Single-Spin Asymmetries and Transverse-Momentum-Dependent Distributions at RHIC

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Spin physics at RHIC

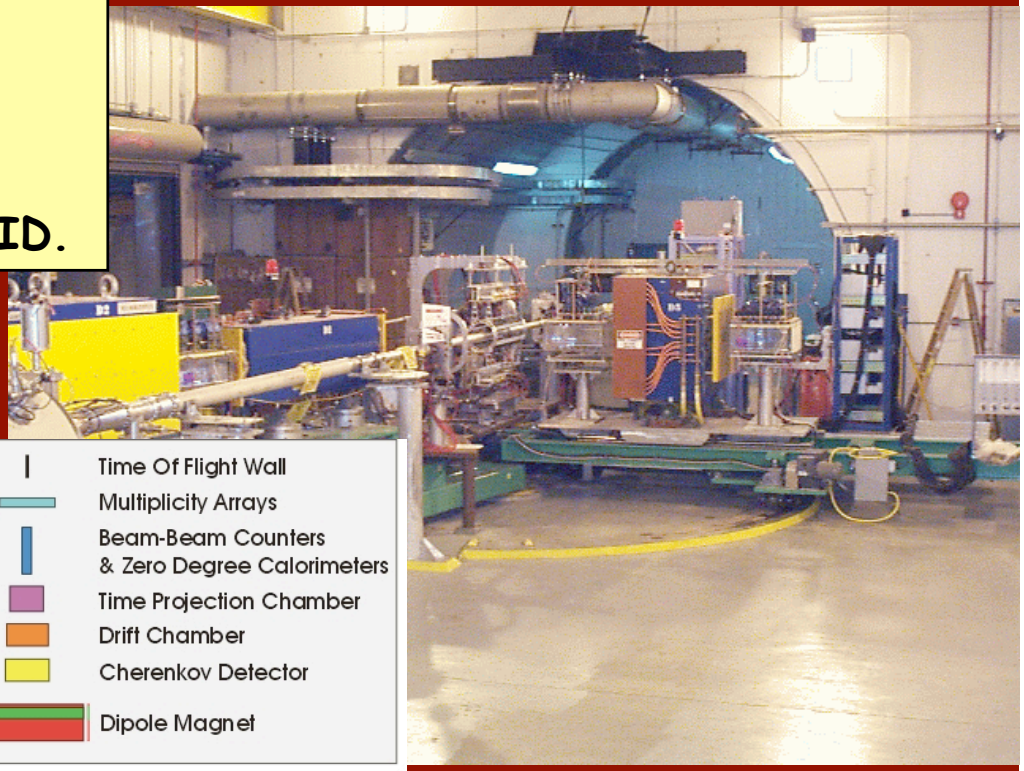
- Polarized protons at RHIC 2002-present
- Mainly $\sqrt{s}$ = 200 GeV, also 62.4 GeV in 2006, started 500 GeV program in 2009

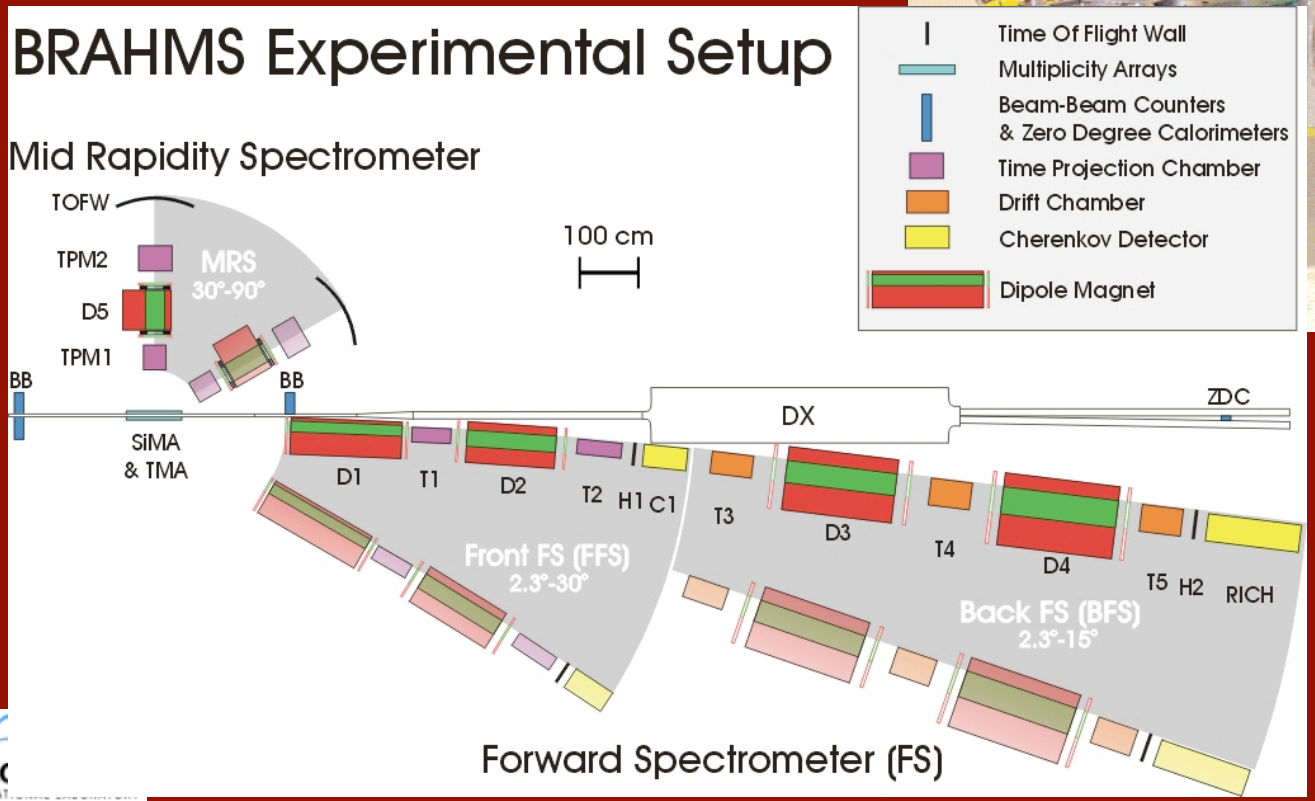
- Two large multipurpose detectors: STAR and PHENIX
  - Longitudinal or transverse polarization
- One small spectrometer until 2006: BRAHMS
  - Transverse polarization only

BRAHMS detector

Philosophy:

Small acceptance spectrometer arms designed with good charged particle ID.





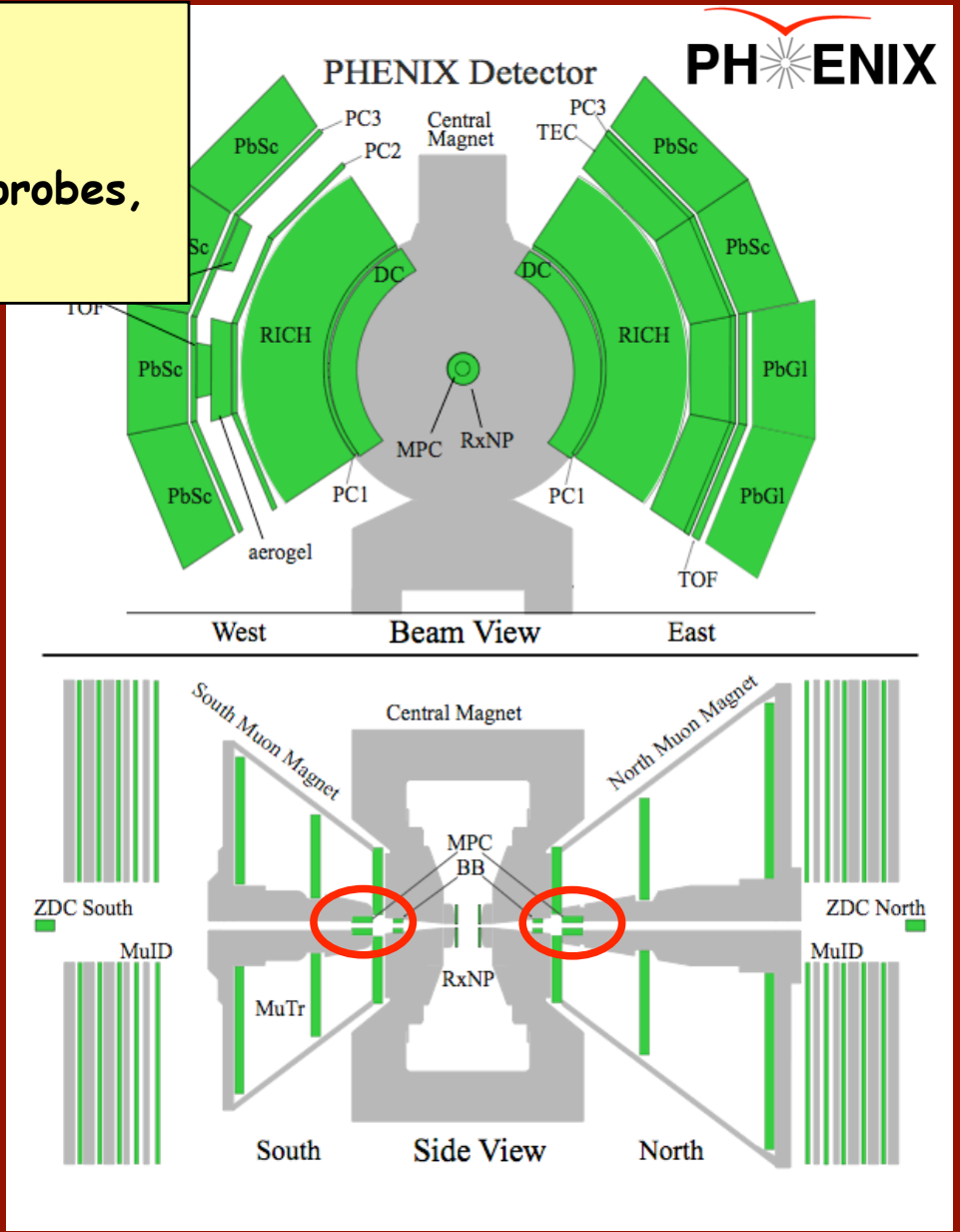
BRAHMS

PHENIX detector

Philosophy:

High rate capability to measure rare probes, limited acceptance.

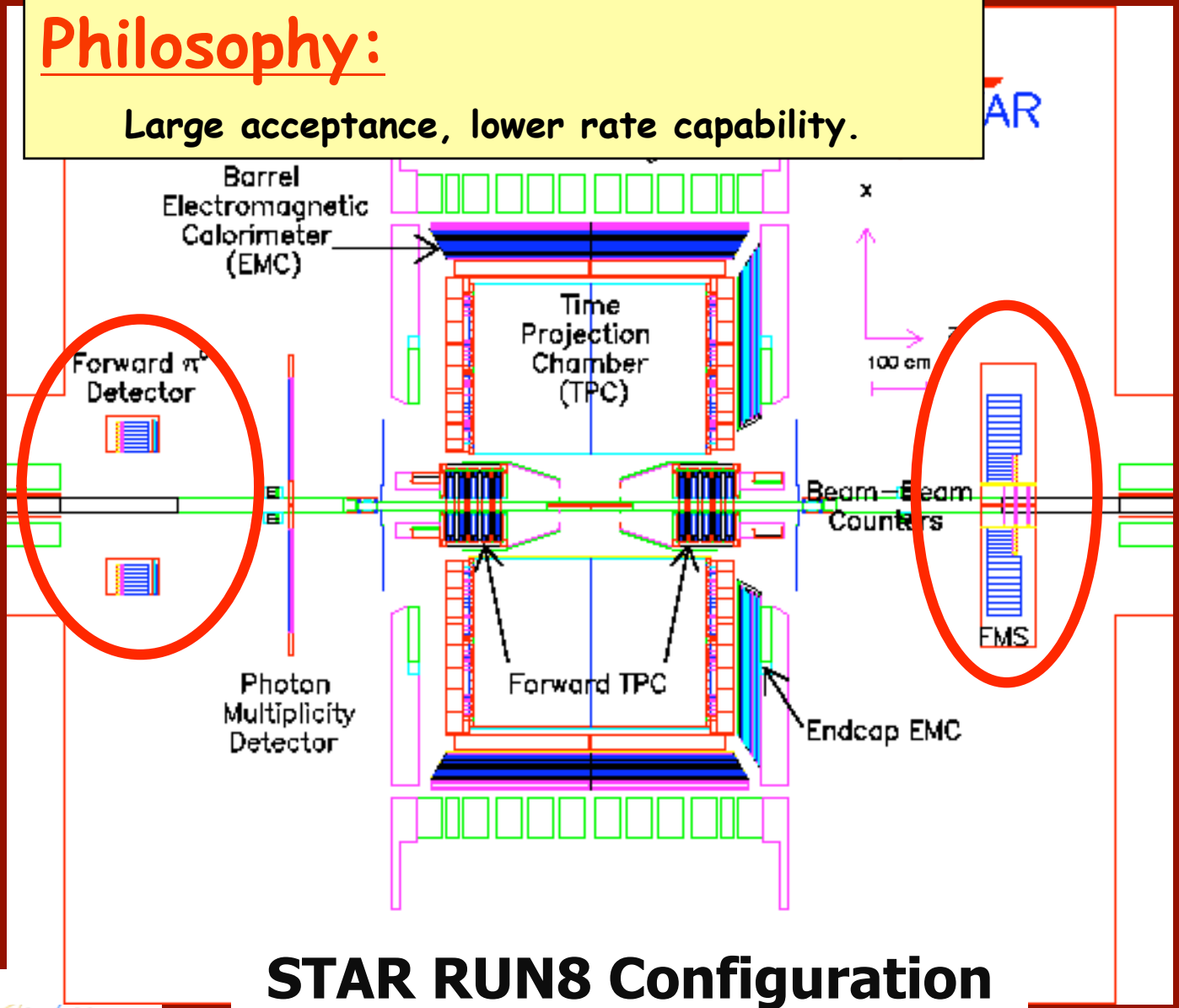
- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes
    $|\eta| < 0.35$
    $90^\circ + 90^\circ$ azimuth
- 2 forward muon spectrometers
  - Identify and track muons
    $1.2 < |\eta| < 2.4$
    2π azimuth
- 2 forward calorimeters (as of 2007)
  - Measure forward pions, etas
    $3.1 < |\eta| < 3.7$
    2π azimuth
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



STAR detector

Philosophy:

Large acceptance, lower rate capability.



STAR RUN8 Configuration

TPC: $-1.0 < \eta < 1.0$
FTPC: $2.8 < |\eta| < 3.8$
BBC : $2.2 < |\eta| < 5.0$
EEMC: $1 < \eta < 2$
BEMC: $-1 < \eta < 1$

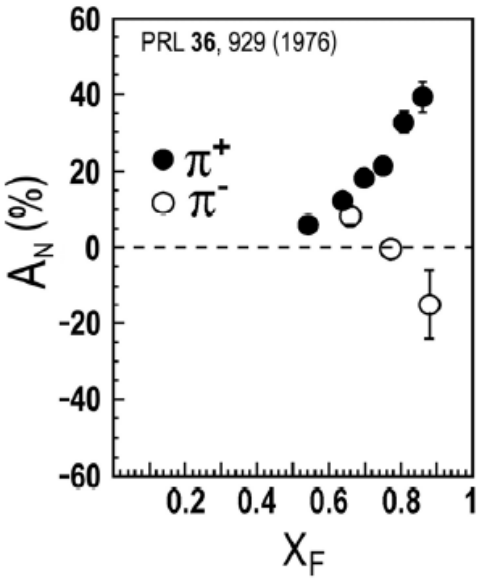
FPD/FPD++:
$\eta \sim 3.3 - 4.1$

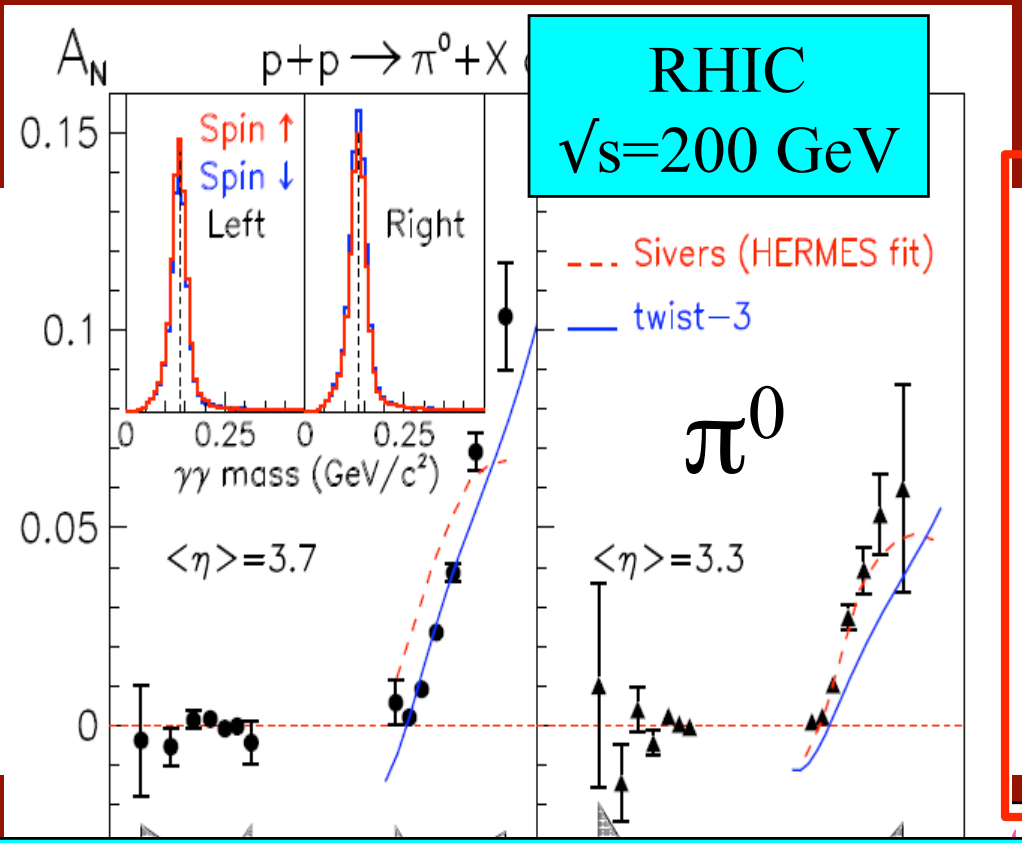
As of 2008
FMS : $2.5 < \eta < 4.1$

Transverse Single-Spin Asymmetries: From Low to High Energies!

BRAHMS

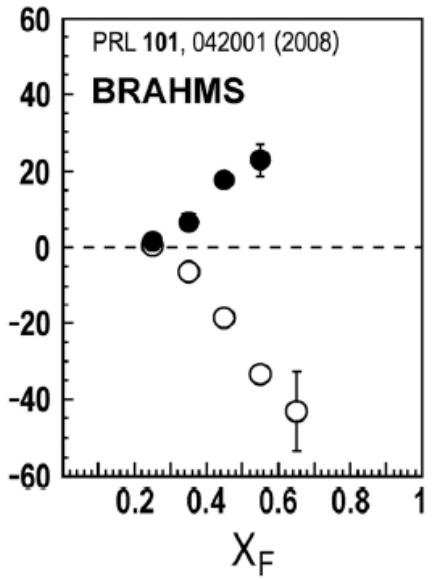
ANL
√s=4.9 GeV





RHIC
√s=200 GeV

RHIC
√s=62.4 GeV



These soft effects—due to QCD *dynamics* within the nucleon—remain relevant up to scales where we can attempt to describe them using pQCD

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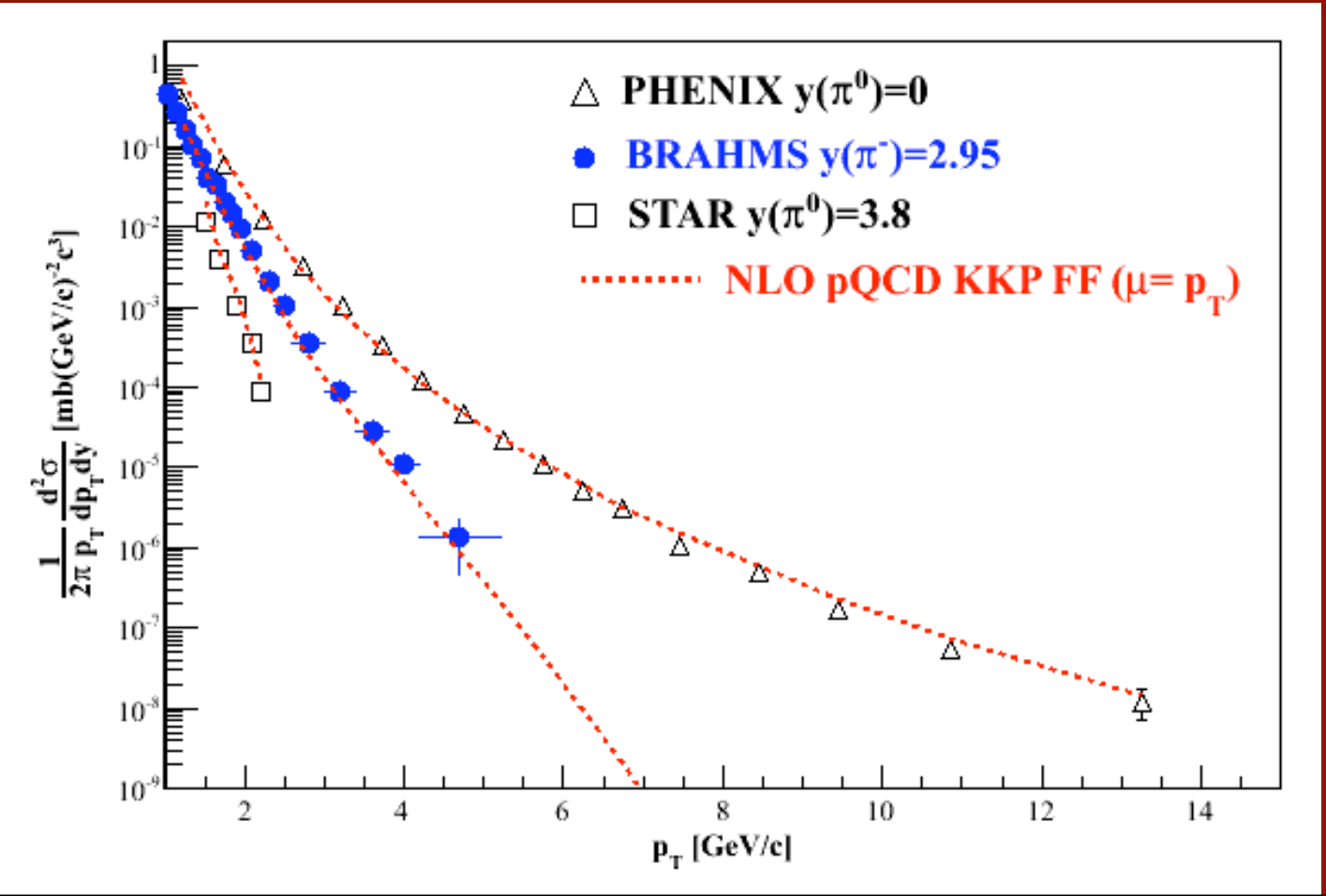
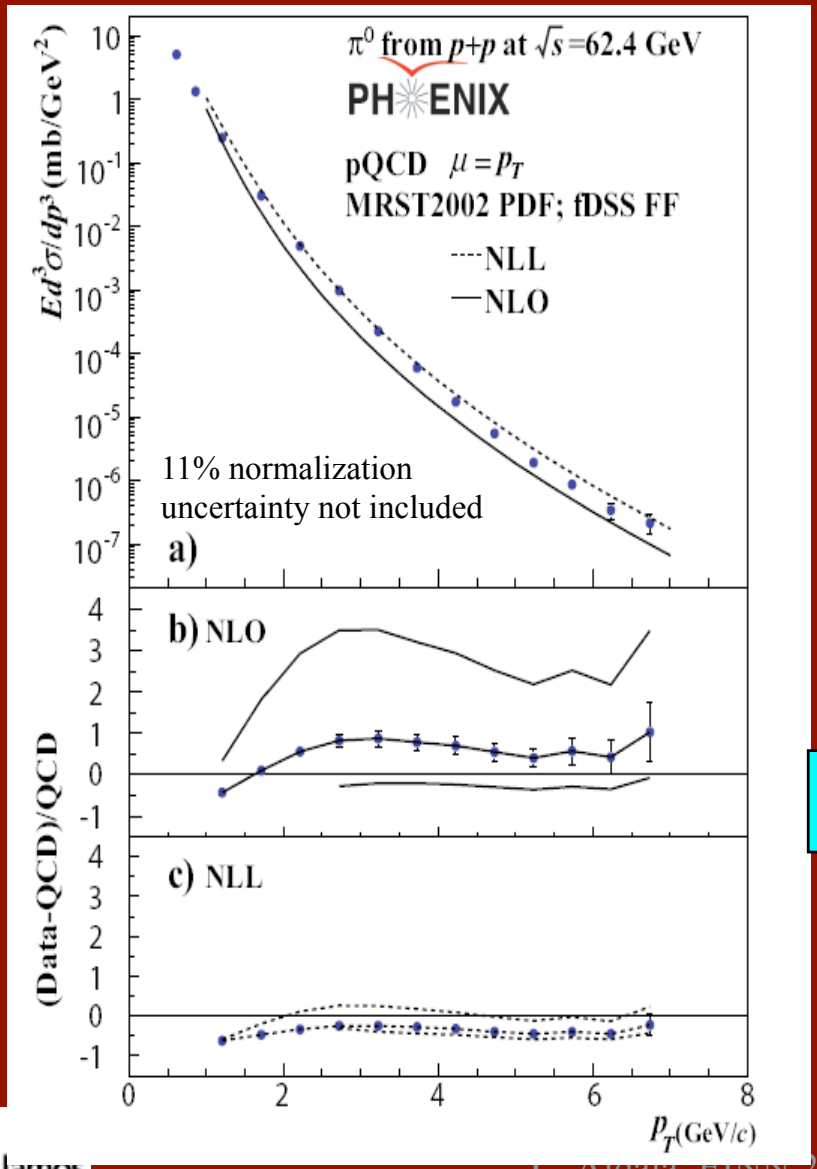
Polarization-averaged cross sections at √s=200 GeV



Good description at 200 GeV over all rapidities down to p_T of 1-2 GeV/c.

Lower energies: √s=62.4 GeV

PRD79, 021002 (2009) *Midrapidity pions*



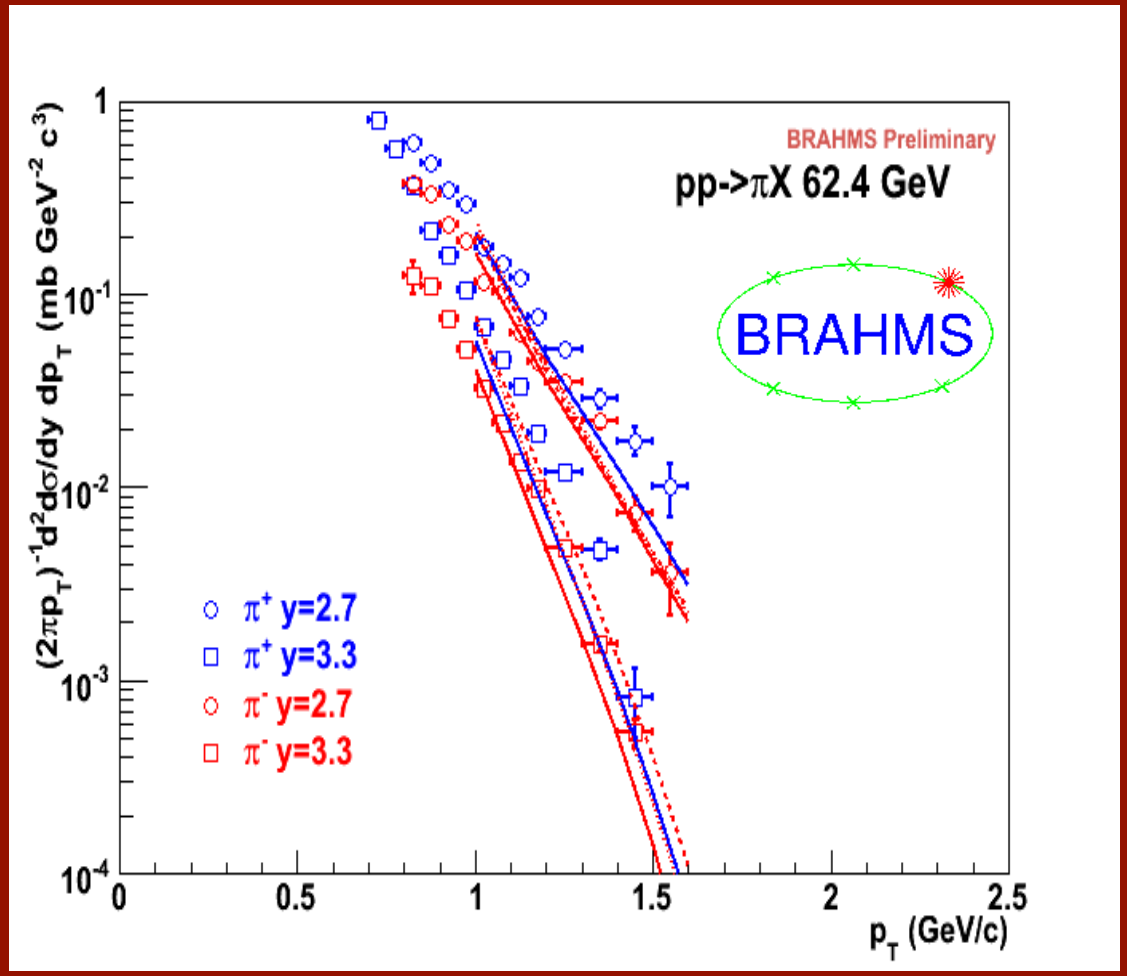
Comparisons to NLO and NLL pQCD calculations using $\mu=p_T$ shown.

Unlike at 200 GeV, scale choice of $\mu=p_T$ underpredicts the data.

→ Threshold logarithm effects still relevant at this intermediate energy?

But—overall, pretty good agreement!

$\sqrt{s}$=62.4 GeV
Forward pions



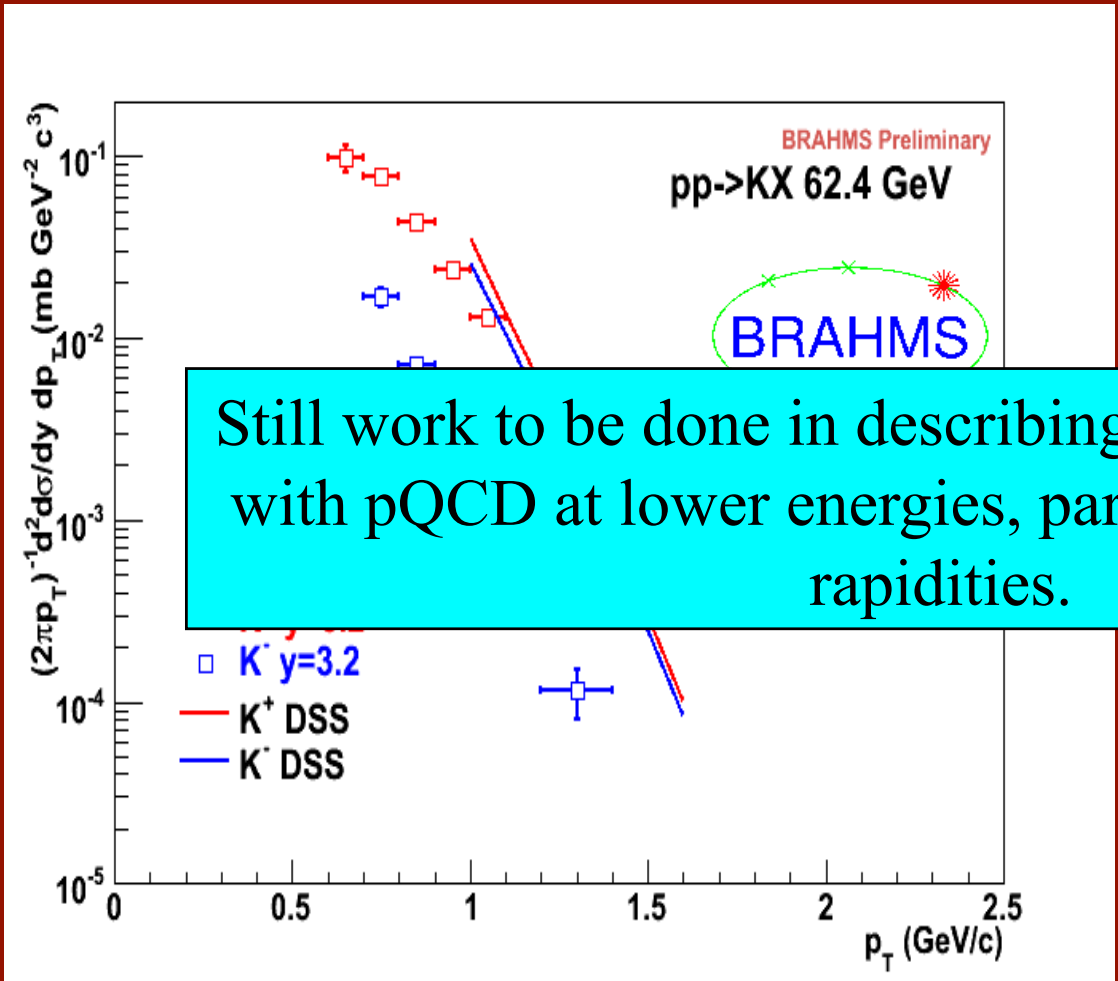
Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of $\mu=p_T$, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

Surprisingly good description of data, in apparent disagreement with earlier analysis of ISR π^0 data at 53 GeV.

No comparison to NLL yet.

Still not so bad!

$\sqrt{s}$=62.4 GeV
Forward kaons



Still work to be done in describing hadronic collisions with pQCD at lower energies, particularly at forward rapidities.

K$^-$ *data* suppressed ~order of magnitude (valence quark effect).

NLO pQCD using recent
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s(??).

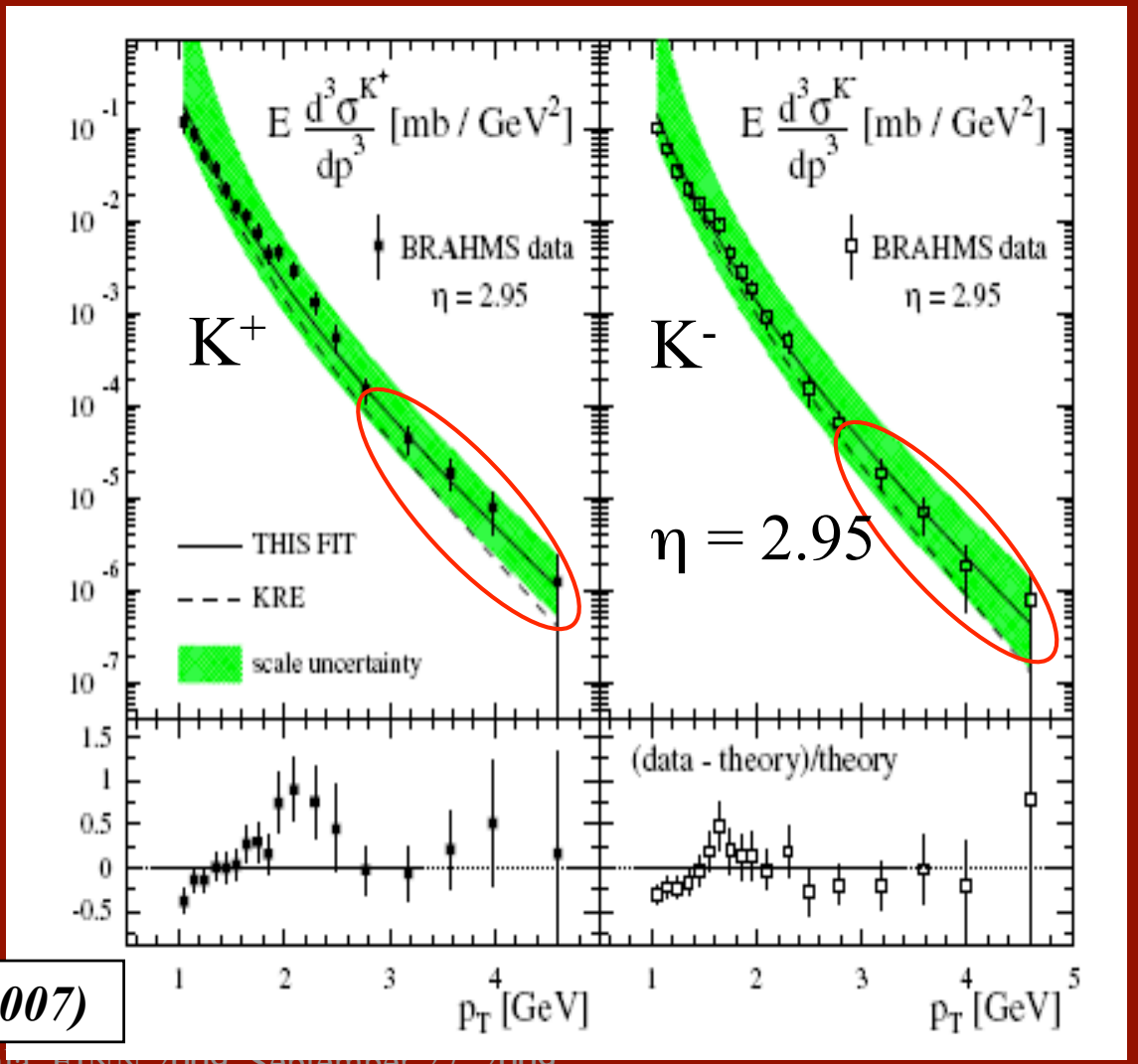
Related to FF's? PDF's??

No comparison to NLL yet.

K$^+$: Not bad!
K$^-$: Hmm…

Improving input to pQCD calculations

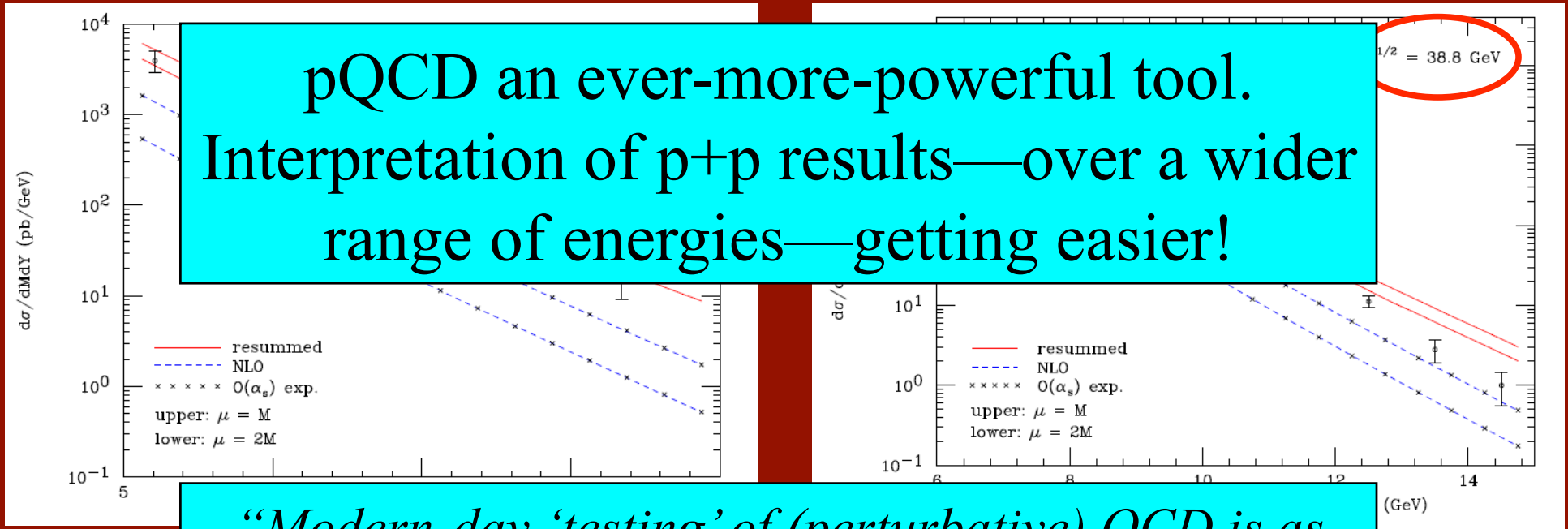
Hadronic collision data now being included in fragmentation function fits
- de Florian, Sassot and Stratmann (PRD **75,** 114010 (2007) and other works)



*BRAHMS data: PRL **98, 252001 (2007)***

Progress in pQCD calculational techniques

38.8 GeV!



pQCD an ever-more-powerful tool. Interpretation of p+p results—over a wider range of energies—getting easier!

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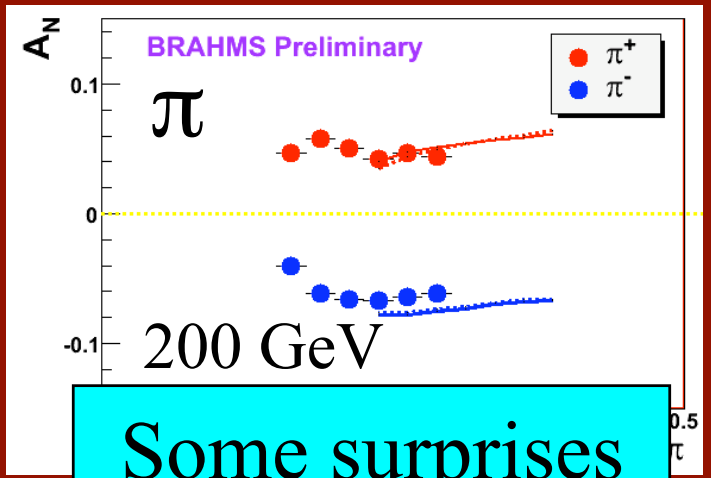
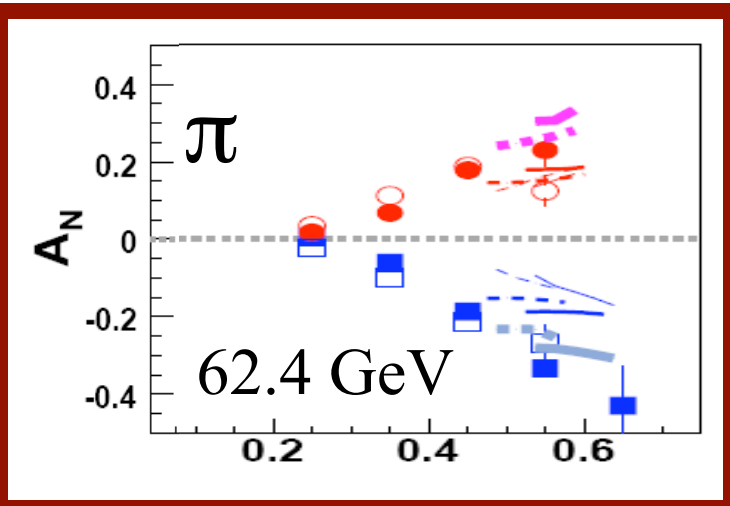
"Modern-day 'testing' of (perturbative) QCD is as much about pushing the boundaries of its applicability as about the verification that QCD is the correct theory of hadronic physics."
– G. Salam, hep-ph/0207147 (DIS2002 proceedings)

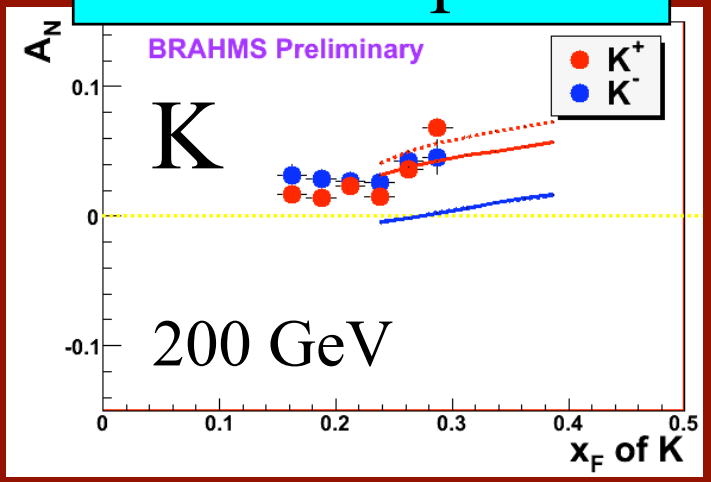


SSAs observed at RHIC: 200 and 62.4 GeV

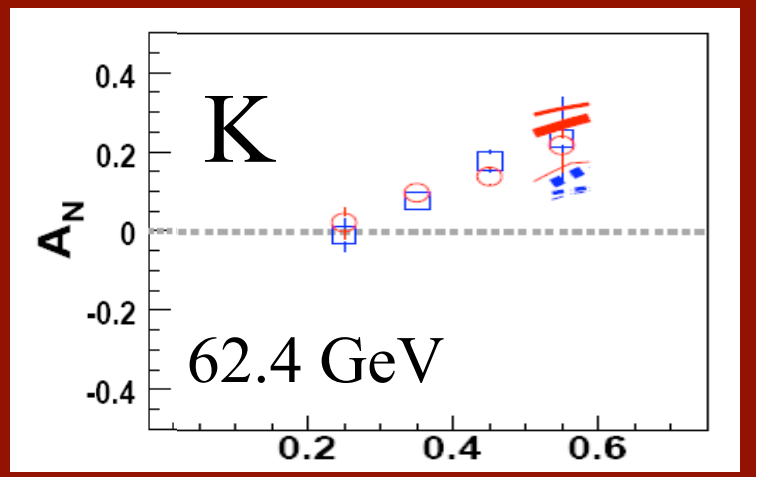


Some surprises

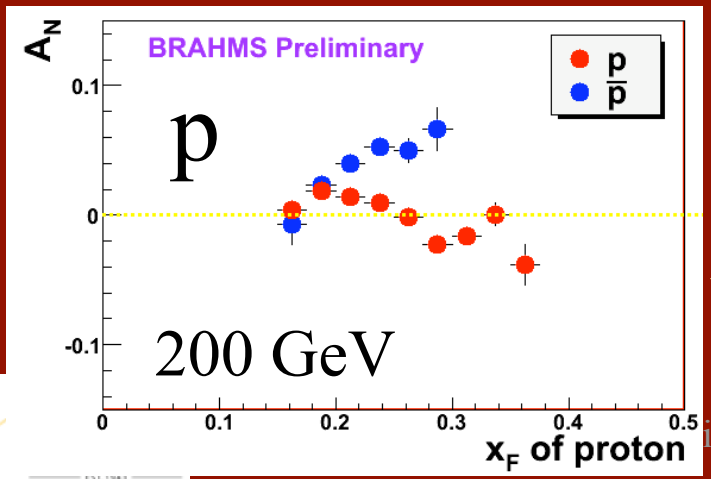
Note different scales



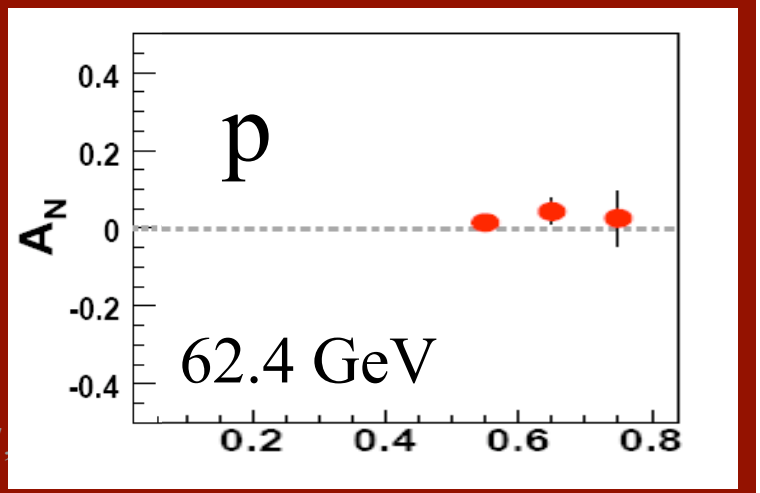
K- asymmetries underpredicted



BRAHMS



Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement



Another Surprise: Transverse Single-Spin Asymmetry in Eta Meson Production

$p^{\uparrow} + p \rightarrow \eta + X \quad \sqrt{s} = 200\,\text{GeV}$

$\eta \rightarrow$

Further evidence against a valence quark effect!

Larger than the neutral pion!

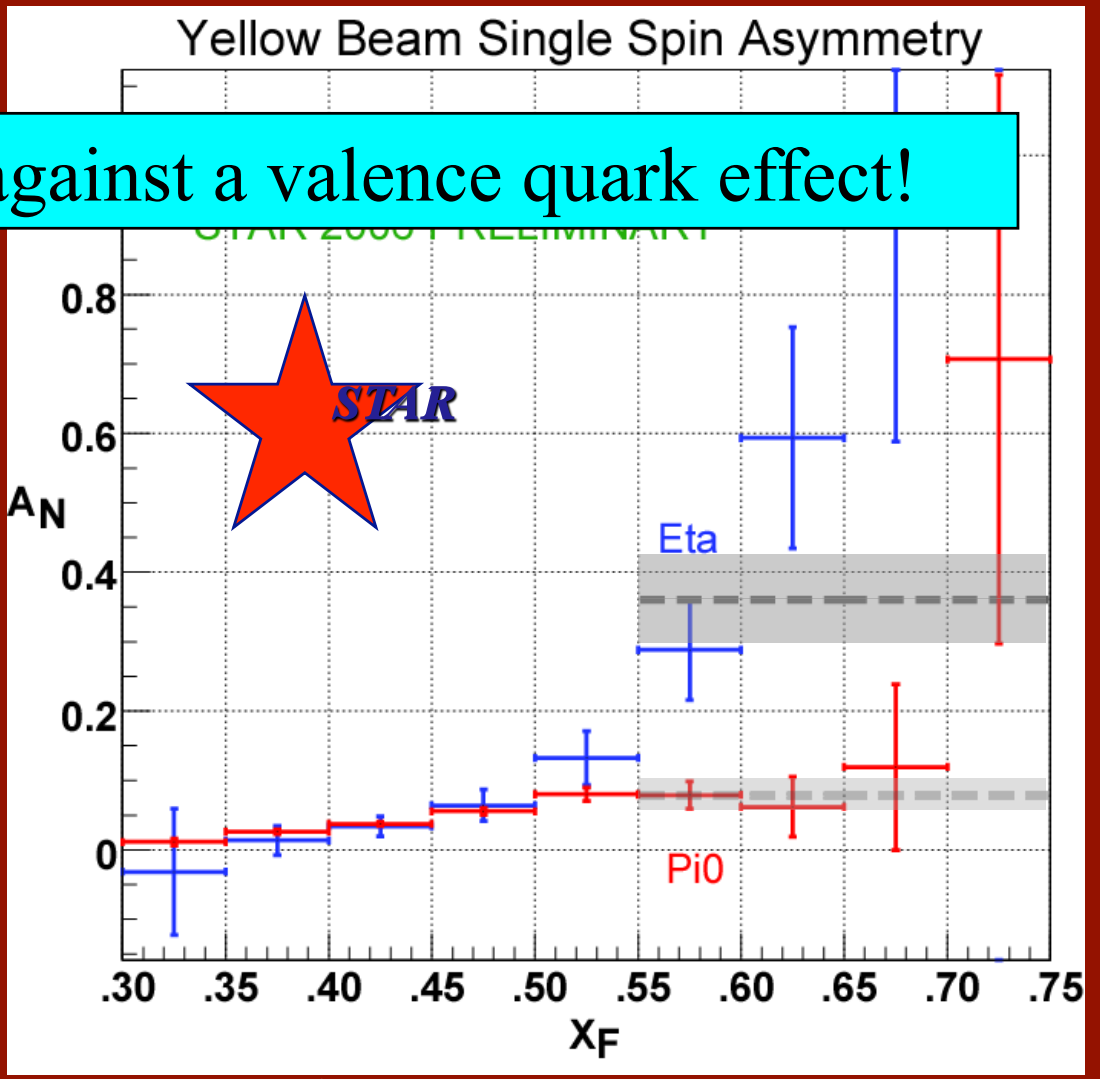
$.55 < X_F < .75$

$\langle A_N \rangle_{\eta} = -0.361 \pm 0.064$

$\langle A_N \rangle_{M} = -0.078 \pm 0.018$

$$\pi^0 \equiv \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$



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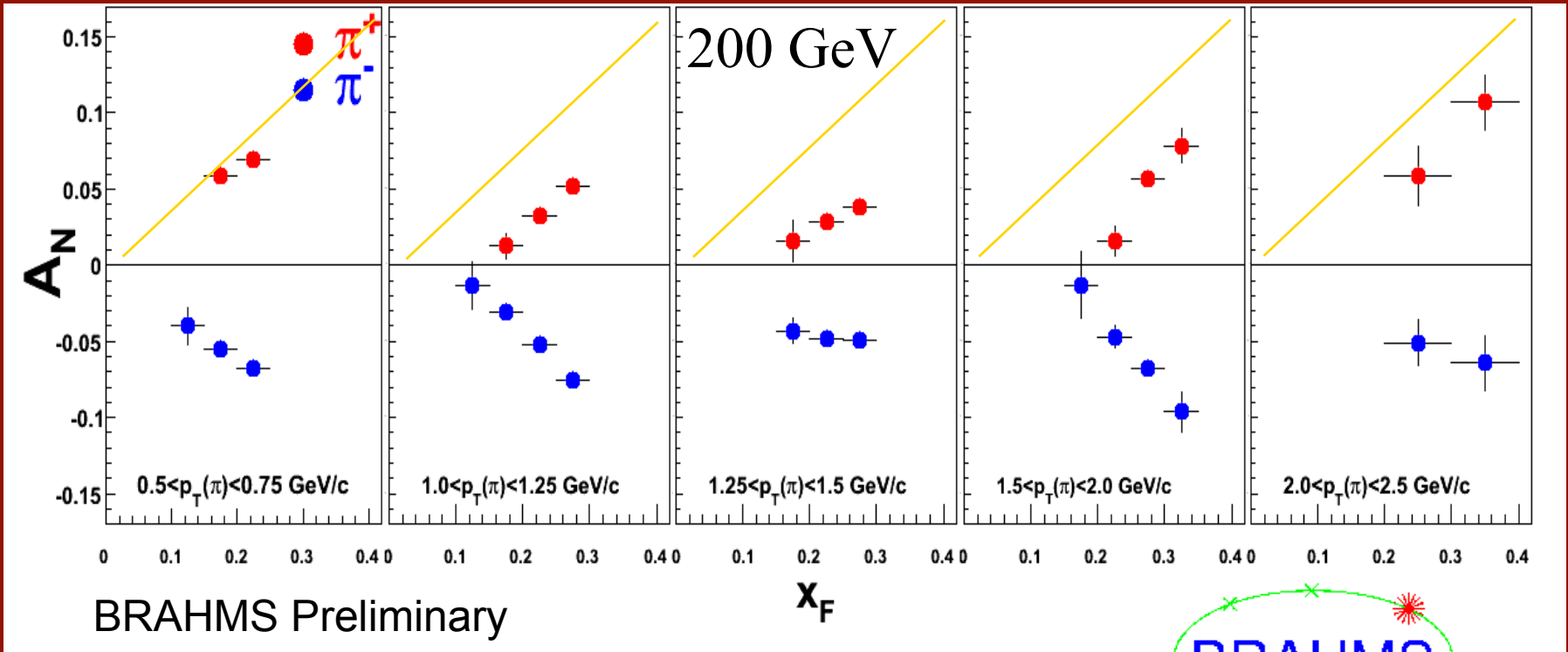
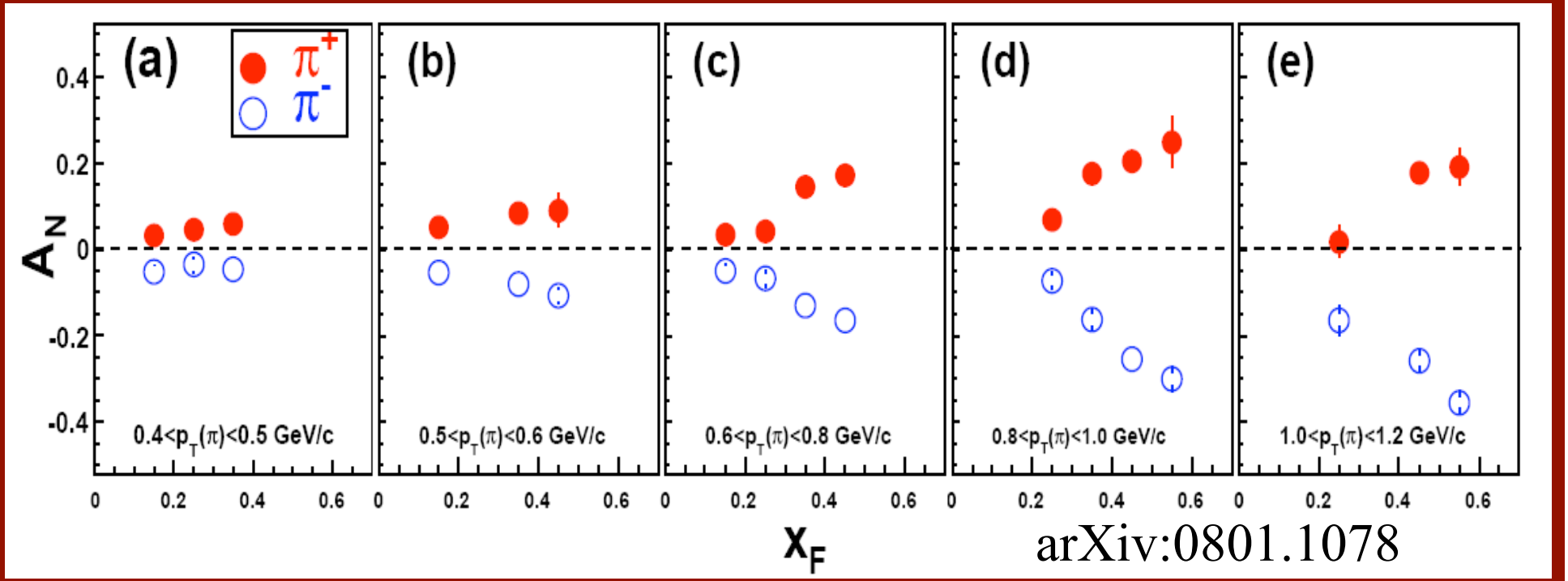
x_F dependence in p_T slices, 200 GeV

- At all p_T, increasing A_N with x_F.
- Magnitude is approximately constant at p_T>1.5 GeV/c



A_N x_F-p_T dependence at $\sqrt{s}$ = 62.4 GeV



At low-p_T $A_N(\pi)$ increases with p_T.
(Theoretically constrained to be 0 at p_T=0)

BRAHMS

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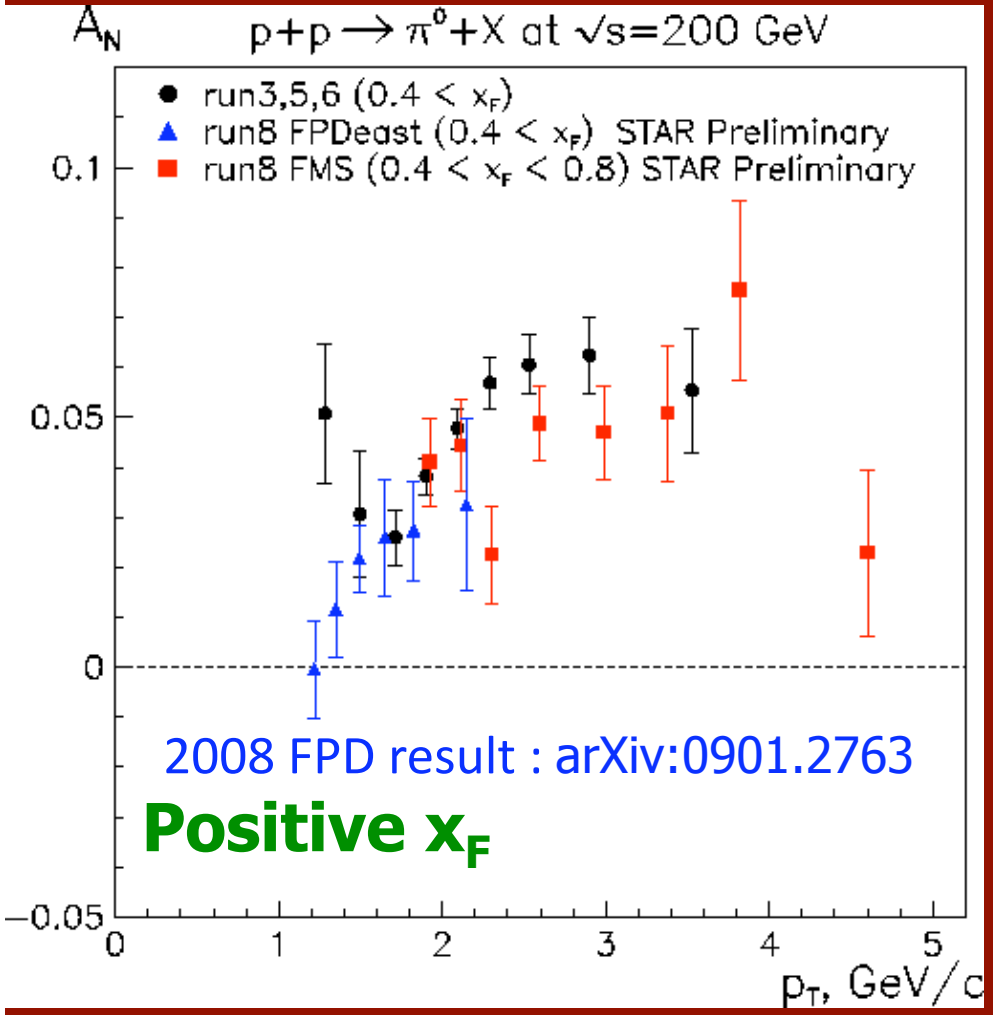
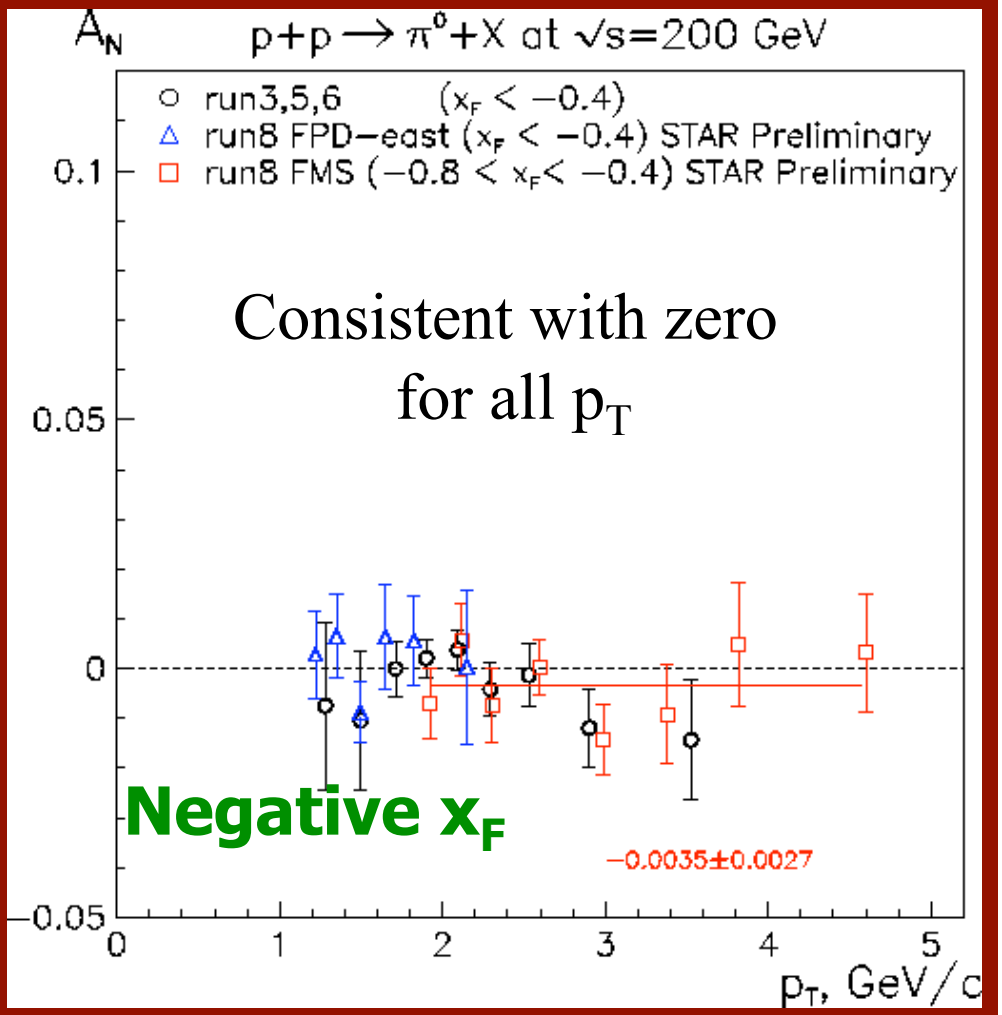
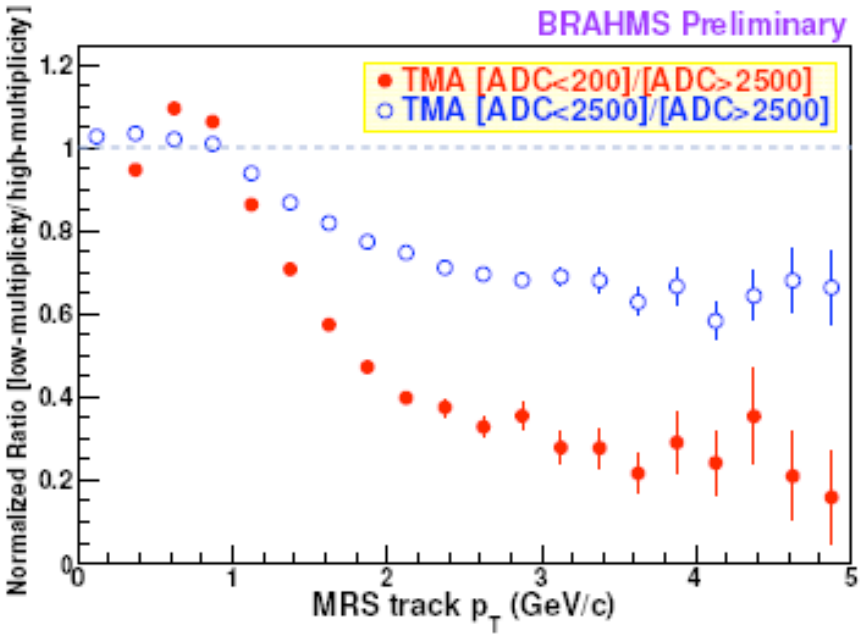
$A_N \rightarrow 0$ for $p_T \rightarrow 0$ now observed

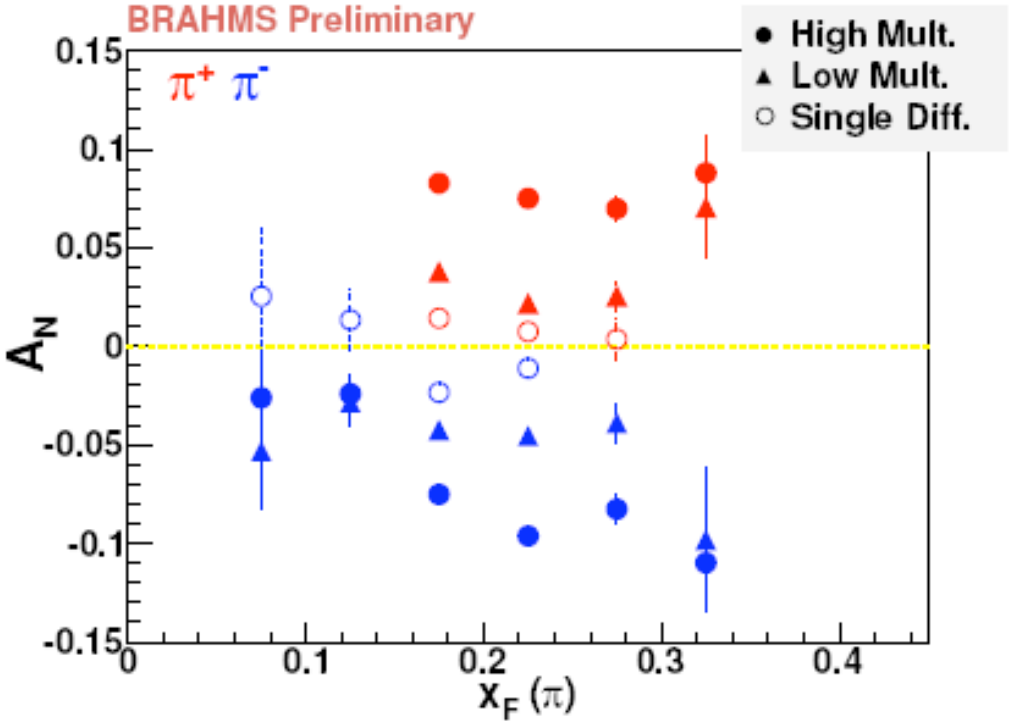




But looks like positive A_N persists up to p_T~5GeV!
Expected decrease as ~$1/p_T$ not observed.

Multiplicity dependence of pion SSA at 200 GeV





Ratio of low to high multiplicity events vs. track p_T

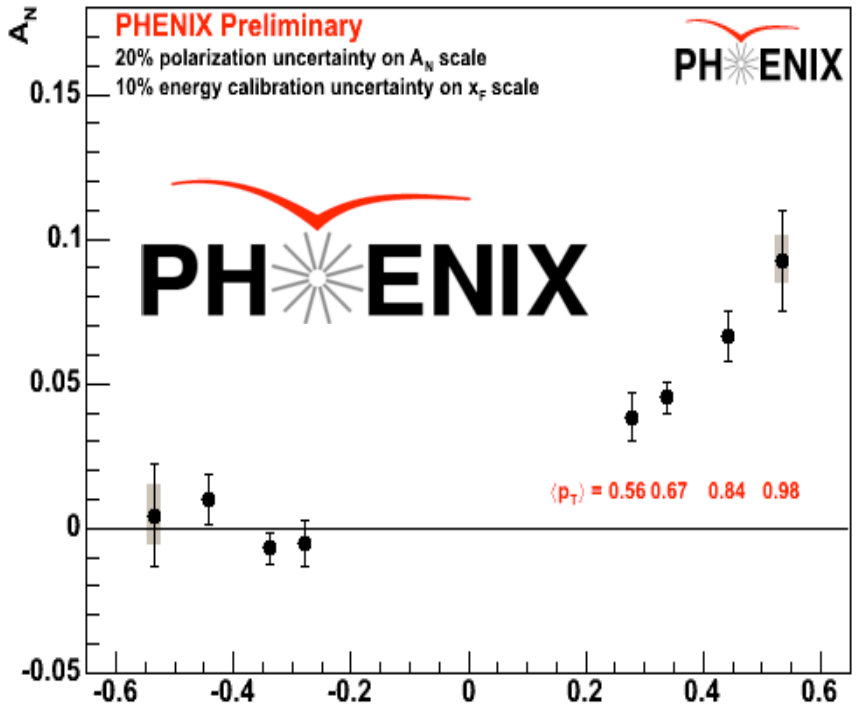
→ Higher multiplicity events correlate with hard scattering

Selecting on higher multiplicity events enhances SSA.

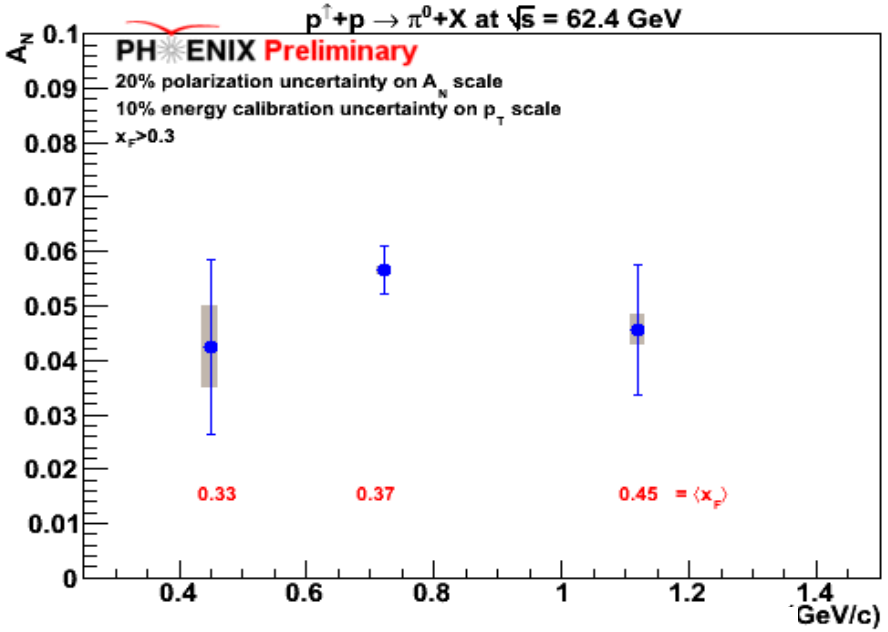
Effect not dominated by p_T dependence of SSA.

Forward π^0 SSA's at $\sqrt{s}$=62.4 GeV

nucl-ex/0701031



x_F



p_T

Sizable asymmetries in forward direction.
Need more data to understand p_T dependence . . .

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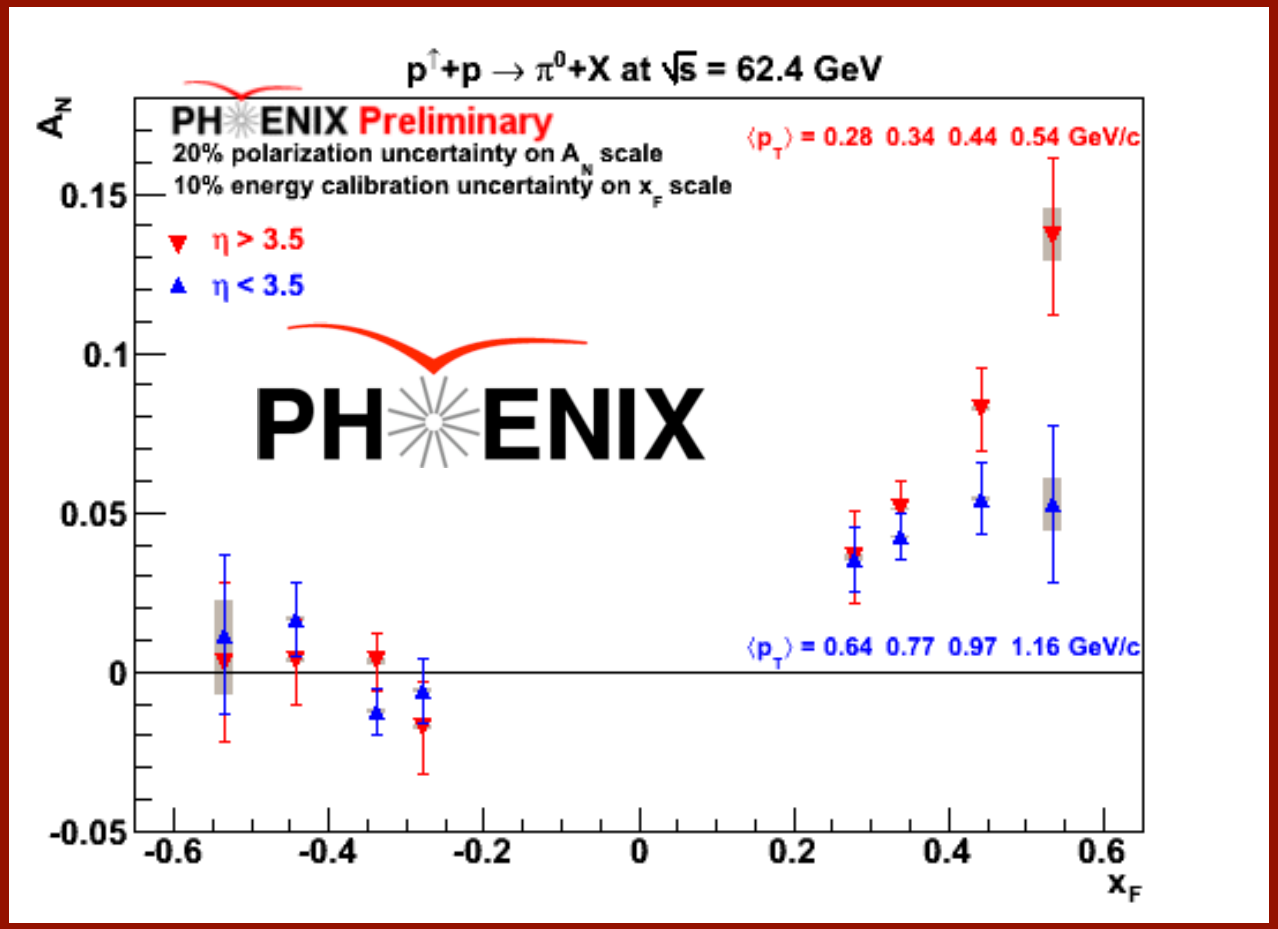
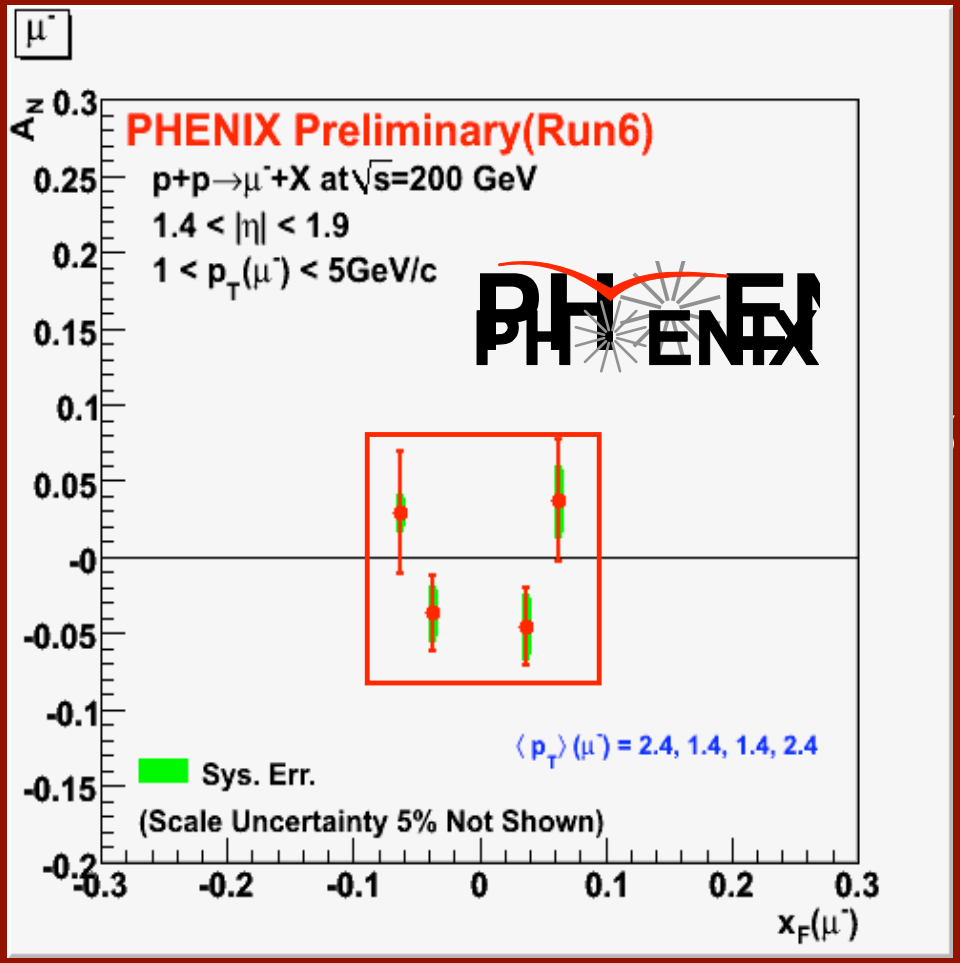
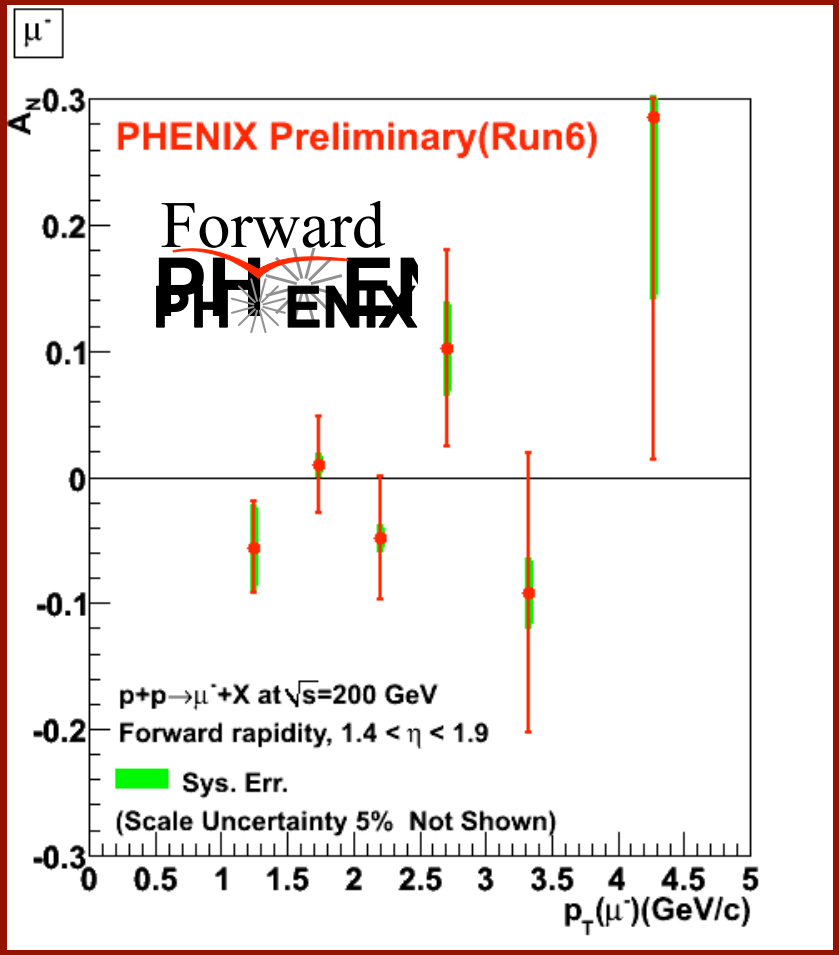
Forward π^0's at $\sqrt{s}$=62.4 GeV: Pseudorapidity dependence



Indication of larger forward asymmetries at higher pseudorapidity

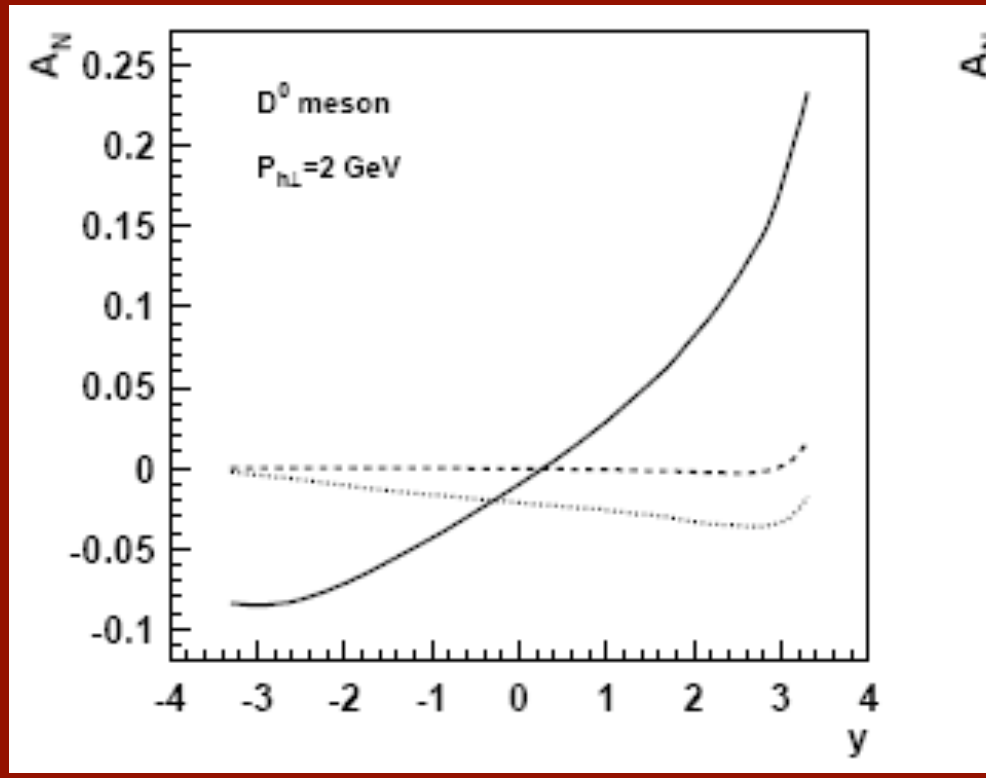
Heavy flavor single spin asymmetries: Isolate gluons

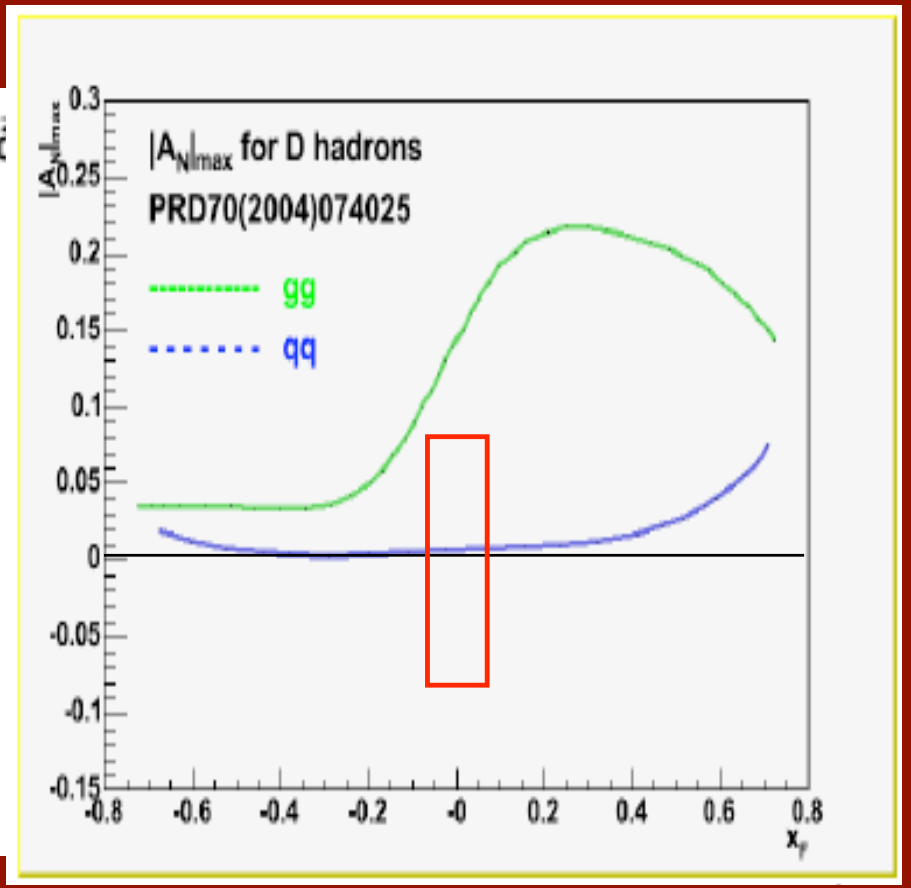




SSA of heavy flavor: predictions

PRD78, 114013 (2008)

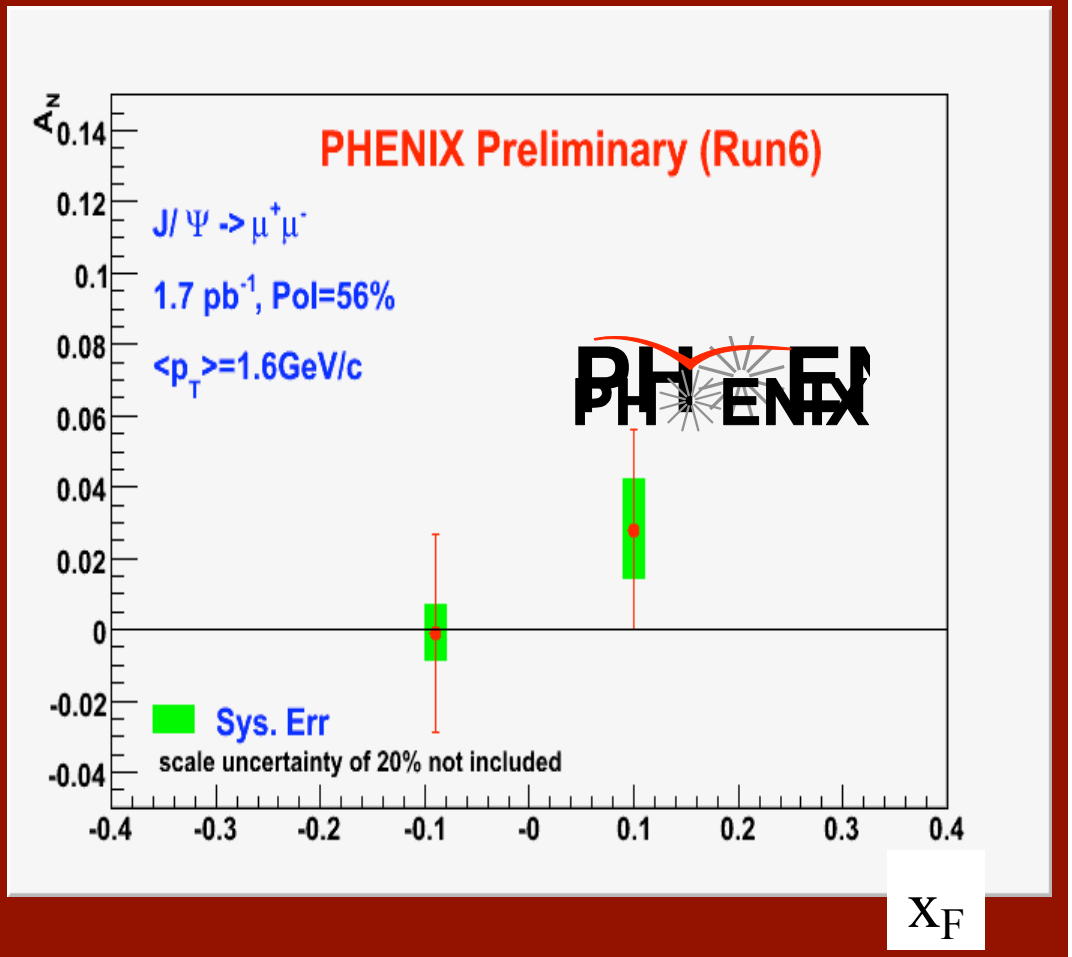




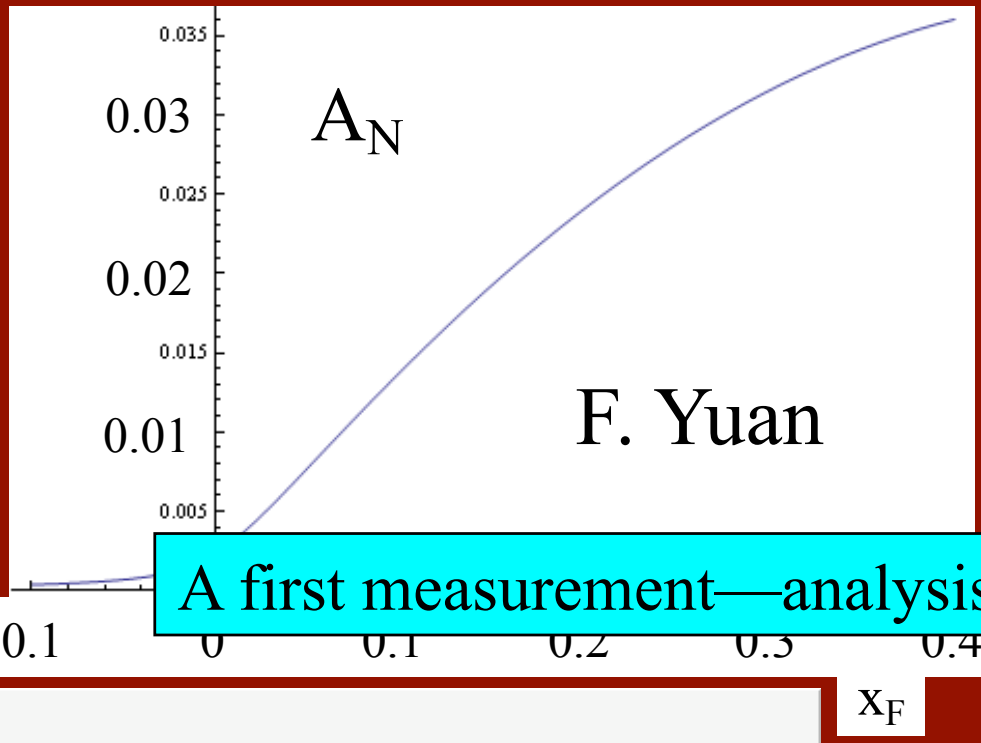
Significantly improved measurements expected after silicon vertex upgrade in 2011.

What about charmonium?

- *Given* a non-zero gluon Sivers function, non-zero transverse SSA expected for J/Psi only in color-singlet model in p+p, only in color-octet in SIDIS—Yuan, PRD78, 014024 (2008)
  - SSA sensitive to production mechanism!
- Application of TMDs to long-standing issues in QCD traditionally considered via other approaches
  - A maturing field!



"Rough" calculation for J/Ψ A_N at RHIC



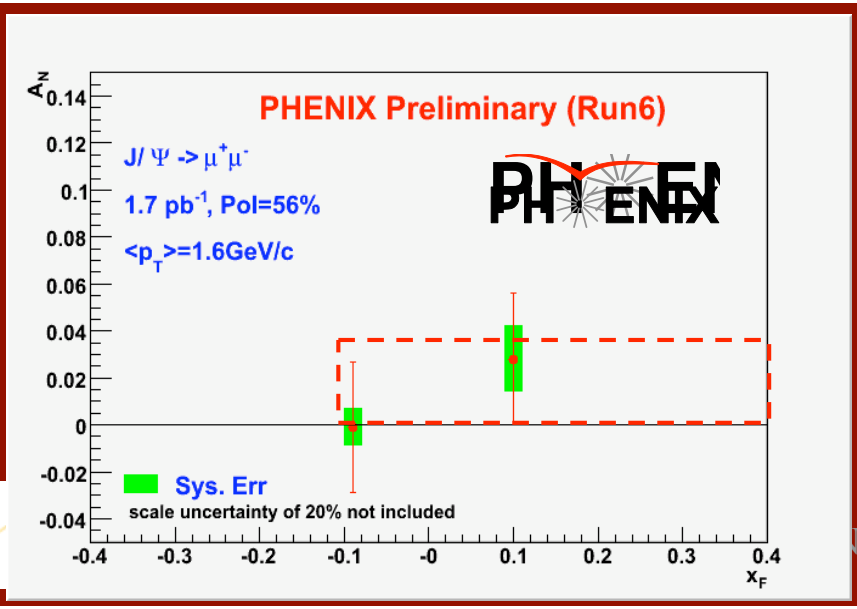
- Assumed gluon Sivers function ~ 0.5 x(1-x) times unpolarized gluon distribution

$$xG_{1T}^{\perp(1/2)}(x) \approx 0.5x(1-x)xG(x)$$

- Assumed 30% J/Ψ from χ_c decays
- No direct contributions!

A first measurement—analysis of 2008 data underway

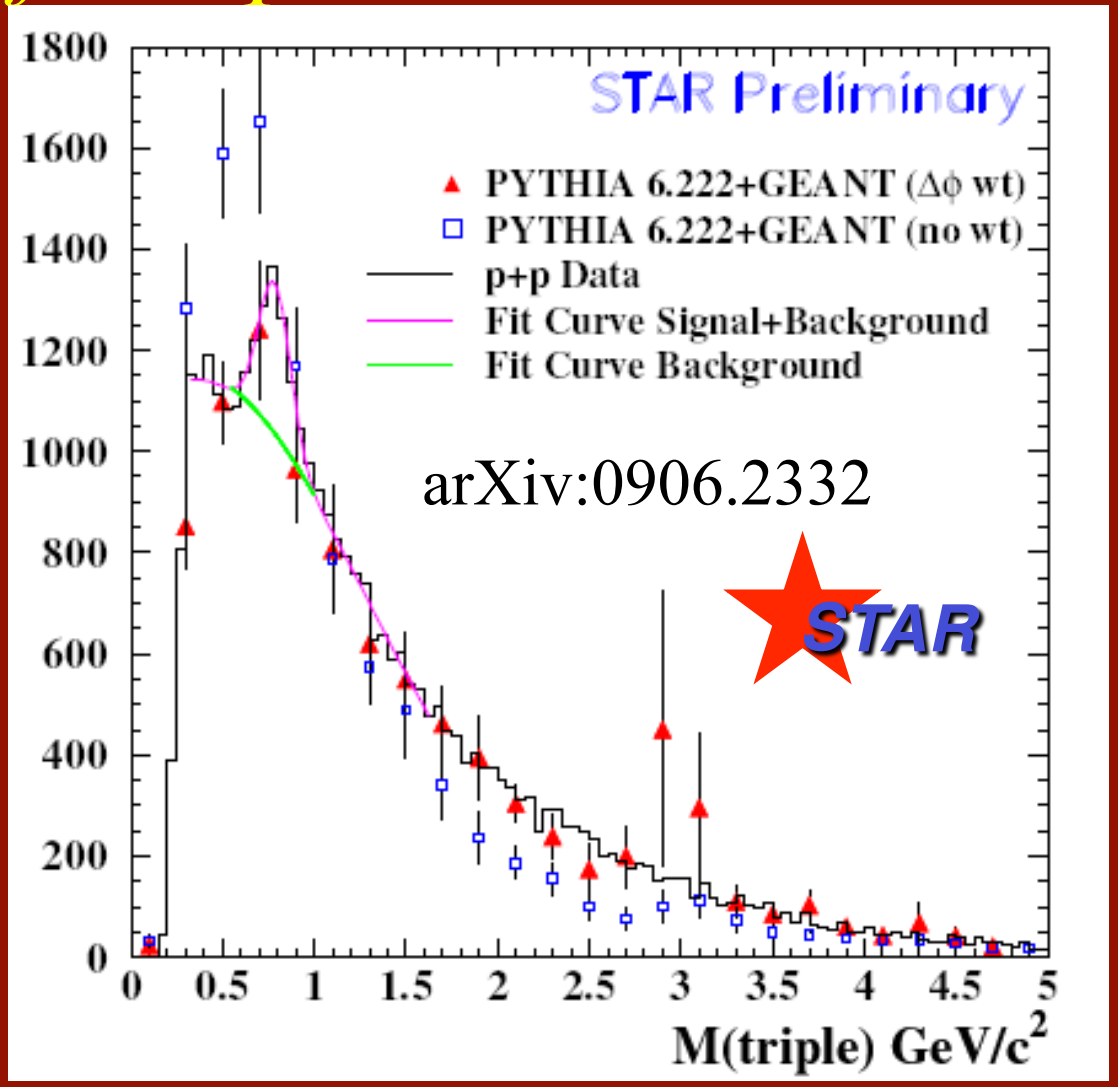
- the cross section
  - Color-octet, FSI/ISI cancel out, SSA vanishes in the limit of $p_T << M_Q$
  - Origin of potential non-zero asymmetry is through χ_c!



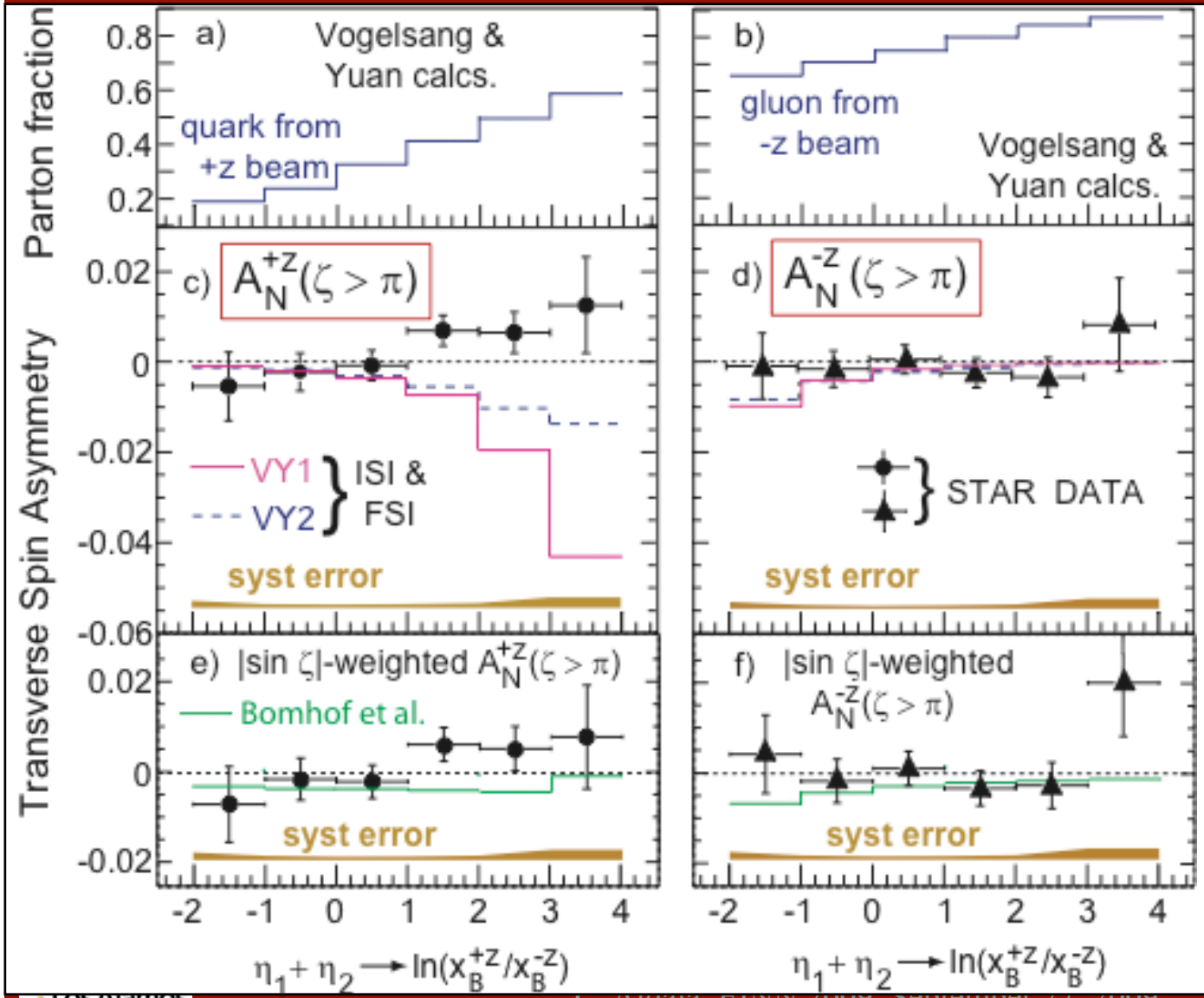
Toward A_N of vector mesons: Opposite sign from pseudoscalars?

3 photon events to look for $\omega \rightarrow \pi^0\gamma$ (BR= 8.9%)

- 2008 data, FMS
- p_T (triplet) > 2.6 GeV/c
- E (triplet) > 30 GeV
- p_T (photon cluster) > 1.5 GeV/c
- p_T (π^0) > 1 GeV/c
- 10σ signal!
- Small S/B currently a challenge in extracting significant asymmetry…work ongoing!



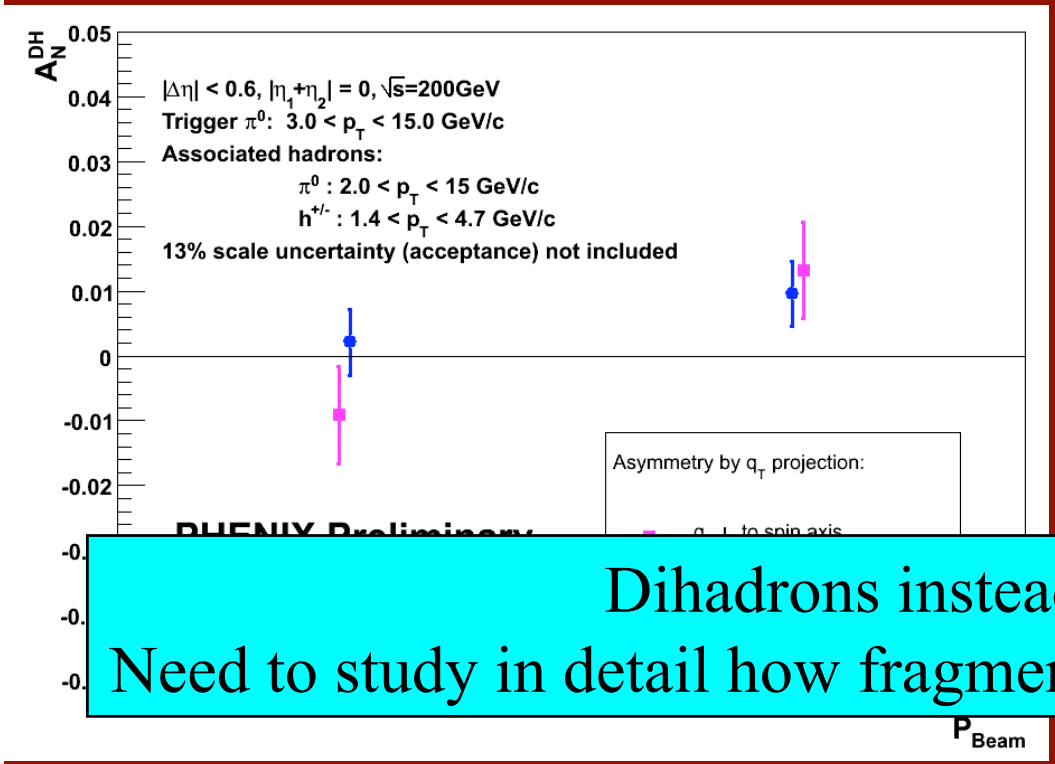
Beyond inclusive measurements: Dijet SSA to probe Sivers effect

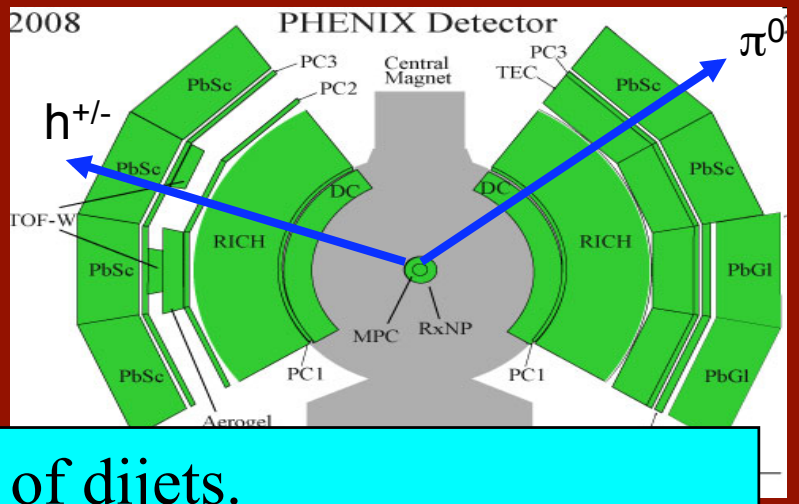


STAR A_N all consistent with zero at midrapidity

STAR

Sivers effect in di-hadron production





Dihadrons instead of dijets.
Need to study in detail how fragmentation effects can contribute.

PHENIX Result from 2006 data:

- Di-hadrons at central rapidities
- Asymmetry consistent with zero
- Analysis with large 2008 data in progress

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

(Work in progress)

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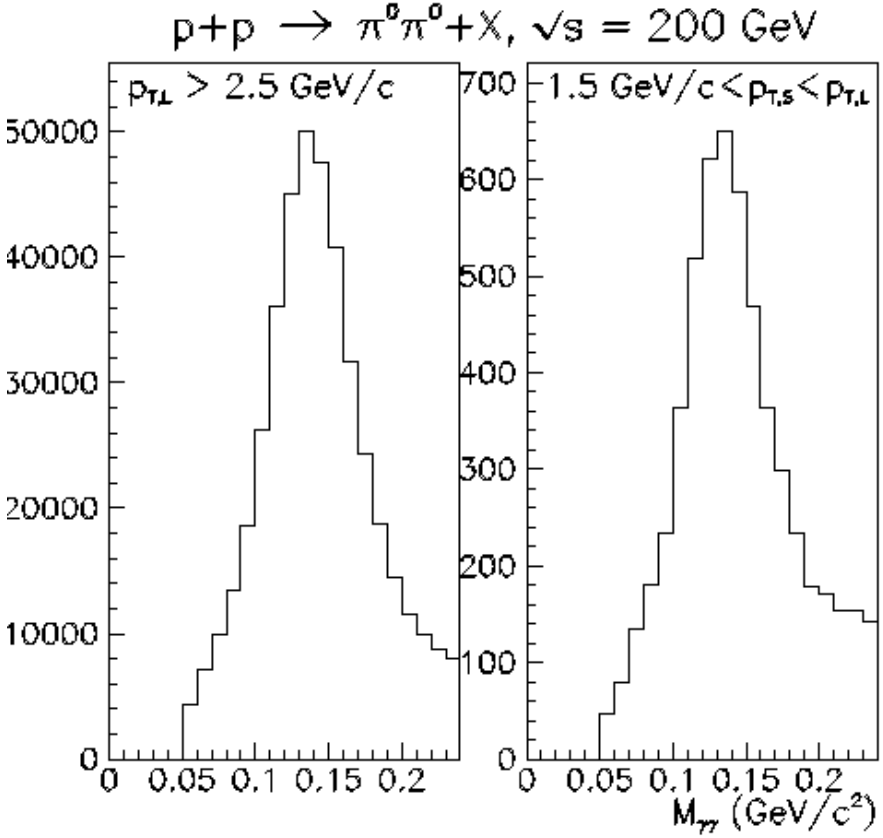
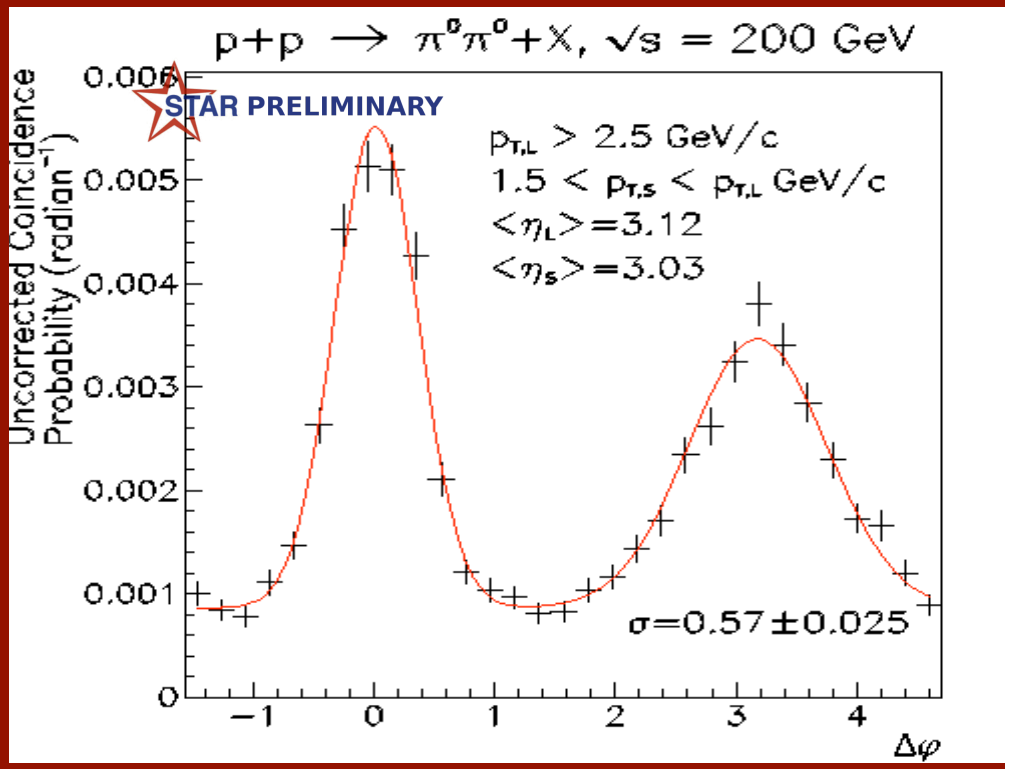
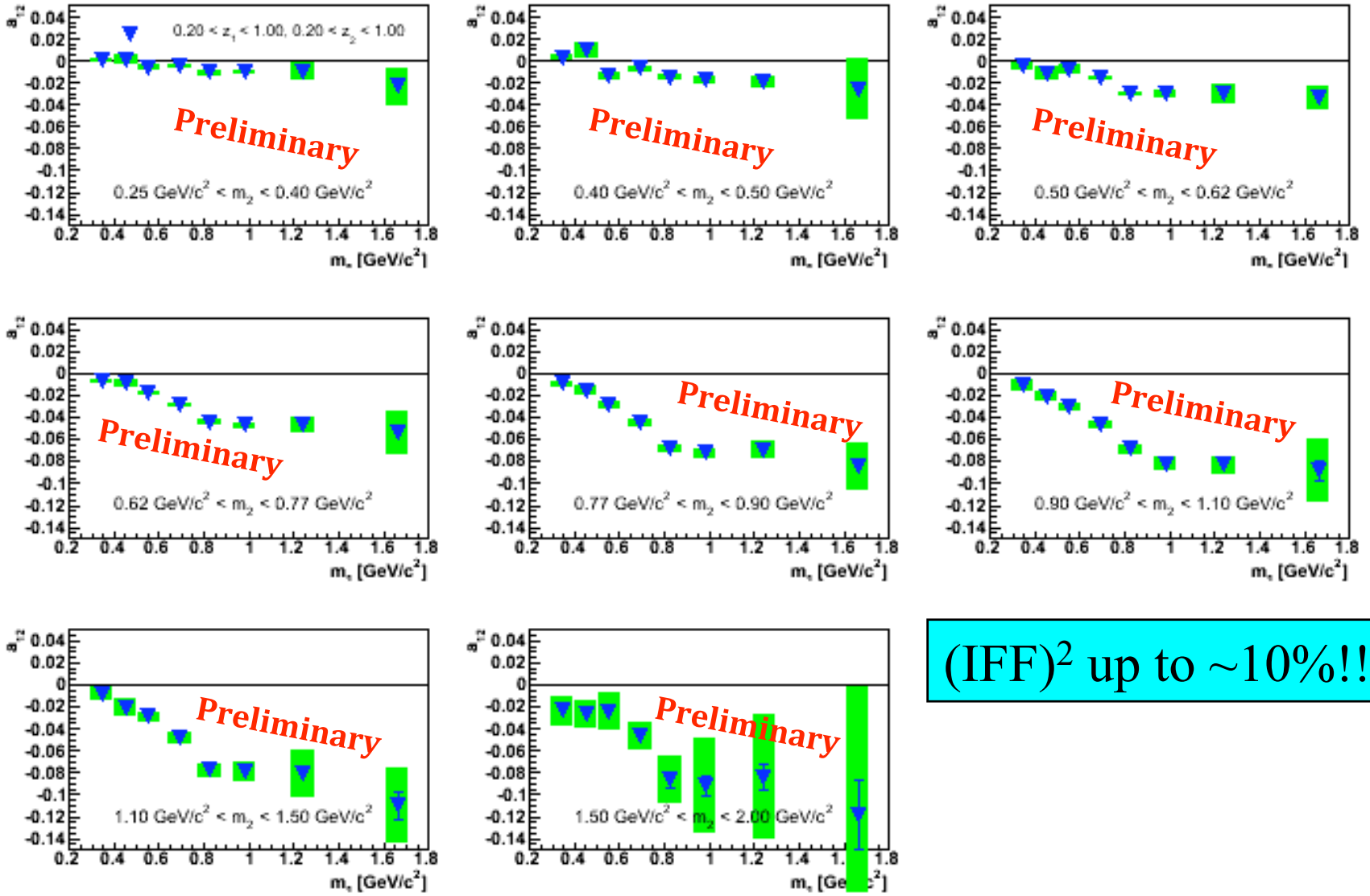
Forward π^0-π^0 azimuthal correlations





- **Possible back-to-back di-jet/di-hadron Sivers measurement**
- **Possible near-side hadron correlation for Collins fragmentation function/Interference fragmentation function + Transversity**

More two-hadron measurements: Interference Fragmentation Function from BELLE

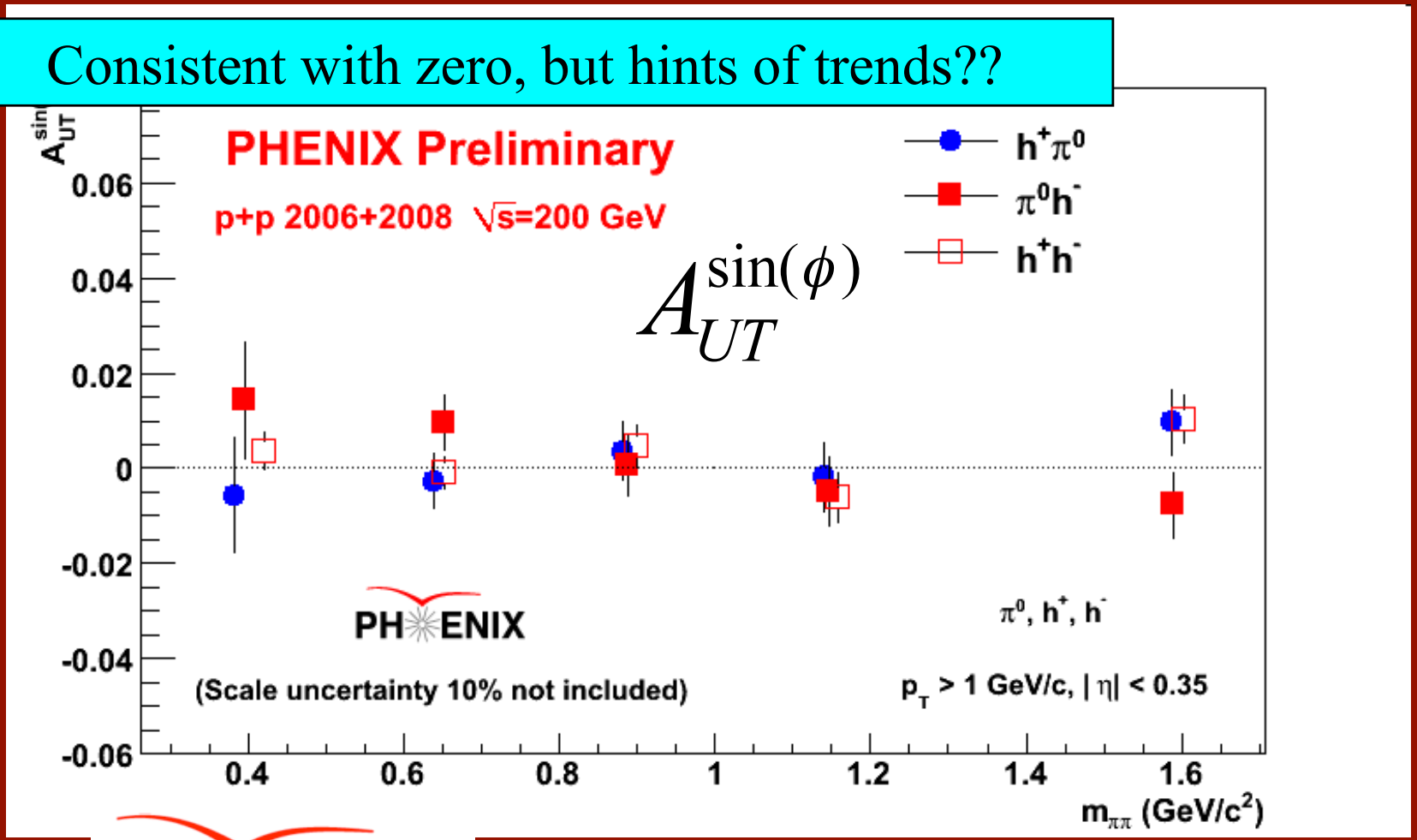


$(IFF)^2$ up to ~10%!!

8x8 m_1 m_2 binning

IFF asymmetry measurement in p+p to probe transversity

Consistent with zero, but hints of trends??



PHENIX

Midrapidity.
Invariant mass dependence

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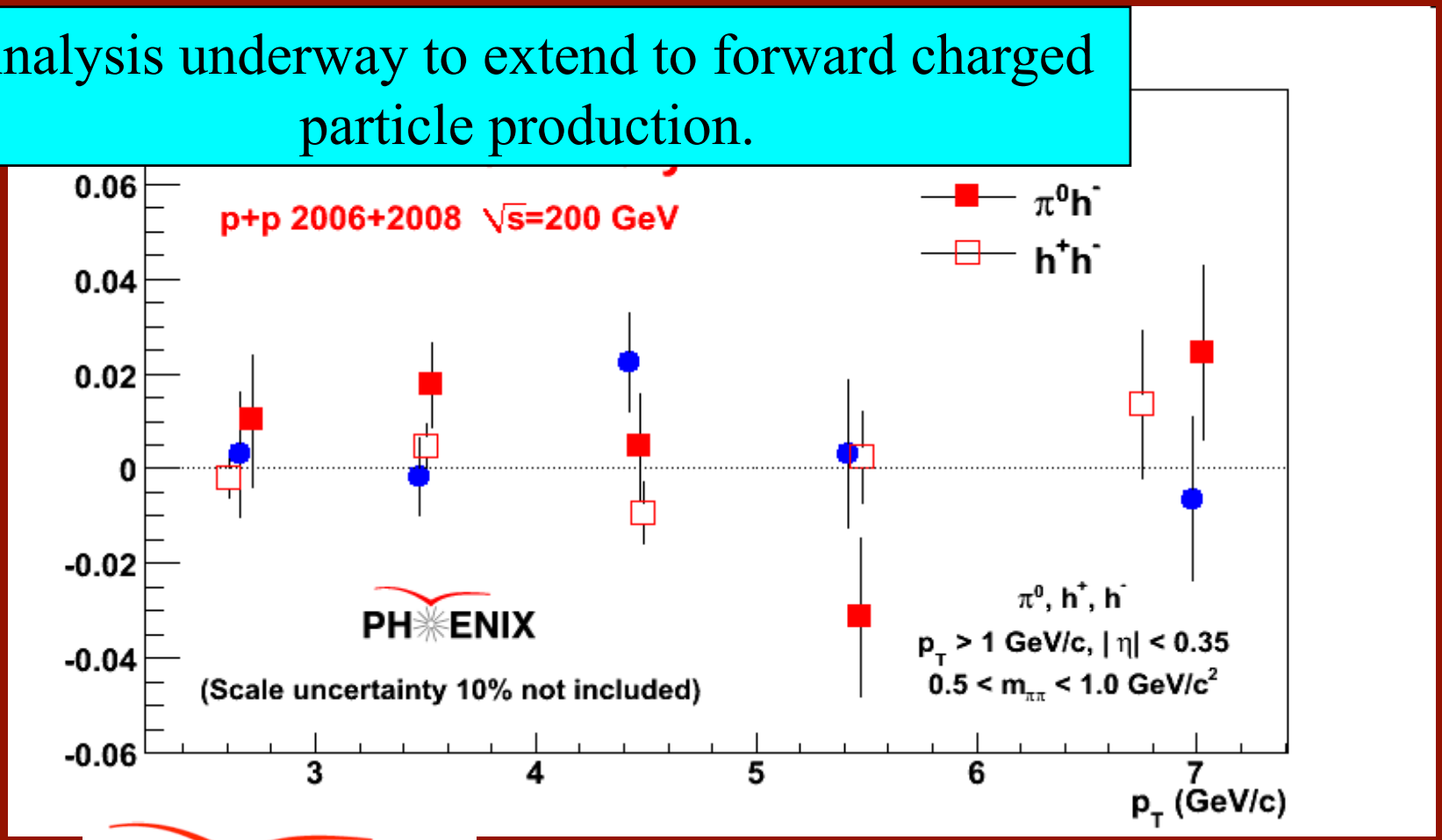
IFF asymmetry measurement in p+p: p_T dependence

Analysis underway to extend to forward charged particle production.



PHENIX

Midrapidity.
p_T dependence

More di-hadrons: Attempting to probe k_T from orbital motion

- Spin-correlated transverse momentum (orbital angular
- Possible helicity dependence
-

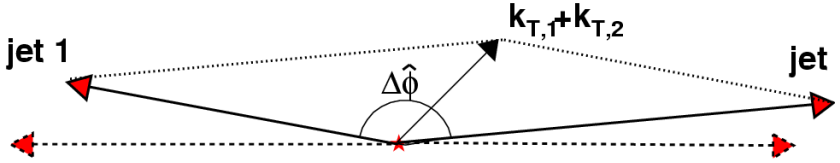
D40, 1989)

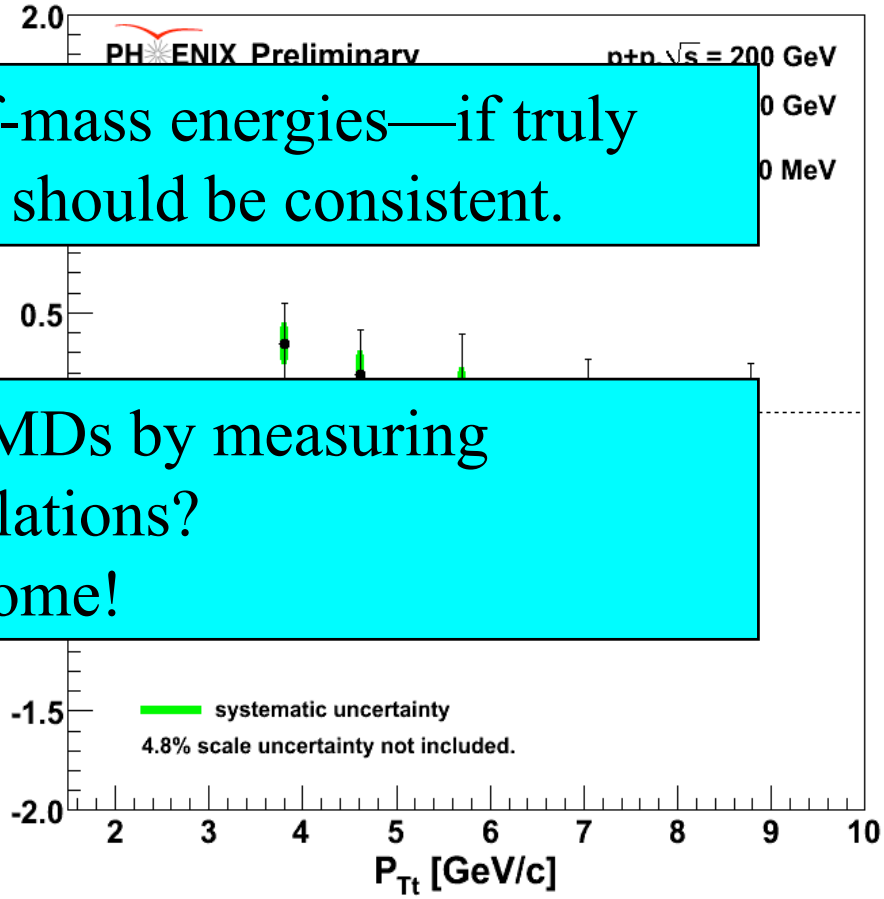
net effect after averaging over impact parameter

hel

Will measure at other center-of-mass energies—if truly probing intrinsic kT, results should be consistent.

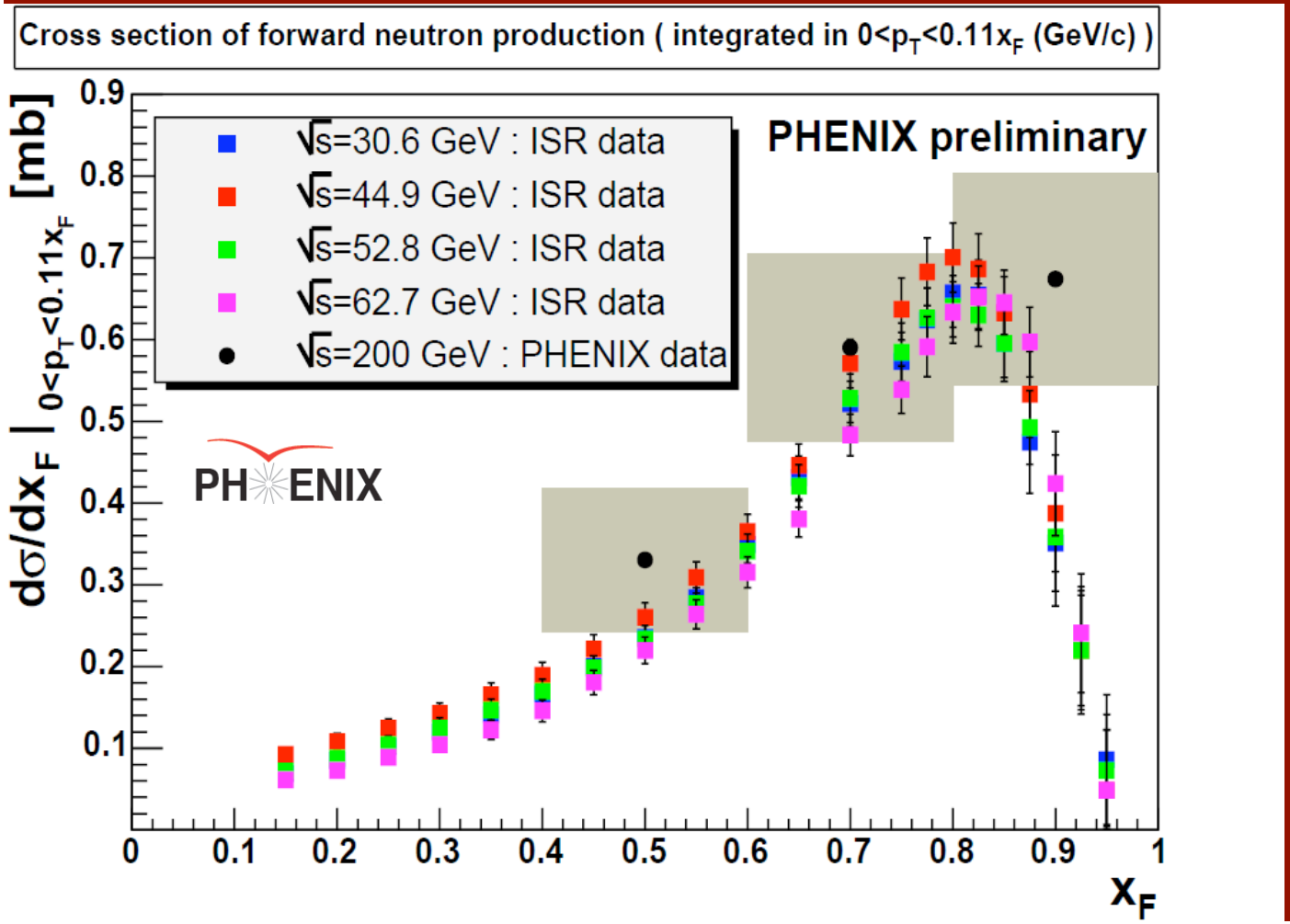
Possible to learn about TMDs by measuring angular modulations?
Input welcome!





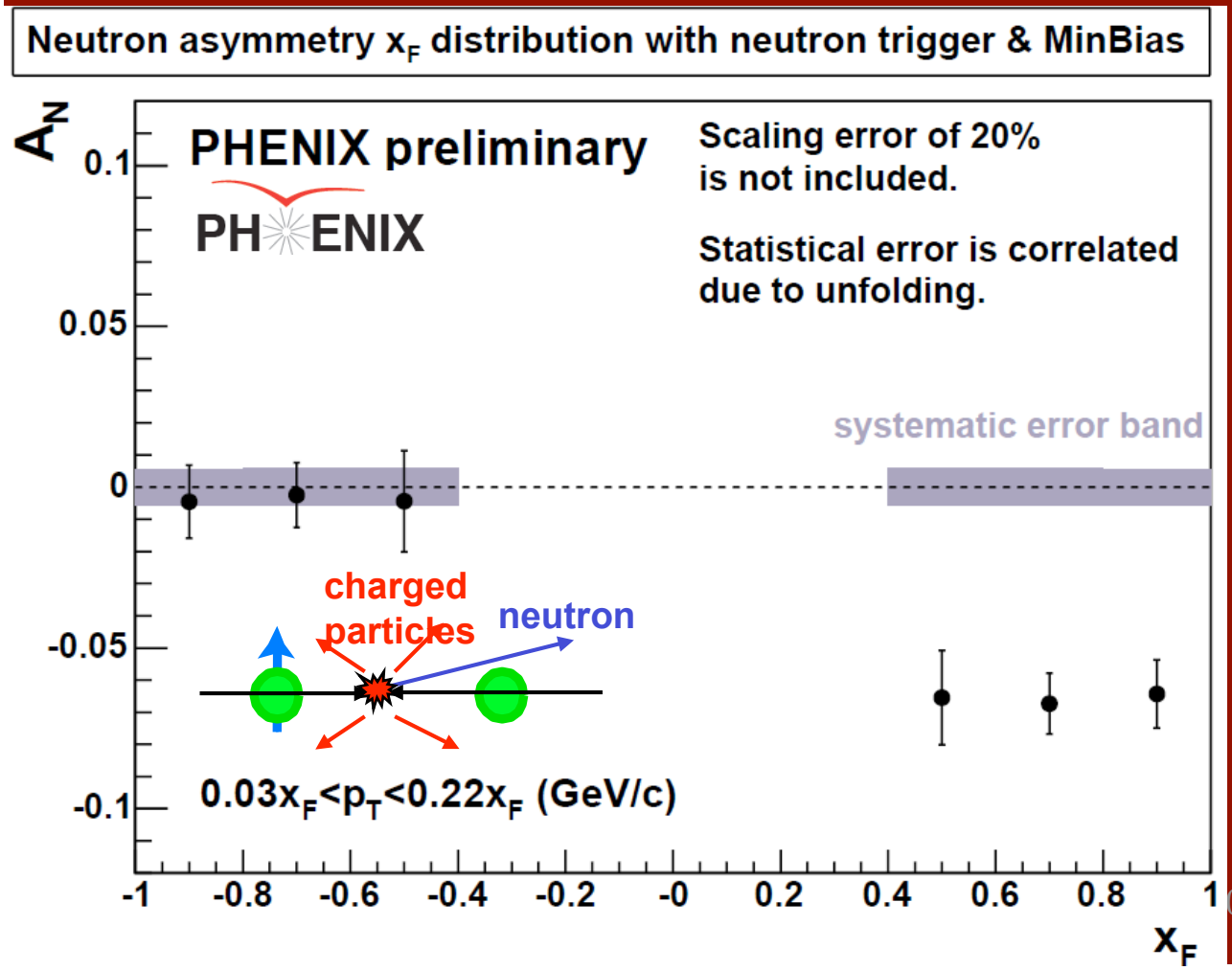
Forward neutrons at √s=200 GeV at PHENIX

Cross section at 200 GeV consistent with ISR data
→ suggests Feynman scaling holds



Forward neutrons at √s=200 GeV at PHENIX

Large negative SSA observed for $x_F>0$, enhanced by requiring concidence with forward charged particles ("MinBias" trigger).
No x_F dependence seen.



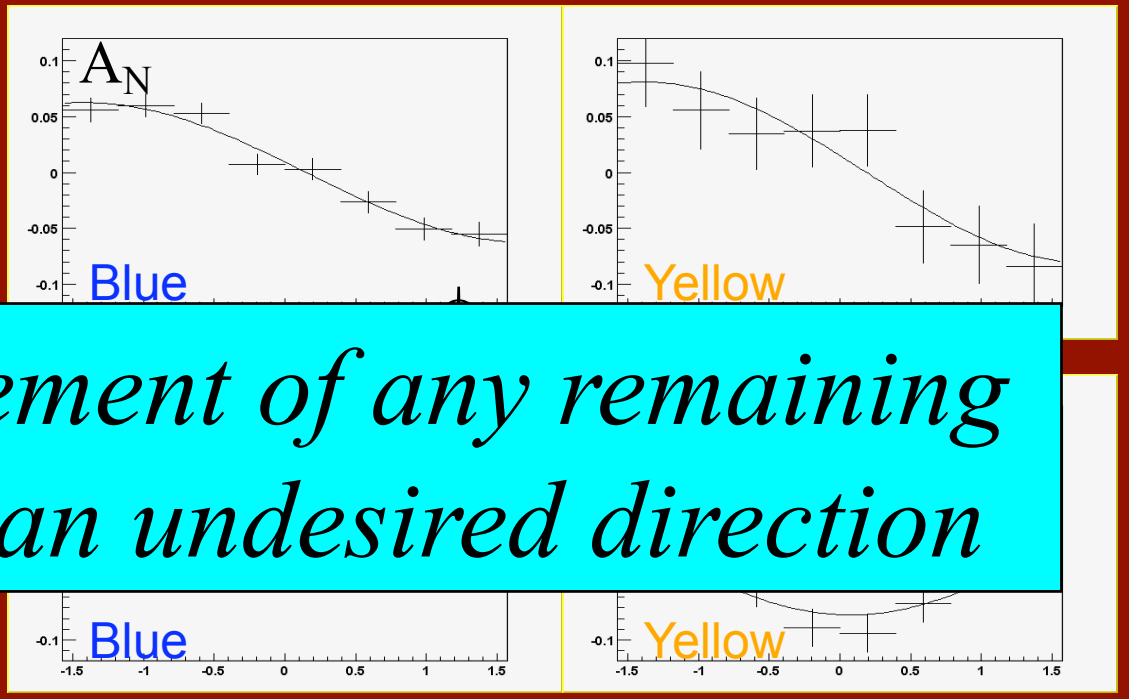
Mean p_T
(Estimated by simulation assuming ISR p_T dist.)
$0.4<|x_F|<0.6$ 0.088 GeV/c
$0.6<|x_F|<0.8$ 0.118 GeV/c
$0.8<|x_F|<1.0$ 0.144 GeV/c

preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

009

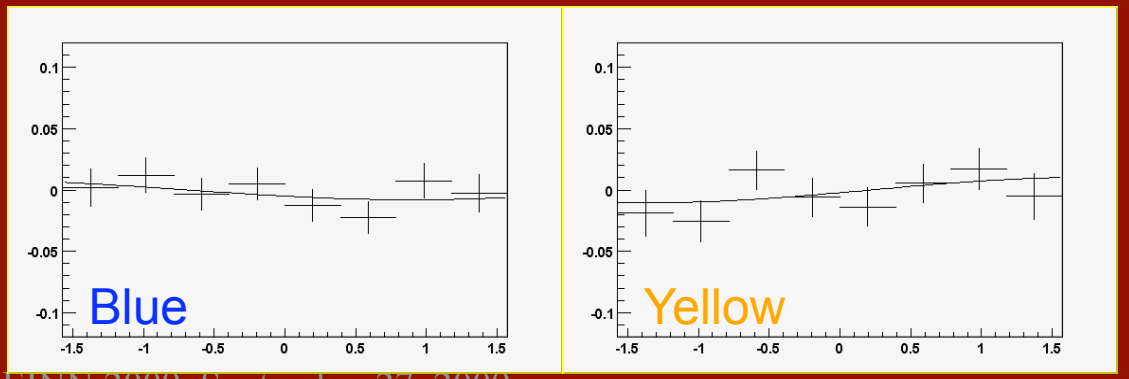
Neutron SSA for local polarimetry

Spin Rotators OFF
Vertical polarization



Allows measurement of any remaining component in an undesired direction

Spin Rotators ON
Longitudinal polarization



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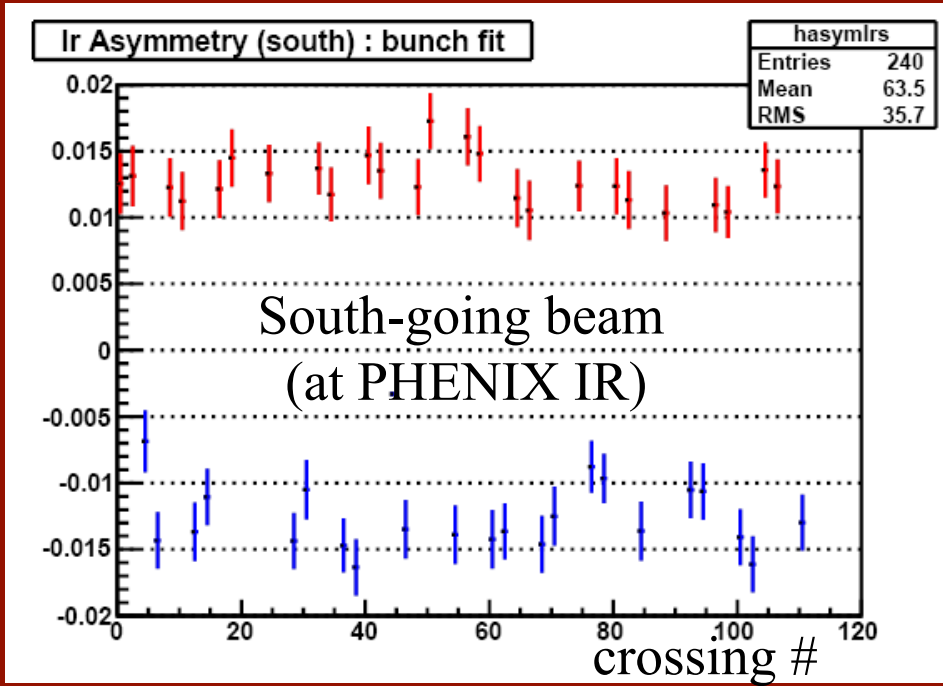
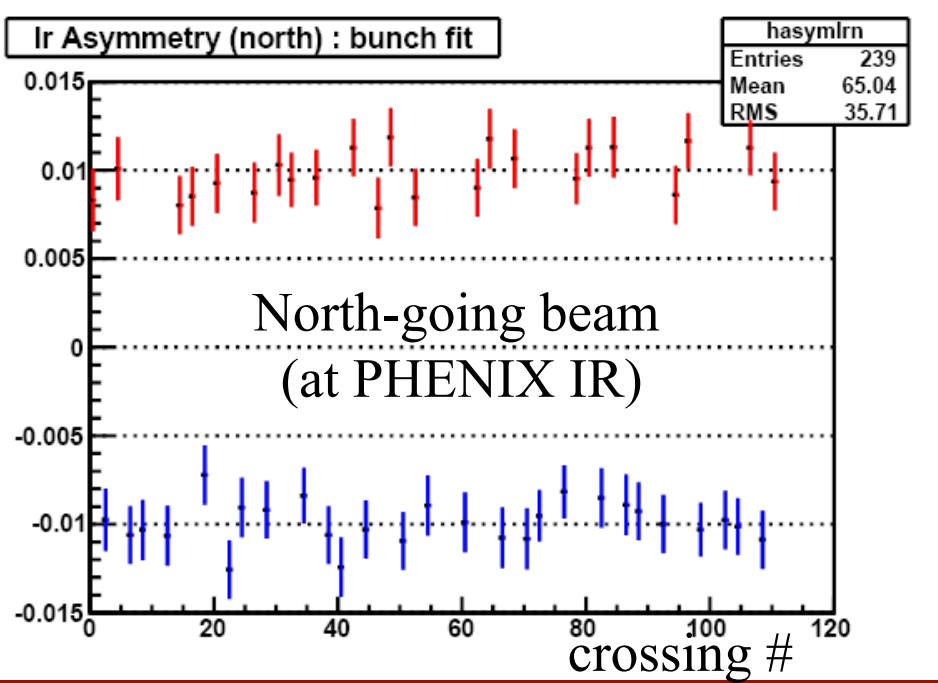
New: Bunch-by-bunch polarization information

From ~10 minutes of 500 GeV commissioning data in March 2009!





With transverse polarization, use scalers to count raw left-right SSA in forward neutron production for each bunch crossing.

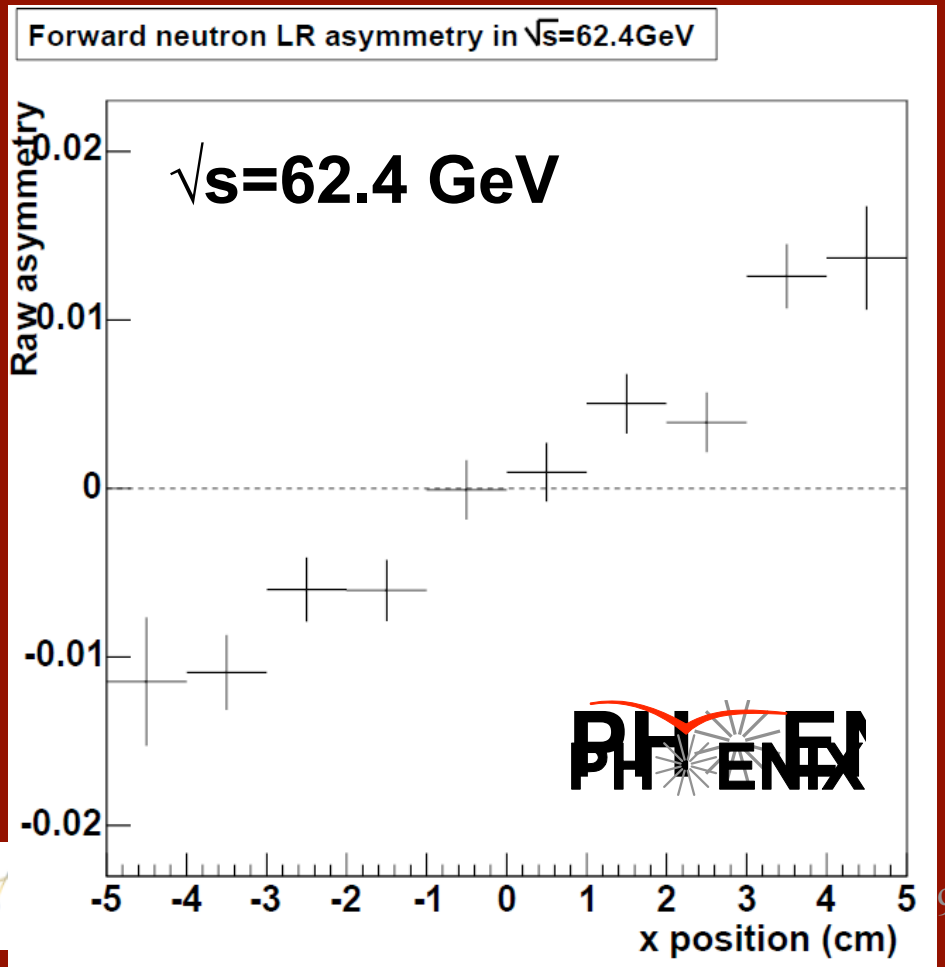
Measurement of *bunch-by-bunch variation* in polarization.

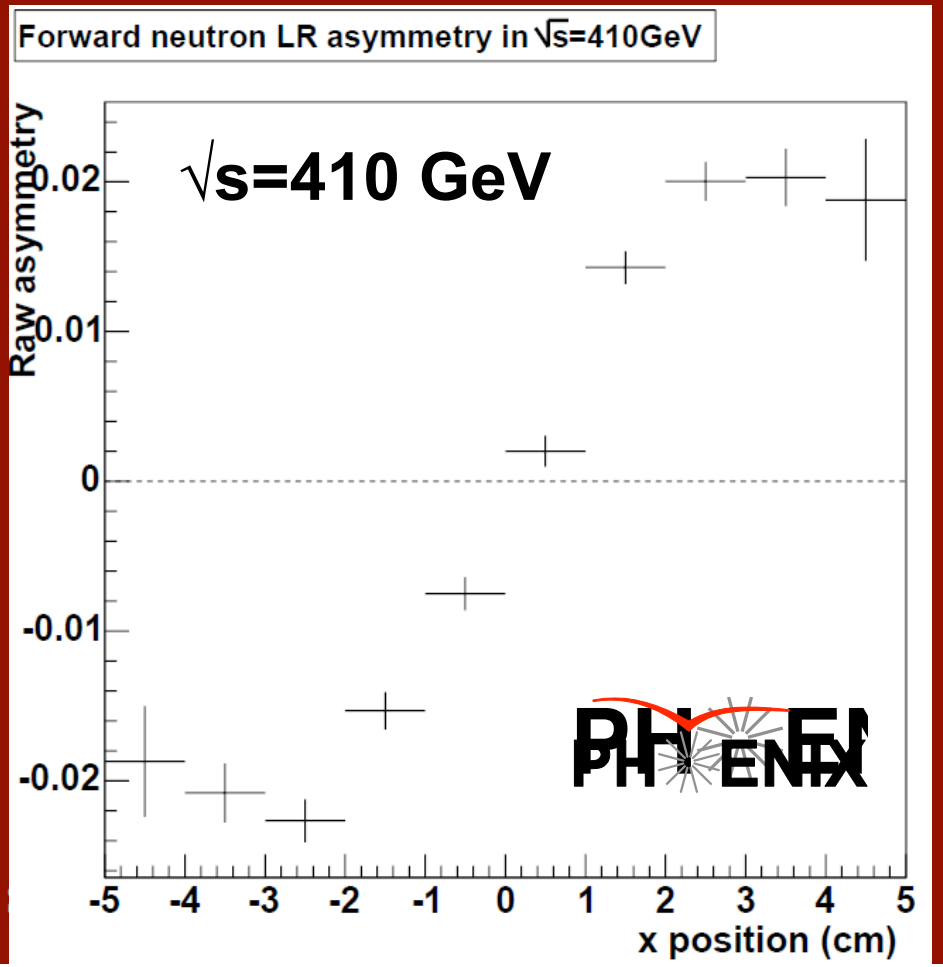
(Sign flip for bunches polarized vertically up vs. down.)

Forward neutrons at other energies

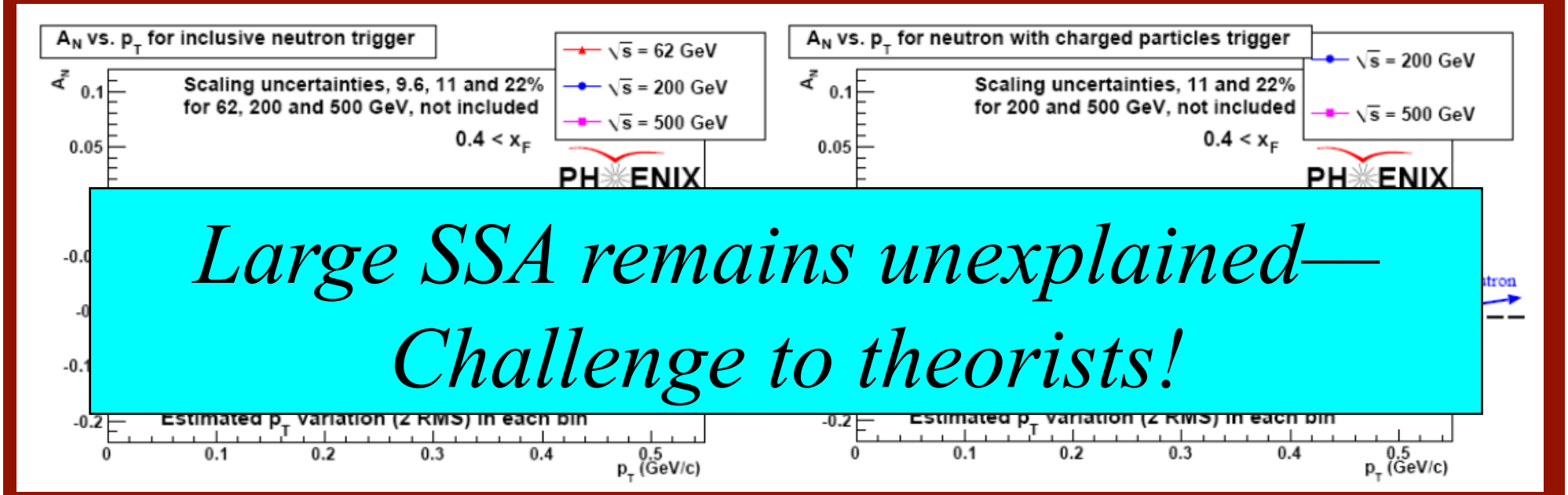
Significant forward neutron asymmetries observed down to 62.4 and up to 410 GeV!

$$A = \frac{N_+ - RN_-}{N_+ + RN_-}$$





p_T scaling of forward neutron SSA?

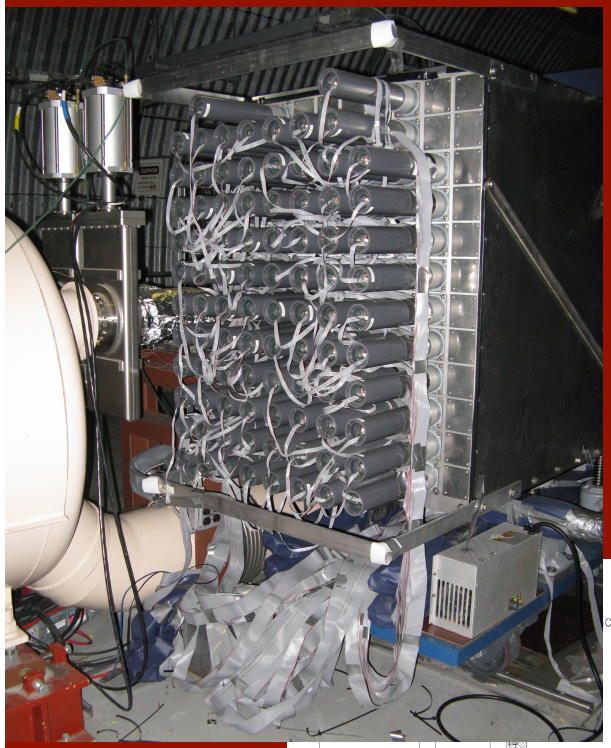


Large SSA remains unexplained—
Challenge to theorists!

Inclusive neutrons
62.4, 200, 500 GeV

Neutrons with charged particle trigger
200, 500 GeV

The future:
Forward Hadron Calorimeter (FHC) at STAR

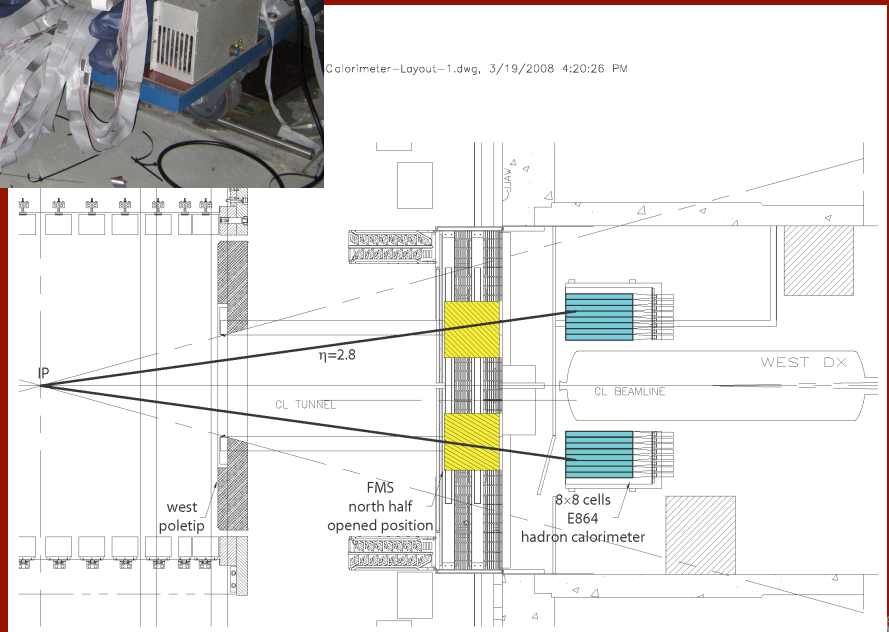


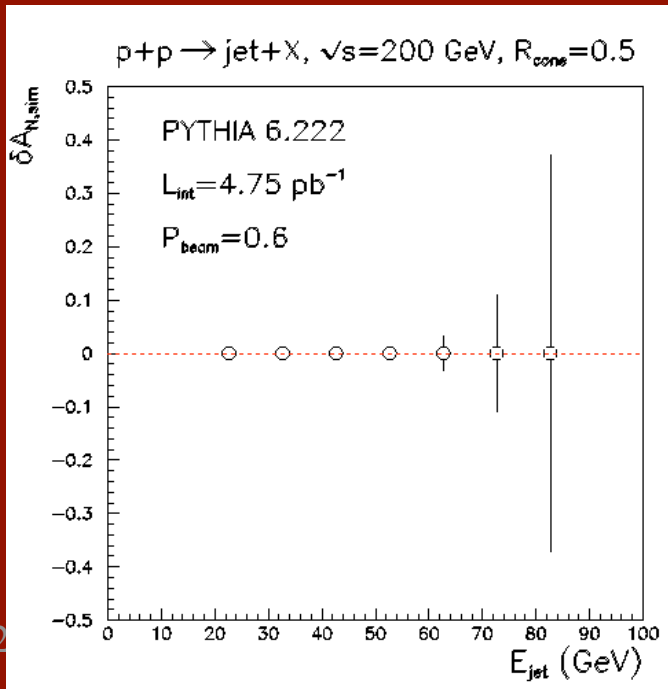
Real jet physics with FMS + FHC

Lambda, Photon (isolation)

BNL-AGS-E864 hadron calorimeter detectors
Refurbished and used by PHOBOS

Estimated statistical precision for uncertainty in analyzing power for $p_{\uparrow}+p \rightarrow jet + X$ at $\sqrt{s}$ = 200 GeV.





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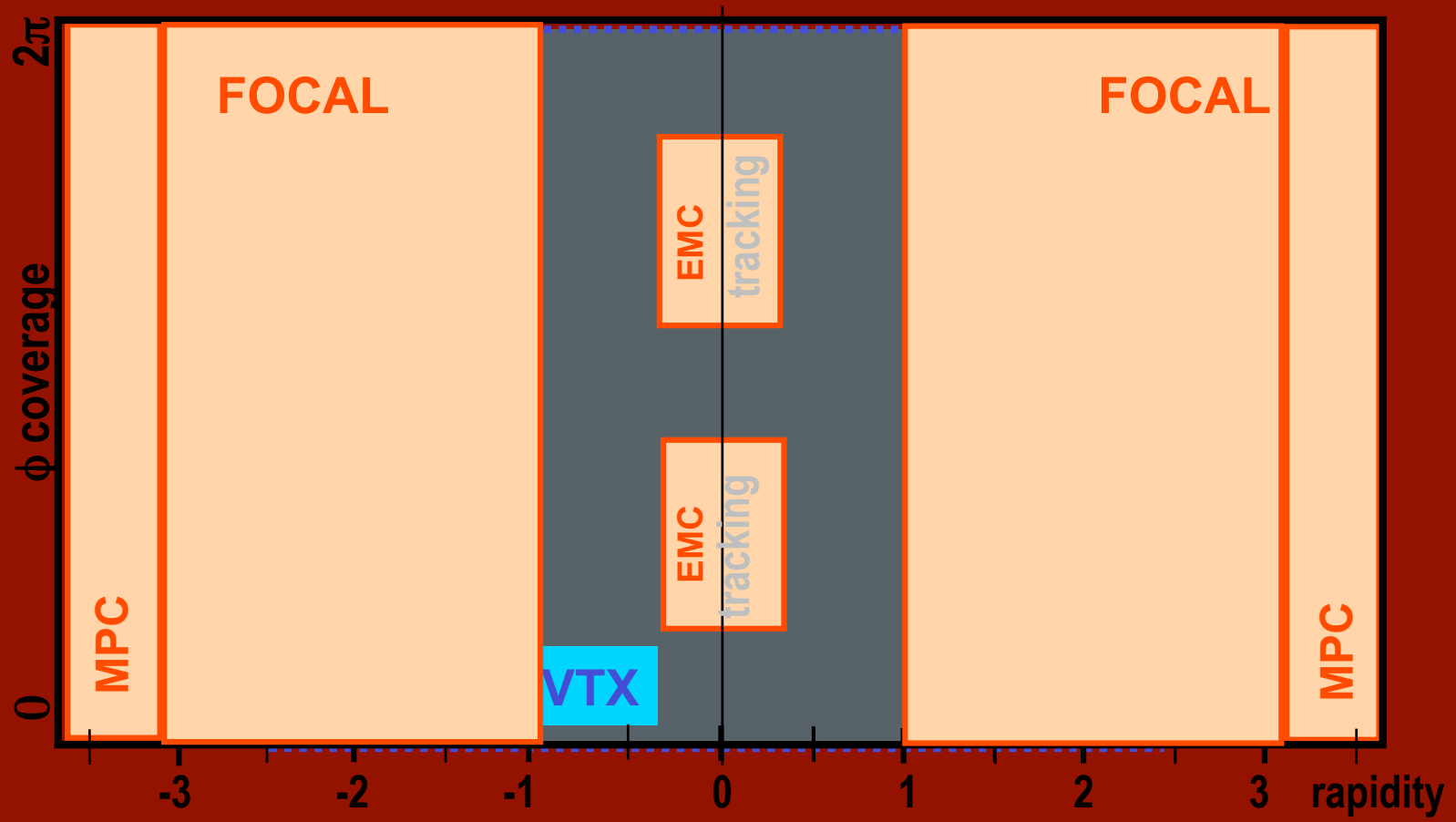
The future: Forward EMCal (FOCAL)at PHENIX



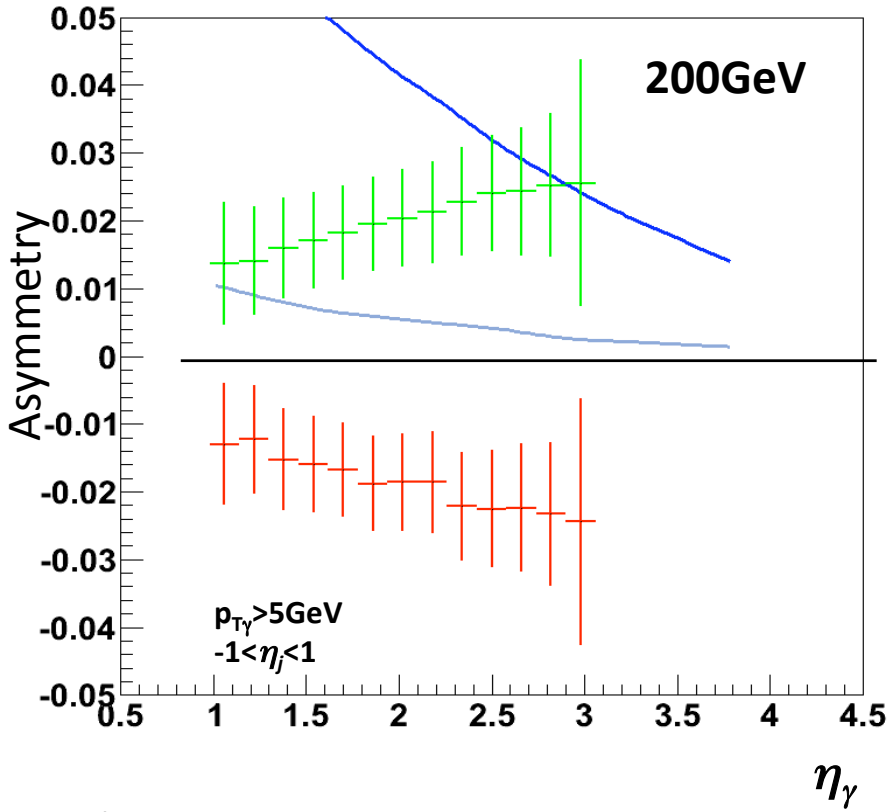
Photon-jet SSA using FOCAL + VTX

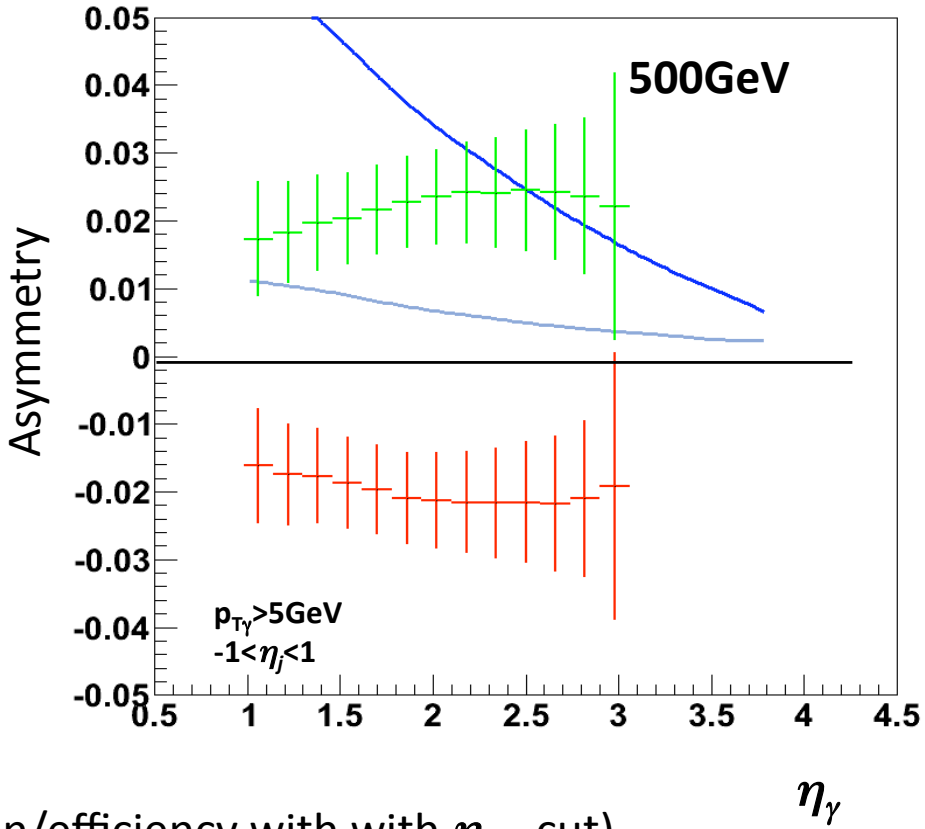
J. Lajoie

2008 Sivers distribution fits

Blue: abs. value of gluon Sivers
Light Blue: abs value of Boer-Mulders
Red: quark Sivers (with process dependence)
Green: quark Sivers (no process dependence)

~5 GeV trigger, 200 pb-1, <P> = 0.65
Assumes FOCAL efficiencies and π^0 contamination are same at 200/500GeV.





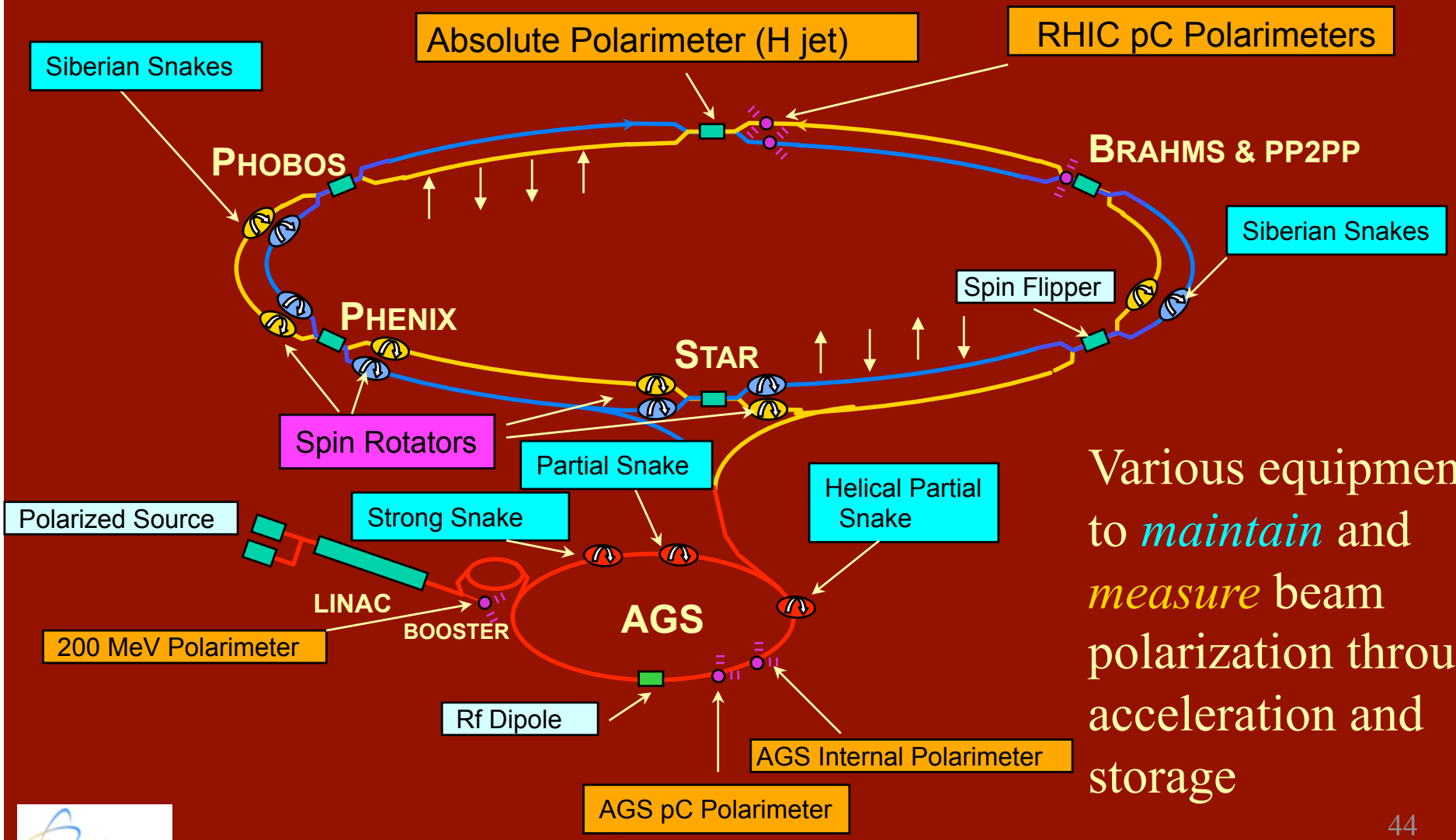
(need to worry about signal contamination/efficiency with with η_{JET} cut)

Conclusions

- Maturing transverse spin programs at RHIC!
  - Not initially planned as a major component of the RHIC spin program, but lots of exciting progress in theory and experiment since ~2002 has greatly increased interest at RHIC
  - Ever-improving "pQCD toolbox" allows one to learn more and more from hadronic collisions
  - Moving beyond "easy" inclusive probes to start to examine various correlation measurements and measure inclusive probes with smaller signal:bg
  - Transverse spin physics a major motivation in latest proposed upgrades for PHENIX and STAR

Extra Slides

RHIC as a Polarized p+p Collider



Various equipment to *maintain* and *measure* beam polarization through acceleration and storage

Polarized Collider Development

Parameter	Unit	2002	2003	2004	2005	**2006**
No. of bunches	--	55	55	56	106	**111**
bunch intensity	10^{11}	0.7	0.7	0.7	0.9	**1.4**
store energy	GeV	100	100	100	100	**100**
β*	m	3	1	1	1	**1**
peak luminosity	$10^{30}cm^{-2}s^{-1}$	2	6	6	10	**35**
average luminosity	$10^{30}cm^{-2}s^{-1}$	1	4	4	6	**20**
Collision points	--	4	4	4	3	**2**
average polarization, store	%	15	35	46	47	**60-65**

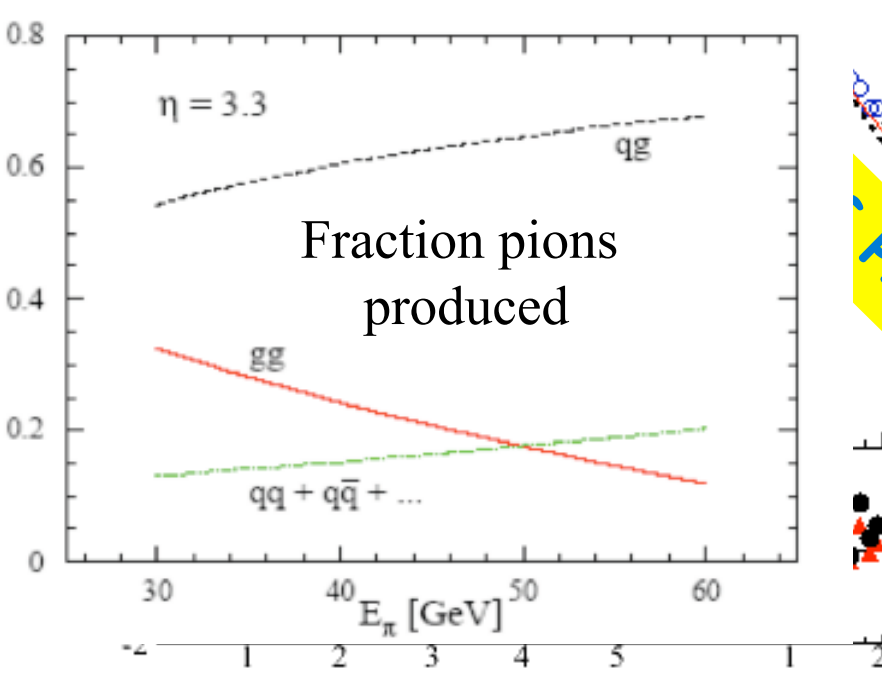
Machine performance: Transverse spin running at PHENIX

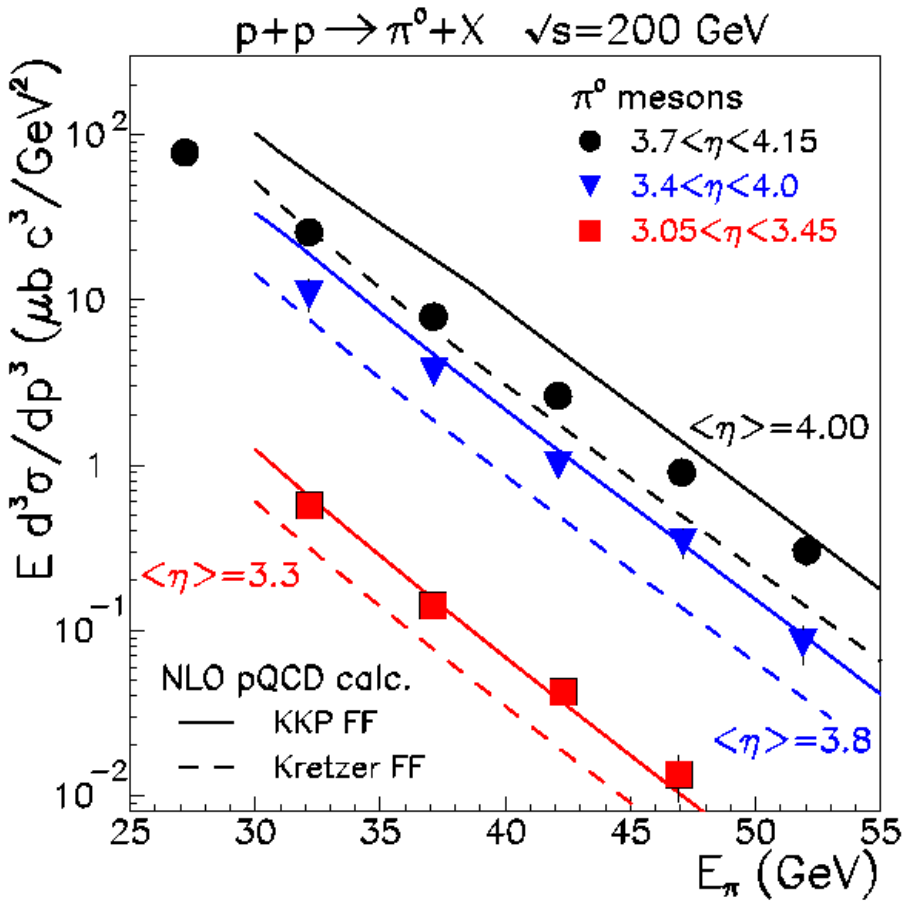
Year	√s [GeV]	Recorded L	Pol [%]	FOM (P^2L)
2001 (Run-2)	200	.15 pb^{-1}	15	3.4 nb^{-1}
2005 (Run-5)	200	.16 pb^{-1}	47	38 nb^{-1}
2006 (Run-6)	200	2.7 pb^{-1}	51	700 nb^{-1}
2006 (Run-6)	62.4	.02 pb^{-1}	48	4.6 nb^{-1}
2008 (Run-8)	200	5.2 pb^{-1}	46	1100 nb^{-1}

Forward Hadron Production at √s=200 GeV

Good agreement between data and NLO pQCD at √s=200 GeV, even at larger rapidities

PRL 97 (2006) 152302





π/K/p SSA Measurements at 200 and 62 GeV

BRAHMS measures identified hadrons (π,K,p,pbar)

in the kinematic ranges of

- $0 < x_F < 0.35$ and $0.2 < p_T < 3.5$ GeV/*c* at $\sqrt{s}$=200 GeV
- $0 < x_F < 0.6$ and $0.2 < p_T < 1.5$ GeV/*c* at $\sqrt{s}$=62 GeV for

- x_F, p_T, flavor, $\sqrt{s}$ dependent SSA
- cross-section of unpolarized hadron production

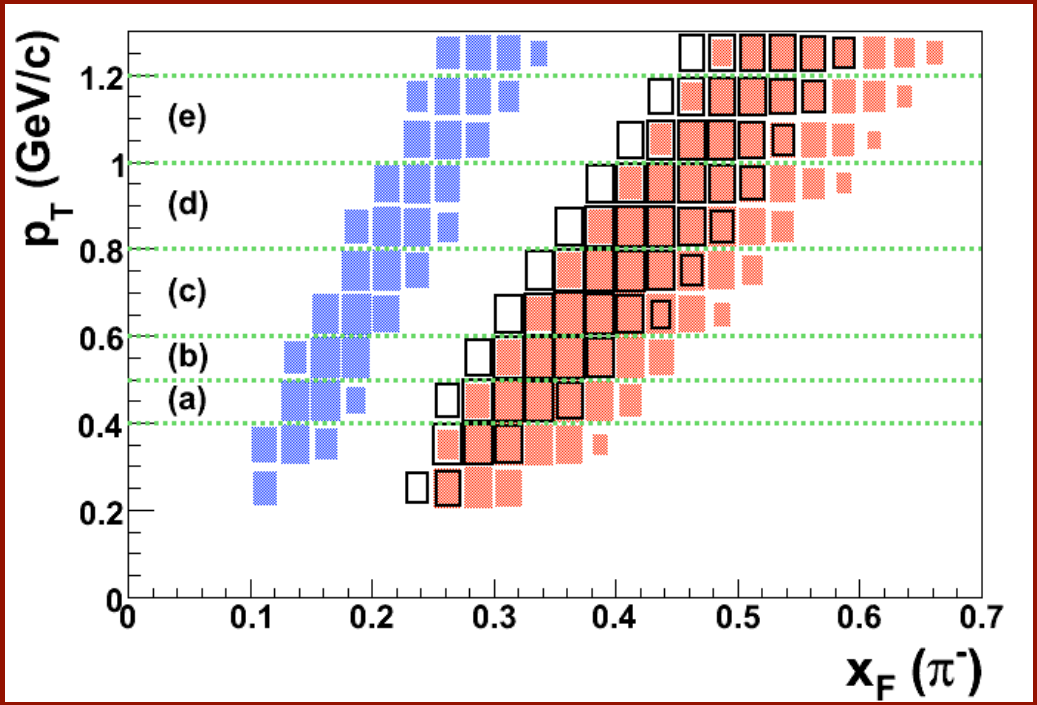
(constraint for theoretically consistent description)

Data:

- Run-5: $\sqrt{s}$ = 200 GeV 2.5 pb^{-1} recorded (polarization:45-50%)
- Run-6: $\sqrt{s}$ = 62 GeV 0.21 pb^{-1} recorded (polarization:45-65%)

Data from Forward Spectrometer at 2.3-4 deg. covering "high"-x_F ($0.15 < x_F < 0.6$) are presented.

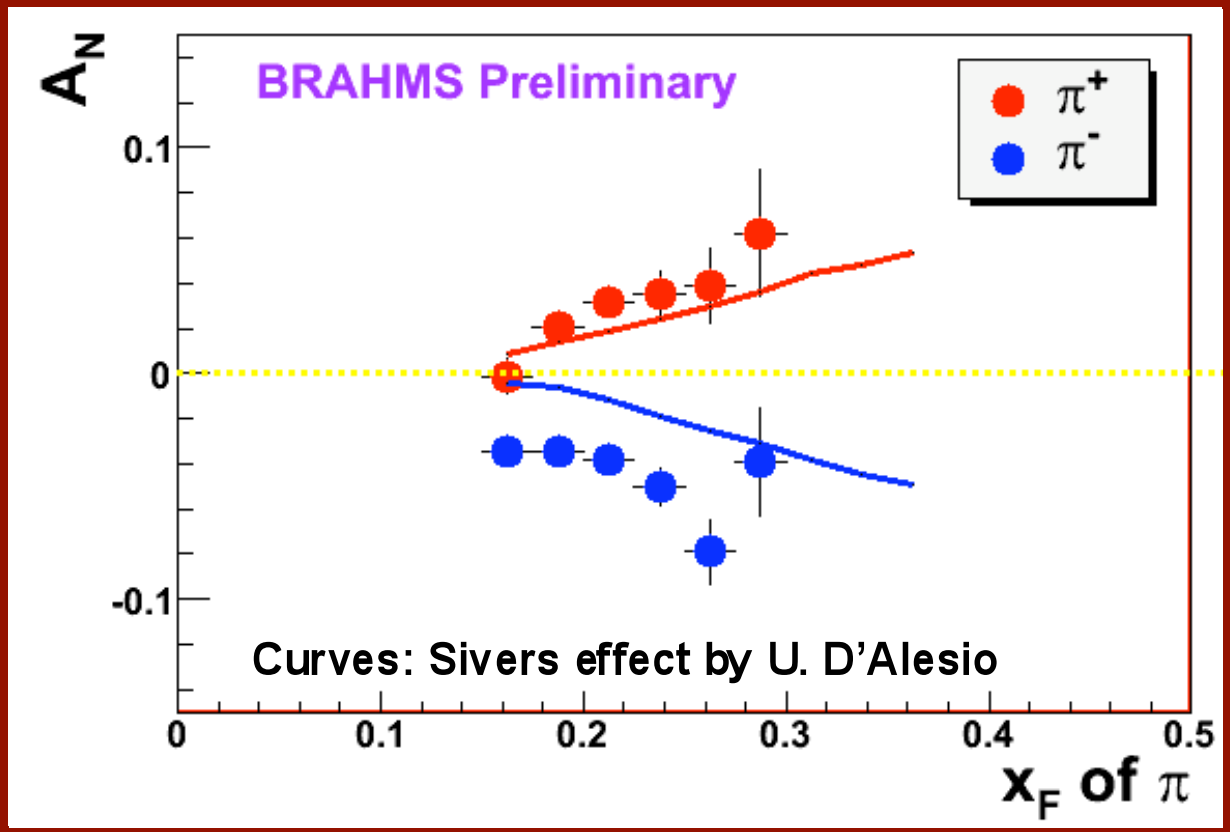
BRAHMS x_F-p_T acceptance at $\sqrt{s}$ = 62.4 GeV



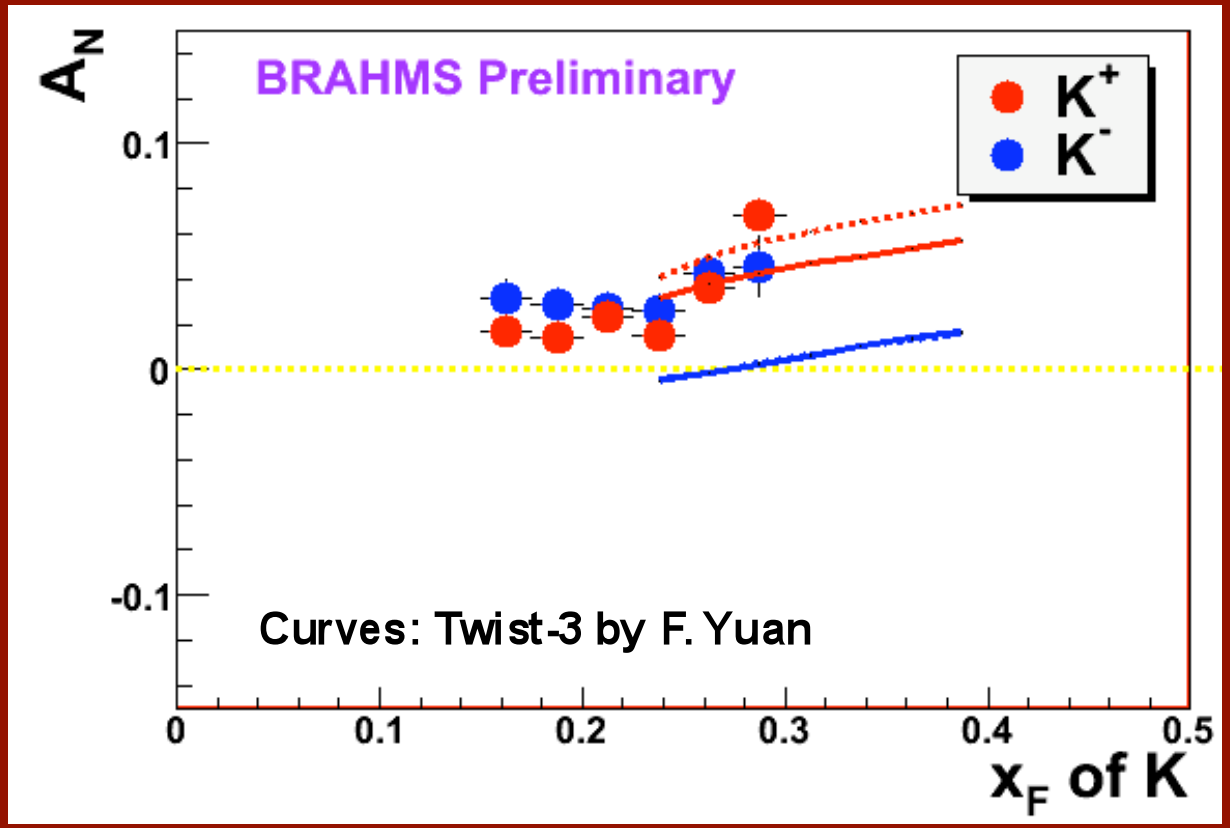
Strong x_F-p_T correlation due to limited spectrometer solid angle acceptance.

Three angle settings of spectrometer used: 2, 3, and 6 deg

$A_N(\pi)$ at 4 deg. at $\sqrt{s} = 200$ GeV

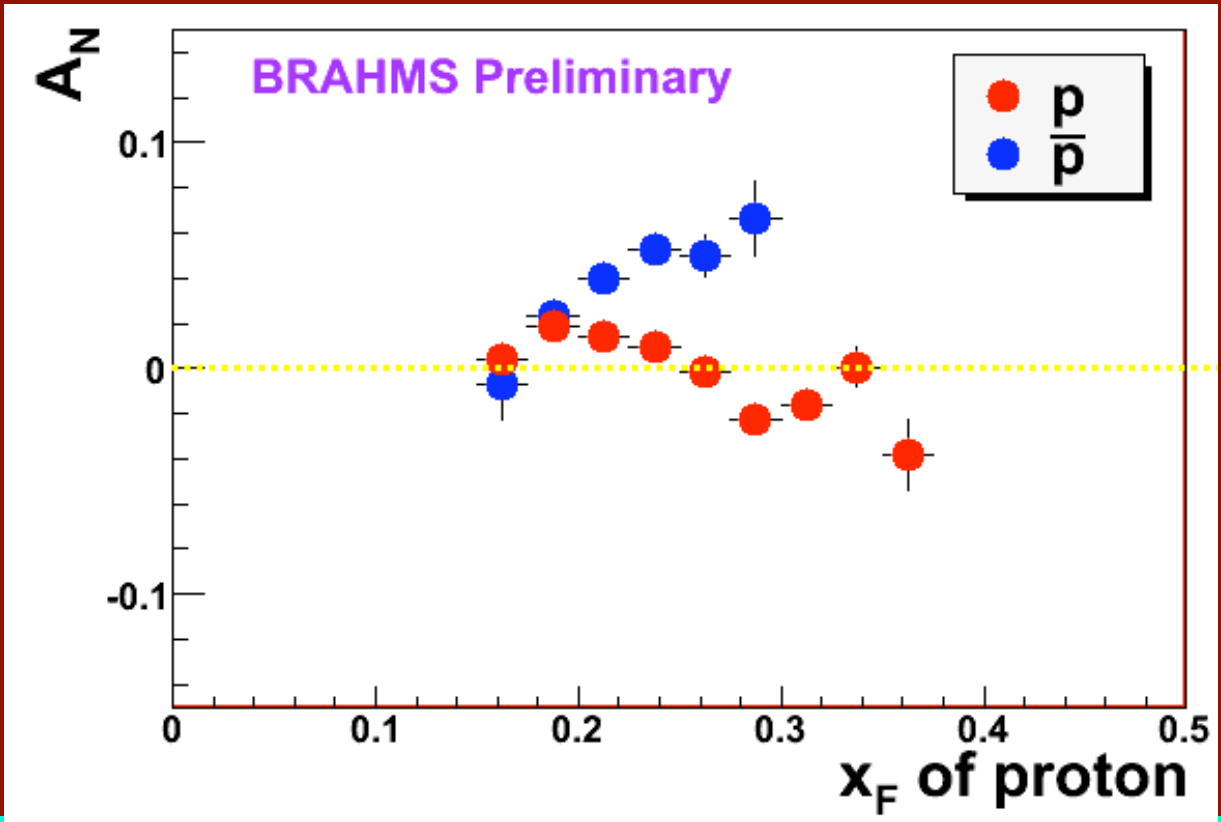


$A_N(K)$ at 2.3 deg at $\sqrt{s}$ = 200 GeV



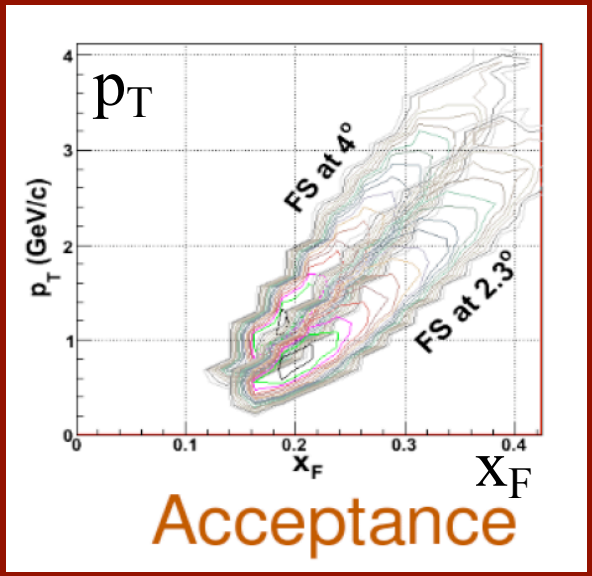
- Solid lines: two-flavor (*u*, *d*) fit
- Dashed lines: valence + sea, anti-quark
- Calculations done only for $\langle p_T(\pi) \rangle > 1$ GeV/c

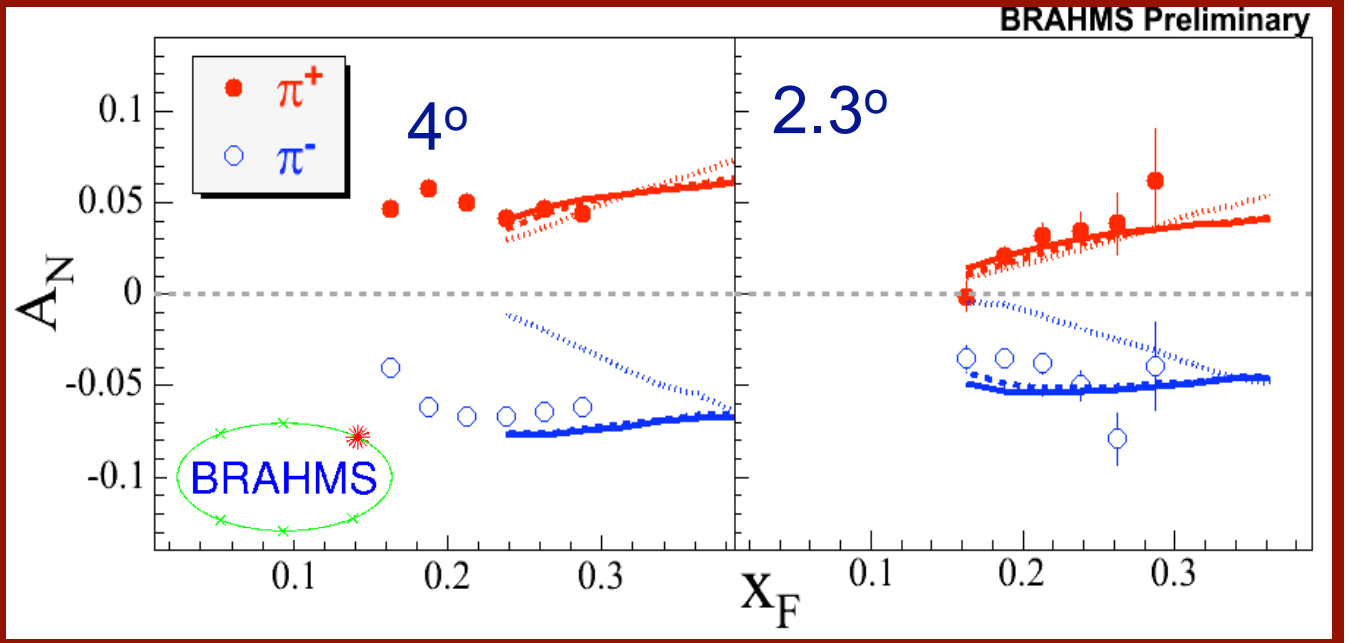
Proton at 2.3 deg. at √s = 200 GeV



- A_N(pbar), $A_N(K^-) > 0$: Accidental? Or contribution from sea-quarks
- $A_N(p) \sim 0$: At this kinematic region, significant fraction of proton are mostly from polarized beam proton, but only ones showing A_N ~0

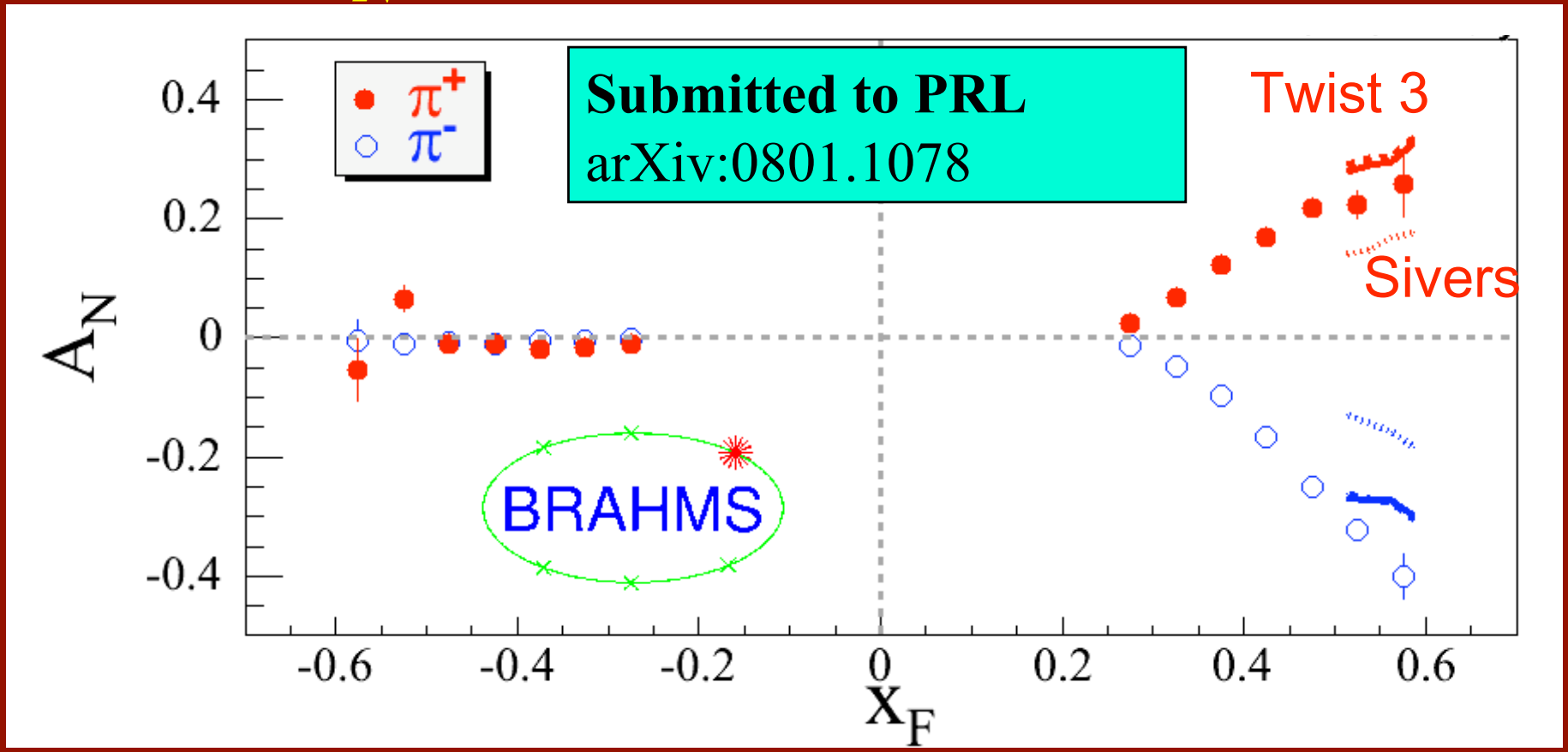
$A_N(\pi)$ at $\sqrt{s}$ = 200 GeV





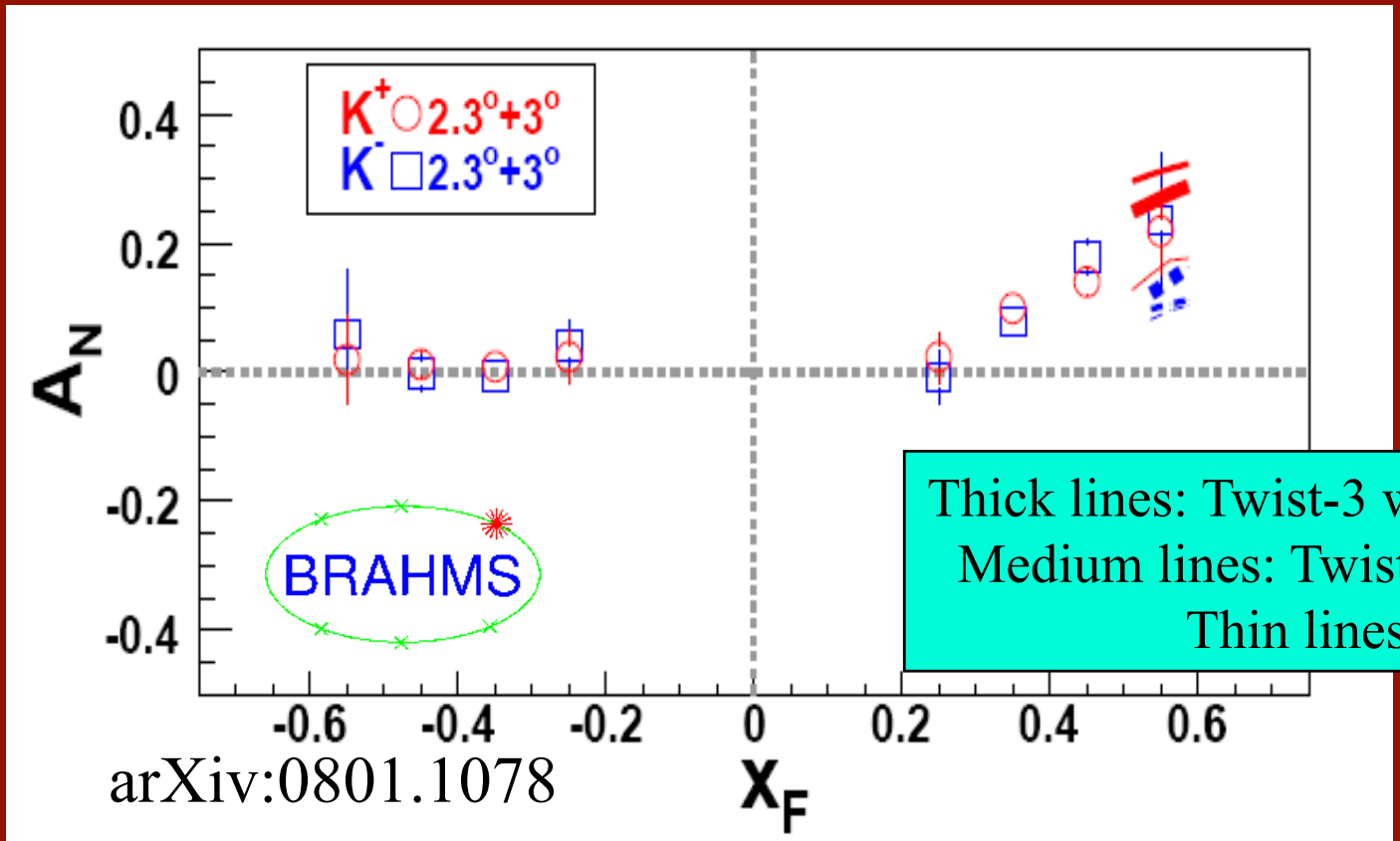
- $A_N(\pi^+)$ positive; $A_N(\pi^-)$ negative
  - 4-6% in $0.15 < x_F < 0.3$
- Behavior consistent with slight decrease with increasing p_T as evident in going from 2.3 deg to 4 deg setting
- Good agreement with twist-3 calculations which also have the $1/p_T$-dependence at higher p_T

$A_N(\pi)$ at $\sqrt{s} = 62.4$ GeV



- Large $A_N(\pi)$: 0.3-0.4 at $x_F \sim 0.6$, $p_T \sim 1.3$ GeV
- Strong x_F-p_T dependence. Though $|A_N(\pi^+)| \sim |A_N(\pi^-)|$, $|A_N(\pi^+)/A_N(\pi^-)|$ decreases with x_F-p_T

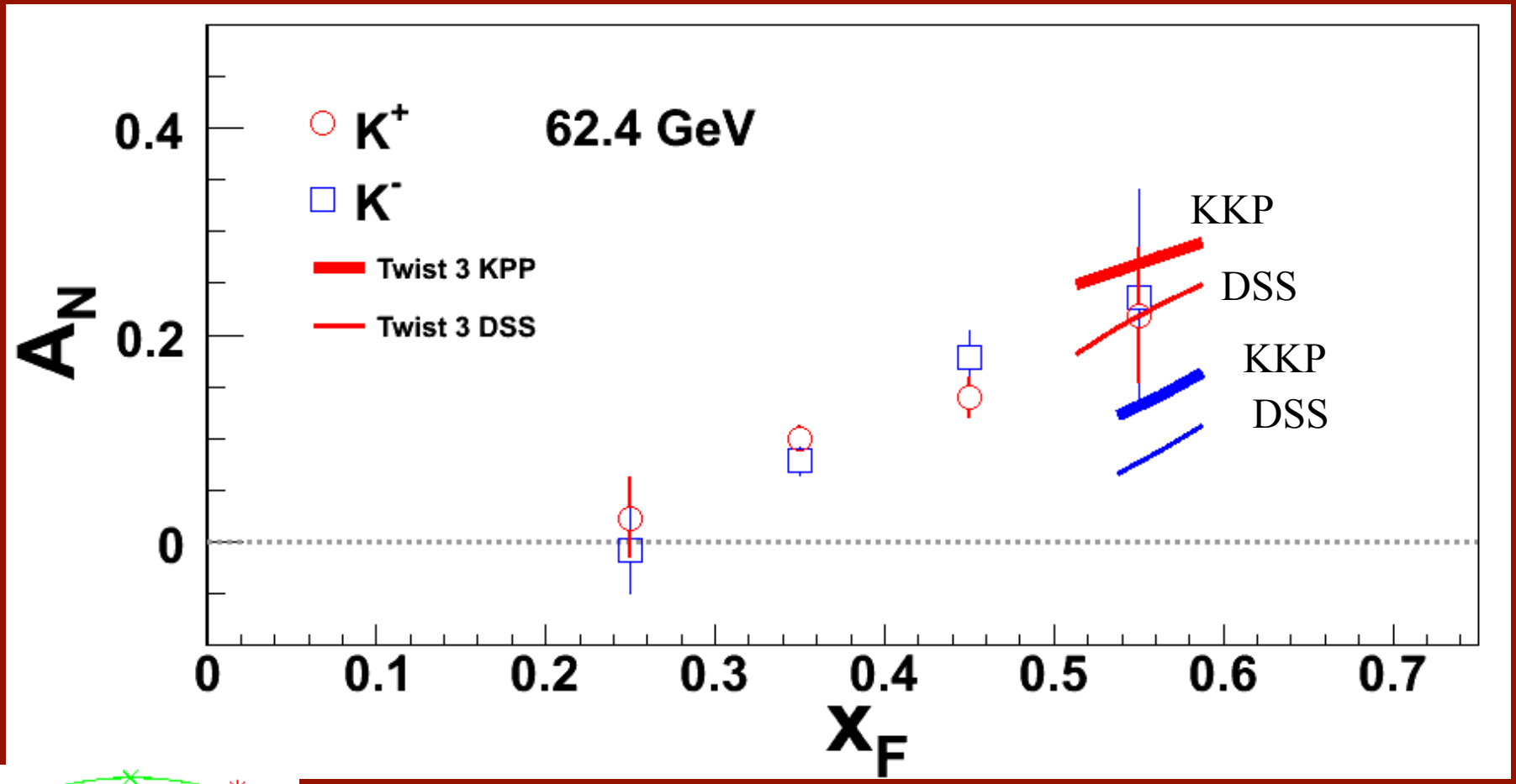
Kaon SSA at 62.4 GeV



Thick lines: Twist-3 w/sea quark contrib.
Medium lines: Twist-3 w/o sea quarks
Thin lines: Sivers

- A_N ~0 at negative x_F
- $A_N(K^+) \sim A_N(K^-)$: positive ~20% at $x_F < 0.5$-0.6
- Calculations get signs correct but underpredict K^-

Sensitivity to fragmentation functions



BRAHMS

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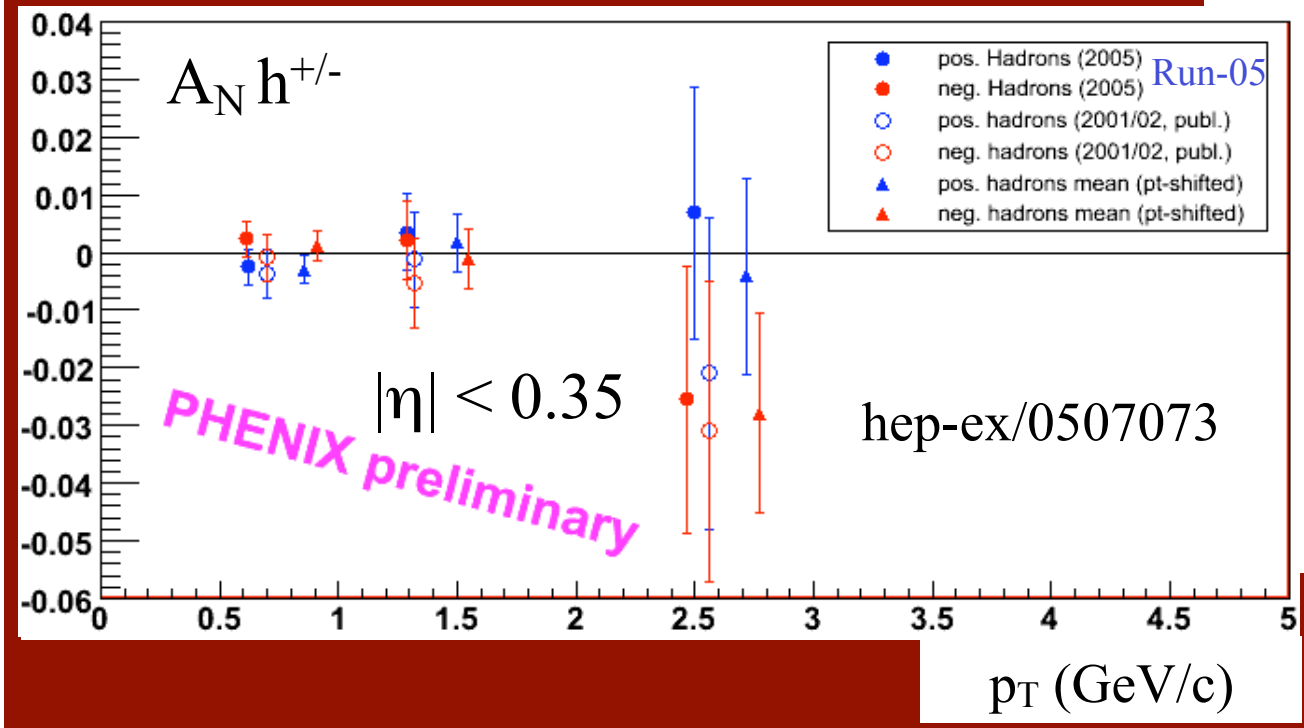
Calculations compared to BRAHMS data

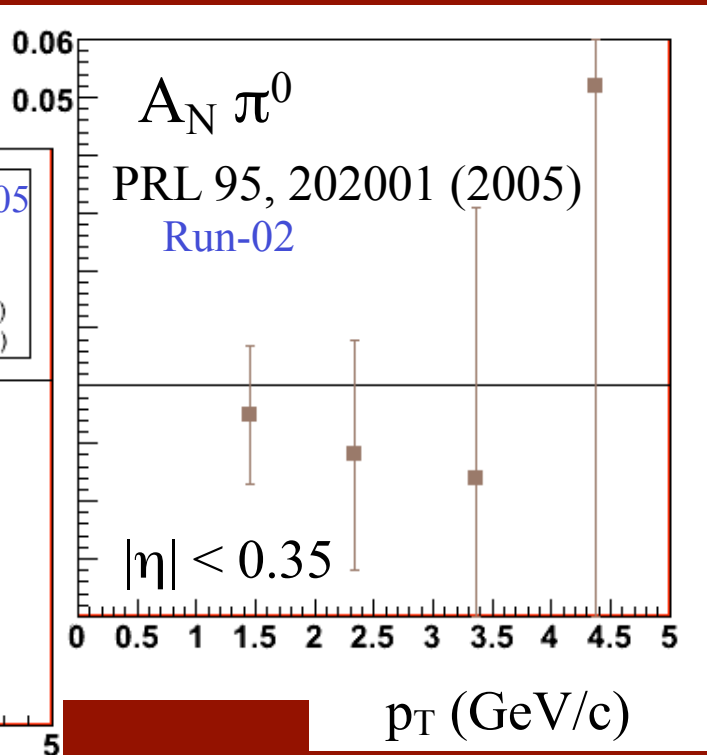
- **Twist-3 parton correlation** calculation provided by F. Yuan
  - Kouvaris, Qiu, Vogelsang, Yuan
  - "Extended" with non-derivative terms ("moderate" effects at BRAHMS kinematics)
  - Two flavor (*u,d*) and valence+sea+antiquark fits

- **Sivers effect** calculations provided by U. D'Alesio
  - Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia

  "Sivers effect with complete and consistent k_T kinematics plus description of unpolarized cross section"

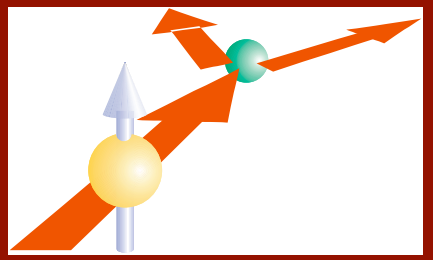
A_N of midrapidity π^0 and $h^{+/-}$ at $\sqrt{s}$=200 GeV

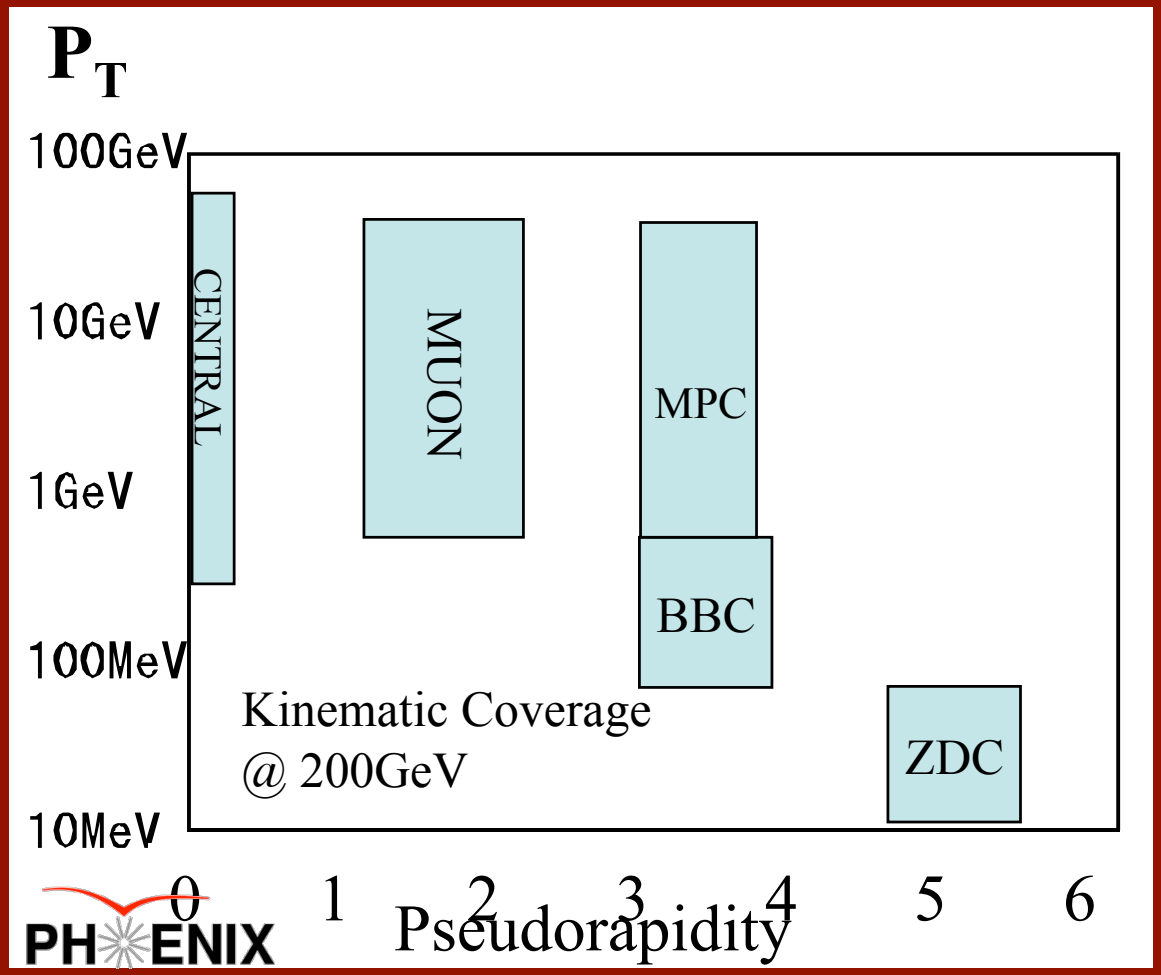




- A_N is zero within 1% → contrast with forward pions
- Constrains Sivers distribution function for gluons (Anselmino et al., PRD74, 094011 (2006))
- Updated π^0 analysis with ~200x improvement(!) in statistical figure-of-merit underway . . .

PHENIX Kinematic Coverage



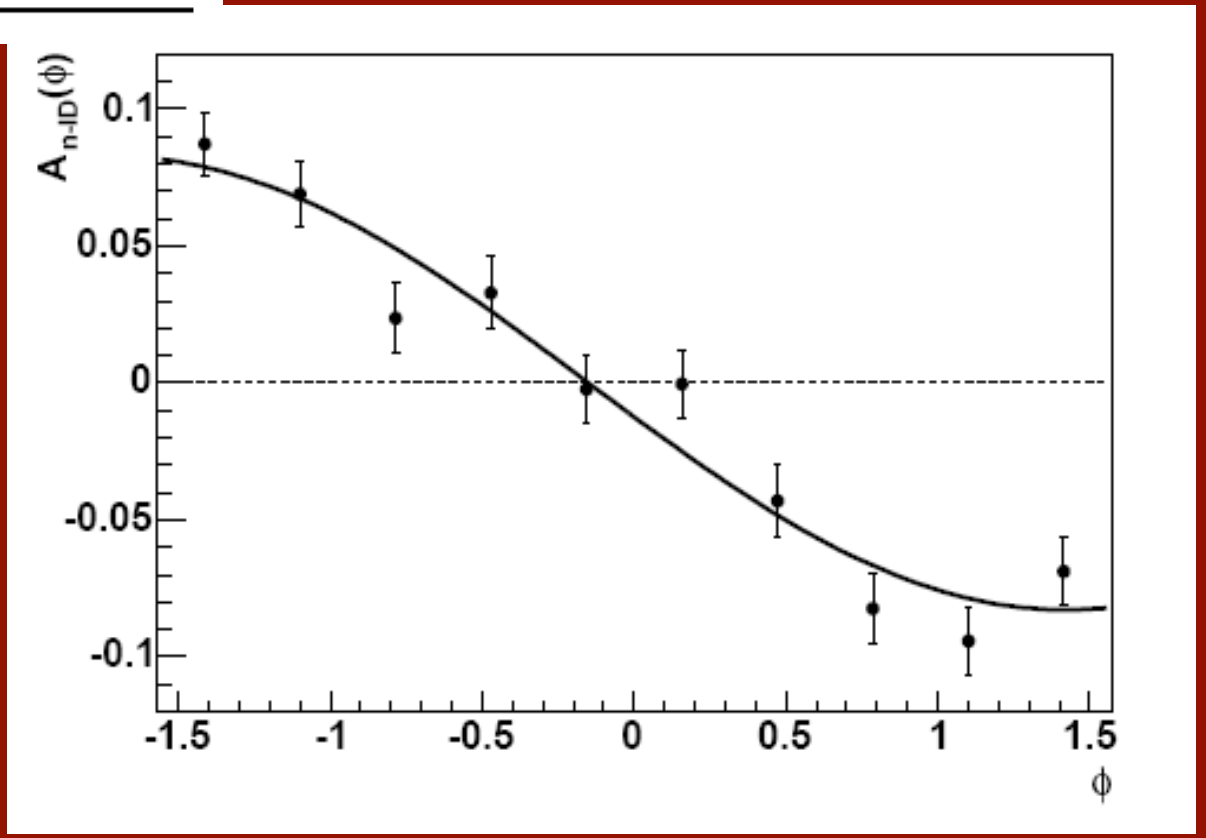


Forward Neutral Particles at IP12

	forward	backward
neutron	$-0.090 \pm 0.006 \pm 0.009$	$0.002 \pm 0.004 \pm 0.003$
photon	$-0.009 \pm 0.015 \pm 0.007$	$-0.020 \pm 0.010 \pm 0.003$
π^0	$-0.022 \pm 0.030 \pm 0.002$	$0.005 \pm 0.021 \pm 0.0005$

$\sqrt{s}$ = 200 GeV

hep-ex/0610030



Forward neutron A_N

- New/recent results (post-SPIN2008?):
- STAR omega peak
- STAR forward pi0-pi0 correlations
- STAR eta
- (STAR low-pT pi0?)

Determination of transverse single spin asymmetries A_N

- Look at left-right asymmetries relative to one transversely polarized proton beam

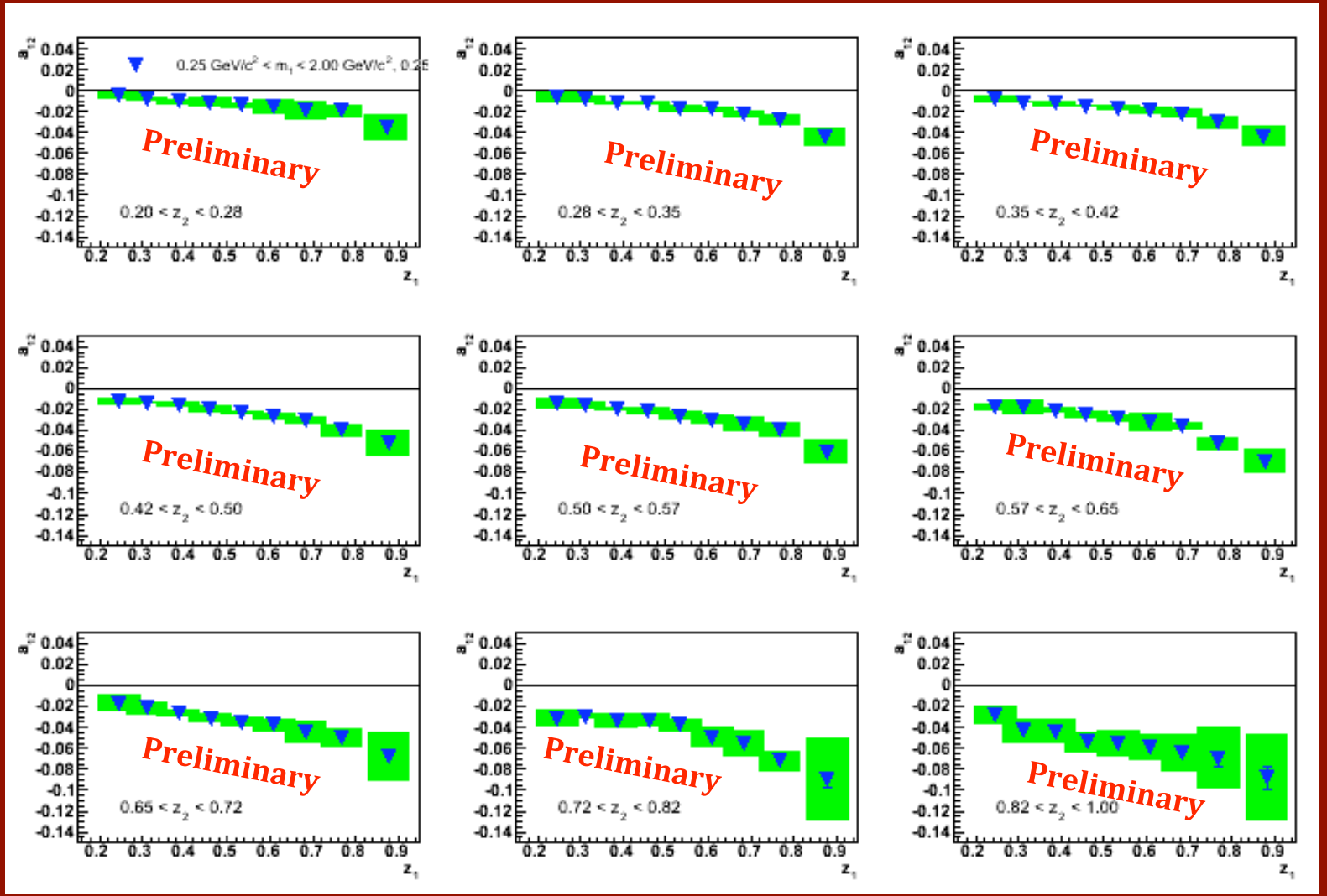
$$A_N^{Left} = \frac{1}{P}\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}}, R = \frac{L^{\uparrow}}{L^{\downarrow}}$$

N.B. Detector acceptance only on one side of beam for BRAHMS
→ Square-root formula not an option

~~so-called square root formula~~

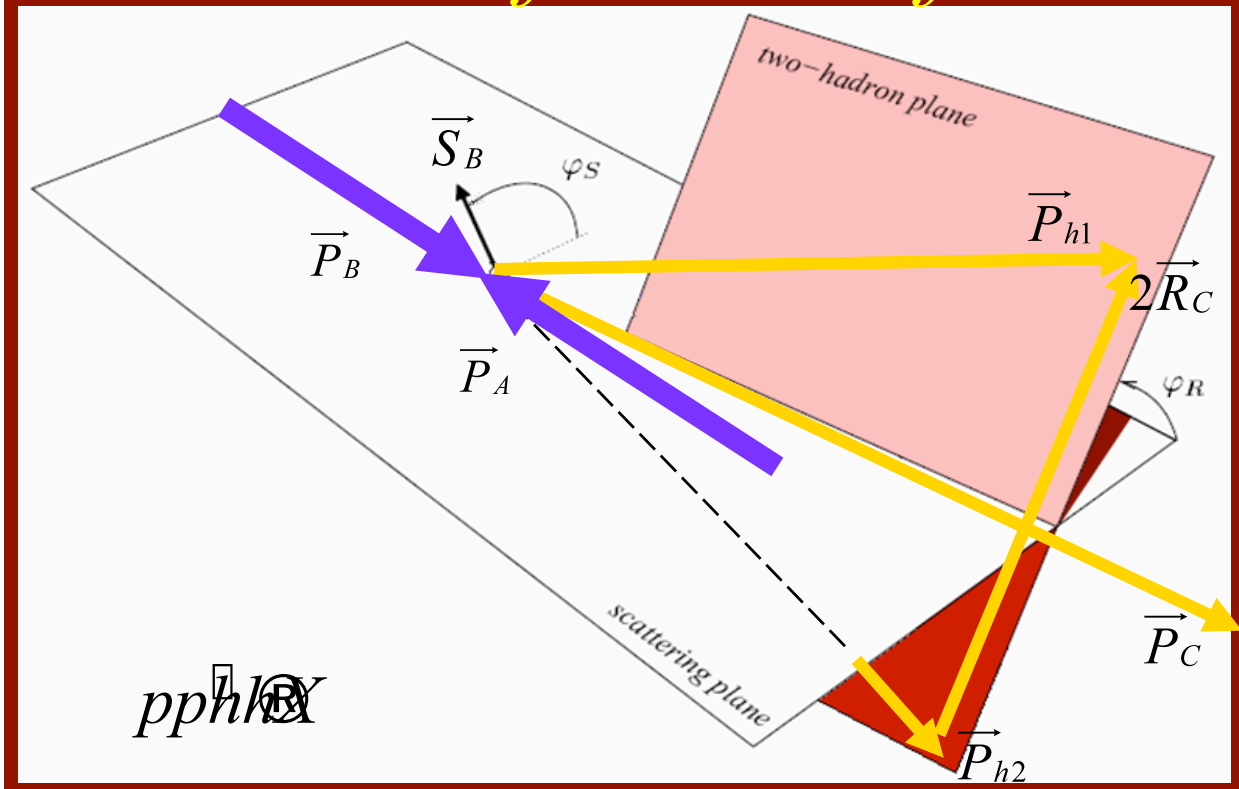
$$A_N = \frac{1}{P}\frac{\sqrt{N_{left}^{\uparrow} \cdot N_{right}^{\downarrow}} - \sqrt{N_{left}^{\downarrow} \cdot N_{right}^{\uparrow}}}{\sqrt{N_{left}^{\uparrow} \cdot N_{right}^{\downarrow}} + \sqrt{N_{left}^{\downarrow} \cdot N_{right}^{\uparrow}}}$$

BELLE IFF: z binning



9x9 z_1 z_2 binning

IFF: Definition of Vectors and Angles



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

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

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

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

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

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

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

A_R : from scattering plane to hadron plane

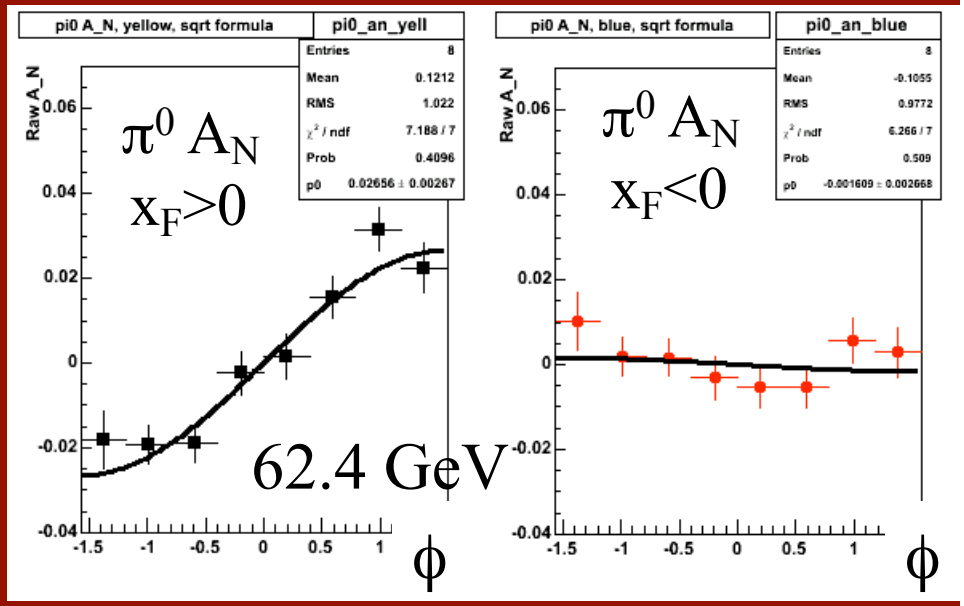
A_S : from polarization vector to scattering plane

$$A_{RS} \sin(\varphi_R + \varphi_S)$$

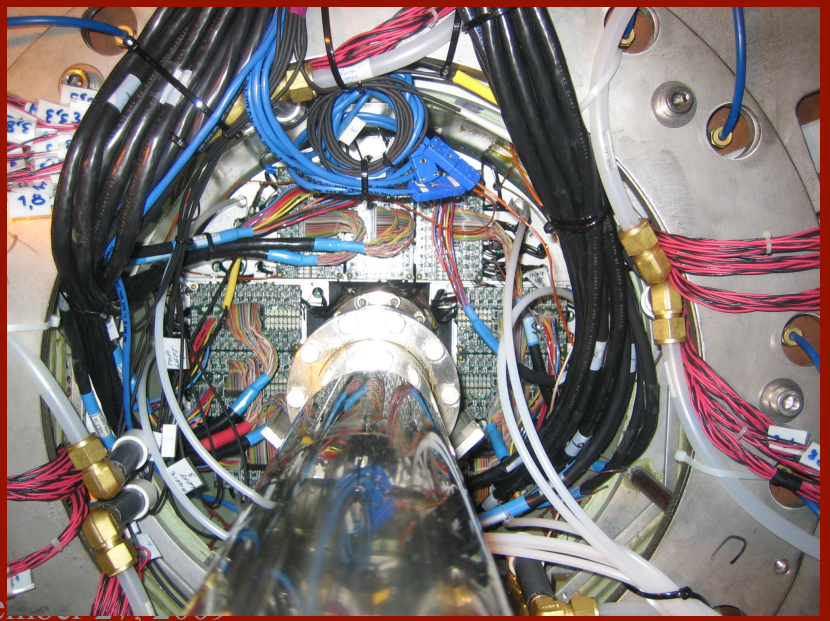
Bacchetta and Radici, PRD70, 094032 (2004)

Improving forward coverage at PHENIX

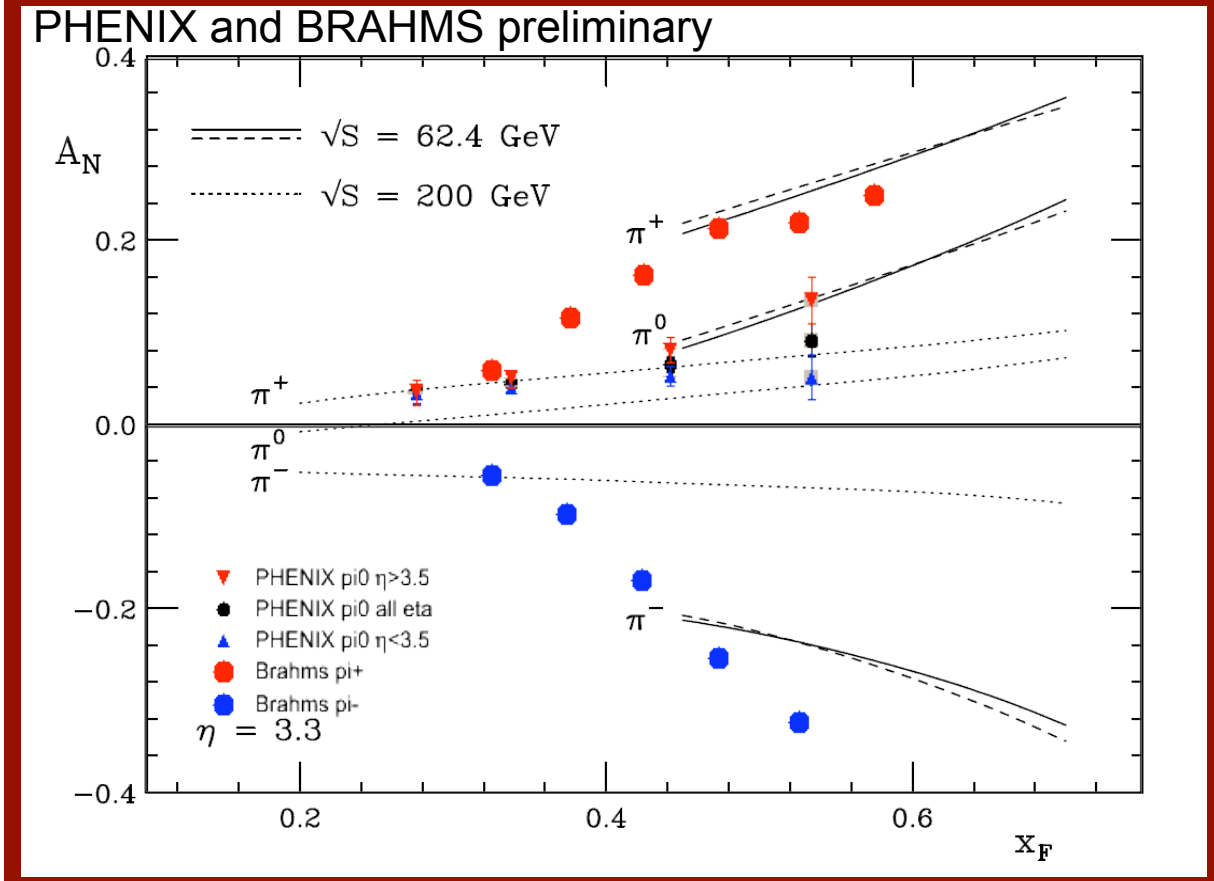
- Muon Piston Calorimeter (MPC): $PbWO_4$ calorimeter
- $3.1 < |\eta| < 3.7$
  - Region of large observed asymmetries
- Single arm commissioned in 2006
- Second arm took data in 2008



Full azimuthal coverage for $3.1 \leq \eta \leq 3.7$ and $2 < E(\pi^0) < 25$ GeV



Charged vs. neutral pions at 62.4 GeV



BRAHMS <η> = 3.44, comparable to PHENIX "all eta" = black circles.

Qualitatively similar behavior to E704 data:
$-\pi^0$ positive, between π^+ and π^-
-Roughly similar magnitude: $A_N(\pi^0)/A_N(\pi^+) \sim 25$-50%

Quantitative comparison between identified pion asymmetries should provide strong test of theories!

Calculations: Kouvaris, Qiu, Vogelsang, Yuan, PRD74:114013, 2006

- **Twist-3 calculation for pions at η = 3.3**
- **Derived from fits to E704 data at √s~20 GeV and then evolved to 62.4 and 200 GeV**
- **Beware that kinematics not exactly matched, since A_N strong function of pT and xF**