Nuclear dependence of transverse single-spin asymmetry in p+p, p+A collisions

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Oct 18th 2019

Heavy Ion Meeting

Outline

- Introduction
  - Spin structure of the proton
  - Proton spin puzzle
  - Transverse Single Spin Asymmetry
- Experiments
  - Polarized proton collision at RHIC
  - PHENIX Experiment
- Recent results in PHENIX
  - Studying HF, hadrons using Muon Spectrometers
  - Recent publications for p+p, p+A
- Outlook

I. Introduction to physics of proton’s spin

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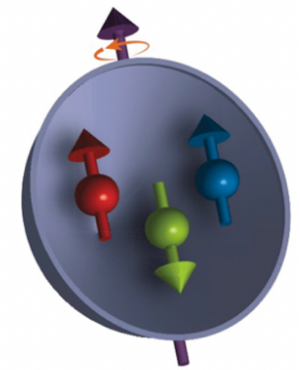
Why we study proton's spin structure

- Protons are one of the three particles that make up atoms, the building blocks of the universe. A proton's spin is one of its most basic properties like mass.
  - Aligning and flipping the polarity of proton spin is the basis for technologies like magneti c resonance imaging (MRI).
- But scientists are still striving to understand how the inner building blocks of protons—the quarks and gluons and sea of quark-antiquark pairs, as well as their motion within the proton—build up the overall particle's spin.
- Understanding how proton spin arises from its inner building blocks may help scientists understand how the complex interactions within the proton give rise to its overall structure, and in turn to the nuclear structure of the atoms that make up nearly all visible matter in our universe—everything from stars to planets to people.
  - The direction and strength of a proton's spin determines its magnetic and electrical prop erties. Changes to the proton's spin also alter its structure.

Proton spin ½? Proton Spin Puzzle

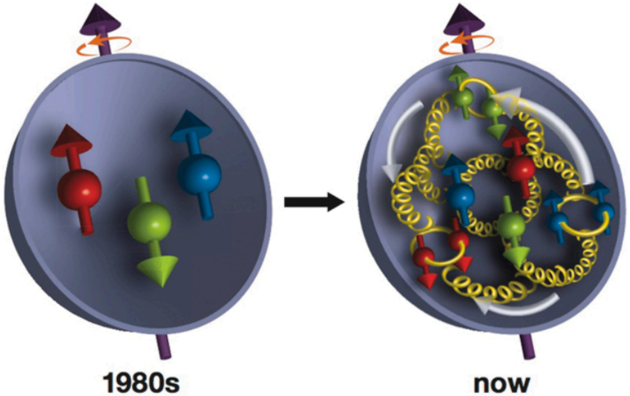
- Proton's spin (1/2) had been assumed to be originated from 3 valence quarks
  - It was a college assignment. However, real answer tur ned out not to be simple at all.
  - The "right" response was disproven by experiments a few years later that turned the field.



- In 1980's European Muon Collaboration (EMC) found
  - only ~20% of the proton spin is carried by quarks
  - Phys.Lett. B206 (1988) 364 (1499 citing articles)
  - Called "proton spin crisis" ➔ "Proton Spin Puzzle"
  - Inspired considerable theoretical activity and new ex periments at CERN, SLAC, DESY, JLAB, BNL

Experiments to study proton spin puzzle

- Polarized inelastic lepton-nucleon scattering and proton-proton collision experiments
  - SLAC : E80, E130, E142, E143, E154, E155
  - CERN : EMC, SMC, COMPASS
  - FNAL : E581, E704
  - DESY : HERMES
  - JLAB : Hall A, B
  - RHIC : PHENIX, STAR, BRAHMS
- Current description : $S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$



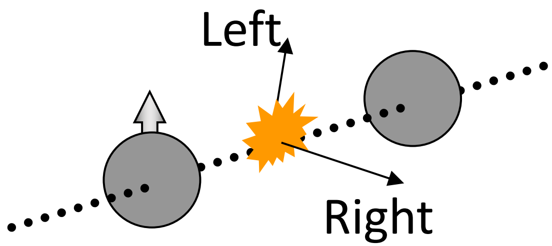
Transverse Nucleon Spin Structure

- The search for orbital angular momentum has motivated new theoretical and experimental investigations of the three-dimensional structure of the nucleon
- Nonzero orbital angular momentum of the valence quarks is expected
- introduces a transverse scale in the physics.
- Transverse Single-Spin Asymmetry in lepton-nucleon and proton-proton scattering

Transverse Single Spin Asymmetry

- Transverse Single-Spin Asymmetry (TSSA)
  - describe the azimuthal-angular dependence of particle production relative to the transverse spin direction of the polarized proton in proton-proton collisions
  - Analyzing power A_N

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

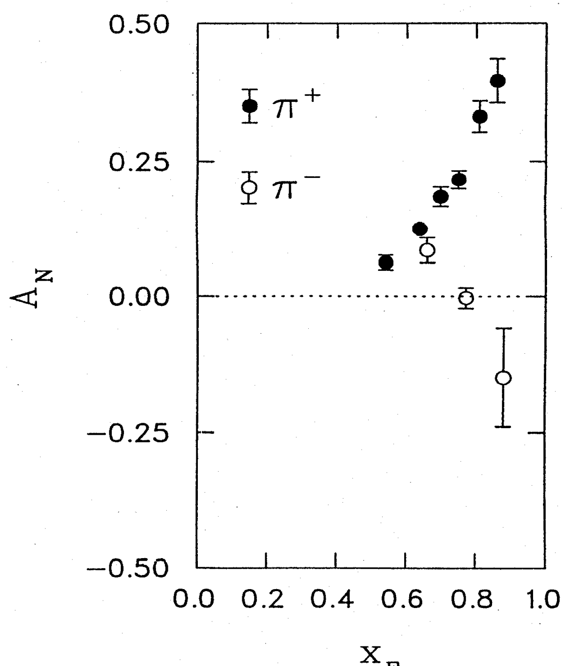


Experiment, theory

- Early attempt expected
  - smaller A_N at high energies
  - Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978)

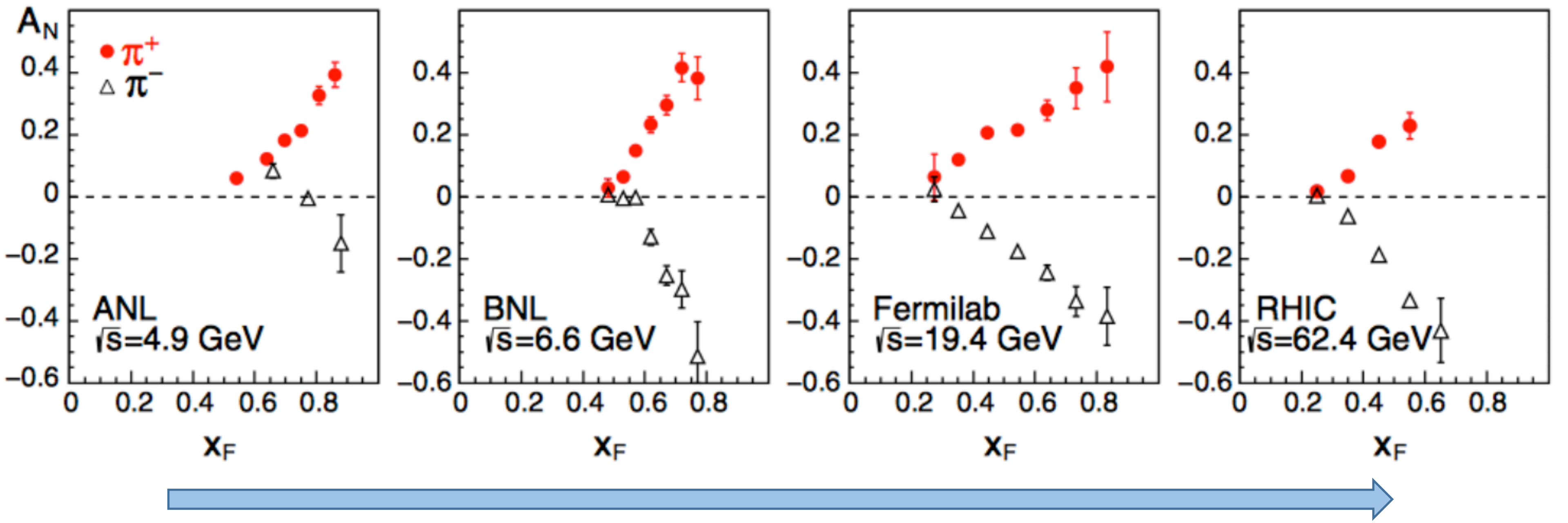
$$A_N \propto \frac{m_q}{\sqrt{s}} \qquad A_N \sim O(10^{-4})$$

- Experiment in late 70’s
  - Argonne ZGS, p(beam) = 12 GeV/c
  - W.H. Dragoset et al., PRL 36, 929 (1976)
  - Large left-right asymmetry is observed at large x_F



$$x_F = \frac{2p_L}{\sqrt{s}}$$

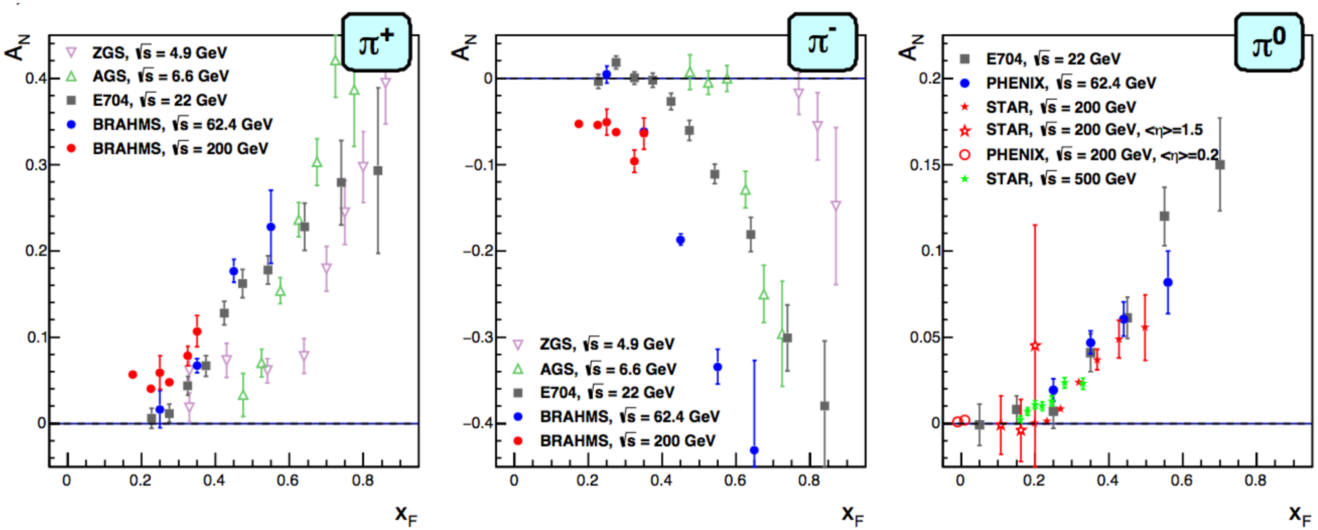
Large TSSA at High Energies



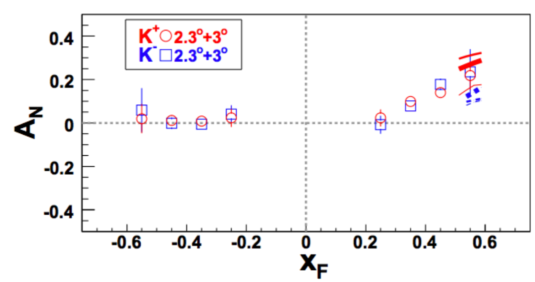
- Large A_N in single hadron production consistently observed up to RHIC energies (up to 500 GeV), over 40 years.

TSSA for forward hadrons from RHIC data

- General features for $p^{\uparrow} + p \rightarrow h + X$
  - Striking effects in large x_F
  - AN survives at large energies
  - AN(π+) and AN(π-) have opposite sign, roughly same magnitude
  - AN(π^0) shows smaller magnitude, positive sign.



- Same sign in K+, K- (BRAHMS)

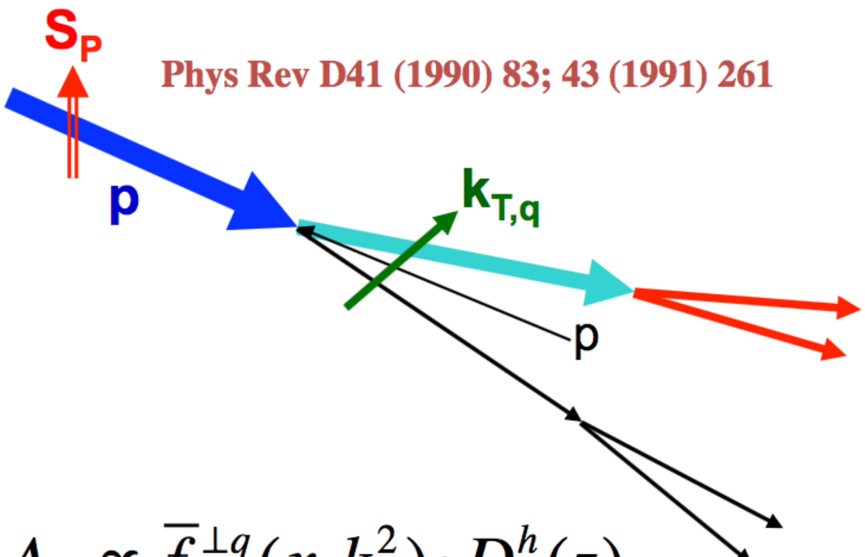


Possible Origin of large TSSA

(i) Sivers mechanism:

correlation between proton spin & parton k_T

Phys Rev D41 (1990) 83; 43 (1991) 261

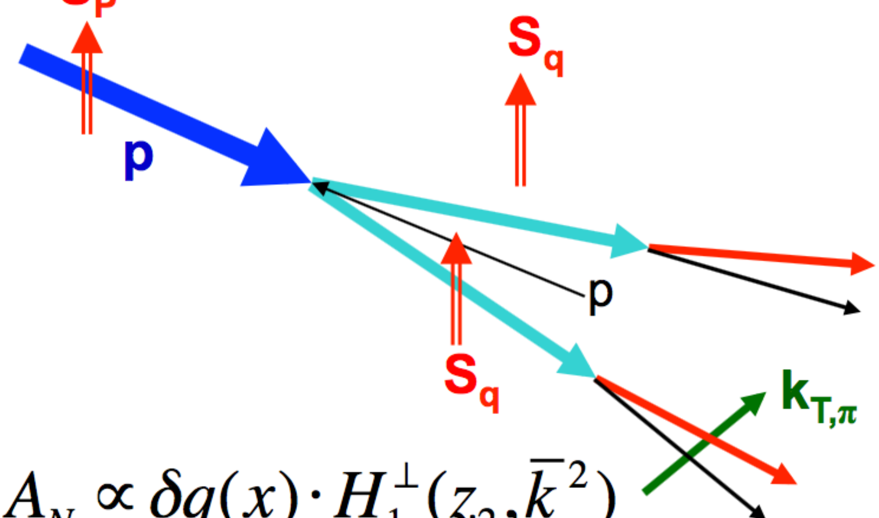


$$A_N \propto \bar{f}_{1T}^{\perp q}(x,k_\perp^2)\cdot D_q^h(z)$$

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

Nucl Phys B396 (1993) 161



$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$$

Collinear Twist-3: quark-gluon/gluon-gluon correlation

Expectation: at large p_T, $A_N \sim 1/Q \sim 1/p_T$

Frameworks

	Transverse-momentum-dependent (TMD) Factorization	Collinear twist-3 Factorization
Applicable	works at $Q \gg p_T \geqq \lambda_{QCD}$ needs 2 scales (Q^2 and p_T)	works at $Q, p_T \gg \lambda_{QCD}$ needs 1 scale (Q^2 or p_T)
p+p observables	*DY, W, Z, Hadron in jet*	π, γ, jet, Heavy Flavor, ...
Initial state	Sivers mechanism – proton spin and quark k_T correlation	Twist-3 multi-parton correlation functions
	related through $T_F^q(x,x) = -\int d^2\mathbf{p}_\perp \frac{\mathbf{p}_\perp^2}{M} f_{1T}^{\perp q}(x,\mathbf{p}_\perp^2)\|_{\text{SIDIS}}$	
Final state	Collins mechanism – proton spin and quark spin correlation, quark spin and hadron k_T correlation	Twist-3 fragmentation functions
	related through $\hat{H}^{h/q}(z) = z^2 \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M_h^2} H_1^{\perp h/q}(z, z^2\vec{k}_\perp^2)$	

Collinear Twist-3 framework

- framework to reproduce the large TSSA in $p^{\uparrow}+p \rightarrow h+X$
- Twist-3 distribution effect of polarized proton (Sivers type)
  - Qiu, Sterman(1998)/ Kouvaris, Qiu,Vogelsang,Yuan(2006)/ Koike,Tomita(2009)/ Beppu,Kanazawa,Koike,Yohida(2014)
  - Twist-3 quark-gluon-quark correlation functions
  - Twist-3 tri-gluon correlation functions
- Twist-3 distribution of unpolarized proton
  - Kanazawa,Koike(2000)
- Twist-3 fragmentation effect
  - Twist-3 fragmentation functions
  - Mets,Pitonyak(2013)

II. Study of TSSA using PHENIX muon arms

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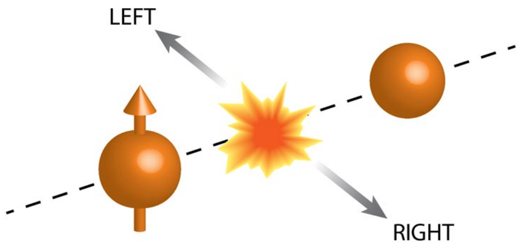
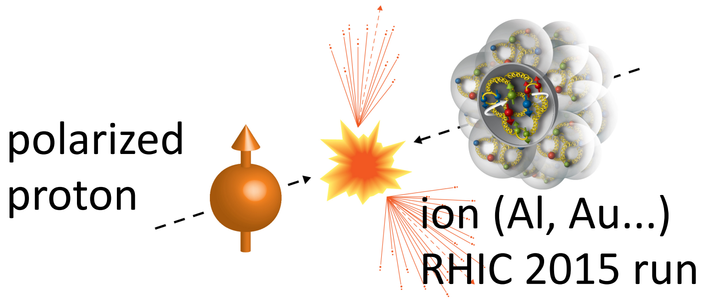
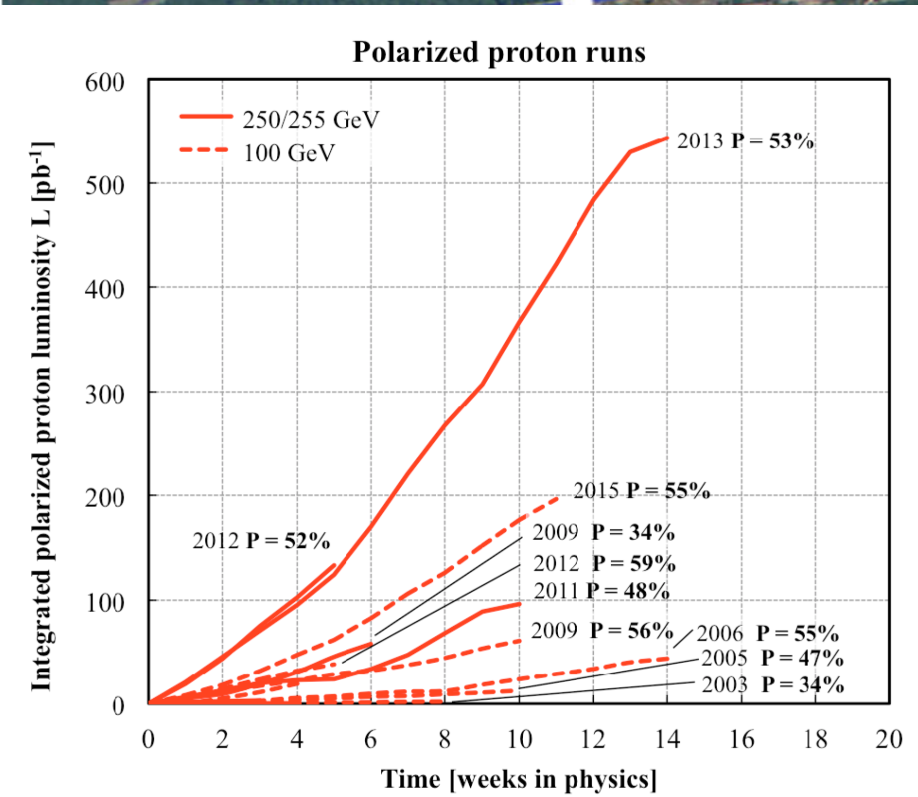
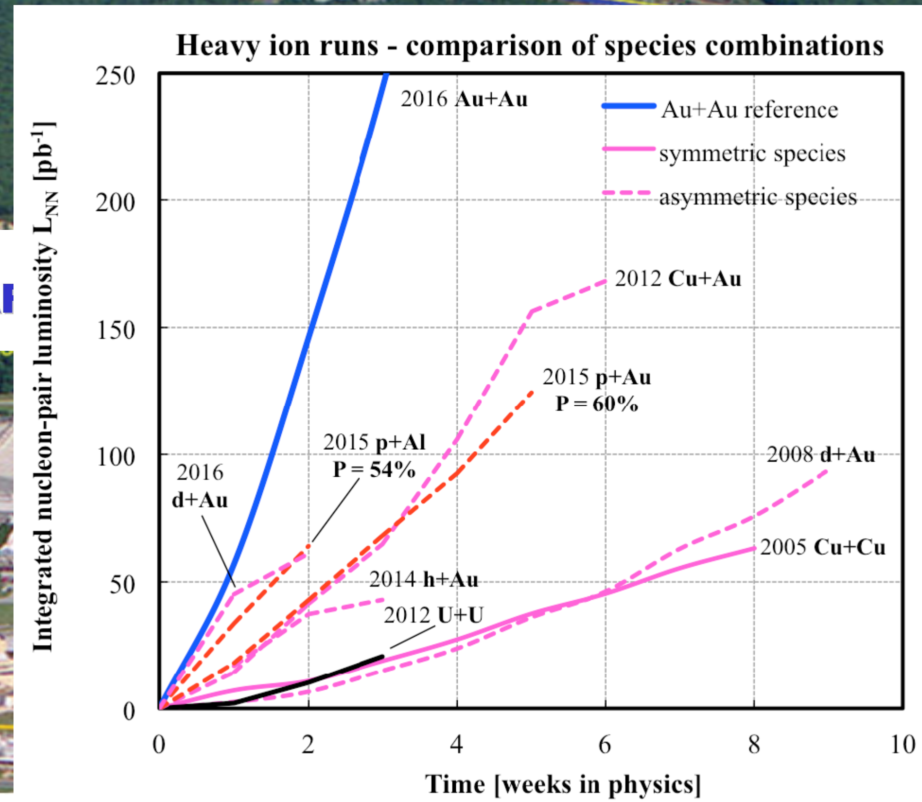
Relativistic Heavy Ion Collider at BNL

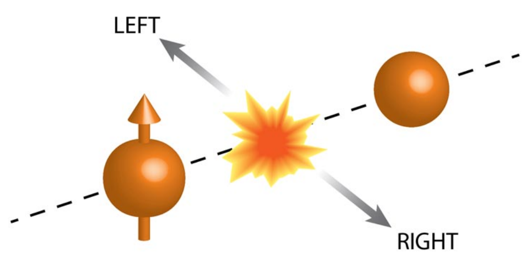


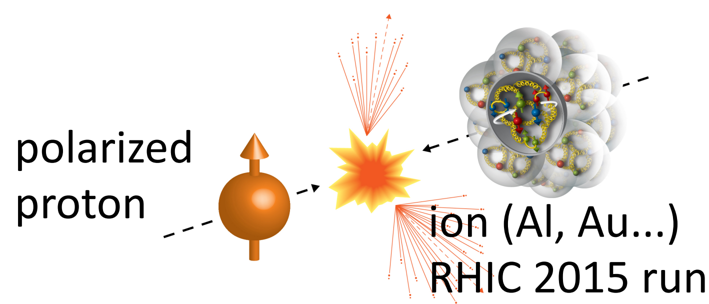


Relativistic Heavy Ion Collider at BNL

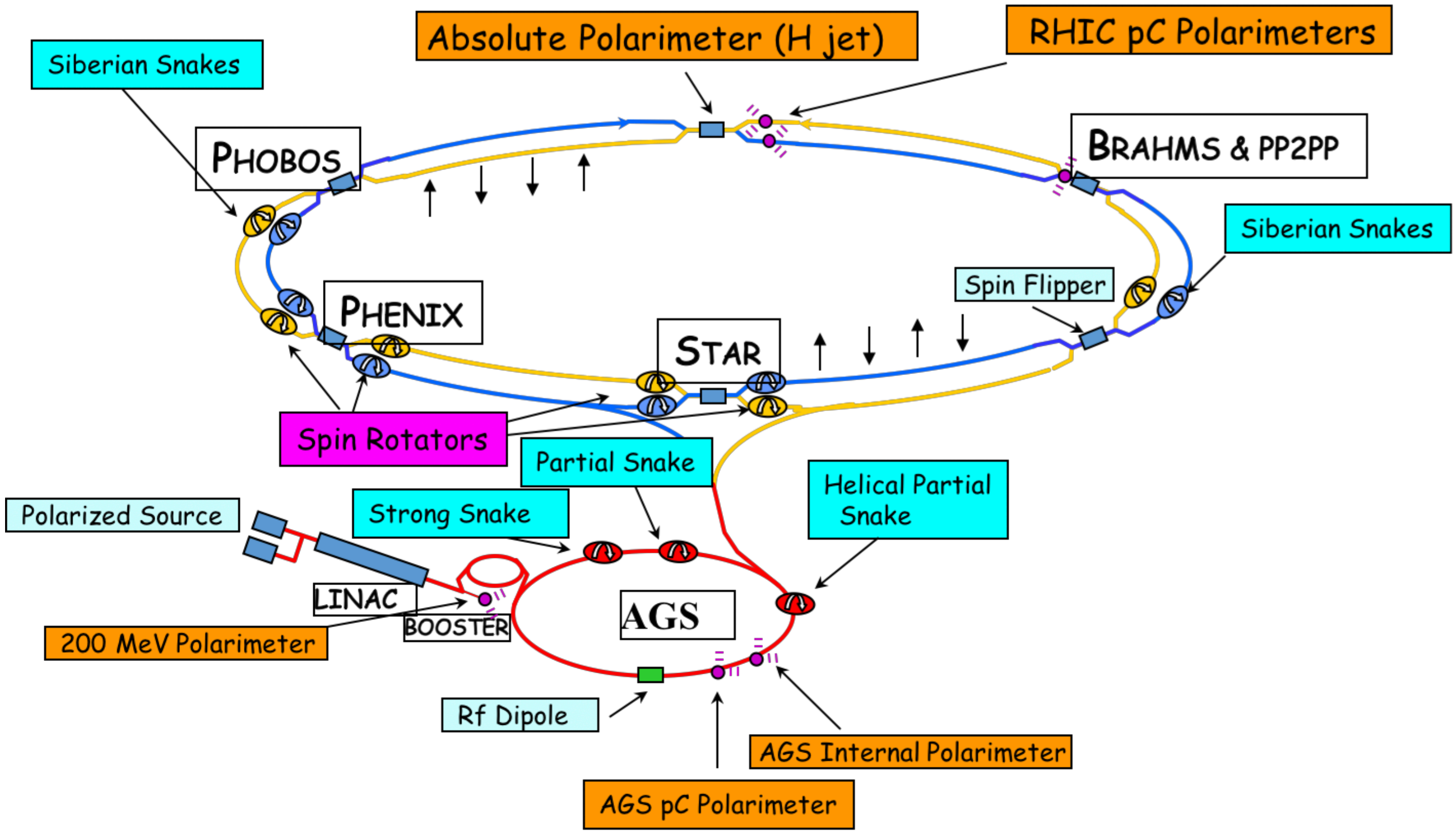




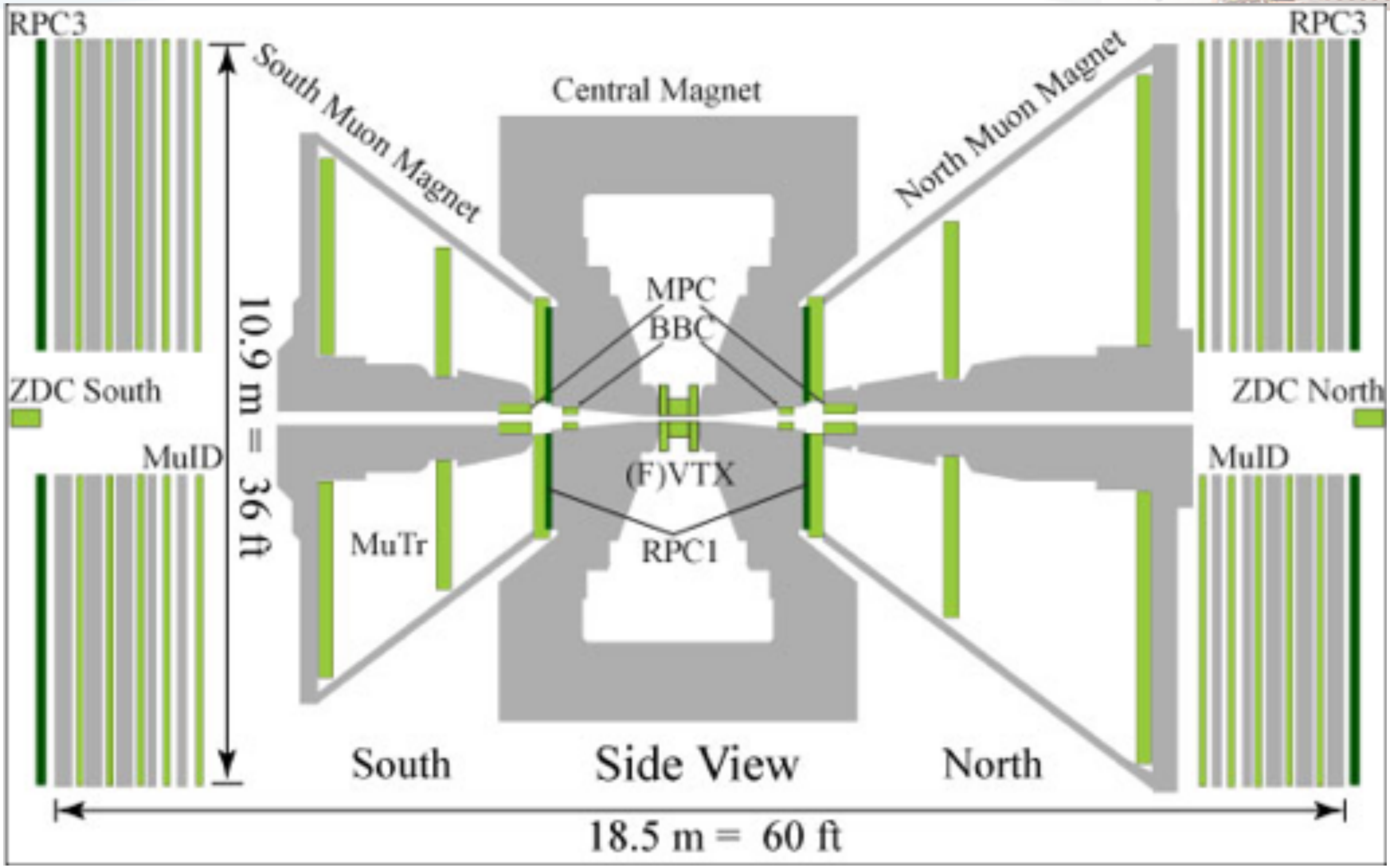




Polarized p+p(A) collisions at RHIC

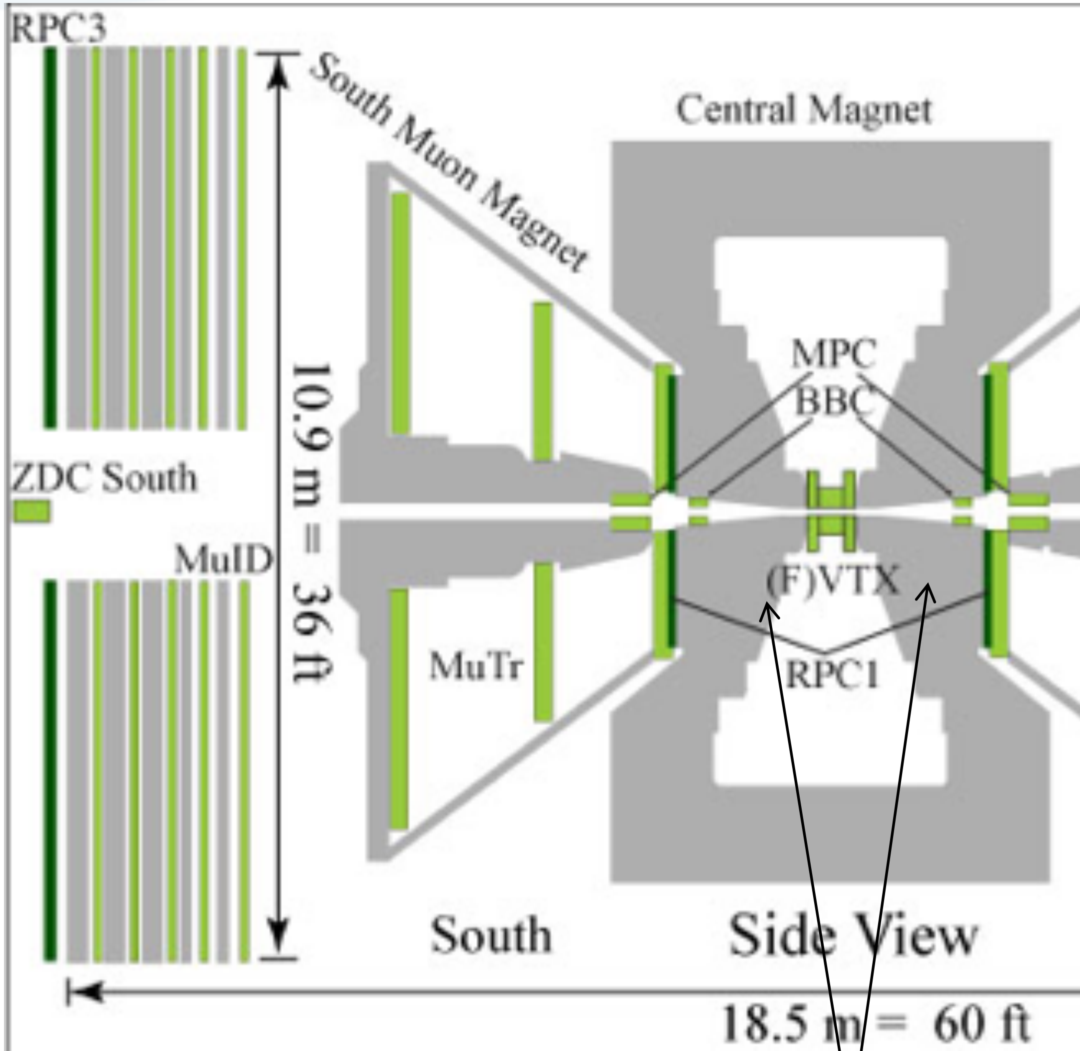


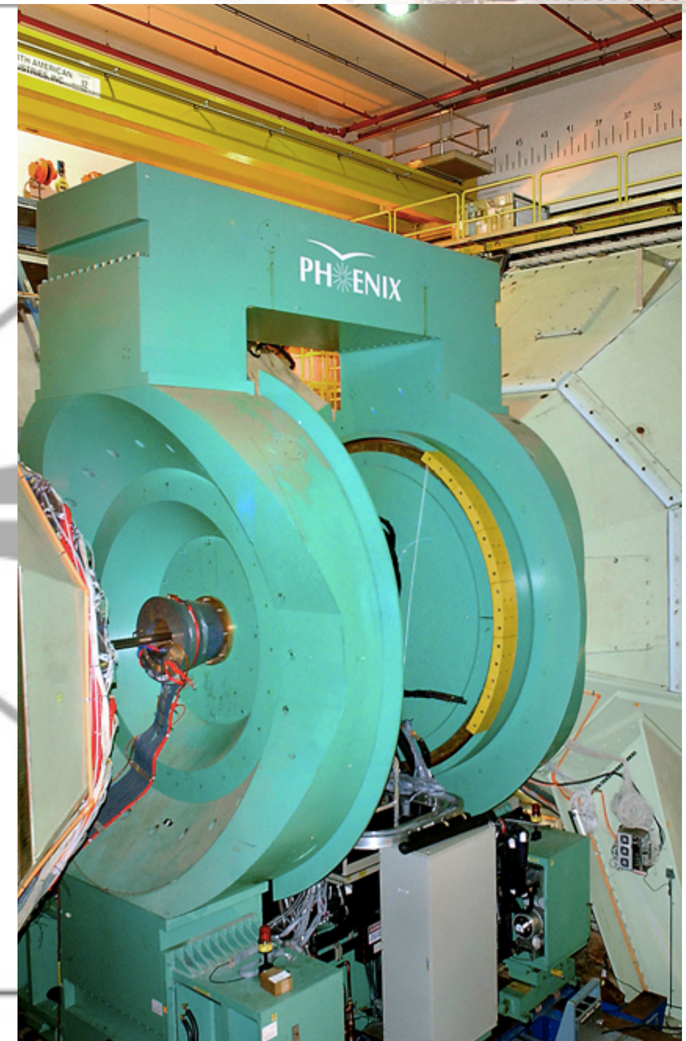
PHENIX Muon Spectrometer



Two Muon spectrometers called South arm ($-2.2<\eta<-1.2$) and North arm ($1.2<\eta<2.4$)

PHENIX Muon Spectrometer

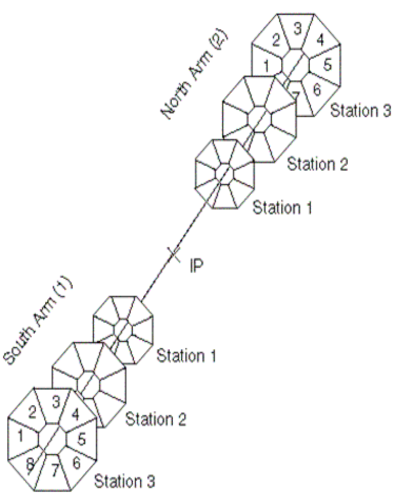


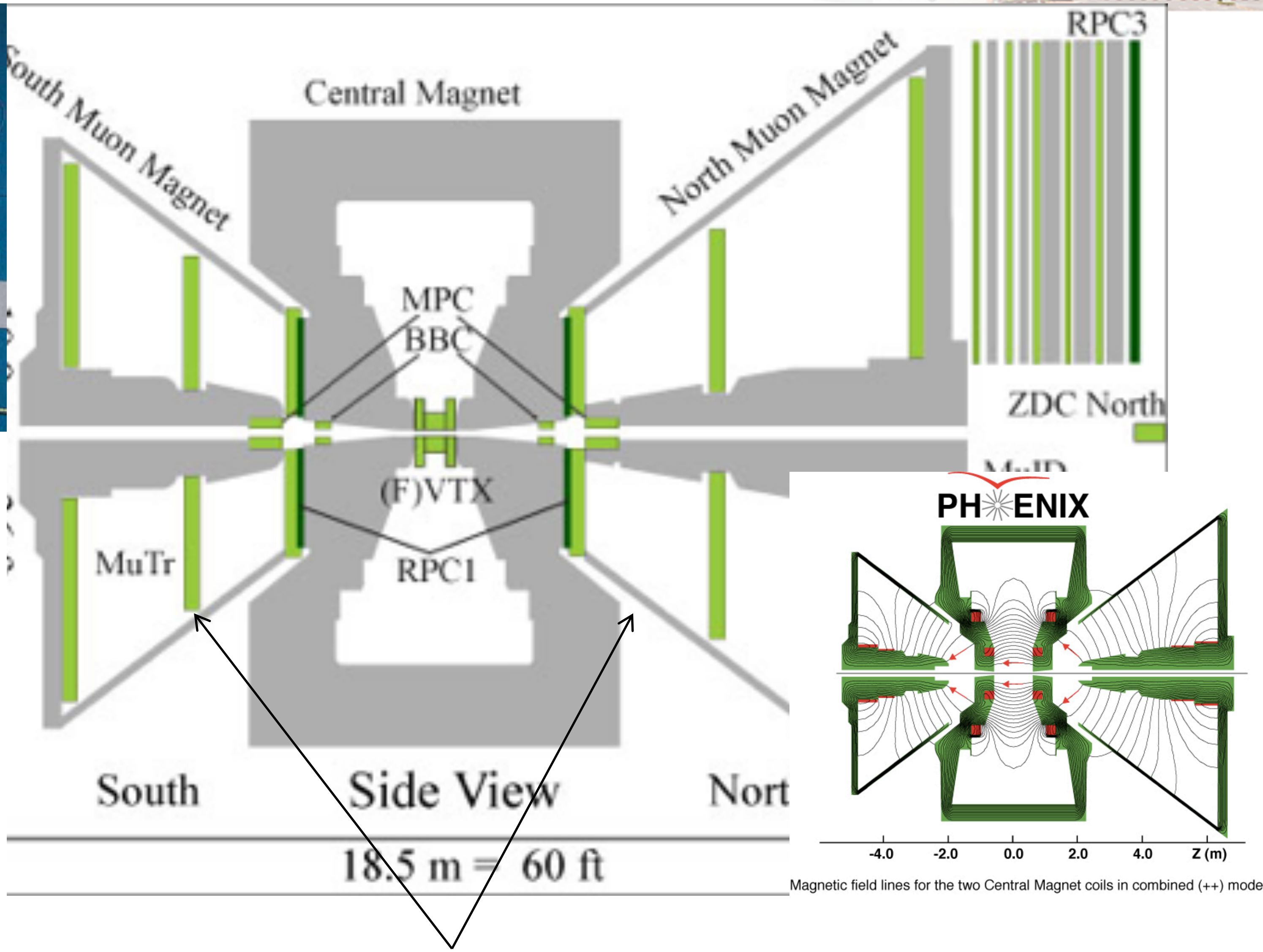


Absorber (Hadron rejection)
19 cm copper, 60 cm iron, and additional stainless steel (36.2 cm)
installed before Run-11

PHENIX Muon Spectrometer

Muon Tracking Nomenclature

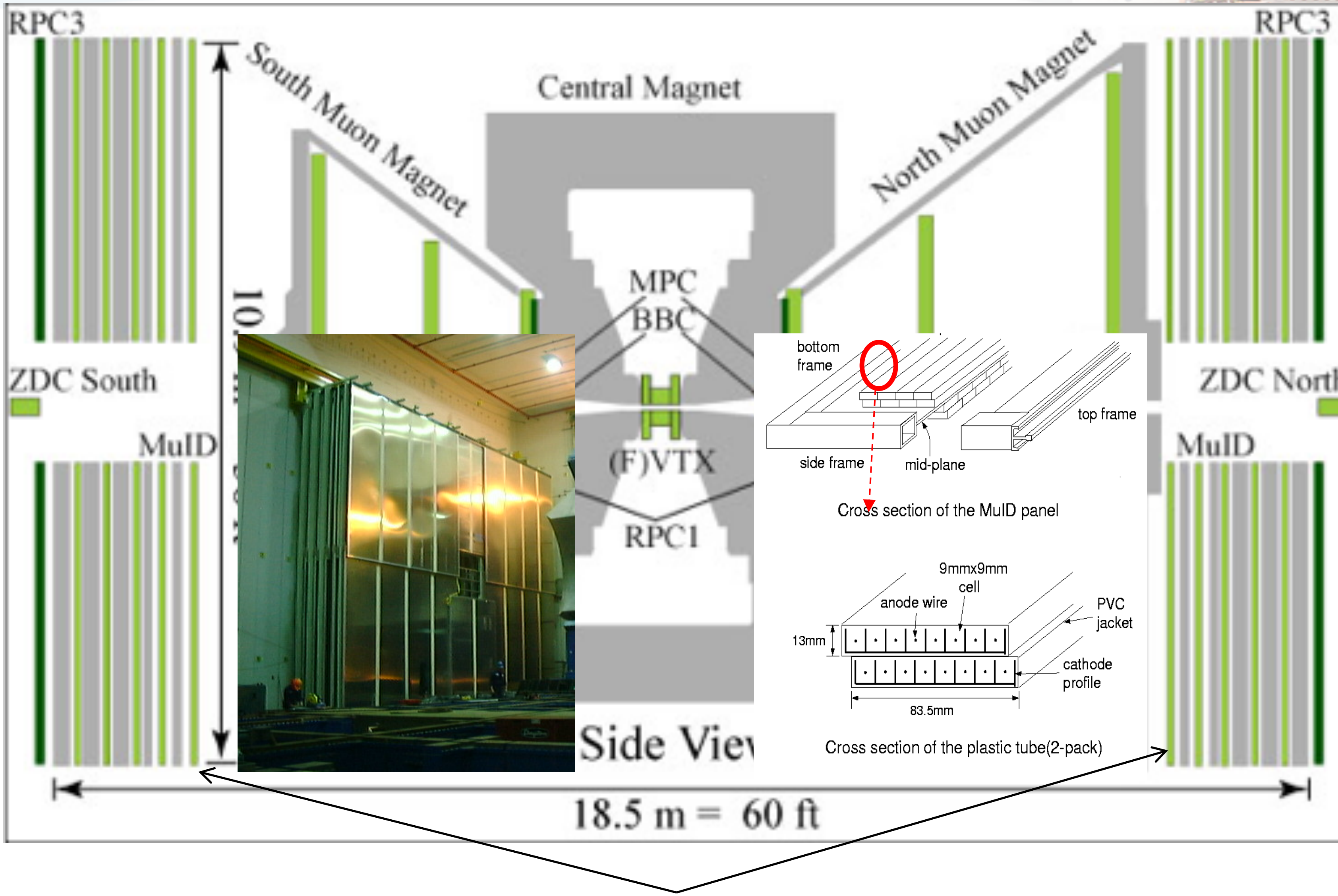




Magnetic field lines for the two Central Magnet coils in combined (++) mode

Muon Tracker (MuTr, Momentum measurement and LL1 trigger)
3 Stations (3/3/2 gaps in each station, 2 planes per gap)
It also provides momentum dependent triggering

PHENIX Muon Spectrometer

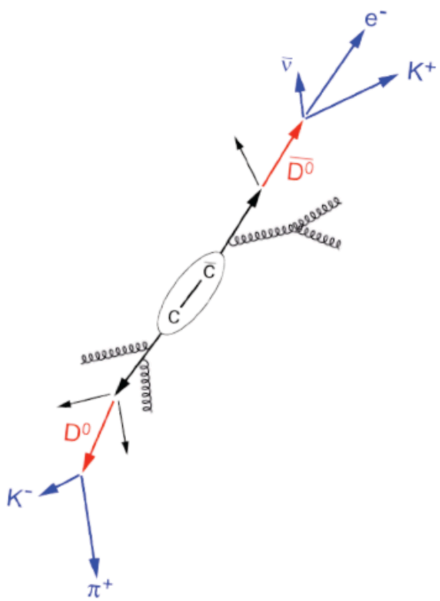


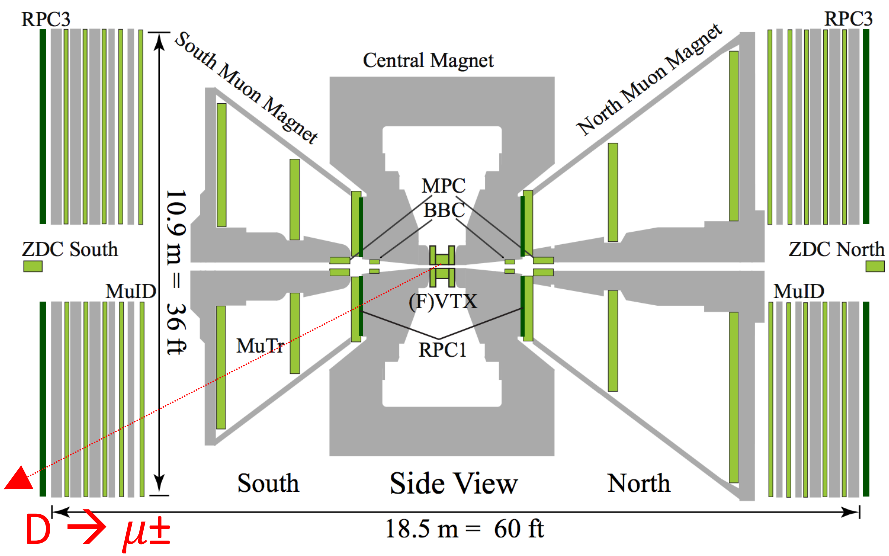
Muon Identifier (MuID, Muon/hadron separation and LL1 trigger)

5 Gaps (Each gap consists of X/Y/absorber planes)

It serves as muon, hadron trigger by selecting tracks stopped or penetrated MUID

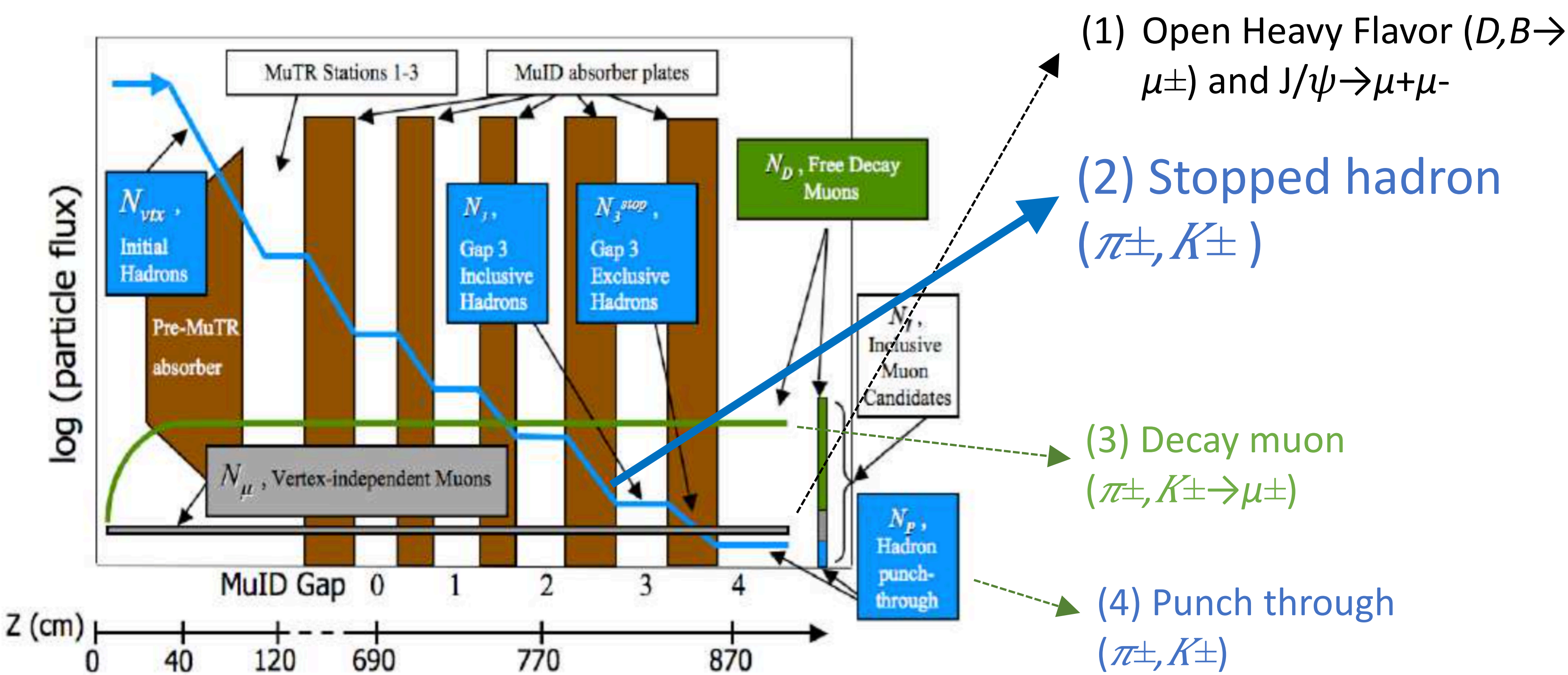
Open Heavy Flavor A_N





- Open Heavy flavor A_N
  - Dominated by gluon-gluon interaction
  - Clean probe for gluon Sivers effect – sensitive to the tri-gluon correlation function in the twist-3 collinear factorization framework.
- Probing HF in PHENIX
  - PHENIX muon spectometer ($1.2<|\eta|<2.4$)
  - D → $\mu\pm$ channel

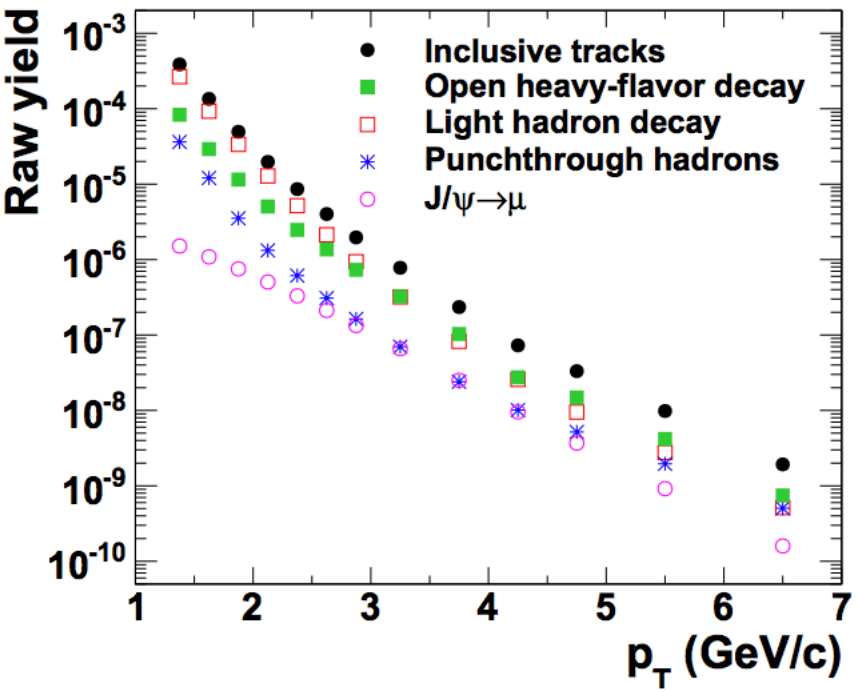
Open Heavy Flavor in Muon Arm



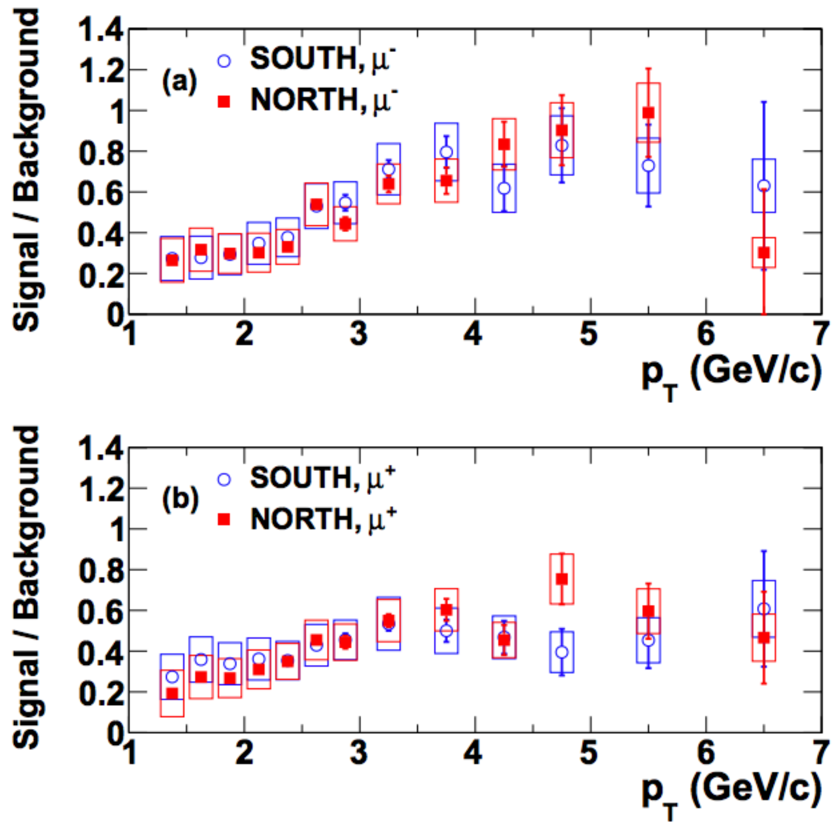
- Charged hadrons stop at MUID gap2,3
- Muons reach to the last gap of MUID(gap4)
- $\pi\pm, K\pm$ are major background in open heavy flavor study

Open Heavy Flavor in Muon Arm

- background estimation using hadron cocktail
  - initial spectra from data + full GEANT simulation



Raw Yield for each contribution

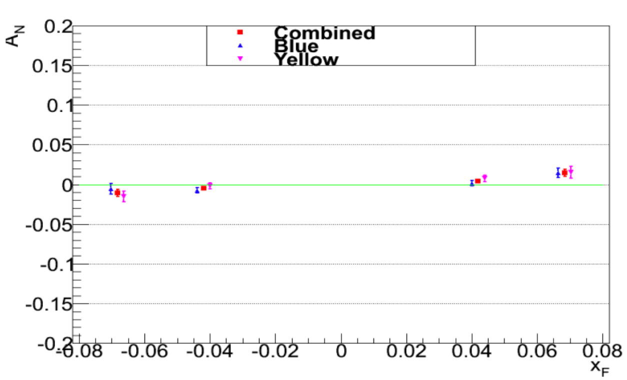


Signal/Background

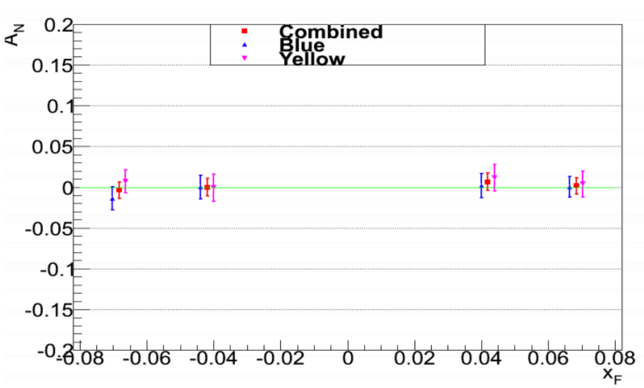
Open Heavy Flavor A_N – Analysis Detail

- Background A_N : pure charged hadron sample at MUID Gap3 tracks
- Inclusive A_N : MUID Gap4 tracks include
  - Signal : Heavy Flavor (D) → $\mu\pm$
  - Background
    - $\pi\pm, K\pm$ (→ $\mu\pm$) : measured with Gap3 tracks
    - J/ψ : from previous result (Phys. Rev. D 85, 092004 (2012))

$$A_N^{Phys} = \frac{A_N^{incl} - r \cdot A_N^{BG}}{1 - r}$$

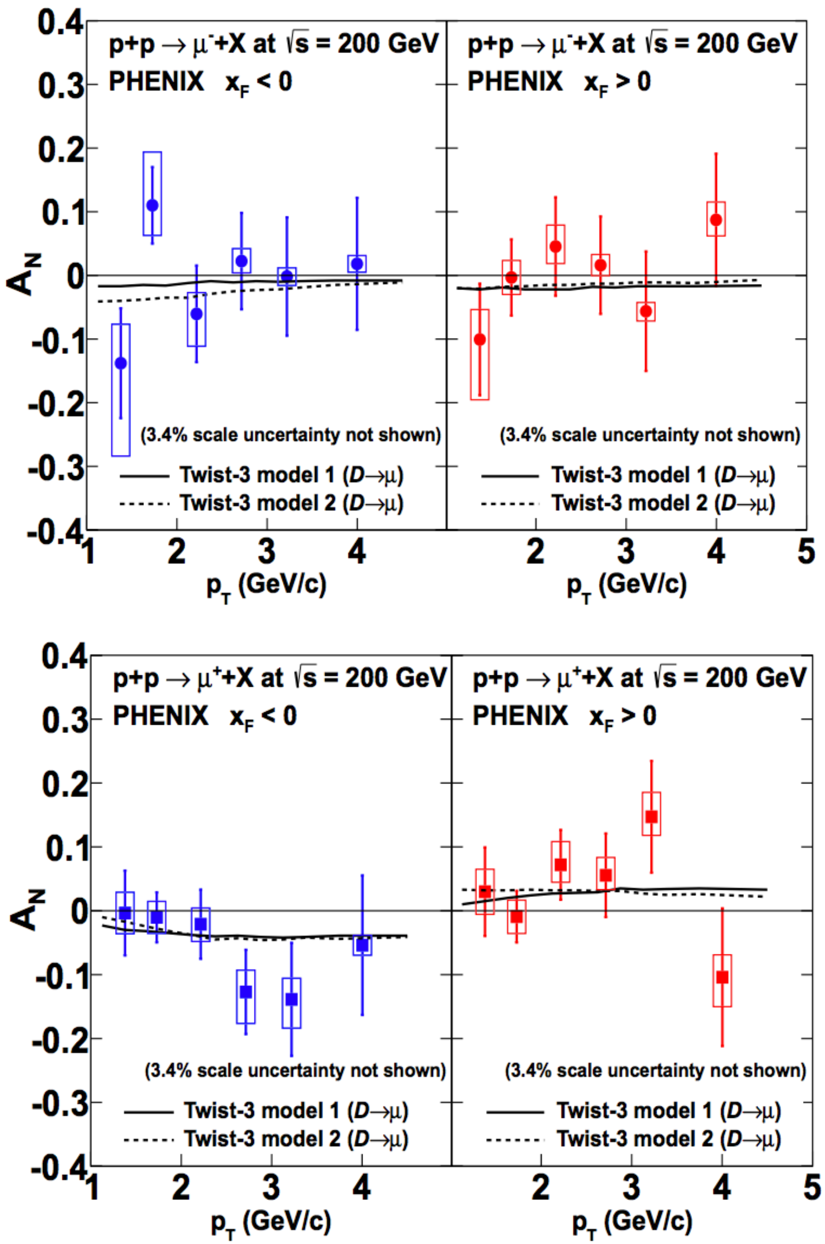


inclusive (MUID Gap4)



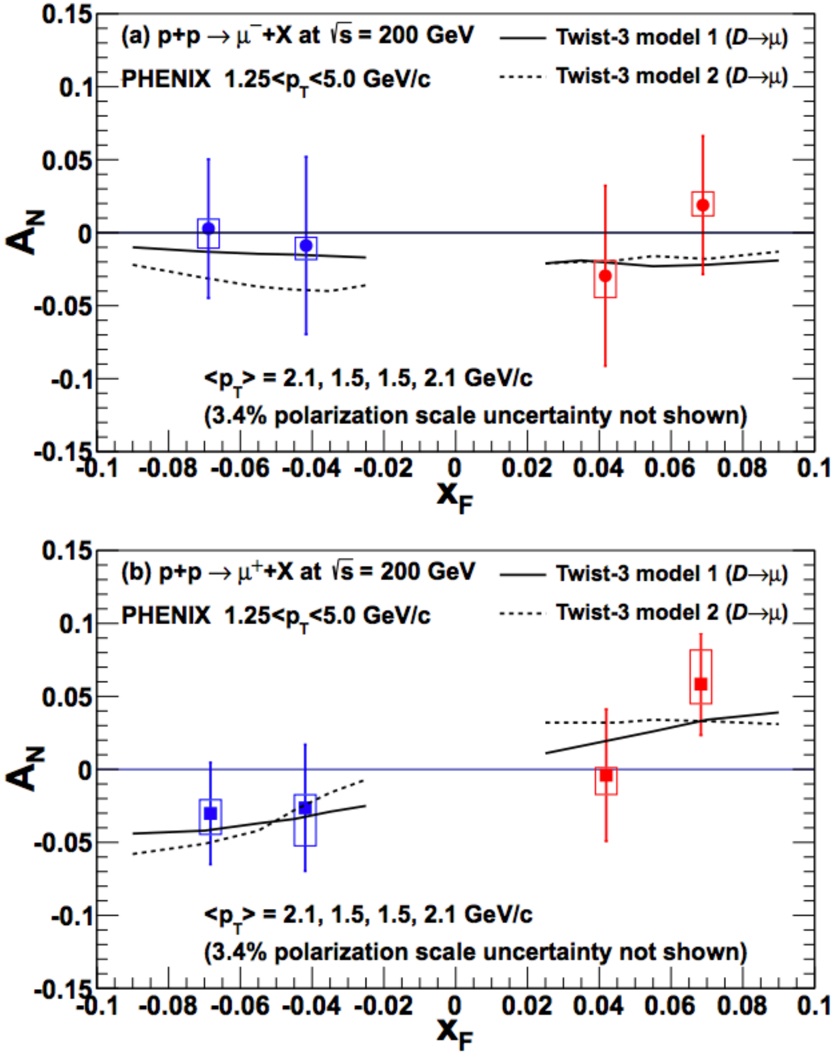
Background (MUID Gap3)

Open Heavy Flavor A_N - Results



- Results for p_T bins
- two models in twist-3 tri-gluon correlation function
- Phys. Rev. D 95, 112001 (2017)

Open Heavy Flavor A_N - Results

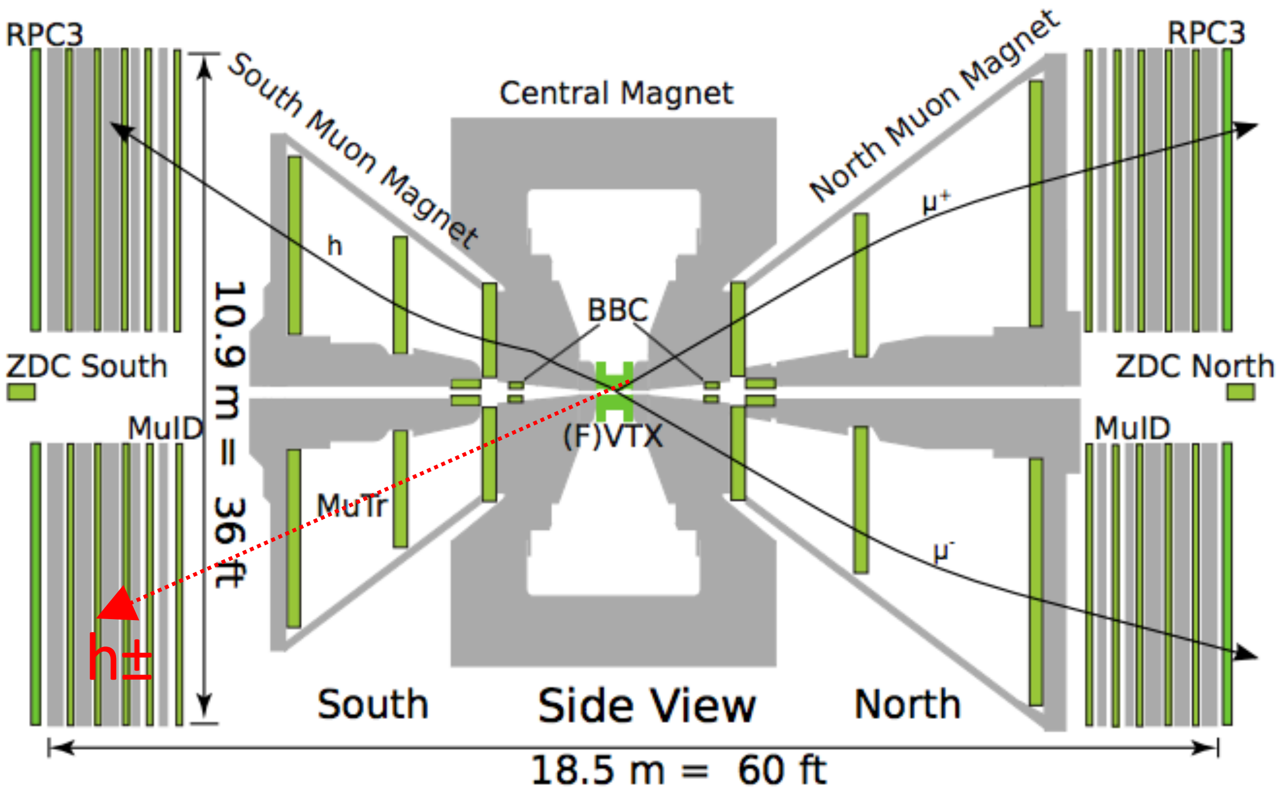


- Results for x_F bins
- two models in twist-3 tri-gluon correlation function
- consistent with theory within uncertainty
- close to zero within uncertainty
- Phys. Rev. D 95, 112001 (2017)

Open Heavy Flavor A_N

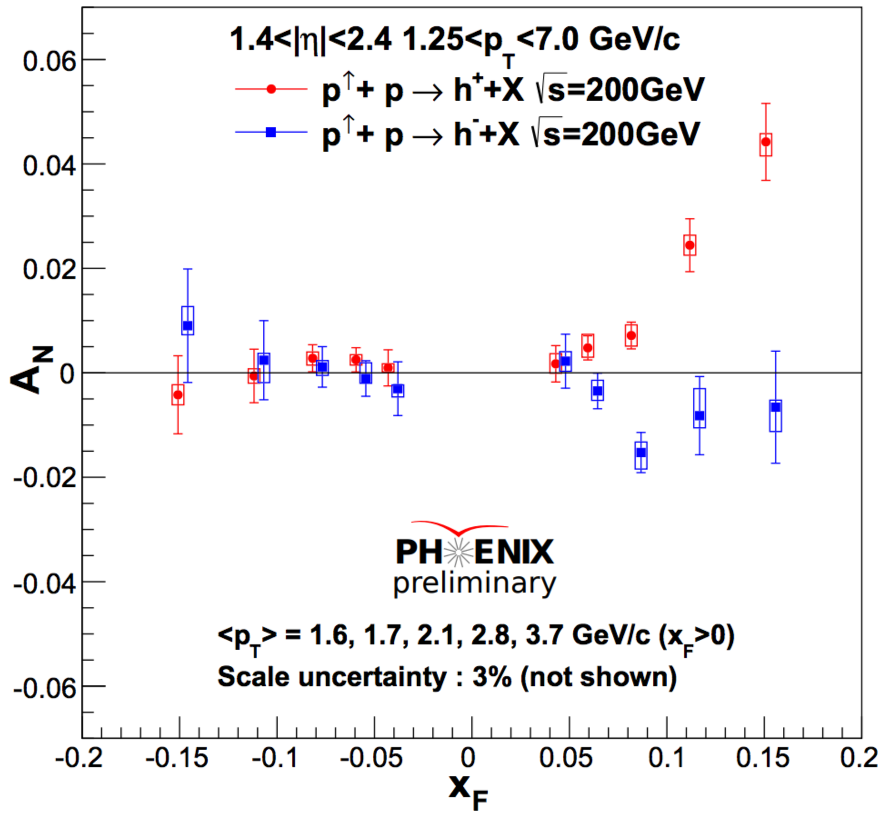
- Sensitive to the tri-gluon correlation function in twist-3 collinear factorization framework
- First measurement of open heavy flavor A_N at RHIC.
- Phys. Rev. D 95, 112001 (2017)
- Future study for Gluon Sivers-like effect
  - PHENIX 2015 data >10x statistics
  - Future projects EIC, fixed target at LHC

Charged Hadron in Muon Arm



- Stopped hadron at MUID Gap2,3 with p_z>~3.5GeV/c
- $\pi\pm, K\pm$ mixture

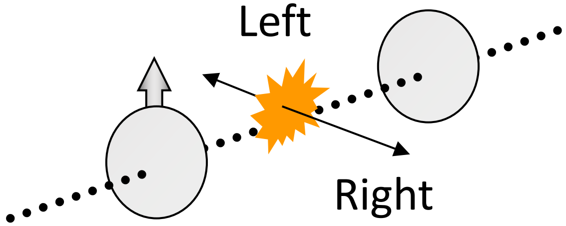
Charged Hadron A_N in p+p



- A_N of (survived) $\pi\pm, K\pm$ mixture
- p+p→h(+)+X at x_F>0 shows positive A_N while h(-) shows small A_N
  - Opposite sign for π-,K- may cause it
- A_N increases as x_F increases for positively charged hadron at x_F>0

polarized p+A collisions at RHIC

$$A_N = \frac{\sigma_L^{\uparrow} - \sigma_R^{\uparrow}}{\sigma_L^{\uparrow} + \sigma_R^{\uparrow}}$$

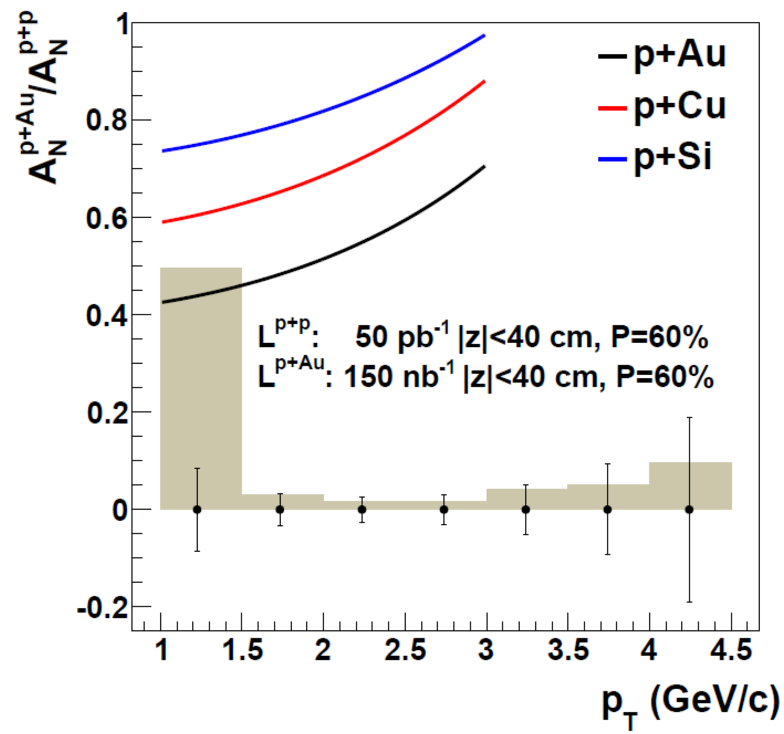


$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

TSSA can act as a probe of the saturation s cale – the p+p reference will also be better understood with new instruments.

A unique capability of RHIC

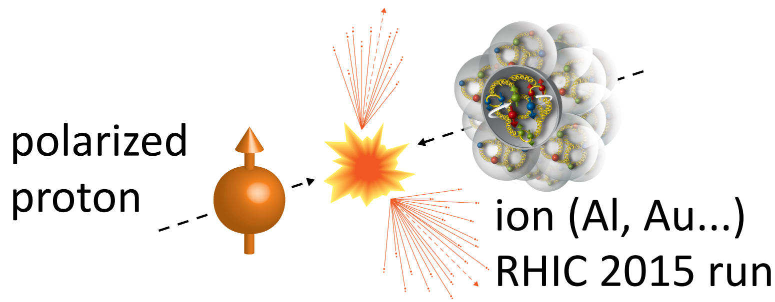
Y. Kovchegov & M.D. Sievert: PRD 86, 034028 (2012)
Kang, Yuan: PRD 84, 034019 (2011)



- Dependence of Q_{sA} on A

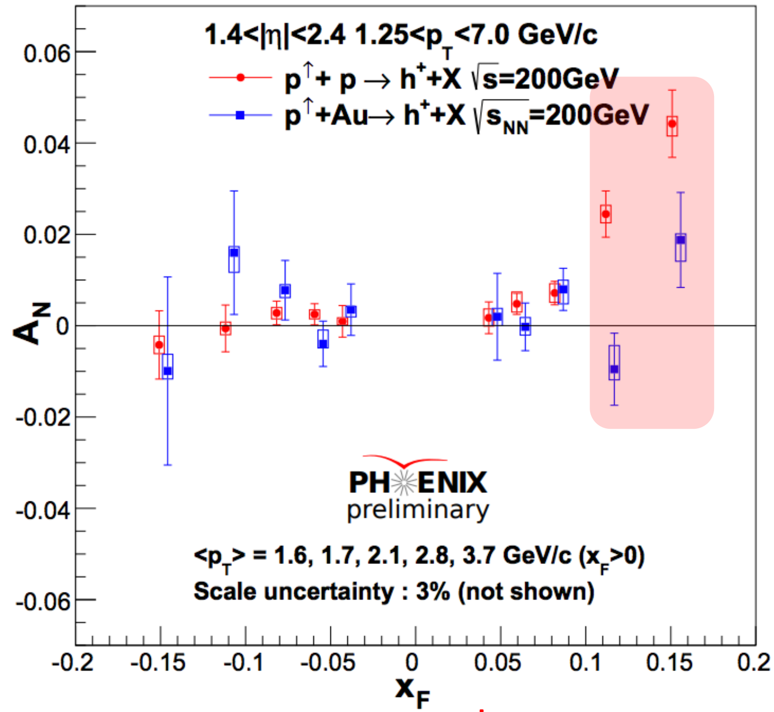
Inclusive hadron A_N in polarized p+A

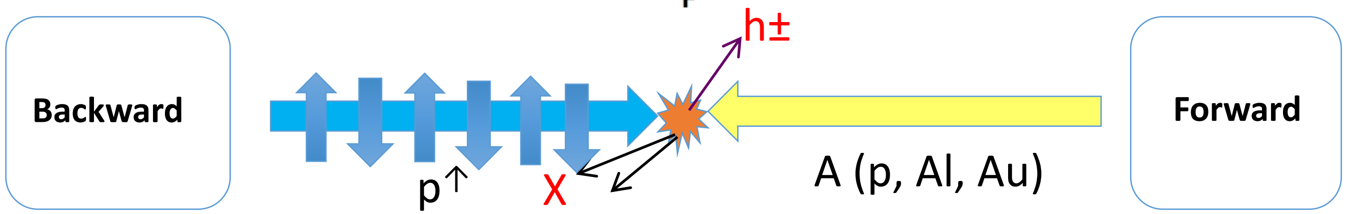
- The first polarized p+A collision at RHIC 2015
  - Novel opportunities to study nuclear effects on parton dynamics



- Inclusive hadron A_N at forward rapidity in polarized p+A
  - Helps us to understand underlying mechanisms of A_N
  - ➔ different mechanism have different A-dependence
    - Hybrid approach (Twist-3 in polarized p, CGC in A)
      - Yoshitaka Hattaa,et al, Phys. Rev. D 94, 054013 (2016), Phys. Rev. D 95, 014008 (2017)
  - Unique opportunities to study low-x gluon and gluon saturation signatures
    - A-dependence of A_N is sensitive to Qs
      - PhysRevD.84.034019, PhysRevD.86.034028

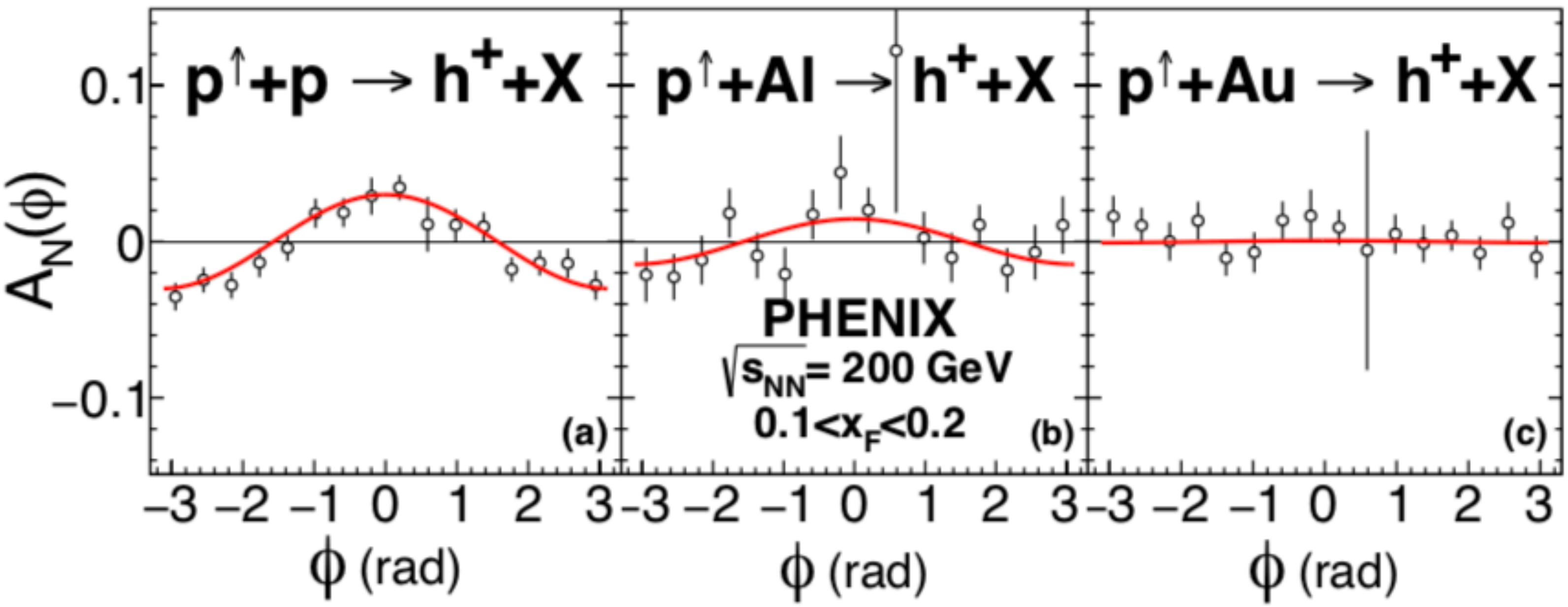
Positively charged hadron A_N in p+p, p+Au





- A_N of (survived) $\pi\pm, K\pm$ mixture.
- p+Au→h(+)+X shows clear suppression of A_N at x_F>0.1

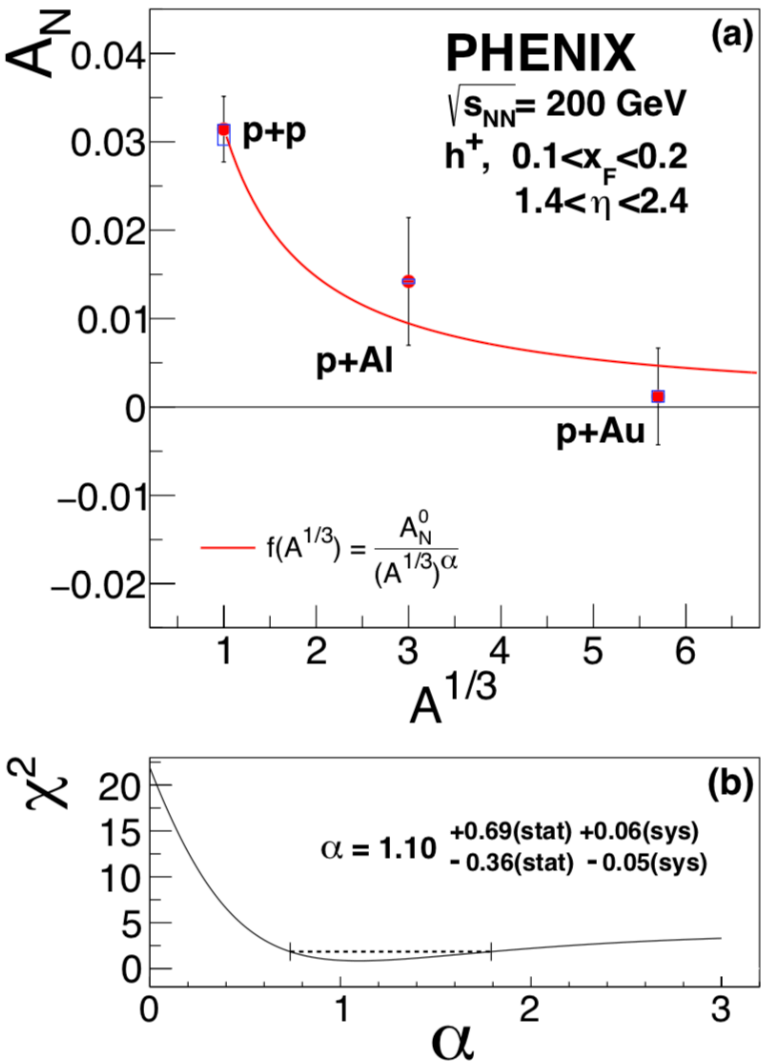
Positively charged hadron A_N in p+p, p+A



- cosine modulations of A_N for positively charged hadron at $0.1<x_F<0.2$
- clear modulation in p+p, weaker one in p+Al, disappears in p+Au

Nuclear dependence of A_N

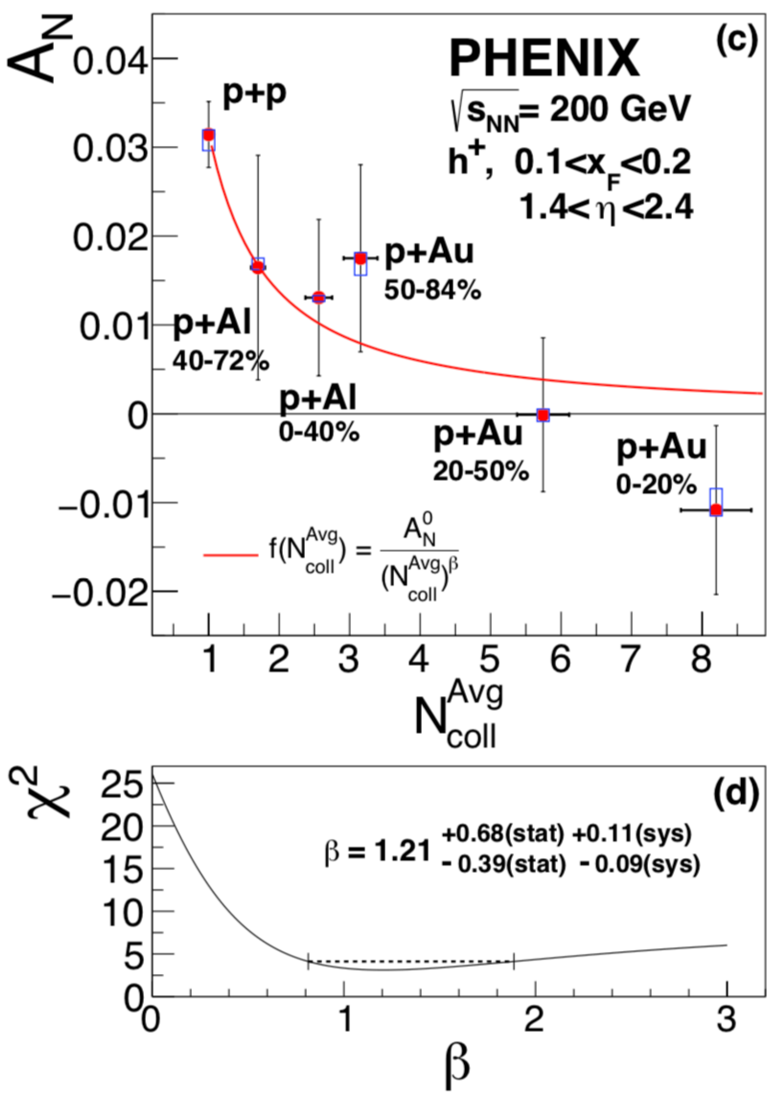
Phys. Rev. Lett. 123, 122001
Published September 2019



- Nuclear dependence of A_N for positively charged hadron at $0.1<x_F<0.2$
  - Fit function is to quantify the A-de pendence, x-axis is $A^{(1/3)}$
  - Bottom panel is χ^2 for wide range of power parameter α
  - Favors A-dependence
  - α =1 corresponds to $A^{(1/3)}$
  - α =0 corresponds to $A^{(0)}$ (A-indepe ndence)
    - χ^2 >20 (stat only)
- Clear nuclear dependence

Nuclear dependence of A_N

Phys. Rev. Lett. 123, 122001
Published September 2019



- Avg.N_{coll} dependence of A_N for positively charged hadron at $0.1<x_F<0.2$
  - x-axis is averaged-N_{coll}, related t o the path length in a nucleus in p+A collisions
  - Bottom panel is χ^2 for wide rang e of power parameter β
  - Favors N_{coll}-dependence

Theory for A_N in p+A

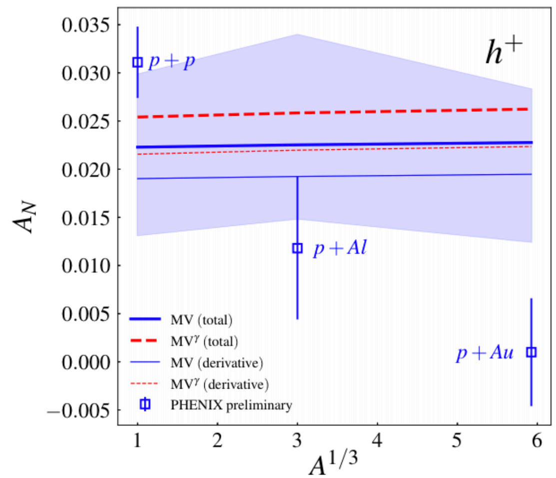
- Hybrid approach in recent theory papers
  - Twist-3 framework for the polarized-proton side and the CGC fram ework for the target-nucleus side
  - A-dependence of the TSSA arises from the saturation scale Q_s, whe re $Q^2_{sA} \propto A^{1/3}$ for the target nucleus
- A_N in p+A is thought to be
  - From twist-3 correlation function : independent of A for $p_T \gg \Lambda_{QCD}$
  - From twist-3 fragmentation function : A-independent or $A^{1/3}$-depe ndent for $Q_s \gg p_T \gg \Lambda_{QCD}$
  - A-independence is expected for high pT in either functions

Striking suppression

- A recemt theory paper describes

PHENIX collaboration found a striking nuclear suppression $A_N \propto A^{-1/3}$

  - Phys.Rev. D99 (2019) no.9, 094012
- A-independence is expected at high pT(>Qs)



- A-dependent term is responsible for nonzero A_N?
- Or, any other nuclear effect?

Summary and Outlook : Analysis

- Studying spin in physics has led to a lot of surprises
- Transverse single-spin asymmetries (TSSAs) in proton-proton collisions have a long history of revealing the richness of QCD.
- TSSA measurements using PHENIX muon spectrometers
  - (1) Open heavy flavor A_N in p+p (Phys. Rev. D 95, 112001 (2017))
    - First measurement of open heavy flavor A_N at RHIC.
    - Sensitive to the tri-gluon correlation function in twist-3 collinear factorization framework
    - 2015 data is being analyzed with much improved statistics.
  - (2) <u>New publication on A-dependence of A_N</u> in hadron production (Phys. Rev. Lett. 123, 122001 (2019))
    - unique opportunThe h(+) result shows striking A-dependence and N_{coll} dependence
    - ities to study low-x gluon and gluon saturation signatures
    - A-dependent term could be the dominant source of A_N in p+p, or nuclear effect?
    - A follow-up paper is in preparation for wide xF range, pT bins, both charges
- This topic has been studied in many experiments and will be studied in future experiments,
  - Current : PHENIX, STAR, JLAB, COMPASS, Fermilab
  - STAR upgrade, sPHENIX, EIC (RHIC, JLAB), Fermilab, LHC target experiment if possible

Thank you

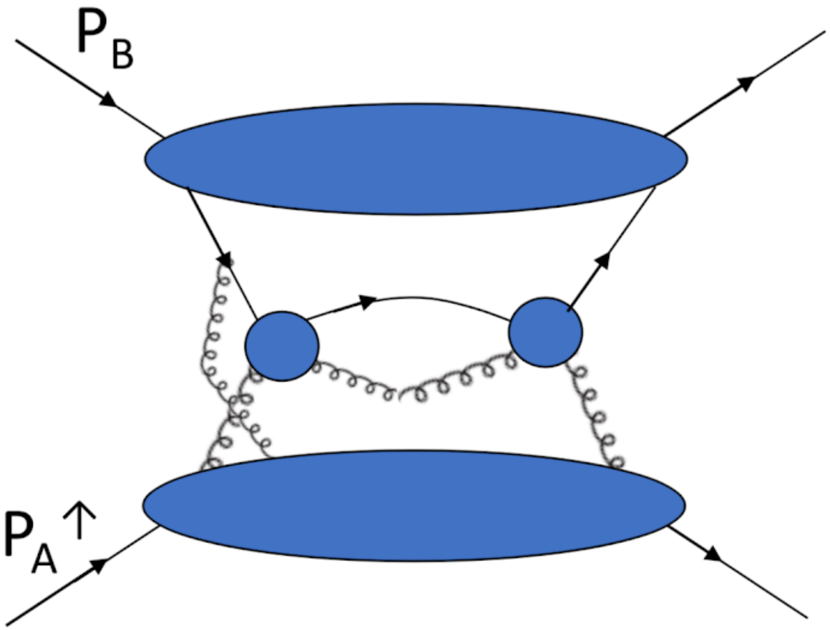
인하대학교

Bacup slides

Higher Twist Functions

Formal definition of twist: “mass dimension minus spin” of the operator in a matrix element within the Operator Product Expansion

Twist 2: traditional PDFs and FFs only consider interactions between one parton in the proton at a time



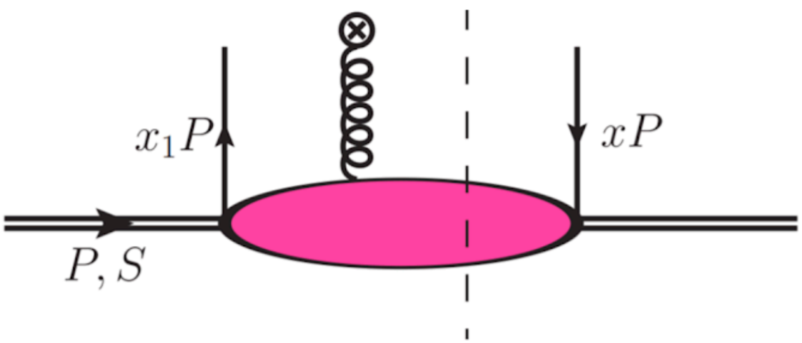
Twist 3: Quantum mechanical interference between one parton versus interacting with two partons at the same relative x

- Can describe spin-momentum correlations in the proton and in hadronization

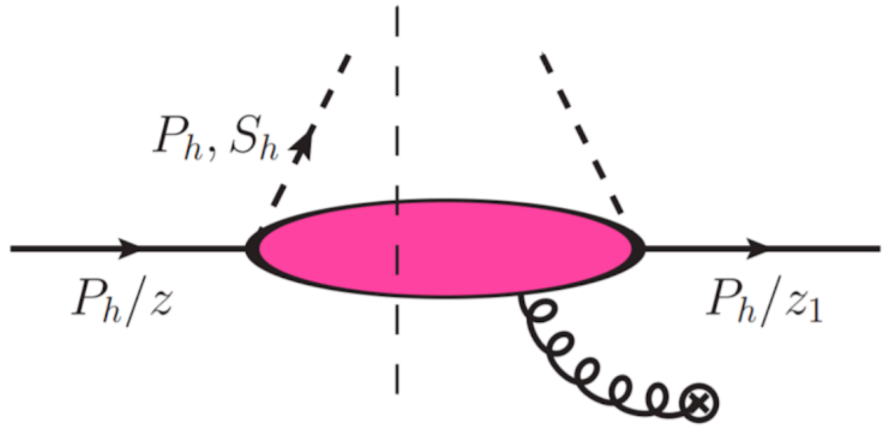
Twist 3 Functions

Multiparton correlations: quantum mechanical interference between scattering off of one versus two partons at the same x

- Quark-Gluon-Quark (qgq) Correlation Function: scattering off of quark and a gluon versus a single quark of the same flavor
- Three-gluon Correlation Function (ggg): two gluons versus one gluon



qgq Twist-3 Initial State



qgq Twist-3 Final State

Daniel Pitonyak *International Journal of Modern Physics A* **31**, No. 32, 1630049 (2016)

Twist-3 framework

- Transversity : if your hadron is polarized upwards, it's the difference between the probability of finding a quark polarized upwards minus the probability of finding a quark polarized downwards