Heavy Quark Transverse Single Spin Asymmetry in p+p Collisions

Ming Liu

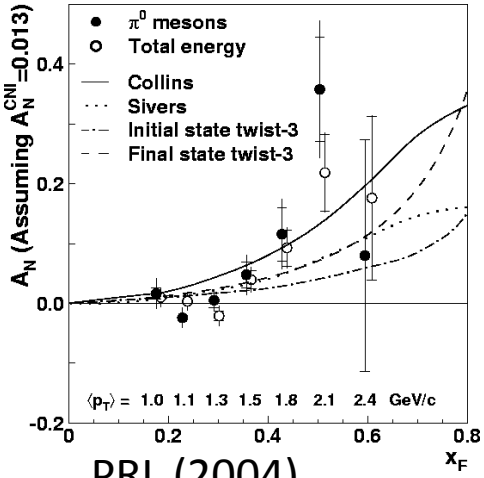
Los Alamos National Laboratory

For the PHENIX Collaboration

Do We Understand the Physics?

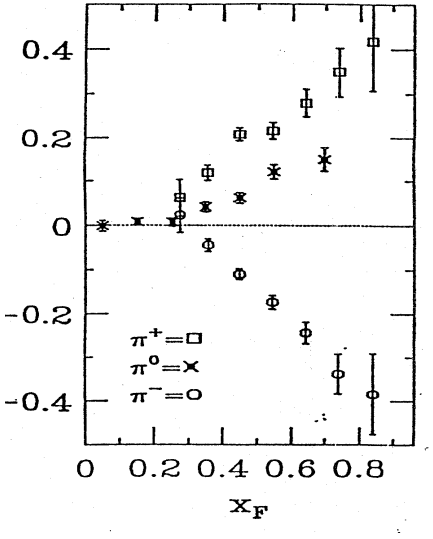
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

RHIC 200 GeV CMS



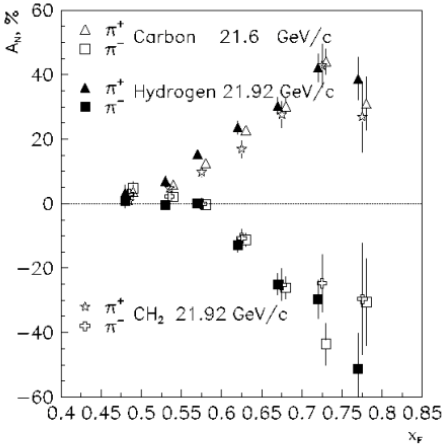
PRL (2004)

FNAL 200 GeV beam



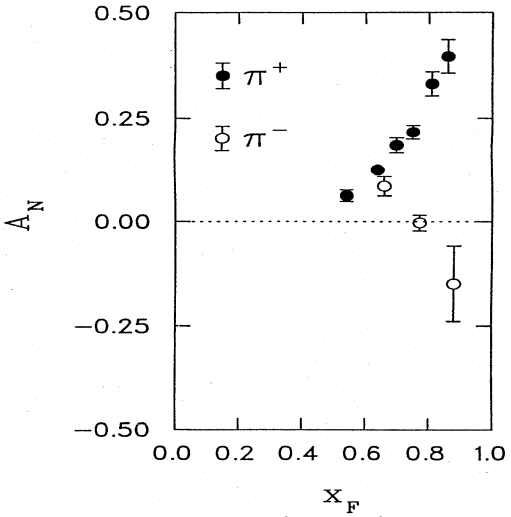
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam

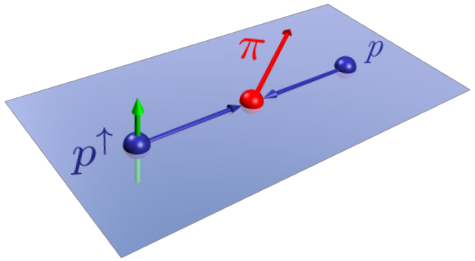


PRD65, 092008 (2002)

ZGS 12 GeV beam



PRL36, 929 (1976)



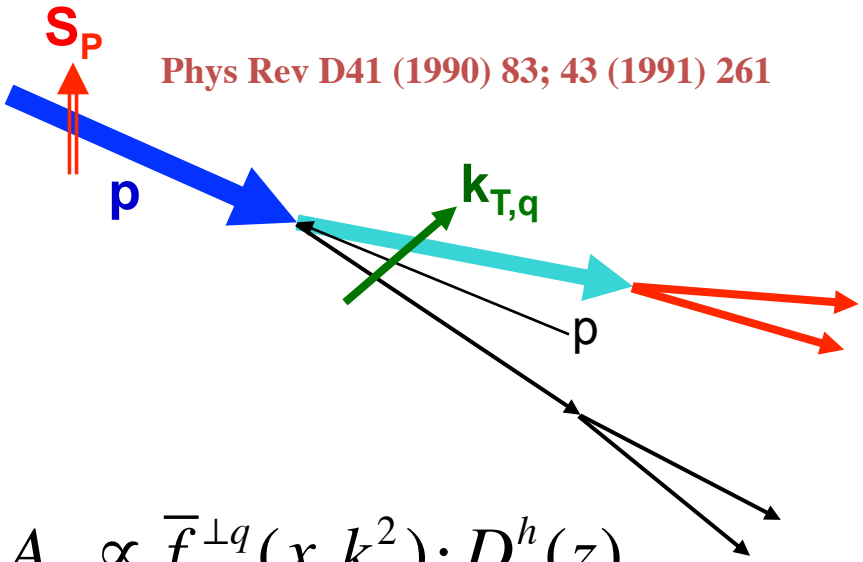
Sivers, Collins, Twist-3 ….

Non-Perturbative cross section → Perturbative cross section

Study the Physics via Hard Scatterings at RHIC

(i) Sivers mechanism:

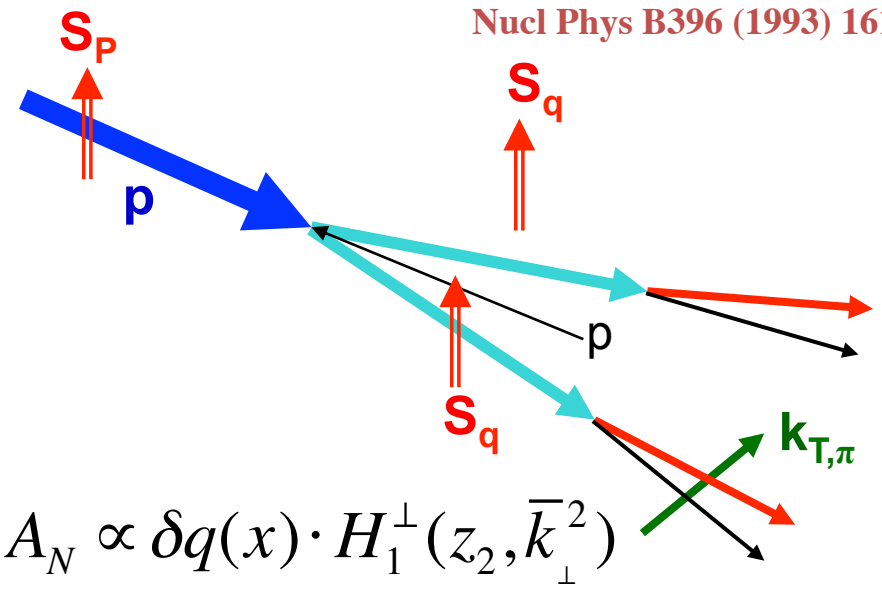
correlation between proton spin & parton k_T



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

(ii) Collins mechanism:

Transversity × spin-dep fragmentation

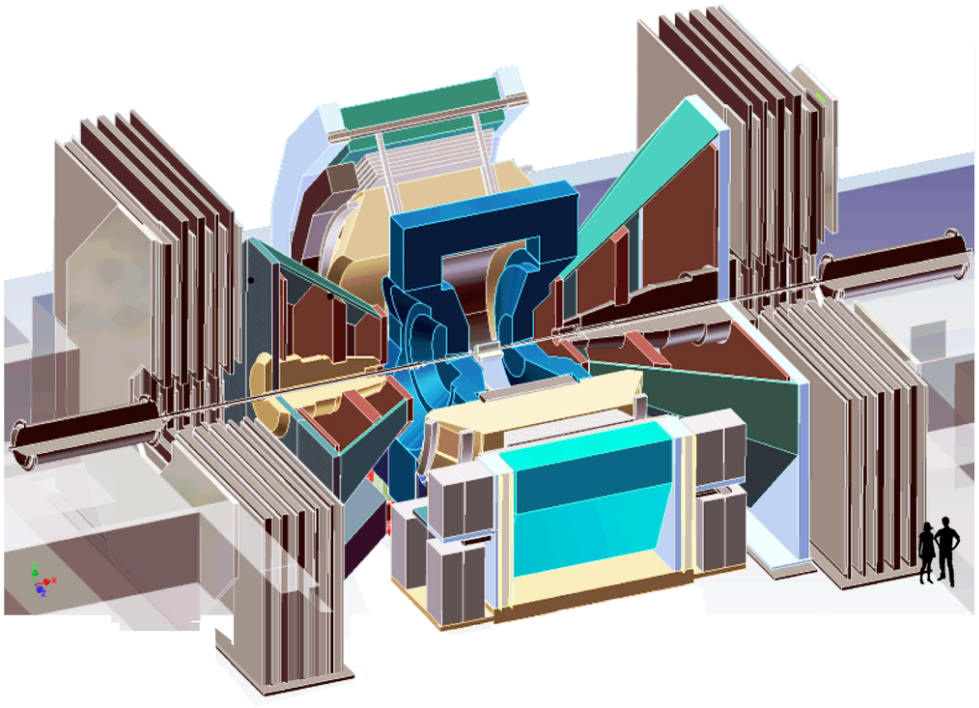


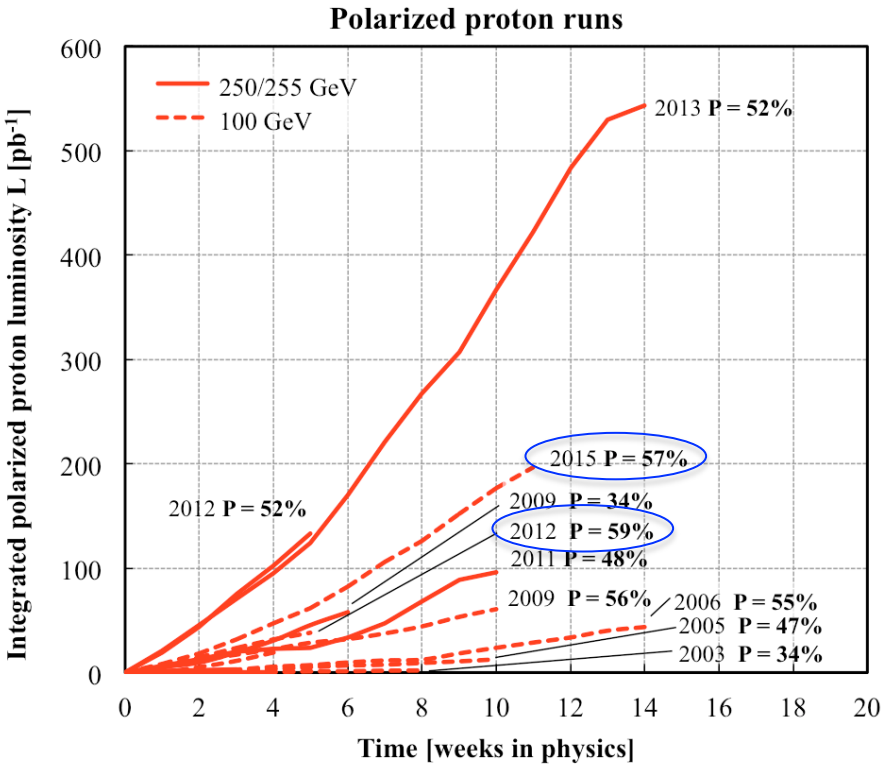
$$A_N \propto \delta q(x)\cdot H_1^\perp(z_2,\bar{k}_\perp^2)$$

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

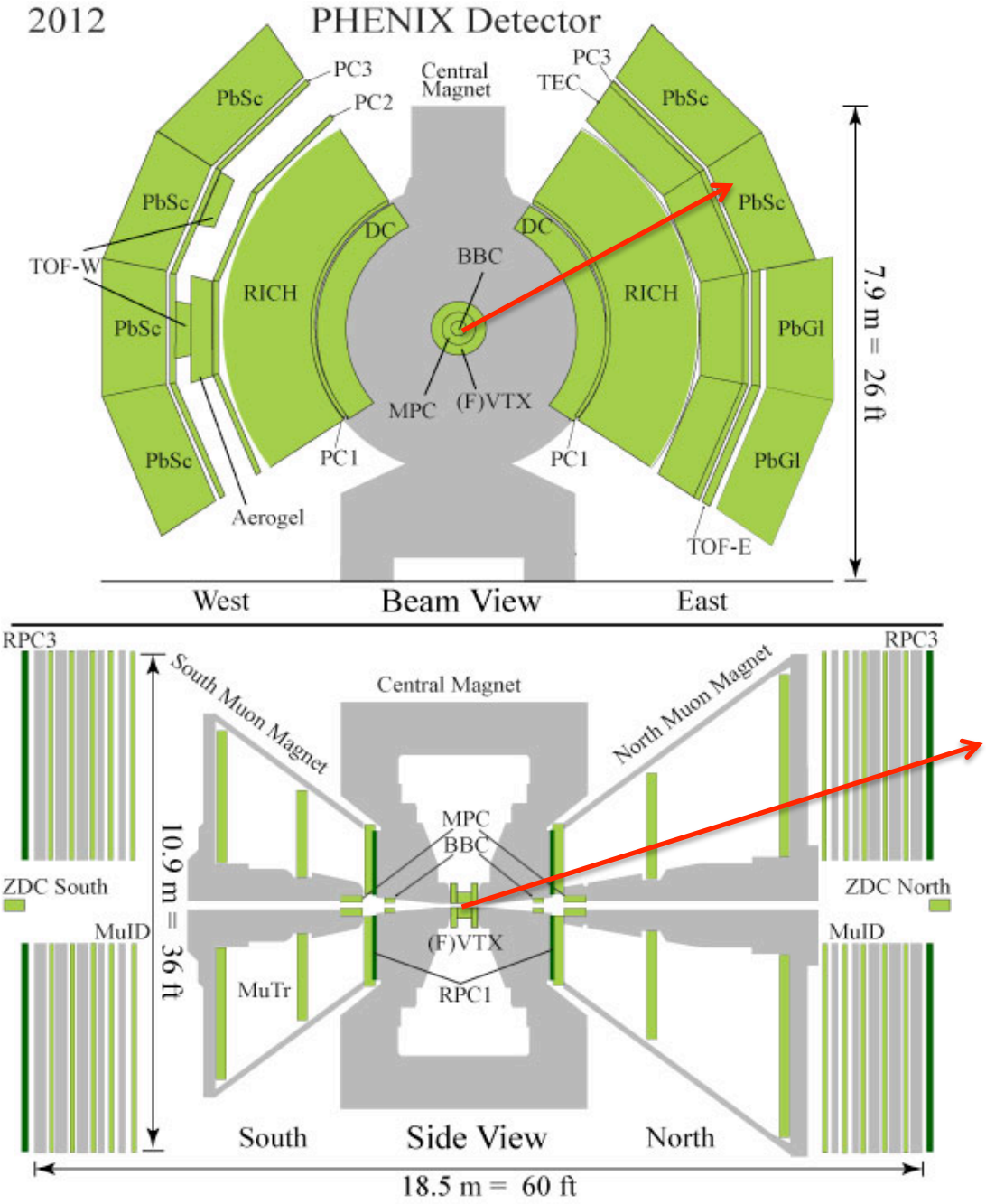
Expectation: at large p_T, $A_N \sim 1/Q \sim 1/p_T$

Recent PHENIX Transverse Spin Runs





Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2015 (Run 15)	200	110 pb^{-1}	57	35 pb^{-1}
2012 (Run 12)	200	9.2 pb^{-1}	59	3.3 pb^{-1}
2008 (Run8)	200	5.2 pb^{-1}	45	1.1 pb^{-1}

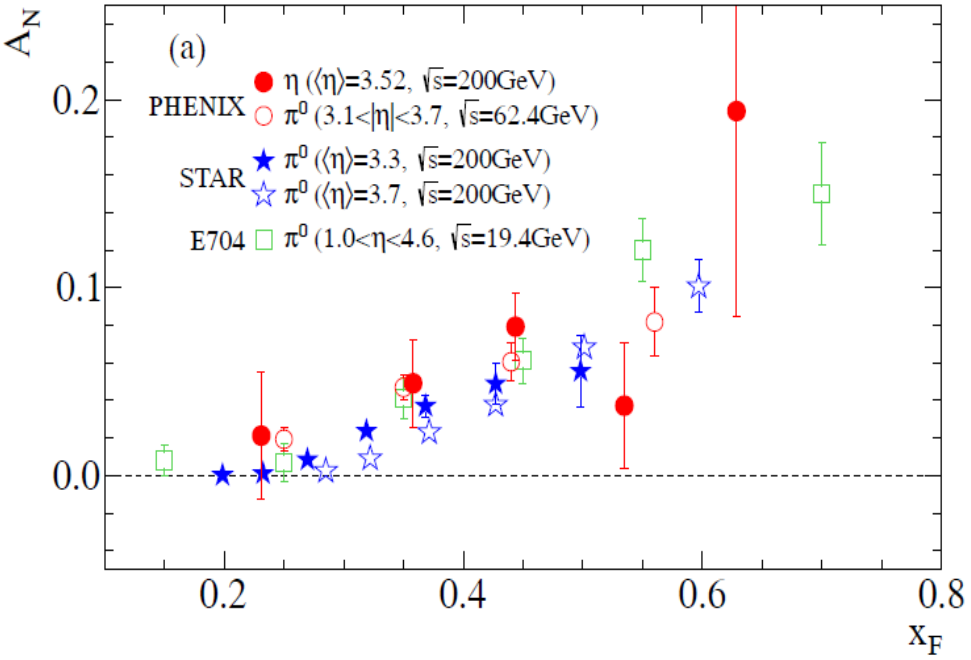


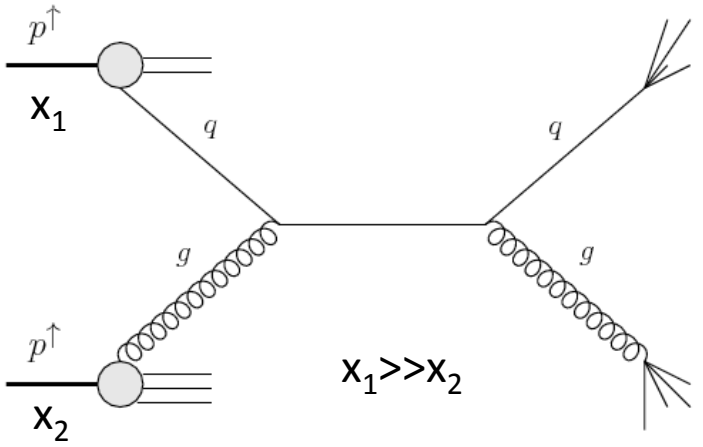
- Philosophy
  - high resolution & high-rate
  - trigger for rare events
- Central Arms
  - $|\eta| < 0.35$, $\Delta\phi \sim \pi$
  - Momentum, EM Energy, PID
  - π^0 and η
- Muon Arms
  - $1.2 < |\eta| < 2.4$
  - Momentum
  - High pT muons
- Muon piston calorimeter
  - $3.1 < |\eta| < 3.9$
  - EM Energy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

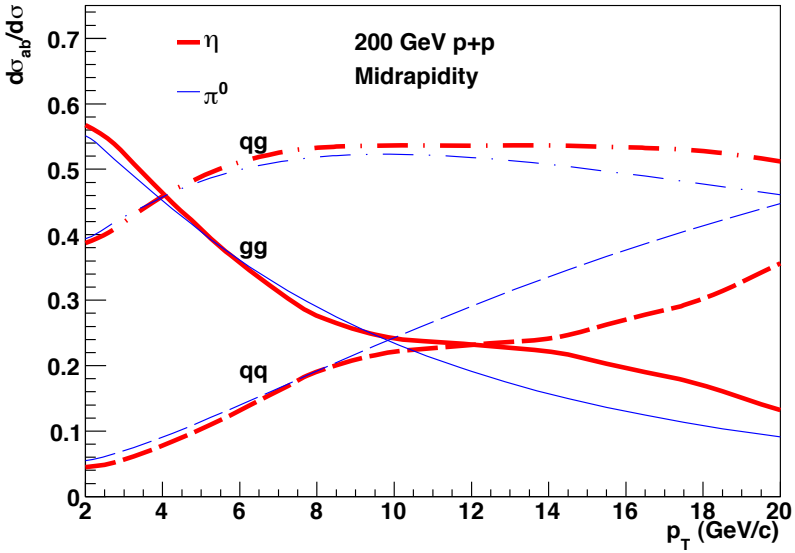
Large TSSA at Forward-Rapidity: π^0 and η

- 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

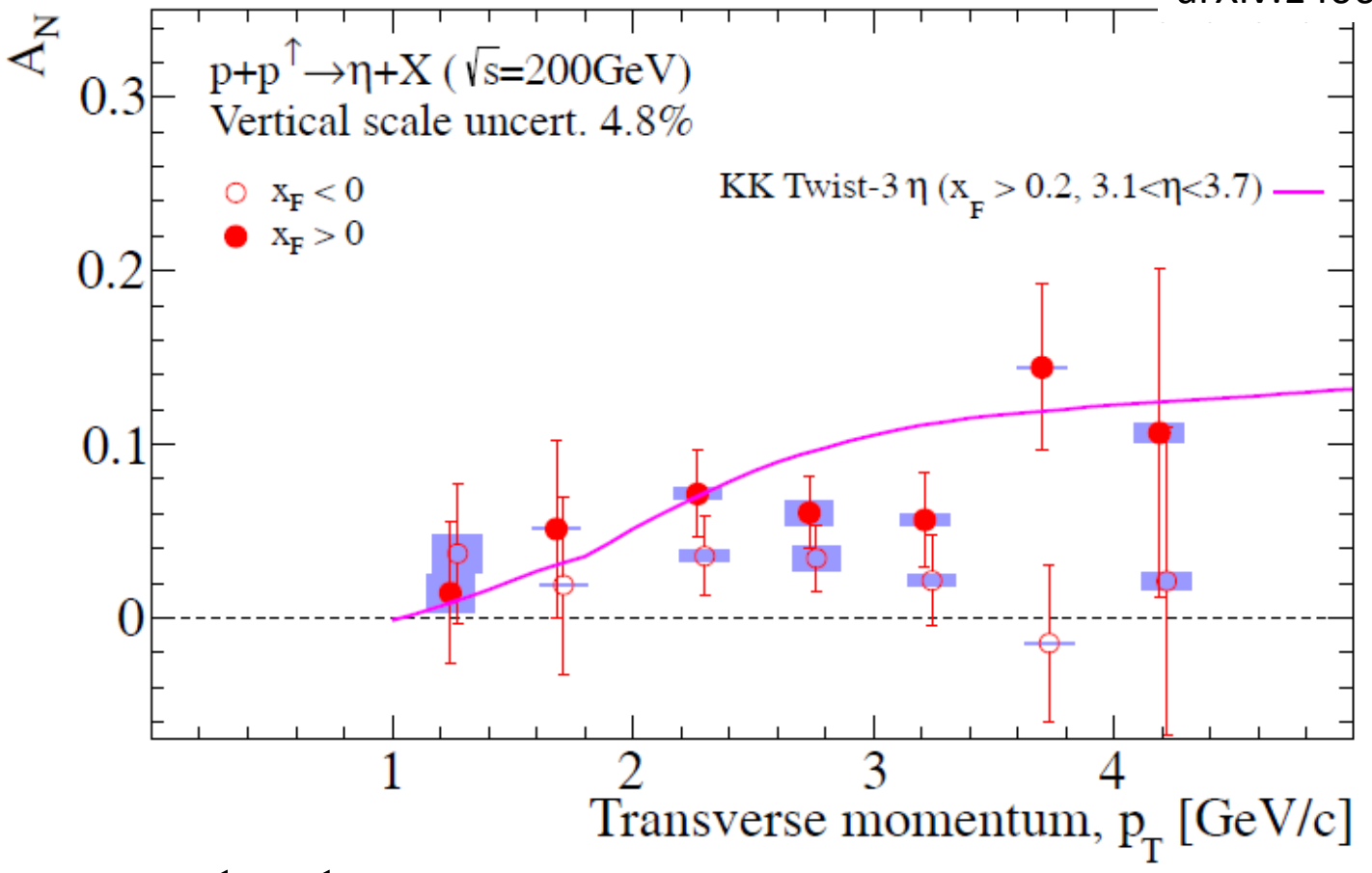






A Puzzle: "little" p_T Dependence

arXiv:1406.3541



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

Naïve expectation at high pT

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

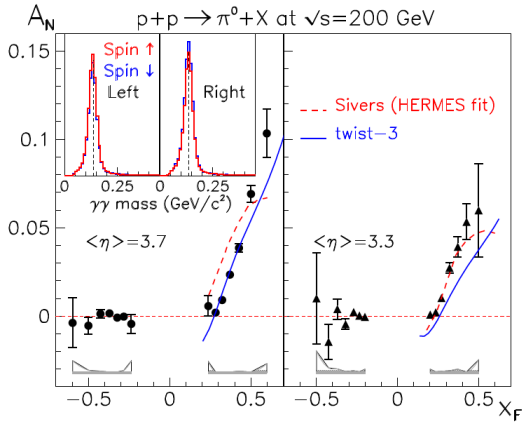
Recent work, Twist-3, Kanazawa & Koike

A Surprise: A_N Sign Mismatch?

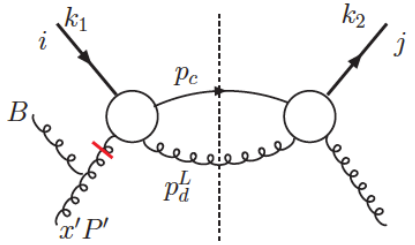
First attempt to check the "Universality of QCD description of TSSA"

Kang, Qiu, Vogelsang, Yuan PRD 2011

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

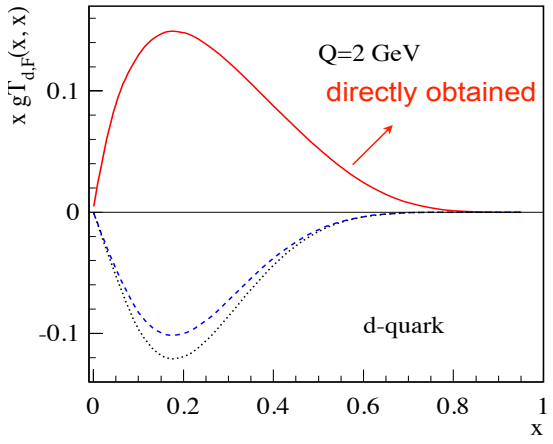


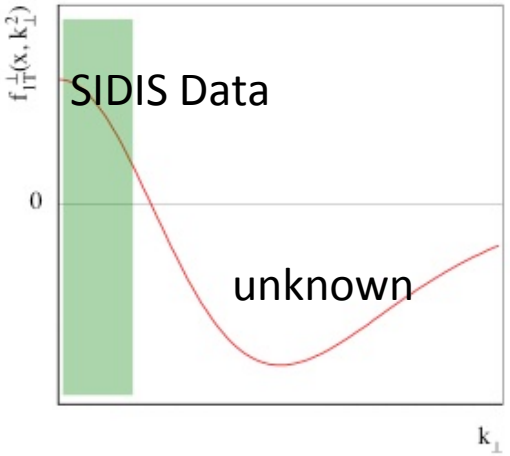
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$



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

A possible solution? Kang, Prokudin PRD (2012)





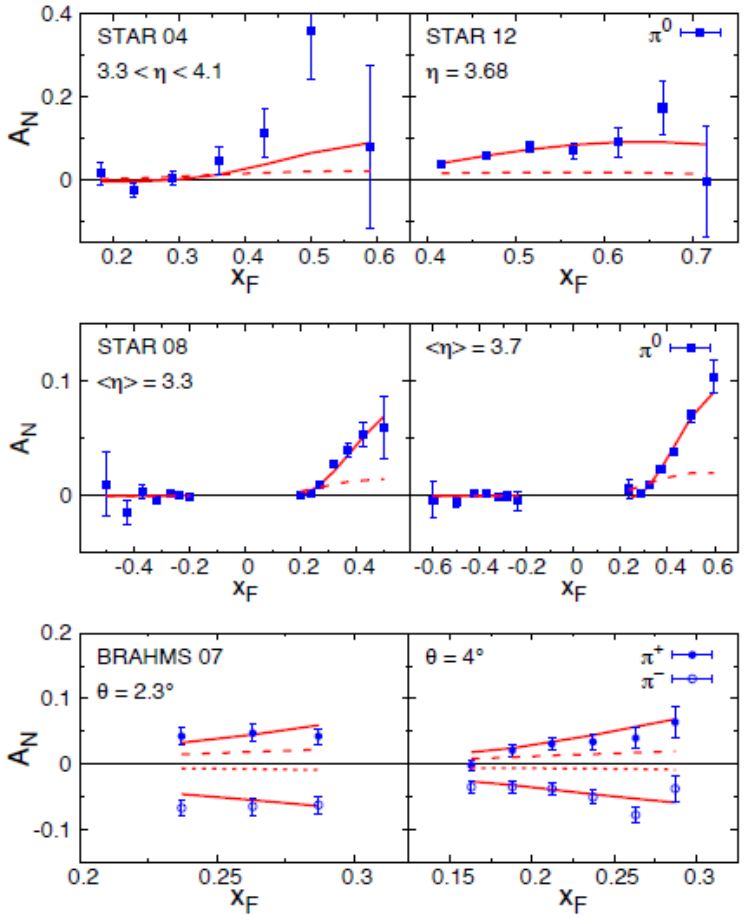
Collins dominates?

Need more data to check other possibilities!

Could "Collins effect" be the Solution?

A_N from twist-3 fragmentation functions

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

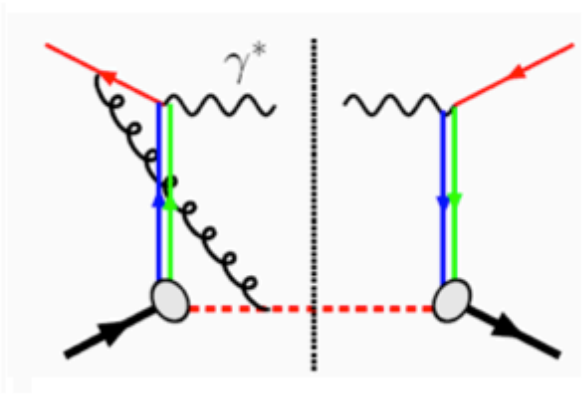


good fit of A_N mainly due to the new twist-3 fragmentation function

Need new direct measurements of Sivers and Collins TSSA in p+p! forward sPHENIX etc.

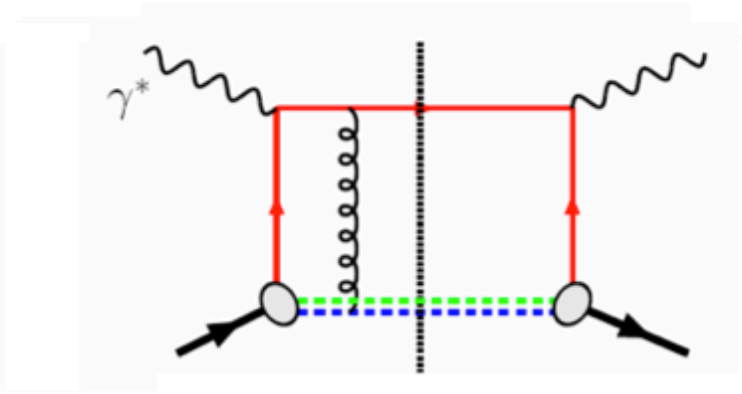
Color Flow in DY and DIS

- The sign change – a new fundamental test of color gauge formalism
- Charm TSSA could provides a new independent experimental test of the underlying physics



$$p^\uparrow + p \to [\gamma^* \to \ell^+\ell^-] + X$$

DY: repulsive



$$\ell + p^\uparrow \to \ell + \pi + X$$

SIDIS: attractive

$$\Delta^N f_{q/h^\uparrow}^{\mathrm{SIDIS}}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\mathrm{DY}}(x, k_\perp)$$

Collins '02

Twist-3: sign change from gluonic-pole in hard parts

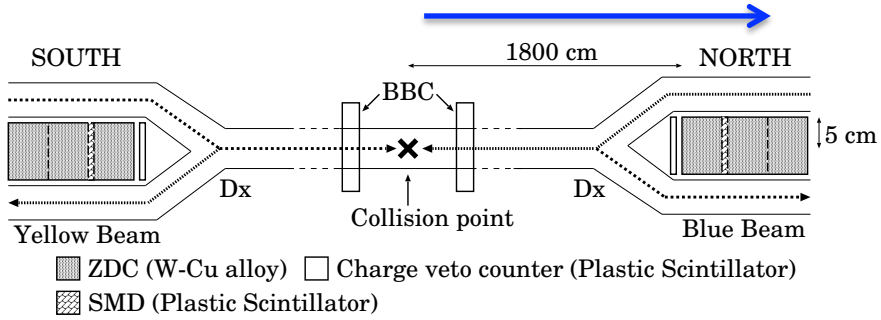
In the overlapped region – consistent description

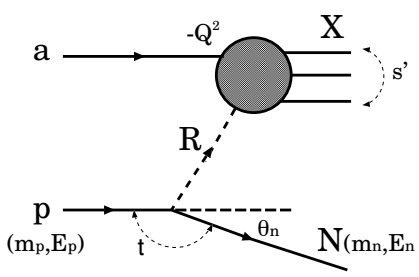
Ji, Qiu, Vogelsang, Yuan '06
Bacchetta, Boer, Diehl, Mulders '08

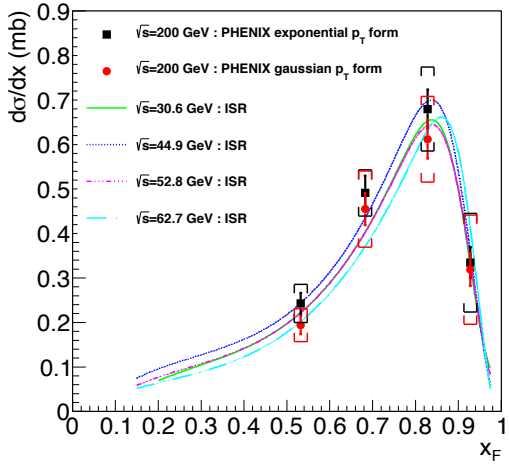
Run15 p+Au: a Surprise?

Forward Leading Neutron A_N

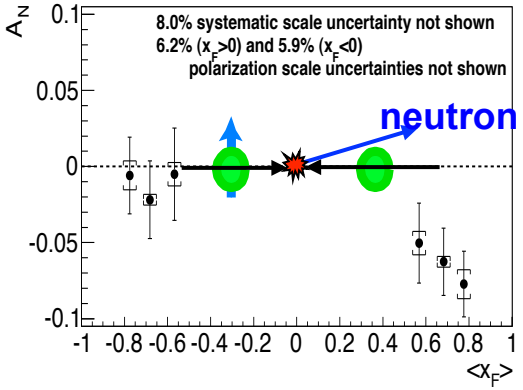
- **A very interesting pAu asymmetries is observed compared to that of pp (work in progress).**
- **A growing interest among the spin group to measure A_N for pAl**

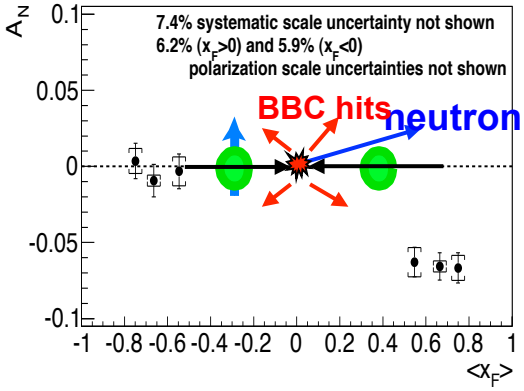






Phys. Rev. D 88, 032006 (2013)





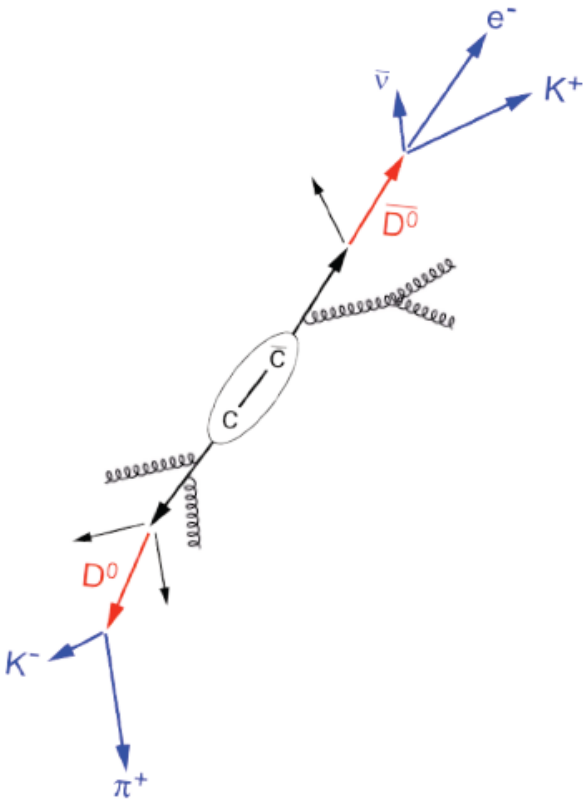
The Goals of Heavy Flavor TSSA Study

Experimental Study of the Color Flow via Open Heavy Quark TSSA

- Poorly known Gluon's Sivers/Twist-3 functions
  - New dynamics and phenomena
- Current understanding of TSSA based on the color gauge invariant QCD formalism
  - TMD, Twist-3 …
  - Expect significant difference between A_N(c) and A_N(c-bar)
- The process dependence of TSSA could be tested experimentally
  - DY vs DIS
  - Charm (quark) vs anti-charm (anti-quark)
  - Other processes ..

Nice Things about Heavy Quarks Produced in p+p Collisions at RHIC

- Experimentally tag Fermion and anti-Fermion
- Theoretically "well-controlled" pQCD
  - $M_Q >> \Lambda_{QCD}$
  - Hard fragmentation
- Gluon-gluon processes
  - No Collins effects
  - Sensitive to the initial state correlations such as tri-gluon correlation functions



Heavy Flavor TSSA @RHIC

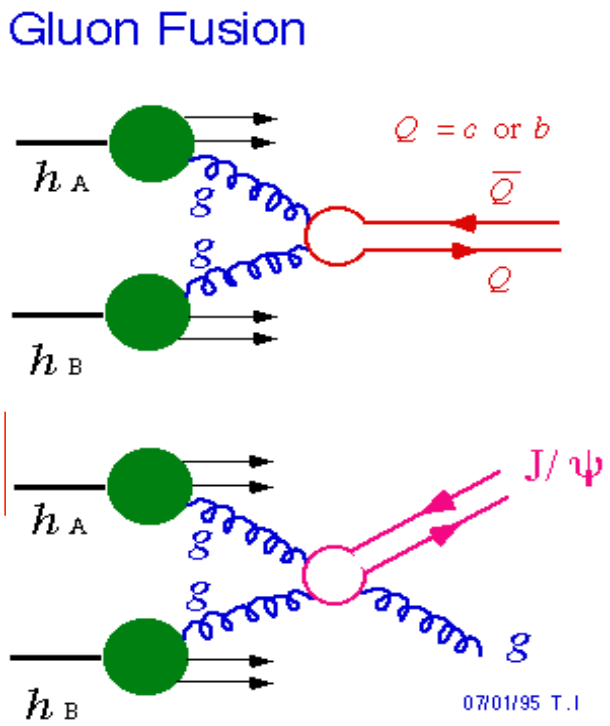
- Sensitive to gluon Sivers function
  * probe gluon's orbital angular momentum?
    -- Minimize Collins' effects
  * heavy flavor production dominated by gluon gluon fusion at RHIC energy
    Pythia 6.1 simulation (LO)

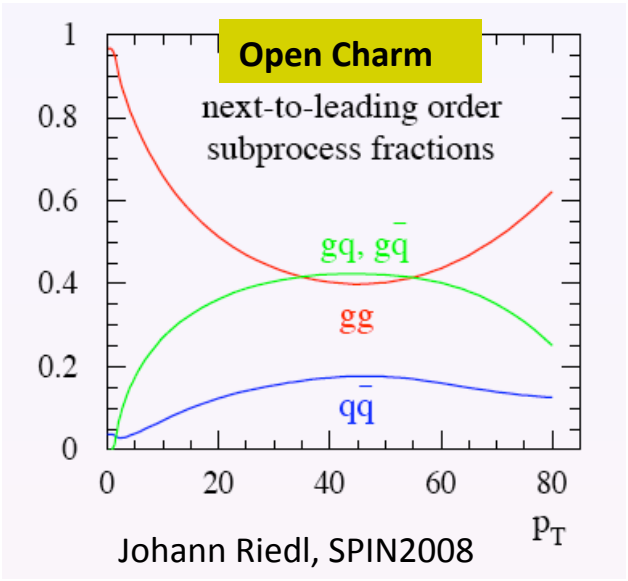
$$c\bar{c}: \; gg \rightarrow c\bar{c} \quad 95\%$$
$$b\bar{b}: \; gg \rightarrow b\bar{b} \quad 85\%$$

  * gluon has zero transversity

- Tri-gluon correlation functions

- Also sensitive to J/ψ production mechanisms and QCD dynamics





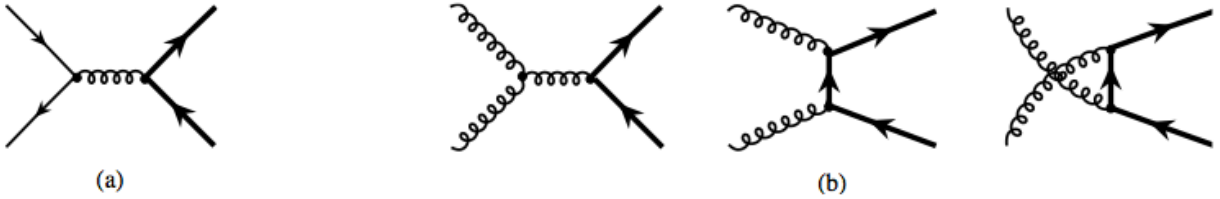
Johann Riedl, SPIN2008

TSSA in Heavy Quark Production in p+p

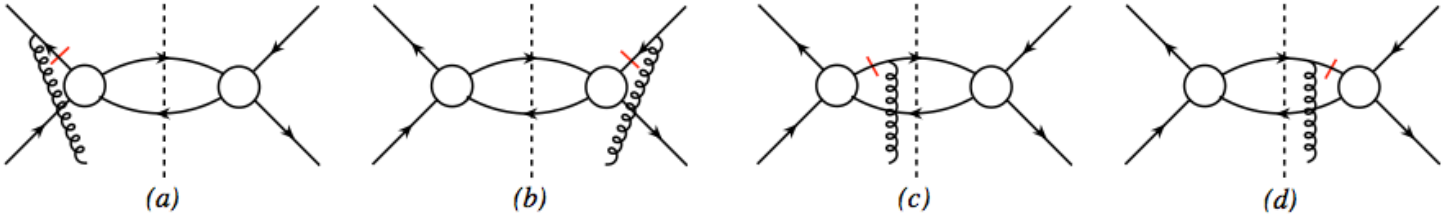
Kang, Qiu, Vogelsang, Yuan, PRD 2008

D-meson production in hadronic collisions

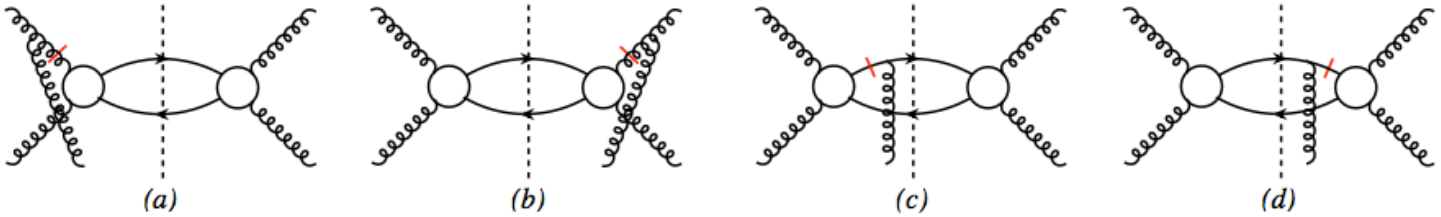
- Two partonic subprocesses:



- Quark-antiquark annihilation:



- Gluon-gluon fusion:



Open Charm TSSA in Twist-3 Approach

Factorized formula for D-meson production

Qiu, 2010

- Same factorized formula for both subprocesses:

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\Big|_{q\bar{q}\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_q \int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{\bar{q}/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\left(T_{q,F}(x,x)-x\frac{d}{dx}T_{q,F}(x,x)\right)H_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})+T_{q,F}(x,x)\mathcal{H}_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})\right],$$

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\Big|_{gg\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_{i=f,d} \int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{g/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\left(T_G^{(i)}(x,x)-x\frac{d}{dx}T_G^{(i)}(x,x)\right)H_{gg\to c}^{(i)}(\tilde{s},\tilde{t},\tilde{u})+T_G^{(i)}(x,x)\mathcal{H}_{gg\to c}^{(i)}(\tilde{s},\tilde{t},\tilde{u})\right],$$

- Hard parts:

$$H_{q\bar{q}\to c}=H_{q\bar{q}\to c}^{I}+H_{q\bar{q}\to c}^{F}\left(1+\frac{\tilde{u}}{\tilde{t}}\right) \qquad H_{gg\to c}^{(i)}=H_{gg\to c}^{I(i)}+H_{gg\to c}^{F(i)}\left(1+\frac{\tilde{u}}{\tilde{t}}\right)$$

All $\mathcal{H}_{q\bar{q}\to c}$ and $\mathcal{H}_{gg\to c}^{I(i)}$ and $\mathcal{H}_{gg\to c}^{F(i)}$ vanish as $m_c^2\to 0$

- Hard parts change sign for $T_G^{(d)}(x,x)$ when $c\longrightarrow\bar{c}$

$$H_{gg\to\bar{c}}^{(f)}=H_{gg\to c}^{(f)}, \qquad H_{gg\to\bar{c}}^{(d)}=-H_{gg\to c}^{(d)},$$
$$\mathcal{H}_{gg\to\bar{c}}^{(f)}=\mathcal{H}_{gg\to c}^{(f)}, \qquad \mathcal{H}_{gg\to\bar{c}}^{(d)}=-\mathcal{H}_{gg\to c}^{(d)}.$$

Charm and anti-Charm TSSA and Color Structure

- Quark and anti-Quark have different color factors in hard scatterings
- Experimentally Charm (quark) and anti-Charm (anti-quark) can be identified through their decays into muons,

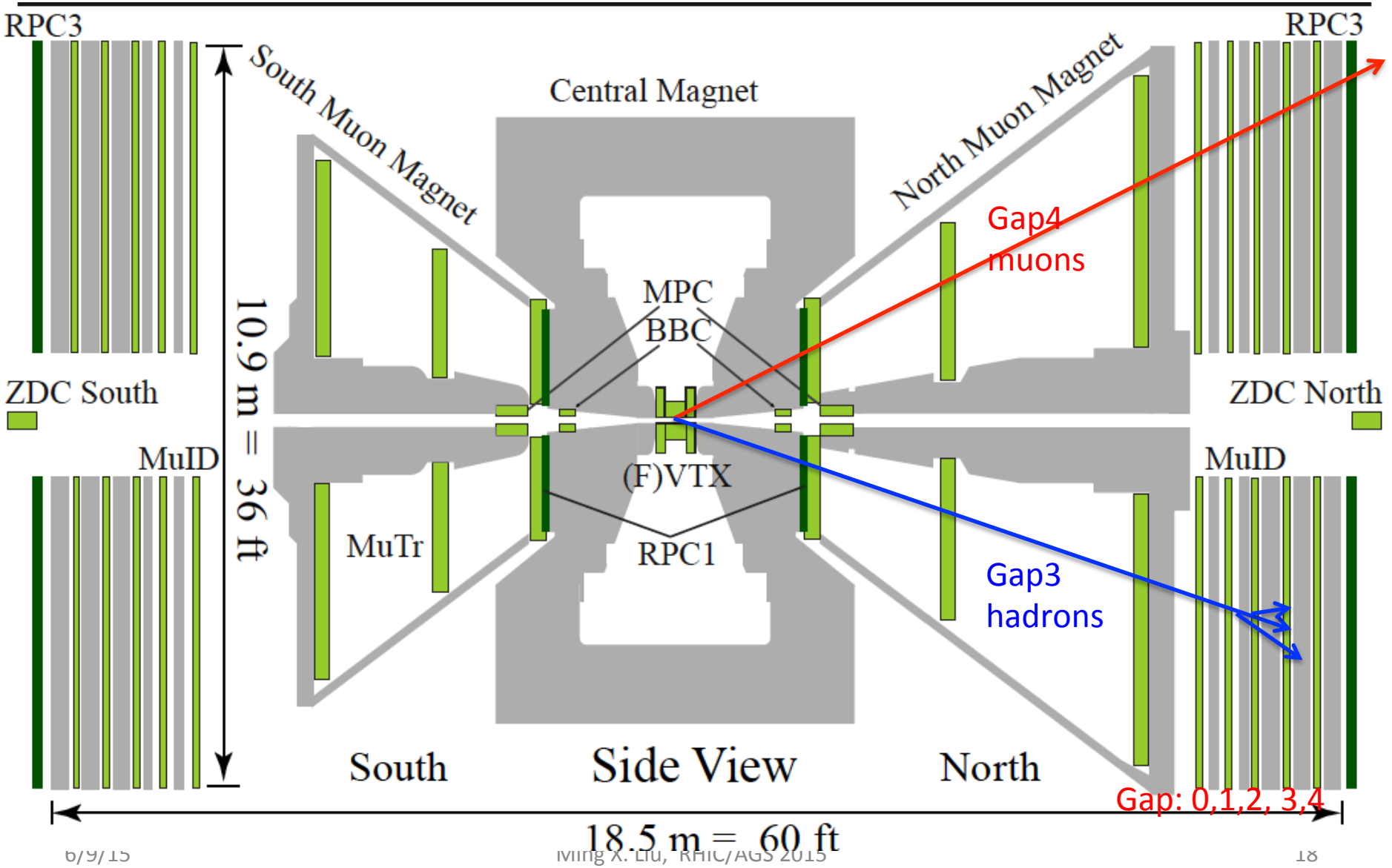
$$A_N(c): \quad c \to \mu^+ + X$$
$$A_N(\bar{c}): \quad \bar{c} \to \mu^- + X$$

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

- A_N(charm) provide new insight to the underlying physics of TSSA
  - Directly test the different color structure for quark and anti-quark

A new clean experimental test of the color coupling to quark vs antiquark in hard scatterings!

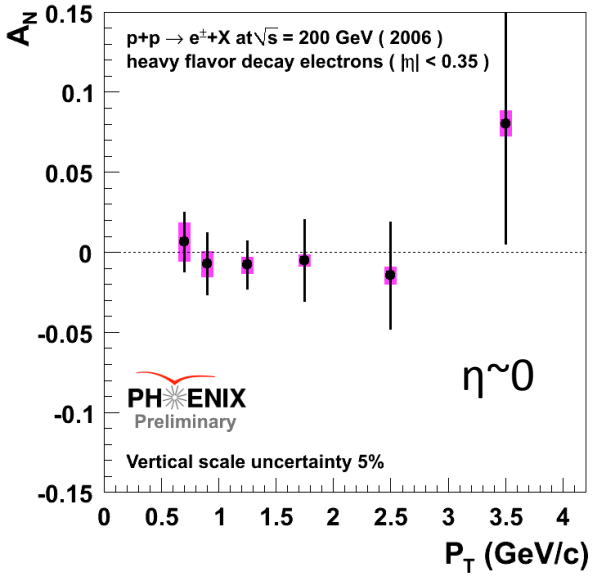
Reconstructed "Muons" tagged at various Gaps
stopped hadrons and muons

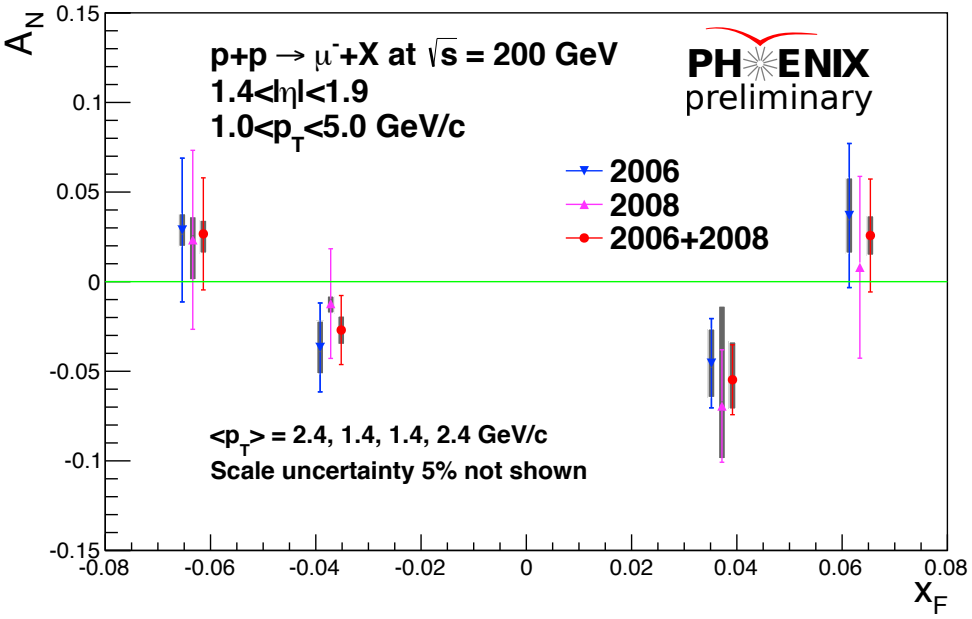


Open Heavy Quark A_N

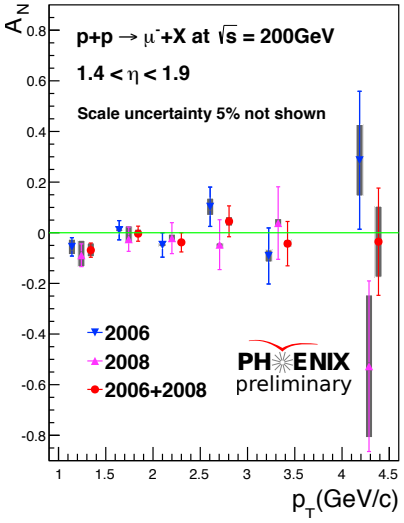
- Forward/backward and central Muon arms
  - Run6, 8
  - Run12 preliminary
  - Run15, much improved w/FVTX (Run15)

NEW

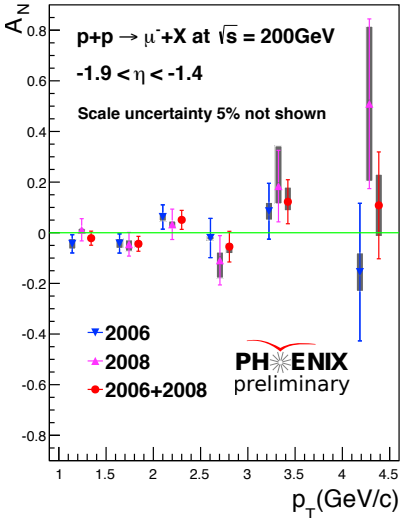




η >>0

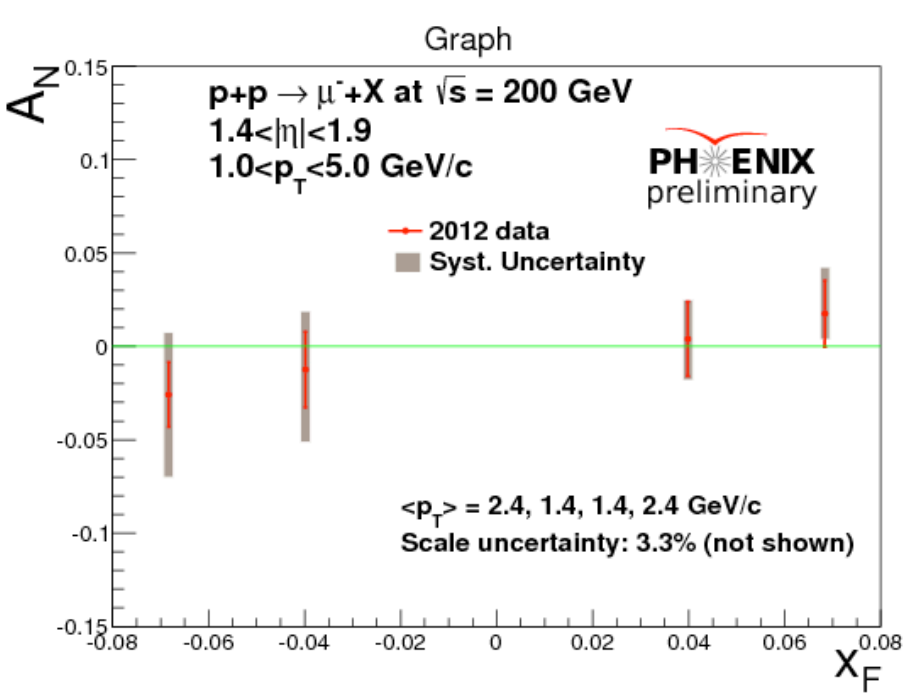


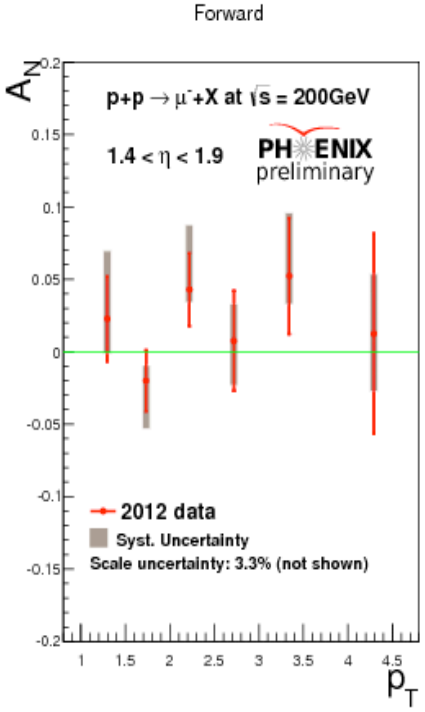
η << 0

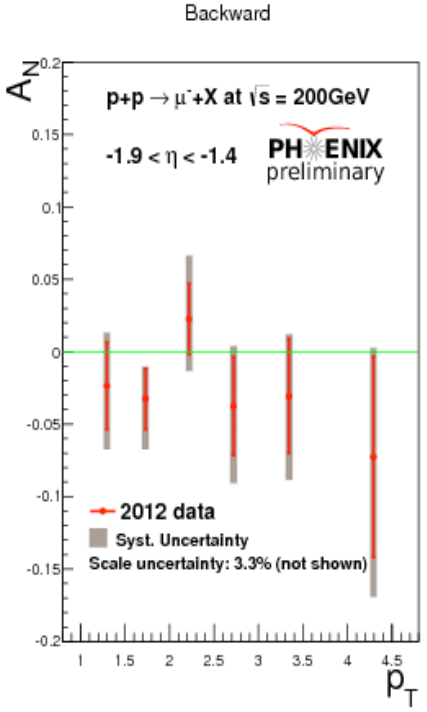


NEW

Run12pp: Heavy Flavor Muon A_N

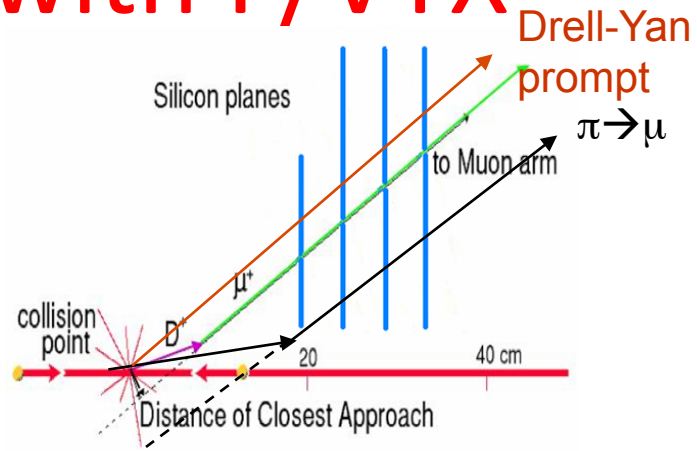




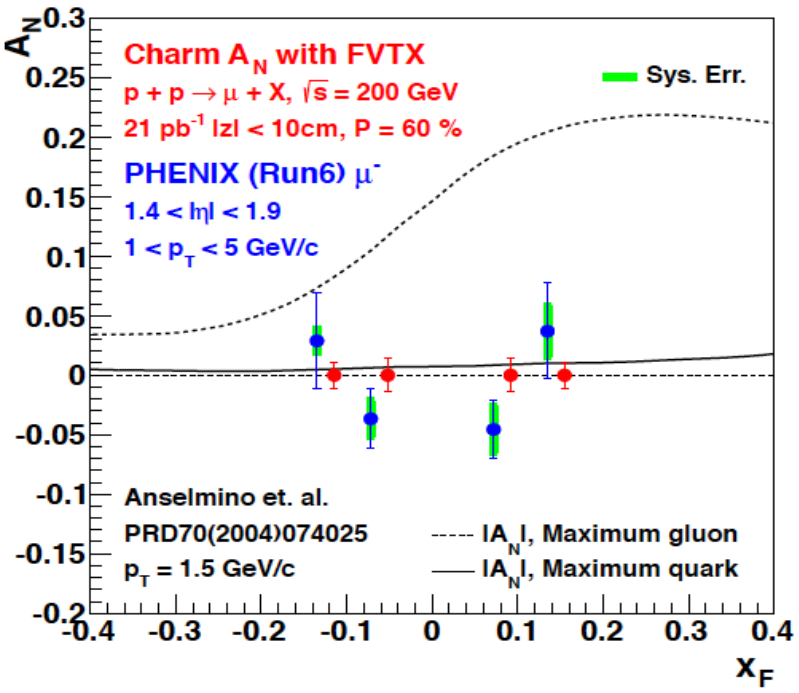


Run 2015 p+p & p+A with F/VTX

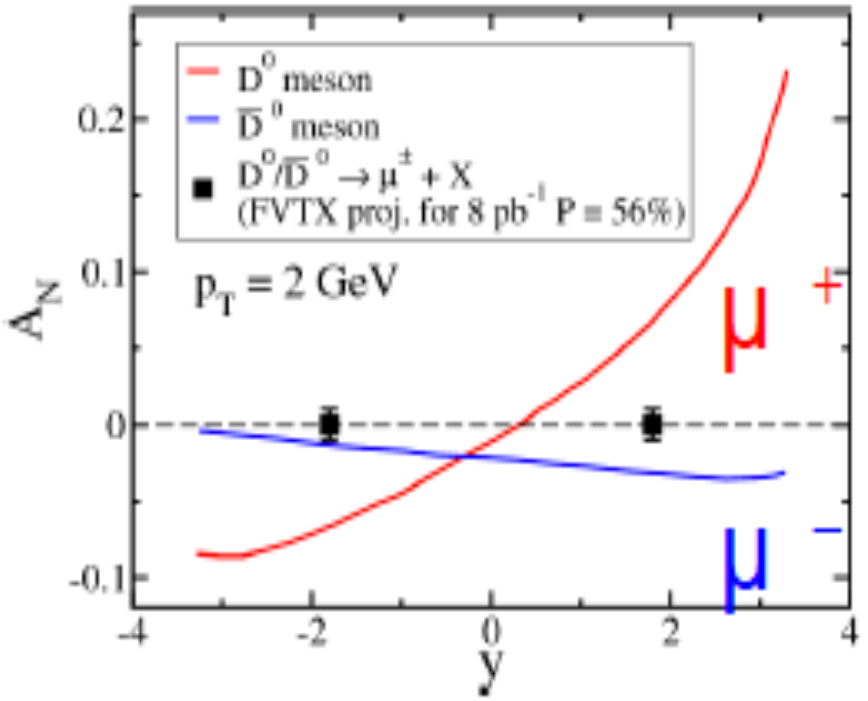
- Expect much improved results from Run 15
  - 110 pb^{-1}, Pol = 57% (Run15)
  - 10x FOM(Run12)



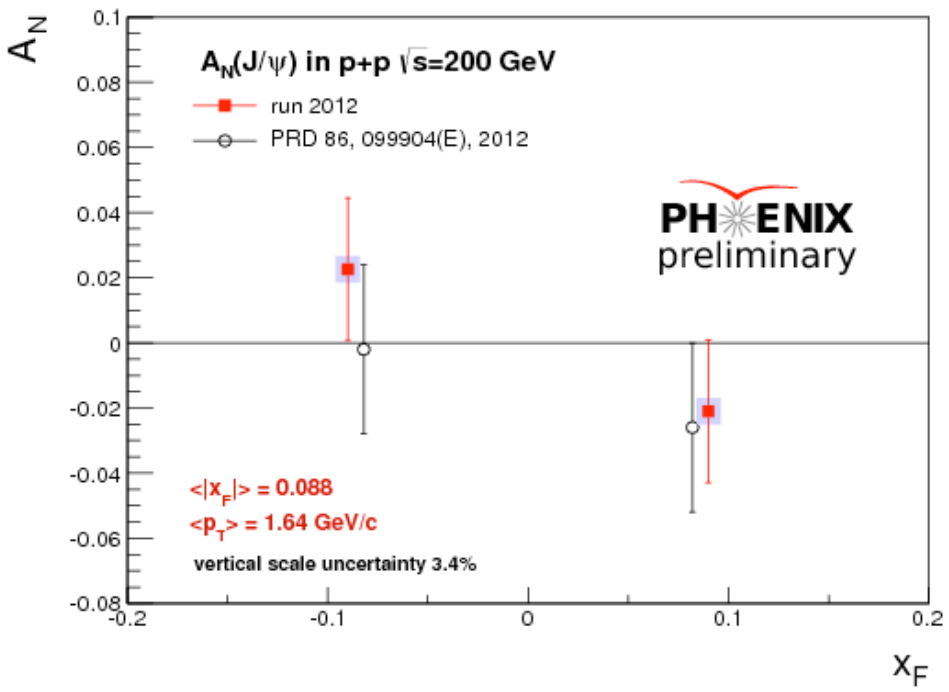
GTMD model

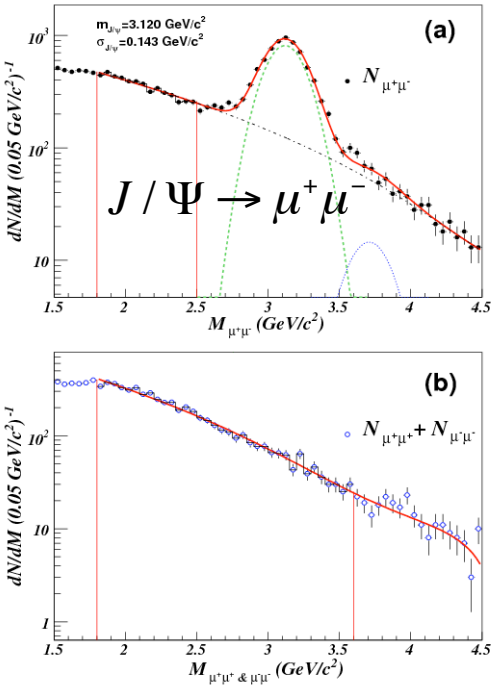


Twist-3 Approach

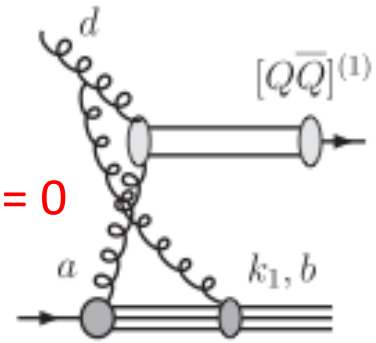


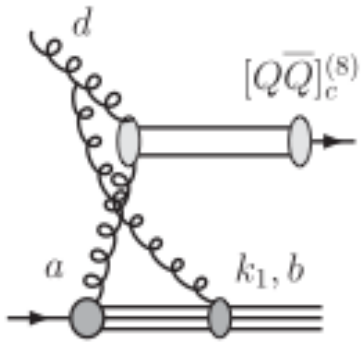
Heavy Flavor: Forward J/ψ A_N



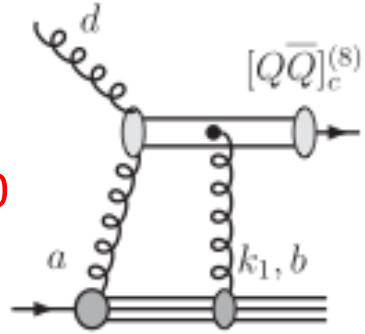


A_N != 0





A_N =0



F. Yuan, PRD 78, 014024(2008)

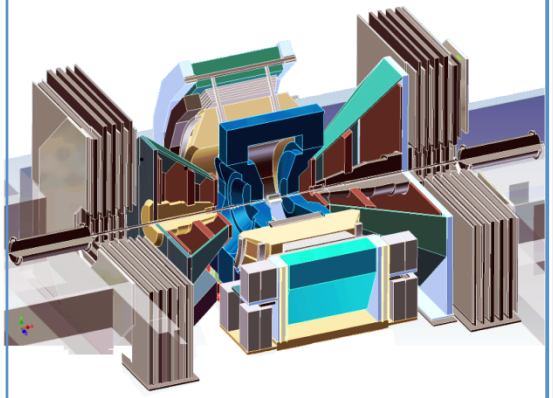
A few Observations and Comments

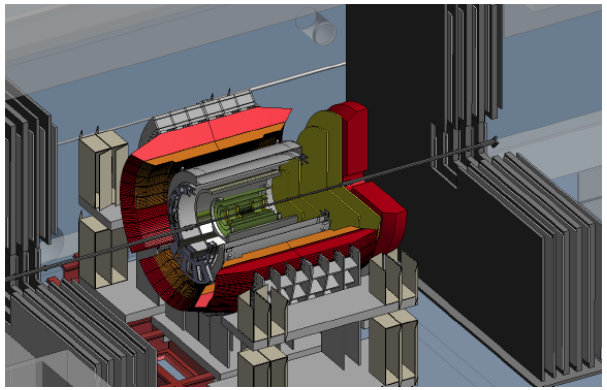
- Twist-3 and TMD Parton Model
  - Color gauge approach
  - Works reasonably well in their own kinematic domains
- Quark sector: good knowledge
  - Quark Sivers and Collins functions
  - Twist-3 quark-gluon correlation functions
- Gluon sector: largely unknown
  - Gluon Sivers function(s)??
  - Twist-3 tri-gluon correlation functions
- Next experimental steps for p+p
  - Heavy quark probe!
    - Directly access the color charge coupling to quark and anti-quark
  - Multi probes in a wide kinematic range
    - Drell-Yan, W/Z, direct-photon etc.
- It is all about the color dynamics in hard scattering
  - TSSA @RHIC-SPIN
  - p/d+A @RHIC
  - Jlab-12, EIC…

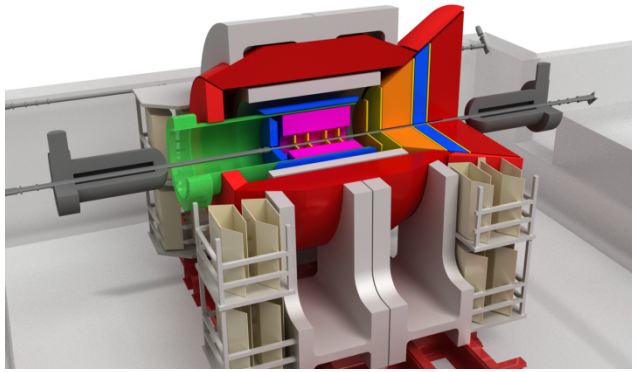
PHENIX -> Forward/sPHENIX->ePHENIX

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







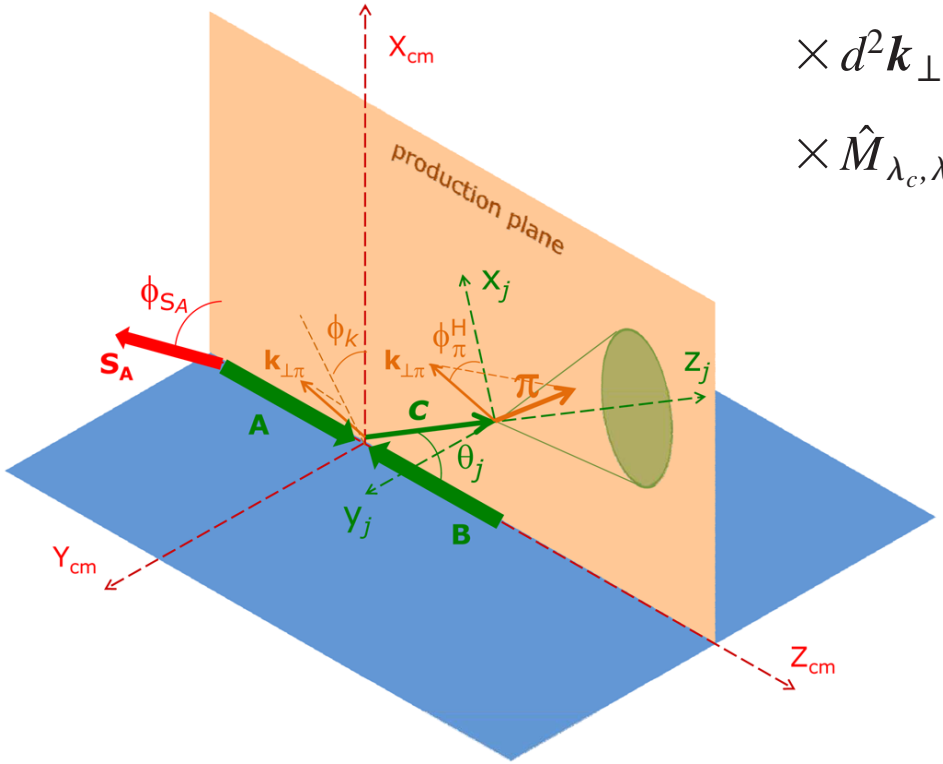
~2000 2017→2020 ~2025 Time

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:

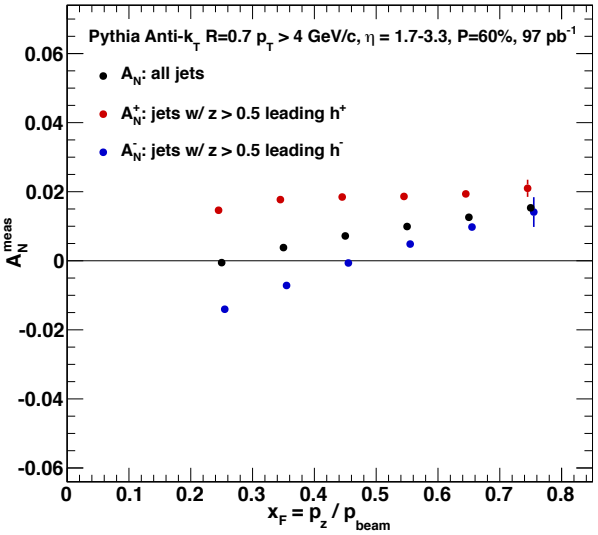
- Jet P_j, xF
- Hadron P_h , PID
- Beam polarization

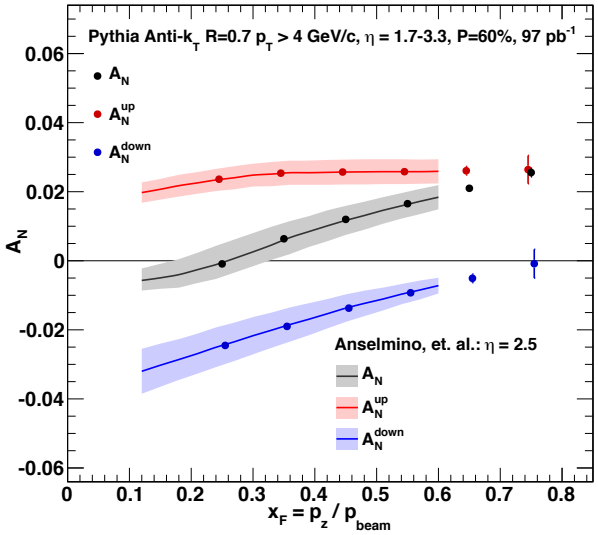
$A_N^{\sin\phi_{S_A}}$ → "Sivers-like"

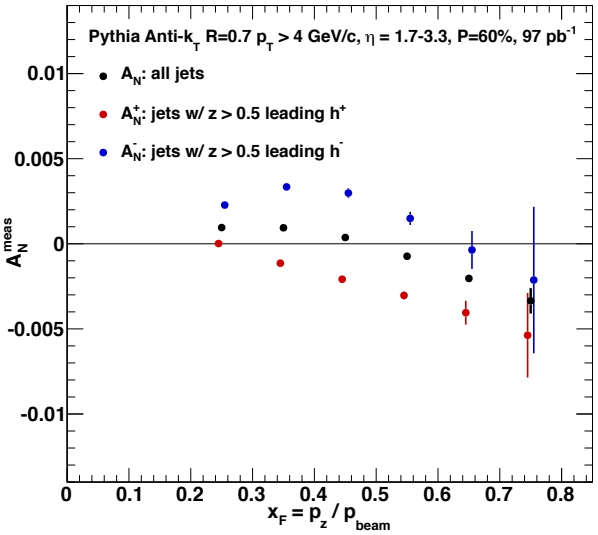
$A_N^{\sin(\phi_{S_A} \mp \phi_\pi^H)}$ → "Collins-like"

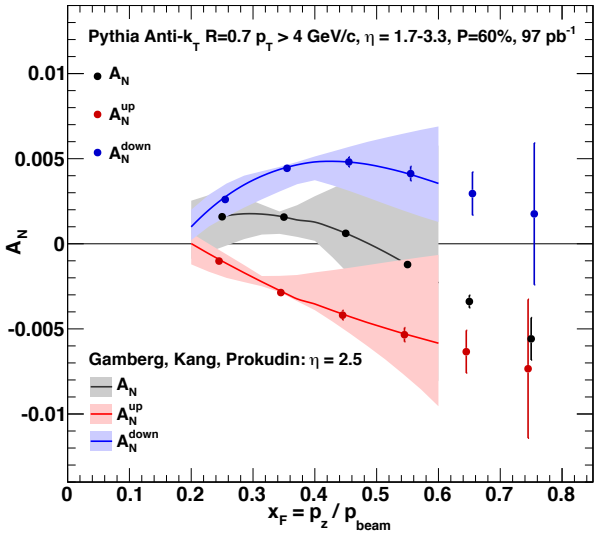
fsPHENIX Projected Jet Sivers Asymmetries

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



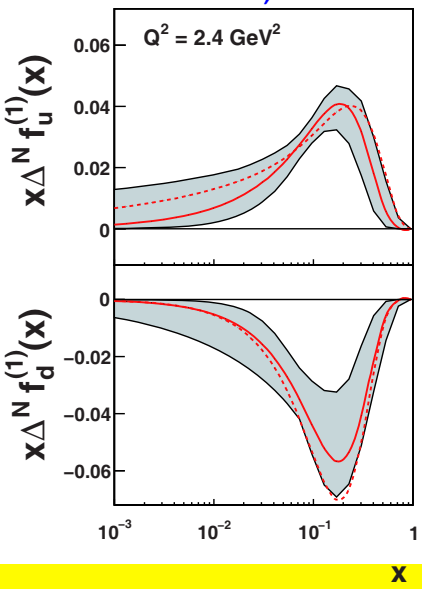






Naïve direct mapping from SIDIS Sivers (GPM)
- "u-quark jet" A_N >0

Sivers, SIDIS fit



With process-dep from SIDIS Sivers (Twist-3)
- "u-quark jet" A_N < 0

Summary and Outlook

- Experimental confirmation (or disproval) of color dynamics in hard scattering is a critical step toward the full understanding of TSSA
  - Charm vs anti-Charm
  - Drell-Yan/W/Z
  - Direct photons

- Future experimental prospects – exciting opportunity!
  - RHIC
    - Forward sPHENIX
  - EIC