New Probes for the Future Transverse Spin Physics @RHIC

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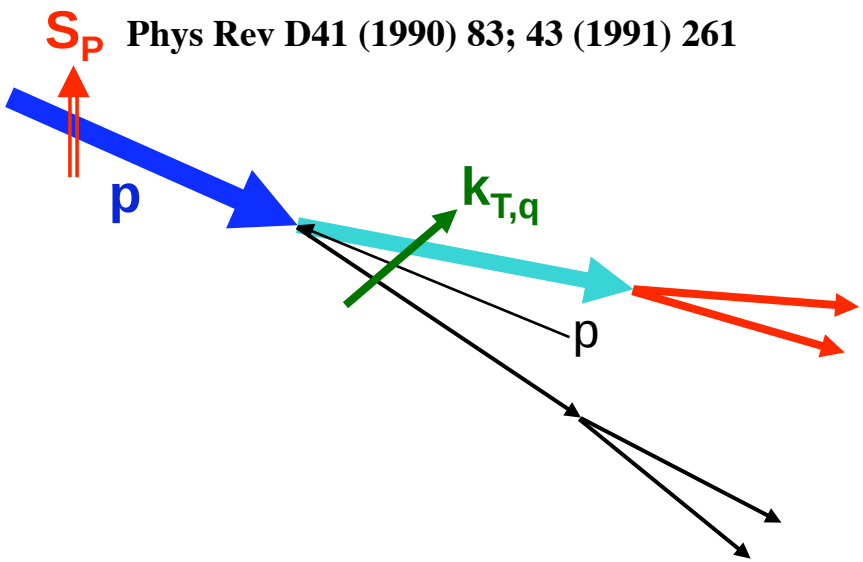
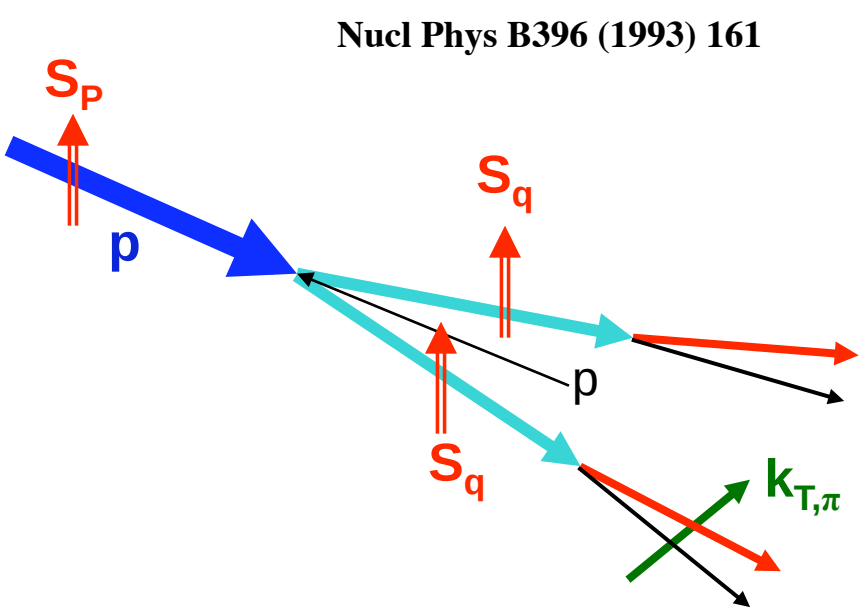
Physics of Transverse Single Spin Asymmetry (TSSA)

1. What have we learned?
2. What more can we learn about TSSA and most importantly, the QCD?
   - High precision data, future EIC …
   - New probes for unknowns @RHIC
     - charm, Drell-Yan etc., RHIC-SPIN

Current Understanding of TSSAs (I)

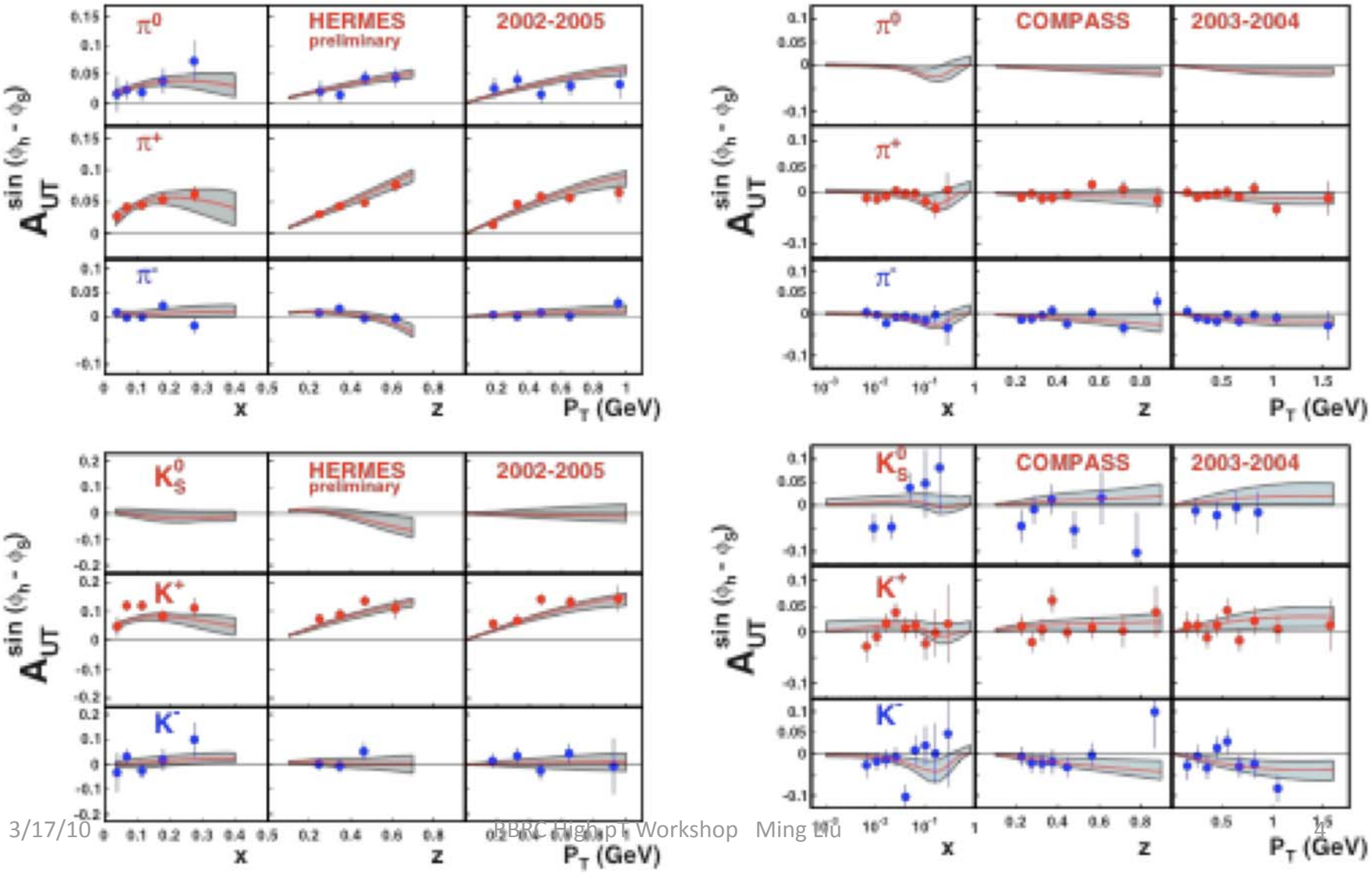
- TMD approach: Transverse Momentum Dependent Distribution Functions
  - Sivers fucntion: nucleon spin and parton kT correlation
  - Collins function: spin dependent fragmentation function
  - and lots of others …





Very Impressive Progress in Recent Years…

Eur. Phys. J A39 89-100 (2009) M. Anselmino et al



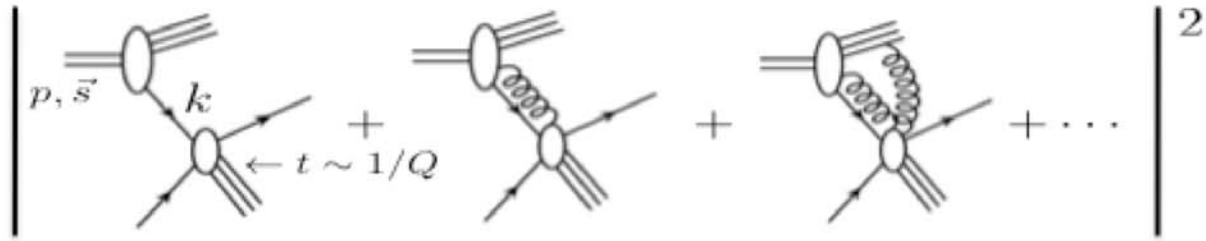
Current Understanding of TSSAs (II)

- Collinear Approach
  - Twist-3 three-parton correlation functions, Qiu-Sterman matrix
  - Twist-3 parton fragmentation functions

❑ A_N – twist-3 effect:

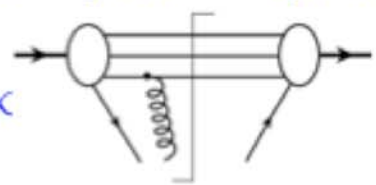
Qiu, Duke Spin workshop '10

$\sigma(Q, \vec{s}) \propto$

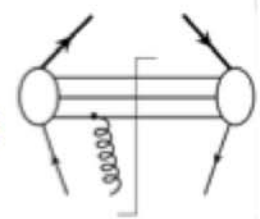


$$\Delta(s_T) \propto T^{(3)}(x,x) \otimes \hat{\sigma}_T \otimes D_f(z) + \delta q_f(x) \otimes \hat{\sigma}_D \otimes D^{(3)}(z,z)$$

$T^{(3)}(x,x) \propto$



$D^{(3)}(z,z) \propto$



Qiu, Sterman, 1991

Kang, Yuan, Zhou, 2010

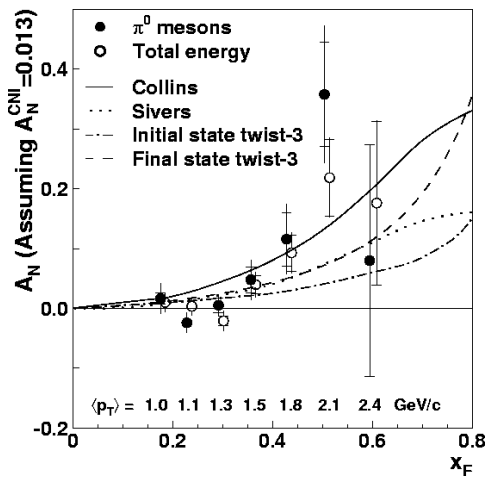
❑ Spin flip:

– Interference of single parton and a two-parton composite state

Transverse SSA's from polarized proton beams

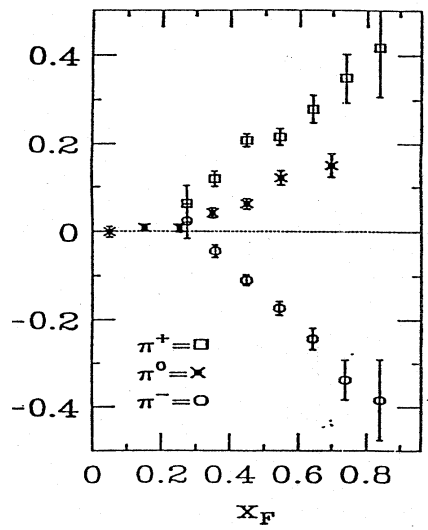
from low to high energies

RHIC 20,000 GeV beam



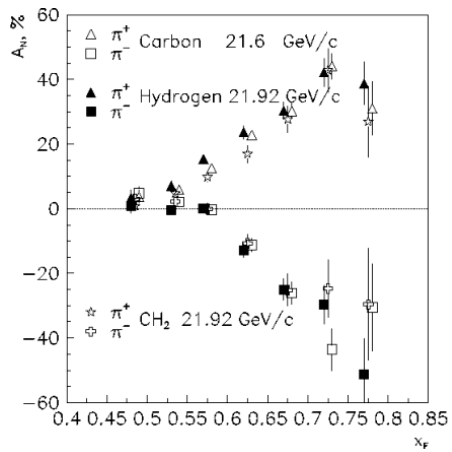
PRL (2004)

FNAL 200 GeV beam



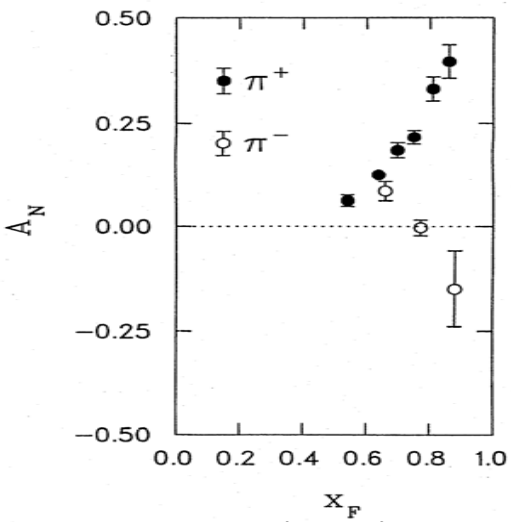
PLB261, 201 (1991)
PLB264, 462 (1991)

AGS 22 GeV beam



PRD65, 092008 (2002)

ZGS 12 GeV beam



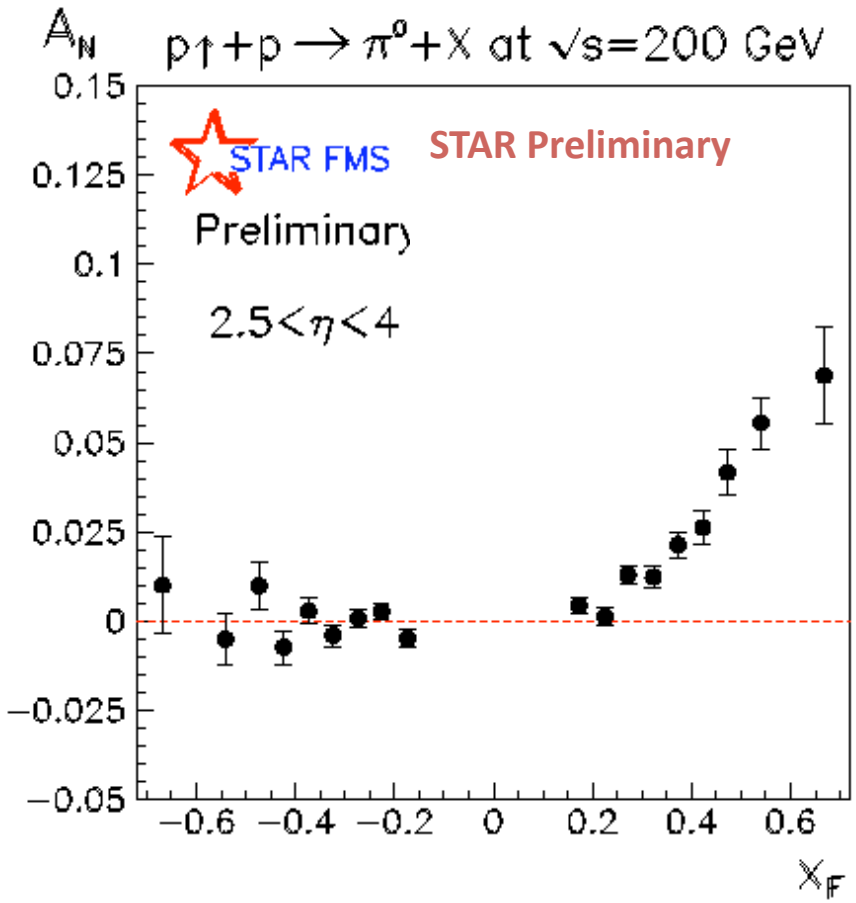
PRL36, 929 (1976)

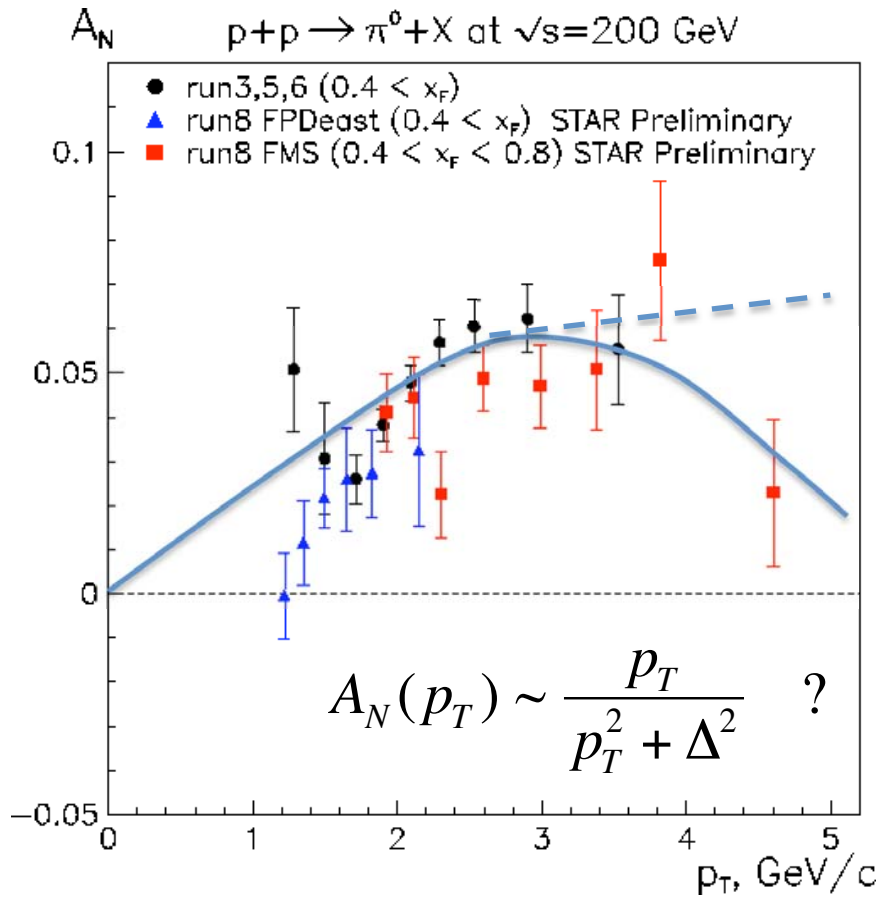
Non-Perturbative cross section → Perturbative cross section

Latest: Preliminary Run8 FMS π^0 A_N

A_N vs. xF

→ Consistent with previous measurements





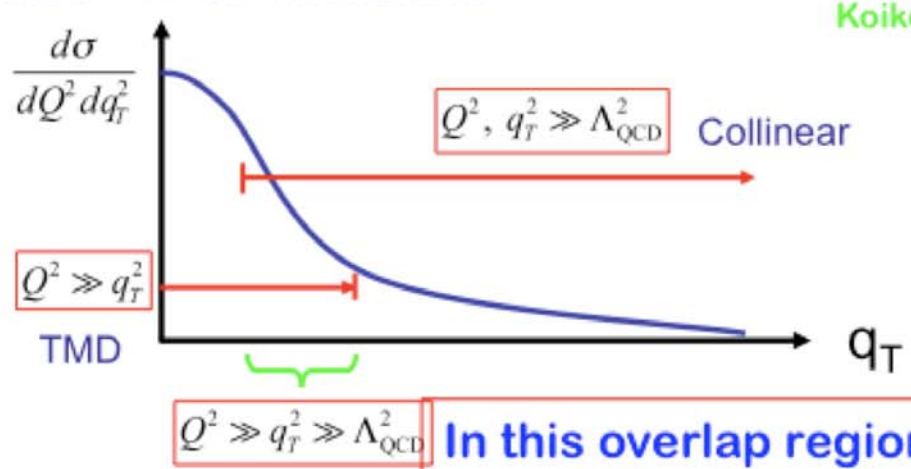
From SPIN08 talk by N. Poljack, arXiv:0901.2828

Qiu, Duke Spin workshop '10

The consistency check

- IF both factorizations are proved to be valid,
  - both formalisms should yield the same result in overlap region
  - Case studies – Drell-Yan/SIDIS

Ji, Qiu, Vogelsang, and Yuan
Koike, Vogelsang, and Yuan



In this overlap region, both formalisms indeed give the same result

- IF one factorization formalism is valid,

Qiu, Vogelsang, and Yuan

  - Its asymptotic form in the overlap region is a necessary condition for the other formalism to match
  - But, it is not sufficient to prove the other factorization formalism

… and the Challenge of Factorization

Kang RBRC '10

Start from conclusion

- Note: TMD and Collinear factorization apply in different kinematic domain

Process	TMD Factorization back-to-back	Collinear Factorization large separation
$\ell + p \to \ell + \pi + X$ $p + p \to \ell^+\ell^- + X$ $e^+e^- \to H_1 + H_2 + X$	✓	✓
$p + p \to H_1 + H_2 + X$ $p + p \to J_1 + J_2 + X$ $p + p \to \gamma + J + X$	✗	✓

Theoretical and Experimental Challenges

- Check consistency in a wide kinematic range
  - (x, Q^2, pT, π, K …) in DIS and p+p, EIC..
- Explore new phenomena in p+p @RHIC
  - Tri-gluon functions in Twist-3
  - Sivers functions in DIS vs Drell-Yan
  - Flavor identified Sivers via W, etc

- Some new TSSA observables
  - Charm
  - Drell-Yan
  - W & Z?

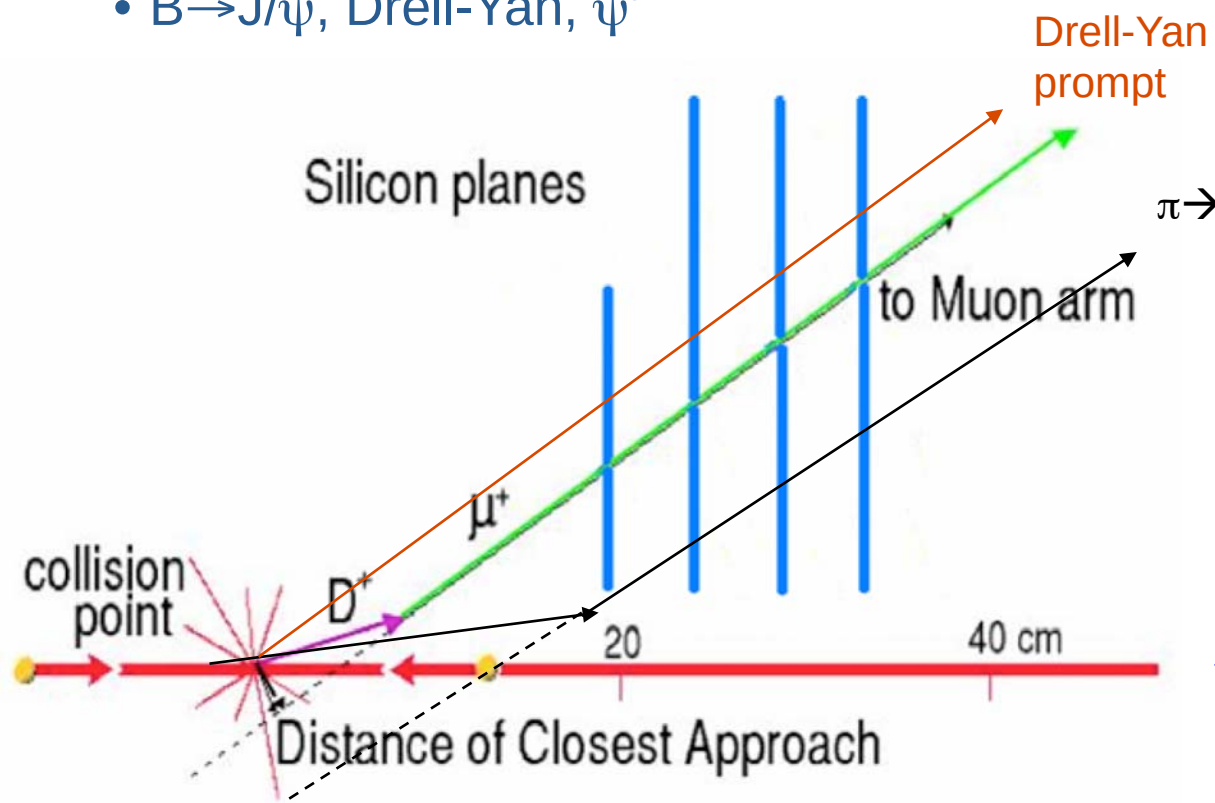
Hard to minimize both…

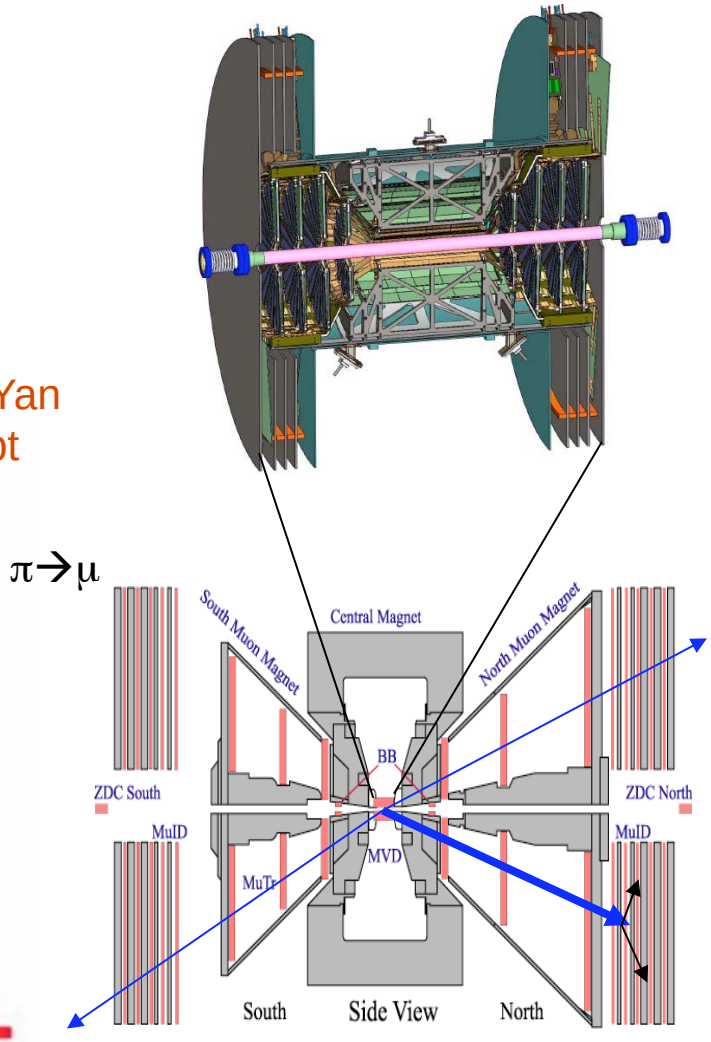
$$\delta E \bullet \delta T \geq \frac{\hbar}{\$\$}$$

- Silicon Vertex Detector Upgrade for PHENIX, available in 2011

- STAR's will come later

  - Precision Charm/Beauty Measurements
  - B→J/ψ, Drell-Yan, ψ'





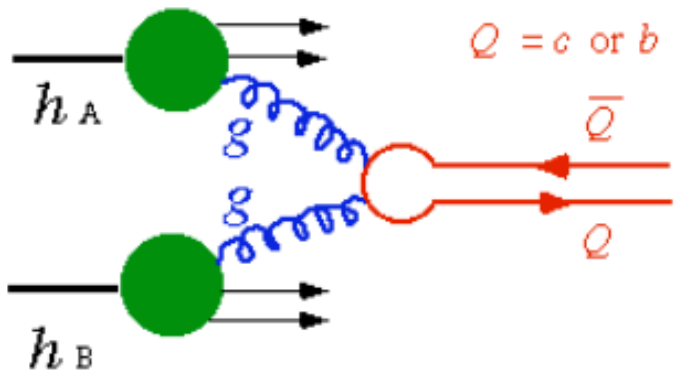
Heavy Quark A_N

- "Simple" gluon Sivers function
- Tri-gluon correlation functions
- Leading charm at forward rapidity

Heavy Quarks to Probe Gluons

D meson A_N

- Production dominated by gluon-gluon fusion at RHIC energy

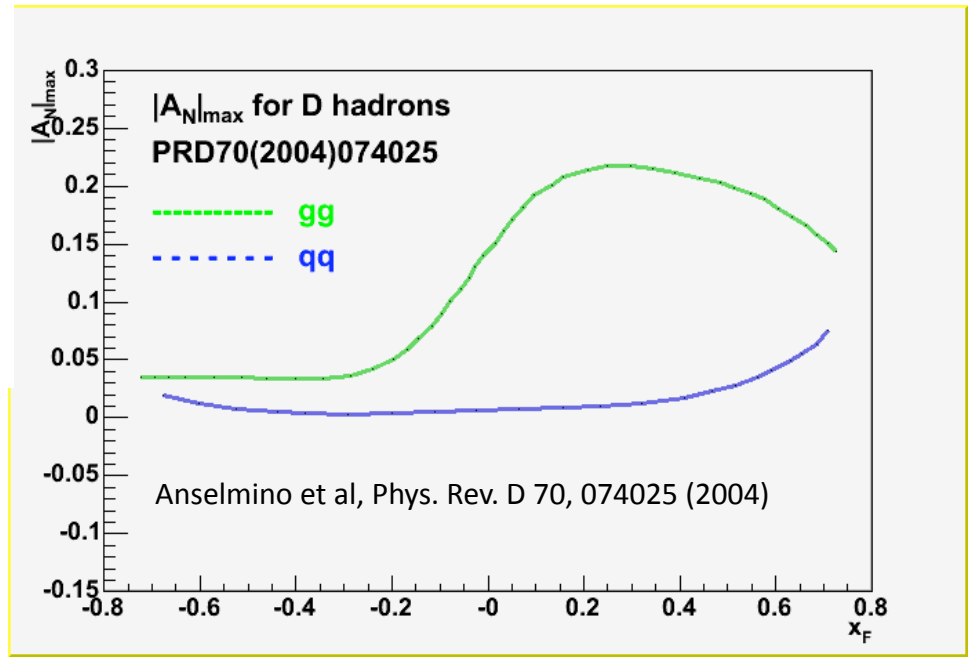


- Gluon transversity zero
→Asymmetry cannot originate from Transversity x Collins

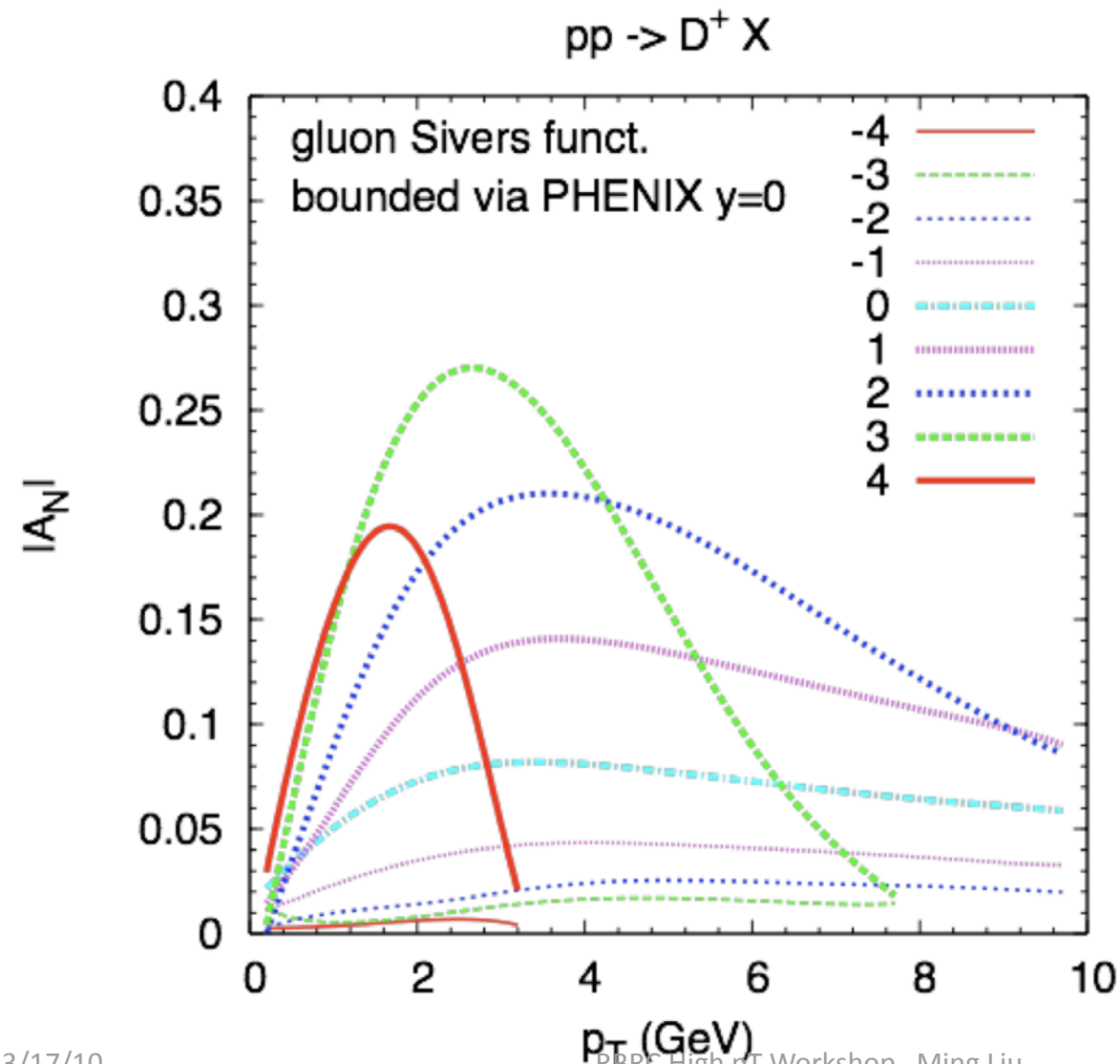
- Sensitive to gluon Sivers effect (poorly constrained by pol DIS)

Theoretical prediction:

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



A Simple Gluon Sivers Model



M. Anselmino et al.

$$A_N(c) \equiv A_N(\bar{c})$$

Tri-gluon Correlation and Open Charm

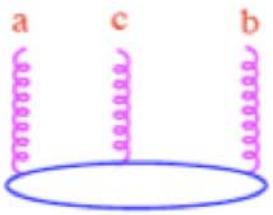
- New, unknown!

Qiu, Duke Tran. Spin Workshop '10

❑ **Two tri-gluon correlation functions – color contraction:**

$$T_G^{(f)}(x,x) \propto i f^{ABC} F^A F^C F^B = F^A F^C (\mathcal{T}^C)^{AB} F^B$$

$$T_G^{(d)}(x,x) \propto d^{ABC} F^A F^C F^B = F^A F^C (\mathcal{D}^C)^{AB} F^B$$



Quark-gluon correlation: $T_F(x,x) \propto \overline{\psi}_i F^C (T^C)_{ij} \psi_j$

❑ **Dependence on tri-gluon correlation functions:**

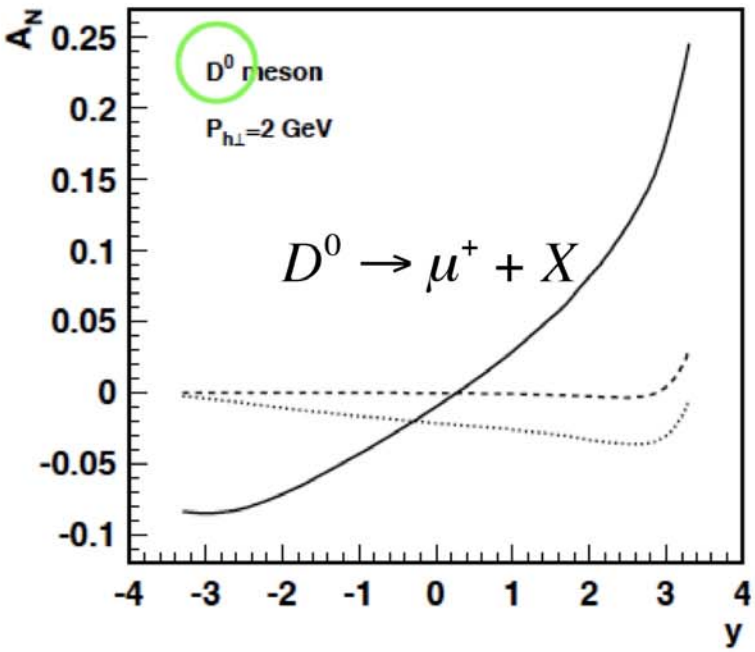
$$D - \text{meson} \propto T_G^{(f)} + T_G^{(d)} \qquad \overline{D} - \text{meson} \propto T_G^{(f)} - T_G^{(d)}$$

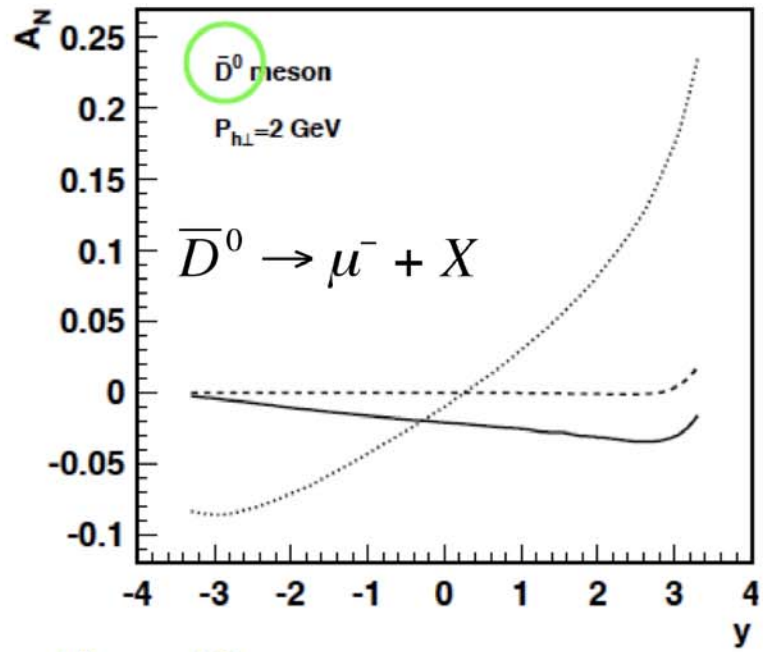
Separate $T_G^{(f)}$ **and** $T_G^{(d)}$ **by the difference between** D **and** $\bar{D}$

A unique opportunity @RHIC to study charm physics!

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

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

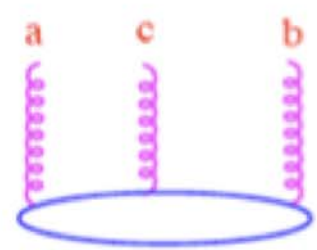




- Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$
- Dotted: $(2)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$
- Dashed: $(3)\lambda_f = \lambda_d = 0$ $\quad T_G^{(d)} = T_G^{(f)} = 0$

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

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



Asymmetry in Leading-Charm Production

- Two component model
  - Leading particle effects and coalescence
    - R.Vogt and S.J. Brodsky, NP B 478 (1996) 311-332

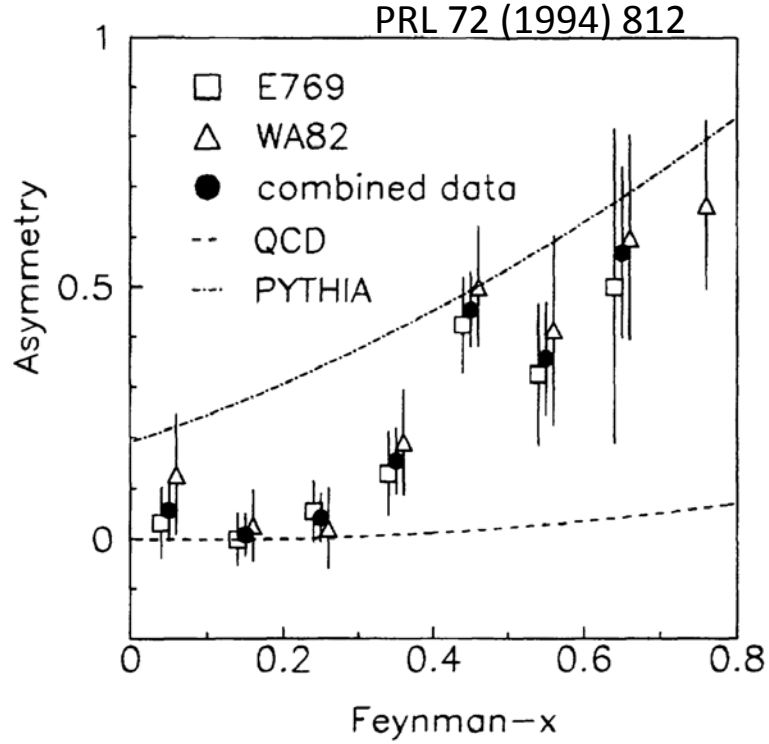
$$\pi^- + A \rightarrow D^{\pm} X$$

$$\pi^- \sim (\bar{u}d)$$

$$D^- \sim (\bar{c}d), \quad D^+ \sim (c\bar{d})$$

$$A(D^-/D^+) = \frac{d\sigma(D^-) - d\sigma(D^+)}{d\sigma(D^-) + d\sigma(D^+)}$$

PRL 72 (1994) 812



Anselmino's model

Prediction of two component model and current limits

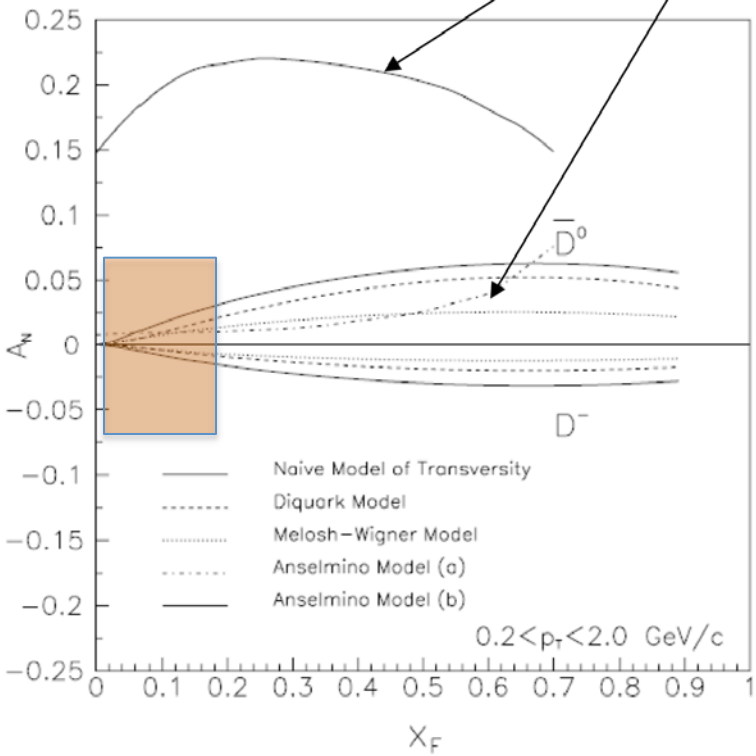


Fig. 6. Comparison of the single spin asymmetries obtained with the model presented here (*solid*, *dash* and *dotted curves*) with those obtained by Anselmino et al. [19] (*solid* in the upper part and *dot dashed curve*)

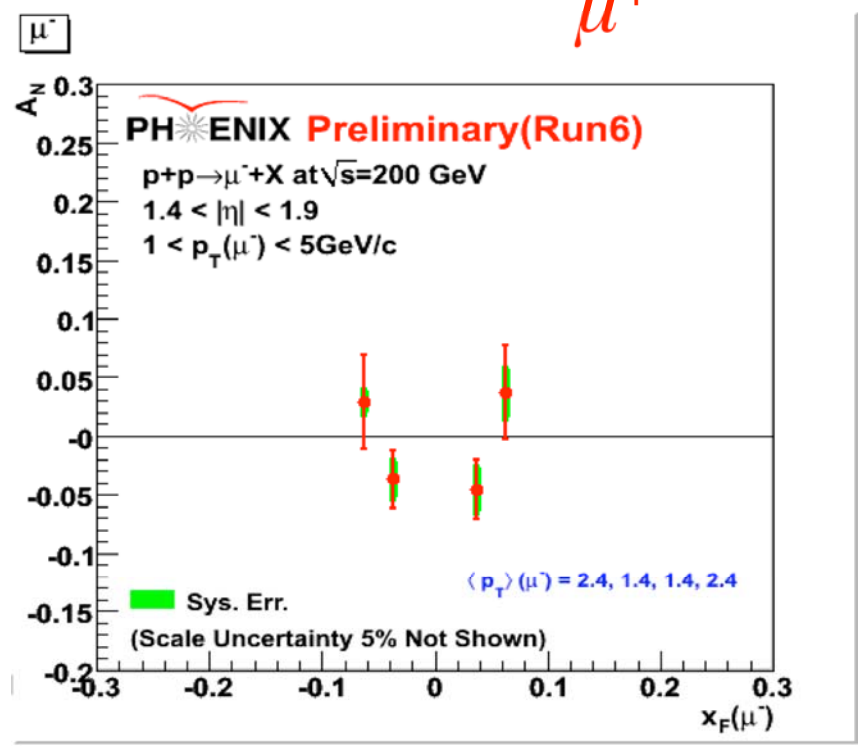
Prediction:

μ^-

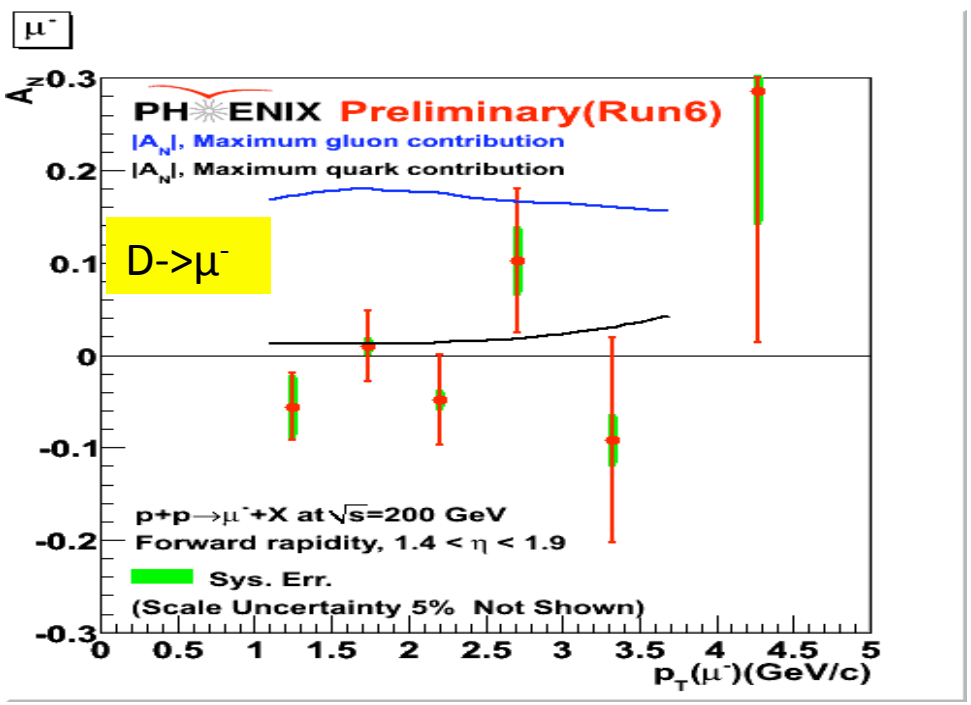
$\overline{D}^0(u\bar{c}), D^-(d\bar{c})$ → Sizable A_N

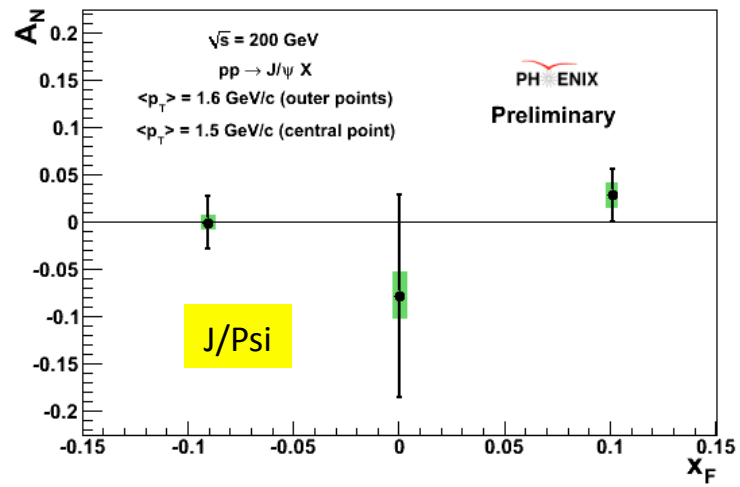
$D^0(\bar{u}c), D^+(\bar{d}c)$ → $A_N = 0$

μ^+



Latest Results of Heavy Quark SSA





- 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)

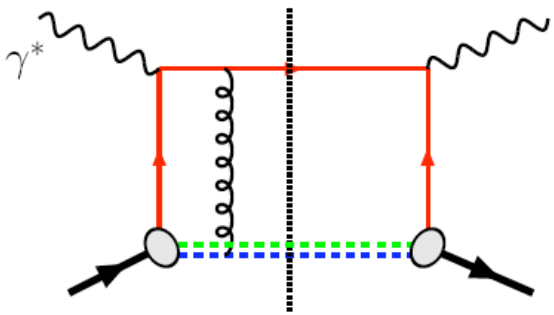
Drell-Yan A_N

- Sign change in A_N compared to DIS
- Scale dependent
  - pT and Mass

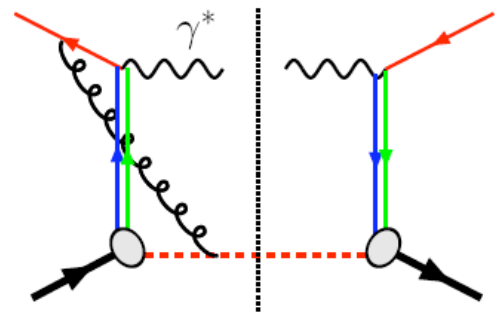
Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive

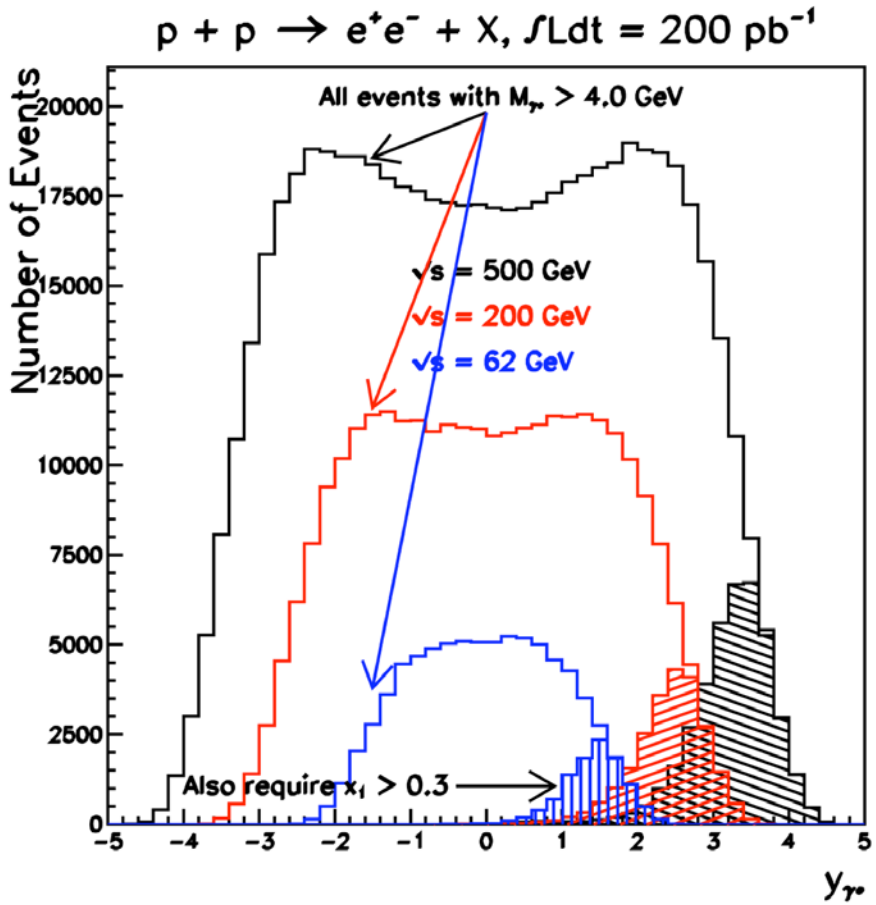


Drell-Yan: repulsive



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

Drell-Yan Production @RHIC

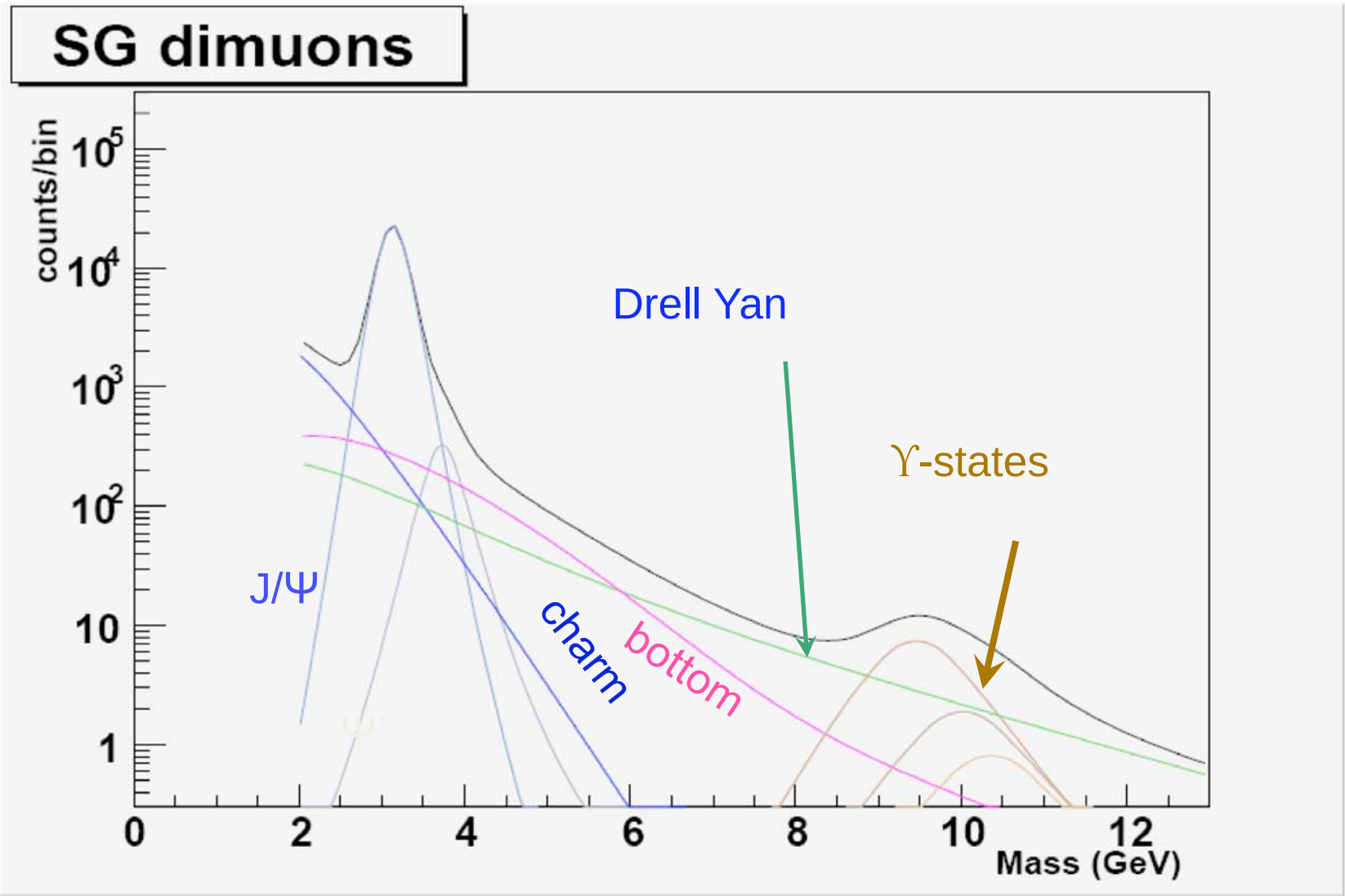


Les Bland

Figure 5: *PYTHIA simulation of the rapidity distribution of $e^+ e^-$ dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with* $x_1 > 0.3$.

Drell-Yan Background @200GeV

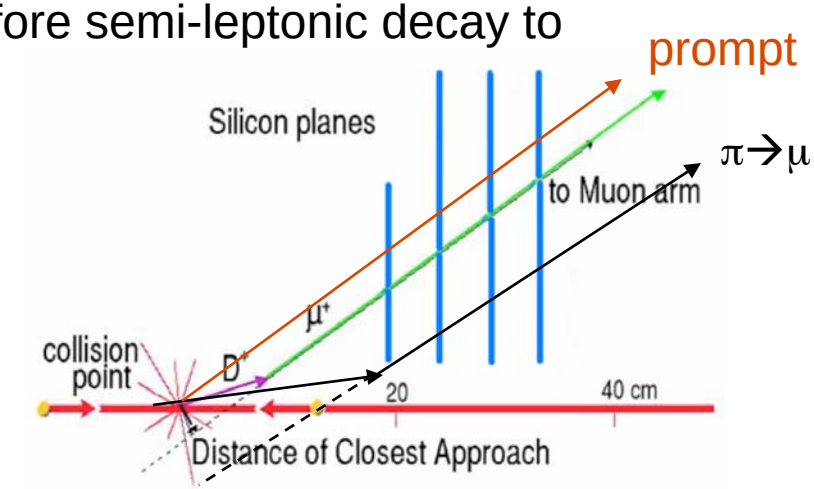
(PYTHIA Simulation benchmarked to PHENIX Data)

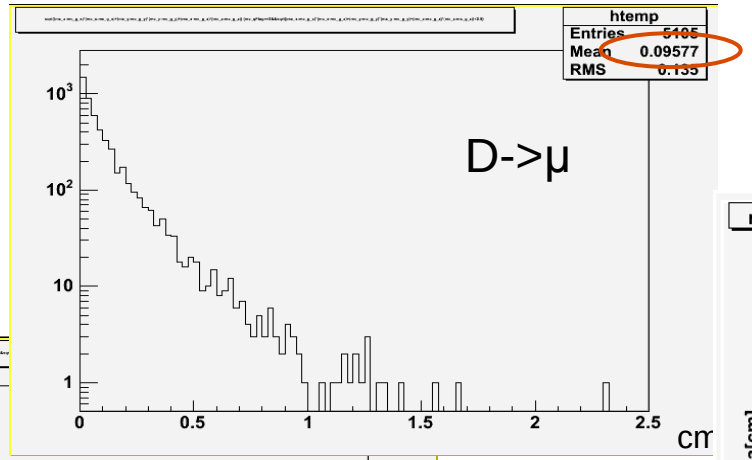


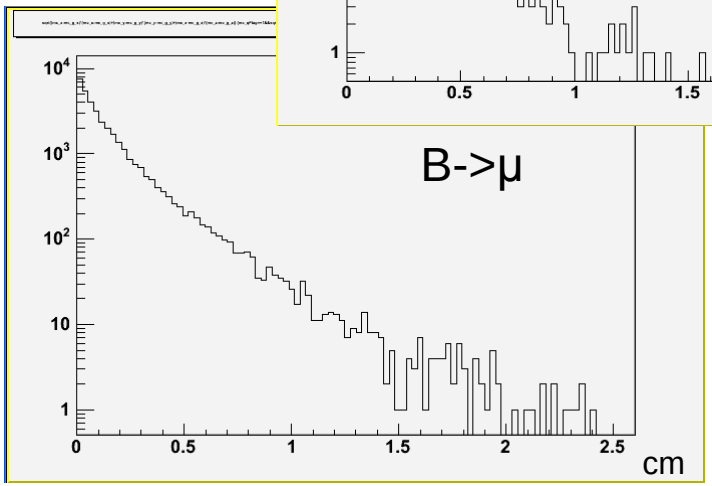
Impact Parameters for muons from D,B and DY

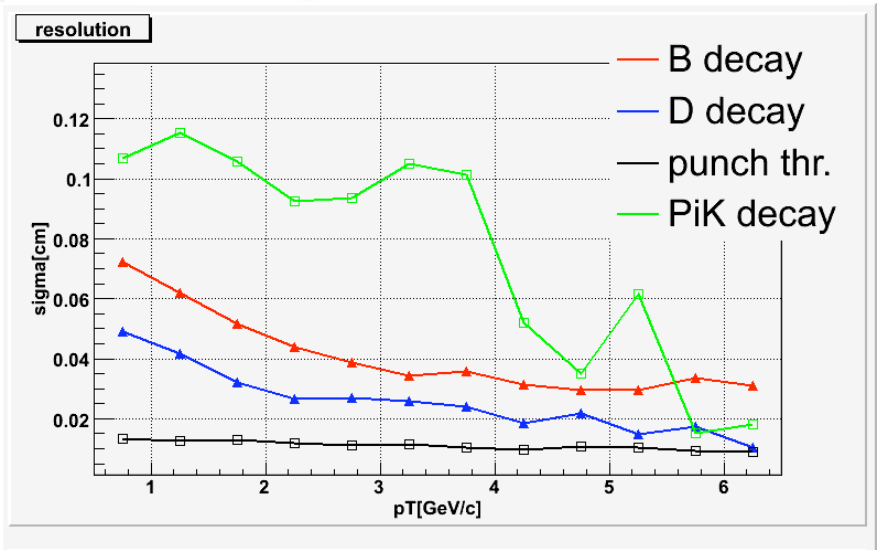
Measuring Charm and Beauty

- D, B mesons travel ~1 mm (with boost) before semi-leptonic decay to muons
- By measuring DCA to primary vertex, can separate D and B from prompt particles and long-lived decays like π, K



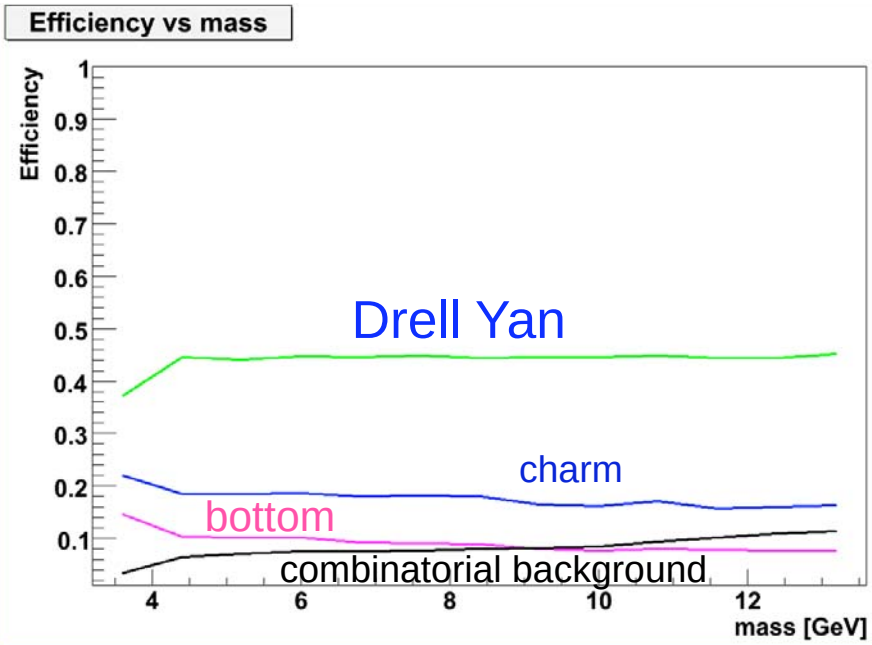




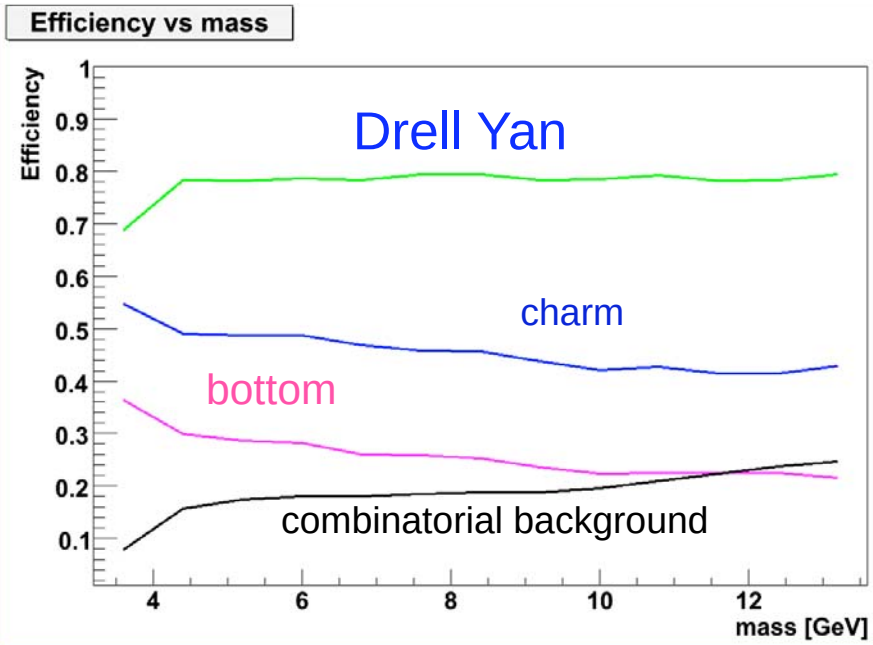


Heavy Quark Background Suppression

DCA < 1 σ cut:
Increase DY/bb ~ 5



DCA < 2 σ
Increase DY/bb ~ 3



PYTHIA vs NLO

Dimuon physics continuum simulation (2)

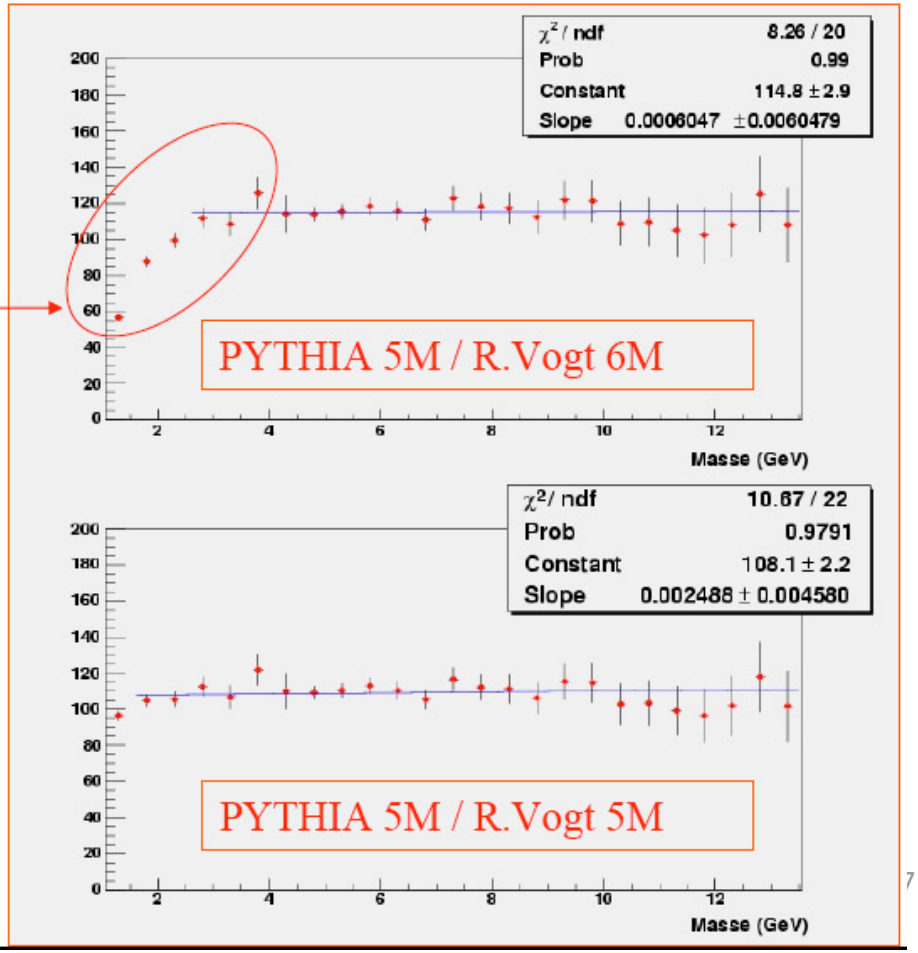
Drell-Yan: reproduction as best as possible of theoretical predictions from R. Vogt (NLO calculation with CTEQ6M)

Comparison:
$(dN/dm)_{Pythia} / (dN/dm)_{R.Vogt}$

This is due to a different behaviour of the two PDFs at low x

(R. Vogt)

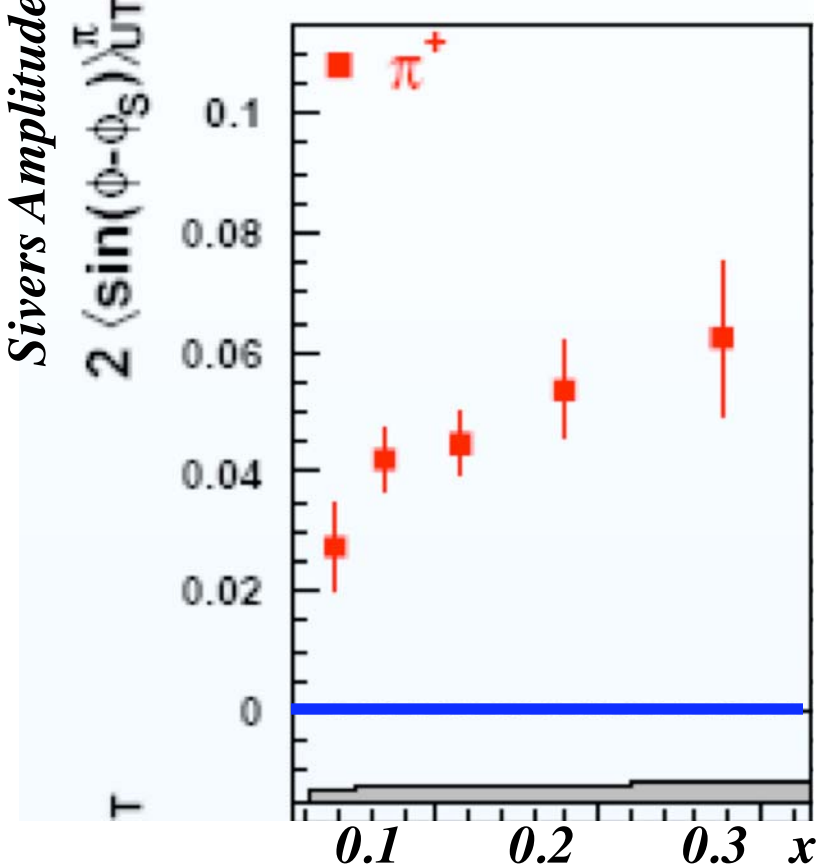
Good agreement between Pythia and QCD@NLO Prediction with same PDF



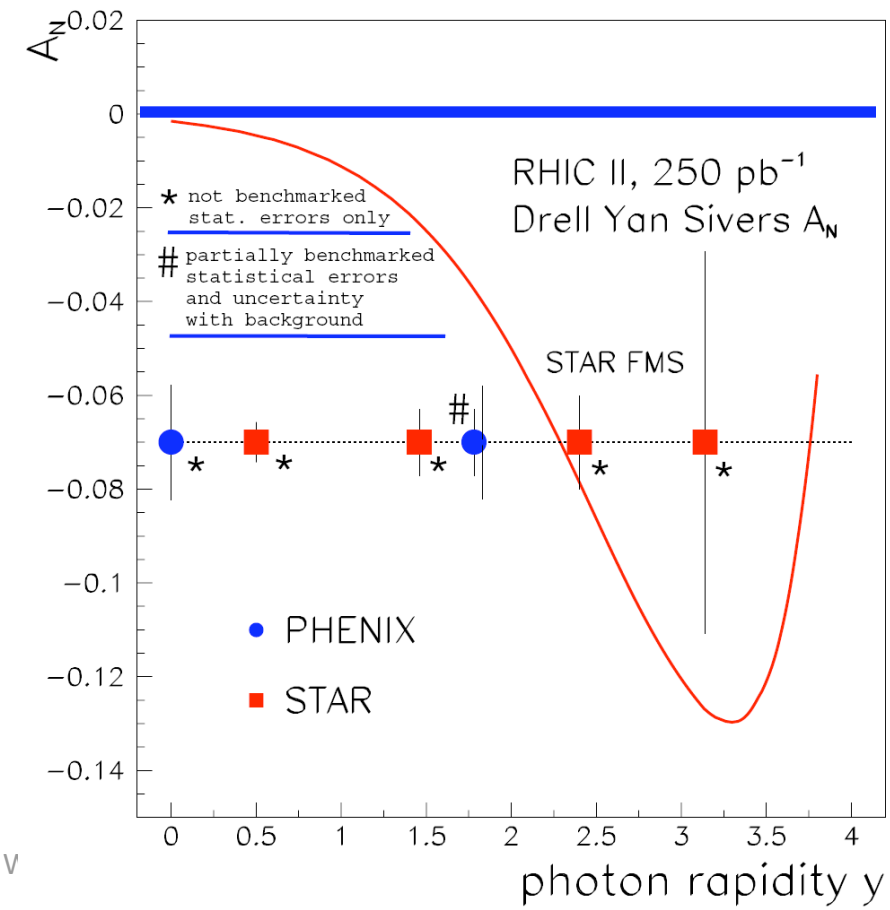
Experiment SIDIS vs Drell Yan: $\text{Sivers}|_{DIS} = -\text{Sivers}|_{DY}$

*** Probes QCD attraction and QCD repulsion ***

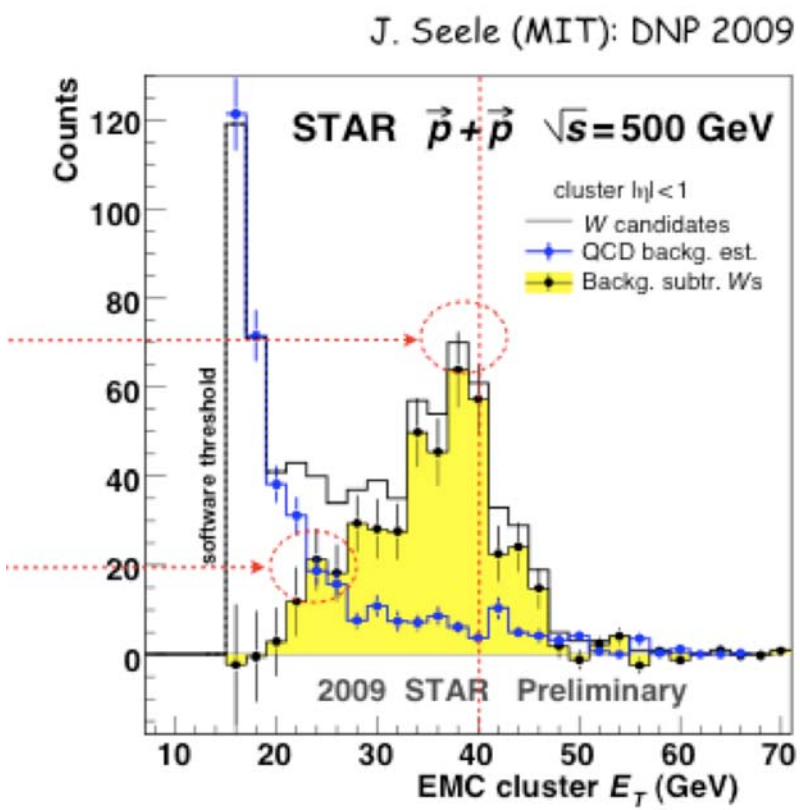
HERMES Sivers Results

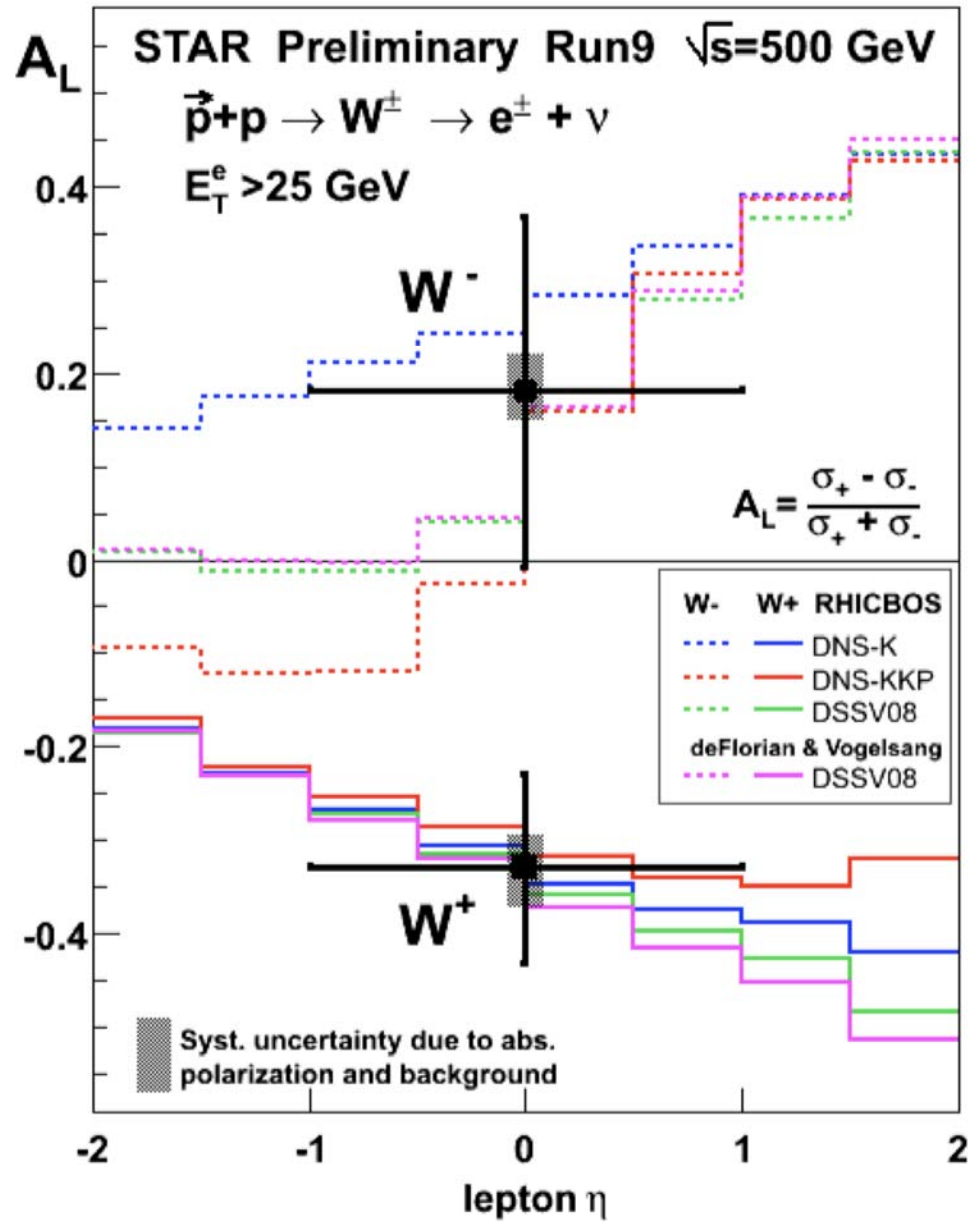


RHIC II Drell Yan Projections



$W^{\pm}$ & 500 pp!


J. Seele (MIT): DNP 2009
STAR $\vec{p}+\vec{p}$ $\sqrt{s}=500$ GeV
cluster $|\eta|<1$
W candidates
QCD backg. est.
Backg. subtr. Ws
software threshold
2009 STAR Preliminary
Counts
EMC cluster E_T (GeV)


A_L
STAR Preliminary Run9 $\sqrt{s}$=500 GeV
$\vec{p}+p \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu$
E_T^e >25 GeV
W^-
W^+
$A_L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$
W- W+ RHICBOS
DNS-K
DNS-KKP
DSSV08
deFlorian & Vogelsang
DSSV08
Syst. uncertainty due to abs. polarization and background
lepton η

$W^{+/-}$ & Z^0 Transverse 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

$$A_N(W^+) \sim \frac{\Delta_T u(x_1)\cdot \bar{d}(x_2) + \Delta_T \bar{d}(x_1)\cdot u(x_2)}{u(x_1)\cdot \bar{d}(x_2) + \bar{d}(x_1)\cdot u(x_2)}$$

Kang & Qiu PRL 103, 172001 (2009)

$W^{+/-}$

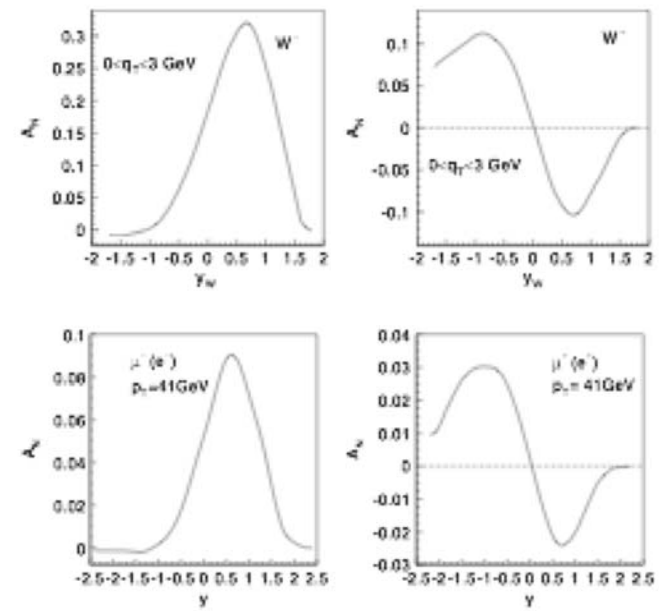


FIG. 3. A_N as a function of lepton rapidity.

Kang & Qiu arX 0912.1319

Z^0

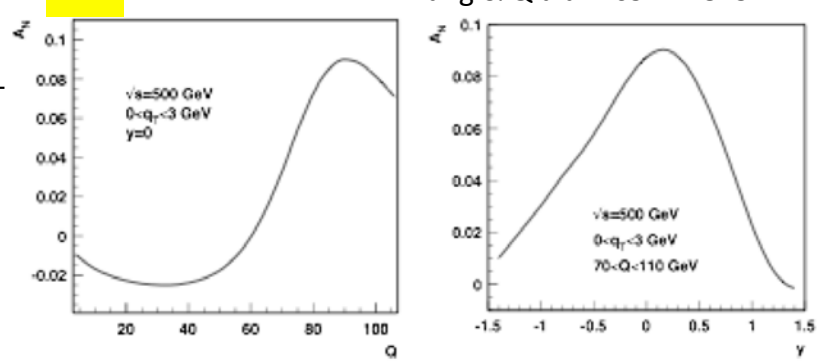
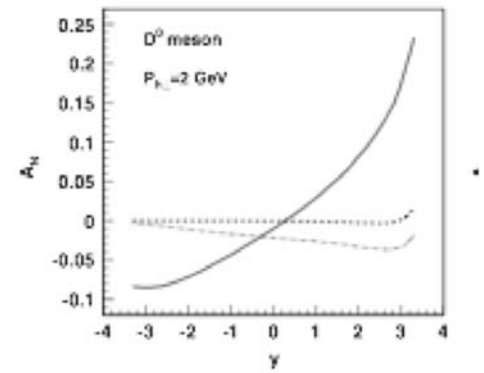
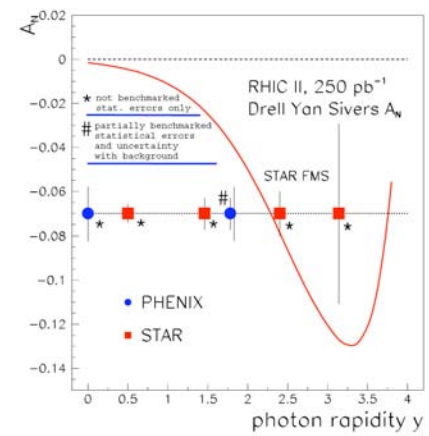


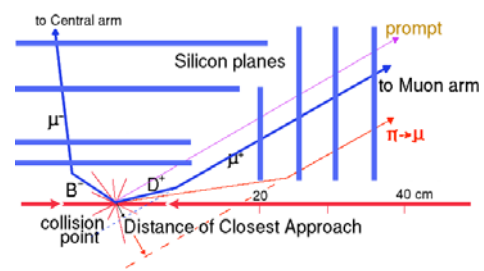
FIG. 3: Left: SSA of lepton pair production as a function of the pair's invariant mass Q. Right: SSA of lepton pair accumulated around Z^0 pole as a function of rapidity.

Summary and Outlook

- Unique opportunity to study QCD dynamics @RHIC
- TSSAs open up a new window to study transverse parton motion inside nucleon and test QCD in completely new domain with new observables
  - Tri-gluon correlation function
  - QCD factorization and sign change in Sivers in DY, W/Z
  - Q^2 evolution
- Complementary to EIC program
- Upgraded PHENIX/STAR detectors







Backup slides

Theoretical Models on Open Charm A_N

G.D. Zacarias et. al., EPJC 51(2007)619

- Two component model (has been used to describe the production asymmetry of charm productions successfully)

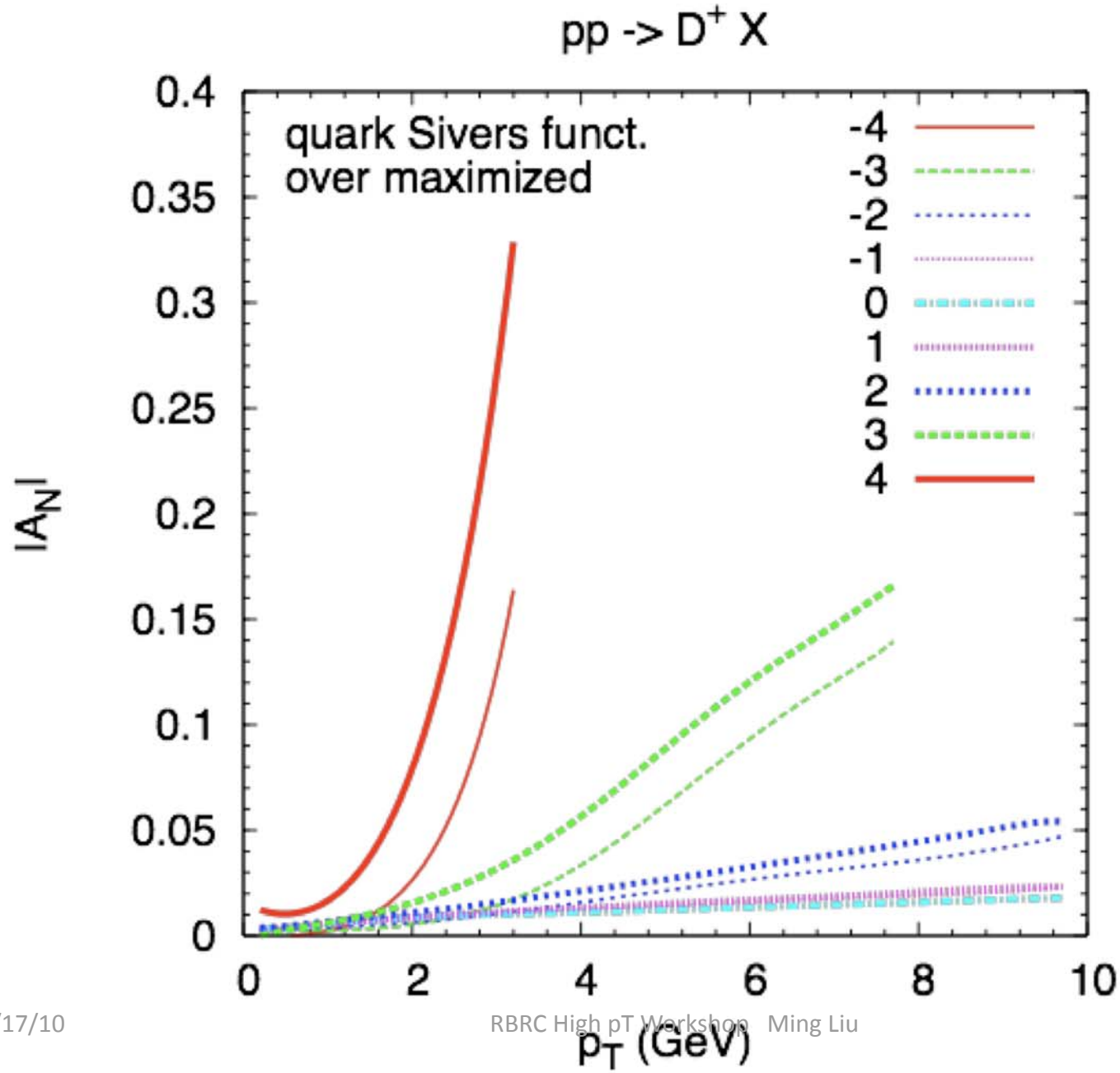
$$\frac{d\sigma^D}{dx_F dp_T} = \frac{d\sigma^D_{rec}}{dx_F dp_T} + \frac{d\sigma^D_{frag}}{dx_F dp_T}$$

-- Recombination process: a quark from the sea joins a valence quark in the initial state

$$\overline{D}^0 : u\overline{c} \qquad D^- : d\overline{c}$$

-- Fragmentation process: assume particles created by the fragmentation process lose information about the spin polarization of the proton in the initial state

$$\frac{d\sigma^{\uparrow}_{frag}}{dx_F dp_T} = \frac{d\sigma^{\downarrow}_{frag}}{dx_F dp_T}$$

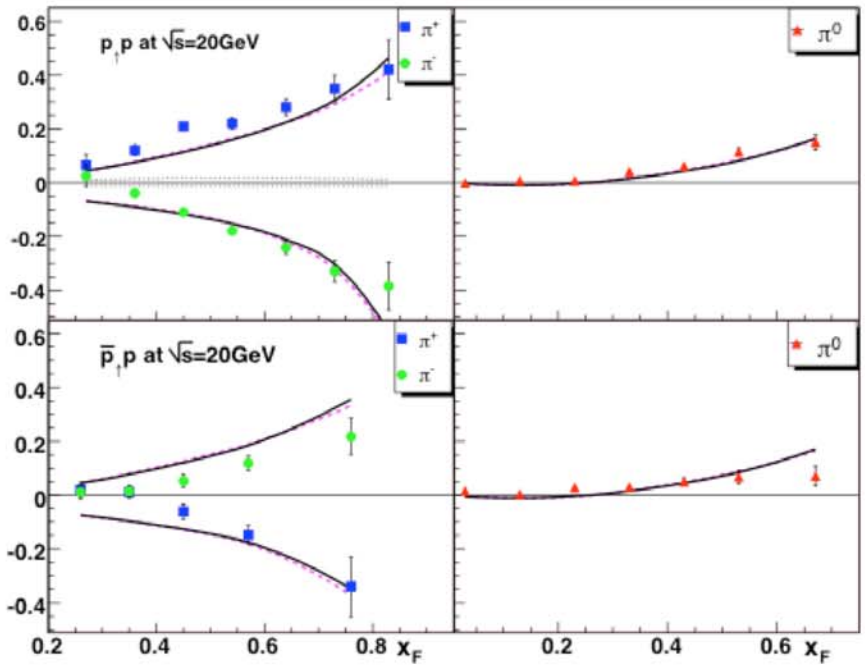

pp -> D+ X
quark Sivers funct.
over maximized
-4
-3
-2
-1
0
1
2
3
4
|AN|
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
2
4
6
8
10
pT (GeV)

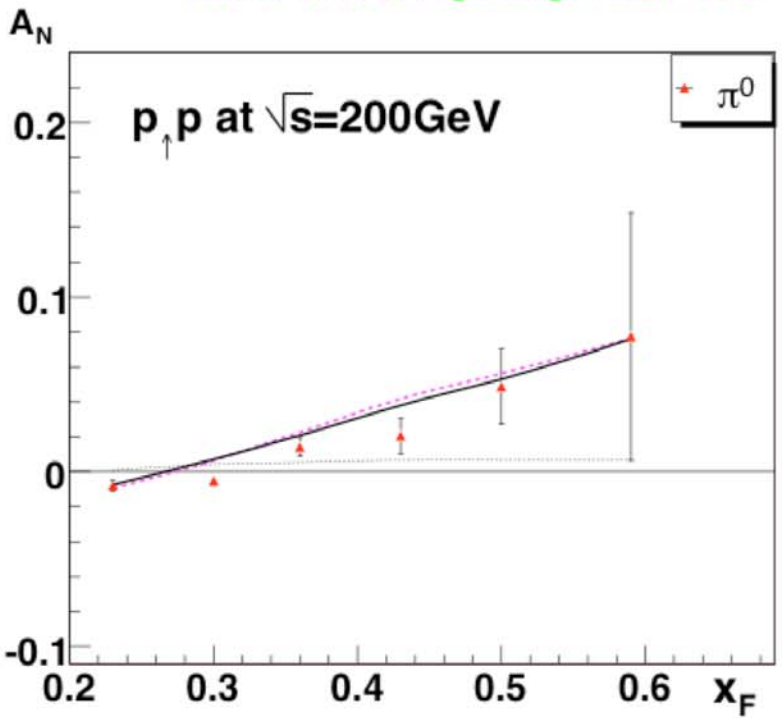
Twist-3 approach to the SSAs

Kang's talk @Duke 03/2010

- Describe both E704 and RHIC data simultaneously

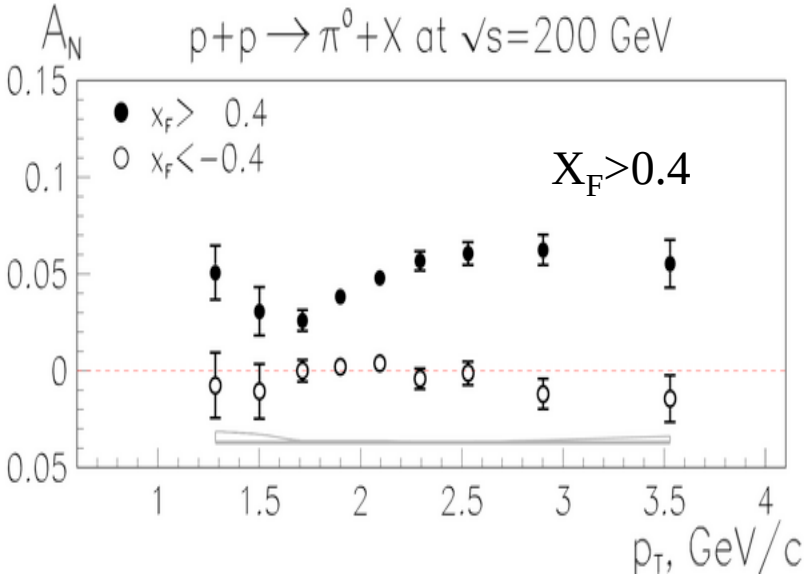
Kouvaris, Qiu, Vogelsang, Yuan, 2006



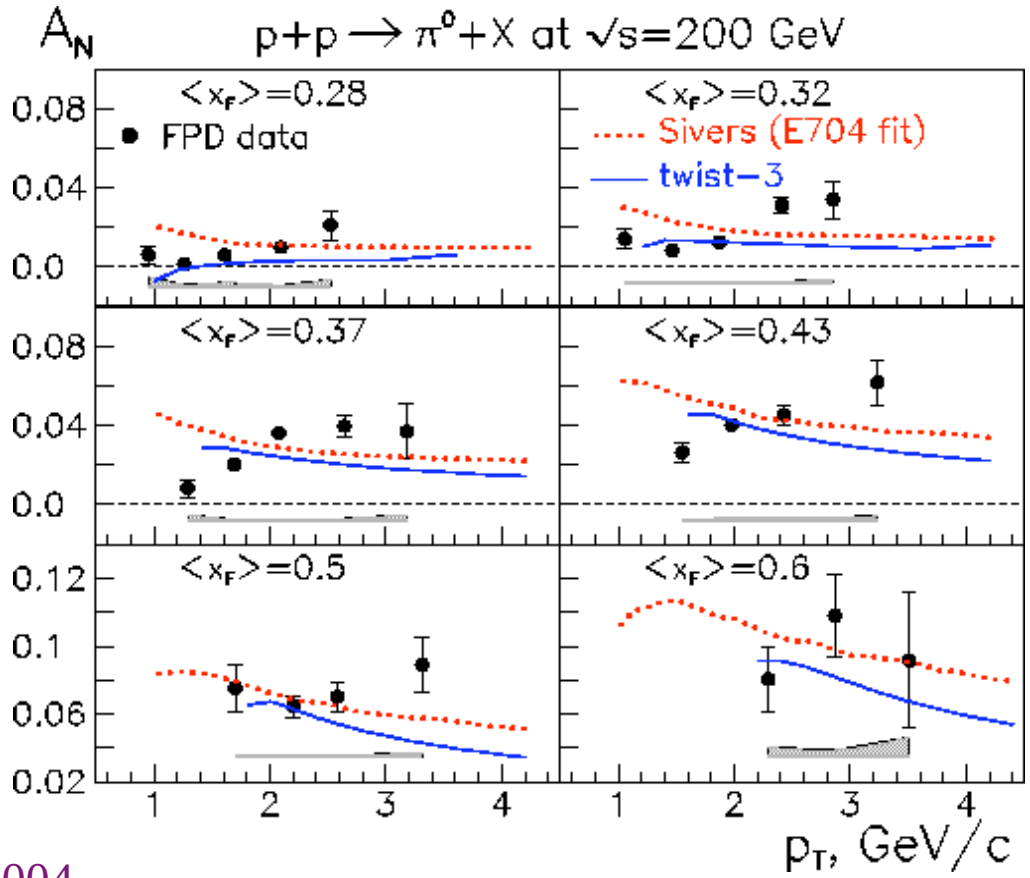


- Energy scale is different at different experiments, one needs the evolution of the correlation functions

Early RHIC Data Challenges



B.I. Abelev et al. (STAR) [arXiv:hep-ex/0801.2990v1],), submitted to PRL

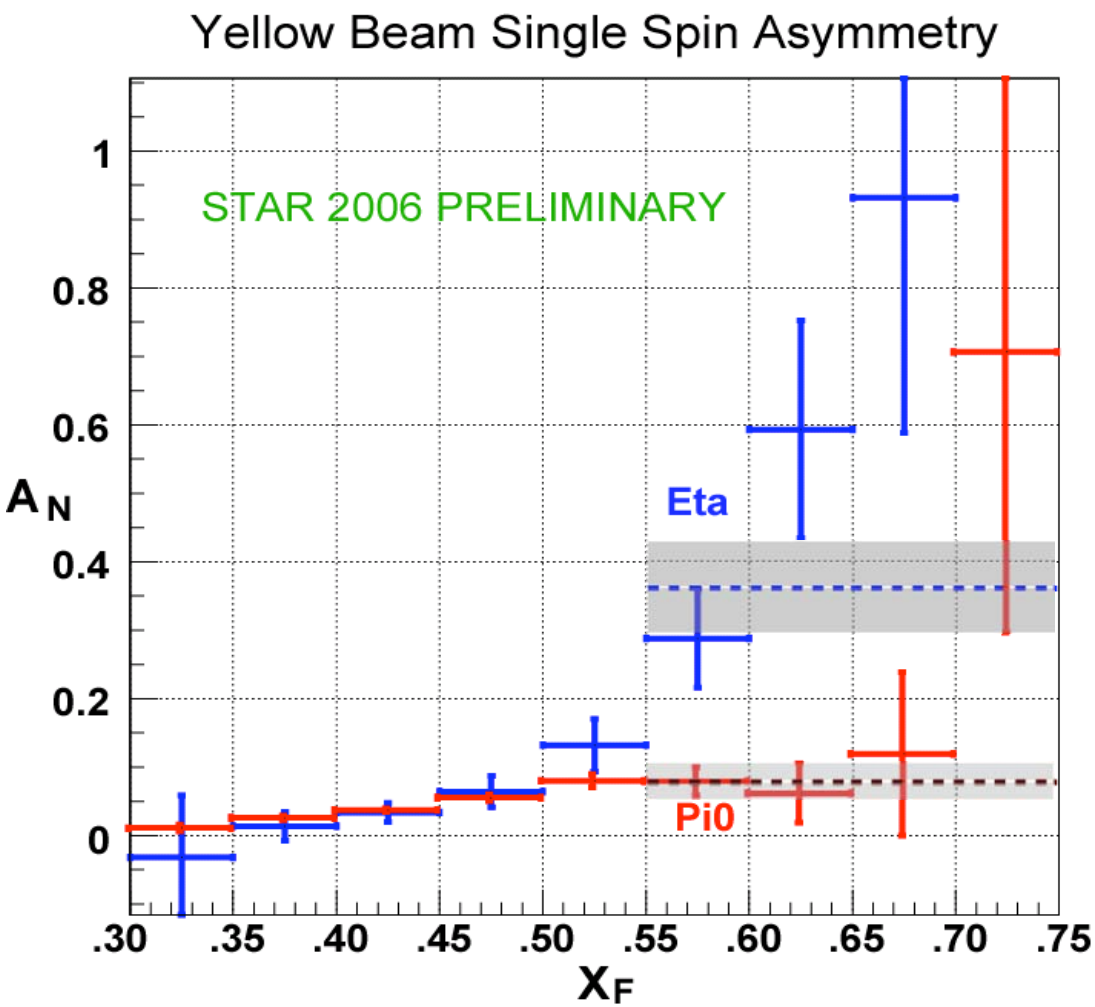


Admixture of Collins and Sivers?

RHIC, STAR, 2004

A_N in π^0 and Eta Mass Regions

$$p^{\uparrow} + p \rightarrow M + X \qquad \sqrt{s} = 200\,GeV$$
$$M \rightarrow \gamma + \gamma$$



1. $N_{photon} = 2$
2. Center Cut (η and ϕ)
3. Pi0 or Eta mass cuts
4. $Z\gamma\gamma < 0.85$
5. Average Yellow Beam Polarization = 56%

$$.55 < X_F < .75$$
$$\langle A_N \rangle_{\eta} = 0.36 \pm 0.065$$
$$\langle A_N \rangle_{\pi^0} = 0.078 \pm 0.018$$

For $.55 < X_F < .75$, the asymmetry in the Eta mass region is greater than 5 sigma above zero, and about 4 sigma above the asymmetry in the π^0 mass region.