Highlights from PHENIX Transverse Spin Physics Program

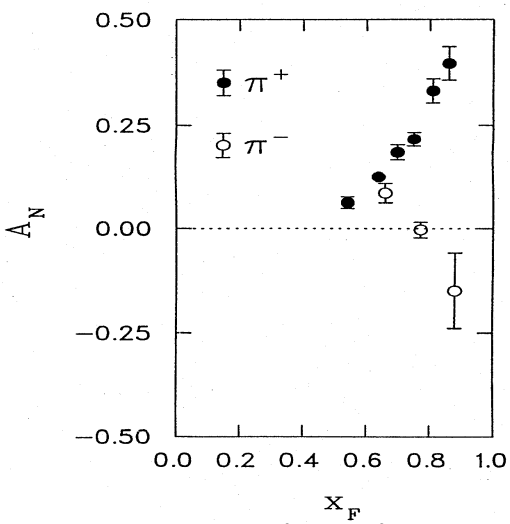
Ming X Liu
Los Alamos National Laboratory
(for the PHENIX Collaboration)

- Latest results from PHENIX
- Opportunities with FVTX and MPC-EX
- Future – forward s/ePHENIX

Do We Understand This?

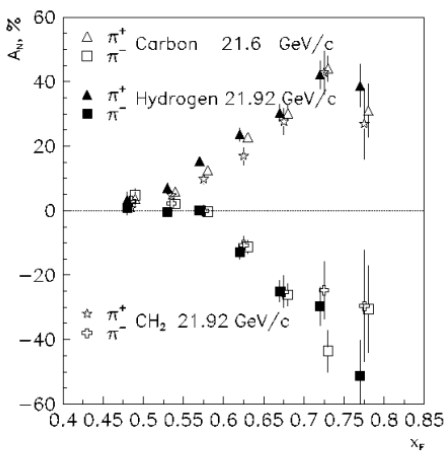
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

ZGS $\sqrt{s} = 5\ GeV$



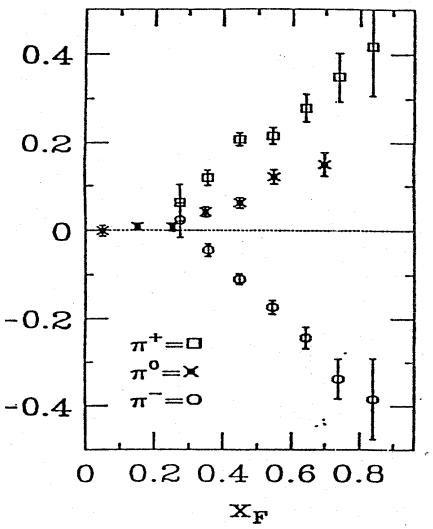
PRL36, 929 (1976)

AGS $\sqrt{s} = 7\ GeV$



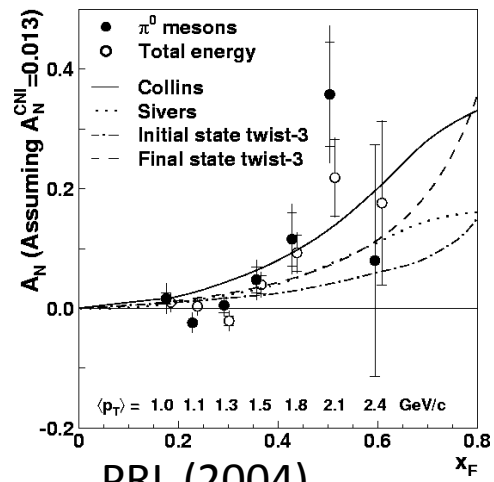
PRD65, 092008 (2002)

FNAL $\sqrt{s} = 20\ GeV$

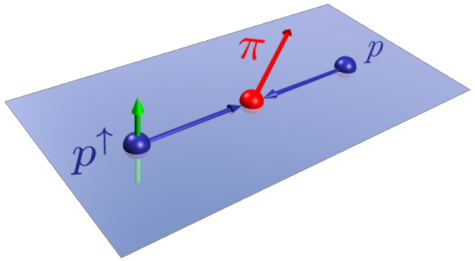


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC $\sqrt{s} = 200\ GeV$



PRL (2004)



Sivers, Collins, Twist-3 ....

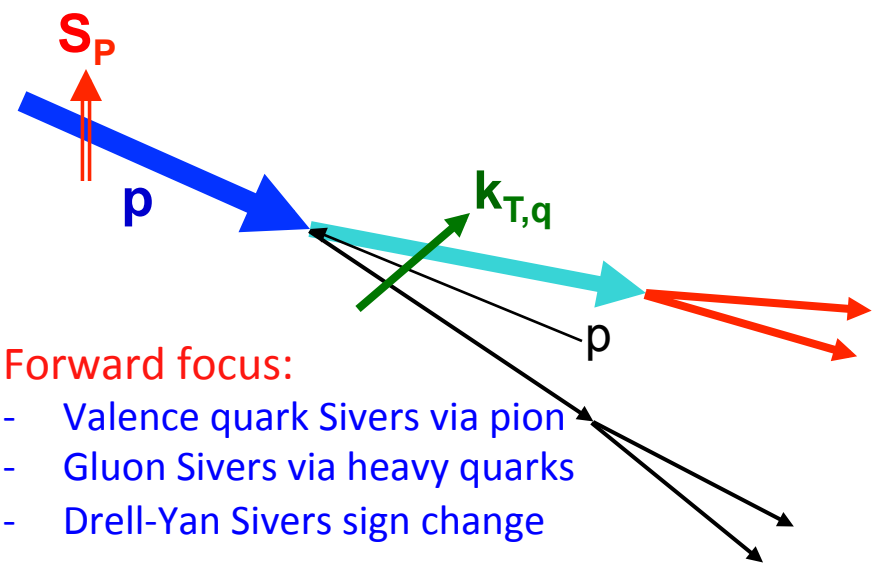
Non-Perturbative cross section → Perturbative cross section

Possible Mechanisms for Transverse Spin Asymmetry

- Quarks' Sivers and Collins TSSA observed in SIDIS
- Gluons' Sivers not constrained in SIDIS @LO

Sivers mechanism: Correlation between nucleon spin and parton k_T

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



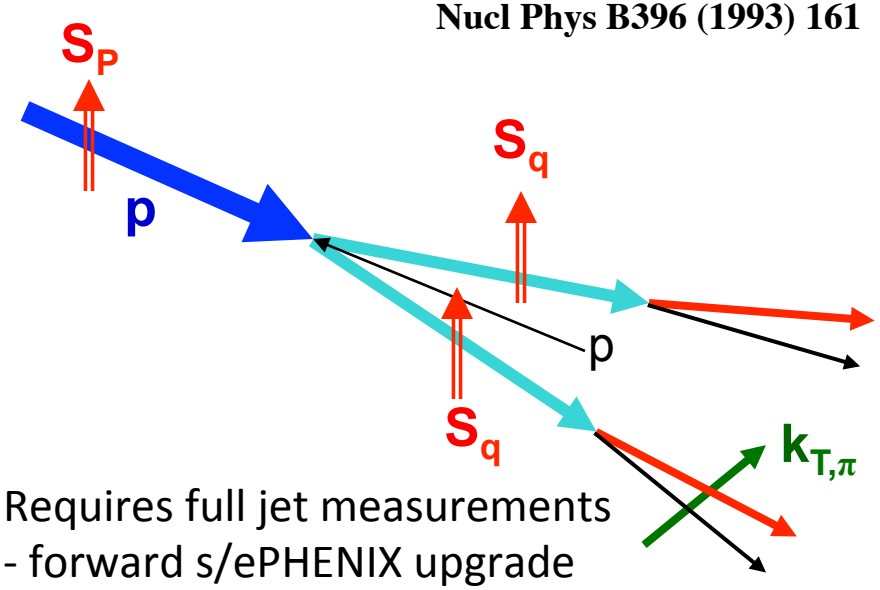
Forward focus:

- Valence quark Sivers via pion
- Gluon Sivers via heavy quarks
- Drell-Yan Sivers sign change

Orbital Angular Momentum?

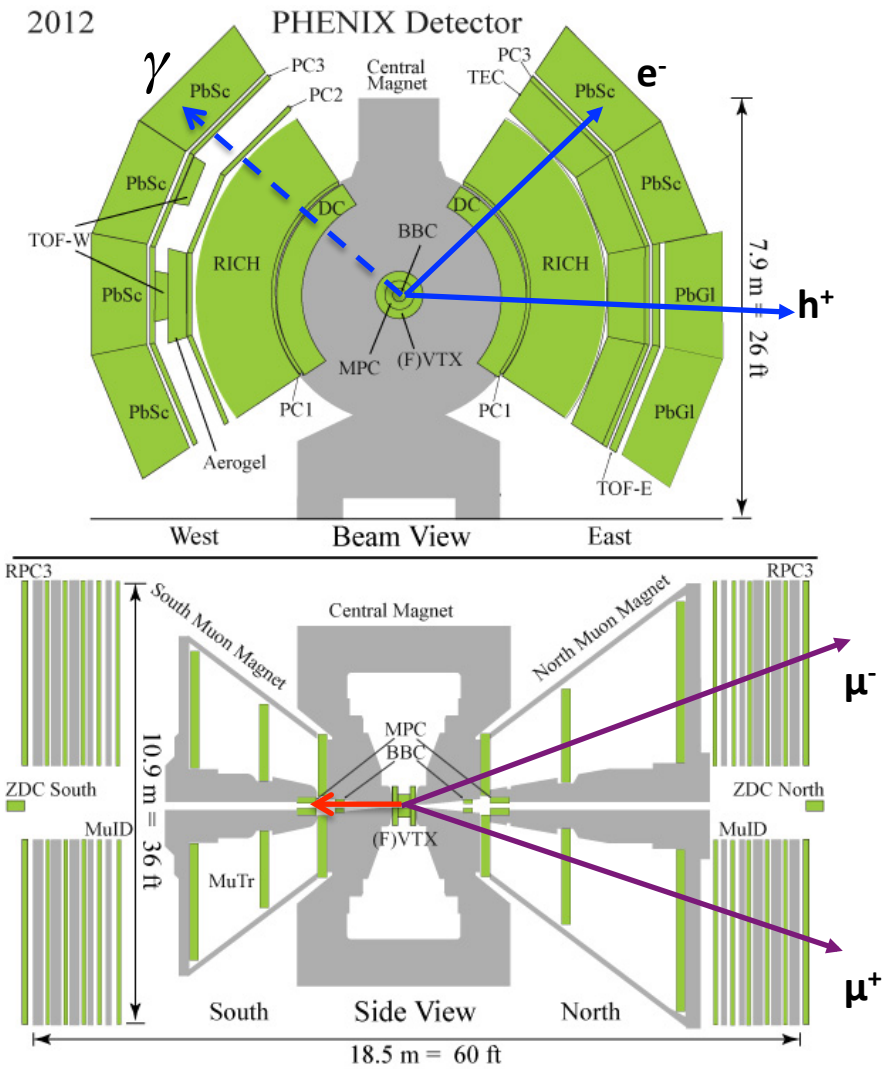
Collins mechanism: Transversity (quark polarization) * Spin-dependence in the jet fragmentation

Nucl Phys B396 (1993) 161



Requires full jet measurements
- forward s/ePHENIX upgrade

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)**

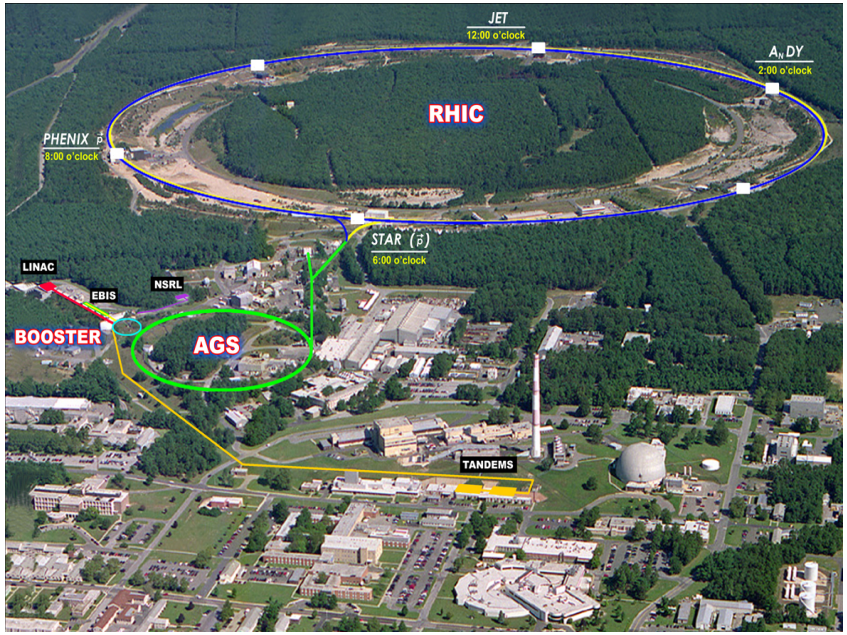
Muon Piston Cal. (MPC) $3.1 < |\eta| < 3.9$

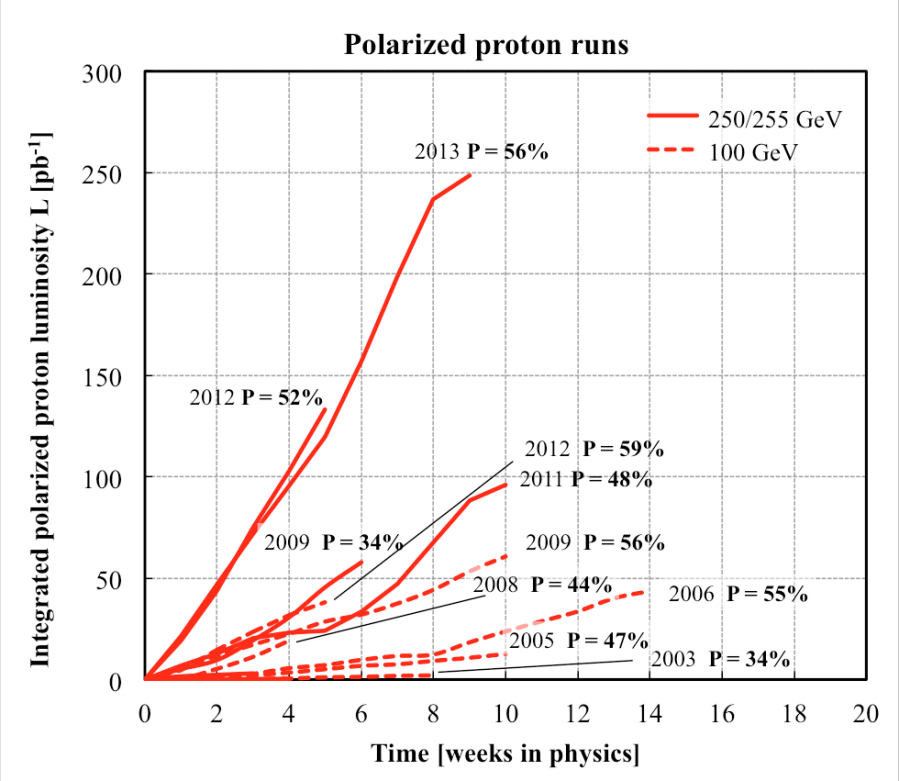
- **photons (π^0, η...)**
- **MPX-EX upgrade(2015)**

Global Detectors (Lumi, Trigger, local Pol.)

- BBC
- ZDC (neutron)

Recent PHENIX Transverse Spin Runs

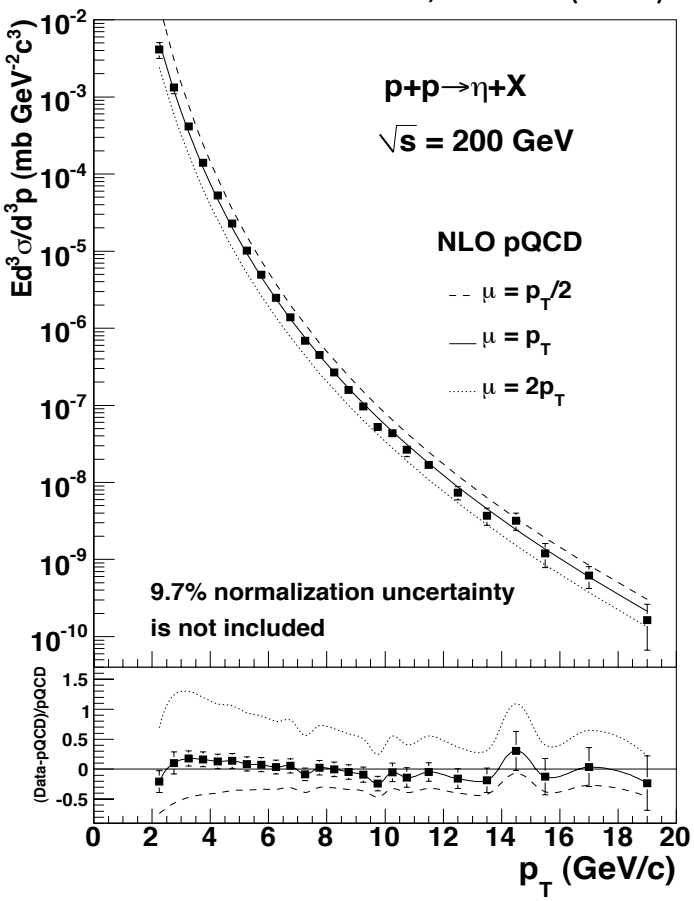


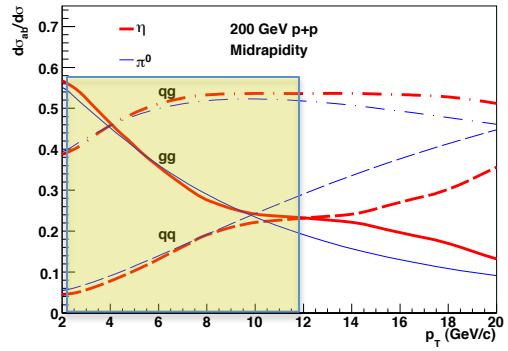


Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2006 (Run 6)	200	2.7 pb^{-1}	50	700 nb^{-1}
2008 (Run 8)	200	5.2 pb^{-1}	45	1100 nb^{-1}
2012 (Run12)	200	9.2 pb^{-1}	60	3300 nb^{-1}

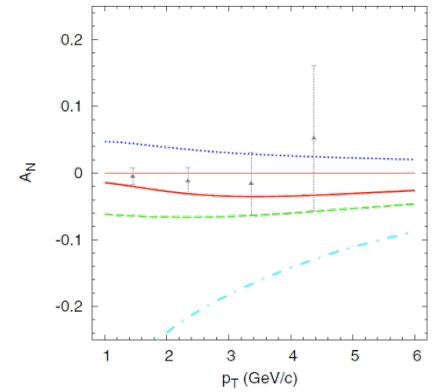
Central Arms: Mid-rapidity π^0 and η

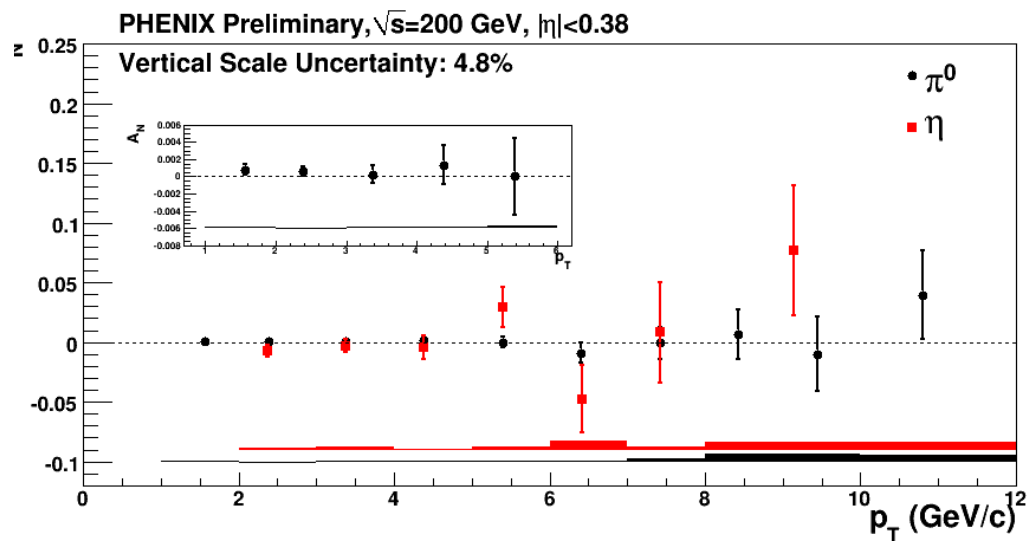
PRD 83, 032001 (2011)





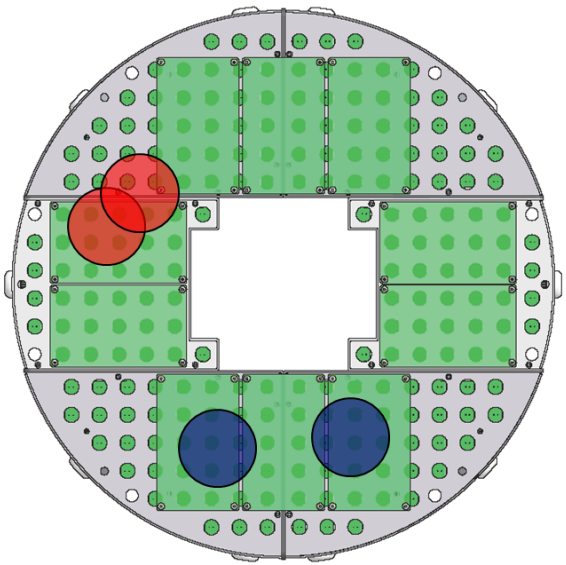
Anselmino et al, PRD 74, 094011 (2006)



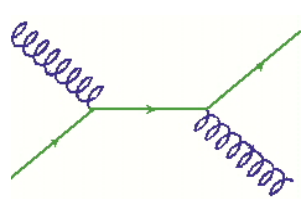


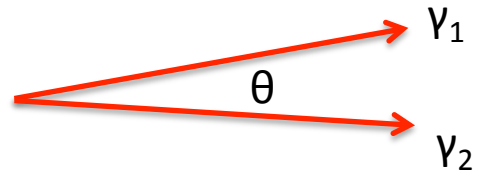
- Cross sections: pQCD in good agreement with RHIC data
- A_N: consistent with zero – {x, Q^2} dependence under investigation

MPC: Forward-rapidity π^0 and η



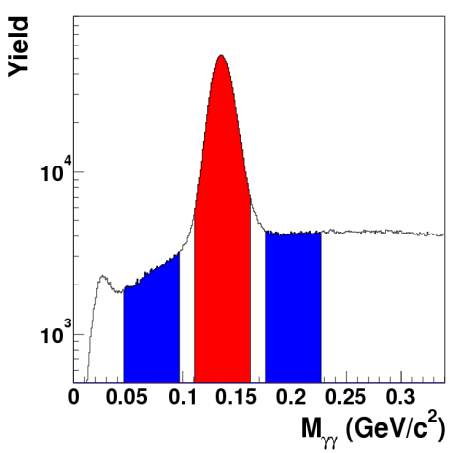
3.1 < |η| < 3.9

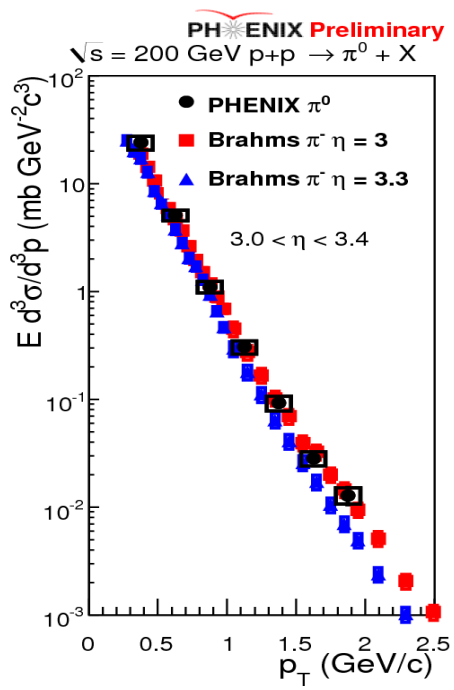


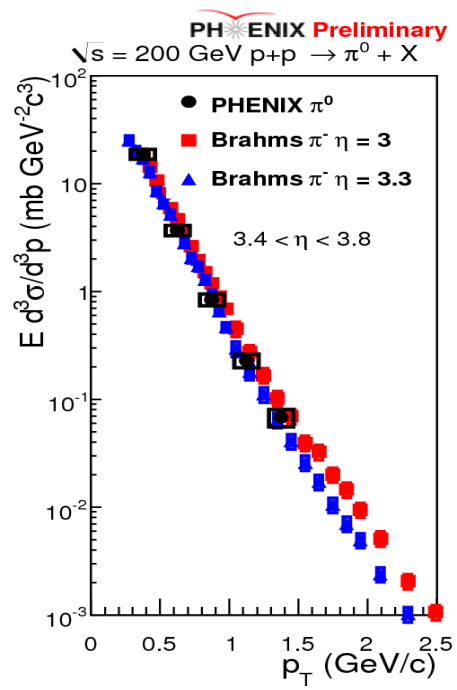


$$m^2_{\gamma\gamma} = 2E_1E_2(1 - cos(\theta))$$

Decay photon impact positions for low and high energy π^0's

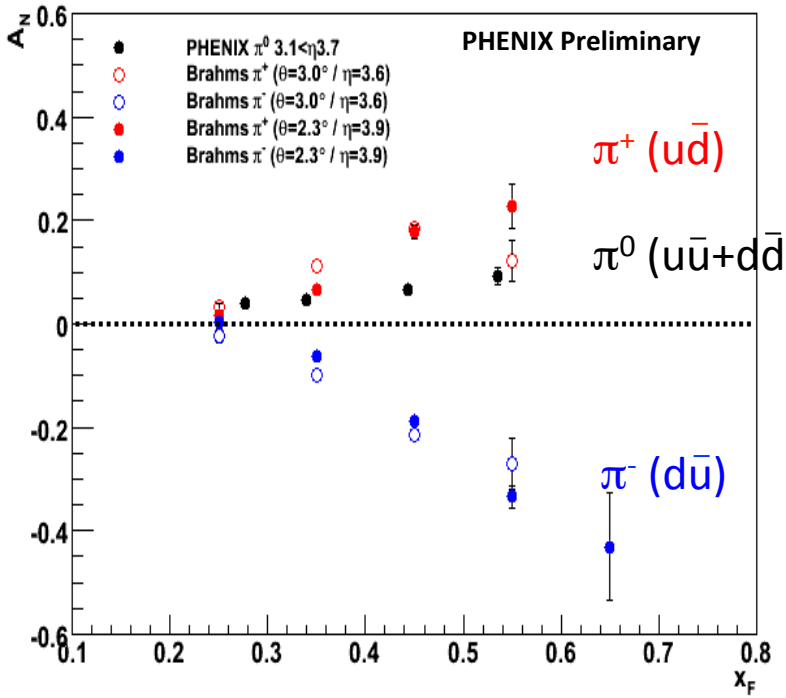




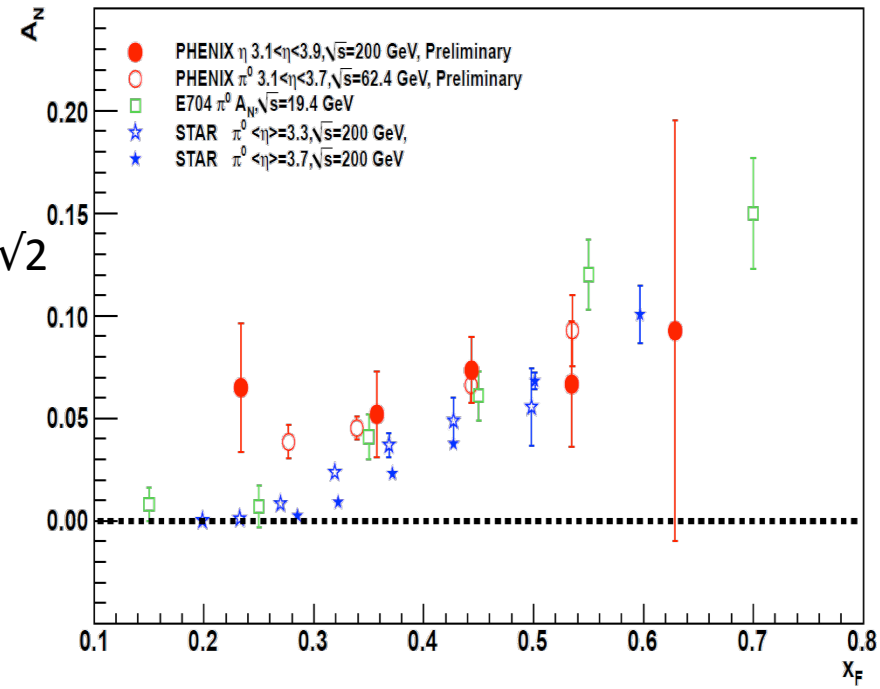


MPC: π^0 and η A_N, $\sqrt{s}$=62.4, 200 GeV

$p^{\uparrow}+p\rightarrow\pi^0+X$ at $\sqrt{s}$=62 GeV/c^2



$p^{\uparrow}+p\rightarrow\eta^0+X$ at $\sqrt{s}$=200 GeV/c^2

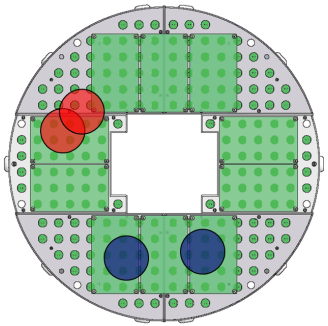


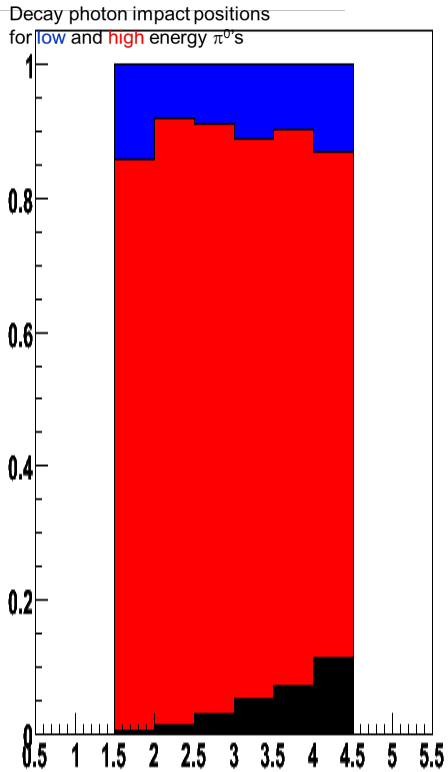
- Quark origins of pions:

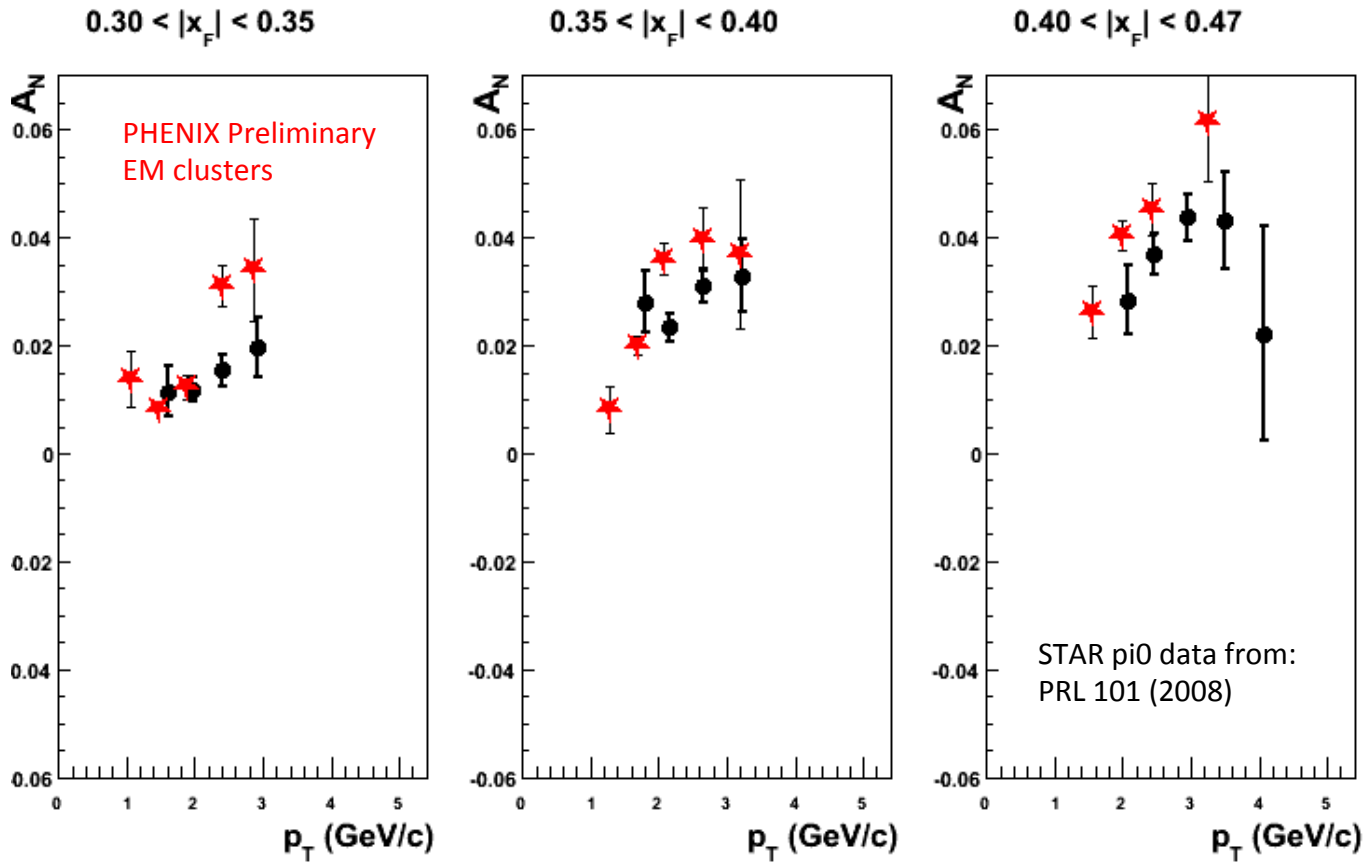
  π^+: ~100% u; π^-: 50/50 d/u; π^0: 25/75 d/u

Access Higher pT: EM Clusters

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





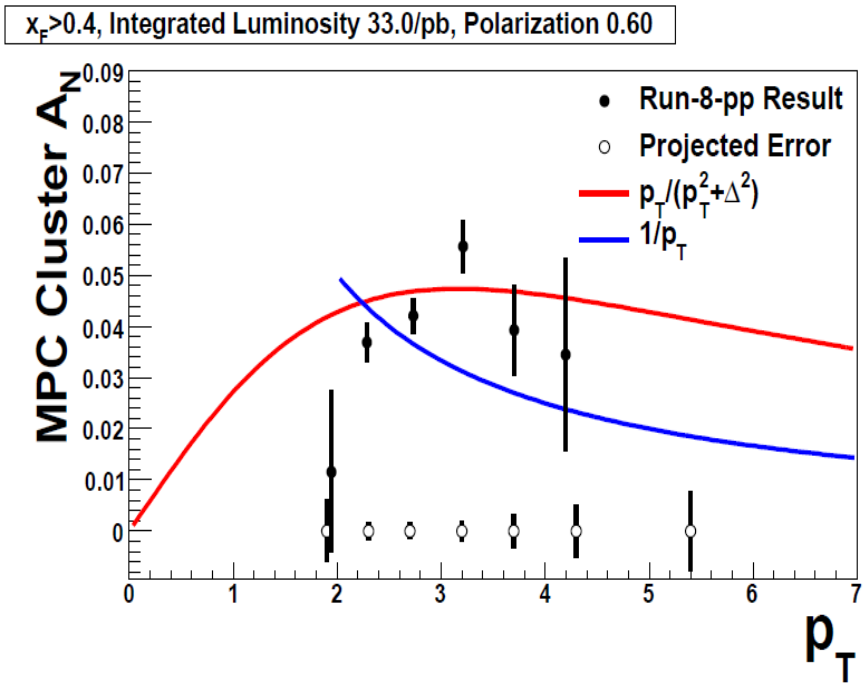


Decay photon
π^0
Direct photon

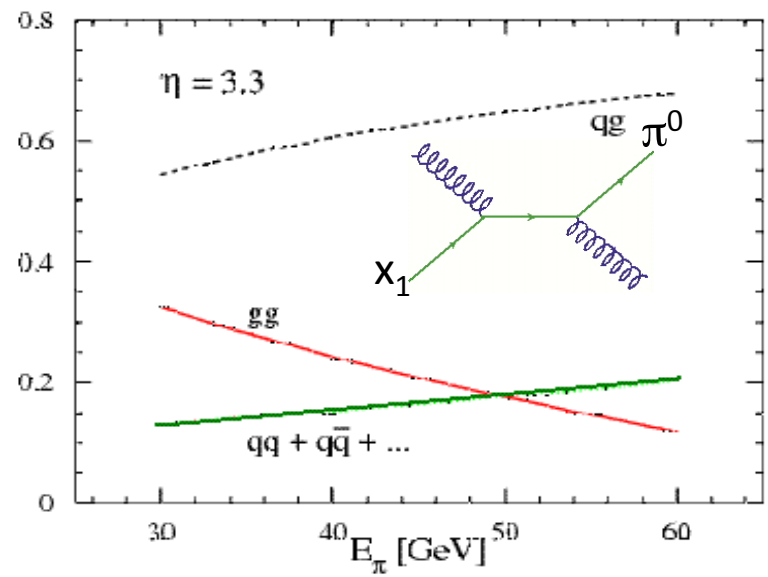
$$A_N(cluster) = A_N^{\pi^0} f^{\pi^0} + A_N^{\eta} f^{\eta} + A_N^{\gamma} f^{\gamma} + \ldots$$

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-dep not trivial
- Much improved with MPC-EX (2015+)

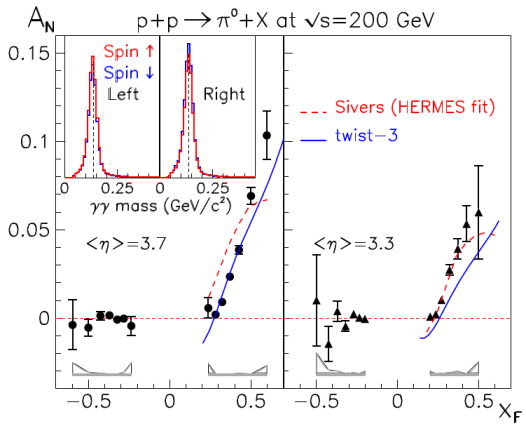
Y. Koike, 2012

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

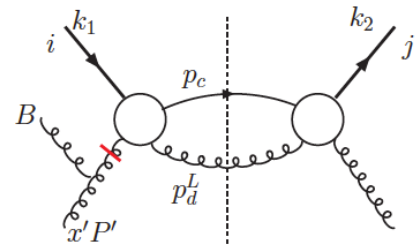
$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

A New Challenge: A_N Sign Mismatch?

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

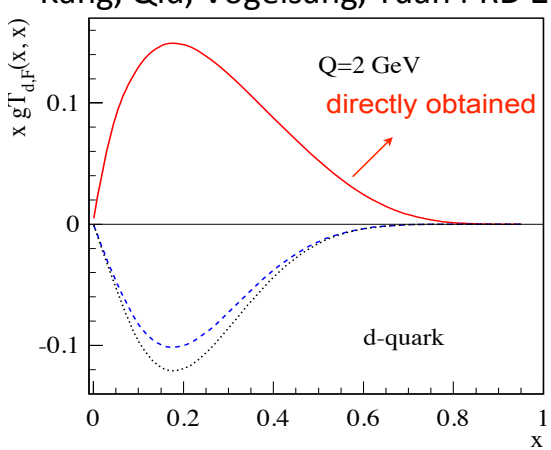


$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

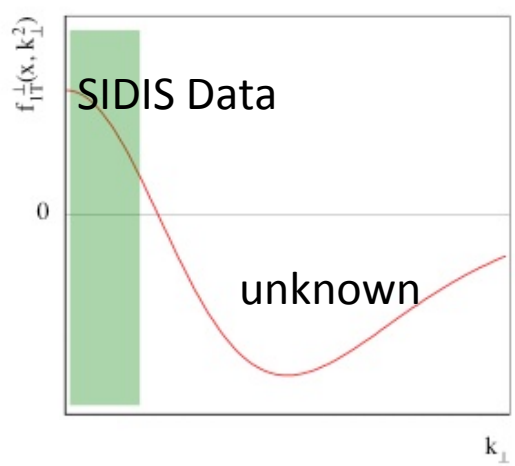


Qiu,Sterman
Kouvaris et al.
Kanazawa,Koike
Kang,Prokudin

Kang, Qiu, Vogelsang, Yuan PRD 2011



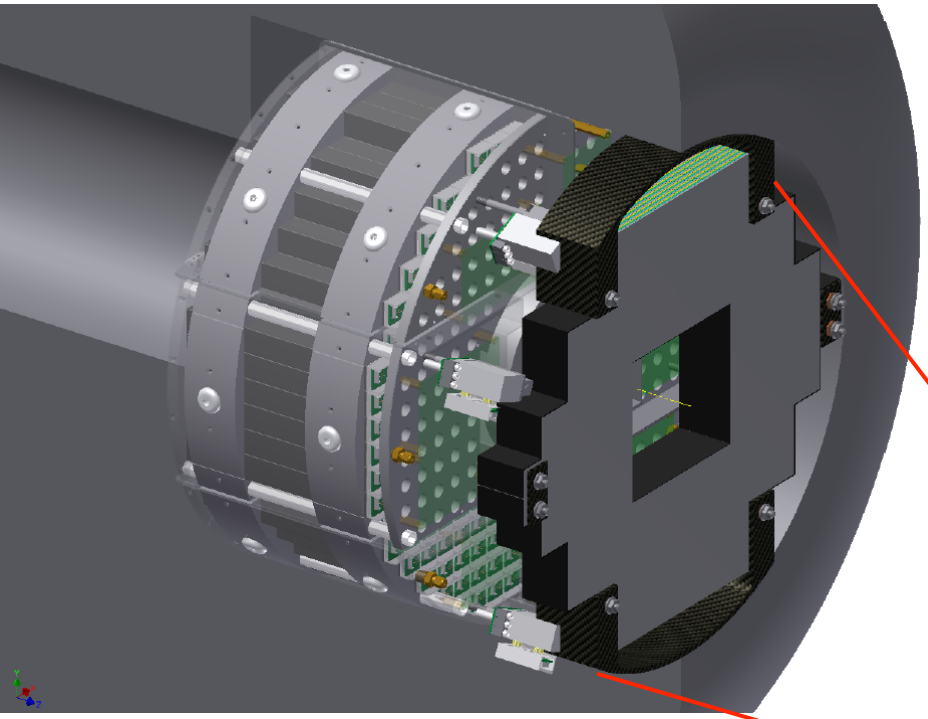
A possible solution? Kang, Prokudin PRD (2012)

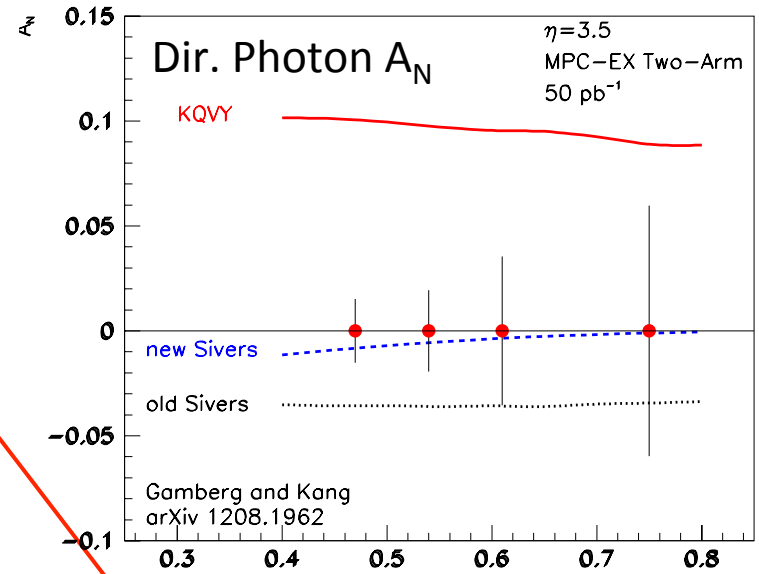


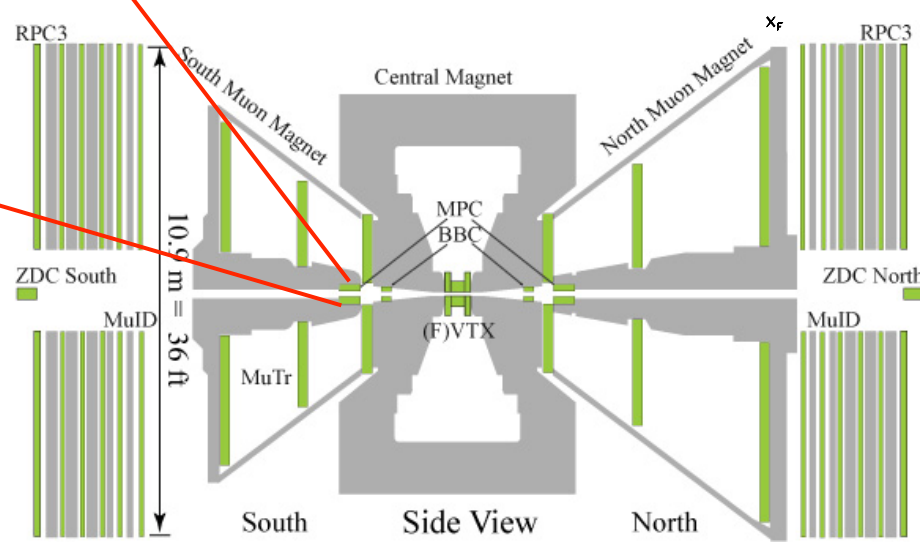
Collins dominates?

Need more data!
- X-coverage important!

Coming soon: MPC-EX (2015+)







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

$3.1<|\eta|<3.9$

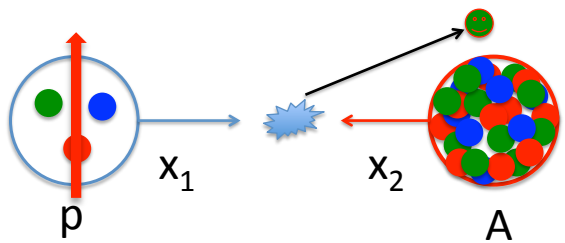
- π^0 rejection → direct photons
- π^0 reconstruction out to >80GeV

Polarized p+A at RHIC(2015+)

"Polarized p+A @RHIC" workshop, Jan., 2013
https://indico.bnl.gov/conferenceDisplay.py?ovw=True&confId=553

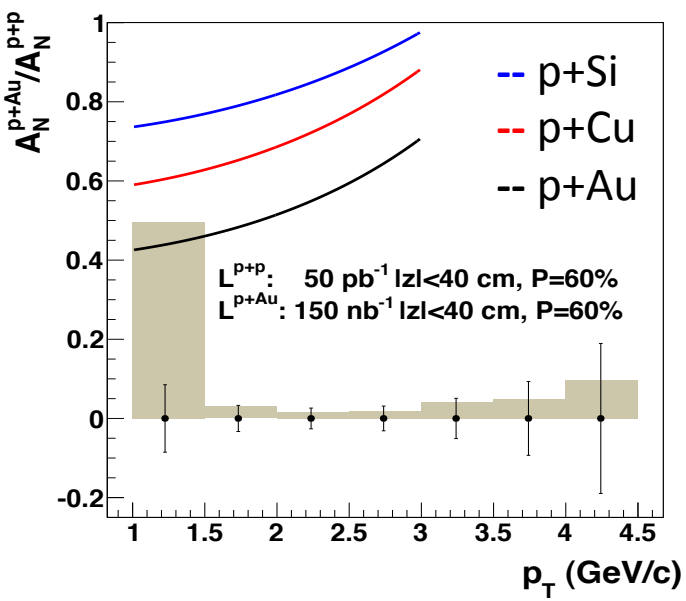
- Large transverse spin asymmetry A_N at forward rapidity – a large analyzing power at large x_1
- Gluon saturation/CGC probed at forward rapidity in p+A – small x_2 in A

A new probe – using a large spin asymmetry to study CGC effects in the forward rapidity



projectile: $x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim 1$ valence

target: $x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$ gluon

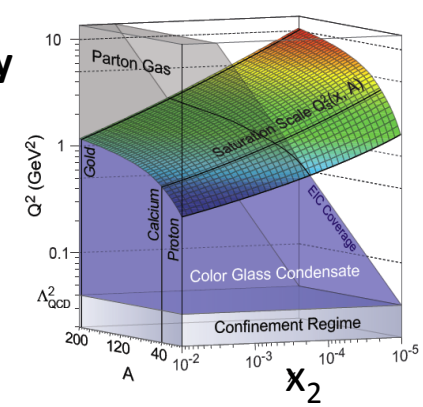


$$\Delta\sigma_{forward} \sim \Delta f(x_1) \otimes g(x_2); \quad x_1 >> x_2$$

Forward Pion Single-Spin Asymmetry

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}}$$

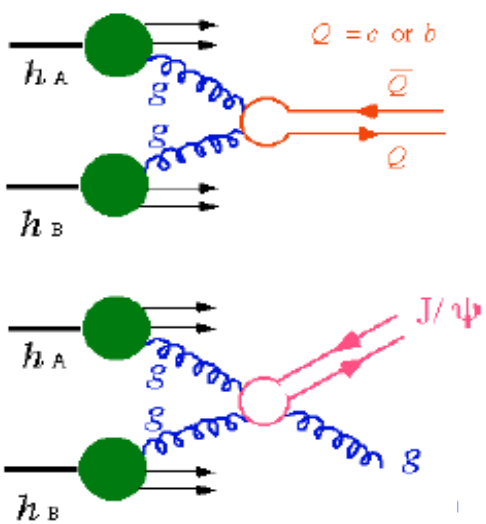
Kang, Yuan (2011)

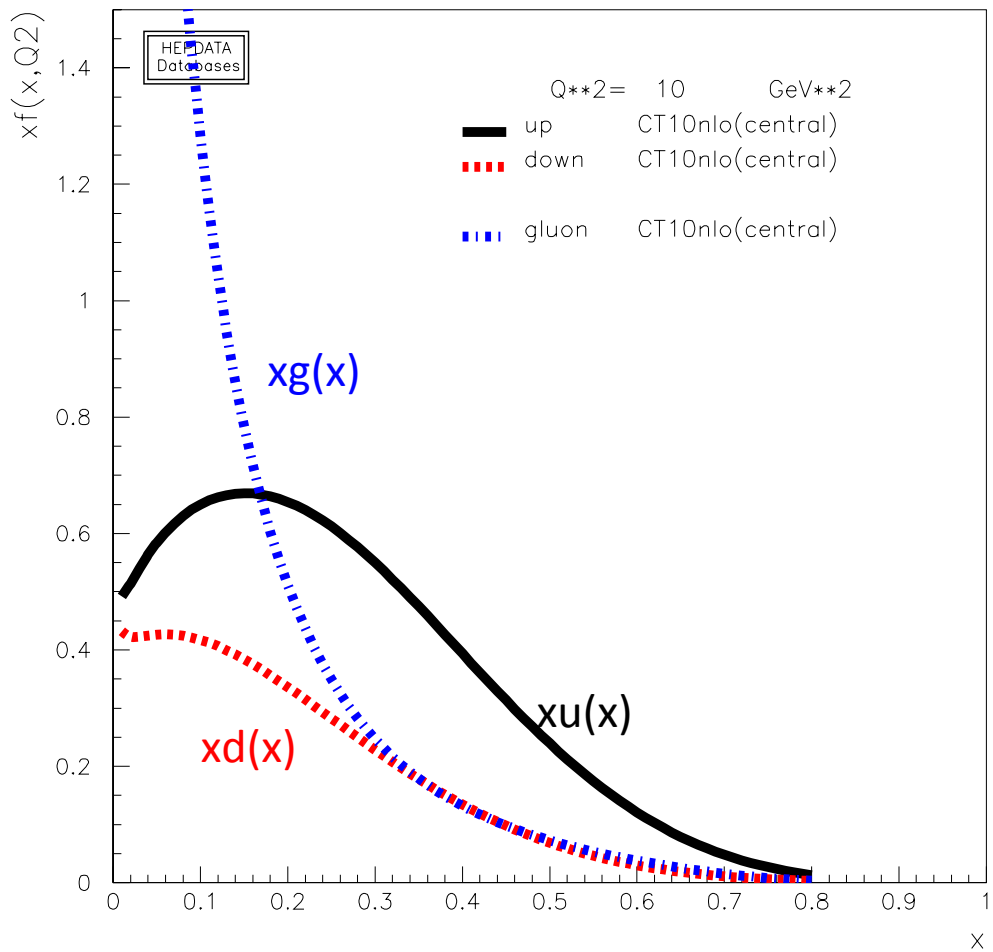


Unique Opportunity @RHIC: Study Gluons!

- How about Gluons?
  - Gluons ~50%
  - Significant gluons at "large x"
  - Twist-3 quark-gluon and gluon-gluon corr. functions
- Probe gluons with heavy quarks

Gluon Fusion





Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation functions

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

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

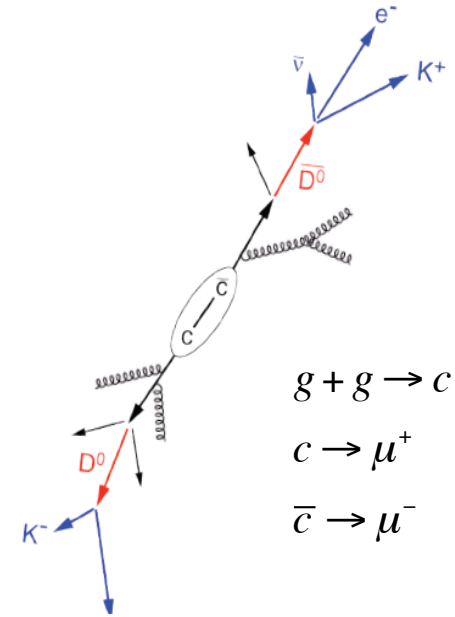
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

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

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

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

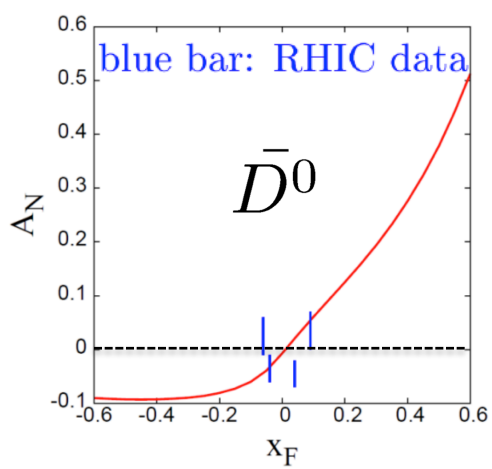
Koike *et. al.* (2011)
Kang, Qiu, Vogelsang, Yuan (2008)

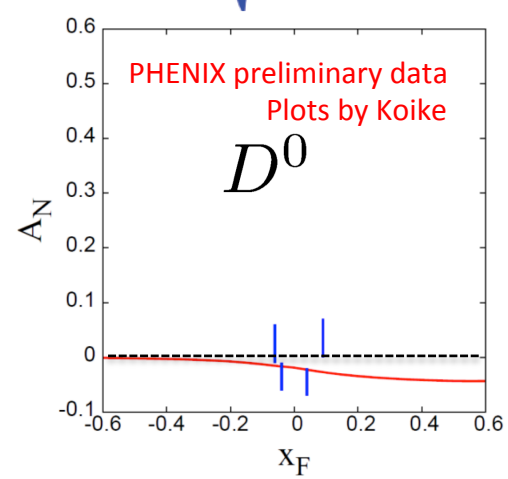


$g + g \rightarrow c + \bar{c}$

$c \rightarrow \mu^+$

$\bar{c} \rightarrow \mu^-$



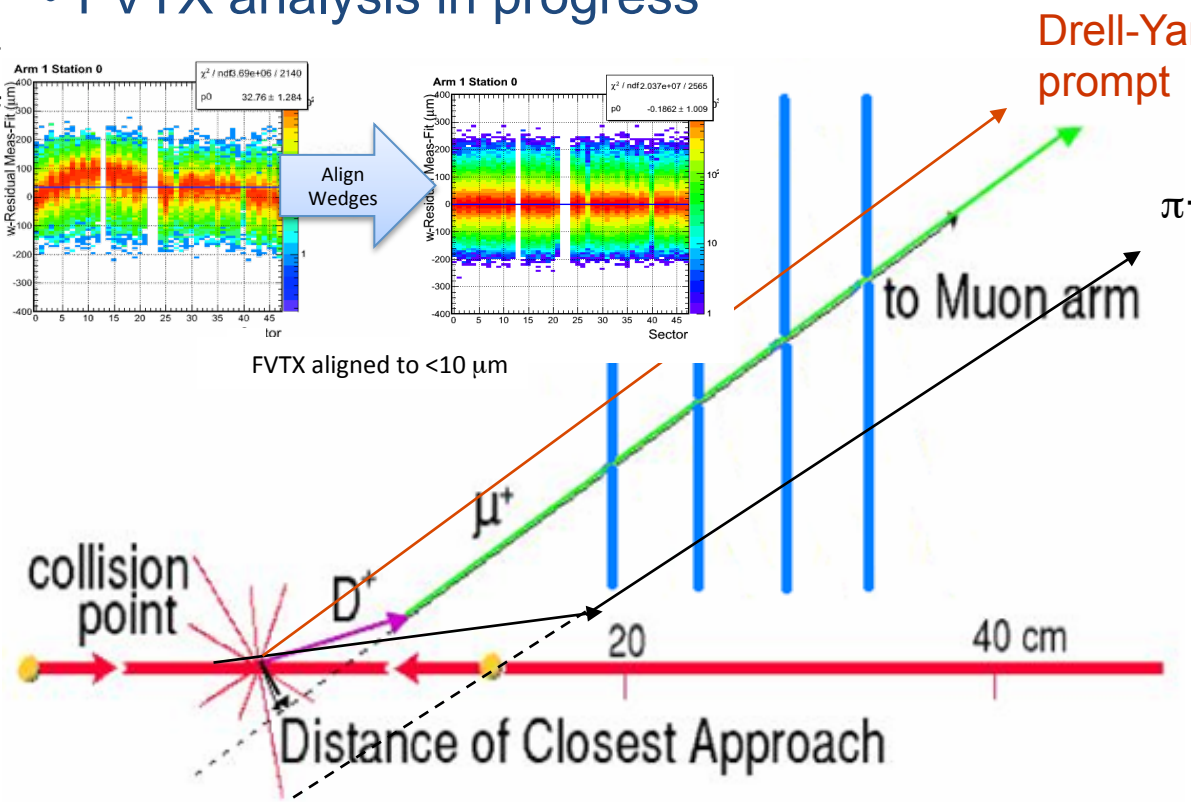


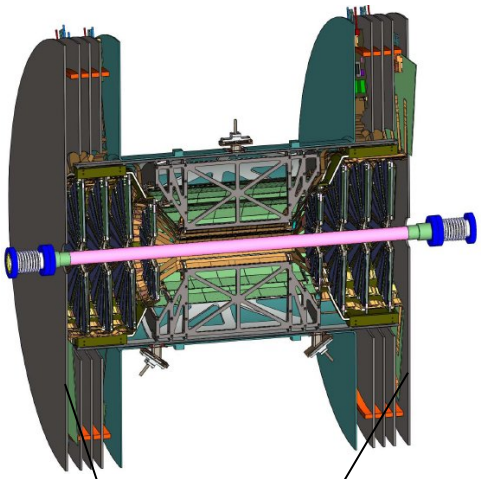
FVTX Upgrade Completed in 2012

New Capabilities of Forward Muon Probes

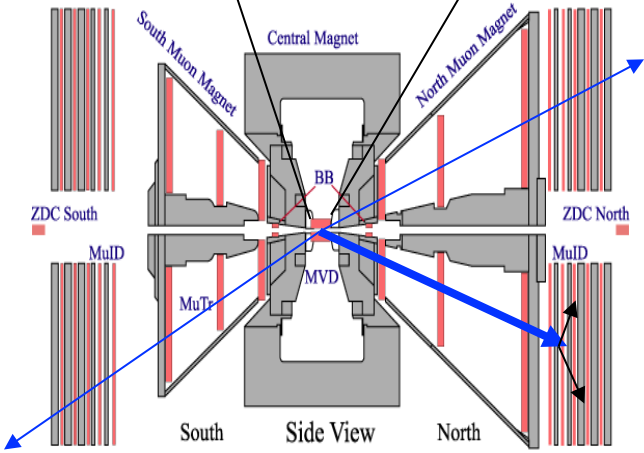
- Precision Charm/Beauty Measurements
- Drell-Yan, J/ψ … via dimuons
- W/Z
- FVTX analysis in progress

FVTX aligned to <10 μm





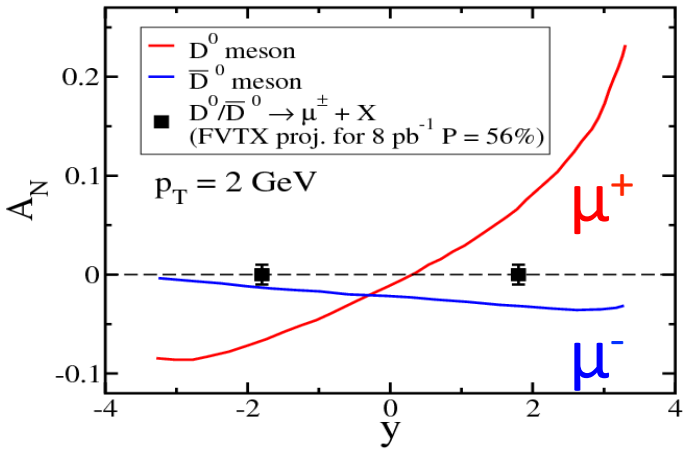
π→μ

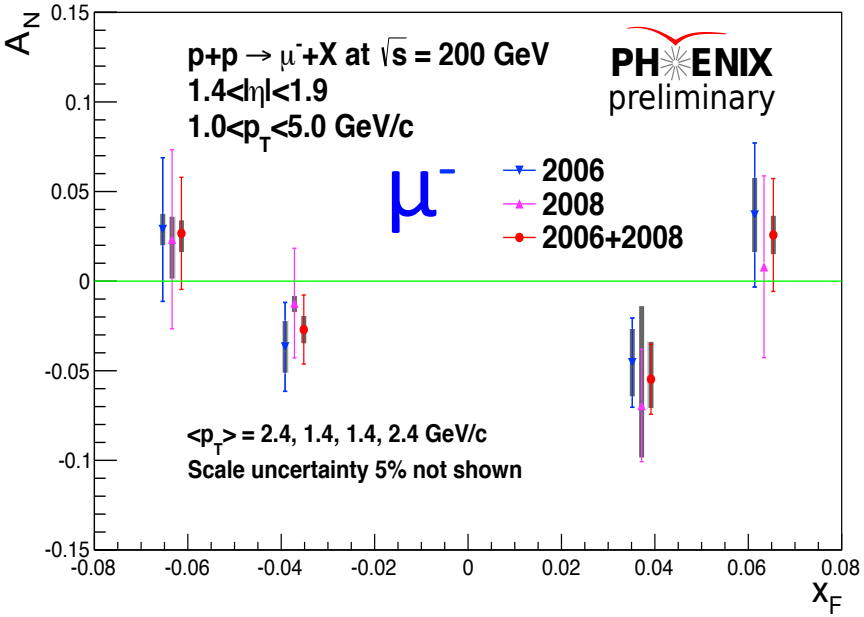


Projected Open Charm TSSA with FVTX

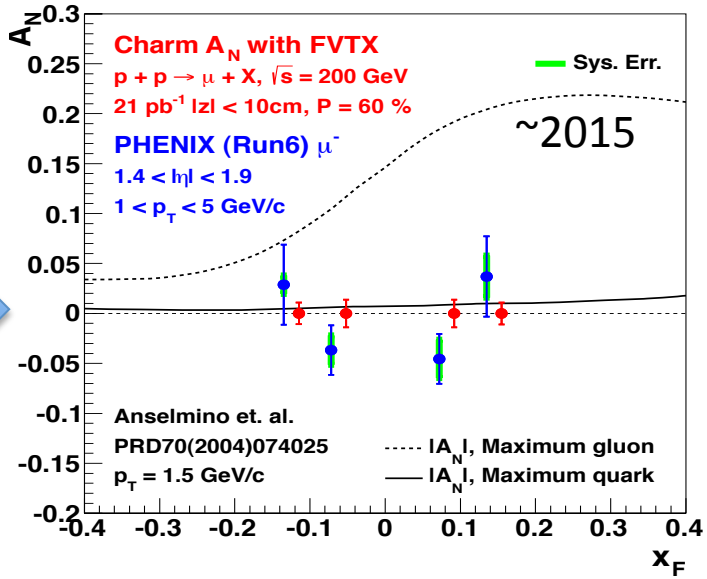
Unique opportunity to study gluon Sivers distributions at RHIC

- Forward Muon arms
  - Run6, 8
  - Run12 work in progress
  - Much improved w/FVTX (Run15)





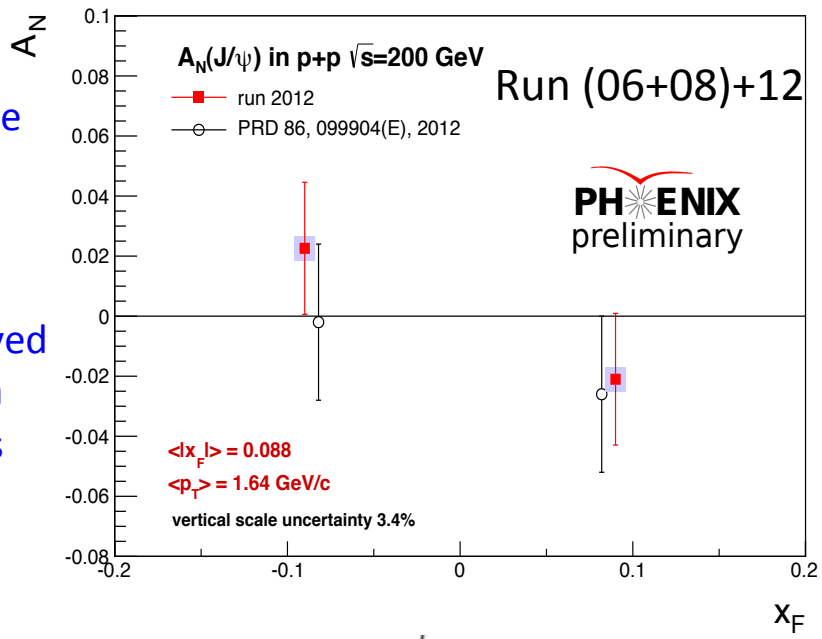
FVTX

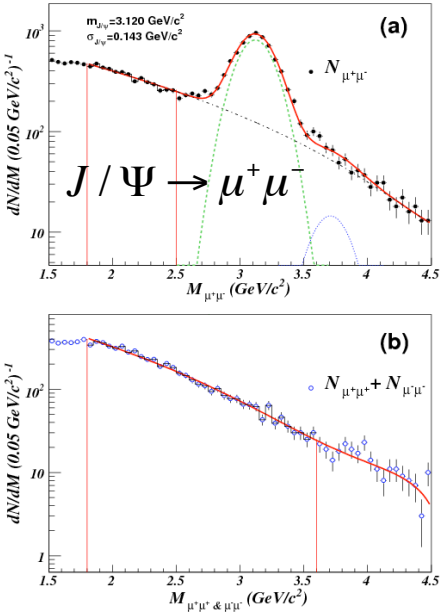


J/ψ A_N Measurement in p+p Collisions

A new tool to study J/Psi production mechanisms in p+p

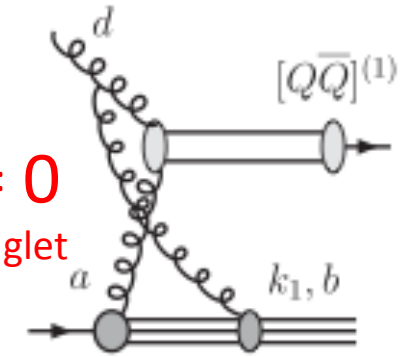
- A new test QCD factorization and role of spin in particle production
- Expect much improved measurements from future high stat runs @RHIC

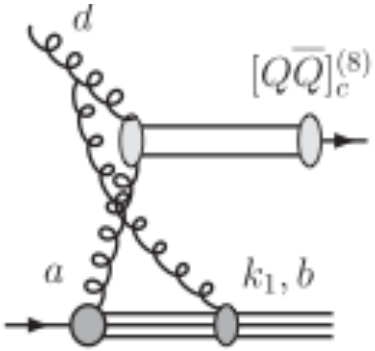




A_N != 0

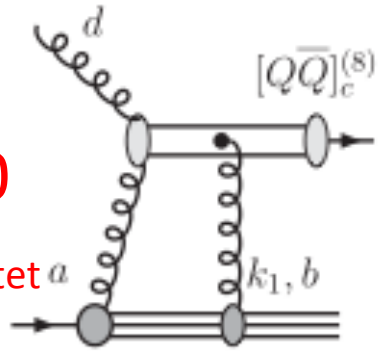
Color singlet





A_N =0

Color Octet



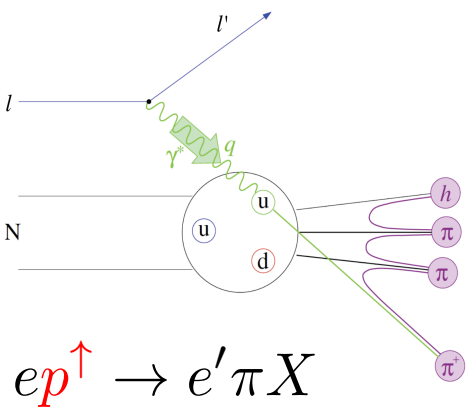
F. Yuan, PRD 78, 014024(2008)

Future Forward Dimuon Drell-Yan A_N Study

fundamentally important test of QCD factorization and gauge-link

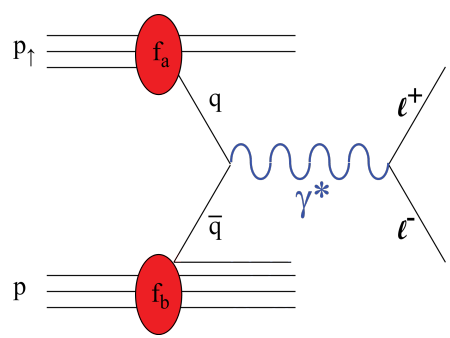
- Drell-Yan A_N accesses quark Sivers effect ($f_{1T}^{\perp}$) in proton
- $f_{1T}^{\perp}$ expected to reverse in sign from SIDIS to DY meas.

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



$ep^{\uparrow} \to e'\pi X$

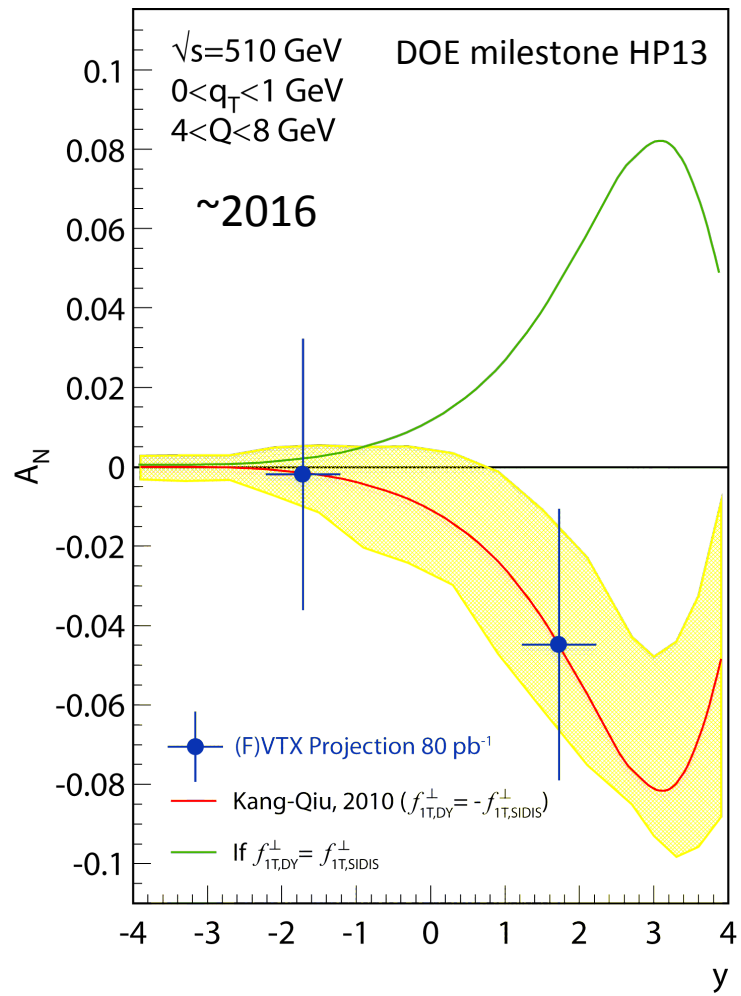
Semi-inclusive DIS (SIDIS)



$pp^{\uparrow} \to \mu^+\mu^- X$

Drell-Yan

RHIC 1-year running projection

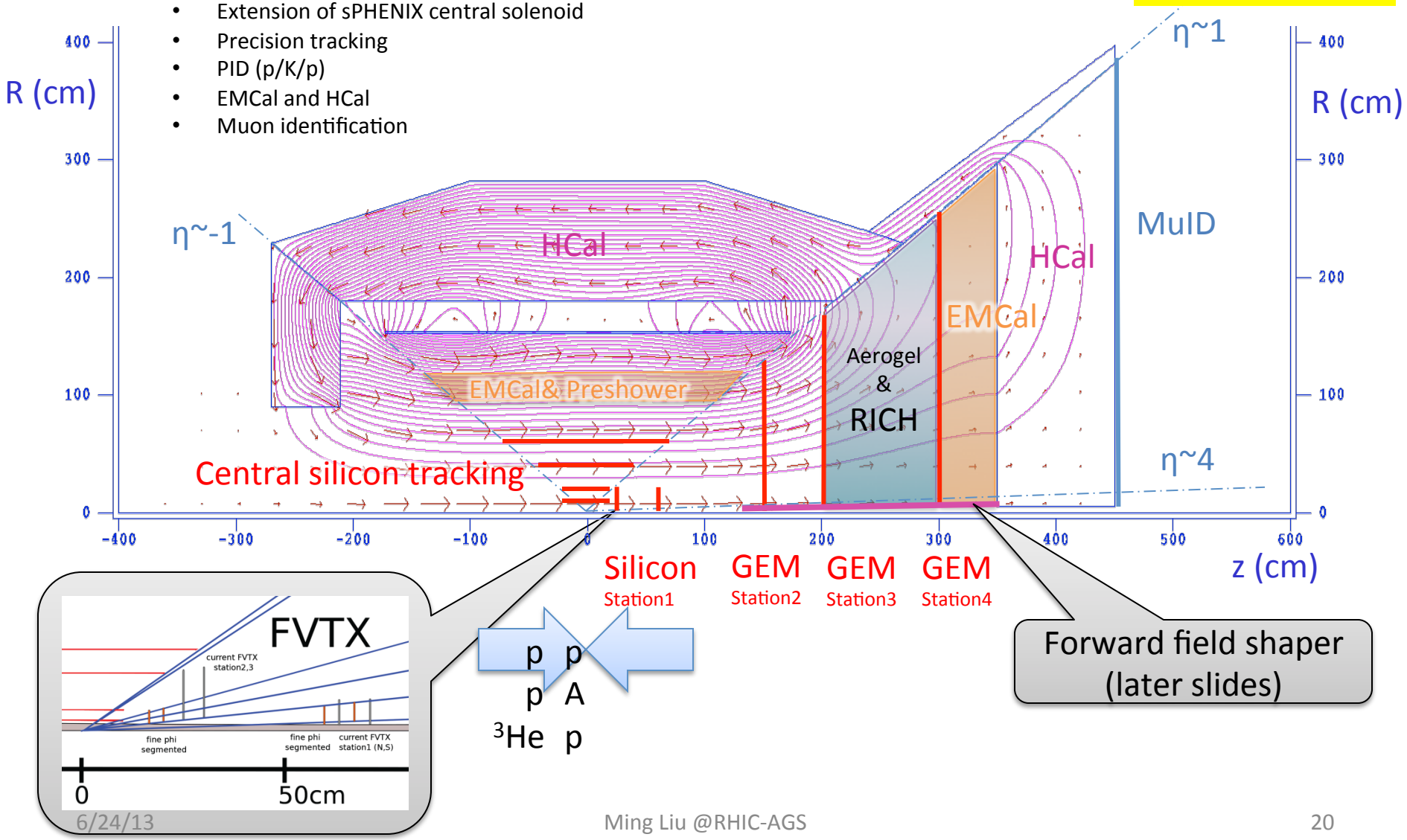


Spin Physics with Forward s/ePHENIX

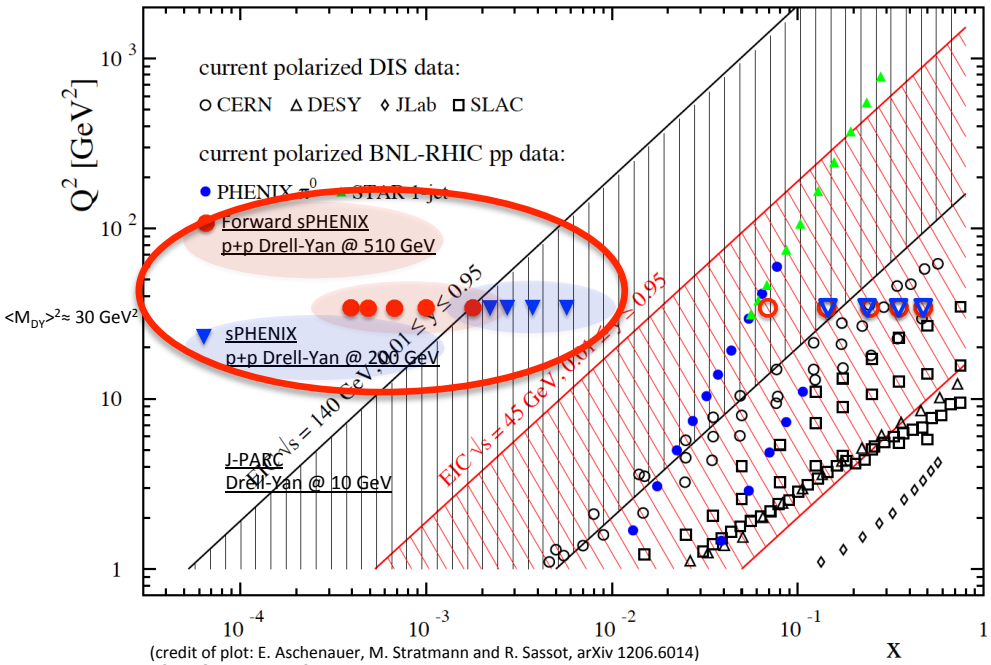
Jin Huang's Talk

Optimized for jets, photons and DY over a large range in rapidity (1<eta<4)

- Extension of sPHENIX central solenoid
- Precision tracking
- PID (p/K/p)
- EMCal and HCal
- Muon identification



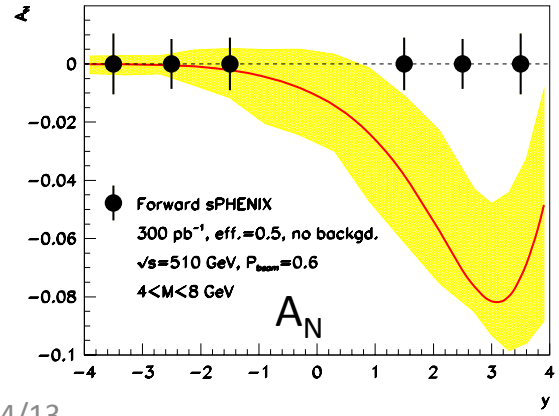
Drell-Yan Kinematics with Forward s/ePHENIX

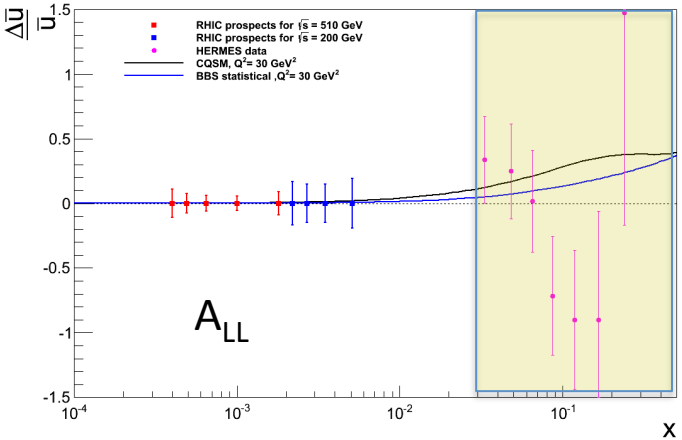


(credit of plot: E. Aschenauer, M. Stratmann and R. Sassot, arXiv 1206.6014)

study sign change and shape!

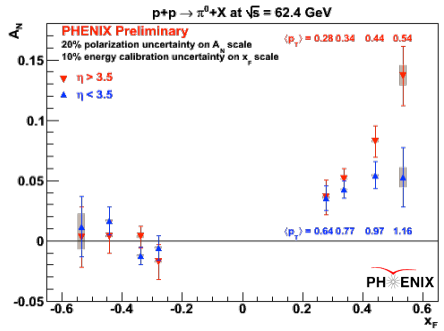
Probe deep sea-quark polarization!

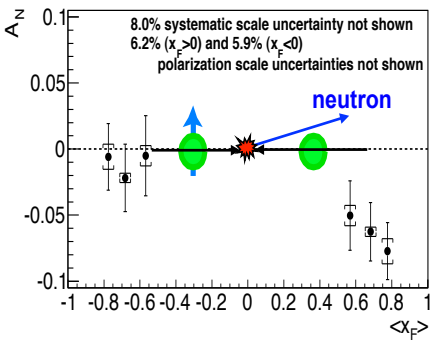


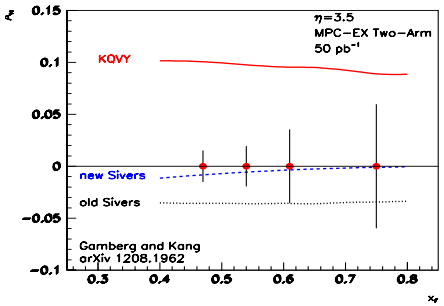


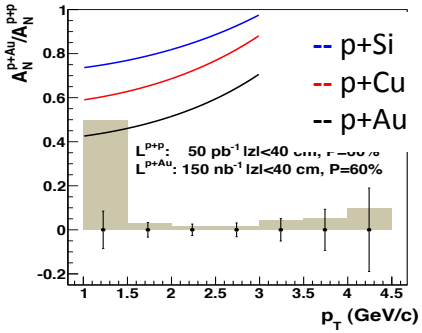
Summary and Outlook

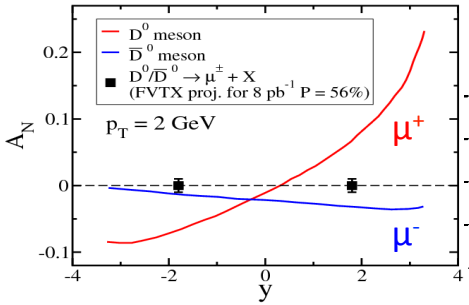
- Significant TSSA observed in the forward rapidity
  - Pion and eta via MPC
  - Leading neutrons in ZDC
- Expect much improved measurements w/ forward MPC-EX
  - larger pT, xF coverage; dir-photon
  - Quarks' Sivers and Collins effects
- Forward muons with FVTX
  - Gluon Sivers
  - Charm vs anti-Charm & tri-gluon
  - Drell-Yan to test QCD
- Forward s/ePHENIX
  - New spin program

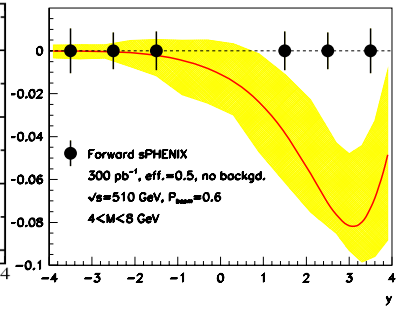








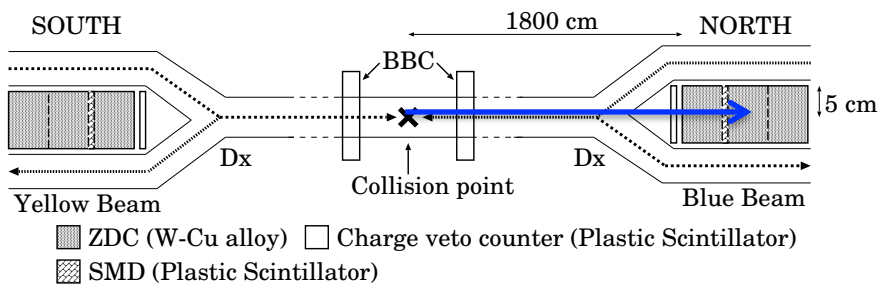


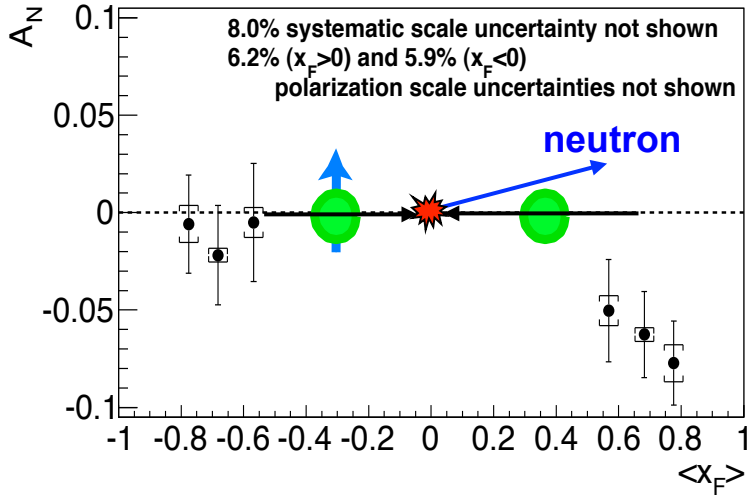


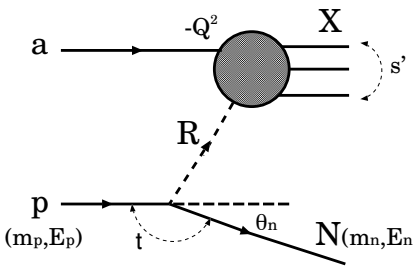
backup

Very Forward Leading Neutron A_N

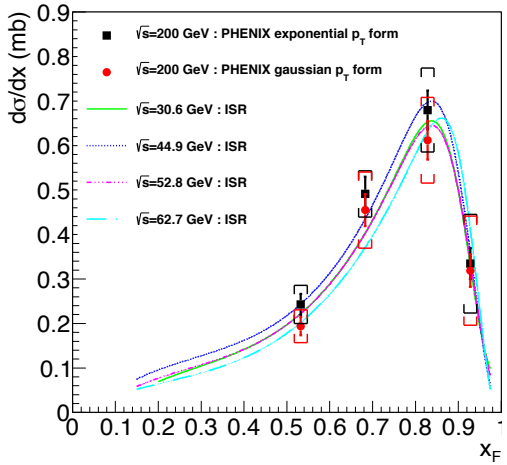
arXiv:1209.3283

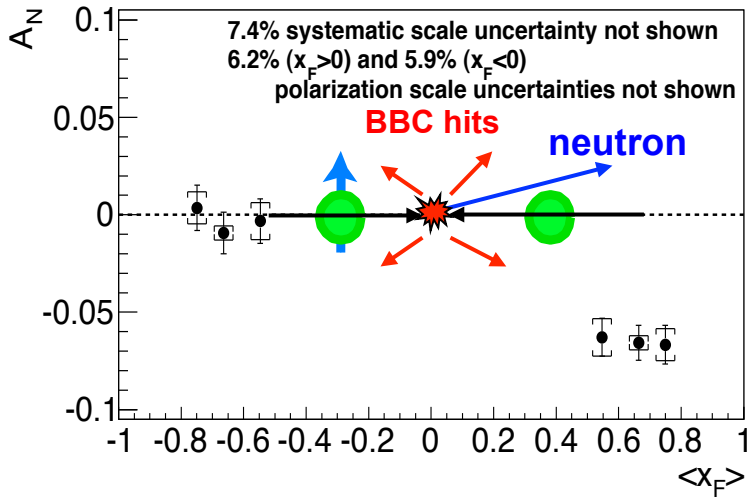






Single pion exchange?





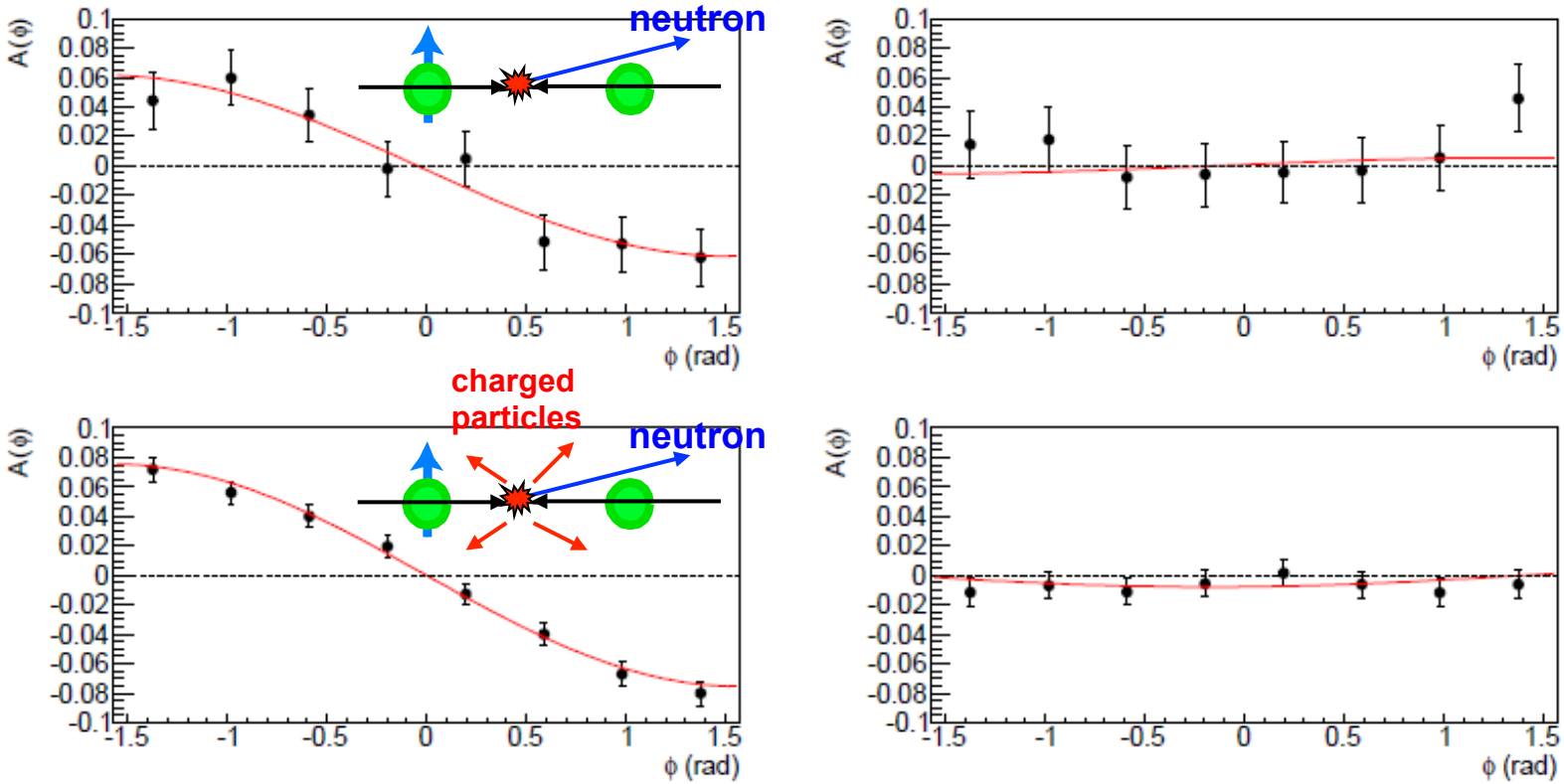
Forward Neutron A_N

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

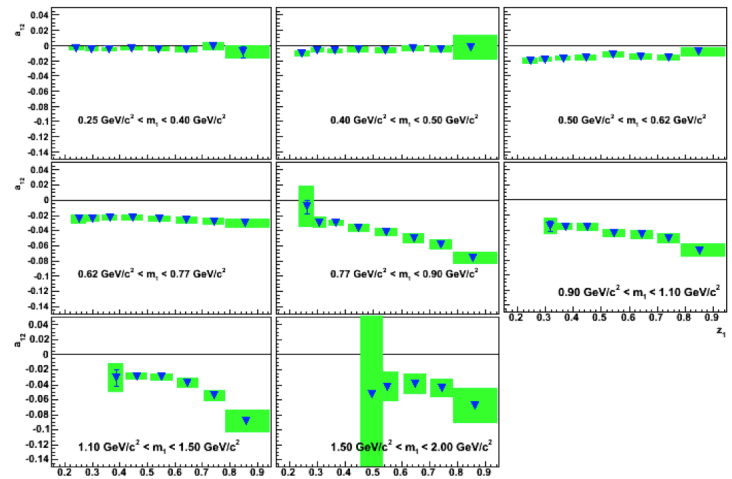
A_N = -0.075±0.004(stat)±0.004(syst)

Backward asymmetry

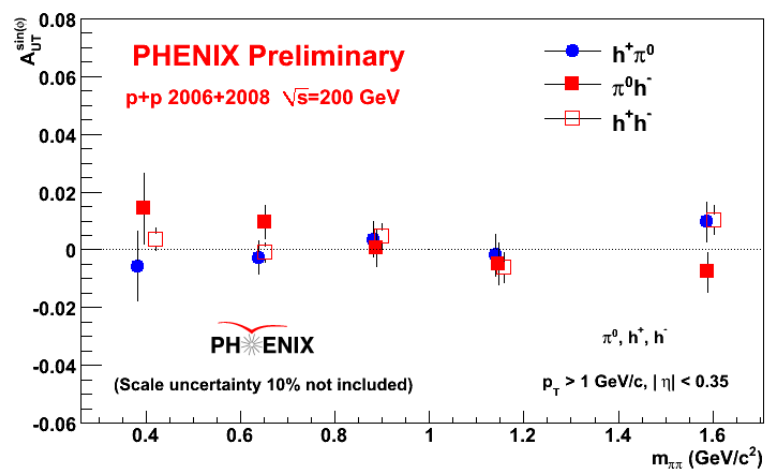
A_N = -0.008±0.005(stat)±0.004(syst)

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



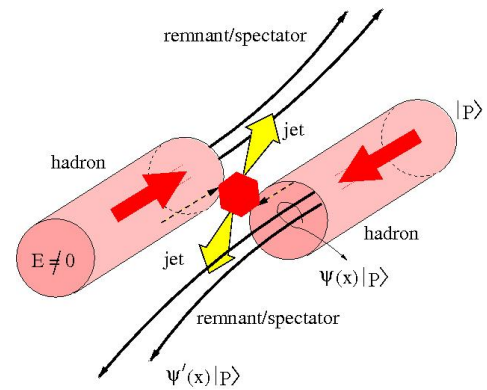
- At PHENIX, couples with transversity
  - Initial data statistically limited
  - Expected improved measurements from future runs

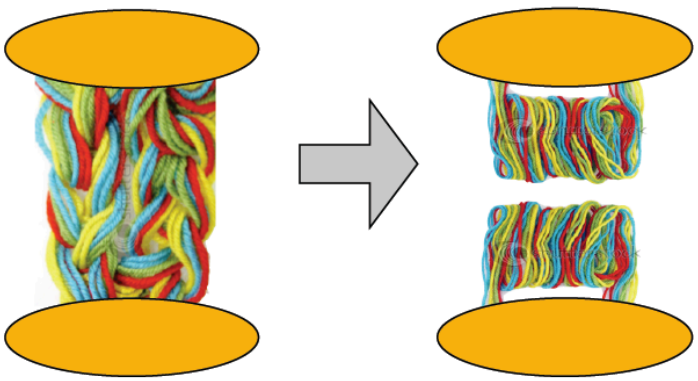


Color Flow in p+p Collisions

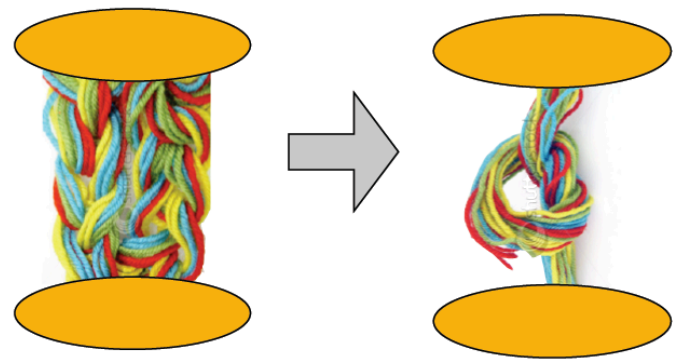
- Theoretical challenges
  - validity of factorization, universality …
  - TMD, Twist-3…

Bacchetta, Mulders@QCD-N12





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



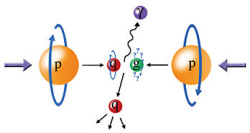
TMD factorization does not work for pp to hadrons.

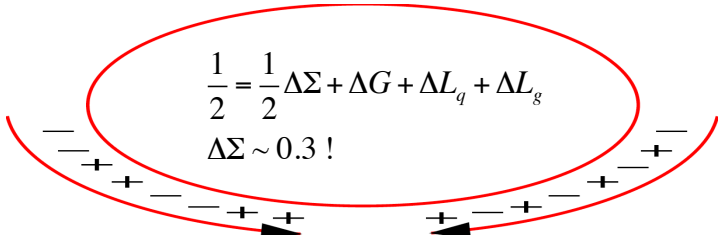
$$\sigma(h) \sim f(x_1) \otimes f(x_2) \otimes \hat{\sigma}^{x_1+x_2 \to h+X}$$

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

Spin Physics Program at RHIC

RHIC is capable of delivering the beams required for precision spin physics now!

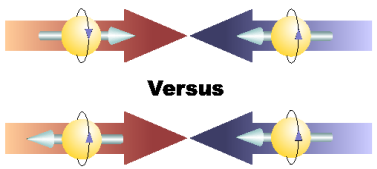




Longitudinal program:
Focus on "Spin Crisis"

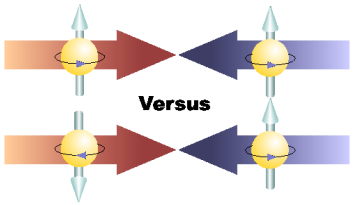
Transverse program:
New tests of QCD

$$A_{LL} = \frac{\sigma(++)-\sigma(+-)}{\sigma(++)+\sigma(+-)}$$



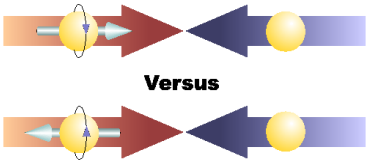
Gluon polarization

$$A_{TT} = \frac{\sigma(\uparrow\uparrow)-\sigma(\uparrow\downarrow)}{\sigma(\uparrow\uparrow)+\sigma(\uparrow\downarrow)}$$



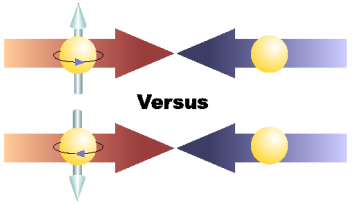
Quark transversity

$$A_L = \frac{\sigma(+)-\sigma(-)}{\sigma(+)+\sigma(-)}$$



Anti-quark polarization

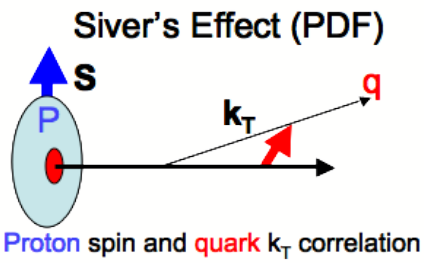
$$A_N = \frac{\sigma(\uparrow)-\sigma(\downarrow)}{\sigma(\uparrow)+\sigma(\downarrow)}$$

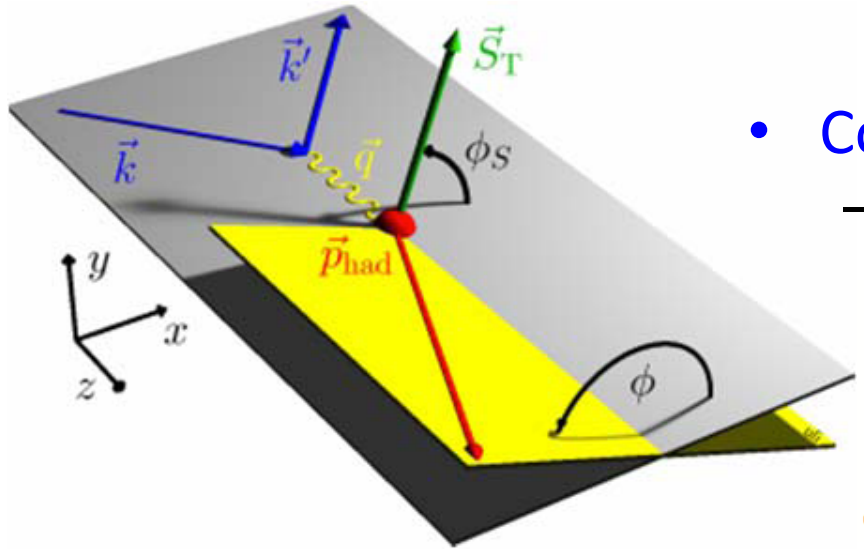


Quark and gluon Sivers and Collins functions

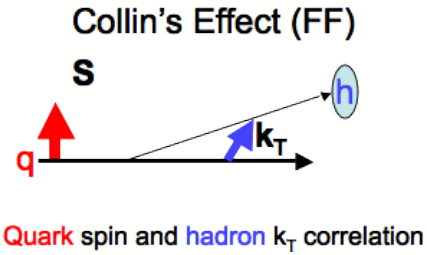
Positive Signals from SIDIS

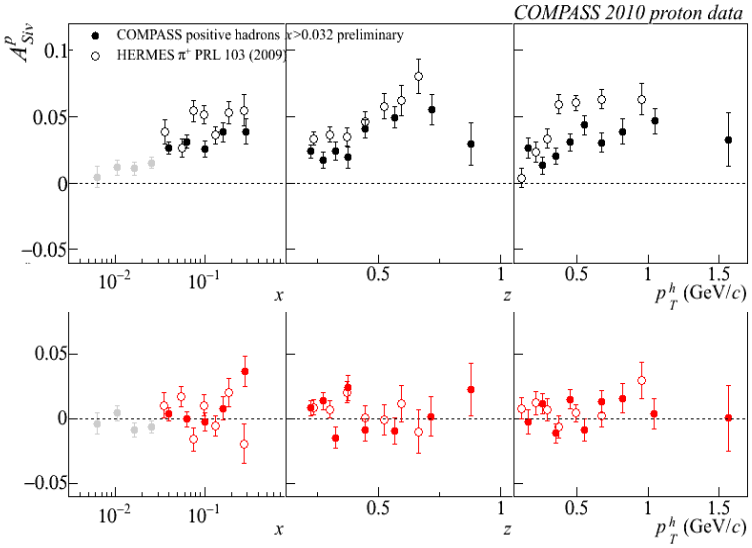
- Sivers
  - <sin(Φ–Φ$_s$)>

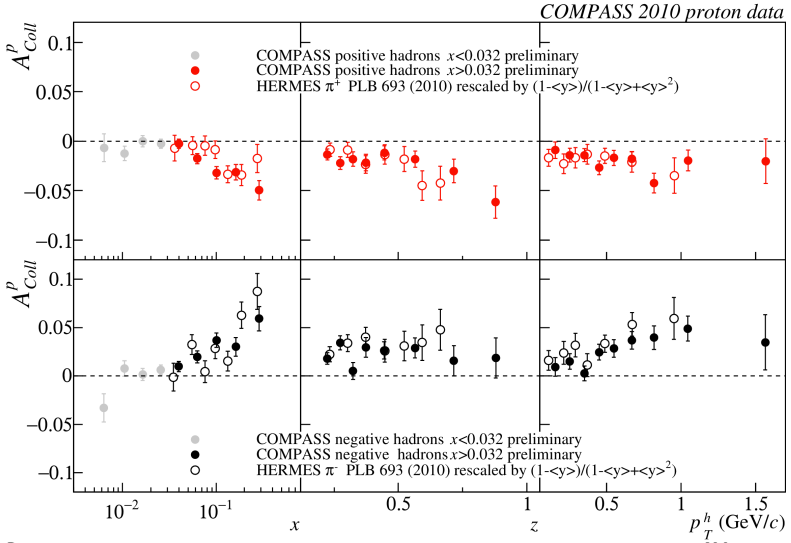




- Collins
  - <sing(Φ+Φ$_s$)>







Forward Hadrons pp @200GeV

BRAHMS PRL (2007)

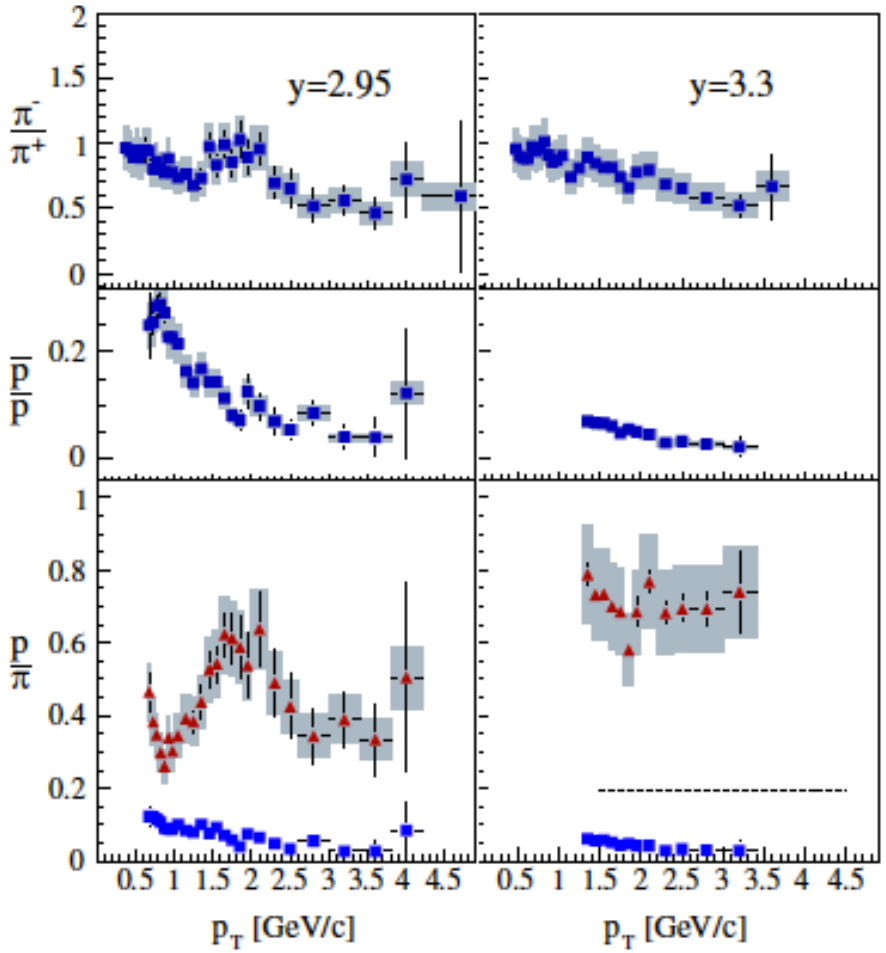
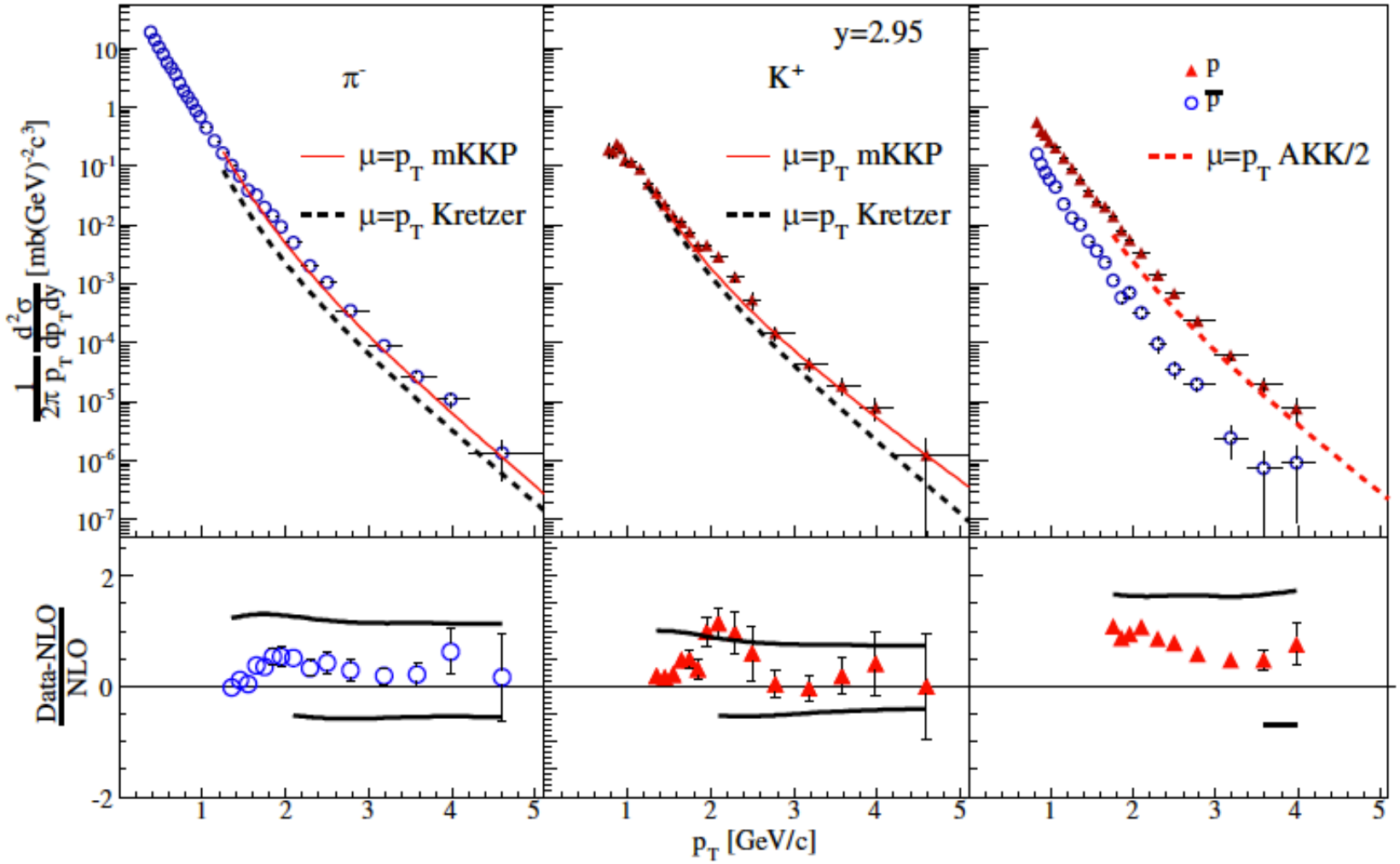


FIG. 2: Particle ratios versus p_T at y=2.95 and 3.3. Top) π^-/π^+, Middle) $\bar{p}/p$ and Bottom) p/π^+ (red circles) and $\bar{p}/\pi^-$ (blue squares). The shaded rectangles indicate an overall systematic error (17%) estimated for these ratios. The dashed line shows an upper limit for the $(p+\bar{p})/(\pi^+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

200 pp Very Forward: y=3

(Data – NLO)/NLO

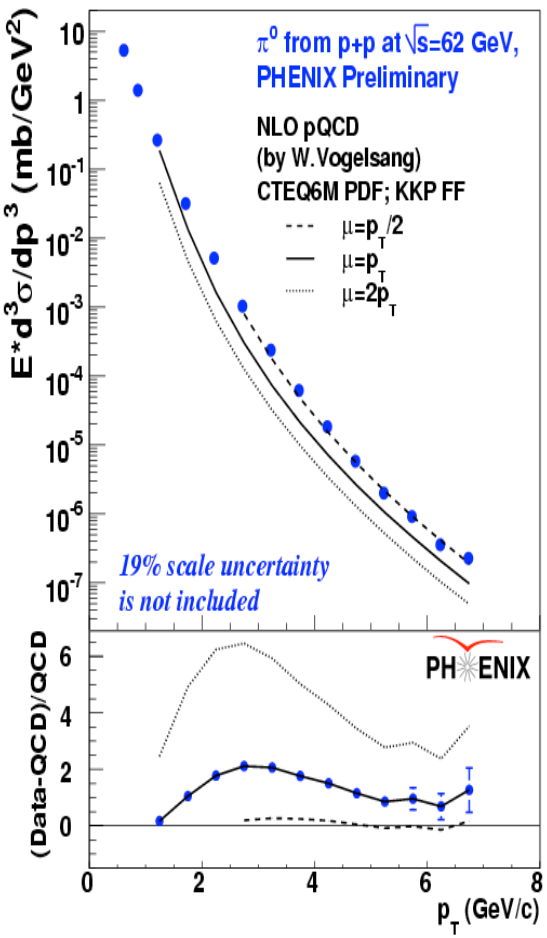
BRAHMS



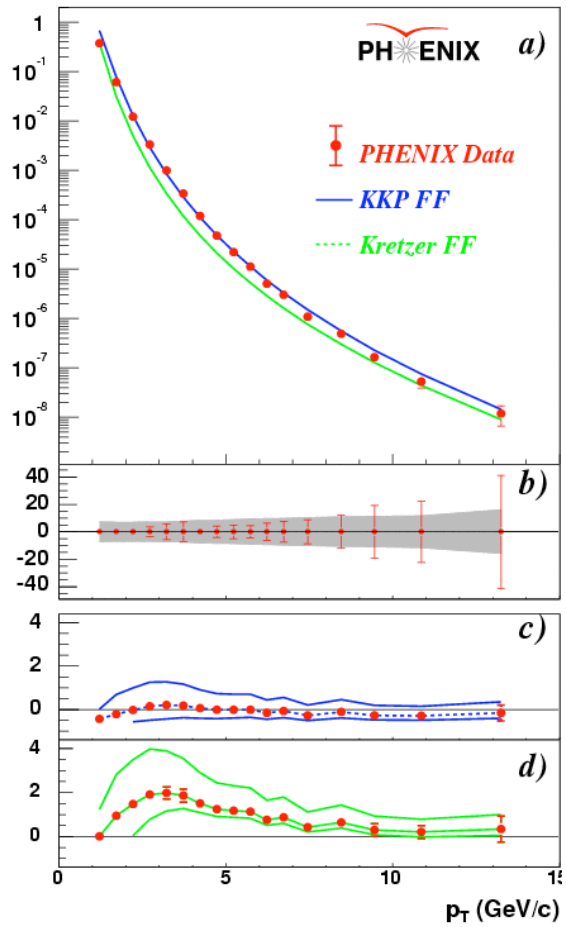
Data vs NLO: |eta|<0.35

(Data - NLO)/NLO

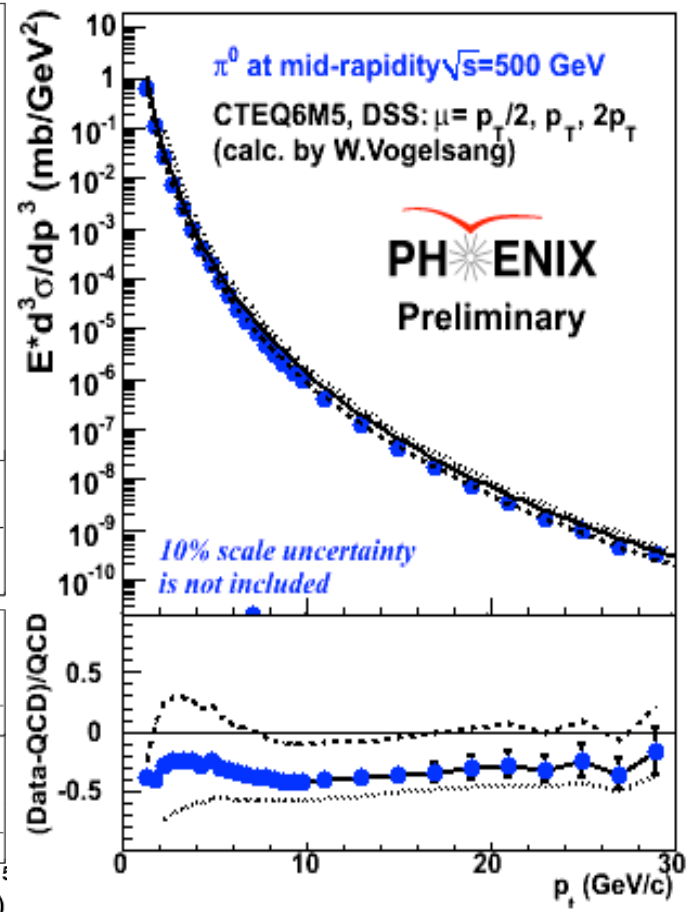
62GeV



200GeV

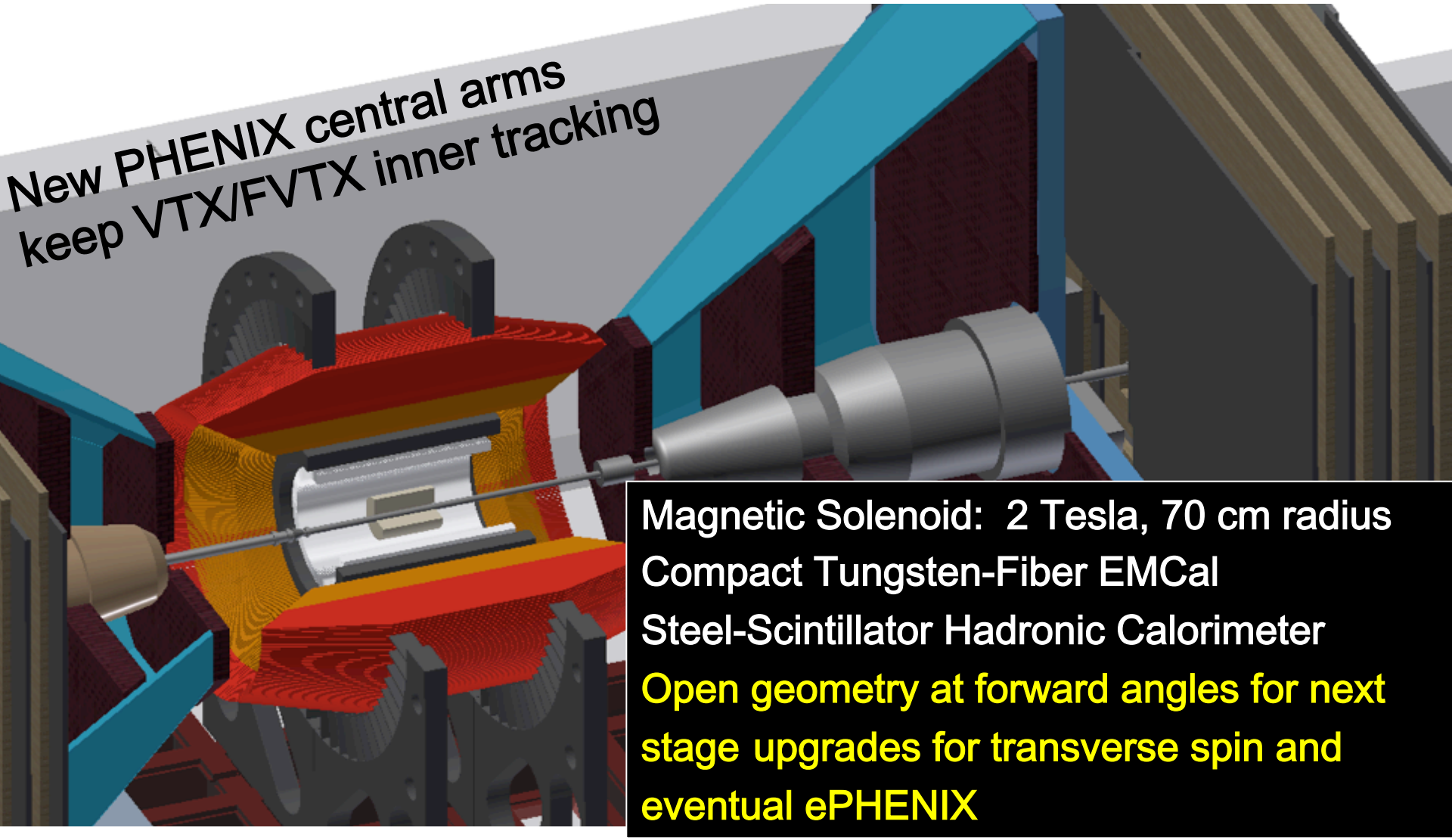


500GeV



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