Investigating the Spin Structure of the Proton at RHIC: Recent Results

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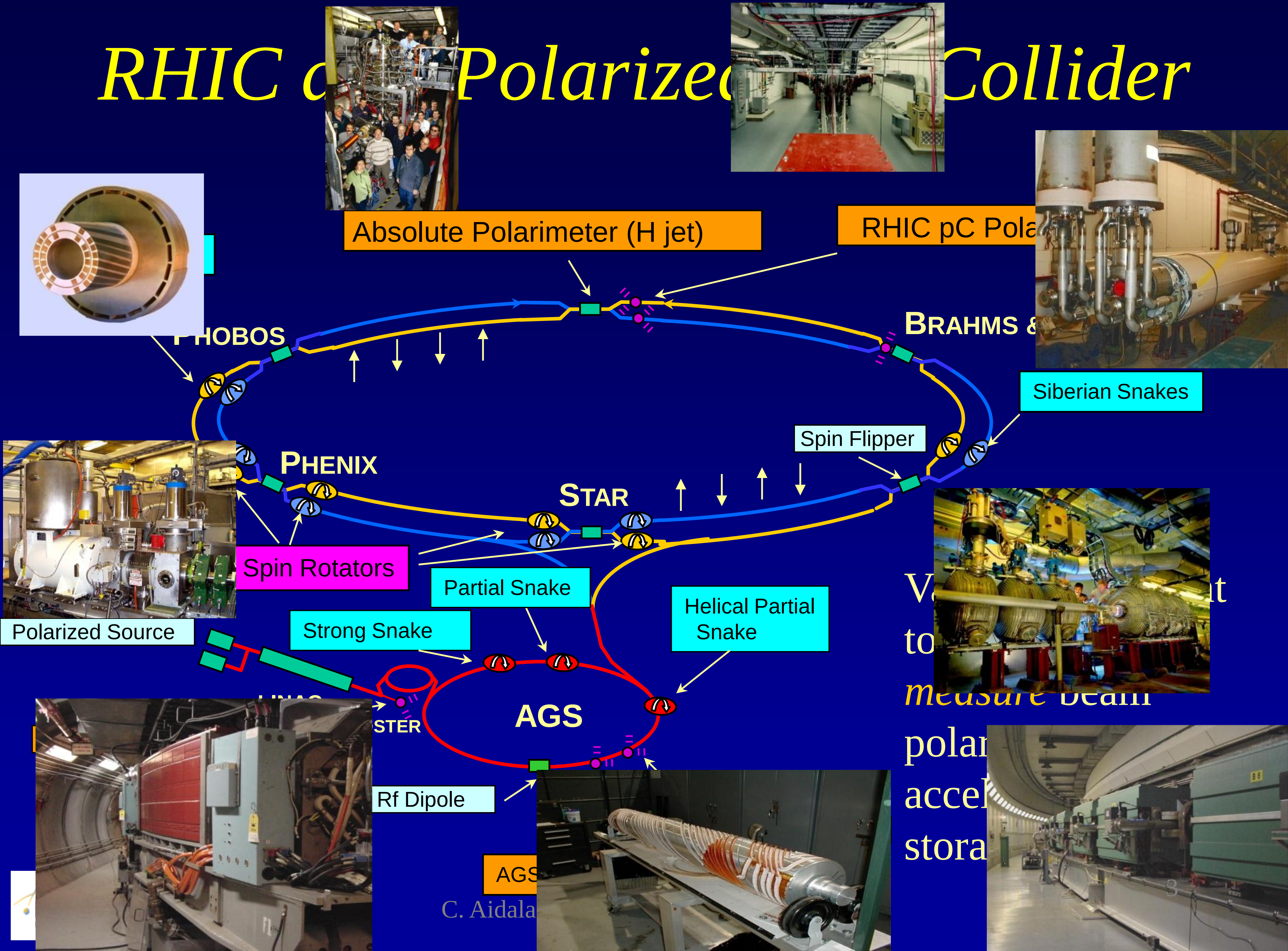
Proton Structure at RHIC

Gluon helicity distribution and ΔG	Flavor–separated sea quark helicity distributions	"Transverse spin" phenomena
π Jets $A_{LL}(gg, gq \rightarrow \pi + X)$ Prompt Photons $A_{LL}(gq \rightarrow \gamma + X)$ Back-to-Back Correlations	W Production $A_L(u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^- \rightarrow \ell^- + \bar{\nu}_l)$	Transversity Transverse-momentum-dependent distributions Single-Spin Asymmetries

Advantages of a polarized *proton-proton collider*:
- Hadronic collisions → Leading-order access to gluons
- High energies → Applicability of perturbative QCD
- High energies → Production of new probes: W bosons

RHIC a… Polarize… Collider



V… t
to
measure beam
polar
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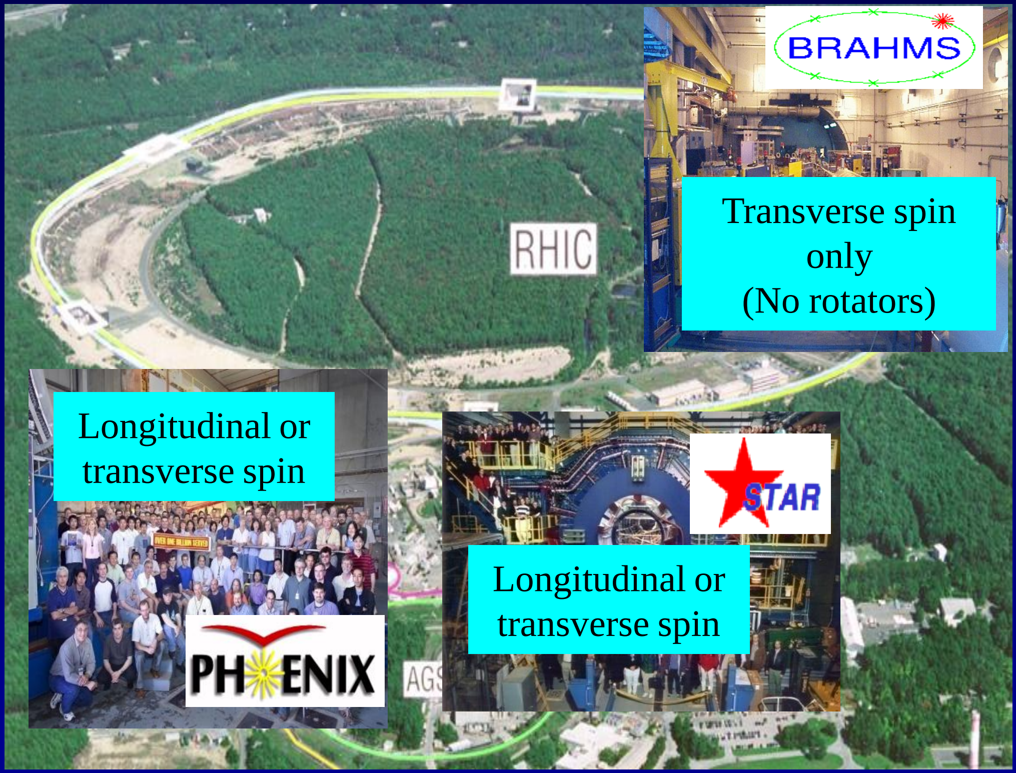
RHIC Spin Physics Experiments

- Three experiments: STAR, PHENIX, BRAHMS
- After 2006 only STAR and PHENIX running



Accelerator performance:
Avg. pol ~55% at 200 GeV (design 70%).
Achieved 5.0×10^{31} cm^{-2} s^{-1} lumi (design ~4x this).

RHIC Integrated Luminosity and Polarization History
(PHENIX lumi values)

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	39	14	2.1×10^{-1}	-	-
2009	200	55	16	1.5×10^{0}	-	-

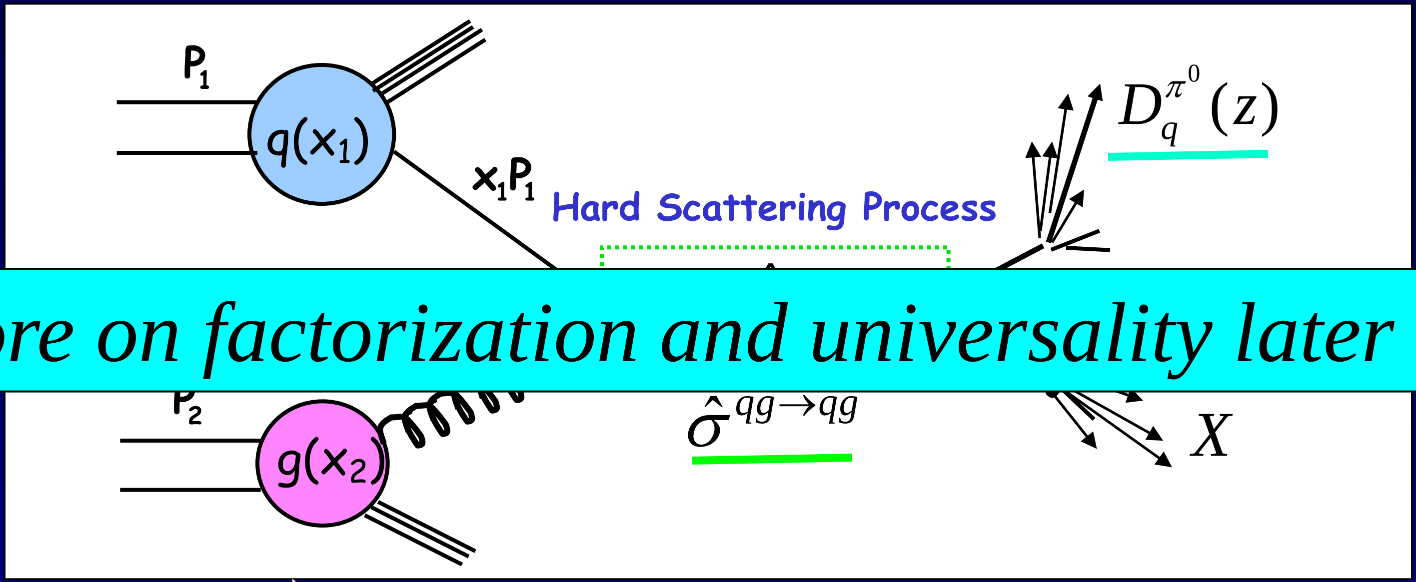
First 500 GeV commissioning run in 2009

Studying Nucleon Structure in p+p: Reliance on Input from Simpler Systems

- Disadvantage of hadronic collisions: much "messier" than DIS! → *Rely on input from simpler systems*

- The more we know from simpler systems such as DIS and e+e- annihilation, the more we can in turn learn from hadronic collisions!

Factorization and Universality in Perturbative QCD



More on factorization and universality later . . .

$$\sigma\left(pp\to\pi^0 X\right)\propto q(x_1)\otimes g(x_2)\otimes\hat{\sigma}^{qg\to qg}(\hat{s})\otimes D_q^{\pi^0}(z)$$

"Hard" probes have predictable rates given:

- Parton distribution functions (need experimental input)
- Partonic hard scattering rates (calculable in pQCD)
- Fragmentation functions (need experimental input)

} Universality (Process independence)

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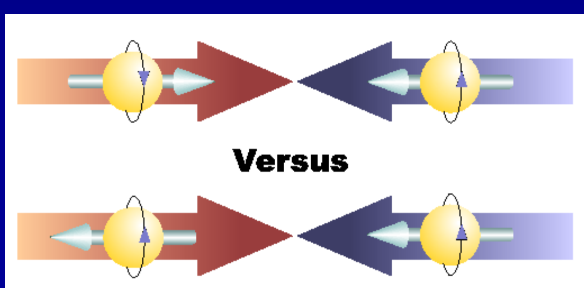
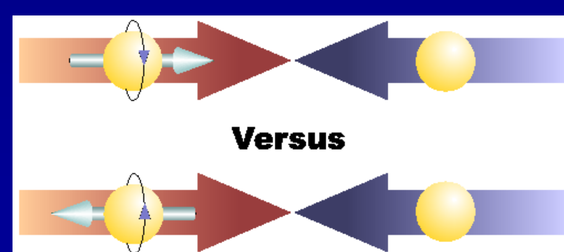
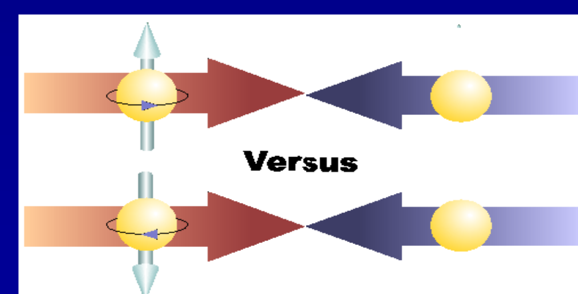
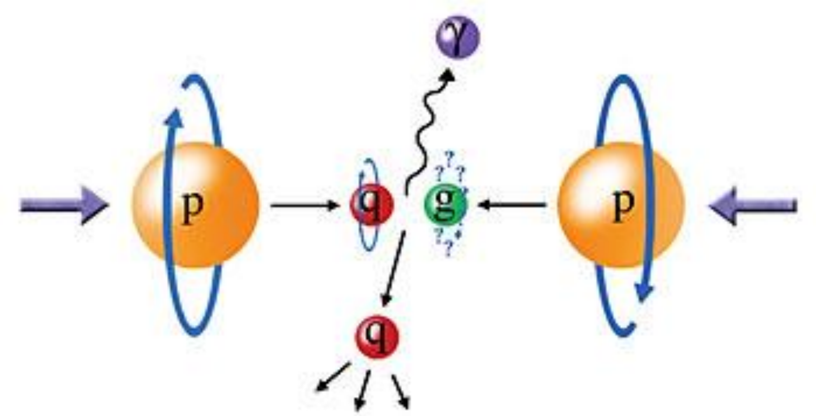






Probing the Helicity Structure of the Nucleon with p+p Collisions

$$A_{LL} = \frac{\Delta\sigma}{\sigma} = \frac{1}{|P_1 P_2|} \frac{N_{++}/L_{++} - N_{+-}/L_{+-}}{N_{++}/L_{++} + N_{+-}/L_{+-}}$$



Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

$$\Delta\sigma(pp \to \pi^0 X) \propto \Delta q(x_1) \otimes \Delta g(x_2) \otimes \Delta\hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

DIS ? pQCD e+e-

Leading-order access to gluons → ΔG

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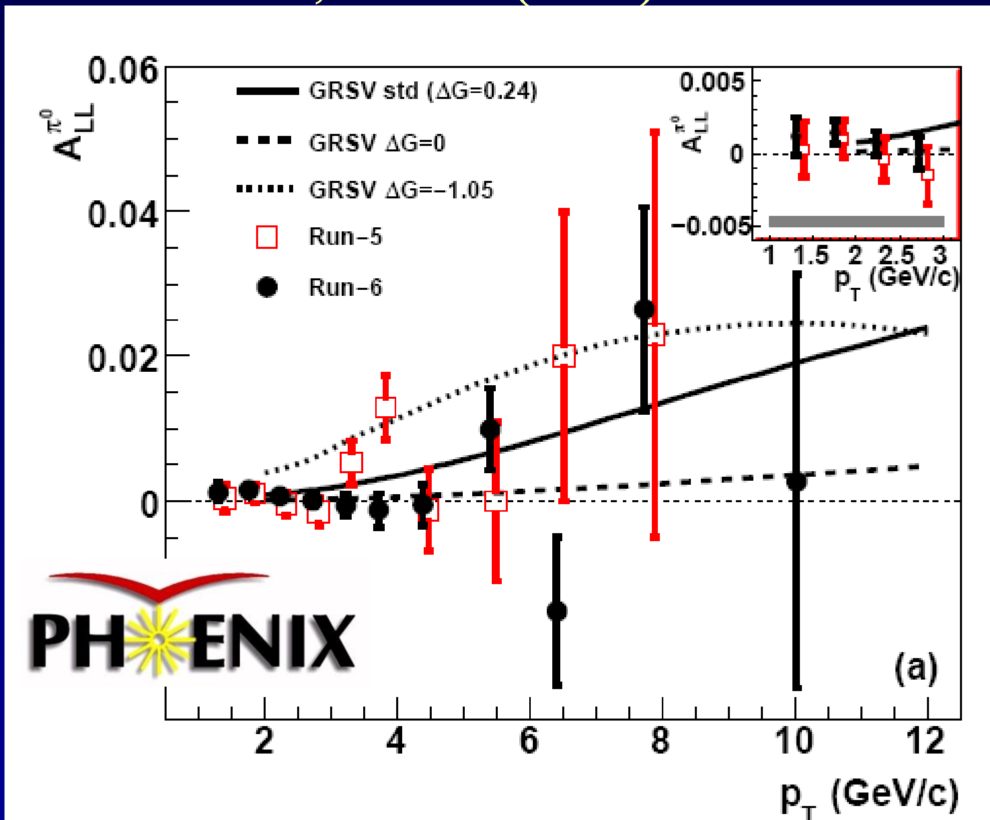
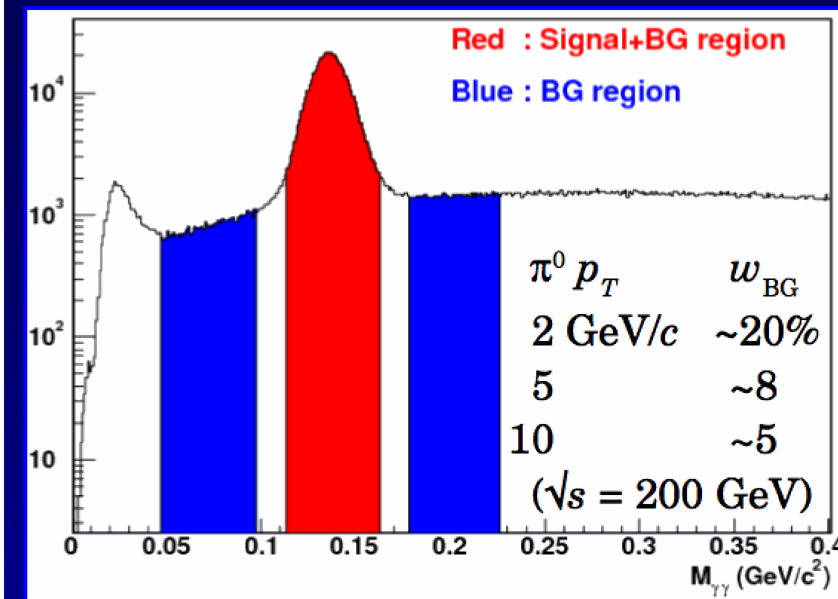
Inclusive Neutral Pion Asymmetry at $\sqrt{s}$=200 GeV

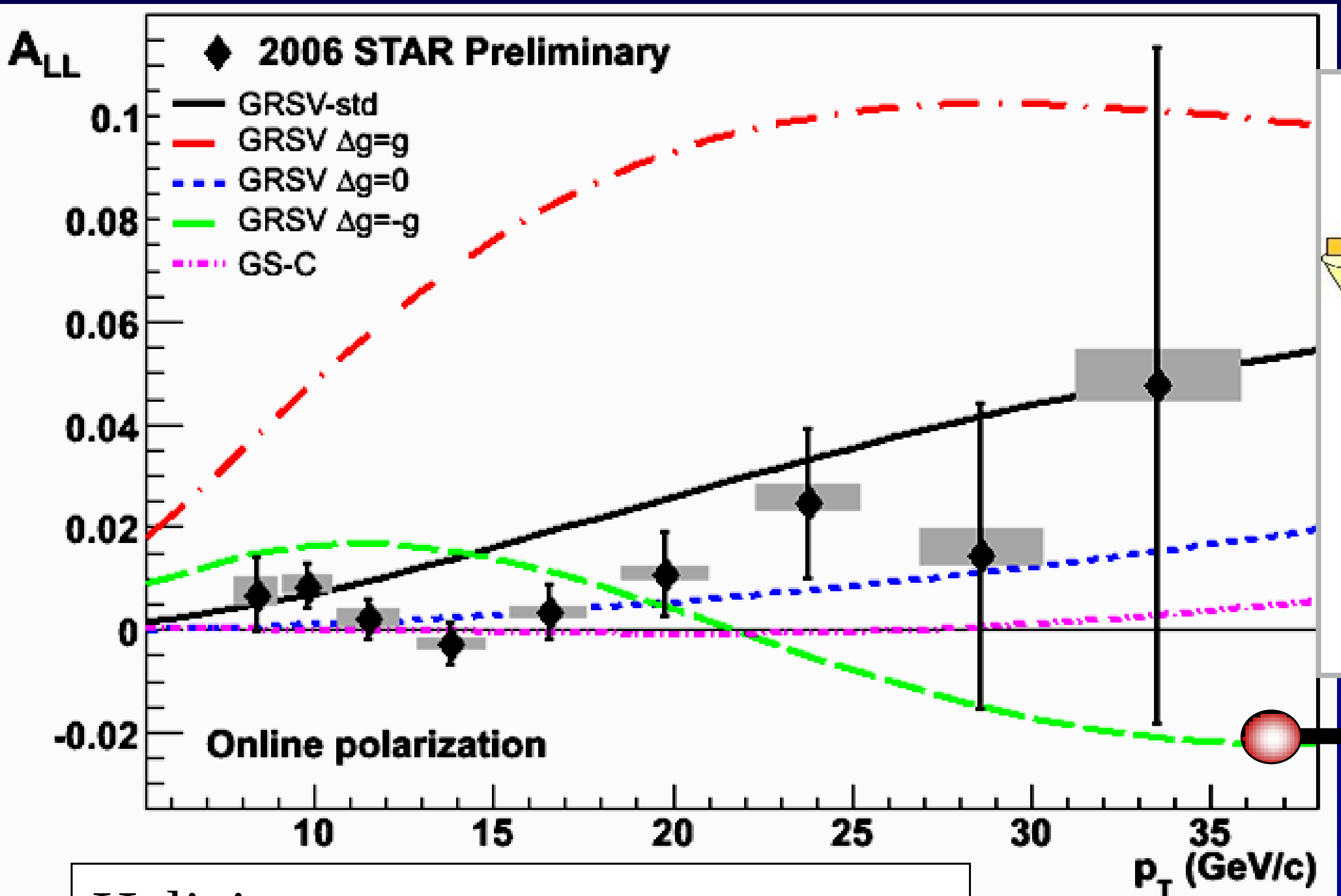
PRL 103, 012003 (2009)

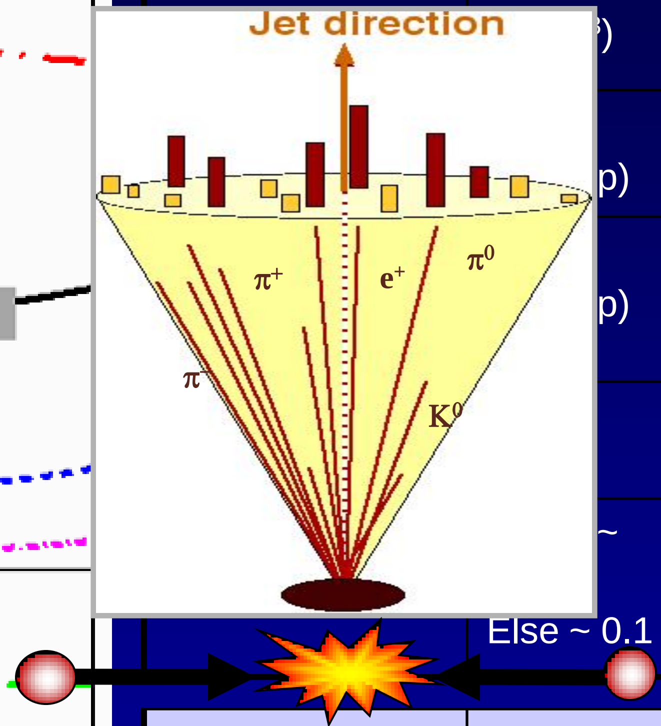


Helicity asymmetry measurement



Inclusive Jet Asymmetry at $\sqrt{s}$=200 GeV





	)
	p)
	p)
	~
	Else ~ 0.1
p_T systematic	±6.7%

Helicity asymmetry measurement

GRSV curves and data with cone radius R= 0.7 and -0.7 < η < 0.9

STAR

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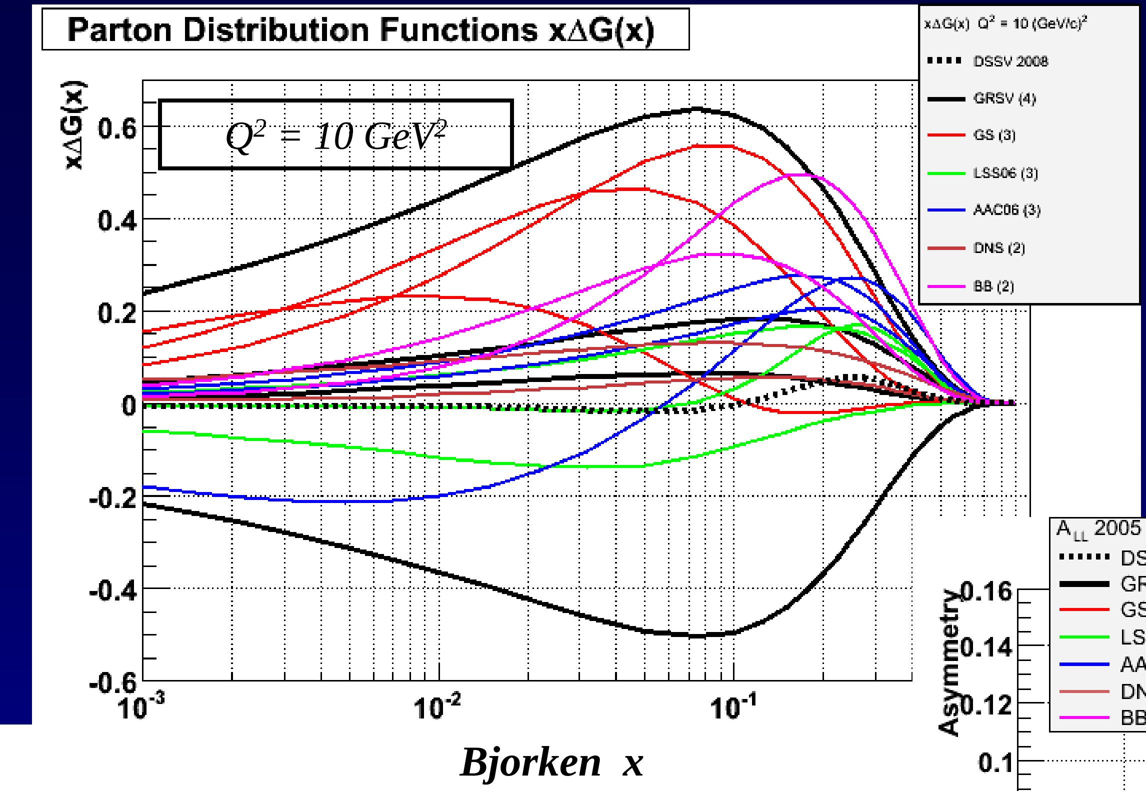
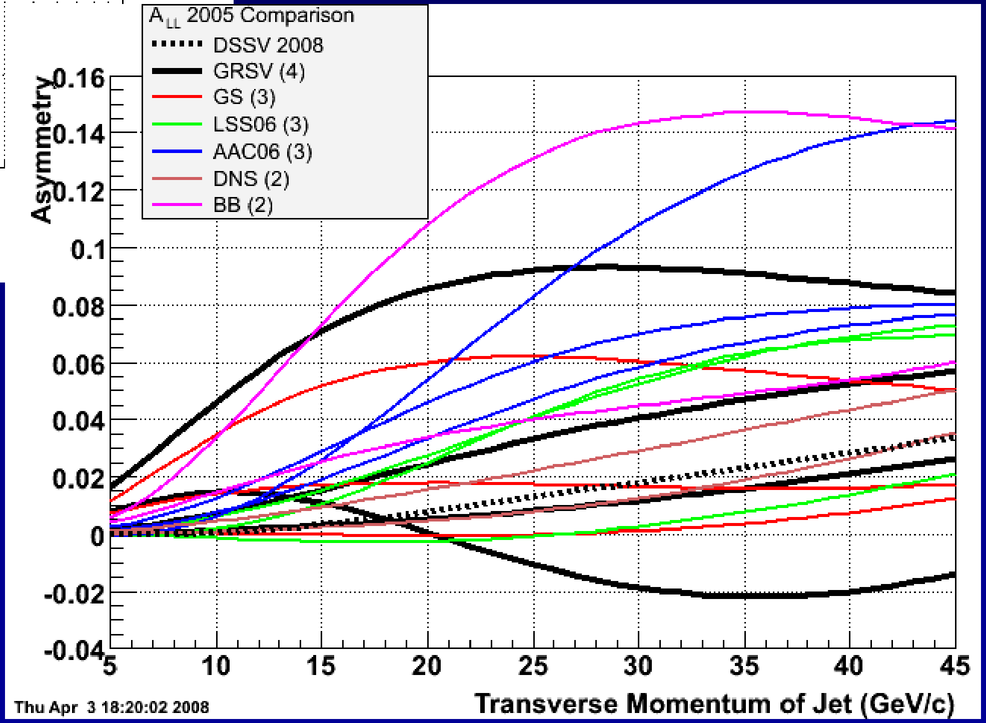
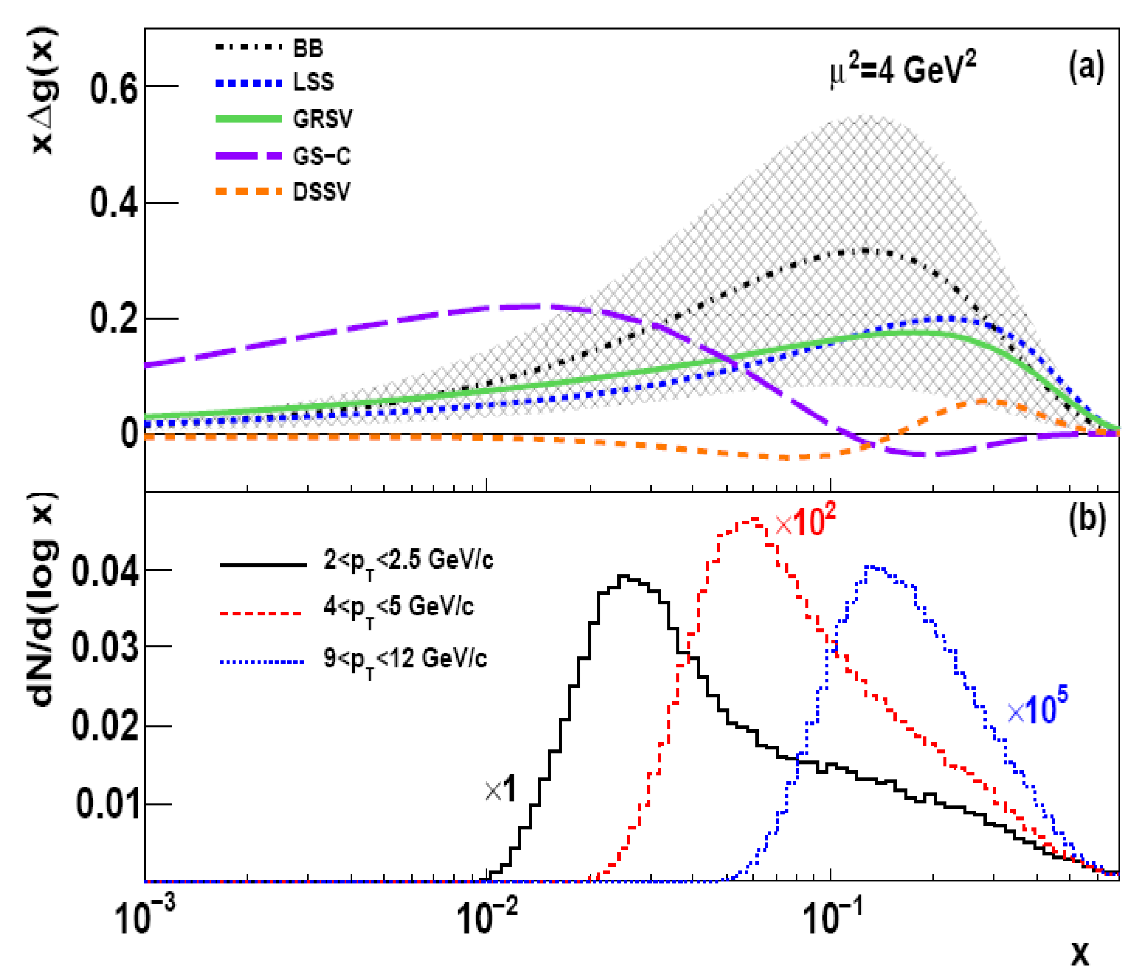




Any parameterization or assumption for $\Delta g(x)$ vs x can be translated into predictions for A_{LL} vs. jet, pion, etc. p_T and compared with RHIC data.

Sampling the Integral of ΔG: π^0 p_T vs. x_{gluon}

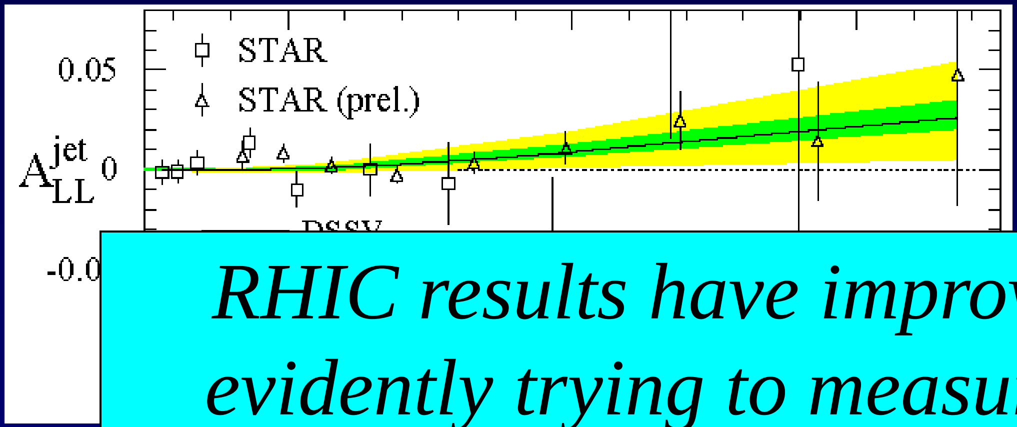
Inclusive asymmetry measurements in p+p collisions sample from wide bins in *x*—sensitive to (truncated) integral of ΔG, not to functional form vs. *x*



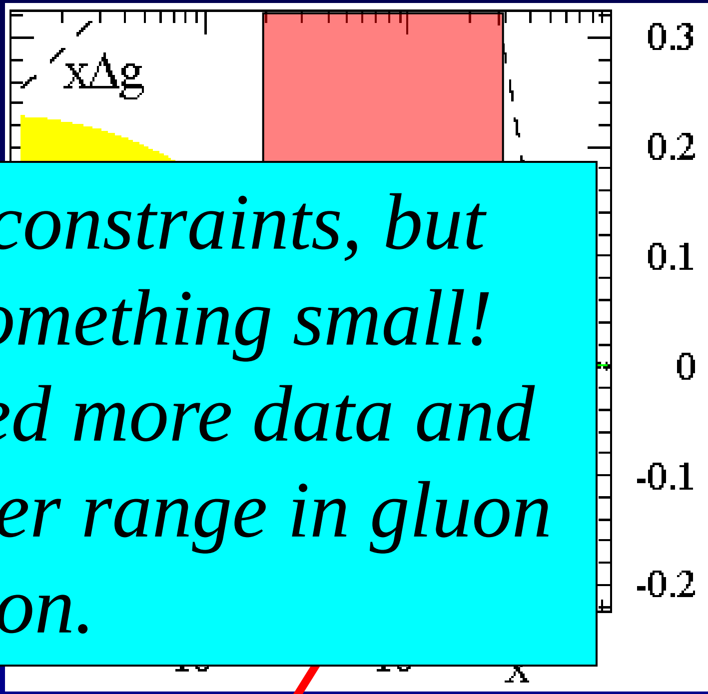
Based on simulation using NLO pQCD as input

PRL 103, 012003 (2009)

Present Status of Δg(x): Global pdf Analyses



de Florian et al., PRL101, 072001 (2008)



RHIC results have improved constraints, but evidently trying to measure something small! Still a long road ahead . . . Need more data and measurements covering a greater range in gluon momentum fraction.

- Truncated moment of Δg(*x*) at moderate *x* found to be small
- Best fit finds node in gluon distribution near *x* ~ 0.1
  - Not prohibited, but not so intuitive . . .

x range covered by current RHIC measurements at 200 GeV

The Pion Isospin Triplet, A_{LL} and ΔG

- At transverse momenta > ~5 GeV/c, midrapidity pions dominantly produced via qg scattering
- Te
fr
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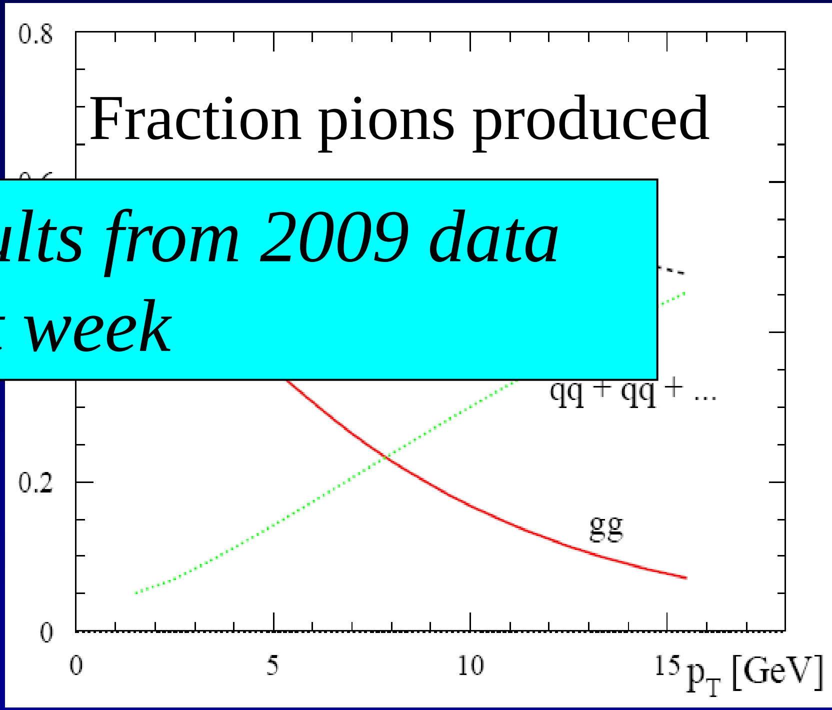
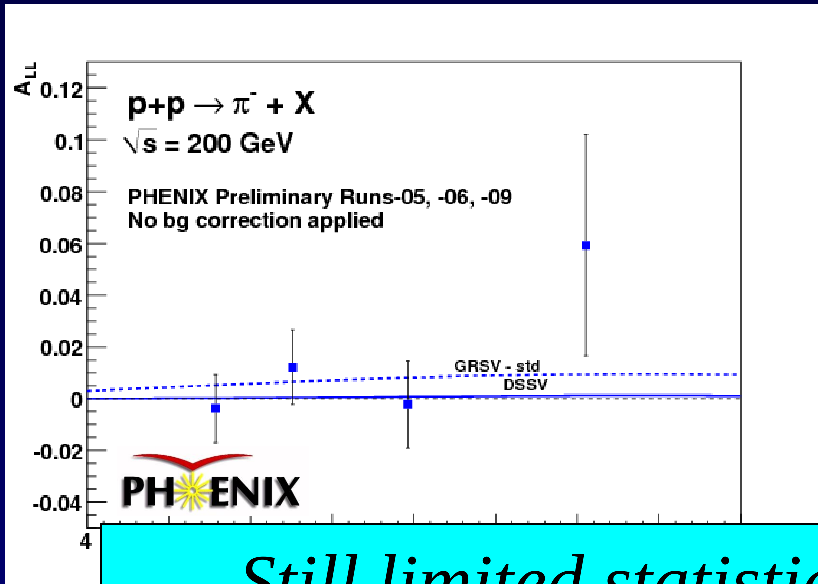
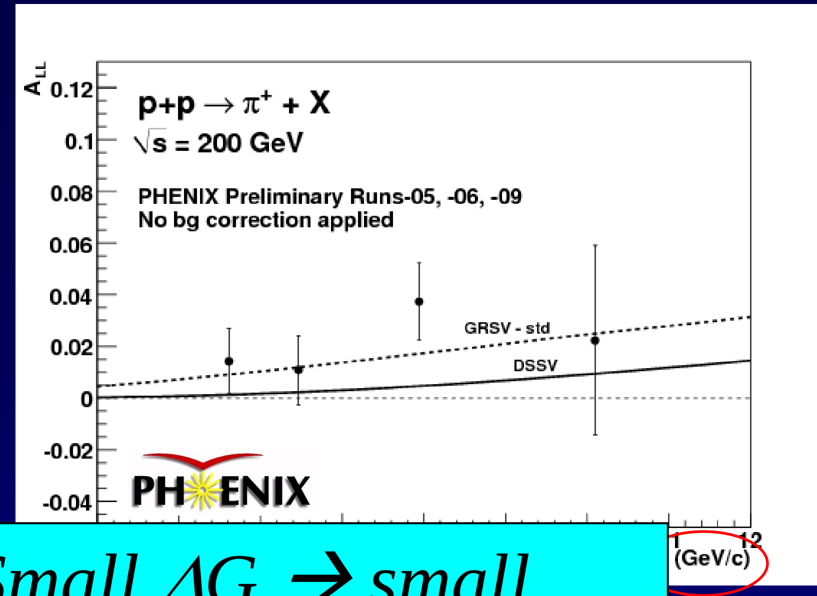
Δu and Δd have opposite signs make A_{LL} of π^+ and π^- differ
- Order of asymmetries of pion species can provide information on the *sign* of ΔG, which remains uncertain . . .



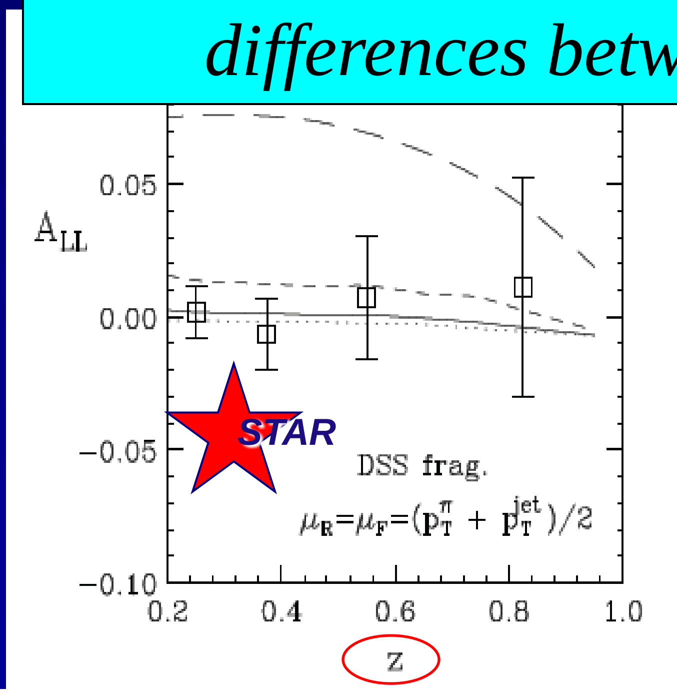
PHENIX preliminary results from 2009 data released last week

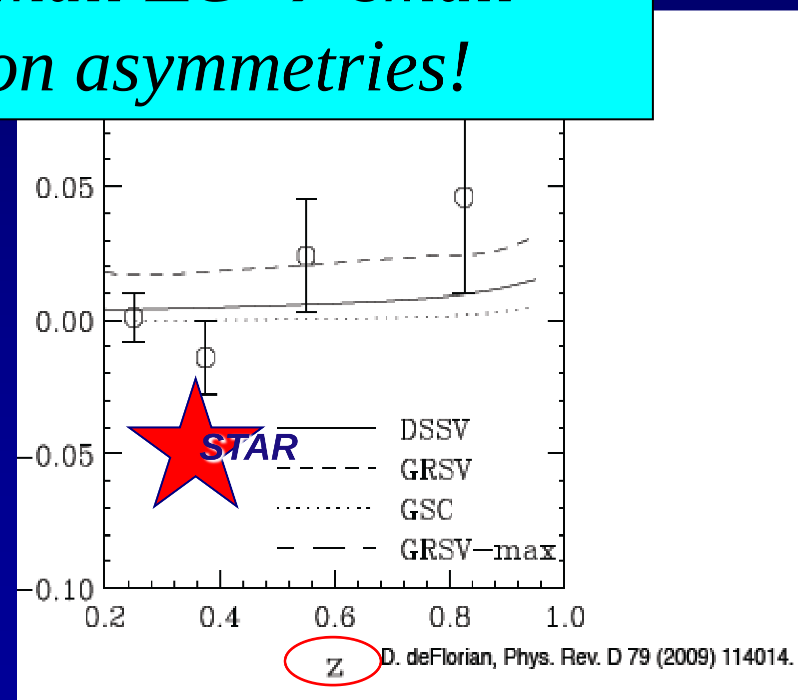
$$\Delta G > 0 \Rightarrow A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-}$$





Still limited statistics. Small ΔG → small differences between pion asymmetries!

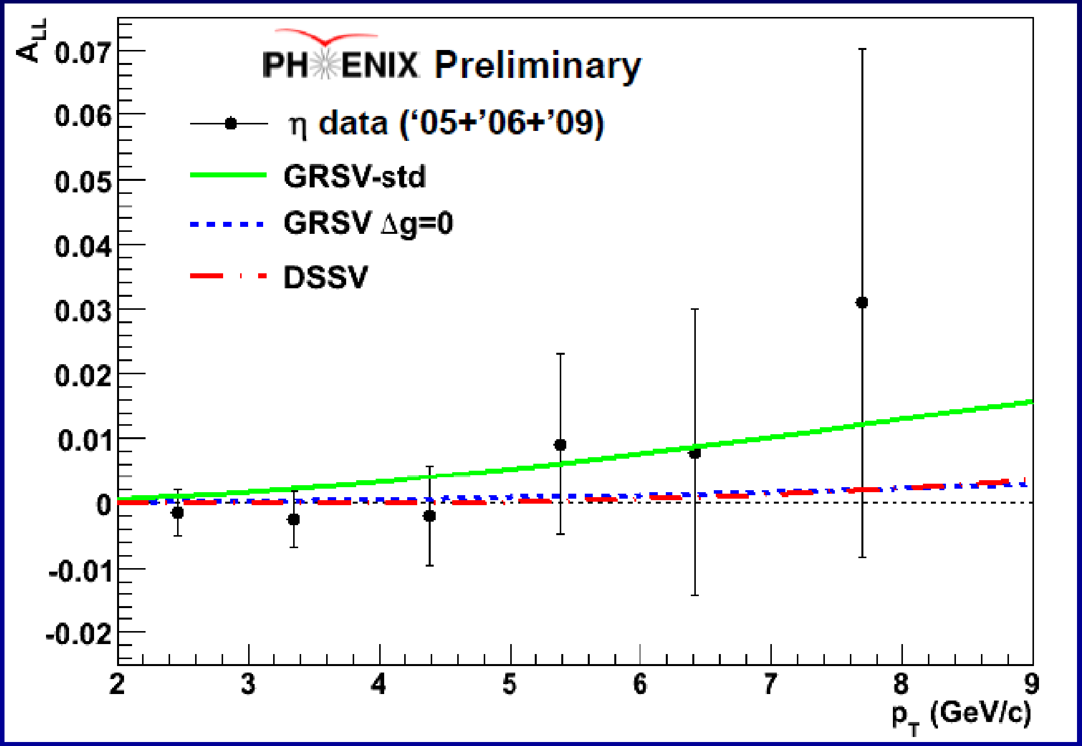




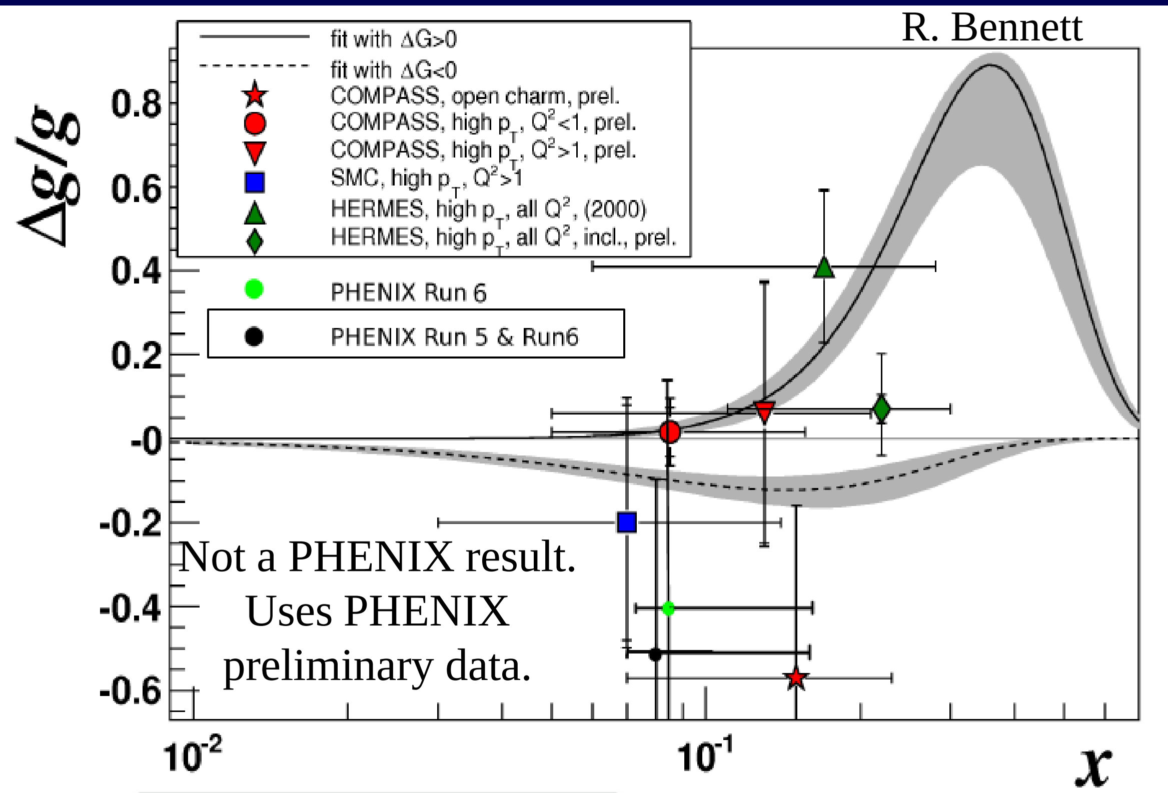
η asymmetry results from PHENIX

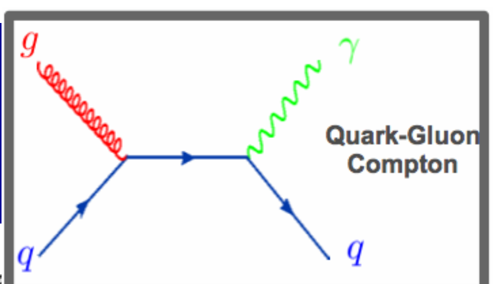
Preliminary results from 2009 data released last week

- η at 200 GeV
  - Analysis and sensitivities similar to π^0
  - Independent confirmation of ΔG, additional statistics
- NLO pQCD calculations enabled by recent parameterization of eta FFs from world data (CAA, J. Seele, M. Stratmann, R. Sassot).
- PHENIX 2005+2006 results and FF paper to be submitted simultaneously to PRD within a few weeks.



$\Delta G/G$ – LO extraction from direct photon A_{LL}





- Statistical uncertainty from 2005 and 2006 data similar to COMPASS open charm result
- New 200 GeV data (16 pb^{-1}, compared to < 10 in current result) from 2009 being analyzed.

The Future of ΔG Measurements at RHIC

- Extend *x* coverage
  - Run at different center-of-mass energies
    - Already results for neutral pions at 62.4 GeV, now first data at 500 GeV
  - Extend measurements to forward particle production
    - Forward calorimetry recently enhanced in both PHENIX and STAR
- Go beyond inclusive measurements—i.e. measure the final state more completely—to better reconstruct the kinematics and thus the *x* values probed.
  - Jet-jet and direct photon – jet measurements – But need higher statistics! STAR expects first results from 2009 data.

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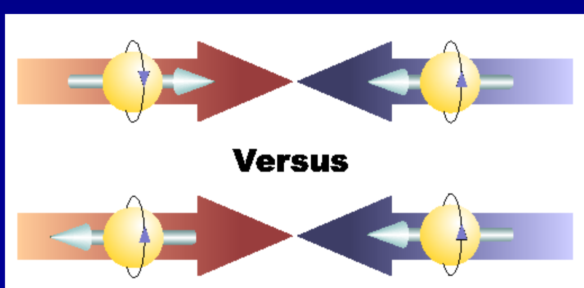
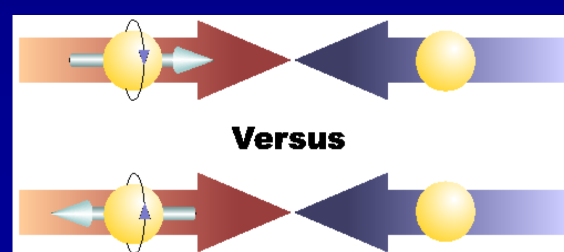
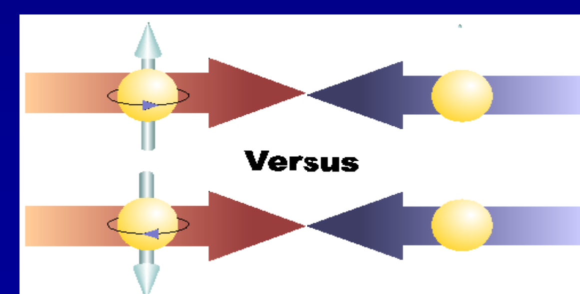




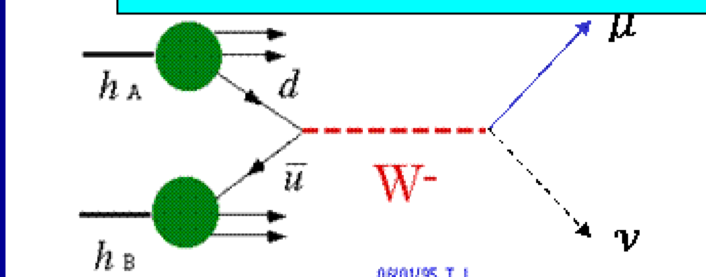


Flavor-Separated Sea Quark Polarizations Through W Production

$$\Delta q(x), \Delta\bar{q}(x)$$

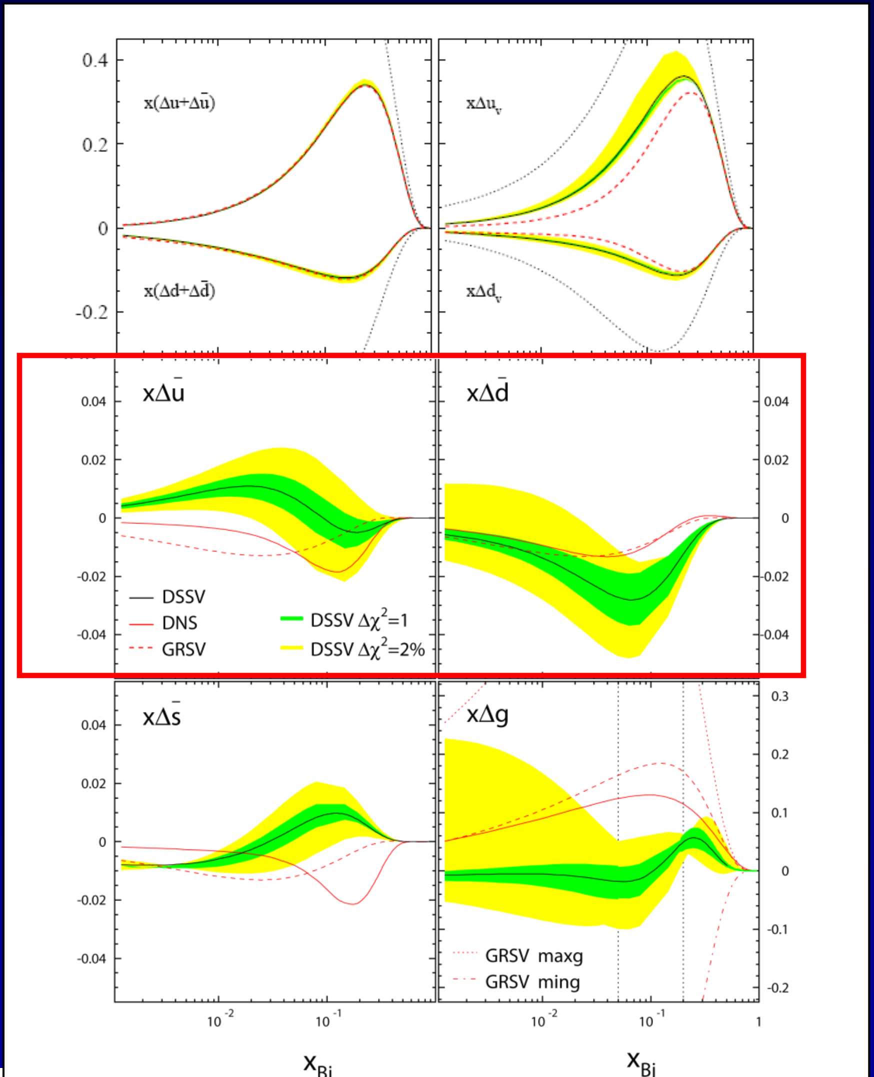
$$A_L^{W^+} \approx -\frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) - \bar{d}(x_1)u(x_2)}$$

Flavor separation of the polarized sea quarks with ***no reliance on FF's,*** *and at* ***much higher scale*** *than previous fixed-target experiments.* ***Complementary*** *to semi-inclusive DIS measurements.*



control over the proton spin orientation gives access to the *flavor* spin structure in the proton!
Measure final-state lepton (e or μ)

Flavor-Separated Sea Quark Polarizations Through W Production



DSSV, PRL101, 072001 (2008)

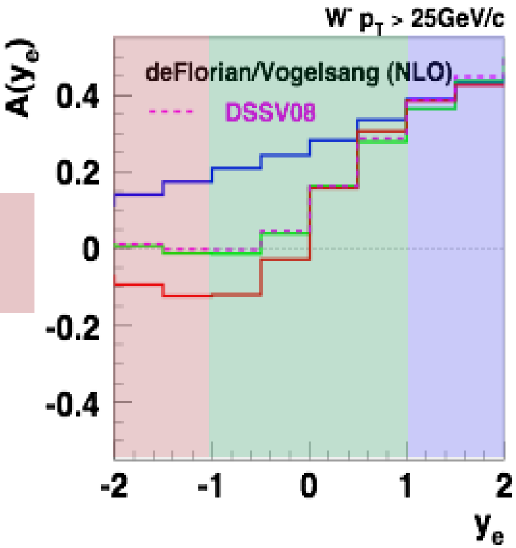
$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

Latest global fit to helicity distributions: Indication of SU(3) breaking in the polarized quark sea (as in the unpolarized sea), but still relatively large uncertainties on helicity distributions of anti-up and anti-down quarks!

Flavor Sensitivies at Different Rapidity

$$A_L^{W^-} = \frac{\Delta \bar{u}}{\bar{u}}$$

$x_1 \ll x_2$



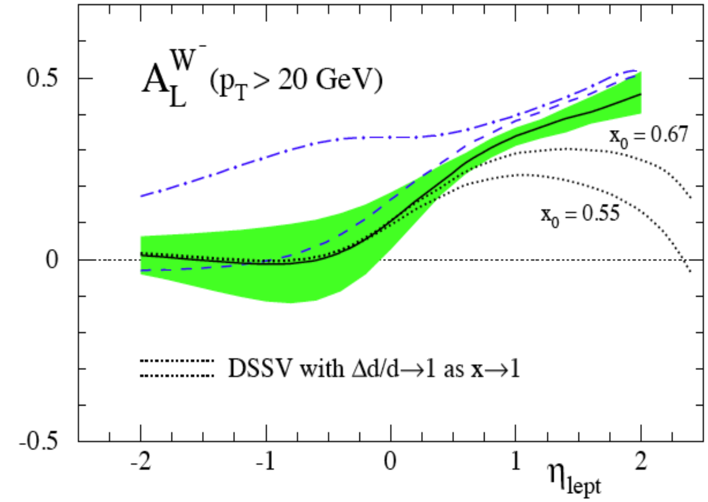
$$A_L^{W^-} = -\frac{\Delta d}{d}$$

$x_1 \gg x_2$

$$A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta \bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right)$$

$x_1 = x_2$

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta \bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$

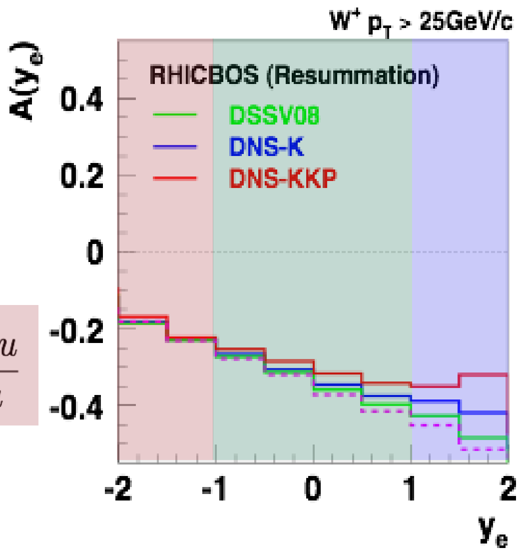


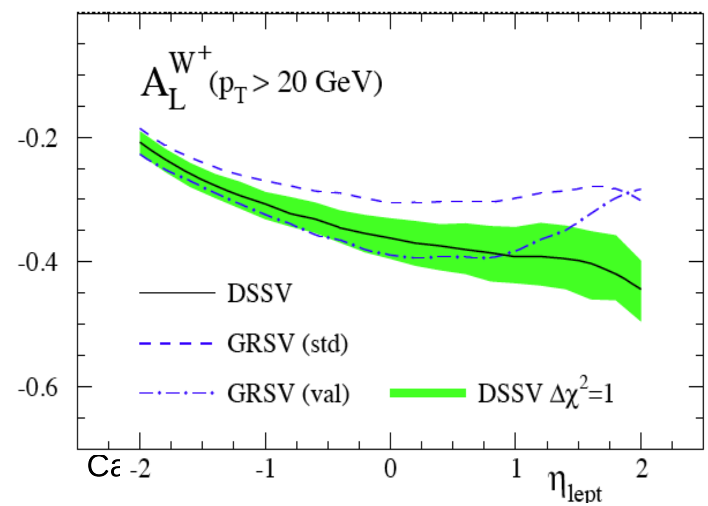
$$A_L^{W^+} = \frac{\Delta \bar{d}}{\bar{d}}$$

$x_1 \gg x_2$

$$A_L^{W^+} = -\frac{\Delta u}{u}$$

$x_1 \ll x_2$





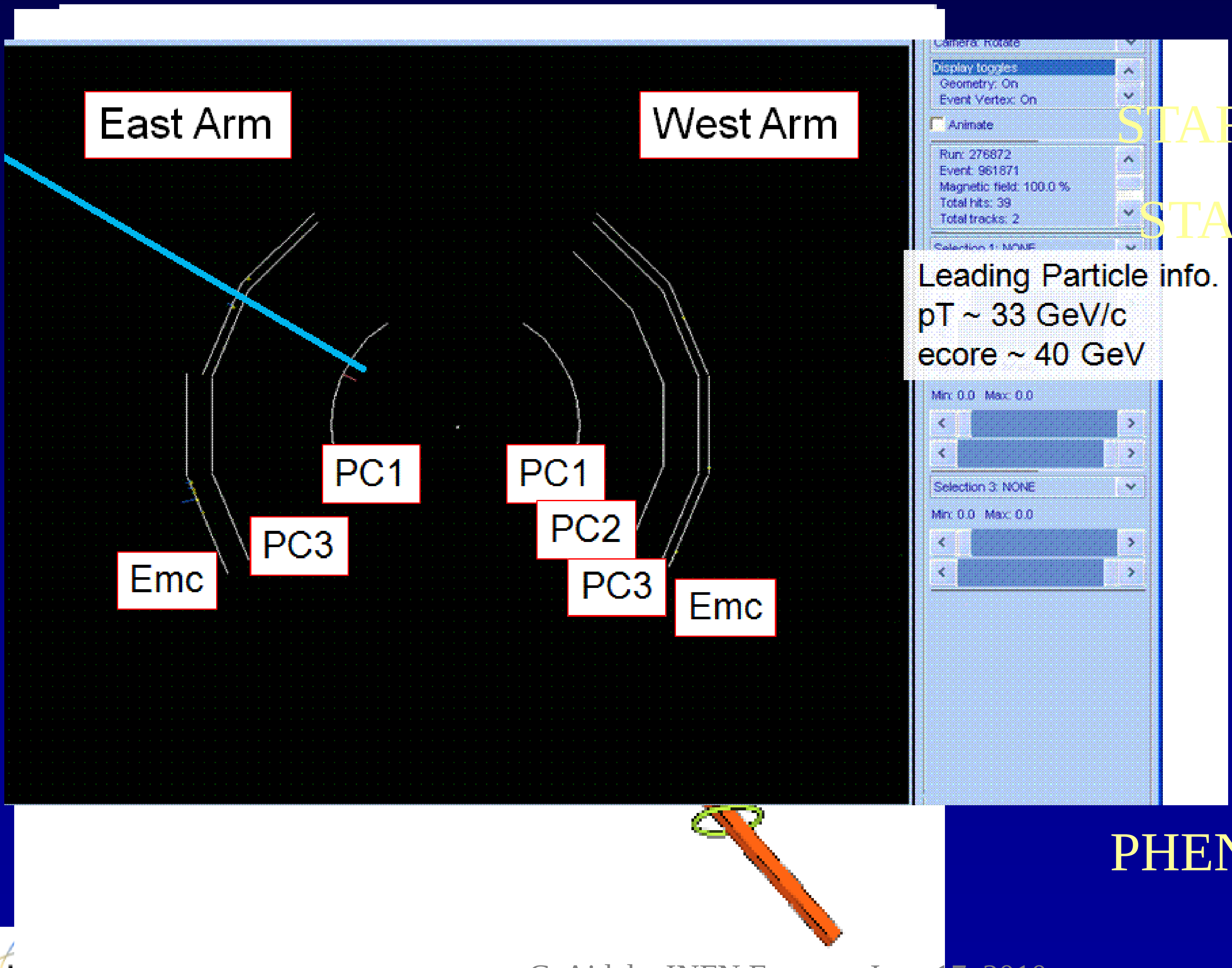
1) RHICBOS: P.M. Nadolsky and C.-P. Yuan, Nucl. Phys. B666 (2003) 31.

2) deFlorian / Vogelsang: D. deFlorian, private communications.

First 500 GeV Data in 2009

- First 500 GeV run took place in February and March 2009
- Largely a commissioning run for the accelerator, the polarimeters, and the detectors
  - Average polarization ~39% —many additional depolarizing resonances compared to 200 GeV
  - Both STAR and PHENIX will finish installing detector/trigger upgrades to be able to make full use of the next 500 GeV run
  - But W $\rightarrow$ e at midrapidity already possible with current data!

The Hunt for W's at RHIC has Begun!



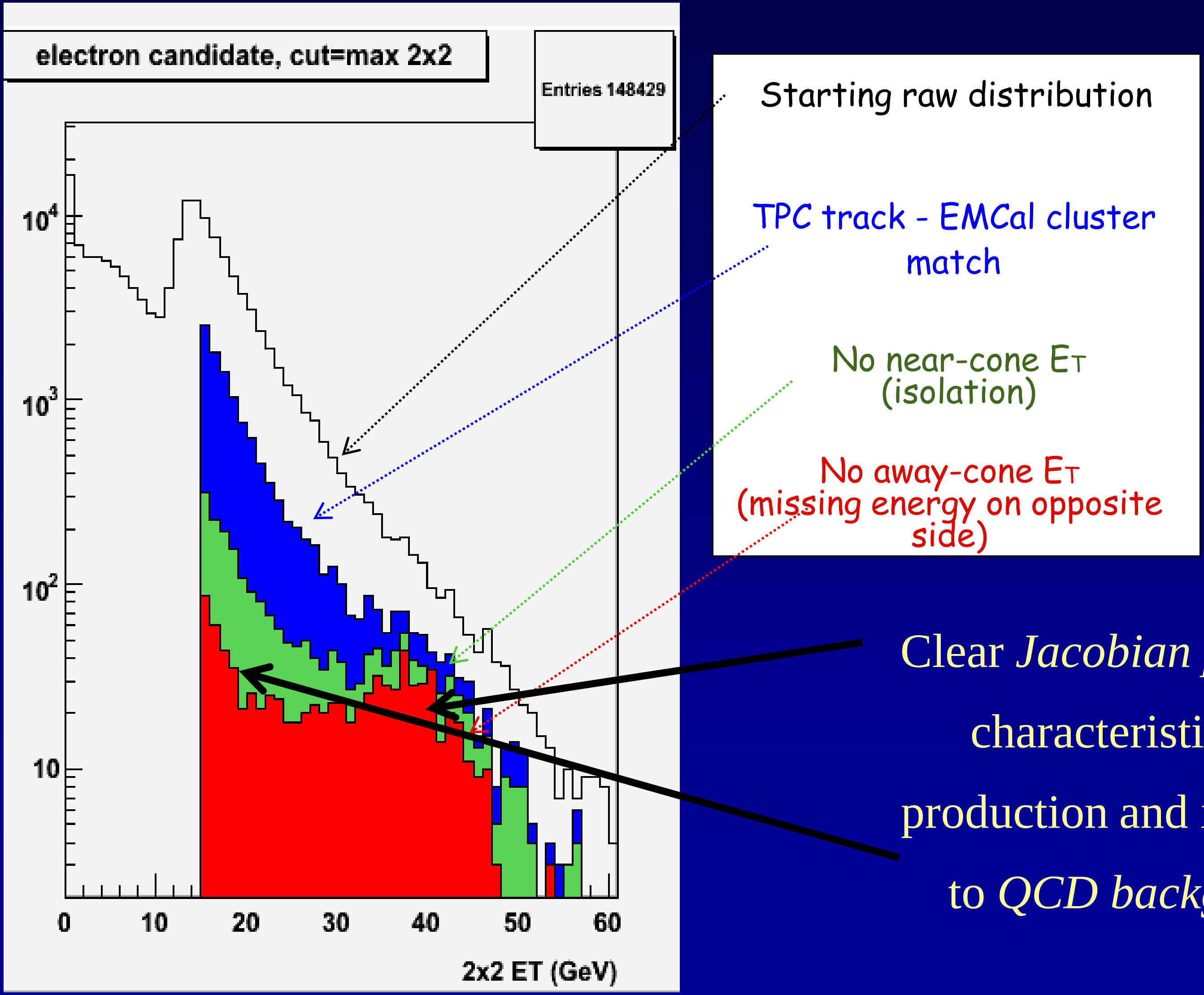
STAR W candidate

STAR dijet event

PHENIX W candidate

STAR W Physics Analysis

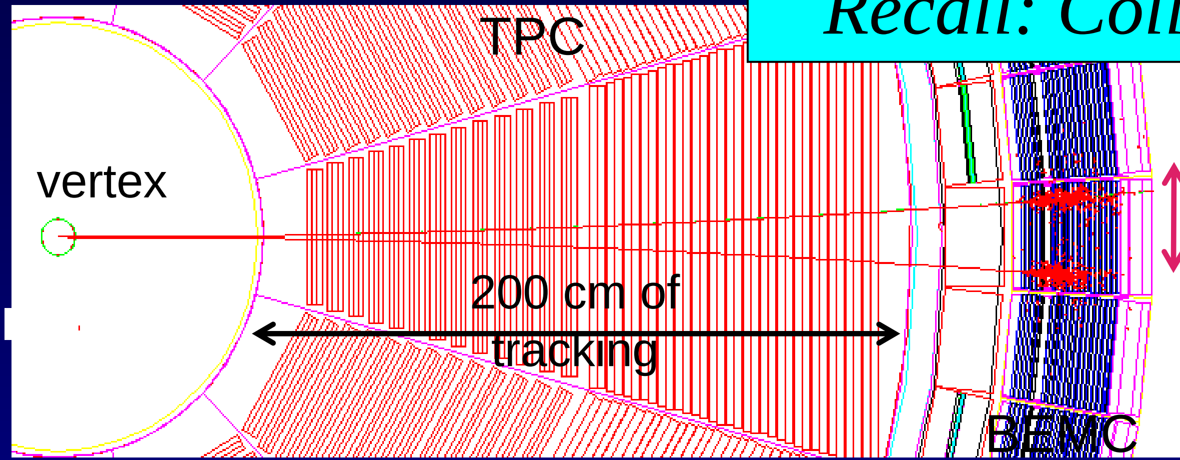
- Evolution of E_T distribution vs. cut ID



Clear *Jacobian peak* seen, characteristic of W production and in contrast to *QCD background*!

Charge Separation at 40 GeV (STAR)

Recall: Collider experiment!



positron p_T = 5 GeV

electron p_T = 5 GeV

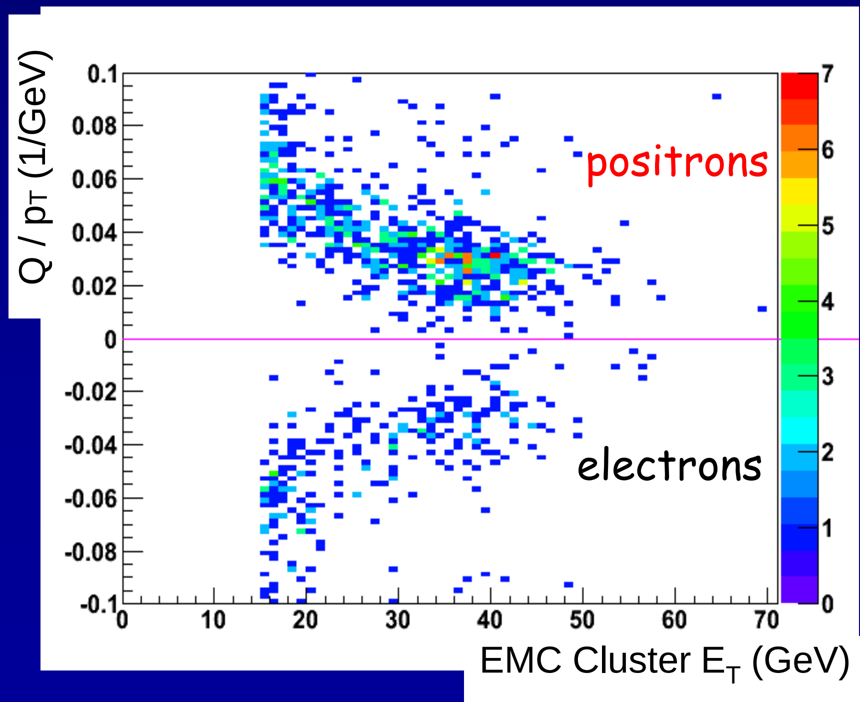
+/- distance D: ~$1/P_T$

p_T = 5 GeV : D ~15 cm

p_T = 40 GeV : D ~2 cm

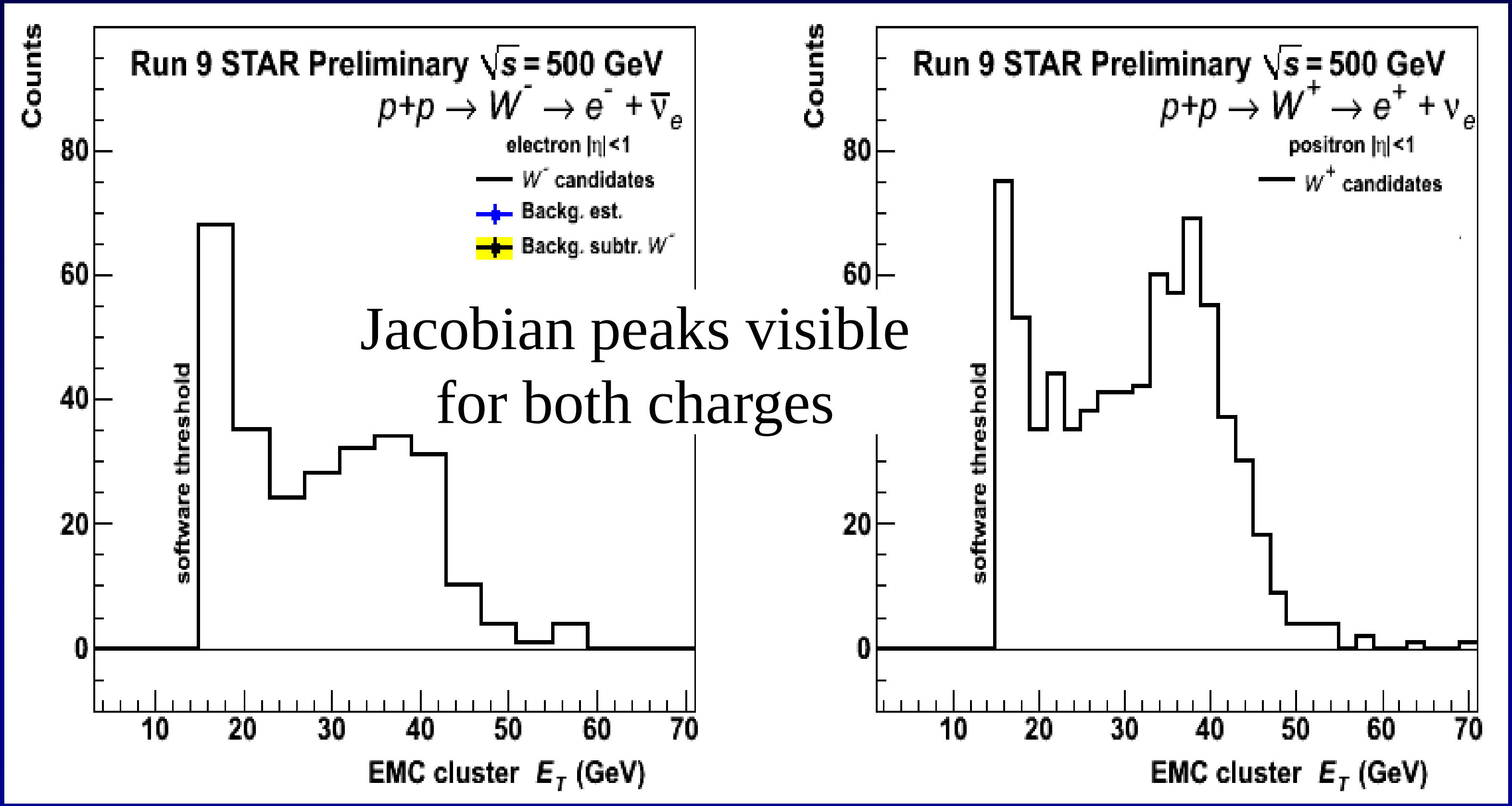
Successful separation of different charge states!

Q: Charge-sign of reconstructed track



Assign:
$Q/p_T > 0$ positrons
$Q/p_T < 0$ to be electrons

Charge-Separated E_T Distributions



Charge-separated W^+/W^- candidate distributions of the EMC cluster transverse energy E_T (GeV) after all cuts (no bg subtraction)

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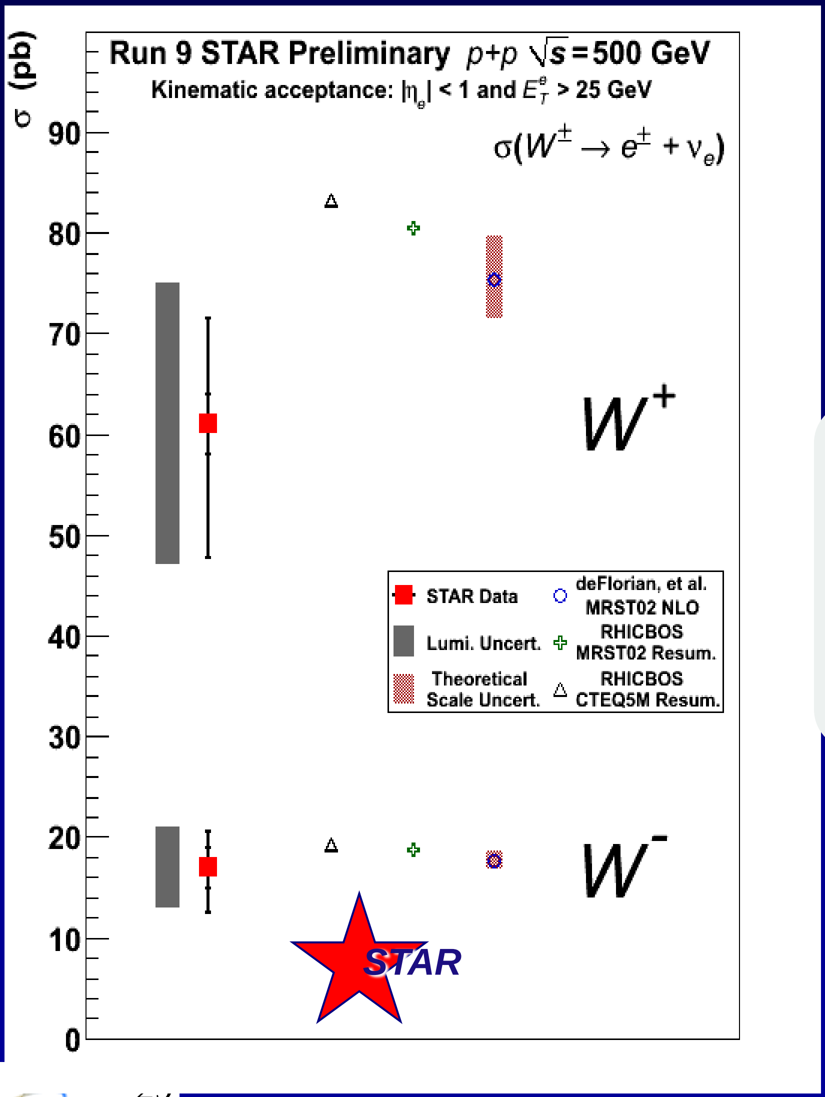
Preliminary W Cross Section Results

Total W^+/W^- cross-section results



	$W^- \rightarrow e^- + \bar{\nu}_e$	$W^+ \rightarrow e^+ + \nu_e$
N_W^{obs}	156	513
N_{back}	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$
ϵ_{total}	$0.56\ ^{+0.11}_{-0.09}$	$0.56\ ^{+0.12}_{-0.09}$
$\int Ldt\ (\mathrm{pb}^{-1})$	13.7 ± 3.2	13.7 ± 3.2

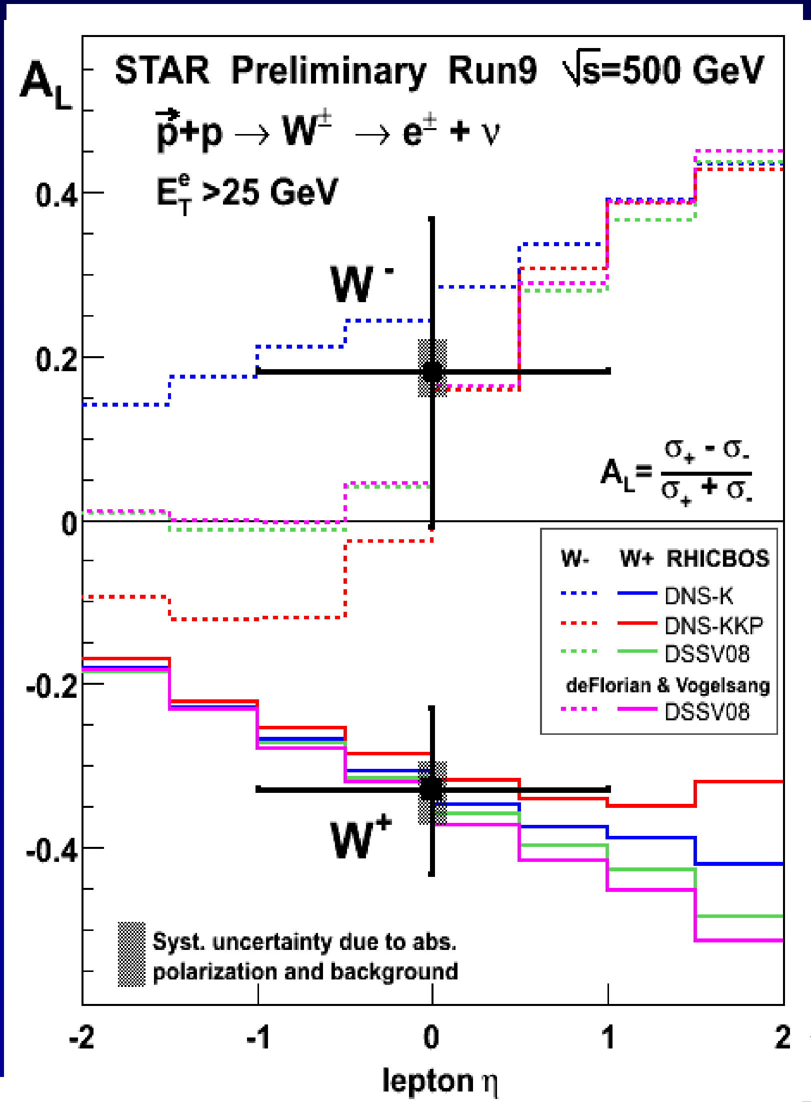
STAR Preliminary Run 9
(p+p √s=500 GeV)

$$\sigma_{W^+\rightarrow e^+ + \nu} = 61 \pm 3\ (\mathrm{stat.})\ ^{+10}_{-13}\ (\mathrm{syst.}) \pm 14\ (\mathrm{lumi.})\ \mathrm{pb}$$

$$\sigma_{W^-\rightarrow e^- + \bar{\nu}} = 17 \pm 2\ (\mathrm{stat.})\ ^{+3}_{-4}\ (\mathrm{syst.}) \pm 4\ (\mathrm{lumi.})\ \mathrm{pb}$$

- Reasonable agreement between measured and theoretical cross-sections within uncertainties!

Preliminary A_L Results from 2009 500 GeV Commissioning Run



STAR Preliminary Run 9
(p+p √s=500 GeV)

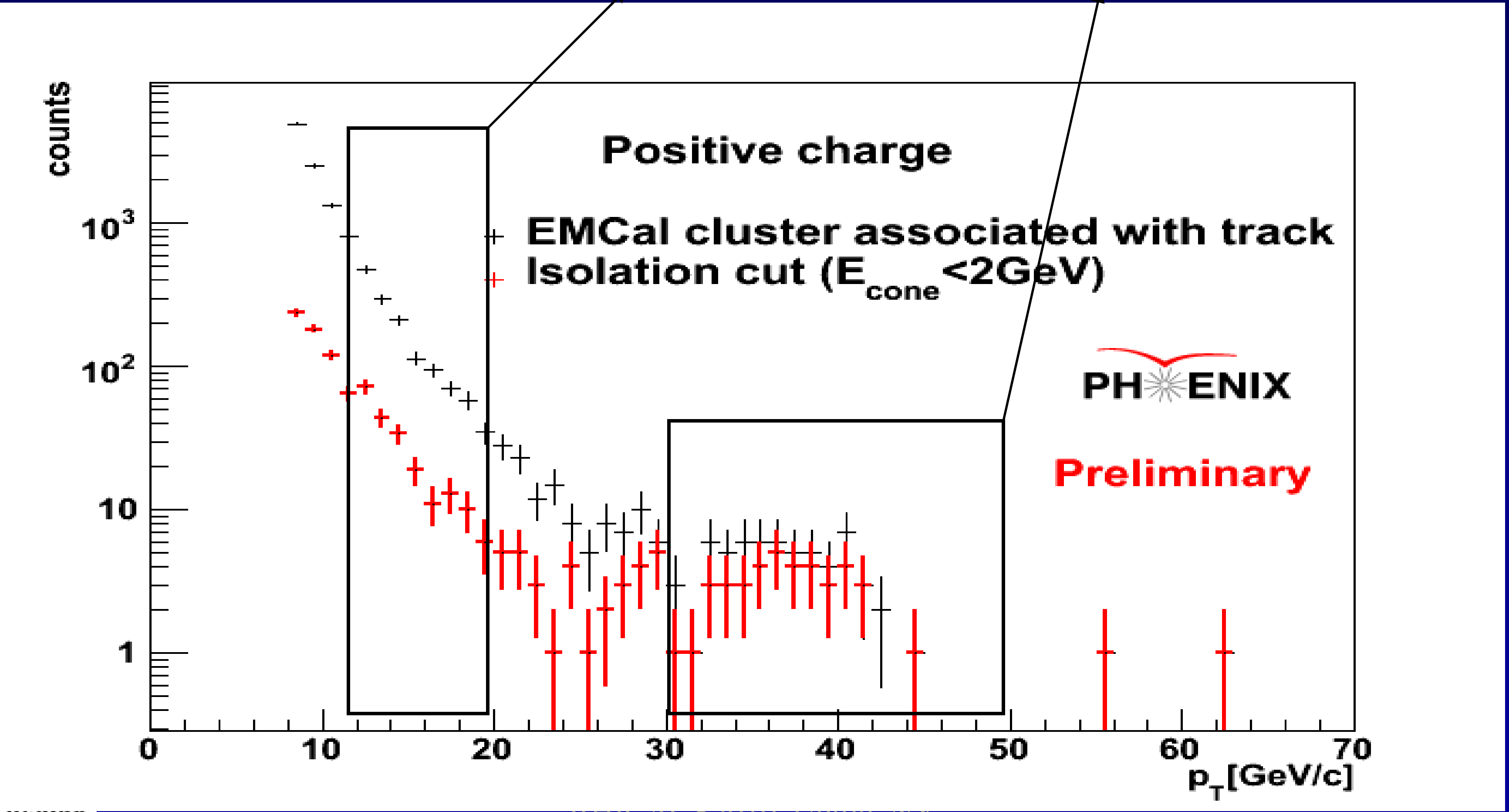
$$A_L(W^+) = -0.33 \pm 0.10(\text{stat.}) \pm 0.04(\text{syst.})$$

$$A_L(W^-) = 0.18 \pm 0.19(\text{stat.}) \ {}^{+0.04}_{-0.03}(\text{syst.})$$

- $A_L(W^+)$ negative with a significance of 3.3σ
  - First non-zero helicity asymmetry at RHIC!
- $A_L(W^-)$ central value positive

PHENIX W Analysis: Raw Asymmetries (e^+)

	Background	Signal
p_T Range (GeV/c)	12-20	30-50
Raw Asymmetry	0.035±0.047	-0.29±0.11

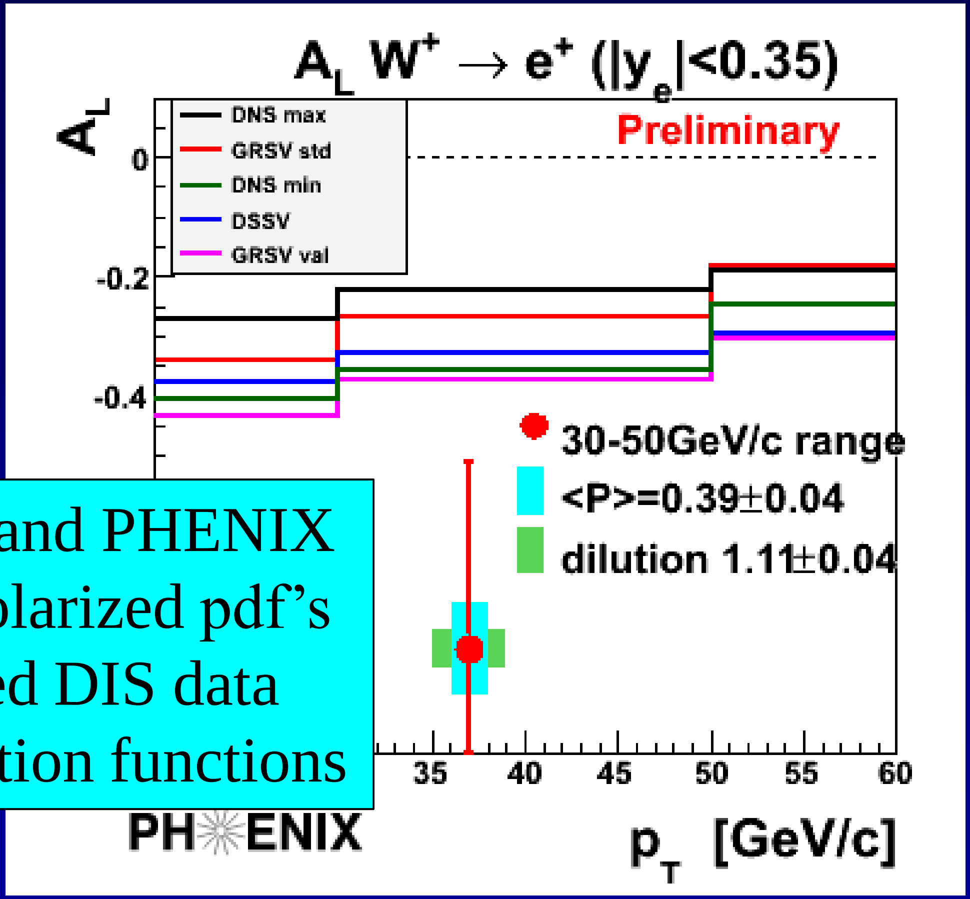


PHENIX W Analysis: Preliminary A_L Results

- Using average polarization 0.39±0.04:

$$A_L^{W^+} = -0.83 \pm 0.31$$

- Asymmetry corrected for dilution by Z and QCD backgrounds

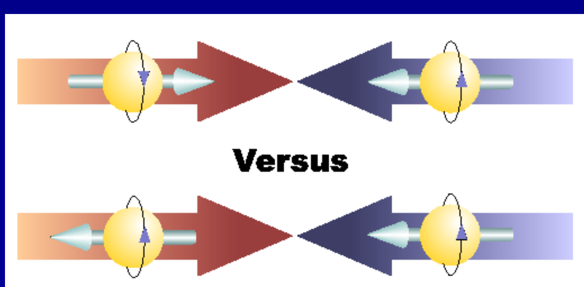


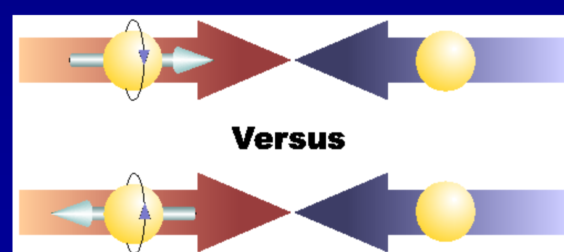
Measured asymmetries by STAR and PHENIX in agreement with theory using polarized pdf’s (DSSV) constrained by polarized DIS data
⇒ Universality of helicity distribution functions

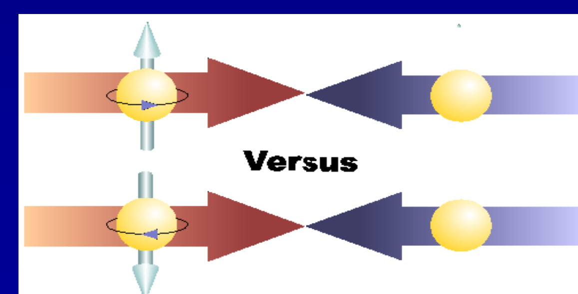
Los Alamos NATIONAL LABORATORY EST. 1943

Proton Spin Structure at RHIC

Gluon helicity distribution and ΔG	Flavor–separated sea quark helicity distributions	"Transverse spin" phenomena
π, Jets $A_{LL}(gg, gq \rightarrow \pi + X)$ Prompt Photons $A_{LL}(gq \rightarrow \gamma + X)$ Back-to-Back Correlations	W Production $A_L(u + \bar{d} \rightarrow W^{+} \rightarrow \ell^{+} + \nu_l)$ $A_L(\bar{u} + d \rightarrow W^{-} \rightarrow \ell^{-} + \bar{\nu}_l)$	Transversity Transverse-momentum-dependent distributions Single-Spin Asymmetries







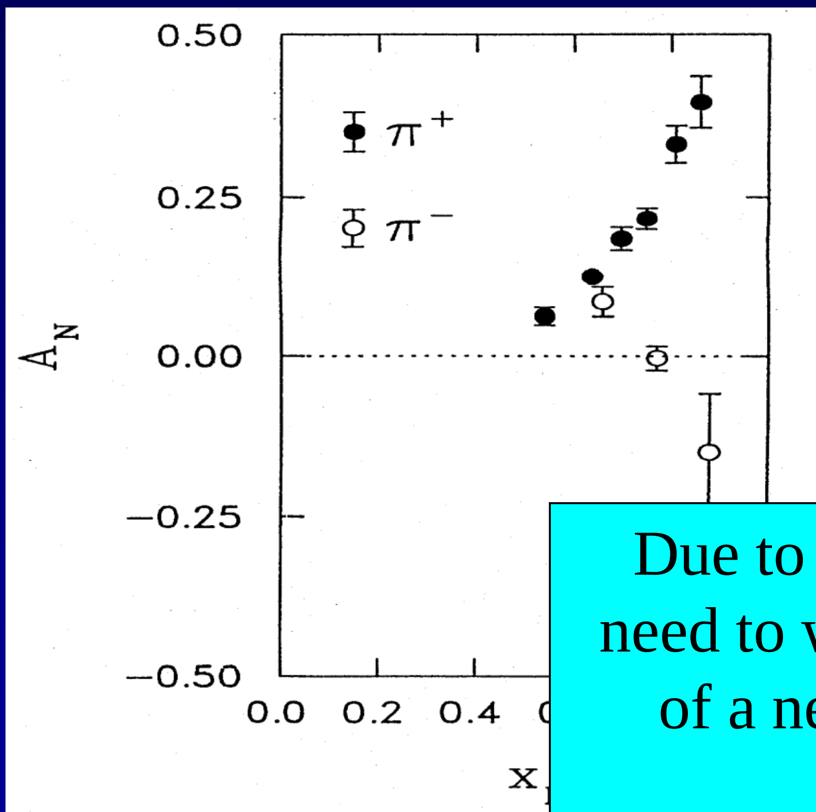
Longitudinal (Helicity) vs. Transverse Spin Structure

- Transverse spin structure of the proton cannot be deduced from longitudinal (helicity) structure
  – Spatial rotations and Lorentz boosts don't commute!
  – Only the same in the non-relativistic limit
- Transverse structure linked to intrinsic parton transverse momentum (k_T) and orbital angular momentum!
  – *Parton dynamics*

1976: Discovery in p+p Collisions!

Large Transverse Single-Spin Asymmetries

Argonne $\sqrt{s}$=4.9 GeV



Charged pions produced preferentially on one or the other side with respect to the transversely polarized beam direction!

Due to transversity? Other effects? We'll need to wait more than a decade for the birth of a new subfield in order to explore the possibilities . . .

W.H. Dragoset et al., PRL36, 929 (1976)

$$x_F = 2 p_{long} / \sqrt{s}$$

Transverse-Momentum-Dependent Distributions and Single-Spin Asymmetries

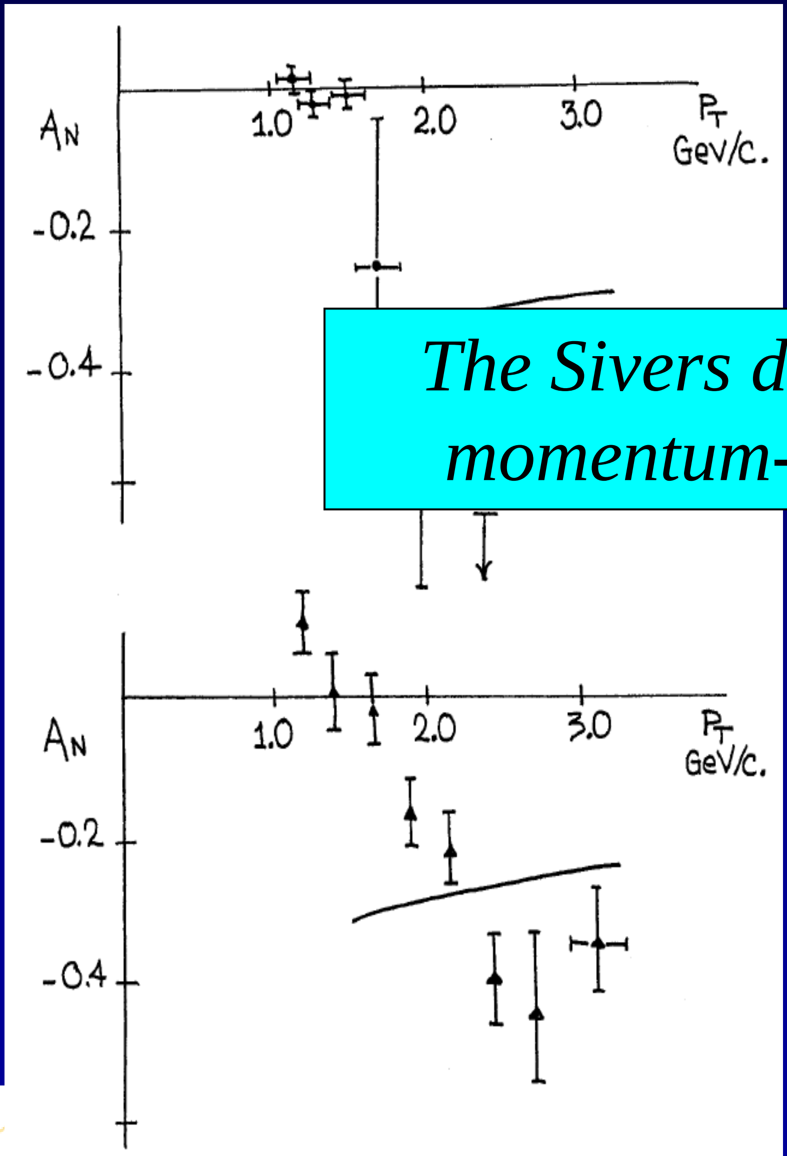


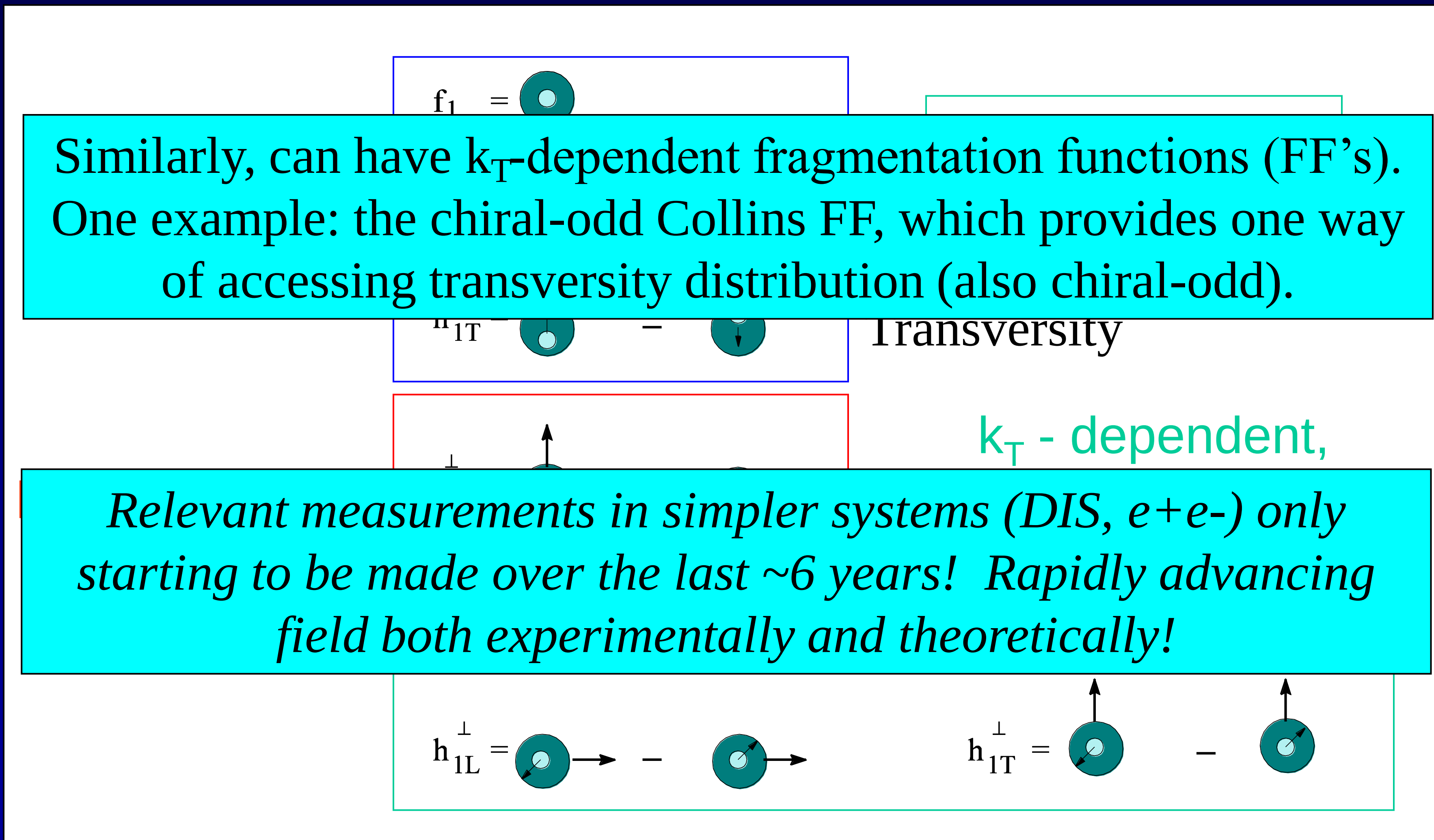
Fig. 1

1989: The "Sivers mechanism" is proposed in an attempt to understand the observed asymmetries.

The Sivers distribution: the first transverse-momentum-dependent distribution (TMD)!

Departs from the traditional *collinear* factorization assumption in pQCD and proposes a correlation between the *intrinsic transverse motion* of the quarks and gluons and the proton's spin

Quark Distribution Functions

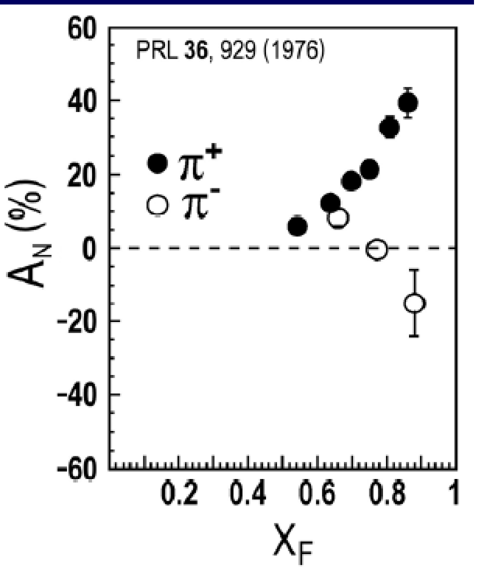


Similarly, can have k_T-dependent fragmentation functions (FF's). One example: the chiral-odd Collins FF, which provides one way of accessing transversity distribution (also chiral-odd).

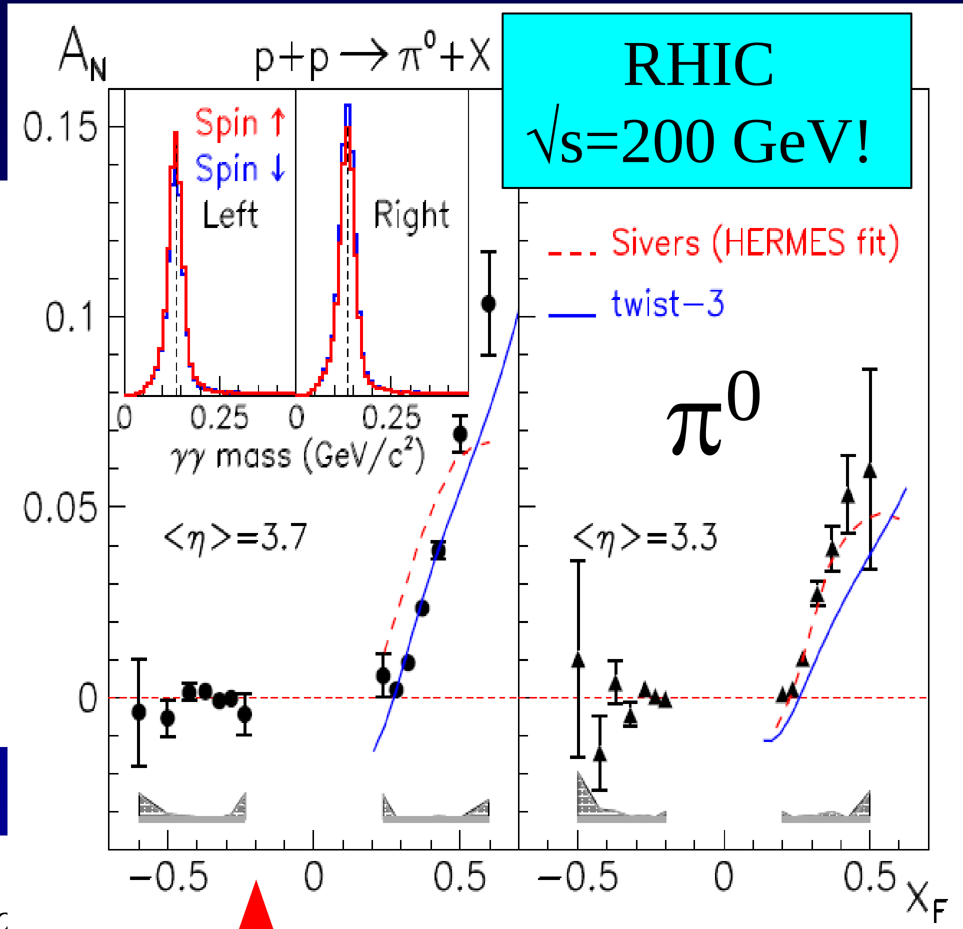
Relevant measurements in simpler systems (DIS, e+e-) only starting to be made over the last ~6 years! Rapidly advancing field both experimentally and theoretically!

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

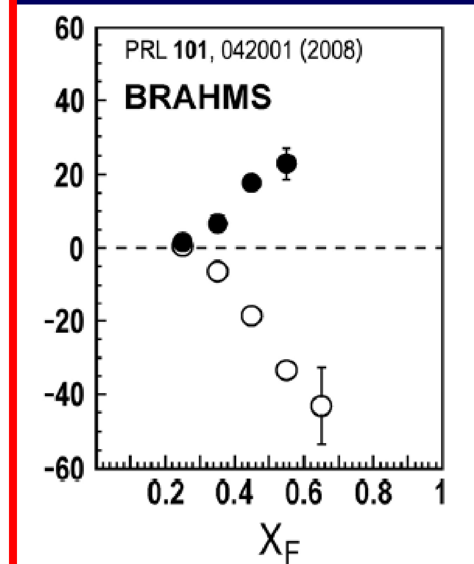
ANL
√s=4.9 GeV

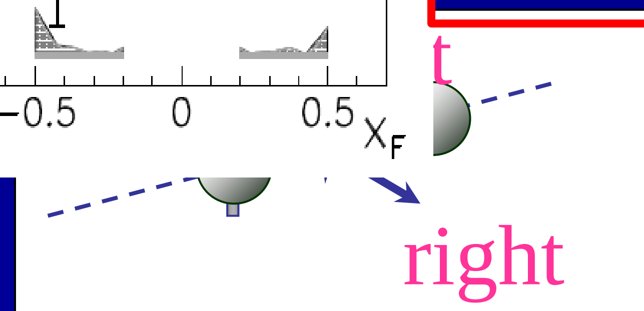


RHIC
√s=200 GeV!



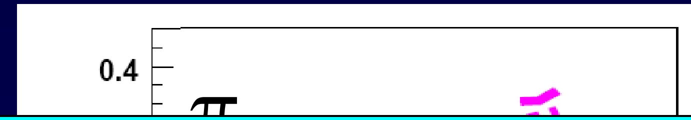
RHIC
√s=62.4 GeV





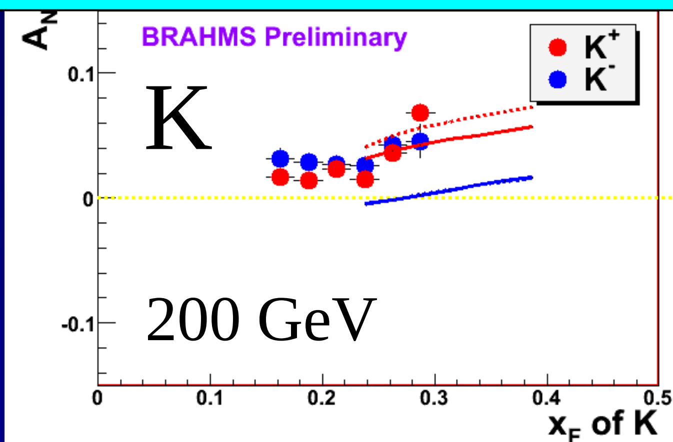
$x_F = 2p_{lc}$

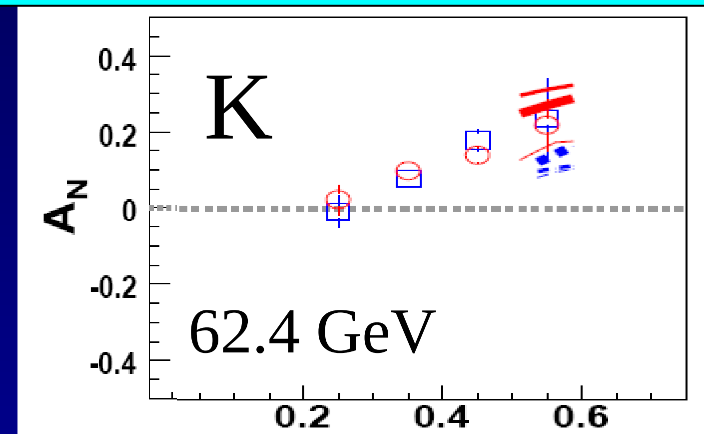
STAR



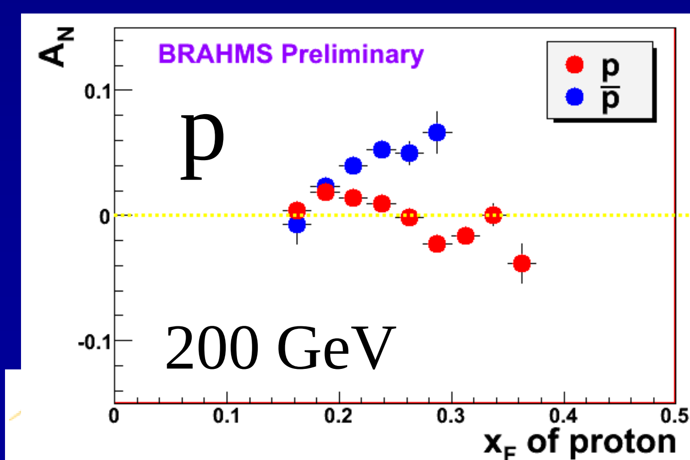
Pattern of pion species asymmetries in the forward direction → valence quark effect.

But this conclusion confounded by kaon and antiproton asymmetries!

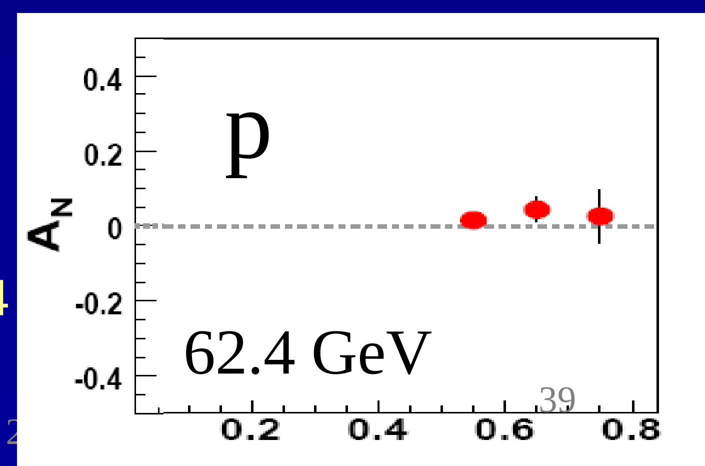




K- asymmetries underpredicted



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 ...
PHENIX a...

Larg...

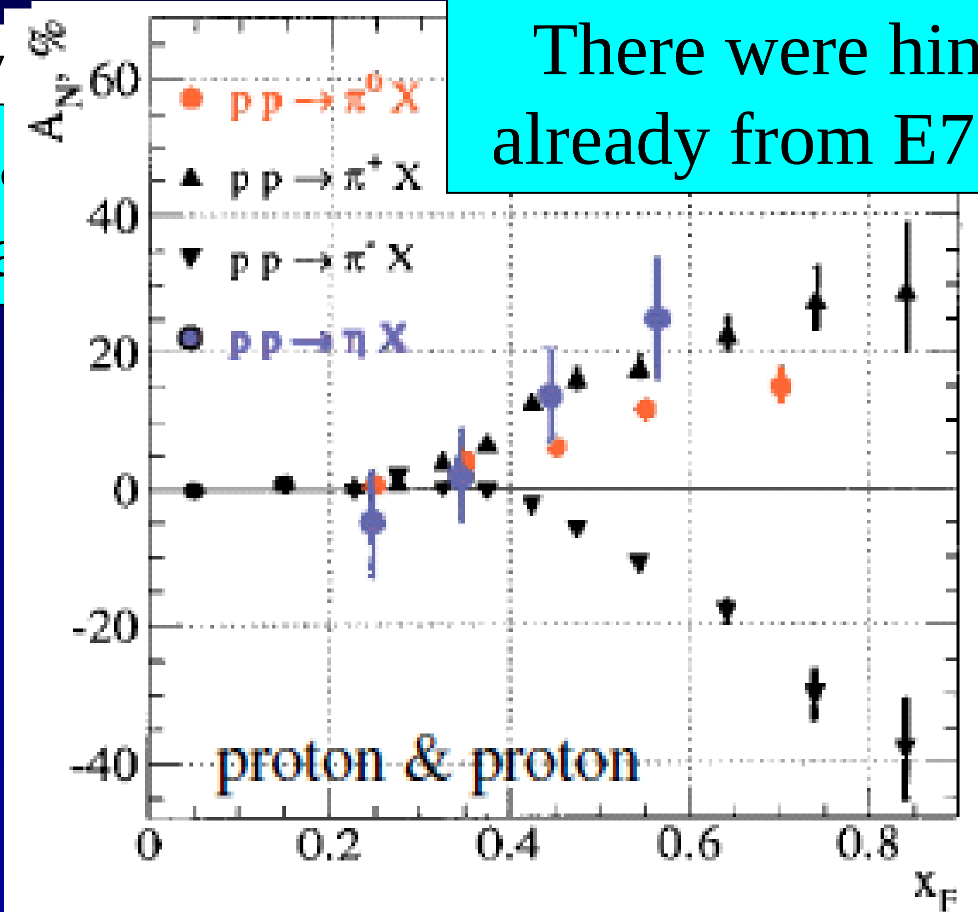
$.55 < X_F < .75$

$\langle A_N \rangle_\eta = 0.361 \pm 0.064$

$\langle A_N \rangle_\pi = 0.078 \pm 0.018$

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

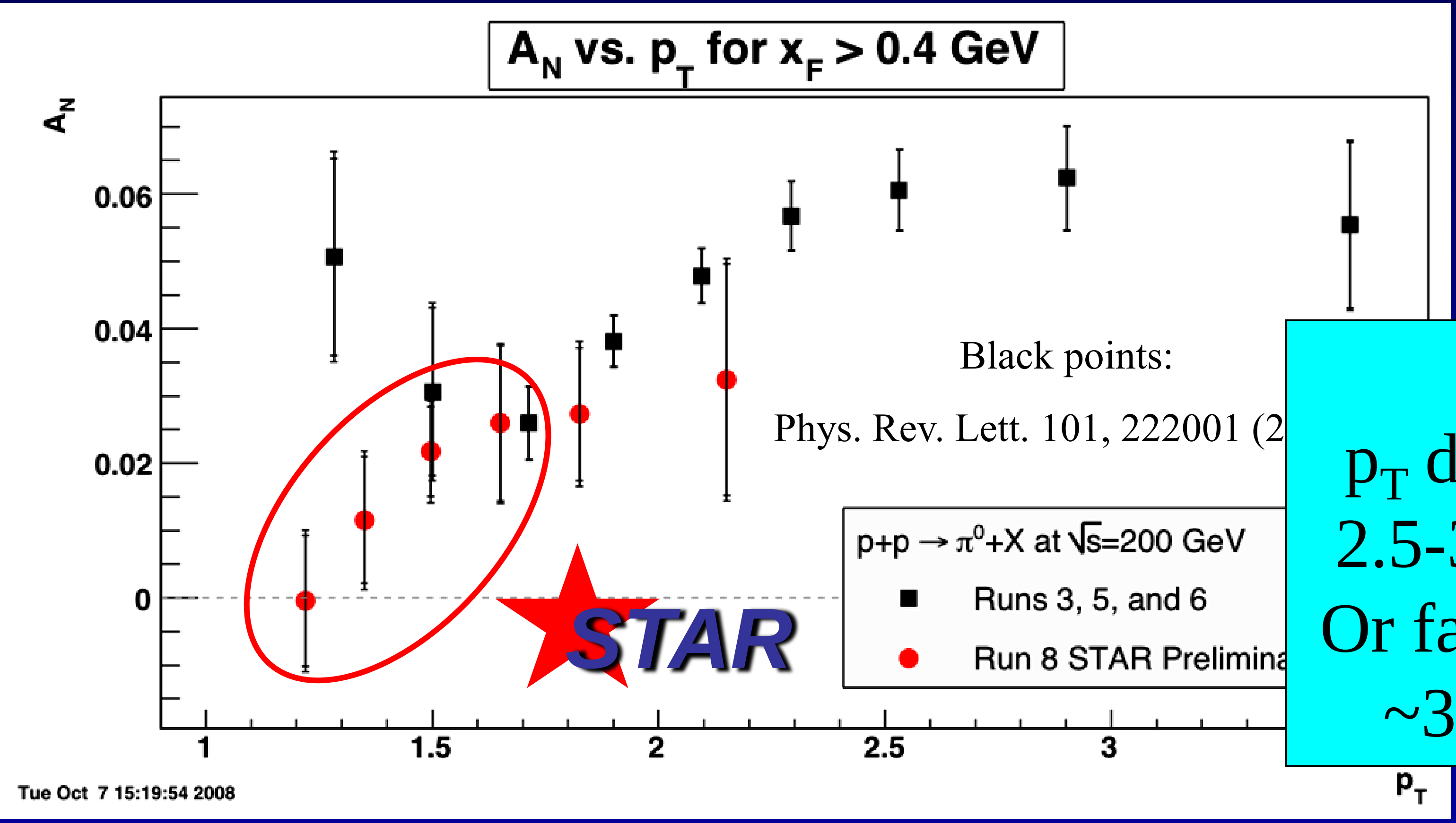
$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$



$\sqrt{s} = 19.4 GeV \quad \langle p_T \rangle \sim 1 GeV/c$

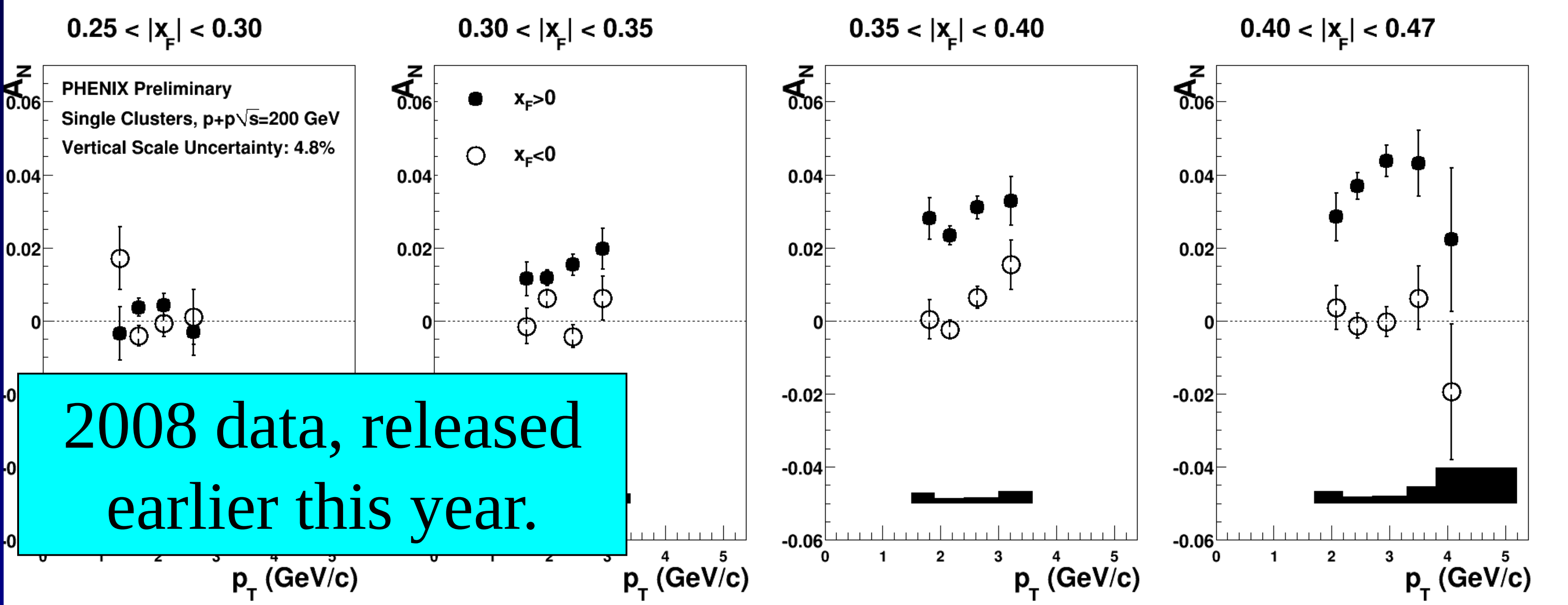
There were hints already from E704!

Neutral Pion Transverse SSA: Expected Decrease at Low p_T Now Observed



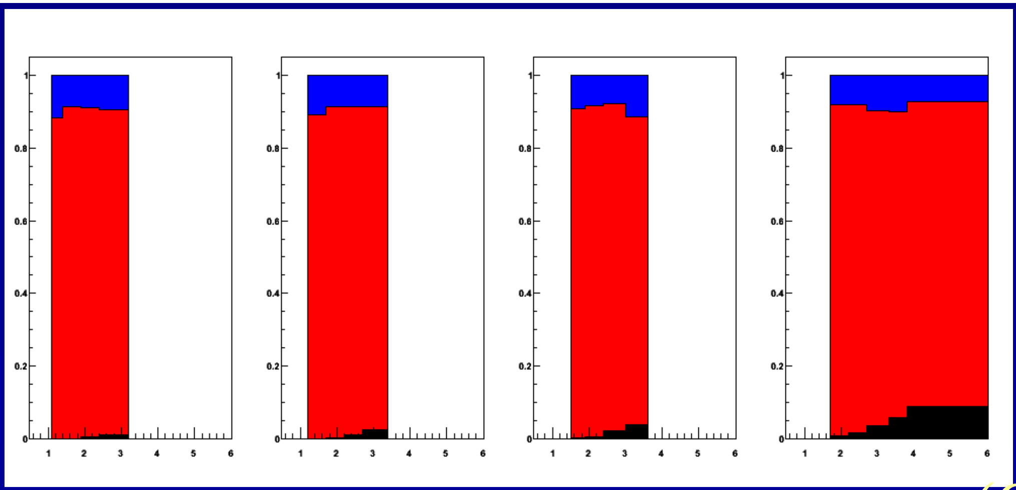
Flat
p_T dependence
2.5-3.5 GeV/c?
Or falling above
~3 GeV/c??

Improved Forward Coverage in PHENIX: A_N of Forward Clusters in MPC at $\sqrt{s}$=200 GeV



2008 data, released earlier this year.

Fraction of clusters

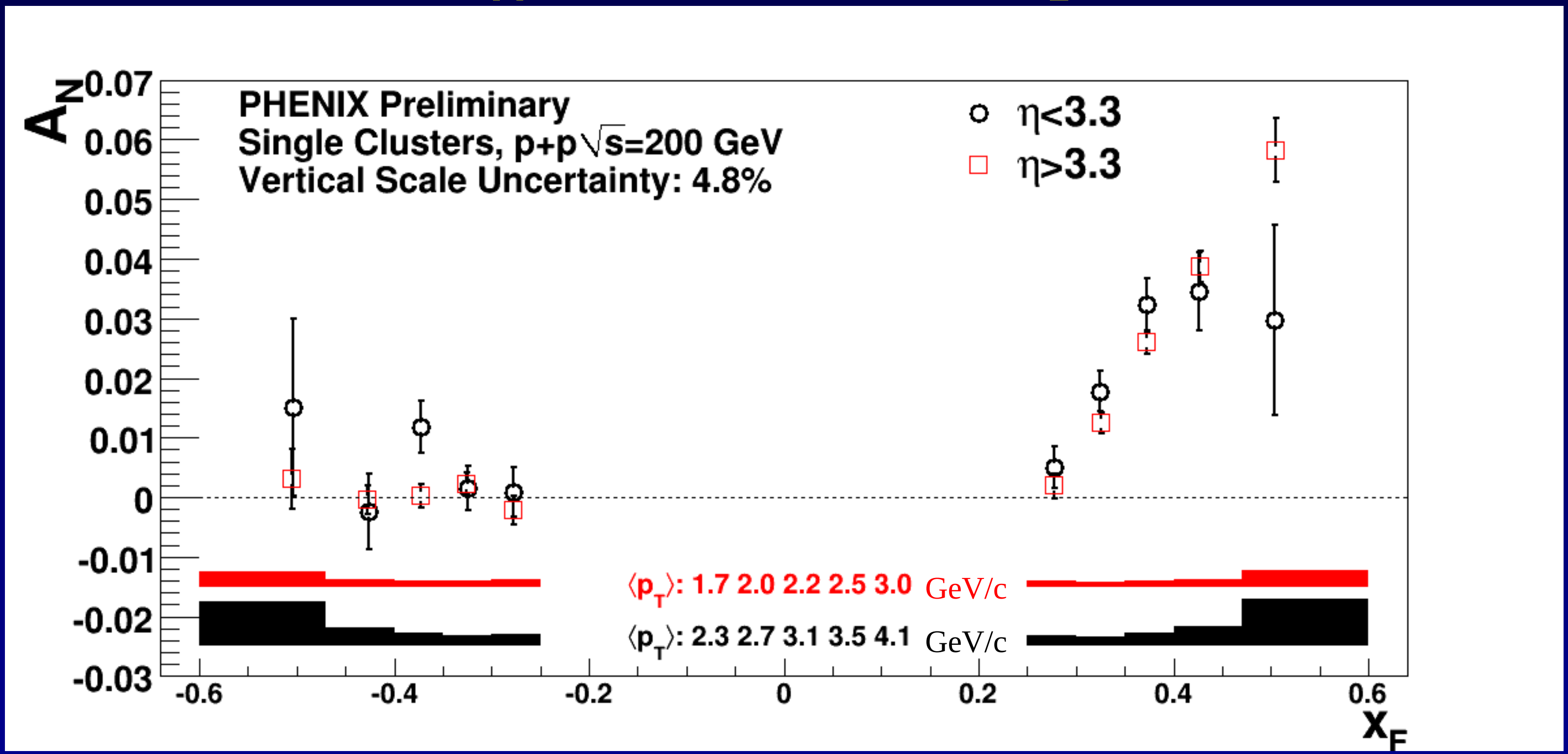


Decay photon
π^0
Direct photon

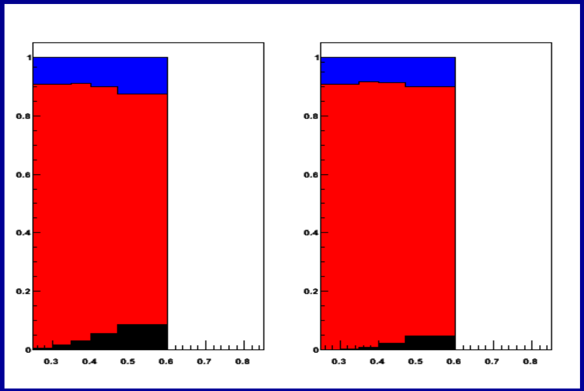
p_T (GeV/c)

Los Alamos NATIONAL LABORATORY EST.1943

PHENIX:A_N of Forward Clusters in MPC for Different Pseudorapidities



Fraction of clusters



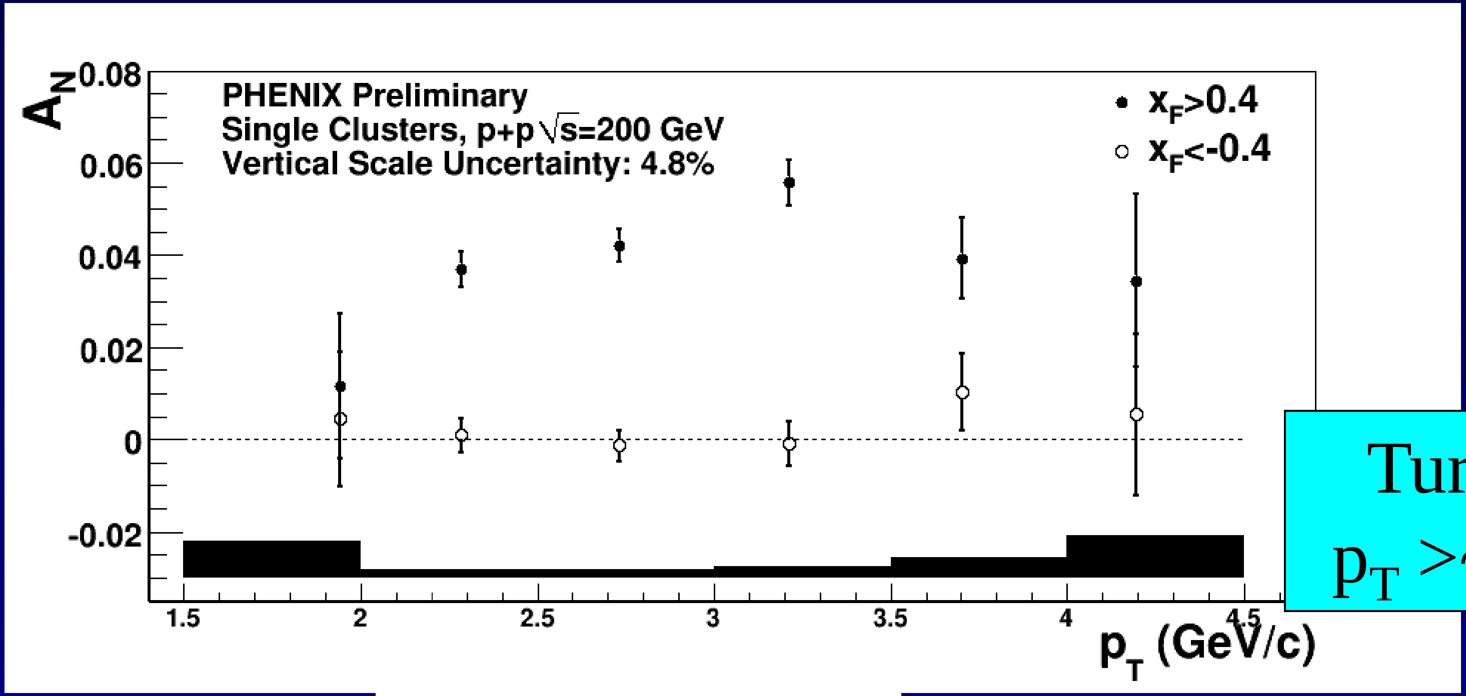
x_F

Decay photon

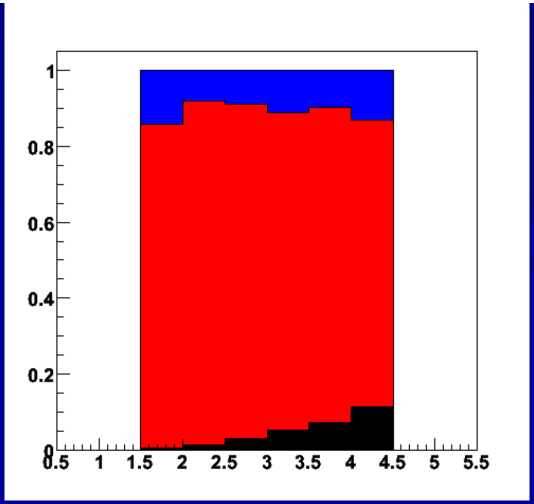
π^0

Direct photon

PHENIX: A_N of Forward Clusters in MPC vs. p_T



Turnover for p_T >~3 GeV/c?



Fraction of clusters

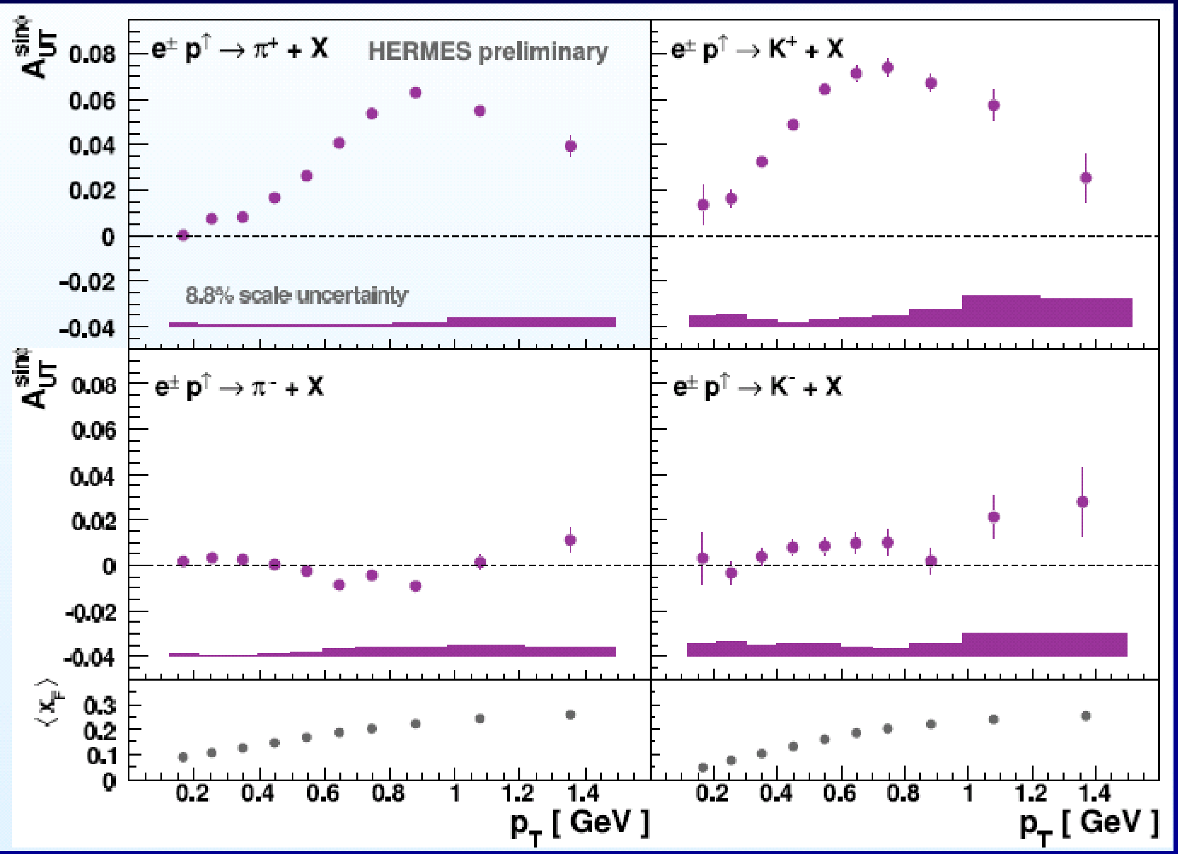
p_T

Decay photon

π^0

Direct photon

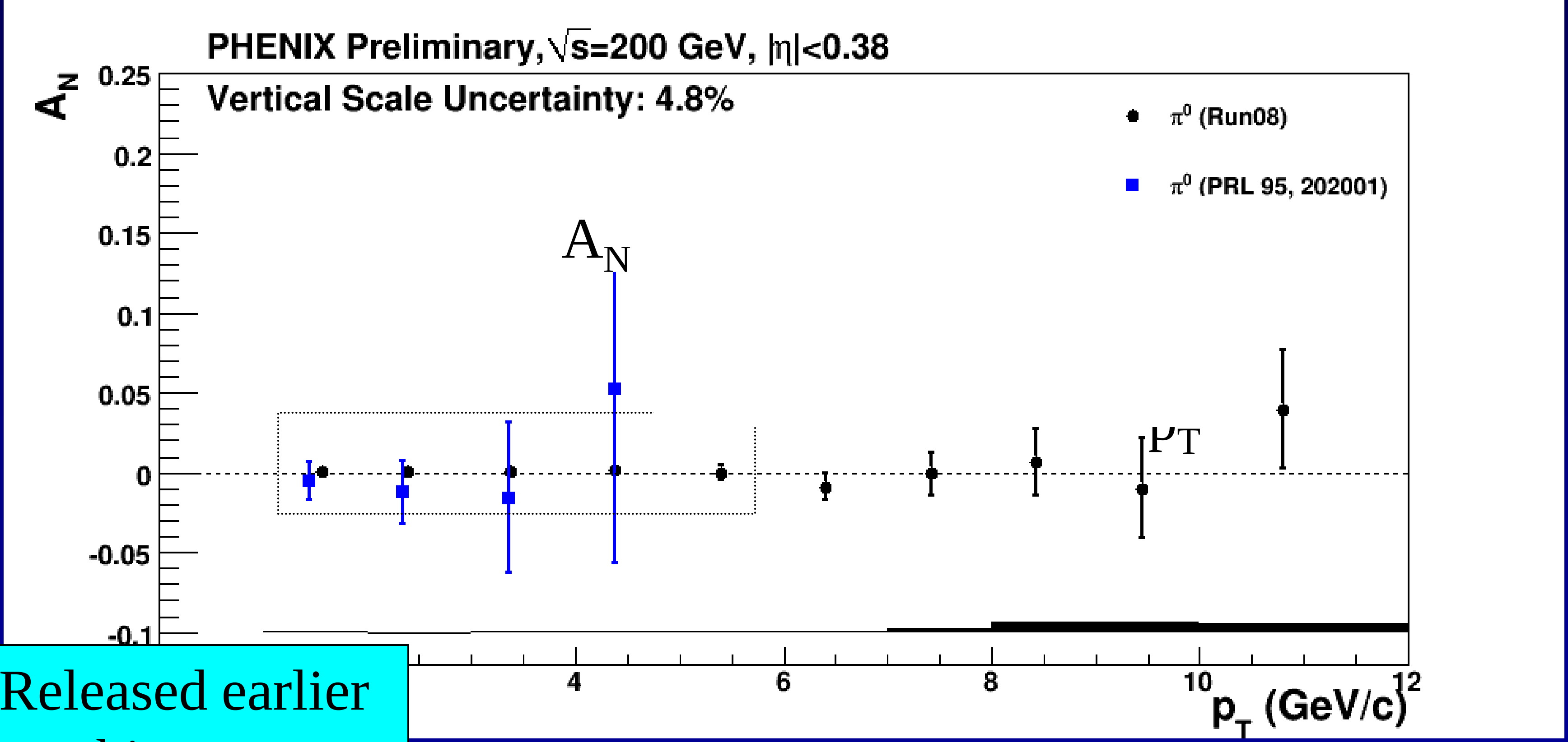
Compare: Recent HERMES Results for SSA in Inclusive Hadron Production



- Non-zero, but smaller magnitudes than low-energy p+p results
- Sharp turnover for p_T>~0.8 GeV/c

PHENIX Results for Midrapidity π^0 A_N

2002 Published Result   2008 Preliminary Result

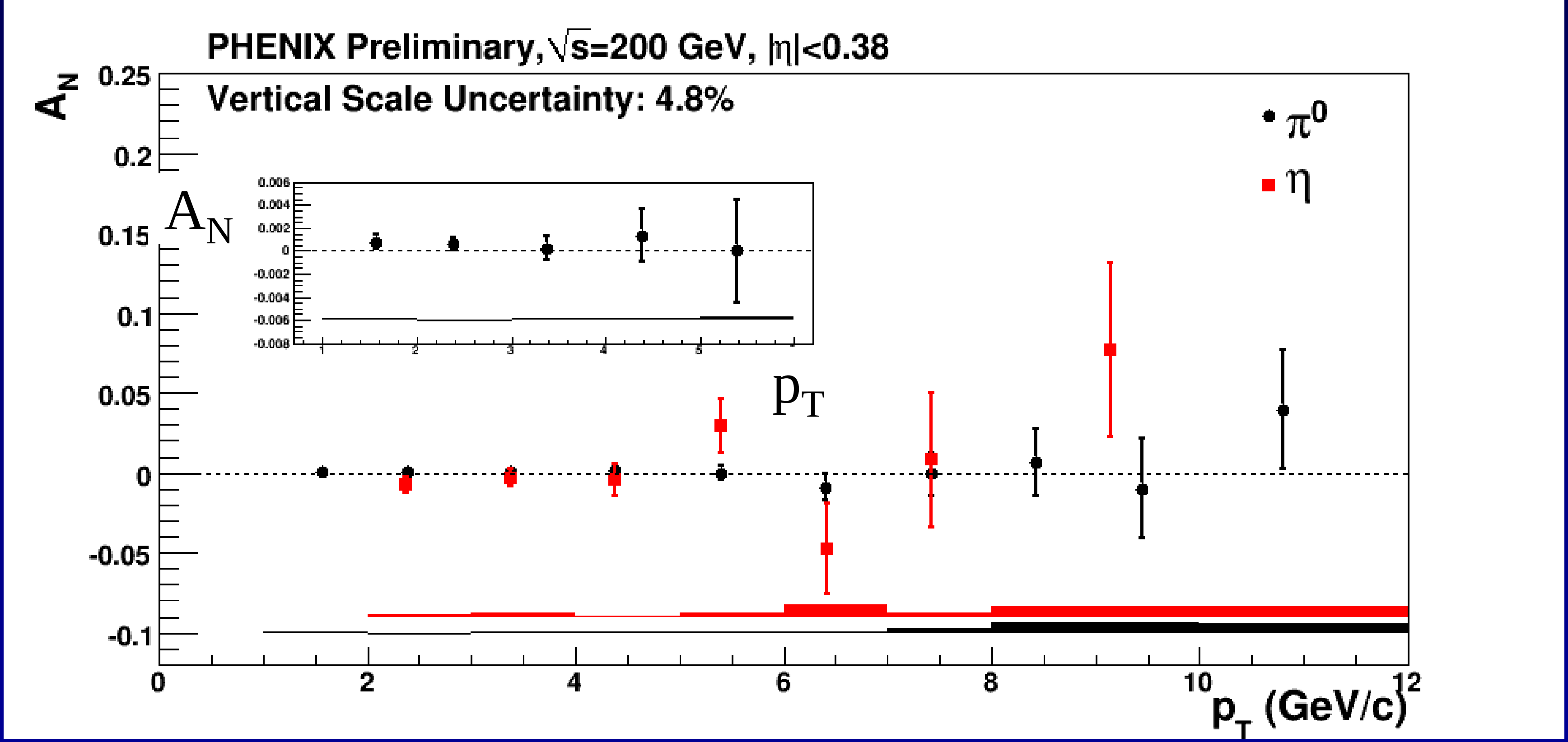


Released earlier this year.

- 20x smaller error bars than 200 result!

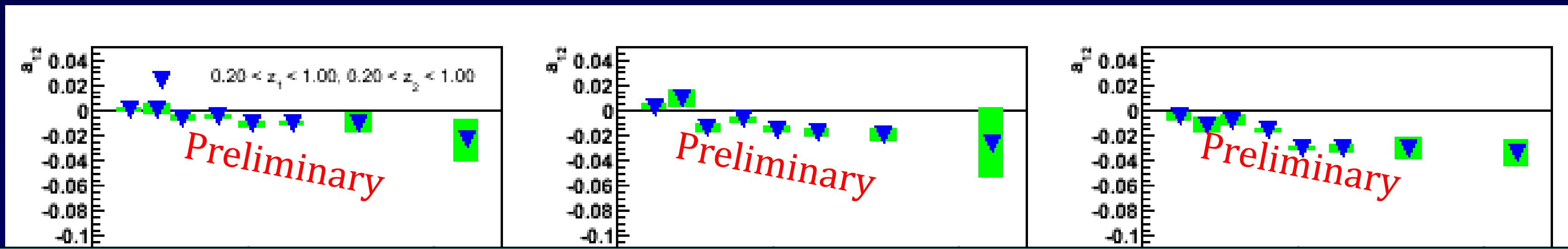
→Large improvement in both polarization and luminosity

PHENIX Results for Midrapidity π^0 and η A_N

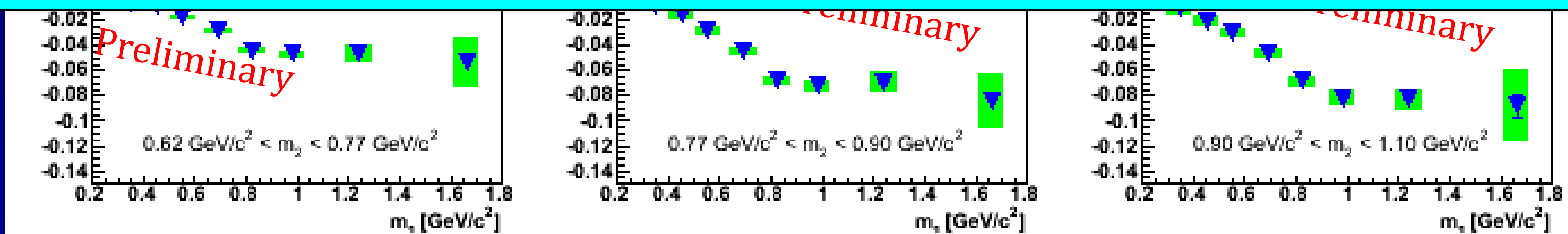


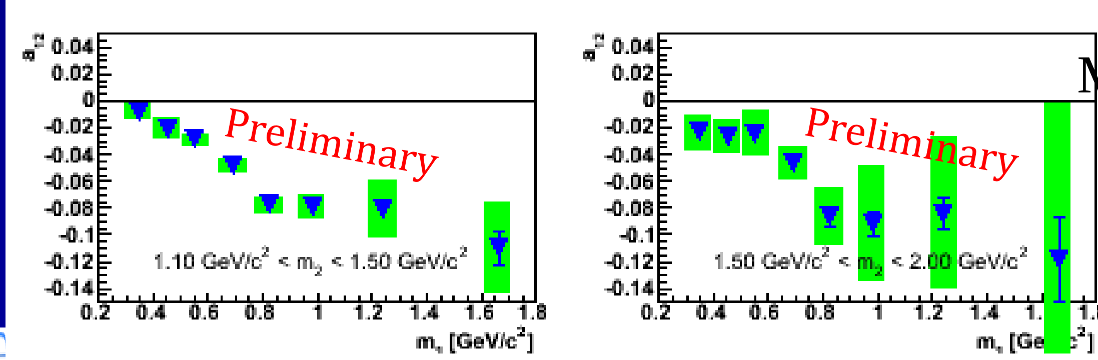
- A_N consistent with zero (at level 10^{-3}!) at midrapidity. Most precise RHIC asymmetry results to date.

BELLE Interference FF Measurement



With measurement from e+e- available, can learn from p+p (probe transversity x IFF)!



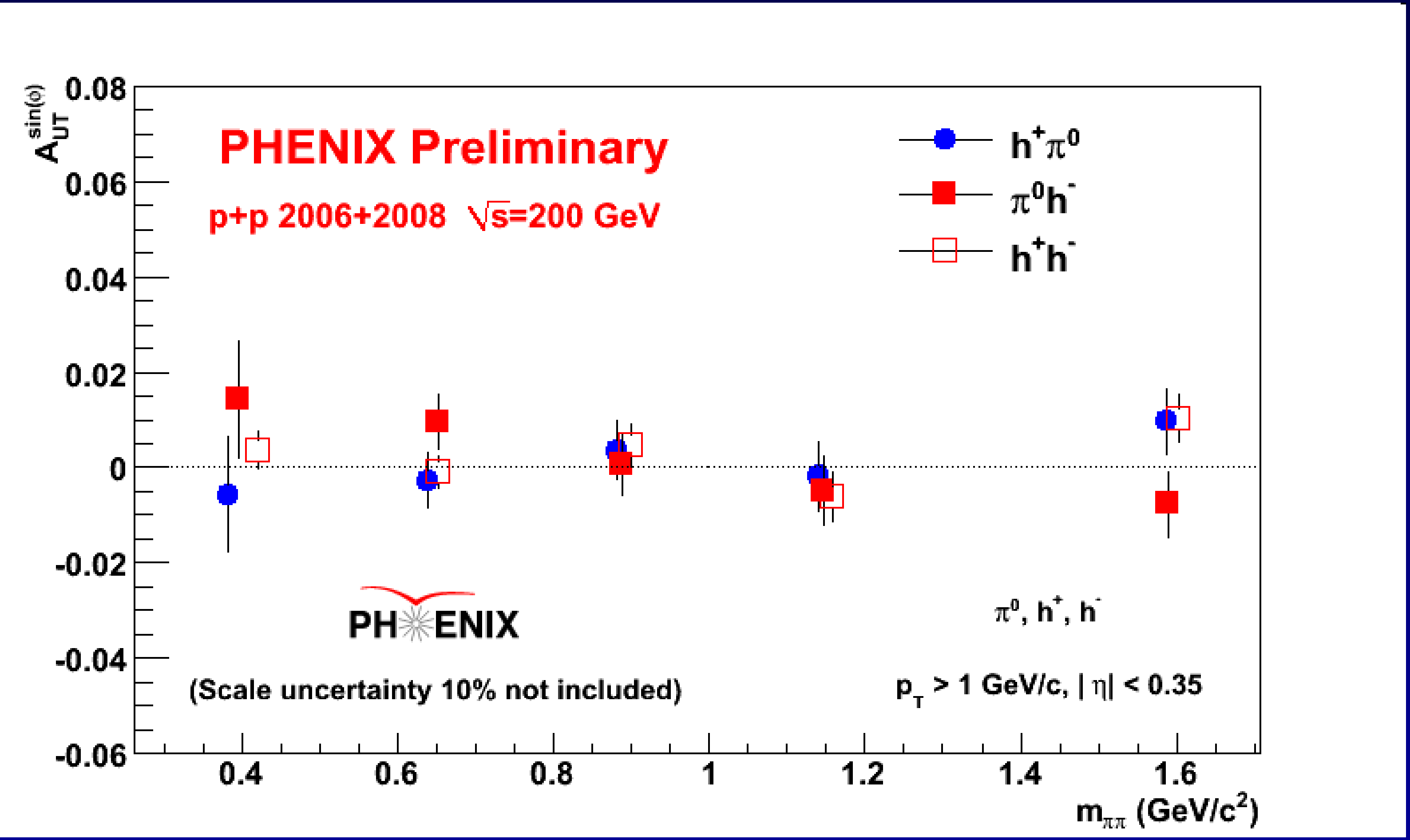


Measurement probes $(H_1^{<})^2$

→Non-zero and large

8x8 m_1 m_2 binning

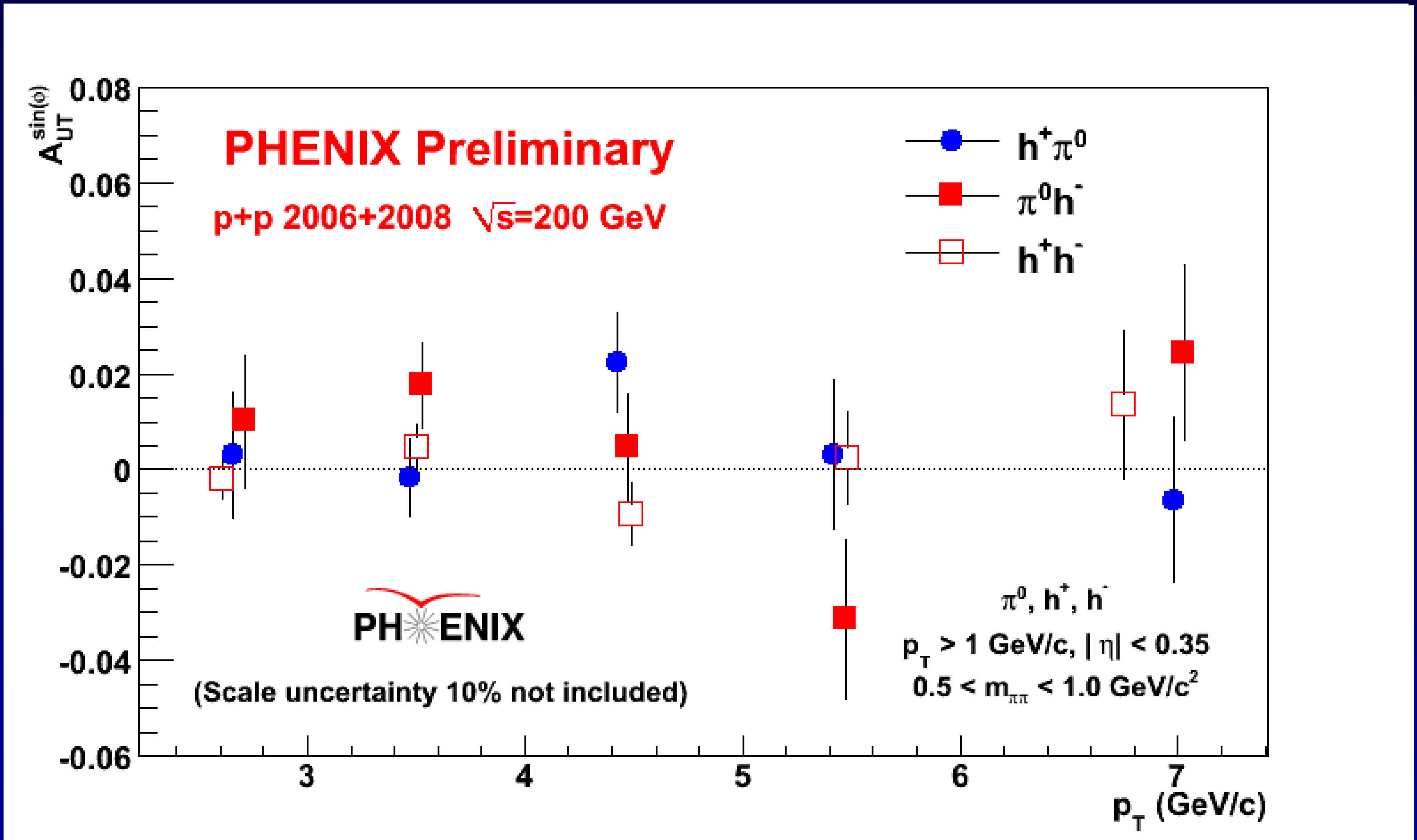
PHENIX IFF Results at Midrapidity vs. Pair Mass



Added statistics from 2008 running

As in DIS measurements, no significant effect observed around rho mass.

PHENIX IFF Results at Midrapidity vs. p_T



Added statistics from 2008 running

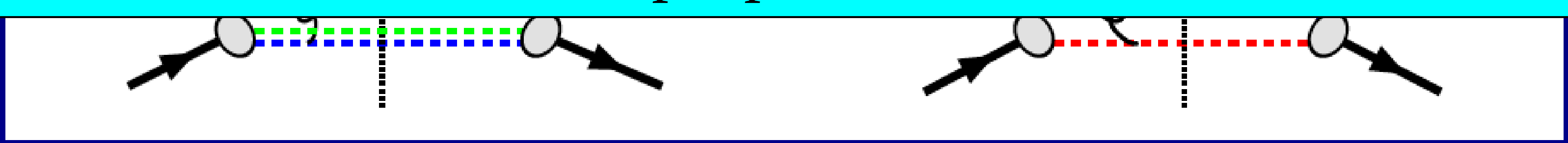
No significant asymmetries seen at mid-rapidity (yet!).

TMD's and Universality:
Modified Universality of Sivers Asymmetries

DIS: attractive FSI

Drell-Yan: repulsive ISI

Measurements in semi-inclusive DIS already exist. A Drell-Yan measurement will be a crucial test of our understanding of QCD! Multiple dedicated polarized Drell-Yan experiments now being proposed.



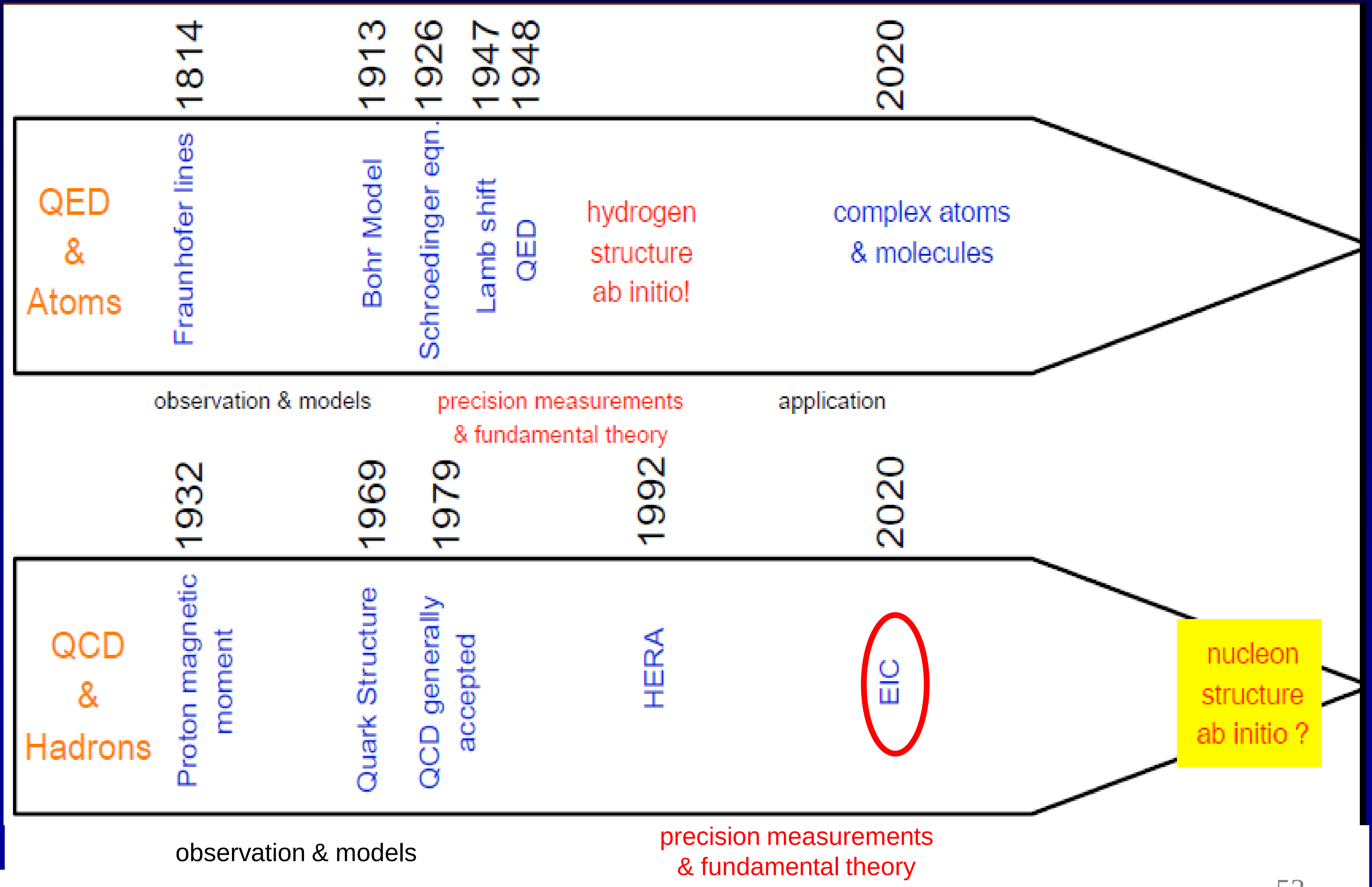
As a result: $\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$

TMDs, Factorization, and Universality in Other Hadronic Reactions

We've known in principle all along that factorization is an approximation! Finally ready to start to move beyond the simplest approximation of hadrons that don't "communicate" in multi-hadron interactions!

- For single-weighted functions still possible . . .
- Solution for non-weighted functions may be to include all hadrons in a *single* soft part

QED vs. QCD


1814
1913
1926
1947
1948
2020
QED
&
Atoms
Fraunhofer lines
Bohr Model
Schroedinger eqn.
Lamb shift
QED
hydrogen
structure
ab initio!
complex atoms
& molecules
observation & models
precision measurements
& fundamental theory
application
1932
1969
1979
1992
2020
QCD
&
Hadrons
Proton magnetic
moment
Quark Structure
QCD generally
accepted
HERA
EIC
nucleon
structure
ab initio ?
observation & models
precision measurements
& fundamental theory

Glancing Into the Future: The Electron-Ion Collider

- Design and build a new facility with the capability of colliding a beam of electrons with a wide variety of nuclei as well as polarized protons and light ions: the Electron-Ion Collider

The EIC: Communities Coming Together

- At RHIC, heavy ions and nucleon spin structure already meet, but in some sense by "chance"
  - Genuinely different physics
  - Communities come from different backgrounds
  - Bound by an accelerator that has capabilities relevant to both

- Proposed EIC a facility where heavy ion and nucleon structure communities truly come together, peering into various forms of hadronic matter to continue to uncover the secrets and subtleties of QCD . . .

Conclusions and Prospects

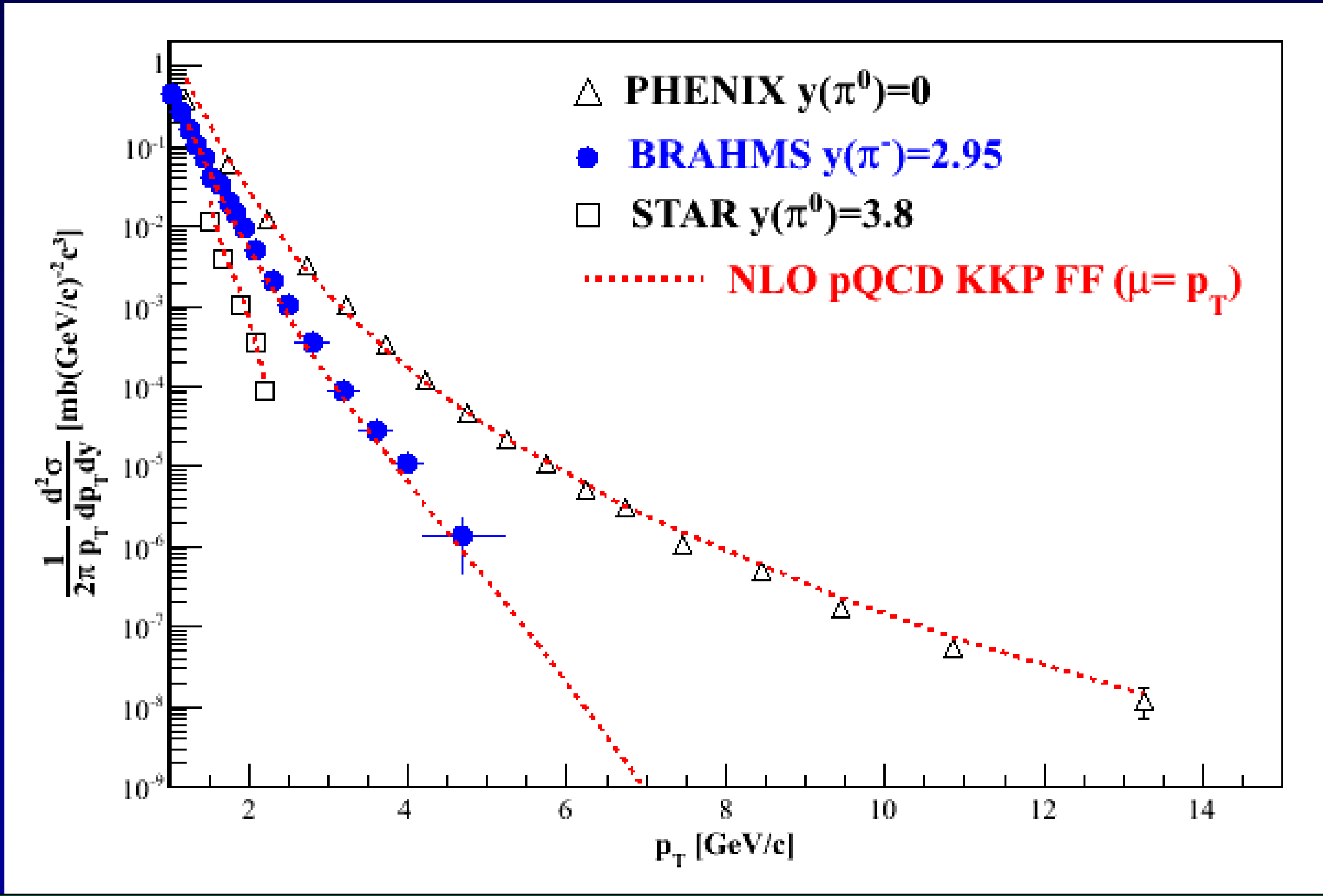
- After > 40 years of studying the internal structure of the nucleon and nuclei, we remain far from the ultimate goal of being able to describe nuclear matter in terms of its quark and gluon degrees of

There's a large and diverse community of people—at RHIC and complementary facilities—driven to continue exploring QCD and coaxing the secrets out of one of the most fundamental building blocks of the world around us.

-
- The EIC promises to usher in a new era of precision measurements that will probe the behavior of quarks and gluons in nucleons as well as nuclei, bringing us to a new phase in understanding the rich complexities of QCD in matter.

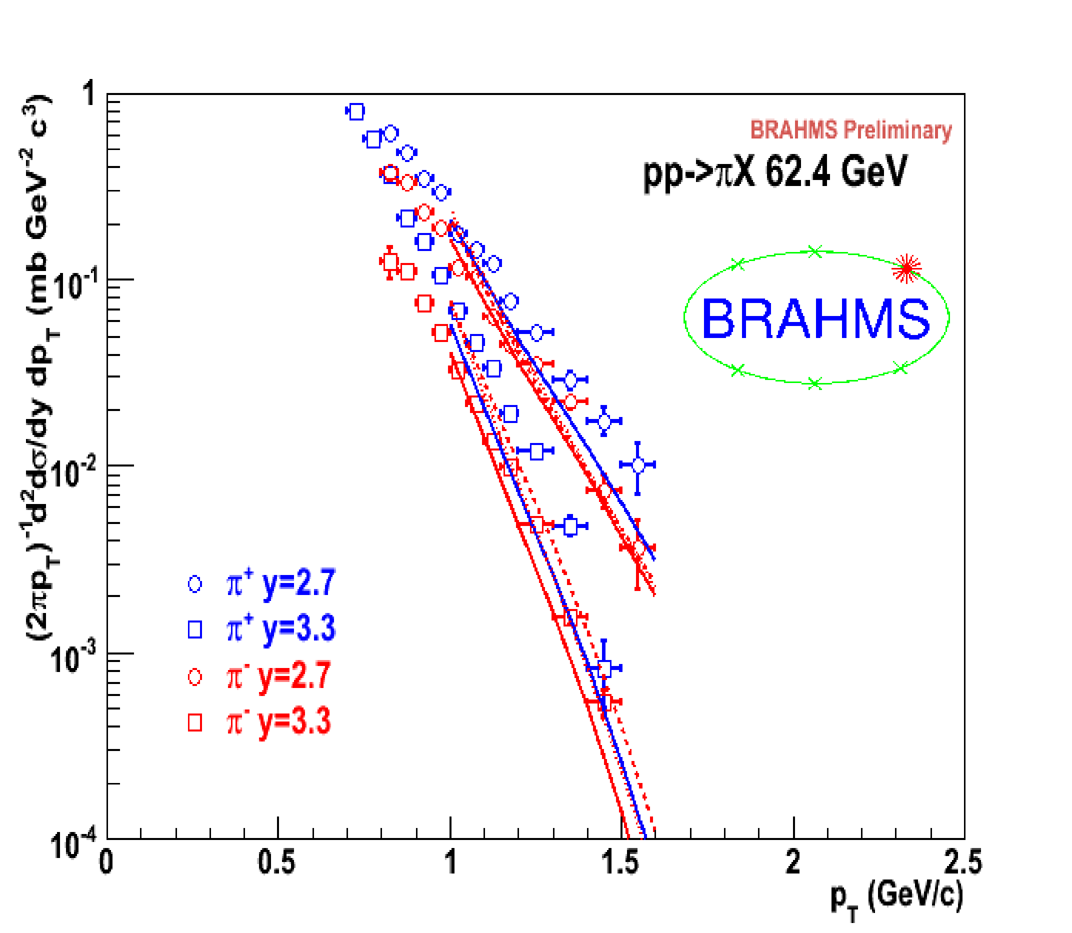
Additional Material

Polarization-averaged cross sections at $\sqrt{s}$=200 GeV



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

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

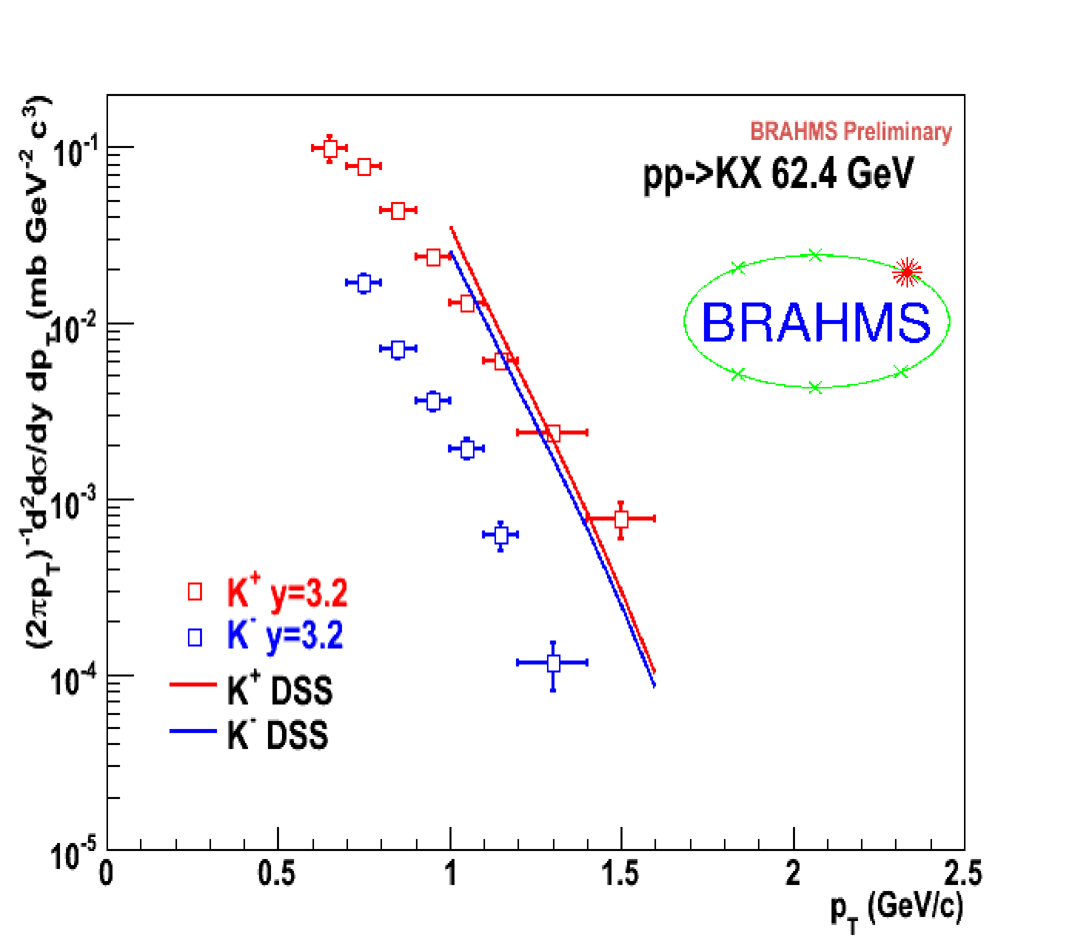


Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of $\mu=p_T$, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

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

Still not so bad!

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



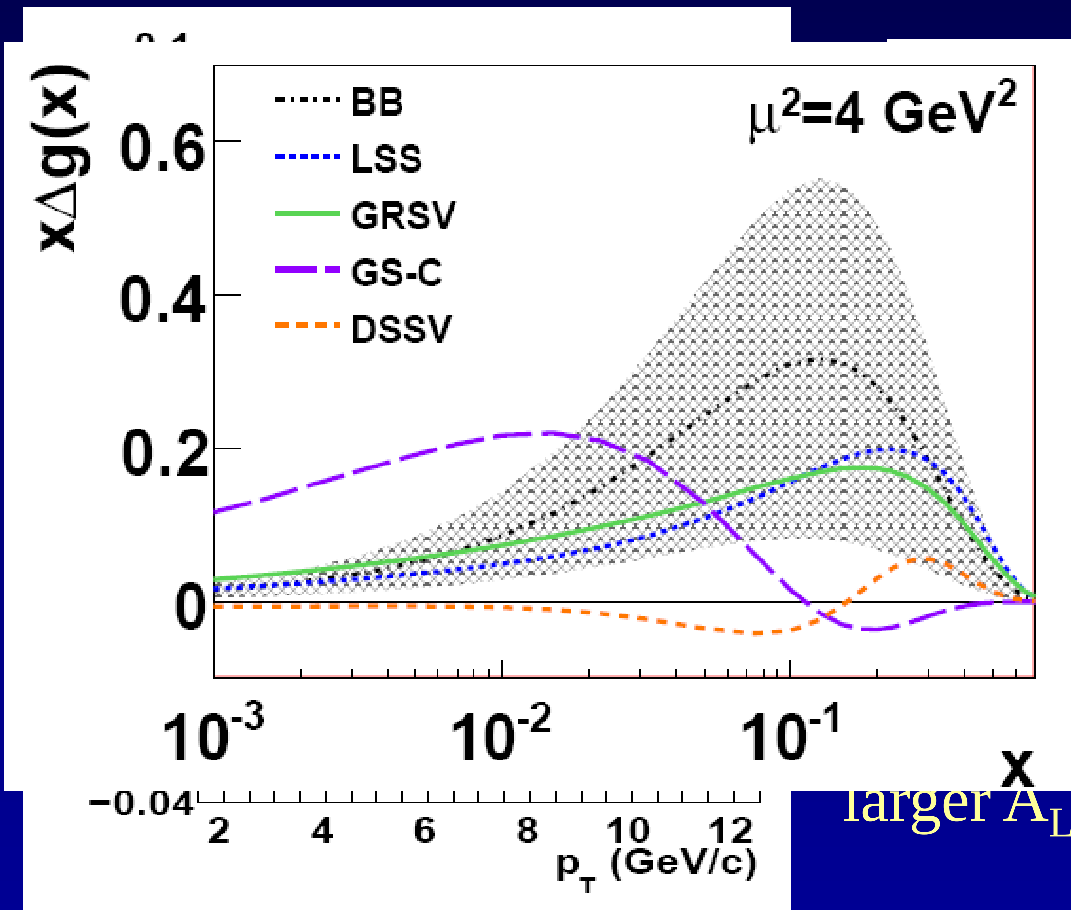
K^- *data* suppressed ~order of magnitude (valence quark effect).

NLO pQCD using recent DSS FF's gives ~same yield for both charges(??).

Related to FF's? PDF's??

K^+: Not bad!
K^-: Hmm…

π^0 A_{LL}: Agreement with Different Parametrizations of $\Delta g(x)$



Published best fit		
$\Delta G^{[0,1]}$	$\Delta G^{[0.02,0.3]}$	χ^2
0.95	0.18	8.3
-0.05	-0.03	7.5
0.60	0.37	22.4
0.67	0.38	14.8
0.93	0.67	69.0

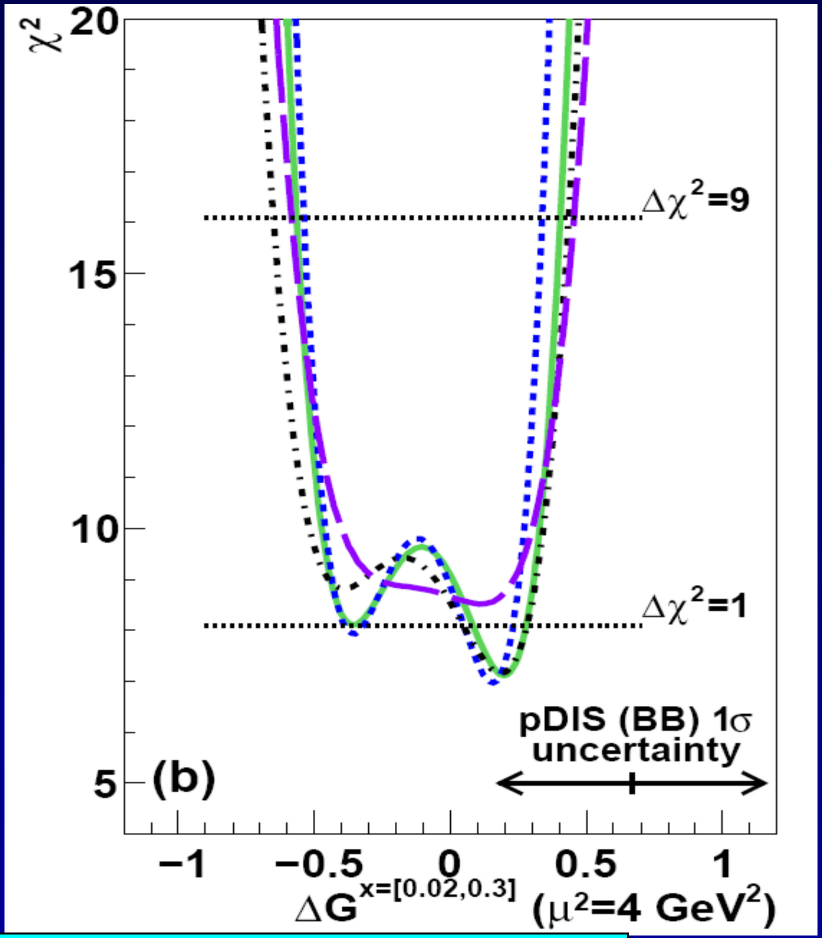
G in our measured *x* region
3 gives small A_{LL} (DSSV and
Large ΔG gives comparatively
larger A_{LL} .

Note small A_{LL} does not necessarily mean small ΔG in the full *x* range!

π^0 A_{LL}: *Agreement with different parametrizations*

For each parametrization, vary $\Delta G^{[0,1]}$ at the input scale while fixing $\Delta q(x)$ and the shape of $\Delta g(x)$, i.e. no refit to DIS data.

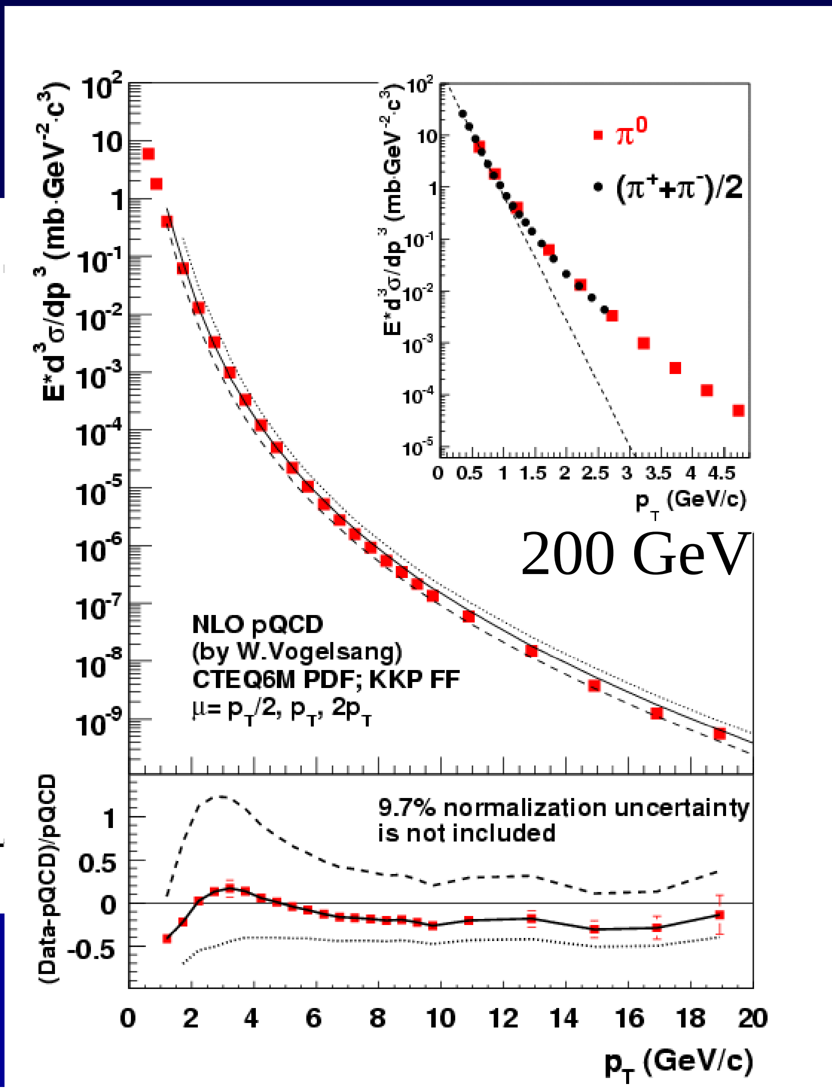
For range of shapes studied, current data relatively insensitive to shape in *x* region covered.



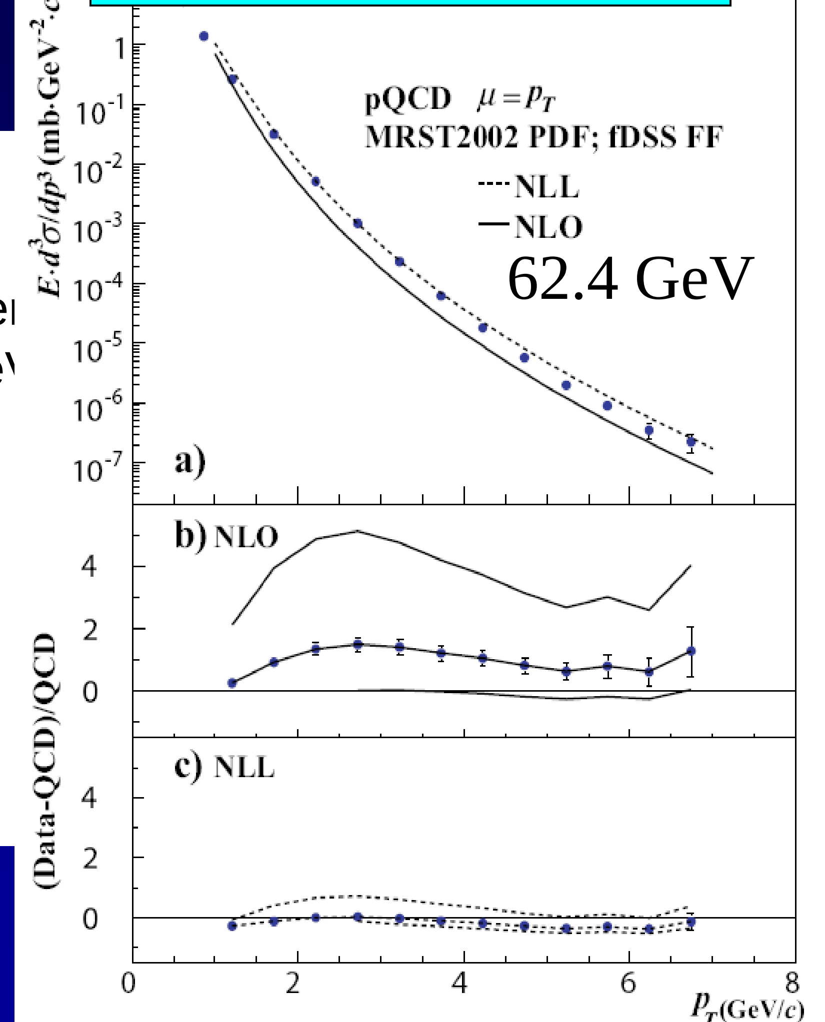
arXiv:0

Need to extend *x* range!

Extending x Coverage

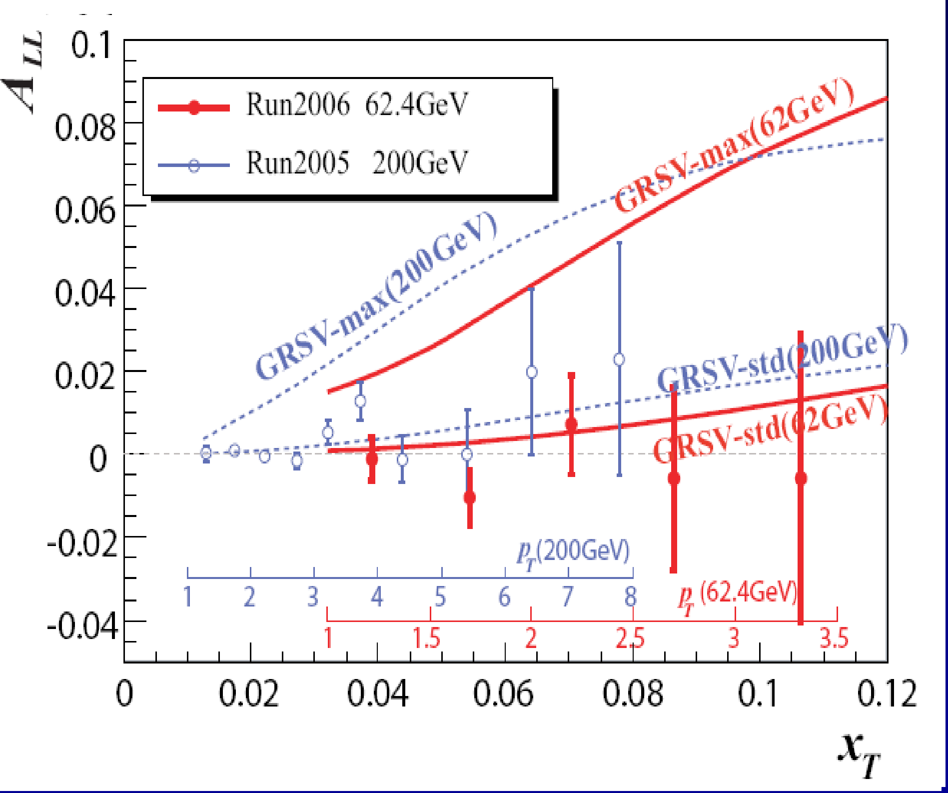


PRD79, 012003 (2009)



Neutral Pion A_{LL} at 62.4 GeV

$$x_T = \frac{2p_T}{\sqrt{s}}$$



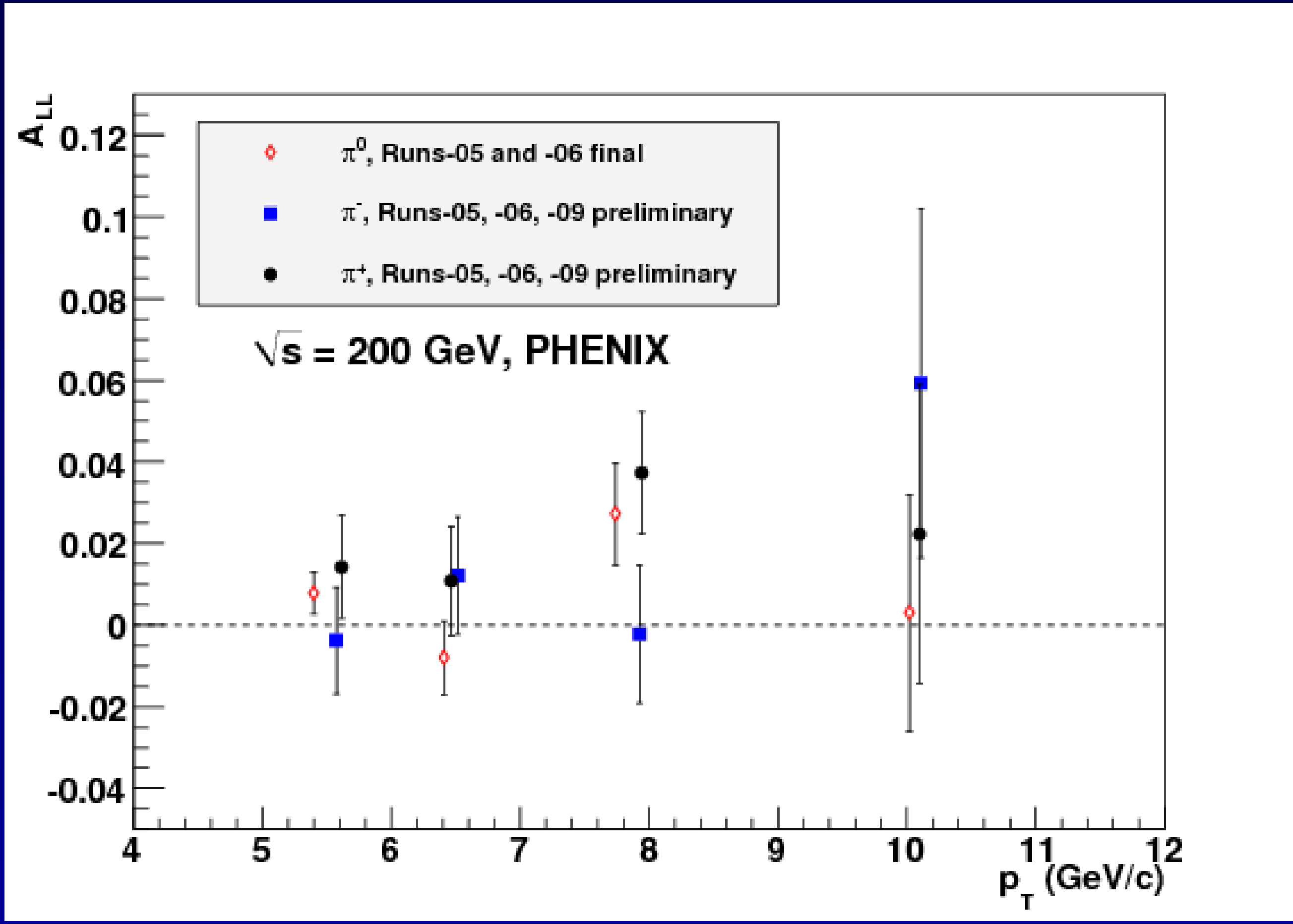
Converting to x_T, can see significance of 62.4 GeV measurement (0.08 pb^{-1}) compared to published data from 2005 at 200 GeV (3.4 pb^{-1}).

$$0.02 < x_{gluon} < 0.3 \quad (\sqrt{s} = 200\,\text{GeV})$$

$$0.06 < x_{gluon} < 0.4 \quad (\sqrt{s} = 62.4\,\text{GeV})$$

PRD79, 012003 (2009)

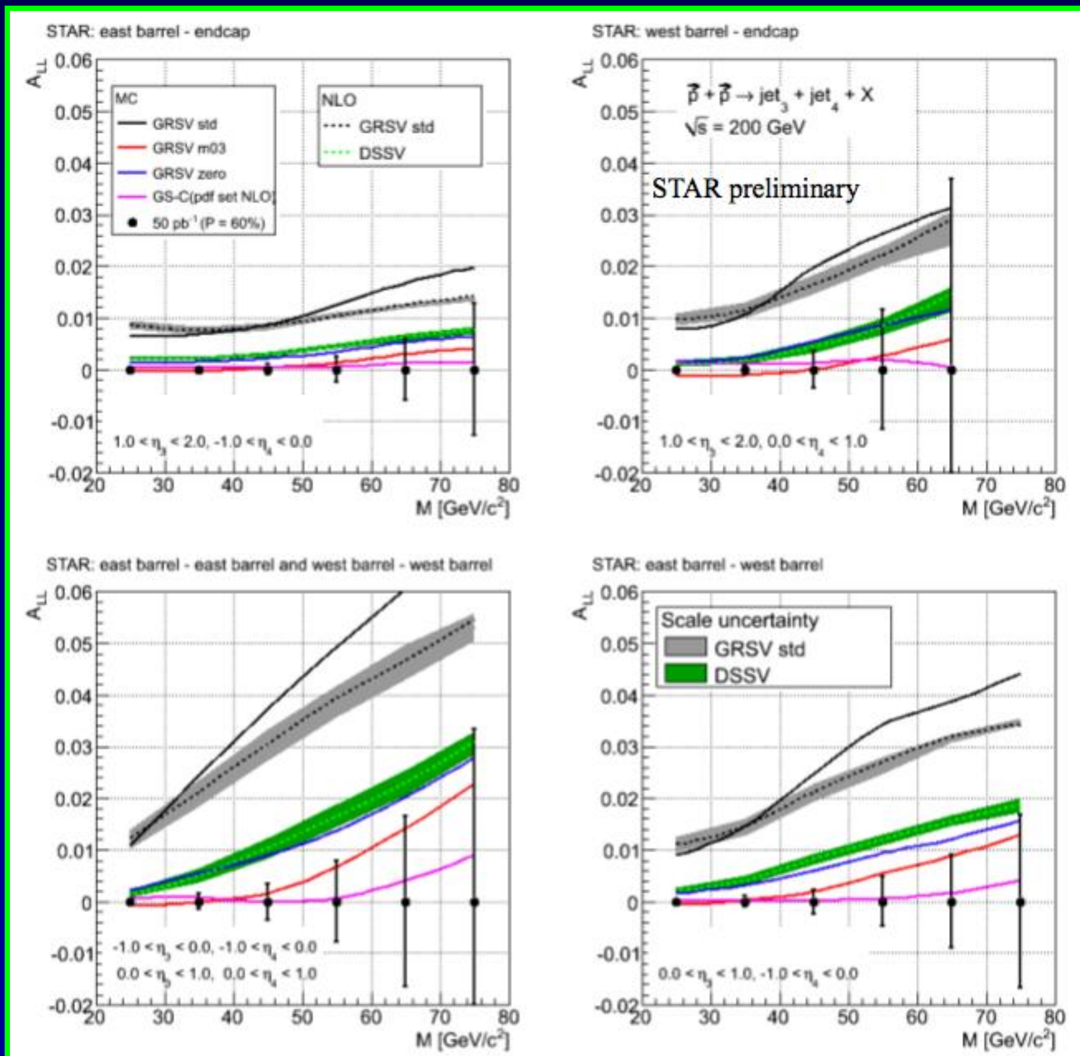
Ordering of A_{LL} for pion species?



Not yet clear.

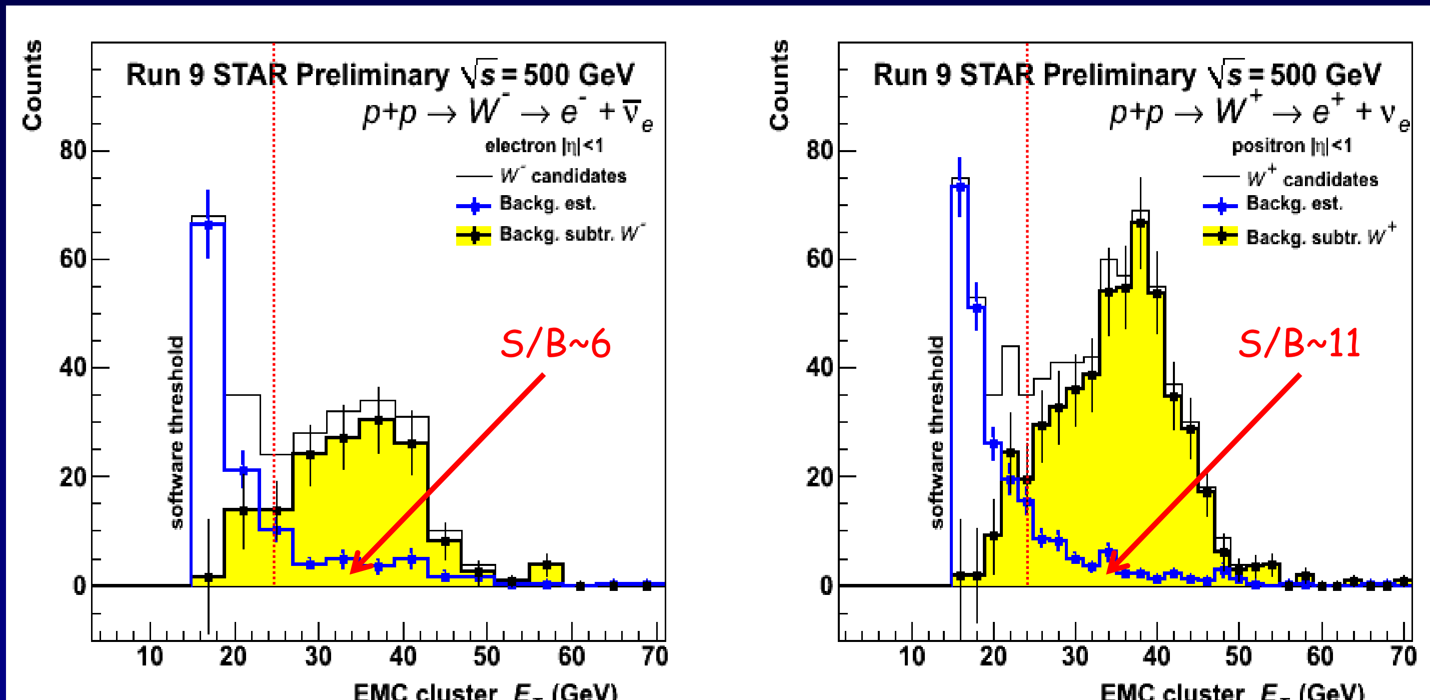
Small ΔG → small predicted differences between asymmetries!

Reduce Integration Bins: Correlation Measurements



Di-Jet and Photon-Jet Asymmetries allows reconstruction of partonic x1 and x2 at leading order.

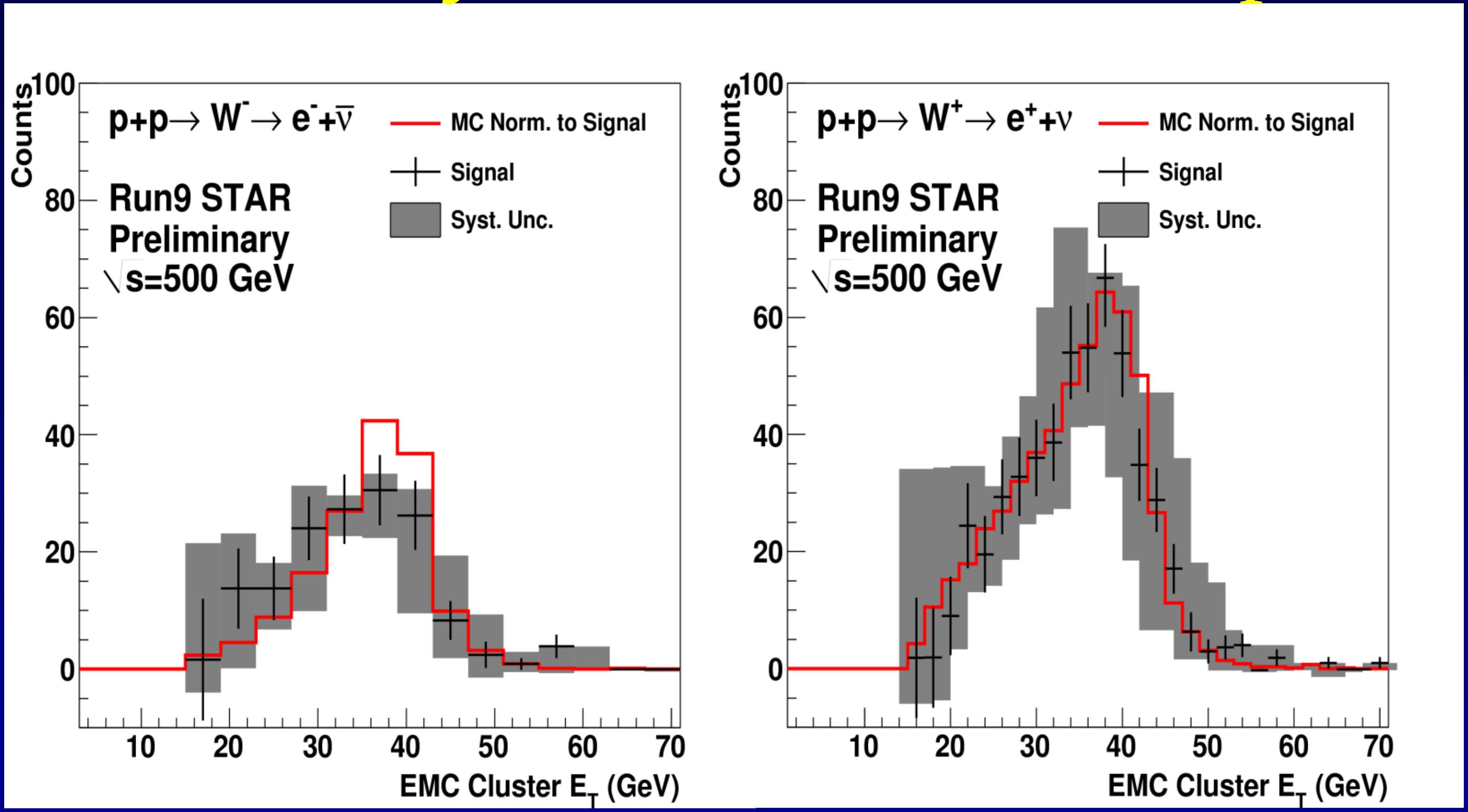
STAR W Analysis: BG Subtraction



- Background distribution and background-subtracted signal distribution
- B/(S+B) (E_T > 25GeV) W^-: 16%
- B/(S+B) (E_T > 25GeV) W^+: 8%

Background Events ($E_T > 25$ GeV)	$W^- \to e^- + \bar{\nu}_e$	$W^+ \to e^+ + \nu_e$
$W \to \tau + \nu_\tau$	2.7 ± 0.7	8.4 ± 2.2
Missing Endcap	14 ± 4	13 ± 4
Normalized QCD	$8.0\ ^{+20}_{-4}$	$25\ ^{+36}_{-9}$
Total	$25\ ^{+21}_{-7}$	$46\ ^{+36}_{-11}$

STAR W Analysis: Data/MC Comparison



- Comparison of data and PYTHIA+GEANT simulations for W signal events at 500GeV
- Systematic uncertainties were estimated by varying cuts and normalization regions for QCD background and by varying BEMC energy scale uncertainty (±7.5%)

STAR W Cross Section: Uncertainties

- Total W^+/W^- cross-section uncertainties
  - W reconstruction systematic uncertainties
    - Track reconstruction: 15 – 20%
    - Vertex reconstruction: 3%
    - BEMC Energy scale: < 1%
  - Normalization / Luminosity systematic uncertainty
    - Vernier scan absolute cross section: 23%
  - Background systematic uncertainty
    - Vary data driven QCD background shape and normalization region (E_T < 17 – 21 GeV)

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STAR W A_L Uncertainties

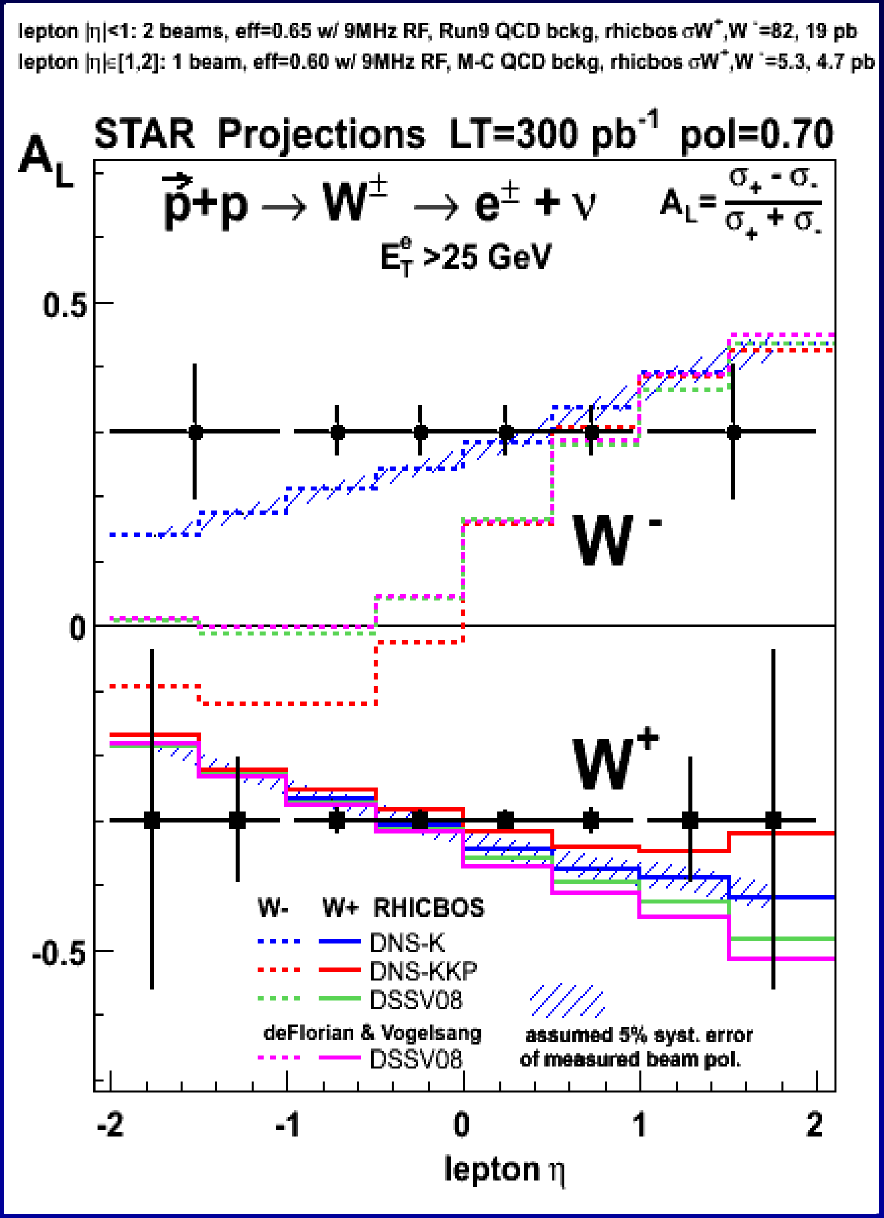
- Parity-violating single-spin asymmetry W^+/W^- A_L uncertainties

W^+		W^-		
high	low	high	low	
0.09	**0.09**	0.09	0.09	Absolute polarization magnitude of both beams (P1+P2) (9.2%)
0.07	0.02	0.13	0.03	QCD unpolarized background
0.07	0.07	**0.14**	**0.14**	QCD pol. bckg. ~0: use 1/2 stat error of this test
0.01	0.00	0.01	0.00	Decay of pol. within fill
0.13	**0.11**	**0.21**	**0.17**	Total syst. in fraction of measured A_L

W Projections (STAR)

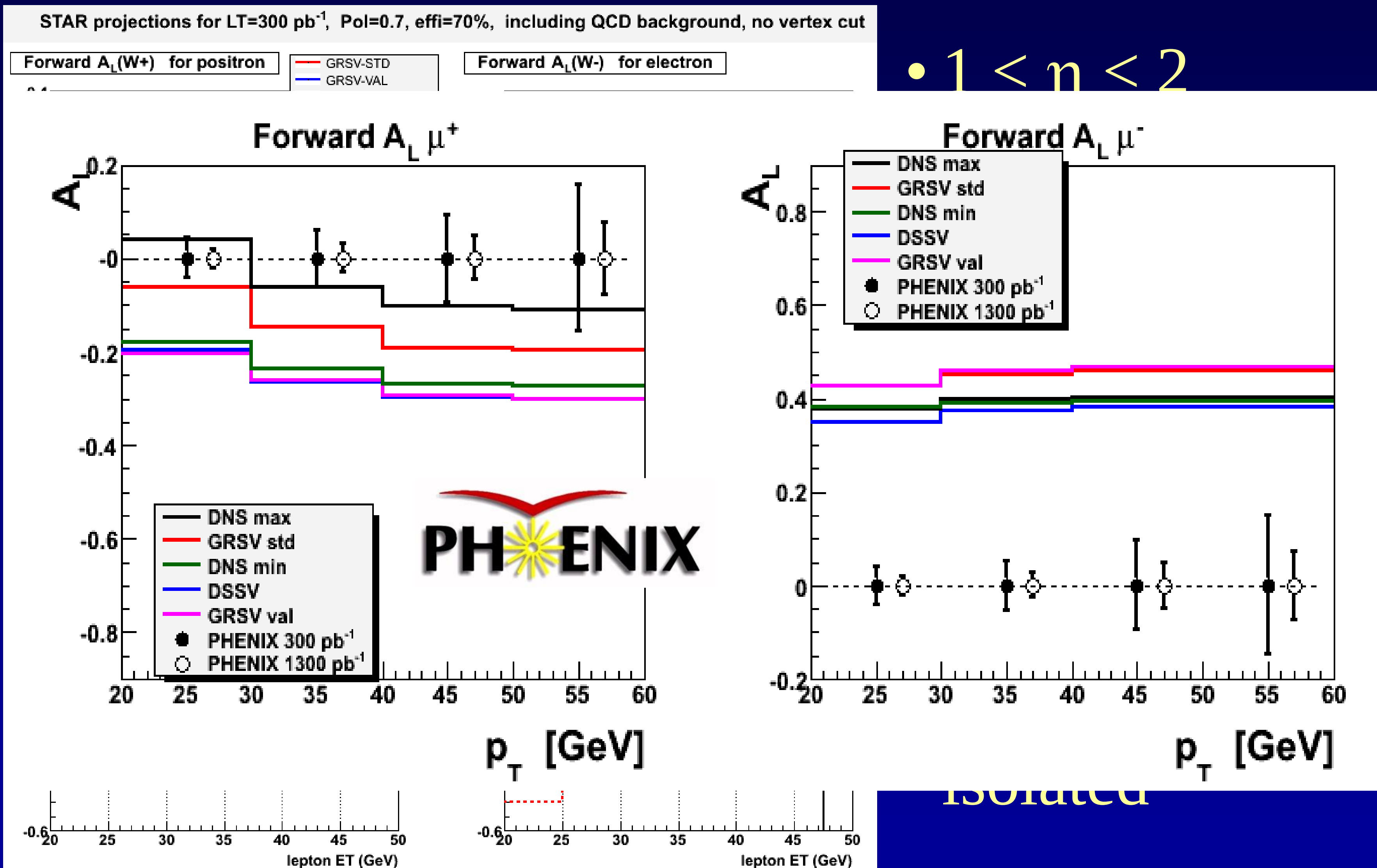
Assumptions:

- Efficiency:
  - Mid-rapidity: 0.65
  - Forward rapidity: 0.60
  - Assume availability of 9MHz RF
- Background:
  - Mid-rapidity: Run 9
  - Forward rapidity: QCD MC simulations
- Full charge-sign discrimination at high-p_T



W Projections vs. p_T

- $1 < \eta < 2$



isolated

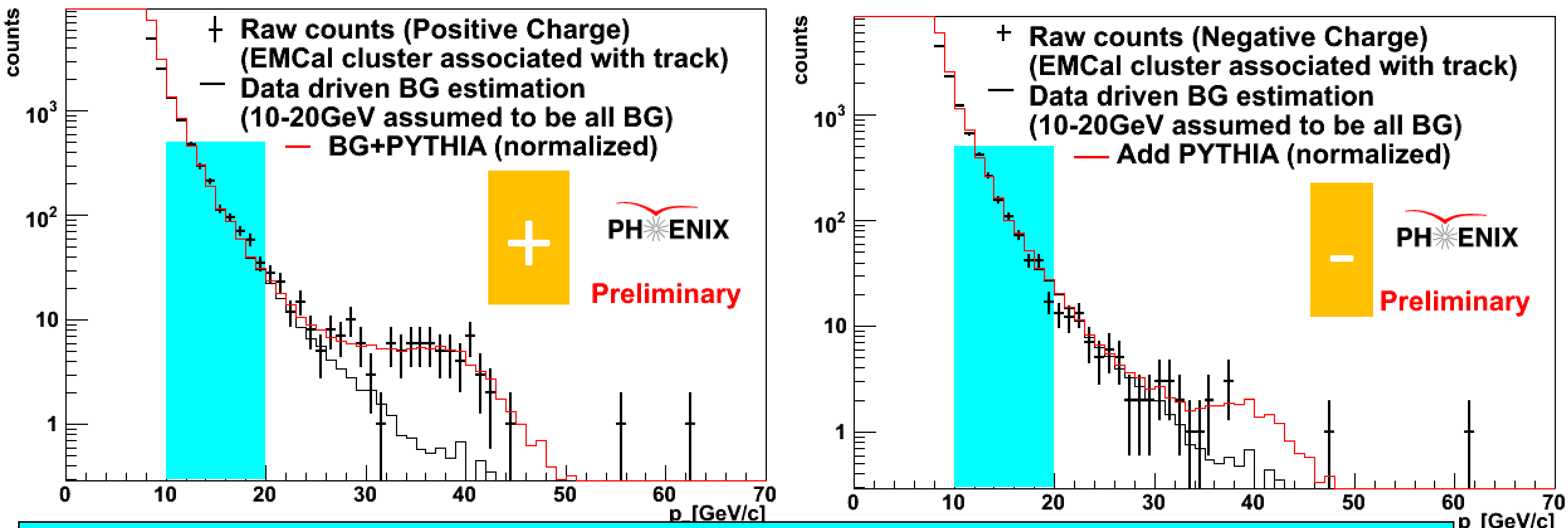
PHENIX W Analysis: Electron p_T Spectra

Data- and MC-driven BG estimation:

EMCal cluster distribution after subtracting cosmic background × (Conversion + Accidental) × Tracking Acceptance

+

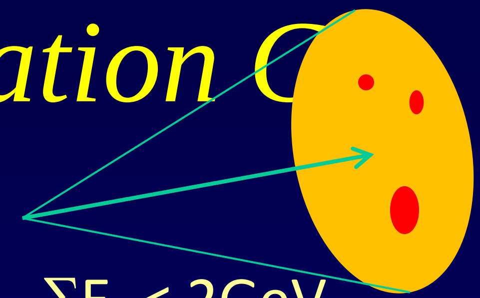
(NLO Hadrons thru Geant + FONLL c/b) × Normalization from fit to 10-20 GeV



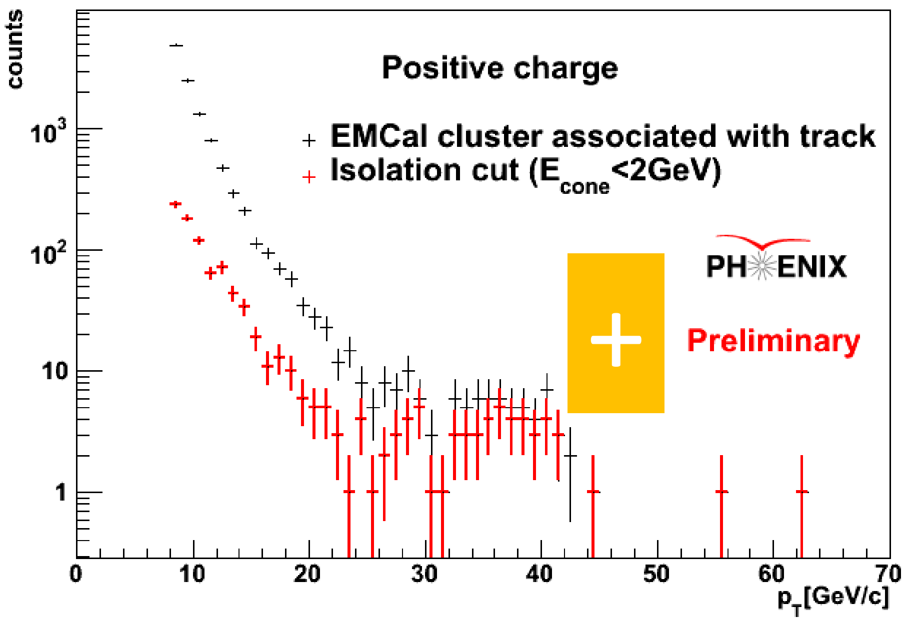
- The same scale factor for PYTHIA was used for W/Z shape.
- $W^- \to e^-$ signal has fewer counts than $W^+ \to e^+$ signal as expected

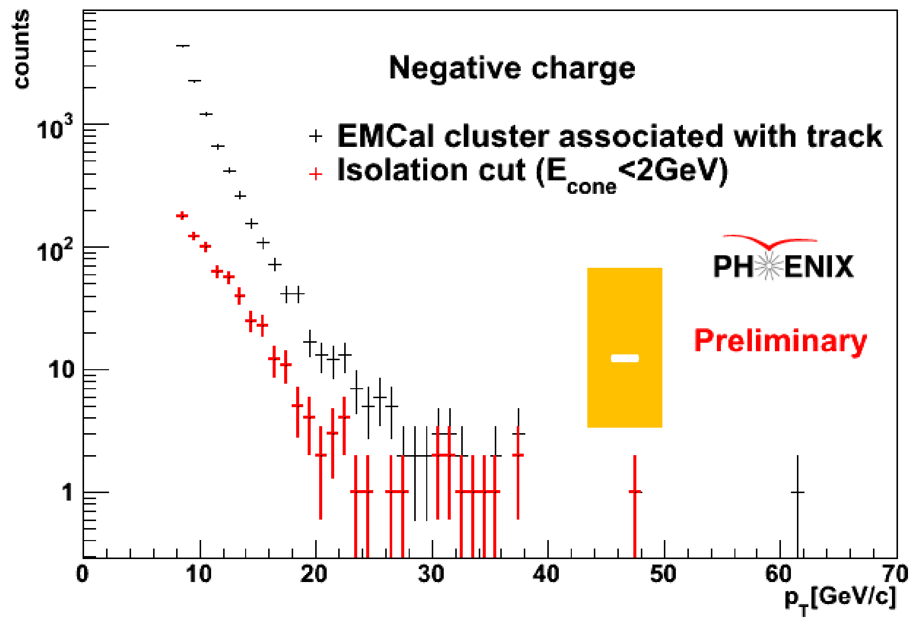
PHENIX W Analysis: Isolation C

- Signature of a W event is that it is isolated
- Sum up energy in a cone around electron and in cone on opposite hemisphere



$\Sigma E < 2GeV$

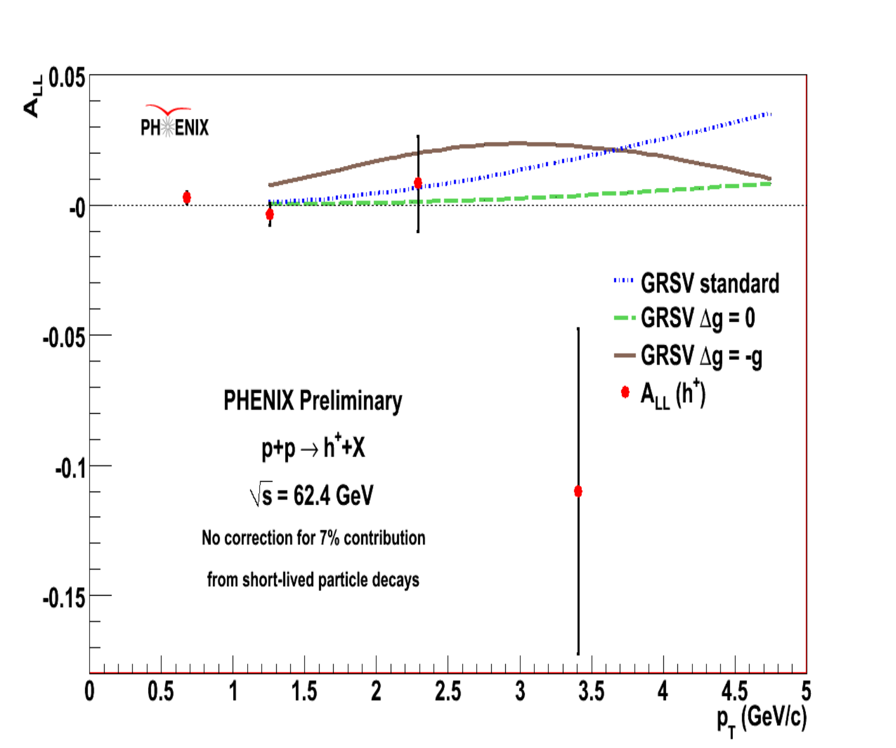


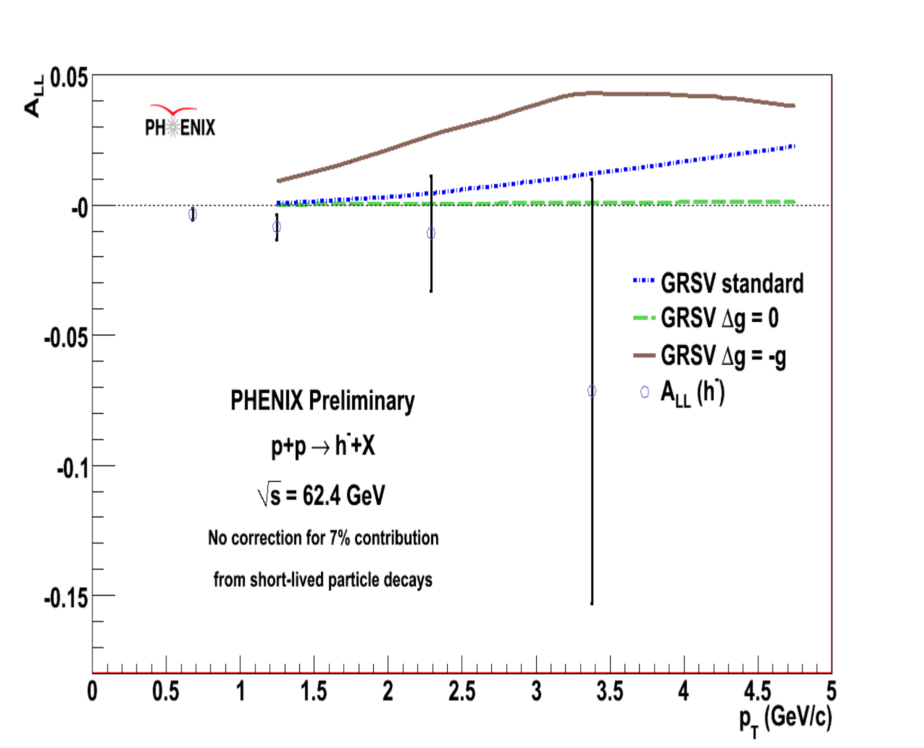


- 90+% of signal is kept (red histograms)
- Factor ~5 reduction in jet dominated region

A_{LL} of Non-identified Charged Hadrons at 62.4 GeV

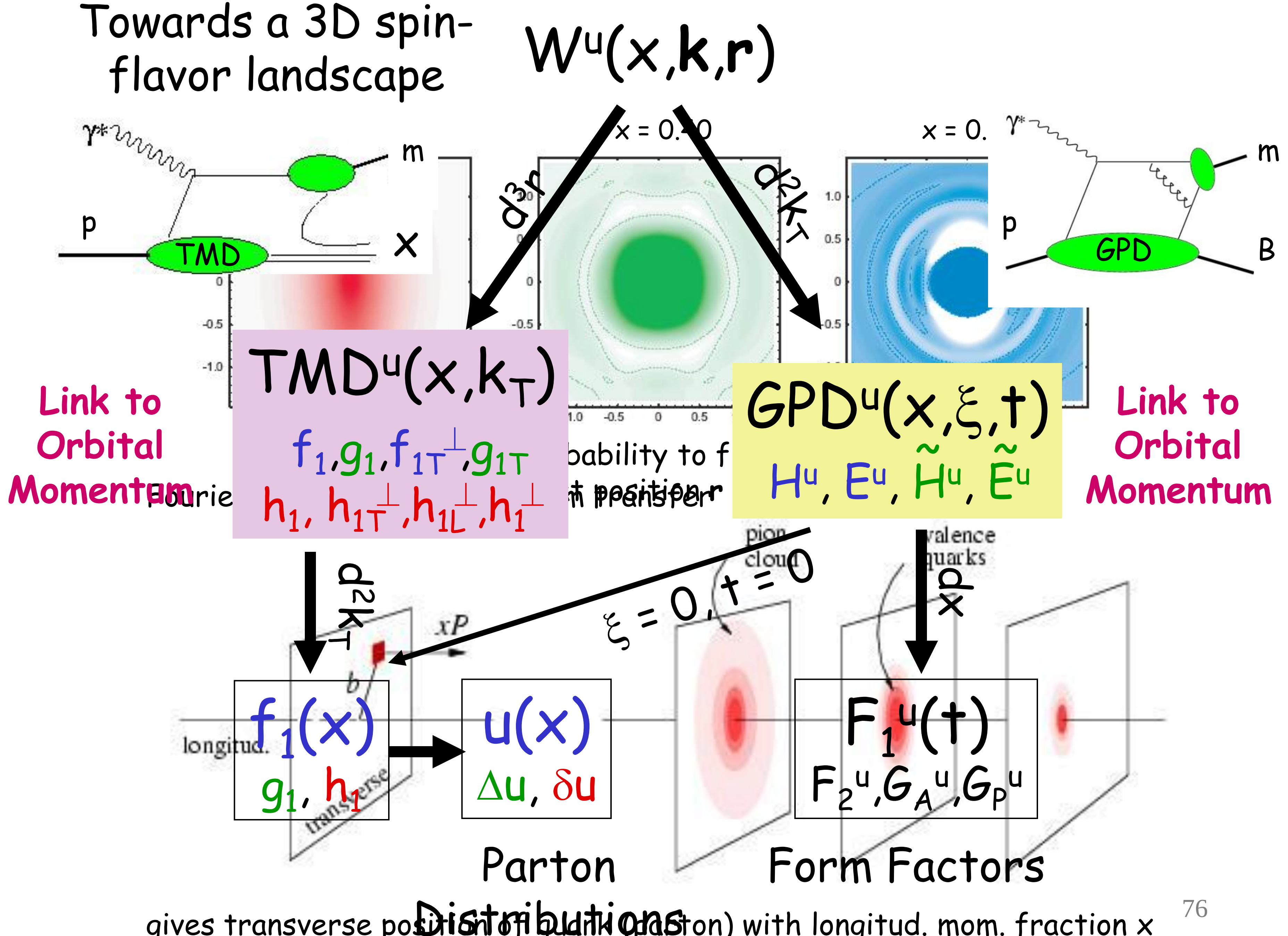
Cross section measurement in progress!





14% polarization uncertainty not included

Towards a 3D spin-flavor landscape



Understanding Transverse Spin

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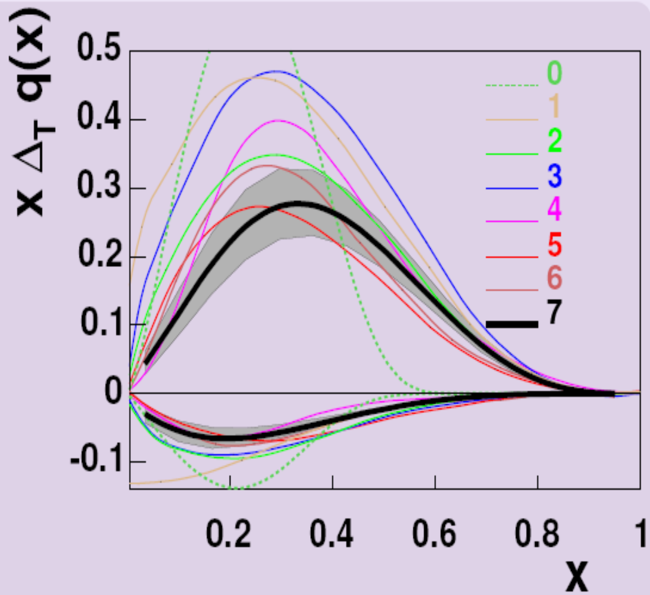
Transversity, comparison with models

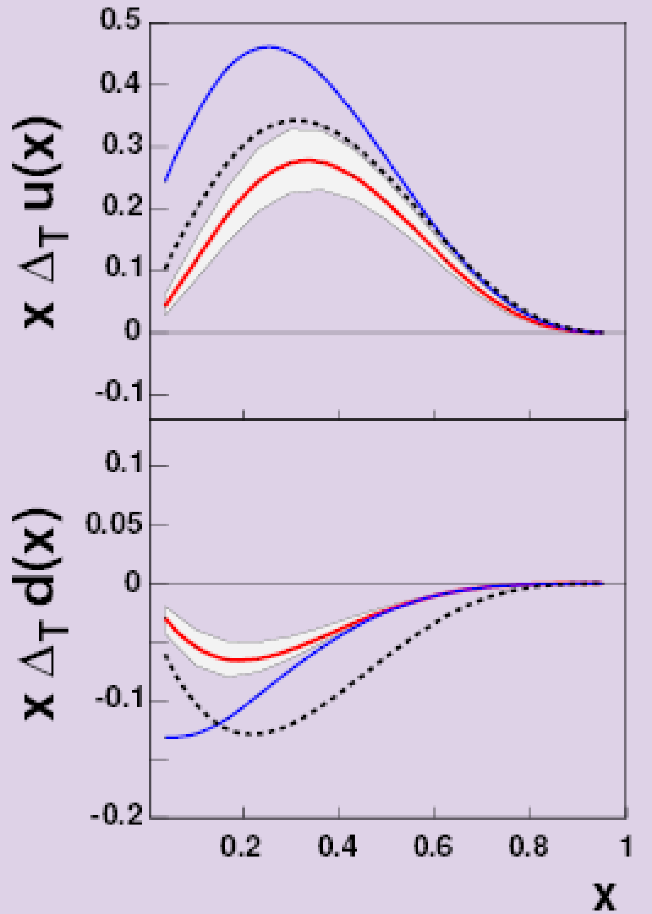
New extraction is close to most models.



0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. This analysis.

Transversity vs. helicity

Prokudin et al. at Ferrara



1. Solid red line – transversity distribution

$$\Delta_T q(x)$$

this analysis at $Q^2 = 2.4\ \mathrm{GeV}^2$.

2. Solid blue line – Soffer bound

$$\frac{q(x) + \Delta q(x)}{2}$$

GRV98LO + GRSV98LO

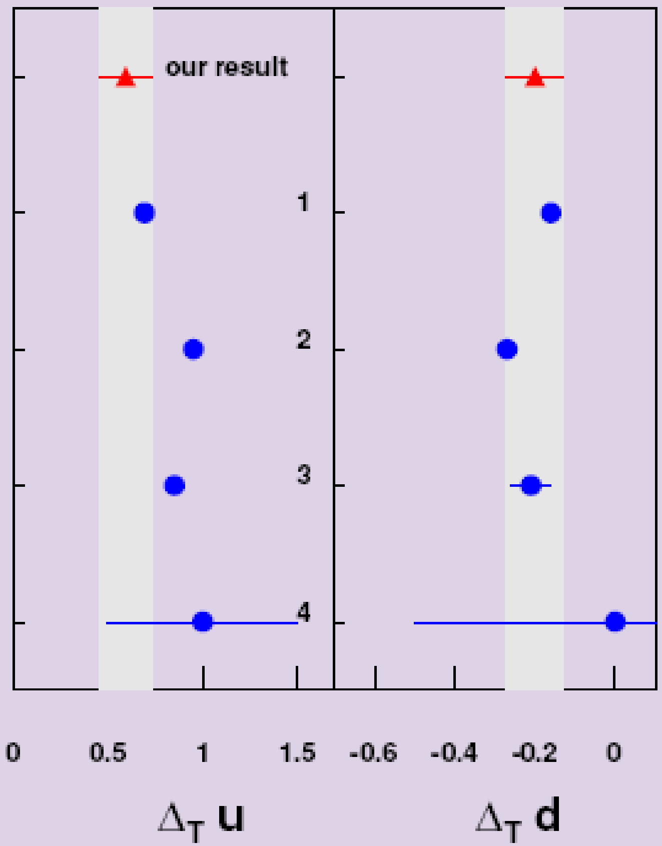
3. Dashed line – helicity distribution

$$\Delta q(x)$$

GRSV98LO

Tensor charges

$$\Delta_T u = 0.59^{+0.14}_{-0.13},\ \Delta_T d = -0.20^{+0.05}_{-0.07} \text{ at } Q^2 = 0.8 \text{ GeV}^2$$



Prokudin et al. at Ferrara

1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB B **653** (2007) 398
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 , $Q^2 =$
   GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2

Improved Forward Coverage in PHENIX:Muon Piston Calorimeter

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

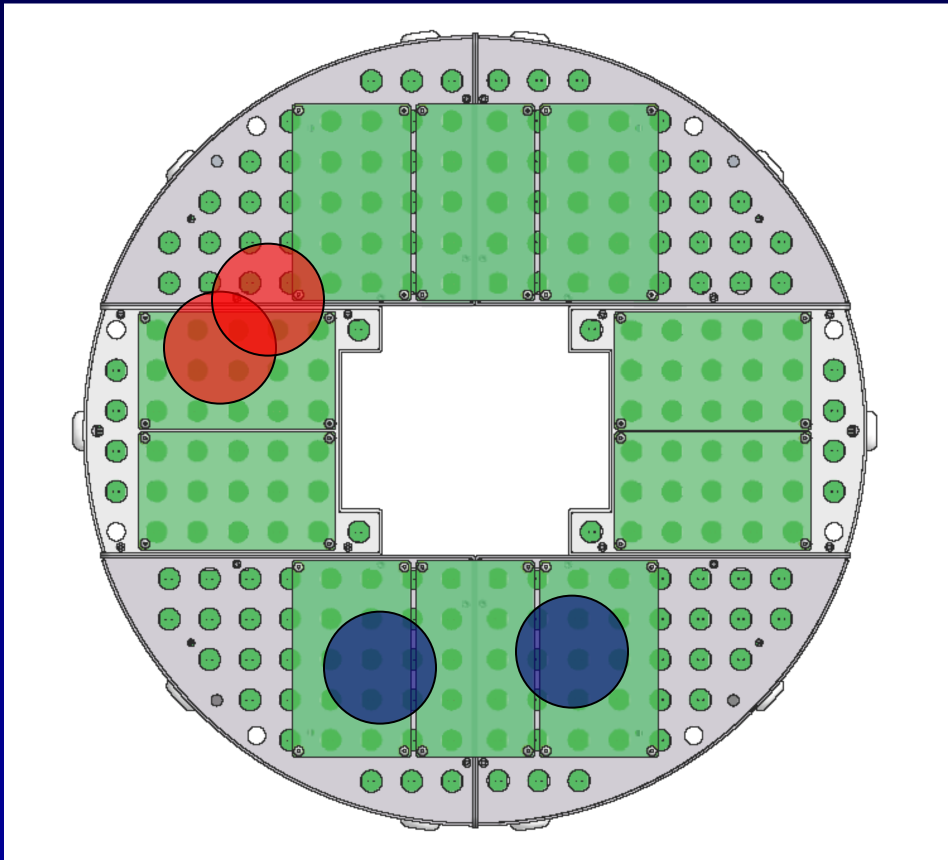
62 GeV

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

200 GeV

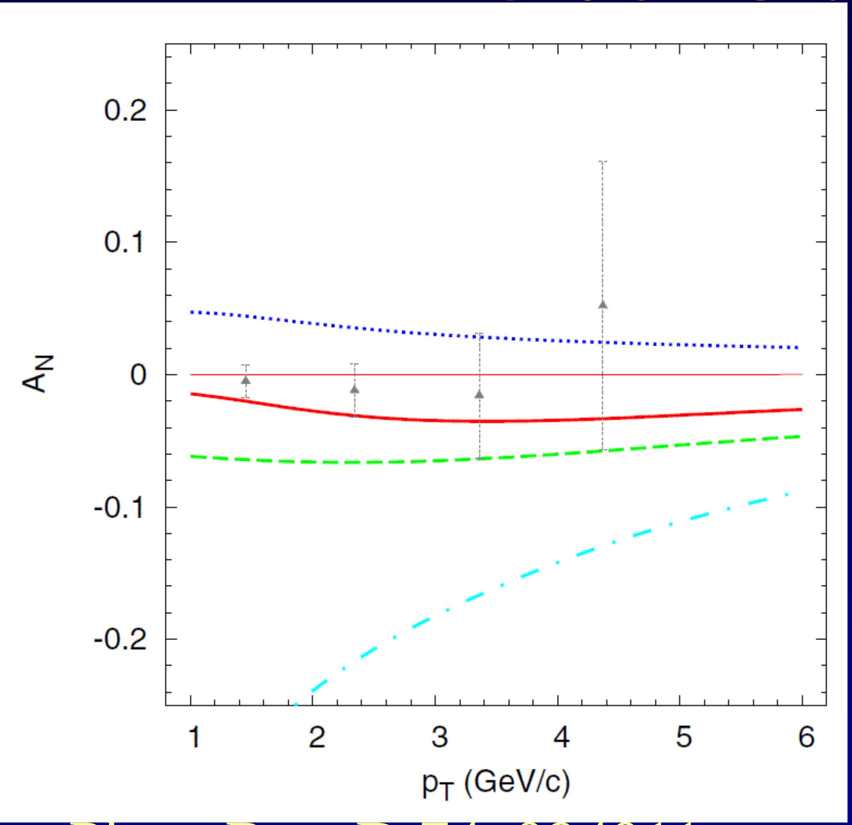
20 GeV → 0.20 x_F : "Single clusters". Yields dominated by π^0's but also get contributions from:

- **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

Midrapidity Neutral Pion SSA: Limit on Gluon Sivers Function



Phys. Rev. D 74, 094011

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

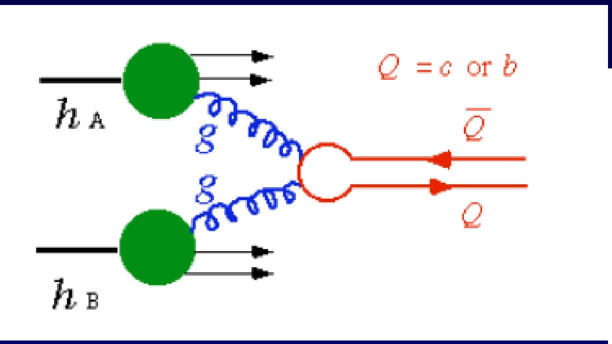
•Cyan: Gluon Sivers Function at positivity bound, no sea quark Sivers

•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

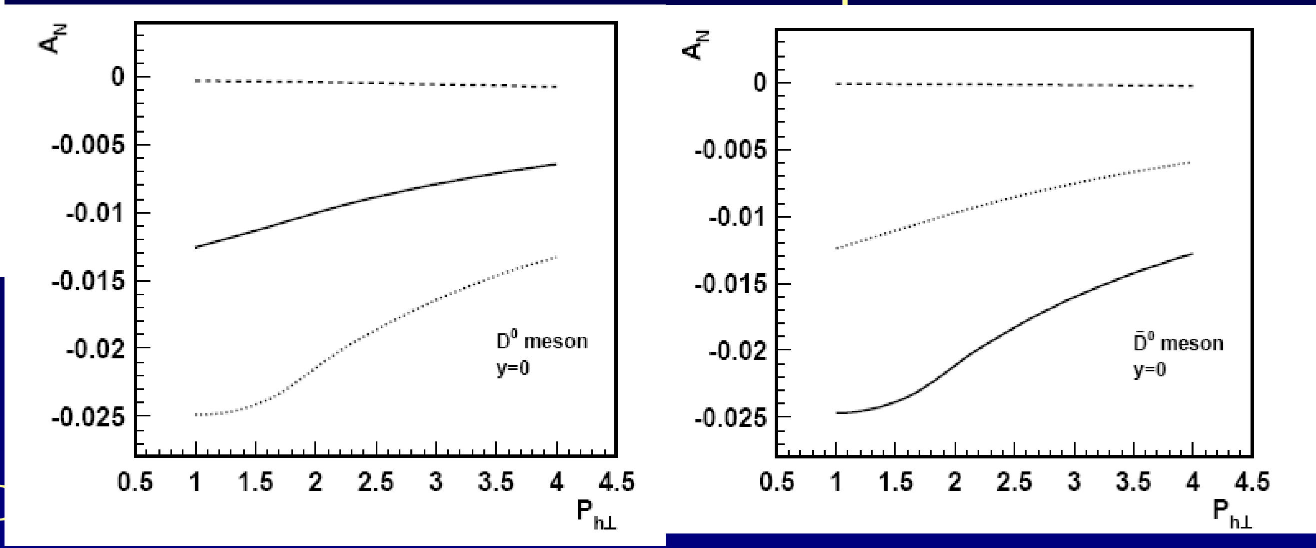
Constraints on Sivers Function: Heavy Flavor



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:



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

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

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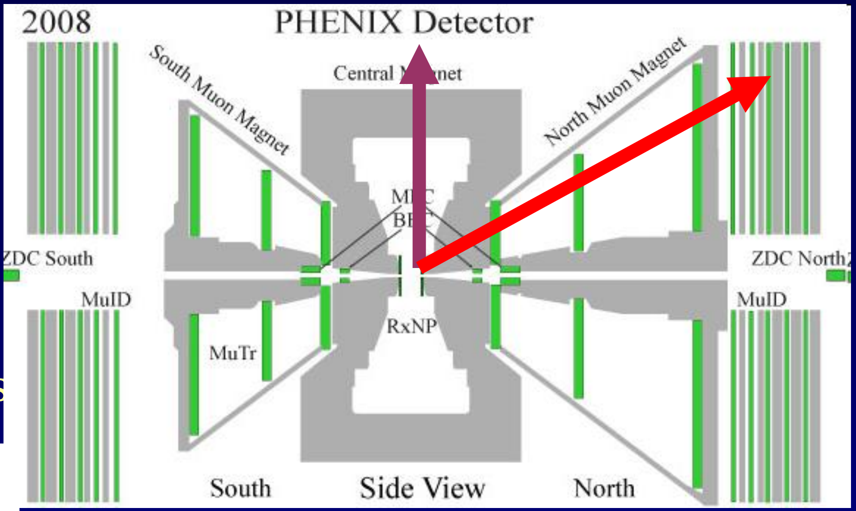
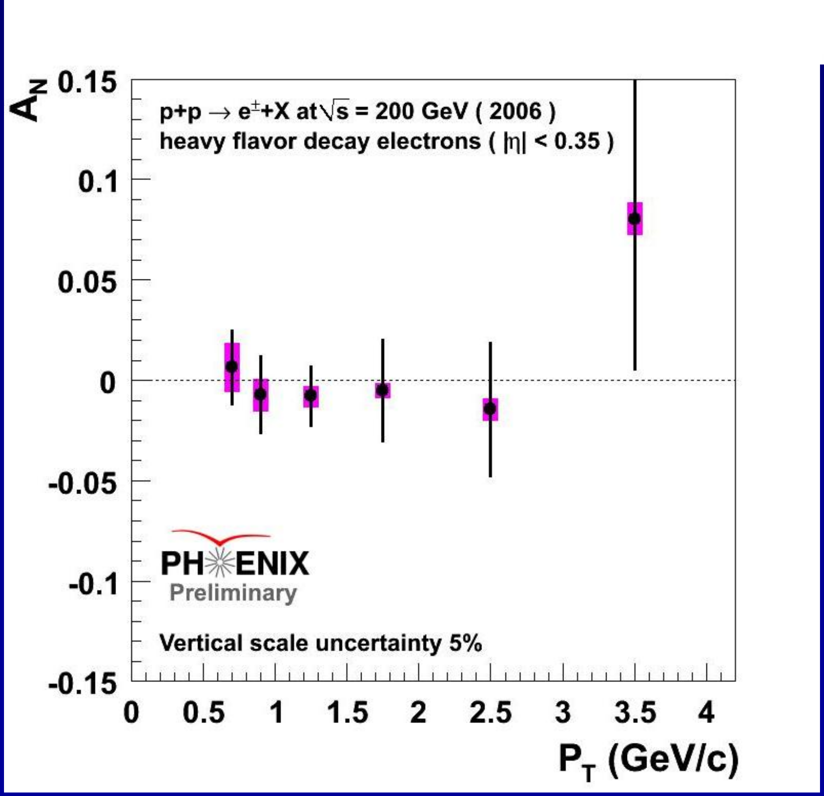
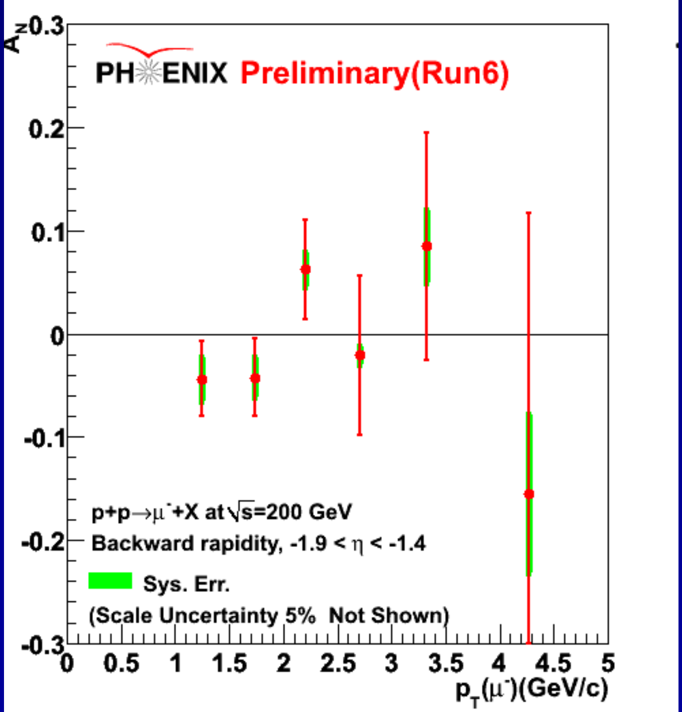
Constraints on Sivers Function: Heavy Flavor

PHENIX: no reconstruction of D meson

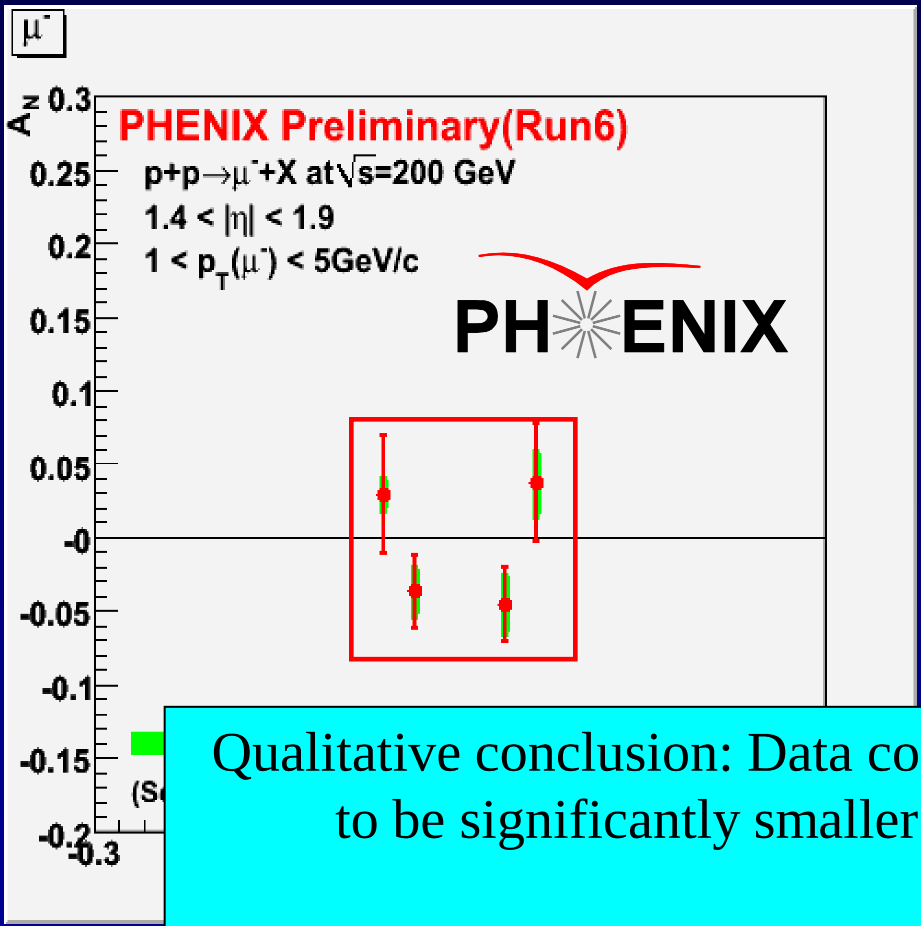
- Dominated by charm production in current kinematic range
- Measurements at mid and forward rapidity
- Constraints on both twist-3 and Sivers functions

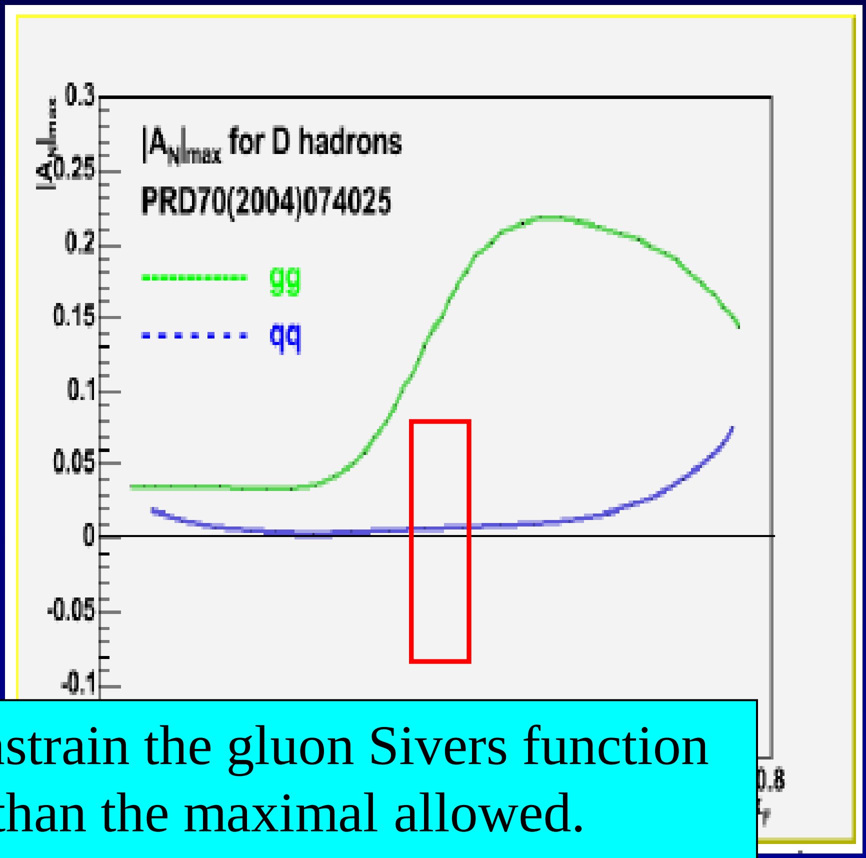






SSA of heavy flavor vs. x_F



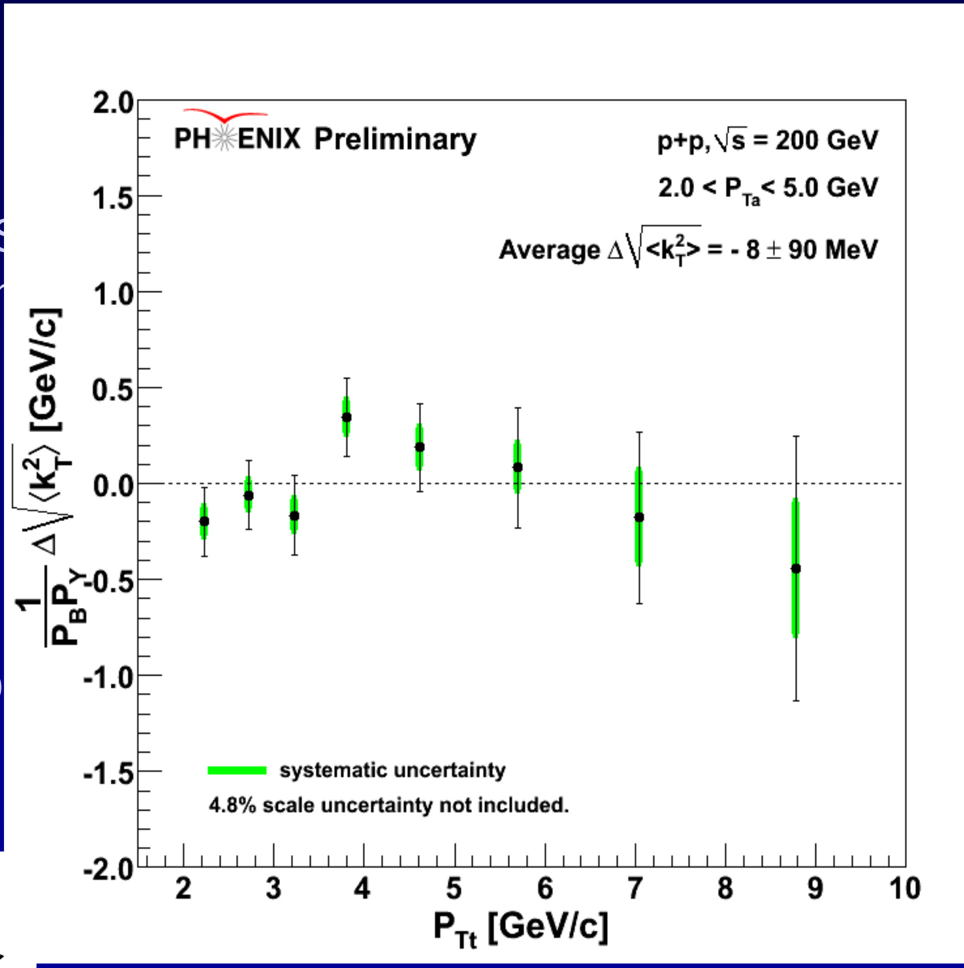


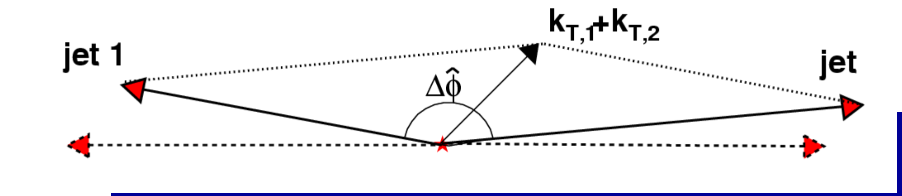
Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed.

Translation between D meson and muon kinematics and estimate of charm vs. bottom components underway such that more quantitative comparison can be made in the future.

Attempting to Probe k_T from Orbital Motion

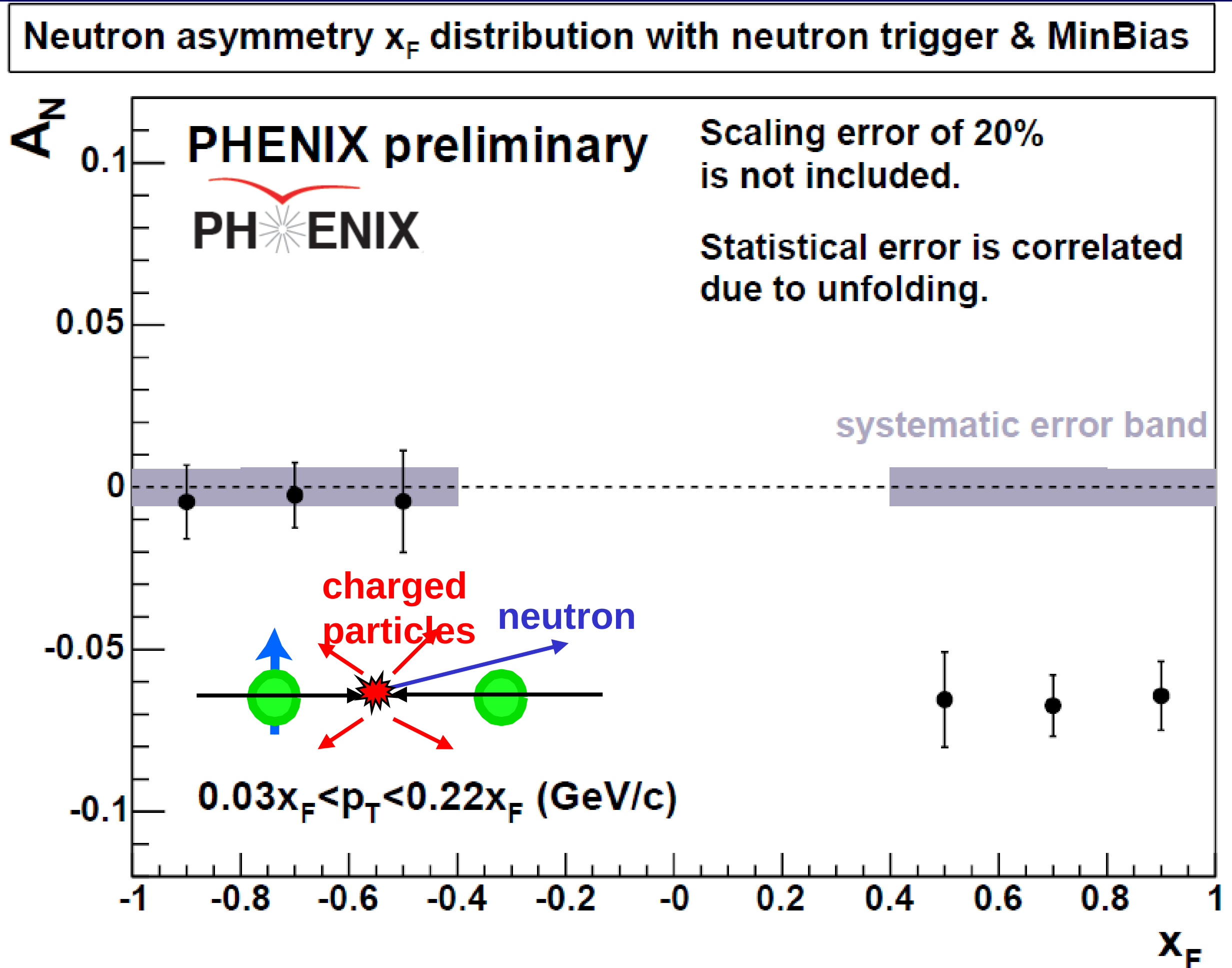
- Spin-correlated transverse momentum (orbital angular momentum) may contribute to jet k_T. (Meng Ta-chung et al., Phys. Rev. D40, 1989)
- Possible helicity dependence
- Would depend on (unmeasured) impact parameter, but may observe net effect after averaging over impact parameter





Forward neutrons at $\sqrt{s}$=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.)

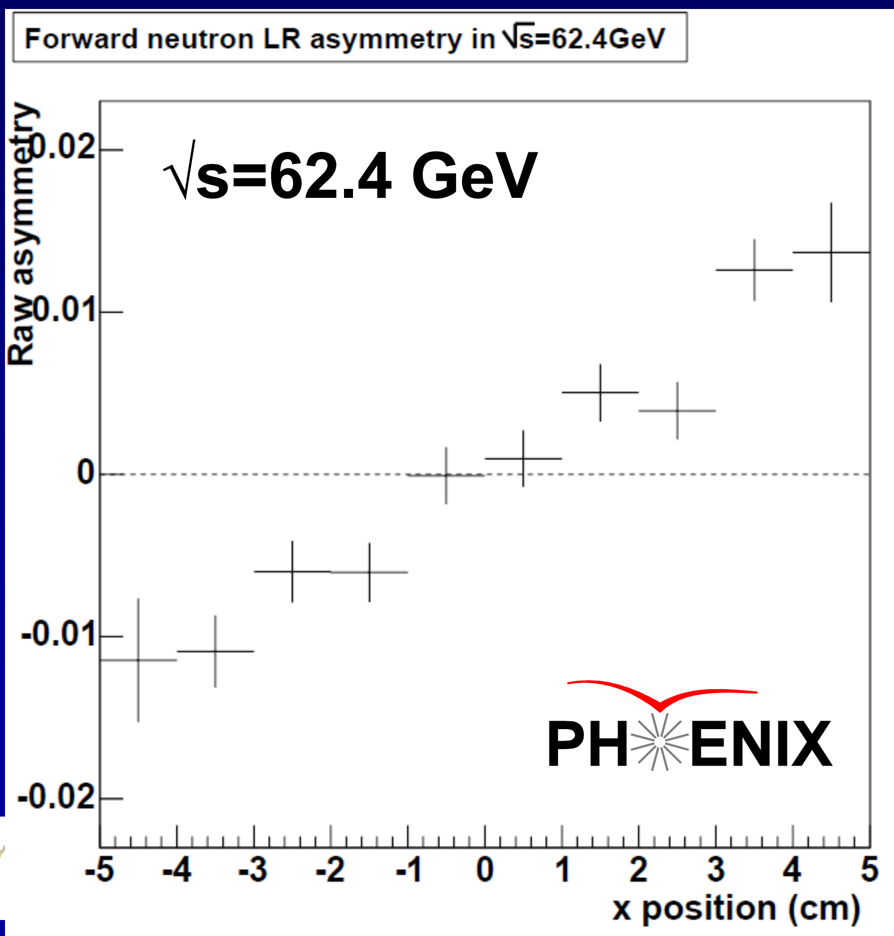
$0.4<|x_F|<0.6$ 0.088 GeV/c
$0.6<|x_F|<0.8$ 0.118 GeV/c
$0.8<|x_F|<1.0$ 0.144 GeV/c

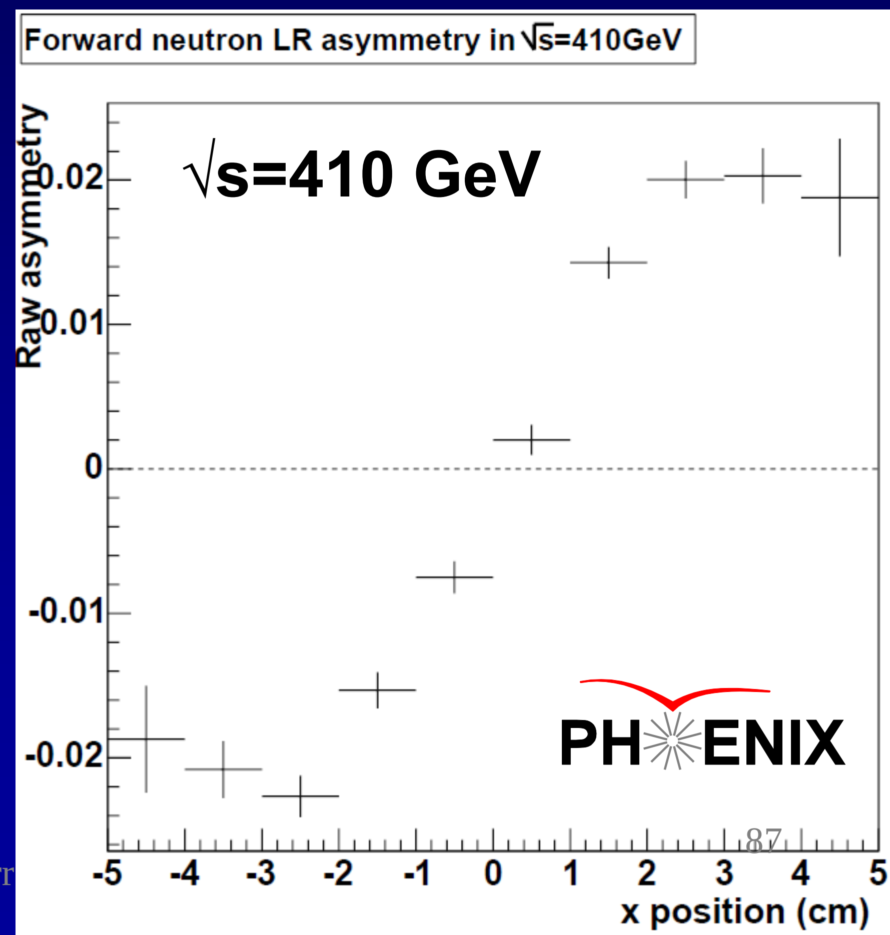
preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

Forward neutrons at other energies

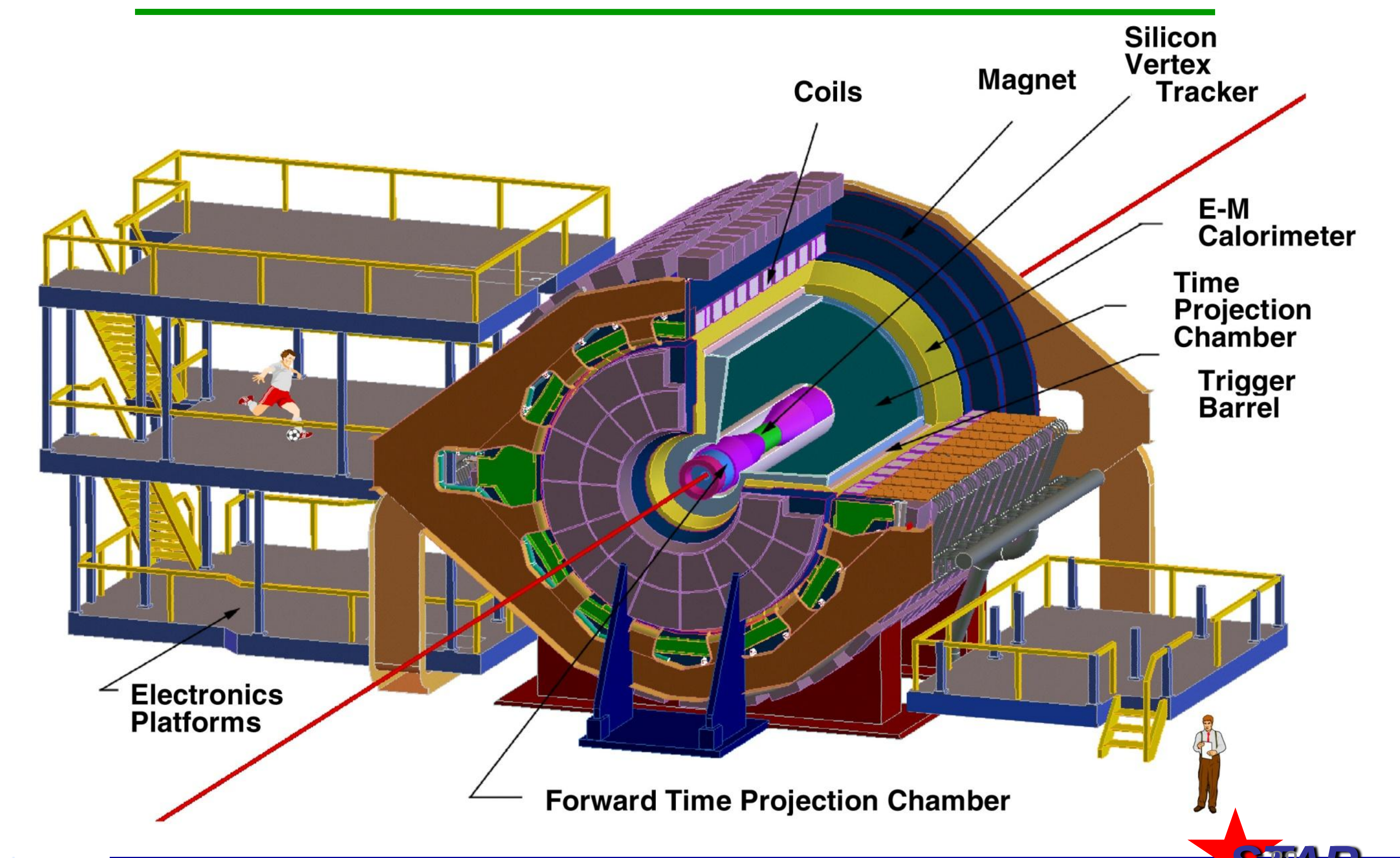
Significant forward neutron asymmetries observed down to 62.4 and up to 410 GeV!

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





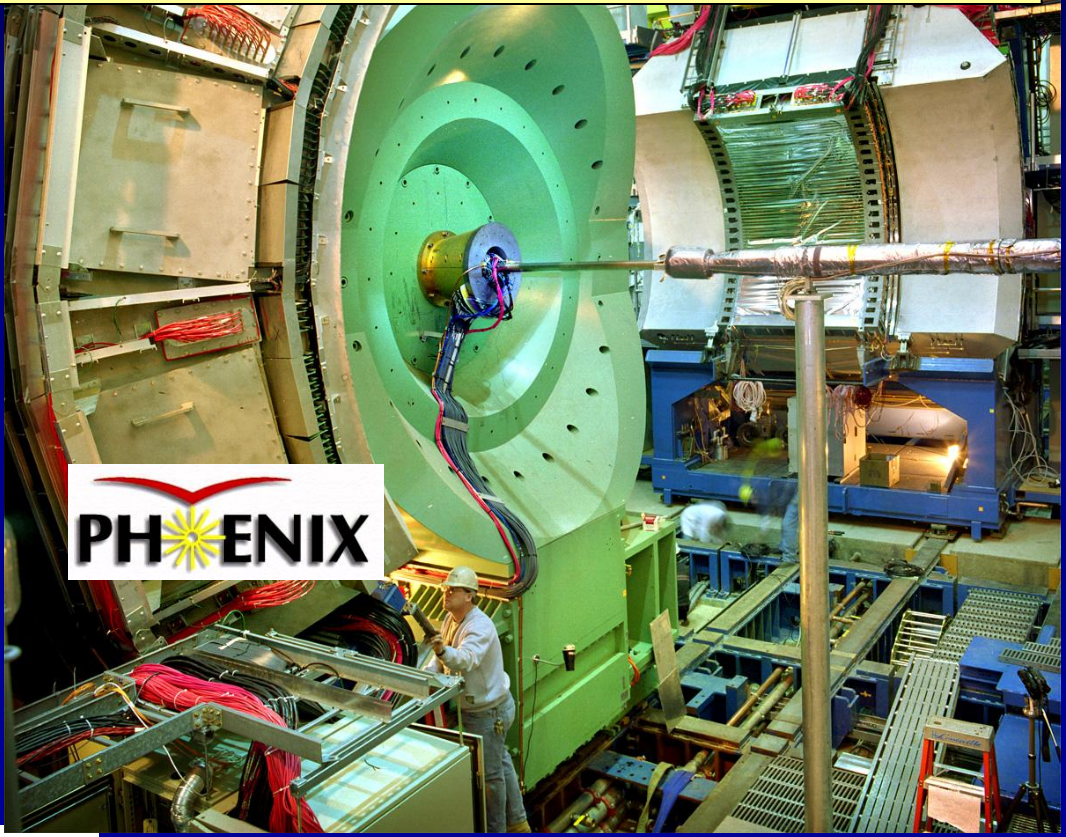
The STAR Detector at RHIC



PHENIX Detector

Philosophy:

High rate capability to measure rare probes, but limited acceptance.



2 central spectrometers

-Track charged particles and detect electromagnetic processes

$90^{\circ} + 90^{\circ}$ azimuth

$|\eta| < 0.35$

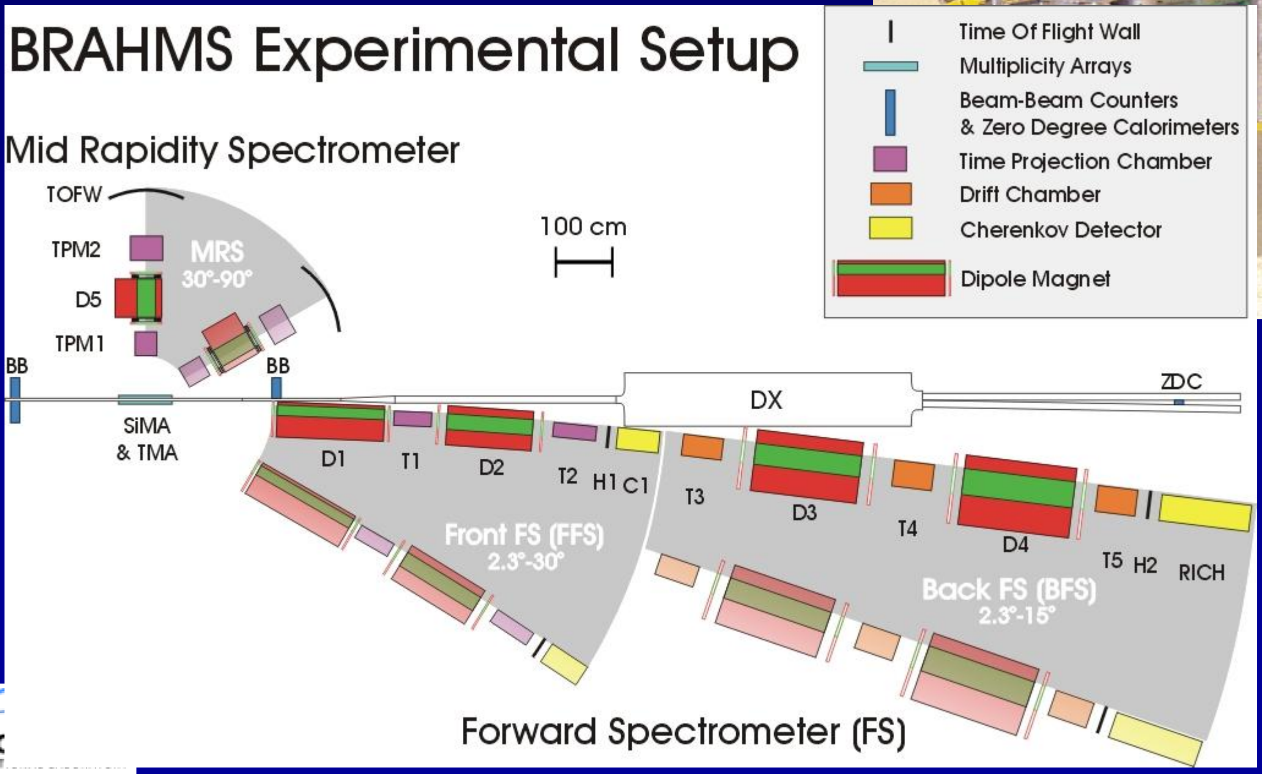
2 forward spectrometers

- Identify and track muons

BRAHMS detector

Philosophy:

Small acceptance spectrometer arms designed with good charged particle ID.



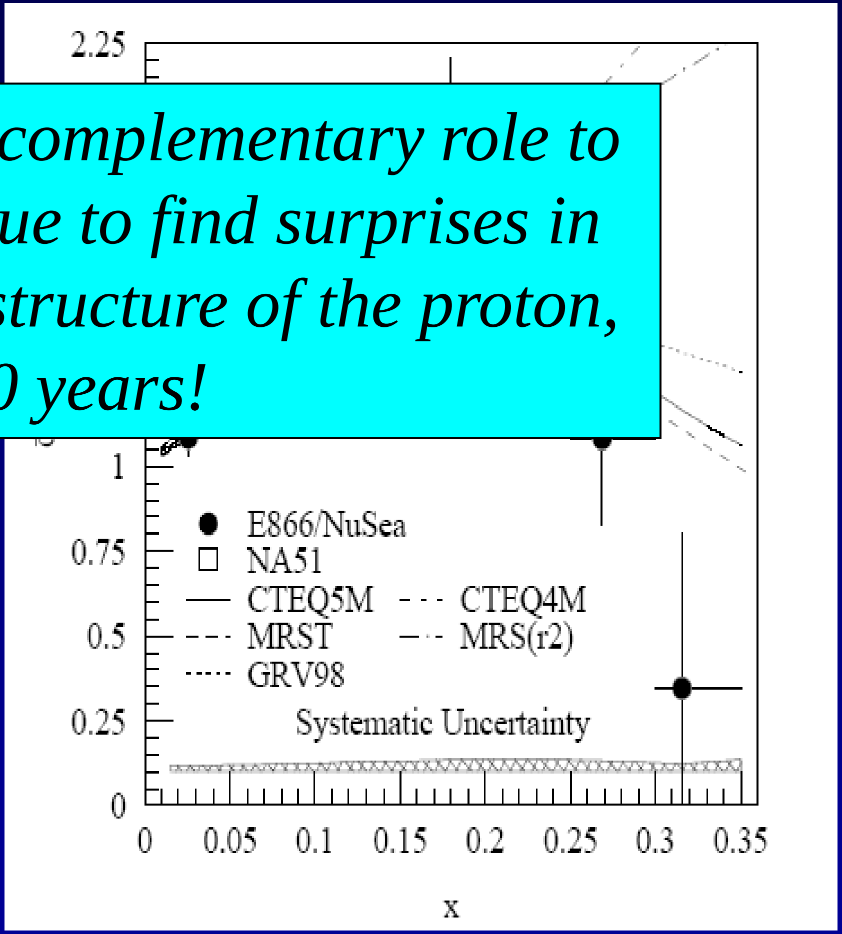
And a (Relatively) Recent Surprise From p+p, p+d Collisions

- Fermilab Experiment 866 use pro coll nuc Drell-Yan process

$$q + \bar{q} \rightarrow \mu^{+} + \mu^{-}$$

- Anti-up/anti-down asymmetry in the quark sea, with an unexpected *x* behavior!

Hadronic collisions play a complementary role to DIS and have let us continue to find surprises in the rich linear momentum structure of the proton, even after 40 years!



PRD64, 052002 (2001)