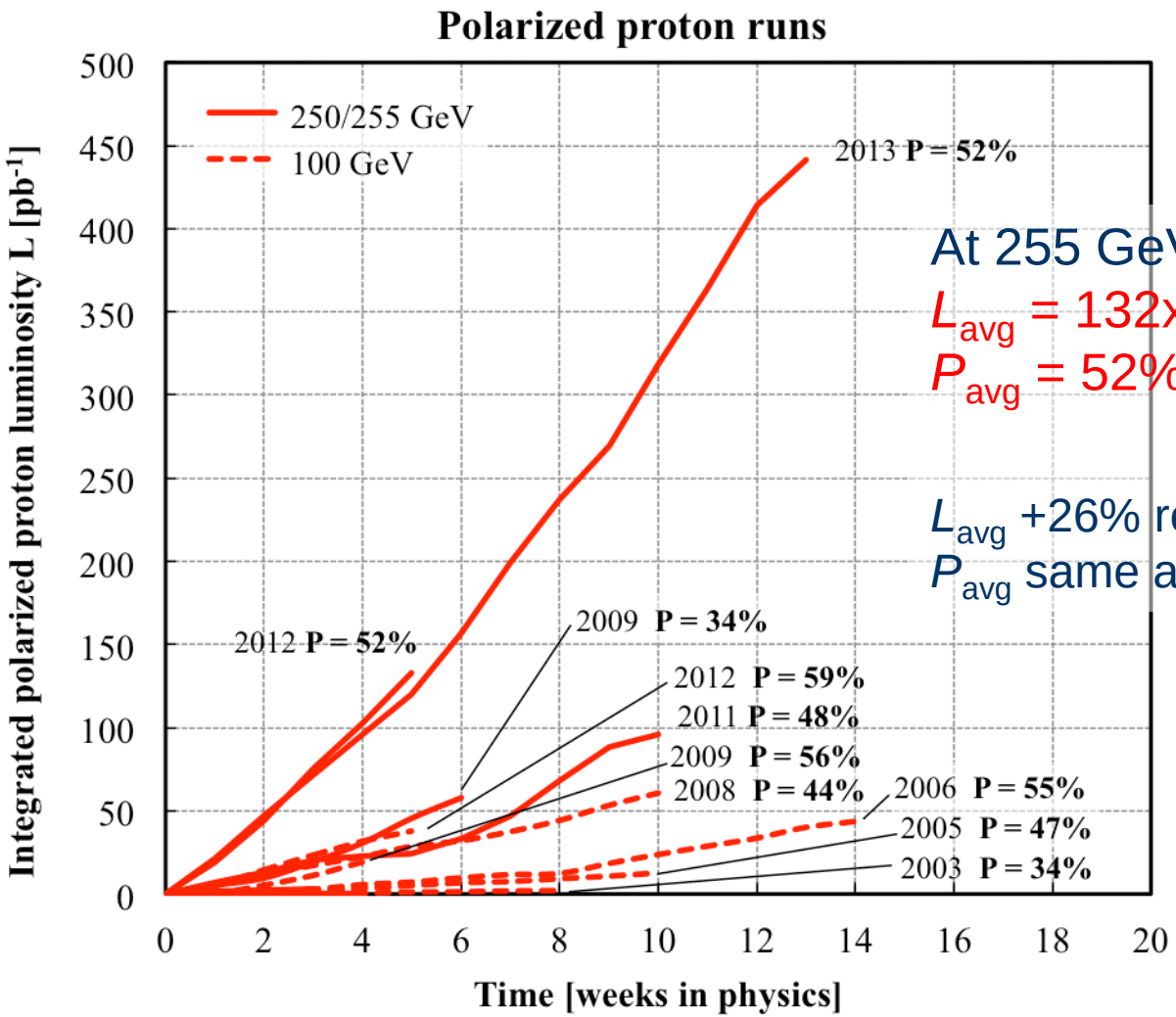


RHIC polarized proton collider



RHIC polarized proton collider

- Luminosity accumulation



At 255 GeV in 2013

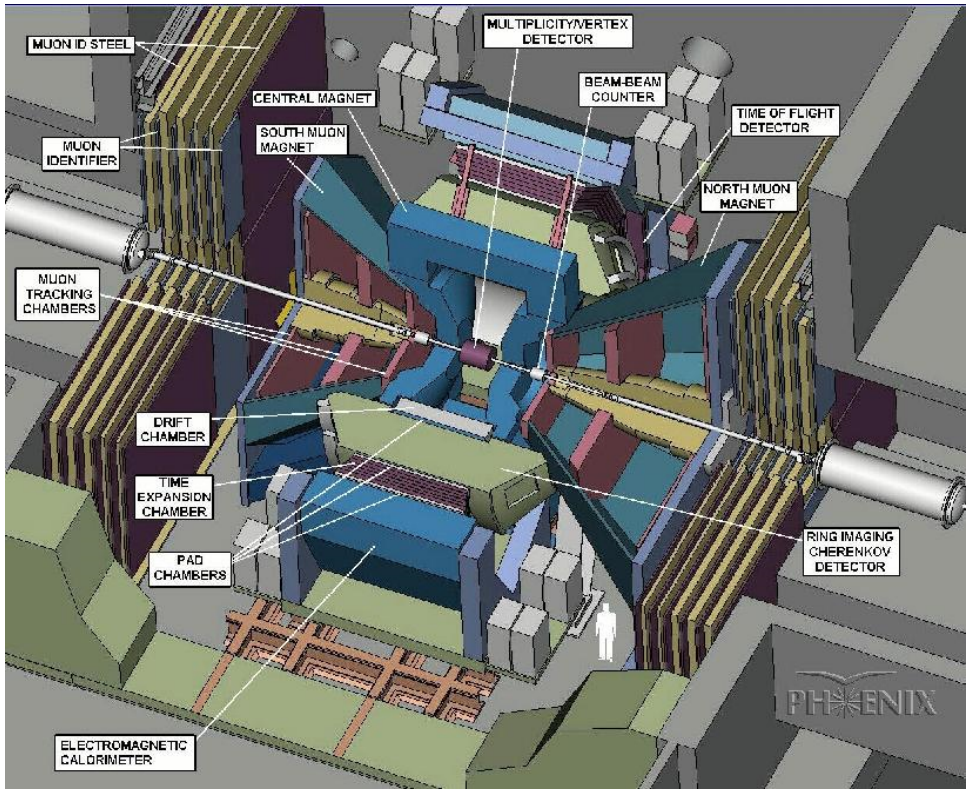
L_{avg} = 132x10^{30}cm^{-2}s^{-1}

P_{avg} = 52%

L_{avg} +26% relative to 2012

P_{avg} same as 2012

PHENIX detector

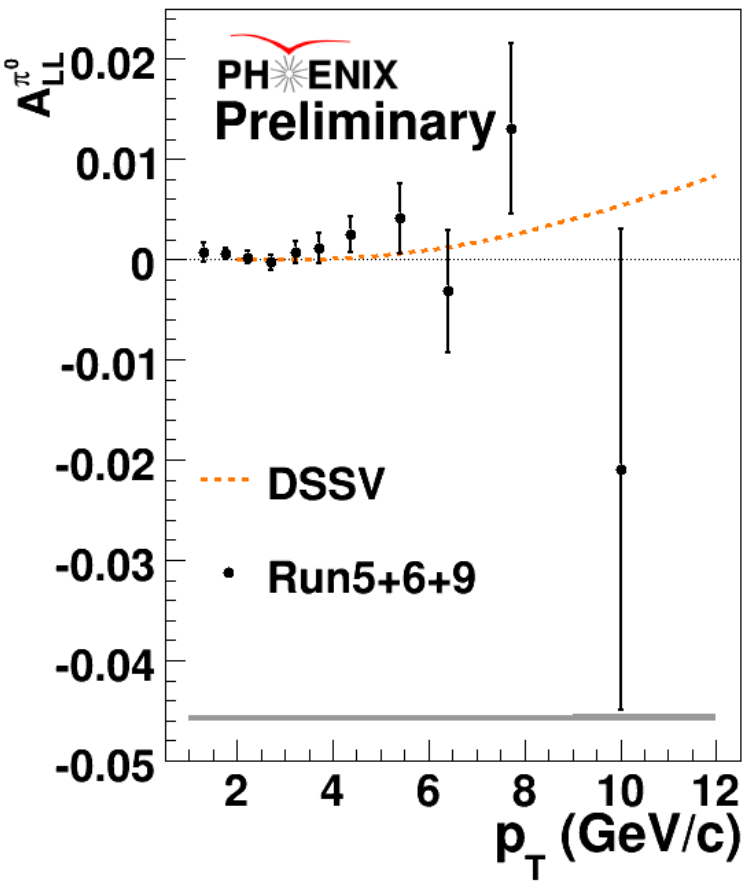


- Philosophy
  - high resolution at the cost of acceptance
  - high rate capable DAQ
  - excellent trigger capability for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi = \pi/2 \times 2$
  - Momentum and energy measurement, particle-ID
  - Detecting electron, photon, hadron
  - Small amount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

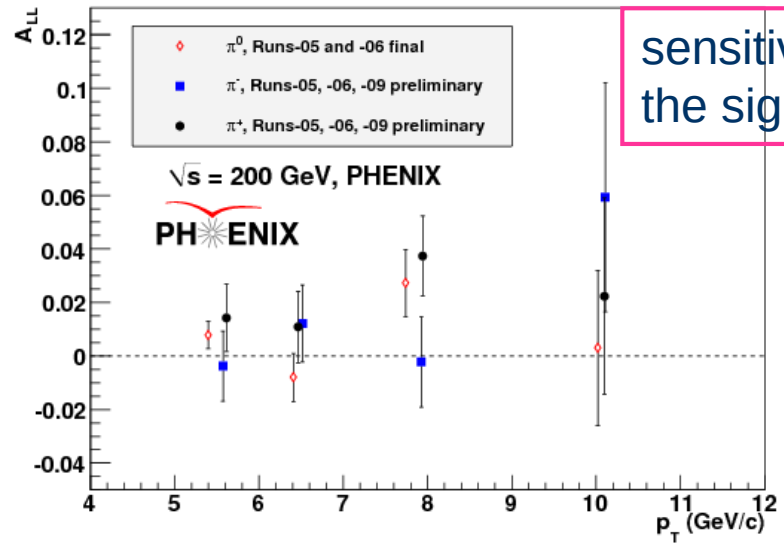
Polarized gluon distribution

- A_{LL} measurements
  - midrapidity

Neutral pion

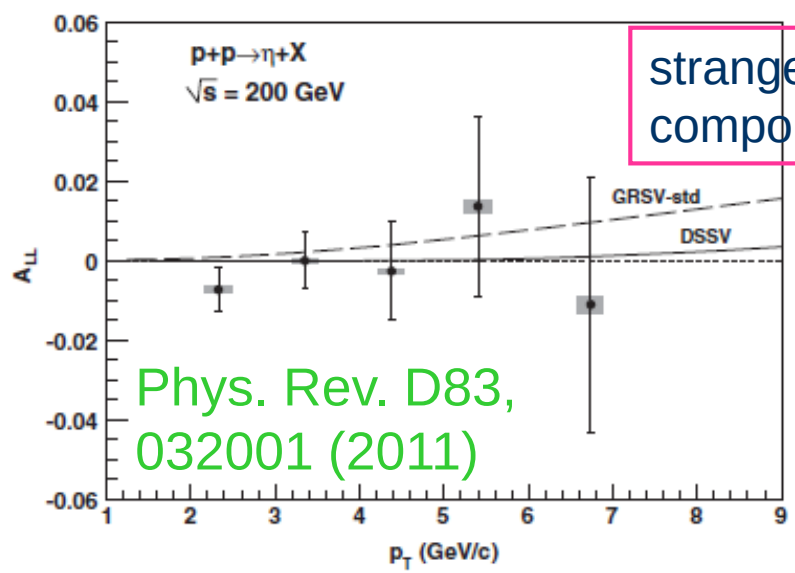


Neutral and charged pion



sensitive to the sign of Δg

η meson



strangeness component

Phys. Rev. D83, 032001 (2011)

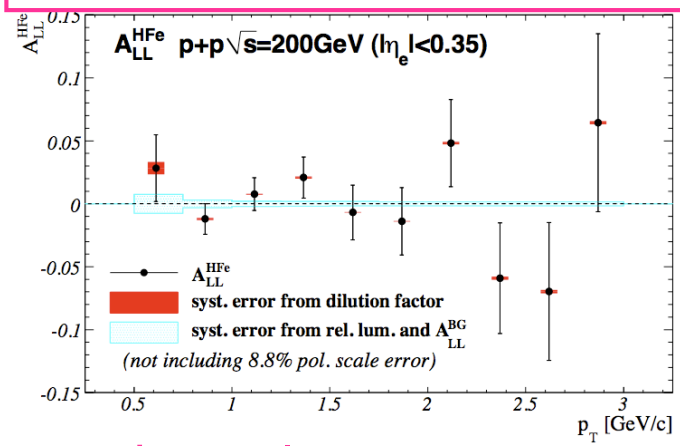
Polarized gluon distribution

- A_{LL} measurements

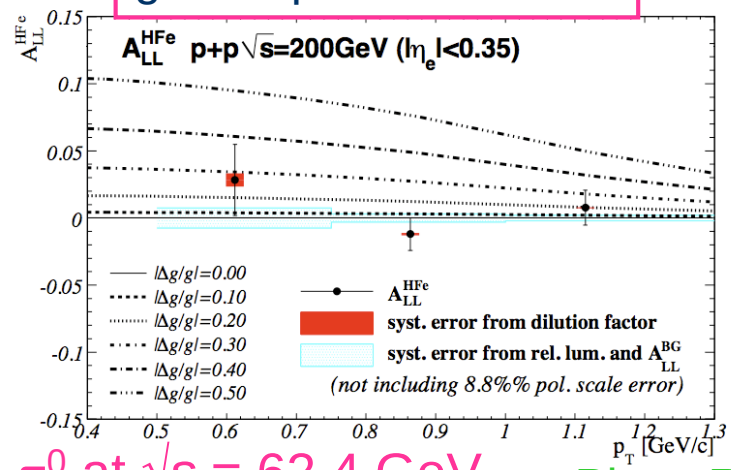
Phys. Rev. D87, 012011 (2013)

Single electron

heavy-quarks produced dominantly by gg interaction

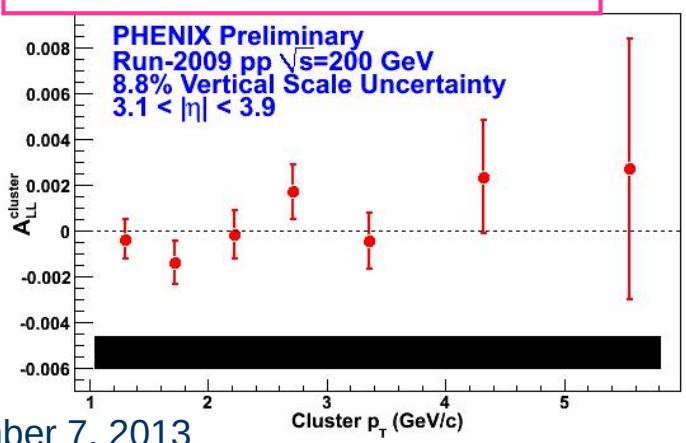


constraint to small-x gluon-spin contribution



Forward EM cluster

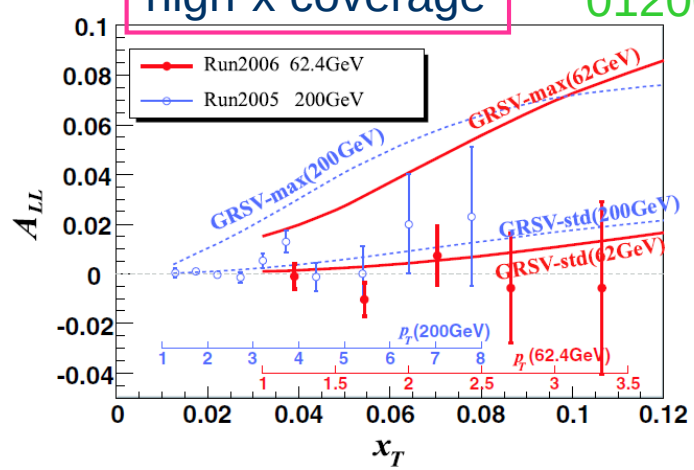
sensitive to small-x ~ 10^{-3}



π^0 at $\sqrt{s}$ = 62.4 GeV

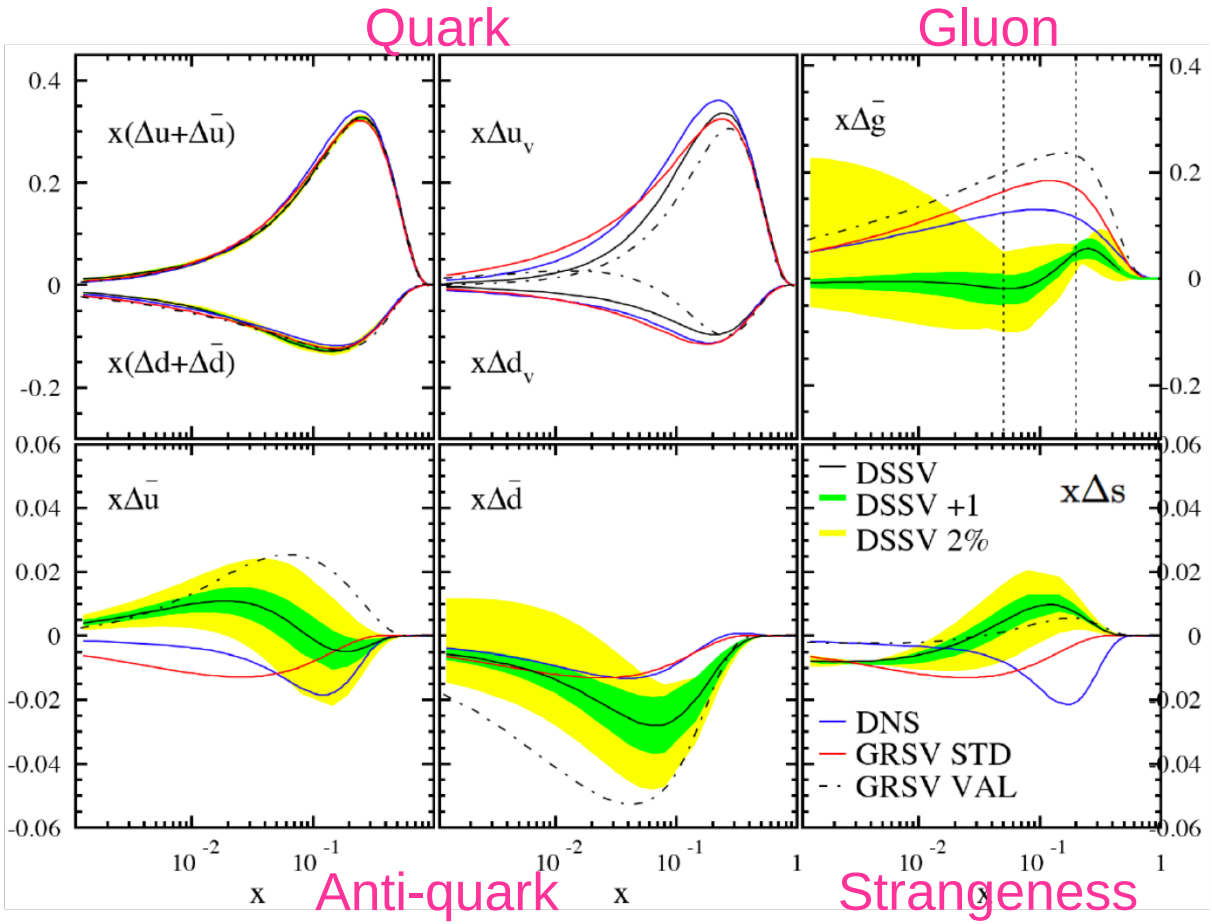
Phys. Rev. D79, 012003 (2009)

high-x coverage



QCD global analysis

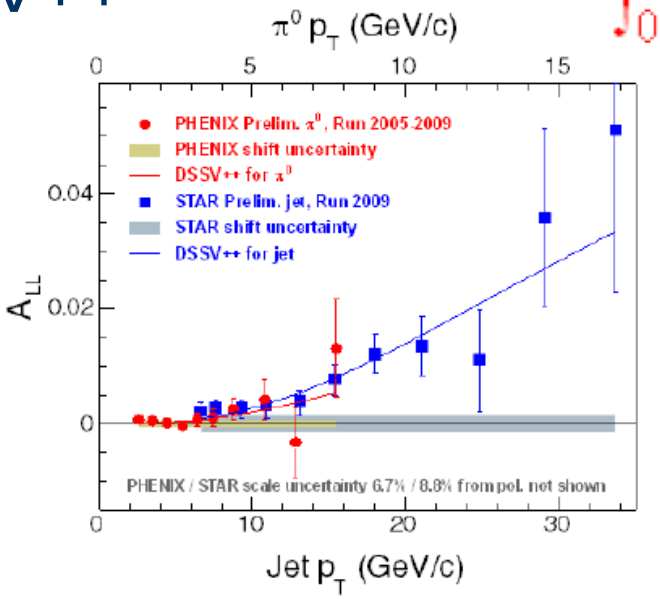
- DSSV group analyzed world data of polarized DIS, SIDIS and *p*+*p* collision
- RHIC *p*+*p* collision data significantly constrained gluon helicity distribution at $0.05 < x < 0.2$

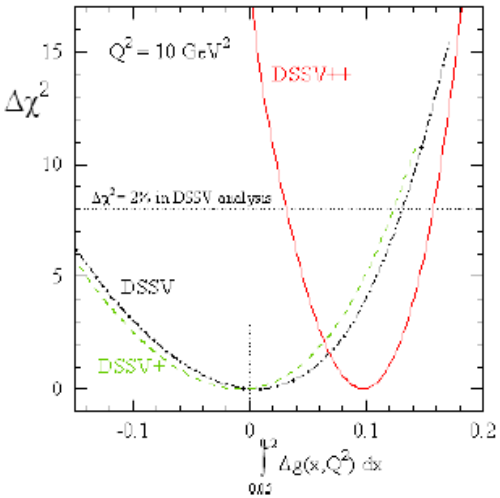


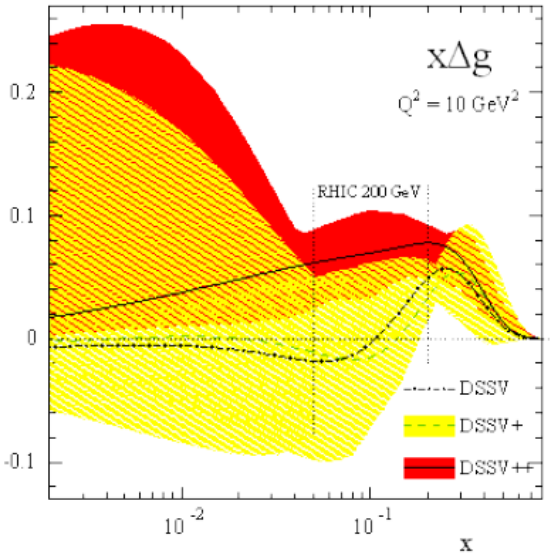
QCD global analysis

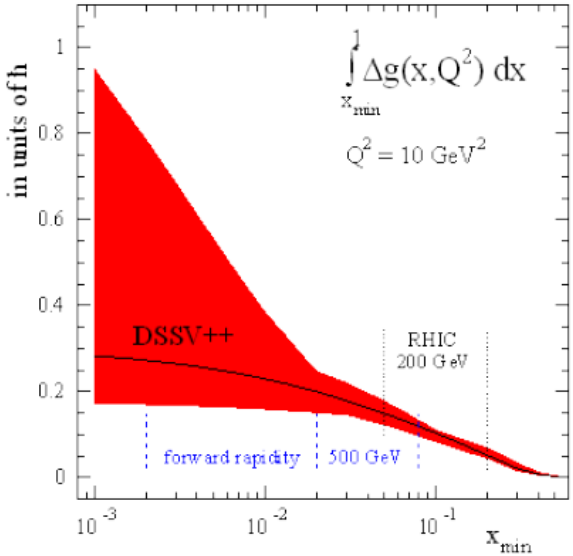
- DSSV++

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





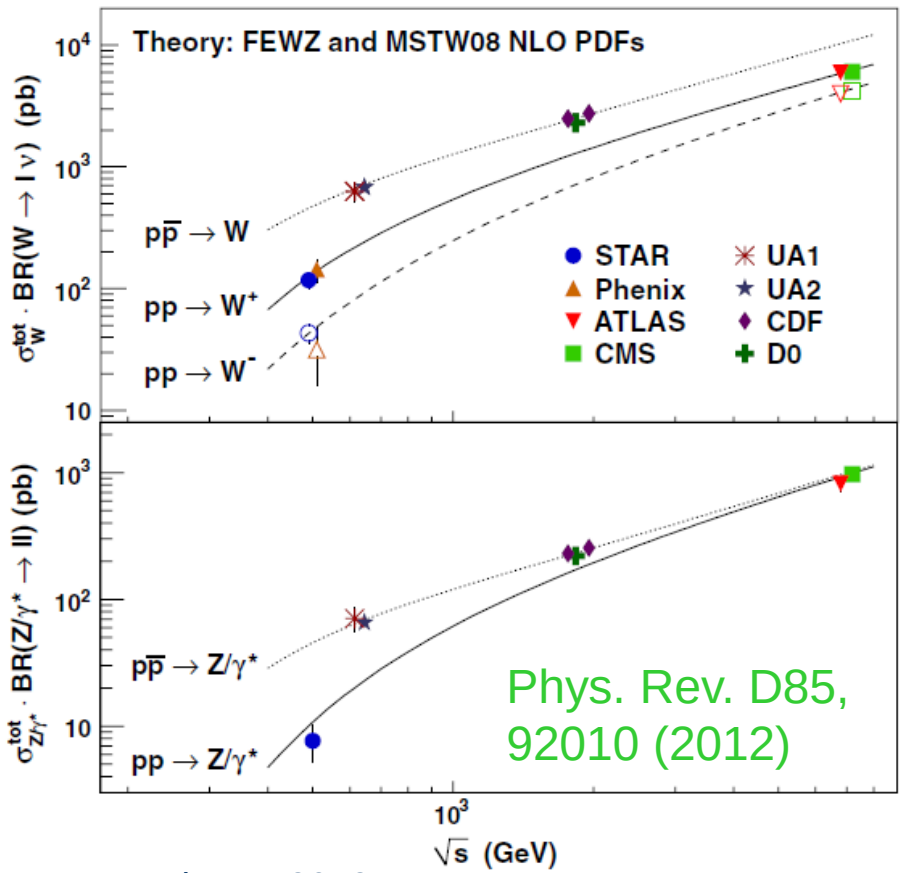




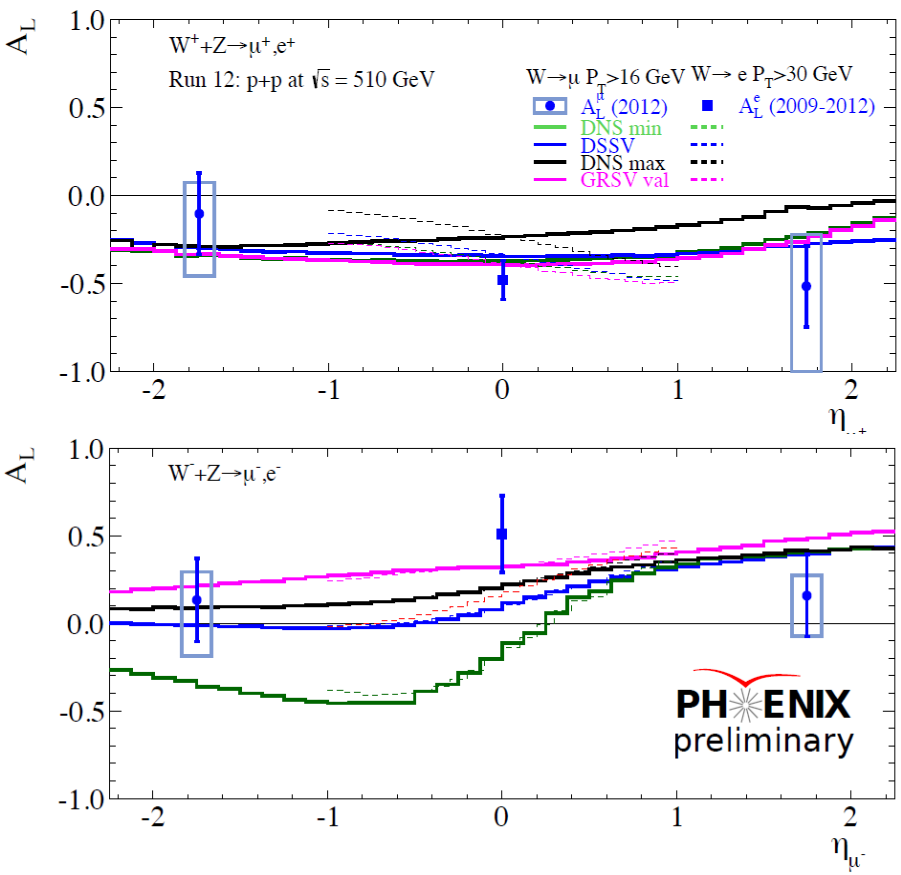
Polarized sea-quark distribution

- Flavor-sorted helicity distribution
  - Weak-boson production at √s = 500-510 GeV
  - Parity-violating single-spin asymmetry measurement

Cross section (midrapidity)



Asymmetry A_L



Transverse structure of the nucleon

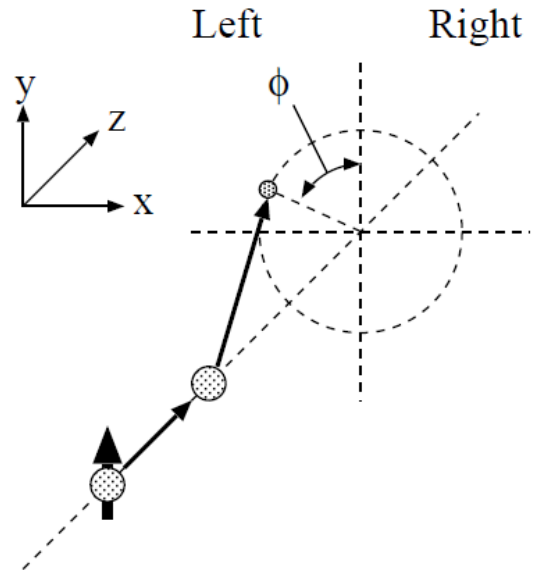
- Single transverse-spin asymmetry

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

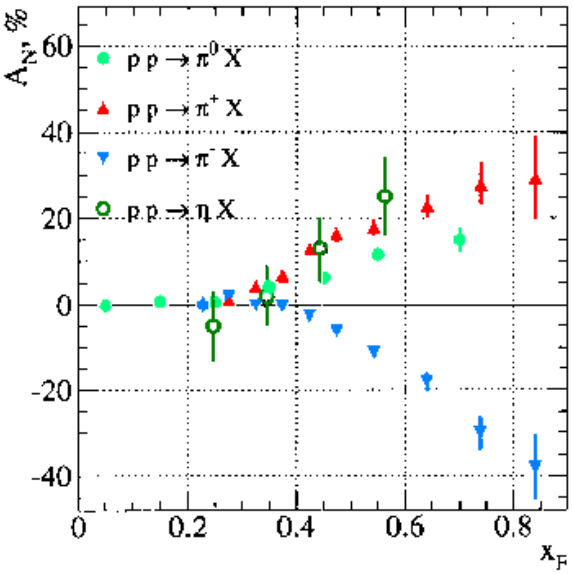
  – Expected to be small in hard scattering at high energies

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

Kane, Pumplin, Repko
PRL 41 1689 (1978)



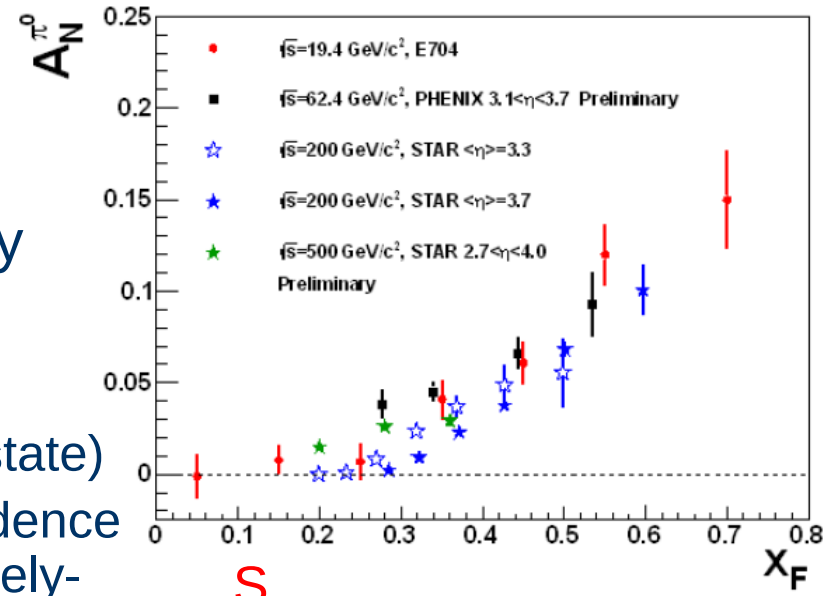
- FNAL-E704
  – Unexpected large asymmetry found in the forward-rapidity region
  – Development of many models based on perturbative QCD

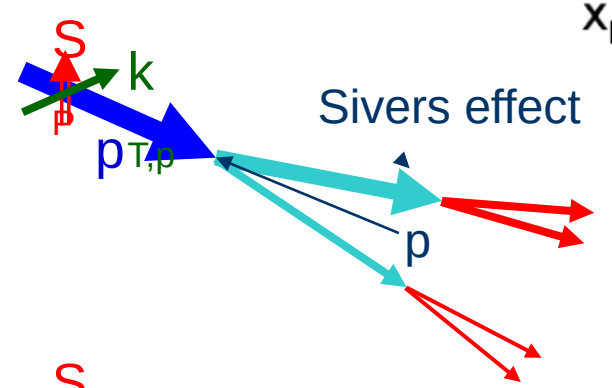


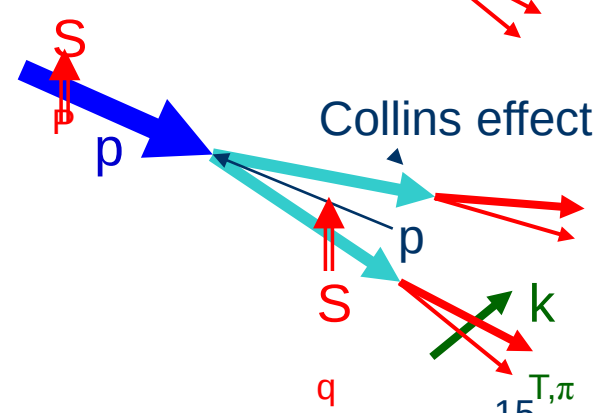
Transverse-spin physics

- For establishment of TMD and higher-twist approach
  - Single transverse-spin asymmetry (SSA) of inclusive hadrons
  - Sivers effect
    - Sivers distribution function (initial state)
      - transverse-momentum dependence of partons inside the transversely-polarized nucleon
  - Collins effect
    - Transversity distribution (initial state)
      - correlation between transversely-polarized nucleon and transversely-polarized partons inside
    - Collins fragmentation function (final state)
  - Higher-twist effect
    - quark-gluon & multi-gluon correlation

Inclusive π^0



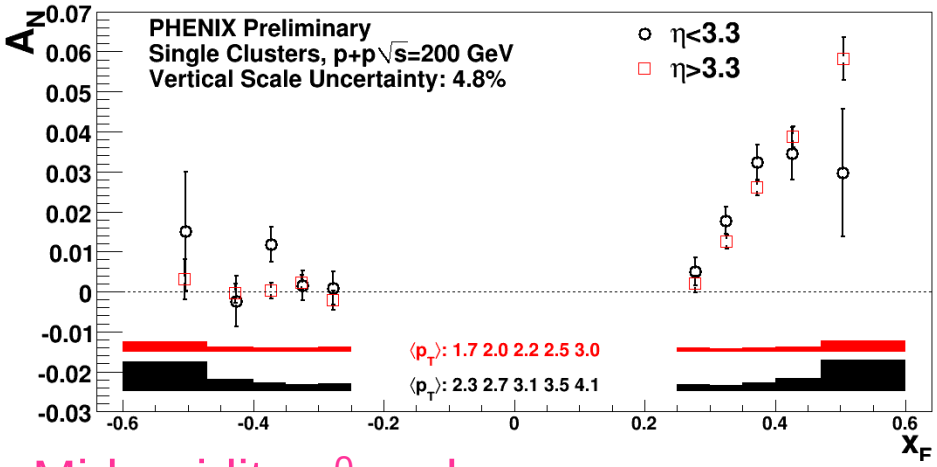




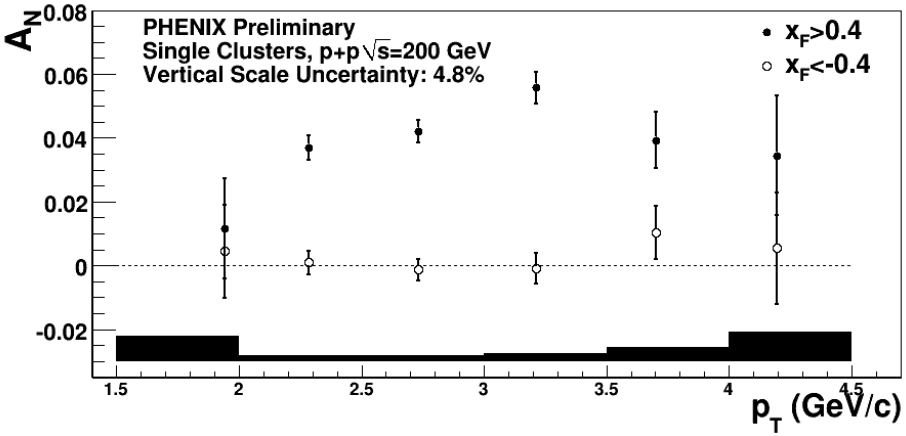
Transverse-spin physics

- A_N measurements

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

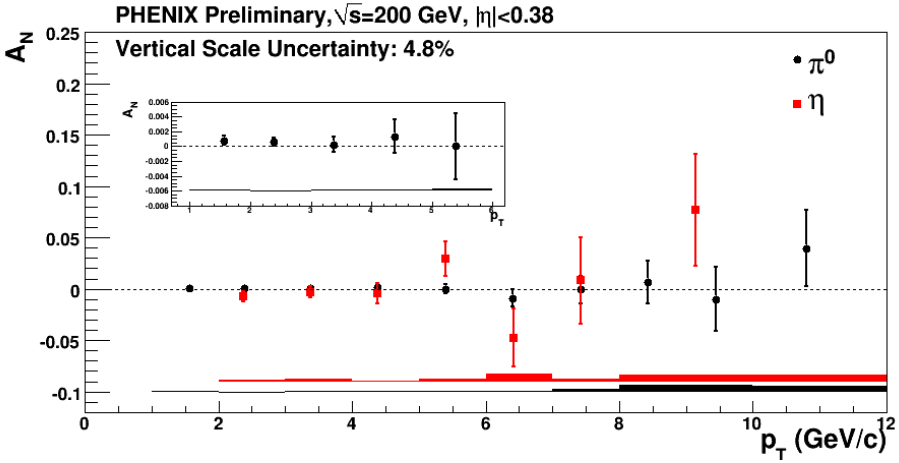


no decrese at high p_T expected from higher-twist effect



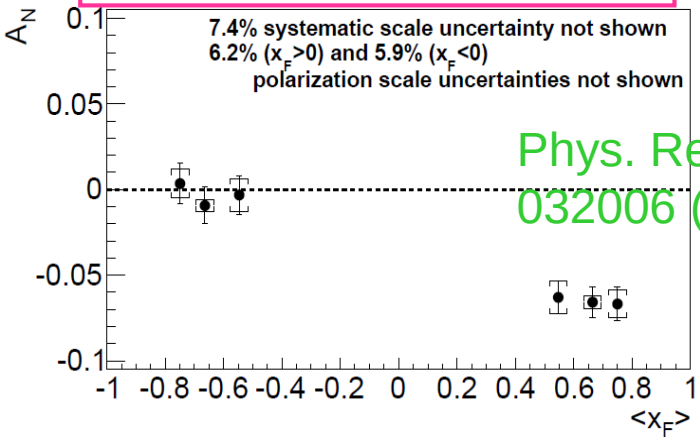
Midrapidity π^0 and η

constrains gluon Sivers effect



Very forward neutron

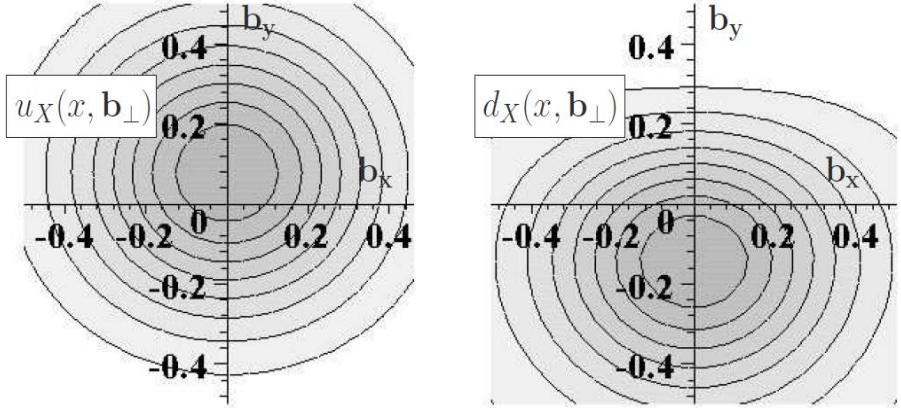
large negative asymmetry used for local polarimetry



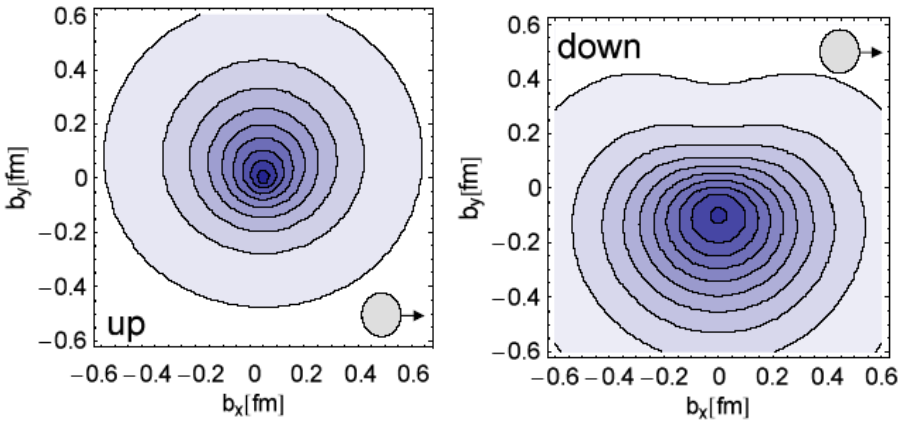
Phys. Rev. D88, 032006 (2013)

3-dimensional nucleon structure

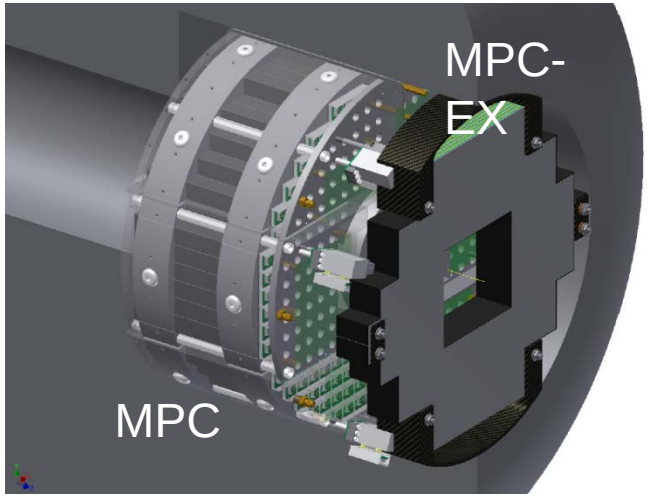
- Nucleon structure beyond the simple parton picture
- Many-body correlation of partons
  - To describe the orbital motion inside the nucleon
- Parton distribution in transverse direction
  - Extended/generalized picture of the parton distribution
  - Transverse-momentum dependence (TMD)
  - Space distribution (tomography)



Phenomenological model with GPD data

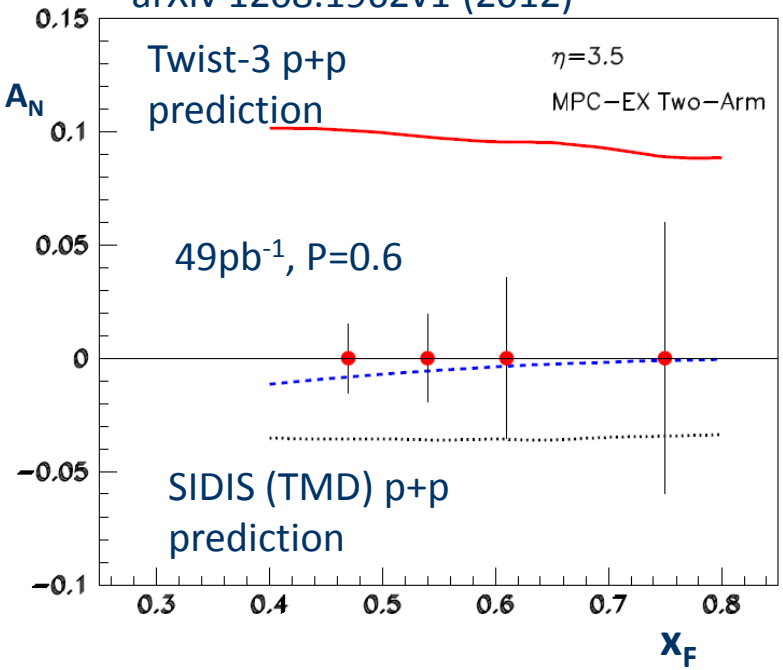


Lattice QCD calculation

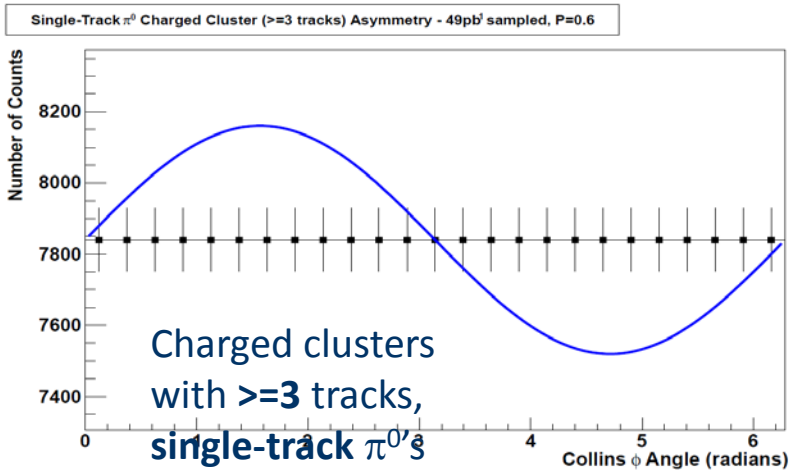


MPC-EX upgrade

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

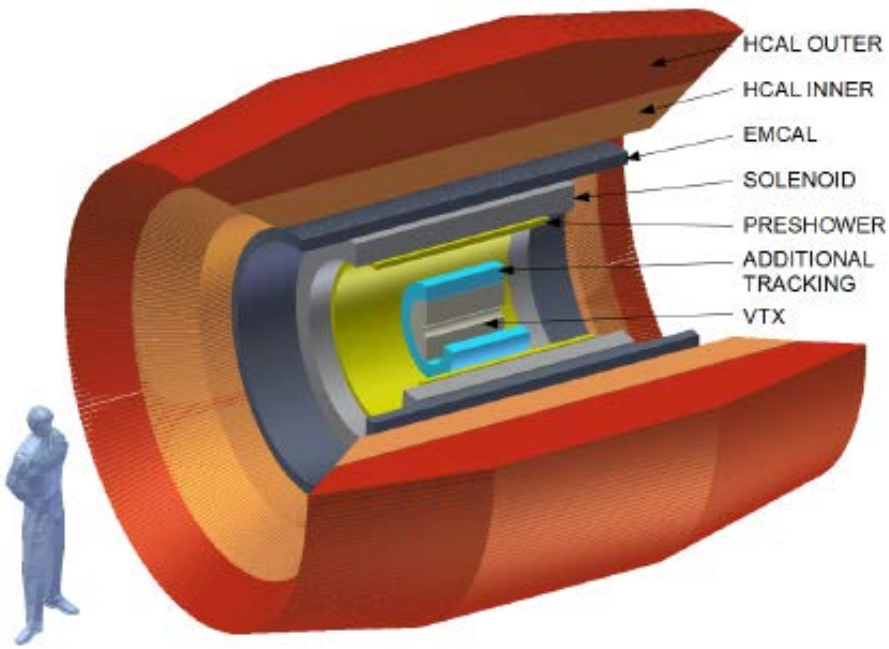


- MPC (Muon Piston Calorimeter)
  - Electromagnetic calorimeter
- MPC-EX
  - Preshower detector
  - Commissioning in 2014
  - Experiment in 2015-2016
- $3.1 < |\eta| < 3.8$
  - Installed in the muon piston
- Direct photon asymmetry
  - To distinguish the Sivers effect and the higher-twist effect
- Collins asymmetry in jets
  - π^0 correlation with jet-like clusters



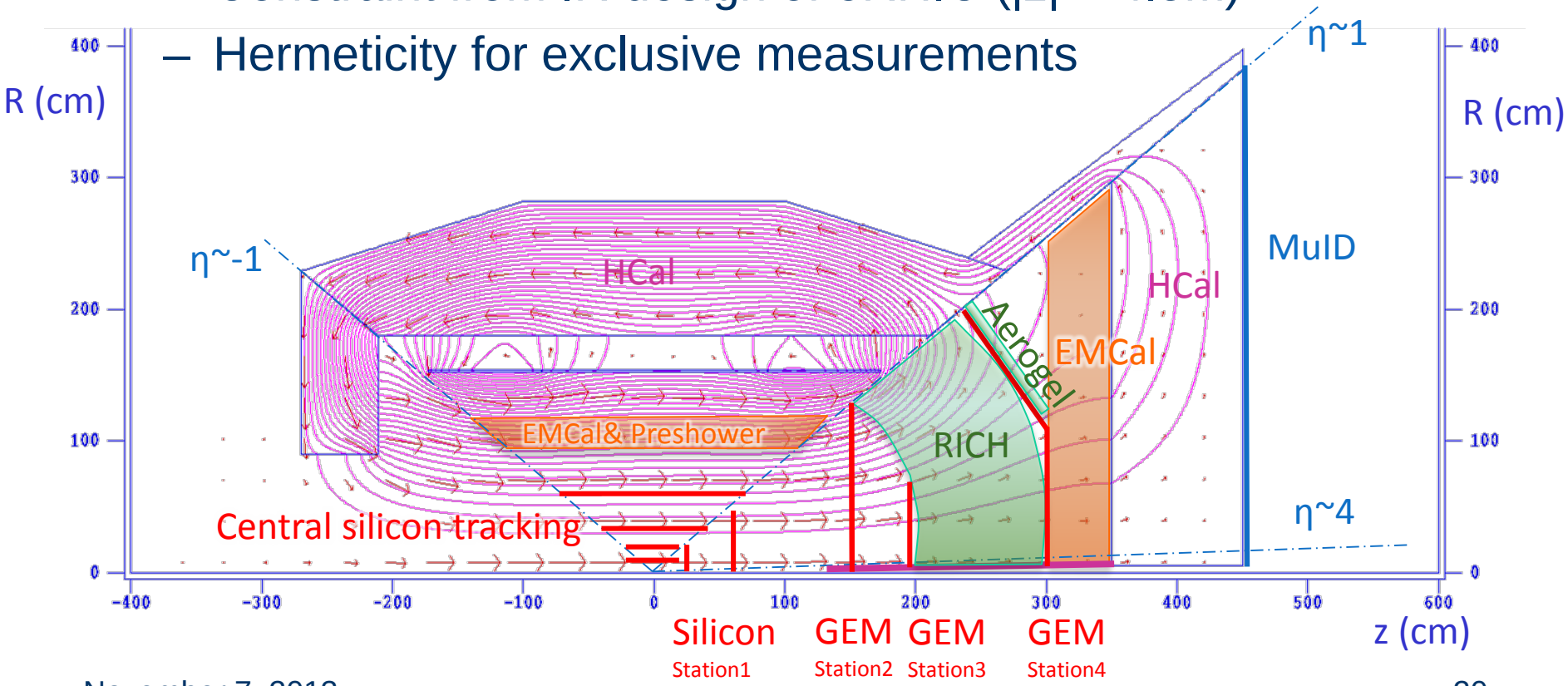
sPHENIX upgrade

- sPHENIX
  - Barrel upgrade
  - Forward upgrade
  - Partial installation and commissioning in 2018-2019
  - Completion and experiment in 2021-2022
- Barrel upgrade baseline
  - Compact jet detector
  - Using upgraded RHIC accelerator
  - For precision measurement of jet, dijet, photon-jet correlation to understand the nature of QGP
- Barrel upgrade extension
  - Additional tracking layers
  - Preshower detector
  - For heavy-flavor and internal jet structure measurements



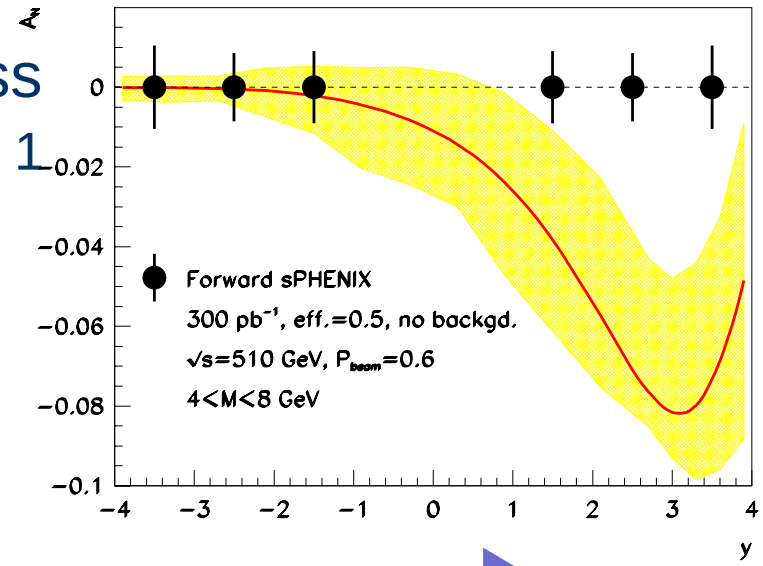
sPHENIX forward upgrade

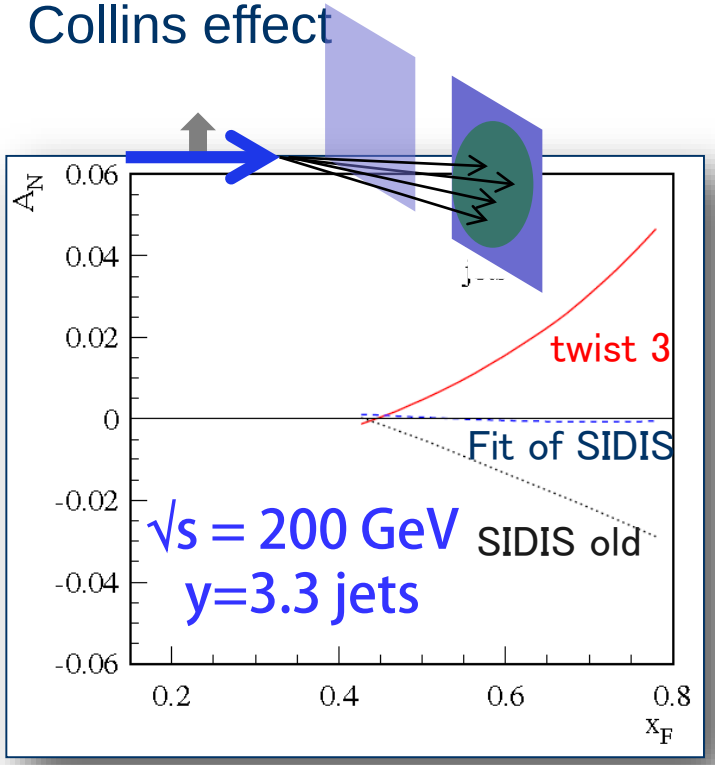
- Open geometry
  - Wide kinematic coverage of photon, jet, leptons and identified hadrons
- Compatible design for eRHIC detector (ePHENIX)
  - Constraint from IR design of eRHIC (|z| < 4.5m)
  - Hermeticity for exclusive measurements

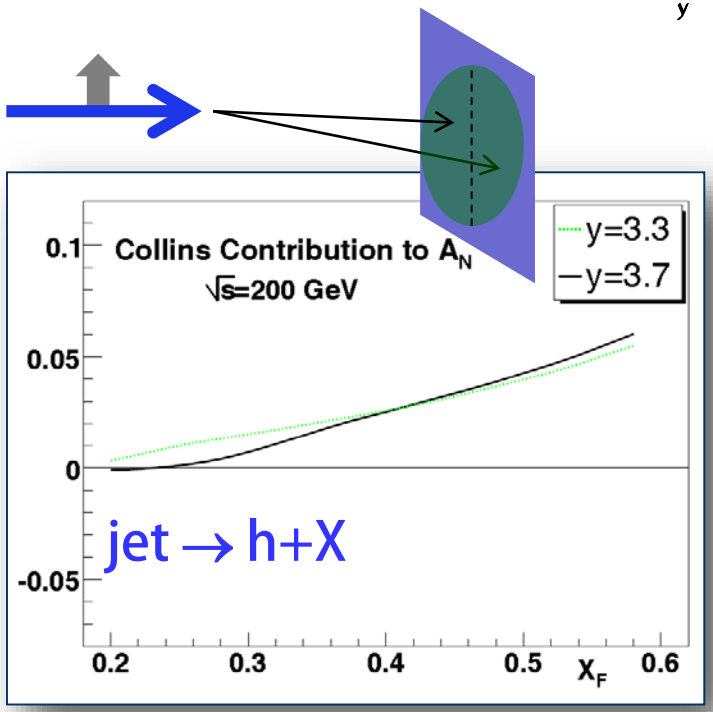


sPHENIX forward upgrade

- Sivers effect in Drell-Yan process
  - Valence quark region at x~0.2 with 1 < η < 4 coverage
- Jet asymmetry
  - Sivers effect or higher-twist effect
- Asymmetry inside of jets
  - Collins effect







Summary

- Origin of the nucleon spin 1/2
  - Gluon-spin contribution
    - A_{LL} measurements
  - Anti-quark contribution
    - A_L measurement of W-boson production
- Understanding of transverse-spin phenomena
  - Sivers effect / Collins effect / higher-twist effect
  - 3-dimensional nucleon structure
  - Many-body correlation of partons
    - A_N measurements
- The forward sPHENIX upgrades toward understanding of the 3-dimensional nucleon structure
  - Polarized Drell-Yan measurement / jet asymmetry and asymmetry inside of jets
  - Evolution to ePHENIX toward electron-proton collisions at eRHIC