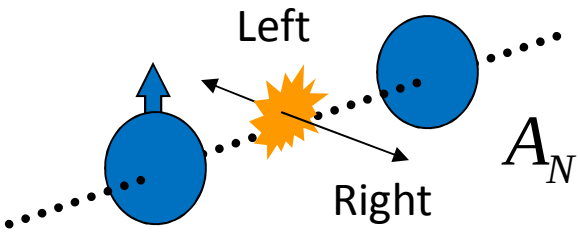
Transverse Spin Results from PHENIX at RHIC

Feng Wei, for the PHENIX Collaboration

New Mexico State University

- Introduction
- PHENIX measurements and results
- Opportunities with new detectors

Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Theory Expectation (twist-2):

Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

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

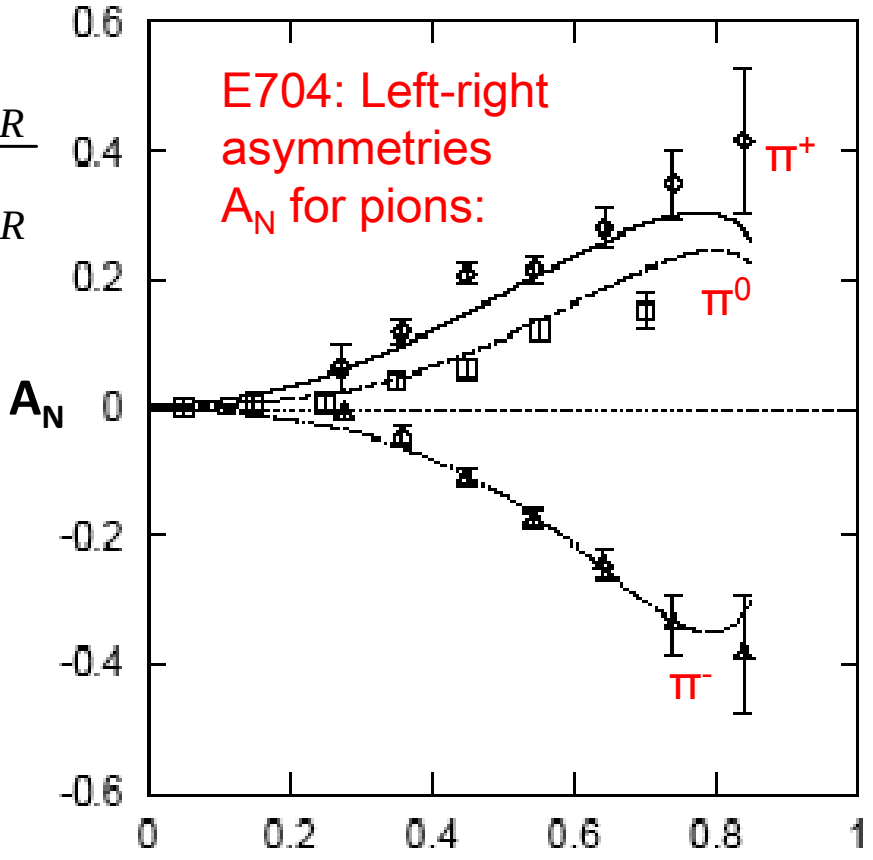
A_N ~O(0.1%) Theory

Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^{\uparrow} \rightarrow \pi + X$$
$$\sqrt{s} = 20\,\mathrm{GeV}$$

A_N ~O(10%) Measured

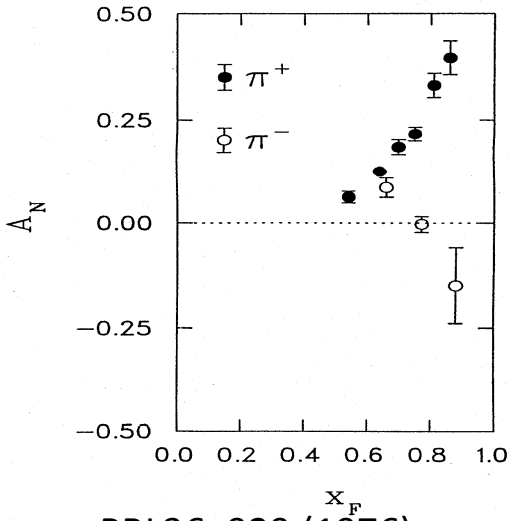


$$x_F = \frac{2p_L}{\sqrt{s}}$$

How can we understand them?

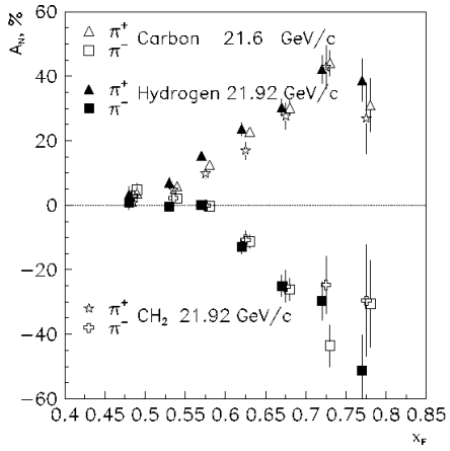
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

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



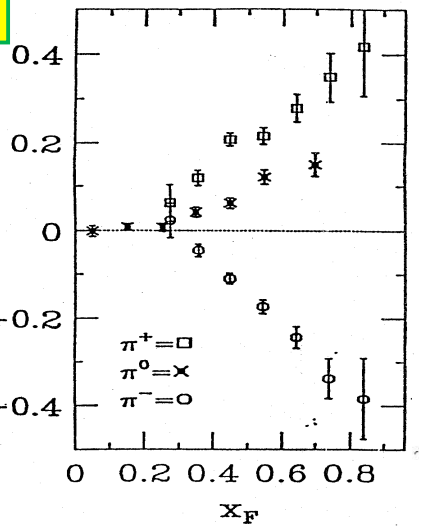
PRL36, 929 (1976)

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



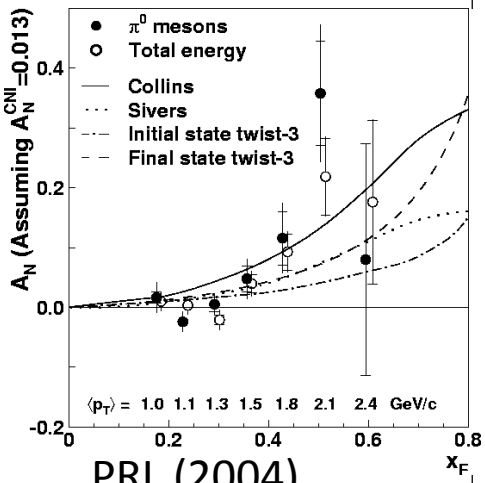
PRD65, 092008 (2002)

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

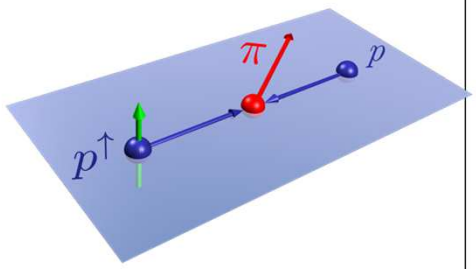


PLB261, 201 (1991)
PLB264, 462 (1991)

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

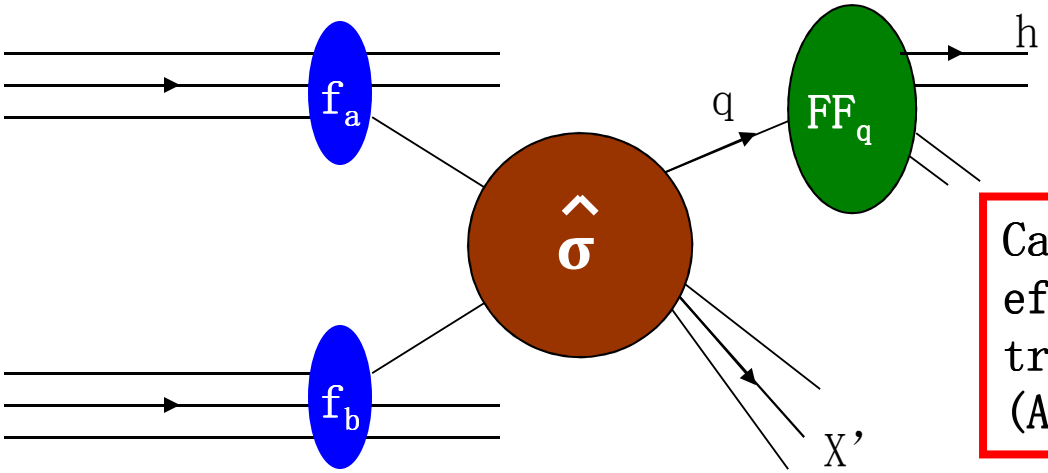


PRL (2004)



Non-Perturbative cross section → Perturbative cross section

Possible Origin of Large SSAs



Can initial and/or final state effects generate large transverse spin asymmetries? (A_N ~10^{-1})

Proton Structure **pQCD**

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow}\rightarrow\pi^{+}X\right)}{dx_1dx_2dz}\propto q_i^{\uparrow}(x_1,k_{q,T})\cdot G(x_2)\times\frac{d^3\hat{\sigma}^{\uparrow}(q_iq_j\rightarrow q_kq_l)}{dx_1dx_2}\times FF_{q_{k,l}}(z,p_{h,T})$$

small spin dependence

fragmentation function

Mechanisms in QCD

TMD mechanism: GPM includes intrinsic transverse momentum

Possible Expansion:

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto f_{1T}^{\perp} \otimes D_1 + \delta q \otimes H_1^{\perp} + \ldots$$

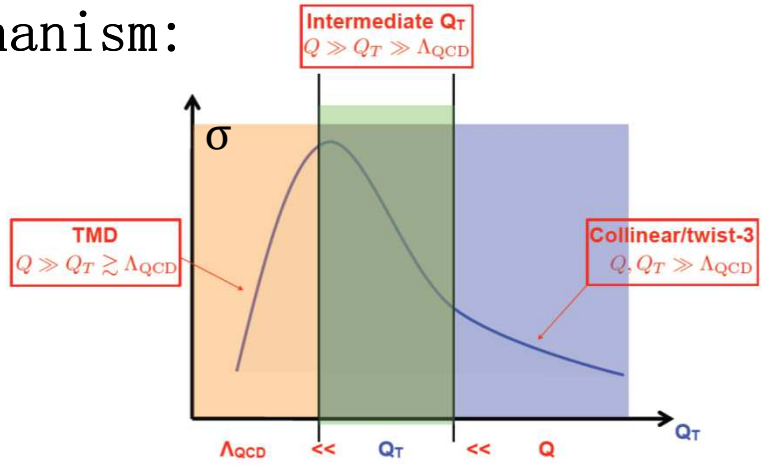
Sivers Function (angular momentum) → Sivers Effect

Transversity (structure)

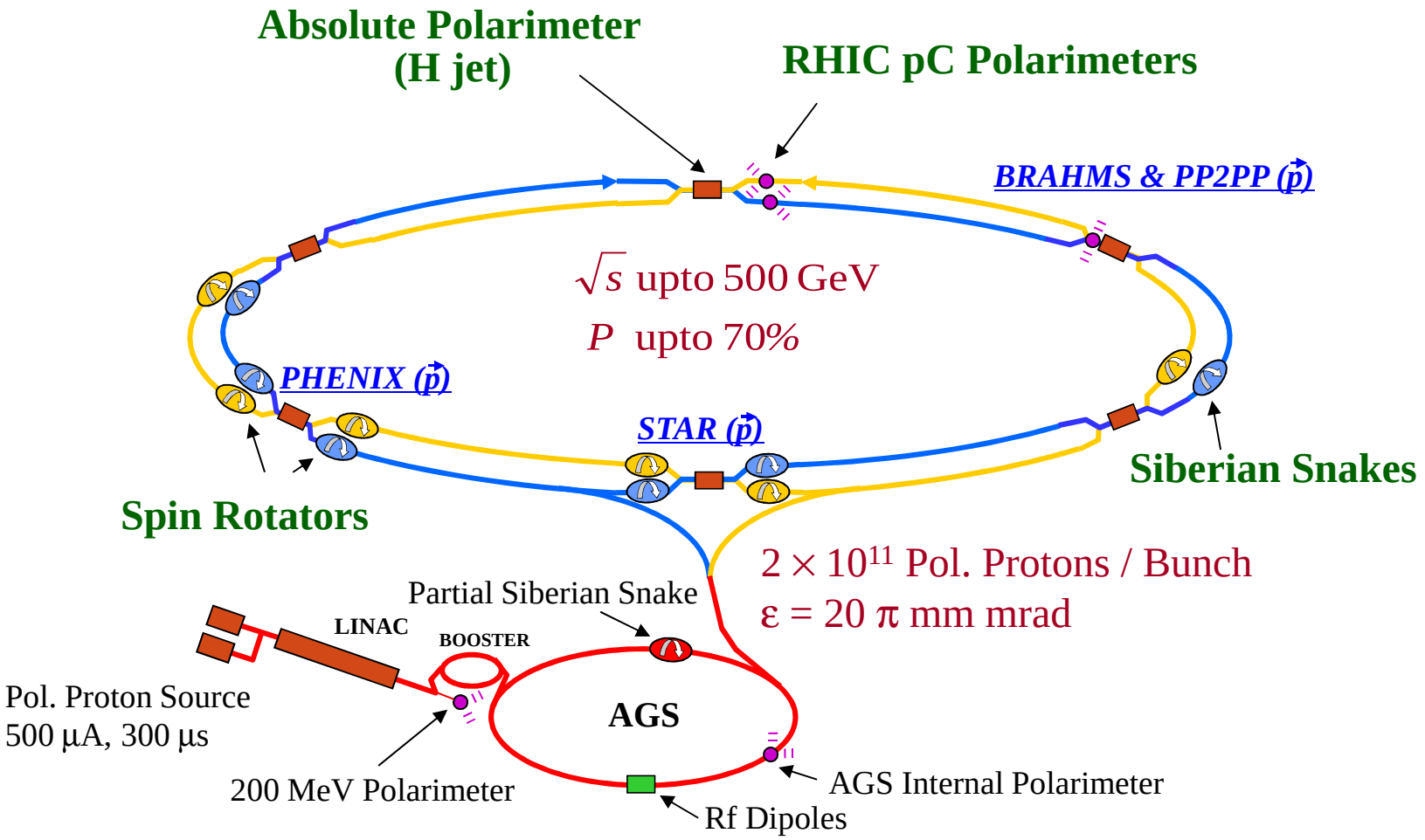
Collins Function (Fragmentation) → Collins Effect

Twist-3 Collinear factorization mechanism:

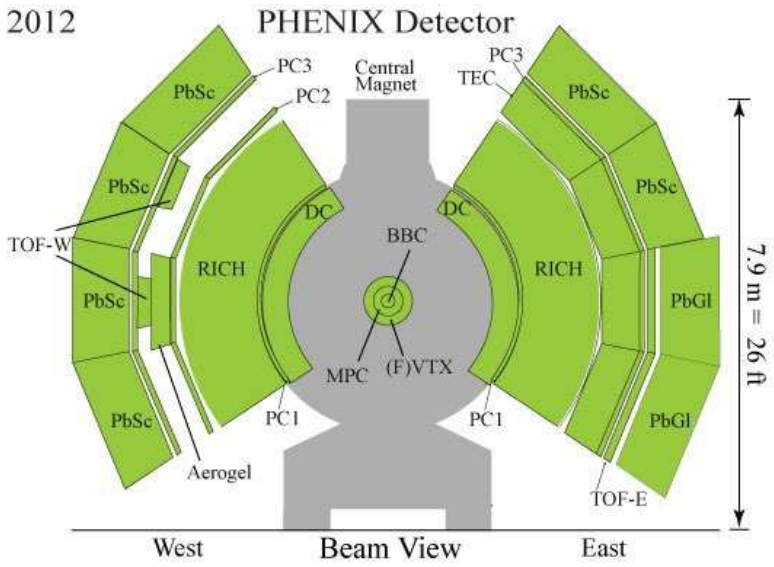
At high transverse momenta : various twist-3 correlation functions, quark-gluon and gluon-gluon correlation functions for both initiate state and final states effects.

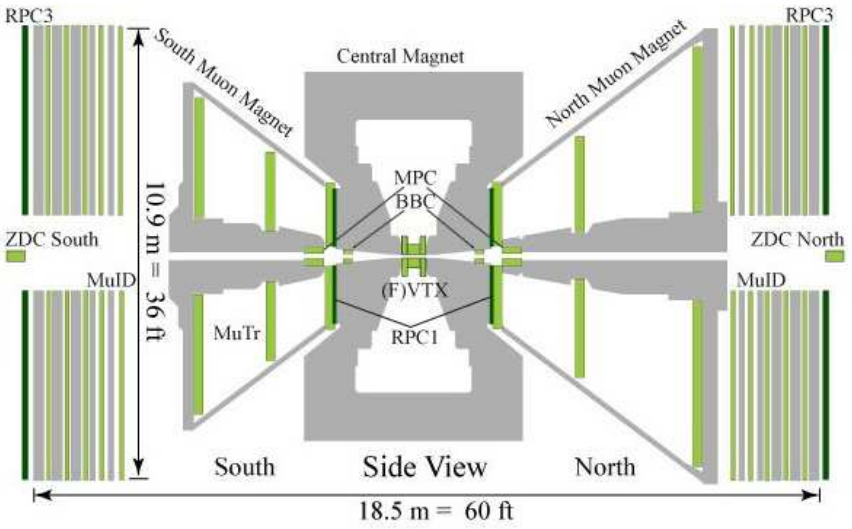


RHIC as Polarized Proton Collider



PHENIX Detectors





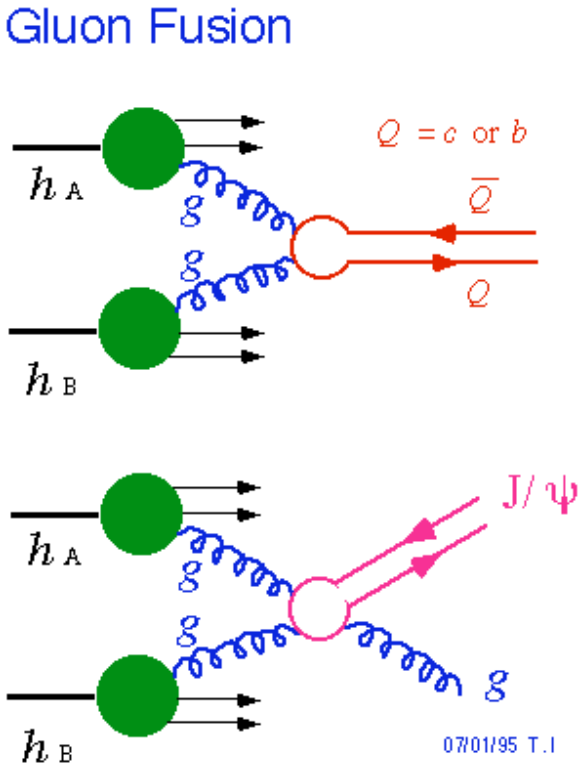
- **Central Arm** **|η|<0.35, Δφ=2 X π/2**
  - Drift Chamber (DC)
  - PbGl and PbSc (EMCal)
  - Ring Imaging Cherenkov Detector(RICH)
  - Pad Chambers (PC)
  - Time Expansion Chamber (TEC)
  - Silicon Vertex Detector (VTX)
- **Muon Arms** **1.2<|η|<2.4, Δφ=2π**
  - Muon tracker (MuTr)
  - Muon Identifier (MuID)
  - RPC (Trig)
  - Forward VTX (FVTX)
- **Muon Piston Cal. (MPC)** **3.1<|η|< 3.9**
  - **Photons**
  - **MPX-EX upgrade (2015)**
- **Global Detectors (Lumi, Trigger, local Pol.)**
  - **BBC**
  - **ZDC (neutron)**

Integrated Luminosity and Polarization

Year of RHIC Run	Energy [GeV]	Polarization [%]	Recorded L [pb^{-1}]	FOM (P^2L) [nb^{-1}]
2002	200	15	0.15	3.4
2005	200	47	0.16	35
2006	**62.4**	**48**	**0.02**	**4.6**
2006	**200**	**50**	**2.7**	**700**
2008	**200**	**45**	**5.2**	**1100**
2012	**200**	**60**	**9.2**	**3300**

PHENIX Measurements and Results

The Gluon distribution measurement



Heavy flavor production dominated by gluon-gluon fusion at RHIC energy

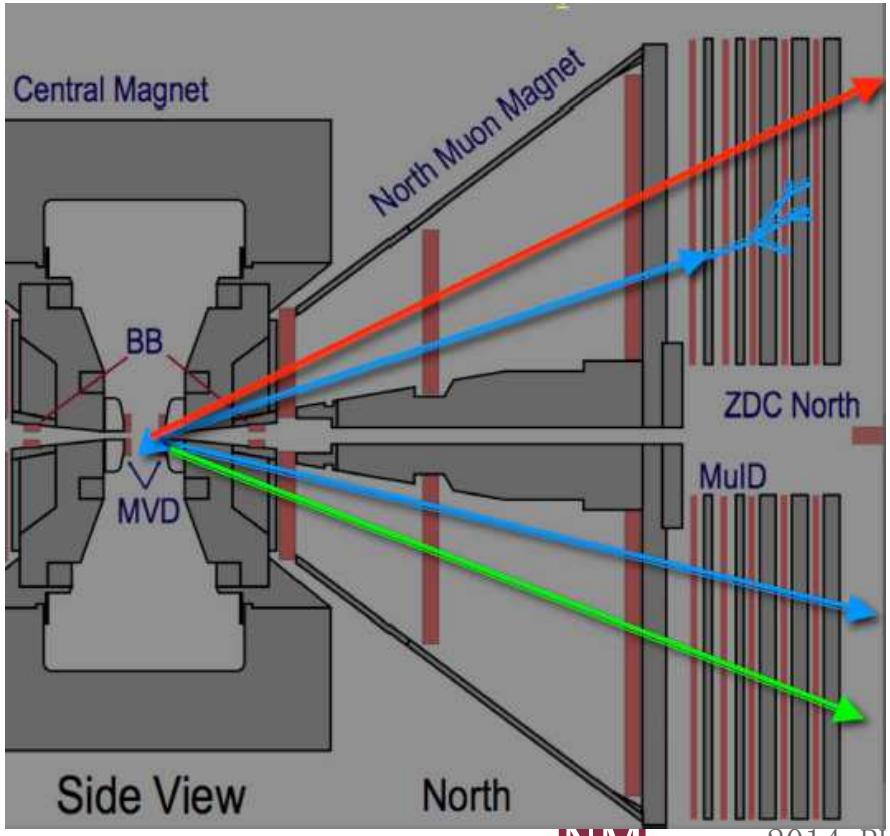
- Heavy Flavor (especially D meson) production is an idea tool to investigate gluon distribution.
- SSA in heavy flavor production revealed the tri-gluon correlations by using the twist-3 collinear factorization framework.
  - Z. Kang, J. Qiu, W. Vogelsang, F. Yuan, PRD78:114013 (2008)
  - Y. Koike, S. Yoshida PRD84:014026 (2011)

Measurement of Heavy flavor decay muon

Muon Spectrometer:

- $1.2<|\eta|<2.4$
- Azimuthal: $\Delta\Phi=2\pi$

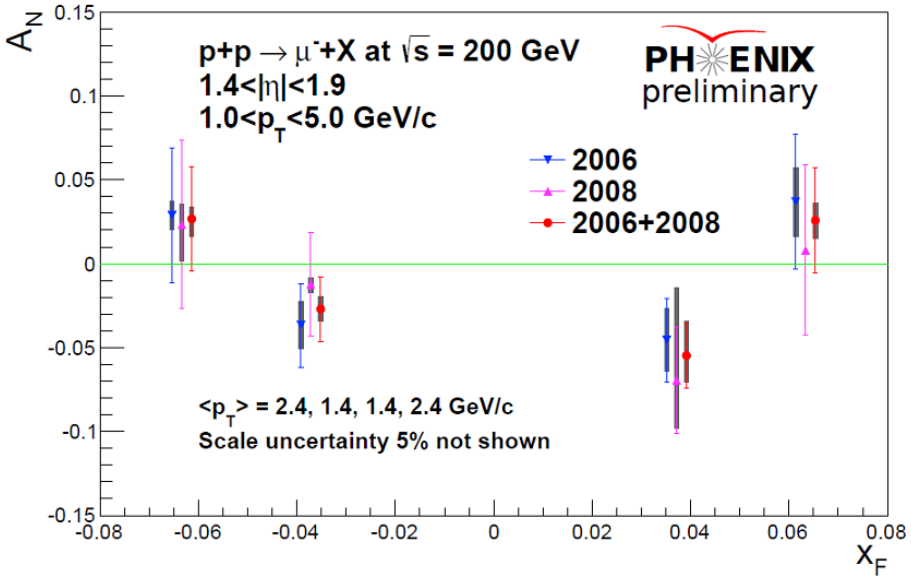
$$A_N^{Phys} = \frac{A_N^{Incl} - r \cdot A_N^{BG}}{1-r} \qquad r = \frac{N^{BG}}{N^{Incl}}$$



Inclusive Muons

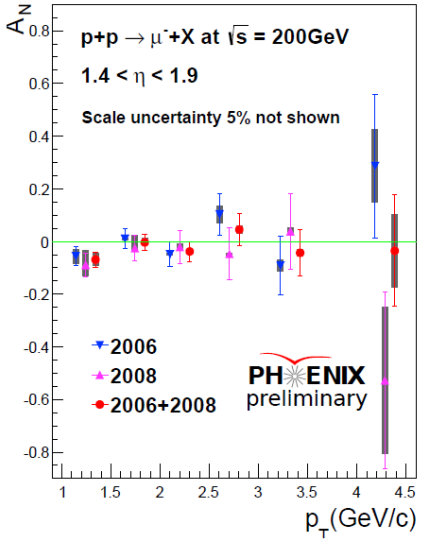
- Heavy Flavor decay muons
- Stopped hadrons → Distinguished background
- Non-distinguished background
- Punch-through hadrons
- Hadron decay muons

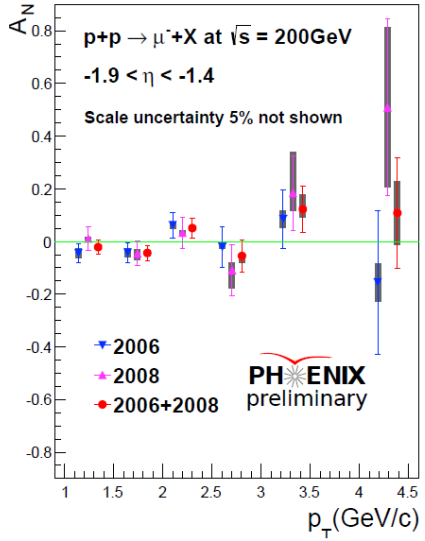
A_N of heavy flavor decay muon



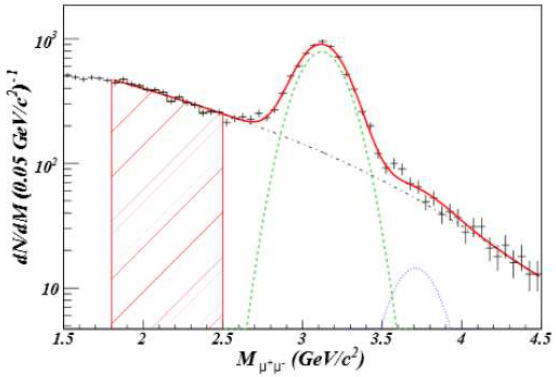
- Currently Measured A_N are consistent with zero.
- 2012 data analysis is very close to be finalized, which significantly constraints the statistical uncertainty in highest p_T bin within ~10%.

- New installed FVTX detector will be expected to provide better rejection on hadron background in 2015 transverse run





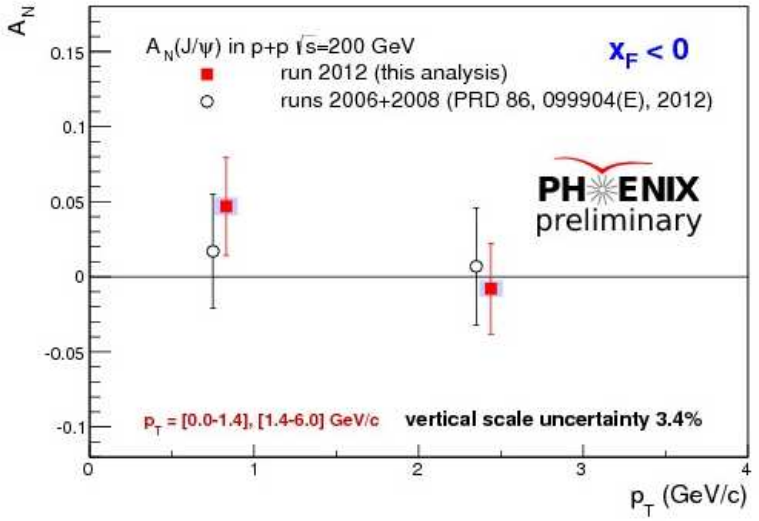
A_N of J/ψ

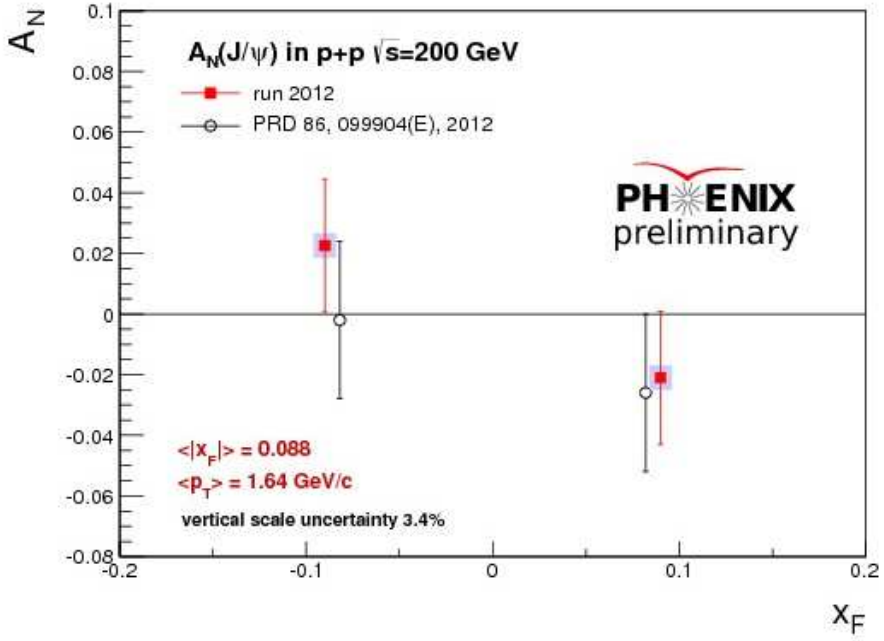


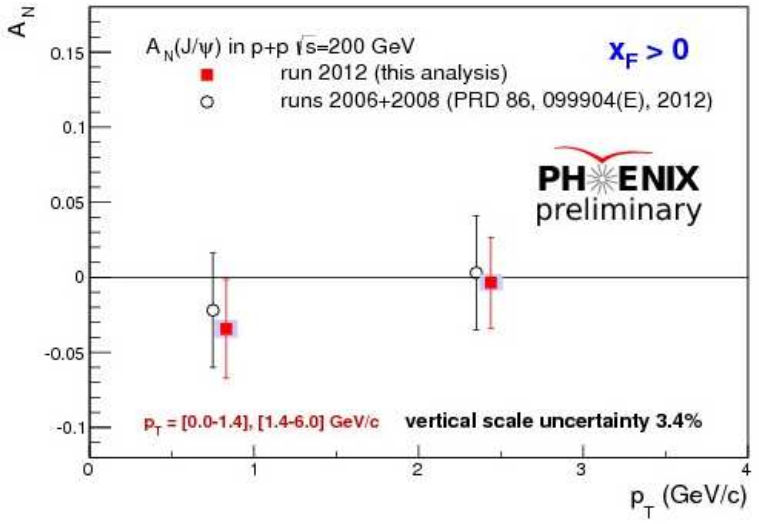
Test production mechanism

- Only color singlet generate SSA

The results are consistent with zero.

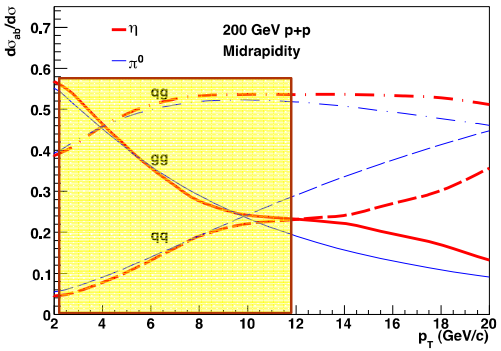


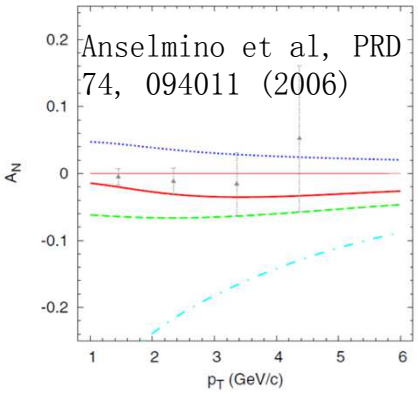


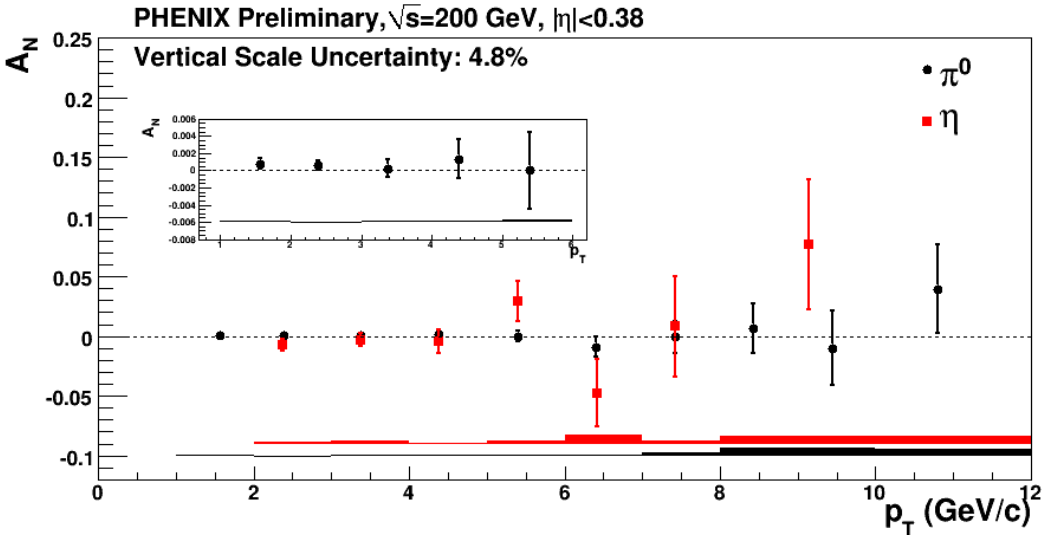


A_N of Mid-rapidity π^0 and η

- The π^0 and η production is sensitive to qg and gg process
- Improved a factor of 20 statistical uncertainties on the previous measurement and extend to higher p_T
  - Phys. Rev. Lett. 95, 202001 (2005)
- Includes η mesons
- Consistent with zero for both π^0 and η

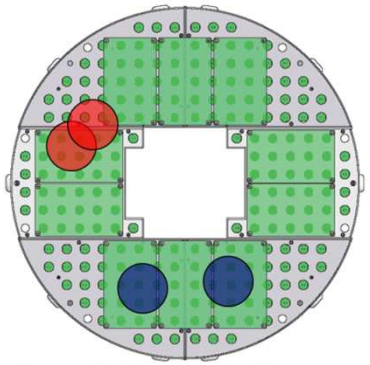






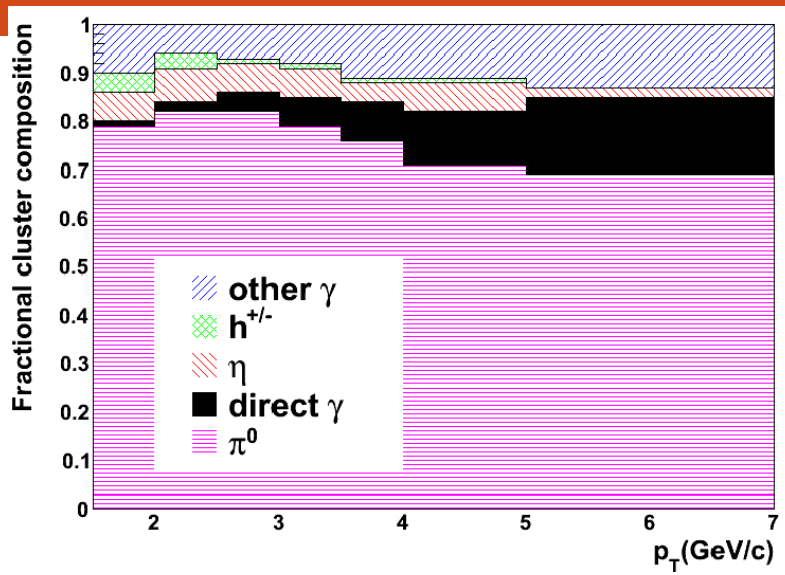
PPG135, Submitted to PRD arXiv:1312.1995

Forward A_N for MPC Clusters

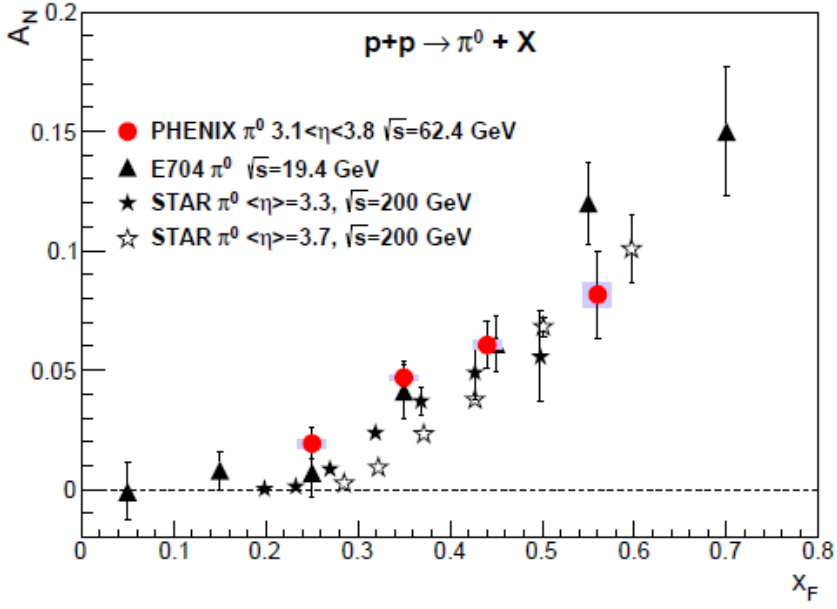


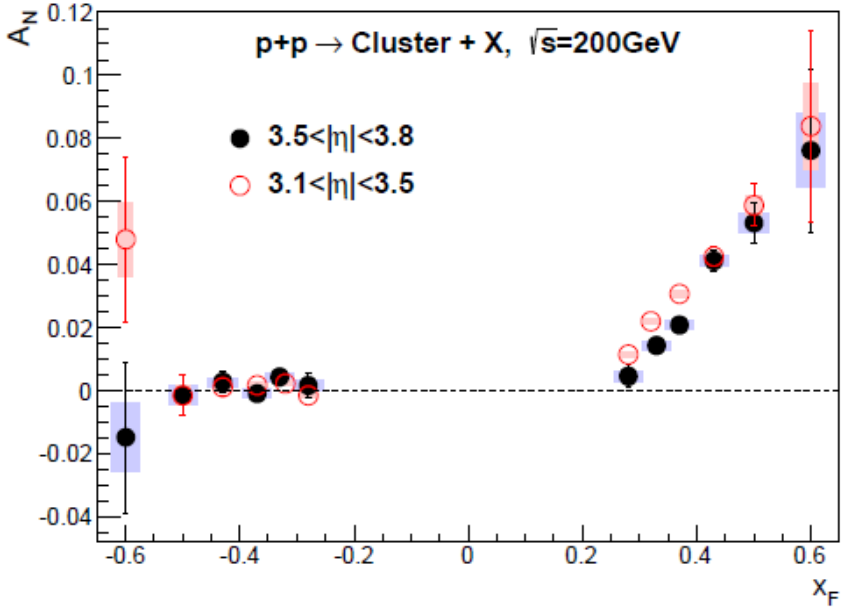
Decay photon impact positions
for low and high energy π^0's

Measurements
from MPC
$3.1<|\eta|<3.9$

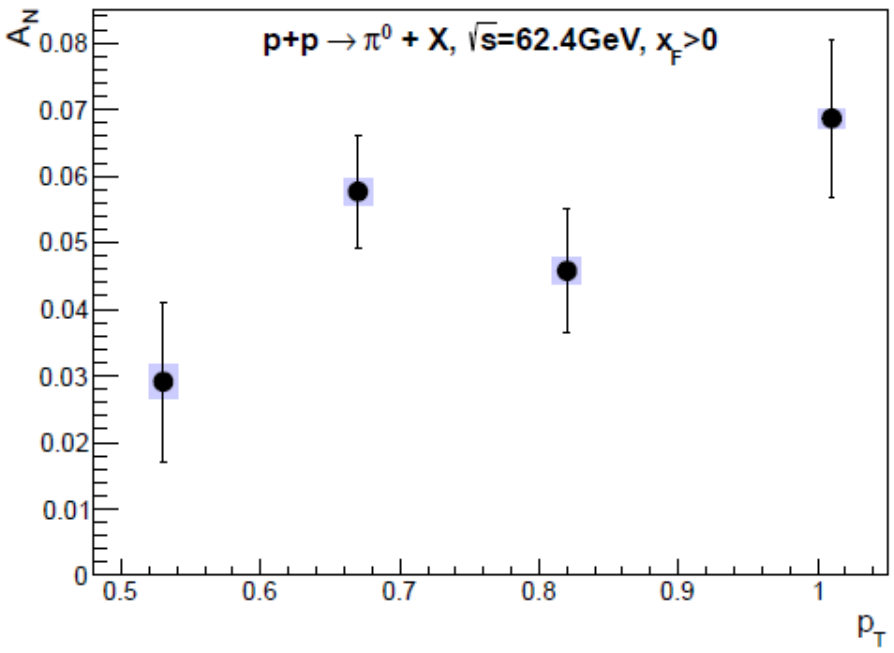


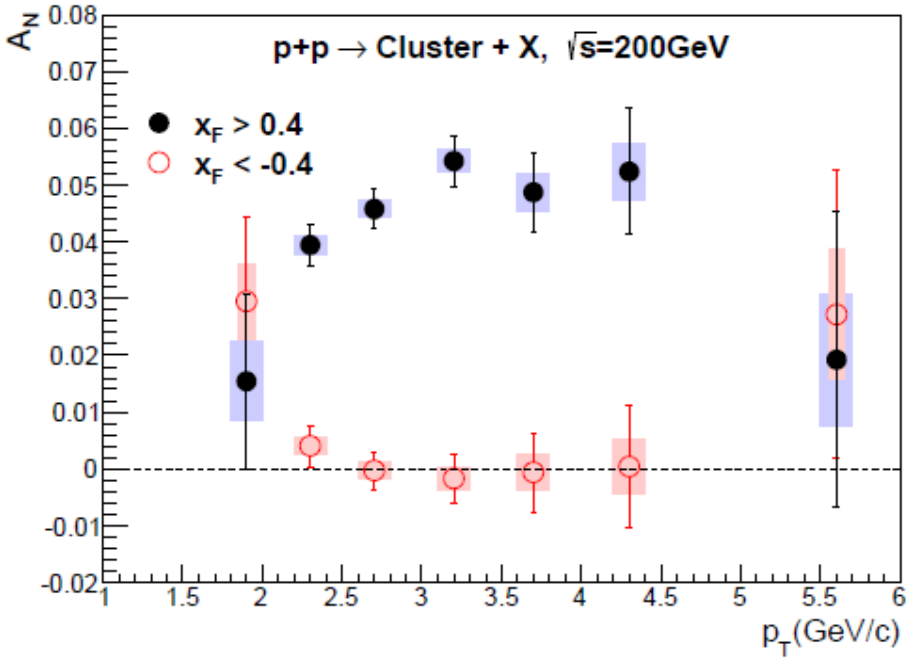
PPG135, Submitted to PRD arXiv:1312.1995





Forward A_N as a function of p_T

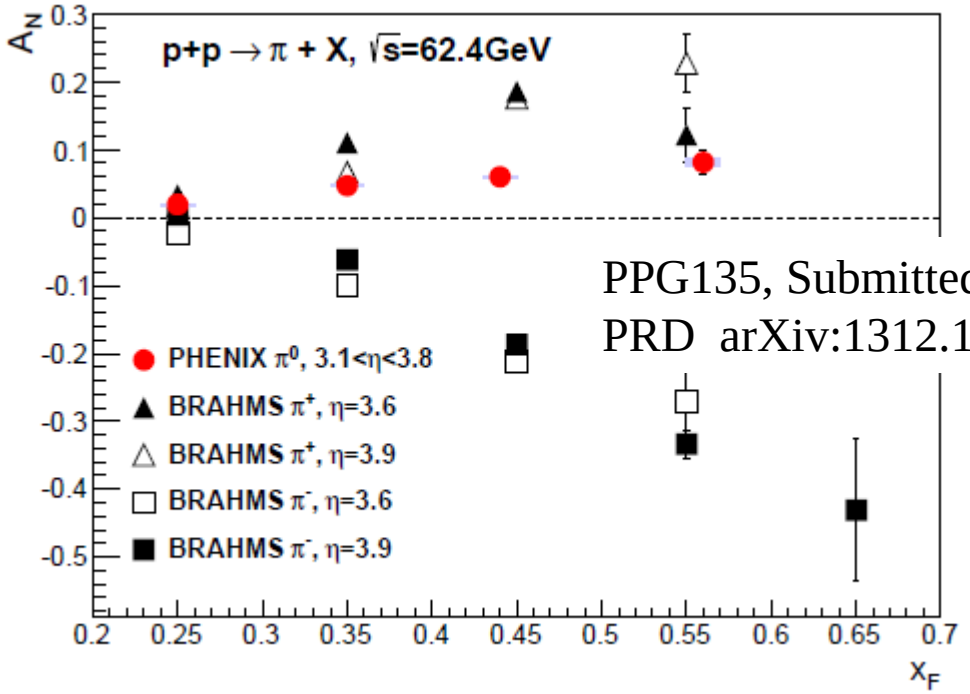




PPG135, Submitted to PRD arXiv:1312.1995

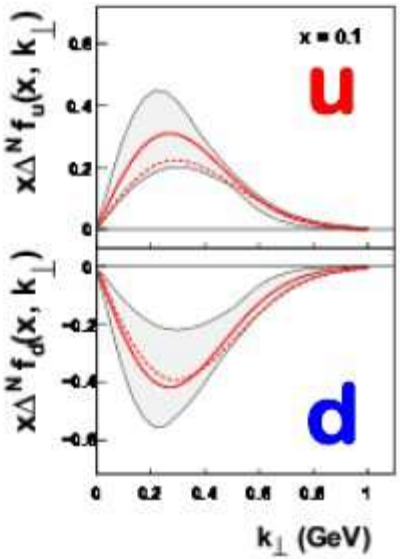
- **Rises and plateaus at high p_T**
- **Consistent with Twist-3 expectation**
  - Y. Koike etc. Phys.Rev. D85 (2012) 034030

Comparison to BRAHMS for MPC at 62.4GeV



PPG135, Submitted to PRD arXiv:1312.1995

Sivers



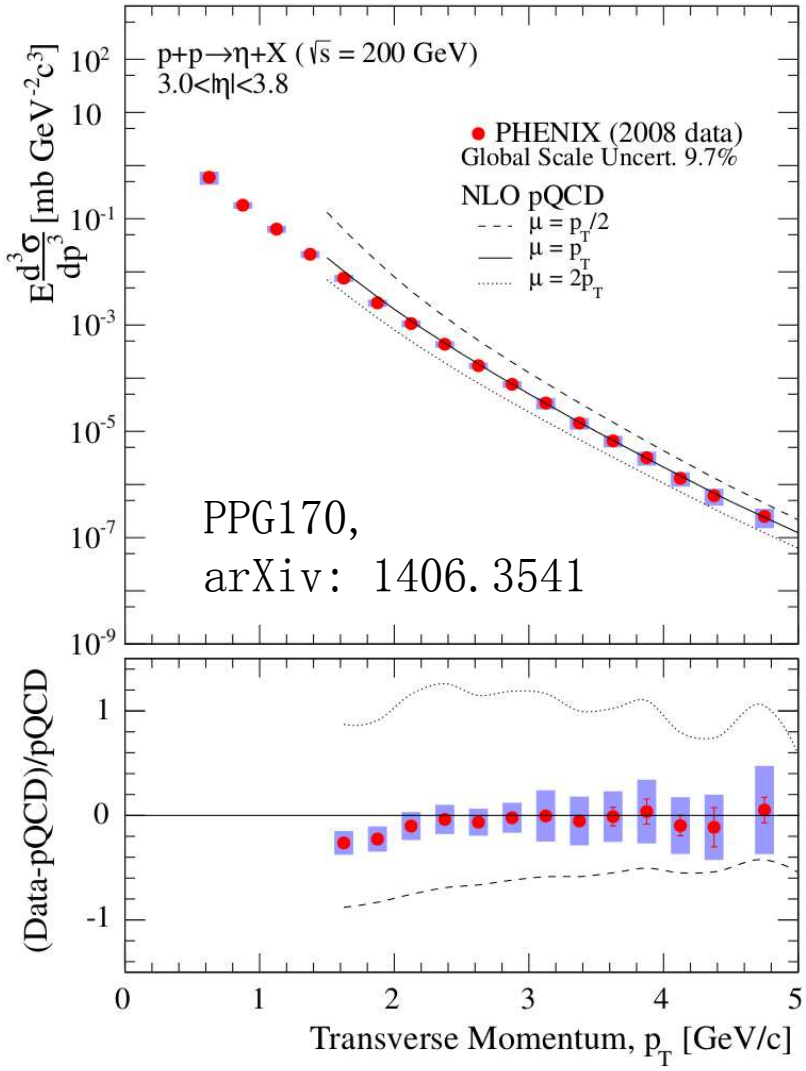
Pion FF studied in PYTHIA

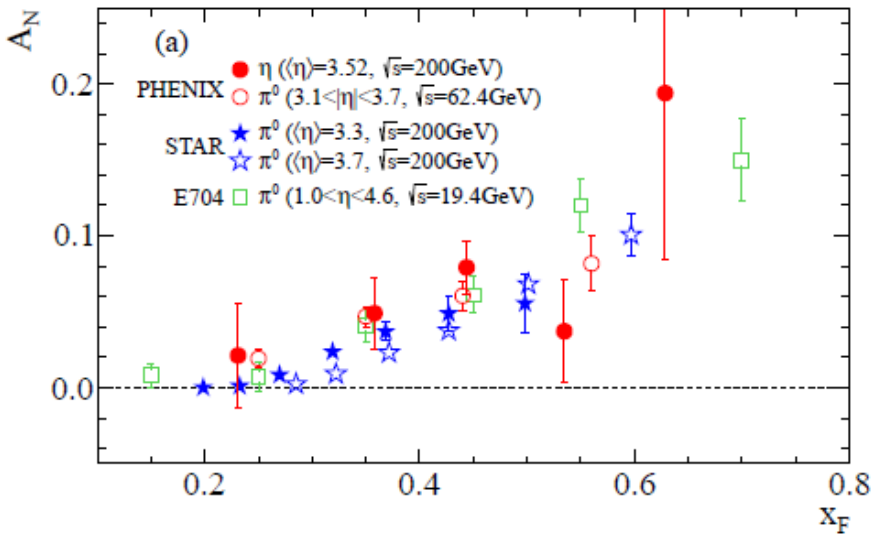
- $u \to \pi^+$, $d \to \pi^+$ (100/0)
- $u \to \pi^-$, $d \to \pi^-$ (50/50)
- $u \to \pi^0$, $d \to \pi^0$ (25/75)

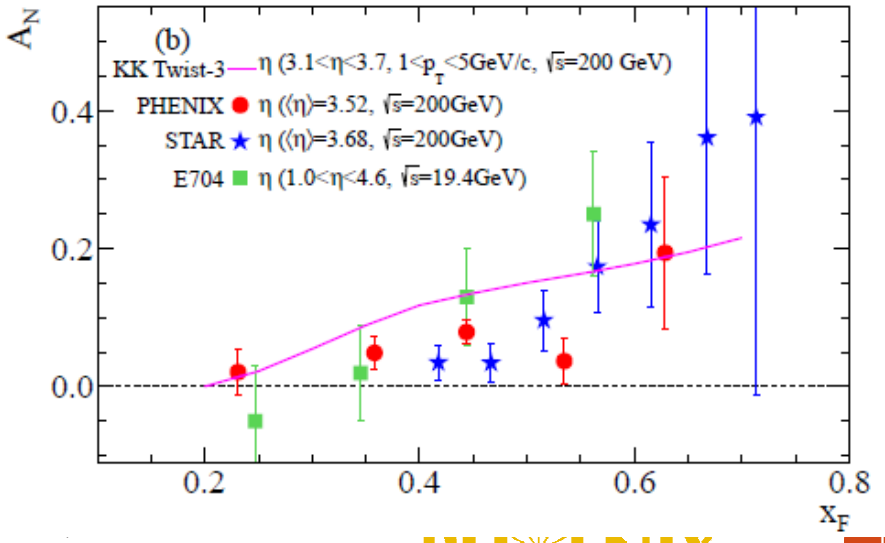
The Origin of A_N not explained by Sivers alone, assuming if

- PYTHIA holds
- u-d Sivers from SIDIS holds in $p^\uparrow + p \to \pi + X$

Forward A_N for η mesons







Interference Fragmentation

Interference Fragmentation Function (H_1):

Fragmentation of a transversely polarized quark q into two spin-less hadron h1, h2 carries an azimuthal dependence

$$d\sigma_{UT} = 2|P_{C\perp}||S_{BT}|\sin(\varphi_S - \varphi_R)\sum_{a,b,c,d}\int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

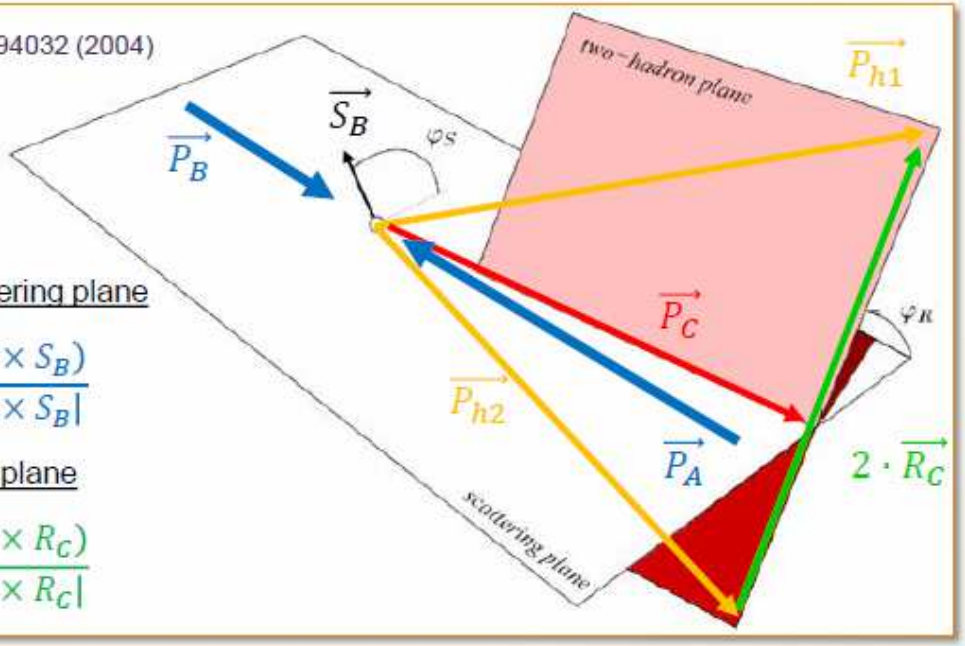
$$A_{UT} = \frac{\sigma_{UT}}{\sigma_{UU}} \longrightarrow d\sigma_{UU} = 2|P_{C\perp}|\sum_{a,b,c,d}\int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a) f_z^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,00}(\bar{z}_c, M_C^2)$$

Transversity

$\otimes$

IFF

A. Bacchetta, M. Radici, PRD 70, 094032 (2004)



from polarization vector to scattering plane

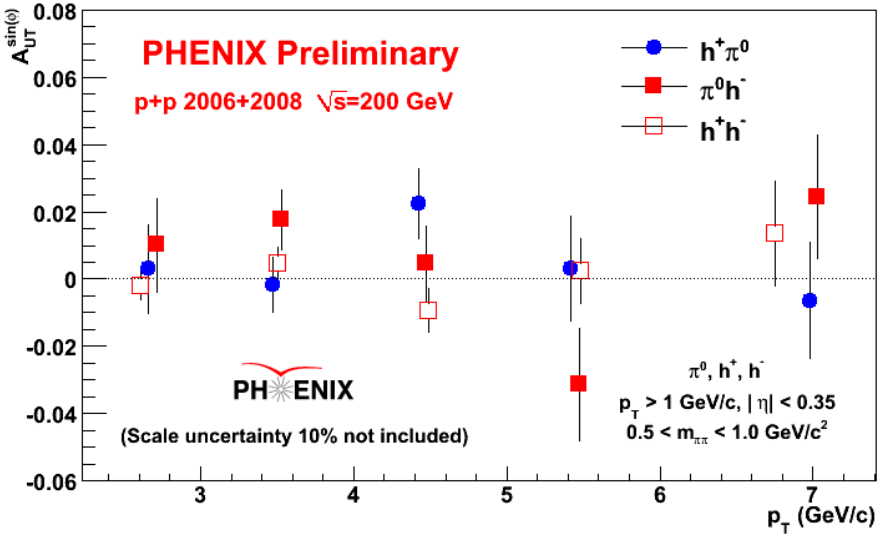
$$\cos\varphi_S = \frac{(P_B \times P_C)}{|P_B \times P_C|}\cdot\frac{(P_B \times S_B)}{|P_B \times S_B|}$$

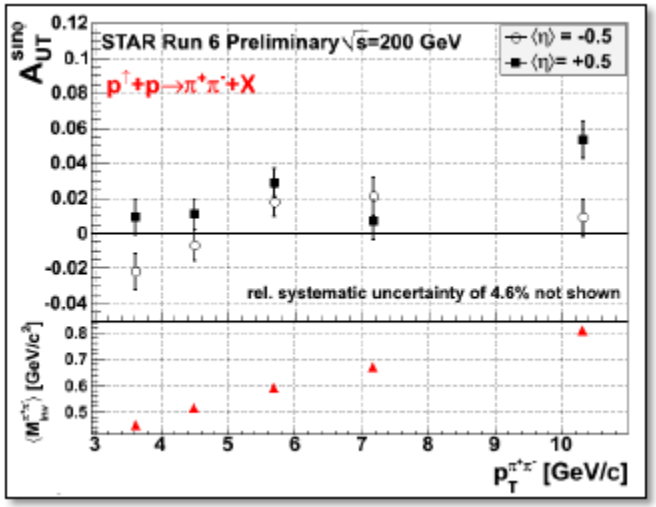
from scattering plane to hadron plane

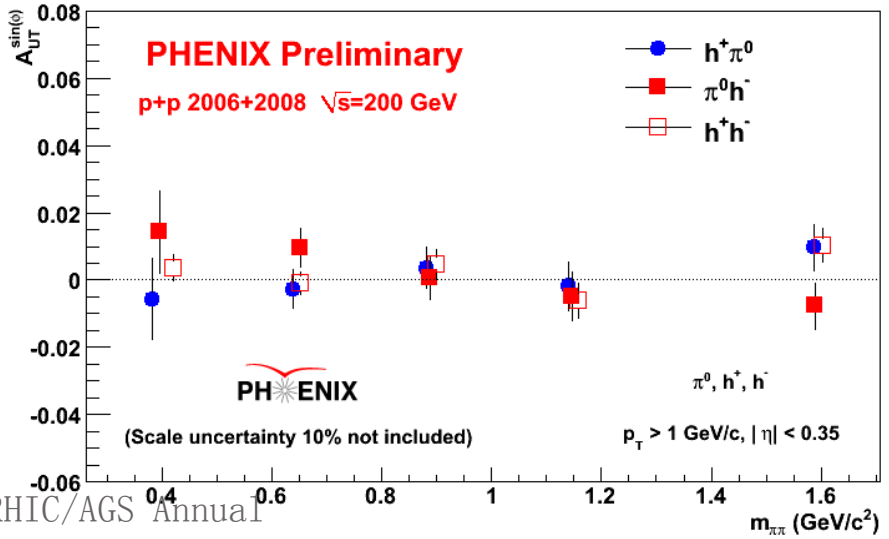
$$\cos\varphi_R = \frac{(P_C \times P_A)}{|P_C \times P_A|}\cdot\frac{(P_C \times R_C)}{|P_C \times R_C|}$$

Mid-Rapidity IFF Measurement

- PHENIX measurements in 2006 and 2008 have seen non-zero asymmetries.
- STAR has also seen non-zero asymmetries
- Move to more forward, MPC-ex upgrade in 2015





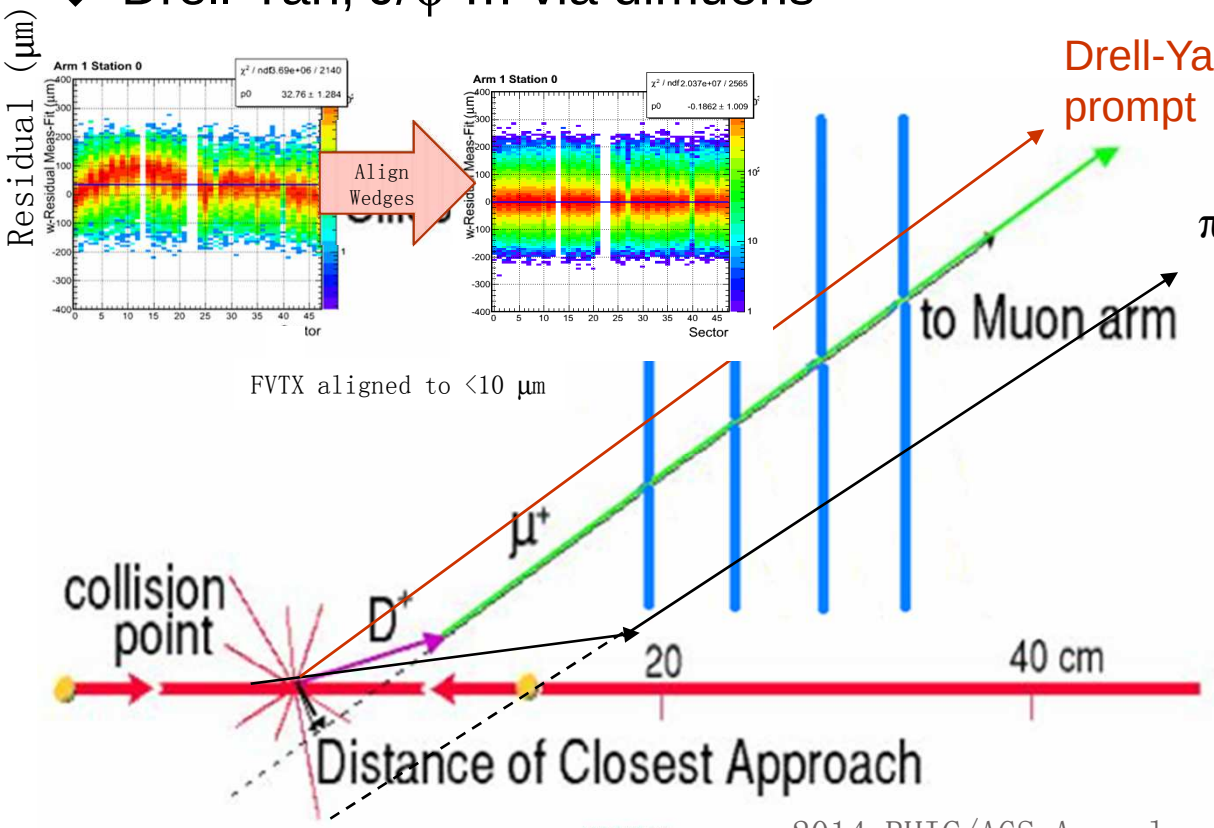


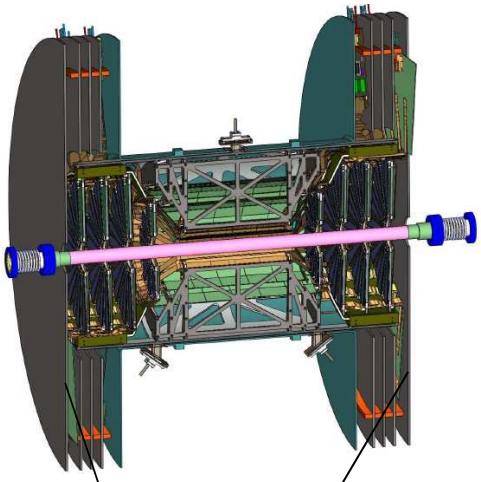
PHENIX Opportunities with New Detectors

FVTX installed in 2012

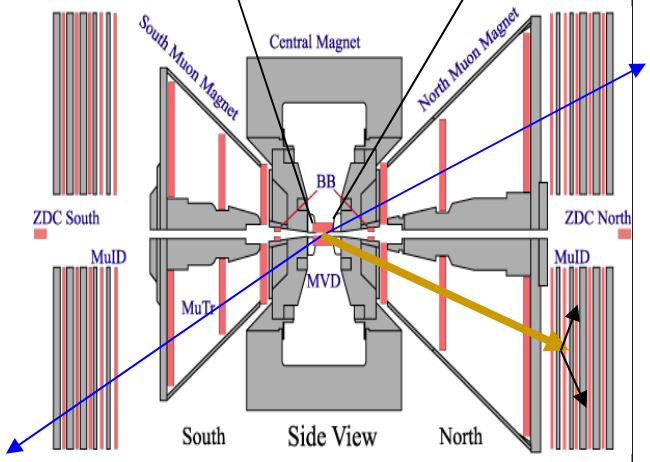
4 layers of FVTX end-caps cover
1.2<|η|<2.4 with resolution ~100um.

- Precise Charm/Beauty, W/Z Measurements
- Drell-Yan, J/ψ … via dimuons



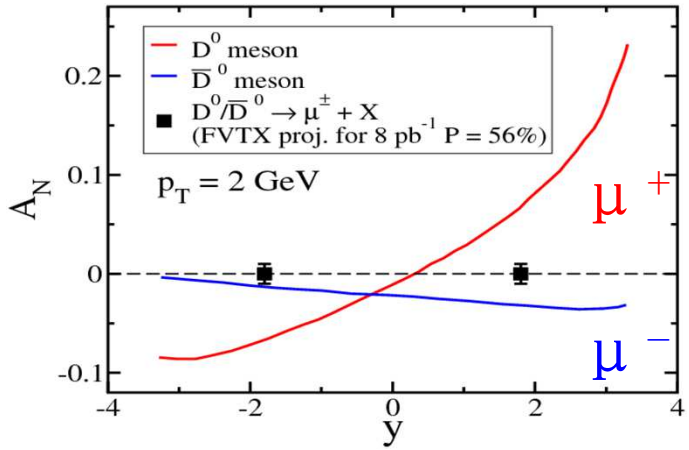


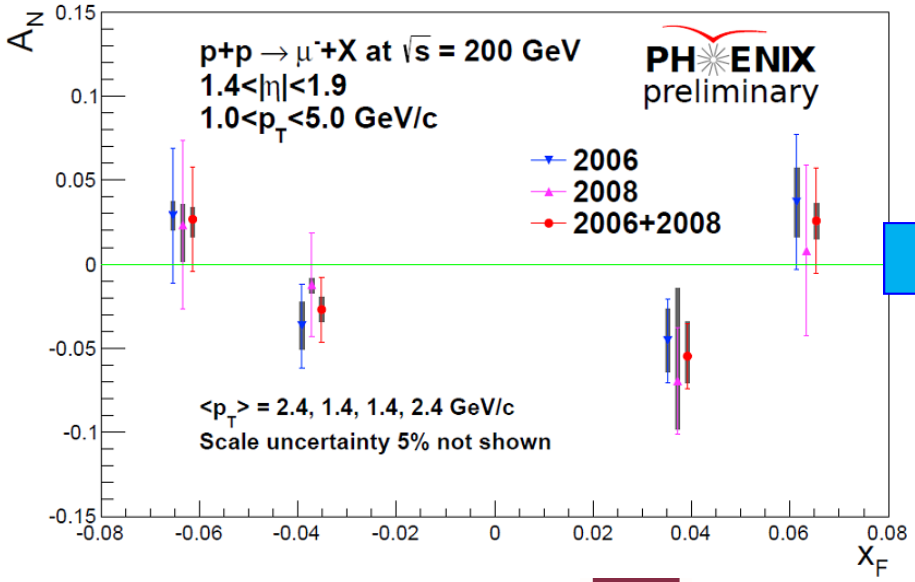
π→μ



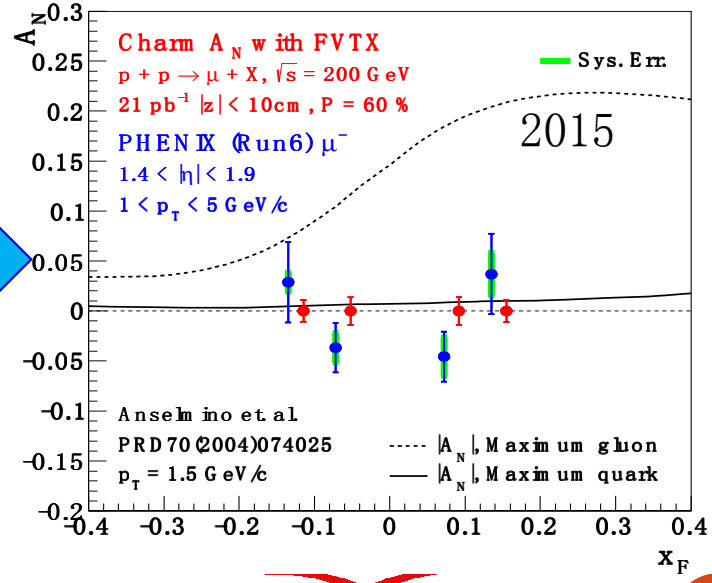
Projected Open Charm A_N with FVTX

- Significant rejection of hadron background
- Limited power on D/B separation
- Transverse spin data expected from 2015



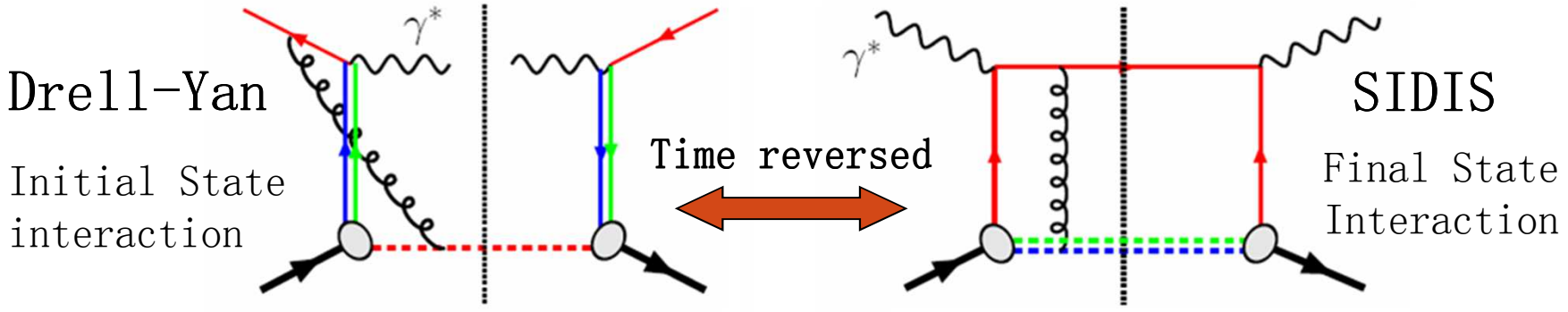


FVTX



Drell-Yan Process

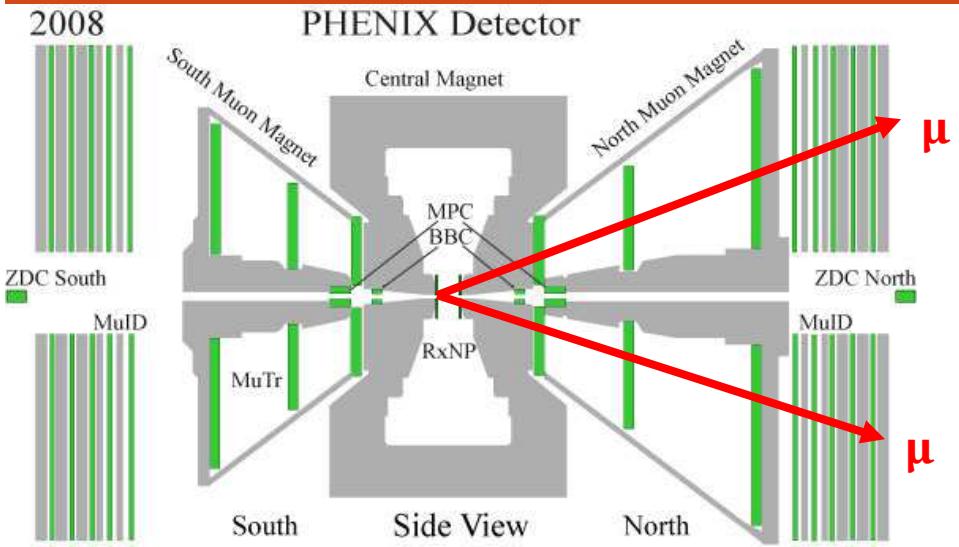
- No fragmentation (no Collins effect folded)
- TMD factorization is valid
- The Sivers function in DY is opposite to that in DIS which can test current SSA QCD mechanisms (TMD & Twist-3)
- A_{TT} in Drell-Yan is sensitive to transversity!

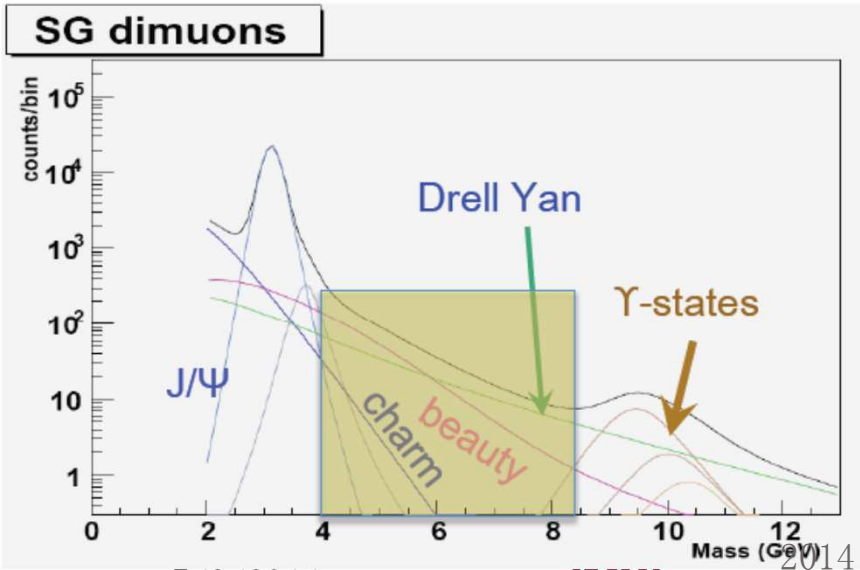


$$p + p \rightarrow l^+ + l^- + X \qquad l + p \rightarrow l + \pi + X$$

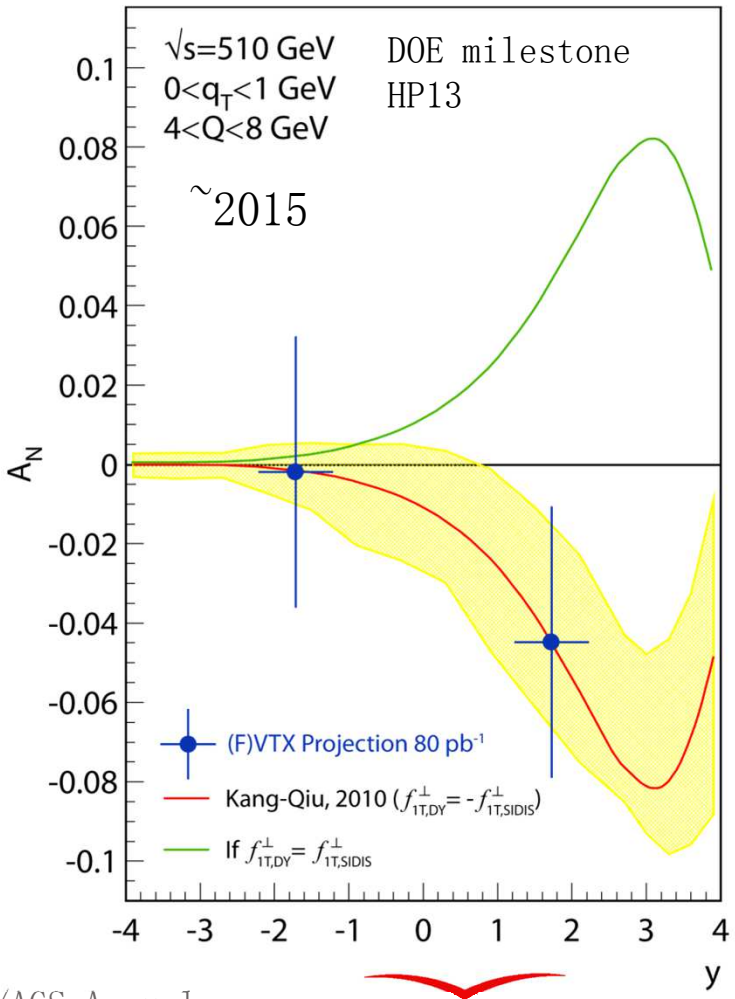
$$\Delta f_{1T}^{\perp}(x, \vec{k}_T^{\,2})\,|_{\text{Drell-Yan}} = -\Delta f_{1T}^{\perp}(x, \vec{k}_T^{\,2})\,|_{\text{SIDIS}}$$

Drell-Yan Projection

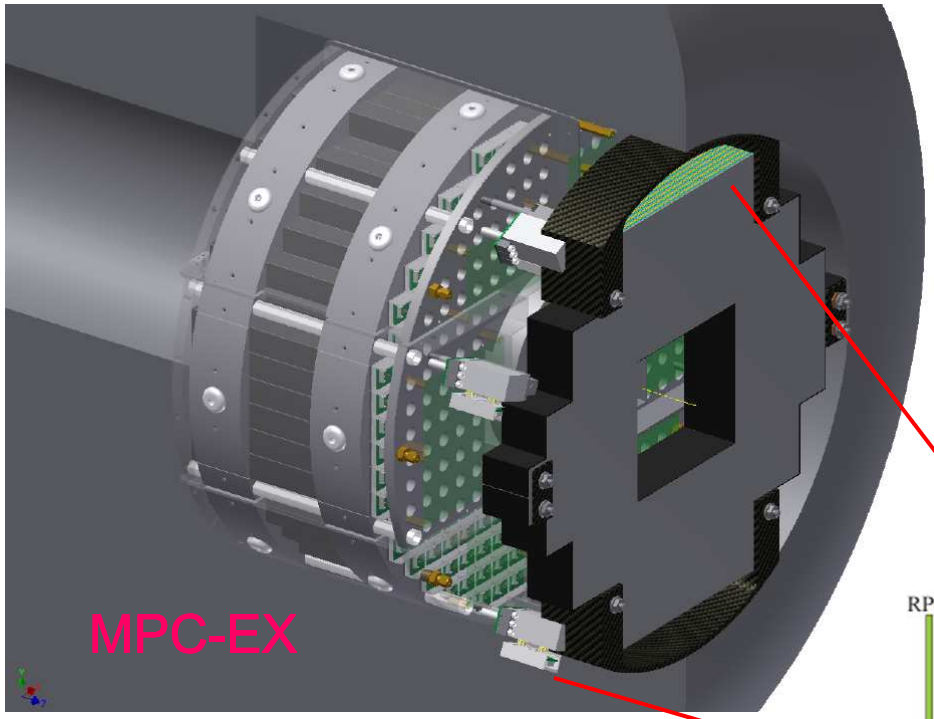


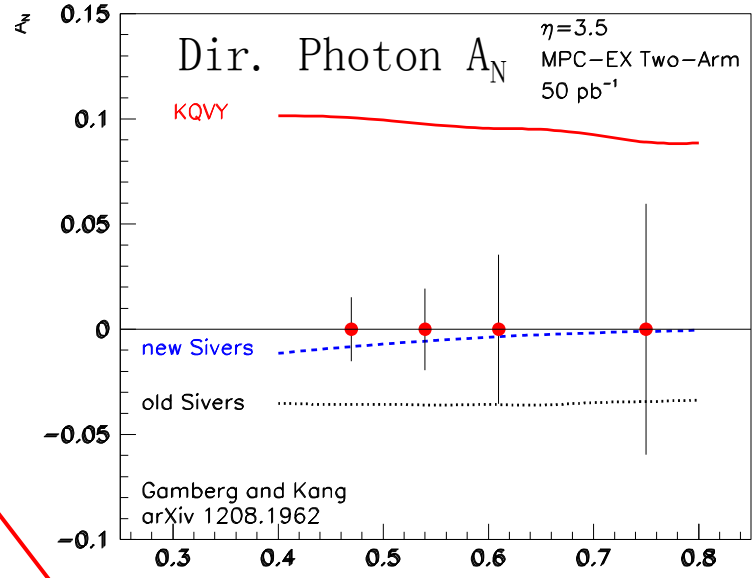


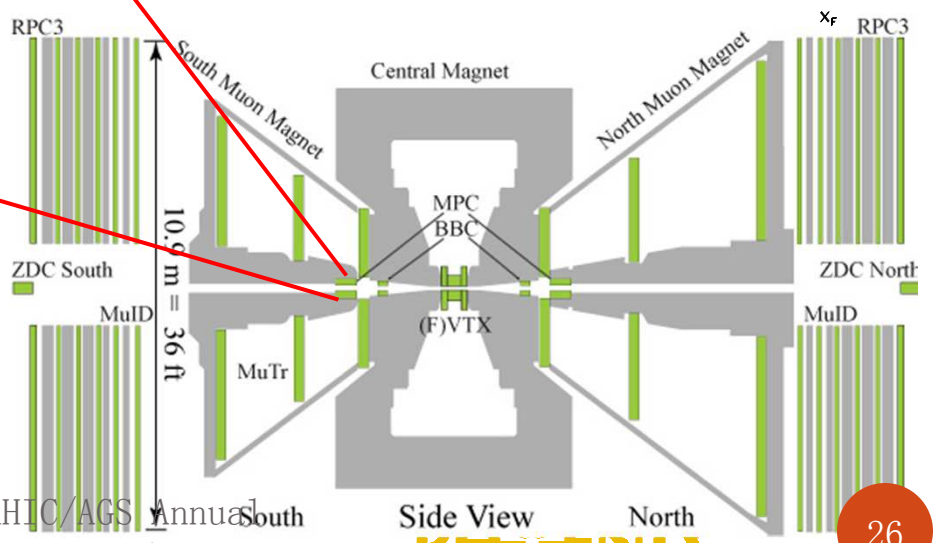
RHIC 1-year running projection



Coming soon: MPC-EX (2015+)







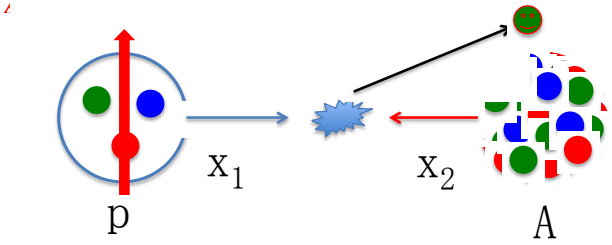
A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

$3.1<|\eta|<3.9$

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

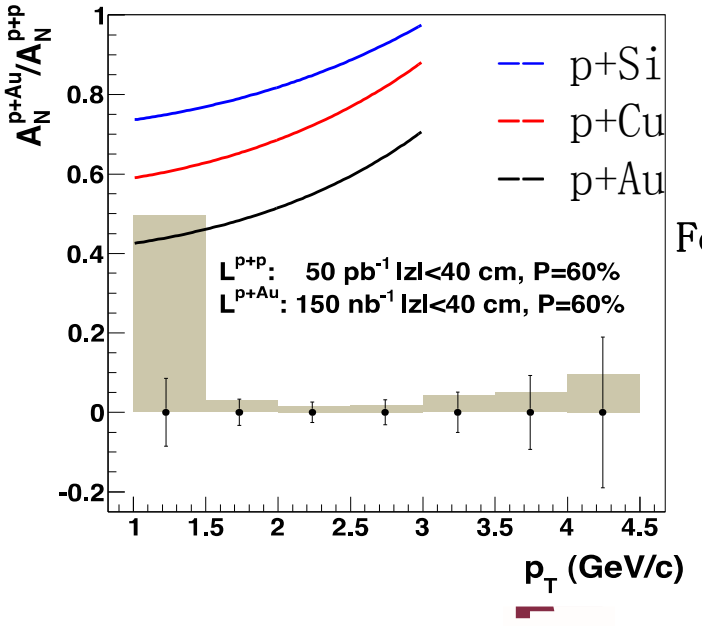
Polarized p+A at RHIC(2015+)

- 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



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

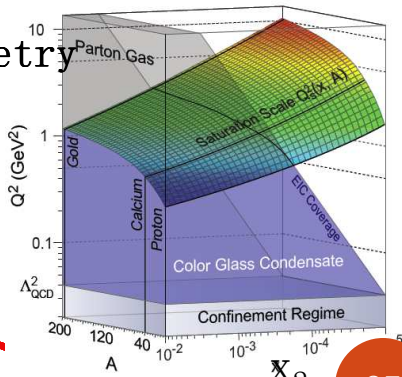
target: $x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$ gluon



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

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)

Summary and Outlook

- **PHENIX has measured A_N in heavy flavor production**
  - Statistics is still limited and 2012 data will be included
  - Previous A_N of J/ψ was published and consistent with 2012 data
- **A_N of π^0 and η at mid- and forward rapidity was measured**
  - Current results prepare to be published
  - Expected much improved measurements with MPC-ex
- **A_N from Interference Fragmentation was measured**
  - Expect 2012 result soon with more forward measurement
- **Forward measurements with FVTX**
  - Expect significant background projection in heavy flavor production
  - Drell-Yan measurement becomes possible
- **More opportunities with polarized p+A experiments in future**

Universidade de São Paulo, Instituto de Física, Caixa Postal 66318, São Paulo CEP05315-970, Brazil
Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
China Institute of Atomic Energy (CIAE), Beijing, People's Republic of China
Peking University, Beijing, People's Republic of China
Charles University, Ovocnytrh 5, Praha 1, 116 36, Prague, Czech Republic
Czech Technical University, Zikova 4, 166 36 Prague 6, Czech Republic
Institute of Physics, Academy of Sciences of the Czech Republic, Na Slovance 2, 182 21 Prague 8, Czech Republic
Helsinki Institute of Physics and University of Jyväskylä, P.O.Box 35, FI-40014 Jyväskylä, Finland
Dapnia, CEA Saclay, F-91191, Gif-sur-Yvette, France
Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS-IN2P3, Route de Saclay, F-91128, Palaiseau, France
Laboratoire de Physique Corpusculaire (LPC), Université Blaise Pascal, CNRS-IN2P3, Clermont-Fd, 63177 Aubiere Cedex, France
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, BP1, F-91406, Orsay, France
Debrecen University, H-4010 Debrecen, Egyetem tér 1, Hungary
ELTE, Eötvös Loránd University, H - 1117 Budapest, Pázmány P. s. 1/A, Hungary
KFKI Research Institute for Particle and Nuclear Physics of the Hungarian Academy of Sciences (MTA KFKI RMKI), H-1525 Budapest 114, POBox 49, Budapest, Hungary
Department of Physics, Banaras Hindu University, Varanasi 221005, India
Bhabha Atomic Research Centre, Bombay 400 085, India
Weizmann Institute, Rehovot 76100, Israel
Center for Nuclear Study, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
Hiroshima University, Kagamiyama, Higashi-Hiroshima 739-8526, Japan
KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan
Kyoto University, Kyoto 606-8502, Japan
Nagasaki Institute of Applied Science, Nagasaki-shi, Nagasaki 851-0193, Japan
RIKEN, The Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan
Physics Department, Rikkyo University, 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan
Department of Physics, Tokyo Institute of Technology, Oh-okayama, Meguro, Tokyo 152-8551, Japan
Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki 305, Japan
Chonbuk National University, Jeonju, Korea
Ewha Womans University, Seoul 120-750, Korea
Hanyang University, Seoul 133-792, Korea
KAERI, Cyclotron Application Laboratory, Seoul, South Korea
Korea University, Seoul, 136-701, Korea
Myongji University, Yongin, Kyonggido 449-728, Korea
Department of Physocs and Astronomy, Seoul National University, Seoul, South Korea
Yonsei University, IPAP, Seoul 120-749, Korea
IHEP Protvino, State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, 142281, Russia
INR_RAS, Institute for Nuclear Research of the Russian Academy of Sciences, prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia
Russian Research Center "Kurchatov Institute", Moscow, Russia
PNPI, Petersburg Nuclear Physics Institute, Gatchina, Leningrad region, 188300, Russia
Saint Petersburg State Polytechnic University, St. Petersburg, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Vorob'evy Gory, Moscow 119992, Russia
Department of Physics, Lund University, Box 118, SE-221 00 Lund, Sweden

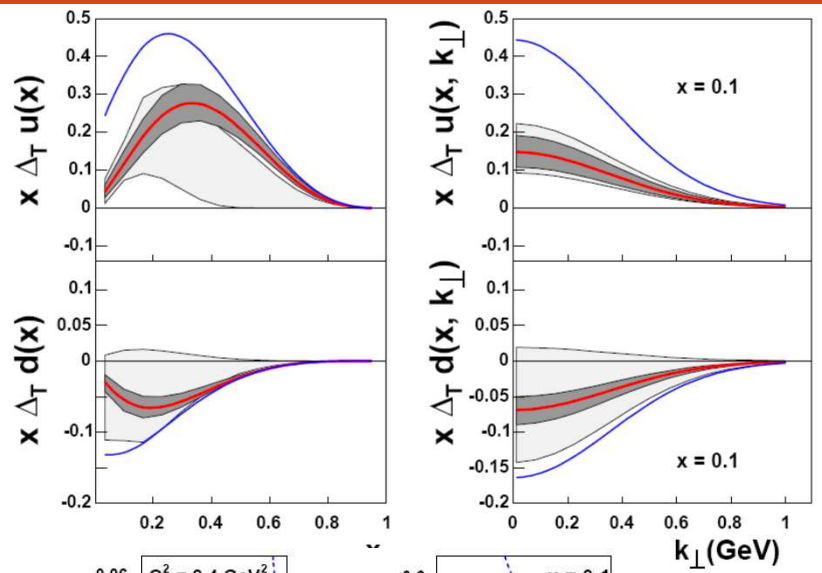
PHENIX 13 Countries; 70 Institutions

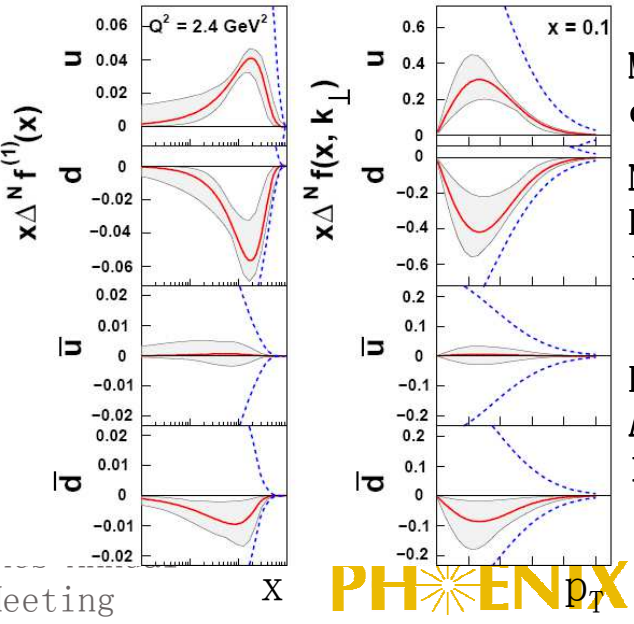
Thanks

Back up

Spin in transversely polarized proton

- Quark transversity
  - Know much better about quark transversity than before.
- Gluon transversity
  - No transversely polarized gluon.
- Parton orbital angular momentum
  - The Sivers function could be related to orbital angular momentum.
  - Quark Sivers function is constrained OK.
  - Gluon Sivers function is not well known.





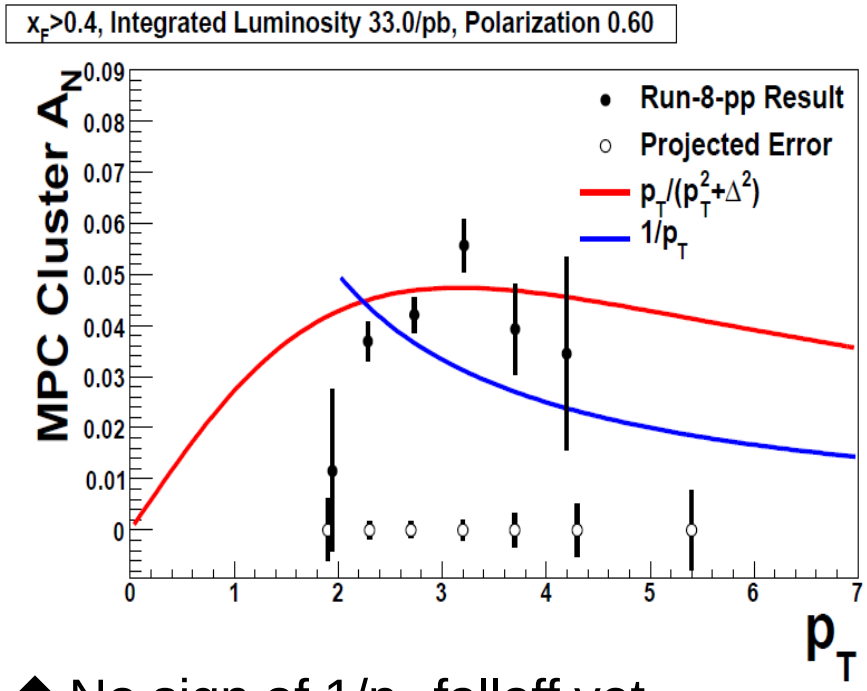
M. Anselmino et. al.

Nucl. Phys. Proc. Suppl. 191, 98 (2009).

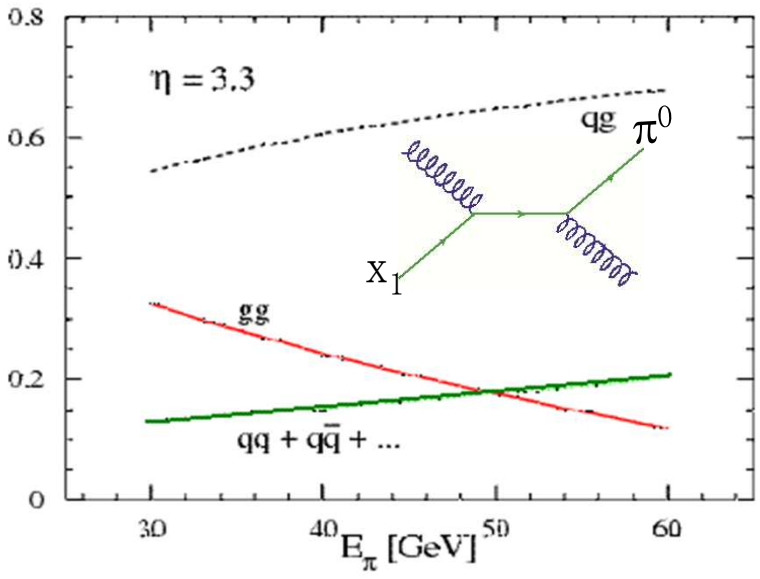
Eur. Phys. J. A39:89-100, 2009

Forward A_N Challenge: p_T Dependence

Valence Quarks' Sivers-like or Collins effects?



Sub-process fractions p+p 200GeV



- No sign of $1/p_T$ falloff yet.
  - Collins?
  - Twist-3 p_T dependent not trivial
- Much improved with MPC-EX (2015+)

$$A_N \sim \frac{1}{Q} \quad @twist-3$$ Y. Koike, 2012

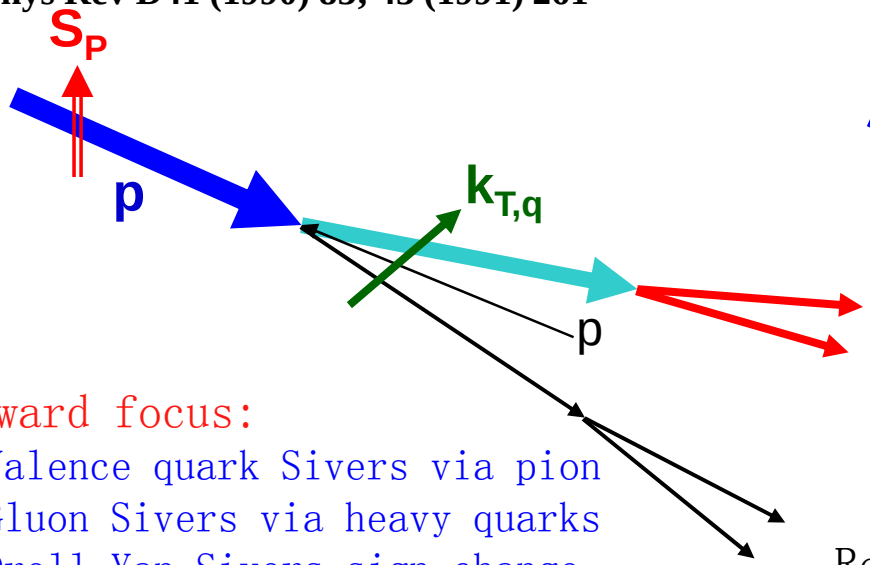
$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

Possible Mechanisms for A_N

- 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

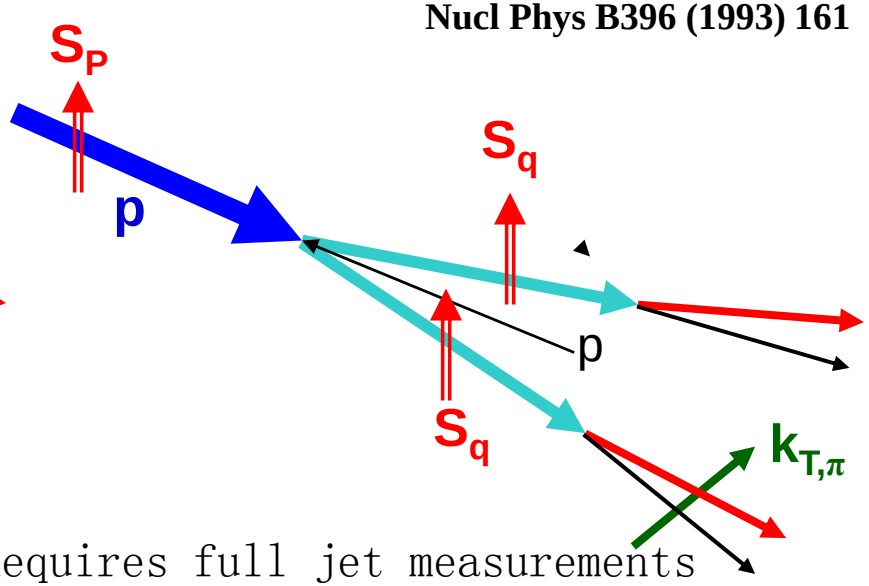


Forward focus:
- Valence quark Sivers via pion
- Gluon Sivers via heavy quarks
- Drell-Yan Sivers sign change

Orbital Angular Momentum?

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

Nucl Phys B396 (1993) 161

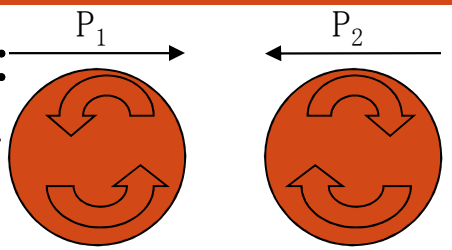


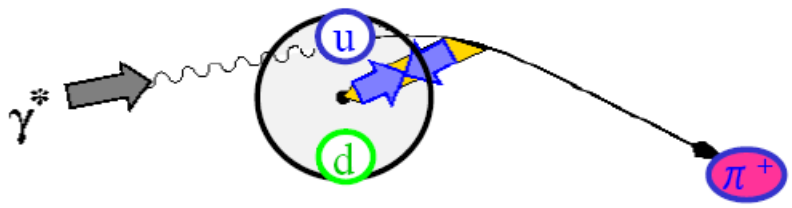
Requires full jet measurements
- forward s/ePHENIX upgrade

Semi-classical Interpretation

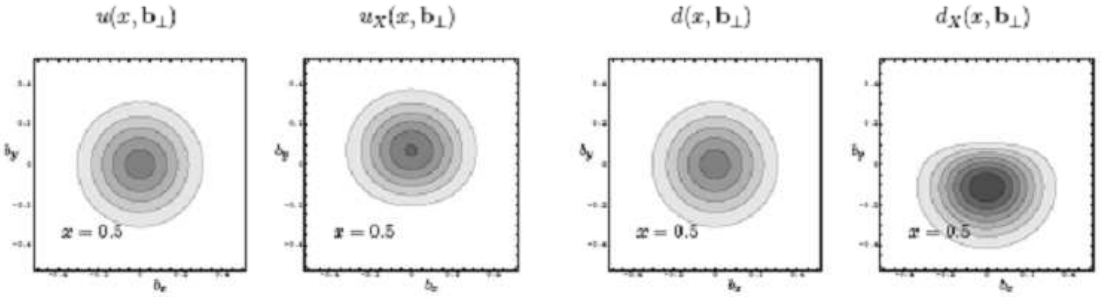
Two Possibilities:

1. Nuclear Shadowing (angular momentum)

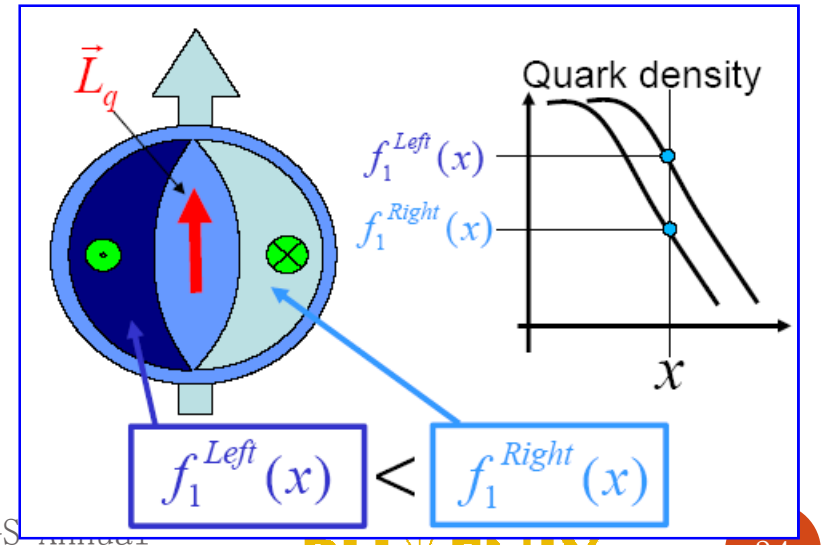




2. Impact Parameter Space Changes with polarization



- Attractive rescattering of hit quark by gluon creates transverse momentum
- M.Burkardt [hep-ph0309269] – impact parameter formalism
- Orbital angular momentum at finite impact parameter
- Observed and true x differ
- Observable left/right asymmetry



Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation functions

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right) \frac{1}{\tilde{u}}$$
$$\times \left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x}\right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x}\right) \hat{\sigma}^{N1}\right].$$

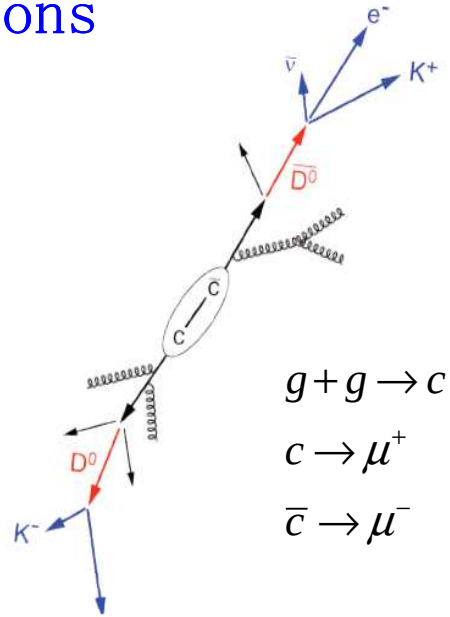
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

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

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

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

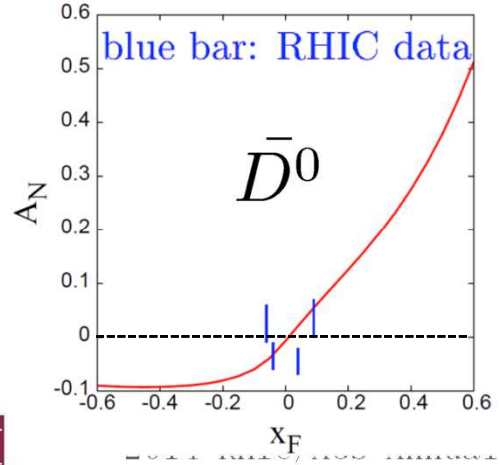
Koike *et. al.* (2011)
Kang, Qiu, Vogelsang, Yuan (2008)

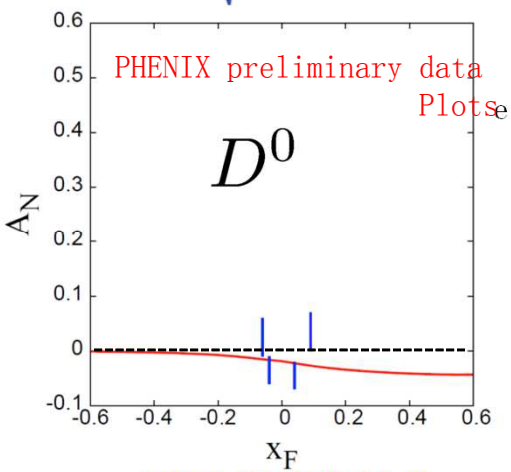


$g + g \to c + \bar{c}$

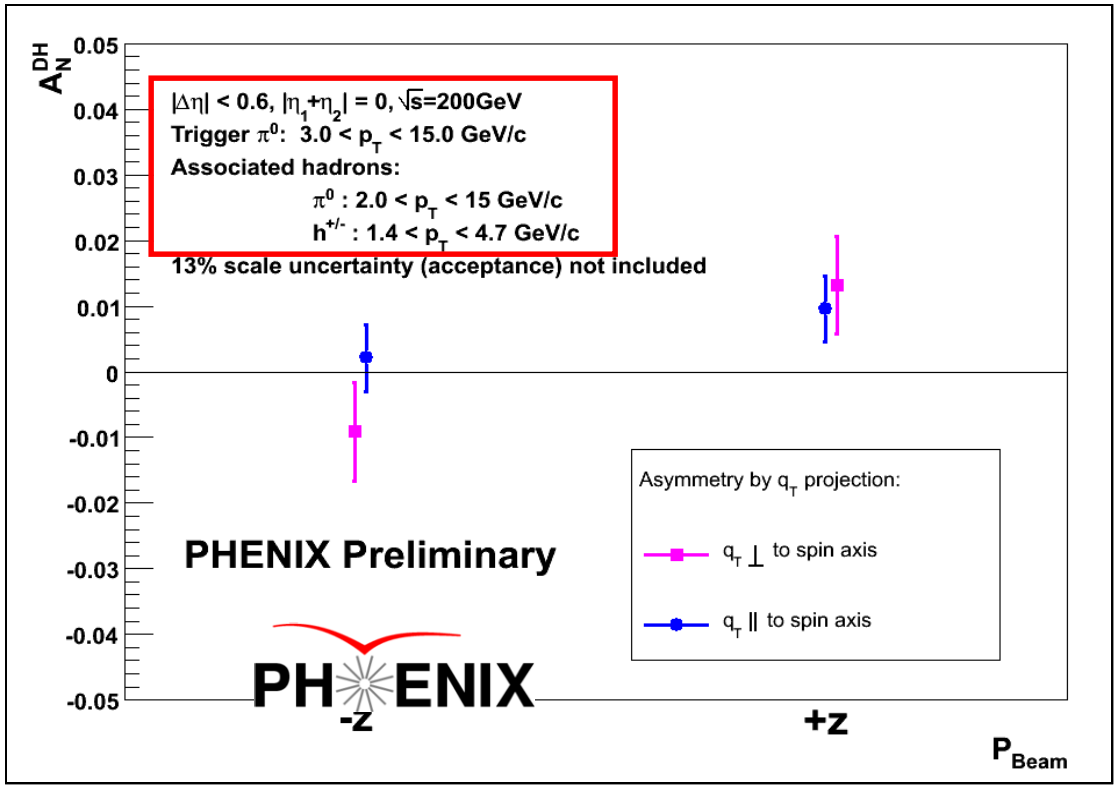
$c \to \mu^+$

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





A_N for Di-hadron



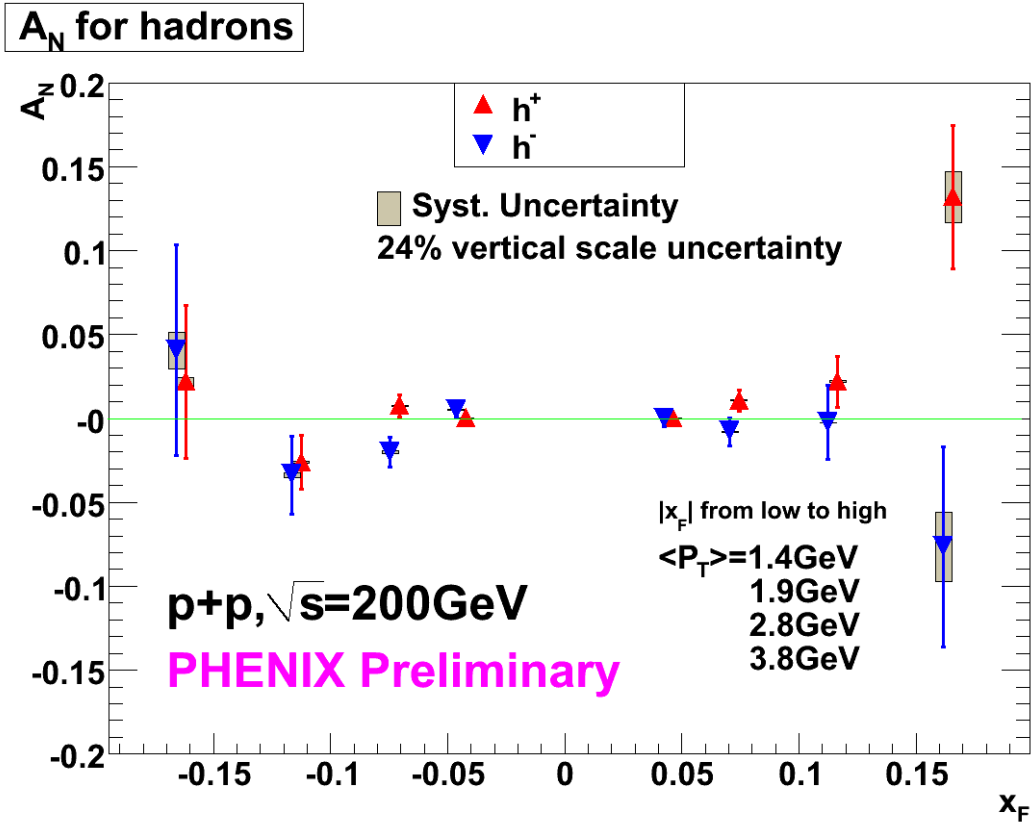
- Sivers asymmetry ($q_T\perp$)
- No asymmetry expected for $q_T\parallel$
- Improved statistics for 2008 data set!

TMD is not valid for back to back di-hadron process in p+p collision

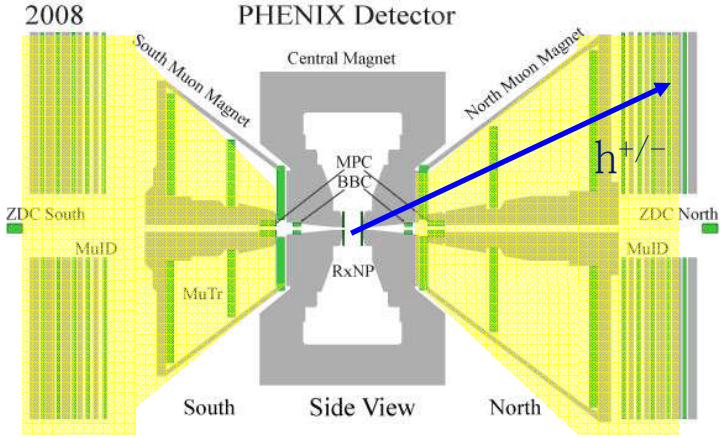
Similar analysis possible in different combinations of rapidity

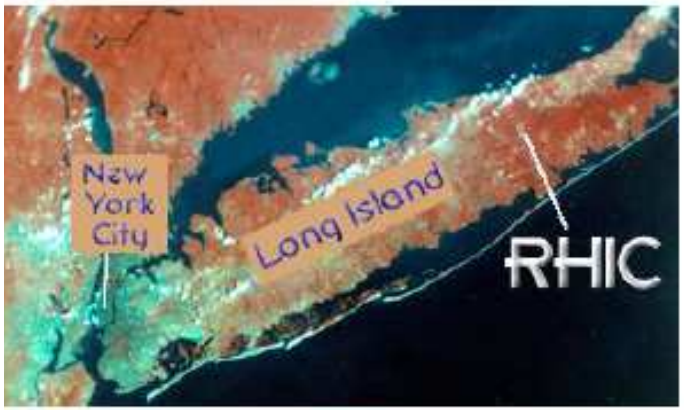
η_{min}	-3.7	-2.4	-0.35	1.2	3.1
η_{max}	-3.1	-1.2	+0.35	2.4	3.9

Forward A_N for Charged Hadrons



- Measured at Muon Arms $1.2<|\eta|<2.4$
- No PID - Unidentified charge hadrons





The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory