Transverse Spin Physics at PHENIX

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Key word: **SSA** = Single Spin Asymmetry

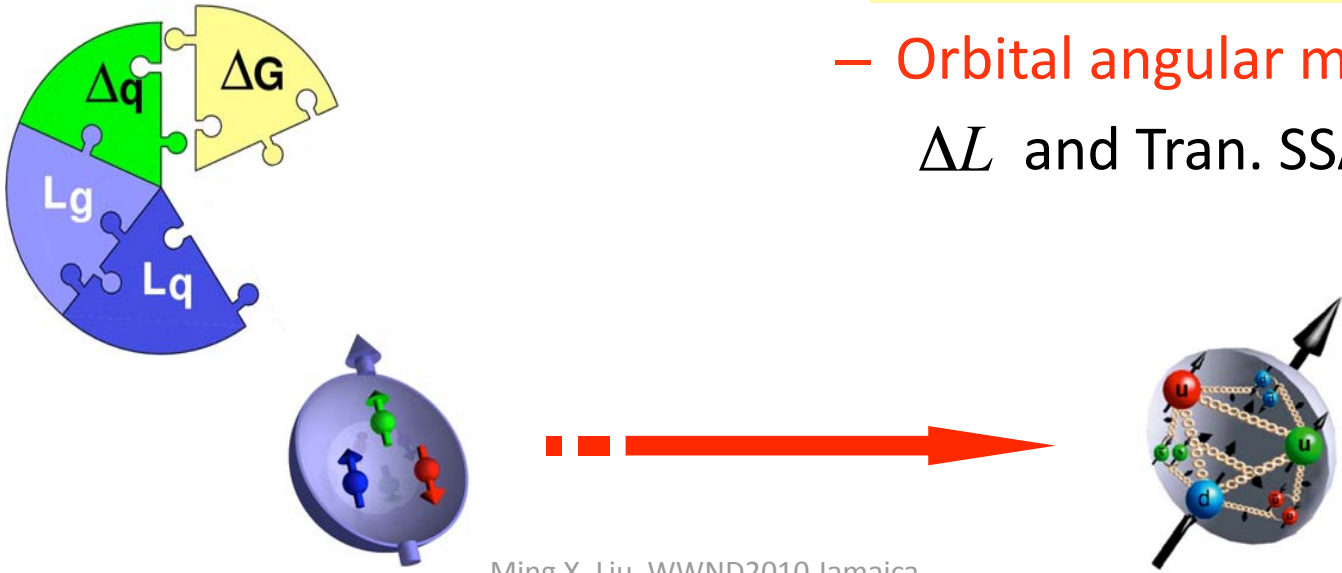
Surprises in Spin Physics (I)

the challenge of "Too Small"

- Proton Spin Puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_q + \Delta L_g$$

$$\Delta\Sigma \sim 0.3! \quad (\sim 1.0\ \mathrm{exp}\,ected)$$



- Spin Physics @RHIC
  - Gluon polarization

$$\Delta G = \int_0^1 dx \cdot \Delta g(x)$$

  - Quark polarization

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \ldots$$

  - Orbital angular mom.?

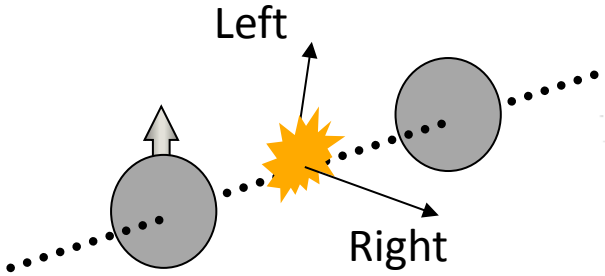
ΔL and Tran. SSA A_N

Surprises in Spin Physics (II)

the challenge of "Too Big"

Transverse Single Spin Asymmetries A_N

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



Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N ~ O(10^{-4}) theory

Experiments:

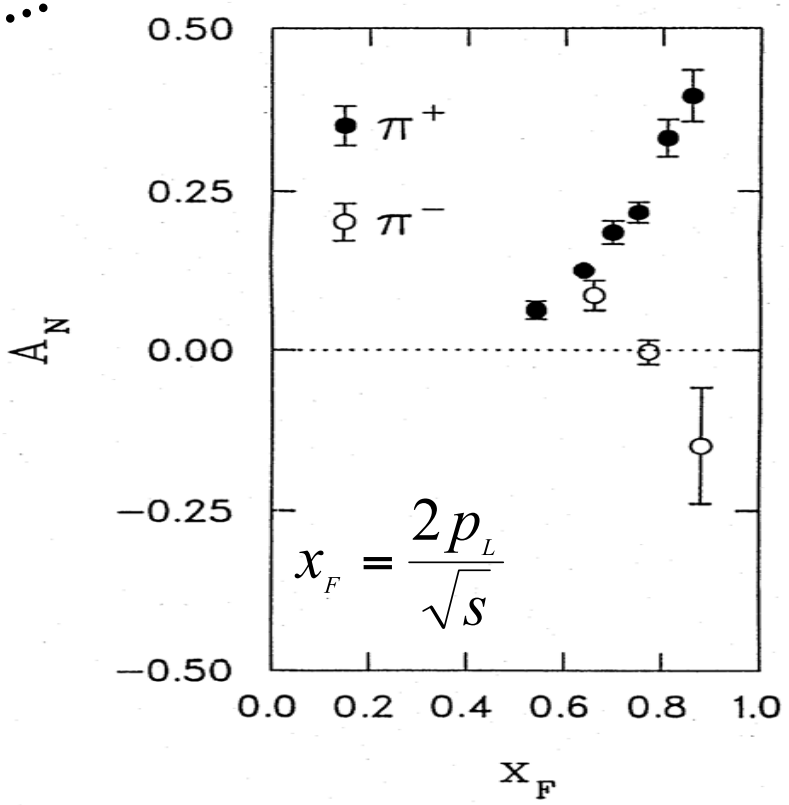
ZGS, AGS, FERMILAB to RHIC

$$pp^{\uparrow} \rightarrow \pi + X$$

A_N ~ O(10^{-1}) observed

$$\sqrt{s} = 5 \sim 500 \text{ GeV}$$

Argonne ZGS, p_{beam} = 12 GeV/c

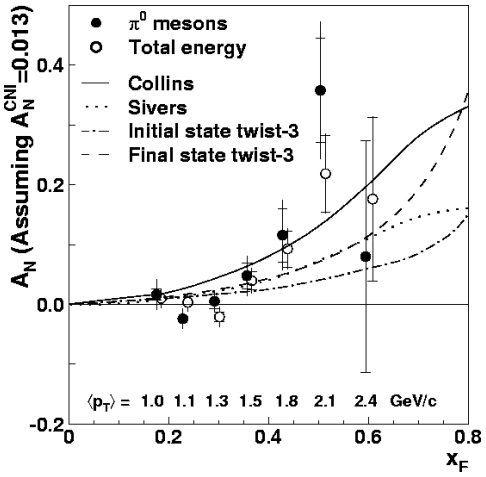


W.H. Dragoset et al., PRL36, 929 (1976)

Transverse SSA's

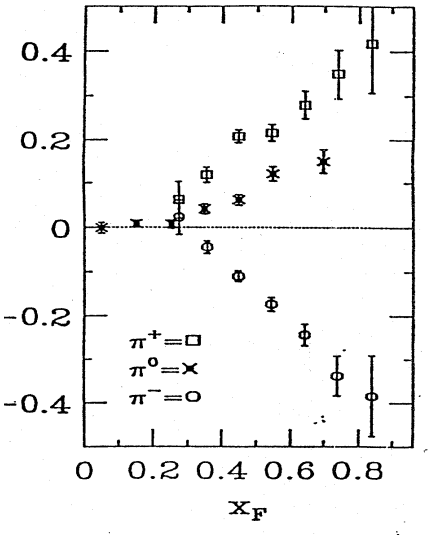
from low to high energies

RHIC 20,000 GeV beam



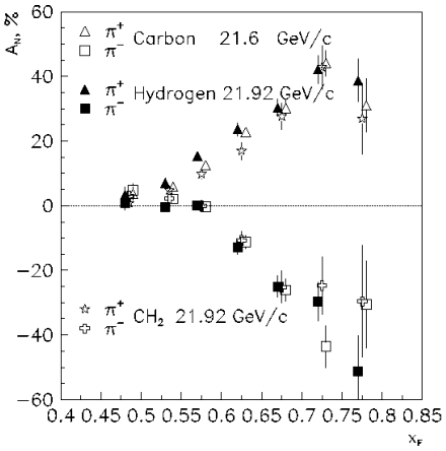
PRL (2004)

FNAL 200 GeV beam



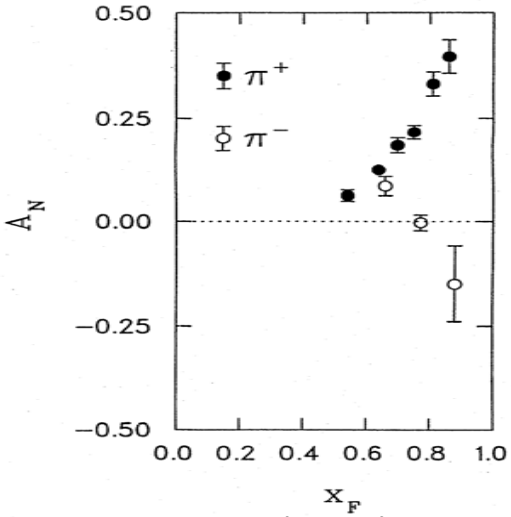
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam



PRD65, 092008 (2002)

ZGS 12 GeV beam



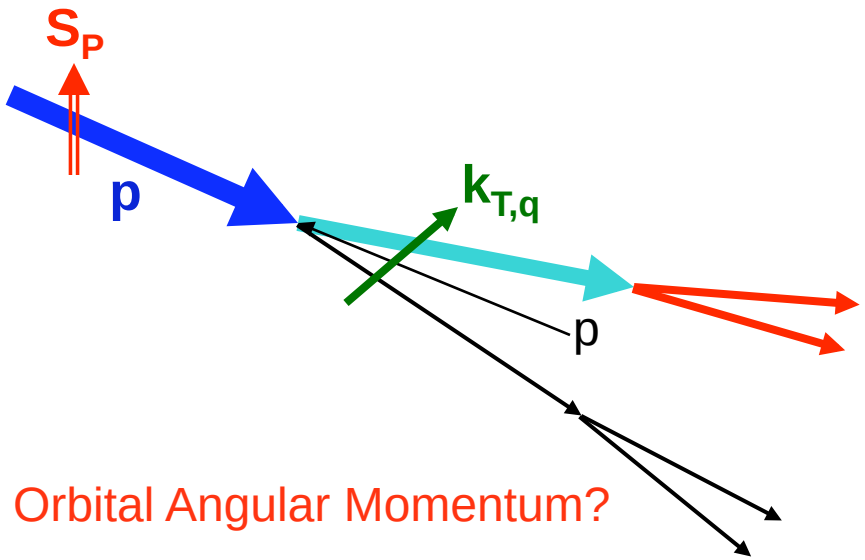
PRL36, 929 (1976)

Non-Perturbative cross section → Perturbative cross section

Possible Mechanisms …

Sivers mechanism: Correlation between nucleon spin and parton k_T

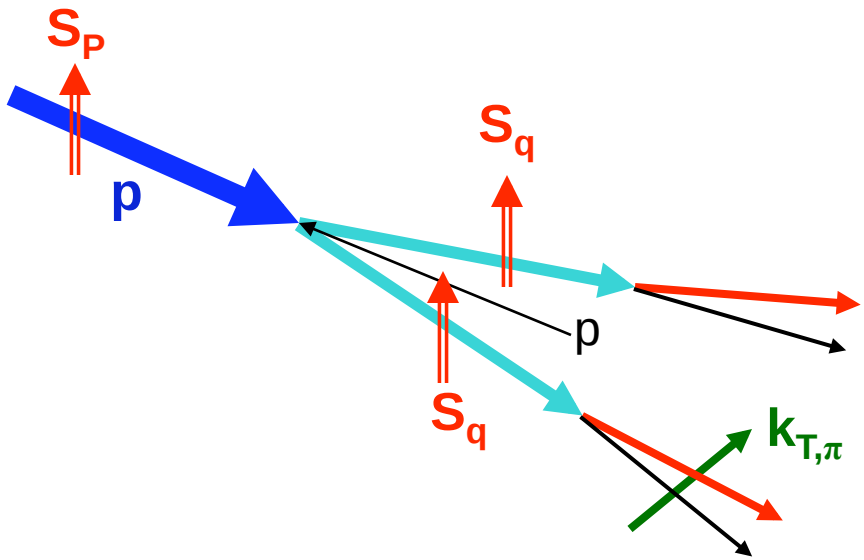
Phys Rev D41 (1990) 83; 43 (1991) 261



Orbital Angular Momentum?

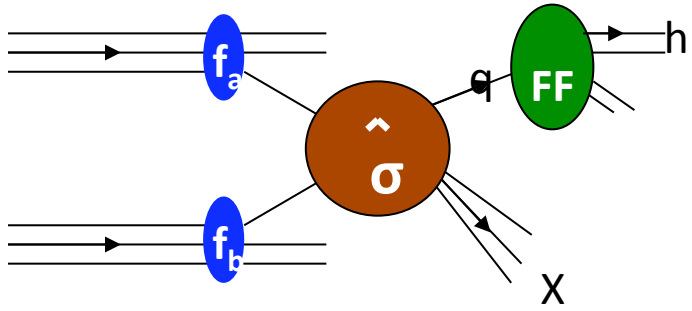
Collins mechanism: Transversity (quark polarization) * asymmetry in the jet fragmentation

Nucl Phys B396 (1993) 161



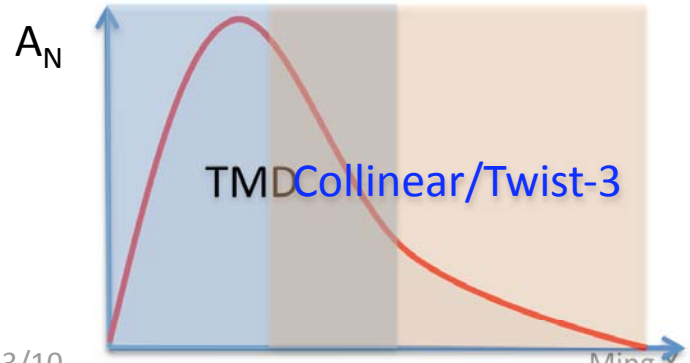
Theory: K_T vs Collinear Factorization

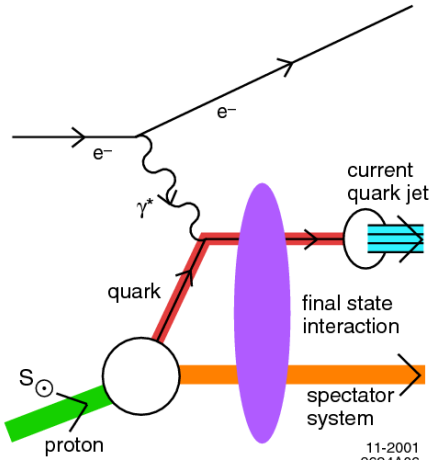
- Tran. Mom. Dep. Funs
  - Sivers Fun
  - Collins Fun

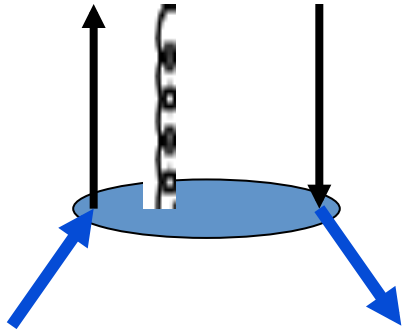


$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow} \to h + X\right)}{dx_1 dx_2 dz} \propto q_i^{\uparrow}(x_1, k_{q,T}) \cdot q_j(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1 dx_2} \times FF_{q_{k,l}}(z, p_{h,T})$$

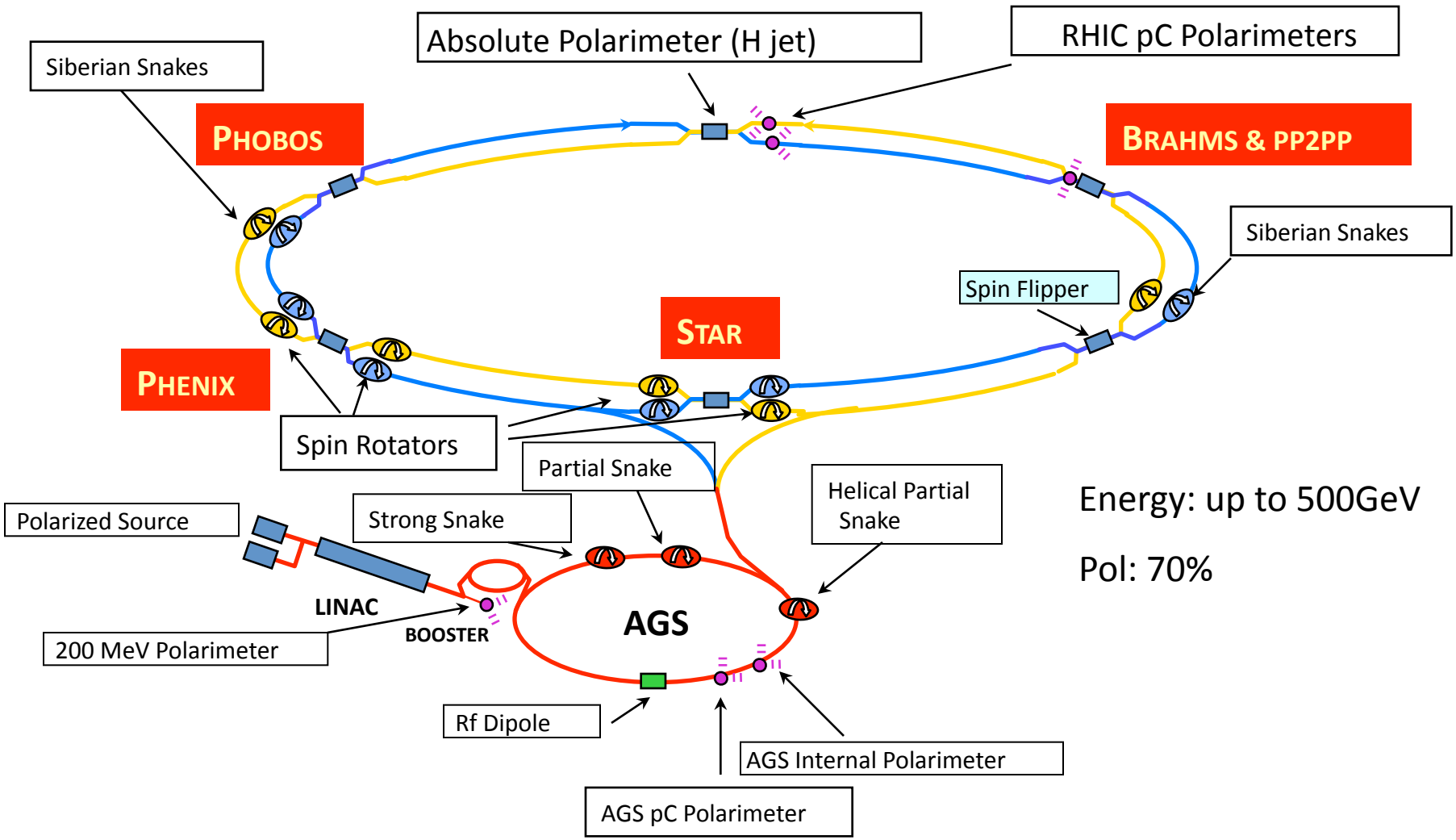
- Twist-3 collinear
  - Quark-gluon correl.
  - Gluon-gluon correl.







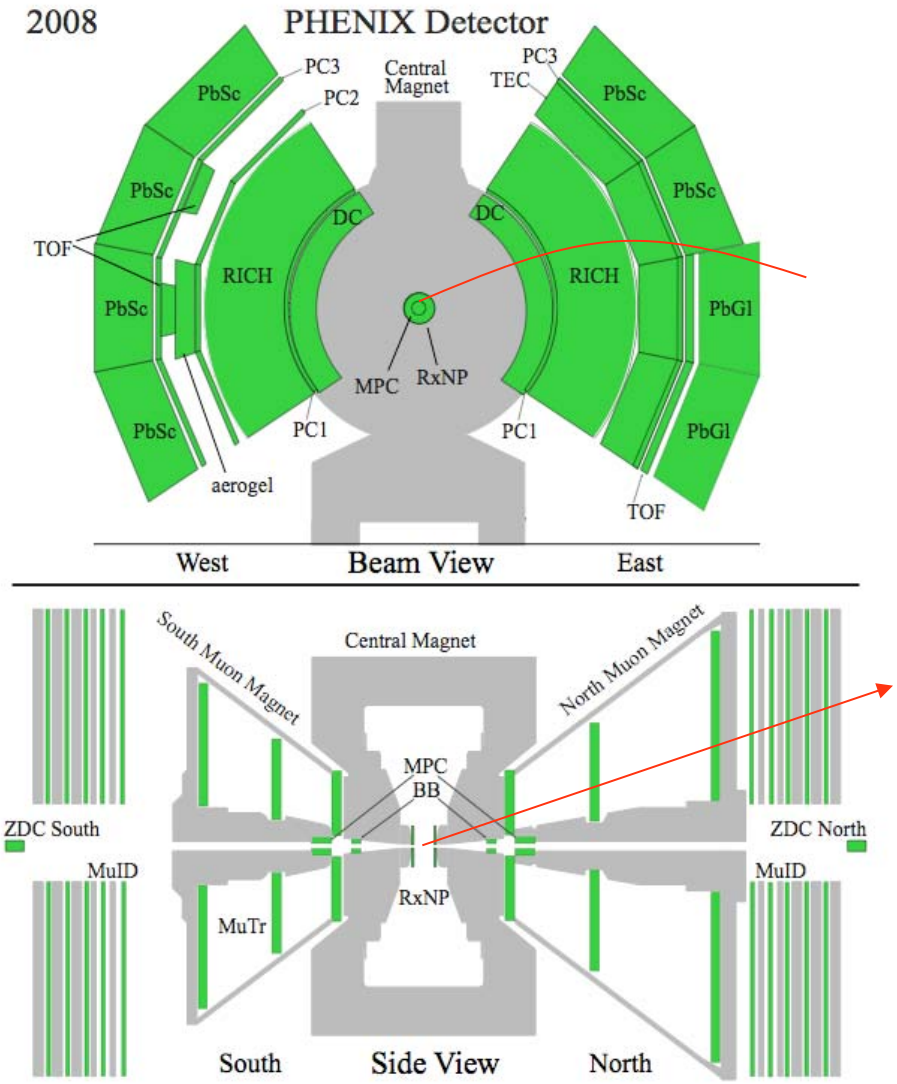
RHIC Polarized Proton Collider



Energy: up to 500GeV

Pol: 70%

Transverse Physics with PHENIX Detector



$$A_N = \frac{1}{P_{Beam}} \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{1}{P_{Beam}} \frac{N^{\uparrow} - R \cdot N^{\downarrow}}{N^{\uparrow} + R \cdot N^{\downarrow}}$$

$$R = \frac{L^{\downarrow}}{L^{\uparrow}}$$

- Central spectrometers
  - Track charged particles and detect electromagnetic processes

  $|\eta| < 0.35$

  $90^{\circ} + 90^{\circ}$ azimuth
- Forward muon spectrometers
  - Identify and track muons

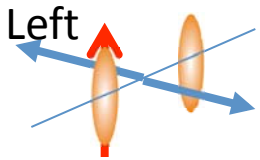
  $1.2 < |\eta| < 2.4$

  2π azimuth
- Forward calorimeters
  - Measure forward photon
  - Pions, eta, gamma …

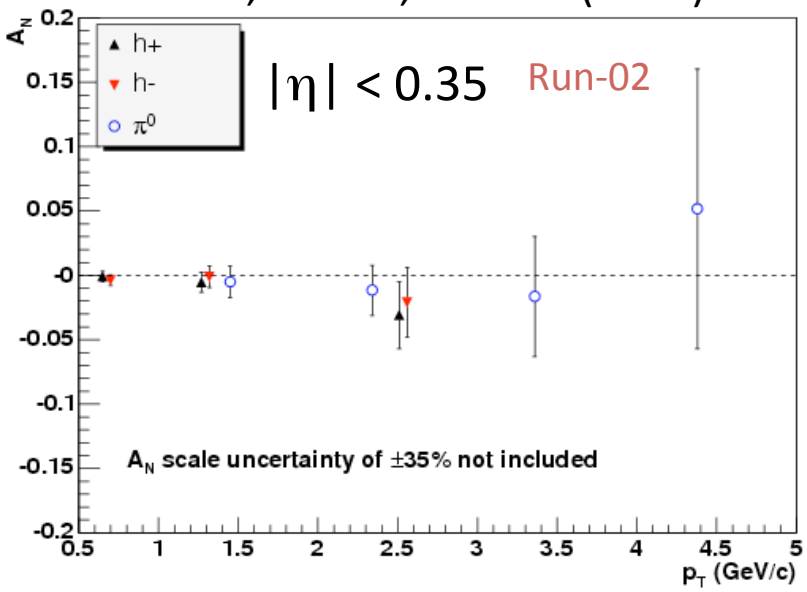
  $3.1 < |\eta| < 3.7$

  2π azimuth
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)

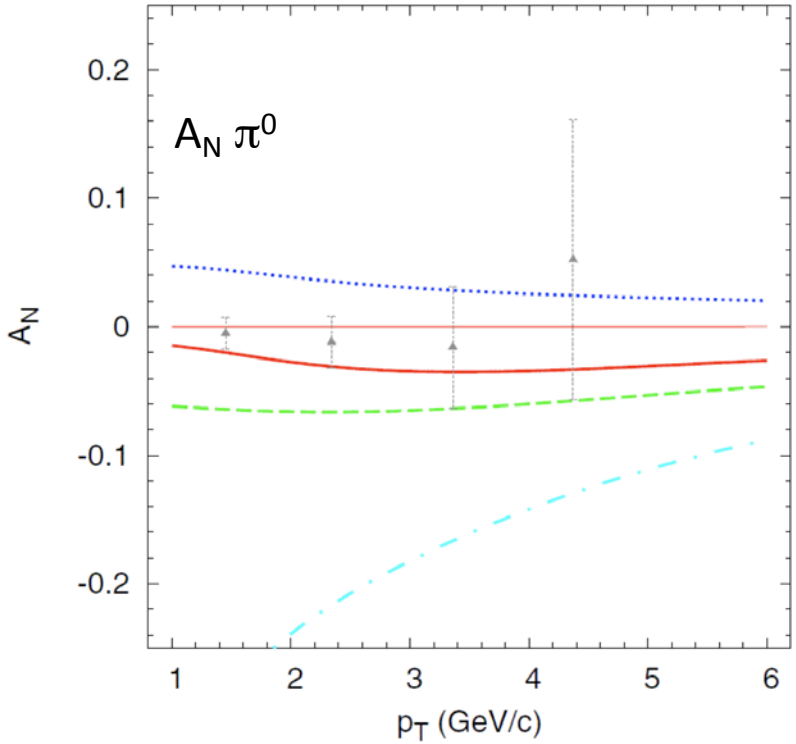
Midrapidity Hadron A_N



PHENIX, PRL 95, 202001 (2005)

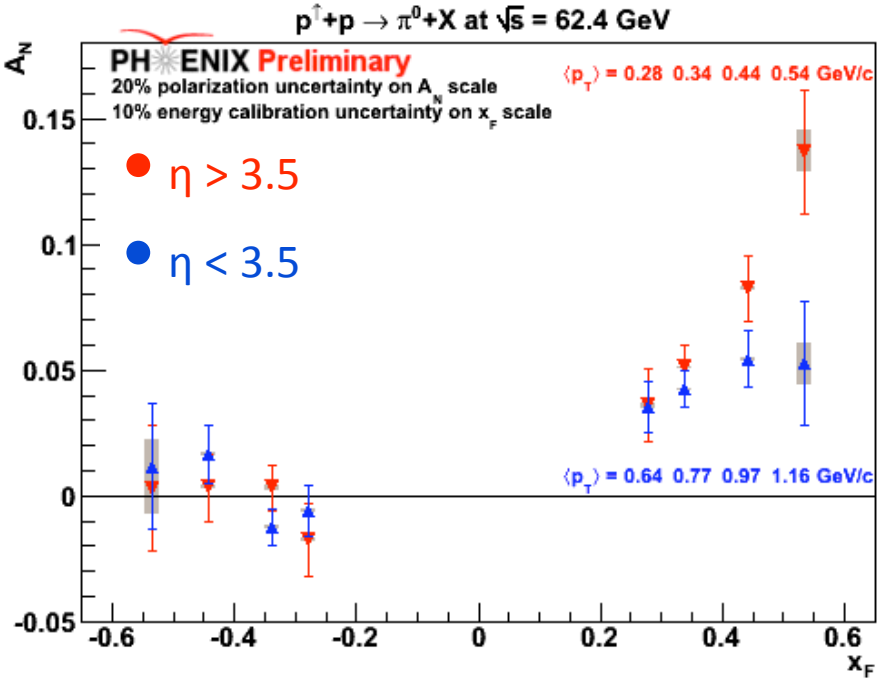


Anselmino et al, PRD 74, 094011 (2006)



- A_N is consistent with zero @1% level
- It constrains Sivers distribution function $\Delta f(x, k_T)$ for gluons.
- Much improved π^0 and η result (with >20x Stat. from Run8) will be available soon

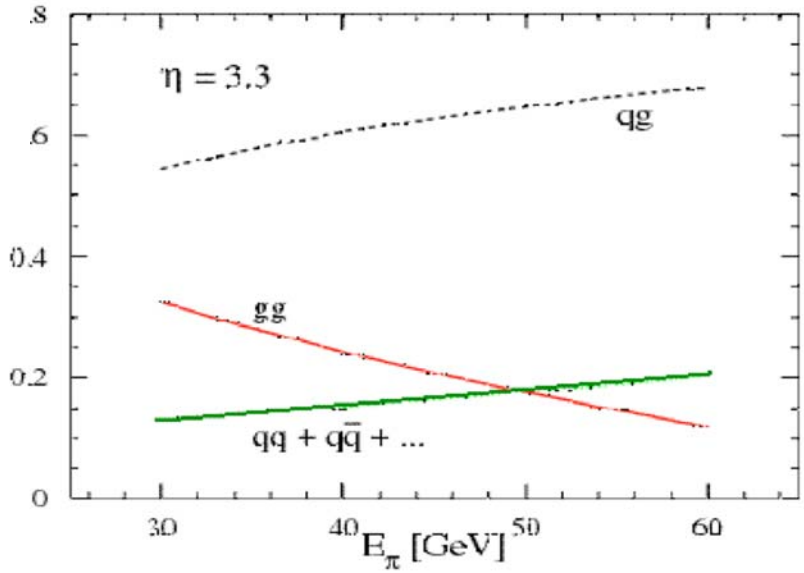
Forward A_N (π^0)



Coming soon from 2008 √s=200 GeV dataset – π^0 and η

5.2 pb^{-1}, 46% Polarization

Guzey et al, PLB **603**,173 (2004)



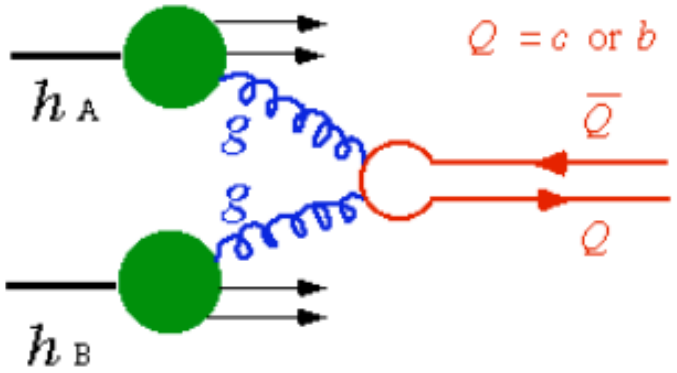
Mix of contributions from

- Sivers
- Transversity x Collins
- Twist-3

New Channels: Heavy Quark

D meson A_N

- Production dominated by gluon-gluon fusion at RHIC energy



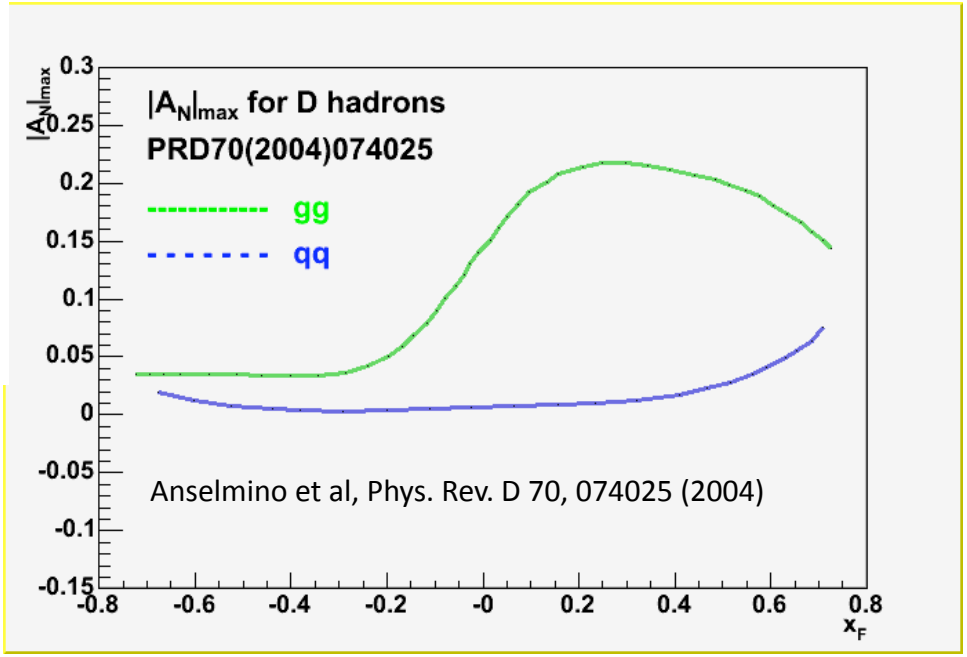
- Gluon transversity zero

→Asymmetry cannot originate from Transversity x Collins

- Sensitive to gluon Sivers effect (poorly constrained by pol DIS)

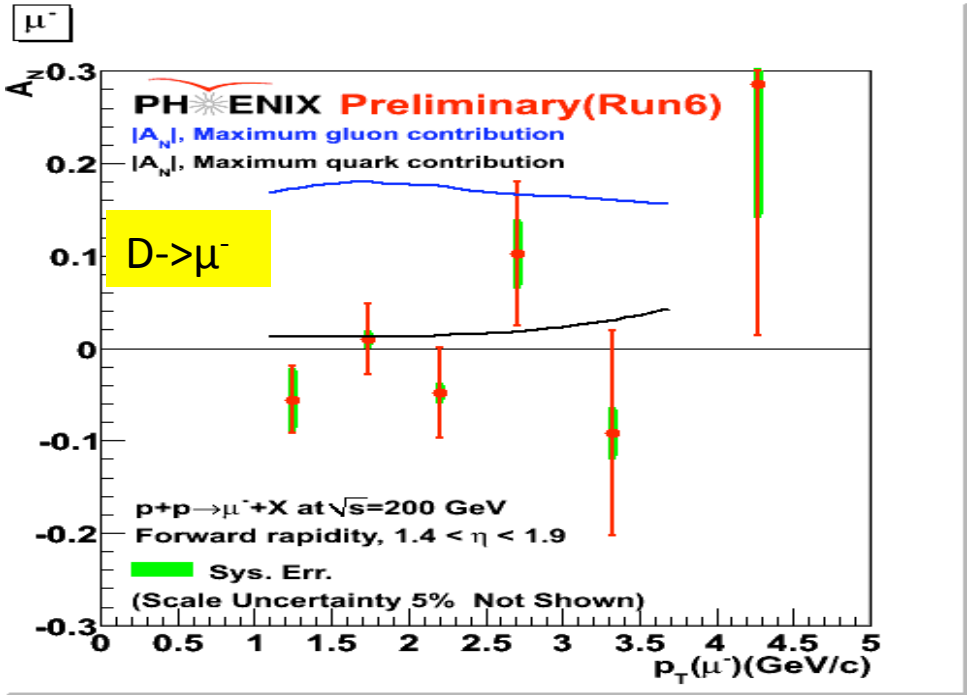
Theoretical prediction:

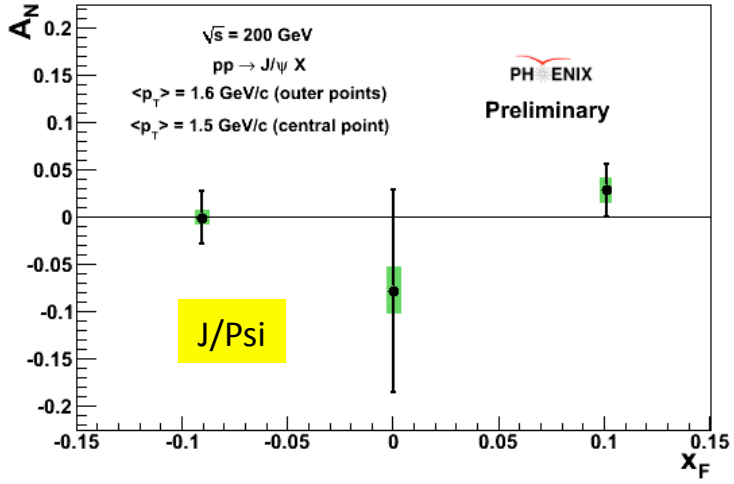
$p^{\uparrow}p \rightarrow DX$



Latest Results of Heavy Quark SSA

Probing Gluon's Sivers Asymmetry

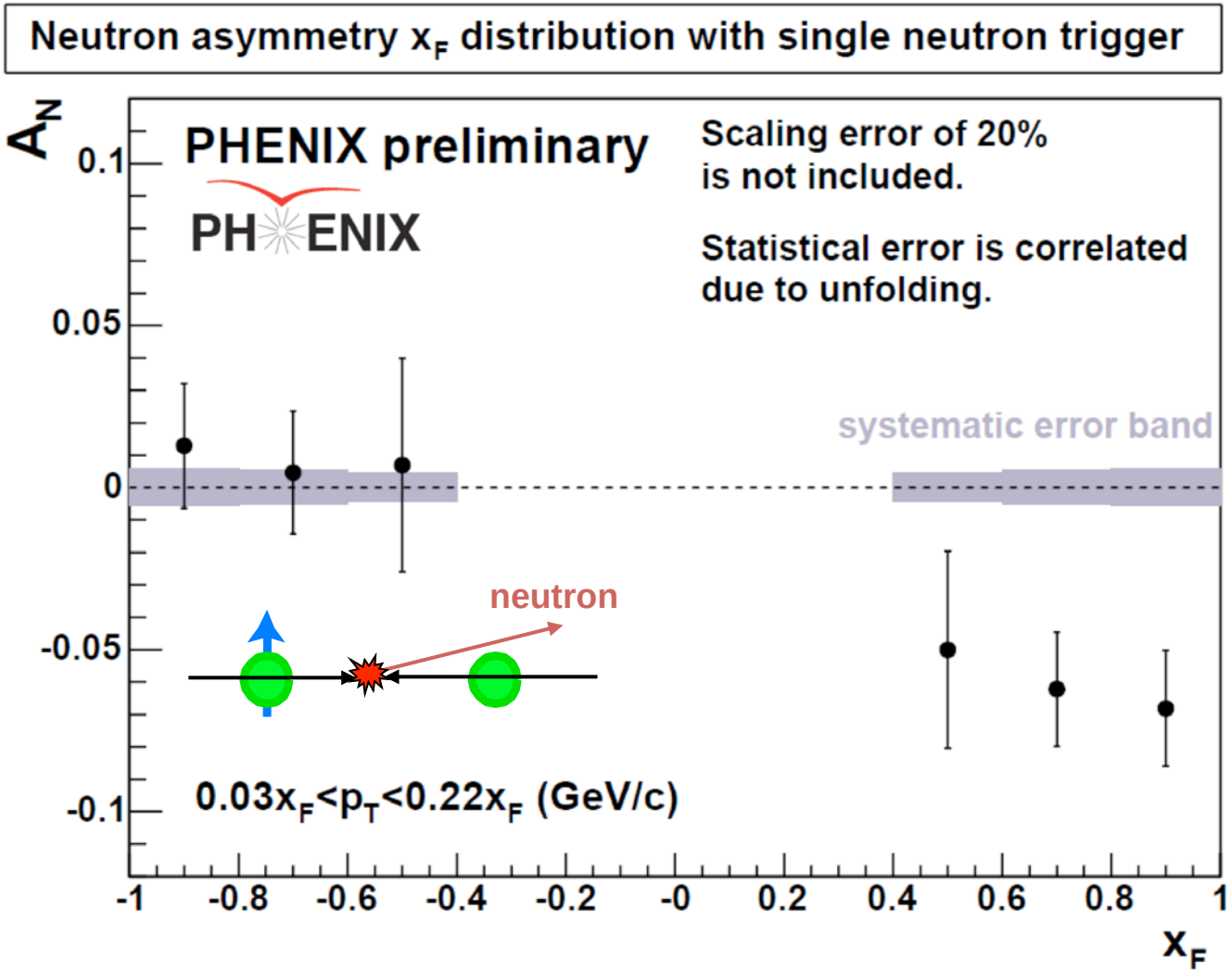




- Gluon's Sivers fun was not constrained well by DIS data
- PHENIX Charm data exclude the maximum gluon Sivers Fun (Anselmino et al, 06)
- Much improved results expected soon (Run6+Run8)

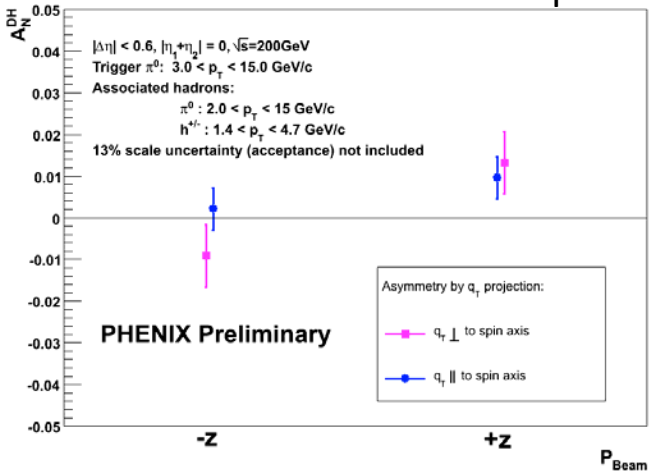
- First measurement of A_N in heavy vector meson J/Psi production
- Motivated new theoretical study
  - Constrains on gluons Sivers function.
  - Led to a new development in spin physics, beyond traditional spin topics, study J/Psi production mechanisms. (F. Yuan 08)

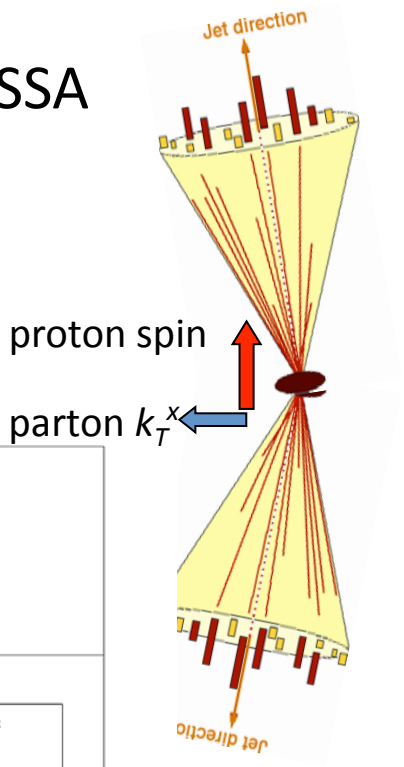
Forward Neutrons at √s=200 GeV



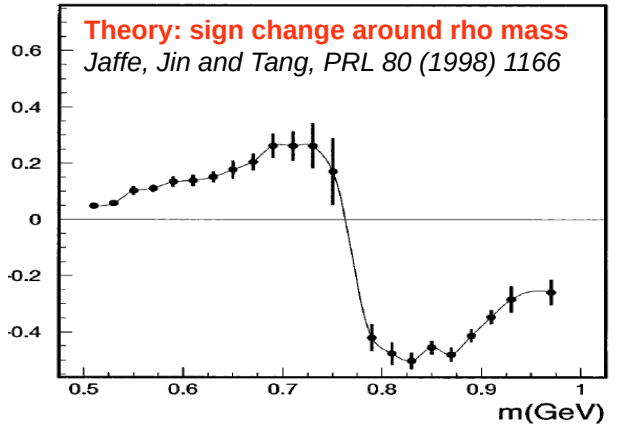
Also Many Other Measurements…

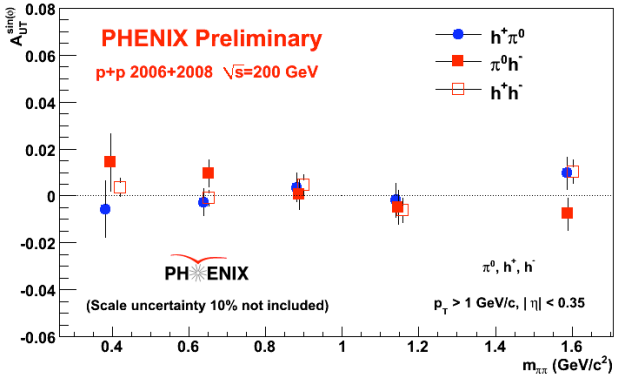
- Sivers effect
  - Di-hadron SSA





- Quark Transversity, Collins effect and IFF (Interf. Frag. Fun.)

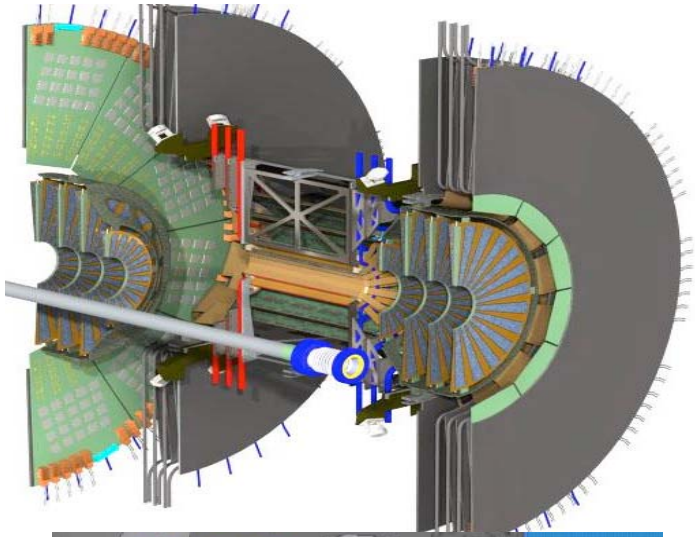




Future Opportunity

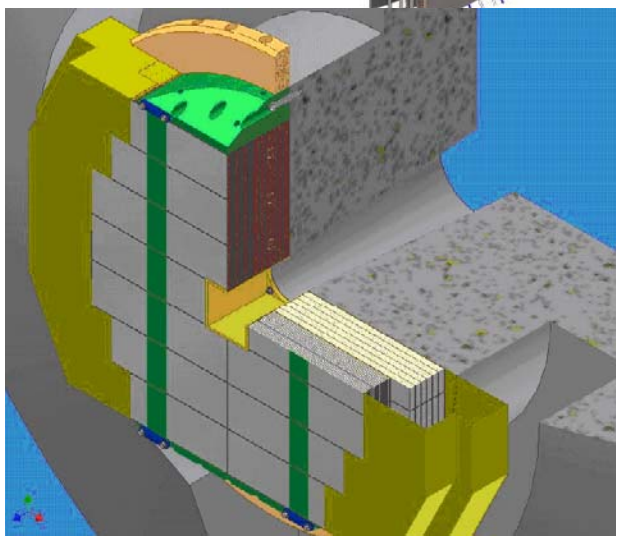
- Vertex Detectors (2011-2012)

  Large acceptance precision tracking
  - Drell-Yan
  - Heavy quarks
  - Jets



- Forward Calorimeter(2012-2013?)

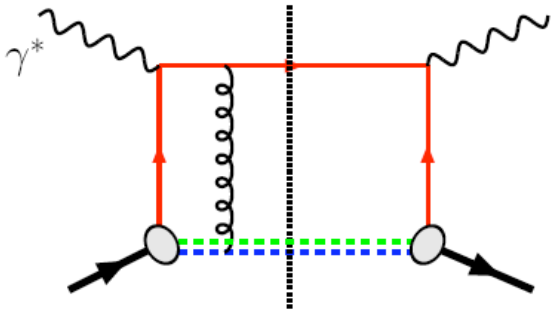
  Proposed PHENIX Upgrade (1 < eta < 3)
  - A_N π^0, Direct γ, γ-Jet
  - Collins-type measurements



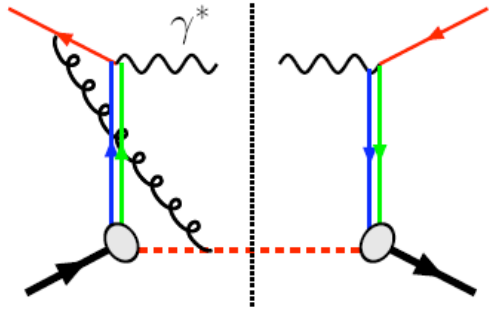
Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive



Drell-Yan: repulsive

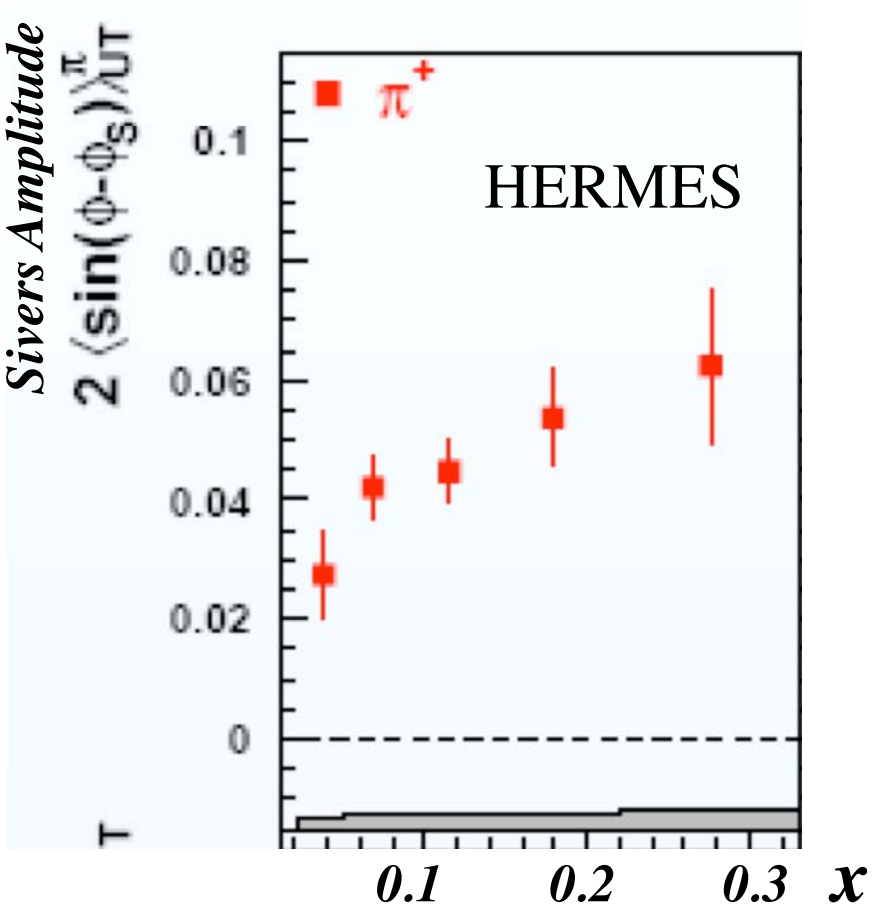


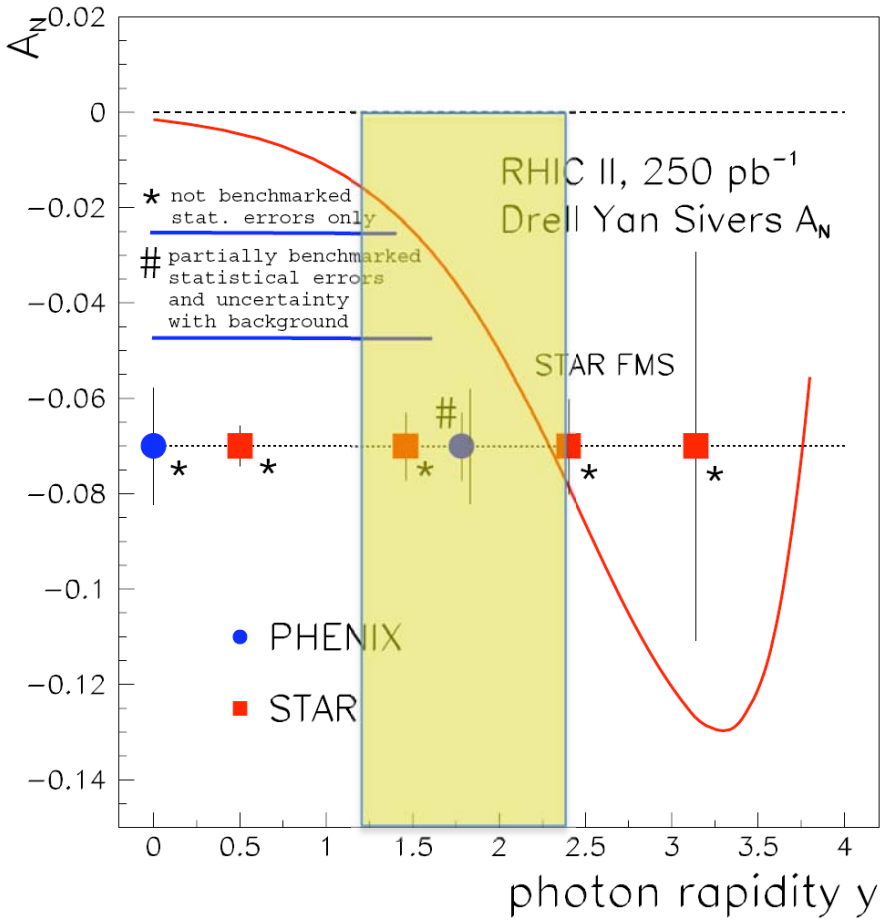
$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Transverse Spin Physics ~2015: A_N (Drell-Yan ->$\mu^+\mu^-$)

"Transverse-Spin Drell-Yan Physics at RHIC" (http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf)

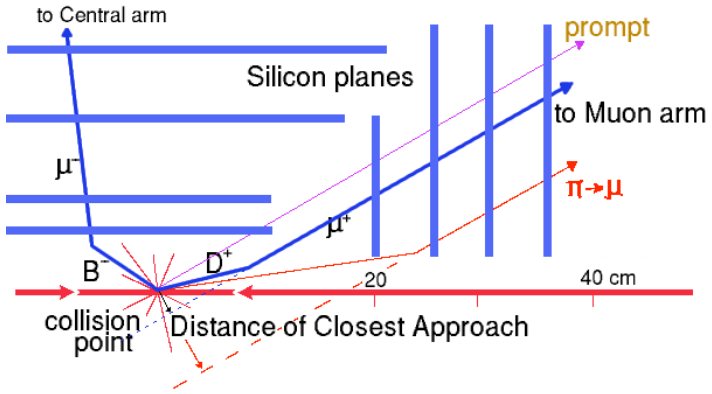
- Important test at RHIC of recent fundamental QCD predictions for the Sivers effect, demonstrating… **attractive vs repulsive color charge forces**

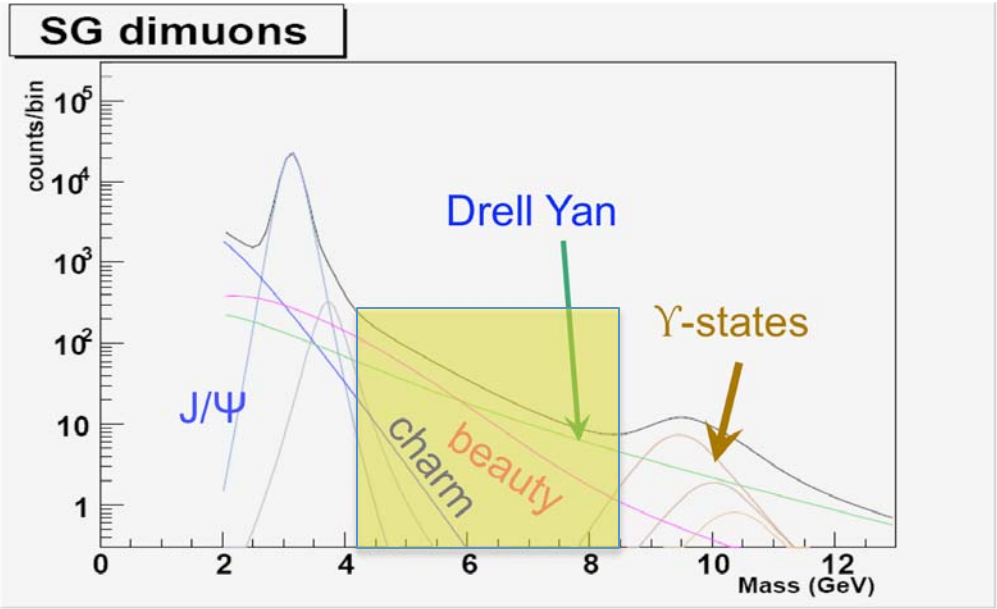




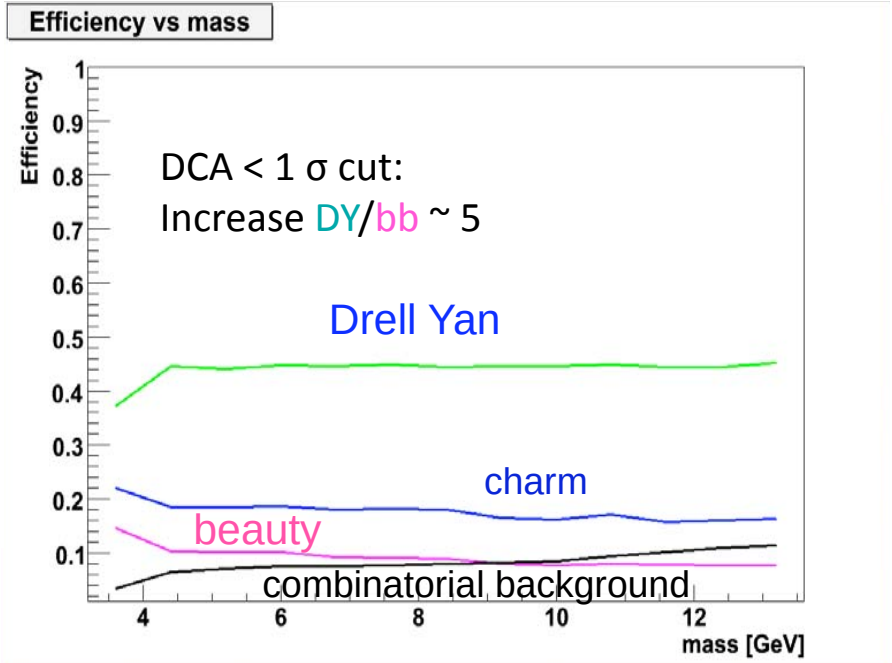
Critical Role of VTX/FVTX for Drell-Yan

- Tracking muons with MuTr+FVTX
  - Prompt muons from DY
  - Displaced tracks from π/K and heavy quark decays





➔DY: 4 GeV < M < 9 GeV; B-background: use FVTX

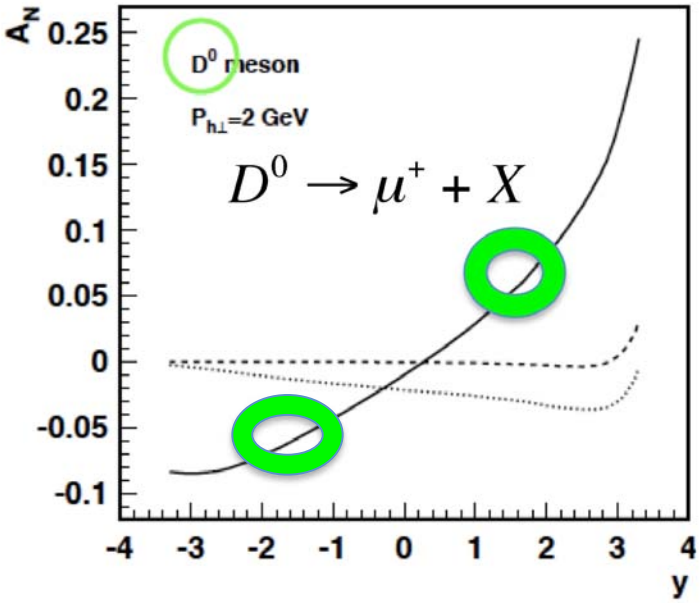


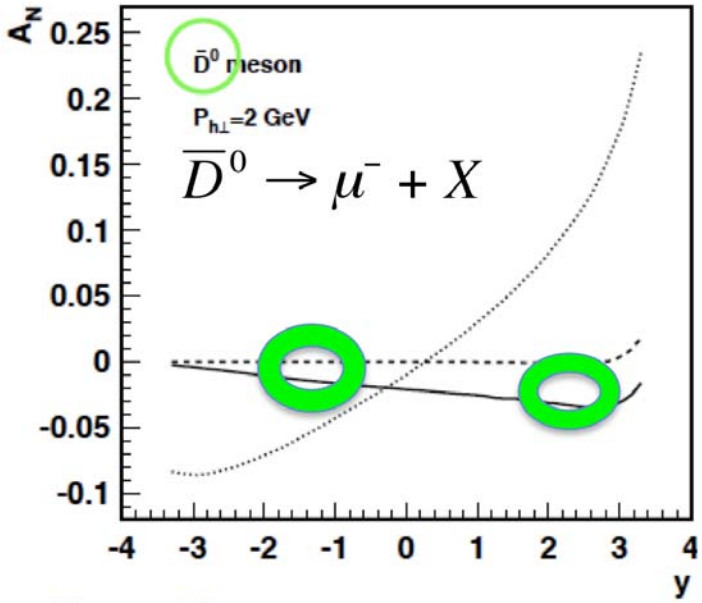
Transverse Spin Physics (cont.)

A unique opportunity @PHENIX to study charm physics!

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

Kang, Qiu, Yuan, Vogelsang, Phys. Rev. D 78,114013(2008)

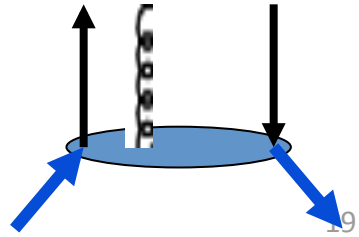




- Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$
- Dotted: $(2)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$
- Dashed: $(3)\lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0$

D meson : Largest A_N happens when $T_G^{(d)} = +T_G^{(f)}$

$\bar{D}$ meson : Largest A_N happens when $T_G^{(d)} = -T_G^{(f)}$



Transverse Physics

$W^{+/-}$ & Z^0 SSA @500GeV ?

- Latest theoretical progress
  - Test time-reversal universality of Sivers functions with W/Z
  - Expect large asymmetry (from DIS fit)
- Flavor-identified Sivers Funs
- Expected Statistics @1fb^{-1} 500GeV
  - $W^{+/-} \rightarrow \mu^{+/-}$ ~20K
  - $Z^0 \rightarrow \mu^+\mu^-$ ~ 1K

$$W^{\pm}: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 6300(6900)$$
$$\approx 1.5\%(1.4\%)$$

$$Z^0: \quad \delta A_N \approx \frac{1}{\sqrt{P^2 \cdot 2 \cdot N}}; \quad P = 0.6, \quad N = 380$$
$$\approx 6.0\%$$

Kang & Qiu PRL 103, 172001 (2009)

$W^{+/-}$

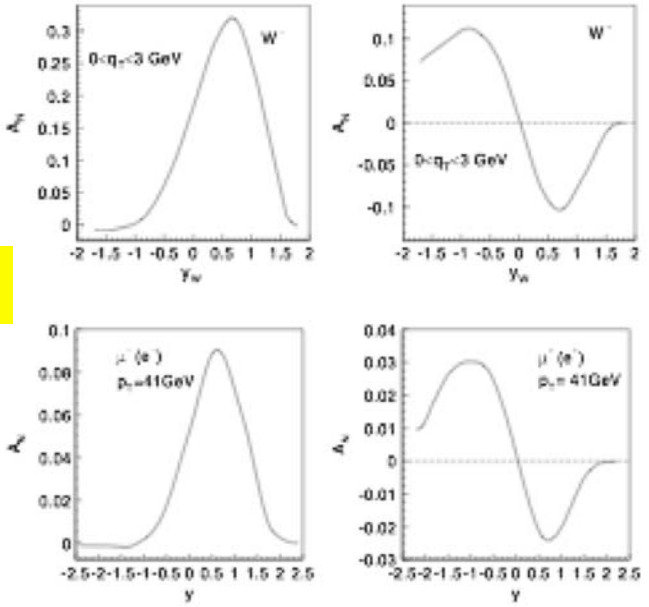


FIG. 3. A_N as a function of lepton rapidity.

Z^0

Kang & Qiu arX 0912.1319

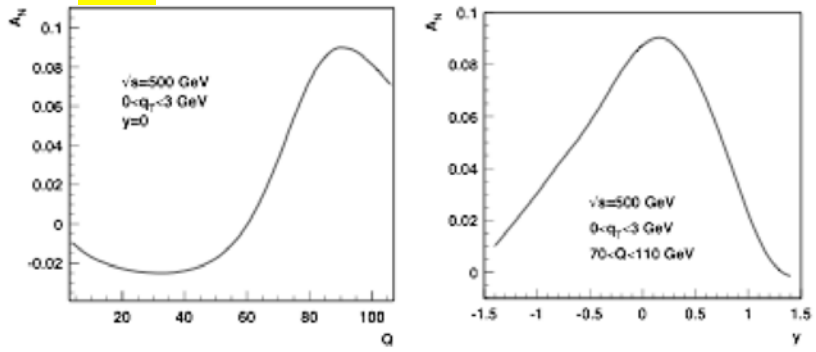
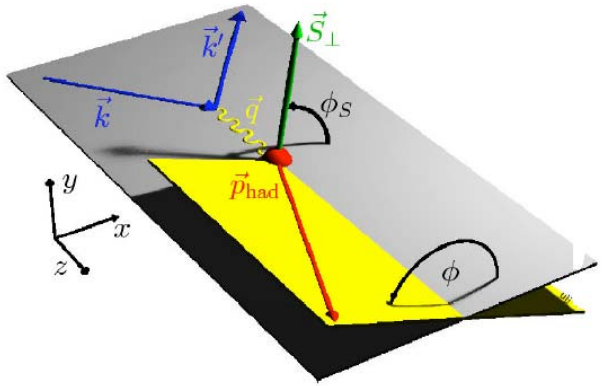
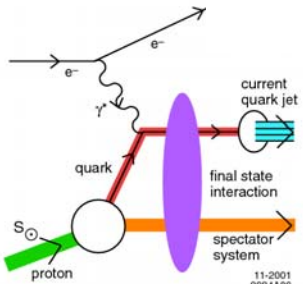


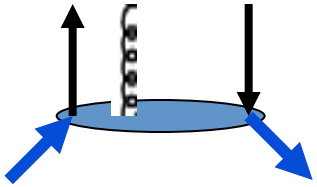
FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q. Right: SSA of lepton pair accumulated around Z^0 pole as a function of rapidity y.

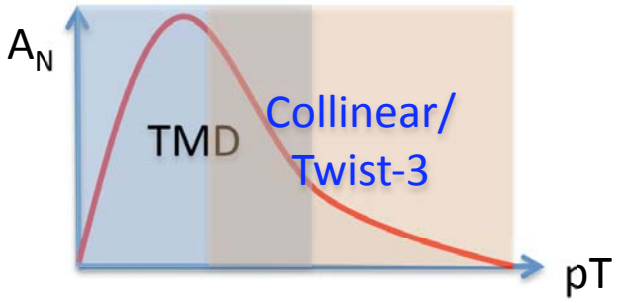
Renaissance of Transverse Spin Physics

- Recent experimental observation of non-Zero Sivers and Collins effects
  - HERMES, 05,09; COMPASS, 05,09 ; BELLE 06
- Very active/rapid theoretical progress
  - Spin-dependent TMD
    - Sivers 90; Colllins 93; Brodsky-Hwang-Schmidt, 02
  - Twist-3 quark-gluon correlations (coll.) in DIS
    - Efremov-Teryaev, 82, 84; Qiu-Sterman, 91,98
  - Twist-3 tri-gluon correlations in p+p
    - Kang-Qiu-Vogelsang-Yuan 08
  - Unified picture of TMD and Twist-3
    - Ji-Qiu-Vogelsang-Yuan 06; Yuan-Zhou, 09
- Opportunity for new study of QCD dynamics
  - Sivers Funs in DIS & DY
  - Flavor Dep. Sivers Fun & OAM
  - quark-gluon and tri-gluon correlation
- Future direction @RHIC-SPIN?
  - Large SSA observed at forward rapidity @RHIC
  - Open charm and beauty
  - Drell-Yan and Vector mesons
  - Light hadrons with MPC/FOCAL









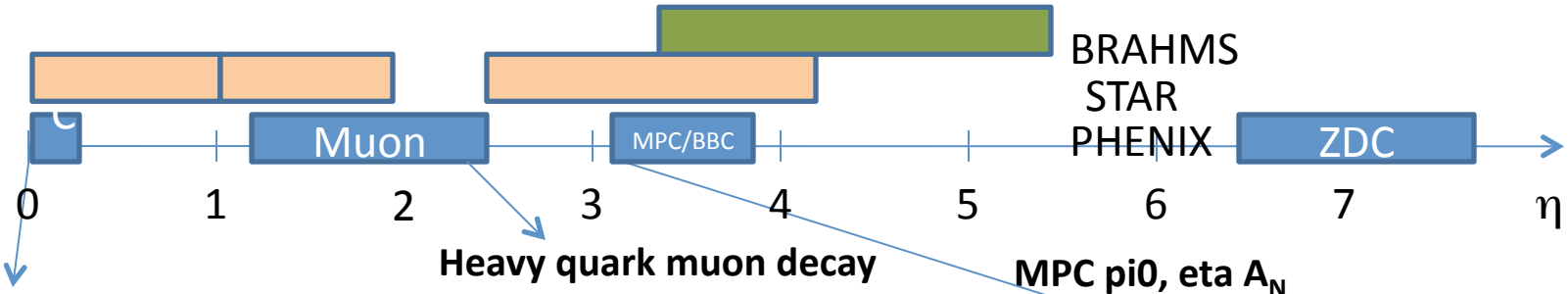
"Polarization data has often been the graveyard of fashionable theories. If theorists had their way, they might just ban such measurements altogether out of self-protection."

J.D. Bjorken

NATO Advanced Research Workshop on
QCD Hard Hadronic Processes
St. Croix, 1987

backup

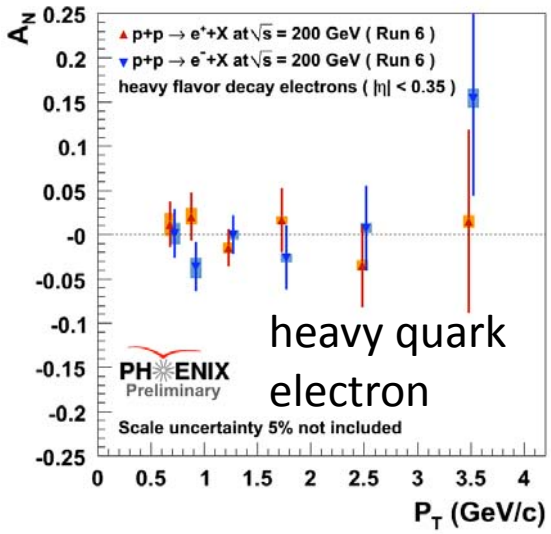
PHENIX Coverage

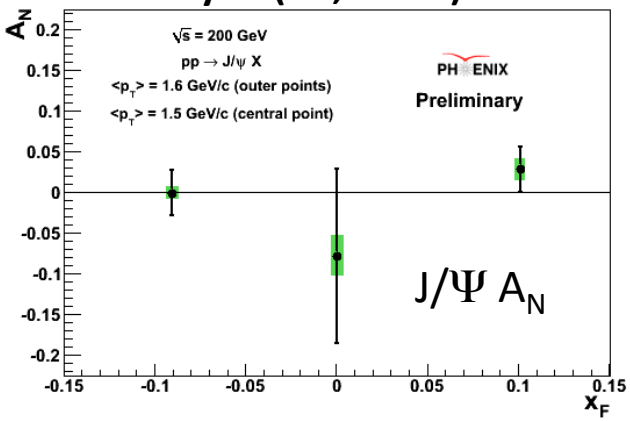


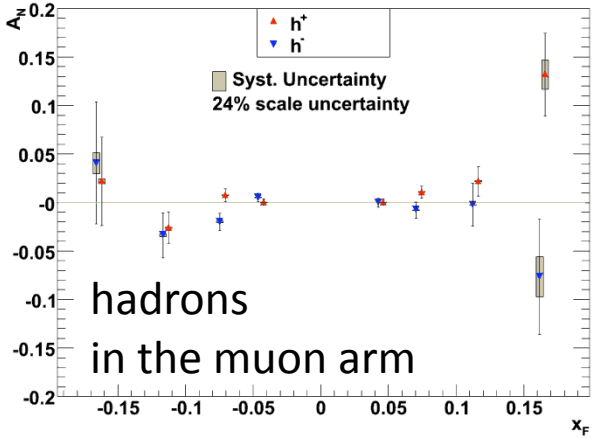
central arm pi0 A_N (Run8pp)
Heavy quark A_N
correlation analysis (IFF, di-Jet)

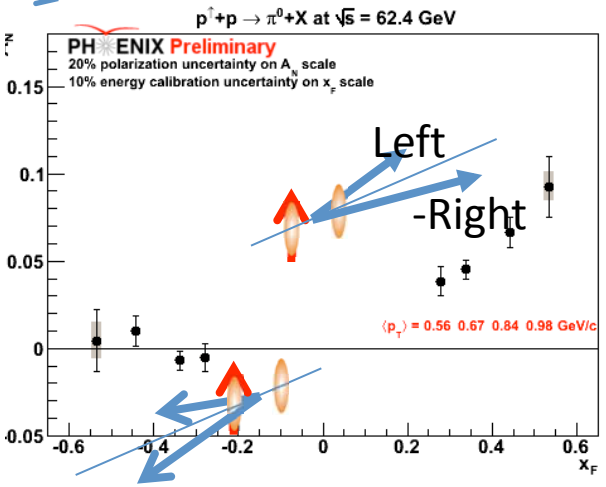
Heavy quark muon decay
punch through hadron
correlation analysis (IFF, di-Jet)

MPC pi0, eta A_N



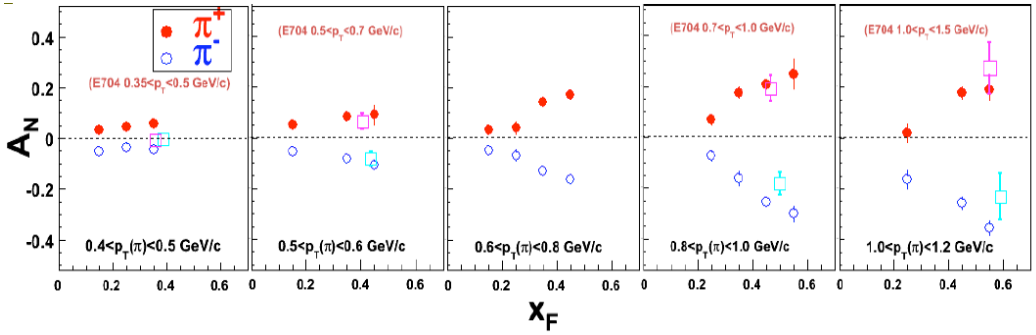


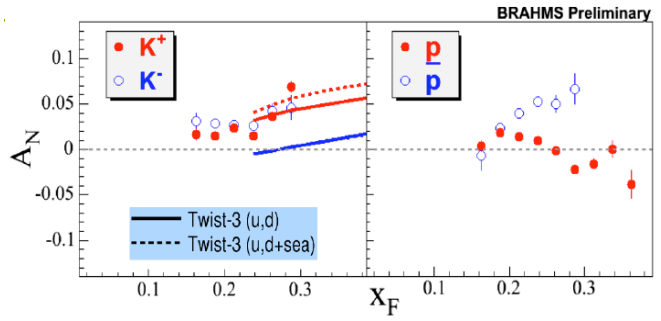


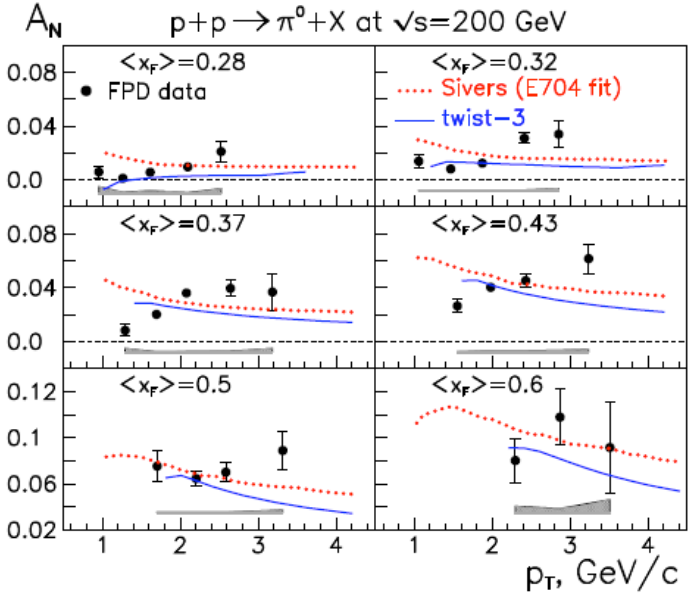


Current Status and Some Puzzles

SIDIS: COMPASS and HERMES disagree on Sivers asymmetry measurements.
RHIC: there are measurements where various mechanisms could be mixed.

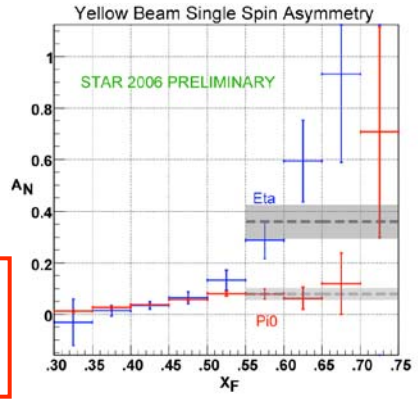






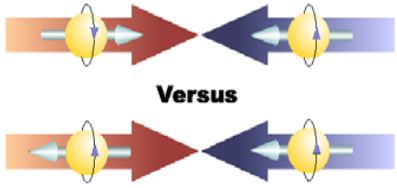
- Particle dependence?
- p_T dependence?

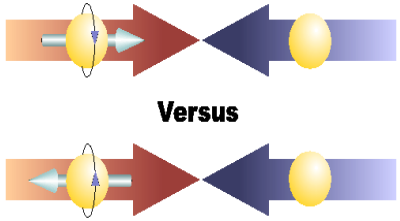
Complementary measurements will disentangle various effects

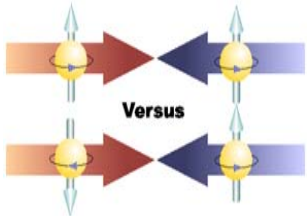


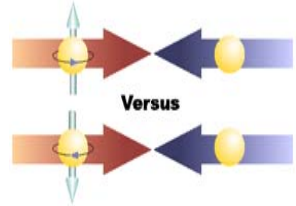
PHENIX Spin Program

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π Production $A_{LL}(gg, gq \to \pi + X)$	W Production	Transversity δq:
Prompt Photon $A_{LL}(gq \to \gamma + X)$	$A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$	π^+, π^- Interference fragmentation: $A_T(p_\perp p \to (\pi^+, \pi^-) + X)$
Heavy Flavors $A_{LL}(gg \to c\bar{c}, b\bar{b} + X)$	$A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Drell Yan A_{TT}
		Single Asymmetries A_N Sivers Effect et al.





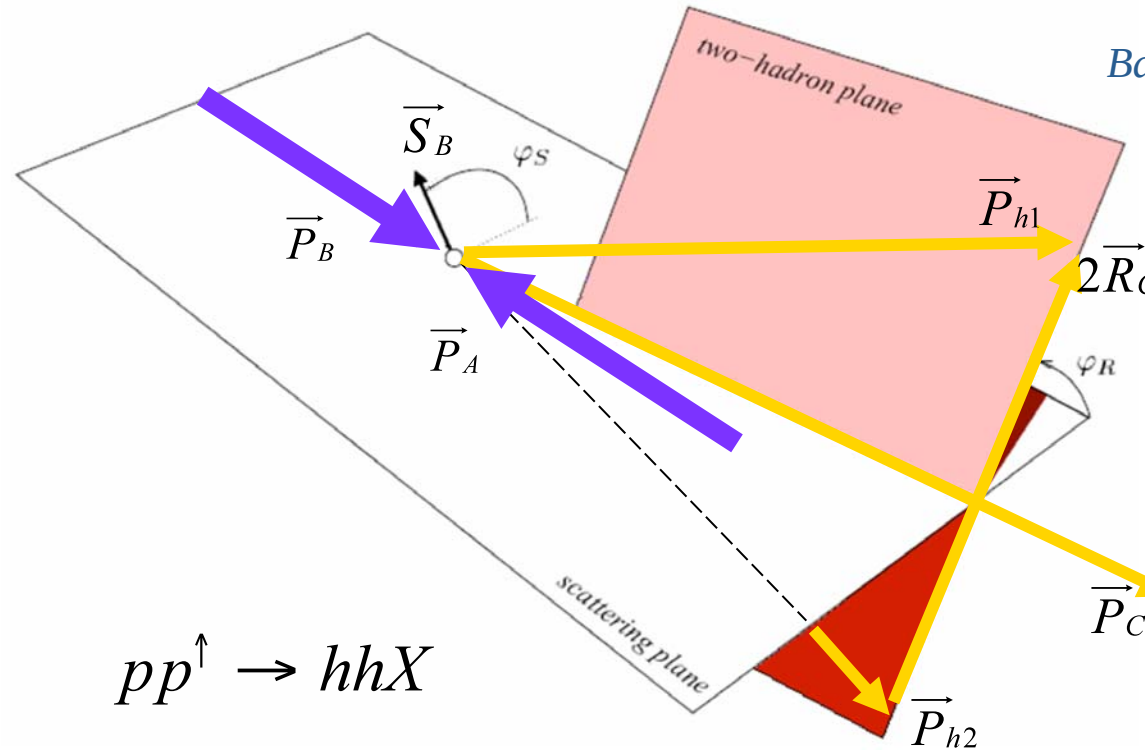




Utilizing high energy polarized proton beams of RHIC

J. Koster DIS09

IFF: Definition of Vectors and Angles



Bacchetta and Radici, PRD70, 094032 (2004)

$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

RHIC/PHENIX Spin Run History and Prospect

RHIC-RUN	Pol(%)	L(pb^{-1})	Results
2002	15%	0.15	first pol p+p run@RHIC! Transverse
2003	30%	0.35	π^0 cross section, $A_{LL}(\pi^0)$
2004	40%	0.12	Pol H-Jet, absolute beam polarization
2005	50%	3.5	$A_{LL}(\pi^0)$ ruled out large Δg, GRSV-Max-Like
2006	60%	7.5	first dedicated long spin run
	2.7		Transverse run
2007	--	--	NO spin run
2008	45%	5.2	short run for HI baseline pp physics
2009	35%	14	first 500GeV run!
	55%	16	200GeV

Goals

800pb^{-1}@500GeV
300pb^{-1}@200GeV

300pb^{-1}@500GeV
70pb^{-1}@200GeV

CAD(10.2009): From Run9 experience, reduced the "enhanced" design goals: P=70%, $\mathcal{L} = 3 \times 10^{31}\ cm^{-2}s^{-1}$ (or ≈ 7.5 pb^{-1}/week) at $\sqrt{s}$ = 200 GeV

12-week Run Delivered: 90pb^{-1}

PHENIX(ε=1/3) = 30pb^{-1}

With hardware upgrade, expect to achieve: 18~83 pb^{-1}/week@500GeV

12-week Run Delivered: 220~1000pb^{-1}

PHENIX(ε=1/2) = 100~500pb^{-1}