Transverse Spin Measurements at PHENIX

- **Motivation**
- **Measurements**
- **Outlook**

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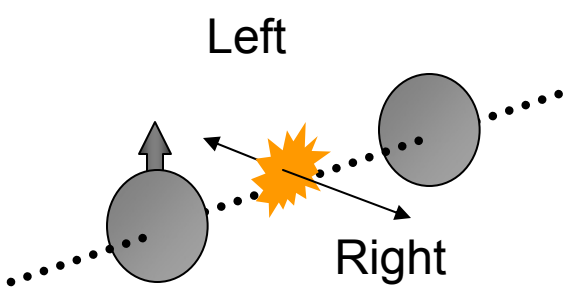
Progress in High-p_T Physics at RHIC
RBRC Workshop
2010/03/18

Single Transverse Spin Asymmetries in pp Collisions



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

A_N difference in cross-section between particles produced to the left and right

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

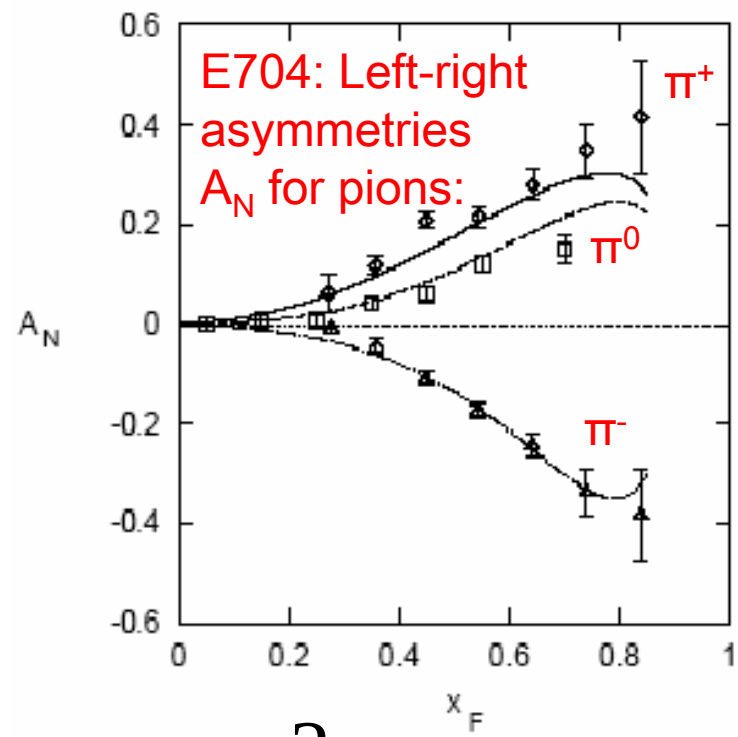
$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N O(10^{-4}) Theory

Experiment:
(E704, Fermi National Laboratory, 1991)

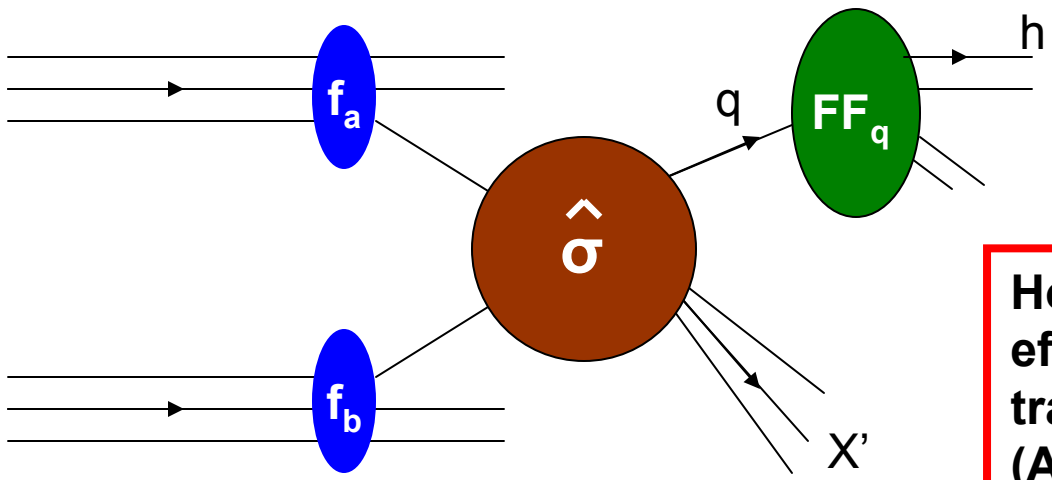
$$pp^\uparrow \rightarrow \pi + X$$
$$\sqrt{s} = 20\,\text{GeV}$$

A_N O(10^{-1}) Measured



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

Possible Origin of Large Single Spin Asymmetries



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

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

small spin dependence

Transverse Spin Effects in p↑p Collisions

PHENIX

(I) Transversity quark distributions and Collins fragmentation function

Correlation between proton & quark spin + spin dependant fragmentation function

$$\propto \underbrace{\delta q(x)}_{\text{Quark transverse spin distribution}} \cdot \underbrace{H_1^{\perp}(z_2, \bar{k}_{\perp}^2)}_{\text{Collins FF}}$$

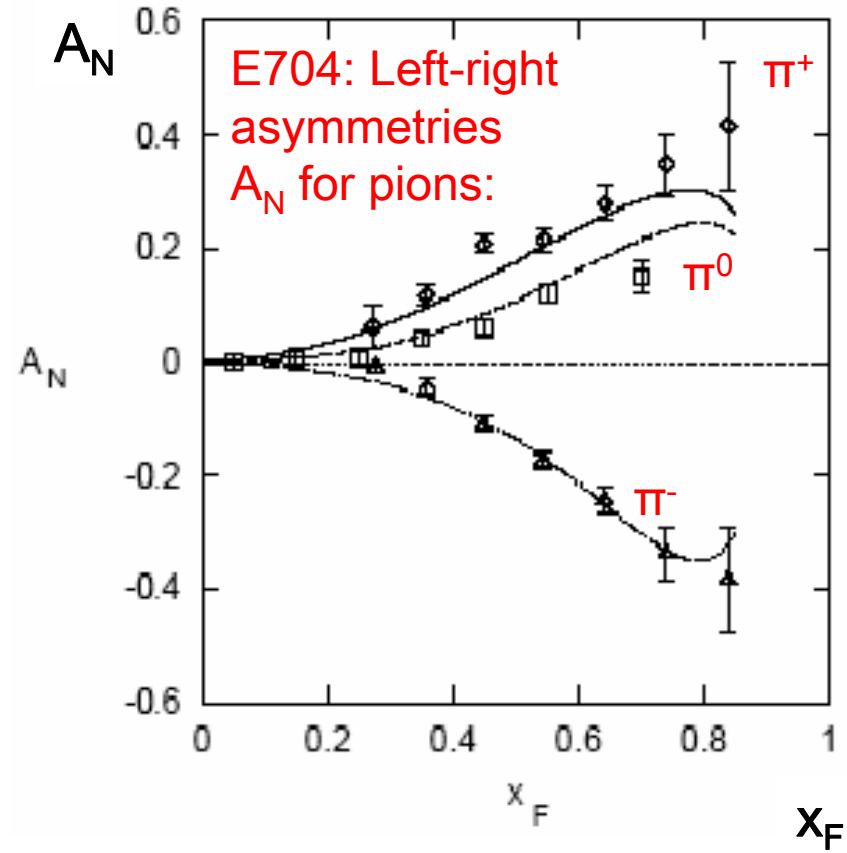
J. C. Collins, Nucl. Phys. **B396**, 161 (1993).

(II) Sivers quark-distribution

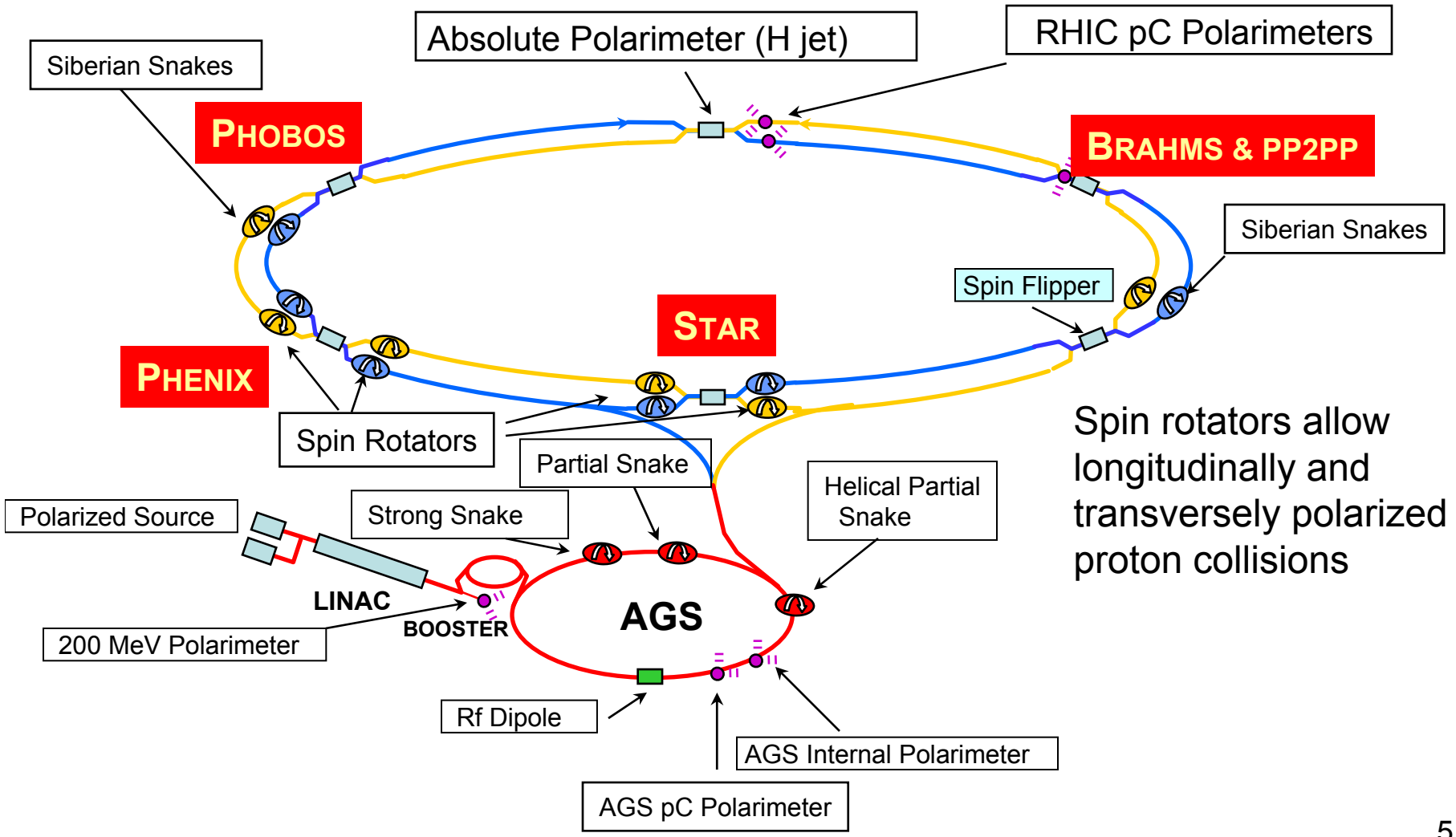
Correlation between proton-spin and transverse quark momentum

$$\propto \underbrace{\bar{f}_{1T}^{\perp q}(x, k_{\perp}^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$

D. Sivers, Phys. Rev. D **41**, 83 (1990).



RHIC Polarized Proton Collider



Spin rotators allow longitudinally and transversely polarized proton collisions

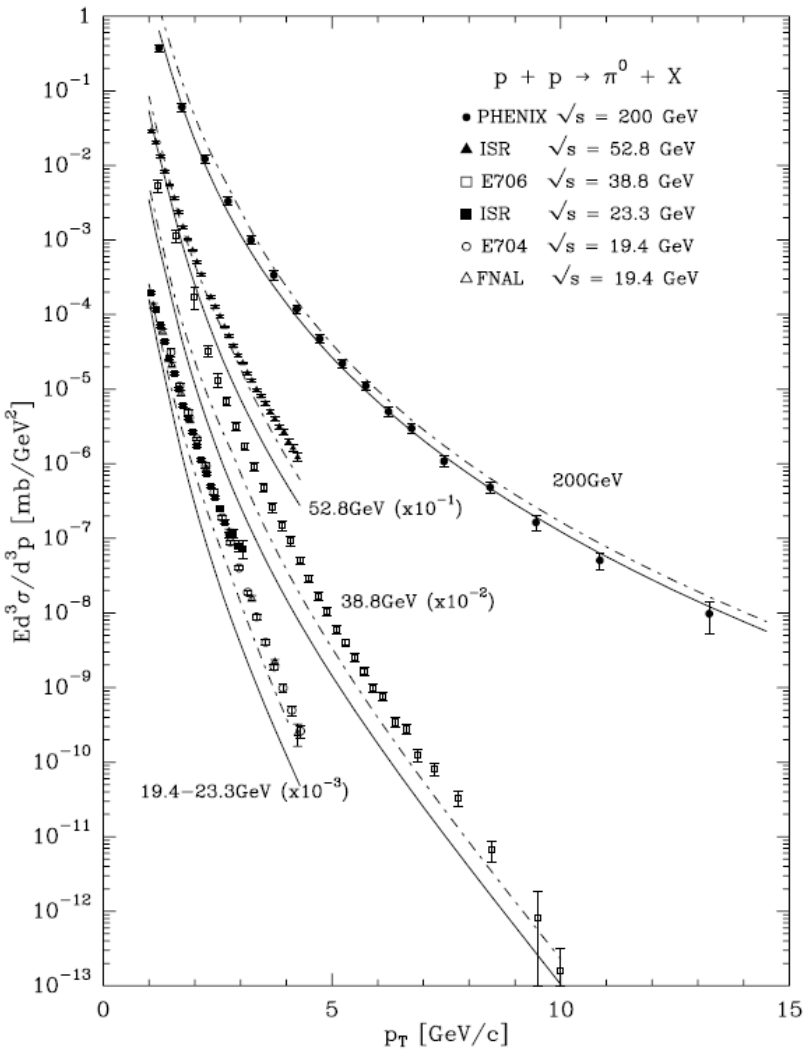
RHIC ∫L* and Polarization

Run	Energy	Polarization	Longitudinal		Transverse	
	[GeV]	[%]	L [pb^{-1}]	LP^4 [pb^{-1}]	L [pb^{-1}]	LP^2 [pb^{-1}]
2002	200	15	-	-	0.15	3.4×10^{-3}
2003	200	27	0.35	1.9×10^{-3}	-	-
2004	200	40	0.12	9×10^{-3}	-	-
2005	200	49 (47)	3.4	2×10^{-1}	0.16	3.5×10^{-2}
2006	200	57 (51)	7.5	7.9×10^{-1}	2.7	7.0×10^{-1}
2006	62	48	0.08	4.2×10^{-3}	0.02	4.6×10^{-3}
2008	200	46	-	-	5.2	1.1×10^{0}
2009	500	35	14	2.1×10^{-1}	-	-
2009	200	55	16	1.5×10^{0}	-	-

Steadily increasing polarization and luminosity

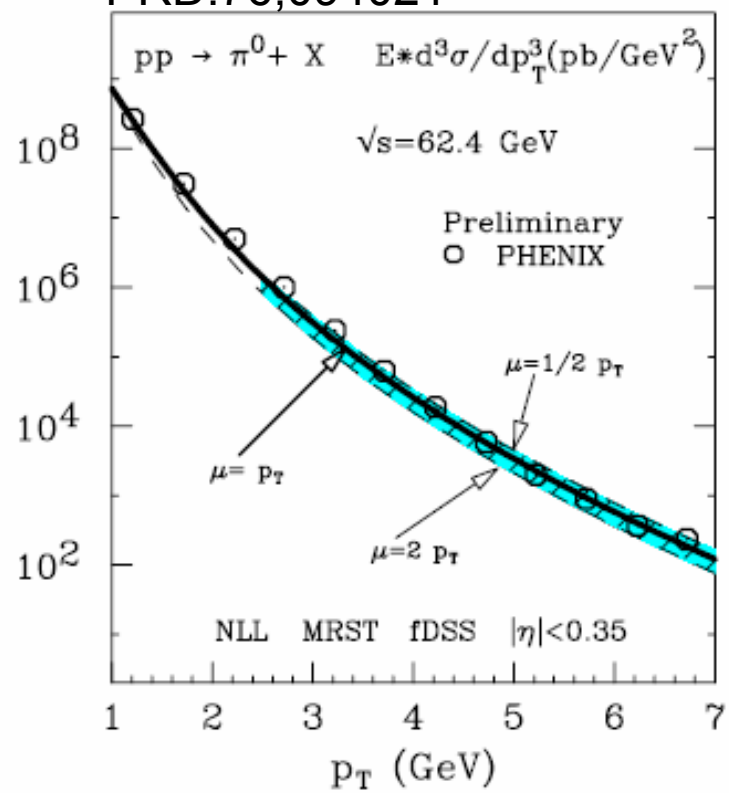
* integrated luminosity for PHENIX central arm

Neutral Pion Cross-Sections Experiment vs pQCD



Eur.Phys.J.C36:371-374,2004

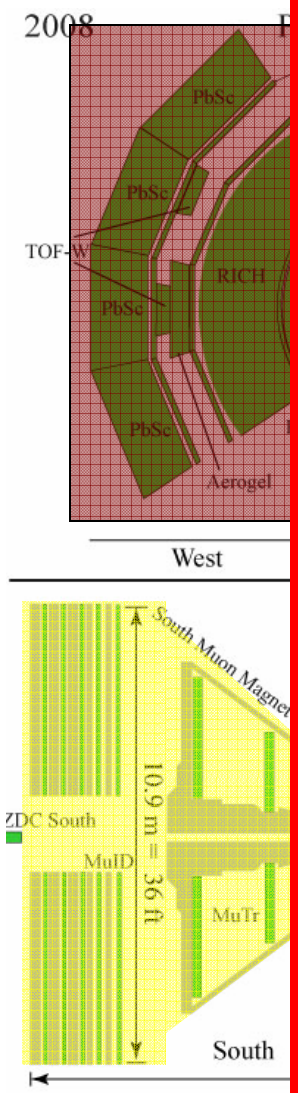
PRD:76,094021



π^0 Cross-Sections at y = 0
Experiment vs Theory

- √s=200 GeV (RHIC) Agreement
- √s=19.4 GeV (FNAL/E704) Different
- **√s=62.4 GeV (RHIC) Agreement**

More work needed to understand fixed target energies



PHENIX strategy:

Measure several observables each sensitive to different transverse spin effects

(i) Forward SSA → Sivers & Collins

Neutral Pions & Charged hadrons

(ii) Transversity-type Asymmetries

Interference Frag. Func. Analysis

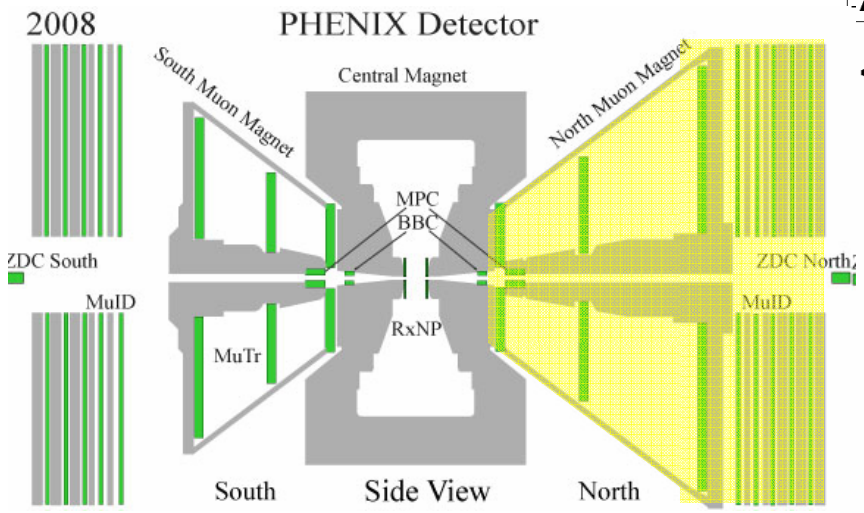
(iii) Sivers-type Asymmetries

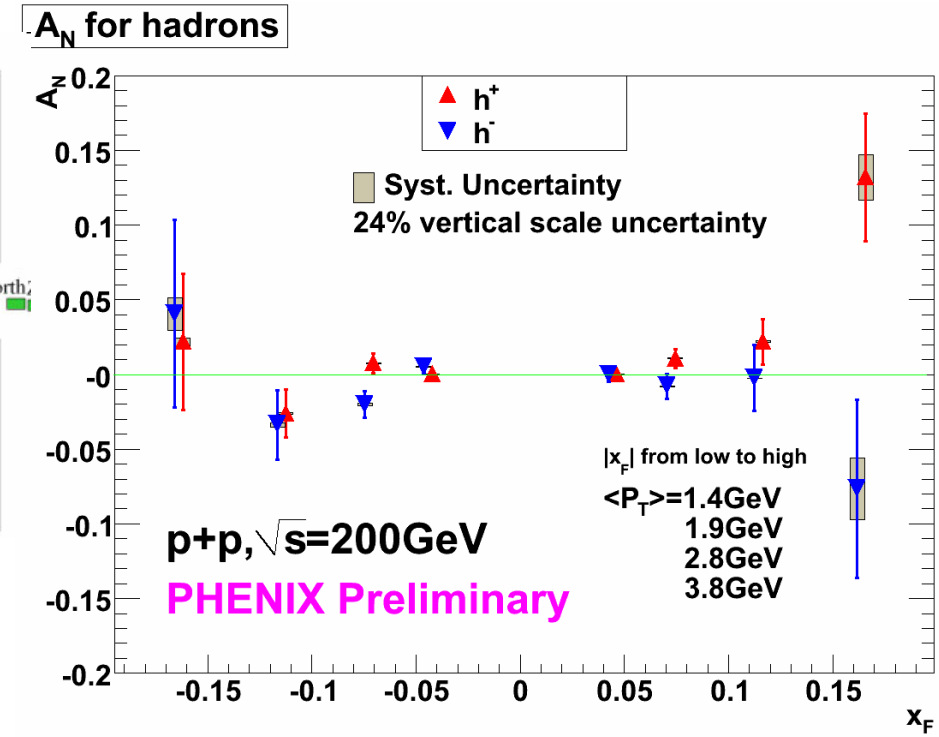
Heavy Flavor

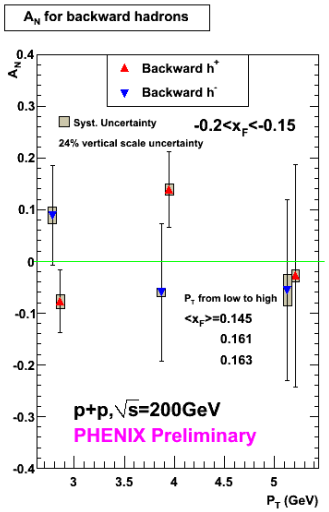
Back to Back Hadrons

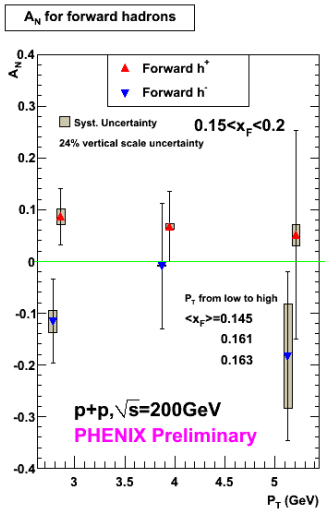
A_N for y~0

(i) Forward SSA A_N Charged Hadrons (1.2<|eta|<2.4)









- Unidentified charged hadron A_N
- Asymmetries corrected for bin sharing and interactions in magnet/absorber
- Non-zero A_N persists to moderate pseudorapidity

(i) Muon Piston Calorimeter A_N

Photon merging effects prevent two-photon π^0 analysis for E>20 GeV (p_T>2 GeV/c)

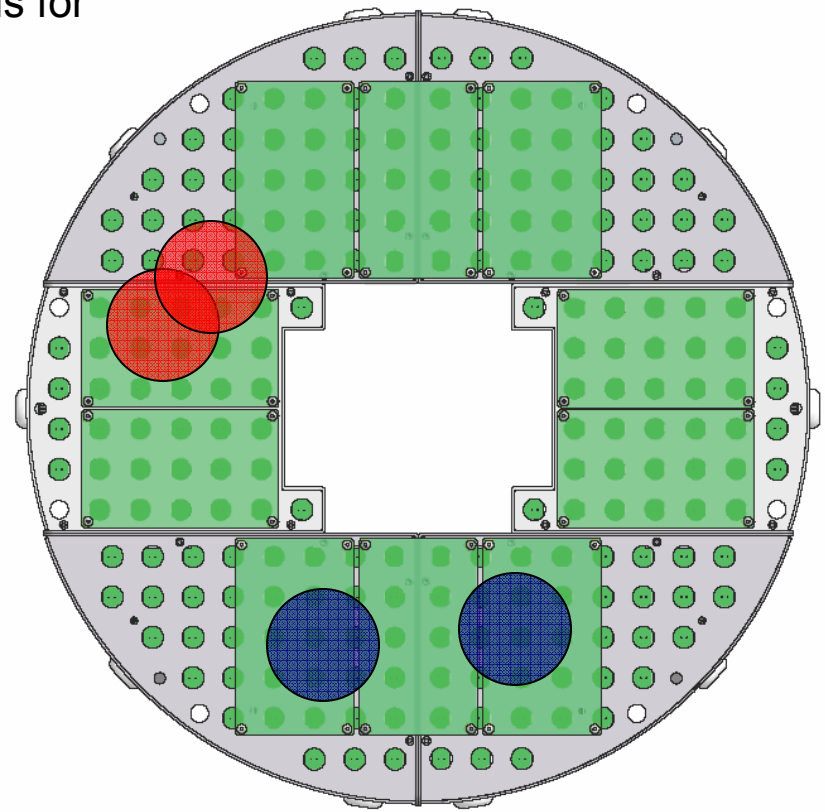
62 GeV

20 GeV → 0.65 x_F:Two-photon π^0 analysis

200 GeV

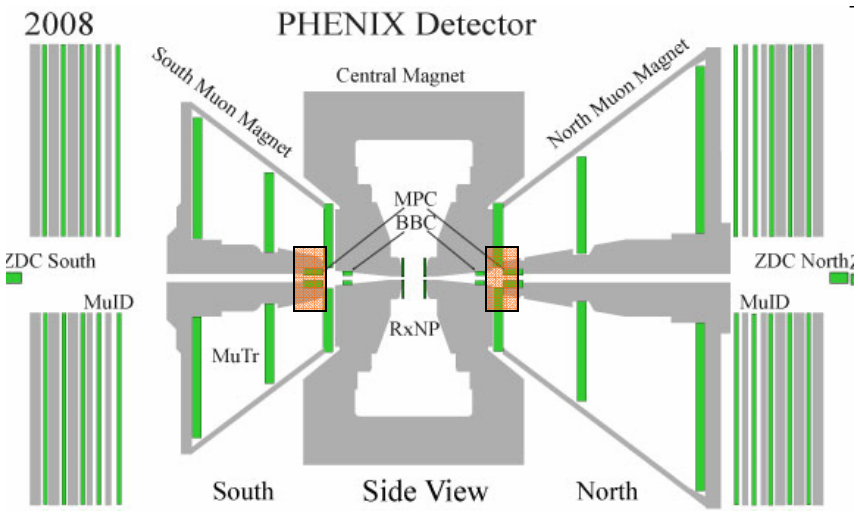
20 GeV → 0.20 x_F : "Single clusters".
Yields dominated by π^0's but also get contributions from:

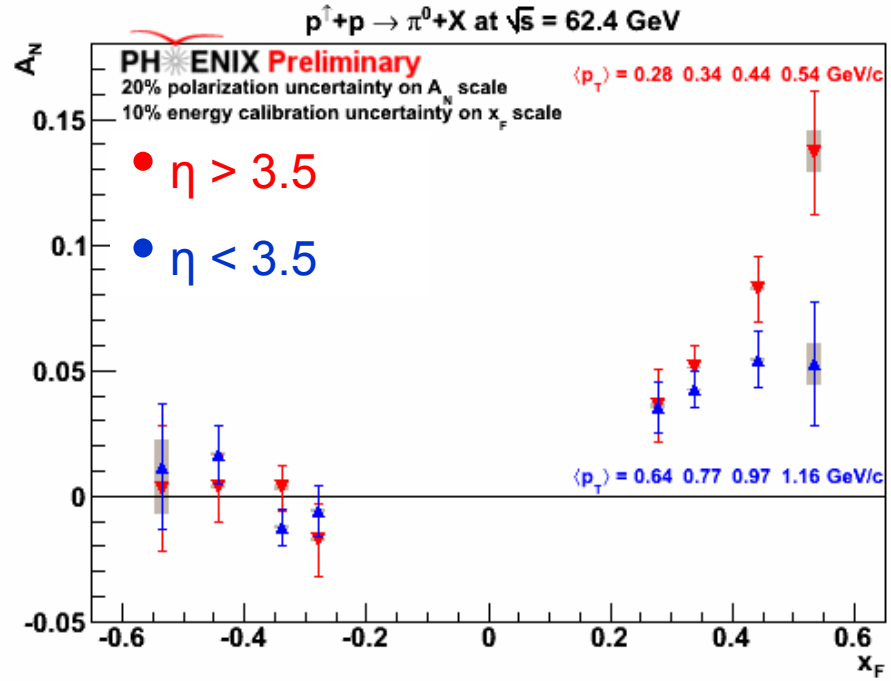
- **Electromagnetic**
  - Direct photons
  - Decay photons (η, etc)
  - Estimated using Pythia (TuneA)
- **Hadronic: ($\pi^{+/-}$, $K^{+/-}$, etc.)**
  - Estimated with Pythia+GEANT.
    Initial estimate is <10% contamination in lowest energy bin with decreasing fraction as deposited energy increases
  - Qualitatively consistent with expected detector behavior



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

(i) Forward SSA A_N π^0 in MPC at $\sqrt{s}$=62 GeV

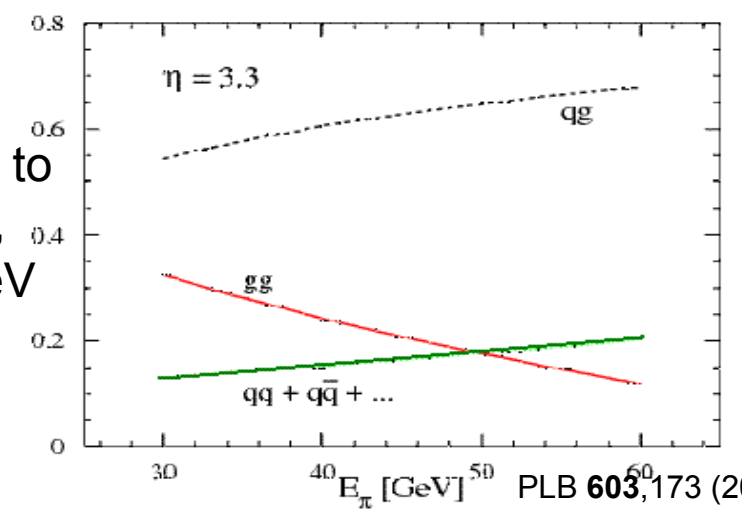




PHENIX π^0 results available for $\sqrt{s}$=62 GeV

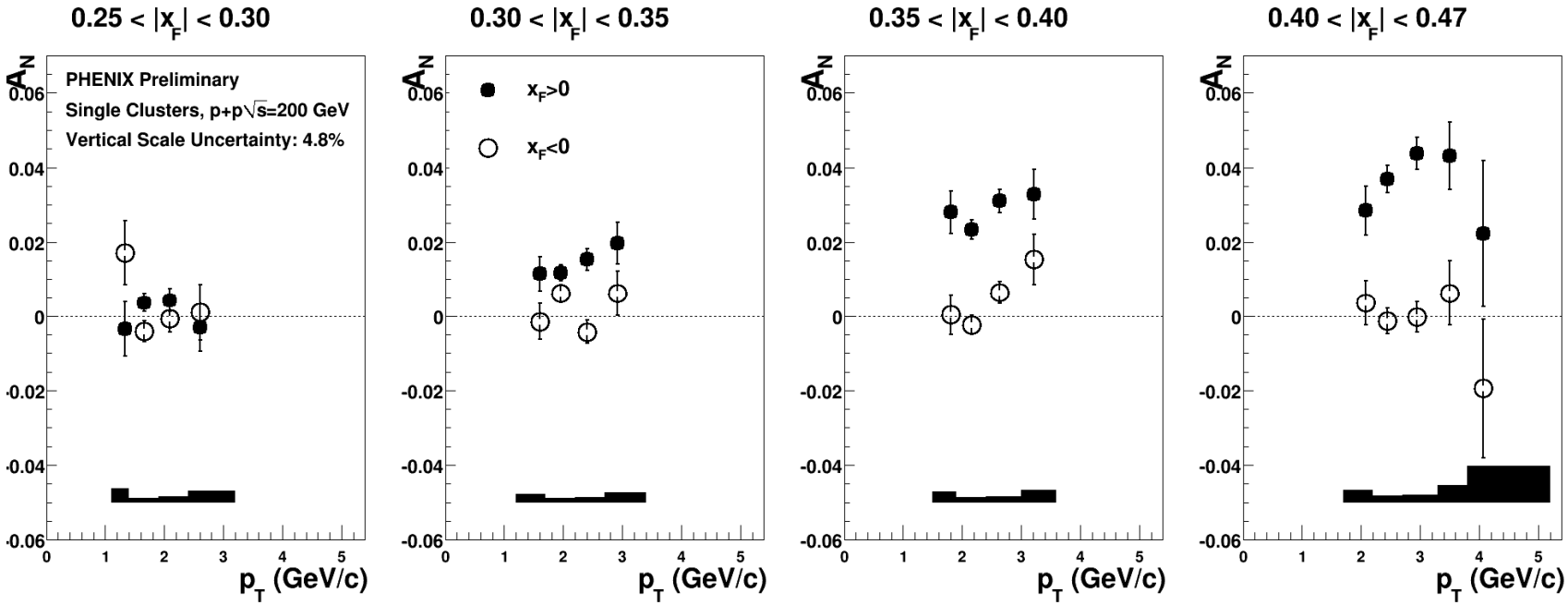
- Production dominated by quark-gluon
- Similar x_F scaling to higher and lower center of masses
- Asymmetries could enter a global analysis on transverse spin asymmetries

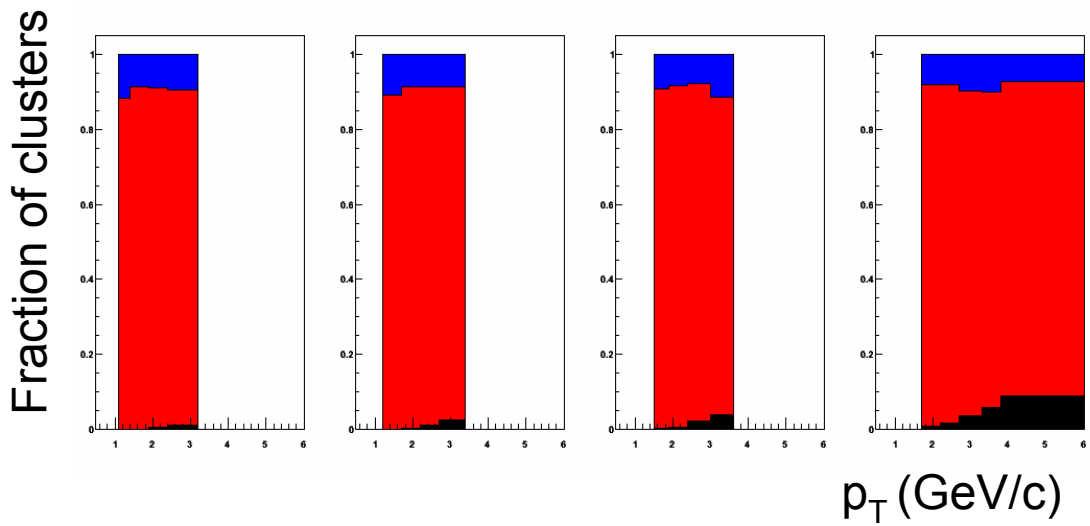
Process contribution to π^0, η=3.3, $\sqrt{s}$=200 GeV



PLB **603**,173 (2004)

(i) Forward SSA A_N Cluster in MPC at $\sqrt{s}$=200 GeV



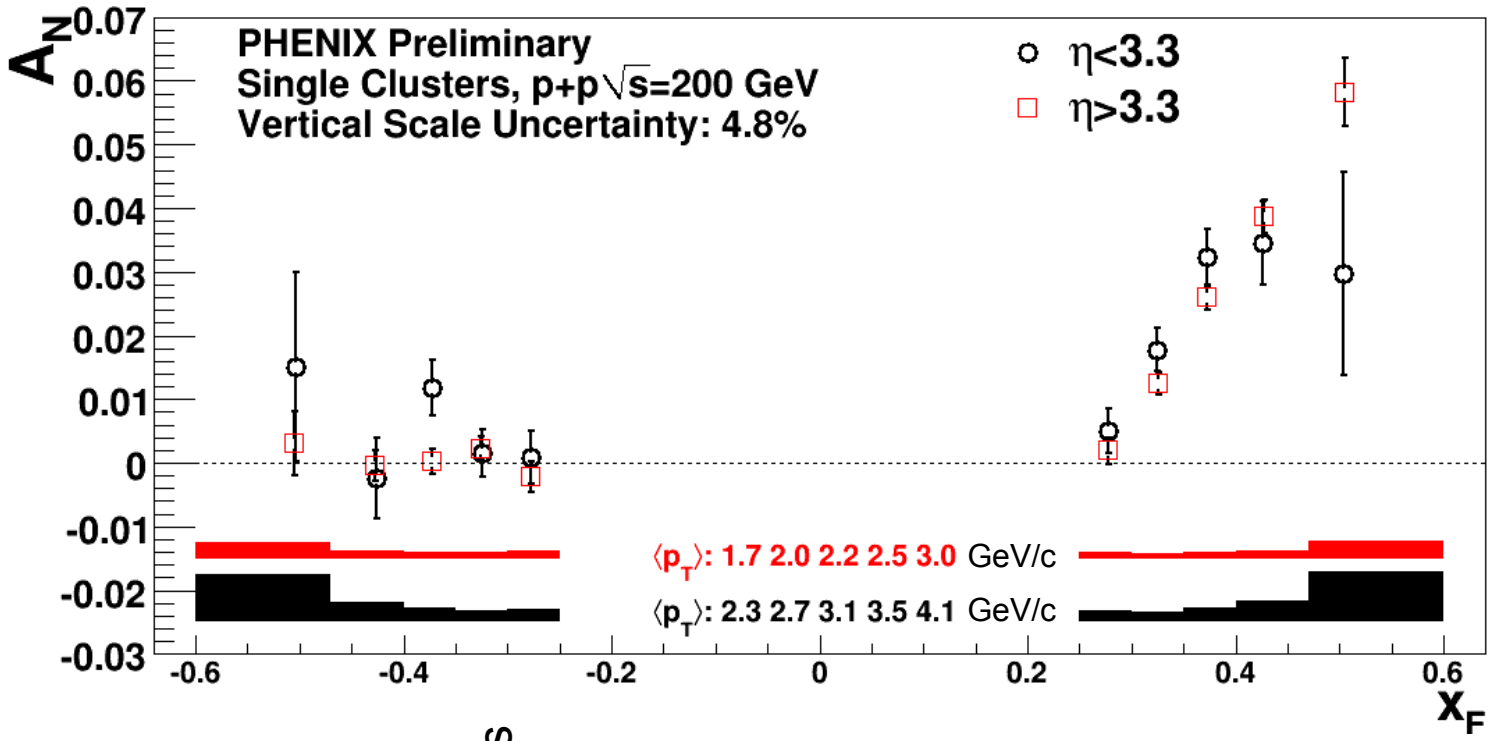


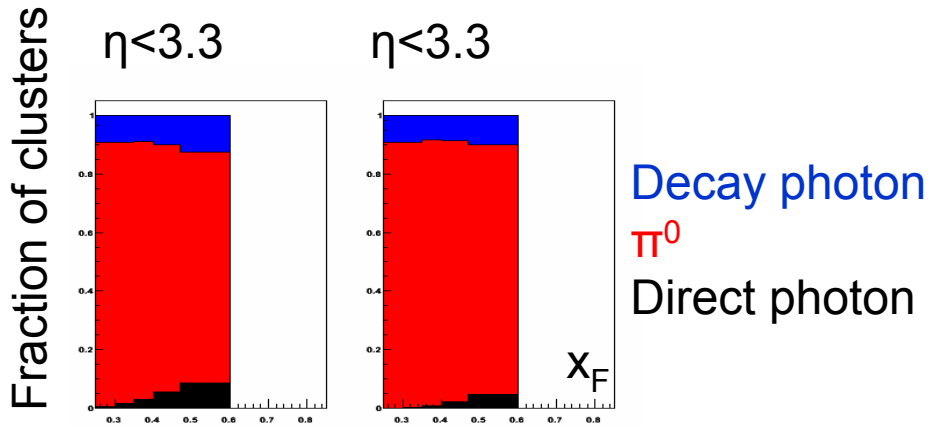
Decay photon

π^0

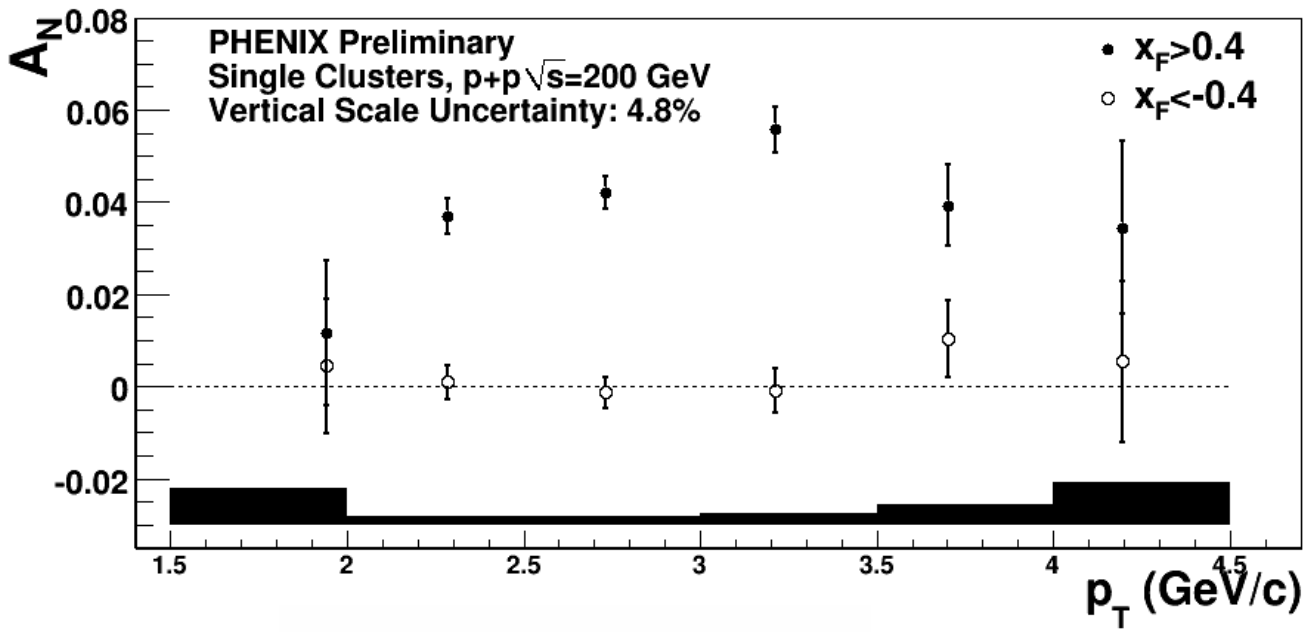
Direct photon

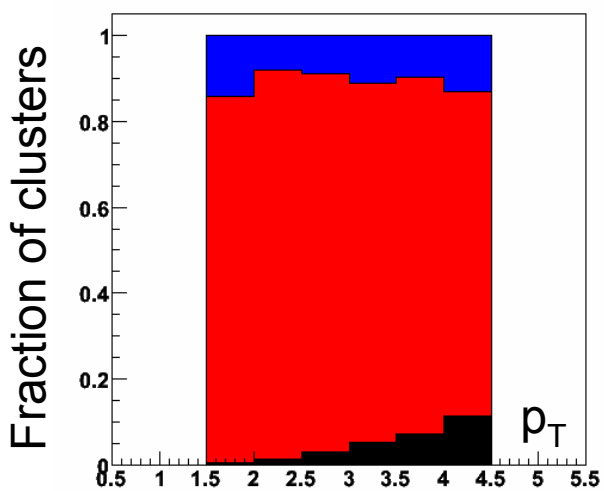
(i) Forward SSA A_N Cluster in MPC at $\sqrt{s}$=200 GeV





(i) Forward SSA A_N Cluster in MPC at $\sqrt{s}$=200 GeV



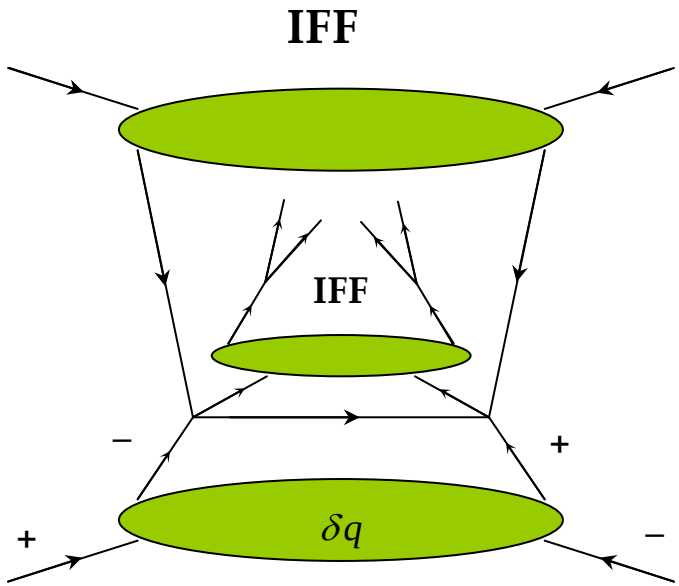


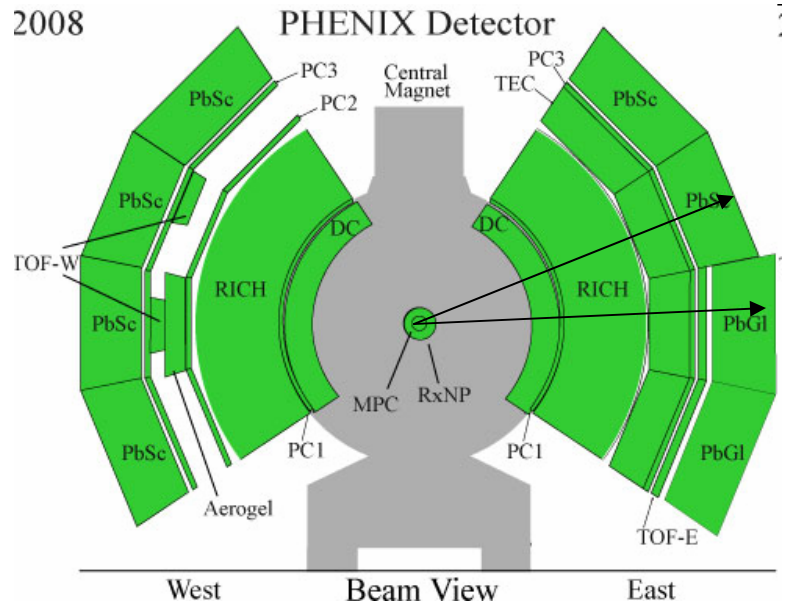
Decay photon

π^0

Direct photon

(ii) Constraints on Transversity: Dihadron IFF Analysis





$$A_{UT,\phi}^{h_1,h_2} = \frac{\sigma_\phi^\uparrow - \sigma_\phi^\downarrow}{\sigma_\phi^\uparrow + \sigma_\phi^\downarrow}$$

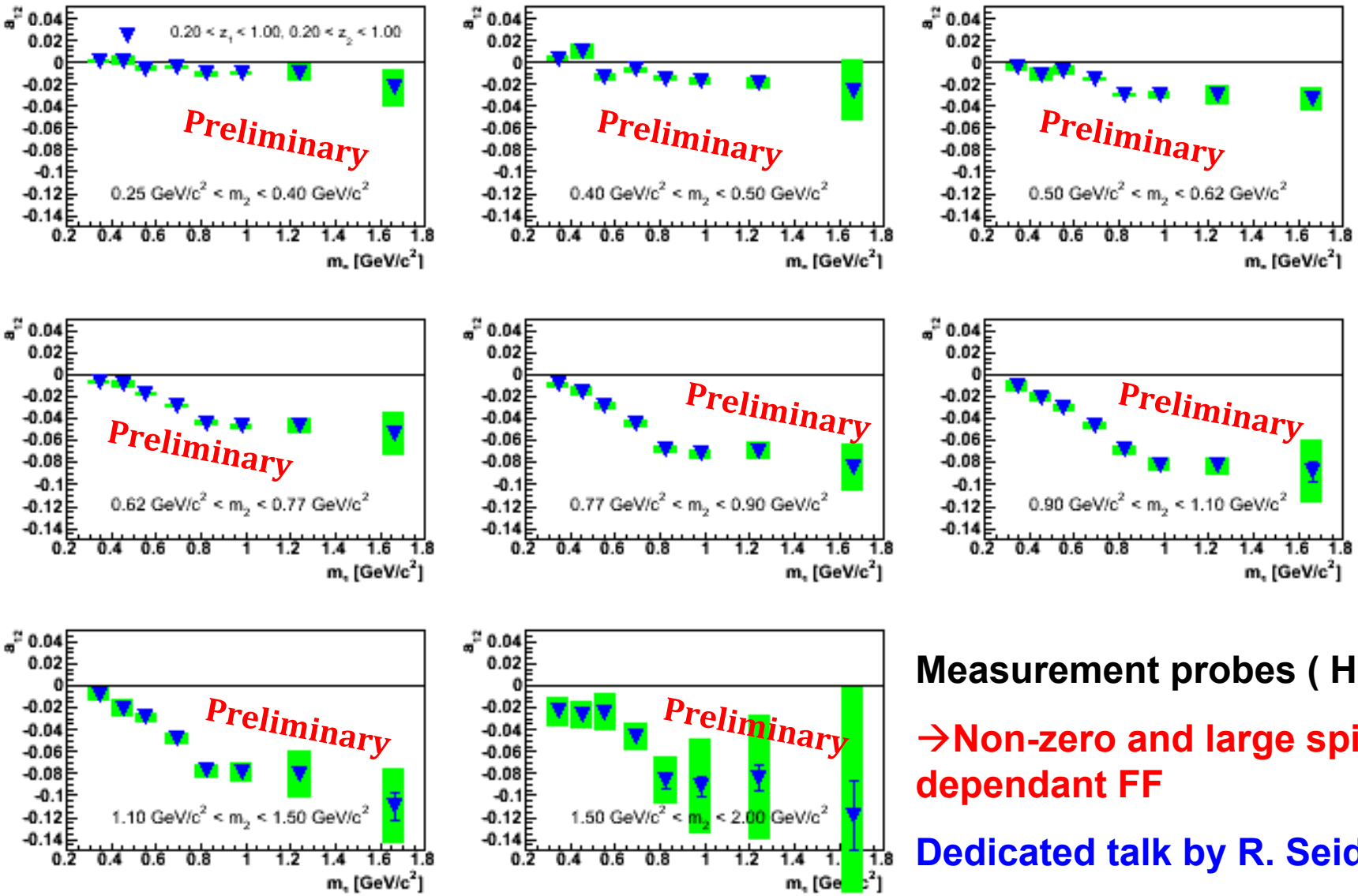
Interference Fragmentation Function Analysis

Measure di-hadron asymmetry with hadron pairs in central arm (π^0,h^+) (π^0,h^-), (h^+,h^-)

- Measures $\delta q(x) \times H_1^{\angle}$

Transversity extraction will become possible with Interference Fragmentation Function ($H_1^{\angle}$)

(ii) IFF Measurement



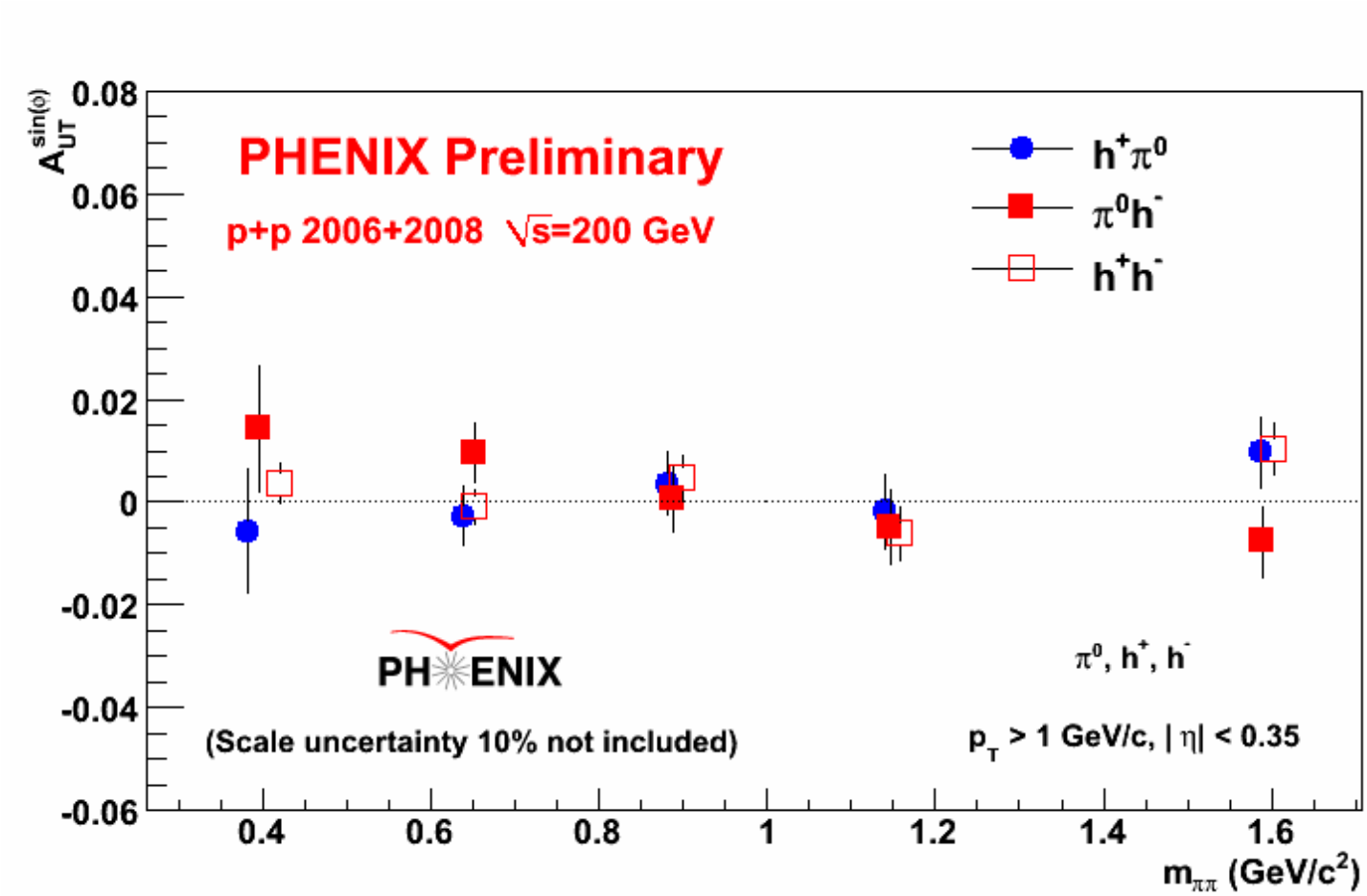
Measurement probes ($H_1^{<}$)^2

→Non-zero and large spin-dependant FF

Dedicated talk by R. Seidl

8x8 m_1 m_2 binning

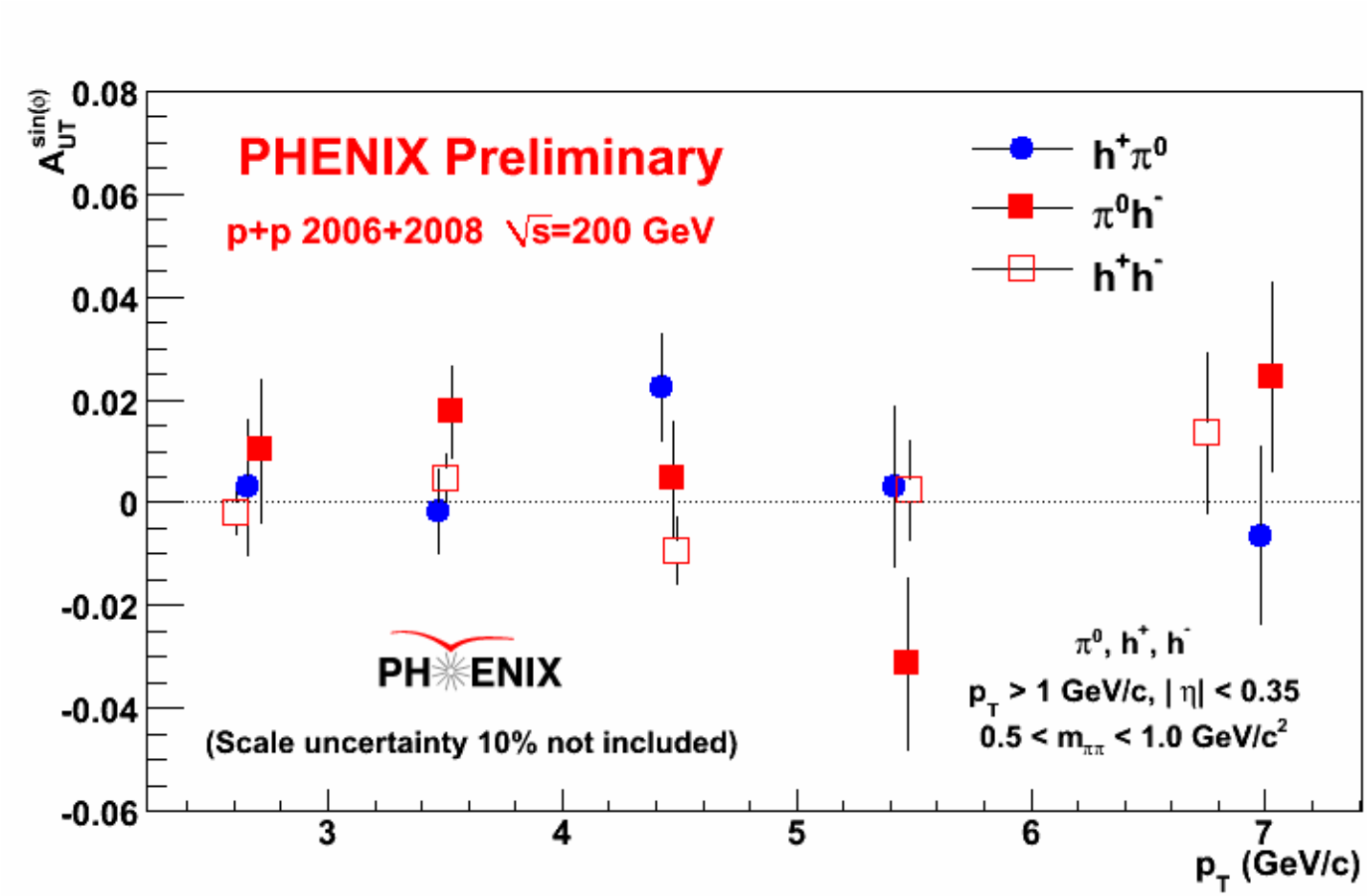
(ii) $A_{UT}^{\sin(\phi)}$ vs pair mass



Added statistics from 2008 running

No significant asymmetries seen at mid-rapidity.

(ii) $A_{UT}^{\sin(\phi)}$ vs pair p_T



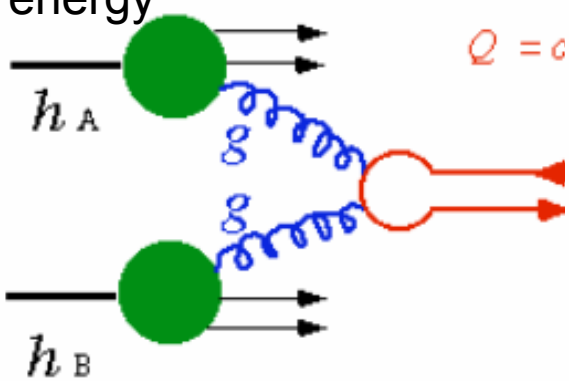
Added statistics from 2008 running

No significant asymmetries seen at mid-rapidity.

(iii) Constraints on Sivers Function: Heavy Flavor

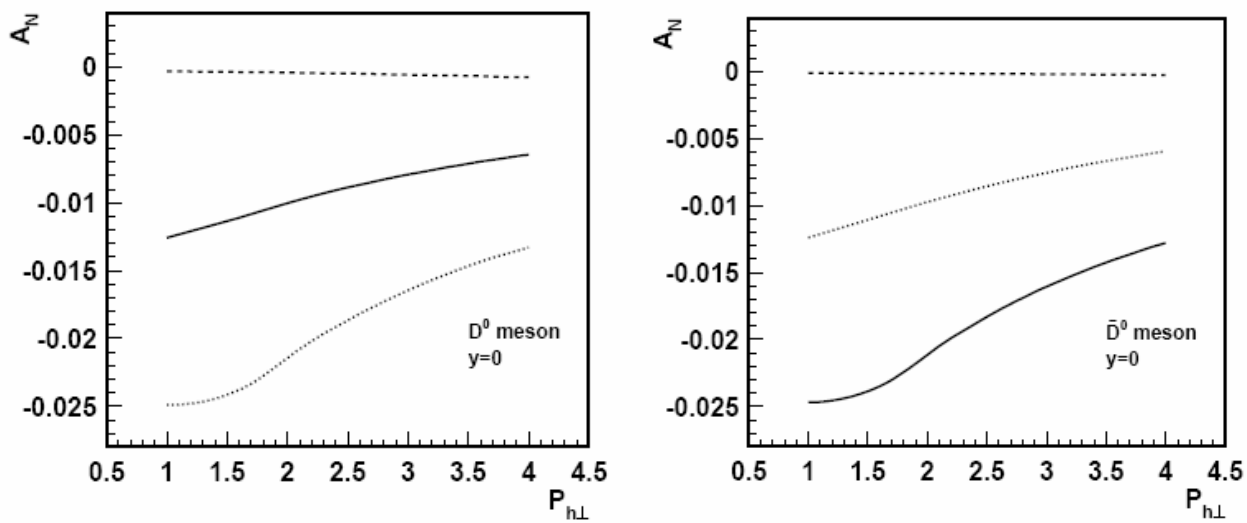
D meson A_N

- Production dominated by gluon-gluon fusion at RHIC energy



- Gluon transversity zero →Asymmetry cannot originate from Transversity x Collins
- Sensitive to gluon Sivers effect

Theoretical predictions:



High twist (PRD 78 114013)

$T_G^{(d)}$, $T_G^{(f)}$ twist 3 gluon correlators

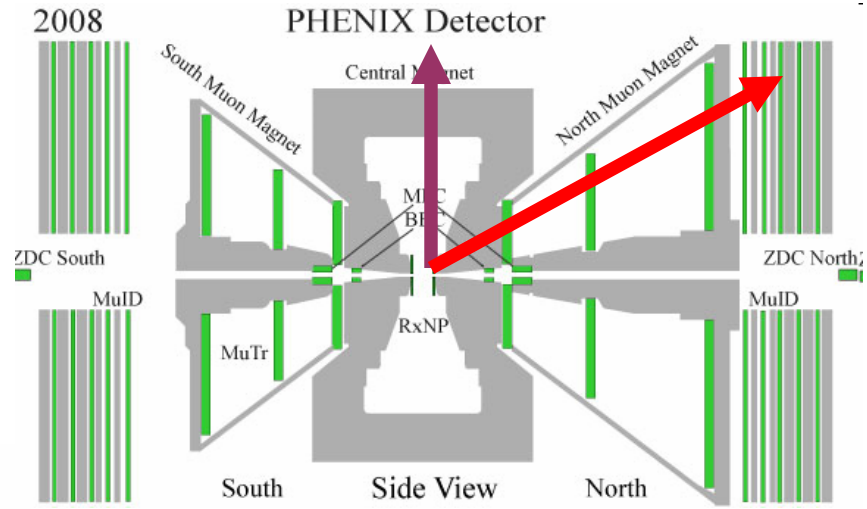
- Solid: $T_G^{(d)}$, $T_G^{(f)}$ same sign
- Dashed: $T_G^{(d)}=T_G^{(f)}=0$
- Dotted: $T_G^{(d)}$, $T_G^{(f)}$ opposite sign

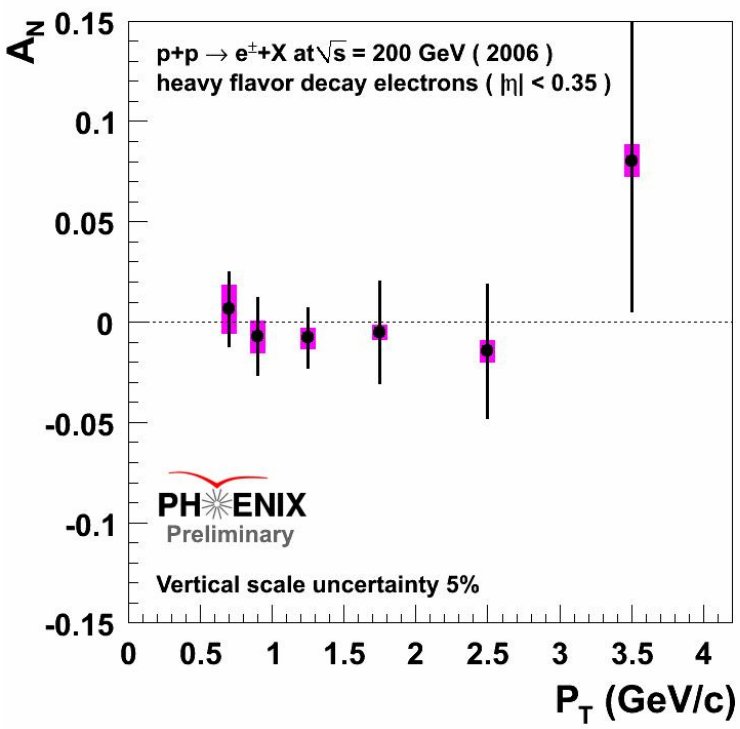
Gluon Sivers=Max
Quark Sivers=0
Gluon Sivers=0
Quark Sivers=Max

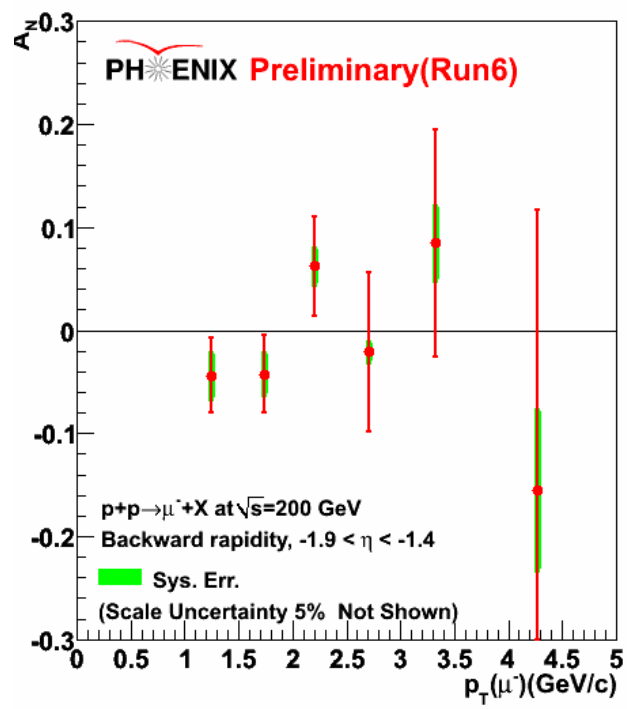
(iii) Constraints on Sivers Function: Heavy Flavor

PHENIX: no reconstruction of D meson

- Dominated by charm production in current kinematic range
- Measurements at **mid** and **forward** rapidity
- Constraints on both twist-3 and Sivers functions

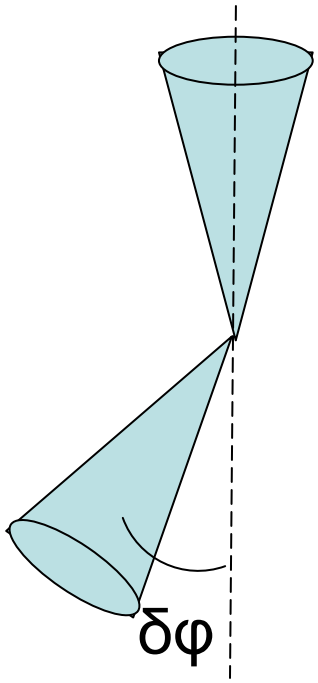


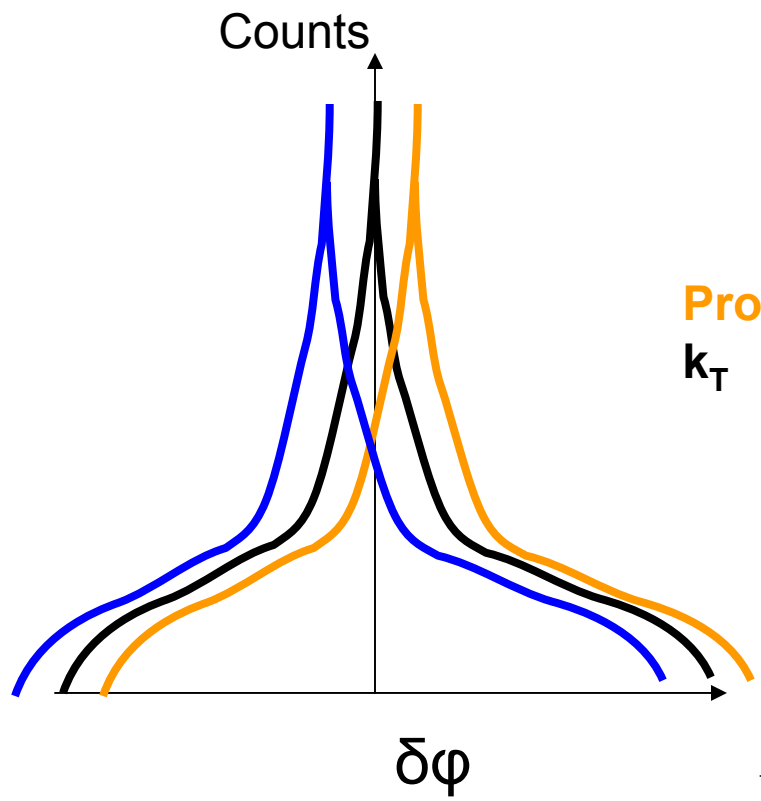


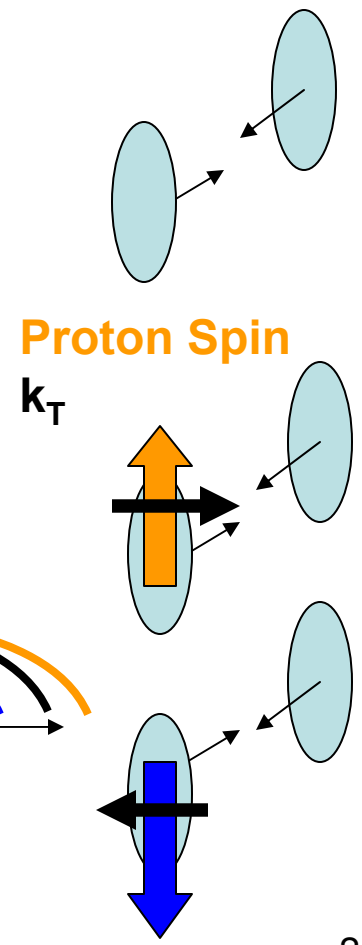


(iii) Constraints on Sivers Function: DiJet Production

Azimuthal distribution of Di-Jet production in pp
Suggested in: **Phys. Rev. D 69, 094025 (2004)**





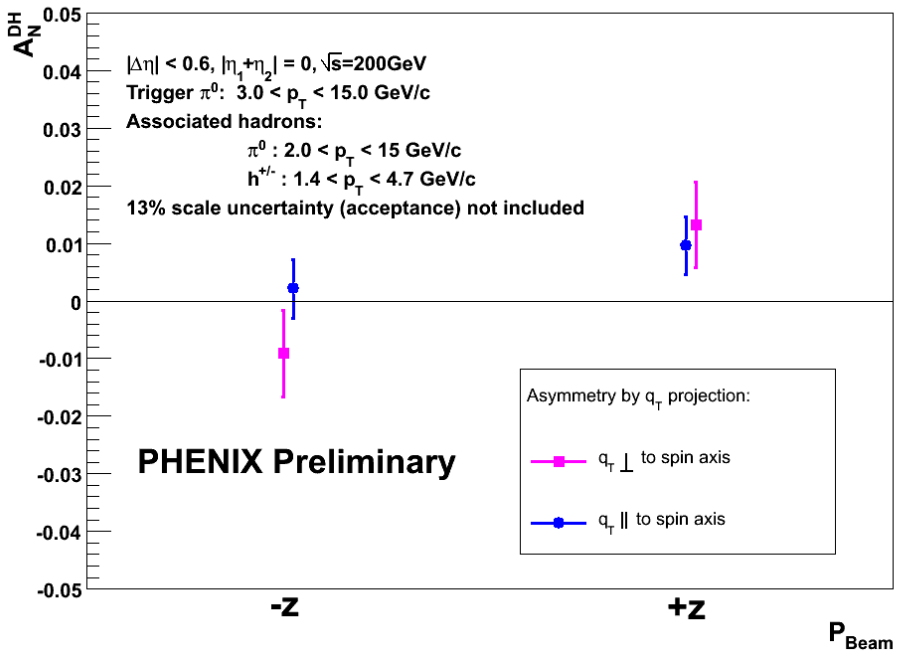


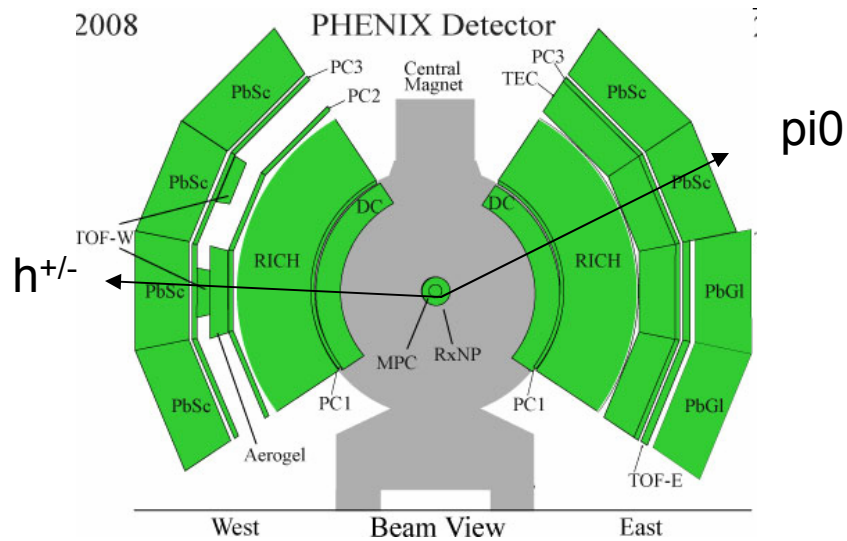
Beam is in and out of page
Look at back-to-back jet opening angles

Sensitive to Sivers function only!

No Collins-type effects

(iii) Constraints on Sivers Function: DiHadron Production





PHENIX Result from 2006 data:

- Done with di-hadrons at $y_1=y_2$~=0
- Asymmetry consistent with zero

Large 2008 data set available!

Similar analysis possible in different combinations of rapidity

η_{min}	-3.7	-2.0	-0.35	1.4	3.1
η_{max}	-3.1	-1.4	+0.35	2.0	3.9

Works in progress…

(iii) Mid-rapidity, $|y|<0.38$, A_N π^0, η Analysis

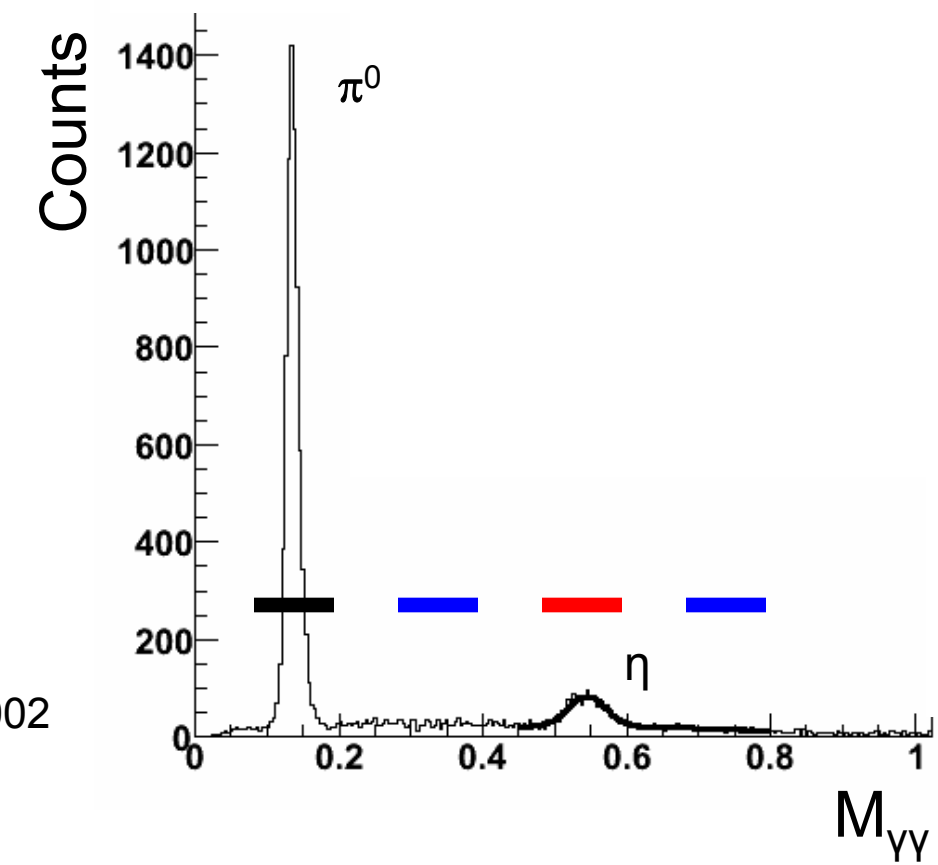
Similar analysis to existing PHENIX A_{LL}

1. Measure A_N in mass window of:
   - π^0 (Signal+Background)
   - η (Signal+Background)
   - **Background**
2. Determine background fractions (r)
3. $$A_N^{Signal} = \frac{A_N^{Signal+Background} - rA_N^{Background}}{1-r}$$

Asymmetries binned in p_T for:

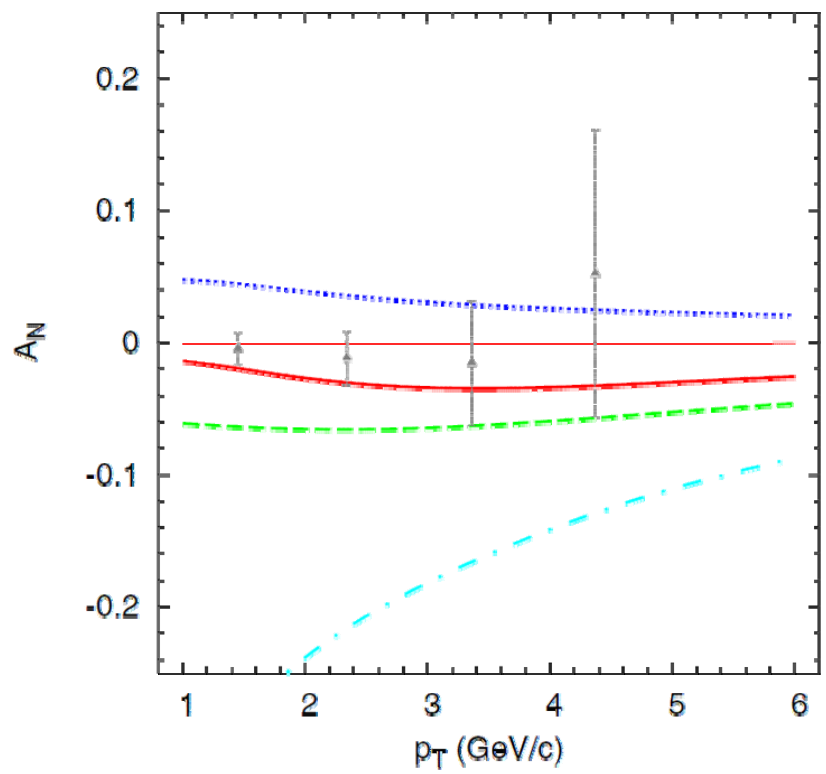
- inclusive selection
- with $x_F > 0.01$, $x_F < -0.01$

Previous π^0 A_N measurement done with 2002 dataset.



(iii) Impact of 2002 result: Limit on Gluon Sivers Function

Comparison of Exp. To Theory



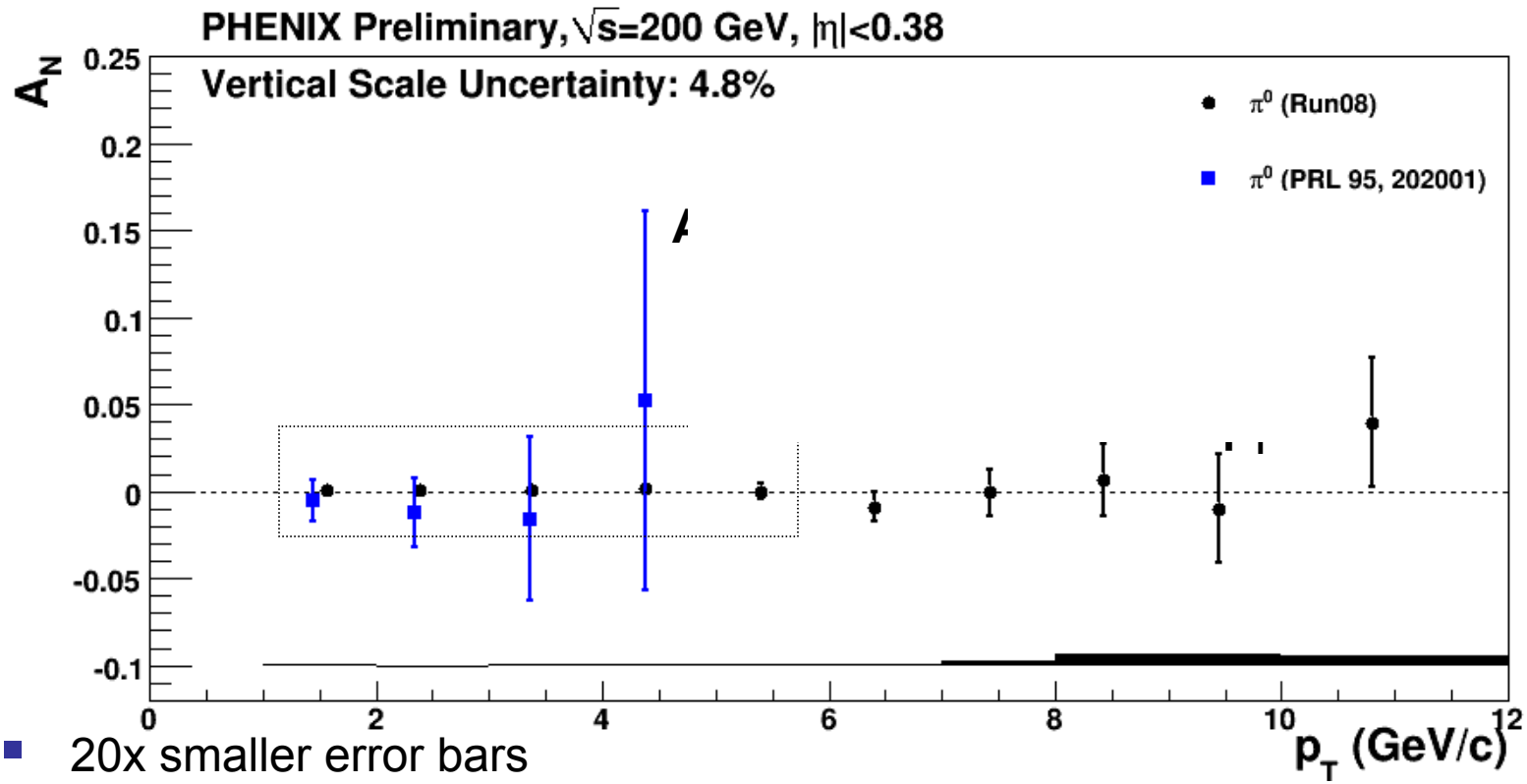
Phys. Rev. D 74, 094011

- Data points: π^0 A_N at x_F=0
- Leading order model-dependant constraints on gluon Sivers function
- Similar storyline to A_{LL}
  - Initial data rules out maximally polarized distributions
  - Later data puts precise determination on distribution

•Cyan: Gluon Sivers Function at positivity bound, no sea quark Sivers
•Thick Red: Gluon Sivers parameterized to be 1 sigma from PHENIX π^0 A_N
•Blue: Asymmetry from Sea quark Sivers at positivity bound
•Green: Asymmetry from Gluon Sivers for case of sea quark at positivity bound

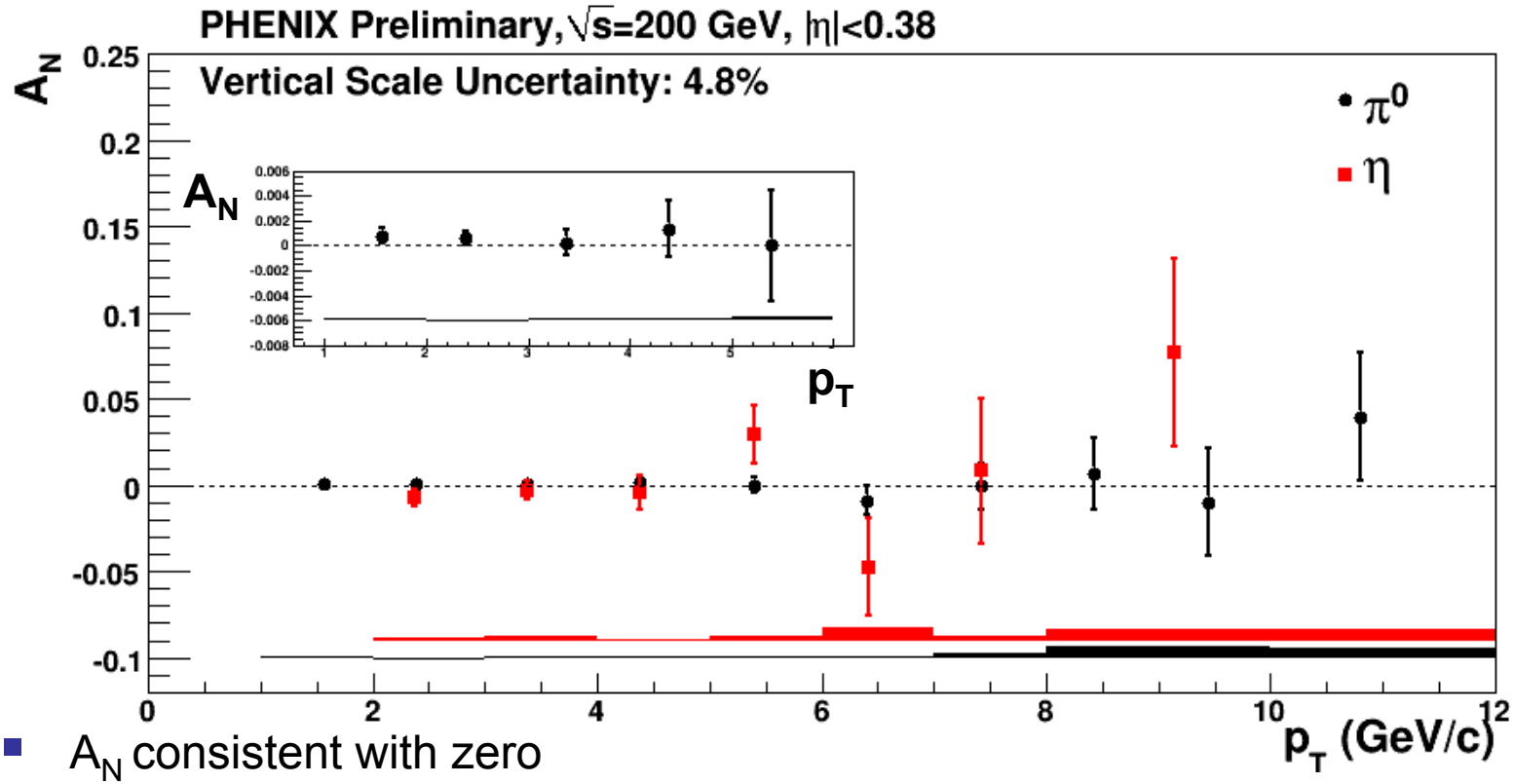
(iii) Results for mid-rapidity π^0 A_N

2002 Published Result **2008 Preliminary Result**



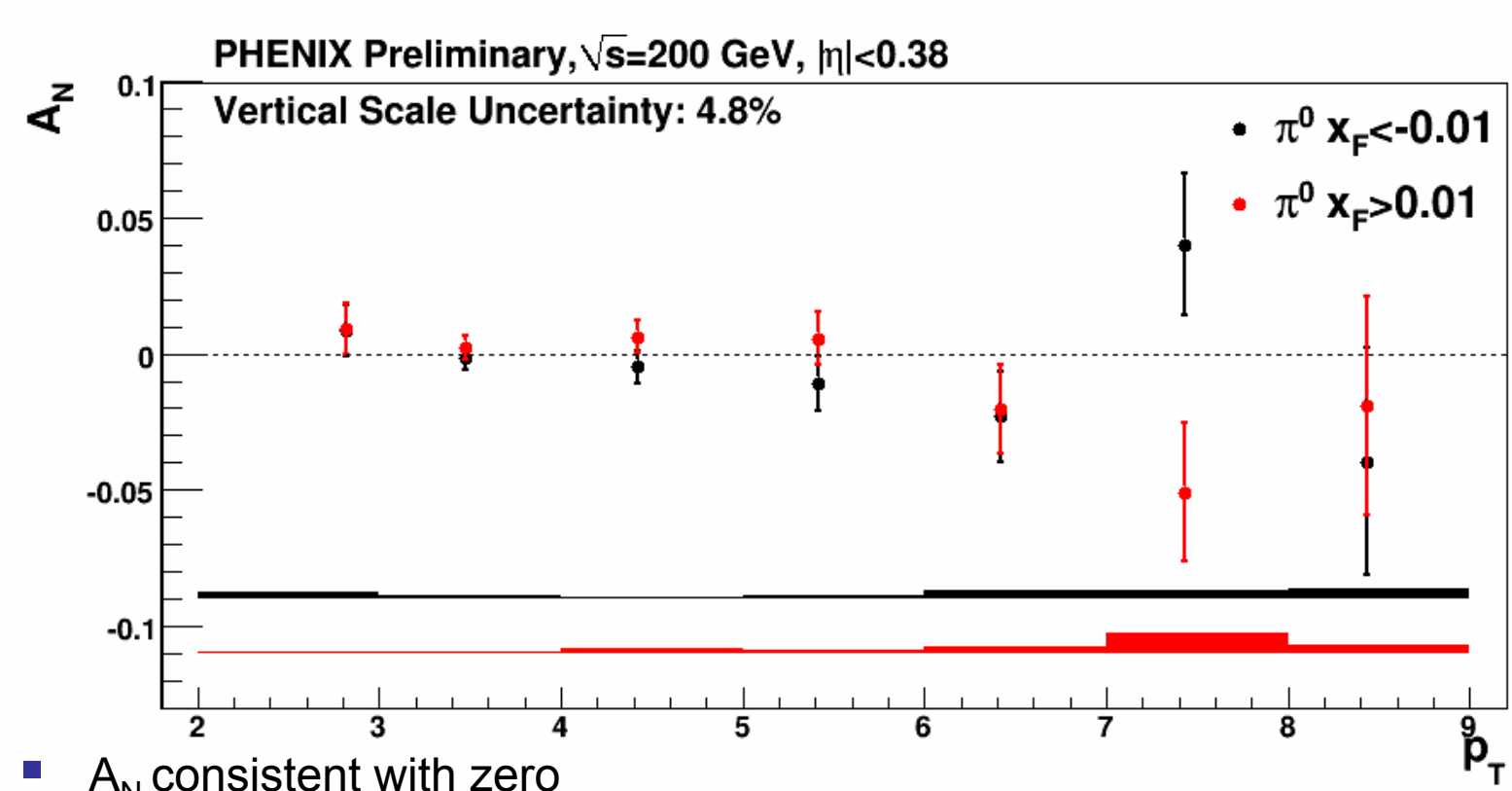
- 20x smaller error bars
- →Large improvement by BNL Collider/Accelerator department in both polarization and luminosity

(iii) Mid-rapidity π^0 and η A_N



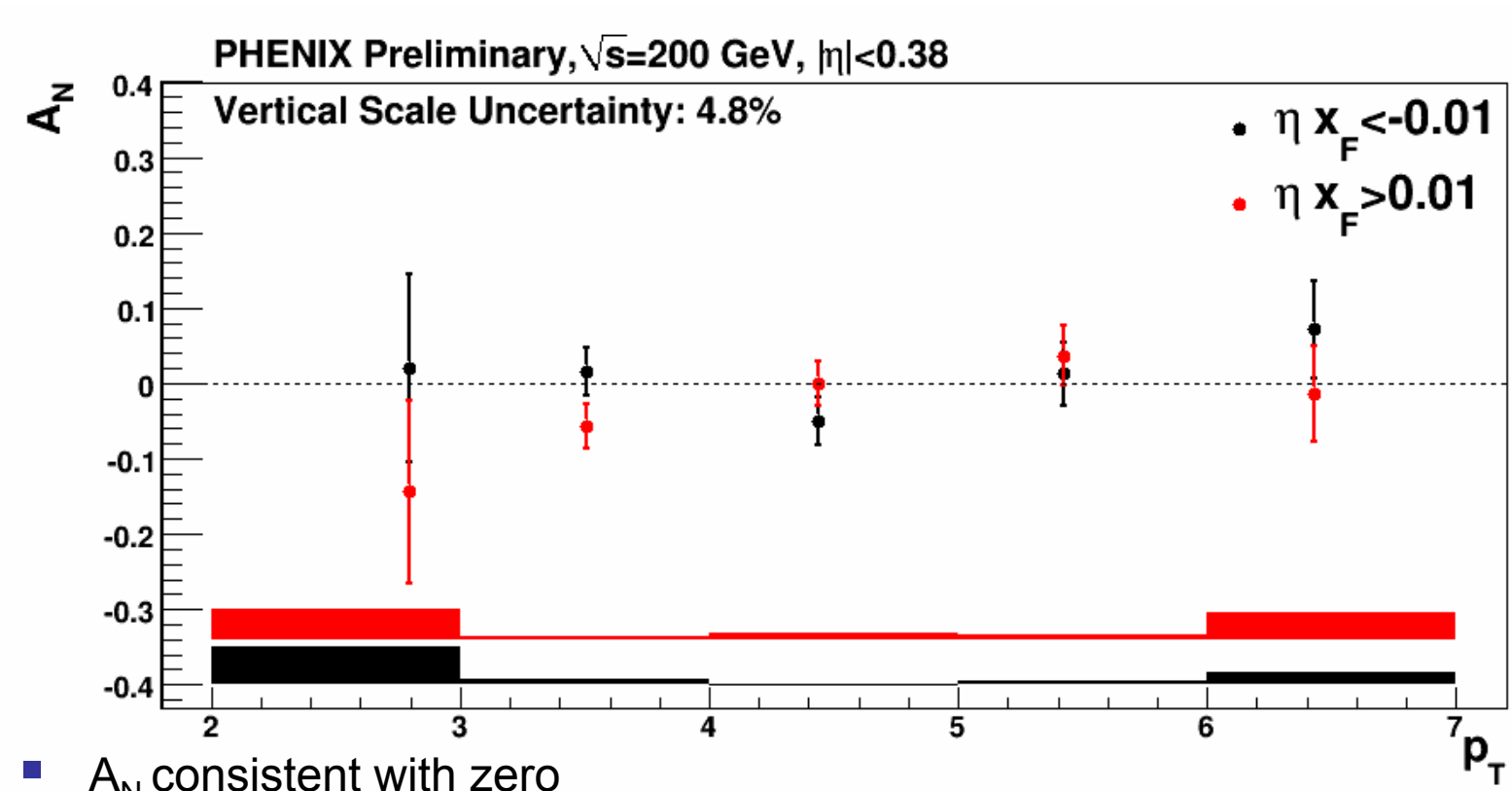
- A_N consistent with zero

(iii) Mid-rapidity π^0 A_N $|x_F|>0.01$



- A_N consistent with zero

(iii) Mid-rapidity η A_N $|x_F|>0.01$



- A_N consistent with zero

Summary

- Non-zero single spin asymmetries in forward region
- Dedicated transversity channels:
  - IFF Analysis
- Sivers function constraints possible with central arm A_N results

Near Term Outlook

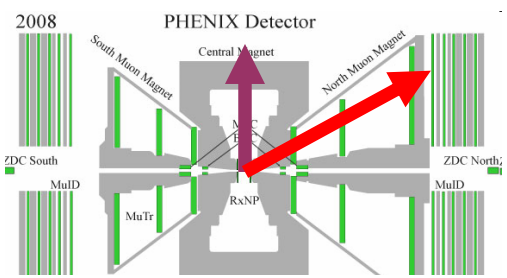
(i) Forward SSA A_N
η at $\sqrt{s}$=200 GeV, confirm huge STAR A_N

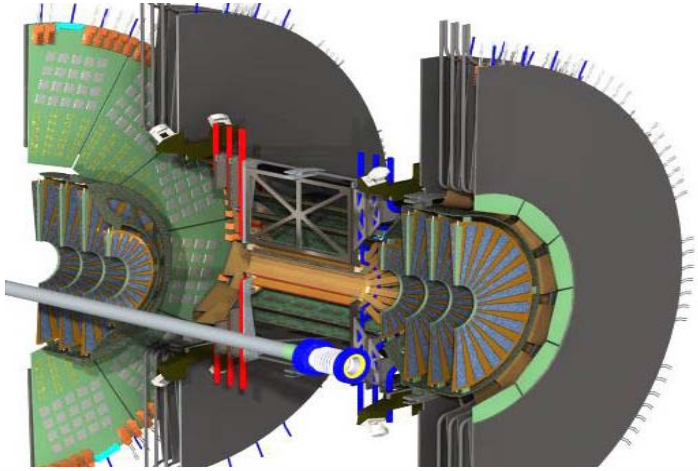
(ii) Transversity-type measurements
Exploring Forward IFF

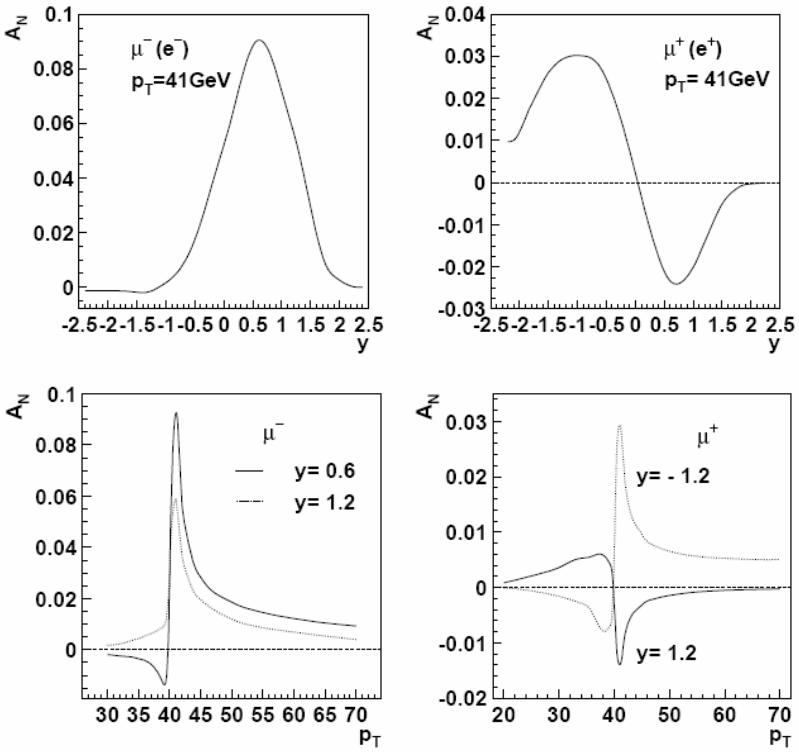
(iii) Sivers-type measurements
Di-Jet analyses will expand to rapidity-separated hadron pairs

~~Long~~ Near Term Outlook with Upgrades

- Vertex Detectors (2010 installation)
  Large acceptance precision tracking
  - Heavy flavor tagging
  - Electrons from charm decays and beauty decays separately
  - c,b-Jet Correlations
  - Expanded IFF analysis
- $W^{+/-}$ A_N
  Suggested in: **Phys.Rev.Lett.103:172001,2009**
  - Flavor sensitive quark Sivers measurement
  - **Instrumentation:**
    Ready : **Upgrade in progress**







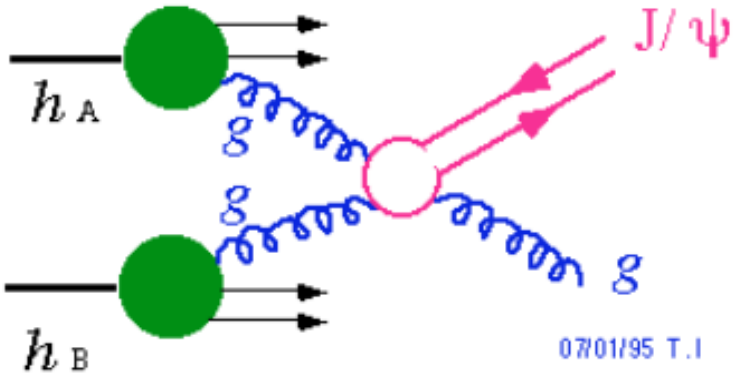
Backup

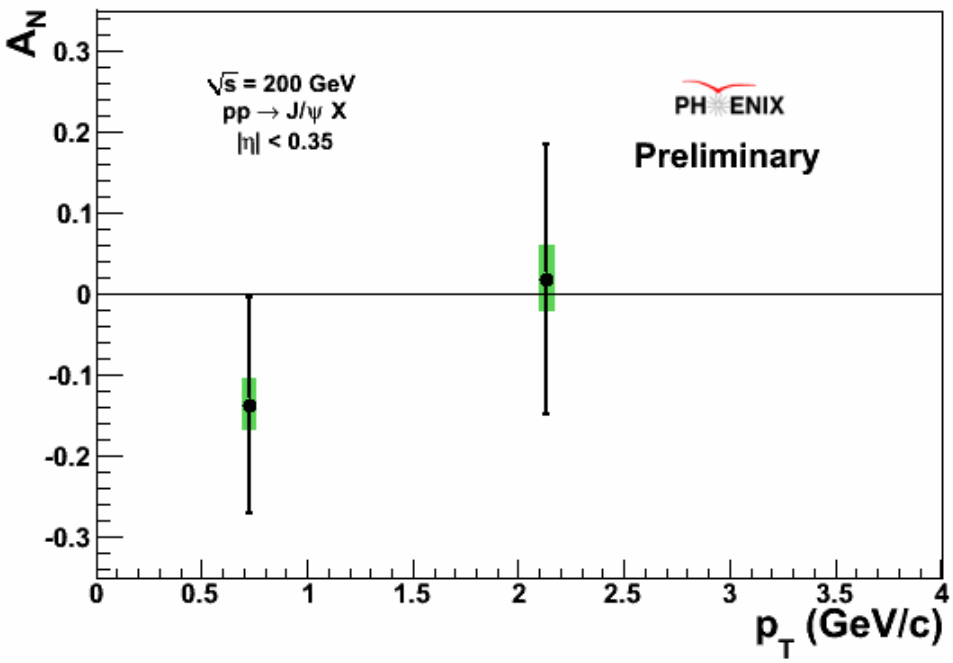
(iii) Constraints on Sivers Function: J/Psi

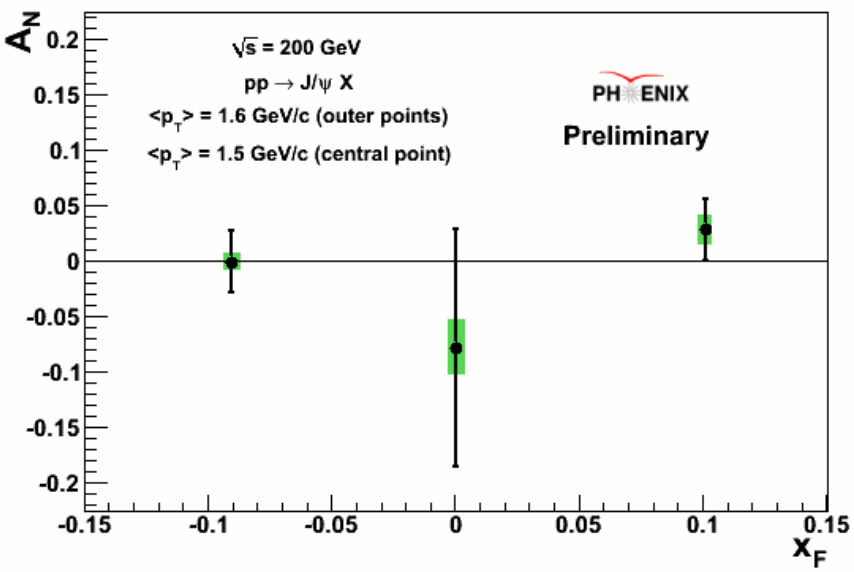
Exploratory measurement of A_N J/Psi

- J/Psi production mechanism not well understood
- Single spin asymmetries may shed light on production mechanism

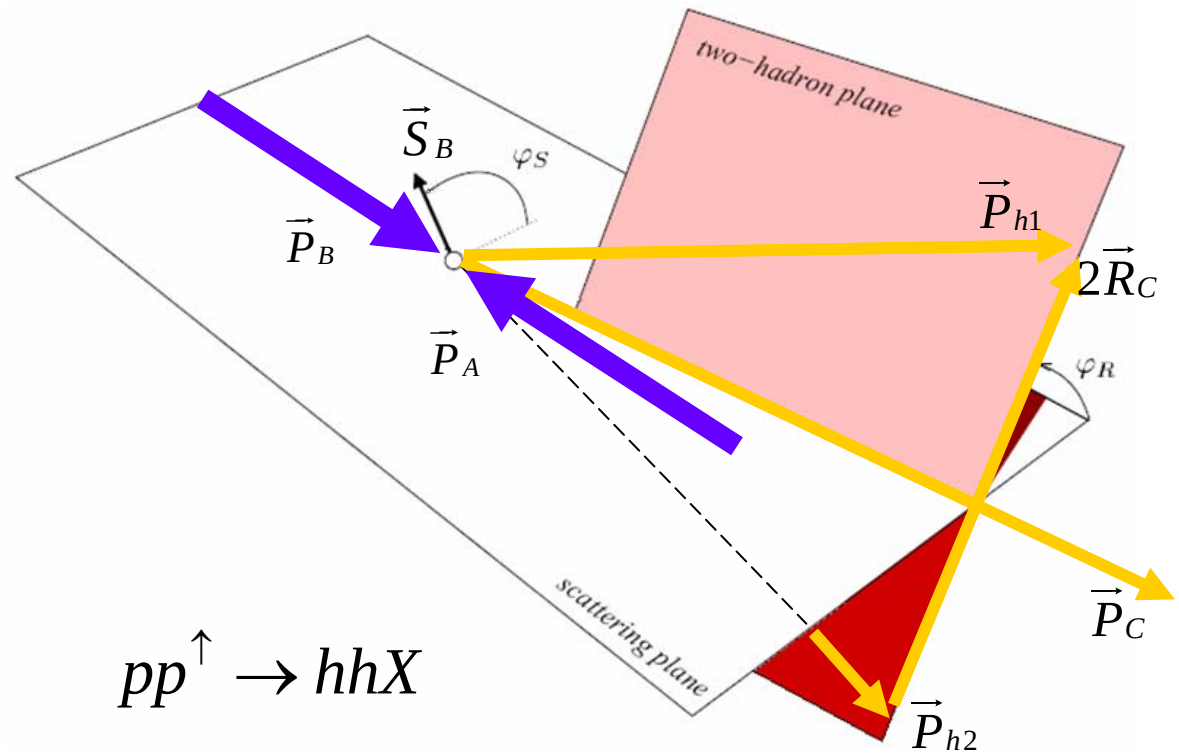
Constraints on gluon Sivers function
PRD78:014024,2008







IFF: Definition of Vectors and Angles



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

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

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

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

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

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

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

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

Bacchetta and Radici, PRD70, 094032 (2004)

IFF: Transversity from di-hadron SSA

Physics asymmetry $A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\sigma_{UT}}{\sigma_{UU}}$

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

Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

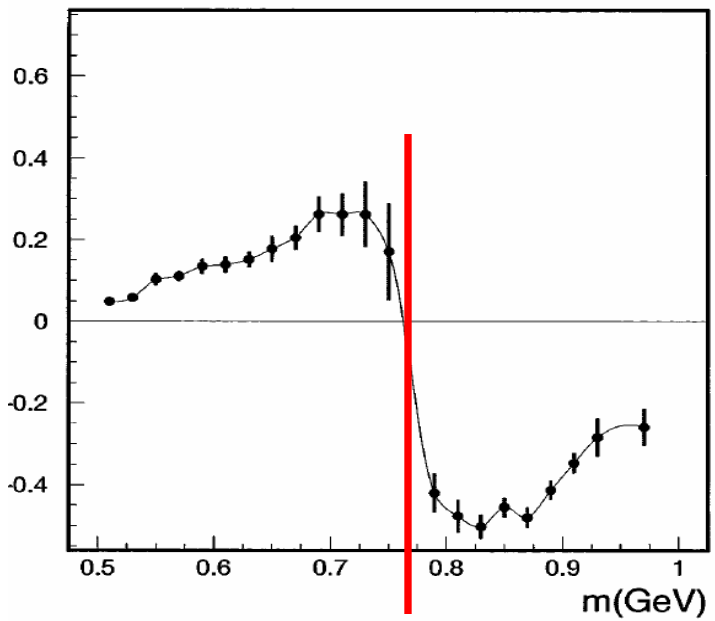
Hard scattering cross section
from pQCD

IFF + Di-hadron FF
to be measured in e+e-

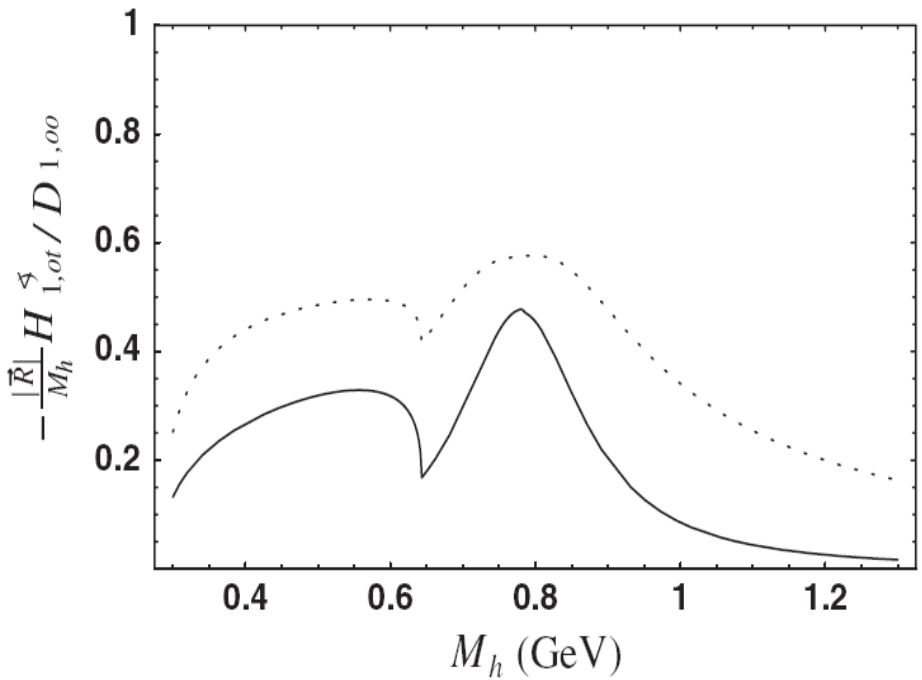
$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab\uparrow\to c\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

Models for Interference Fragmentation Function

$$H_1^{\sphericalangle sp} \sim \delta\hat{q}_I(z)\ \sin\delta_0\ \sin\delta_1\ \sin(\delta_0 - \delta_1)$$



- Use partial wave analysis of $\pi\pi$ phase shift data to model IFF
- $q \to (\rho, \sigma) \to \pi\pi$
- **Sign change around ρ mass**
- *Jaffe, Jin and Tang, PRL 80 (1998) 1166*

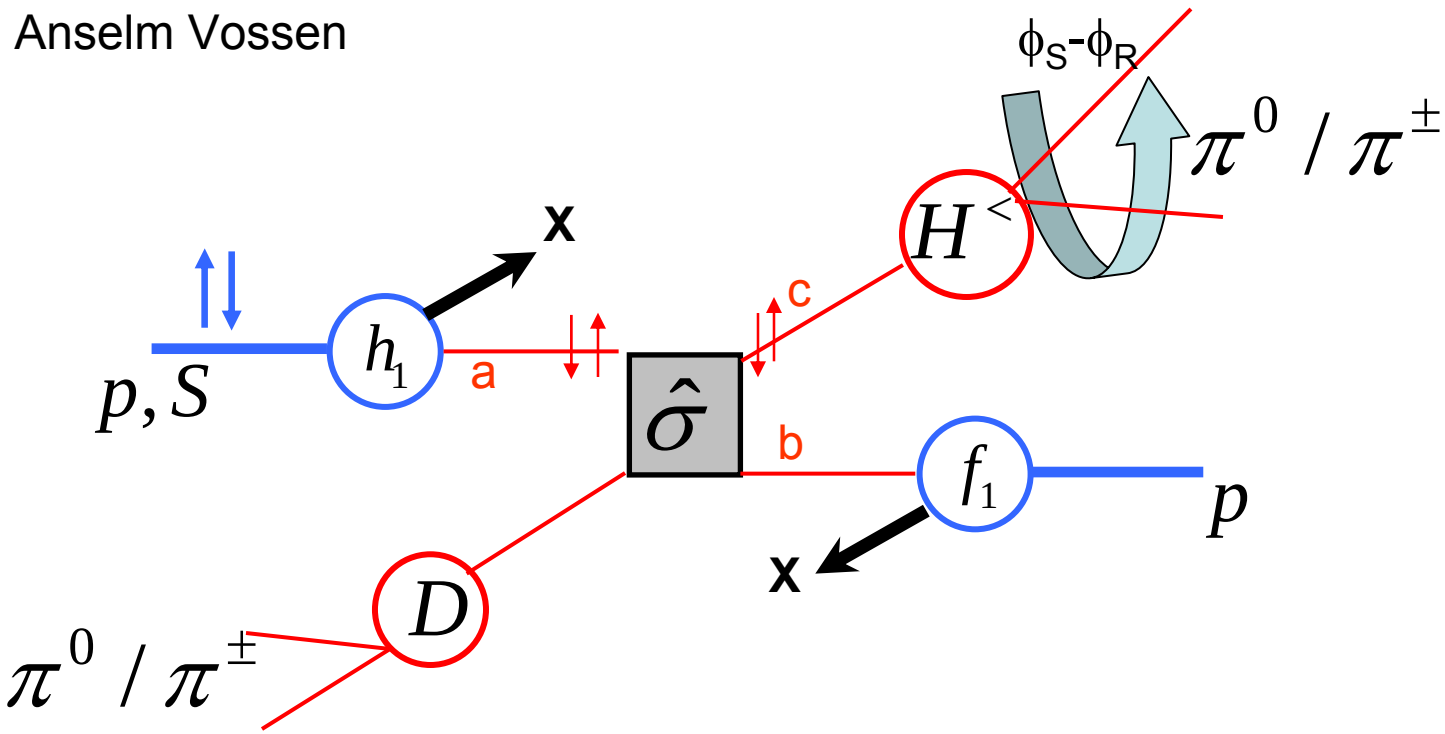


- Breit-Wigner shape for ρ wave
- **No sign change around ρ mass**
- Trend consistent with HERMES results
- *Bacchetta and Radici, Phys. Rev. D 74, 114007 (2006)*

Analysis done in mass bins above and below the ρ mass

Interference Fragmentation Function in p-p

Slide from Anselm Vossen

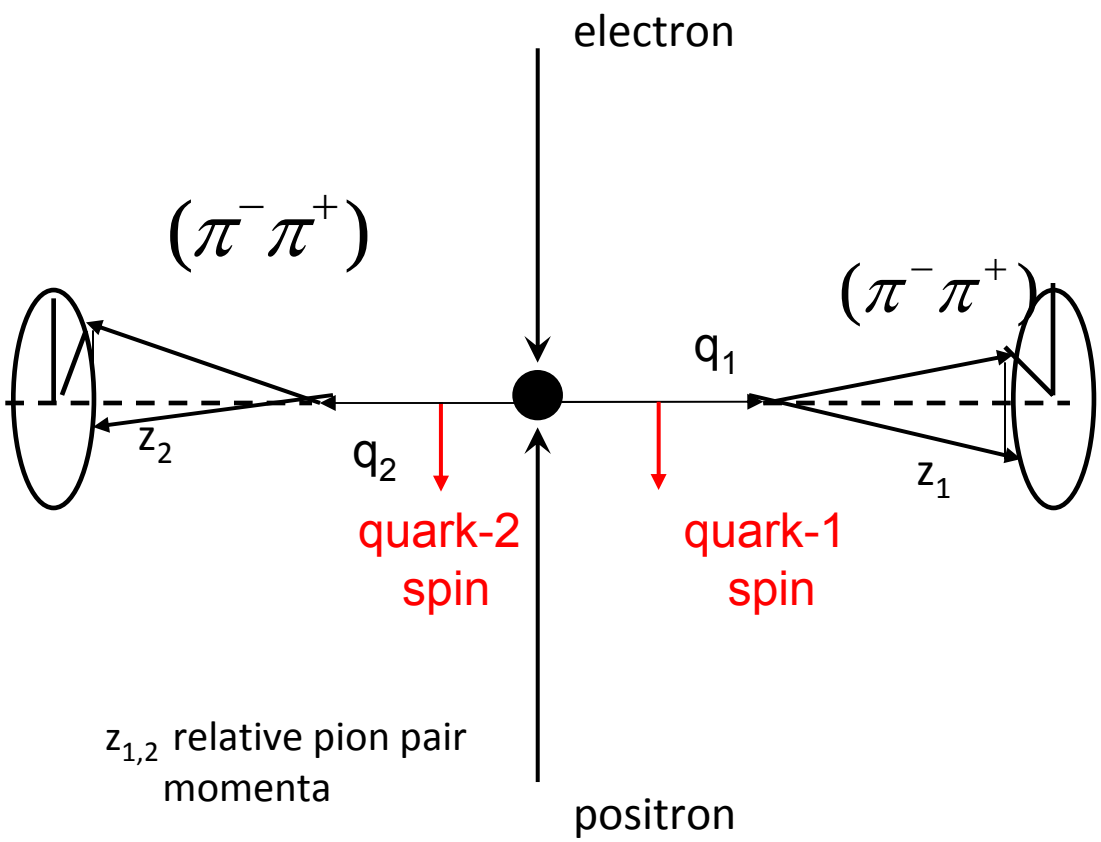


$$\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}(\phi_S - \phi_R) = A_{UT}\sin(\phi_S - \phi_R) \qquad A_{UT} \propto h_1 \otimes H_1^<$$

ϕ_S: Angle between polarisation vector and event plane
ϕ_R: Angle between two hadron plane and event plane

Measuring di-Hadron Correlations In e^+e^- Annihilation into Quarks

Slide from Anselm Vossen



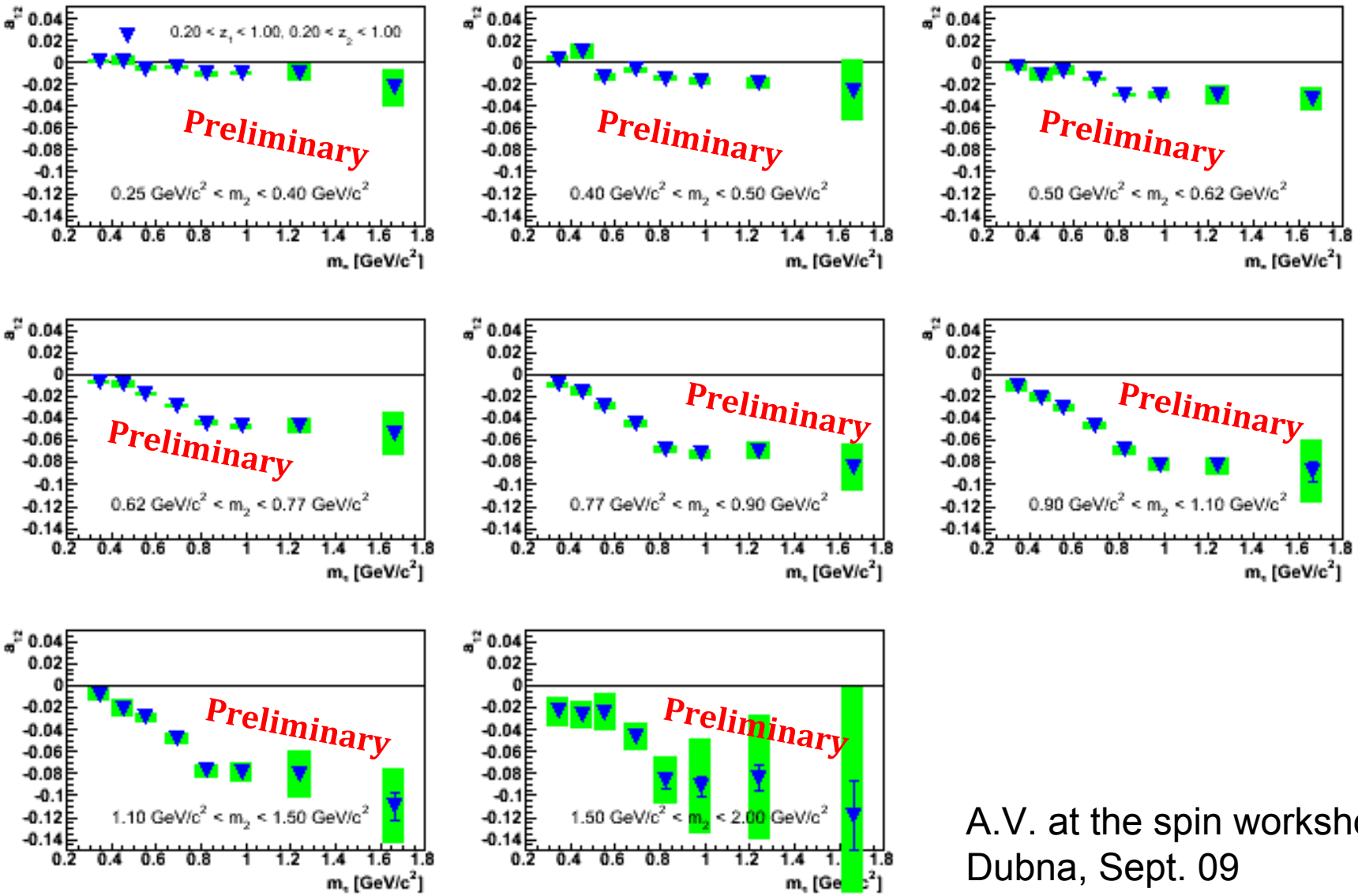
Interference effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

Experimental requirements:

- Small asymmetries ➔ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

Slide from Anselm Vossen

Belle: Asymmetries in $e^+ e^-$

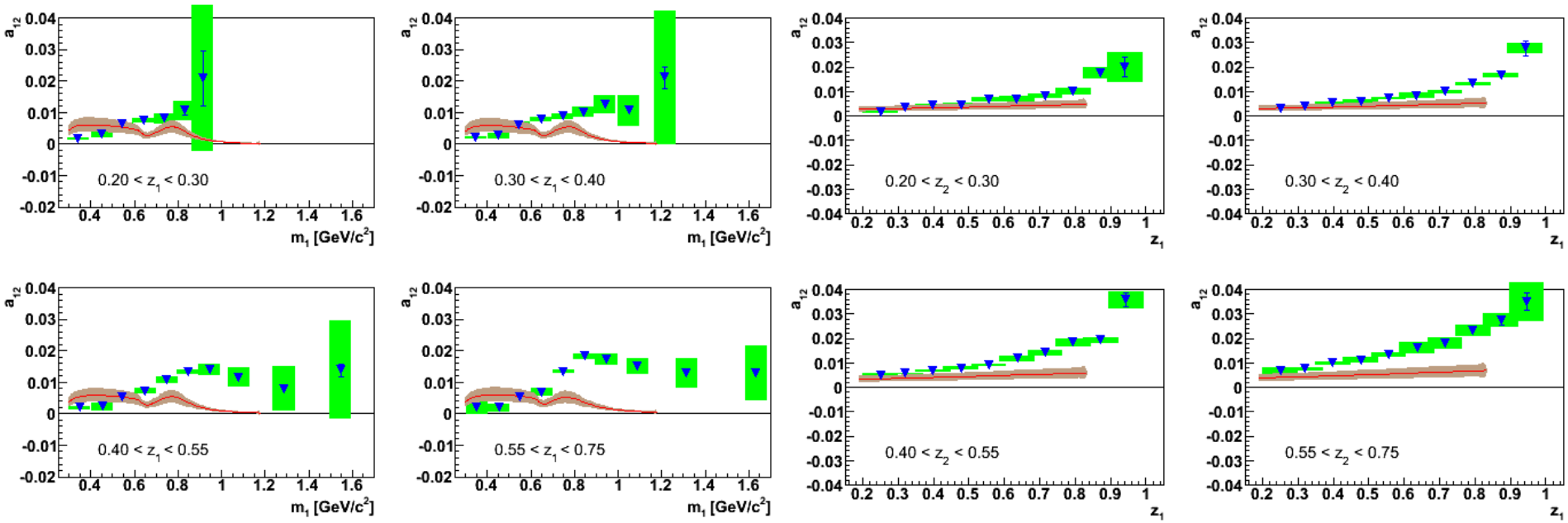


8x8 m_1 m_2 binning

A.V. at the spin workshop in Dubna, Sept. 09

Slide from Anselm Vossen

Comparison to Theory Predictions



Initial model description by Bacchetta,Checcopieri, Mukherjee, Radici : **Phys.Rev.D79:034029,2009**.

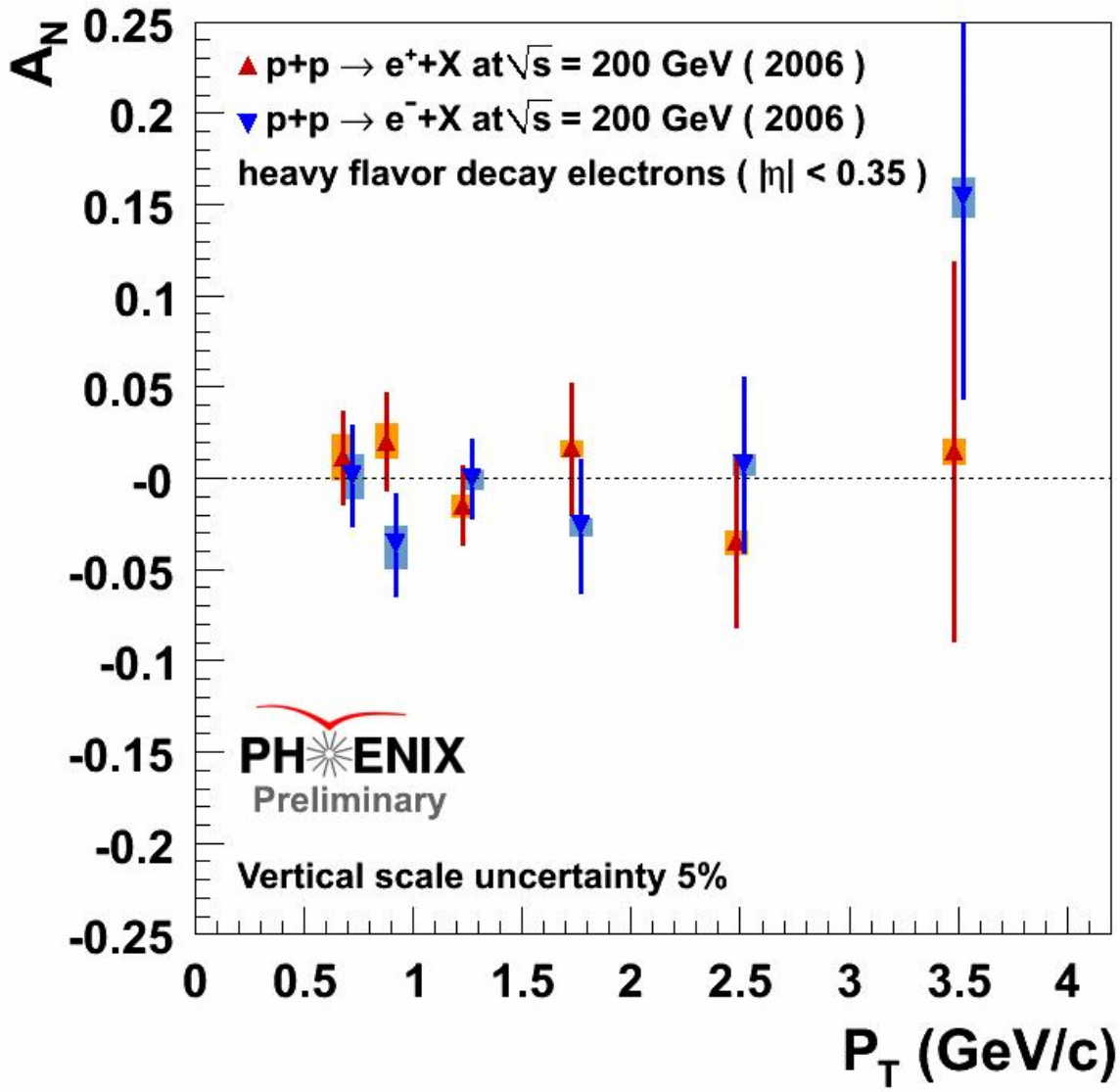
Leading order,

Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)

Z dependence : Rising behavior steeper

However: Theory contains parameters based on HERMES data which already fail to explain COMPASS well

Central arm charge-separated heavy flavor A_N



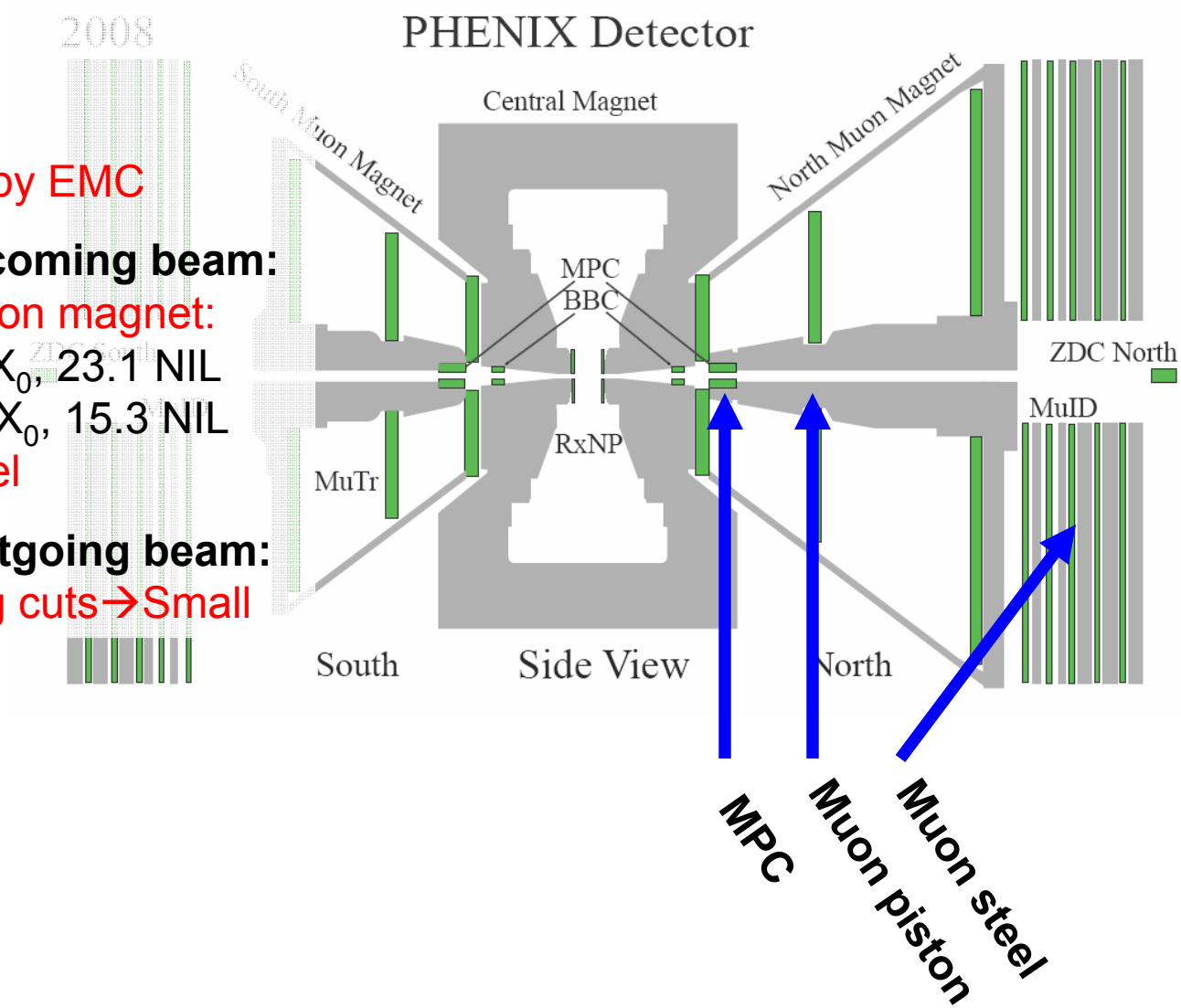
Beam backgrounds in the MPC

Three considerations:

1) **Charged hadrons**
   Naturally suppressed by EMC

2) **Background from incoming beam:**
   Shielded by muon piston magnet:
   North: 387.4 cm, 220 X_0, 23.1 NIL
   South: 256.9 cm, 146 X_0, 15.3 NIL
   Shielded by muon steel

3) **Background from outgoing beam:**
   Evaluated using timing cuts→Small



The tunes

QCD_hard_p100

```
roots   200
proj    p
targ    p
frame   cms
msel    0       // turn on all prod.
mechanisms manually
msub    11 1    // QCD jets
msub    12 1
msub    13 1
msub    28 1
msub    53 1
msub    68 1
msub    96 1
ckin    3  2.0
pytune 100
```

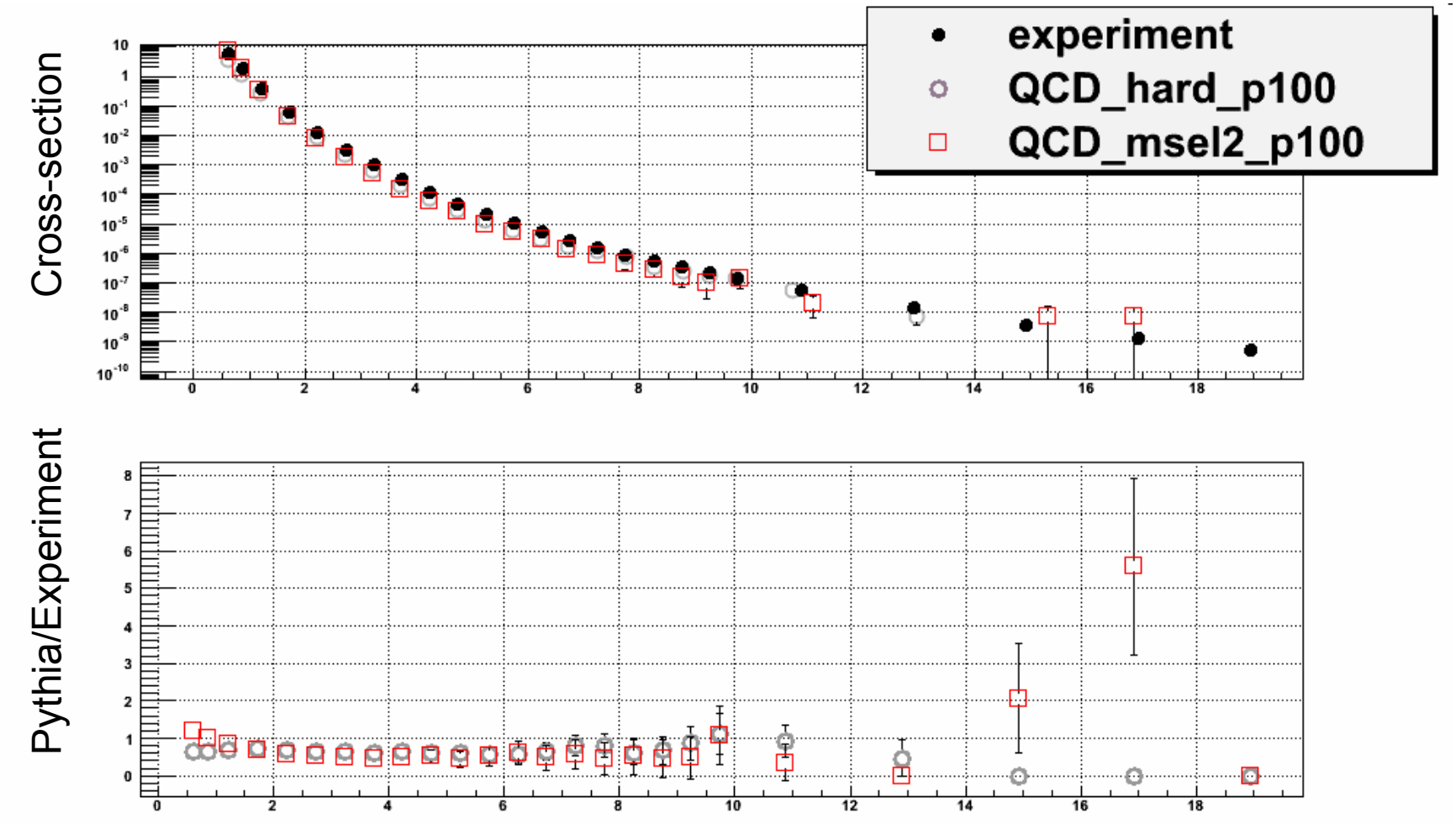
QCD_dgam_p100

```
roots   200
proj    p
targ    p
frame   cms
msel    0
msub    14 1
msub    18 1
msub    29 1
msub    114 1
msub    115 1
ckin    3  2.0
pytune 100
```

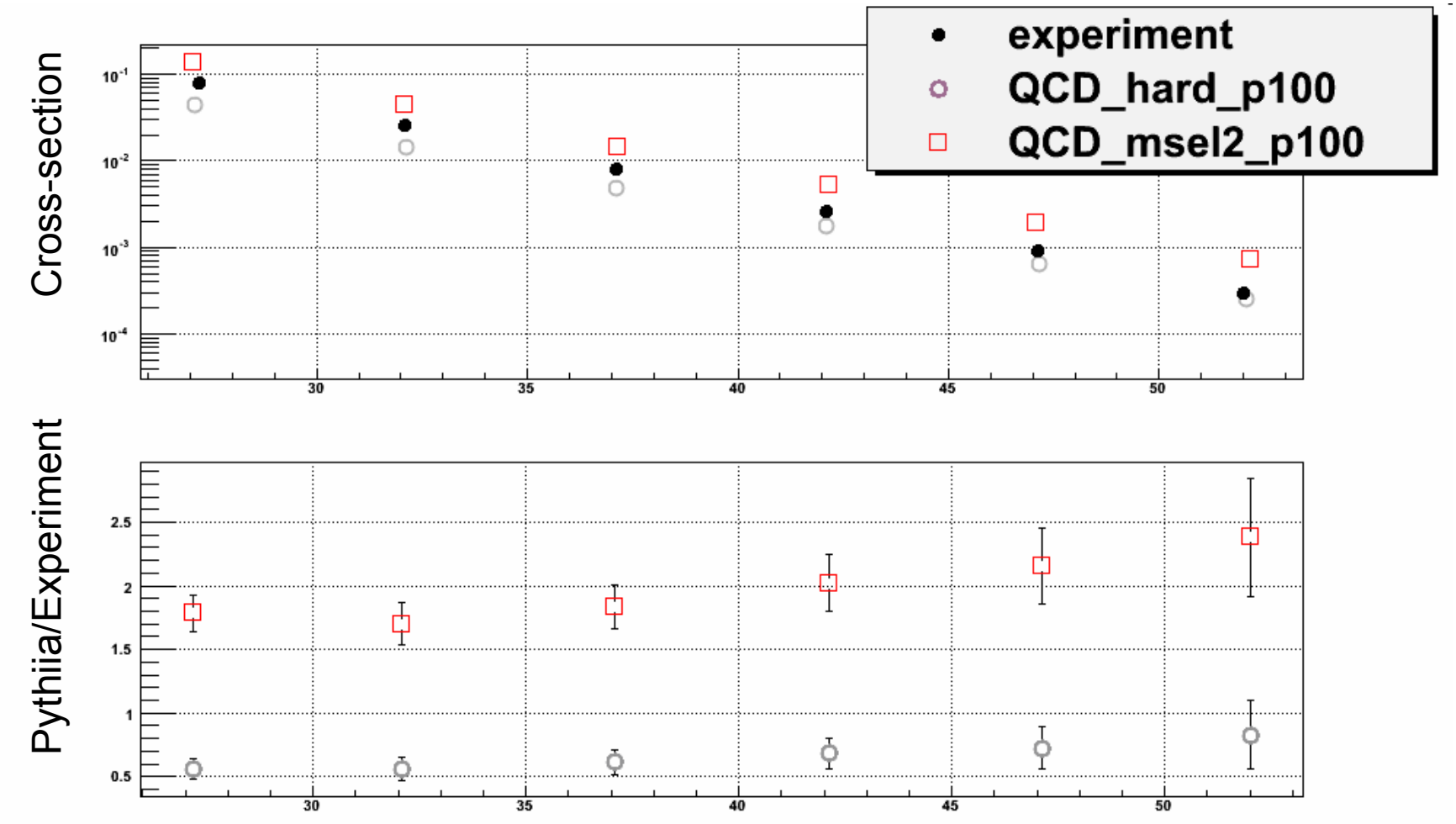
QCD_msel2_p100

```
roots   200
proj    p
targ    p
frame   cms
msel    2
pytune 100
```

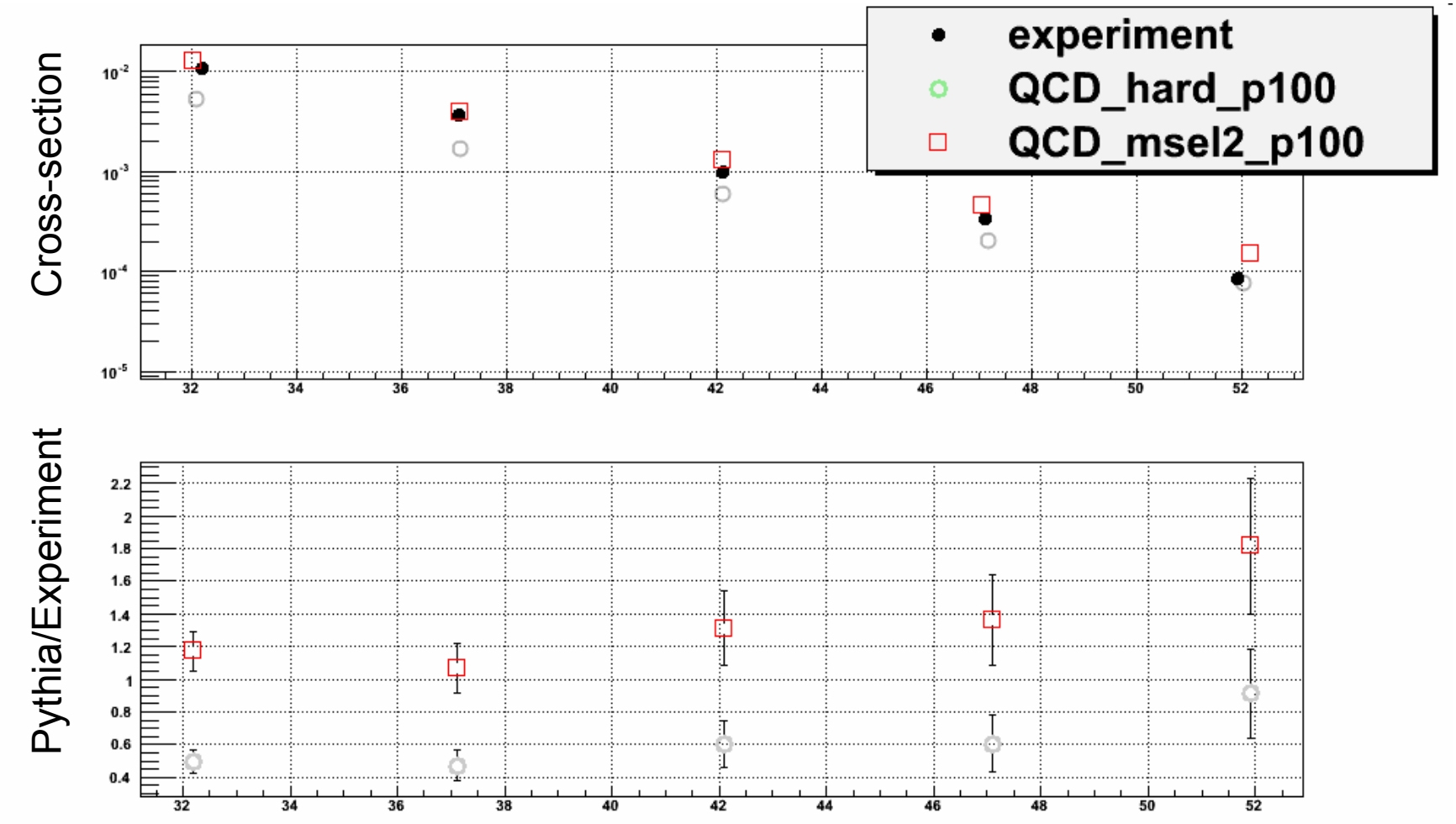
PHENIX pi0 central arm comparison



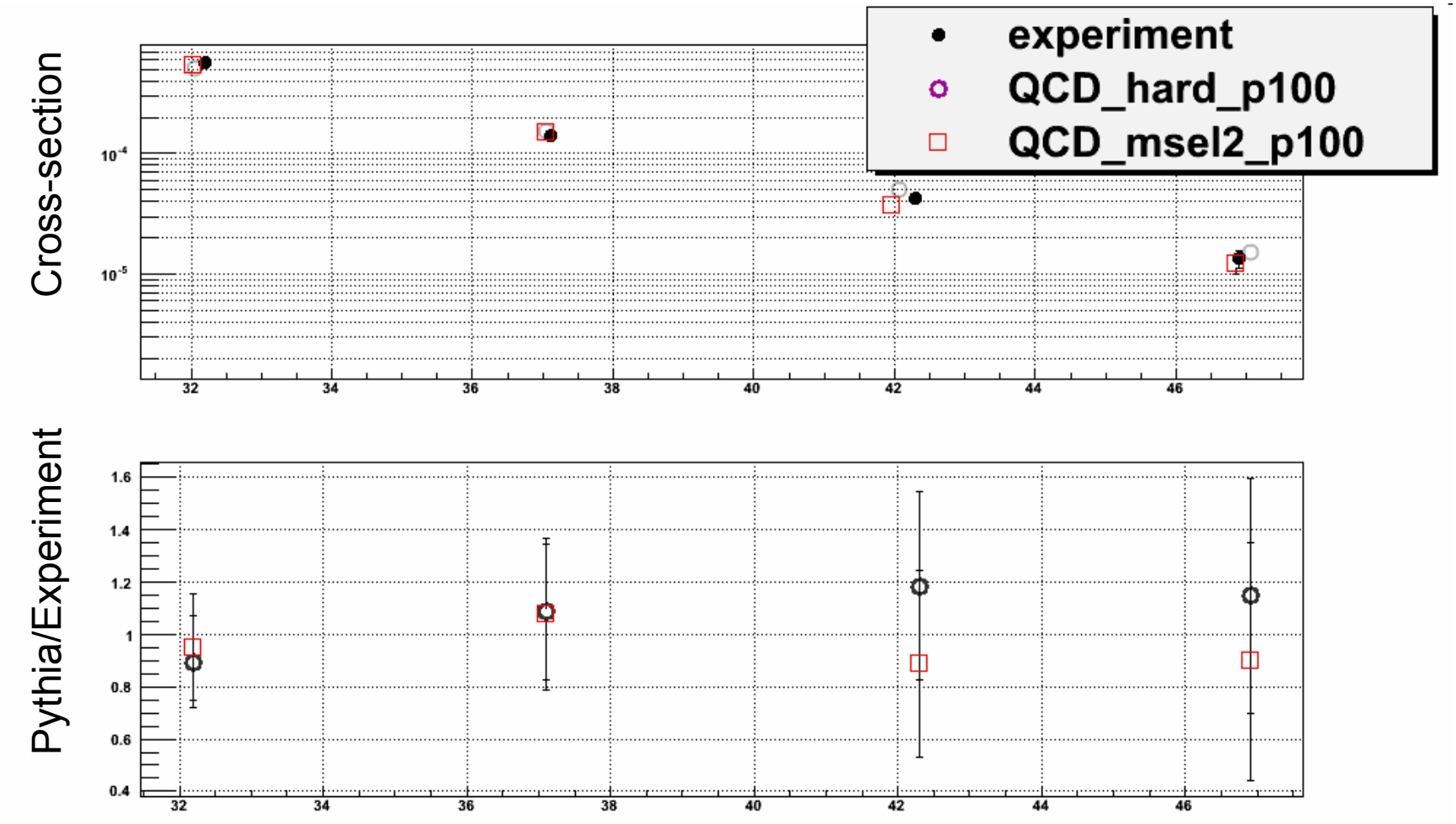
STAR pi0 Comparison (3.7<eta<4.15)



STAR pi0 Comparison (3.4<eta<4.0)

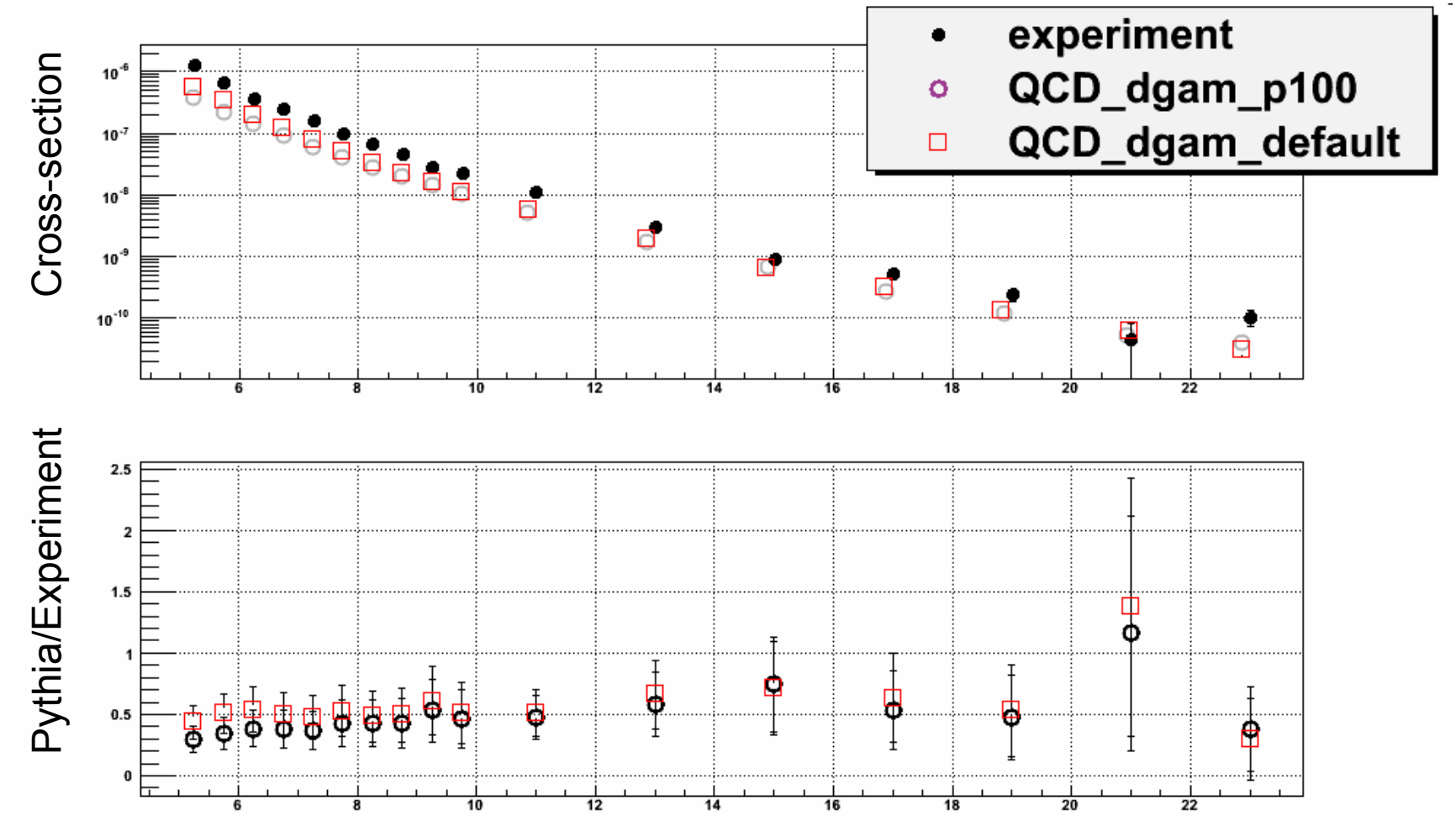


STAR pi0 Comparison (3.05<eta<3.45)



Set QCD_hard_p100 k-factor = 1

PHENIX Direct photon comparison



Set QCD_dgam_p100 k-factor = 2