Transverse spin physics in p+p and p+A collisions using the PHENIX muon spectrometer

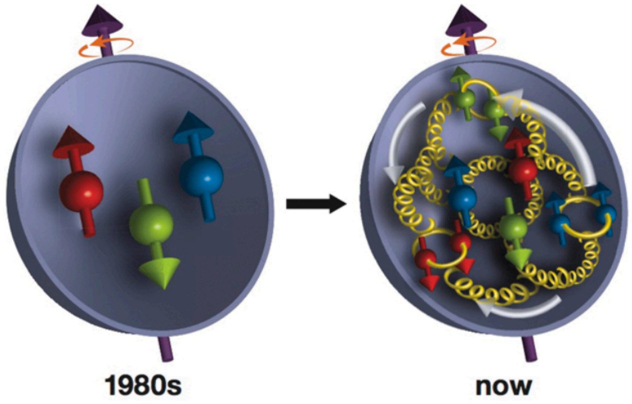
Jeongsu Bok (Inha Univ)

May 24th 2019

Heavy Ion Meeting

How did the proton get its spin

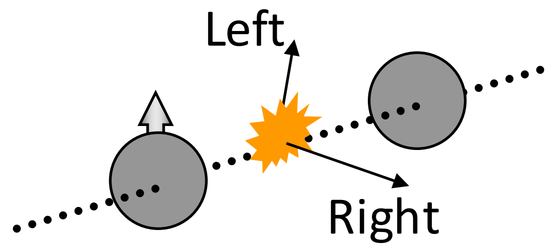
- Protons are one of the three particles that make up atoms, the building blocks of the universe. A proton's spin is one of its most basic properties.
- used to be an easy college assignment. However, the "right" response was disproven by experiments that turned the field upside-down.
  - In 1980's EMC at CERN : nothing from quark → recent experiments suggest 25~30%
  - ➔"Proton Spin Puzzle"



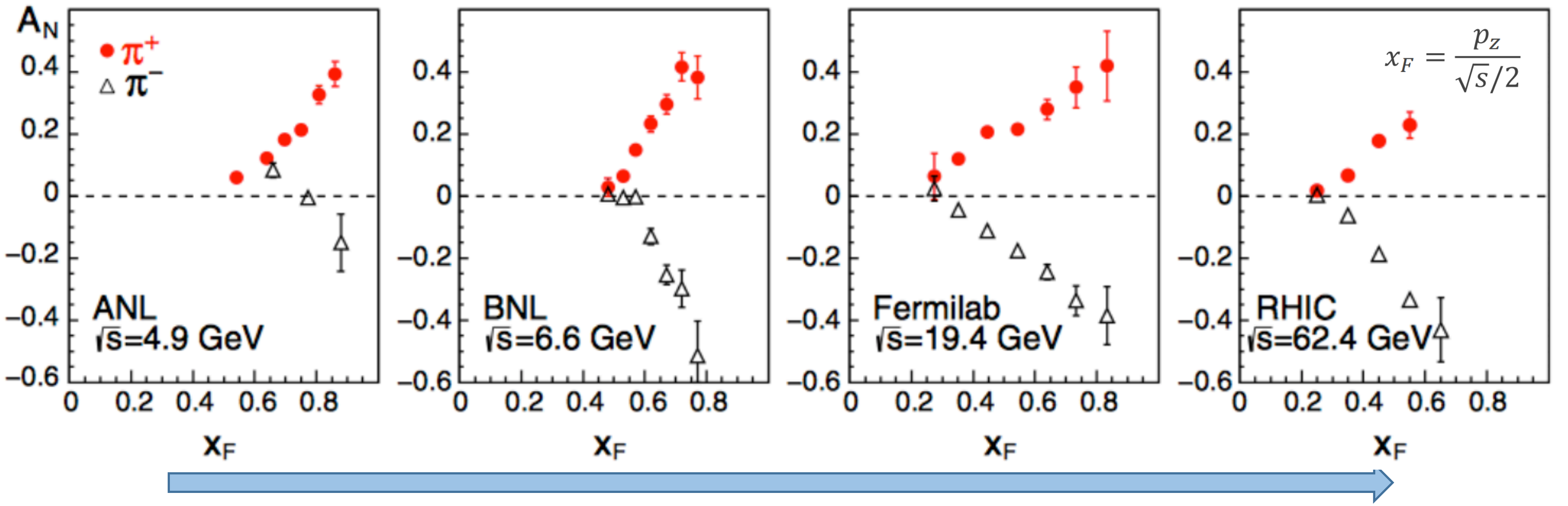
Spin structure of the proton (transverse)

- Studying the transverse spin structure of the proton provides an opportunity to understand the 3-D structure of the proton.
- A tool : Transverse Single Spin Asymmetry (A_N)
  - polarized proton scattering on an unpolarized proton or nucleus.
  - A_N describes the azimuthal-angular dependence of particle production relative to the transverse-spin direction of the proton
  - measured in fixed target experiments and ignored for a couple decades because it was assumed that they came incalculable soft QCD interactions.

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



Transverse Single Spin Asymmetry (A_N)



- Small asymmetry is expected at high energies
- Over 40 years, Large A_N in single hadron production consistently observed up to RHIC energies, well into the perturbative regime of QCD
- Their origin remains poorly understood. → Another long-standing puzzle

Understanding of TSSA

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

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

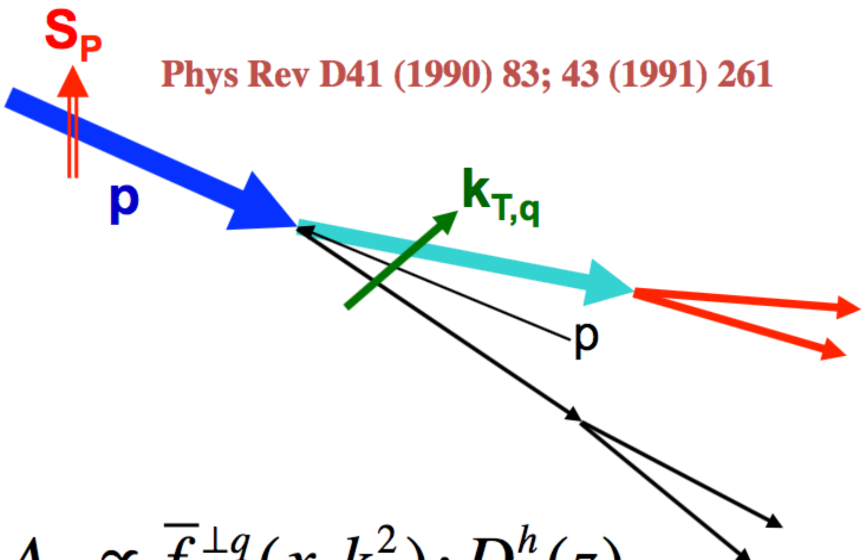
- Current understanding
  - TMD factorization
    - For two scale observables : $Q \gg p_T \geqq \lambda_{QCD}$
    - DY, W, Z, Hadron in jet, …
  - Twist-3 Collinear factorization
    - For one scale observables : $Q,\ p_T \geqq \lambda_{QCD}$
    - π , γ, jet, Heavy Flavor, ...

Origin of A_N

(i) Sivers mechanism:

correlation between proton spin & parton k_T

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

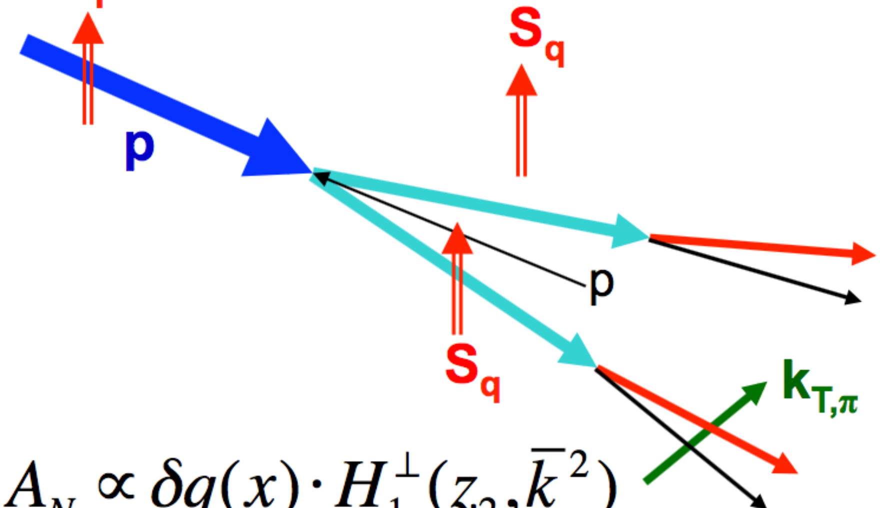


$$A_N \propto \bar{f}_{1T}^{\perp q}(x,k_\perp^2)\cdot D_q^h(z)$$

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

Nucl Phys B396 (1993) 161

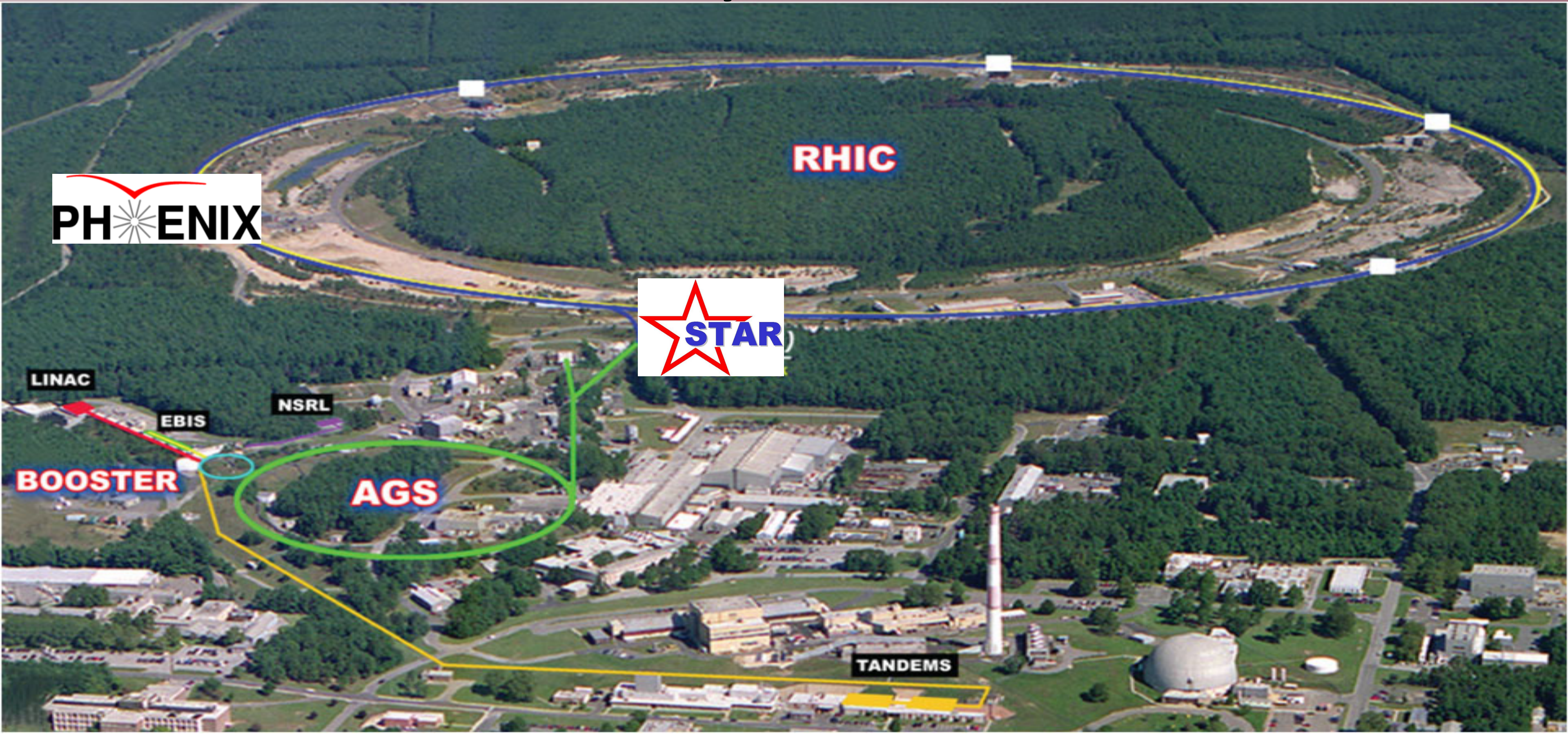


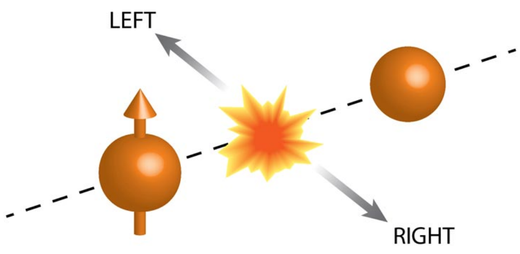
$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$$

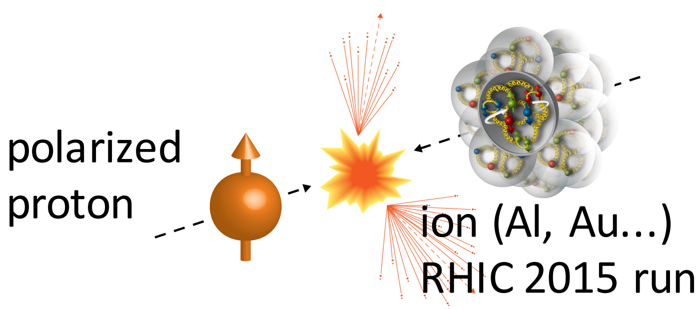
Collinear Twist-3: quark-gluon/gluon-gluon correlation

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

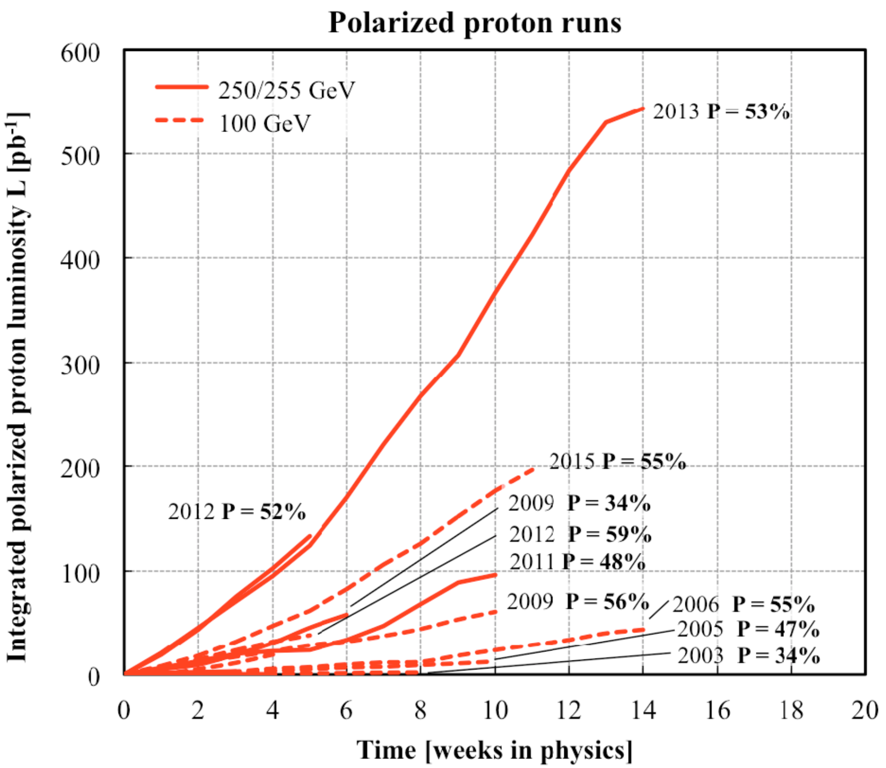
Relativistic Heavy Ion Collider at BNL

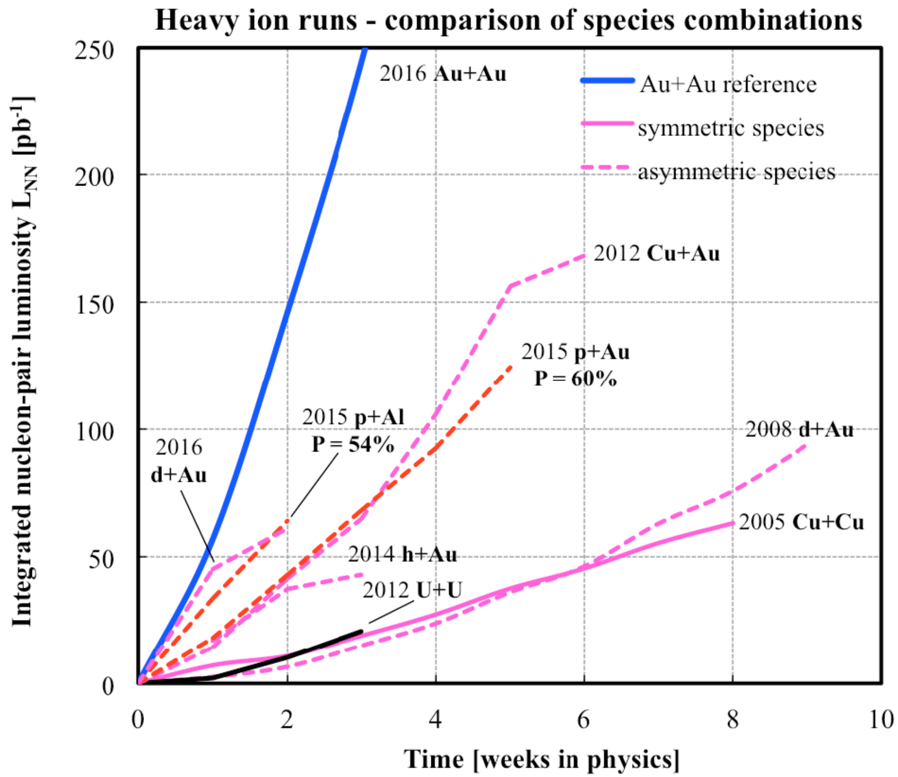


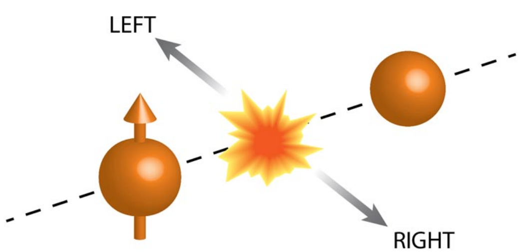


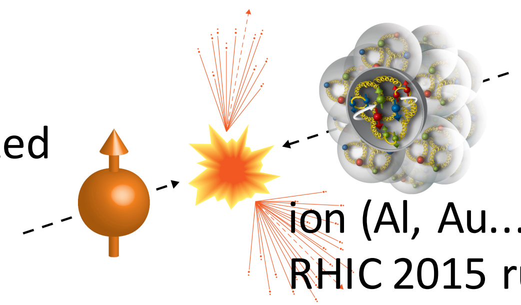


Polarized *p*+*p*(A) collision at RHIC

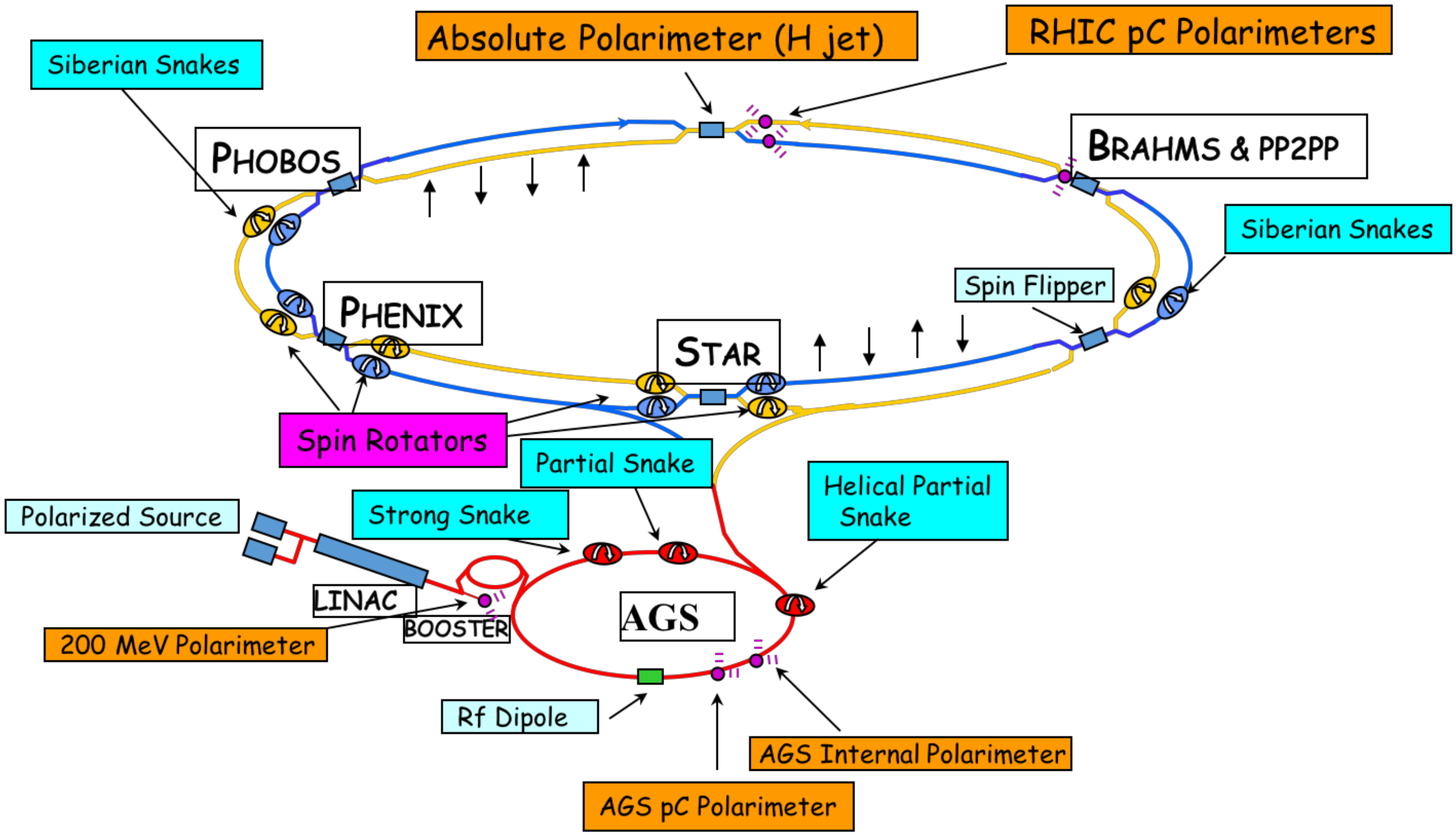


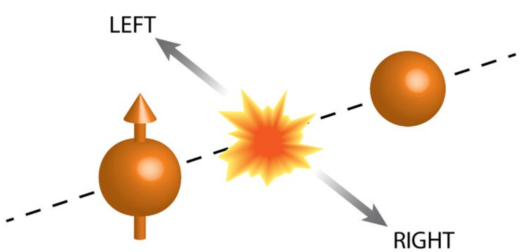


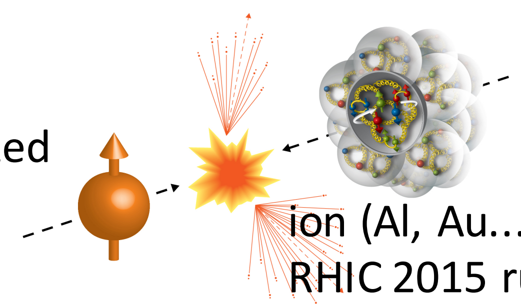




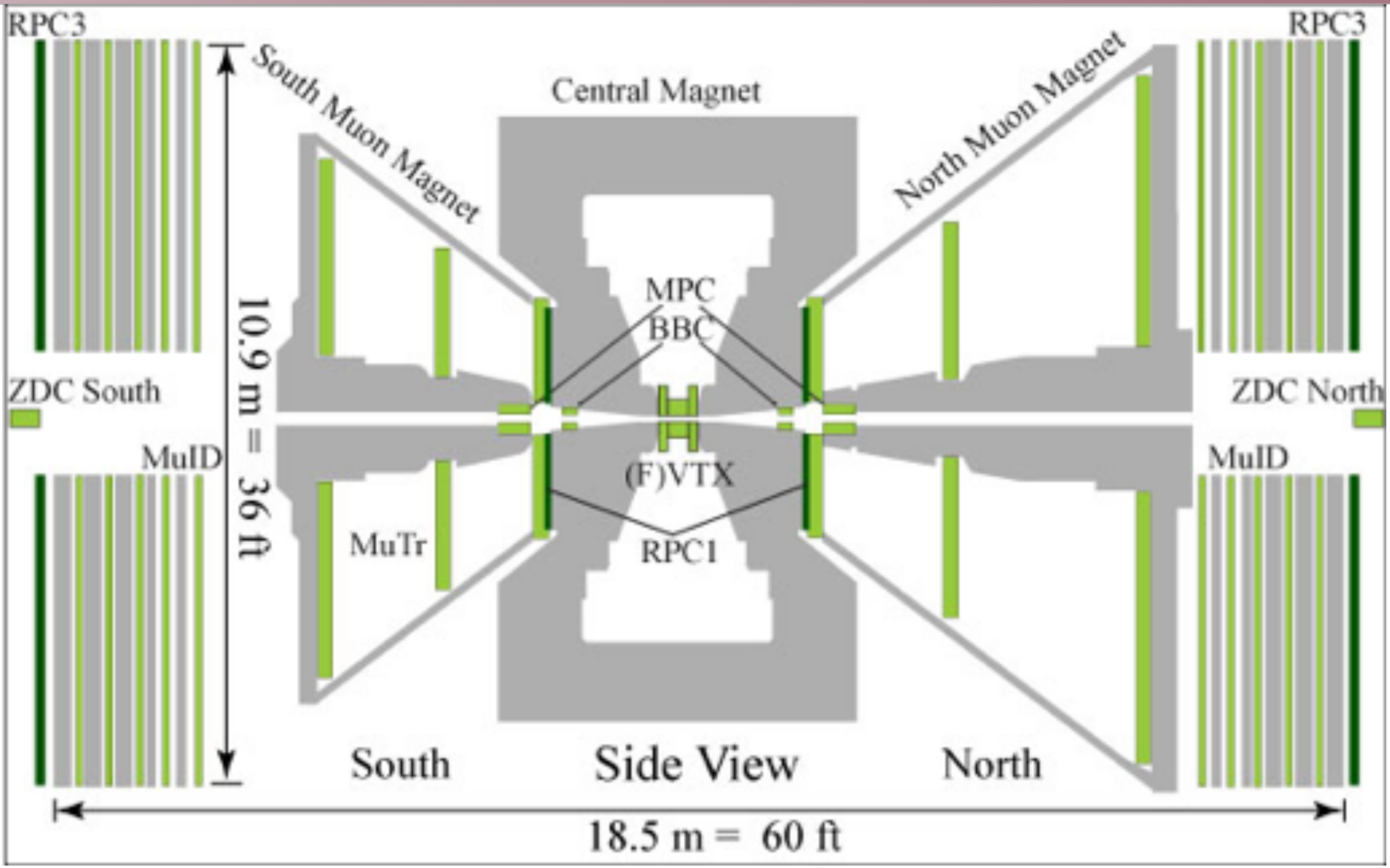
Polarized *p*+*p*(A) collision at RHIC





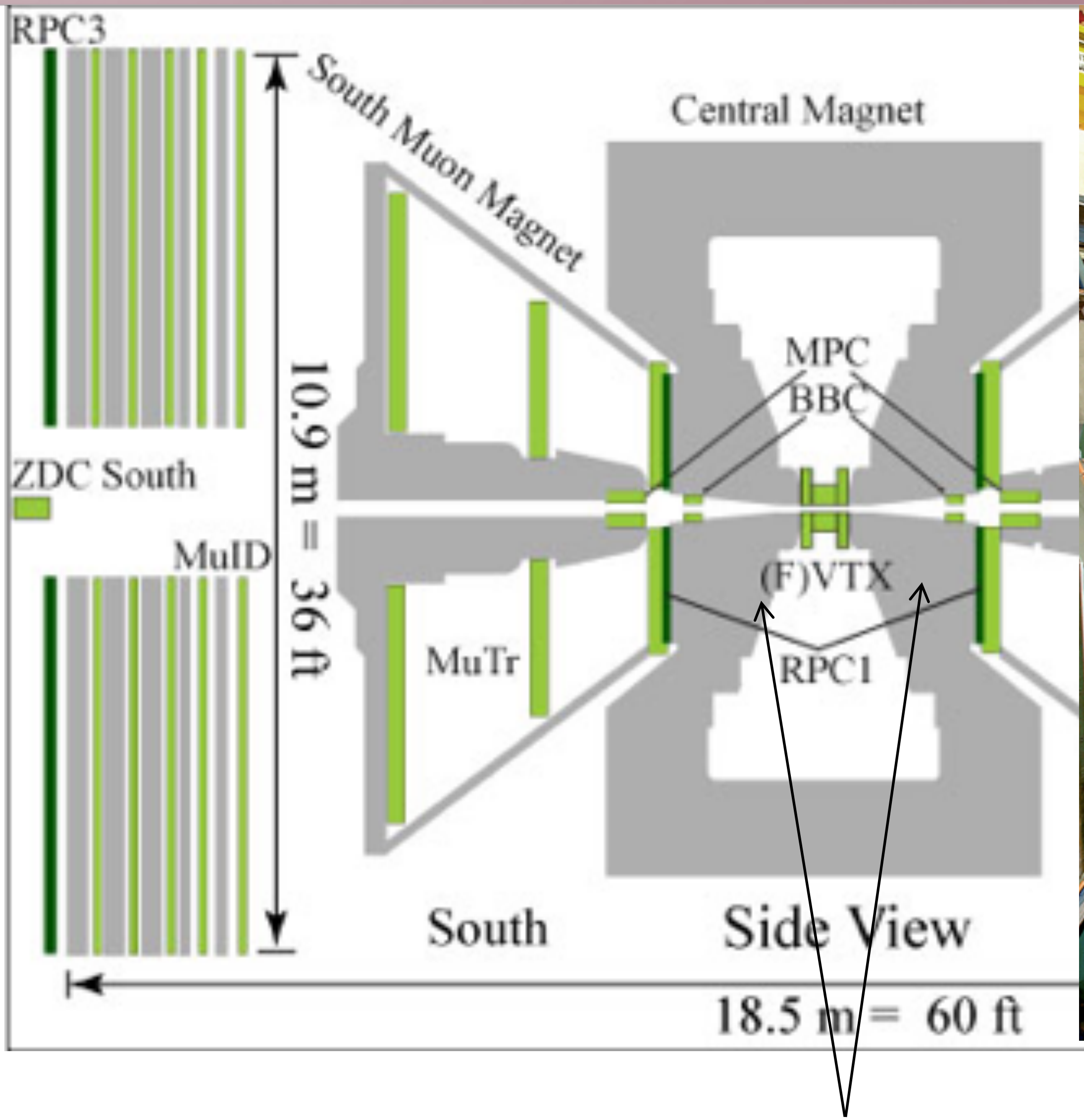


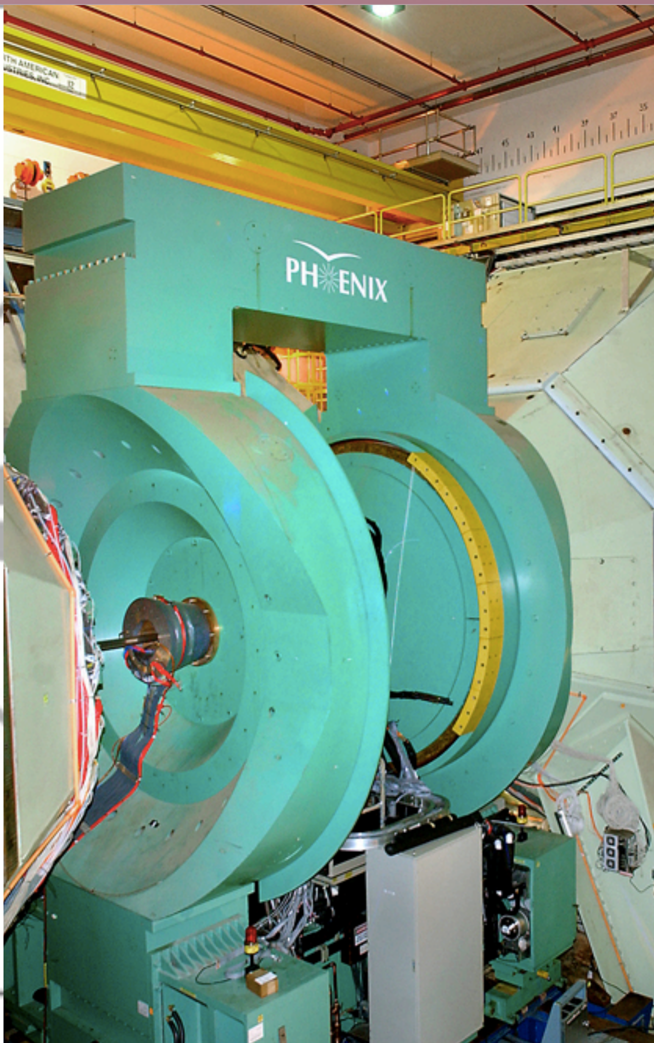
PHENIX Muon Spectrometer



Two Muon spectrometers called South arm (-2.2<η<-1.2) and North arm (1.2<η<2.4)

PHENIX Muon Spectrometer

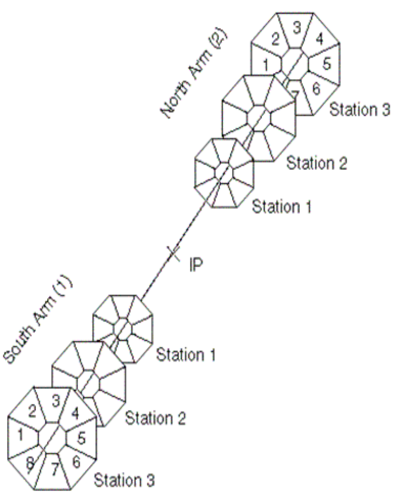


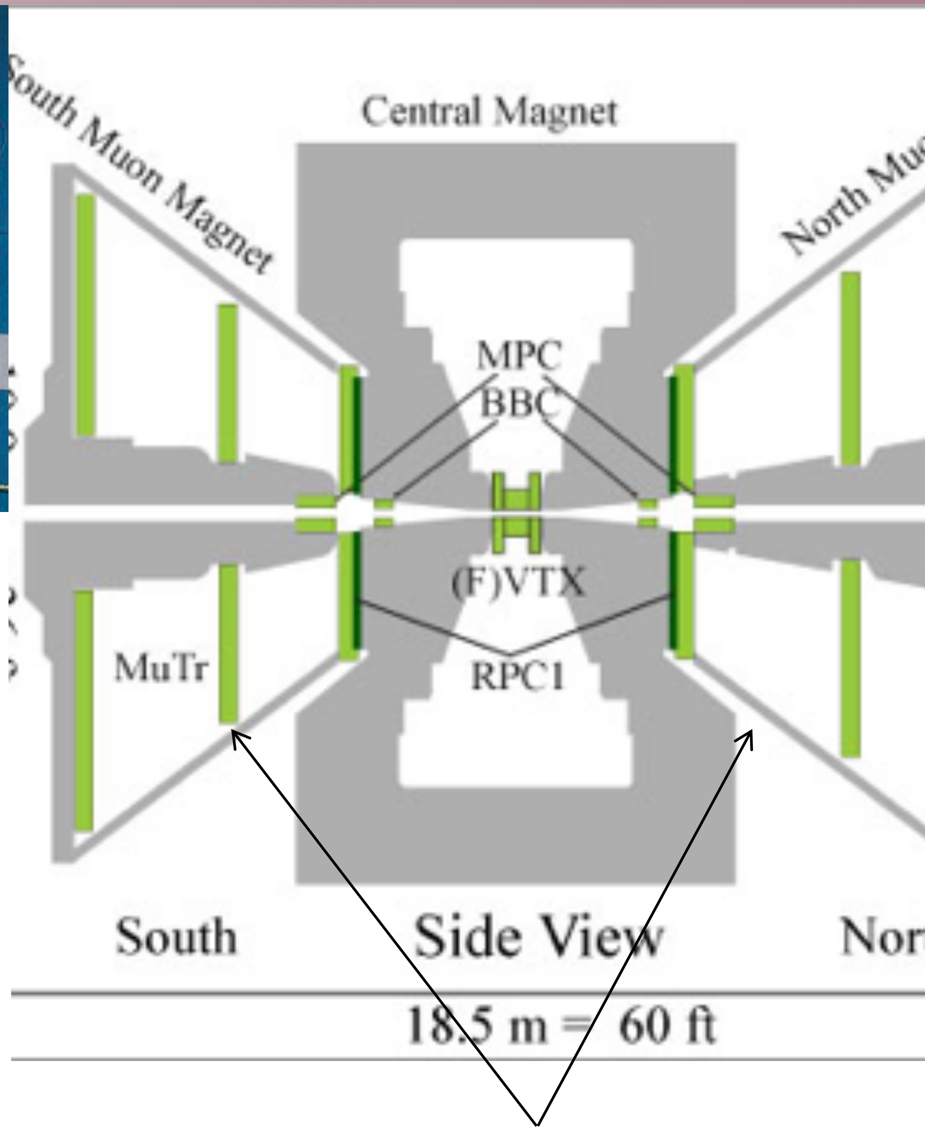


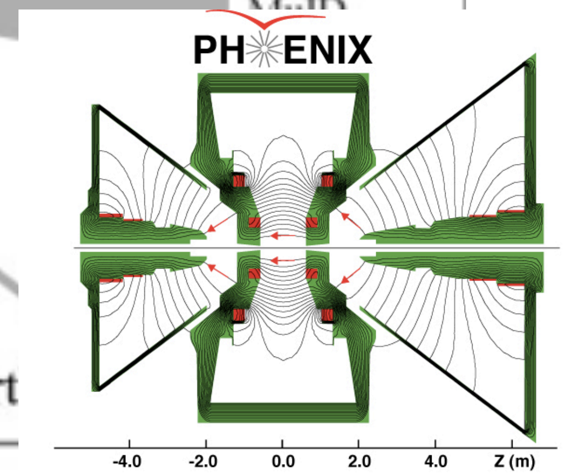
Absorber (Hadron rejection)
19 cm copper, 60 cm iron, and additional stainless steel (36.2 cm) installed before Run-11

PHENIX Muon Spectrometer

Muon Tracking Nomenclature



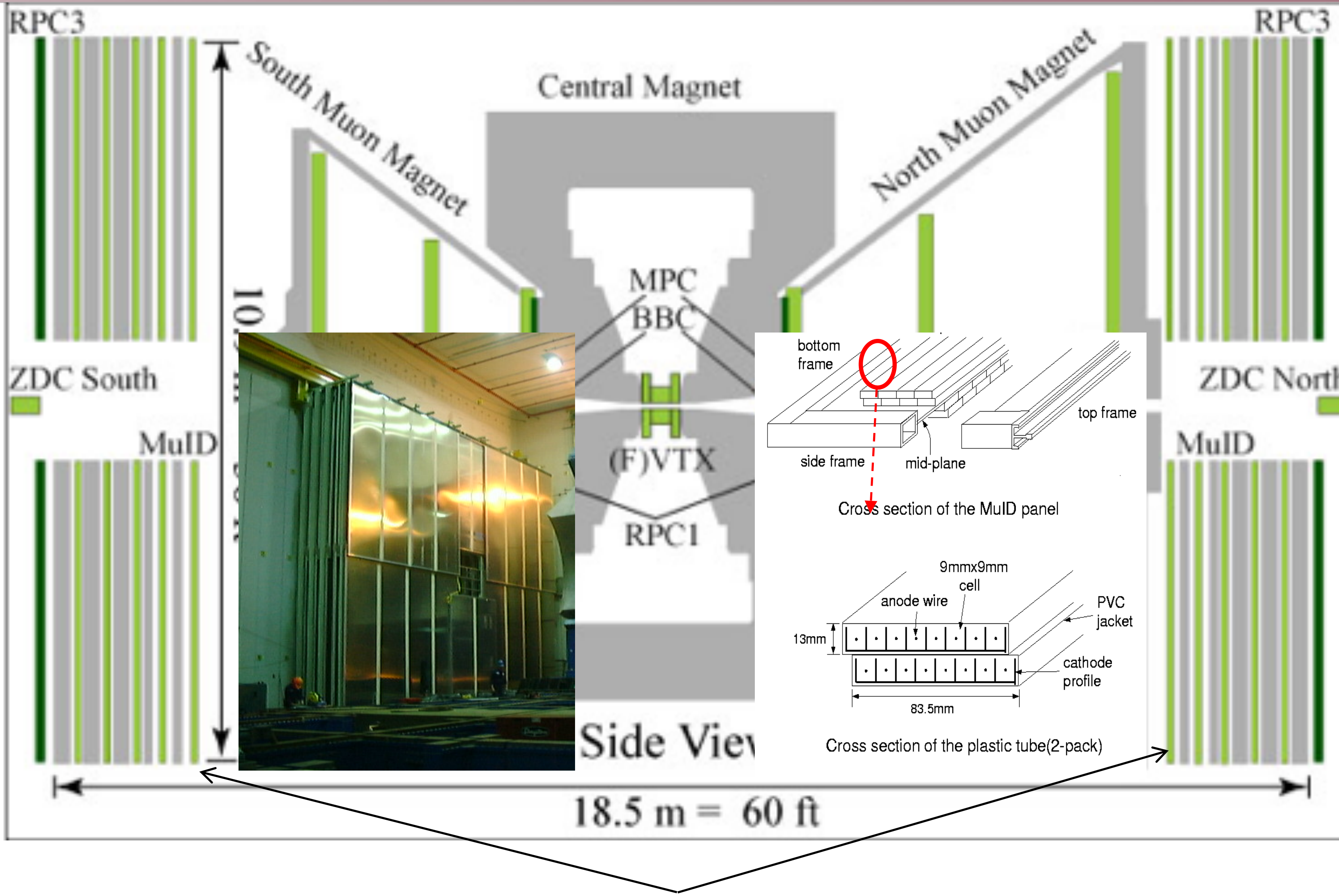




Magnetic field lines for the two Central Magnet coils in combined (++) mode

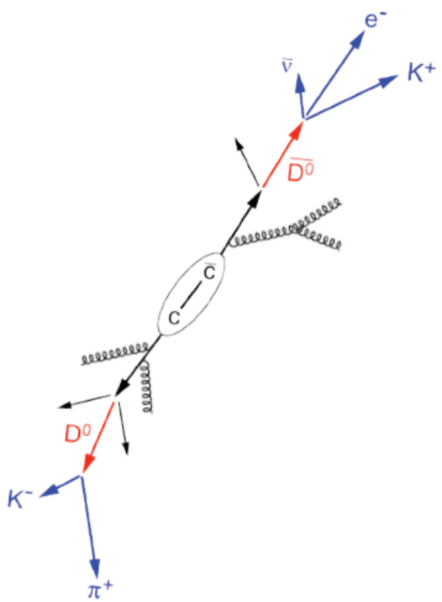
Muon Tracker (MuTr, Momentum measurement and LL1 trigger)
3 Stations (3/3/2 gaps in each station, 2 planes per gap)

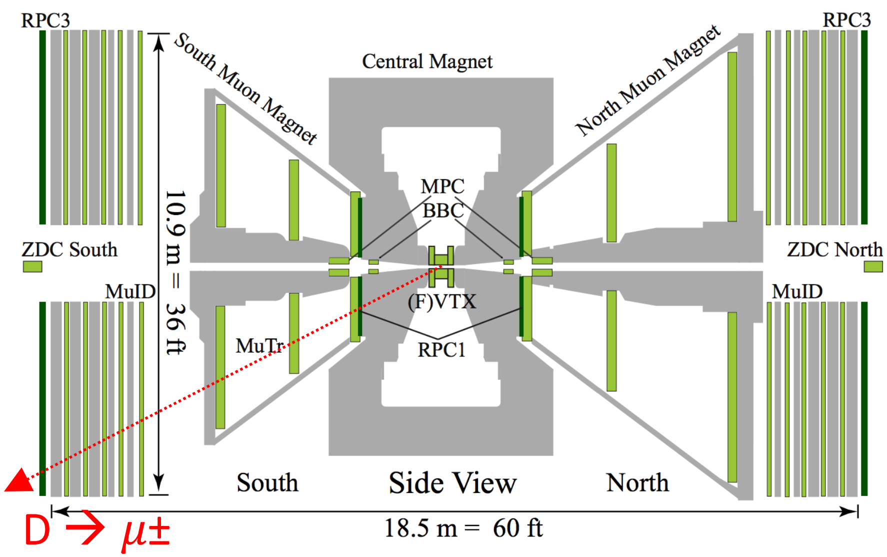
PHENIX Muon Spectrometer



Muon Identifier (MuID, Muon/hadron separation and LL1 trigger)
5 Gaps (Each gap consists of X/Y/absorber planes)

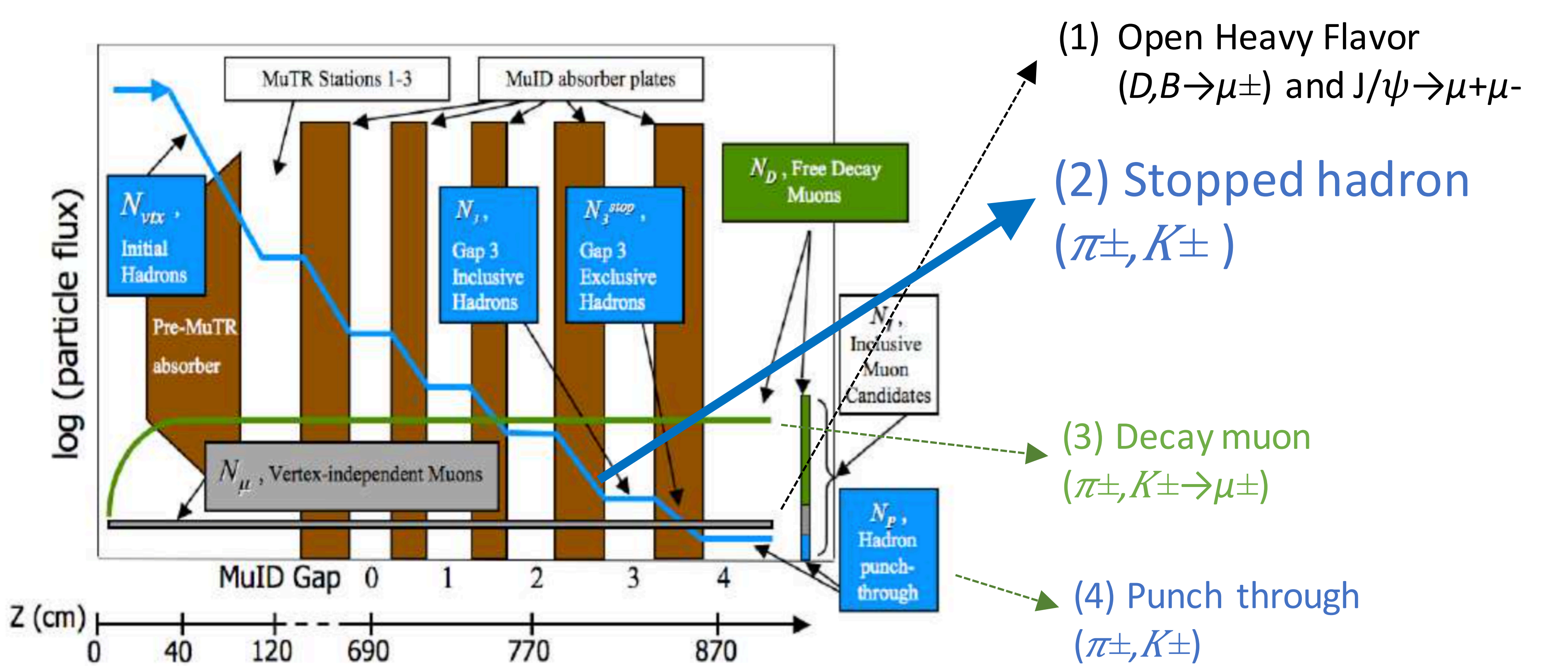
Open Heavy Flavor A_N





- 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

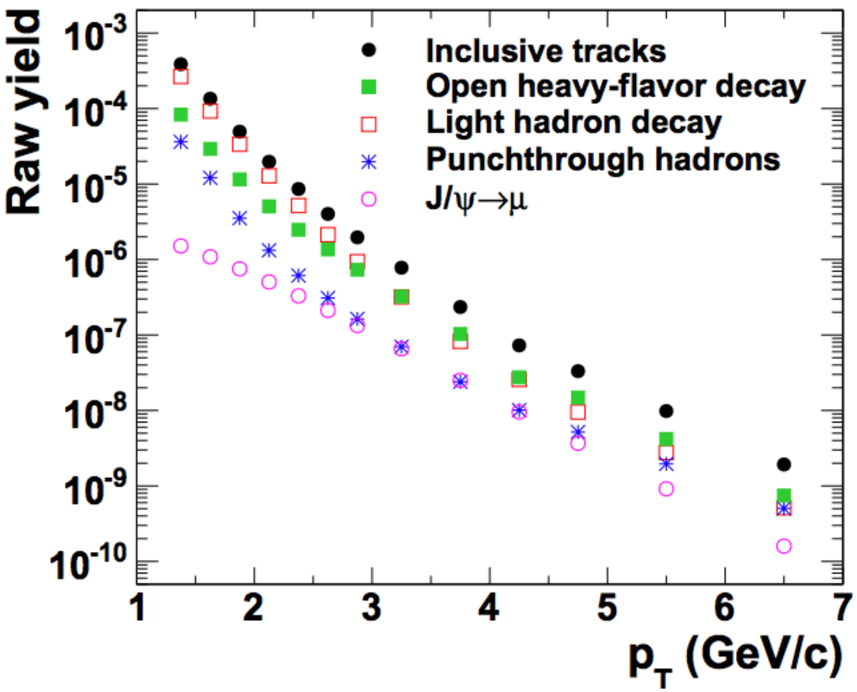
Open Heavy Flavor in Muon Arm



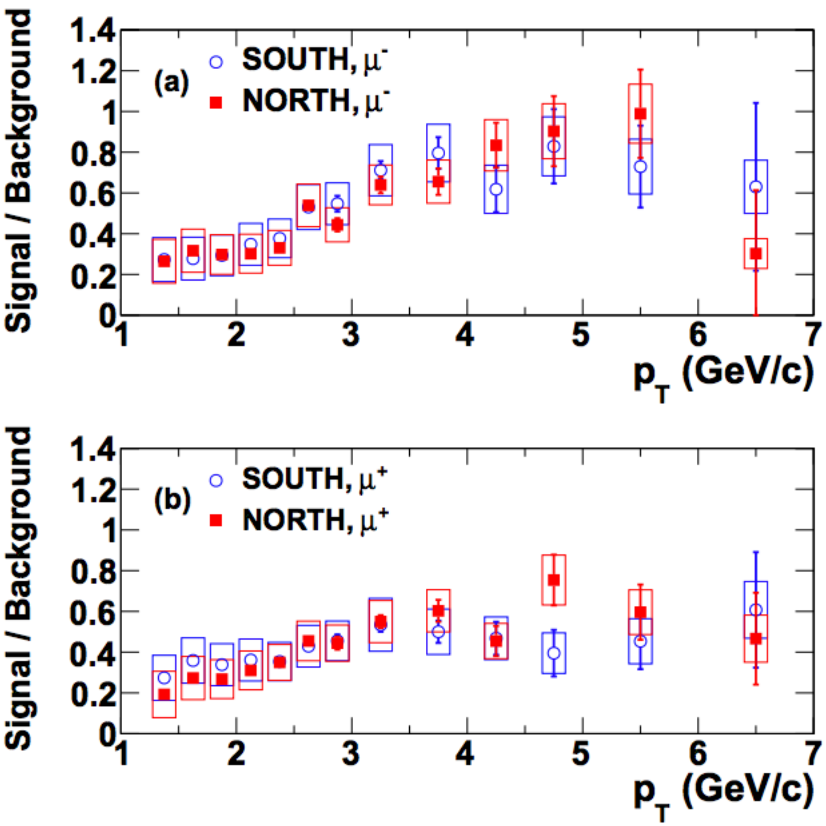
- Charged hadrons stop at MUID gap2,3
- Muons reach to the last gap of MUID(gap4)
- $\pi\pm, K\pm$ are major background in open heavy flavor study

Open Heavy Flavor in Muon Arm

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



Raw Yield for each contribution

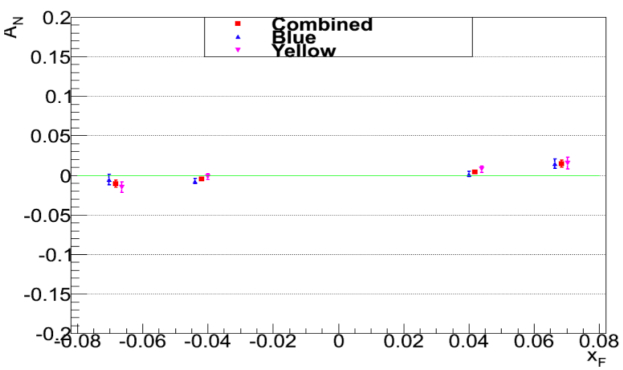


Signal/Background

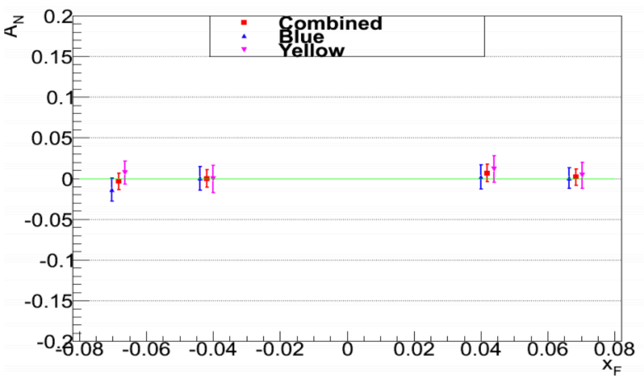
Open Heavy Flavor A_N – Analysis Detail

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

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

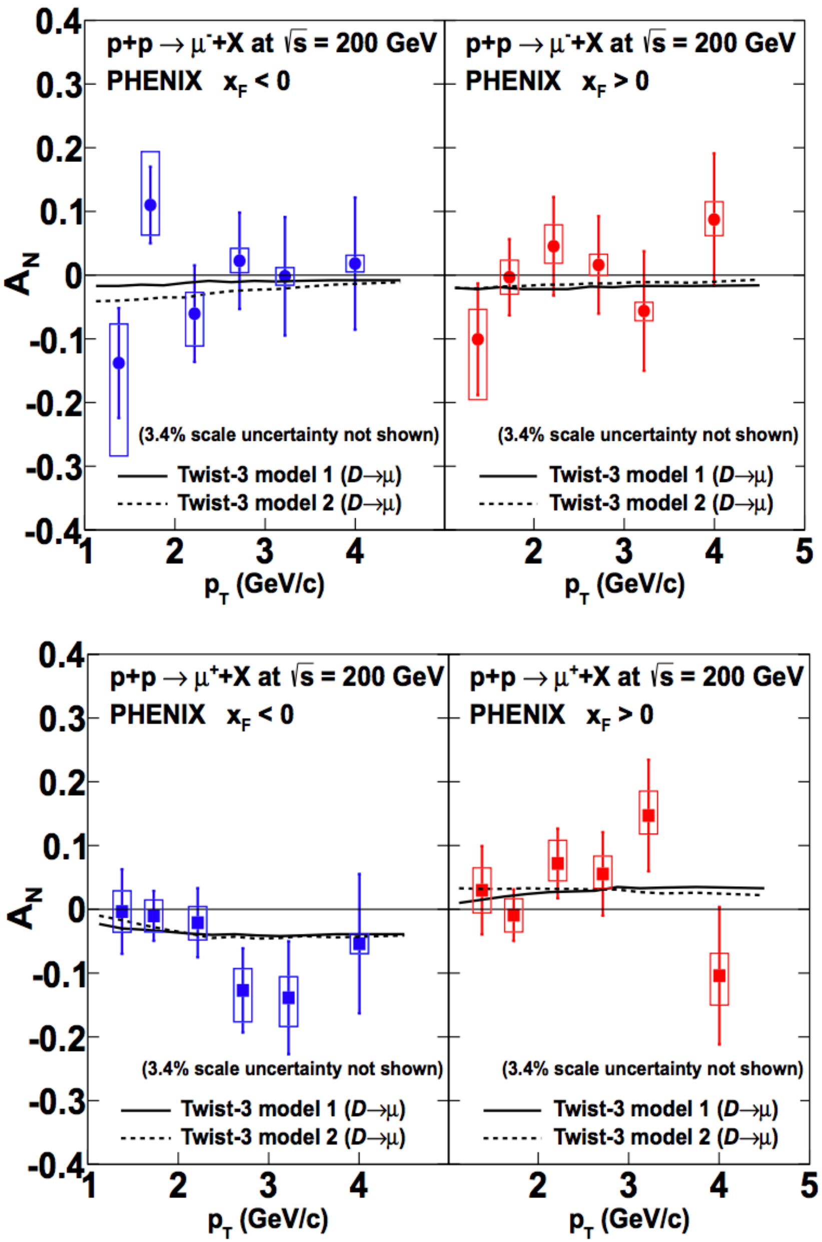


inclusive (MUID Gap4)



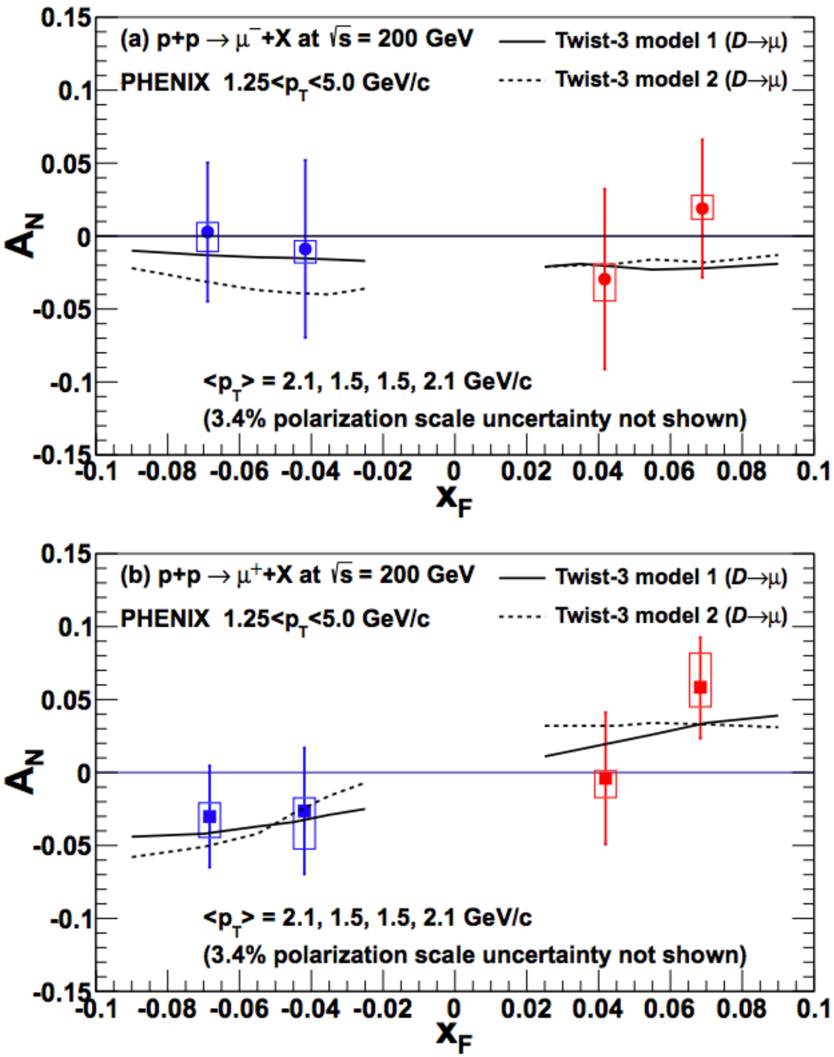
Background (MUID Gap3)

Open Heavy Flavor A_N - Results



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

Open Heavy Flavor A_N - Results

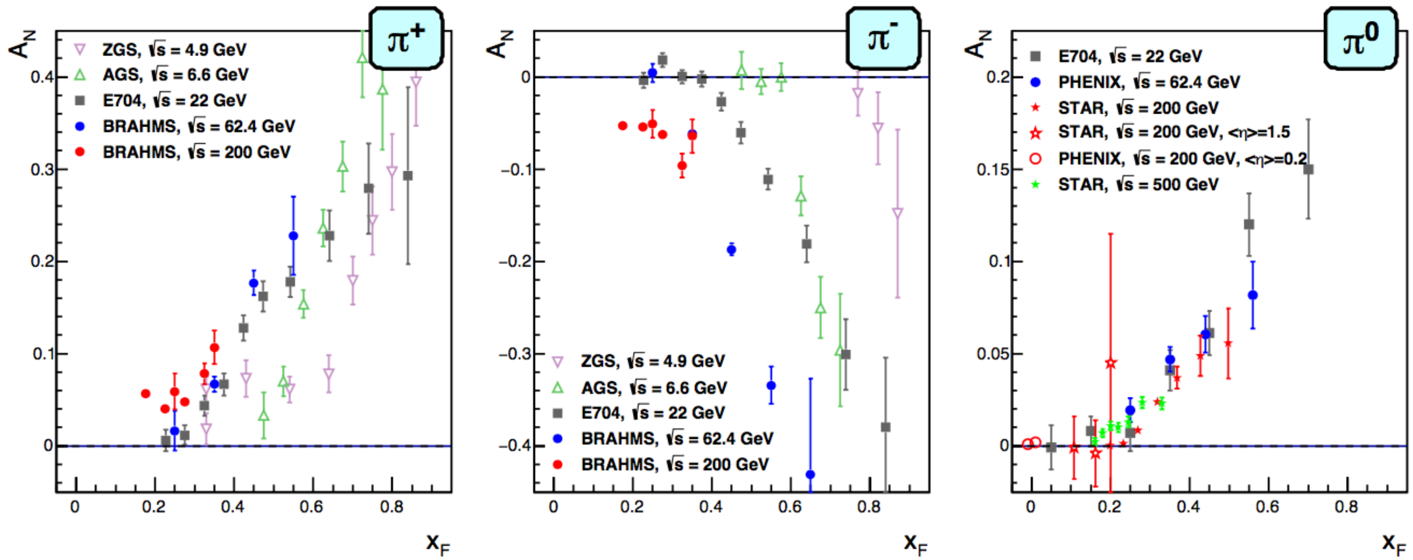


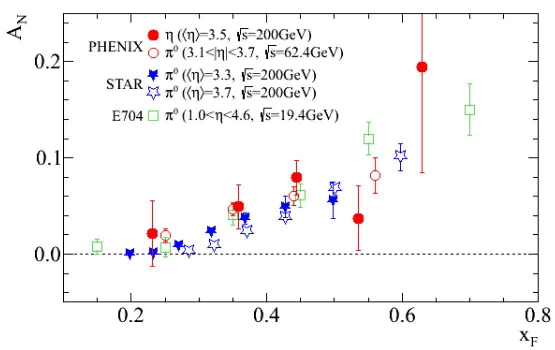
- Results for x_F bins
- dashed, dotted lines : two models in twist-3 tri-gluon correlation function
- consistent with theory within uncertainty
- Phys. Rev. D 95, 112001 (2017)

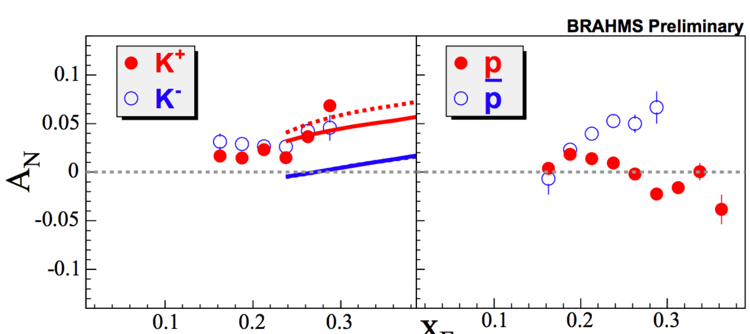
Open Heavy Flavor A_N - Results

- 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
  - Future projects EIC, fixed target at LHC

Charged Hadron A_N – RHIC Data

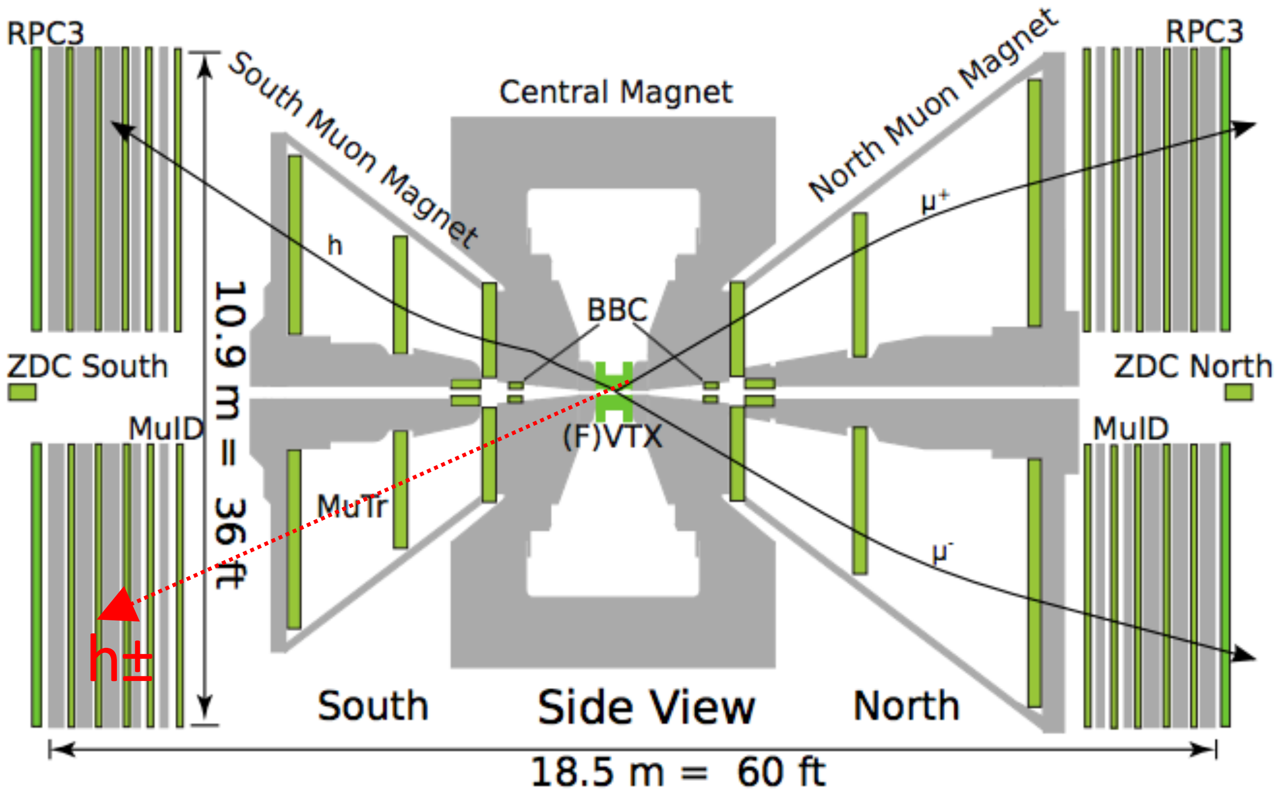






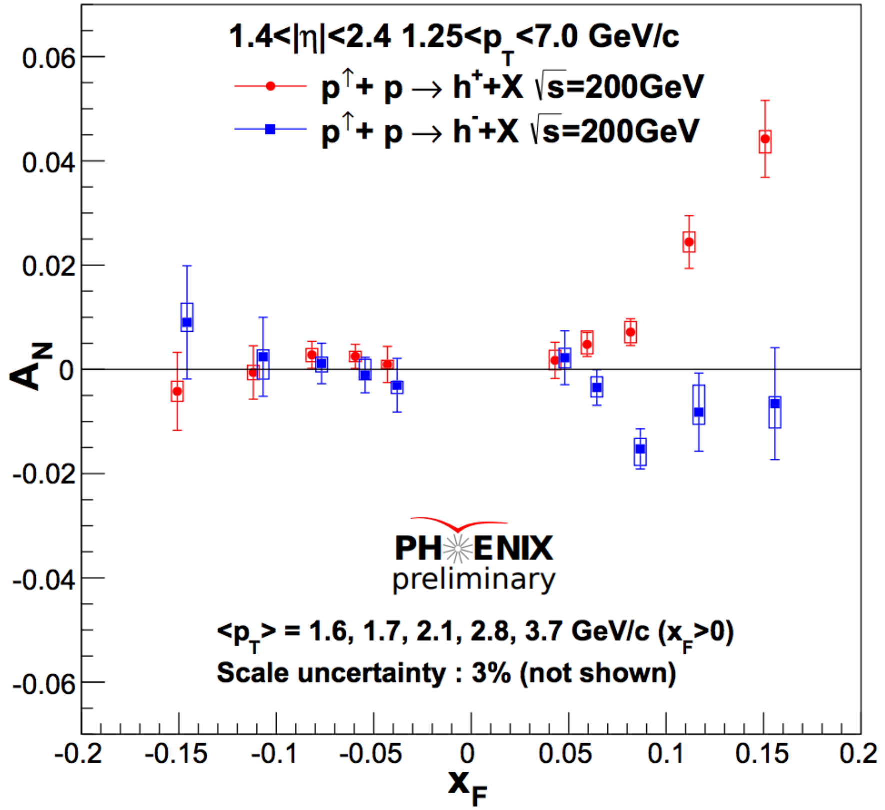
- Opposite sign in π+, π-
- Same sign in K+,K- at BRAHMS (200GeV Preliminary)
- positive A_N in π^0

Charged Hadron in Muon Arm



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

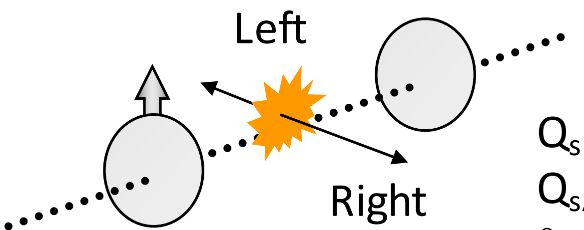
Charged Hadron A_N in p+p



- 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
- A_N increases as x_F increases for positively charged hadron at x_F>0

polarized p+A collisions at RHIC

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



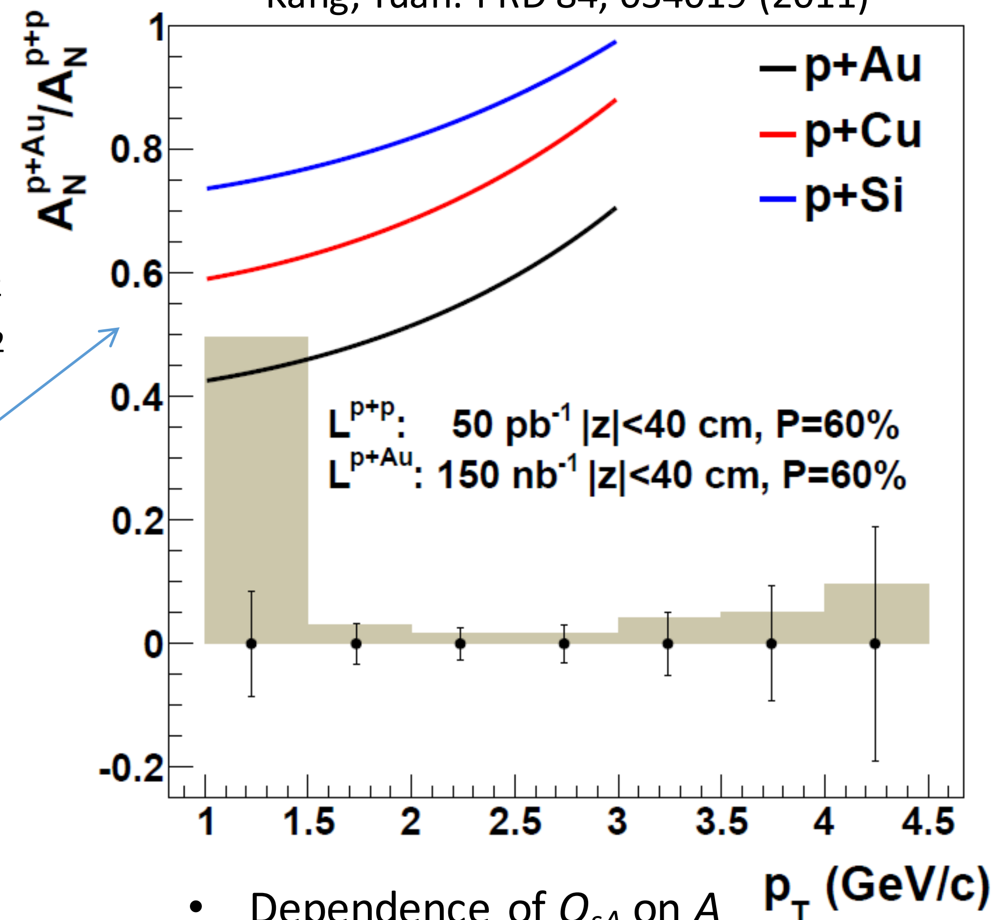
$Q_{sp}^2 = (1.0\ \text{GeV})^2$
$Q_{sA}^2 = (2.5\ \text{GeV})^2$
$\delta = 0.16$ GeV

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

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

A unique capability of RHIC

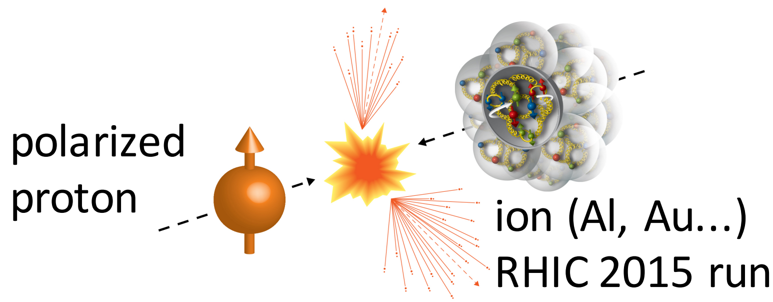
Y. Kovchegov & M.D. Sievert: PRD 86, 034028 (2012)
Kang, Yuan: PRD 84, 034019 (2011)



- Dependence of Q_{sA} on A
- Combined with other measurements this can estimate Q_{sp}

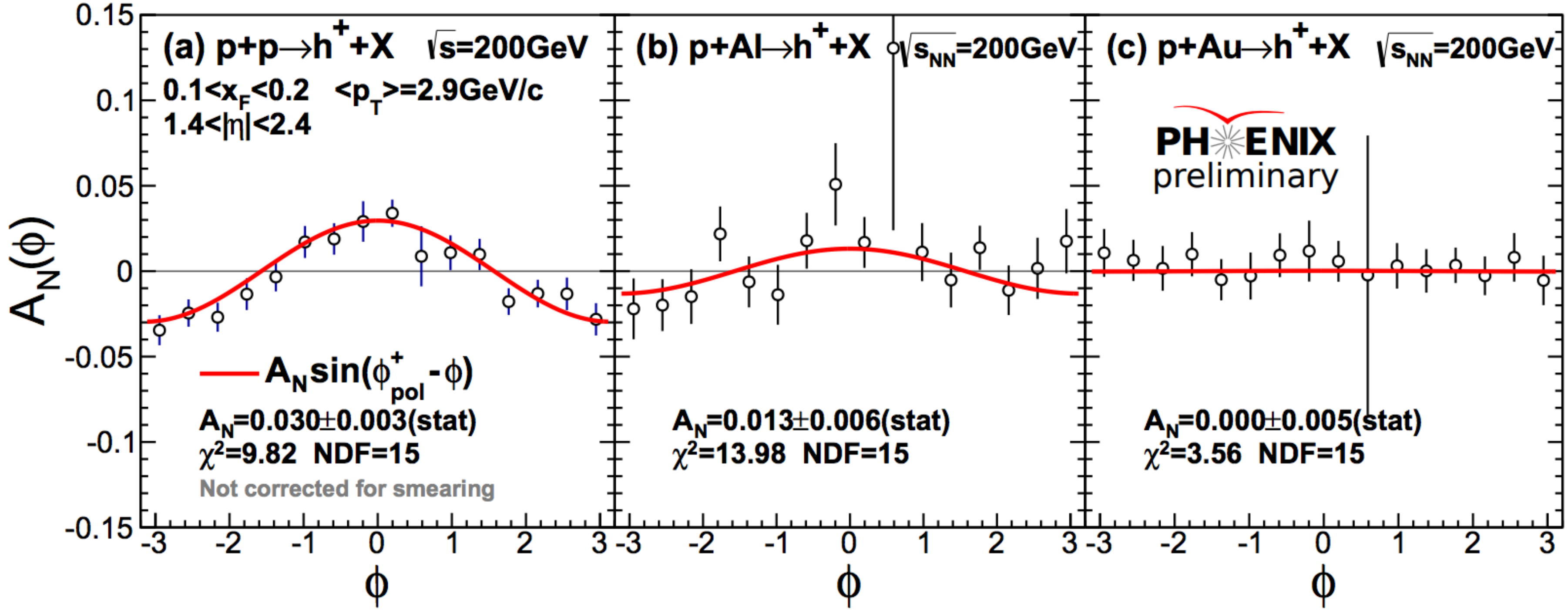
Inclusive hadron A_N in polarized p+A

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



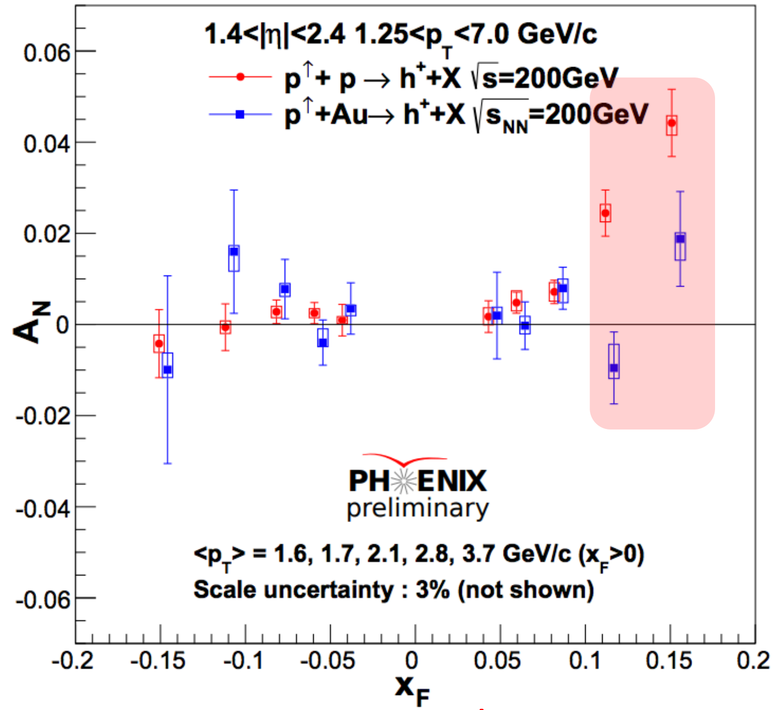
- Inclusive hadron A_N at forward rapidity in polarized p+A helps us to understand
  - Underlying mechanisms of A_N ➔ different mechanism have different A-dependence
    - Hybrid approach (Twist-3 in polarized p, CGC in A)
      - Yoshitaka Hattaa,et al, Phys. Rev. D 94, 054013 (2016), Phys. Rev. D 95, 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

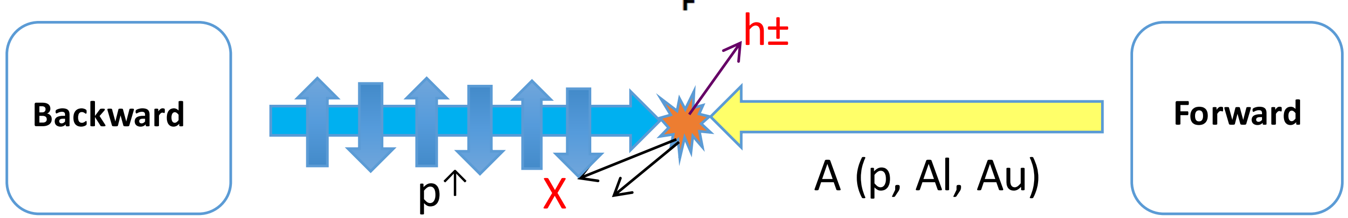
Positively charged hadron A_N in p+p, p+A



- 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

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

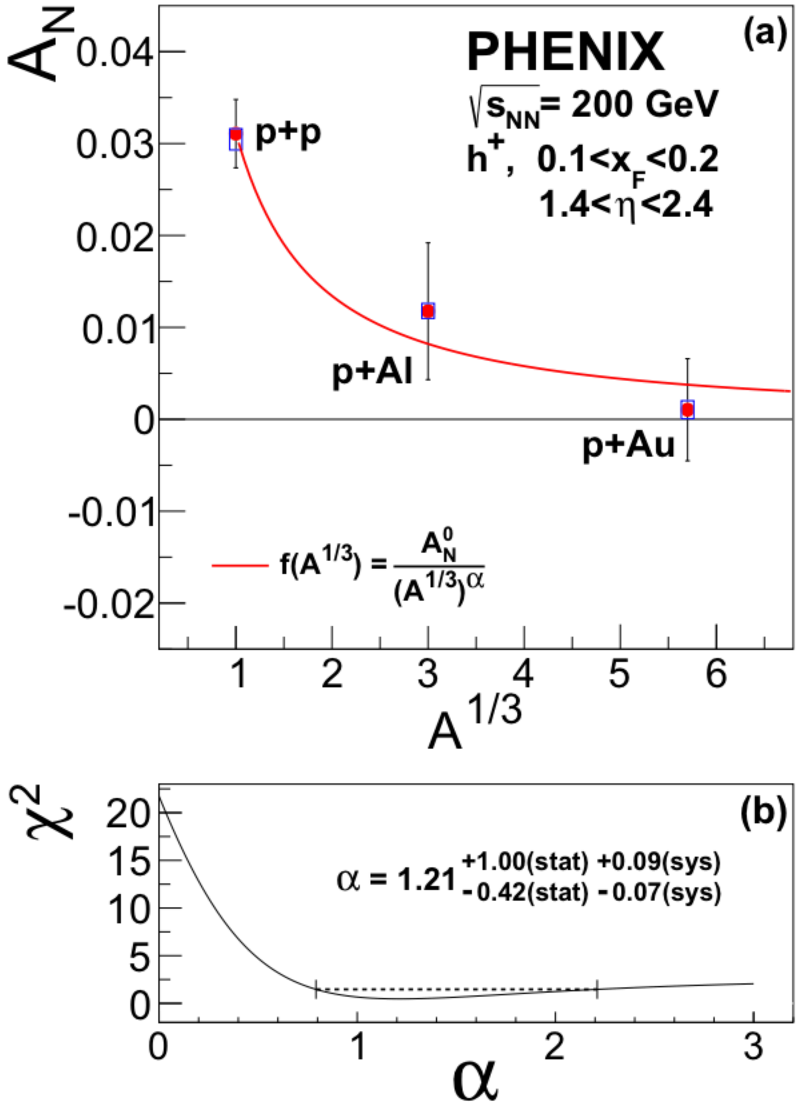




- A_N of (survived) $\pi\pm, K\pm$ mixture.
- p+Au→h(+)+X shows clear suppression of A_N at x_F>0.1

Nuclear dependence of A_N

arXiv:1903.07422

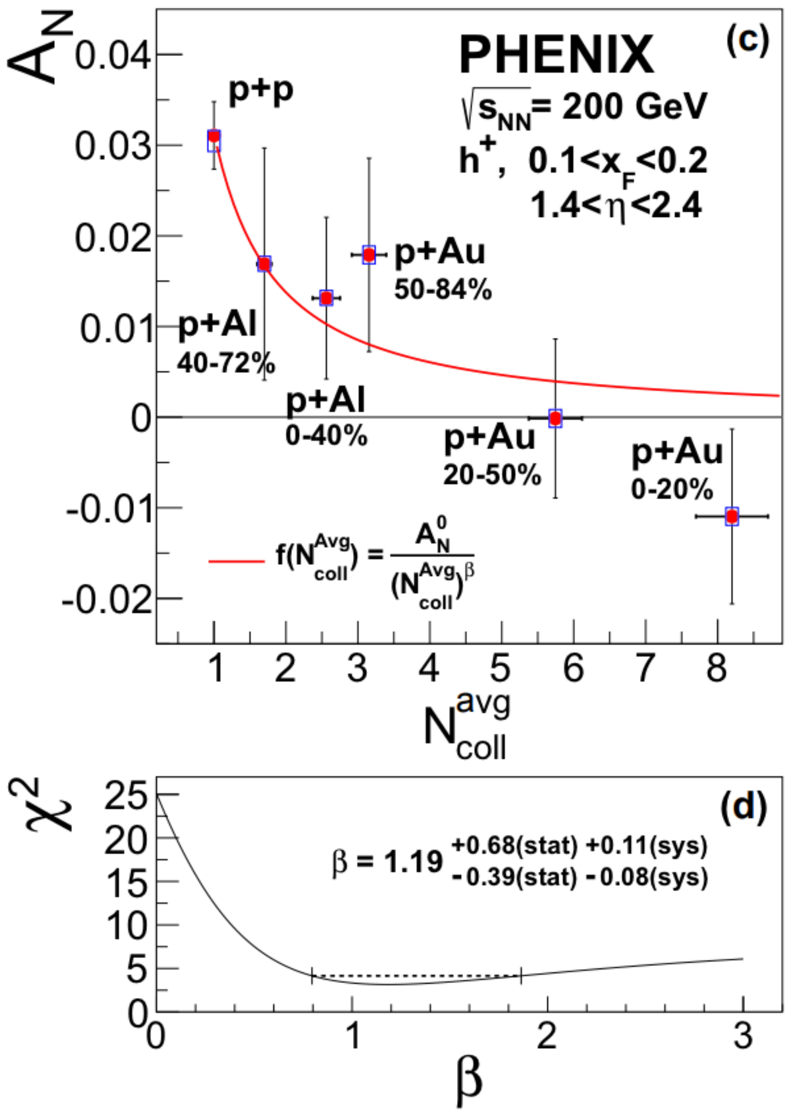


- Nuclear dependence of A_N for positively charged hadron at $0.1<x_F<0.2$
  - Fit function is to quantify the A-dependence, x-axis is $A^{(1/3)}$
  - Bottom panel is χ^2 for wide range of power parameter α
  - Favors A-dependence
  - α =1 corresponds to $A^{(1/3)}$
  - α =0 corresponds to $A^{(0)}$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

- Submitted to PRL, arXiv:1903.07422

Nuclear dependence of A_N

arXiv:1903.07422



- 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 to the path length in a nucleus in p+A collisions
  - Bottom panel is χ^2 for wide range of power parameter β
  - Favors N_{coll}-dependence
- Submitted to PRL, arXiv:1903.07422

Nuclear dependence of A_N

- First result of Nuclear dependence of A_N in inclusive charged hadron production
- Shows clear A-dependence and N_{coll} dependence
- ➔ A-dependent term could be the dominant source for A_N in inclusive hadron production

Nuclear dependence of A_N

- Hybrid approach in recent theory papers
  - Twist-3 framework for the polarized-proton side and the CGC framework for the target-nucleus side
  - A-dependence of the TSSA arises from the saturation scale Q_s, where $Q^2_{sA} \propto A^{1/3}$ 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 $A^{1/3}$-dependent for $Q_s \gg p_T \gg \Lambda_{QCD}$
- Unexpected A-dependence in high p_T
  - Recent paper Phys.Rev. D99 (2019), 094012 (arXiv:1811.10589)

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

  - Making theorists confused. Need more experiment.

Summary

- Studying spin in physics has led to a lot of surprises
- Transverse single-spin asymmetries (TSSAs) of 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
  - First measurement of open heavy flavor A_N at RHIC.
  - Sensitive to the tri-gluon correlation function in twist-3 collinear factorization framework
- (2) Charged hadron A_N in p+p, p+A
  - unique opportunities to study low-x gluon and gluon saturation signatures
  - The h(+) result shows striking A-dependence and N_{coll} dependence
  - A-dependent term could be the dominant source of A_N in p+p
- This topic has been studied in many experiments and will be studied in future experiments,
  - Current : PHENIX, STAR, JLAB, COMPASS, Fermilab …
  - STAR upgrade, EIC (RHIC, JLAB), LHC target experiment if possible …

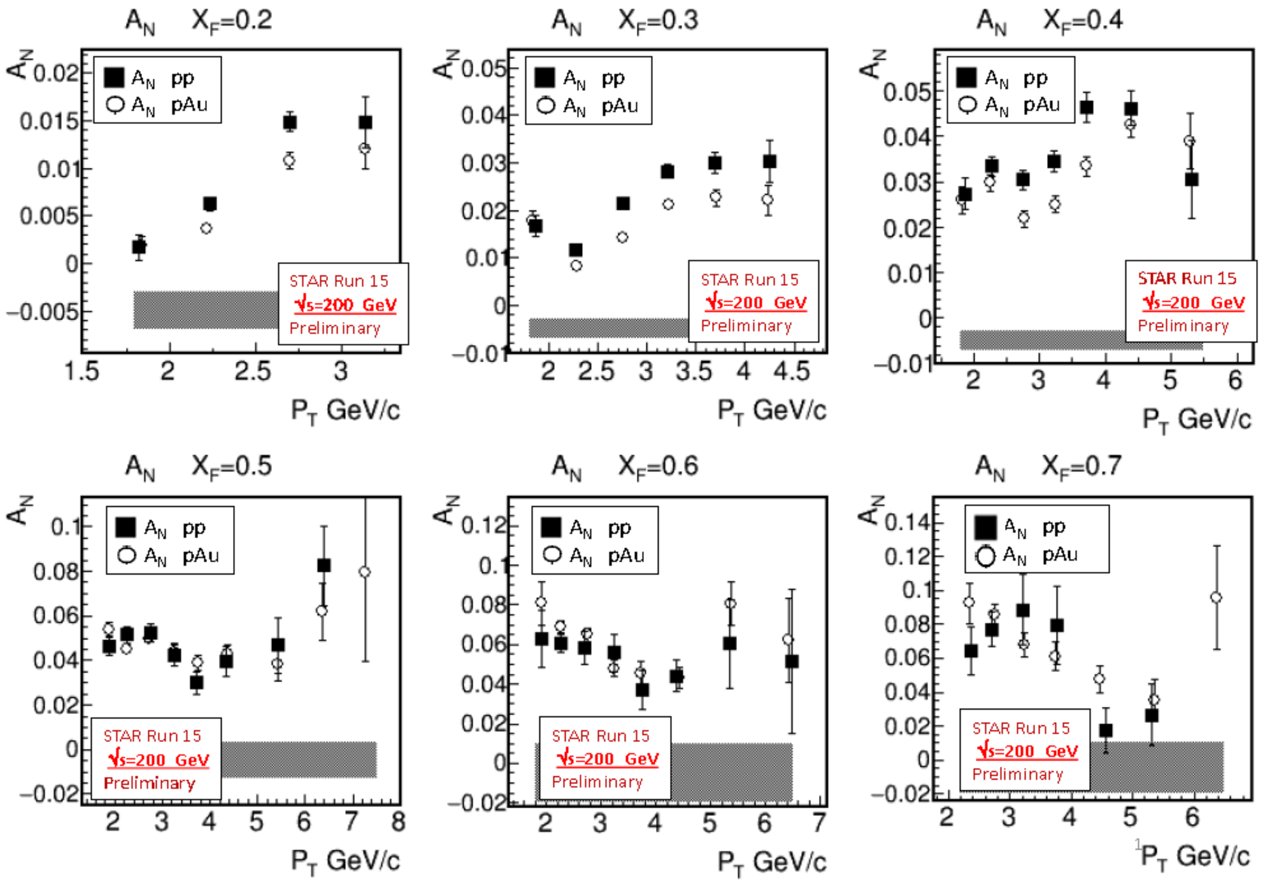
THANK YOU

backup slides

Mechanisms for A_N

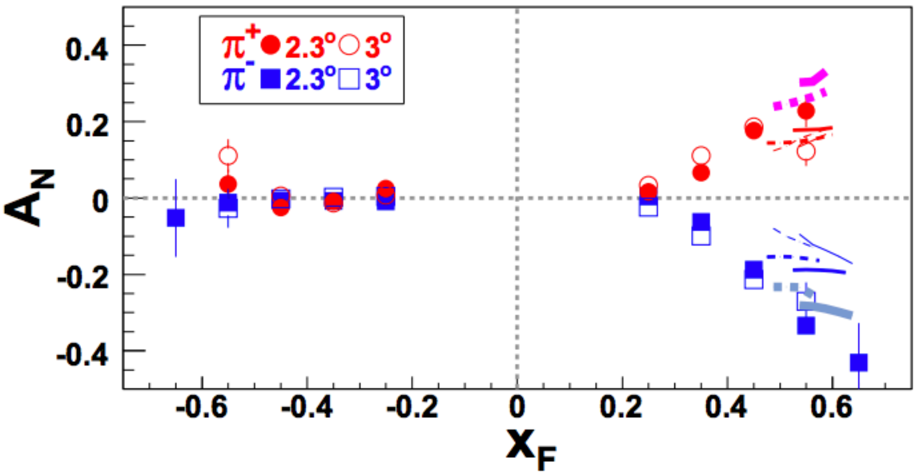
	Transverse-momentum-dependent (TMD) Factorization	Collinear twist-3 Factorization
Applicable	works at $Q \gg p_T \geqq \lambda_{QCD}$ needs 2 scales (Q^2 and p_T)	works at $Q, p_T \gg \lambda_{QCD}$ needs 1 scale (Q^2 or p_T)
p+p observables	*DY, W, Z, Hadron in jet*	π, γ, jet, Heavy Flavor, ...
Initial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

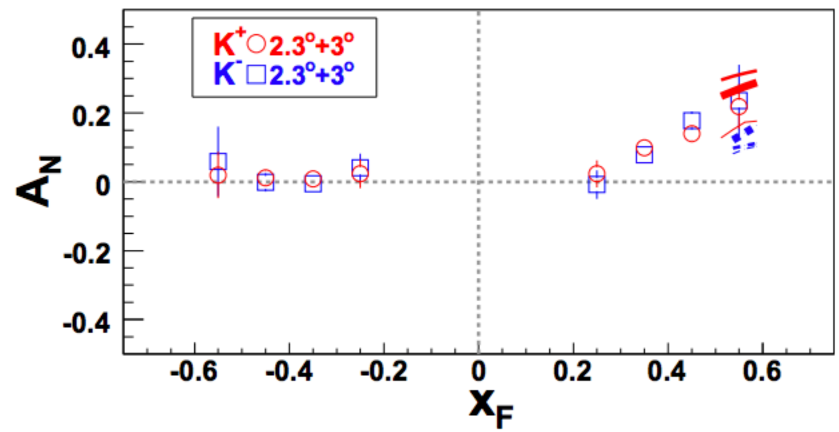
Comparison with other result



- small to no A-dependence in forward π^0 at STAR
- larger x_F

charged hadron at BRAHMS





- 62.4 GeV
- Phys. Rev. Lett. 101, 042001 (2008).

Twist-3 collinear factorization