# Highlights from PHENIX Transverse Spin Physics Program

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(for the PHENIX Collaboration)

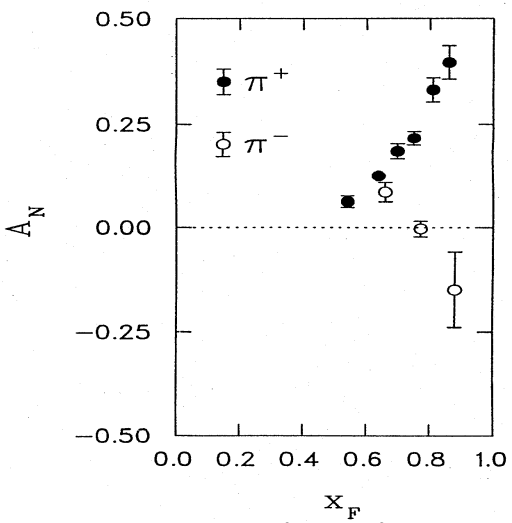
- Current Challenges
- PHENIX Capability
- Highlights and Outlook

# What are the Physics Origins?

## A Challenge of "Too Large"

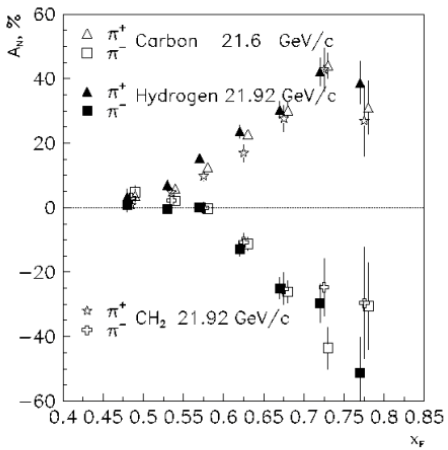
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

ZGS 12 GeV beam



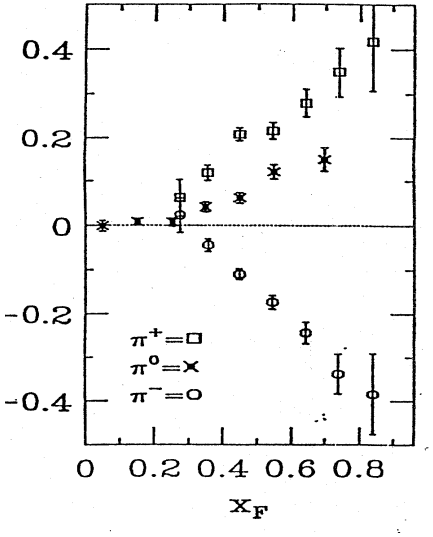

PRL36, 929 (1976)

AGS 22 GeV beam



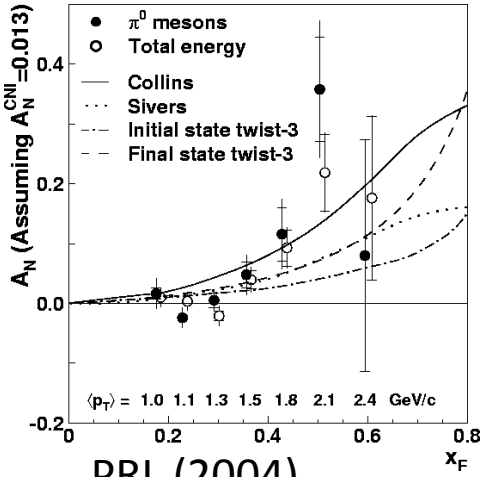

PRD65, 092008 (2002)

FNAL 200 GeV beam

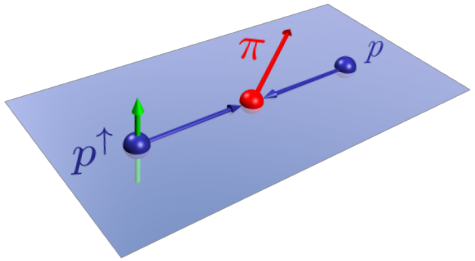



PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC 20,000 GeV beam




PRL (2004)

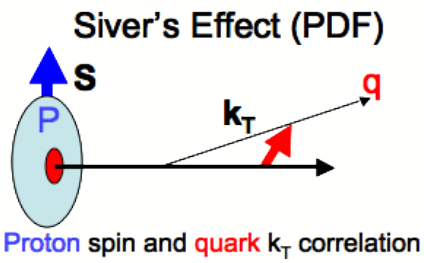


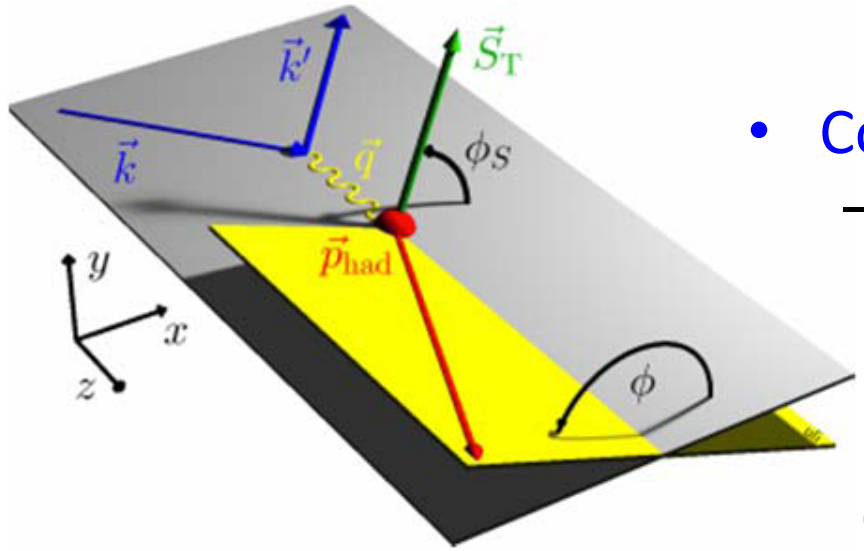

Sivers, Collins, Twist-3 ....

Non-Perturbative cross section → Perturbative cross section

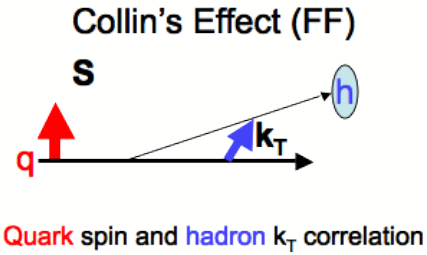
# Positive Signals from SIDIS

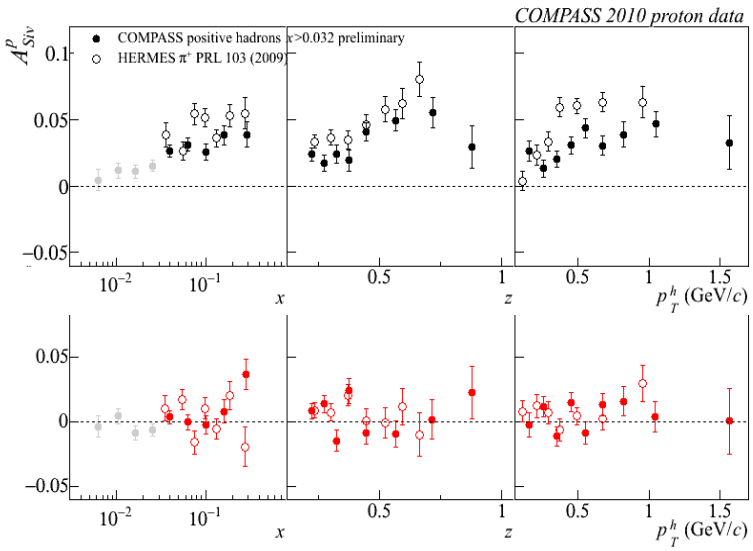
- Sivers
  - <sin(Φ–Φ$_s$)>

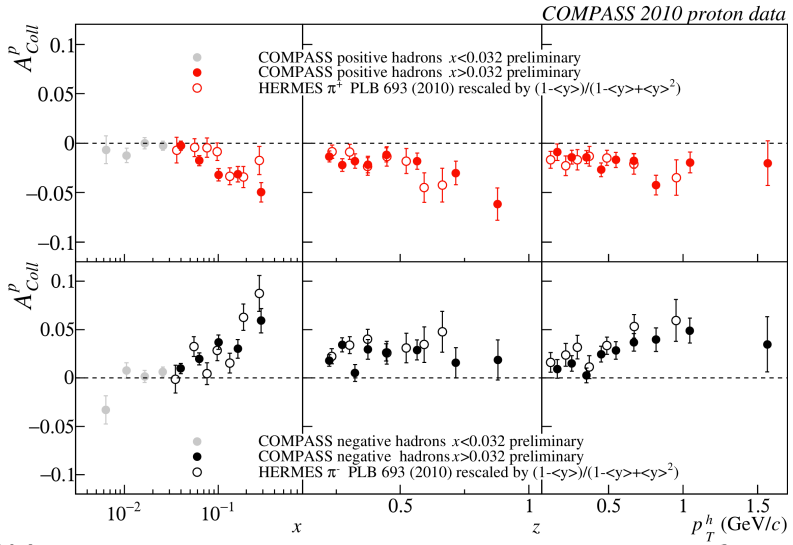



- Collins
  - <sing(Φ+Φ$_s$)>



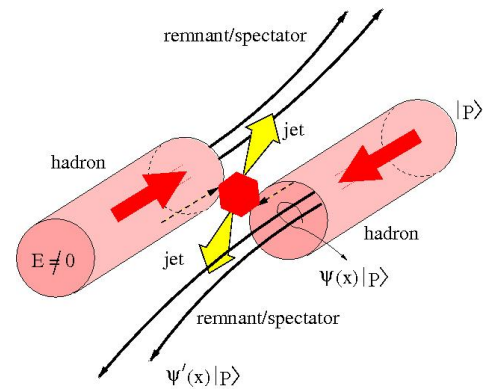



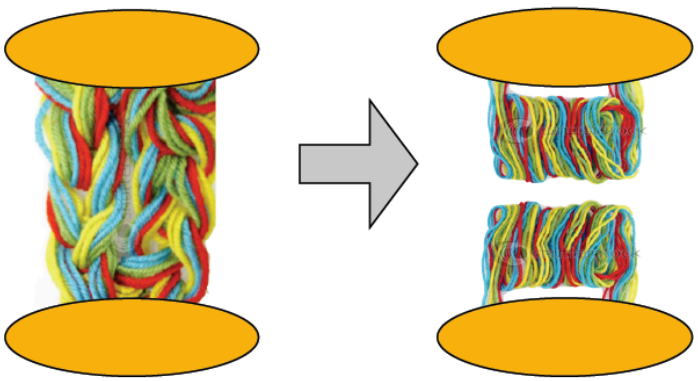



# Complex Color Interaction in p+p Collisions

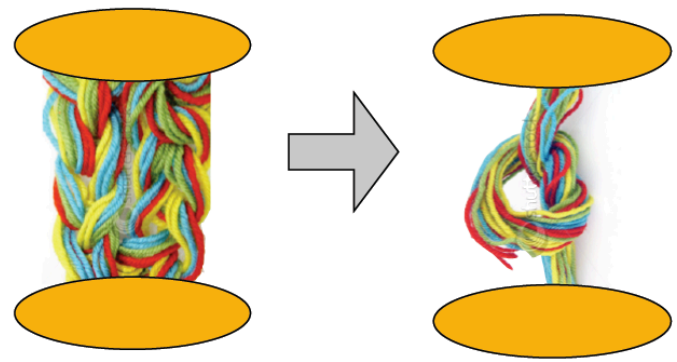
- Theoretical challenges
  - validity of factorization, universality …
  - TMD, Twist-3…

Bacchetta, Mulders@QCD-N12



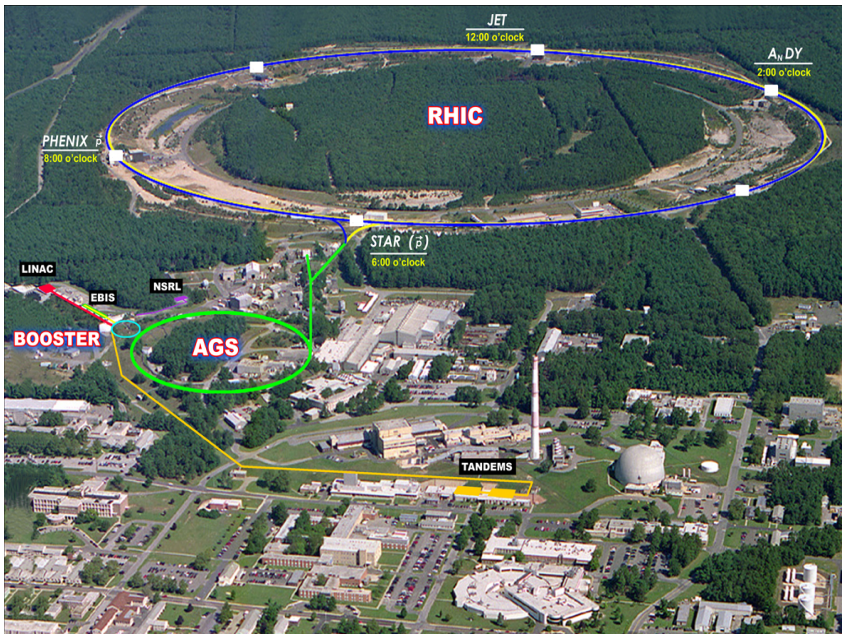
TMD factorization works at leading twist for SIDIS, $e^-e^+$ annihilation, Drell-Yan (pp to leptons)

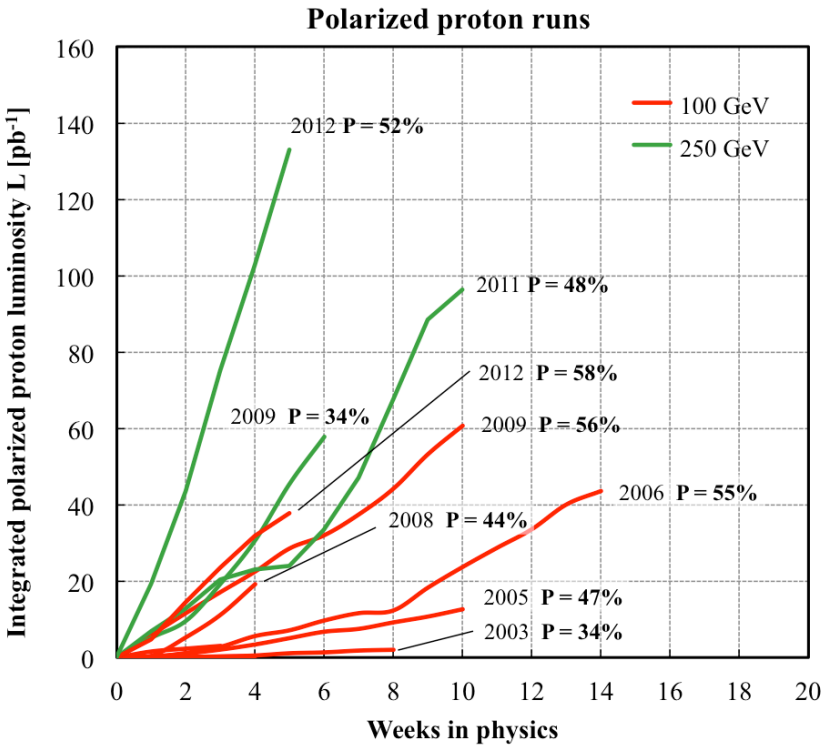


TMD factorization does not work for pp to hadrons.

Breakdown of TMD in p+p
Experiment + Theory joint efforts

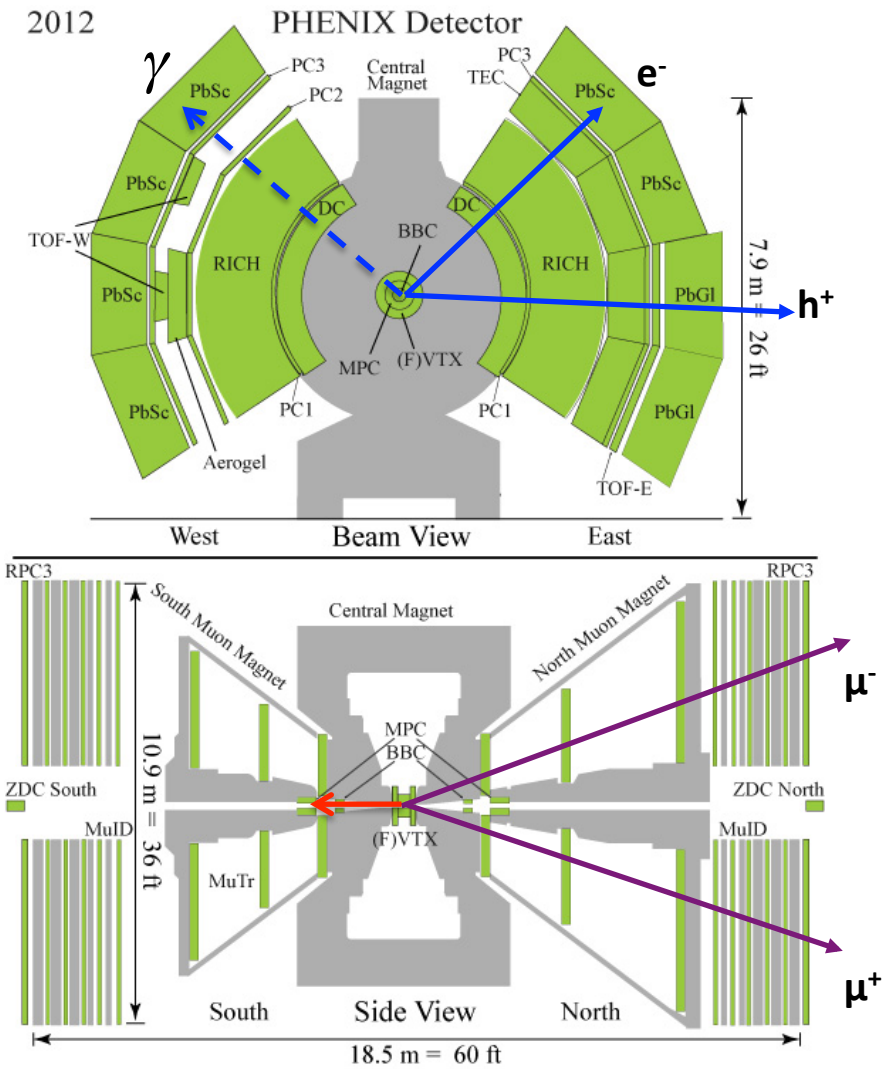
# Recent PHENIX Transverse Spin Runs




| 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 $nb^{-1}$ |

# PHENIX Detectors




**Central Arm** $|\eta| < 0.35$

- Drift Chamber (DC)
- PbGl and PbSc (EMCal)
- Ring Imaging Cherenkov Detector (RICH)
- Pad Chambers (PC)
- Time Expansion Chamber (TEC)
- Silicon Vertex Detector (VTX)

**Muon Arms** $1.2 < |\eta| < 2.4$

- **Muon tracker (MuTr)**
- **Muon Identifier (MuID)**
- **RPC (Trig)**
- **Forward VTX (FVTX)**

**Muon Piston Cal. (MPC)** $3.1 < |\eta| < 3.9$

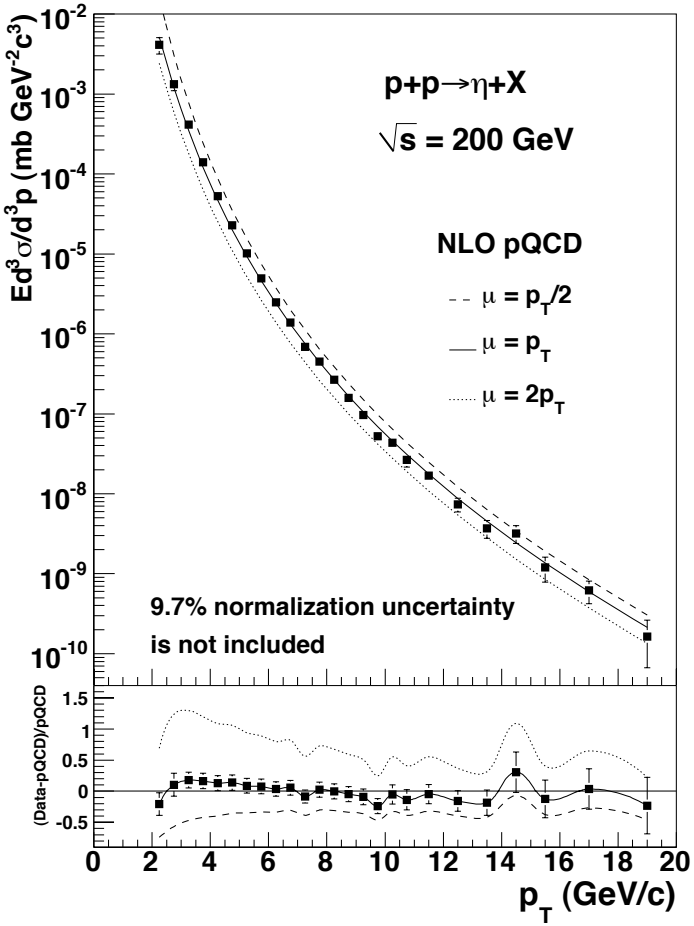
- **photons ( $\pi^0, \eta$...)**
- **MPX-EX upgrade(2015)**

**Global Detectors (Lumi, Trigger, local Pol.)**

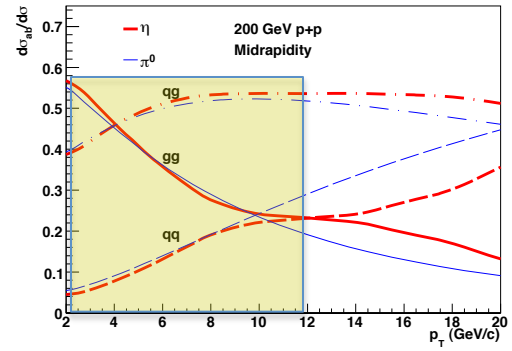
- BBC
- ZDC (neutron)

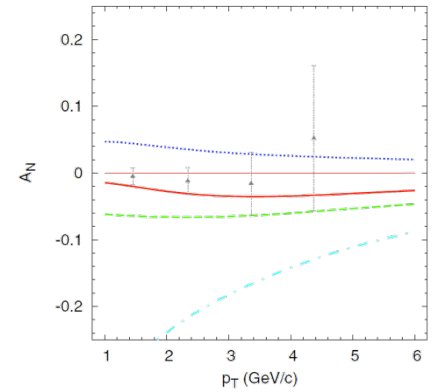
# Central Arms: Mid-rapidity $\pi^0$ and $\eta$

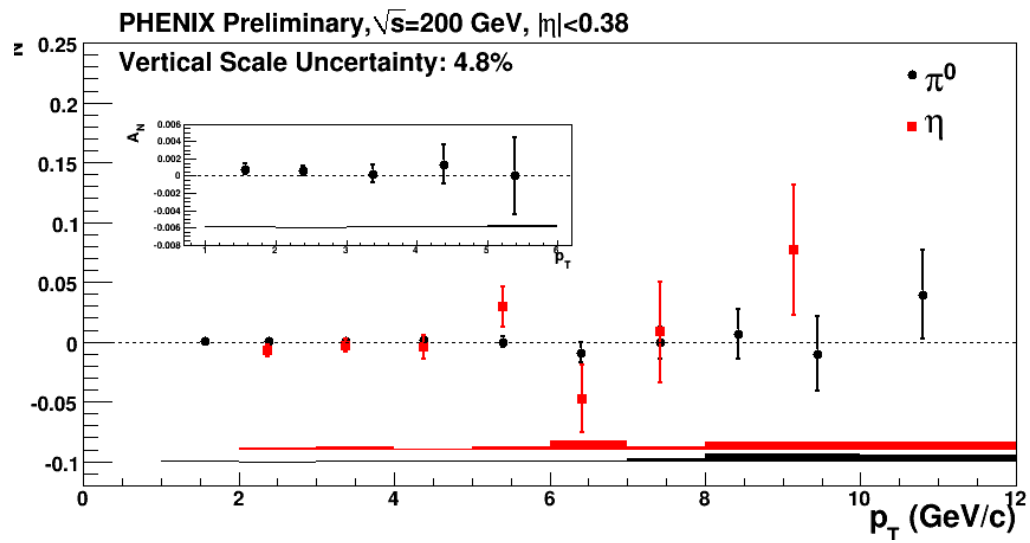
PRD 83, 032001 (2011)




Anselmino et al, PRD 74, 094011 (2006)



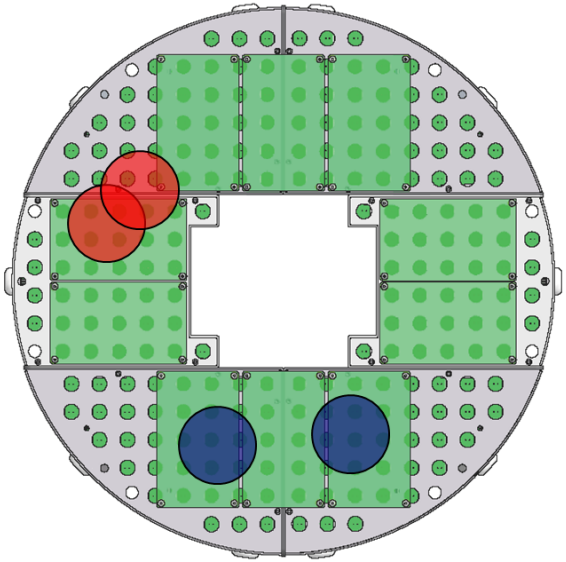



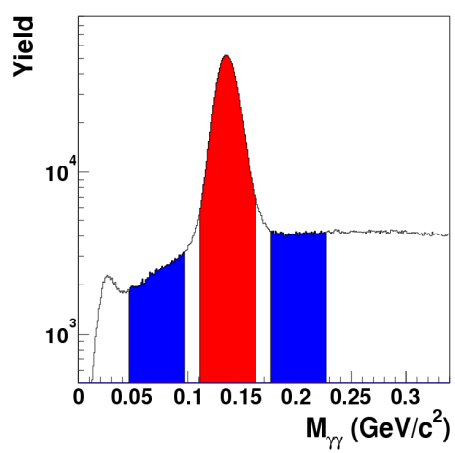

Cross sections:pQCD good agreement with RHIC data

$A_N$: consistent with zero

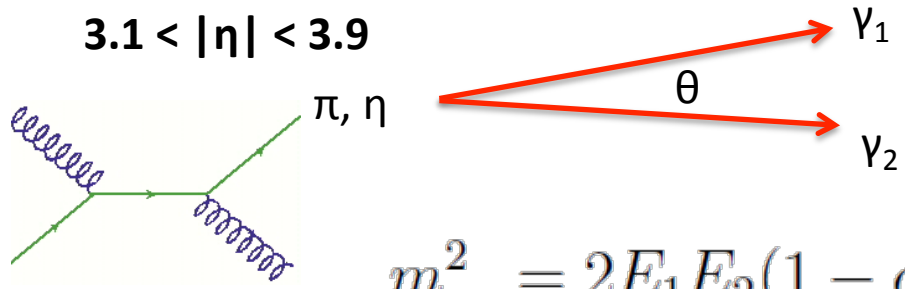
# MPC: Forward-rapidity $\pi^0$ and $\eta$



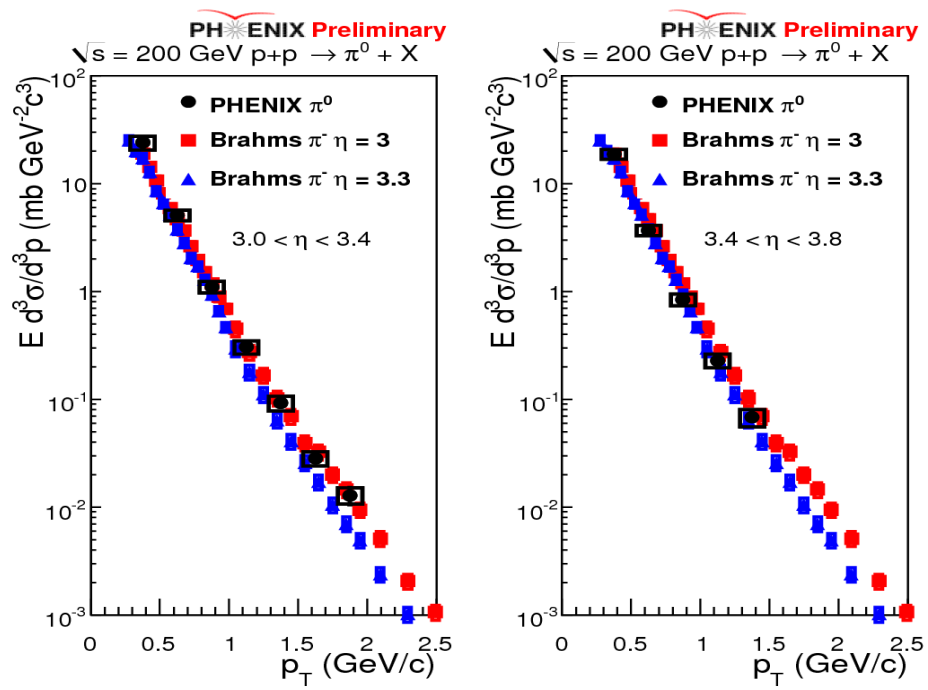
Decay photon impact positions for low and high energy $\pi^0$'s



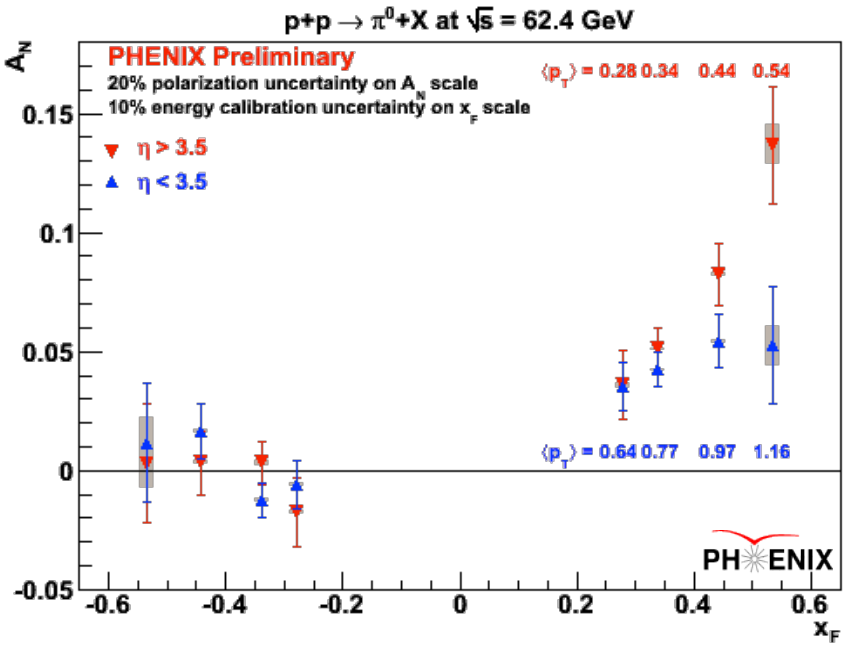

**3.1 < |η| < 3.9**

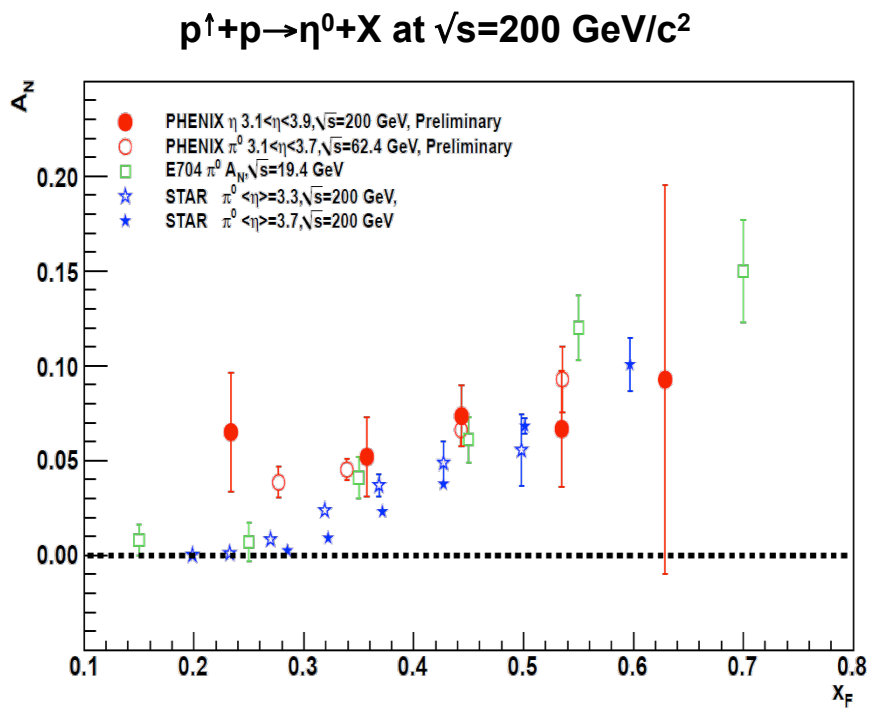



$$m^2_{\gamma\gamma} = 2E_1E_2(1 - cos(\theta))$$



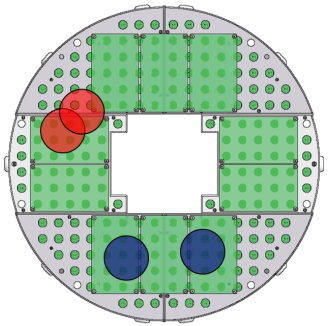
# MPC: $\pi^0$ and $\eta$ $A_N$, $\sqrt{s}$=62.4, 200 GeV

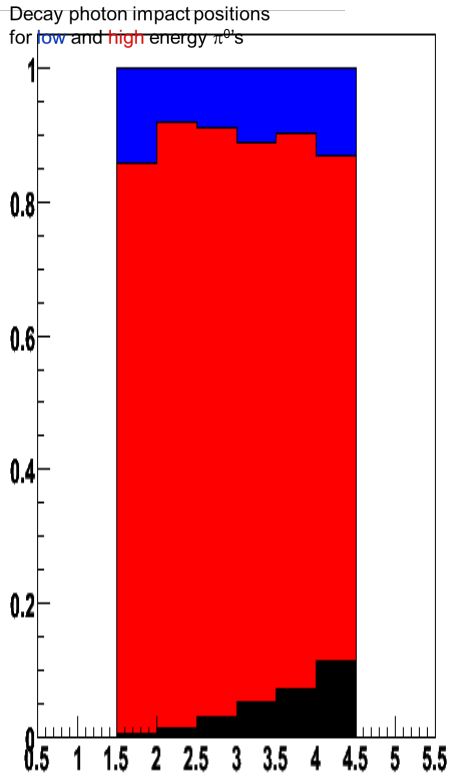


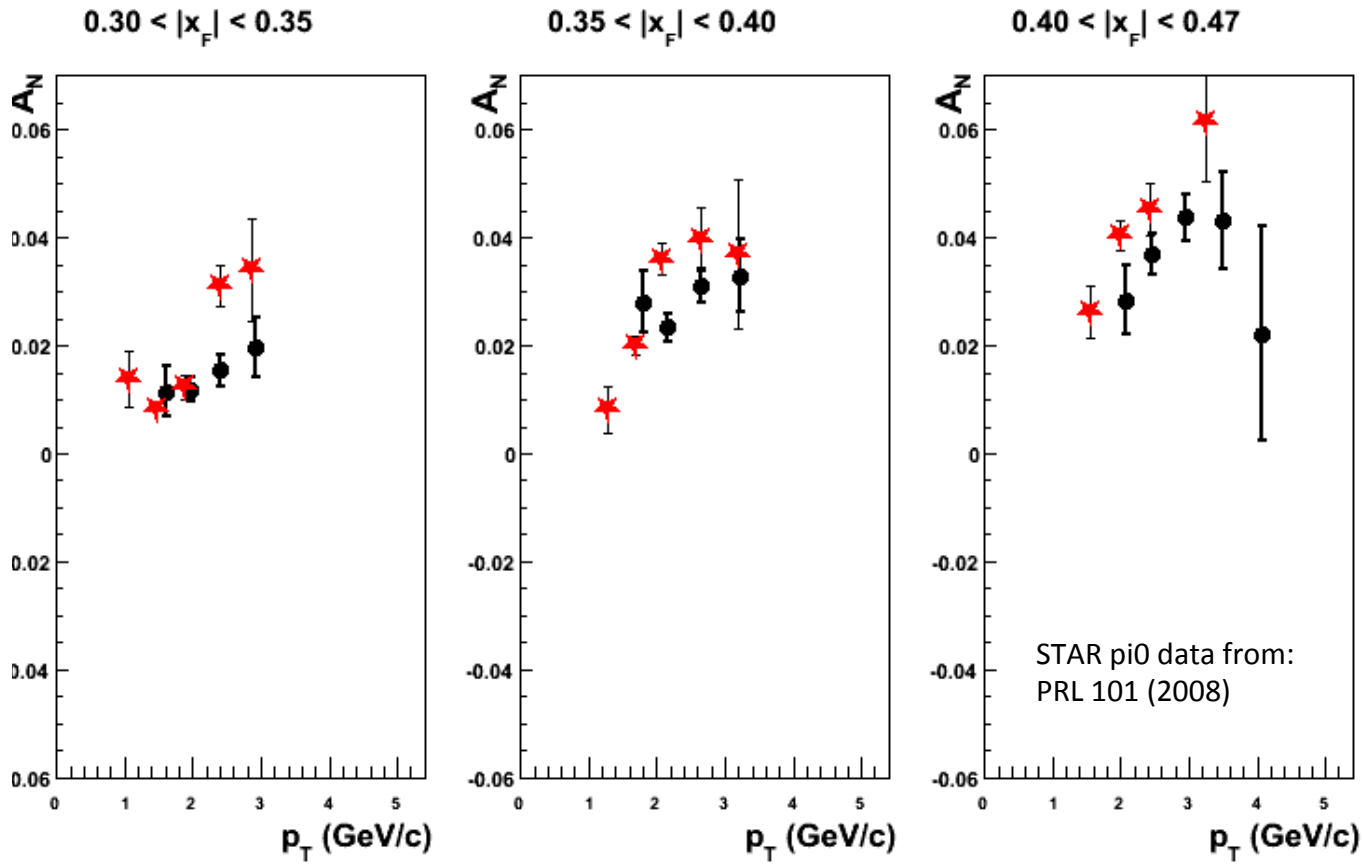



# Access Higher pT: EM Clusters

## $A_N$ vs pT, $\sqrt{s}$=200 GeV





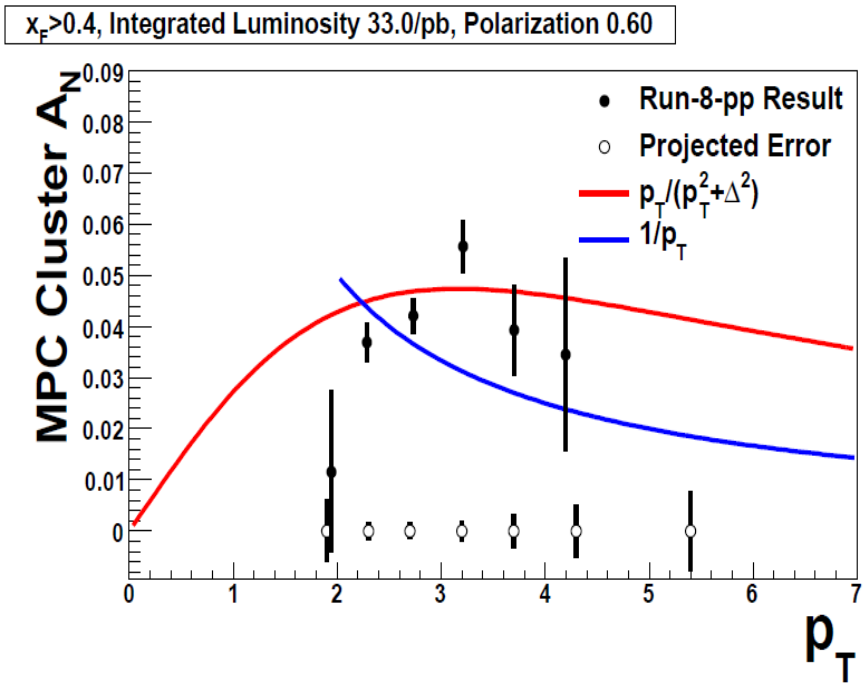




**Decay photon**
**$\pi^0$**
**Direct photon**

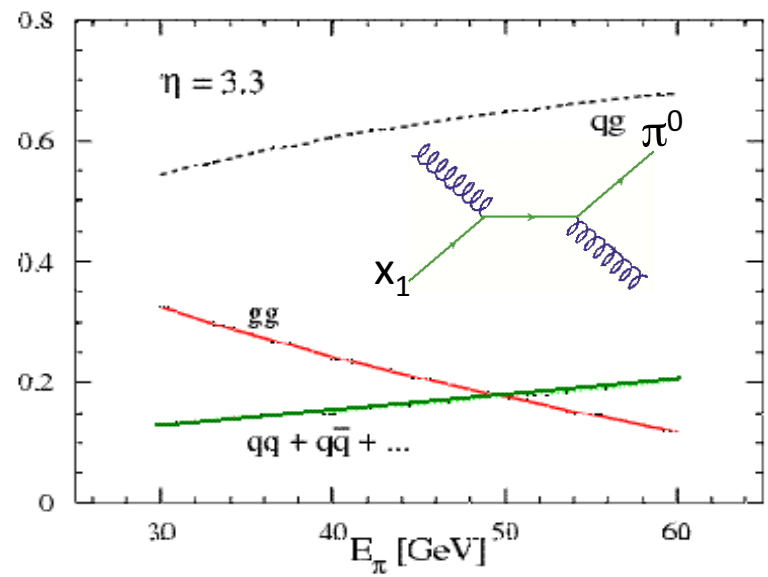
$$A_N(cluster) = A_N^{\pi^0} f^{\pi^0} + A_N^{\eta} f^{\eta} + A_N^{\gamma} f^{\gamma} + \ldots$$

# Forward $A_N$ Challenge: pT Dependence

## Valence Quarks' Sivers or Collins effects?




Sub-process fractions p+p 200GeV




- No sign of $1/p_T$ falloff yet.
  - Collins?
  - Twist-3 pT not trivial

- Much improved ~2015 with MPC-EX

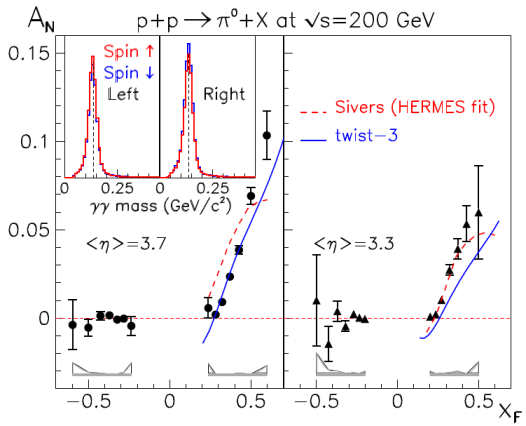
Y. Koike @QCD-N12

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

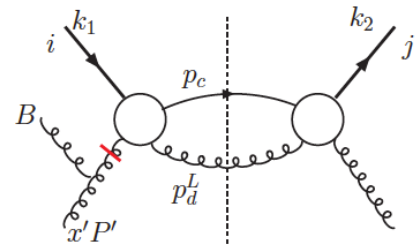
$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

# A New Challenge: $A_N$ Sign Mismatch?

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

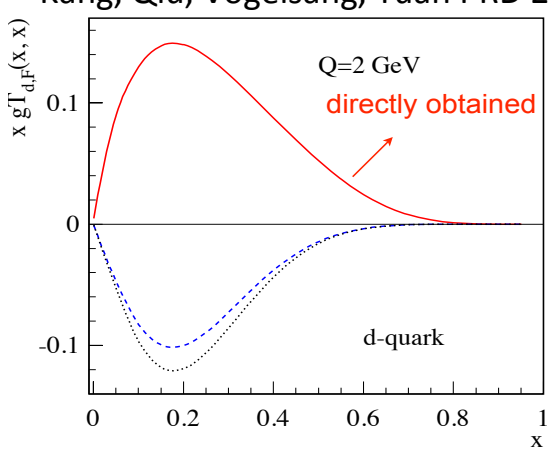



$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

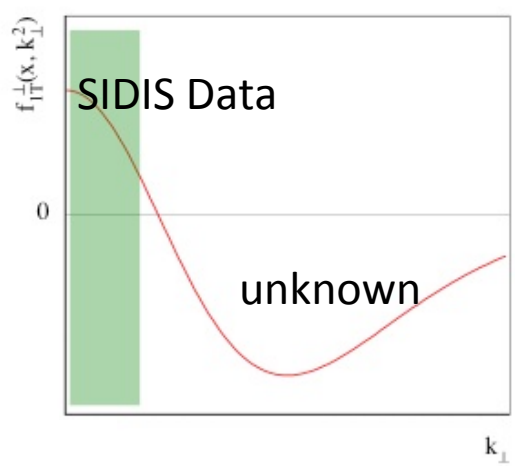



Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin

Kang, Qiu, Vogelsang, Yuan PRD 2011



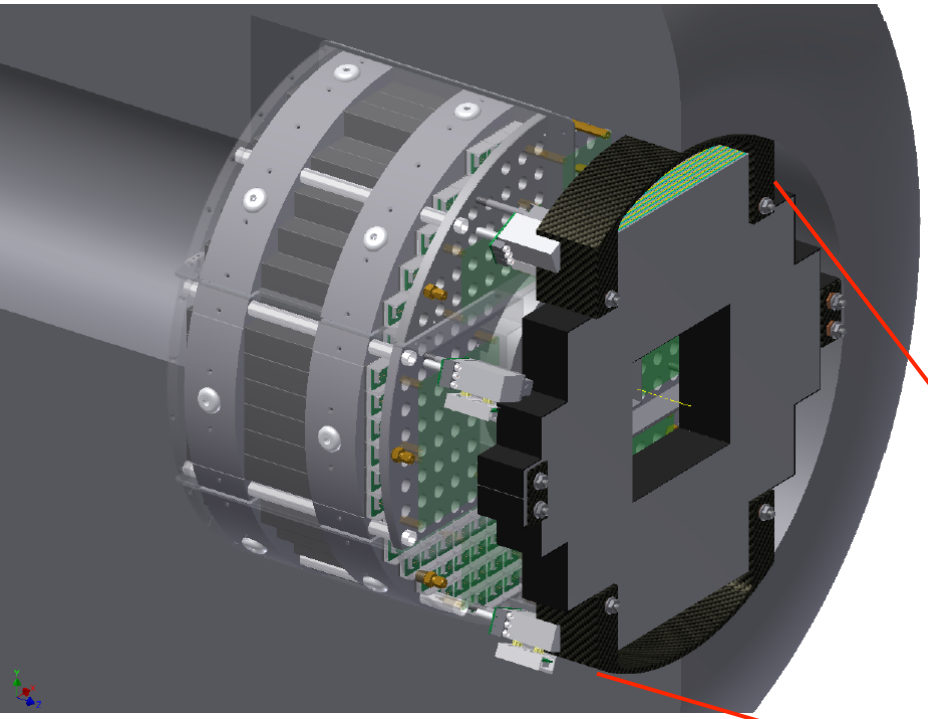

A possible solution? Kang, Prokudin PRD (2012)

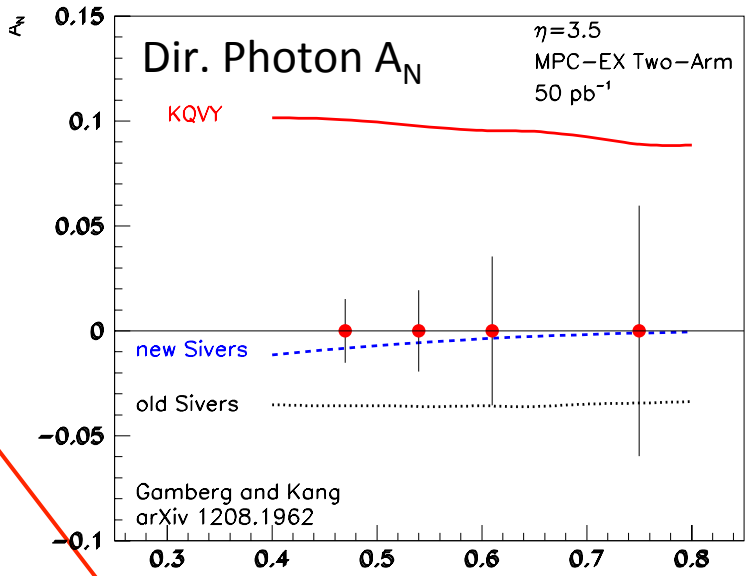


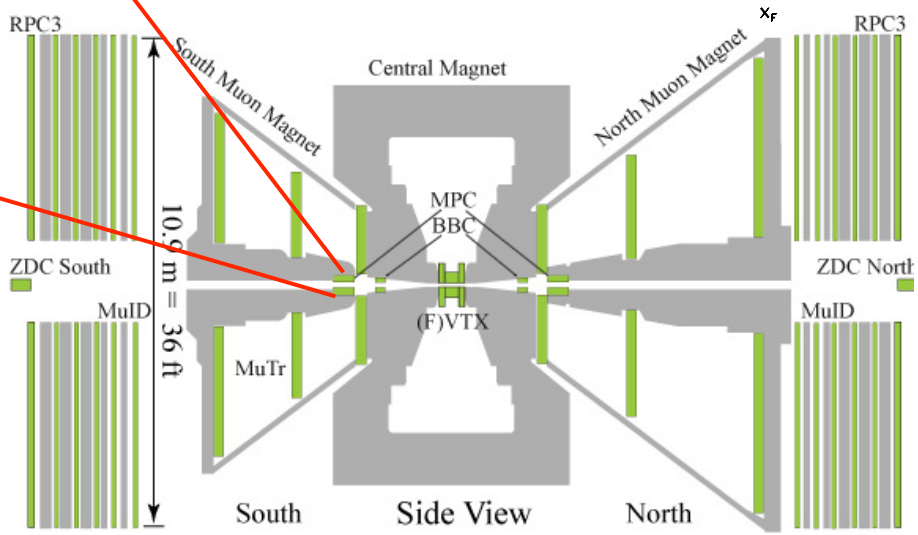

Collins dominates?
U. D'Alesio@QCDN12

Need more data!

# Next Step: MPC-EX (for Run15+)





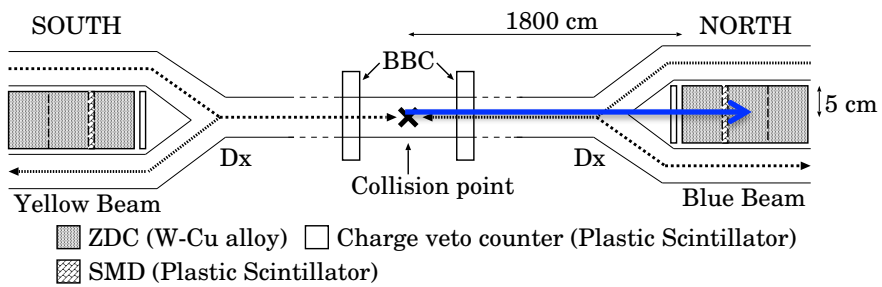

A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

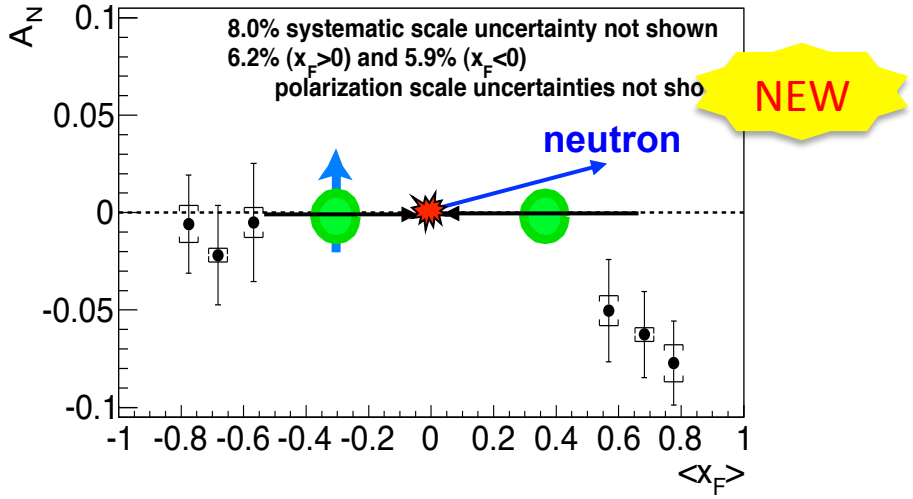
$3.1<|\eta|<3.9$

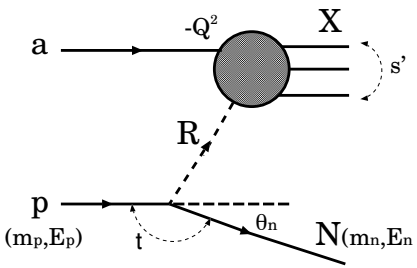
- $\pi^0$ rejection → direct photons
- $\pi^0$ reconstruction out to >80GeV

# Forward Leading Neutron $A_N$

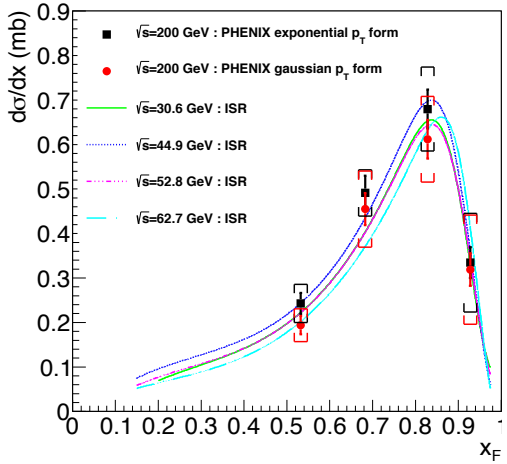
arXiv:1209.3283

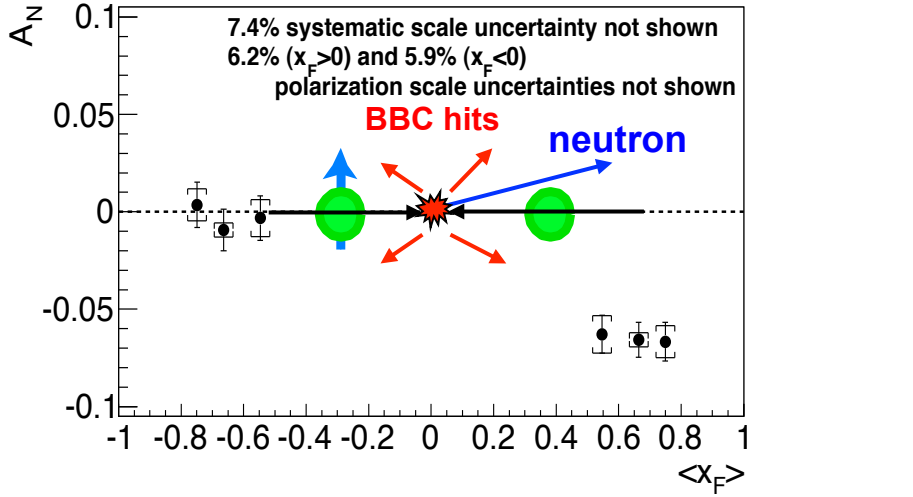



Single pion exchange?



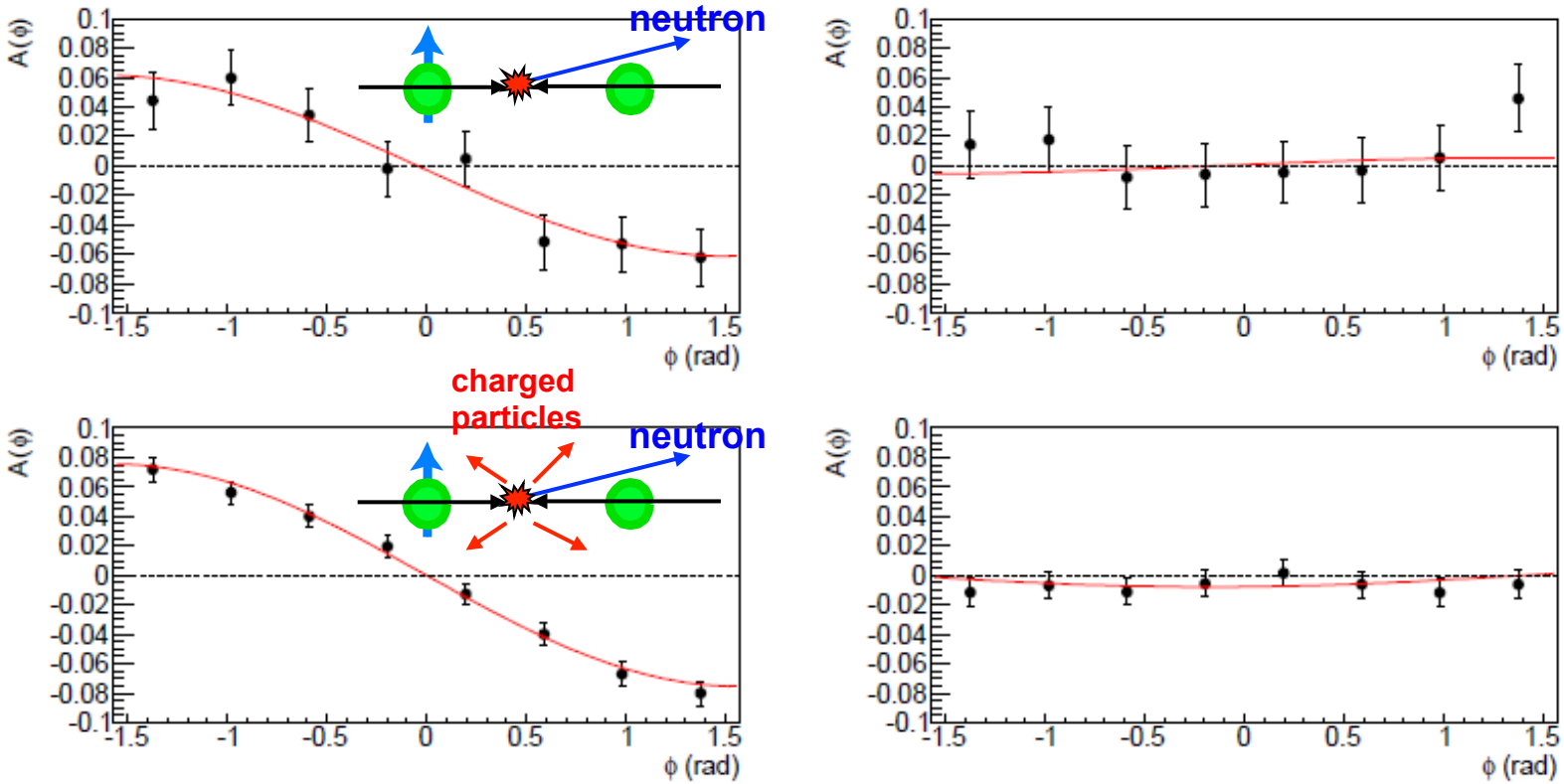
# More on Forward Neutron $A_N$

Forward asymmetry

$A_N$ = -0.061±0.010(stat)±0.004(syst)

Backward asymmetry

$A_N$ = -0.006±0.011(stat)±0.004(syst)




Interaction trigger with charged particles in beam-beam counter (ZDC⊗BBC trigger)

Forward asymmetry

$A_N$ = -0.075±0.004(stat)±0.004(syst)

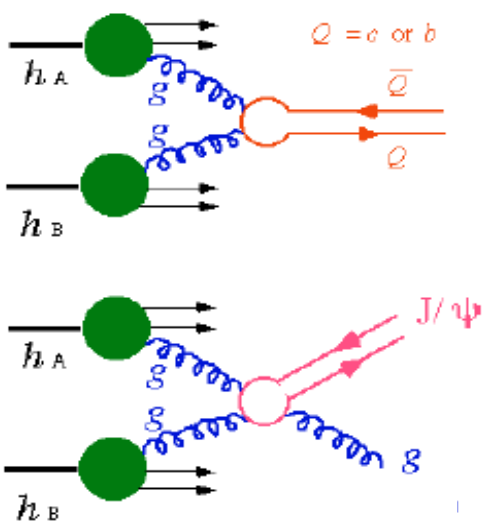
Backward asymmetry

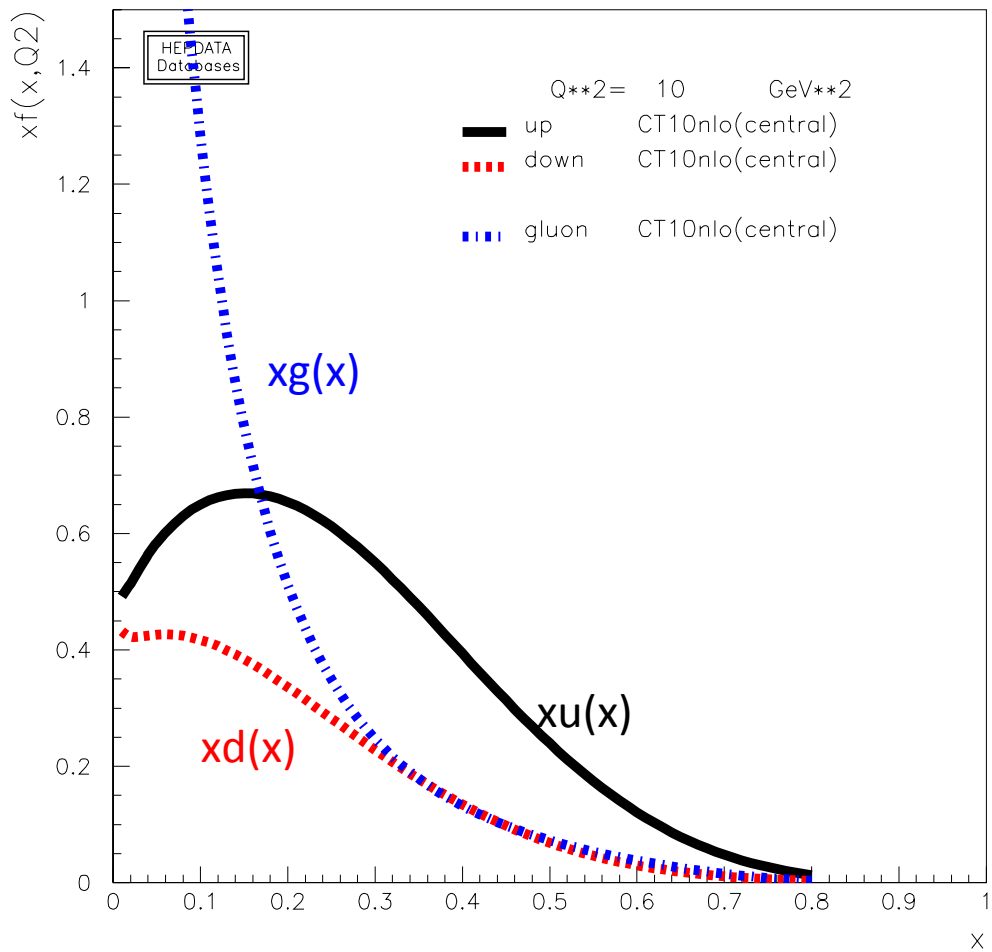
$A_N$ = -0.008±0.005(stat)±0.004(syst)

# More on Future New Observables at RHIC

- How about Gluons?
  - Gluons ~50%
  - Significant gluons at large x
  - Twist-3 quark-gluon and gluon-gluon corr. Funs
- Drell-Yan and direct photon
  - Test of pQCD

Gluon Fusion



# Heavy Quark TSSA at RHIC

## Twist-3 tri-gluon correlation Funs

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

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

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

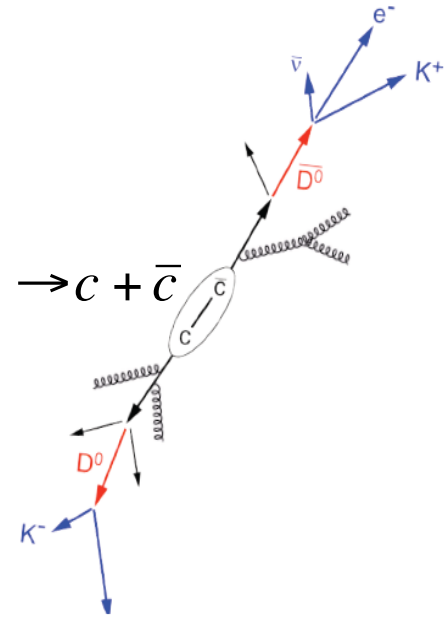
$\delta_f = +1(c); \ -1(\bar{c})$

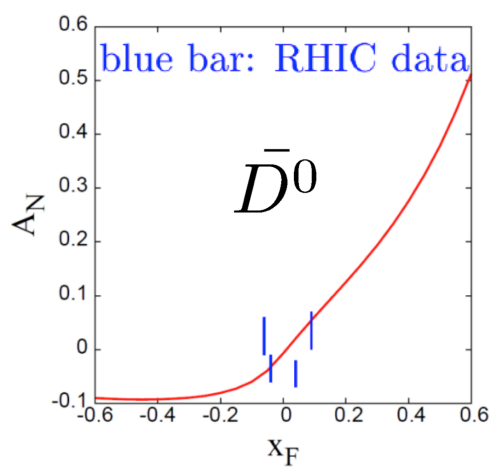
$$A_N(D) \overset{?}{\neq} A_N(\bar{D})$$

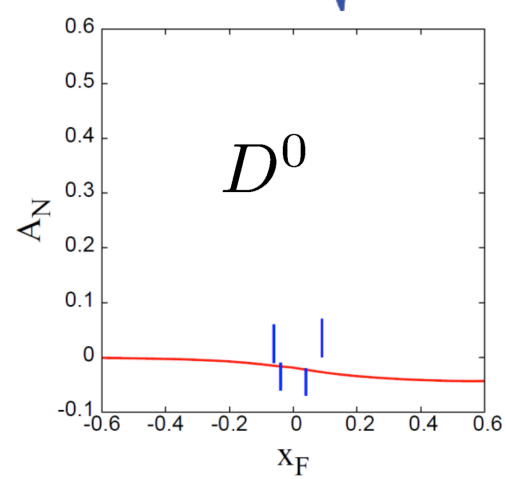
Model 1:
$O(x) = 0.004 x G(x)$

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

$g + g \rightarrow c + \bar{c}$



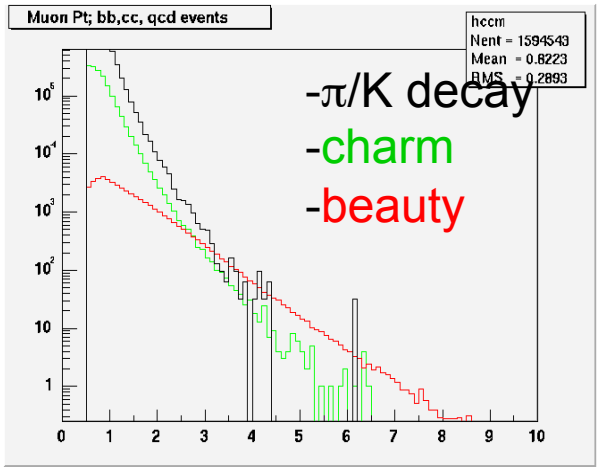



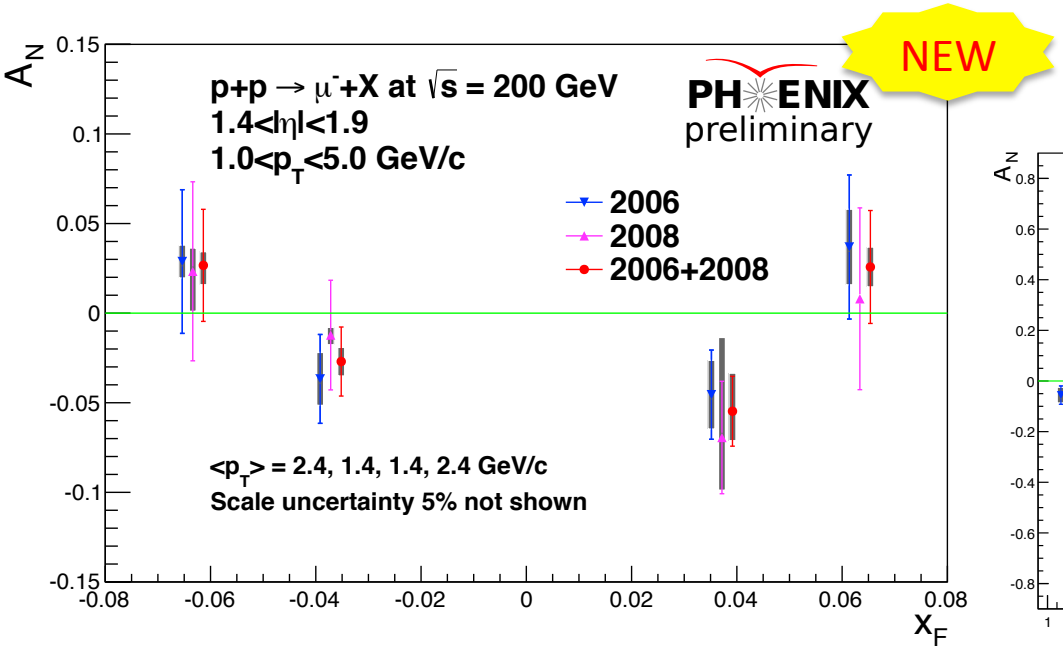



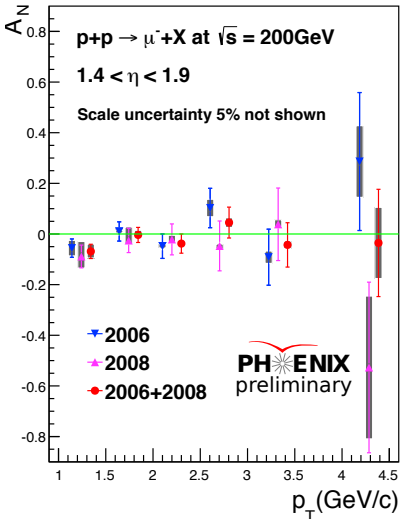
# Open Heavy Quark $A_N$

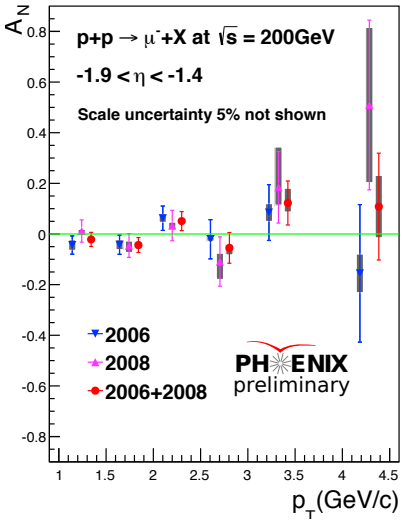
- Forward Muon arms
  - Run6, 8
  - Run12 work in progress
  - Will be much improved w/FVTX

1.2 < |eta| < 2.4



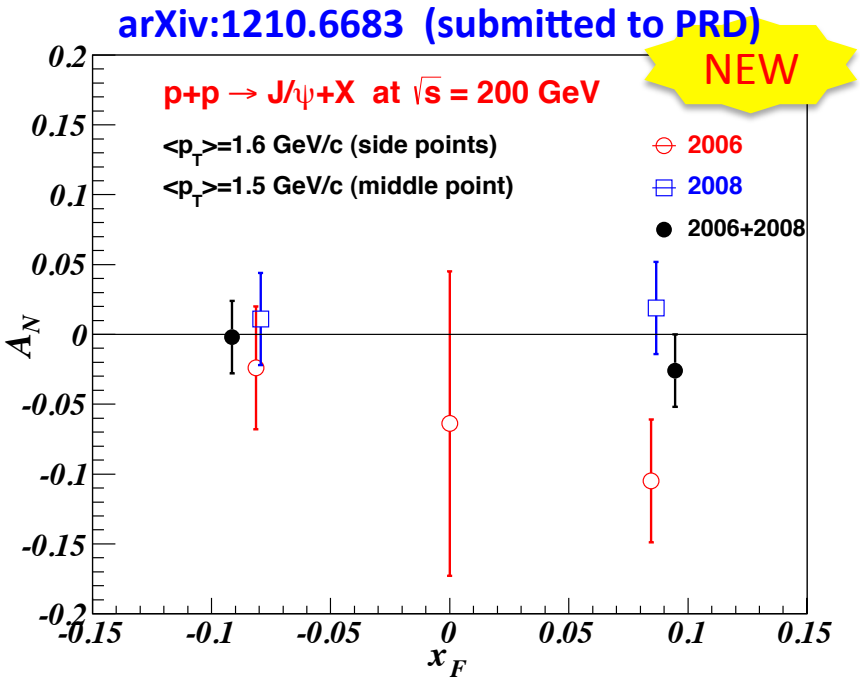



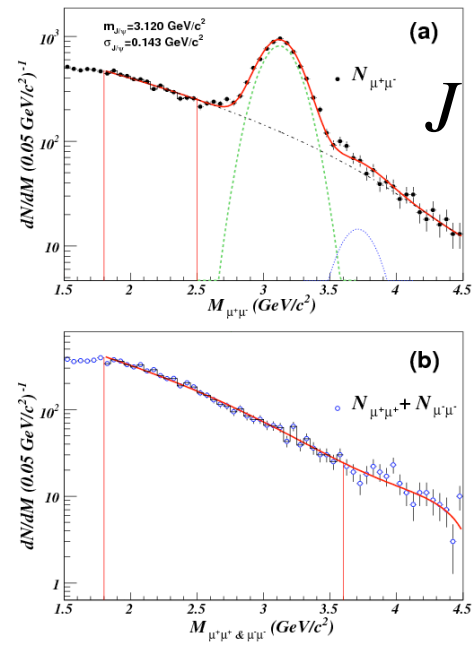



# $J/\psi$ $A_N$ vs $x_F$

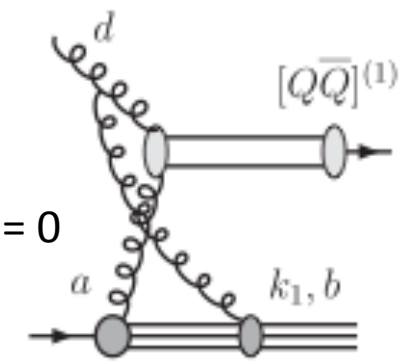
arXiv:1210.6683 (submitted to PRD)

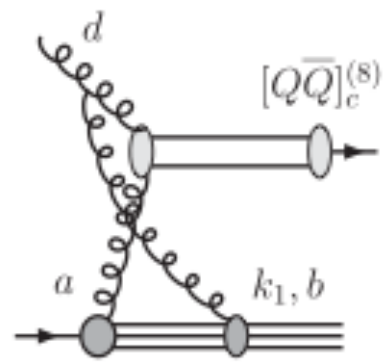


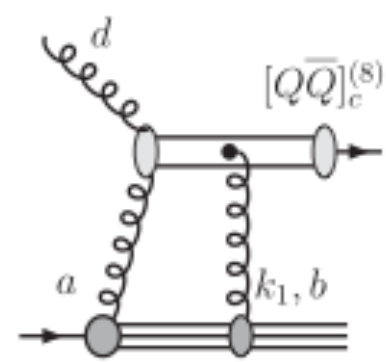

$J/\Psi \rightarrow \mu^+\mu^-$

$A_N$ != 0




$A_N$ =0

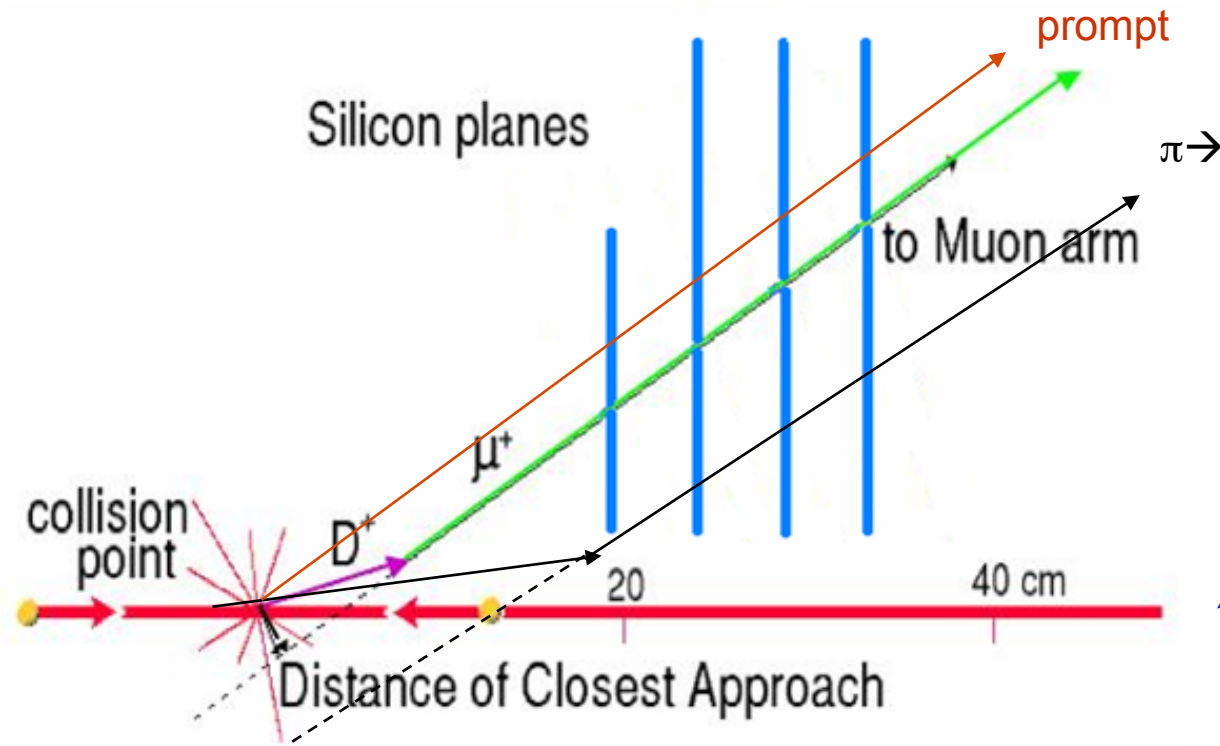


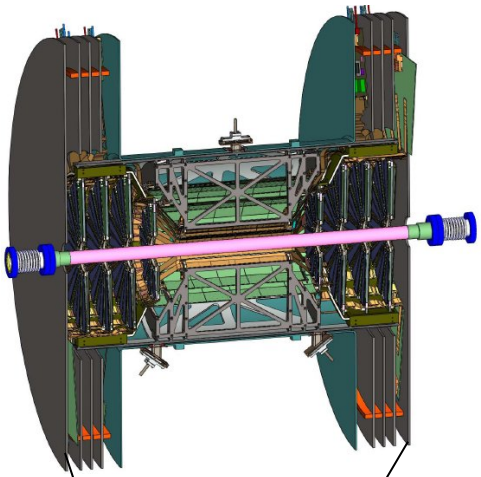

F. Yuan, PRD 78, 014024(2008)

# Much Improved Forward Muon Probes

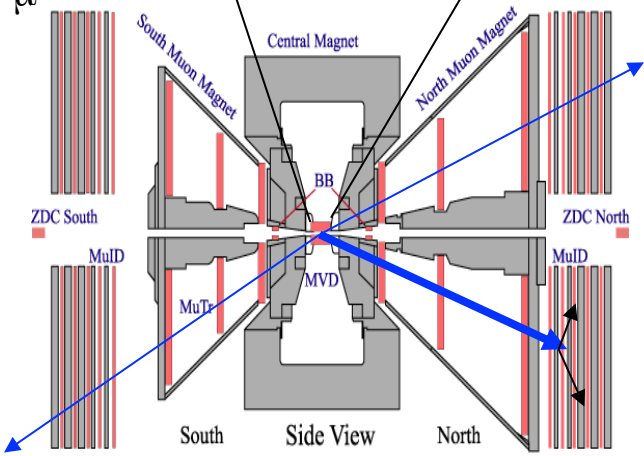
PHENIX Silicon VTX/FVTX Upgrades: first data 2012

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



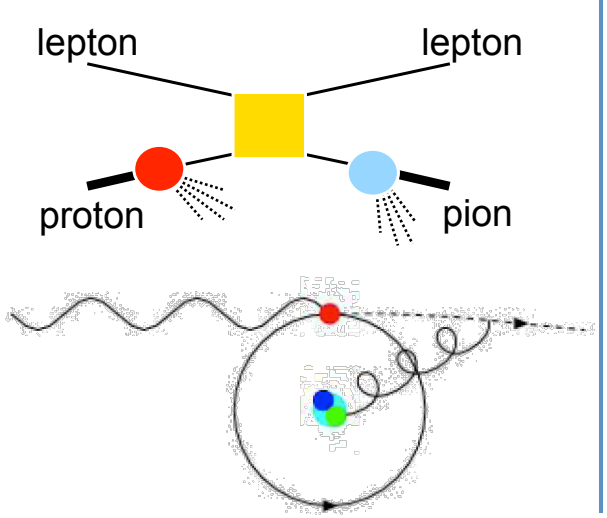
π→μ



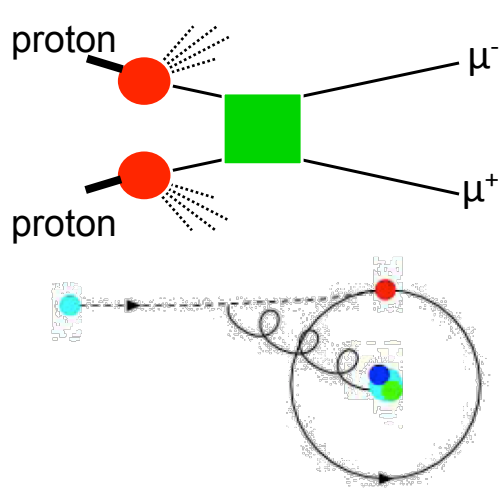
# Forward Dimuon Drell-Yan $A_N$

- 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.

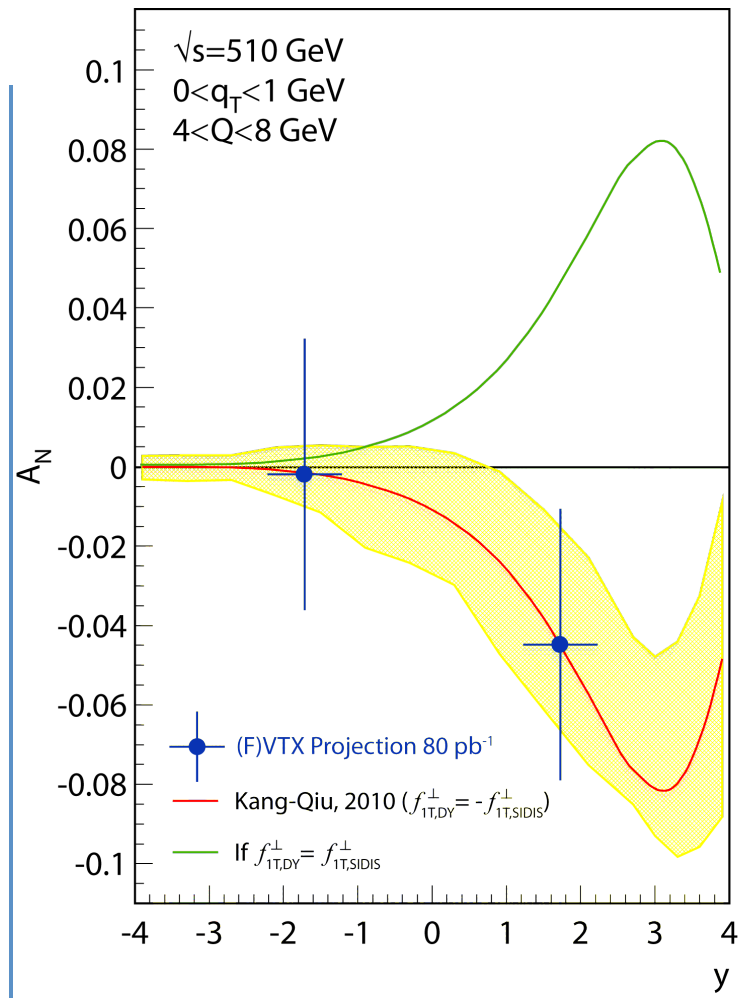
Semi-inclusive DIS (SIDIS)




Drell-Yan

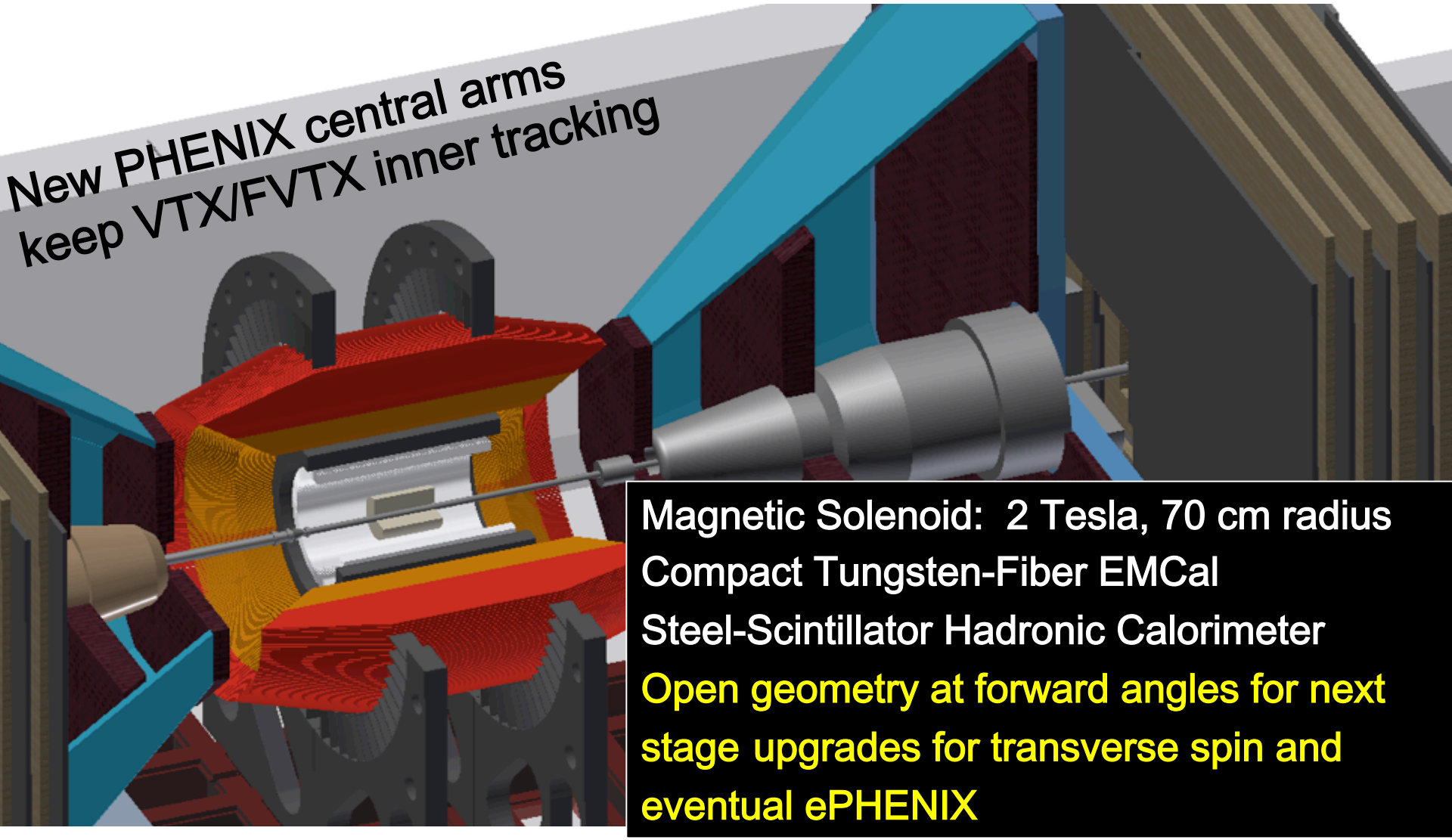



1-year running projection



# The sPHENIX Upgrade (2018)

*PHENIX Collaboration arXiv:1207.6378v1*




Magnetic Solenoid: 2 Tesla, 70 cm radius

Compact Tungsten-Fiber EMCal

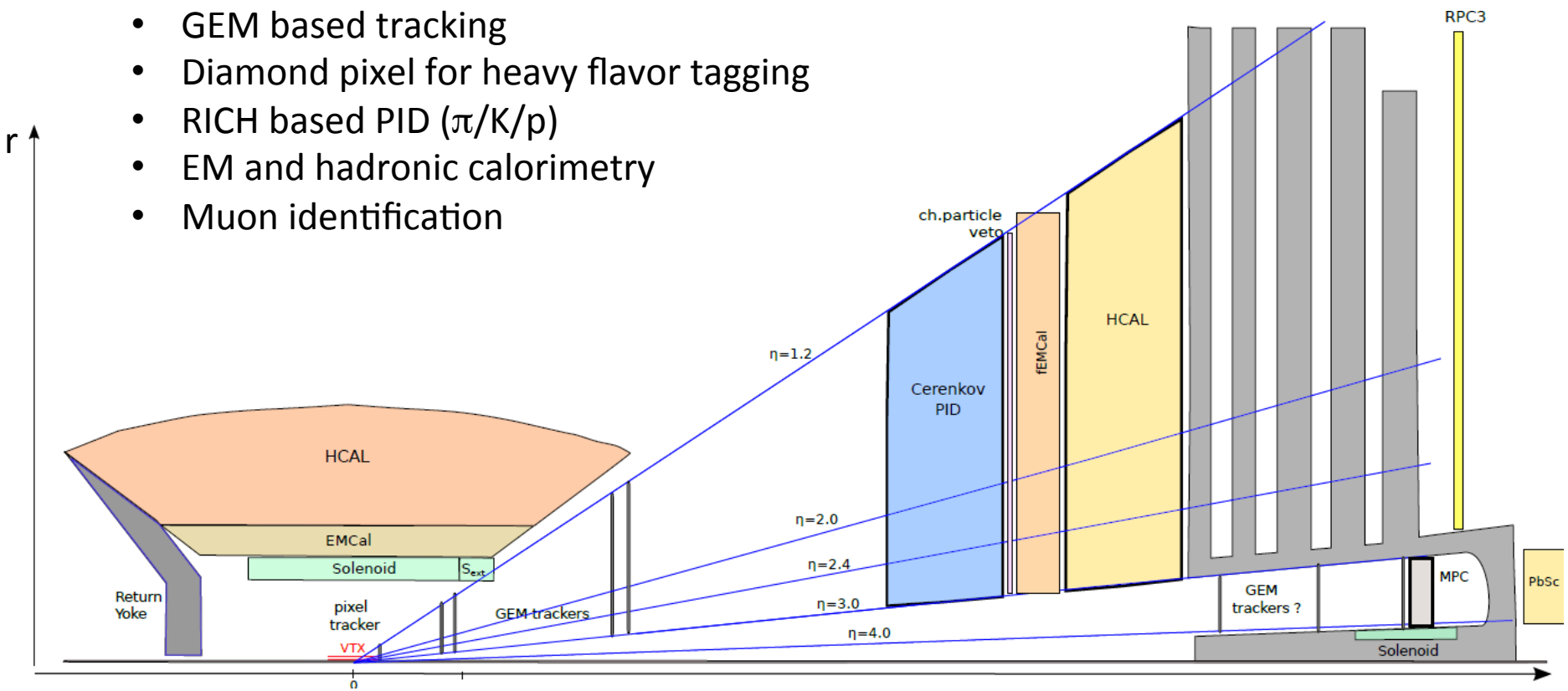
Steel-Scintillator Hadronic Calorimeter

Open geometry at forward angles for next stage upgrades for transverse spin and eventual ePHENIX

# PHENIX Forward Upgrade Proposal

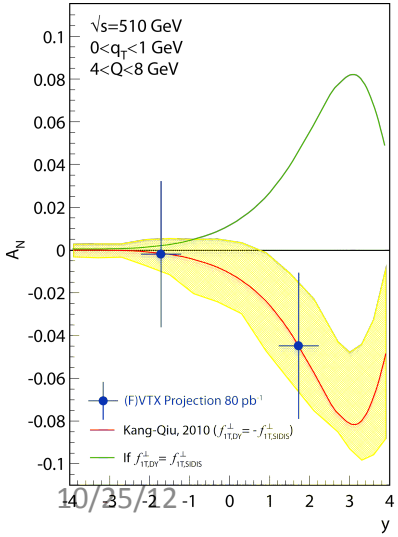
**Optimized for jets, photons and DY over a large range in rapidity (1.2<η<4)**

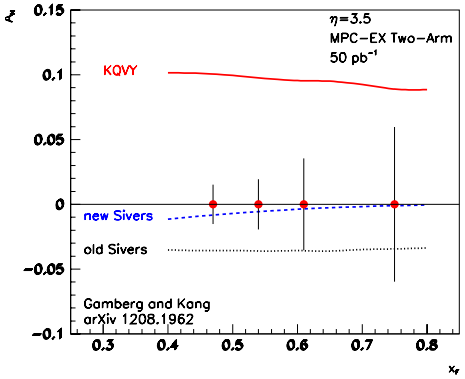
- Extension of sPHENIX central solenoid
- GEM based tracking
- Diamond pixel for heavy flavor tagging
- RICH based PID (π/K/p)
- EM and hadronic calorimetry
- Muon identification



# Future Challenges

- Significant TSSA observed in the forward rapidity
- Much improvement w/ MPC-EX
  - larger pT, xF coverage; dir-photon
  - Quarks' Sivers and Collins effects
- Forward muons with FVTX
  - Charm vs anti-Charm & tri-gluon
  - Drell-Yan test QCD predictions
- Forward sPHENIX
  - New spin program



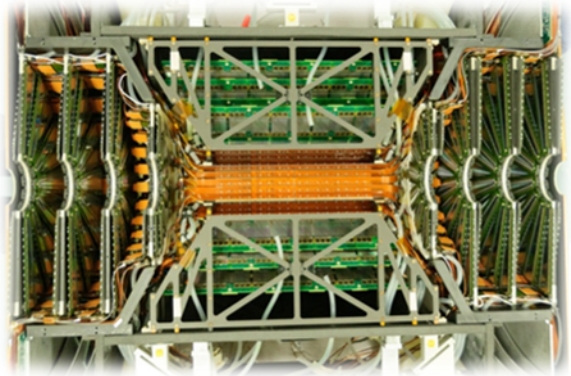
2012/10/23

# Forward Upgrades Completed for Run 2012

## (I) Muon Trigger for W-physics in polarized p+p at √500 GeV

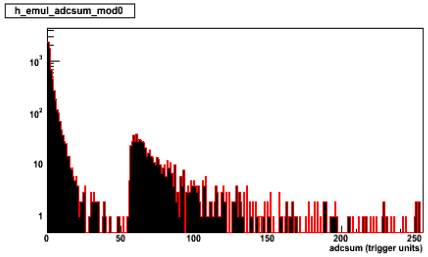
## (II) Forward Vertex Tracker for heavy flavor physics in pp, pA, AA

FVTX



DOE, Los Alamos, BNL

## (III) MPC FEE/Trigger Upgrade for forward spin measurements




PHENIX-HBD, BNL

# Forward Hadrons pp @200GeV

BRAHMS PRL (2007)

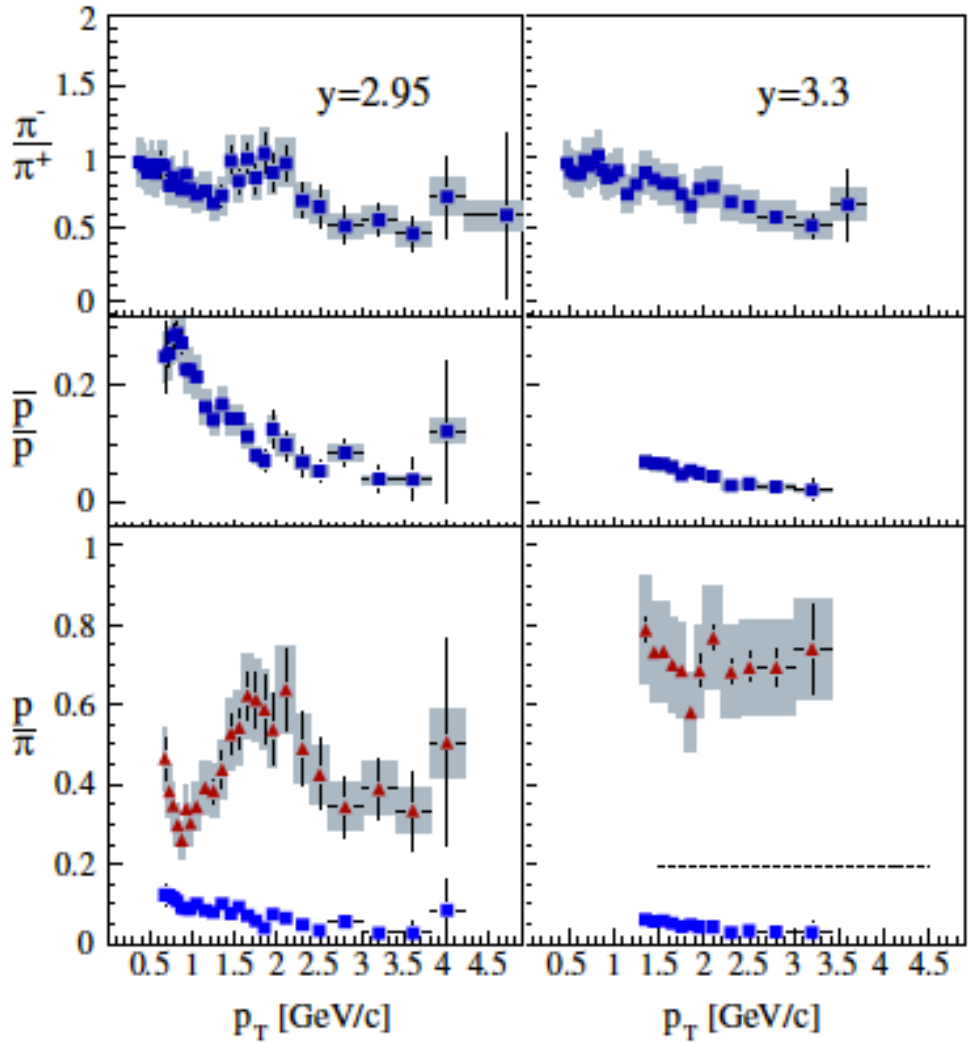
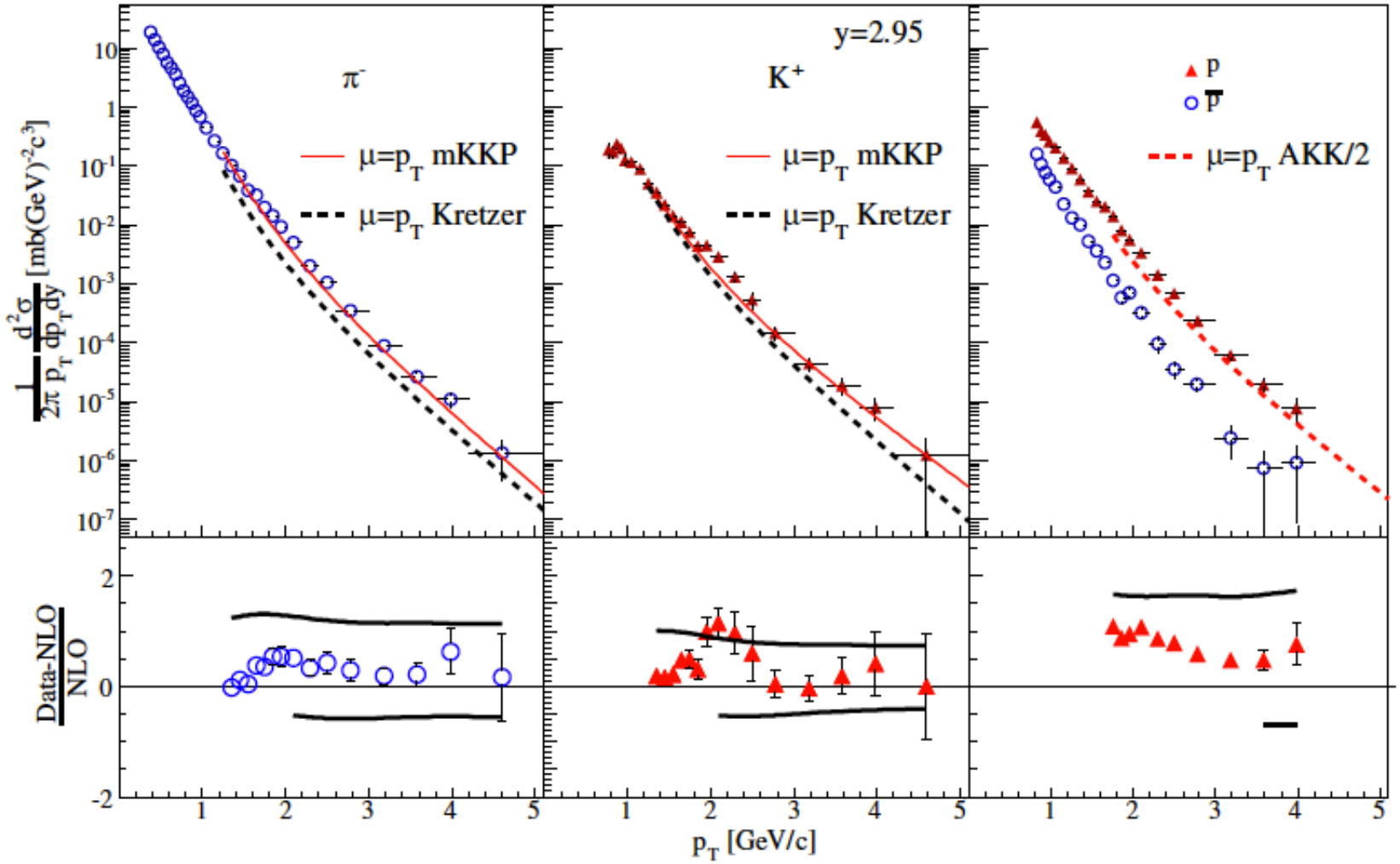



FIG. 2: Particle ratios versus $p_T$ at y=2.95 and 3.3. Top) $\pi^-/\pi^+$, Middle) $\bar{p}/p$ and Bottom) $p/\pi^+$ (red circles) and $\bar{p}/\pi^-$ (blue squares). The shaded rectangles indicate an overall systematic error (17%) estimated for these ratios. The dashed line shows an upper limit for the $(p+\bar{p})/(\pi^+ + \pi^-)$ ratio from $e^+e^-$ collisions.

# 200 pp Very Forward: y=3

## (Data – NLO)/NLO

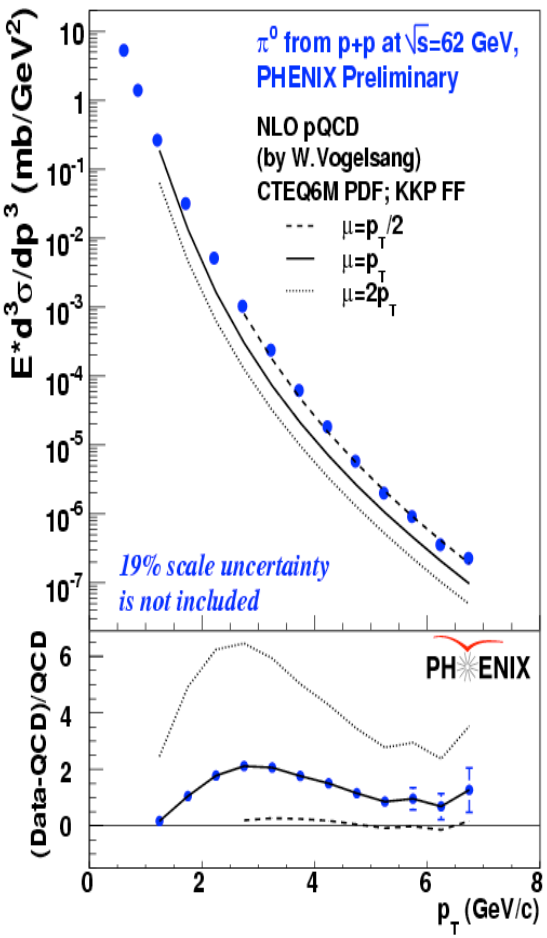
BRAHMS



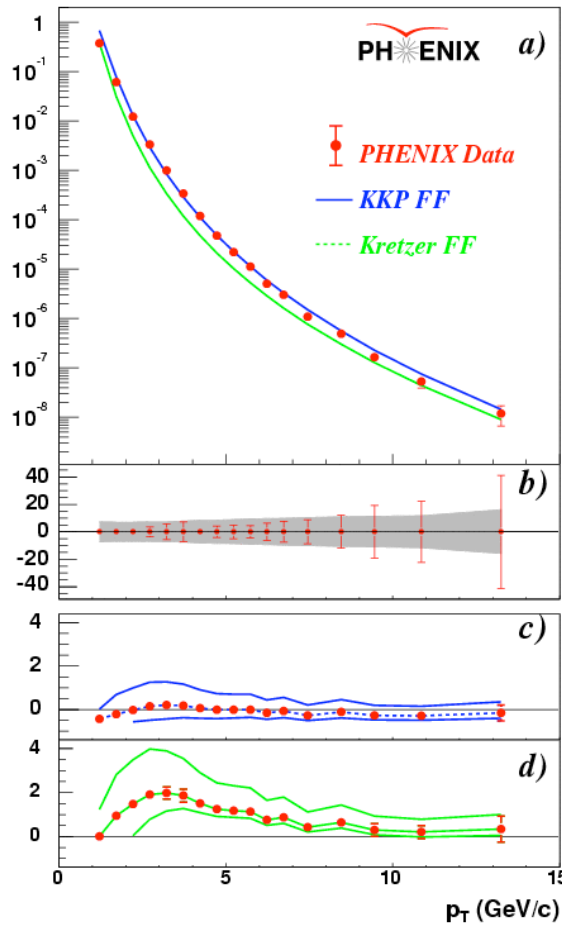
# Data vs NLO: |eta|<0.35

## (Data - NLO)/NLO

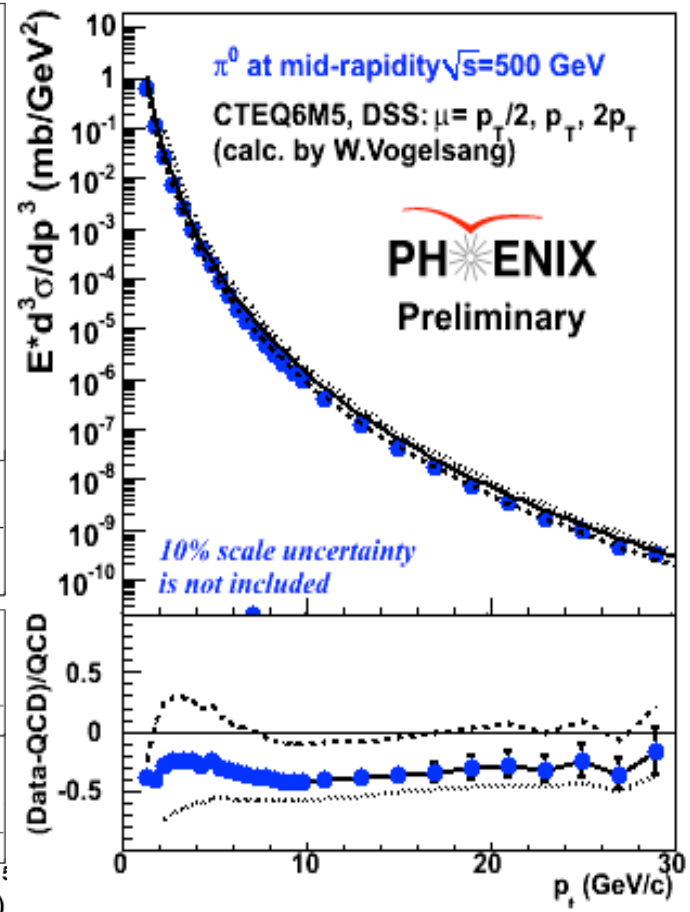
62GeV




200GeV

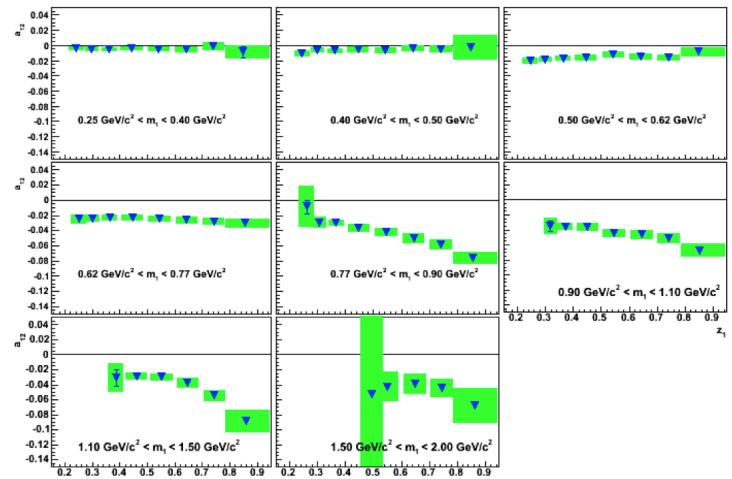


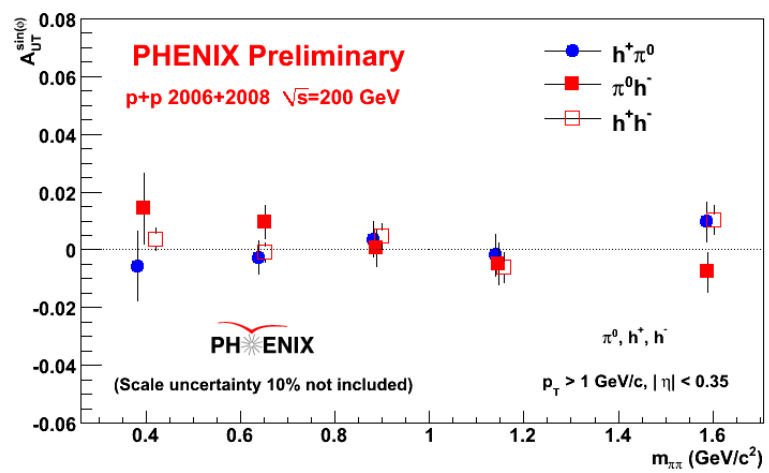

500GeV



# Another Route to Transversity

- Interference Fragmentation Function (IFF)
  - Measured at BELLE
  - Collinear (no $k_T$ dependence)
  - Correlates quark spin with produced hadron pair angular momentum




- At PHENIX, couples with transversity
  - Initial data do not have needed sensitivity
  - Expected data in next few year will be precise enough