Transverse Spin Physics at PHENIX

Ming Liu

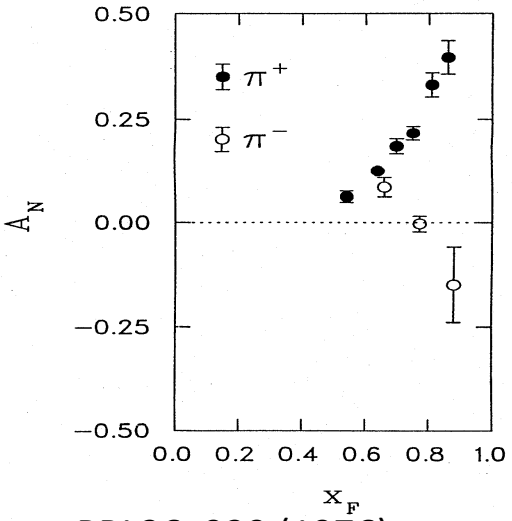
Los Alamos National Laboratory

Note: TSSA = Transverse Single Spin Asymmetry

Do We Understand the Physics?

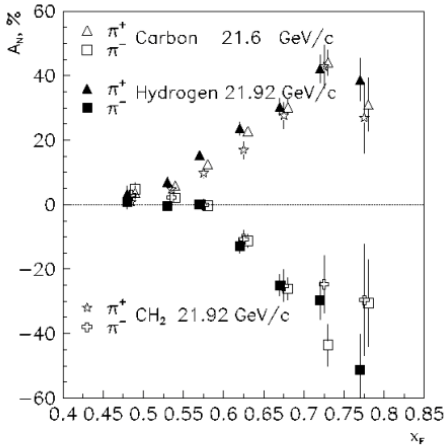
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

ZGS 12 GeV beam



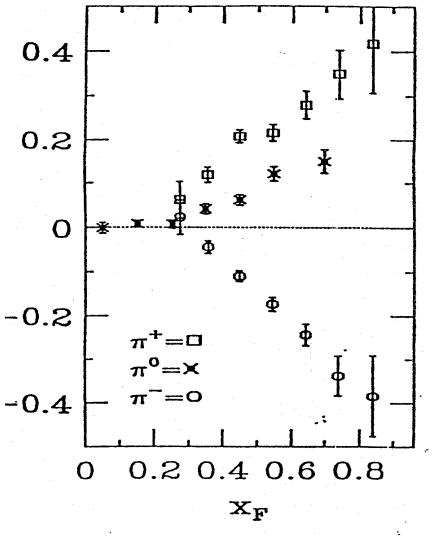
PRL36, 929 (1976)

AGS 22 GeV beam



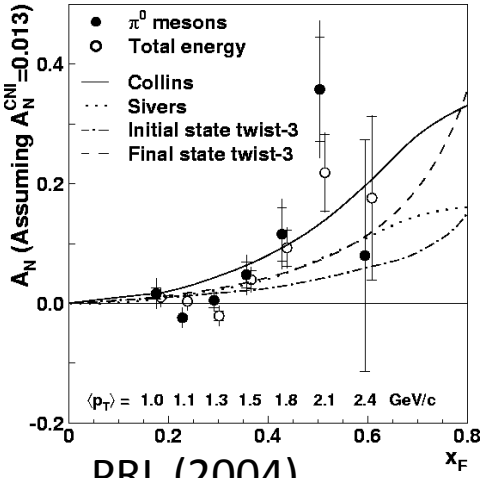
PRD65, 092008 (2002)

FNAL 200 GeV beam

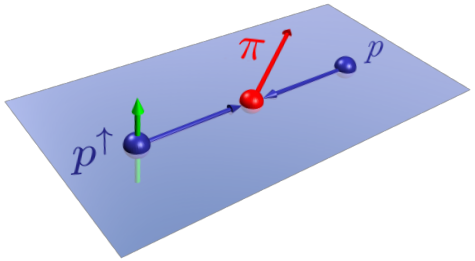


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC 200 GeV CMS



PRL (2004)



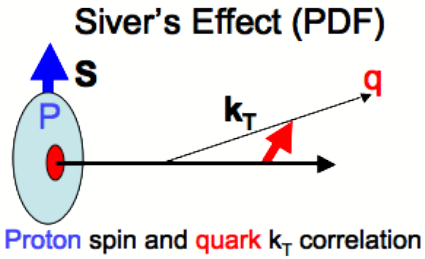
Sivers, Collins, Twist-3 ….

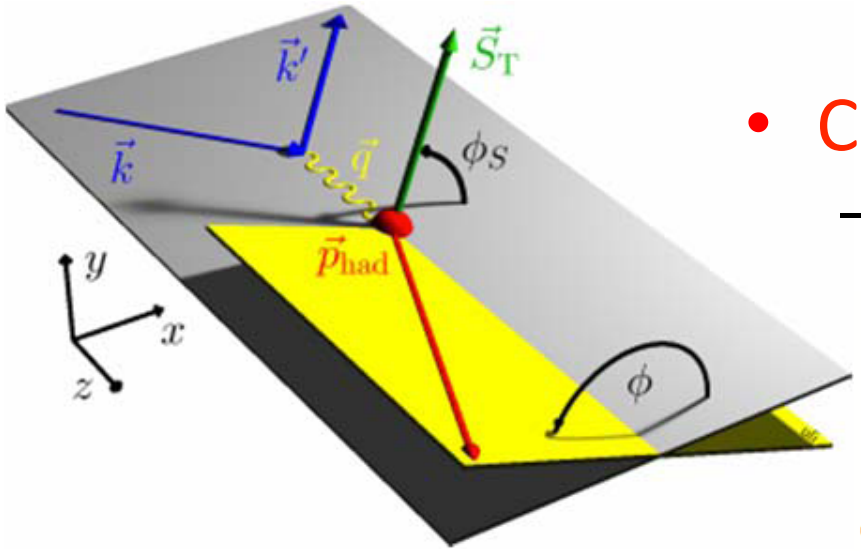
Non-Perturbative cross section → Perturbative cross section

TSSA: Sivers and Collins Mechanisms

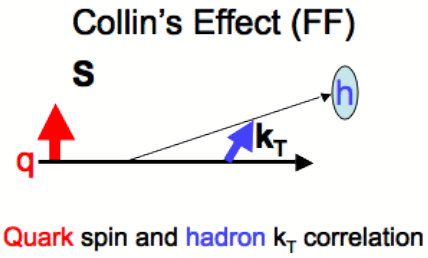
Significant Asymmetries Observed in Polarized Target SIDIS

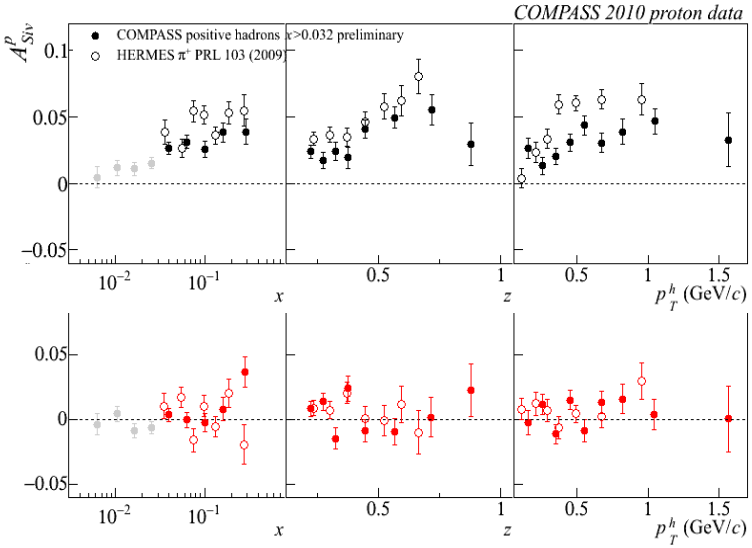
- Sivers
  - $\langle \sin(\Phi - \Phi_s) \rangle$

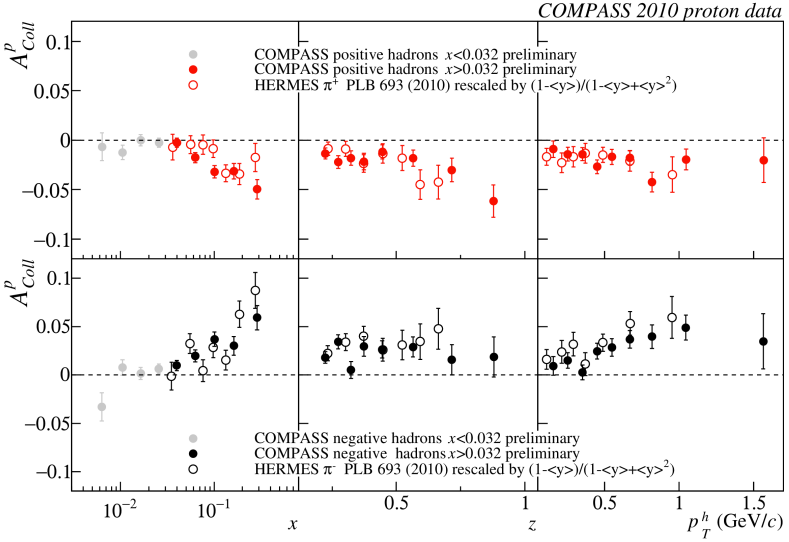




- Collins
  - $\langle \sin(\Phi + \Phi_s) \rangle$



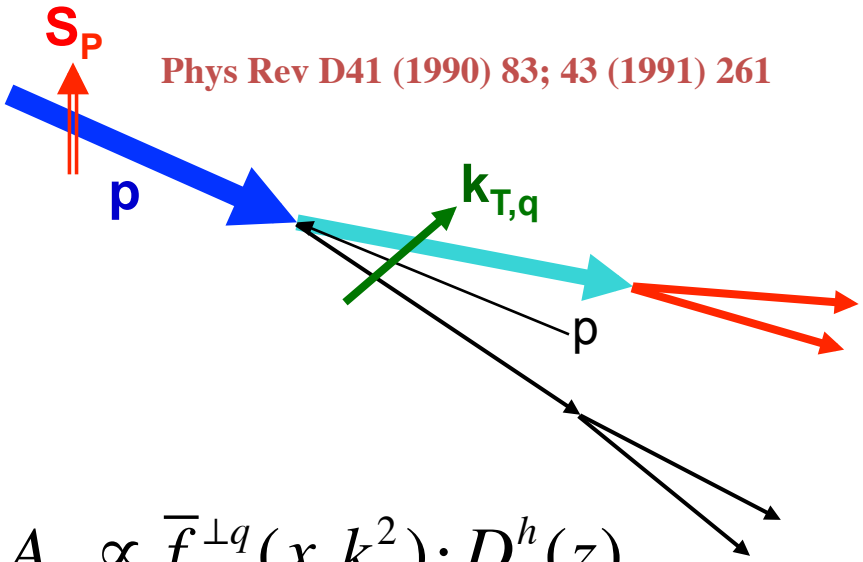




Study the Physics via Hard Scatterings at RHIC

(i) Sivers mechanism:

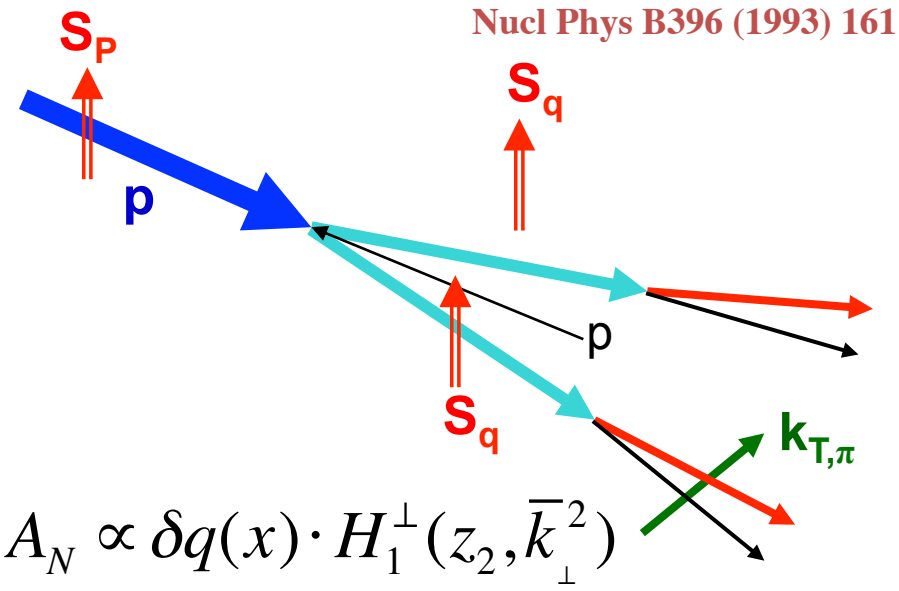
correlation between proton spin & parton k_T



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

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

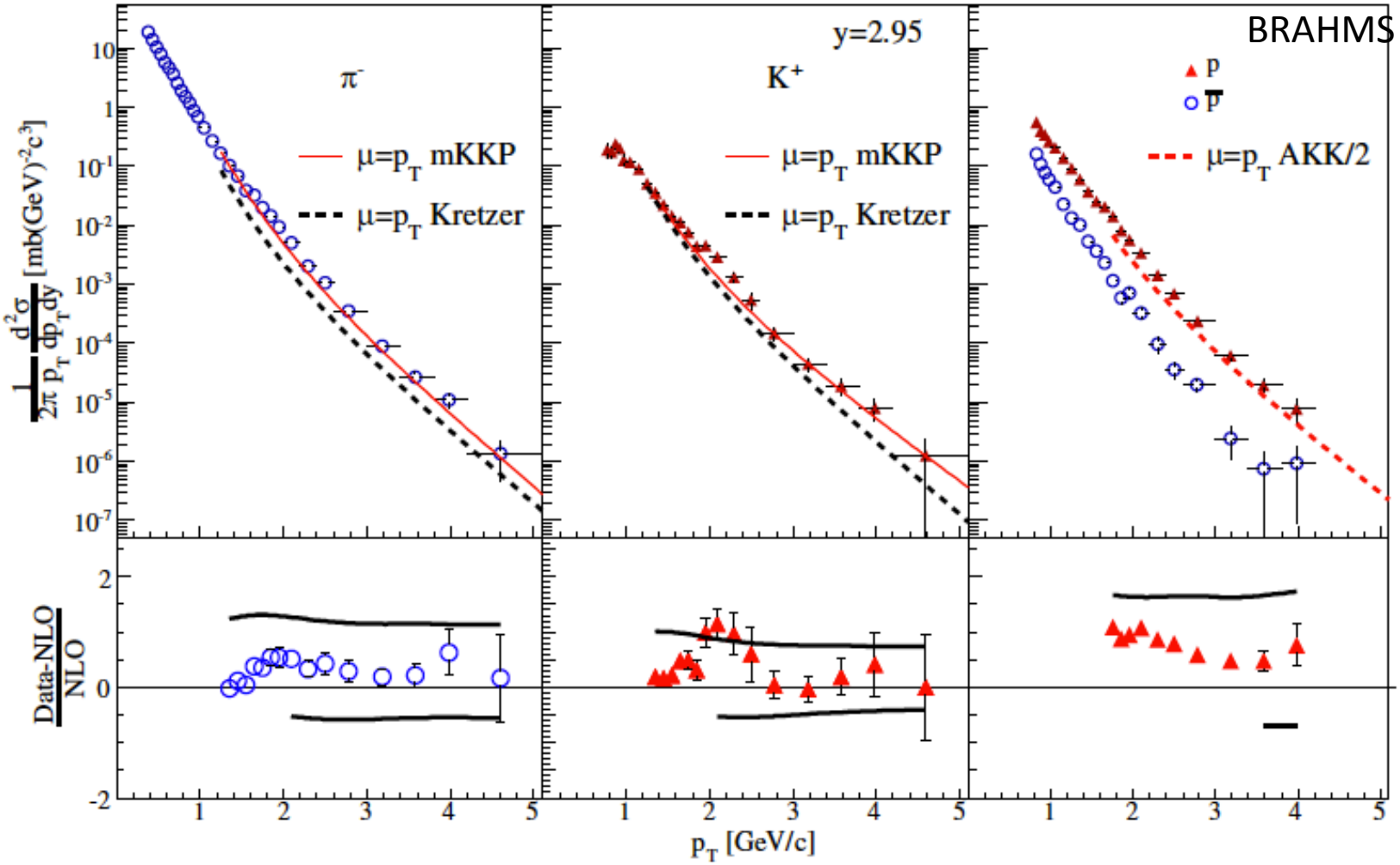


$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\overline{k}_\perp^2)$$

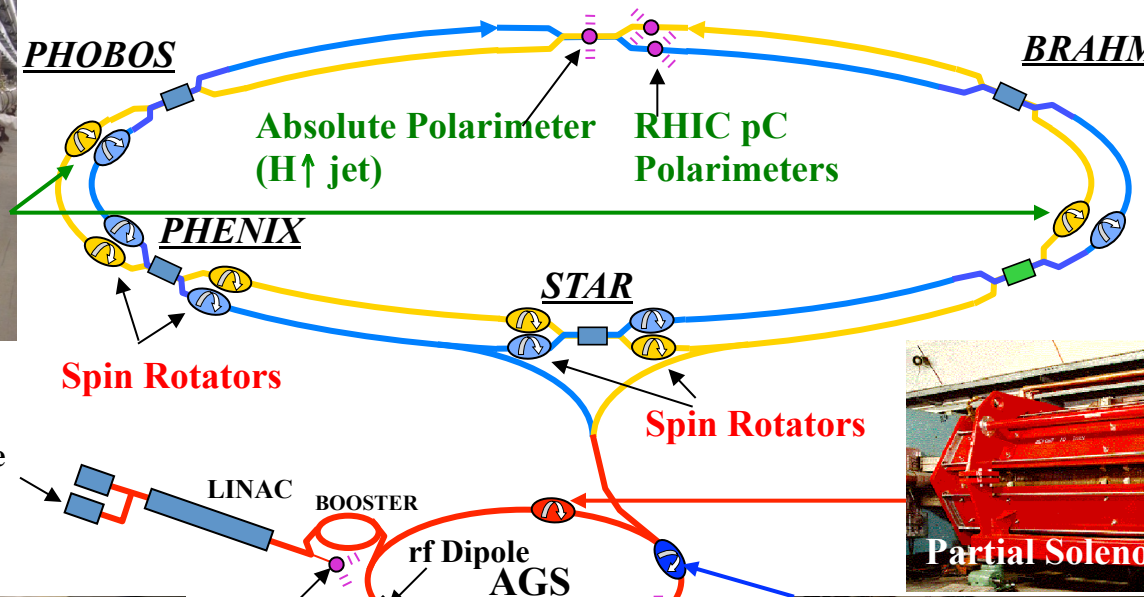
Collinear Twist-3: quark-gluon/gluon-gluon correlation

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

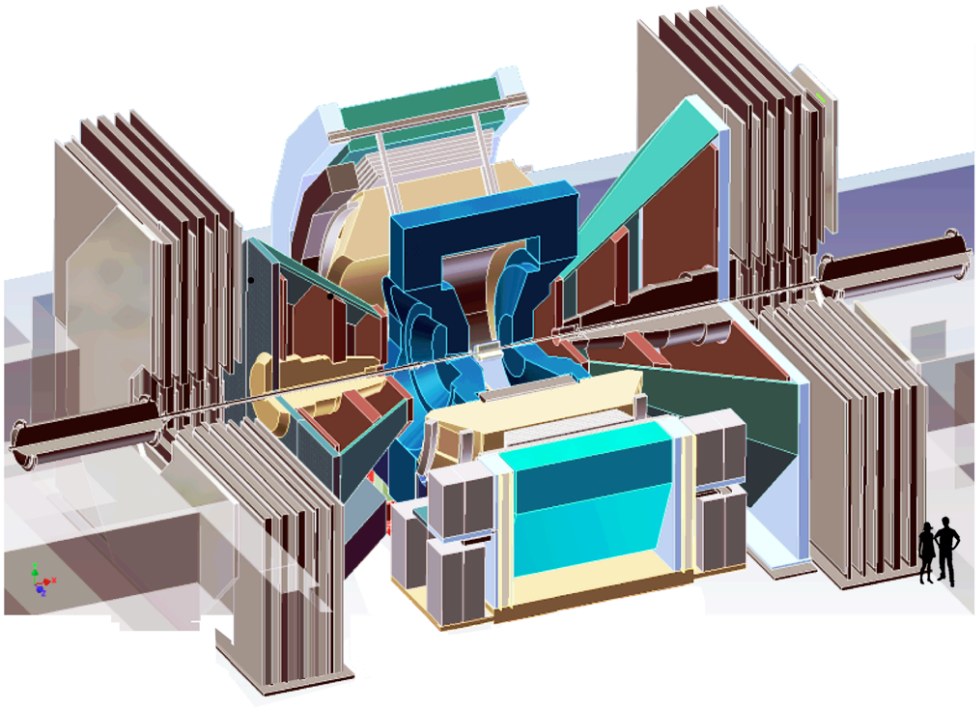
NLO pQCD and Forward Hadron Production at RHIC

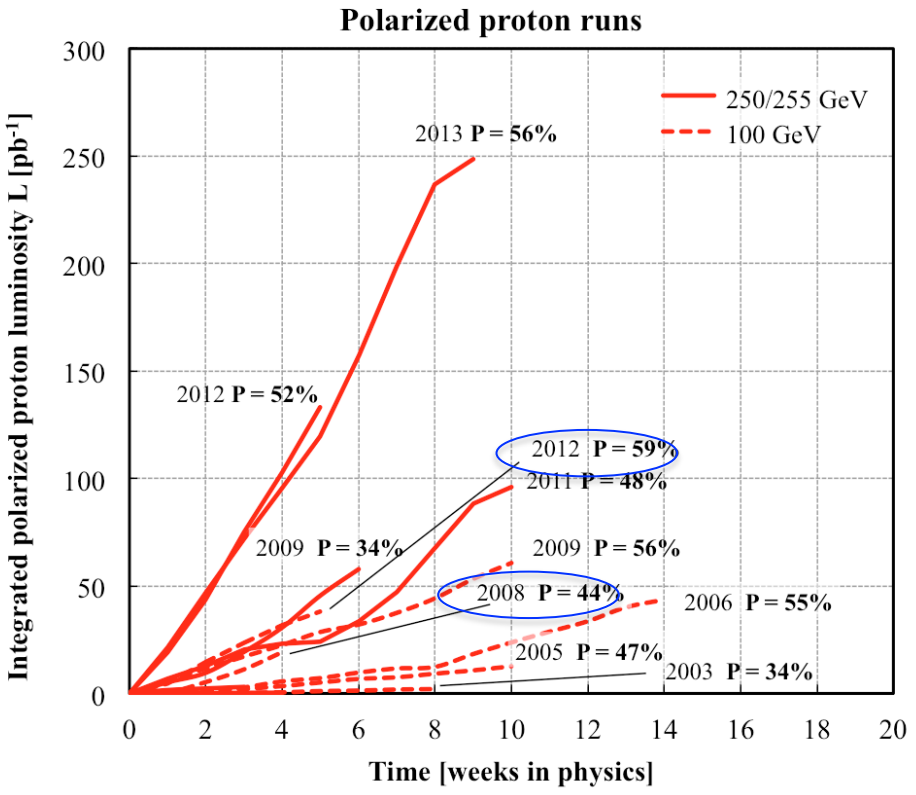


Polarized Proton Collider at RHIC

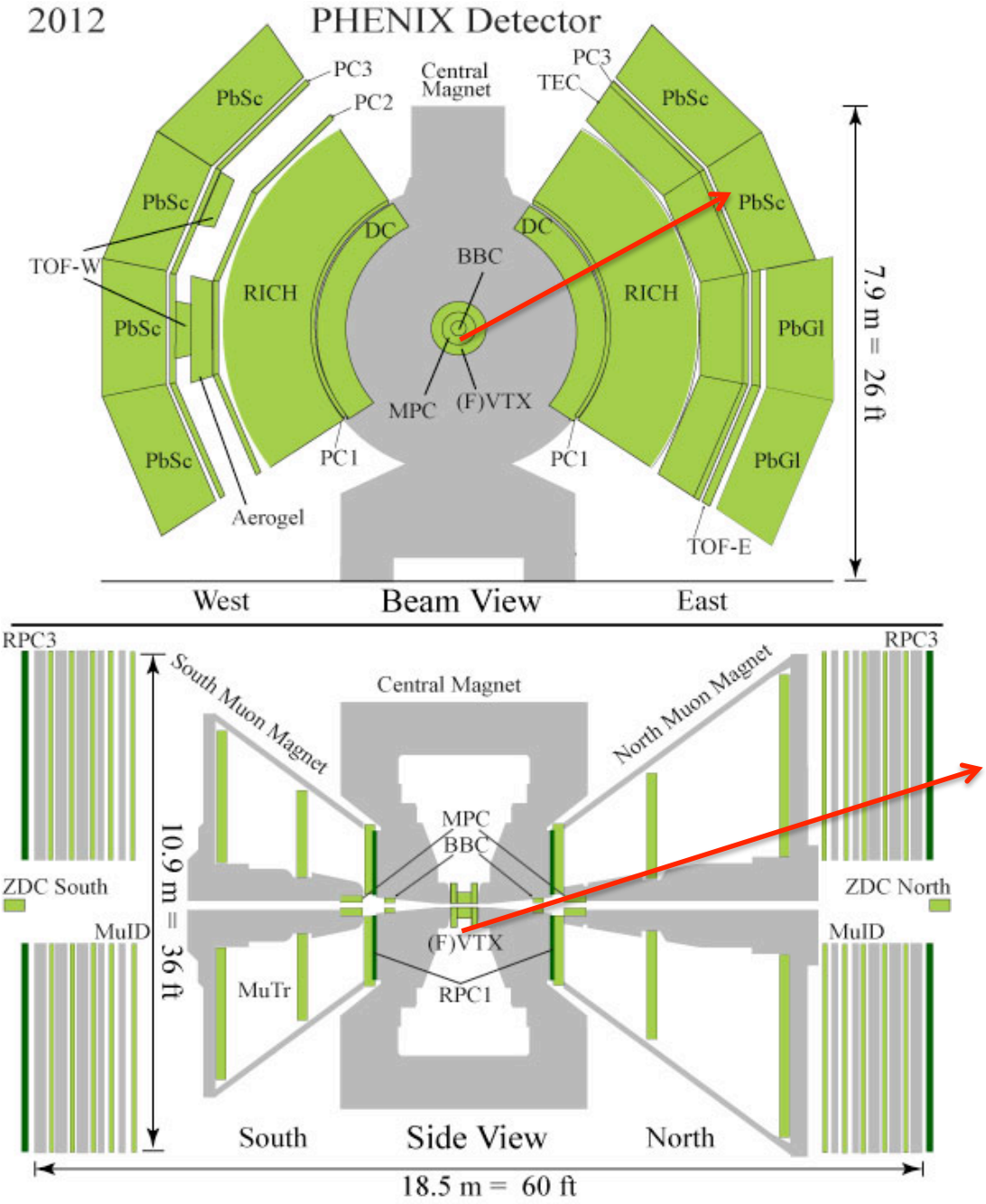


Recent PHENIX Transverse Spin Runs





Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2006 (Run 6)	200	2.7 pb^{-1}	50	700 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	45	1100 nb^{-1}
2012 (Run12)	200	9.2 pb^{-1}	60	3300 nb^{-1}

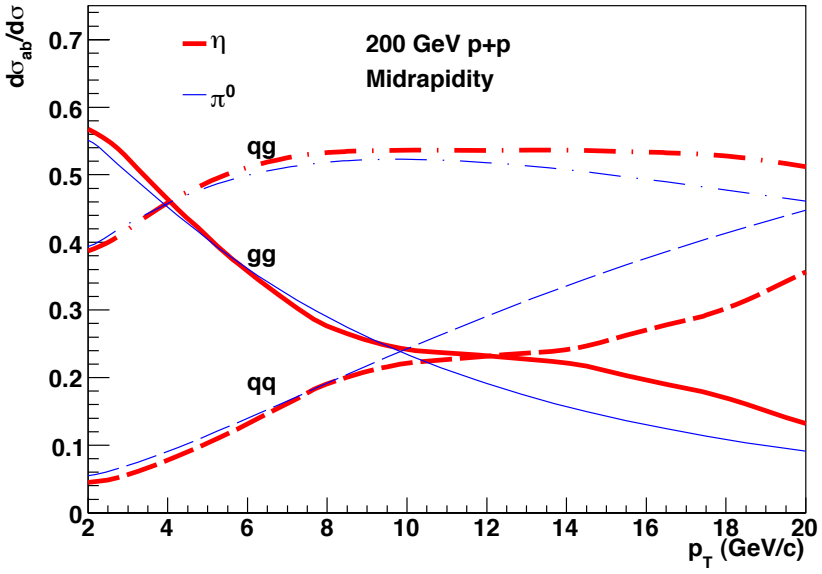


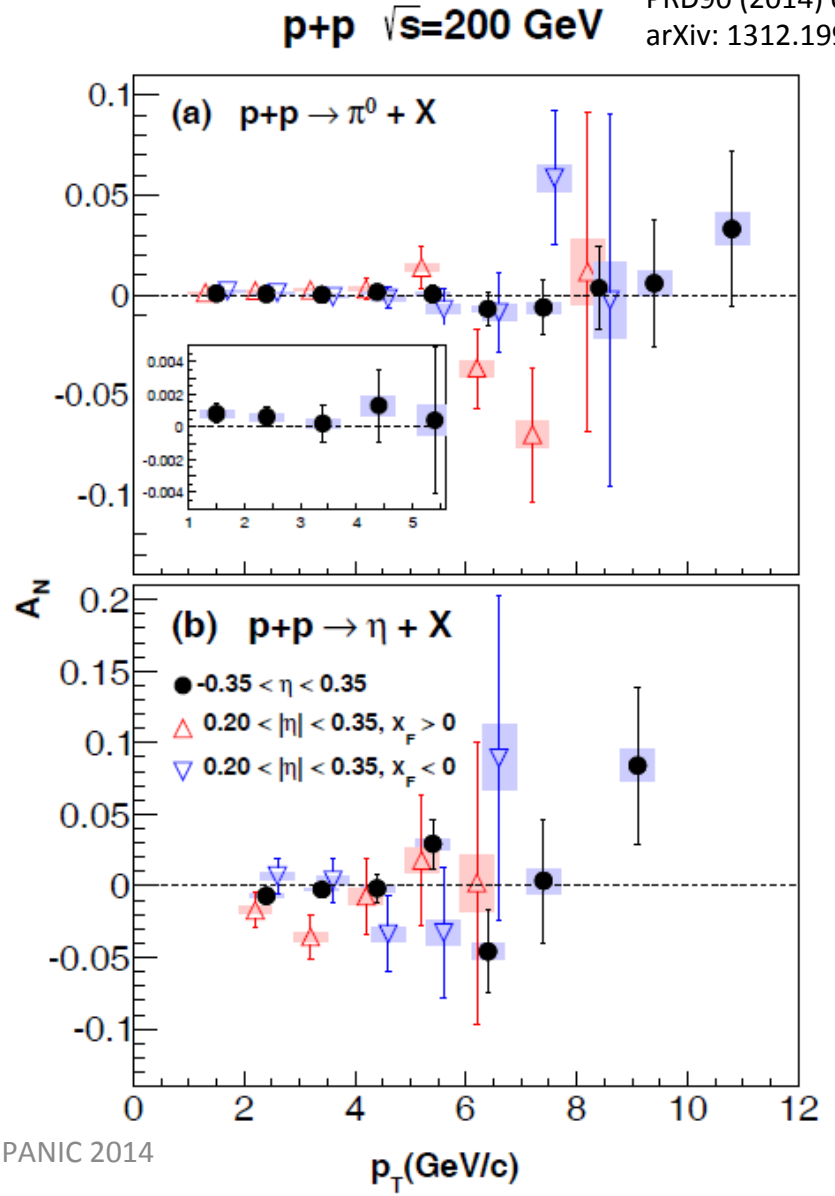
- Philosophy
  - high resolution & high-rate
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - Momentum, EM Energy, PID
  - π^0 and η
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum
  - High pT muons
- Muon piston calorimeter
  - $3.1 < |\eta| < 3.9$
  - EM Energy
  - π^0 and η

Mid-Rapidity π^0 and η

- Much improved measurements
  - 20x in statistics
- $A_N \sim 0$ (<0.1%)
  - contrast with forward hadrons
- Theories need to be developed
  - Q^2 evolution dilutes the asymmetry?
  - Cancelation of different processes?
  - Gluon Sivers small?

PRD90 (2014) 012006
arXiv: 1312.1995

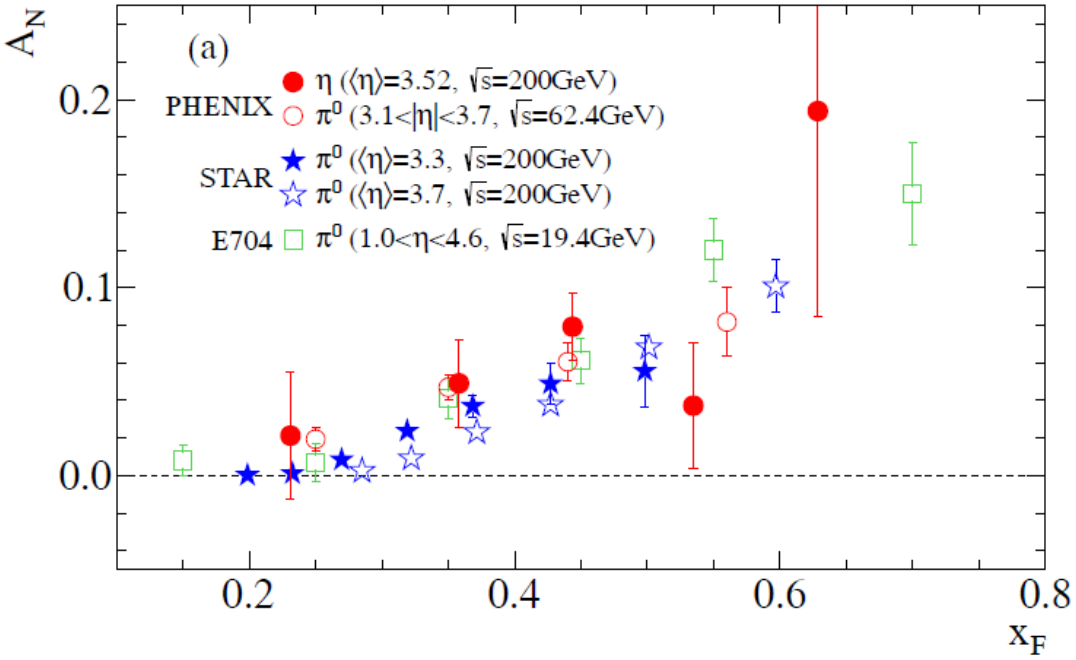


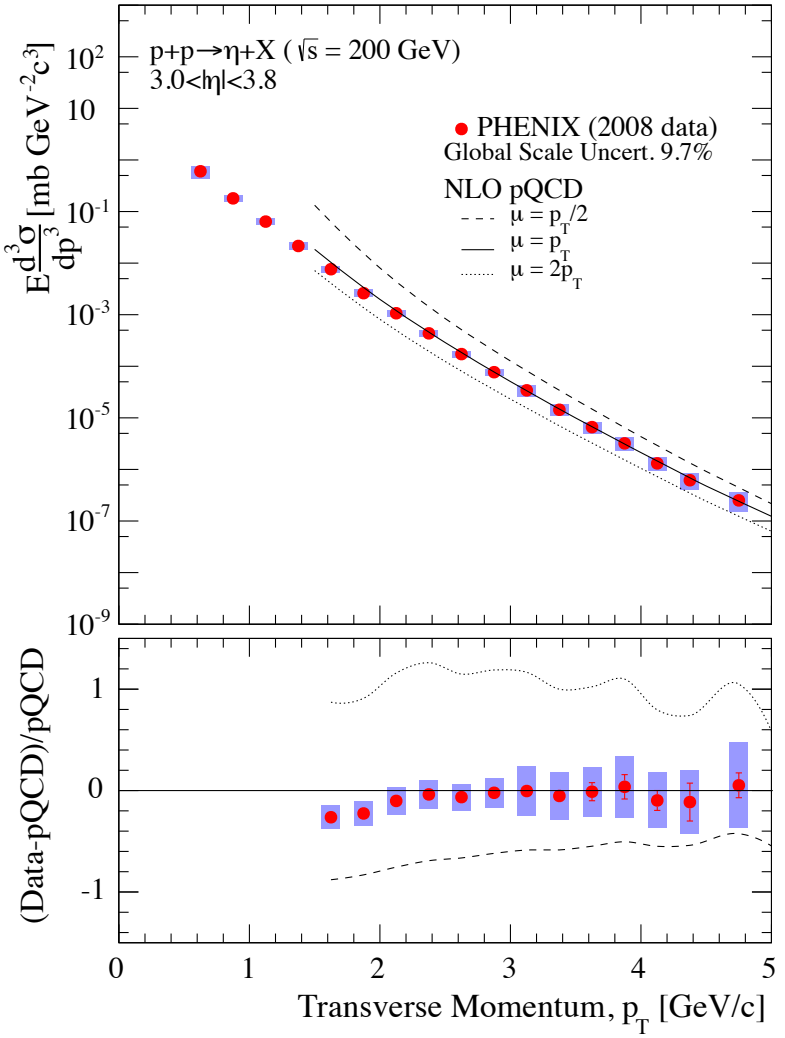


Forward-Rapidity: π^0 and η

- Production well described by pQCD
- A_N is independent of collision energy
  - xF scaling?
- Similar for Pion and eta
  - No mass dependence?

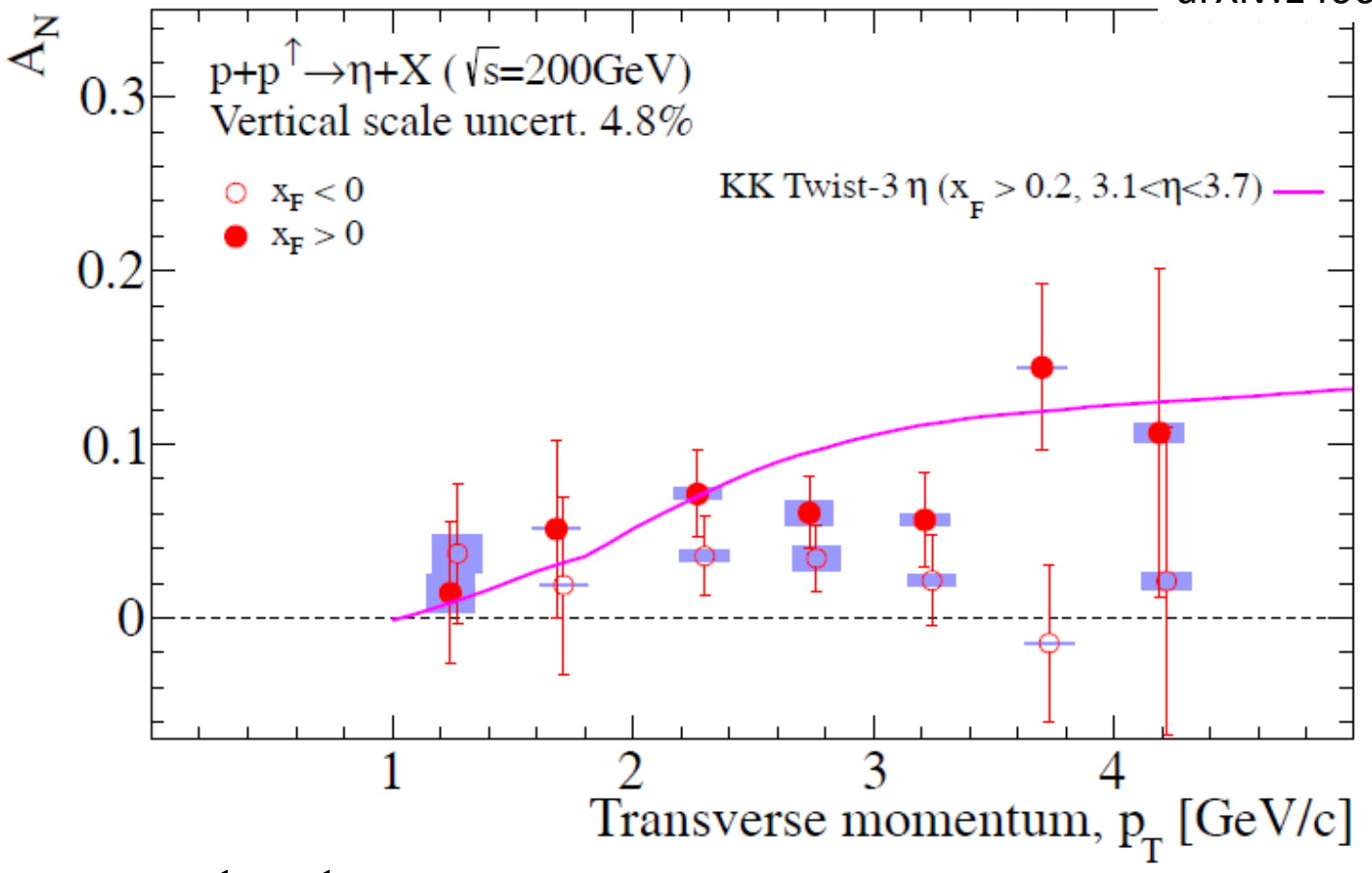
arXiv:1406.3541





Forward η : "little" p_T Dependence

arXiv:1406.3541



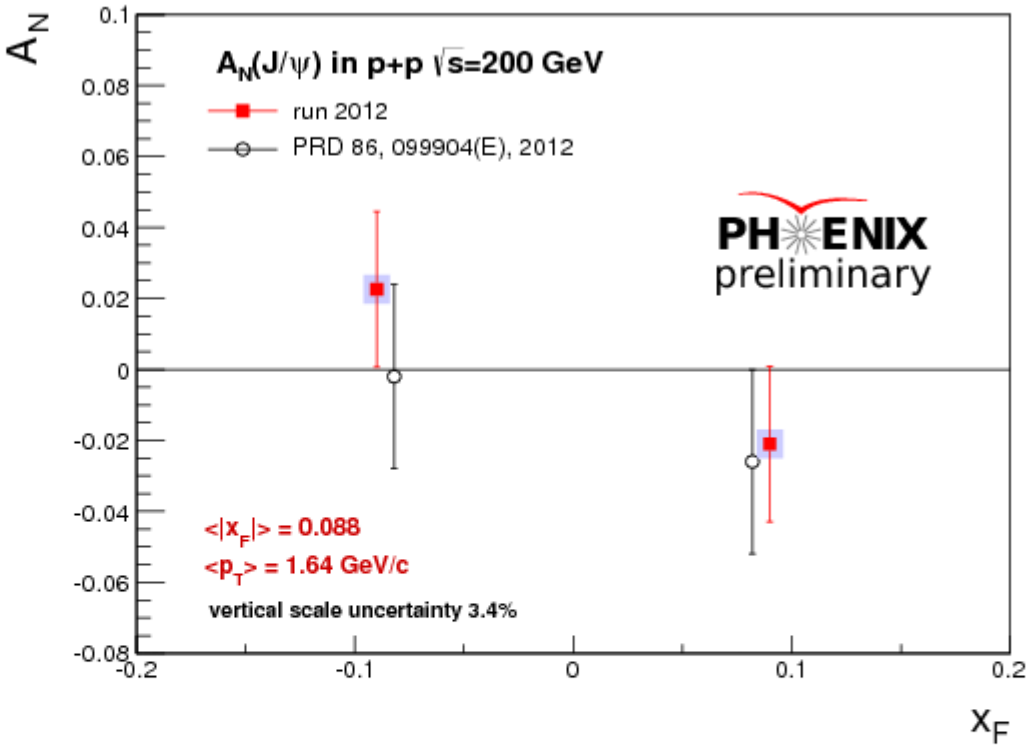
$$A_N \sim \frac{1}{Q} \sim \frac{1}{p_T} \quad @twist-3$$

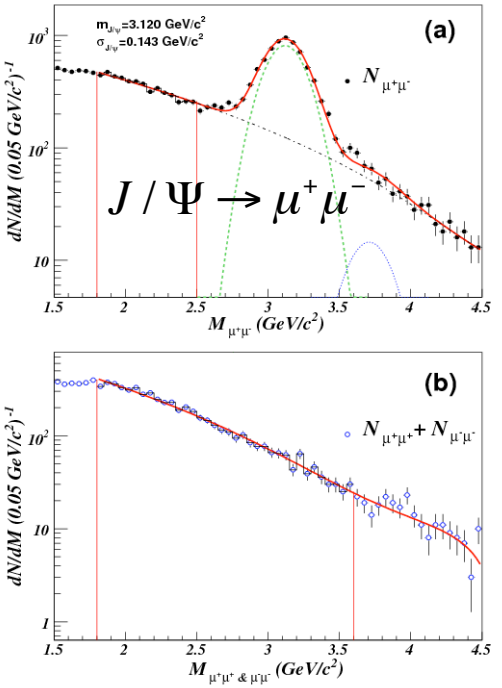
Naïve expectation at high pT

$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

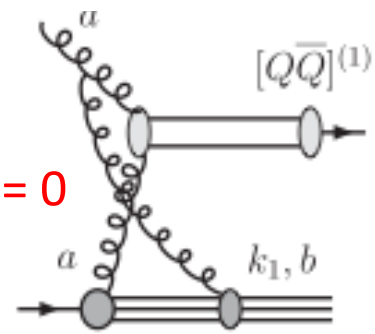
Recent work, Twist-3, Kanazawa & Koike

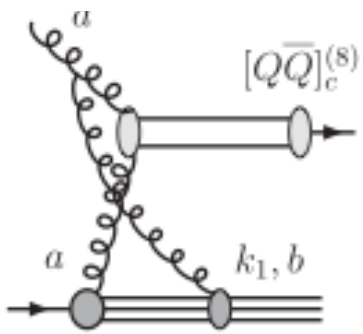
Heavy Flavor: Forward J/ψ A_N



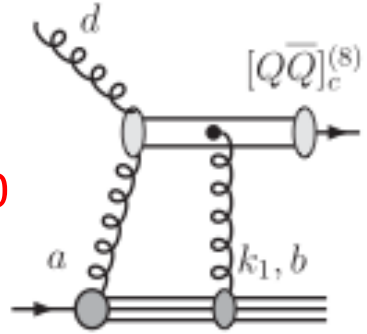


A_N != 0





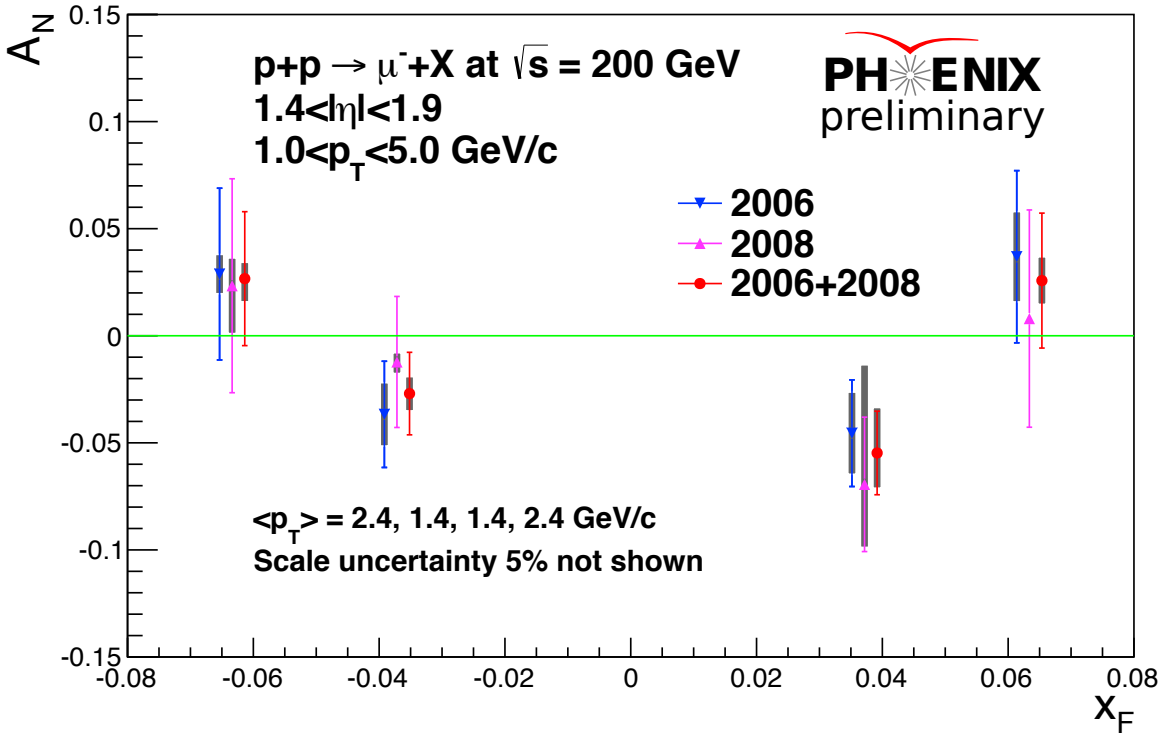
A_N =0



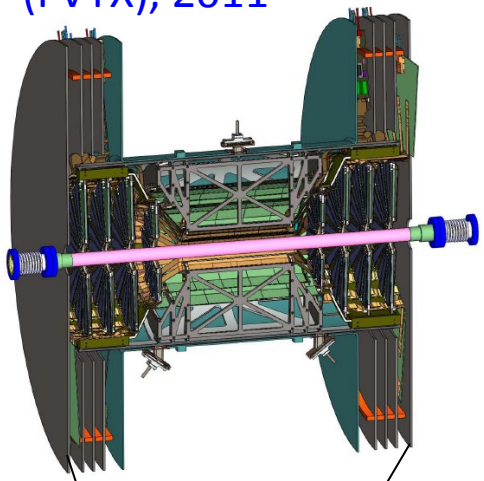
F. Yuan, PRD 78, 014024(2008)

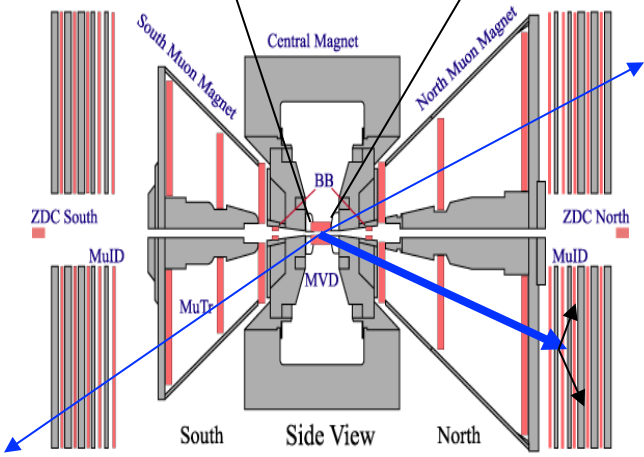
Open Heavy Quark A_N

- Forward Muon Arms
  - Run6, 8
  - Run12, work in progress
  - Expect much improved w/ FVTX from Run2015 first transverse p+p data



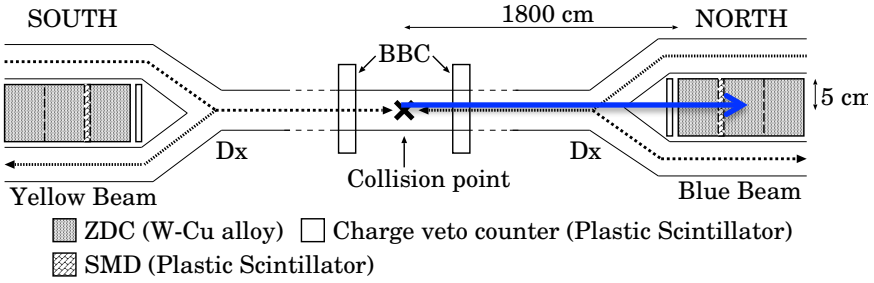
Forward Silicon Vertex Detector Upgrade (FVTX), 2011

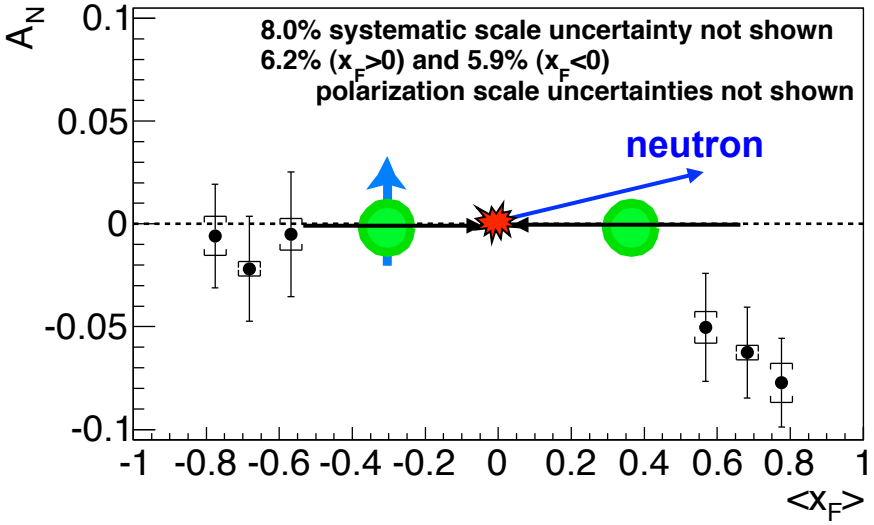


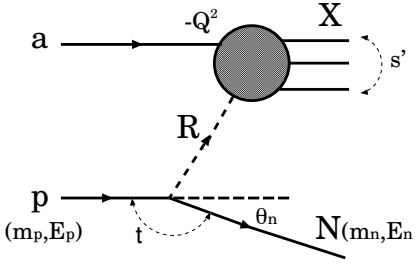


Forward Leading Neutron A_N

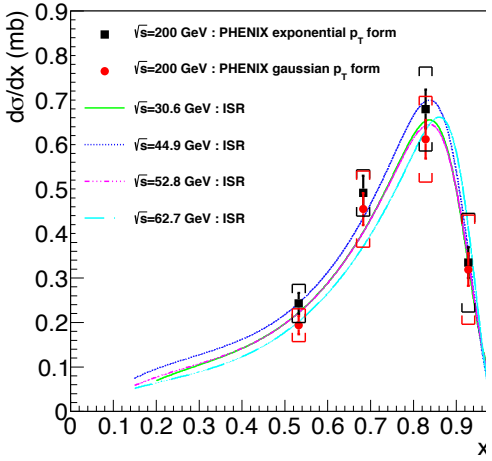
Phys. Rev. D 88, 032006 (2013)

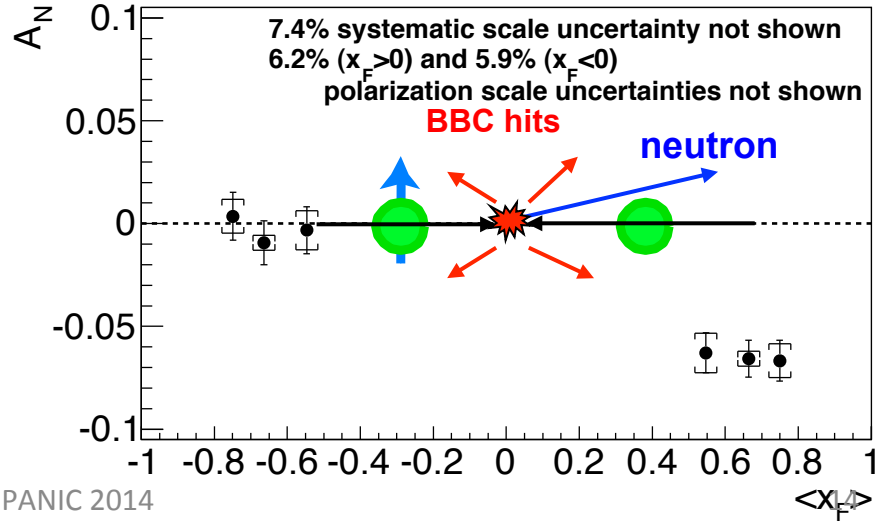






Single pion exchange?

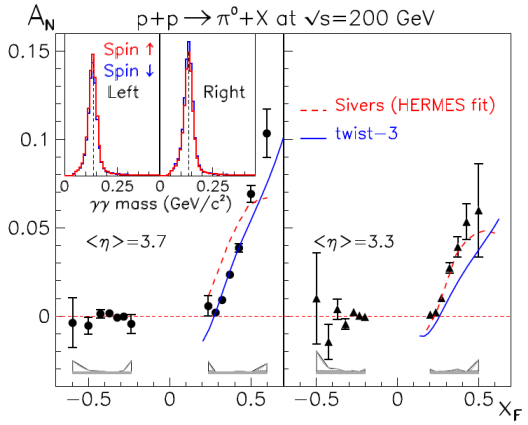




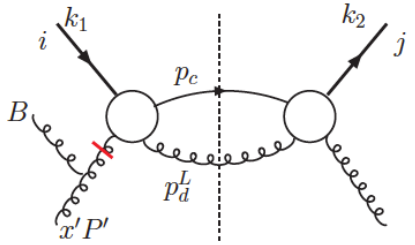
A Surprise: A_N Sign Mismatch?

First attempt to check the "Universality of QCD description of TSSA"

- Twist-3 (RHIC) v.s. Sivers (SIDIS)

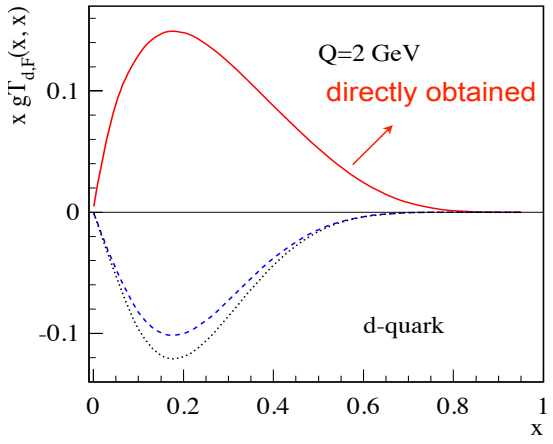


$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

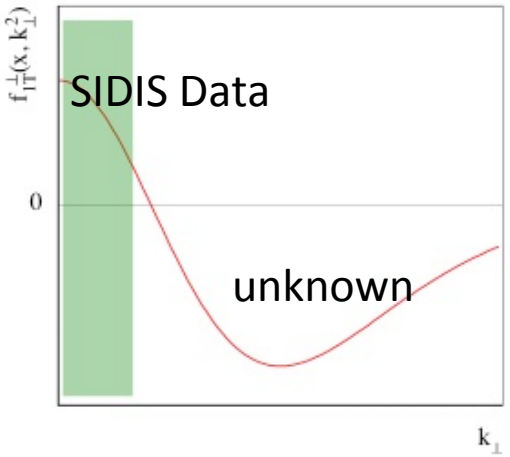


Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin

Kang, Qiu, Vogelsang, Yuan PRD 2011



A possible solution? Kang, Prokudin PRD (2012)

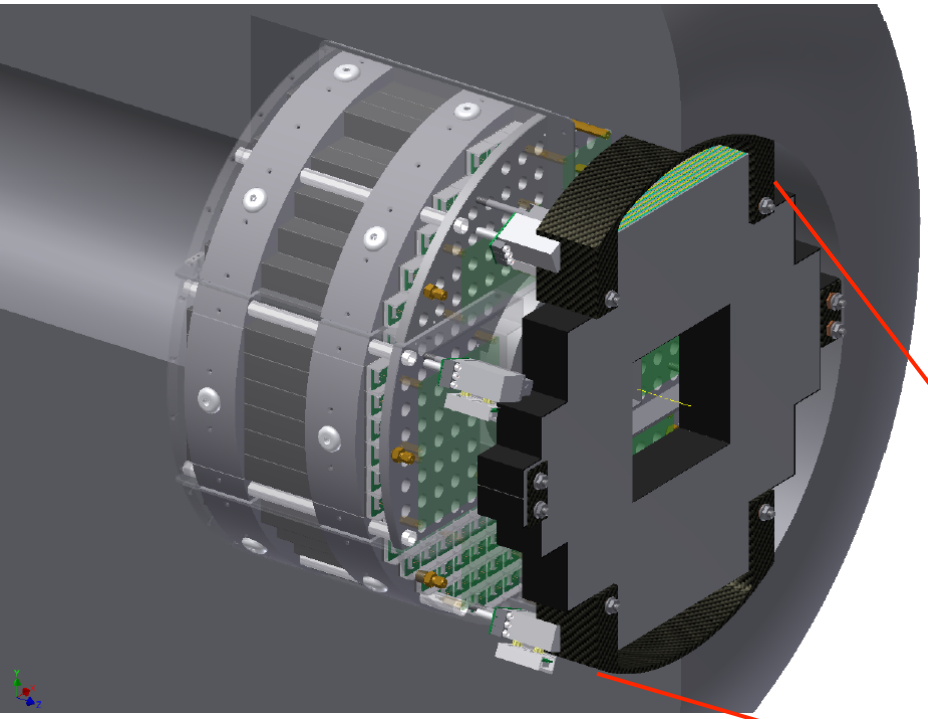


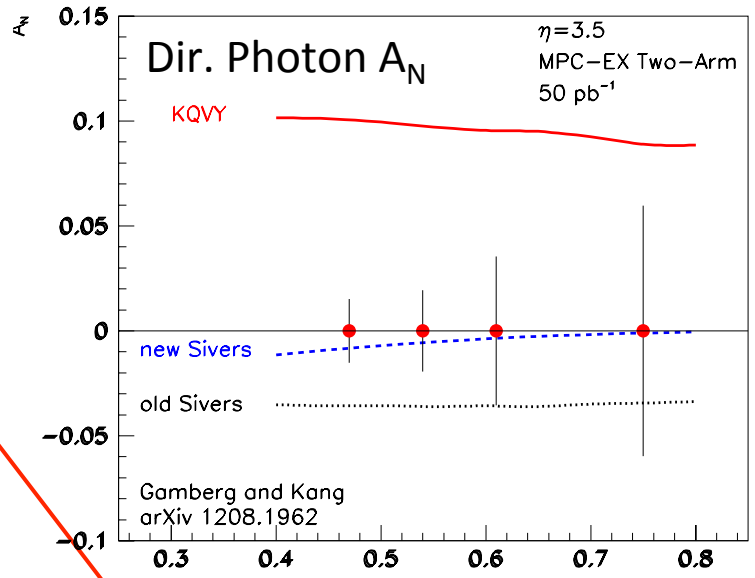
Collins dominates?

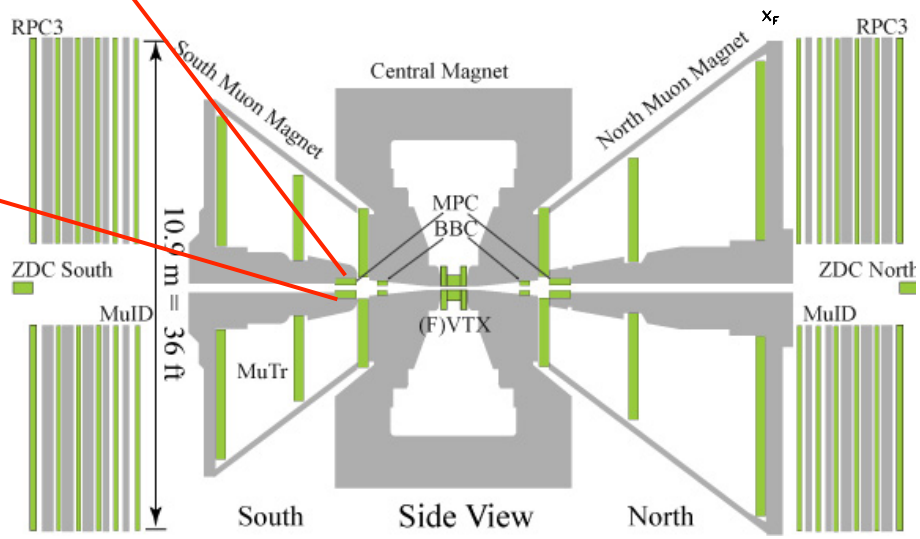
Need more data!

Direct Photon TSSA with MPC-EX Upgrade

(for Run2015+)







A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

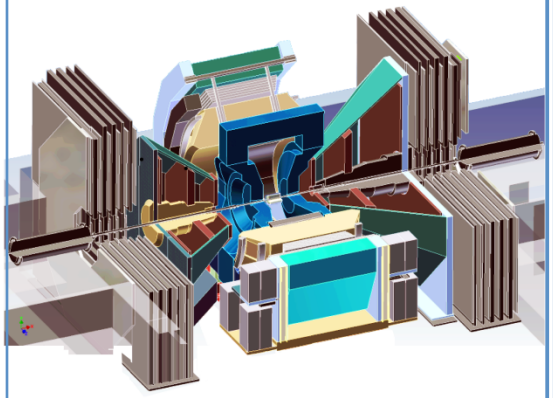
$3.1<|\eta|<3.9$

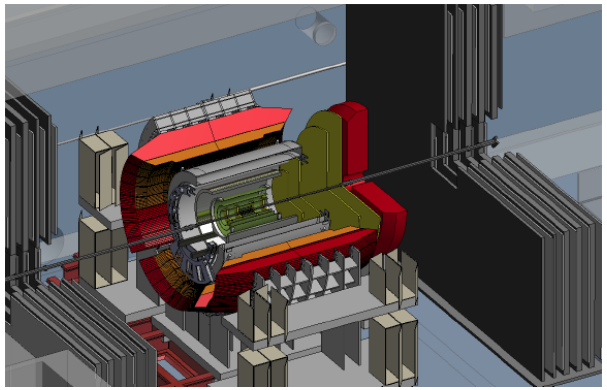
- π^0 rejection → direct photons
- π^0 reconstruction out to >80GeV

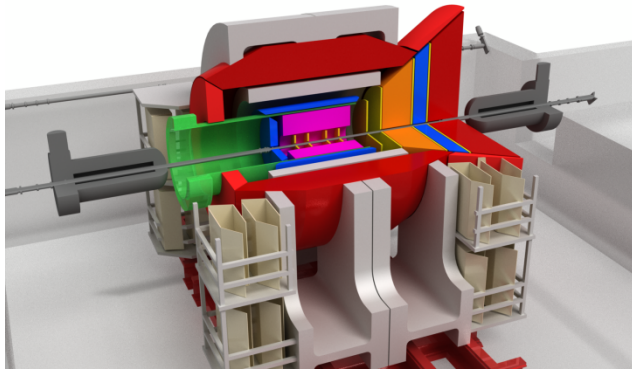
PHENIX -> Forward/sPHENIX->ePHENIX

Documented: http://www.phenix.bnl.gov/plans.html

Current PHENIX	*f*/sPHENIX	An EIC detector
• Current PHENIX as discussed in many previous talks • 14y+ work 100+M$ investment • 130+ published papers to date • Last run in this form 2016	▸ Comprehensive central upgrade based on BaBar magnet ▸ fsPHENIX: forward tracking, HCal and muon ID ▸ Key tests of theoretical frameworks for transverse spin	▸ Path of PHENIX upgrade leads to a capable EIC detector ▸ Large coverage of tracking, calorimetry and PID ▸ New collaboration/new ideas







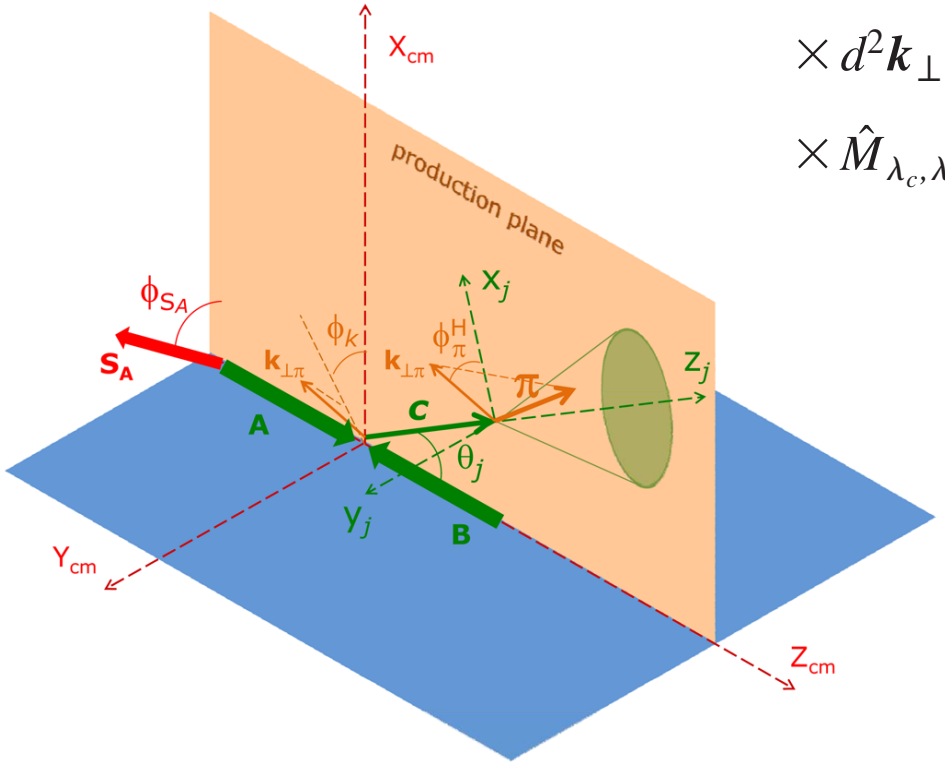
~2000 2017→2020 ~2025 Time

RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

Access Sivers and Collins with Jet and Hadron Azimuthal Distributions in Transversely Polarized p+p Collisions

Feng Yuan, PRL 100, 032003 (2008)
Umberto D'Alesio et al PRD 83 034021 (2011)



$$\frac{E_j d\sigma^{A(S_A)B\to \text{jet}+\pi+X}}{d^3\boldsymbol{p}_j dz d^2\boldsymbol{k}_{\perp\pi}} = \sum_{a,b,c,d,\{\lambda\}} \int \frac{dx_a dx_b}{16\pi^2 x_a x_b s} d^2\boldsymbol{k}_{\perp a}$$
$$\times d^2\boldsymbol{k}_{\perp b} \rho^{a/A,S_A}_{\lambda_a\lambda'_a} \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \rho^{b/B}_{\lambda_b\lambda'_b} \hat{f}_{b/B}(x_b,\boldsymbol{k}_{\perp b})$$
$$\times \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b} \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \delta(\hat{s}+\hat{t}+\hat{u}) \hat{D}^{\pi}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp\pi}).$$

Experimental variables:

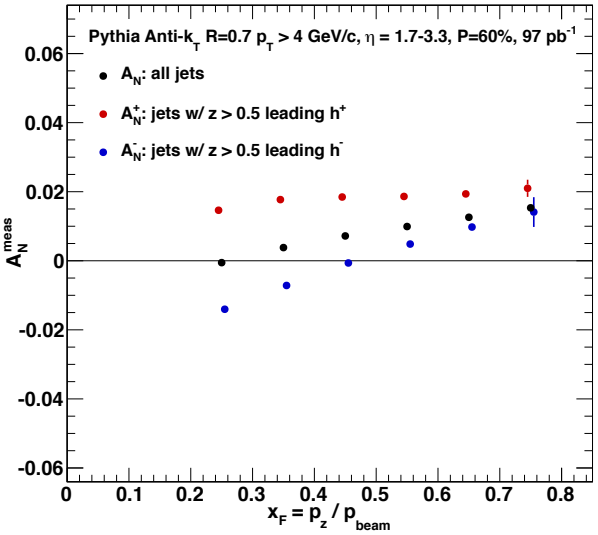
- Jet P_j, xF
- Hadron P_h , PID
- Beam polarization

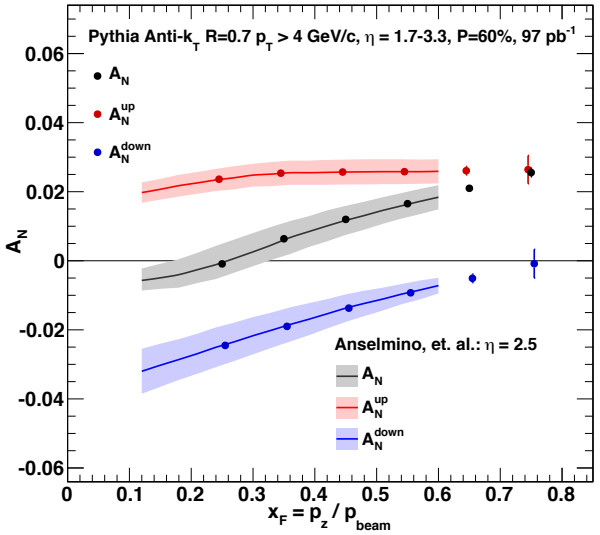
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

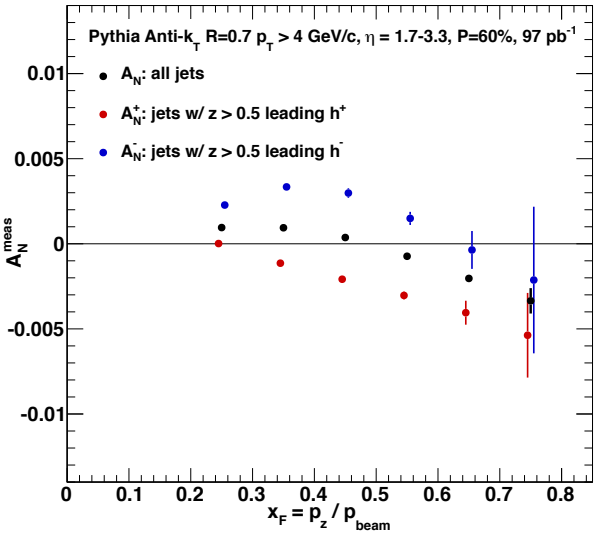
$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ → "Collins-like"

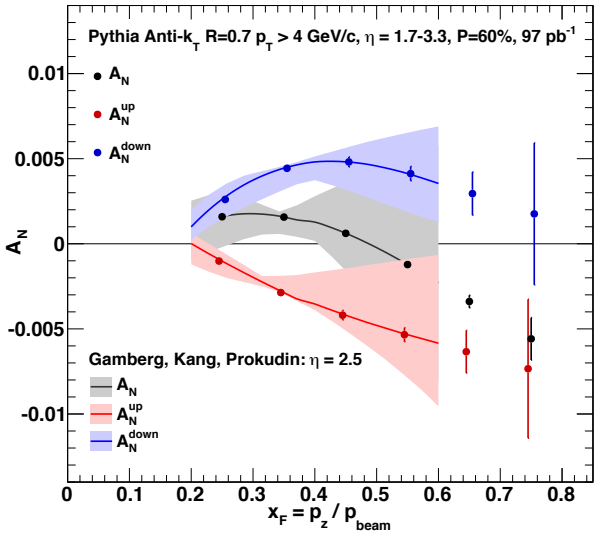
fsPHENIX Projected Jet Sivers Asymmetries

Test the universality of QCD description of TSSA: pp vs SIDIS





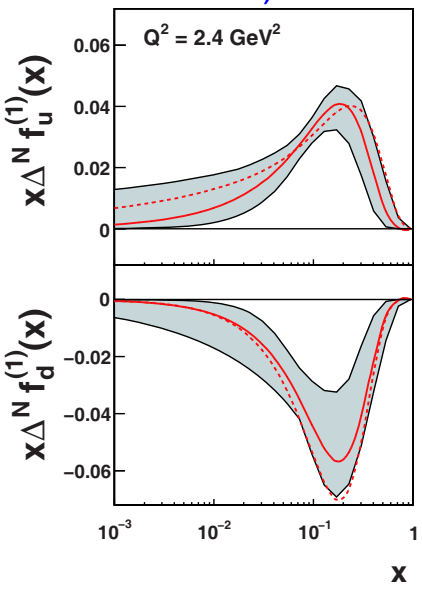




Naïve direct mapping from SIDIS Sivers

- "u-quark jet" A_N >0

Sivers, SIDIS fit

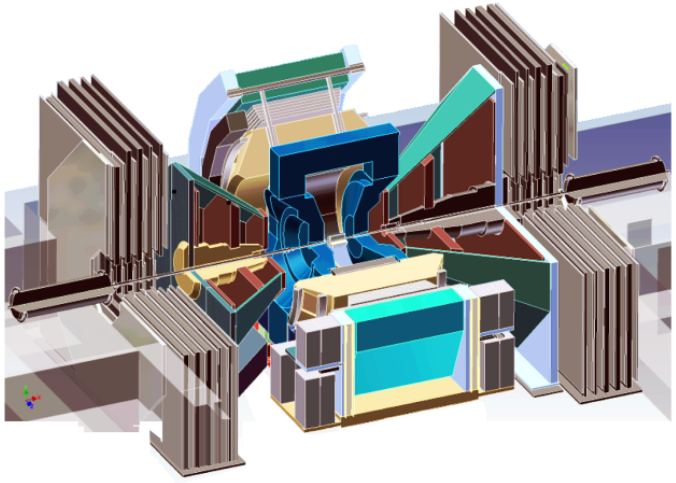


With process-dep from SIDIS Sivers

- "u-quark jet" A_N < 0

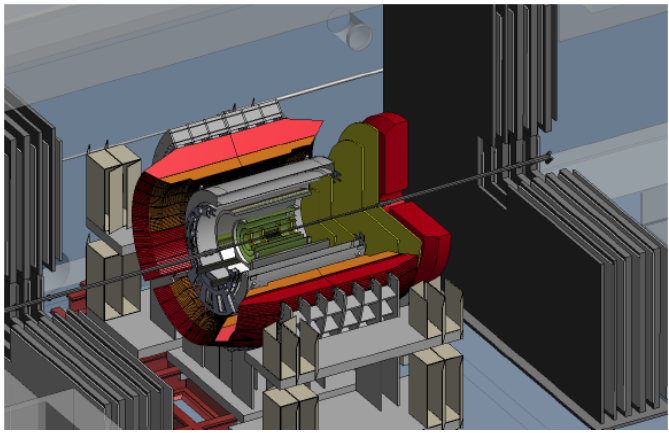
Summary and Outlook

- Central rapidity
  - A_N ~ 0 for π^0 and η
- Forward rapidity
  - Non-zero A_N for π^0 , η and EM Clusters
    - Collins, Sivers, and twist-3 effects
- New physics capabilities with upgrades
  - FVTX: forward heavy-flavor program (μ, J/ψ)
  - MPC-EX: forward A_N (γ) to test the "non-universality" of Sivers



~2020

- Proposed new Forward Spectrometers (fsPHENIX)
  - First direct precision study of Sivers-like and Collins-like TSSA in p+p
    - Sivers w/ forward quark-flavor tagged jets
    - Collins w/ hadron TSSA inside a jet
  - Drell-Yan TSSA to test the "sign change" and Q^2 evolution effects



Pioneering High Energy Nuclear Interaction EXperiment

“Hot Topics” in Transverse Spin physics

- Non-universality of TMD distribution functions
  - Opposite-sign contribution of TMD distribution function to TSSA in semi-Inclusive DIS (SIDIS) process and Drell-Yan process

$$f_{1T}^{\perp q}|_{\mathrm{SIDIS}} = -f_{1T}^{\perp q}|_{\mathrm{DY}}$$

  - Fundamental property based on Gauge-Link formalism of QCD
  - Experimental verification needed

- Sign mismatch of SIDIS/TMD and pp/Higher-twist
  - TMD description at low p_T region, higher-twist description at high p_T region, and consistent description in the middle region

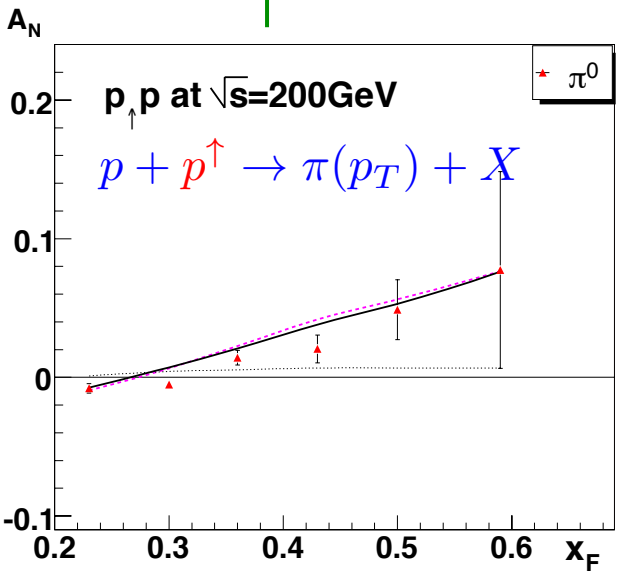
$$T_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp^2|}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$

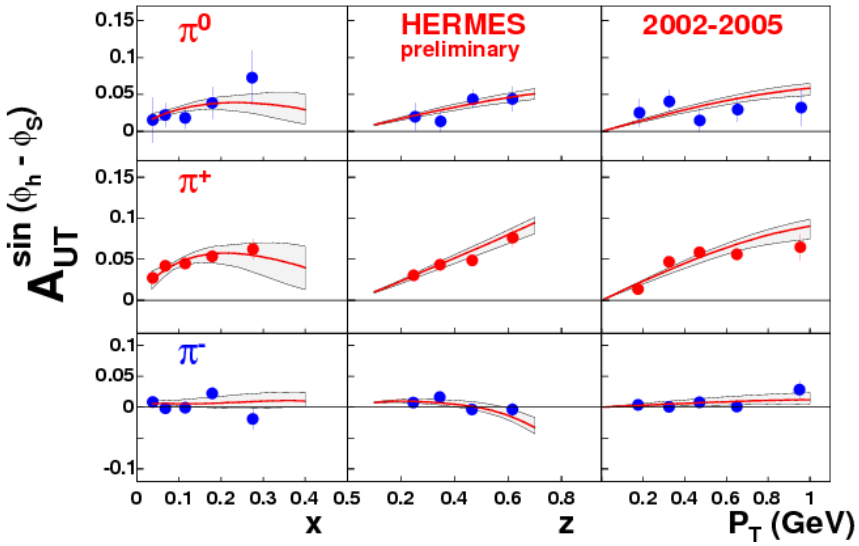
  - But, sign mismatch of each description obtained from experiments

pQCD models for SIDIS and pp TSSA Are They Really Consistent?

Kang, Qiu, Vogelsang, Yuan (2011)

$$gT_{q,F}(x,x) \stackrel{?}{=} -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$



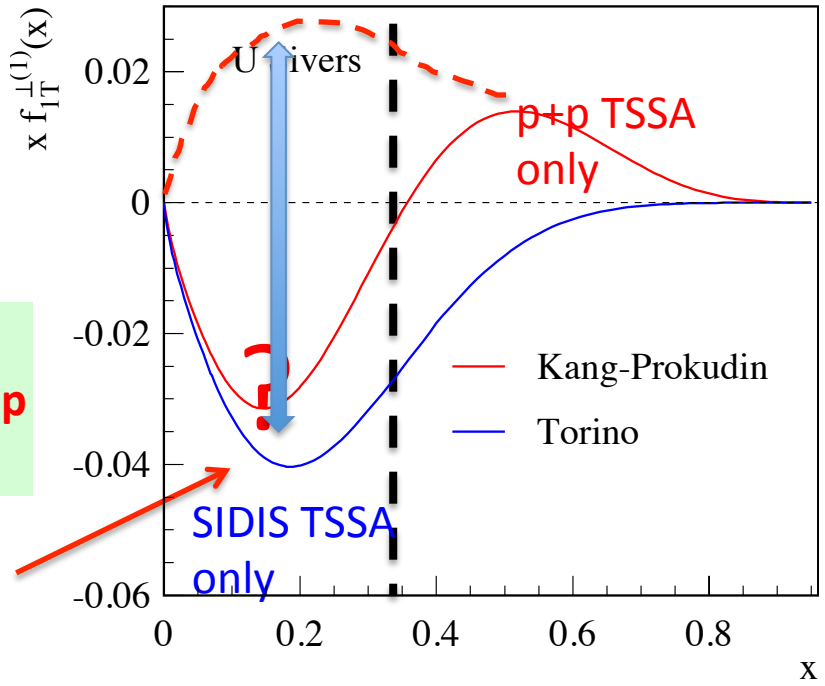


Sign mismatch Puzzle

- Significant TSSA observed in both SIDIS and pp, but are they from the same physics?
- Current SIDIS and pp data don't cover the same kinematics range!

=> fsPHENIX

$$gT_{q,F}(x,x) \overset{?}{=} -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\mathrm{SIDIS}}$$



Kang, Prokudin PRD (2012)

u and d quarks' Sivers and Collins in p+p @ x = 0 ~ 0.4

p+p TSSA: xF > 0.3

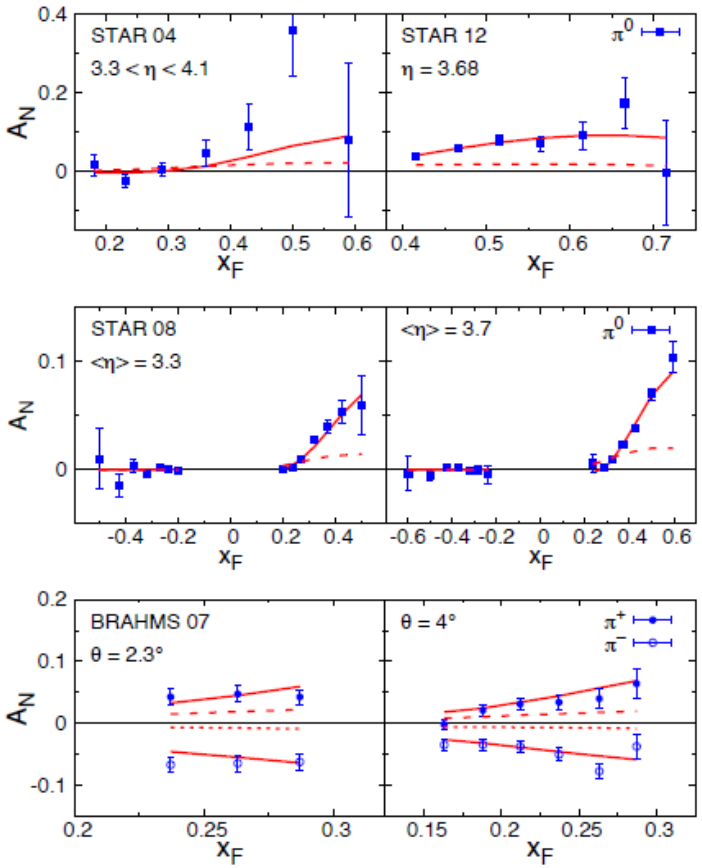
SIDIS TSSA: xB < 0.3

Could "Collins effect" be the Solution?

A_N from twist-3 fragmentation functions

(Kanazawa, Koike, Metz, Pitoniak, arXiv:1404.1033)

Alexei's Lecture @Spinfest



good fit of A_N mainly due to the new twist-3 fragmentation function

Need new direct measurements of Sivers and Collins in p+p!

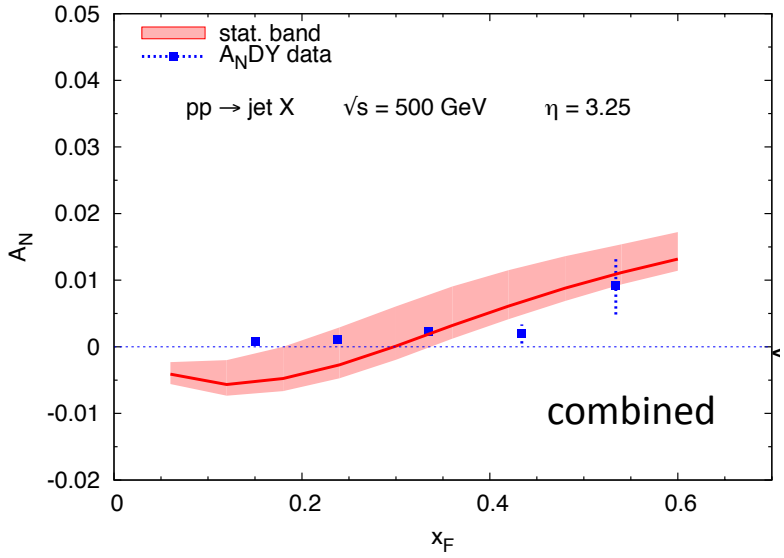
fsPHENIX!

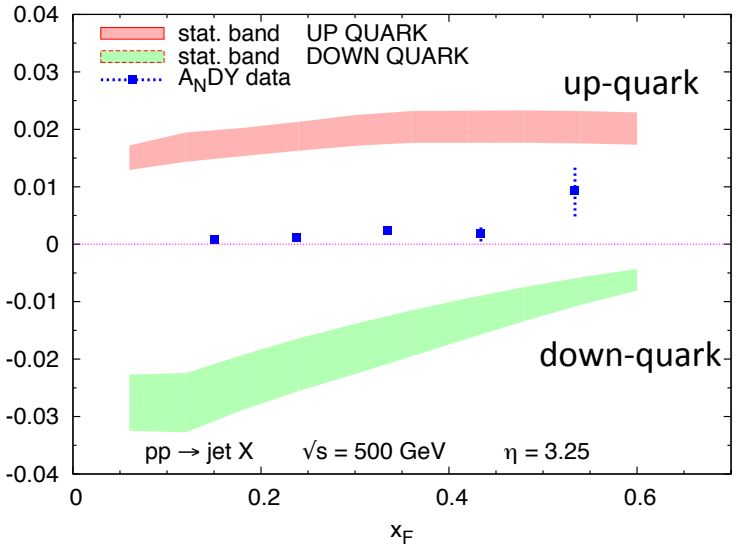
Flavor Tagged Jet Sivers Asymmetry

- Jet and leading h^+ and h^-
- jet_eta= [1,4]

We can do this!

Directly use Sivers function from SIDIS fit





Study Novel Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation Funs

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right) \frac{1}{\tilde{u}}$$

$$\left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \right) \hat{\sigma}^{N1} \right].$$

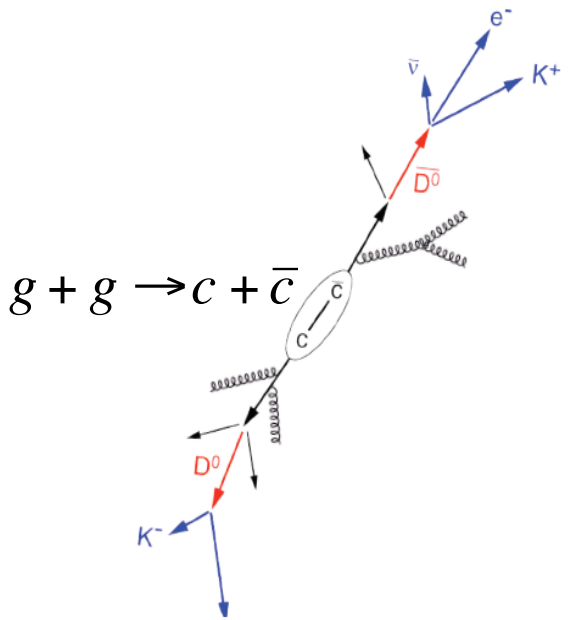
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

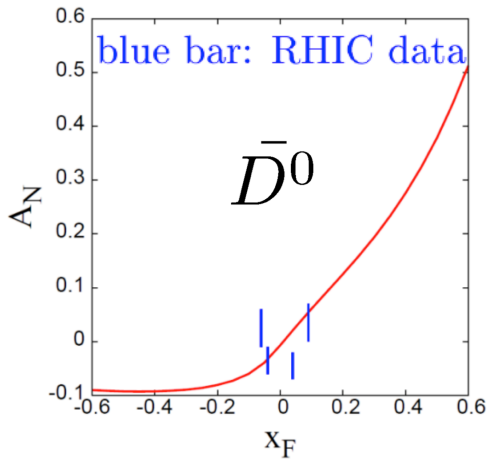
$\delta_f = +1(c); \ -1(\bar{c})$

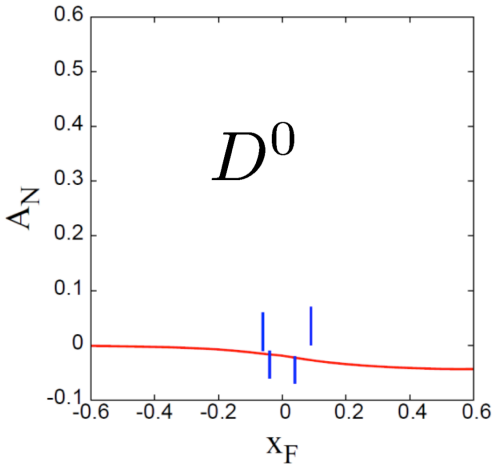
$$A_N(D) \overset{?}{\neq} A_N(\bar{D})$$

Model 1:
$O(x) = 0.004 x G(x)$

Koike *et. al.* (2011)
Kang, Qiu, Vogelsang, Yuan (2008)





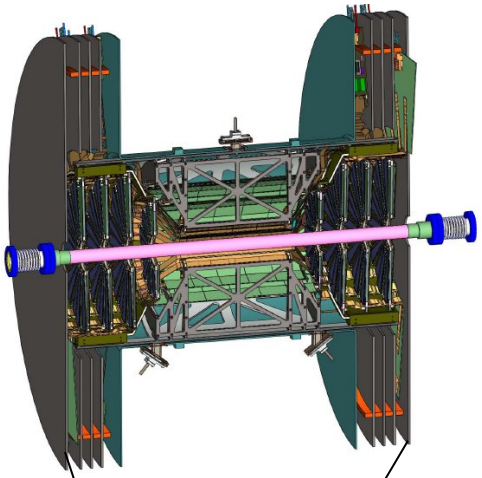


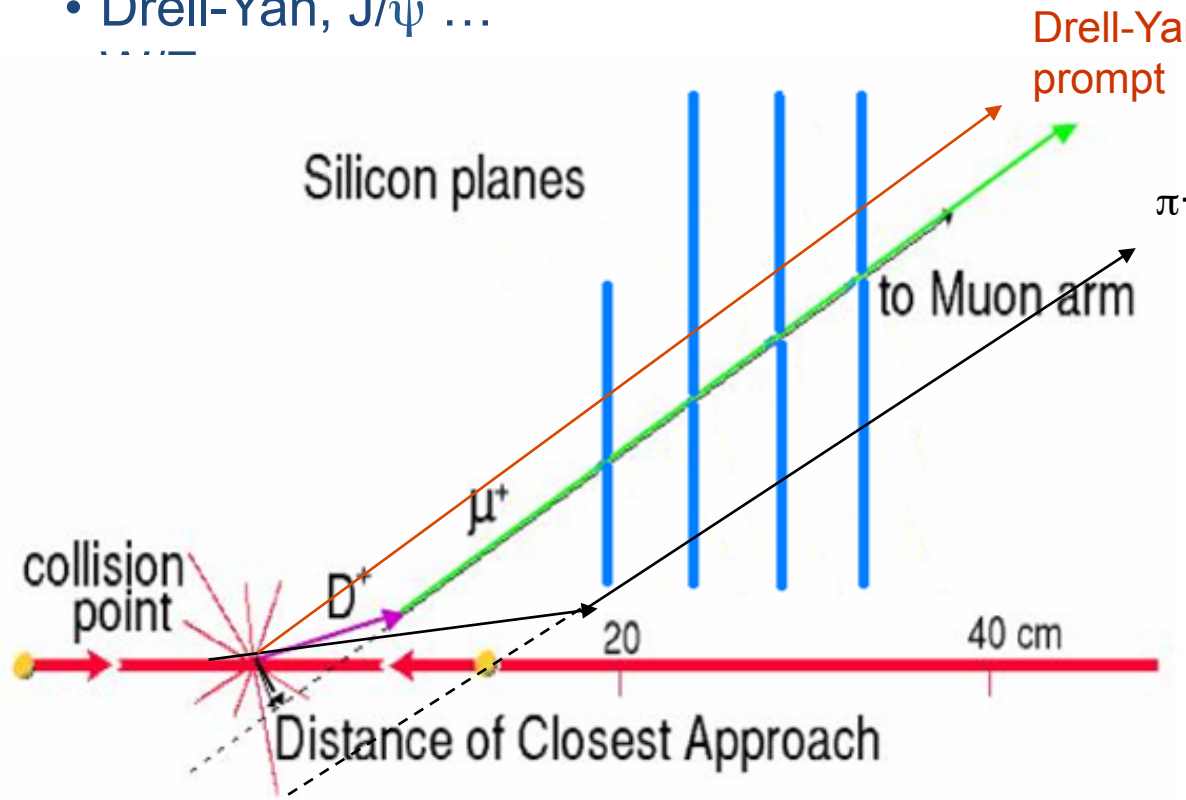
Much Improved Forward Muon Probes

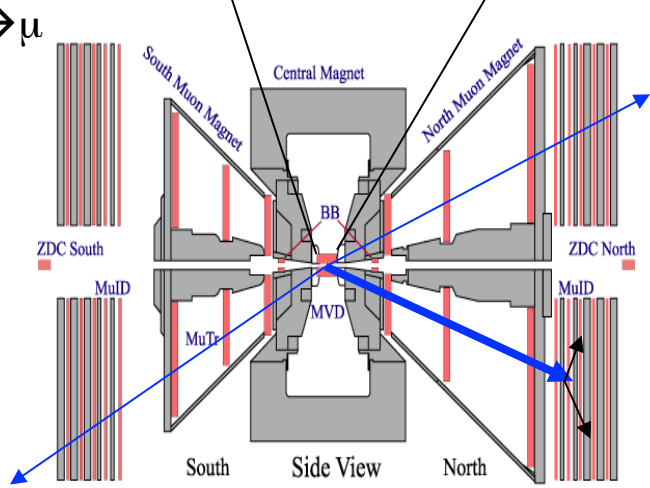
PHENIX Silicon VTX/FVTX Upgrades:

First transverse p+p data: 2015

- Precision Charm/Beauty Measurements
- Drell-Yan, J/ψ …



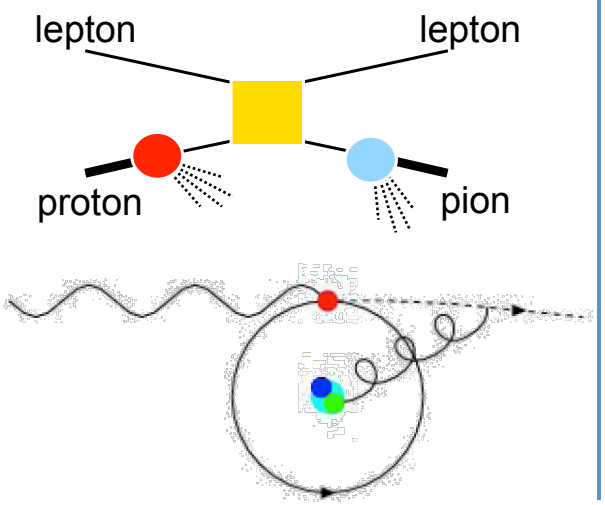




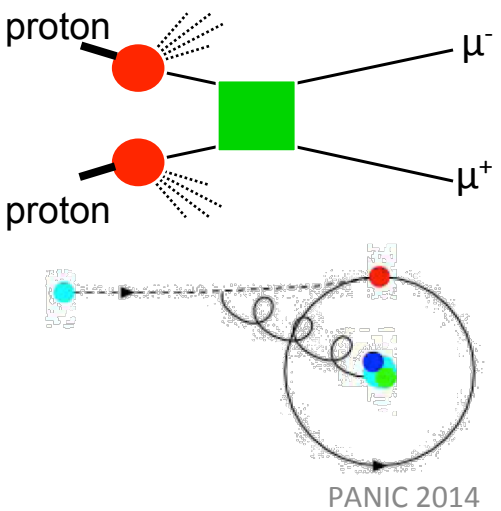
Forward Dimuon Drell-Yan A_N

- DY A_N accesses quark Sivers effect ($f_{1T}^{\perp}$) in proton
- $f_{1T}^{\perp}$ expected to reverse in sign from SIDIS to DY meas.

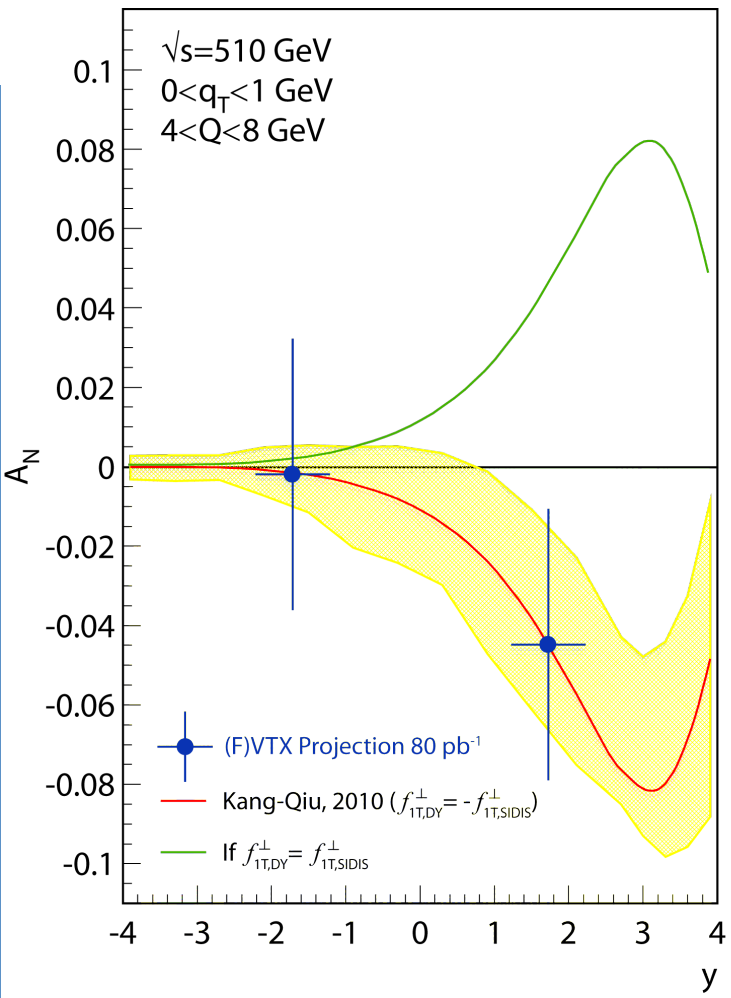
Semi-inclusive DIS (SIDIS)

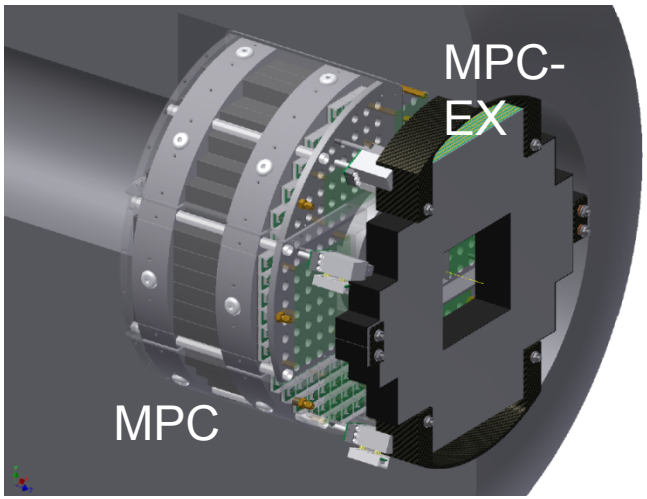


Drell-Yan



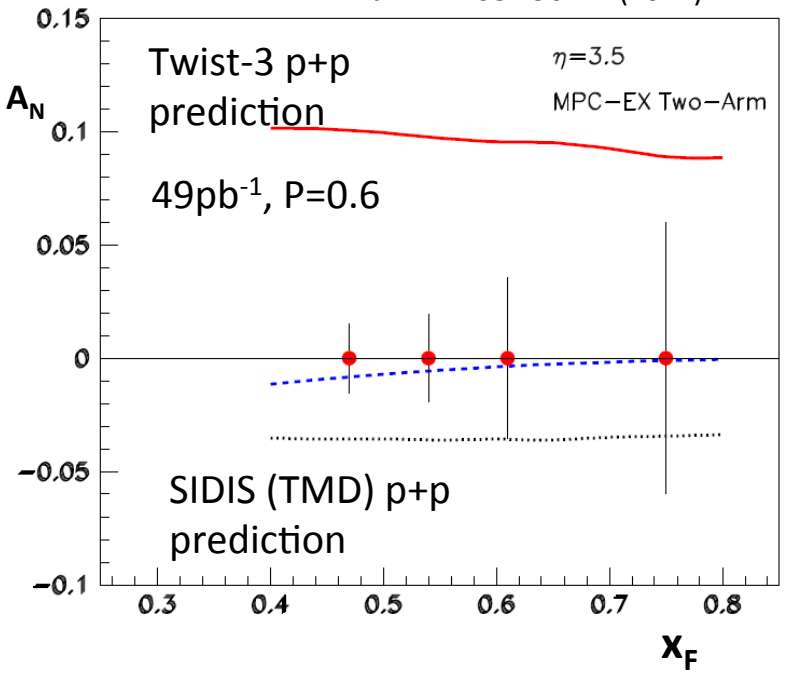
1-year running projection





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