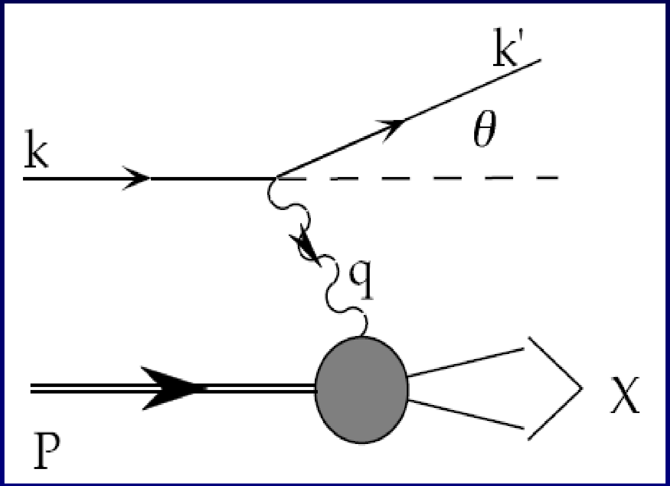
Investigating the Spin Structure of the Proton at the Relativistic Heavy Ion Collider

Christine Aidala
Los Alamos National Lab

DESY
October 5-6, 2010

How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

Deep-Inelastic Scattering: A Tool of the Trade

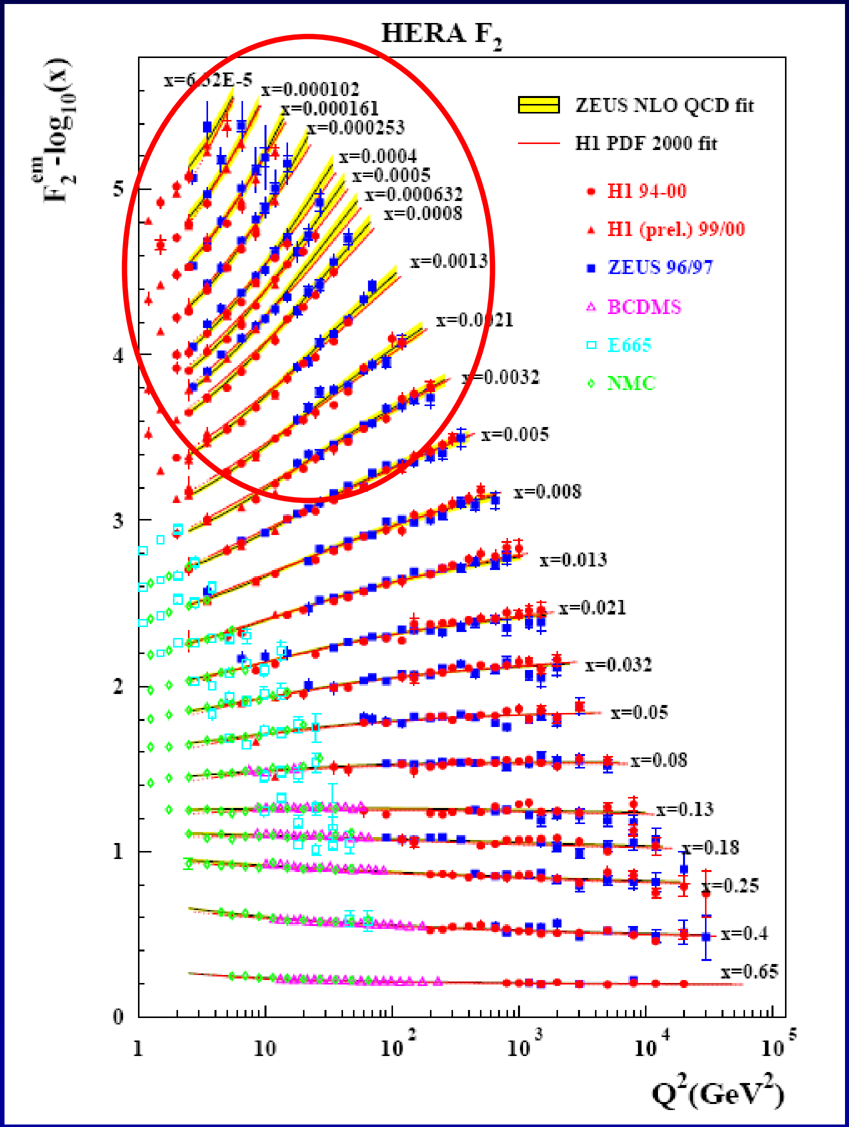


- Probe nucleon with an electron or muon beam
- Interacts electromagnetically with (charged) quarks and antiquarks
- "Clean" process theoretically—quantum electrodynamics well understood and easy to calculate
- Technique that originally discovered the parton structure of the nucleon in the 1960's!

Decades of DIS Data: What Have We Learned?

$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2_{e.m.}}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

- Wealth of data largely from HERA (thanks!!)
- Rich structure at low *x*
- Half proton's linear momentum carried by gluons!

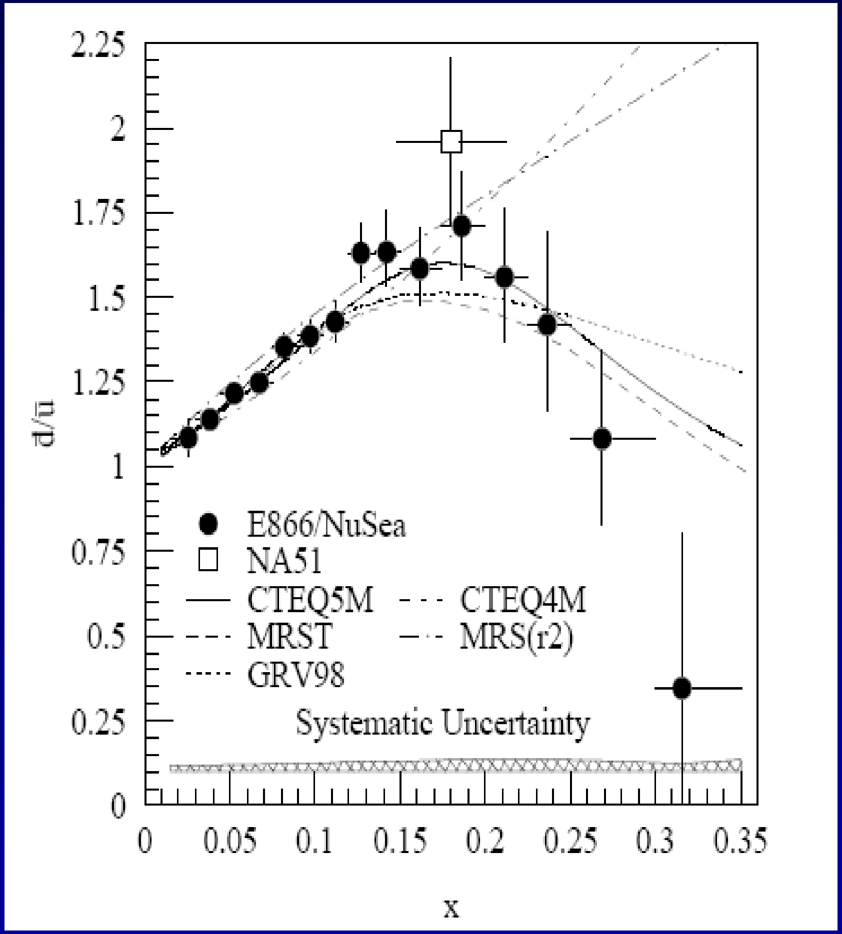


And a (Relatively) Recent Surprise From p+p, p+d Collisions

- Fermilab Experiment 866 used proton-hydrogen and proton-deuterium collisions to probe nucleon structure via the Drell-Yan process

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

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



PRD64, 052002 (2001)

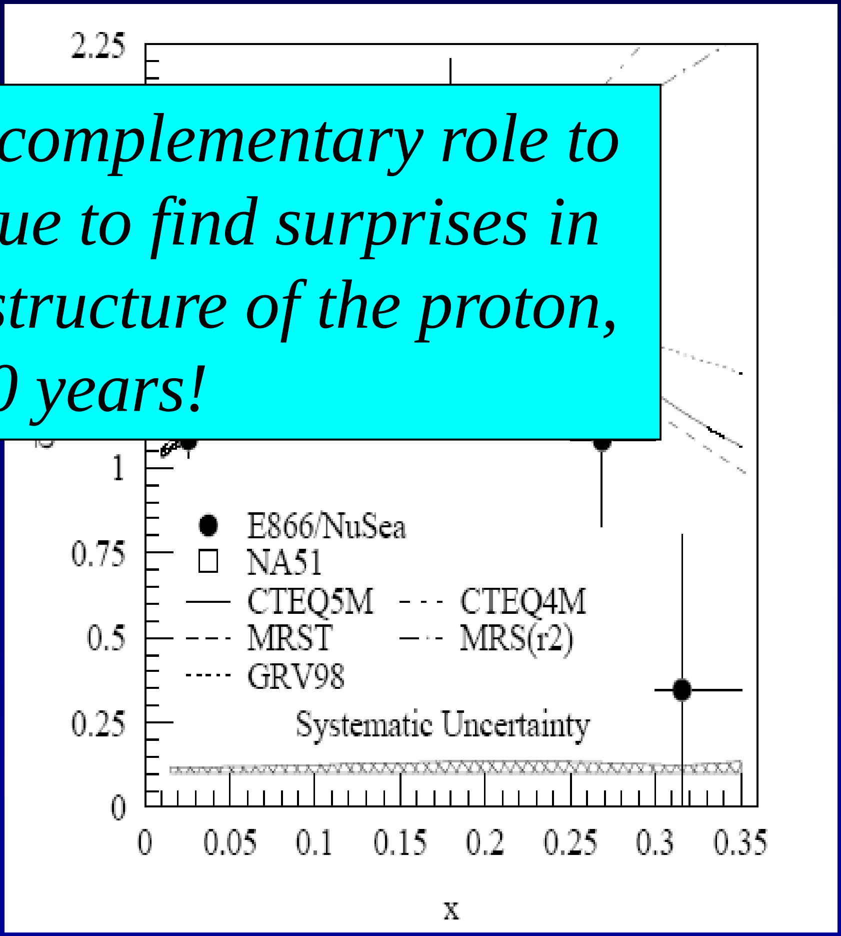
And a (Relatively) Recent Surprise From p+p, p+d Collisions

- 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)

What about the angular momentum structure of the proton?

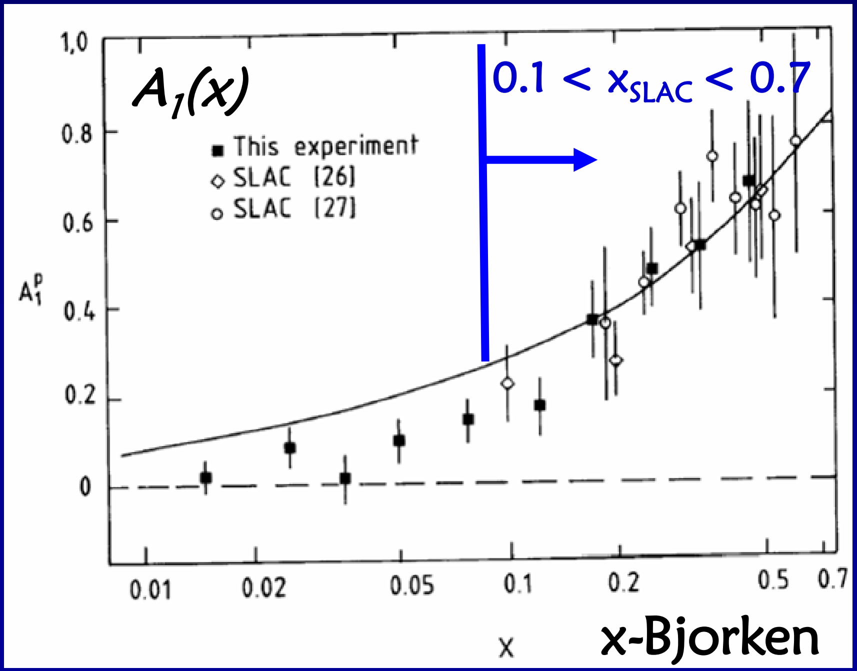
Proton "Spin Crisis"

SLAC: $0.10 < x < 0.7$

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

$\Delta\Sigma_{SLAC} \sim 0.6$ Quark-Parton Model expectation!

E130, Phys.Rev.Lett.51:1135 (1983)
428 citations

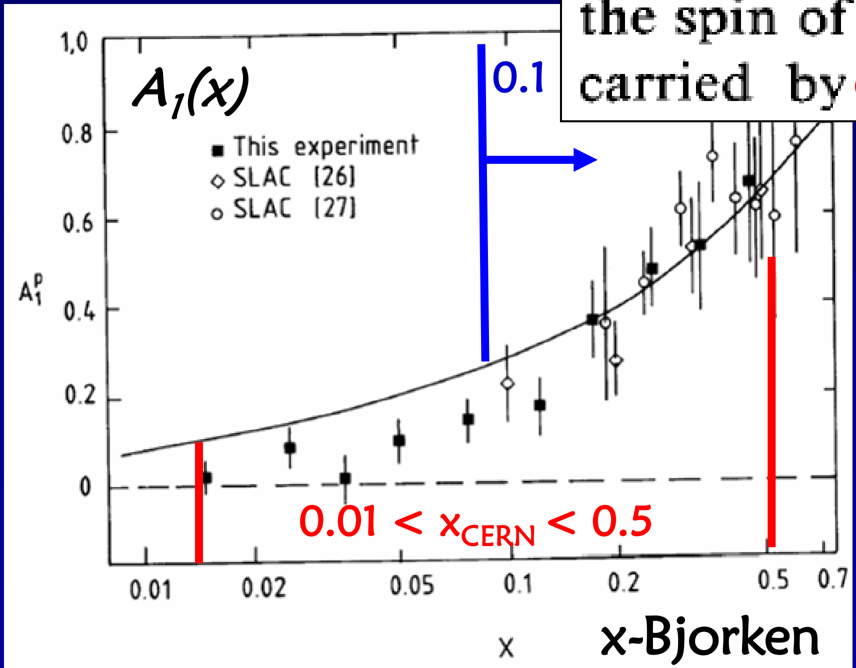


Proton "Spin Crisis"

SLAC: *0.10 < x <0.7*
CERN: *0.01 < x <0.5*

$$\frac{1}{2} = \frac{1}{2} \cdot \Delta\Sigma + \Delta G + L_{G+q}$$

Hence (14 ± 9 ± 21)% of the proton spin is carried by the spin of the quarks. The remaining spin must be carried by gluons or orbital angular momentum



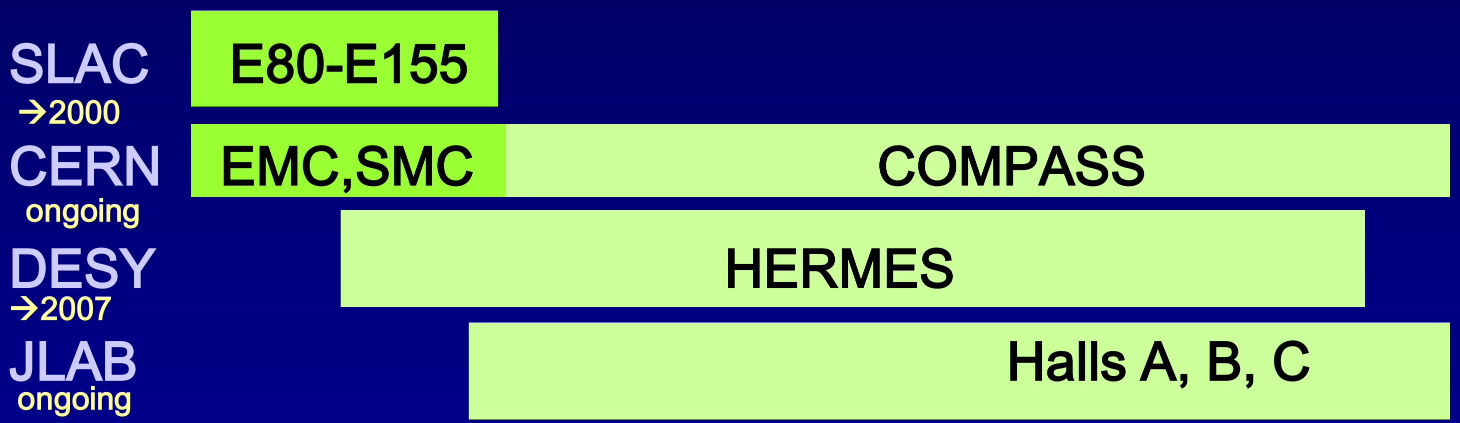
These haven't been easy to measure!

EMC (CERN), Phys.Lett.B206:364 (1988)
1491 citations!

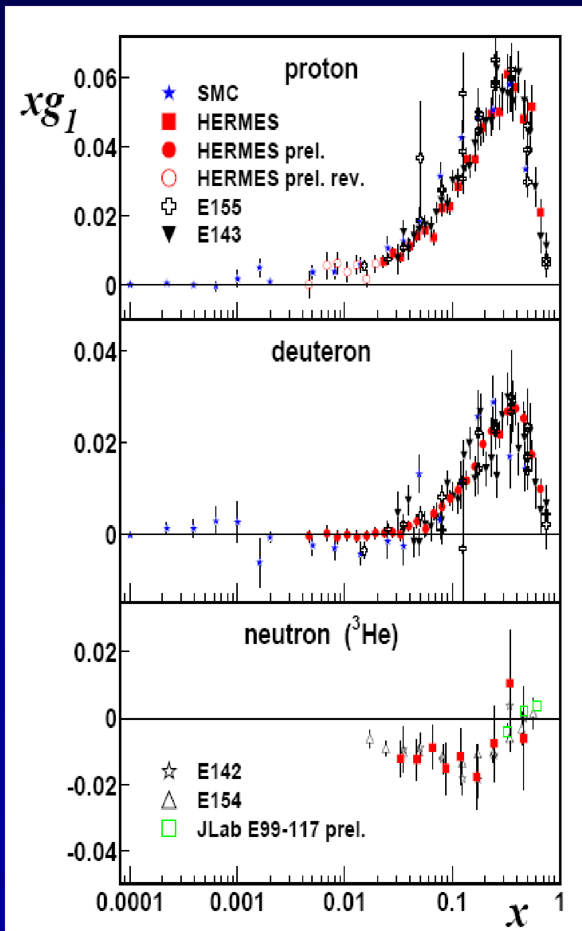
"Proton Spin Crisis"

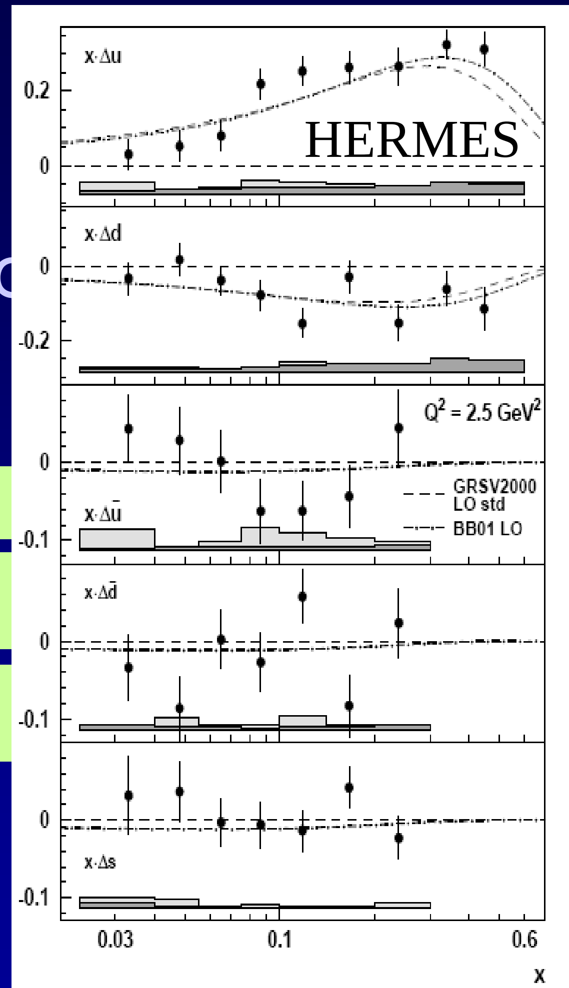
Decades of Polarized DIS

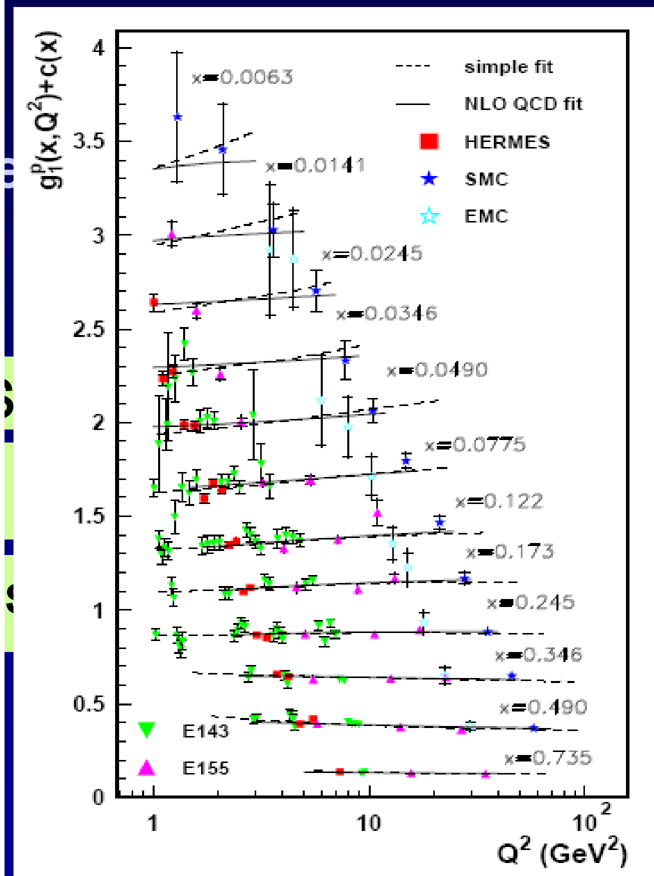
Quark Spin – Gluon Spin – Transverse Spin – GPDs – L_z



Decades of Polarized DIS

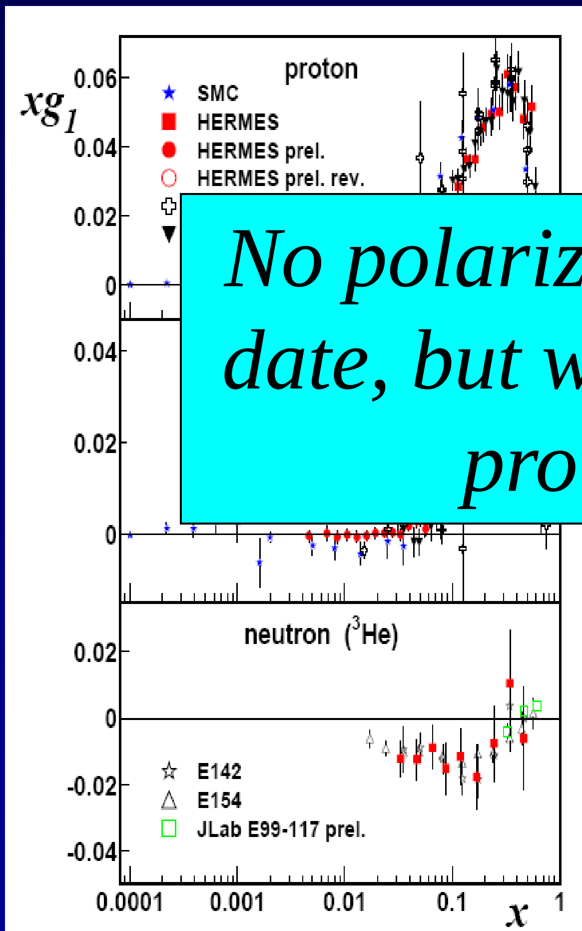


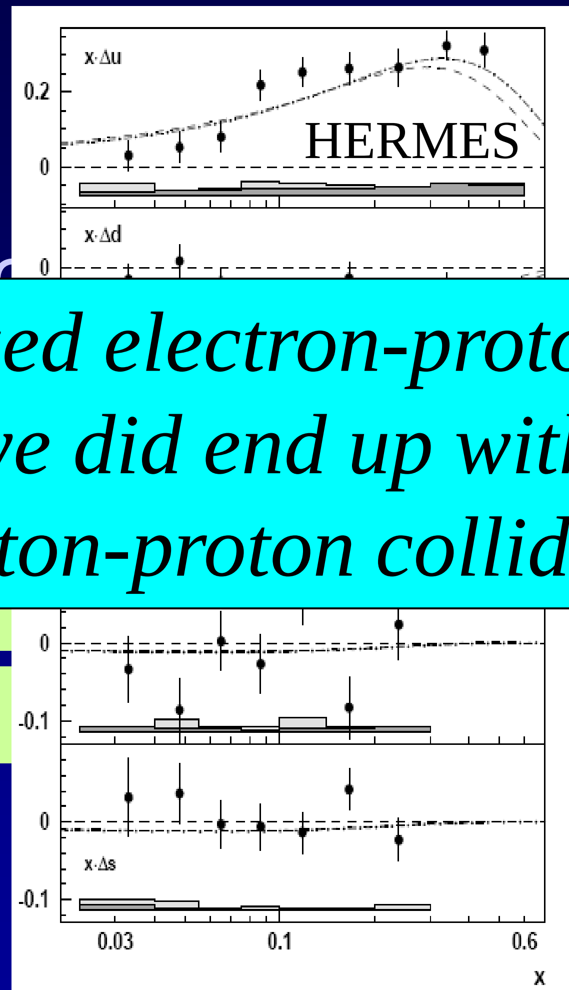


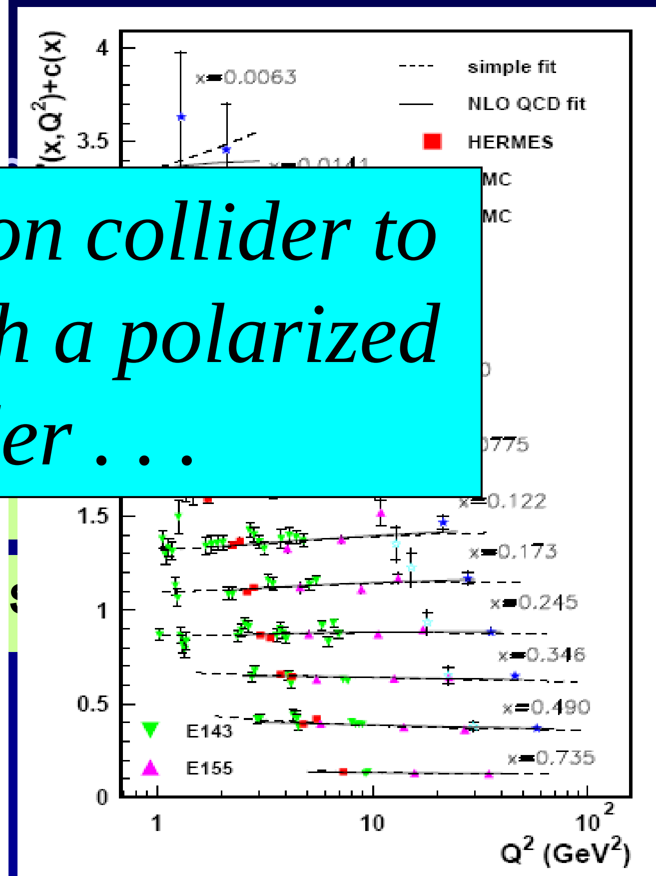


PRL92, 012005 (2004)

Decades of Polarized DIS



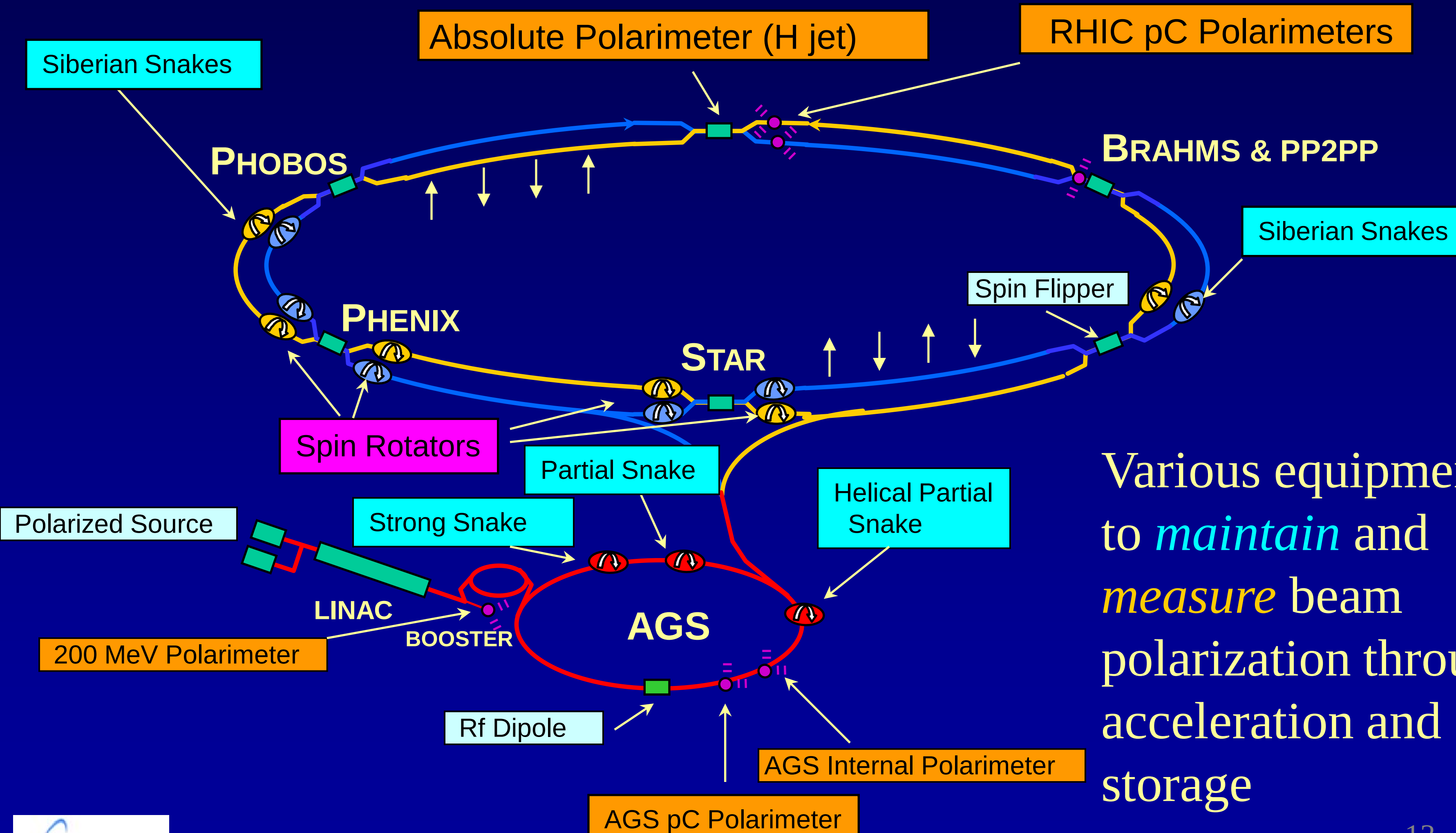




No polarized electron-proton collider to date, but we did end up with a polarized proton-proton collider . . .

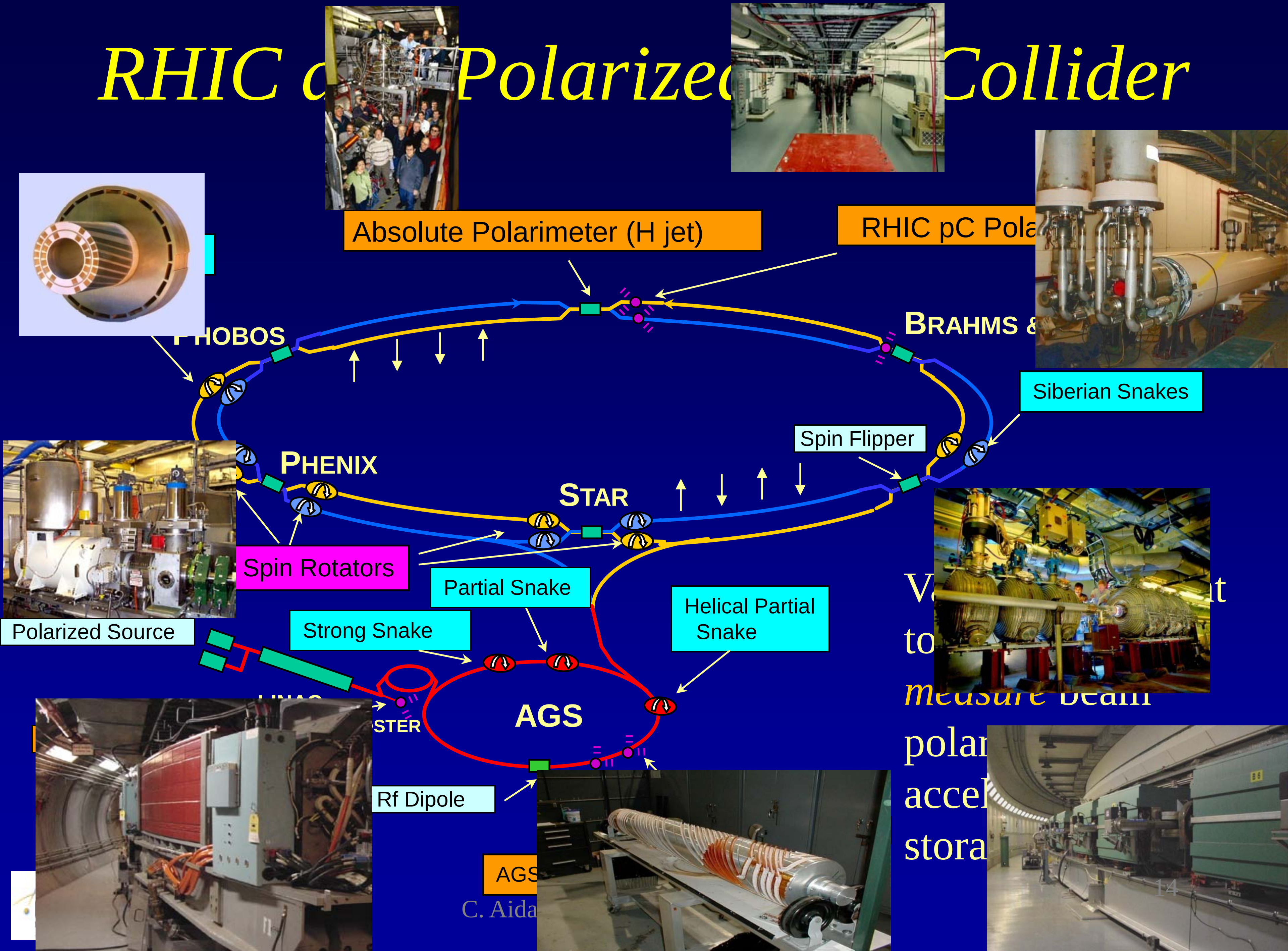
PRL92, 012005 (2004)

RHIC as a Polarized p+p Collider



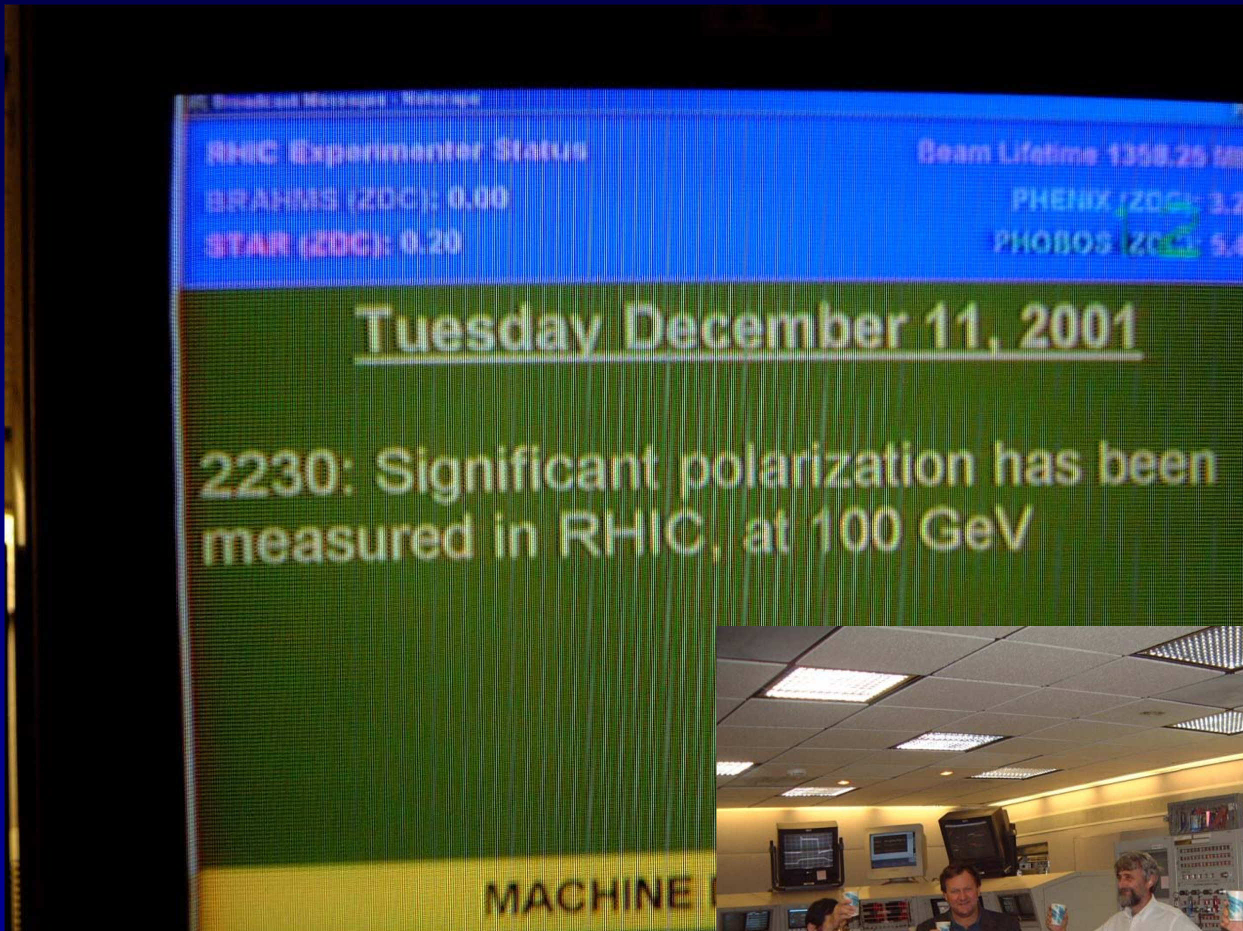
Various equipment to *maintain* and *measure* beam polarization through acceleration and storage

RHIC a… Polarize… Collider



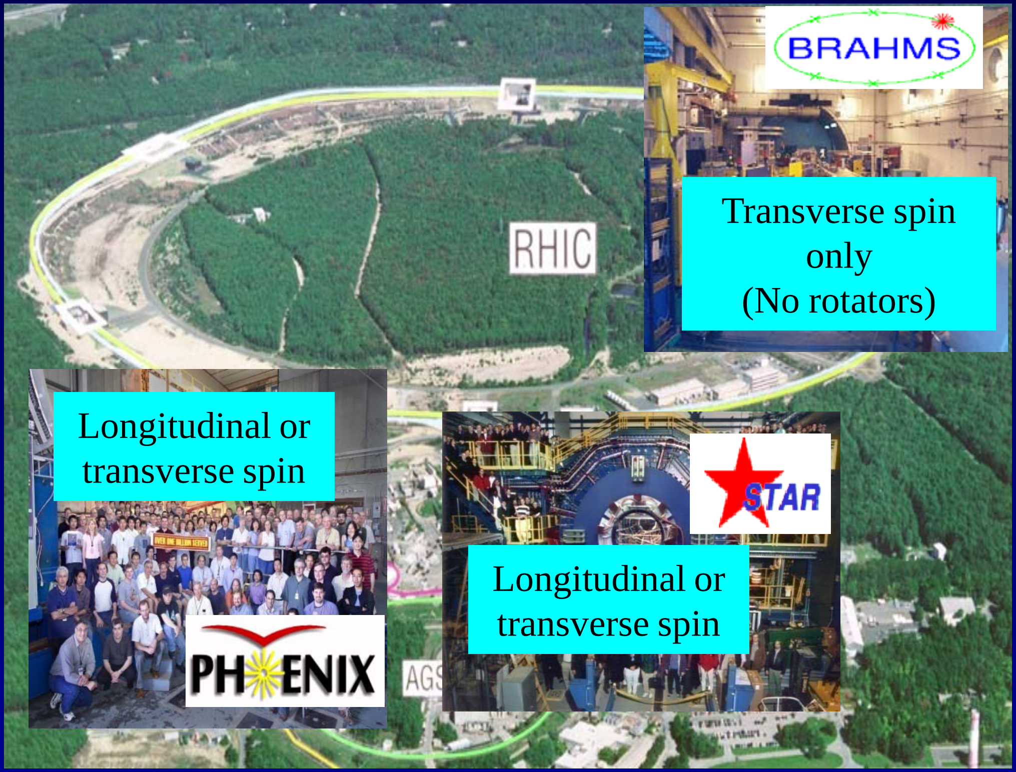
V… t
to
measure beam
polar…
accel…
stora…

December 2001: News to Celebrate



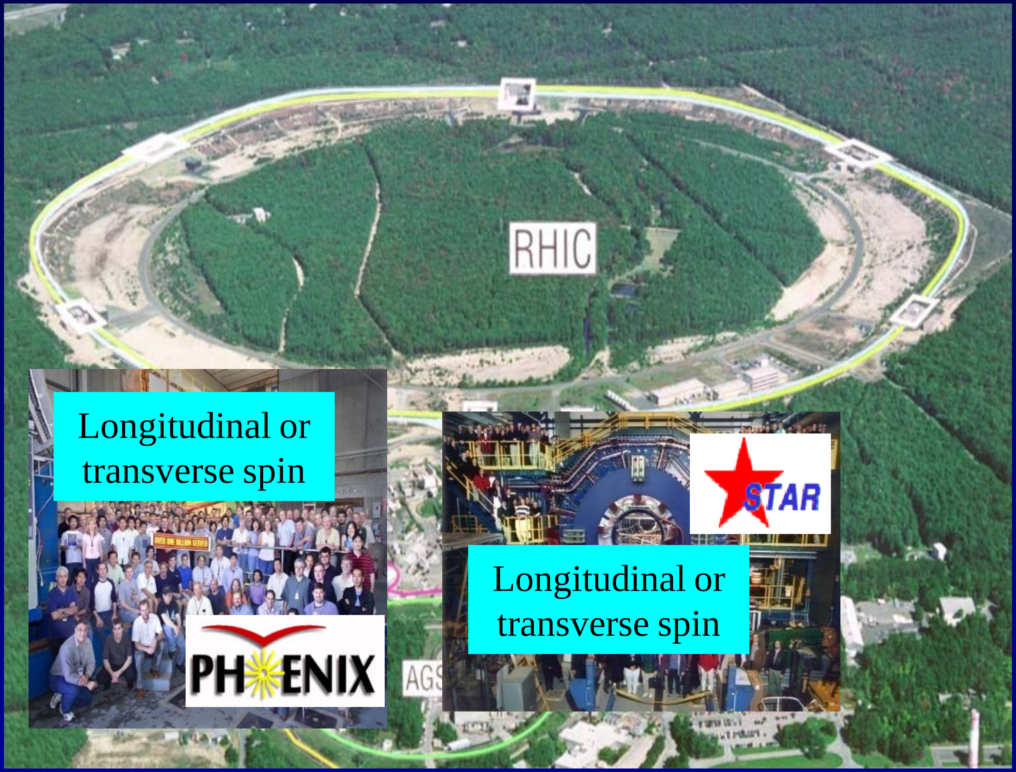
RHIC Spin Physics Experiments

- Three experiments: STAR, PHENIX, BRAHMS



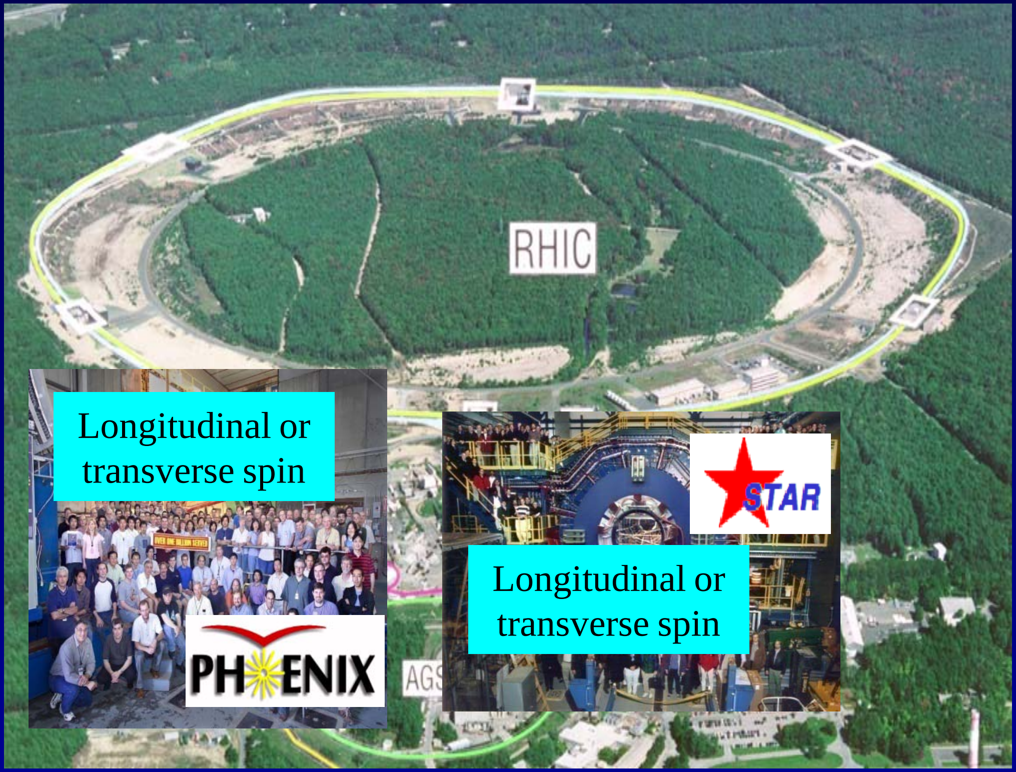
RHIC Spin Physics Experiments

- Three experiments: STAR, PHENIX, BRAHMS
- Future running only with STAR and PHENIX



RHIC Spin Physics Experiments

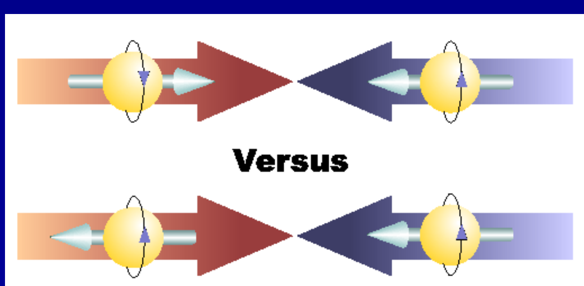
- Three experiments: STAR, PHENIX, BRAHMS
- Future running only with STAR and PHENIX

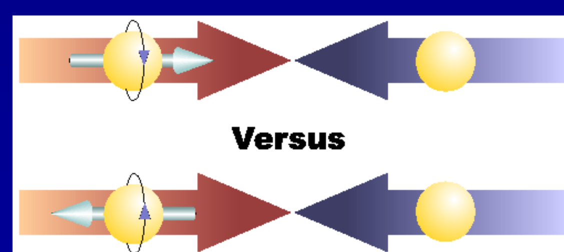


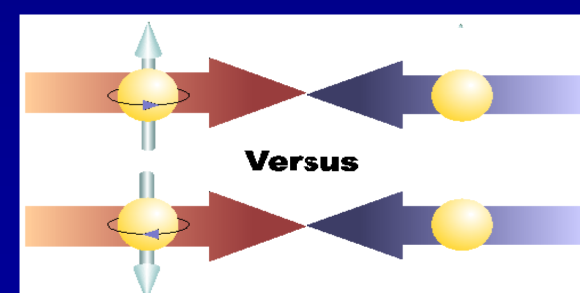
Accelerator performance:
Avg. pol ~57% at 200 GeV (design 70%).
Achieved $5.0\text{x}10^{31}$ cm^{-2} s^{-1} lumi (design ~4x this).

Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
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







Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
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

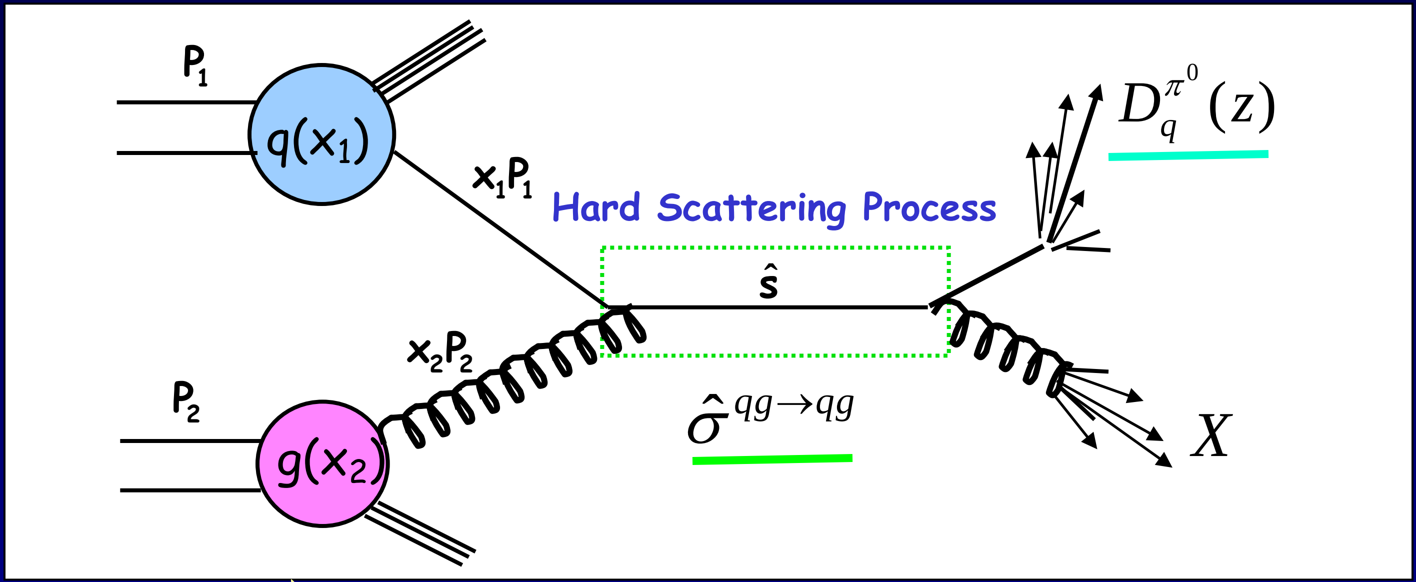
Los Alamos NATIONAL LABORATORY EST.1943

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



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

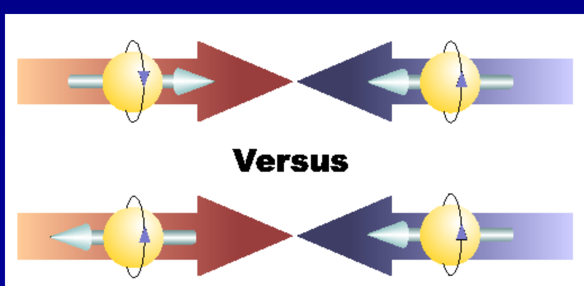
"Hard" probes have predictable rates given:

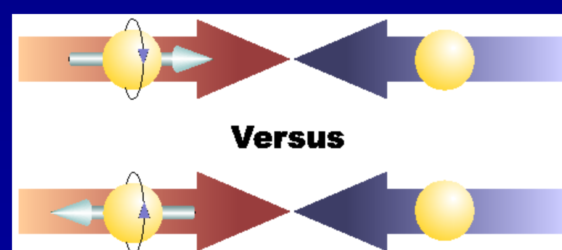
- Parton distribution functions (need experimental input)
- Partonic hard scattering rates (calculable in pQCD)
- Fragmentation functions (need experimental input)

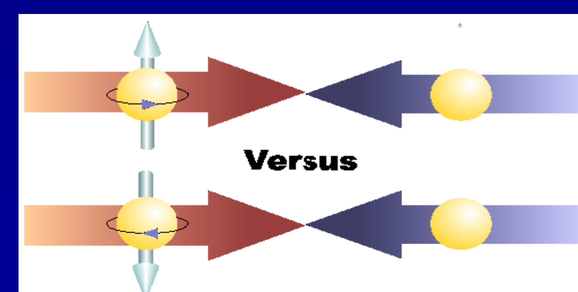
Universality (Process independence)

Proton Spin Structure at RHIC

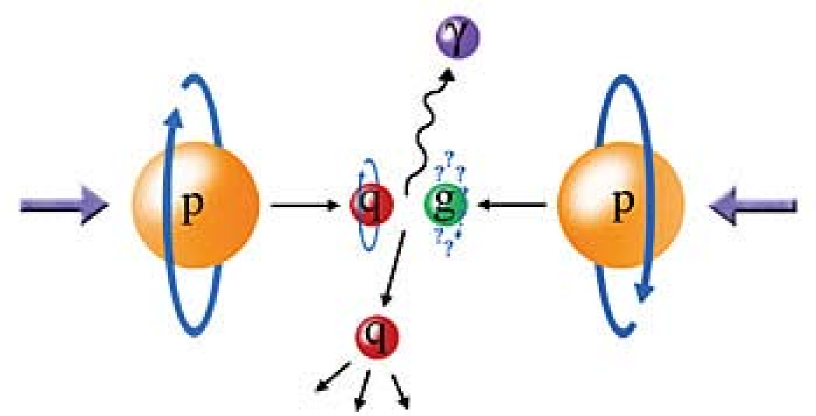
Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Prompt Photons $A_{LL}(gq \to \gamma + X)$ Back-to-Back Correlations	W Production $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	Transversity Transverse-momentum-dependent distributions Single-Spin Asymmetries







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



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

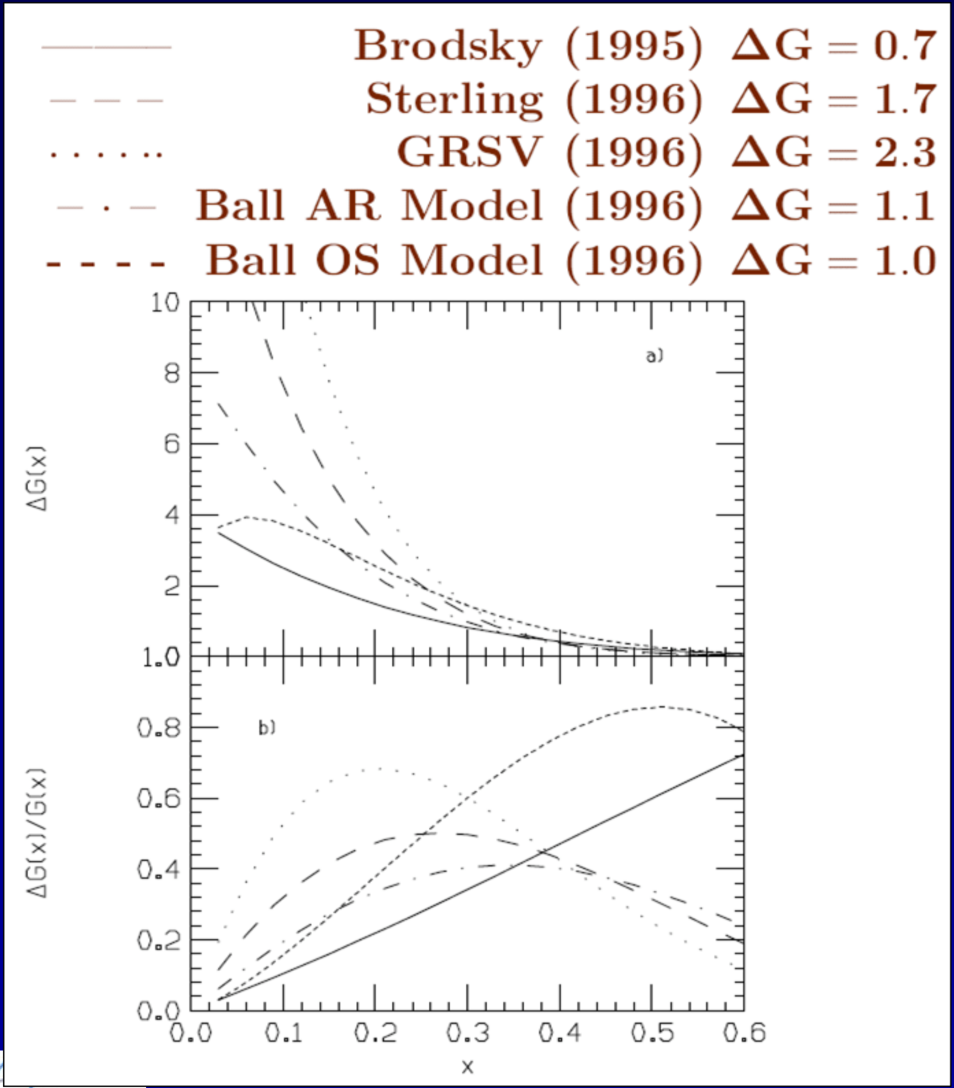
Study difference in particle production rates for same-helicity vs. opposite-helicity proton collisions

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

DIS ? pQCD e+e-

Leading-order access to gluons → ΔG

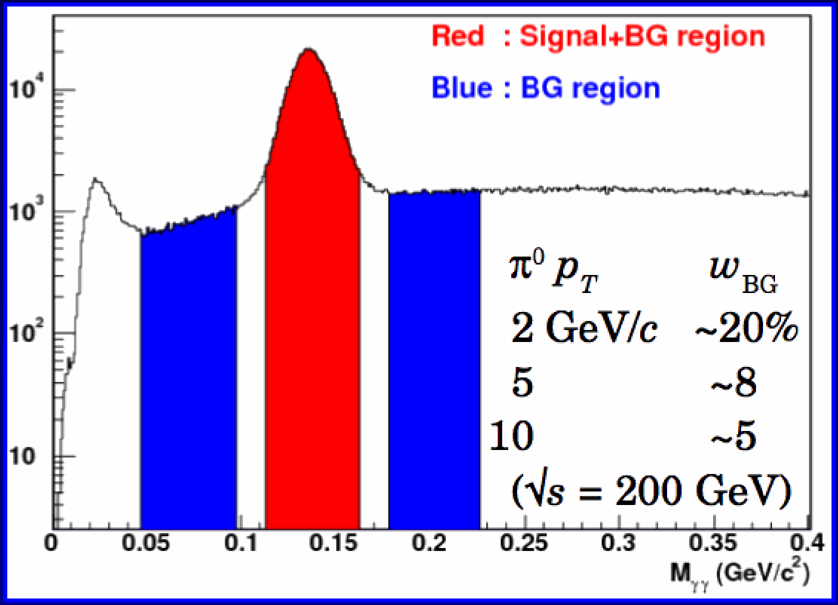
The Quest for ΔG, the Gluon Spin Contribution to the Spin of the Proton



- With experimental evidence already indicating that only about 30% of the proton's spin is due to the spin of the quarks, in the mid-1990s, predictions for $\Delta G(x)$ at $x=0.1$ ranged from 2 to 10(!)

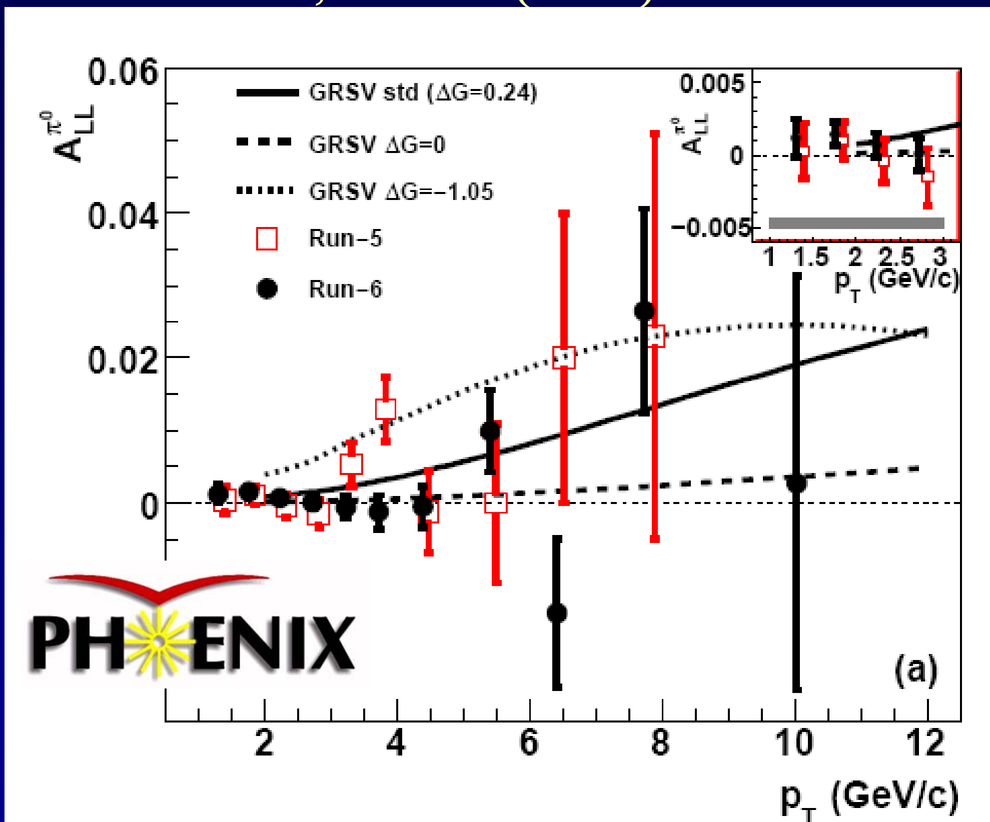
Inclusive Neutral Pion Asymmetry at $\sqrt{s}$=200 GeV

PHENIX: Limited acceptance and fast EMCal trigger → Neutral pions have been primary probe
- Subject to fragmentation function uncertainties, but easy to reconstruct

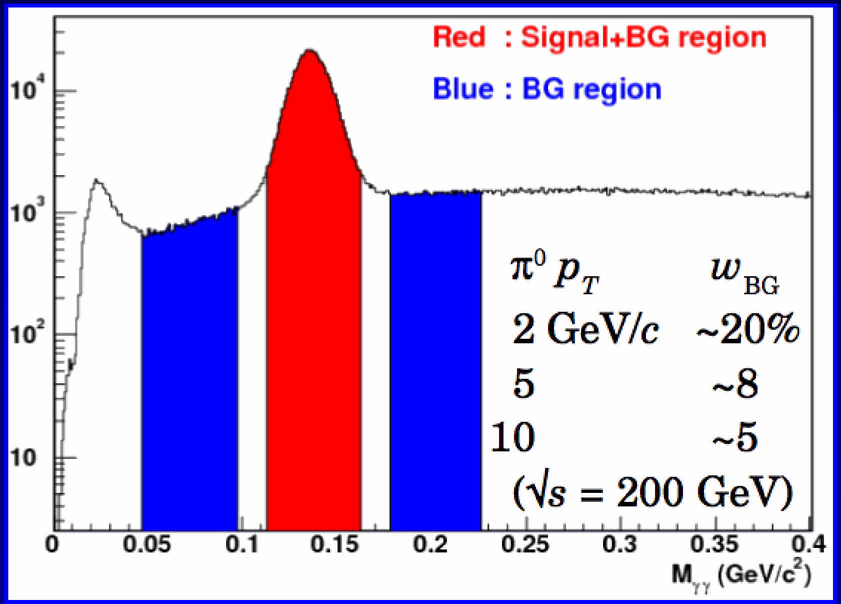


Inclusive Neutral Pion Asymmetry at $\sqrt{s}$=200 GeV

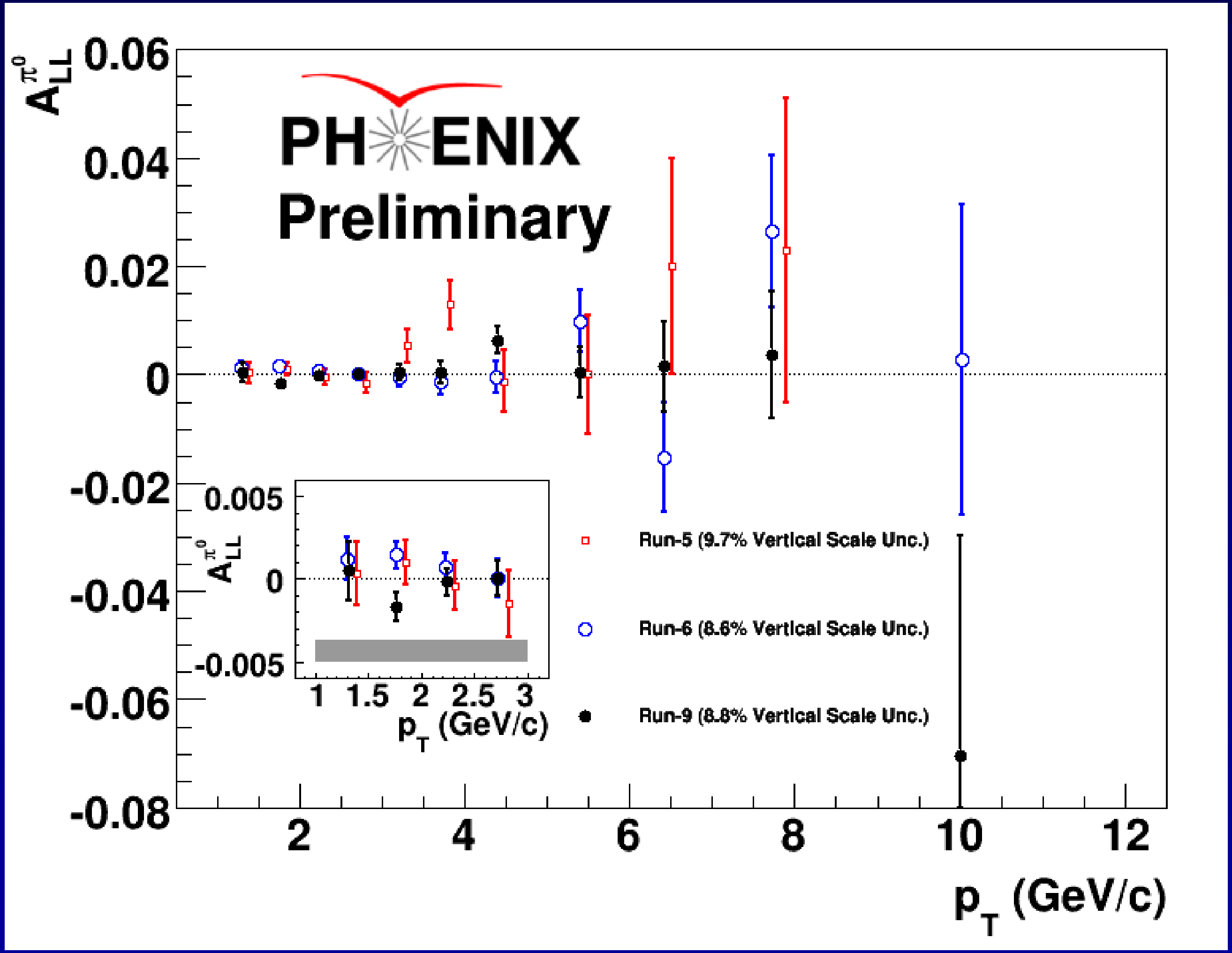
PRL 103, 012003 (2009)



Helicity asymmetry measurement



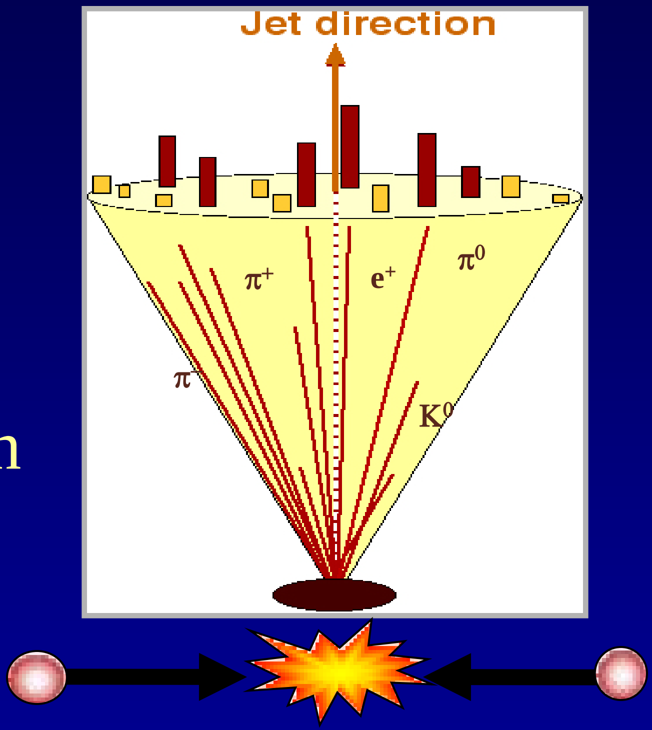
Inclusive Neutral Pion Asymmetry at $\sqrt{s}$=200 GeV



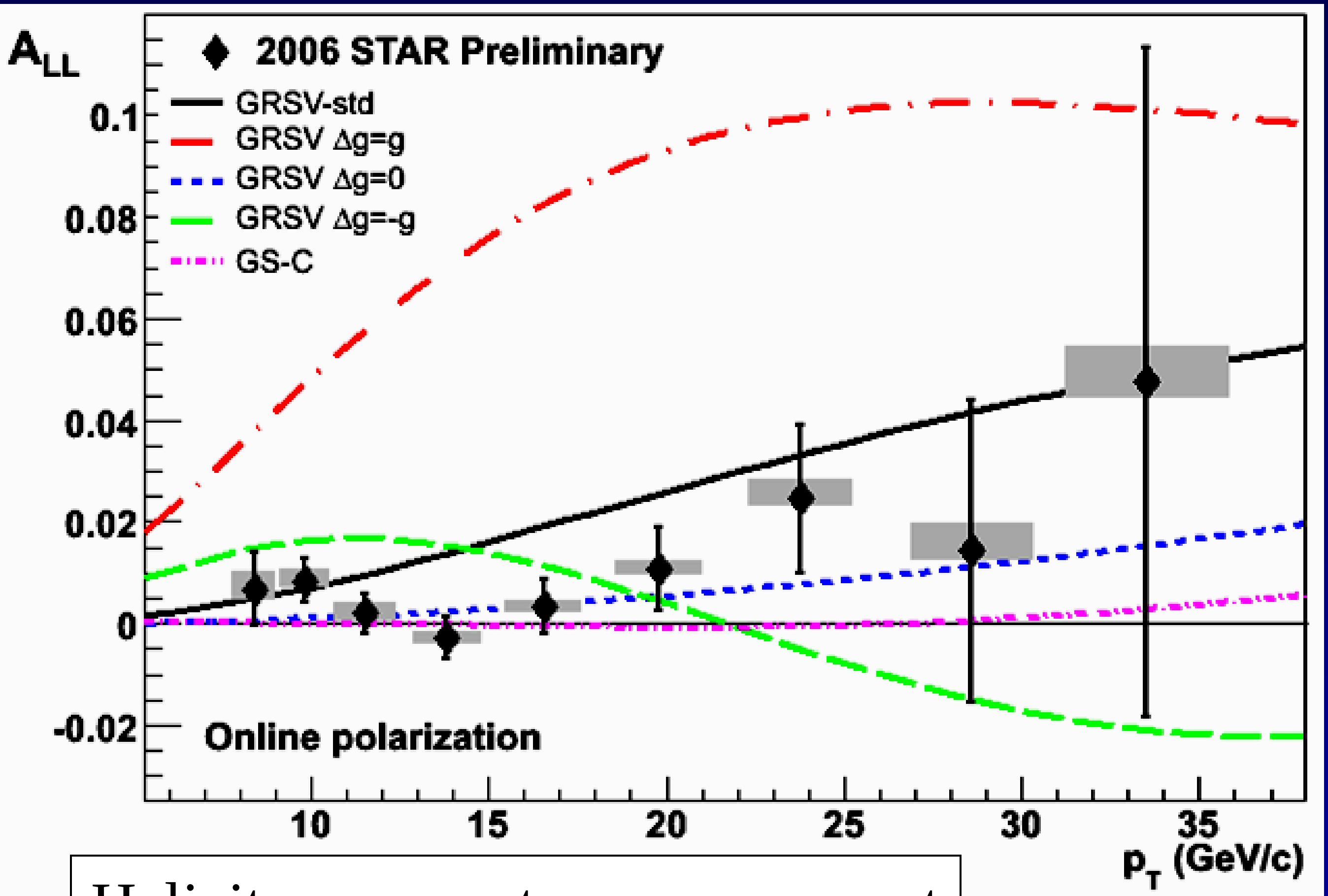
New results from 2009 data released at SPIN 2010 last week! Still no evidence for a non-zero asymmetry!

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

STAR: Large acceptance
→ Jets have been primary probe
- Not subject to uncertainties on fragmentation functions, but need to handle complexities of jet reconstruction



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



Helicity asymmetry measurement

A_{LL} systematics	(x 10^{-3})
Reconstruction + Trigger Bias	[-1,+3] (p_T dep)
Non-longitudinal Polarization	~ 0.03 (p_T dep)
Relative Luminosity	0.94
Backgrounds	1st bin ~ 0.5 Else ~ 0.1

p_T systematic	±6.7%

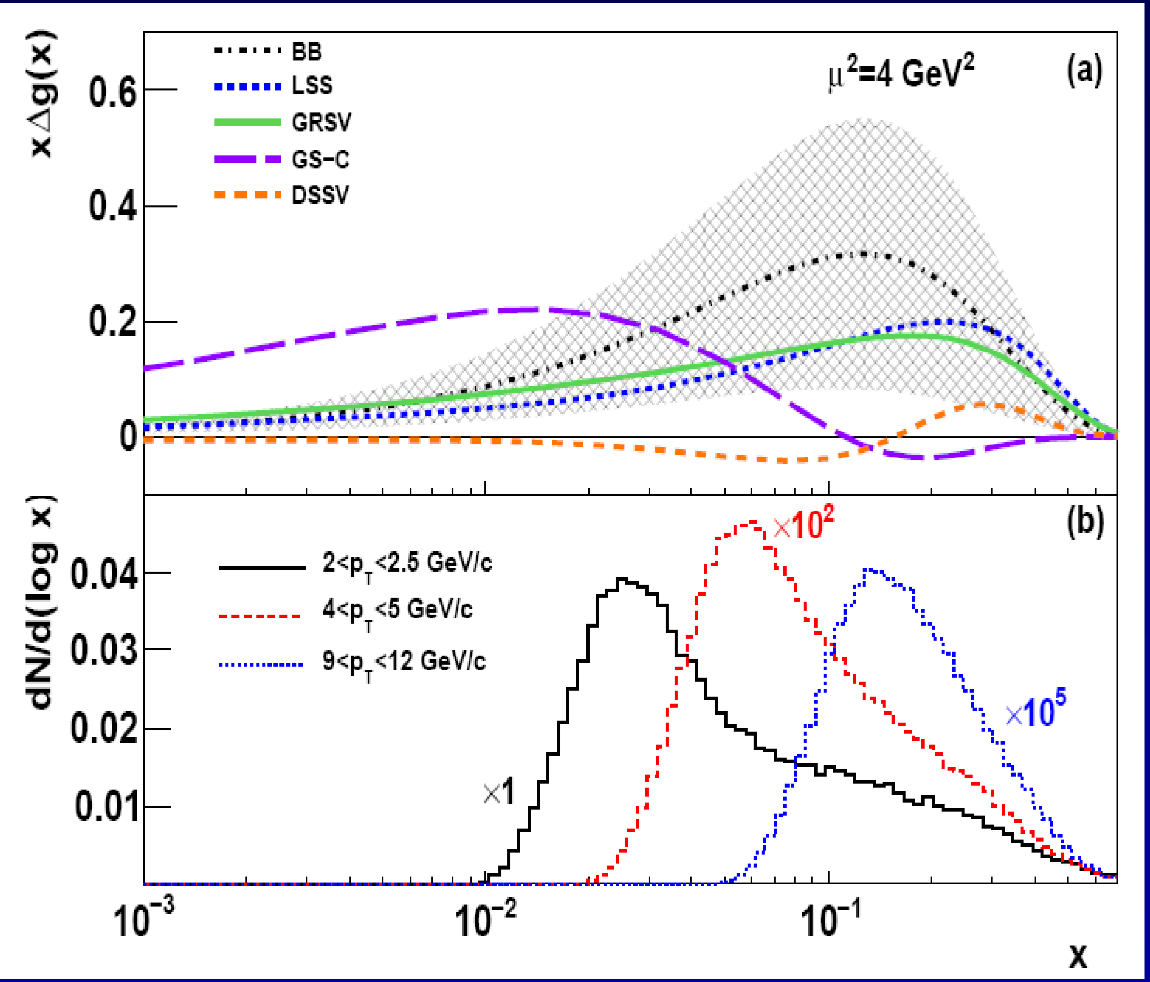
GRSV curves and data with cone radius R= 0.7 and -0.7 < η < 0.9

STAR

30

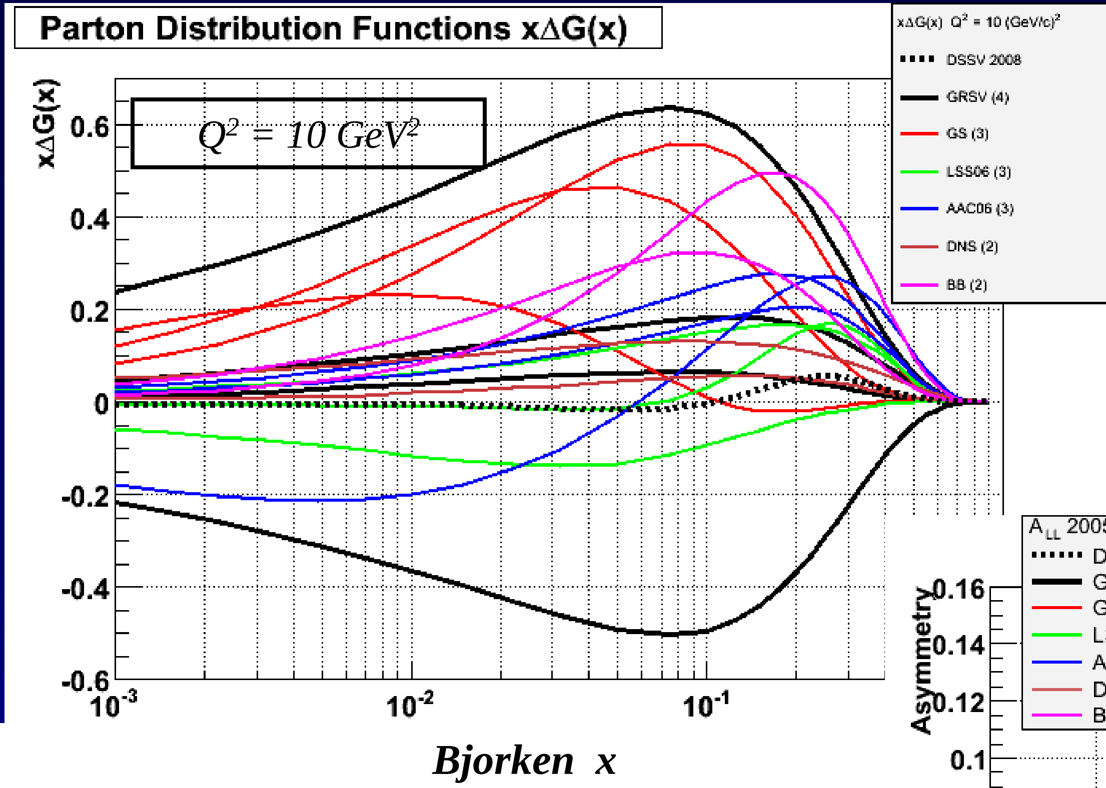
Sampling the Integral of ΔG: π^0 p_T vs. x_{gluon}

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*



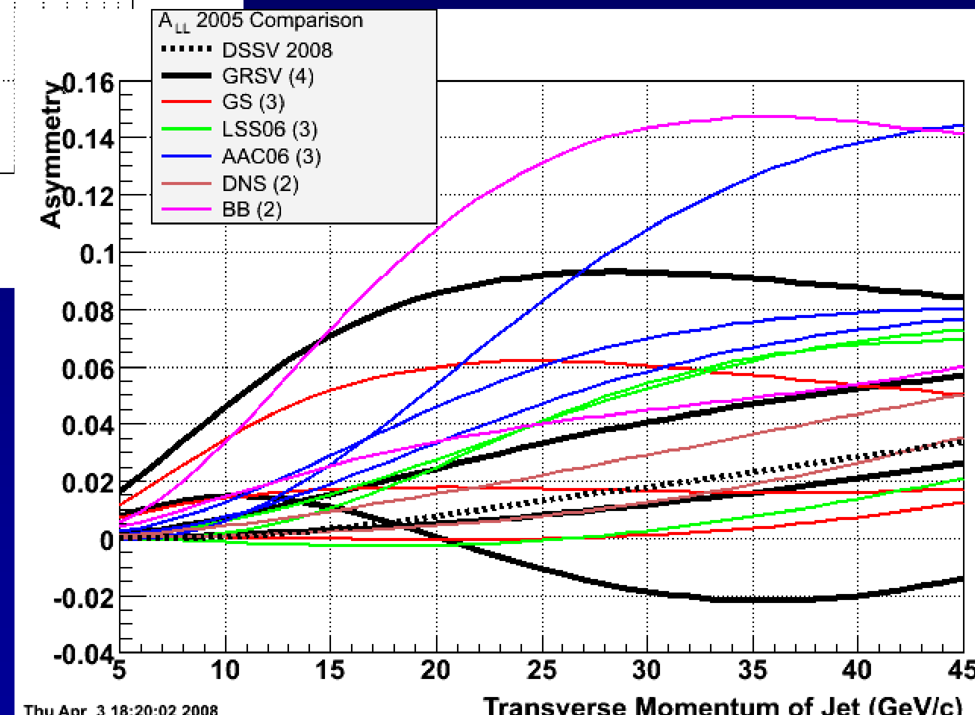
Based on simulation using NLO pQCD as input

PRL 103, 012003 (2009)



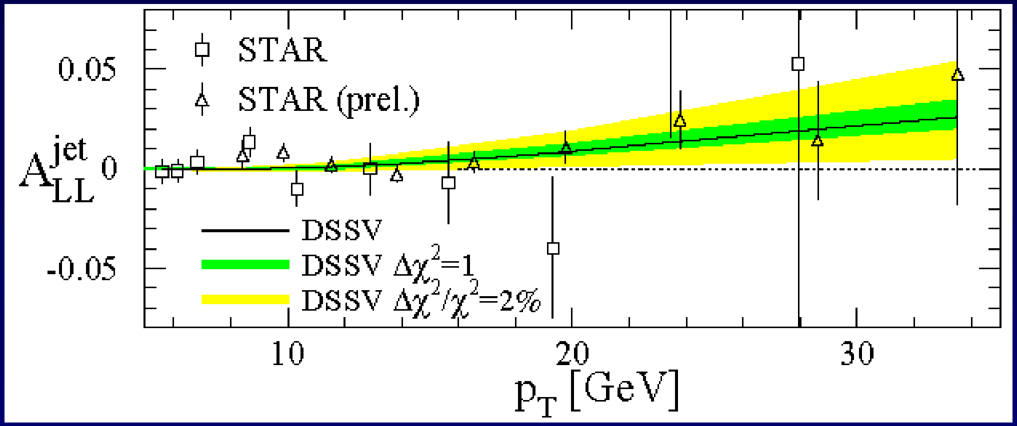
$x\Delta g(x)$

A_{LL}

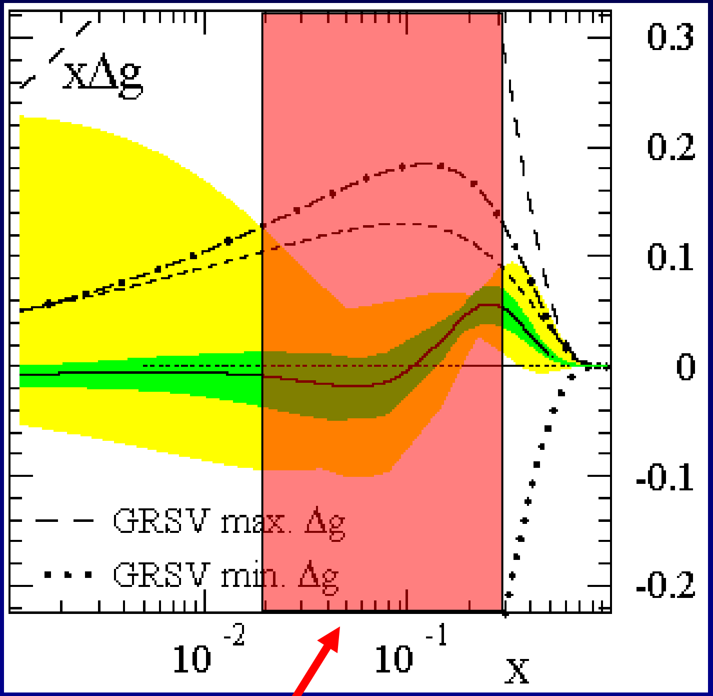


There are many predictions for $\Delta g(x)$ vs x which can be translated into predictions for A_{LL} jet, pion, etc. vs p_T and compared with RHIC data.

Present Status of $\Delta g(x)$: Global pdf Analyses



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

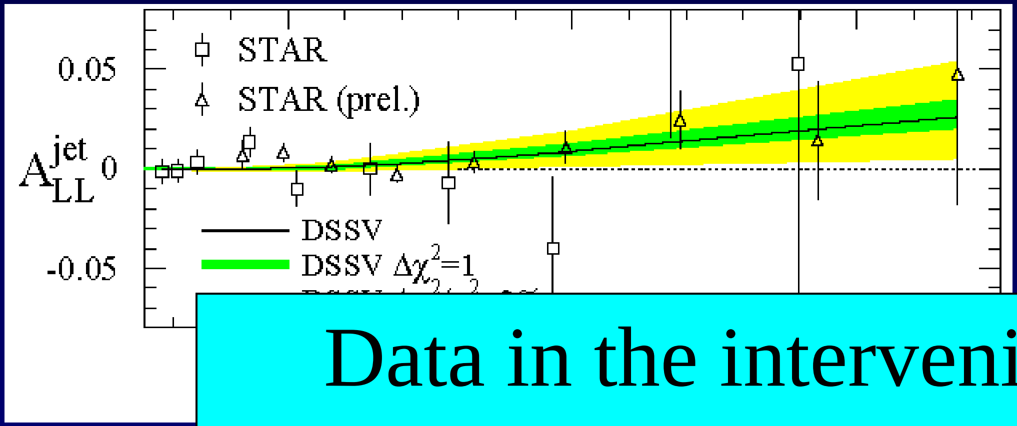


- First global NLO analysis to include *inclusive DIS, semi-inclusive DIS, and RHIC p+p data* (200 and 62.4 GeV) on equal footing
- Best fit finds node in gluon distribution near $x \sim 0.1$ (not prohibited, but not so intuitive . . .) and $\Delta G < 0.5$ near x=0.1, 4-20 times smaller than predictions in 1990's!

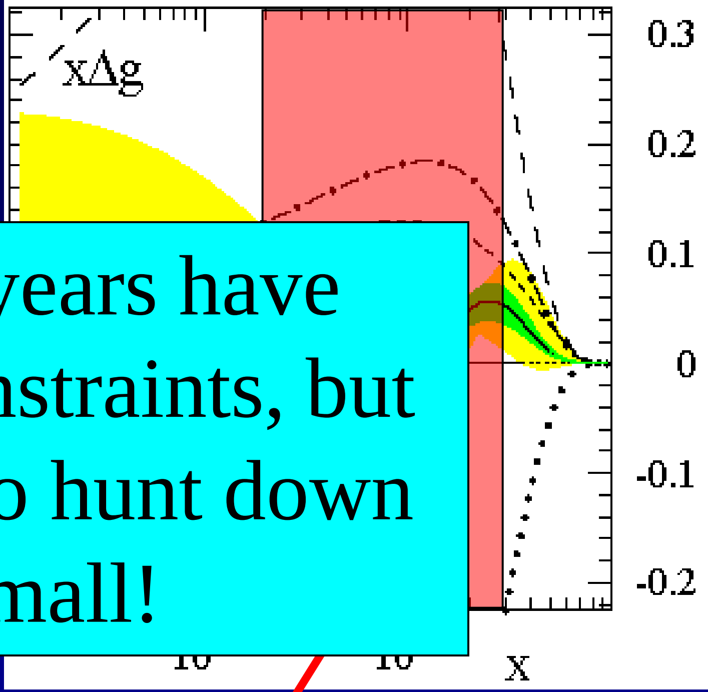
x range covered by current RHIC measurements at 200 GeV

Los Alamos NATIONAL LABORATORY EST.1943

Present Status of Δg(x): Global pdf Analyses



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



Data in the intervening years have significantly improved constraints, but it looks like we're trying to hunt down something pretty small!

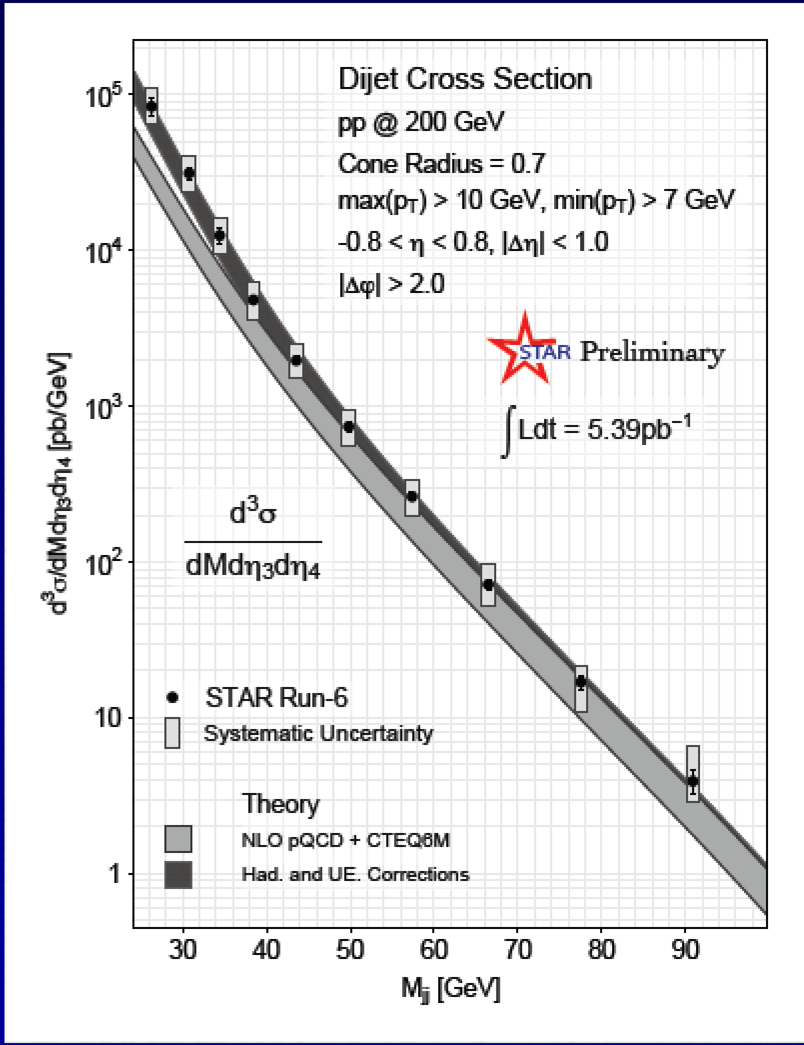
- First *inclu* *RHIC* equa
- Best fit finds node in gluon distribution near x ~ 0.1 (not prohibited, but not so intuitive . . .) and ΔG < 0.5 near x=0.1, 4-20 times smaller than predictions in 1990's!

x range covered by current RHIC measurements at 200 GeV

The Future of ΔG Measurements at RHIC

- ΔG seems to be small! We've got a more challenging task than we anticipated!
- Extend *x* coverage (more low-x surprises in store?)
  - 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

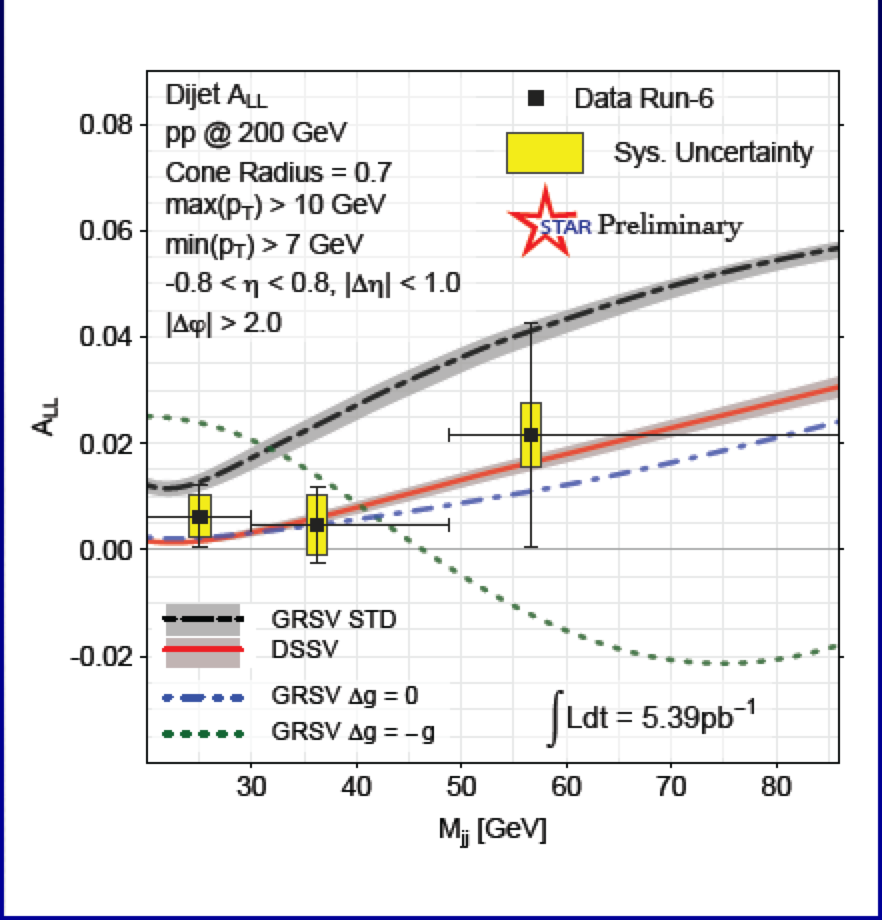
Dijet Cross Section and Double Helicity Asymmetry



- Dijets as a function of invariant mass
- More complete kinematic reconstruction of hard scattering—pin down *x* values probed

New! Released at SPIN 2010 last week!

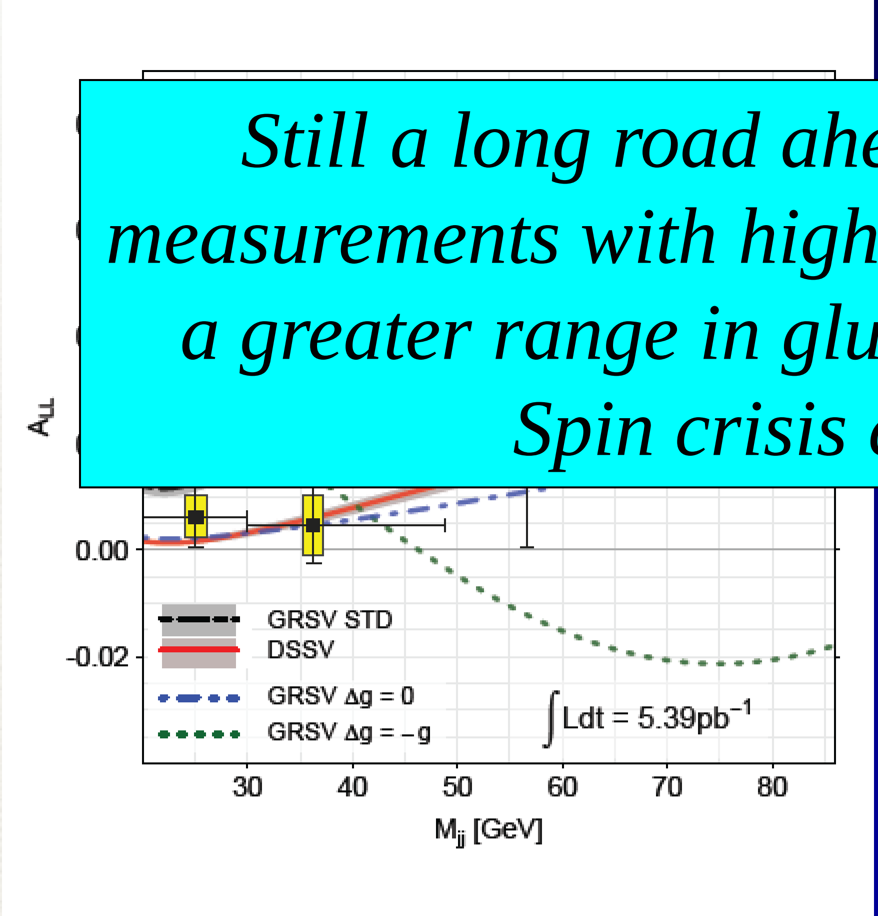
Dijet Cross Section and Double Helicity Asymmetry



- Dijets as a function of invariant mass
- More complete kinematic reconstruction of hard scattering—pin down *x* values probed

New! Released at SPIN 2010 last week!

Dijet Cross Section and Double Helicity Asymmetry



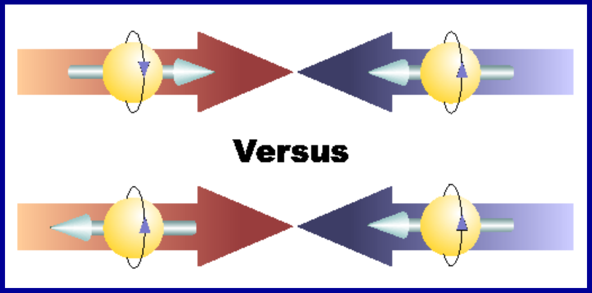
- Dijets as a function of invariant mass

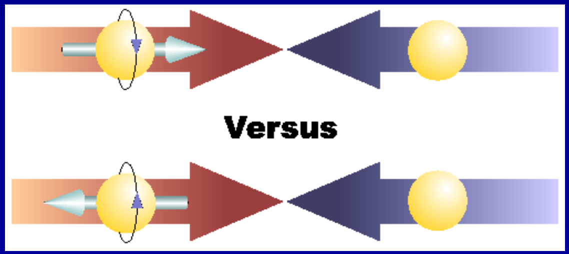
Still a long road ahead! Need to perform measurements with higher precision and covering a greater range in gluon momentum fraction. Spin crisis continues . . .

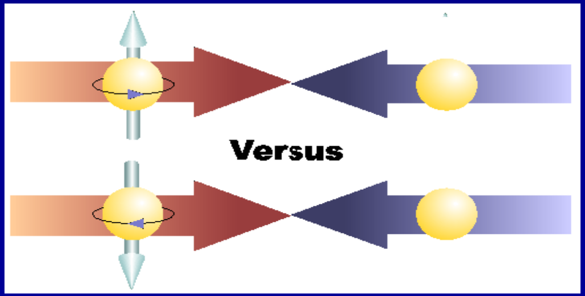
New! Released at SPIN 2010 last week!

Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
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



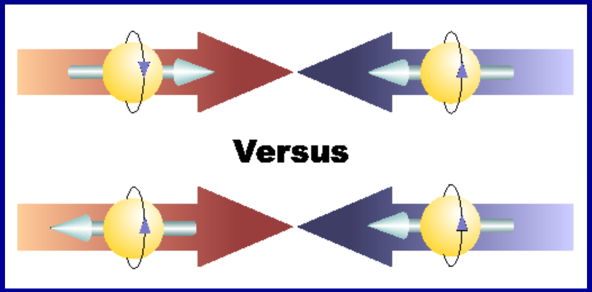


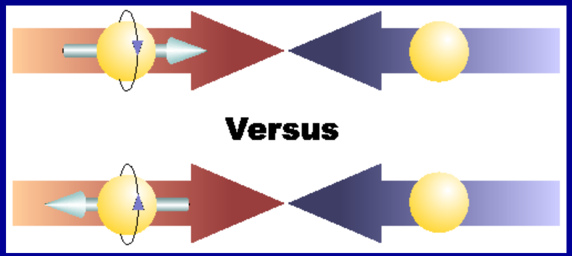


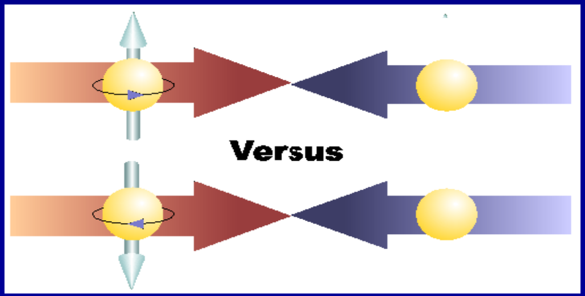
Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Je… Prom… Back…		…m- …ons …s

Not expected to resolve spin crisis, but of particular interest given surprising isospin-asymmetric structure of the unpolarized sea discovered by E866 at Fermilab.





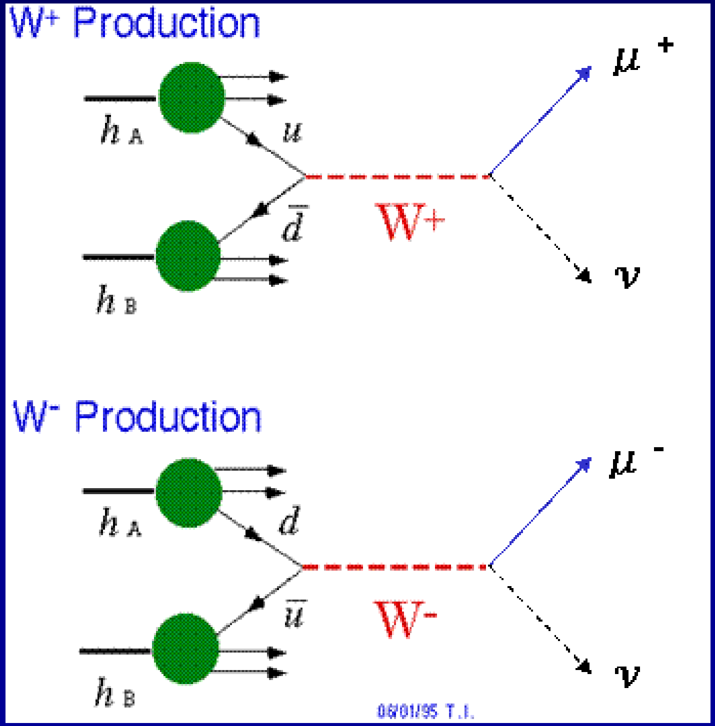


Flavor-Separated Sea Quark Polarizations Through W Production

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

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

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



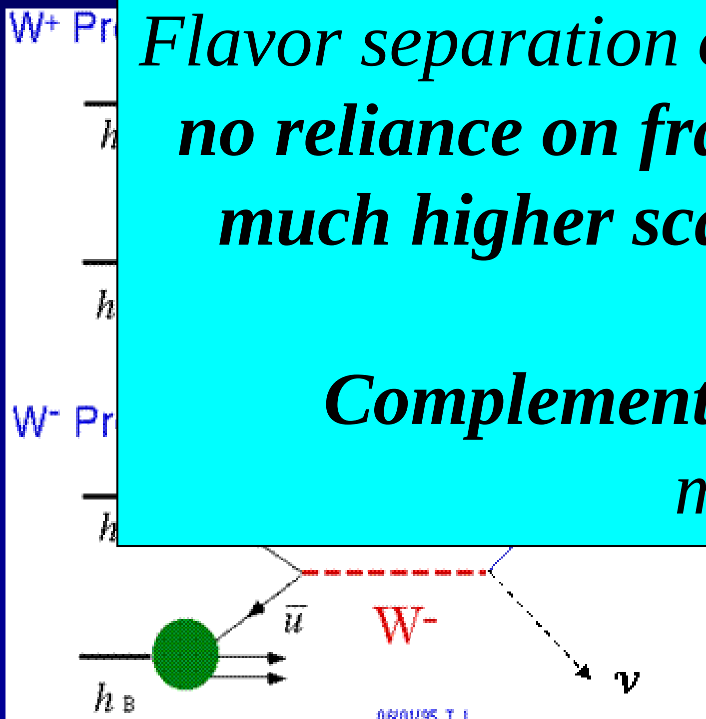
Parity violation of the weak interaction in combination with control over the proton spin orientation gives access to the *flavor* spin structure in the proton!

Flavor-Separated Sea Quark Polarizations Through W Production

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

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

$$\ldots d(x_2) \ldots (x_2)$$

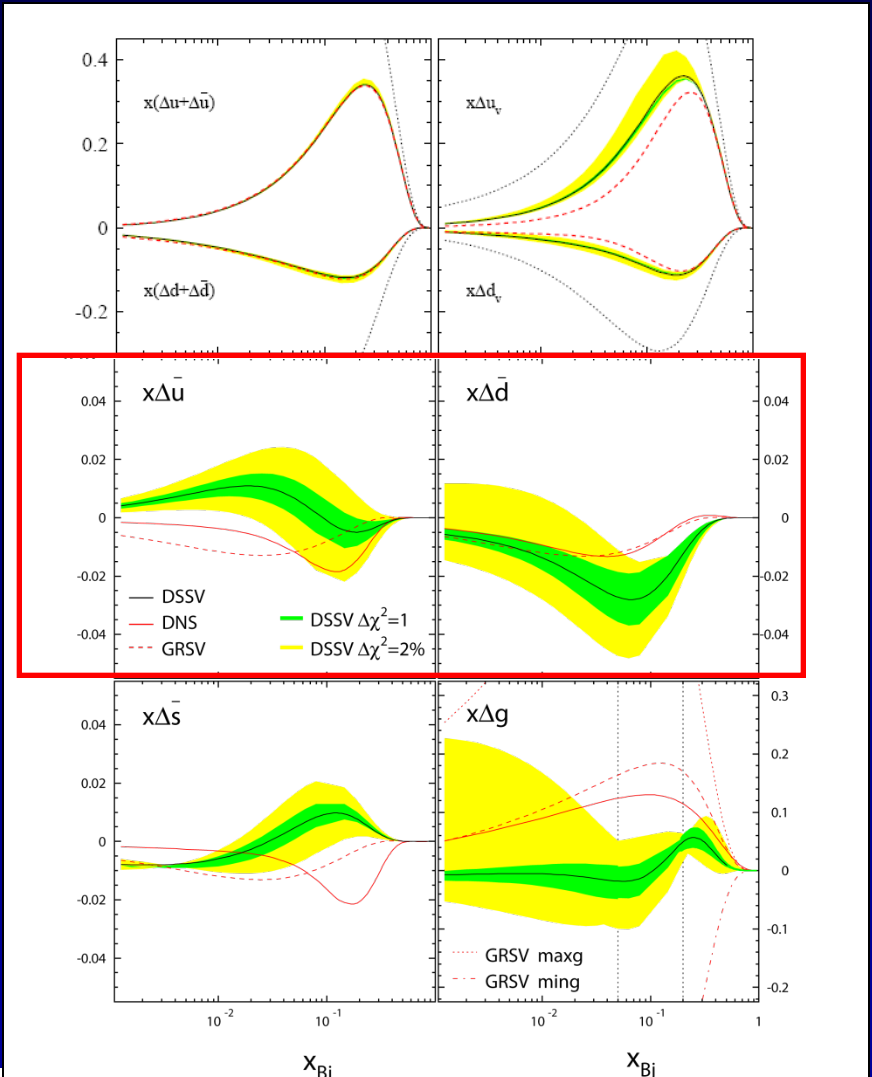


Flavor separation of the polarized sea quarks with ***no reliance on fragmentation functions,*** *and at* ***much higher scale*** *than previous fixed-target experiments.*

Complementary *to semi-inclusive DIS measurements.*

orientation gives access to the *flavor* spin structure in the proton!

Flavor-Separated Sea Quark Polarizations Through W Production



DSSV, PRL101, 072001 (2008)

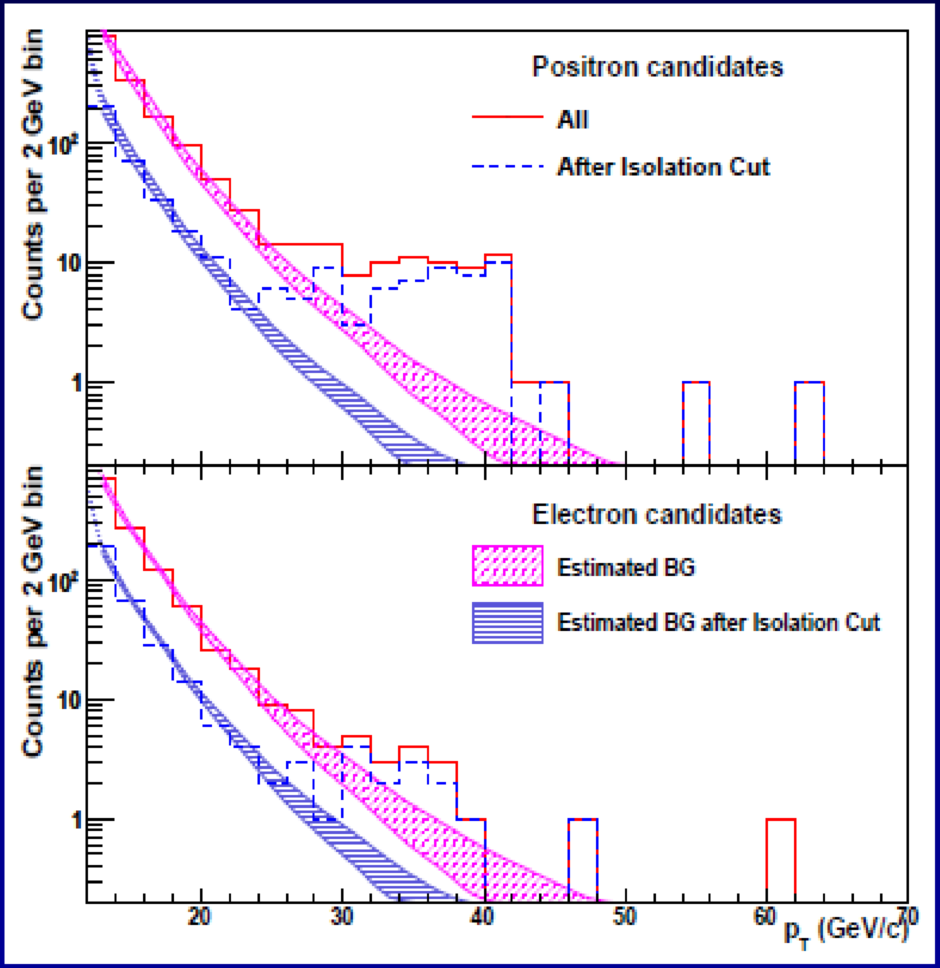
$$A_L = \frac{1}{P}\frac{N^+/L^+ - N^-/L^-}{N^+/L^+ + N^-/L^-}$$

2008 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!

First 500 GeV Data in 2009

- Largely a commissioning run for the accelerator, the polarimeters, and the detectors
  - Average polarization ~39% —many additional depolarizing resonances compared to 200 GeV
  - W → e at midrapidity already possible with current data
  - PHENIX finished installing forward detector/trigger upgrades to be able to make full use of 2011 500 GeV run
  - STAR will be ready for forward rapidity measurements in 2012
- B. Surrow, DESY seminar, July 2010

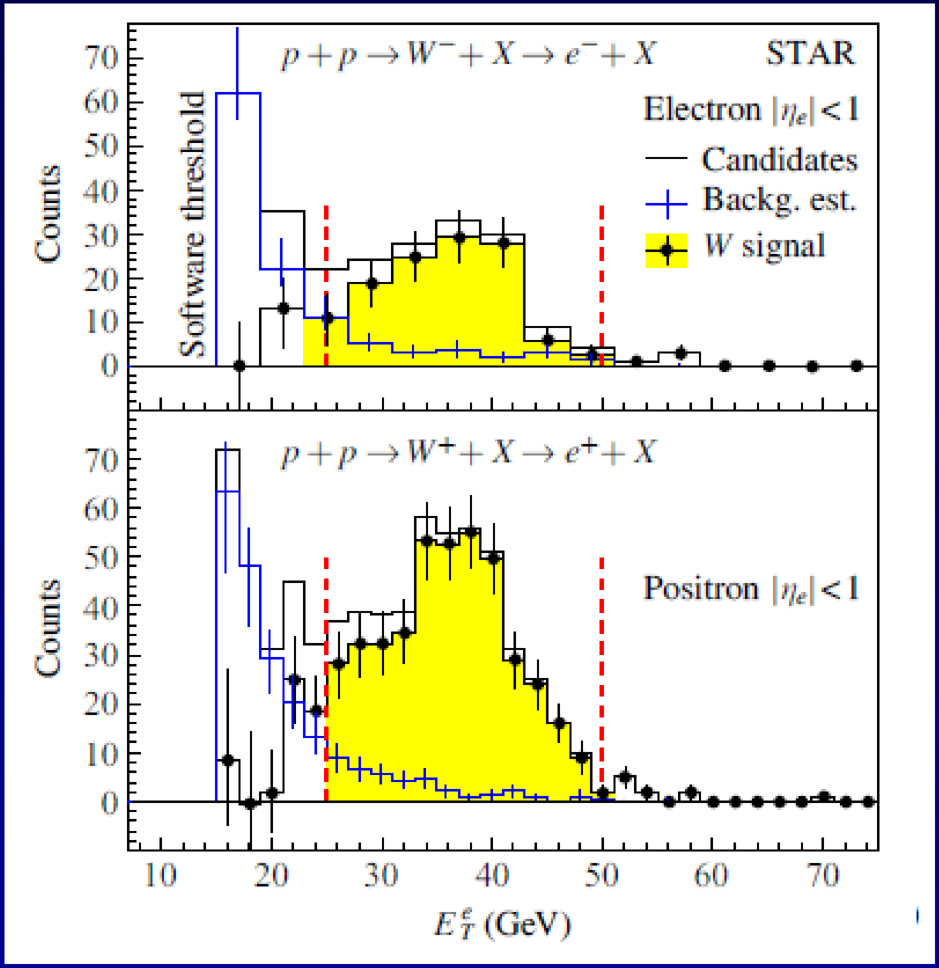
Final W Results from 2009 Data



PHENIX: arXiv:1009.0505

- New since July—results from STAR and PHENIX submitted simultaneously for publication in September

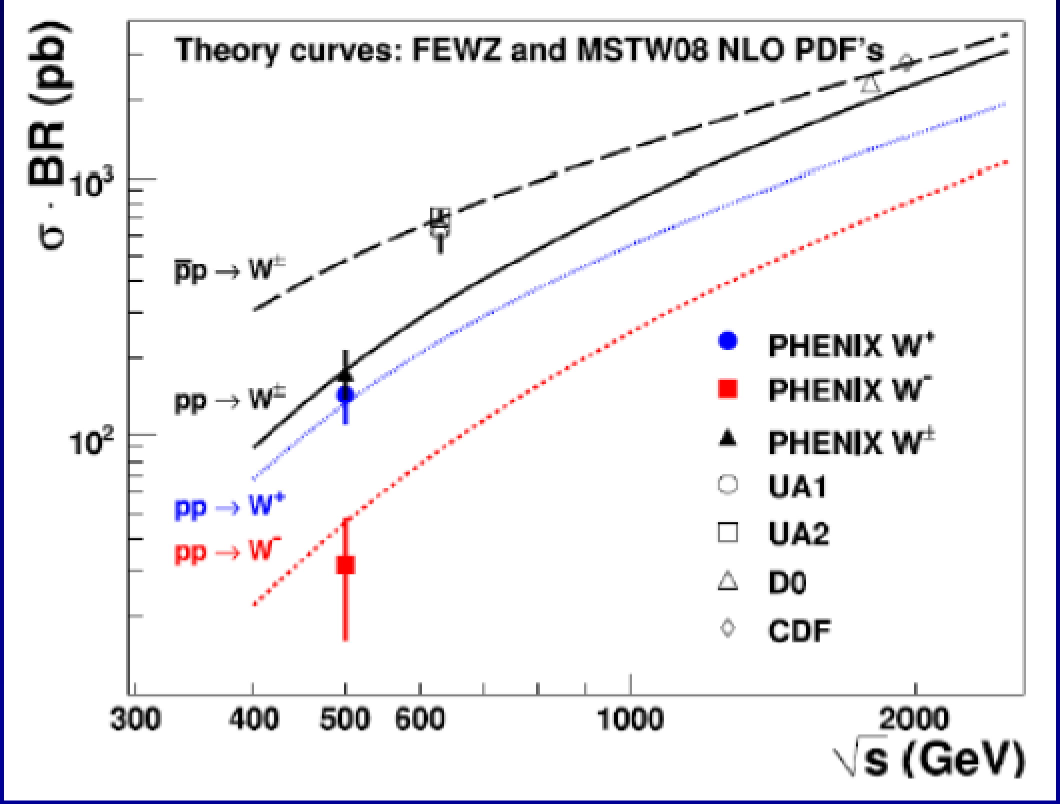
Final W Results from 2009 Data



STAR: arXiv:1009.0326

- New since July—results from STAR and PHENIX submitted simultaneously for publication in September

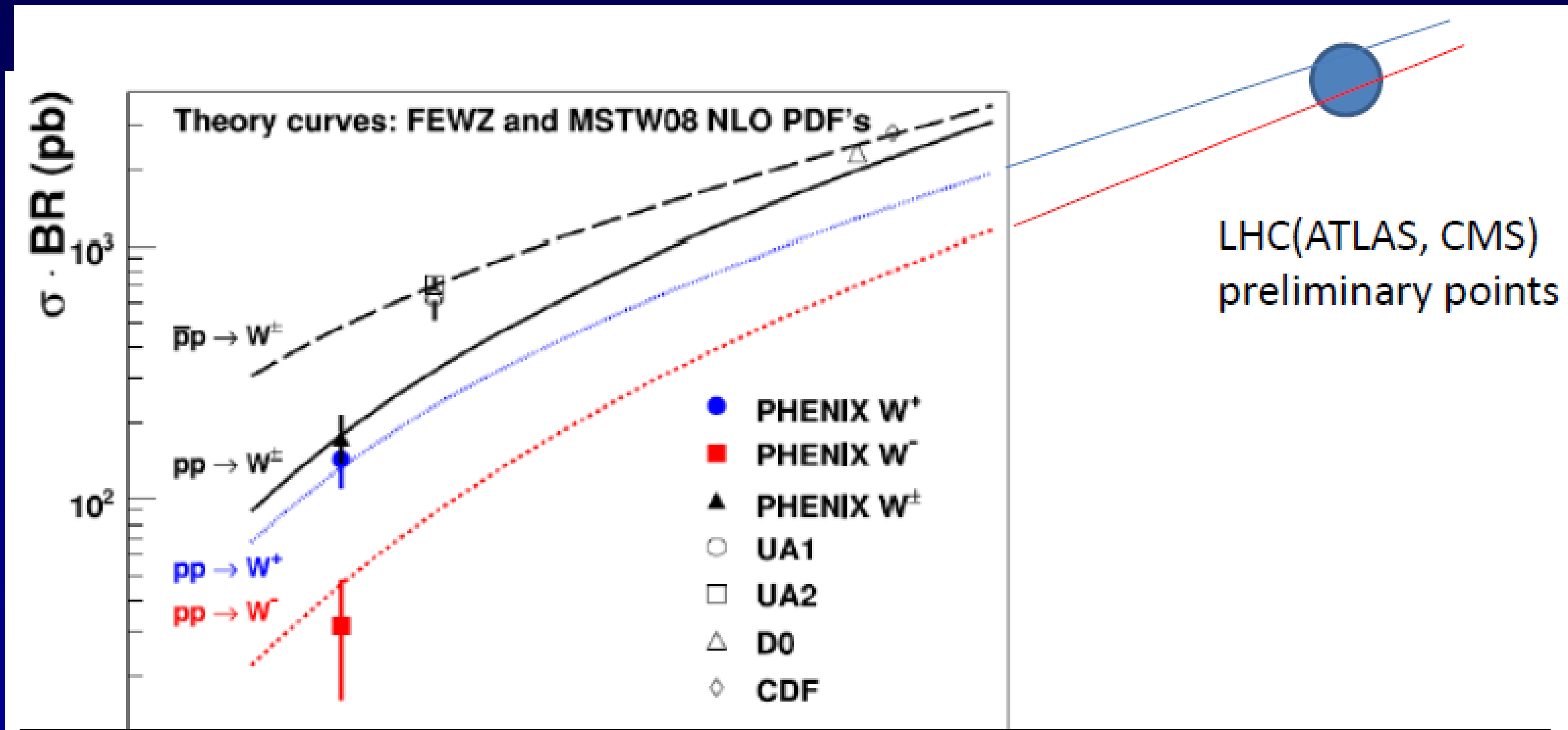
Total W Cross Section



- Correct from PHENIX acceptance (p_T^e>30 GeV/c, $|\eta|$<0.35) to total cross section
- In agreement with predictions
- First W measurement in p+p collisions (at least first submitted for publication . . .!)

PHENIX: arXiv:1009.0505

Total W Cross Section



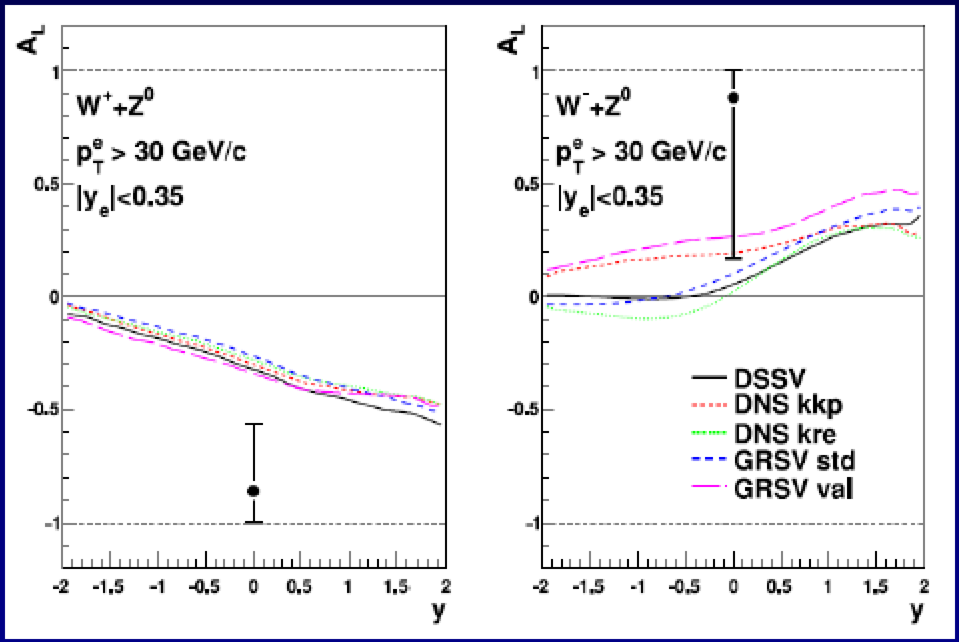
HENIX
>30
5) to
on
ith

ement
ns (at
itted for
..!)

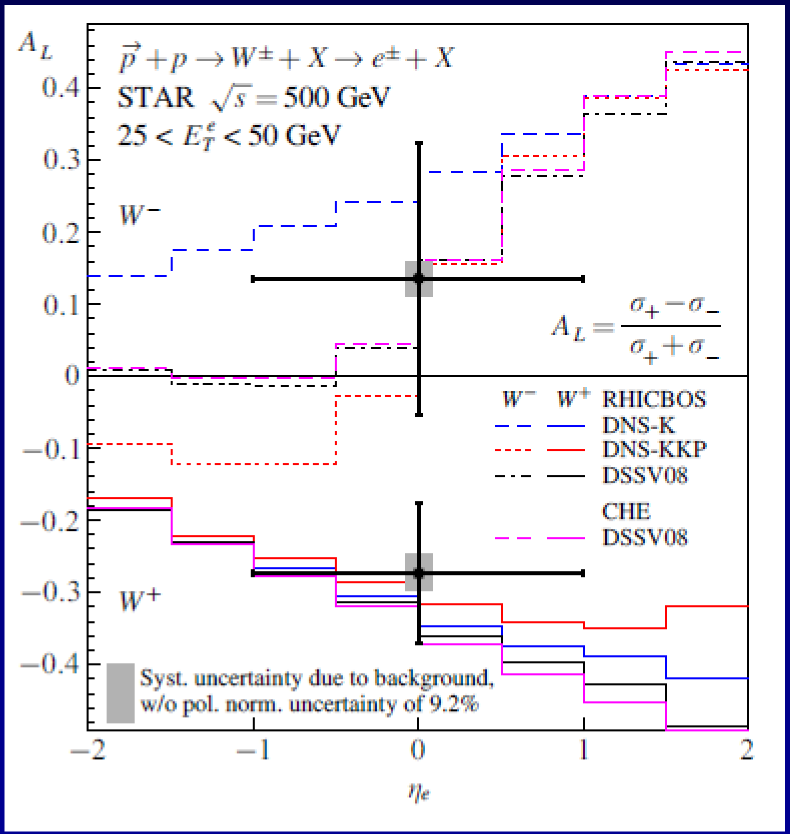
Now preliminary LHC results! Consistent with predictions as well.

PHENIX: arXiv:1009.0505

First Glimpse at Parity-Violating Single-Helicity Asymmetries



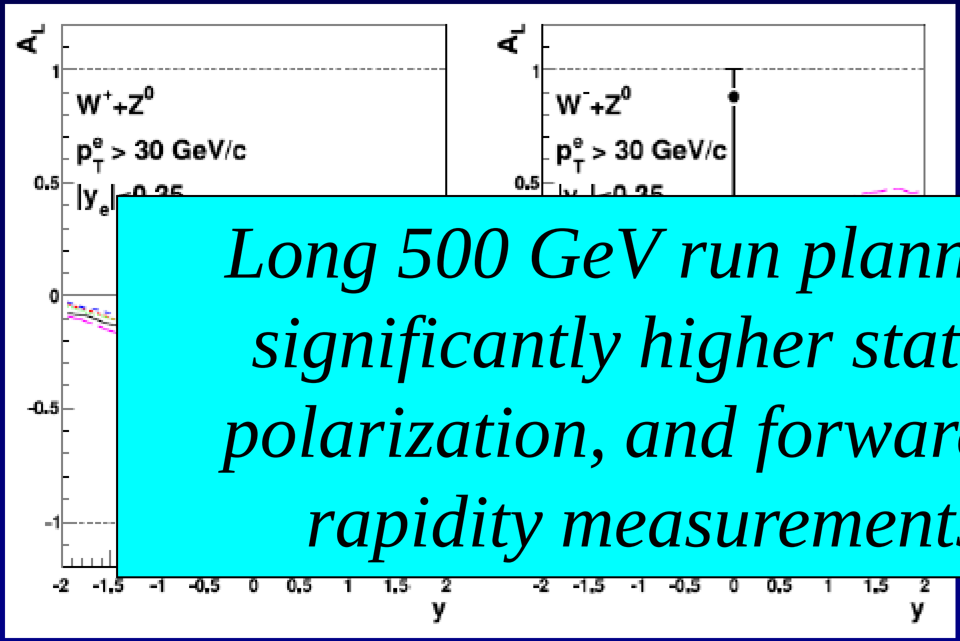
PHENIX: arXiv:1009.0505



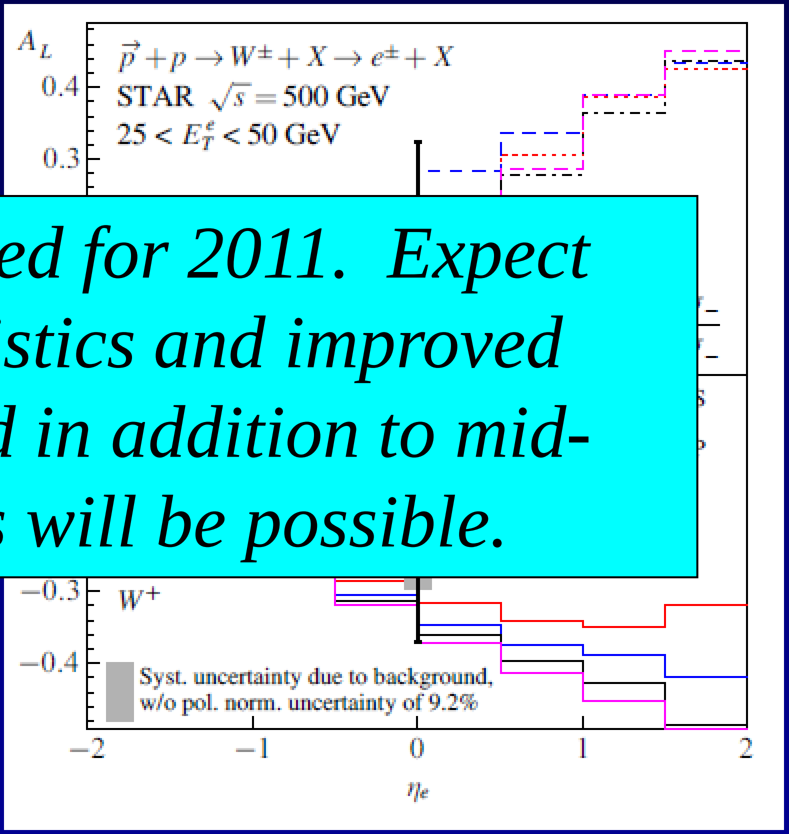
STAR: arXiv:1009.0326

Negative parity-violating asymmetry seen by both PHENIX and STAR for W+. Consistent with SIDIS results, but not yet enough data to improve constraints on anti-u and anti-d helicity distributions.

First Glimpse at Parity-Violating Single-Helicity Asymmetries



PHENIX: arXiv:1009.0505



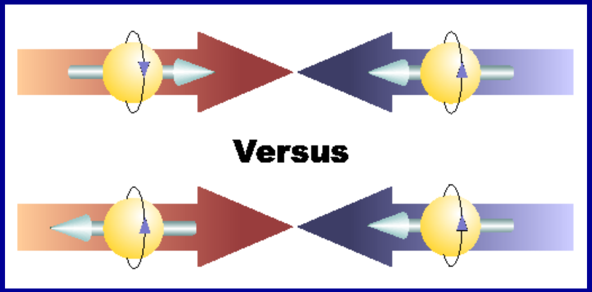
STAR: arXiv:1009.0326

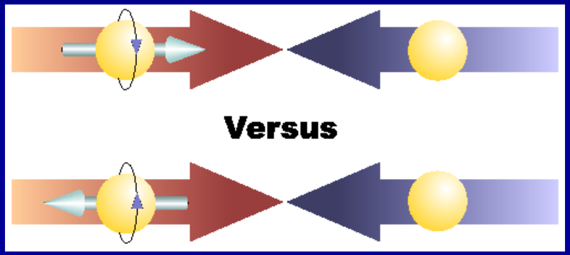
Long 500 GeV run planned for 2011. Expect significantly higher statistics and improved polarization, and forward in addition to mid-rapidity measurements will be possible.

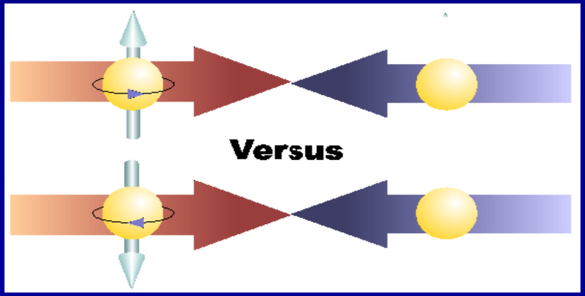
Negative parity-violating asymmetry seen by both PHENIX and STAR for W+. Consistent with SIDIS results, but not yet enough data to improve constraints on anti-u and anti-d helicity distributions.

Proton Spin Structure at RHIC

Gluon Polarization ΔG	Flavor decomposition $\frac{\Delta u}{u}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta d}{d}, \frac{\Delta \bar{d}}{\bar{d}}$	Transverse Spin
π, Jets $A_{LL}(gg, gq \to \pi + X)$ Prompt Photons $A_{LL}(gq \to \gamma + X)$ Back-to-Back Correlations	**W Production** $A_L(u + \bar{d} \to W^+ \to \ell^+ + \nu_l)$ $A_L(\bar{u} + d \to W^- \to \ell^- + \bar{\nu}_l)$	**Transversity** **Transverse-momentum-dependent distributions** Single-Spin Asymmetries





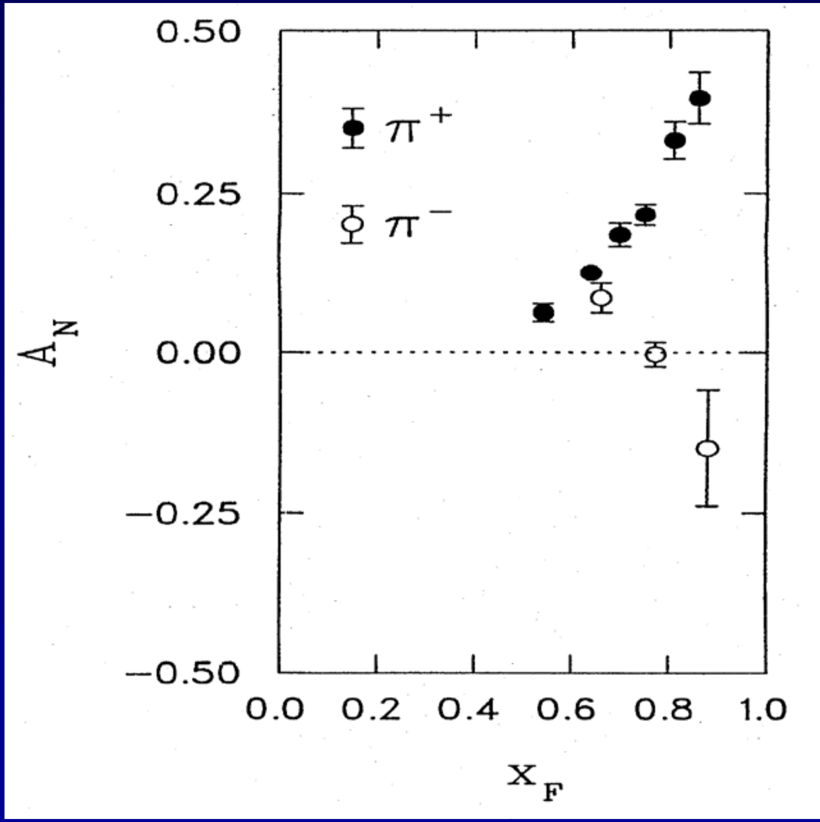


Longitudinal (Helicity) vs. Transverse Spin Structure

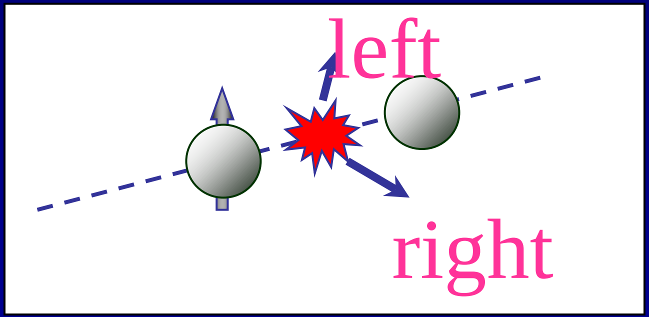
- Transverse spin structure of the proton cannot be deduced from longitudinal (helicity) structure
  - Spatial rotations and Lorentz boosts don't commute!
  - Only the same in the non-relativistic limit
- Transverse structure linked to intrinsic parton transverse momentum (k_T) and orbital angular momentum!

1976: Discovery in p+p Collisions!
Large Transverse Single-Spin Asymmetries

Argonne √s=4.9 GeV



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

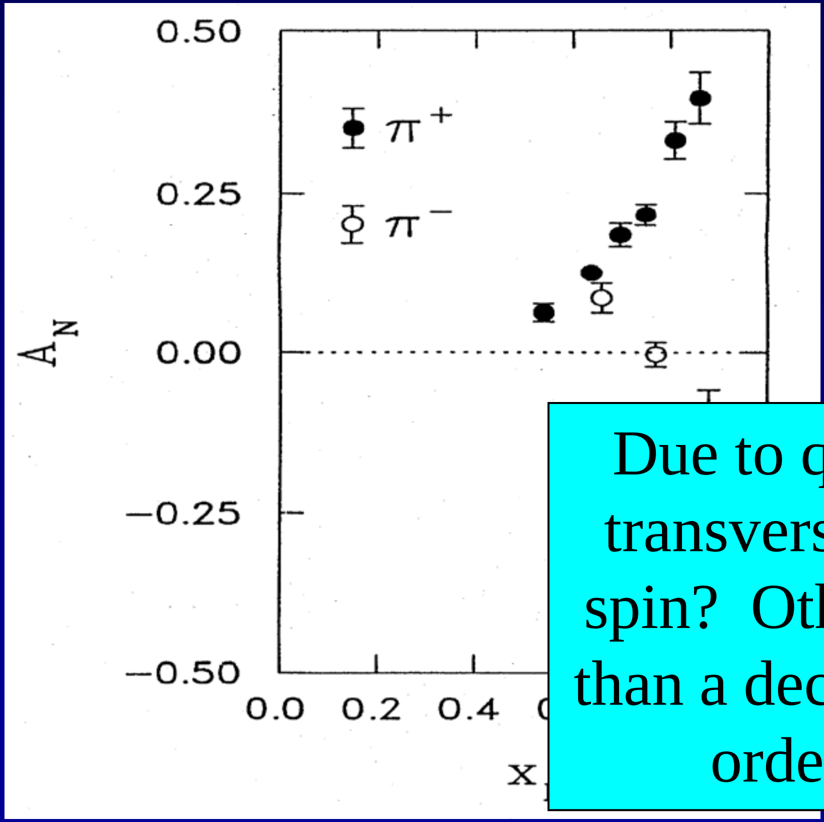


W.H. Dragoset et al., PRL36, 929 (1976)

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

1976: Discovery in p+p Collisions!
Large Transverse Single-Spin Asymmetries

Argonne √s=4.9 GeV



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

Due to quark transversity, i.e. correlation of transverse quark spin with transverse proton spin? 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)

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

Transverse-Momentum-Dependent Distributions and Single-Spin Asymmetries

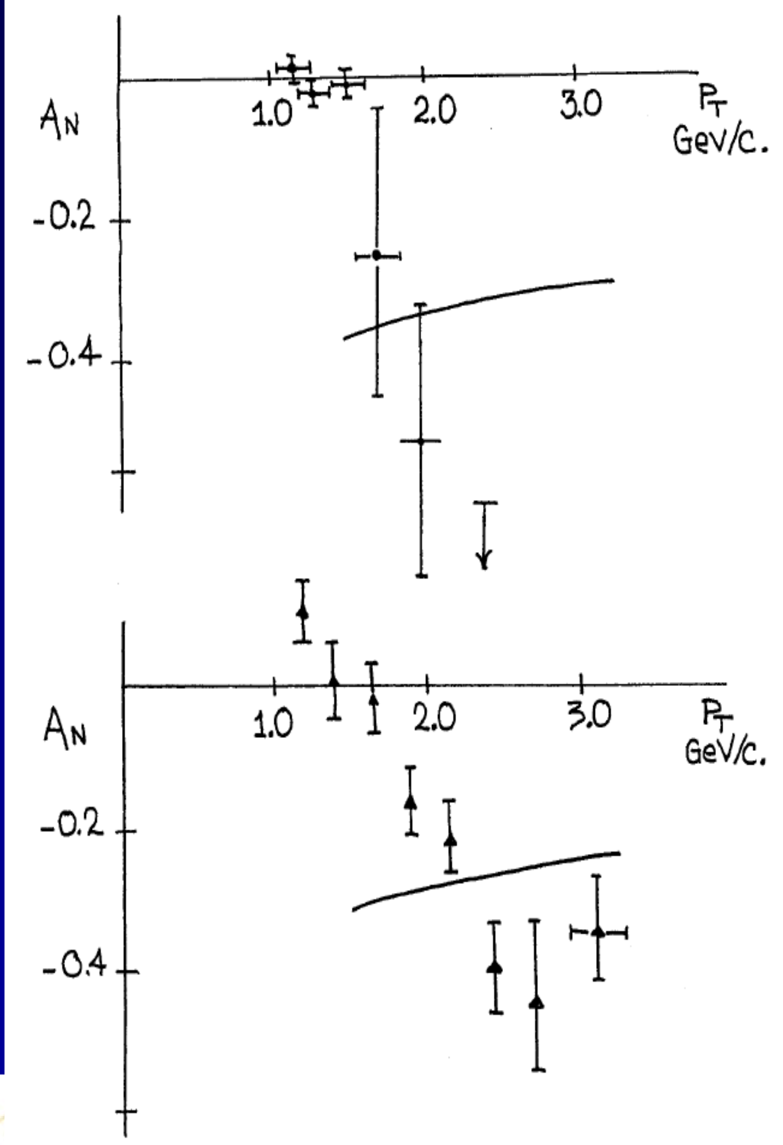


Fig. 1

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

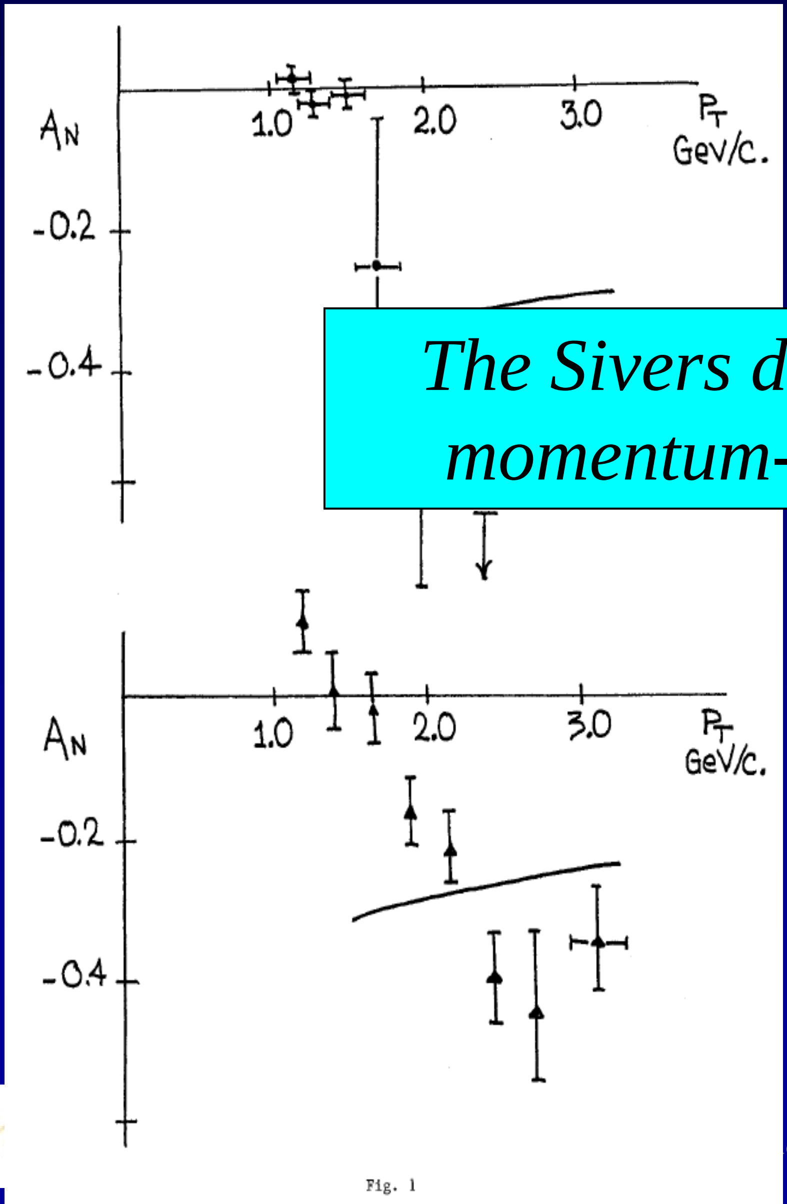
D.W. Sivers, PRD41, 83 (1990)

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

$$\boxed{s \cdot (p_1 \times p_2)}$$

Spin and momenta can be of partons or hadrons

Transverse-Momentum-Dependent Distributions and Single-Spin Asymmetries



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

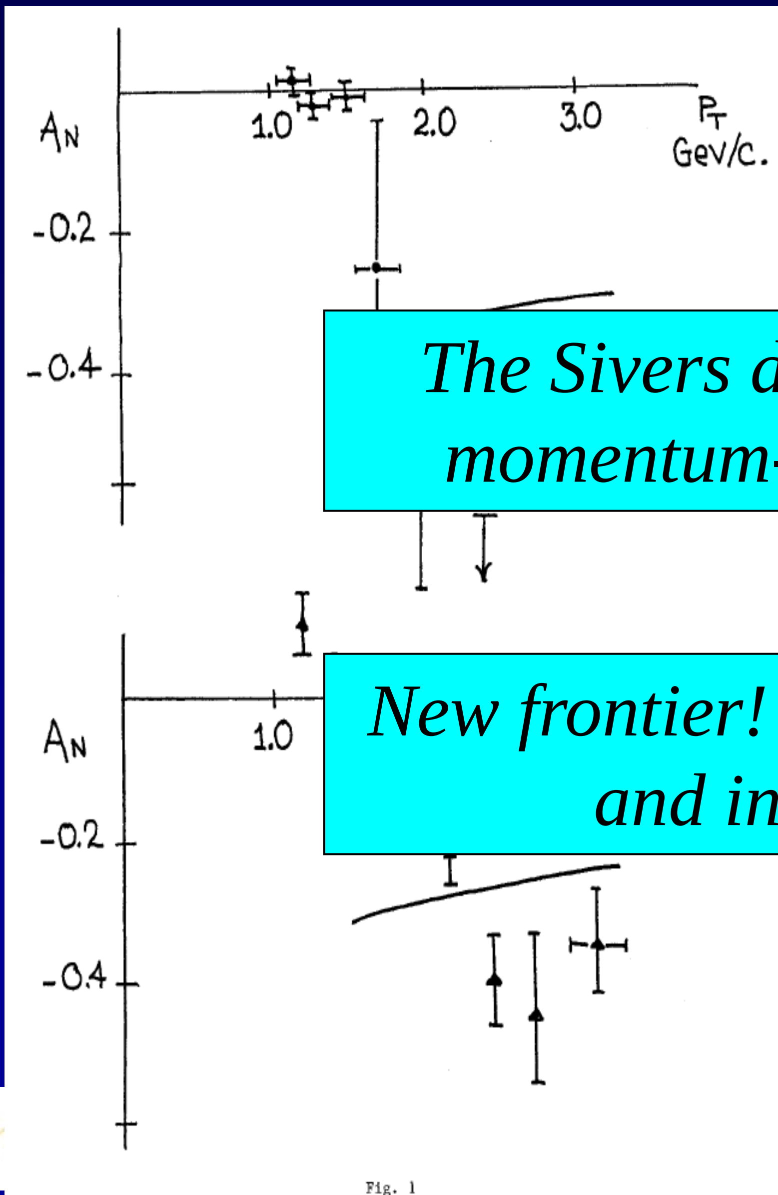
The Sivers distribution: the first transverse-momentum-dependent distribution (TMD)!

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

$$\boxed{s \cdot (p_1 \times p_2)}$$

Spin and momenta can be of partons or hadrons

Transverse-Momentum-Dependent Distributions and Single-Spin Asymmetries



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

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

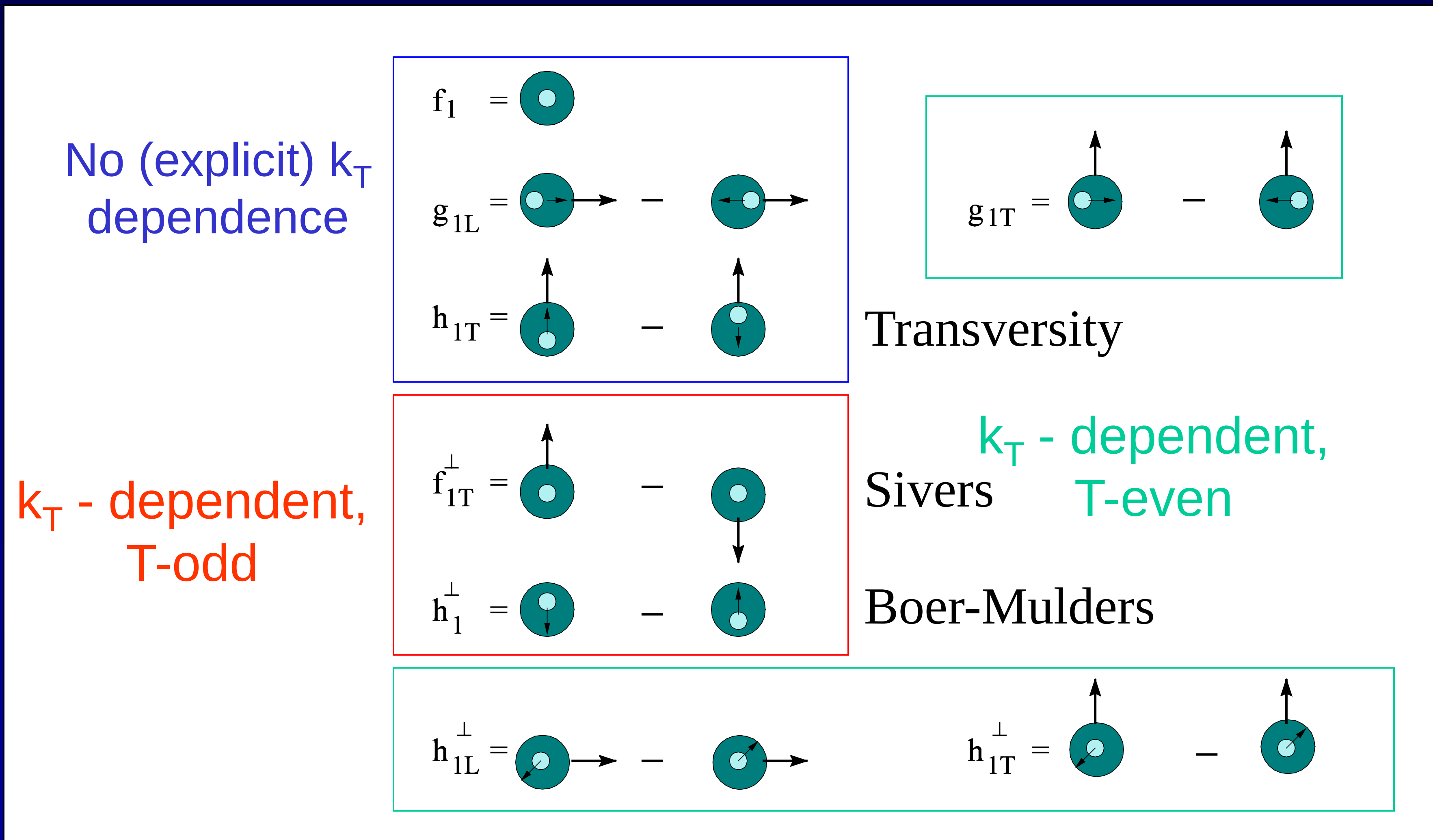
factorization assumption in pQCD and proposes a correlation between the

*New frontier! Parton **dynamics** inside hadrons, and in the hadronization process*

$$s \cdot (p_1 \times p_2)$$

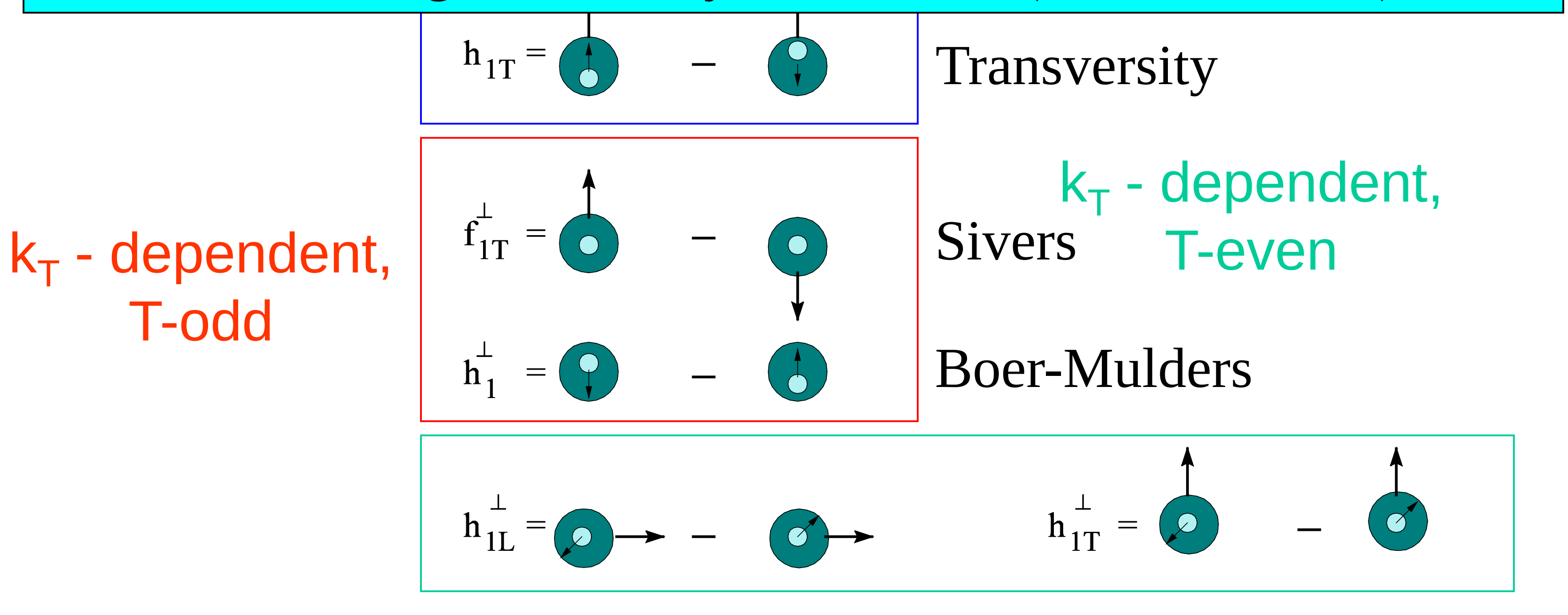
Spin and momenta can be of partons or hadrons

Quark Distribution Functions



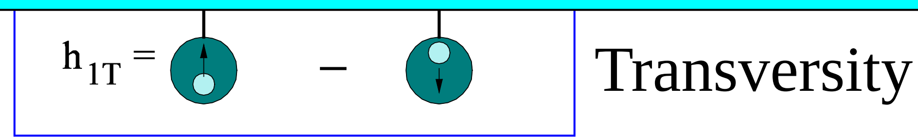
Quark Distribution Functions

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



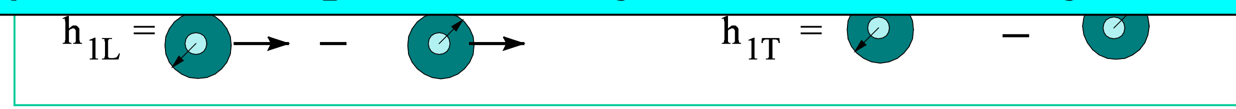
Quark Distribution Functions

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



k_T - dependent,

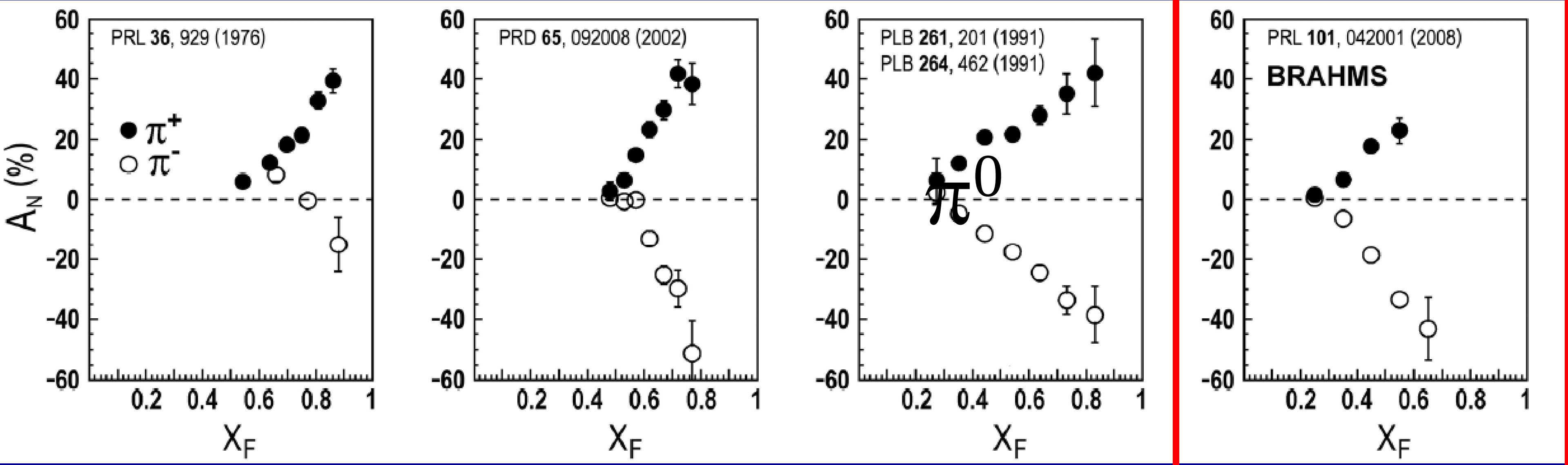
Relevant measurements in simpler systems (DIS, e+e-) only starting to be made over the last ~5 years, providing evidence that many of these correlations are finite in nature! Rapidly advancing field both experimentally and theoretically!



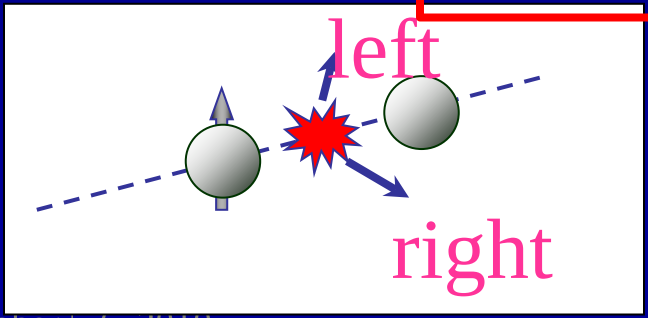
Transverse Single-Spin Asymmetries: From Low to High Energies!

BRAHMS

ANL	BNL	FNAL	RHIC
$\sqrt{s}$=4.9 GeV	$\sqrt{s}$=6.6 GeV	$\sqrt{s}$=19.4 GeV	$\sqrt{s}$=62.4 GeV

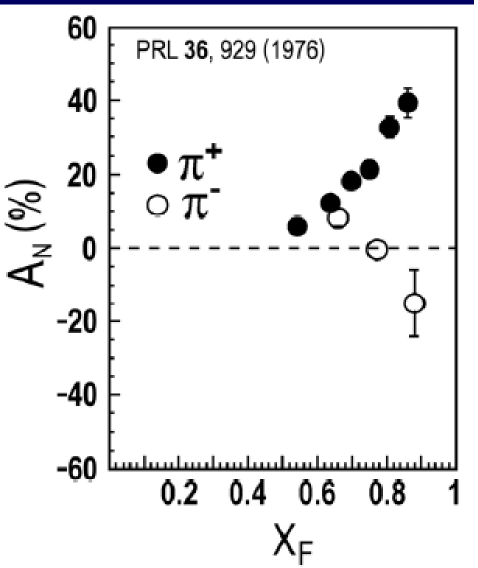


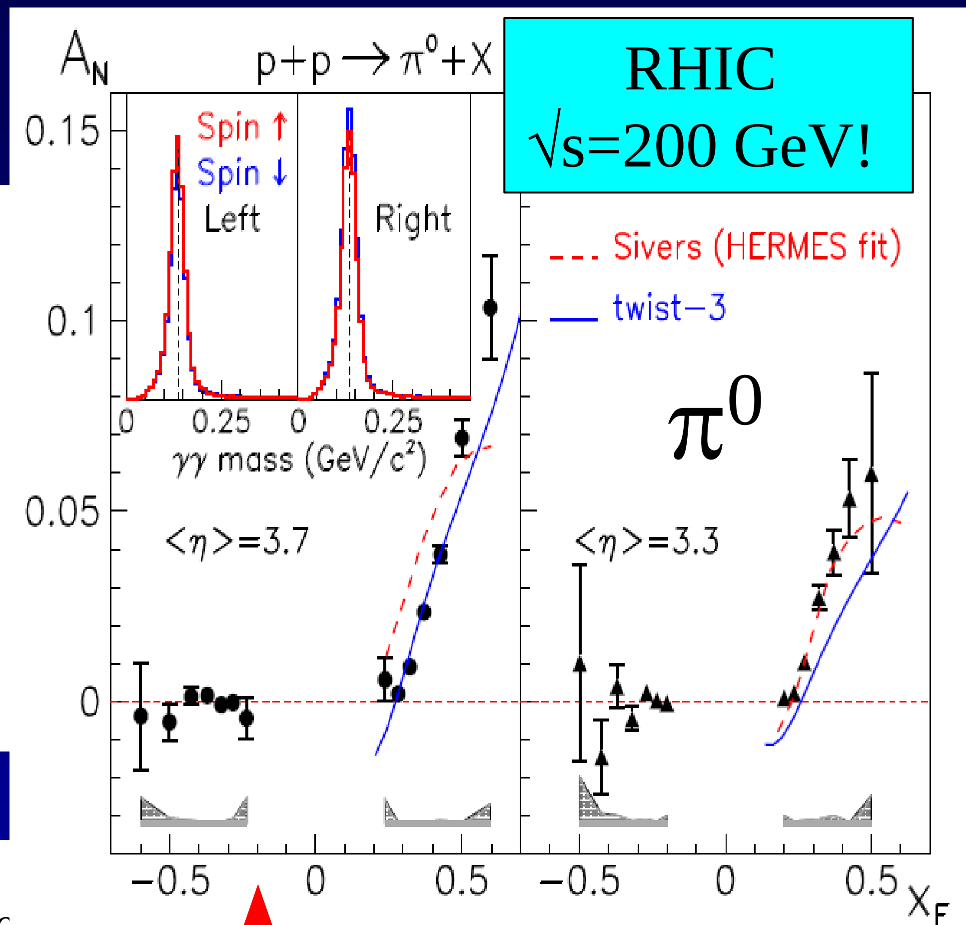
$$x_F = 2 p_{long} / \sqrt{s}$$



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

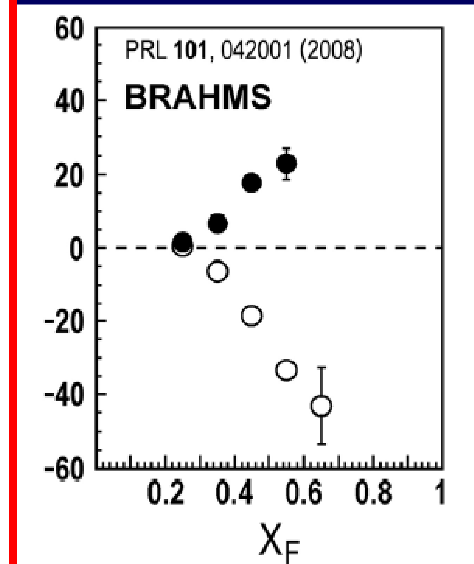
ANL
√s=4.9 GeV



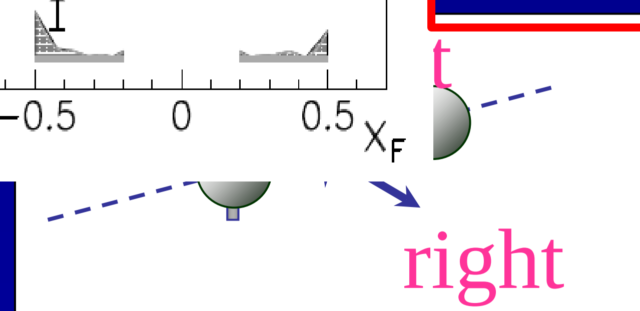


RHIC
√s=200 GeV!

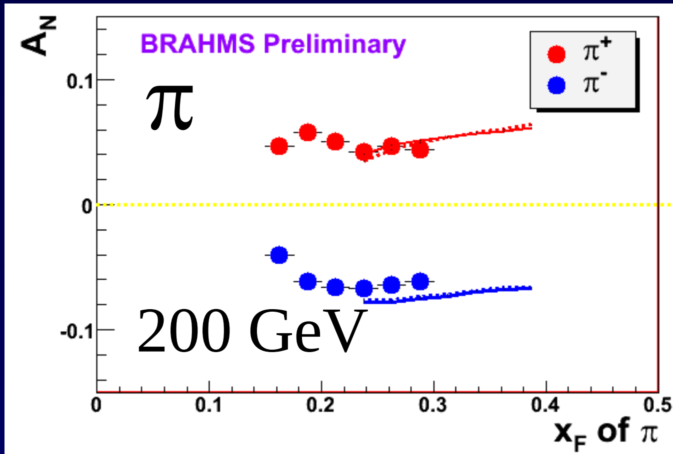
RHIC
√s=62.4 GeV

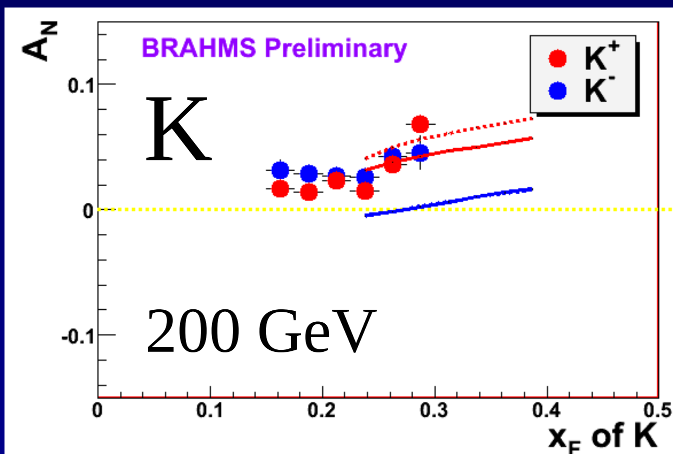


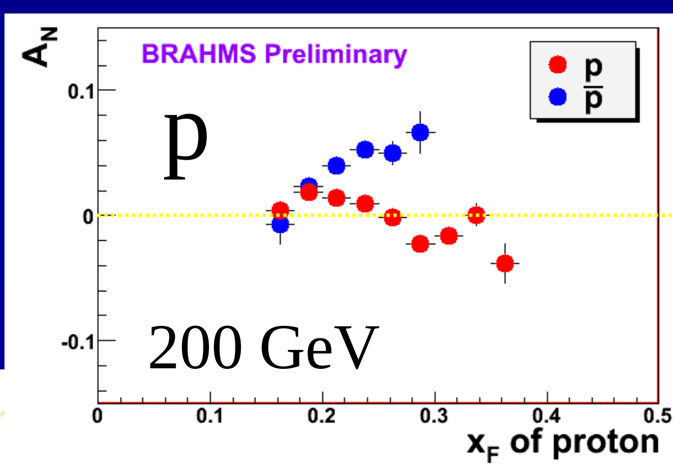
$x_F = 2p_{lc}$



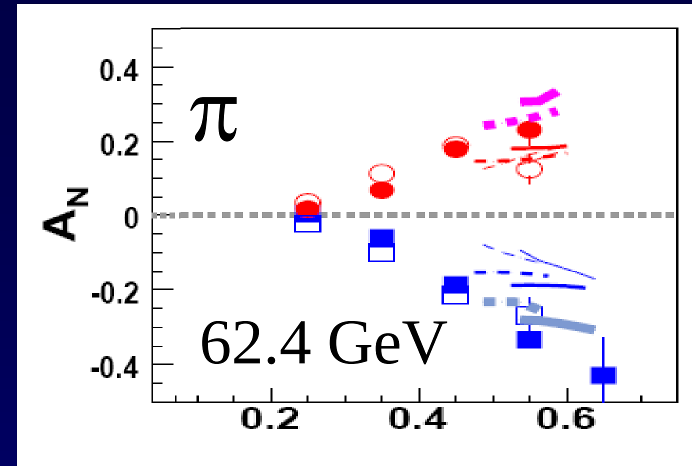
STAR



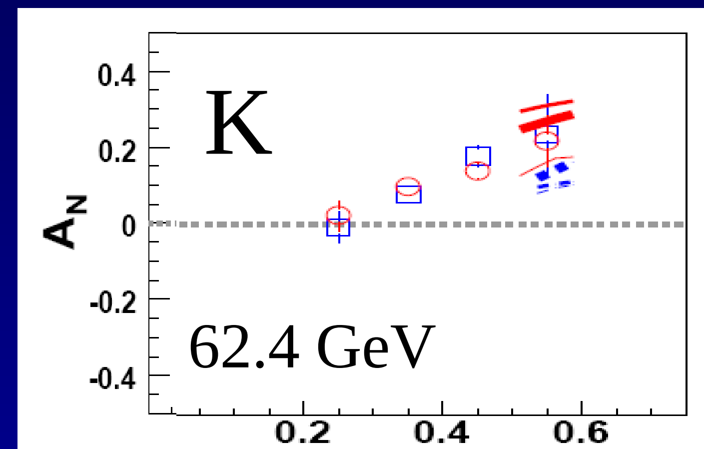




π, K, p at 200 and 62.4 GeV

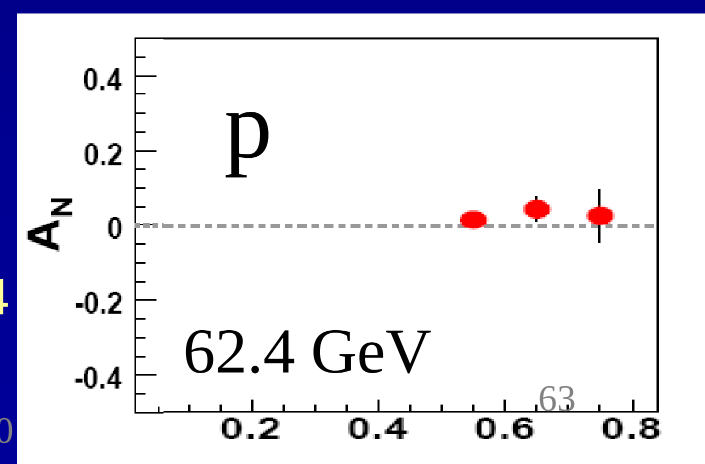


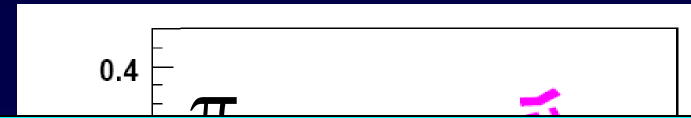
Note different scales →



K- asymmetries underpredicted

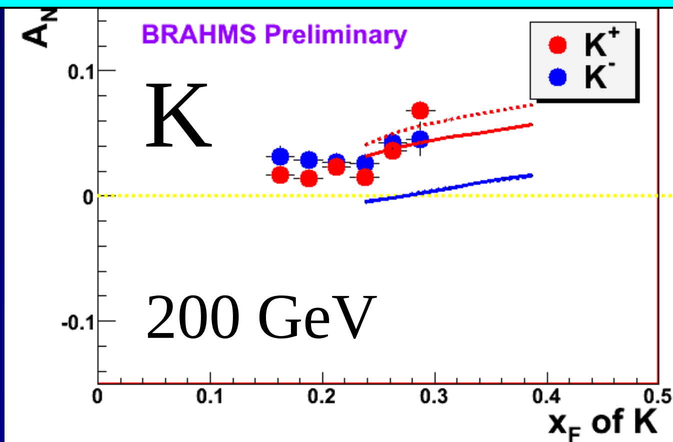
Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement

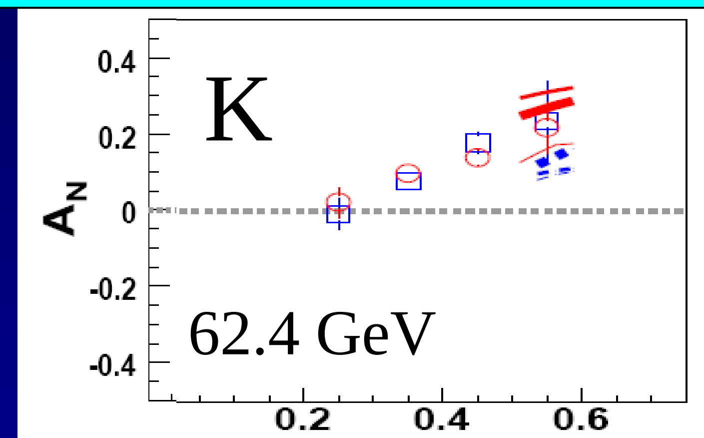




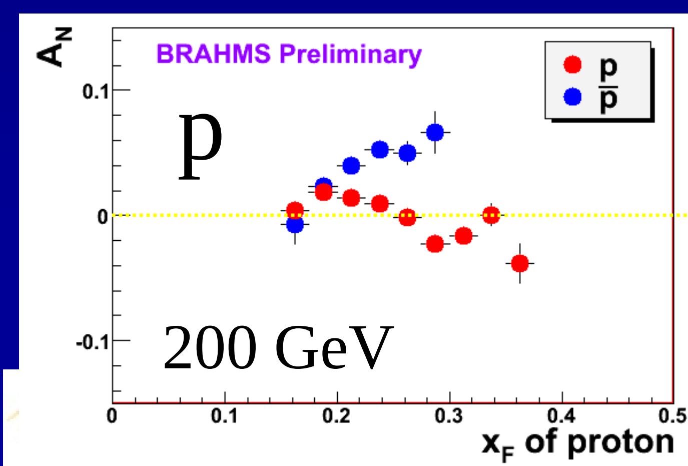
Pattern of pion species asymmetries in the forward direction → valence quark effect.

But this conclusion confounded by kaon and antiproton asymmetries!

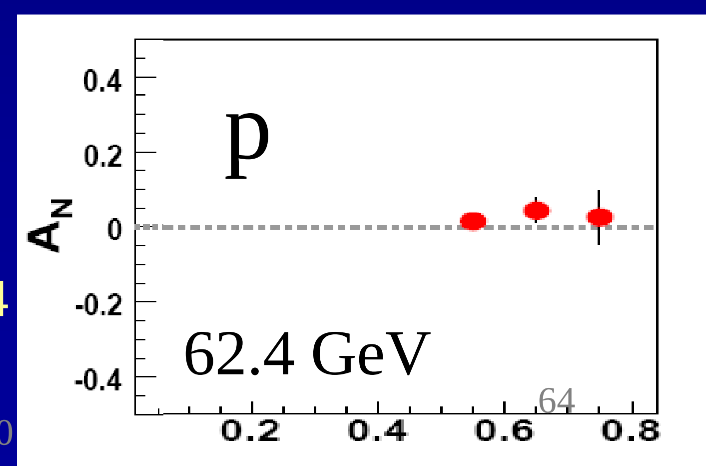




K- asymmetries underpredicted



Large antiproton asymmetry?? Unfortunately no 62.4 GeV measurement



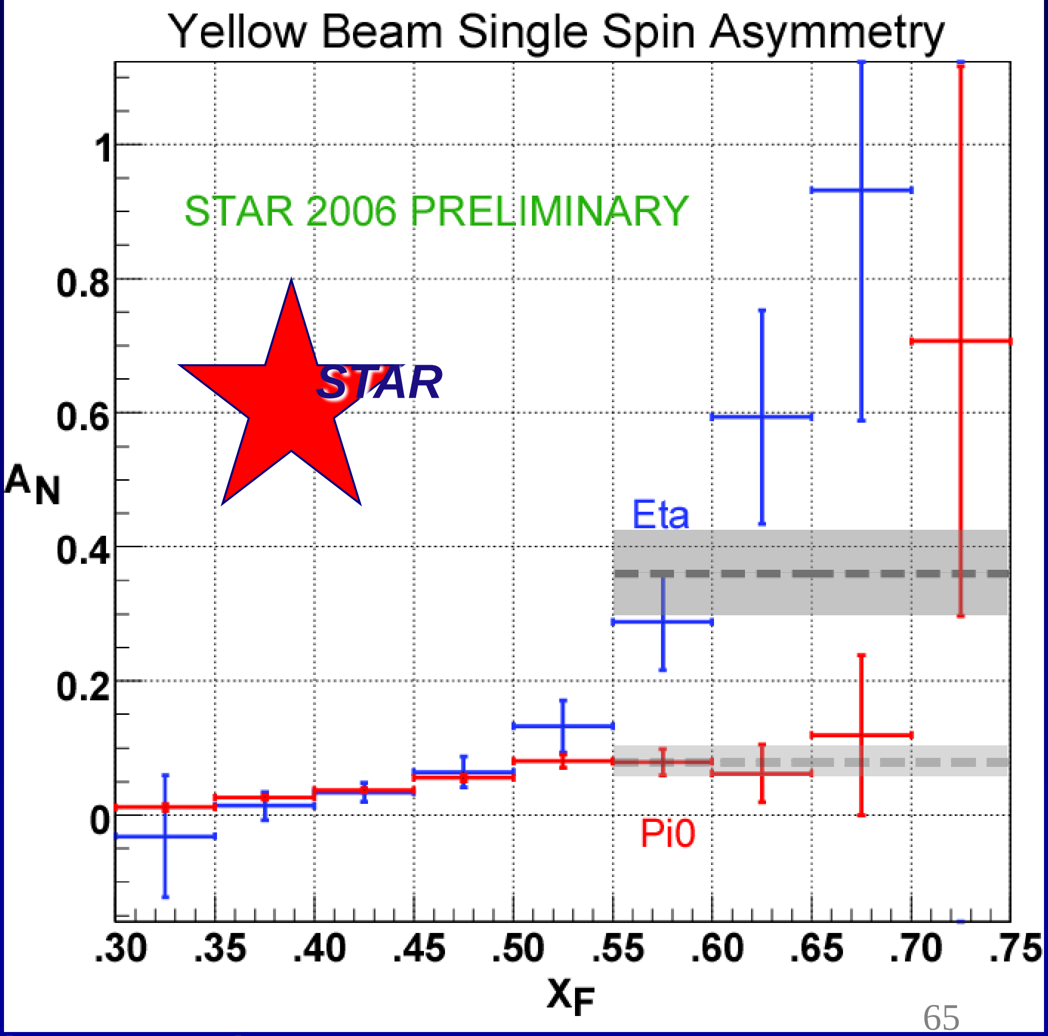
Another Surprise: Transverse Single-Spin Asymmetry in Eta Meson Production

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

Larger than the neutral pion!

$$.55 < X_F < .75$$
$$\langle A_N \rangle_\eta = 0.361 \pm 0.064$$
$$\langle A_N \rangle_\pi = 0.078 \pm 0.018$$

$$\pi^0 \equiv \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$
$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$



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

$$p^{\uparrow} + p \to \eta + X \quad \sqrt{s} = 200\ \mathrm{GeV}$$

$$\eta \to$$

Further evidence against a valence quark effect!

Larger than the neutral pion!

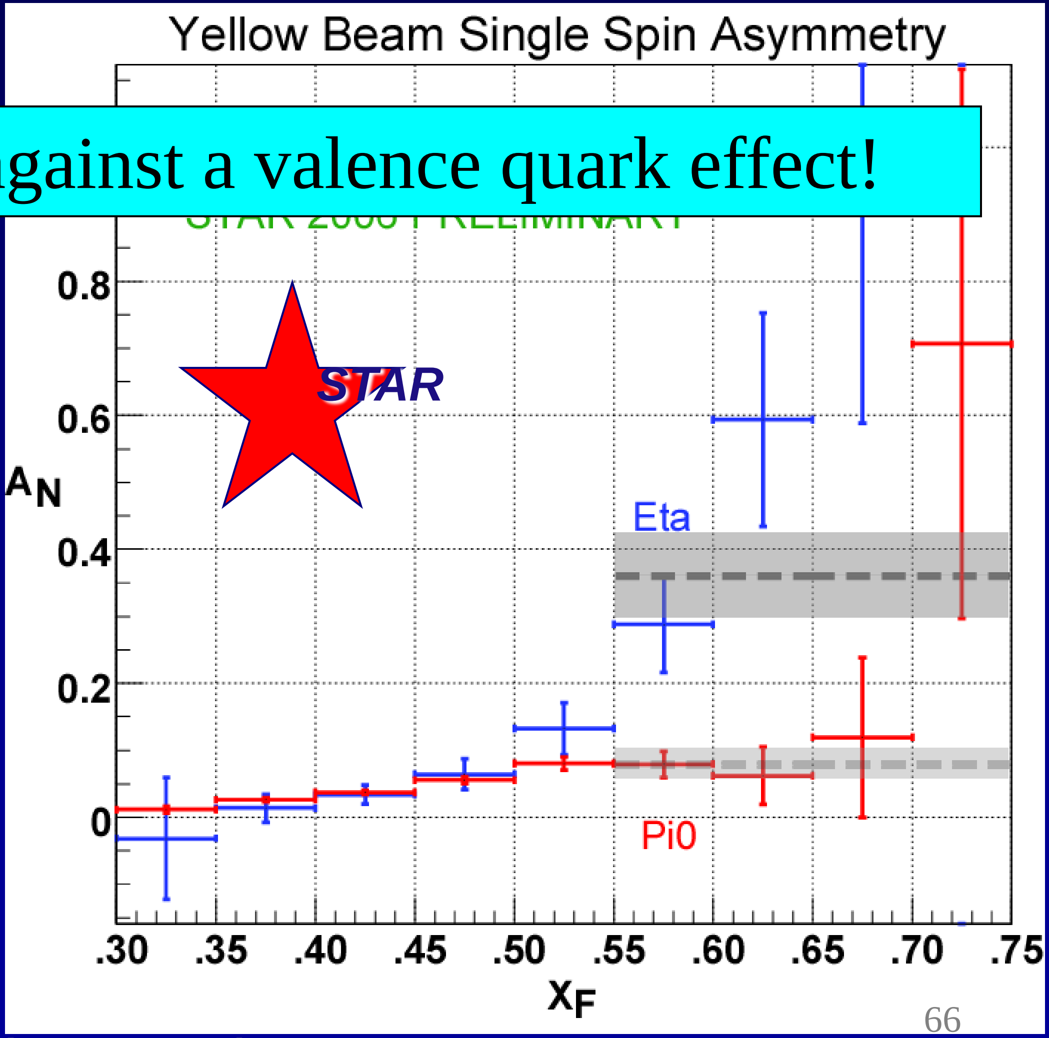
$$.55 < X_F < .75$$

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

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

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

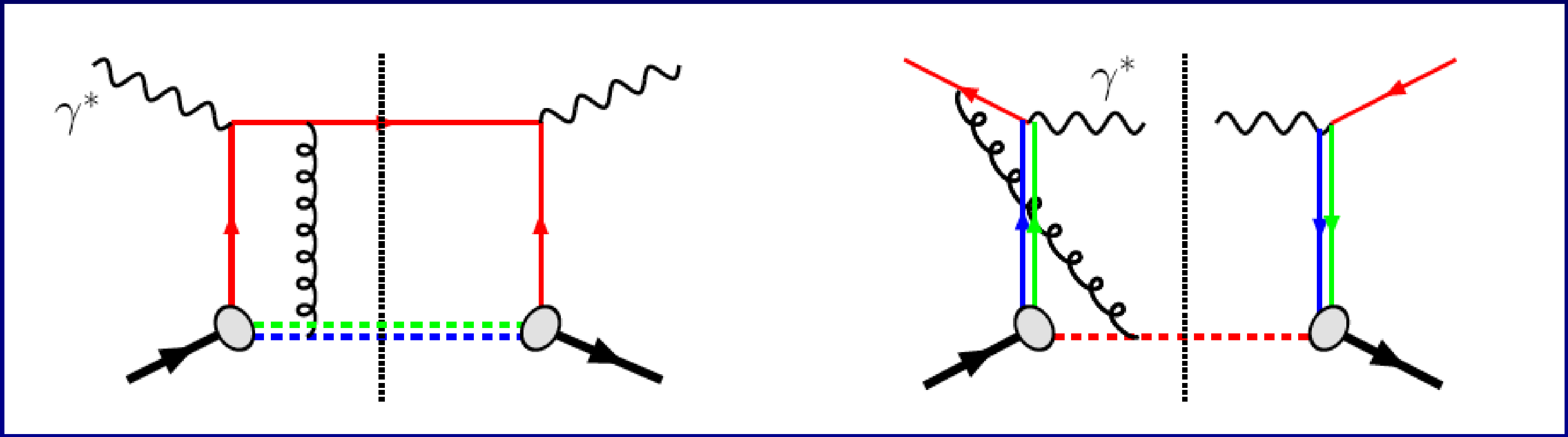
$$\eta \equiv \frac{u\bar{u} + d\bar{d} - 2s\bar{s}}{\sqrt{6}}$$



TMDs and Universality:
<u>Modified Universality</u> of Sivers Asymmetries

DIS: attractive FSI

Drell-Yan: repulsive ISI



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

TMDs and Universality:
<u>Modified Universality</u> of Sivers Asymmetries

DIS: attractive FSI

Drell-Yan: repulsive ISI

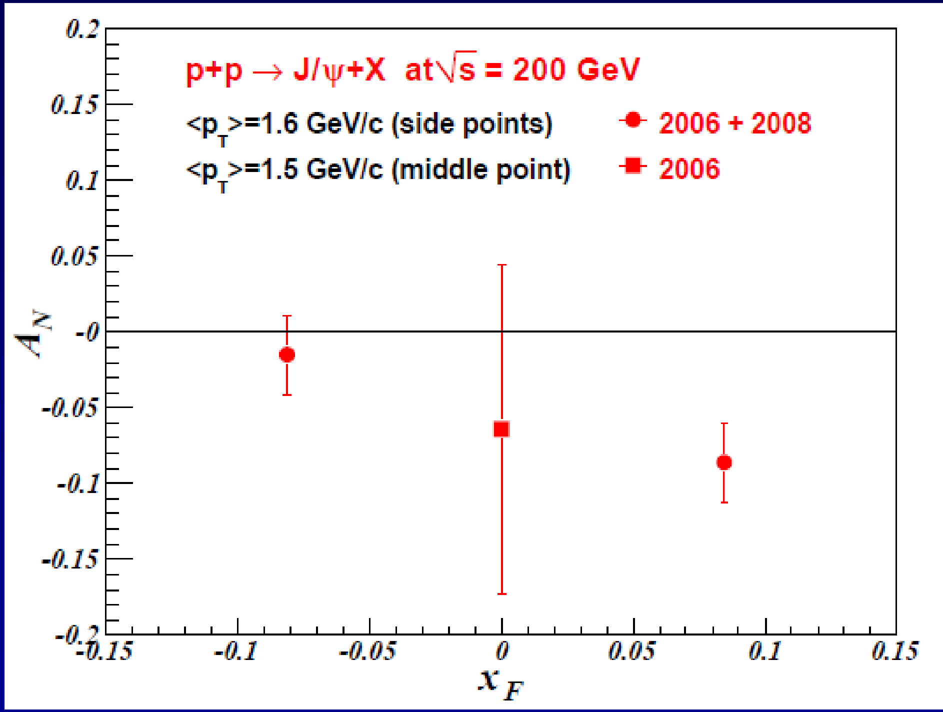
Measurements in semi-inclusive DIS already exist. A p+p measurement will be a crucial test of our understanding of QCD! But Drell-Yan in p+p requires large integrated luminosity—small, dedicated experiment currently being set up at RHIC to take transversely polarized data during 500 GeV running (longitudinal polarization at PHENIX and STAR for W program).

As a result:

$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

J/Psi A_N and Gluon Correlations with the (Transverse) Spin of the Proton

- Other consequences of non-universality of Sivers TMD (and other T-odd TMDs) starting to be realized!
  - PRD 78, 014024 (2008)—F. Yuan predicts that J/Psi transverse single-spin asymmetry sensitive to J/Psi production mechanism, with different expectations for p+p vs. SIDIS
- No SIDIS measurement yet, but PHENIX just submitted result for publication!

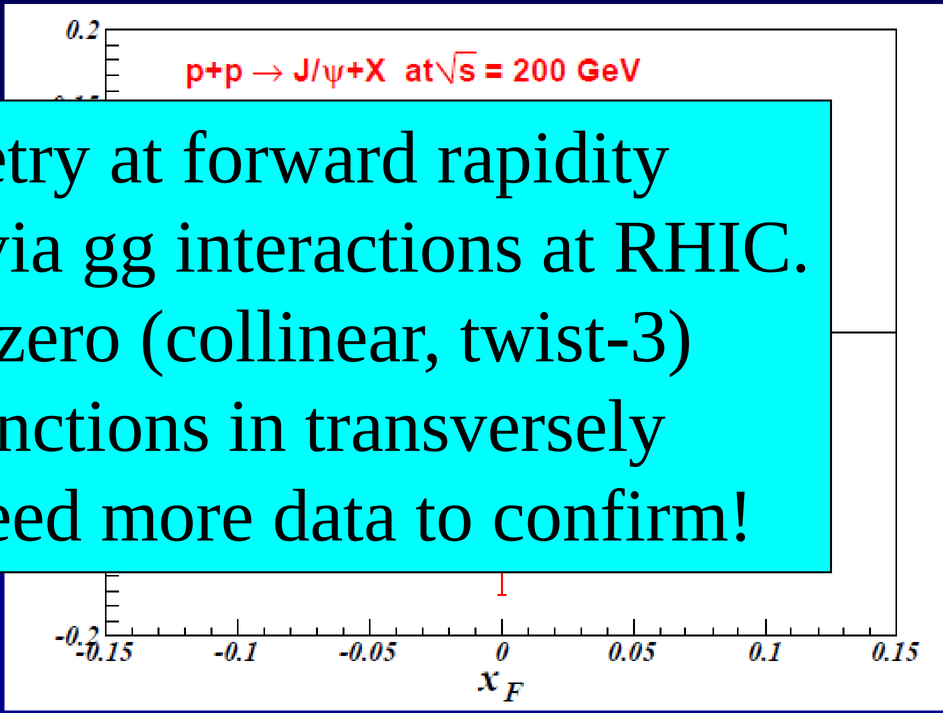


arXiv:1009.4864 [hep-ex]

J/Psi A_N and Gluon Correlations with the (Transverse) Spin of the Proton

- Other consequences of non-
  u
  (a
  st
  - production mechanism, with different expectations for p+p vs. SIDIS

3.3σ negative asymmetry at forward rapidity observed. J/Psi produced via gg interactions at RHIC. Suggests possible non-zero (collinear, twist-3) trigluon correlation functions in transversely polarized proton. Will need more data to confirm!

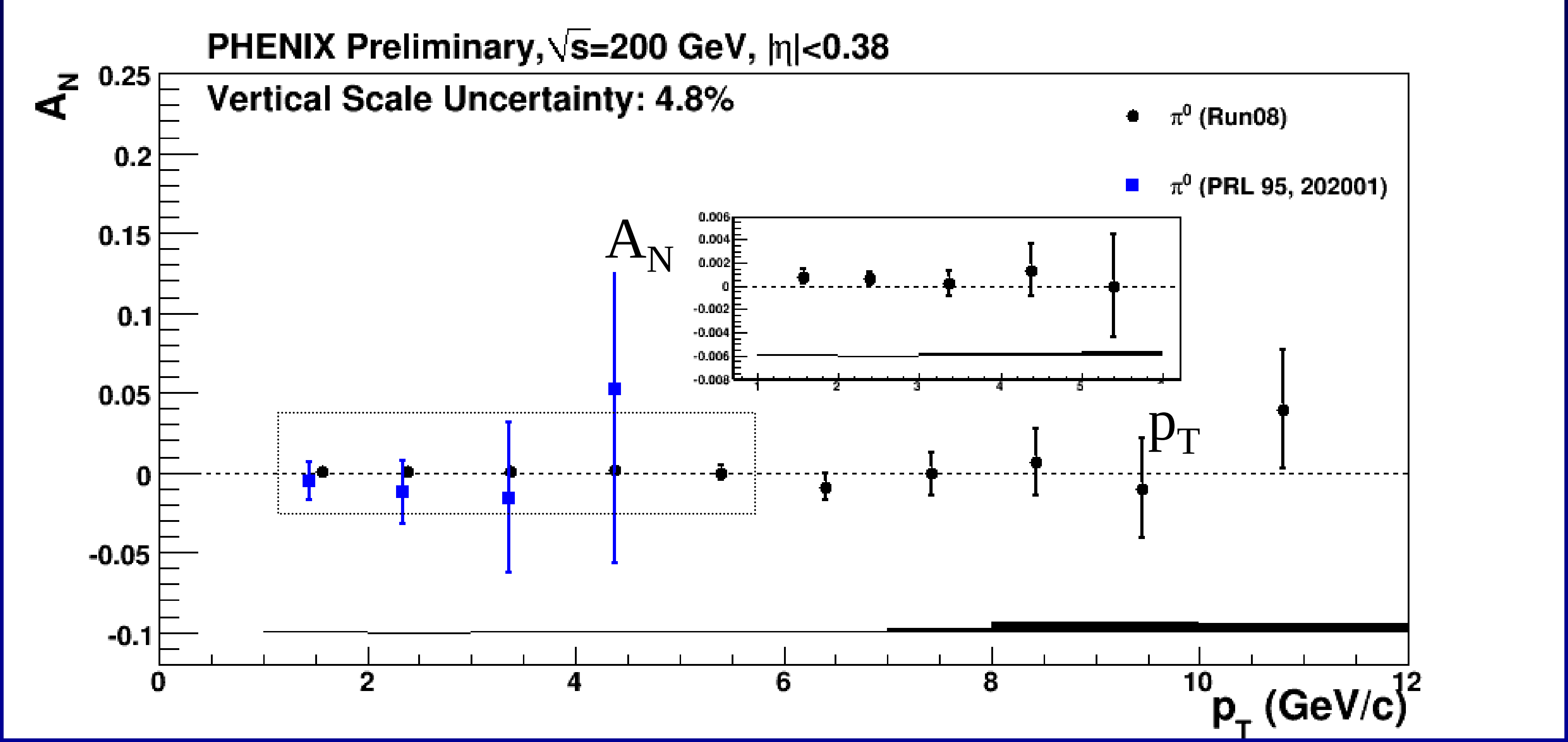


arXiv:1009.4864 [hep-ex]

- No SIDIS measurement yet, but PHENIX just submitted result for publication!

Gluons Look Different for Pions at Midrapidity??

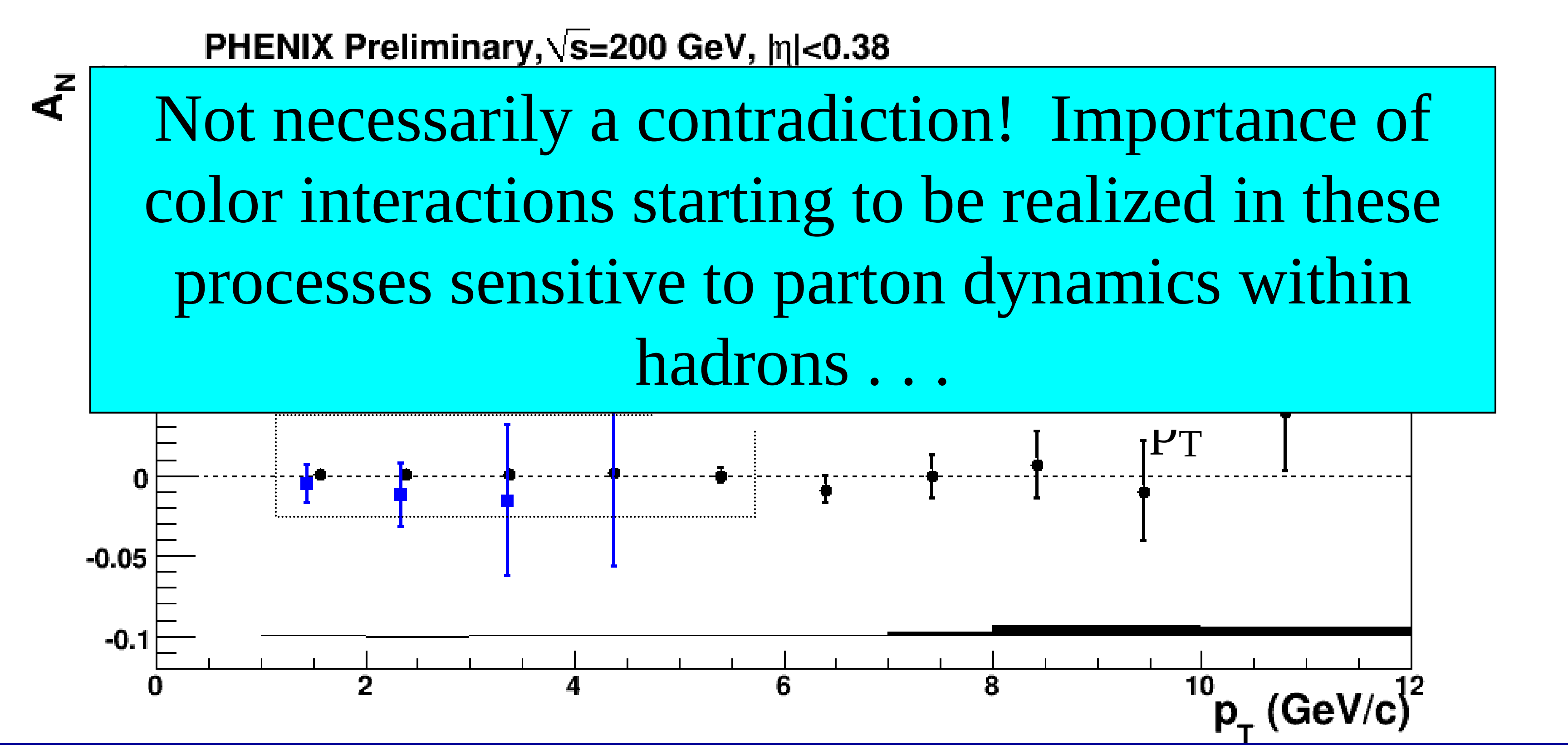
2002 Published Result 2008 Preliminary Result



Midrapidity pion production at 200 GeV dominated by gg scattering up to p_T~5 GeV/c, but transverse single-spin asymmetry measured to be tiny . . . Contradicts J/Psi result??

Gluons Look Different for Pions at Midrapidity??

2002 Published Result 2008 Preliminary Result



Not necessarily a contradiction! Importance of color interactions starting to be realized in these processes sensitive to parton dynamics within hadrons . . .

Midrapidity pion production at 200 GeV dominated by gg scattering up to p_T~5 GeV/c, but transverse single-spin asymmetry measured to be tiny . . . Contradicts J/Psi result??

Factorization and Color

- Earlier this year—groundbreaking work by T. Rogers, P. Mulders claiming that pQCD factorization is broken in processes involving more than two hadrons total if parton k_T is taken into account (TMD pdfs and/or FFs)
  - PRD 81, 094006 (2010)
  - No unique color flow

Factorization and Color

- Earlier this year—groundbreaking work by T.
  R
  fa
  m en
  into account (TMD pdfs and/or FFs)
  - PRD 81, 094006 (2010)
  - No unique color flow

An exciting sub-field—lots of recent experimental activity, and theoretical questions probing deep issues of both universality and factorization in (perturbative) QCD!

Nucleon Structure and Spin-Momentum Correlations

Transversity : correlation between transverse proton spin and quark spin

S_p– S_q – coupling?

Sivers : correlation between transverse proton spin and quark transverse momentum

S_p-- L_q– coupling???

Boer-Mulders: correlation between transverse quark spin and quark transverse momentum

S_q-- L_q– coupling???

Nucleon Structure and Spin-Momentum Correlations

Transversity : correlation between transverse proton spin and quark spin

Long-term goal: Description of the nucleon in terms of the quark and gluon wavefunctions!

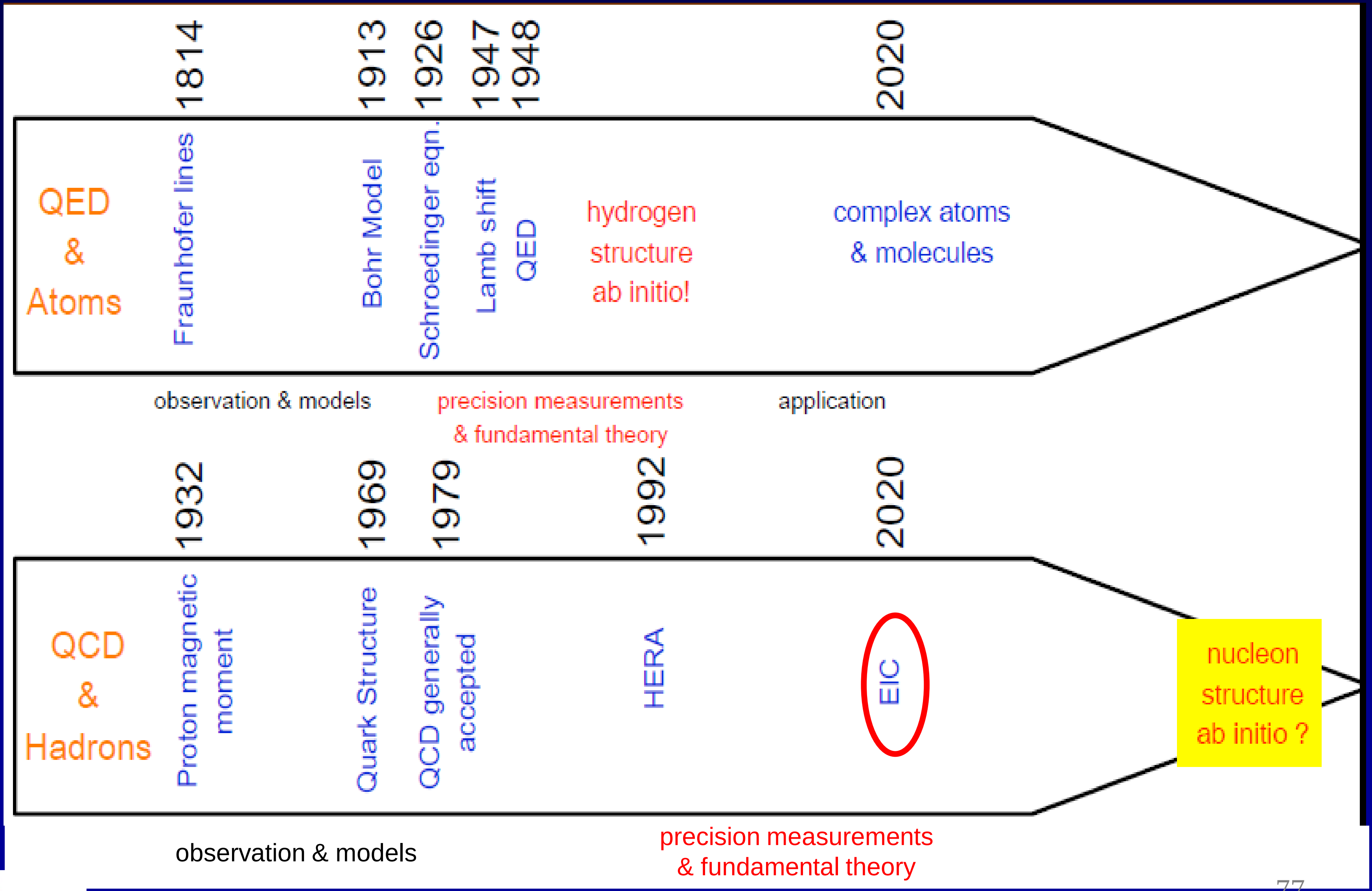
spin and quark transverse momentum

S_p-- L_q– coupling???

Boer-Mulders: correlation between transverse quark spin and quark transverse momentum

S_q-- L_q– coupling???

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

Add electron ring to RHIC at BNL, or hadron facility to CEBAF at JlLab.
Ongoing INT workshop in Seattle this fall:
http://www.int.washington.edu/PROGRAMS/10-3/

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 freedom!

- Further data from RHIC will better constrain the gluon and flavor-separated sea quark helicity distributions in the proton, and continue to push forward knowledge of the quantum mechanical spin-momentum correlations of partons in nucleons.
  - Documents outlining plans for the next decade submitted to BNL management by PHENIX and STAR last week!

- 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.

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 coaxing the secrets out of one of the most fundamental building blocks of the world around us.

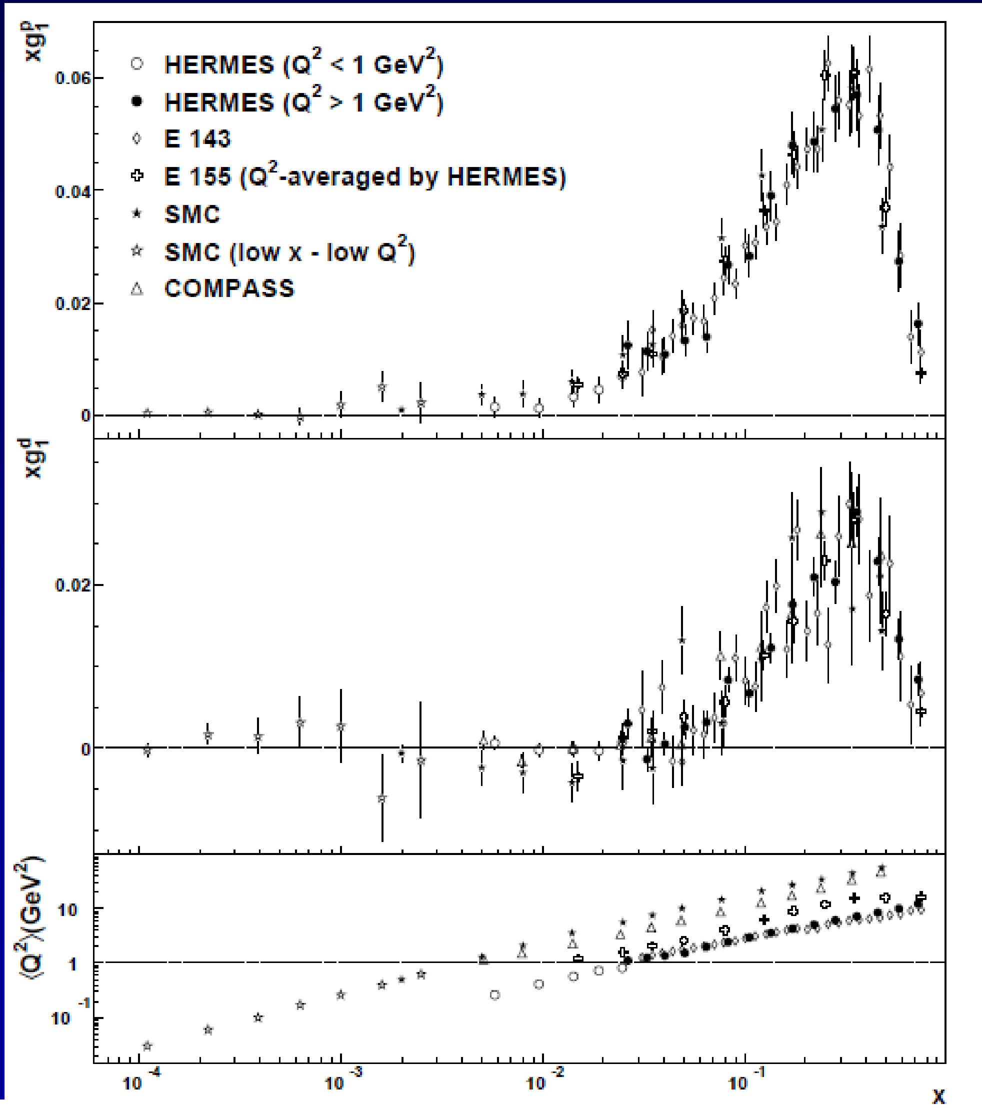
- ... or-

  – Documents outlining plans for the next decade submitted to BNL management by PHENIX and STAR last week!

- 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.

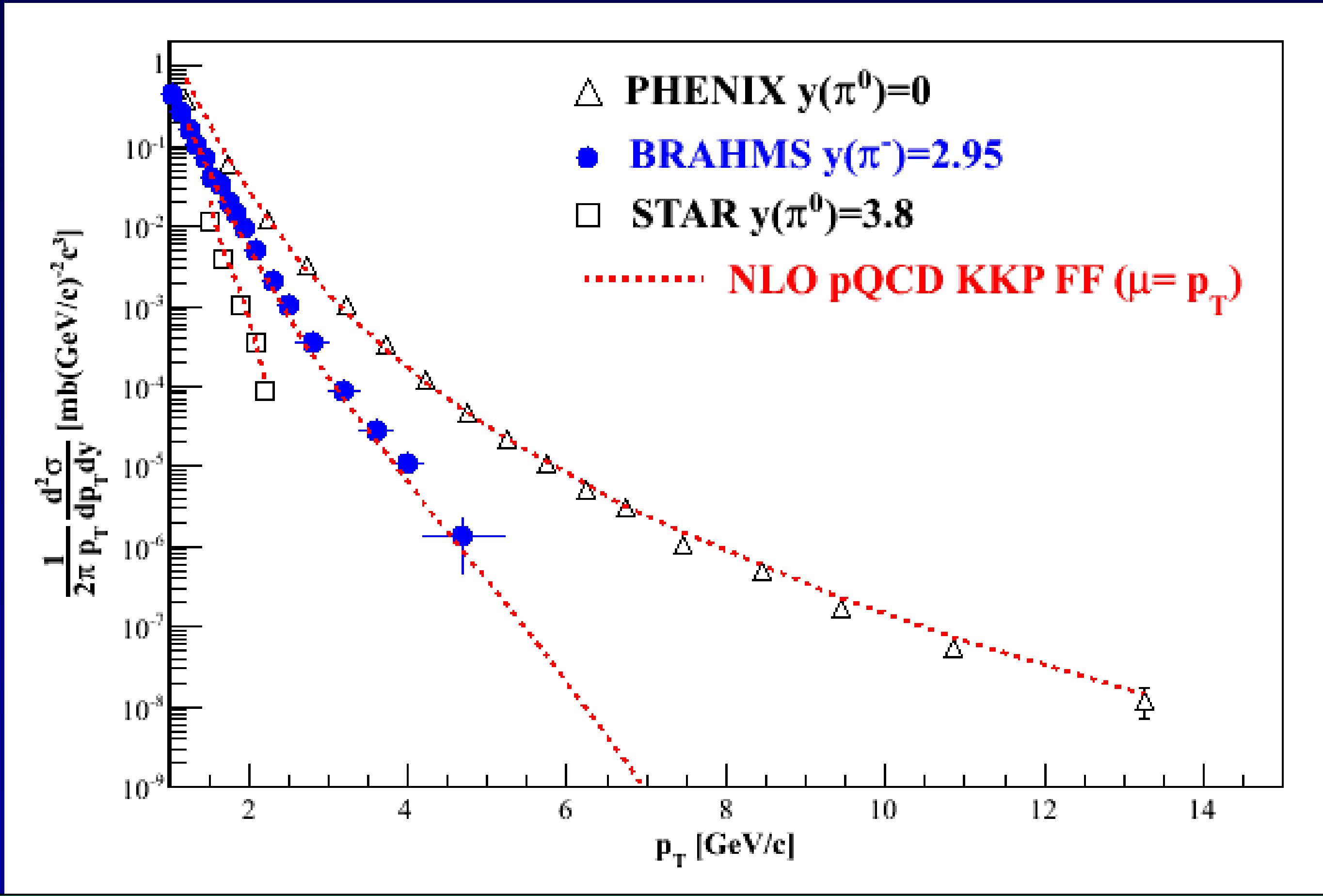
Additional Material

xg_1^p: Compilation of recent results



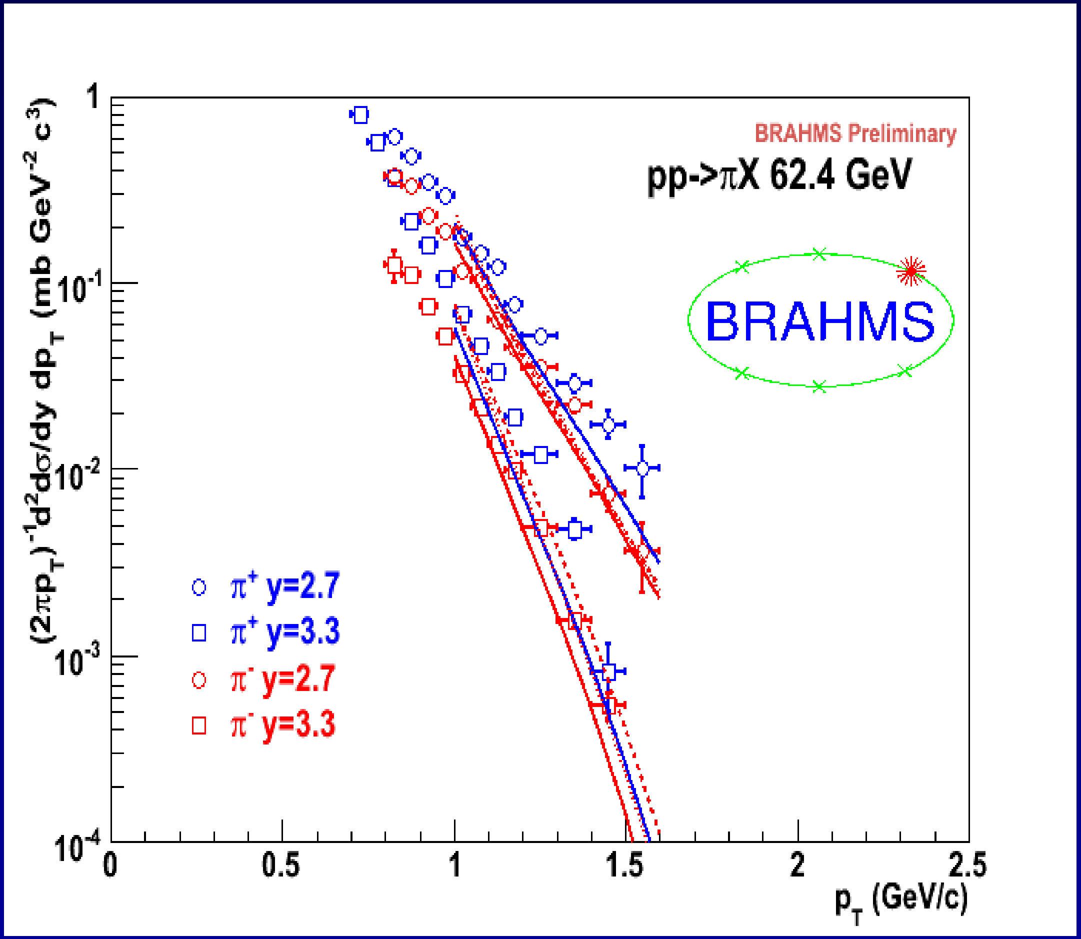
Phys.Rev.D75:012007,2007

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

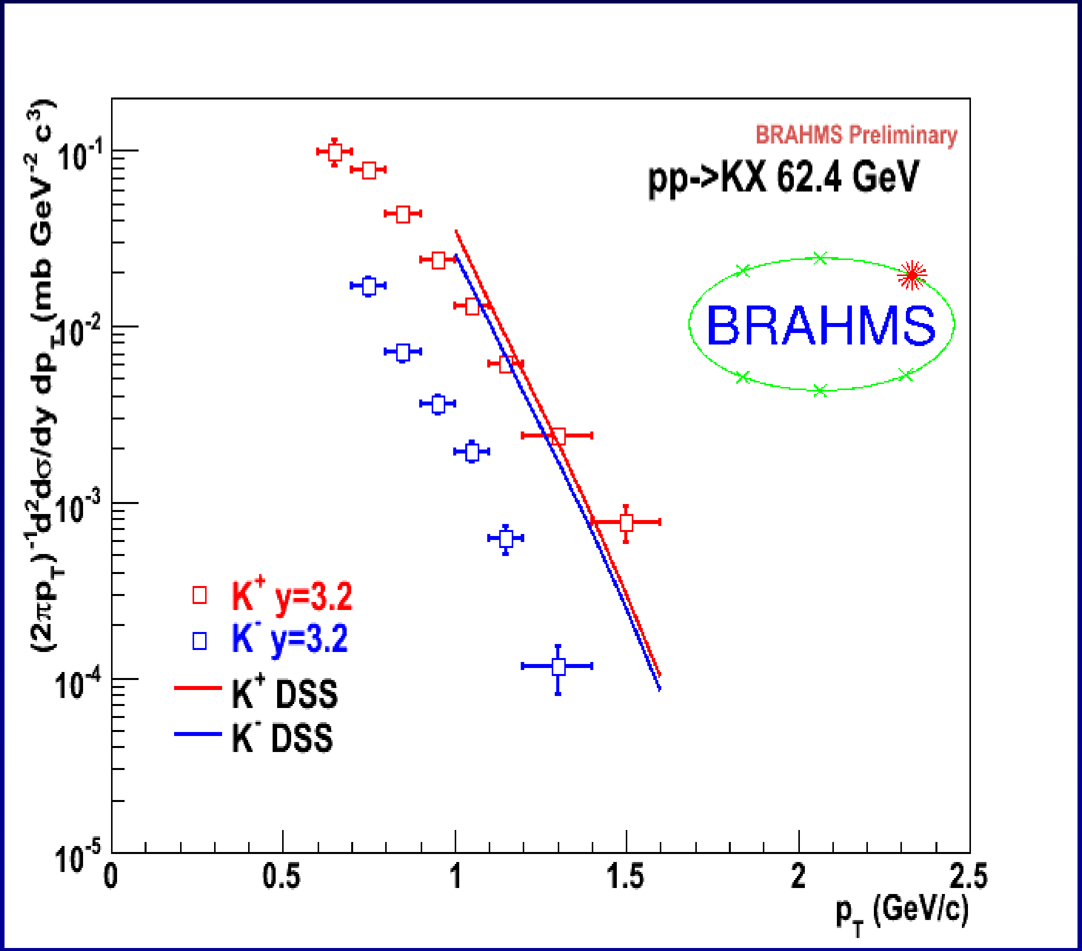


Comparison of NLO pQCD calculations with BRAHMS π data at high rapidity. The calculations are for a scale factor of $\mu = p_T$, KKP (solid) and DSS (dashed) with CTEQ5 and CTEQ6.5.

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(??).

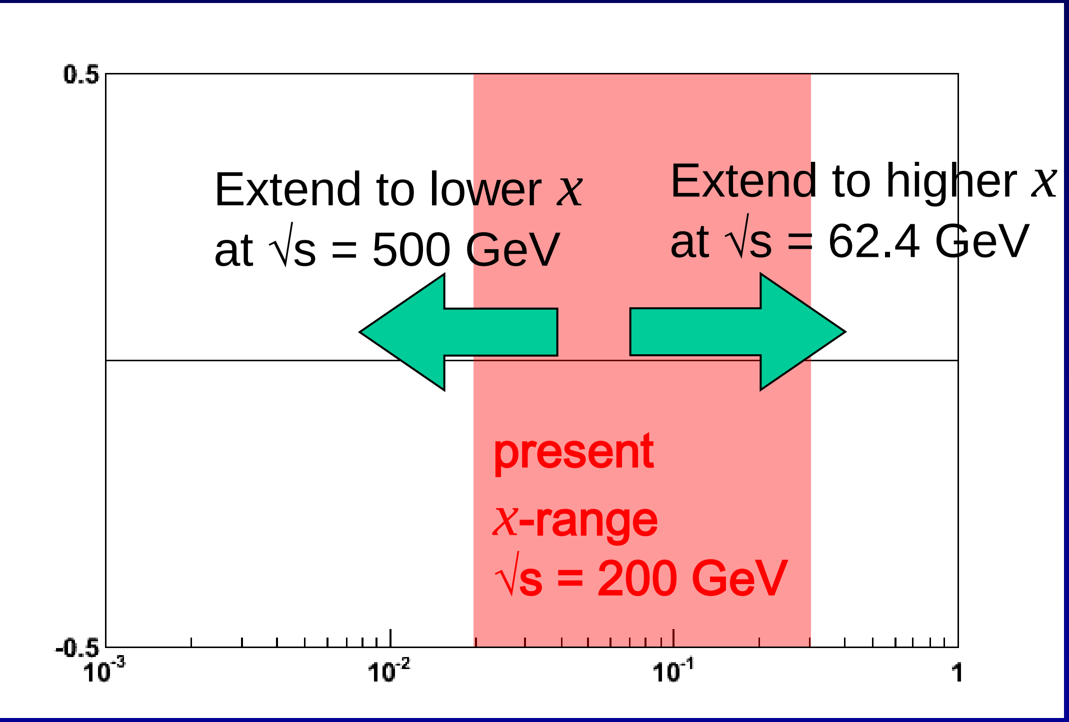
Related to FF's? PDF's??

K^+: Not bad!
K^-: Hmm…

Fragmentation Functions (FF's): Improving Our Input for Inclusive Hadronic Probes

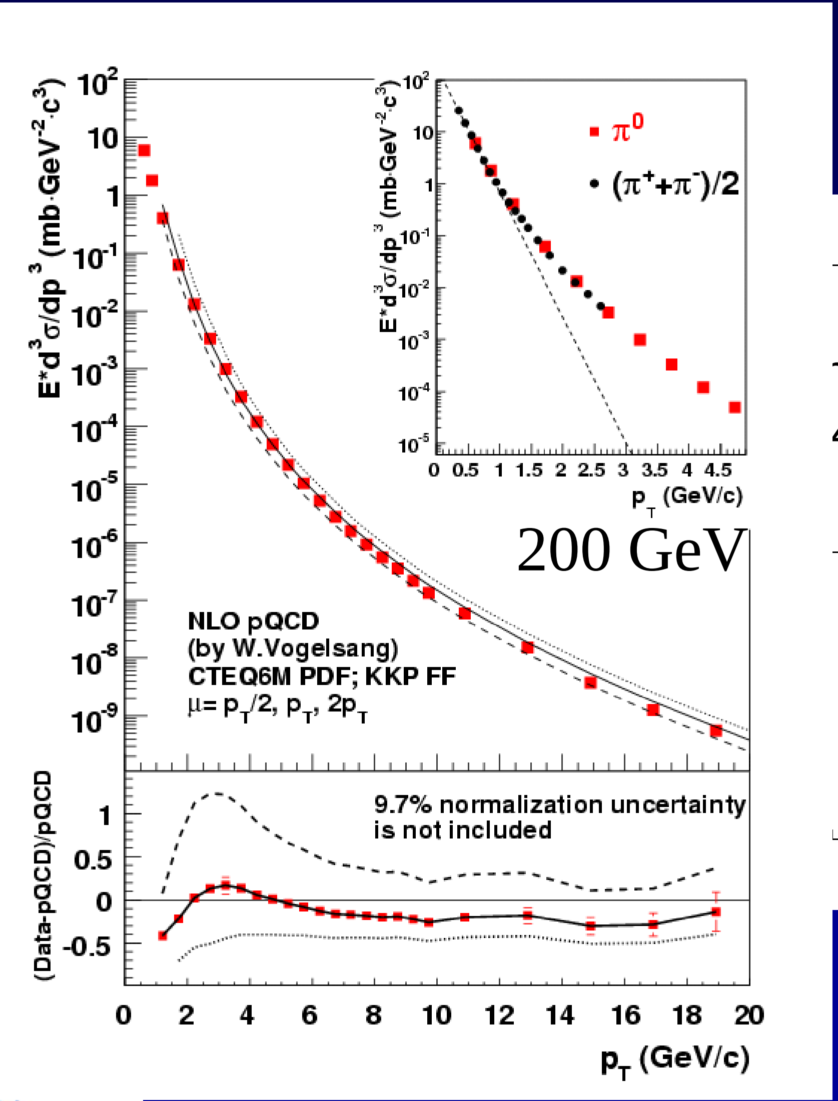
- FF's not directly calculable from theory—need to be measured and fitted experimentally
- The better we know the FF's, the tighter constraints we can put on the polarized parton distribution functions!
- Traditionally from e+e- data—clean system!
- Framework now developed to extract FF's using all available data from deep-inelastic scattering and hadronic collisions as well as e+e-
  - de Florian, Sassot, Stratmann: PRD75:114010 (2007) and arXiv:0707.1506

Extending x Coverage

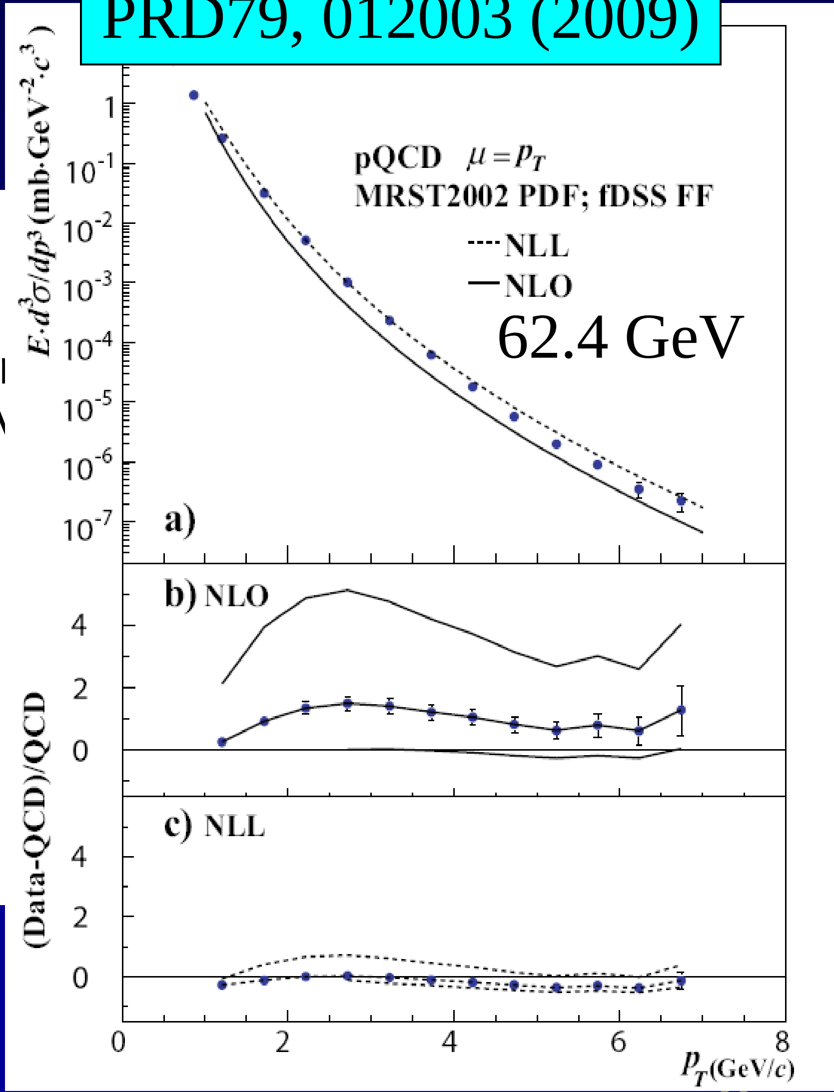


- Measure in different kinematic regions
  - e.g. forward vs. central
- Change center-of-mass energy
  - Most data so far at 200 GeV
  - Brief run in 2006 at 62.4 GeV
  - First 500 GeV data-taking to start next month!

Extending x Coverage

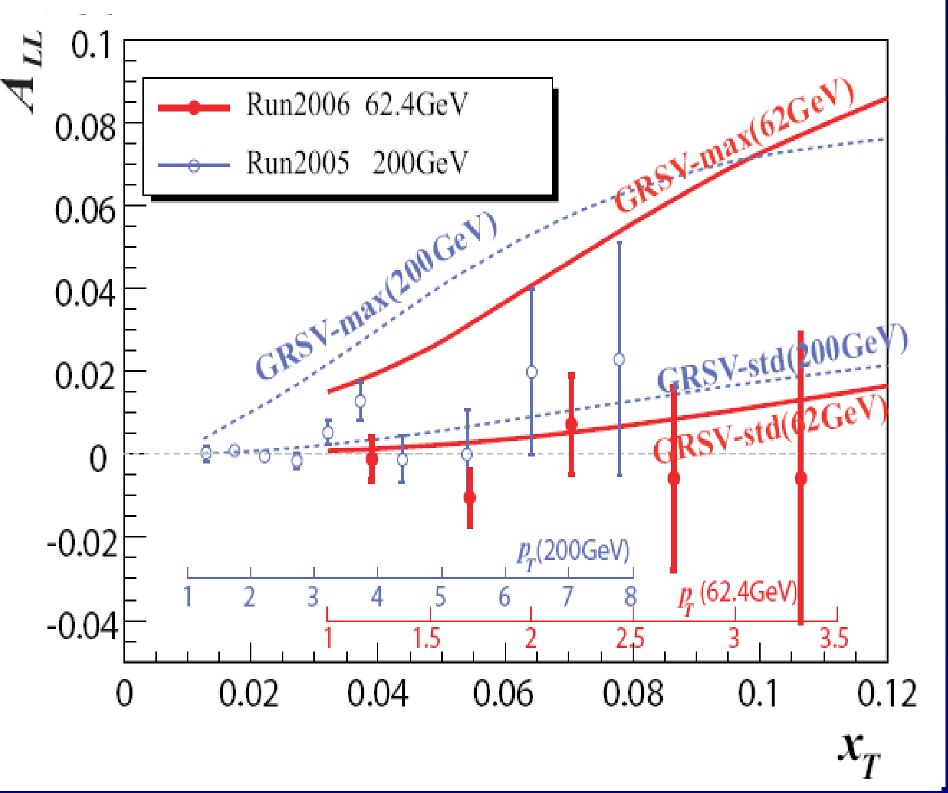


PRD79, 012003 (2009)



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}).

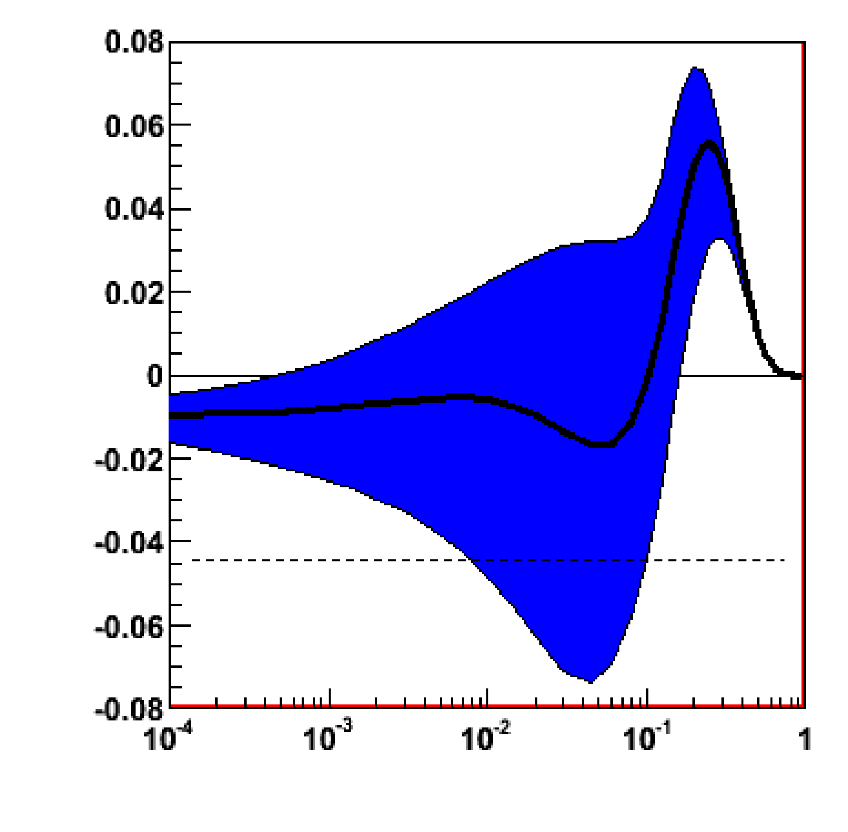
$$0.02 < x_{gluon} < 0.3 \quad (\sqrt{s} = 200\,\text{GeV})$$

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

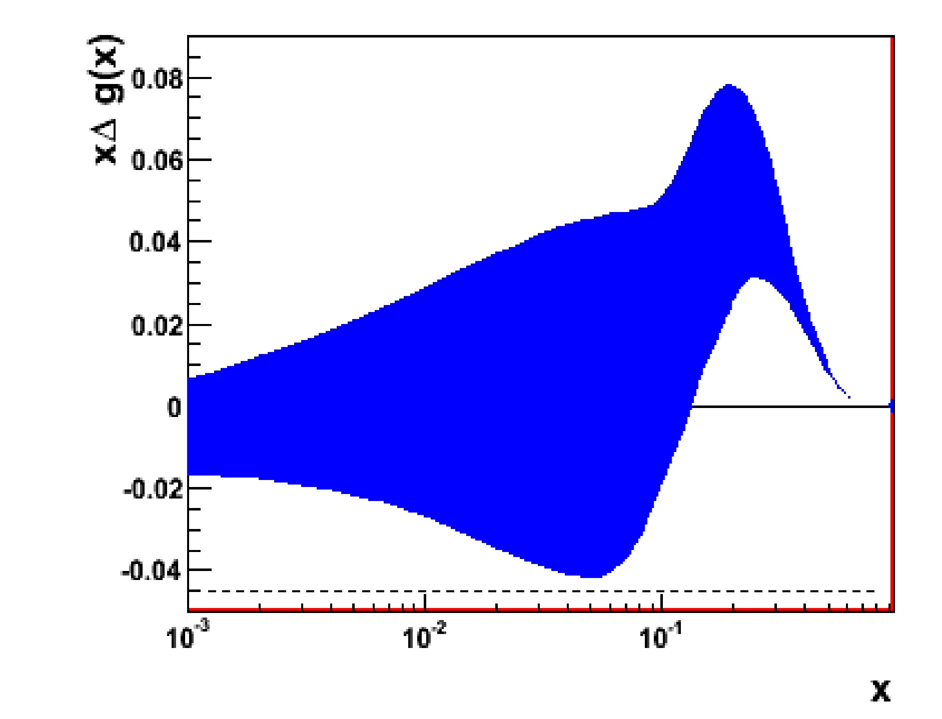
PRD79, 012003 (2009)

Inclusion of New 2009 PHENIX π^0 A_{LL}

- K. Boyle, SPIN 2010
- Include new π^0 A_{LL} data from PHENIX within DSSV framework



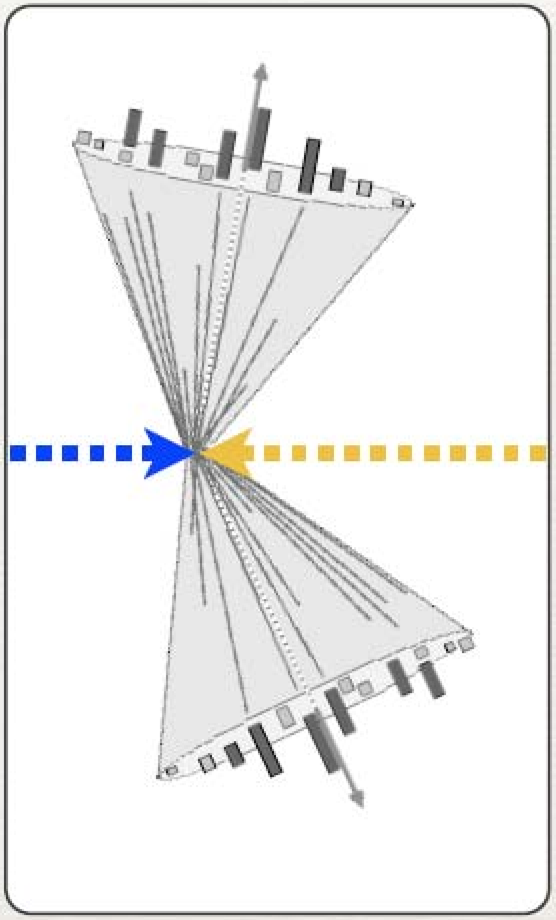
Previously (DSSV)



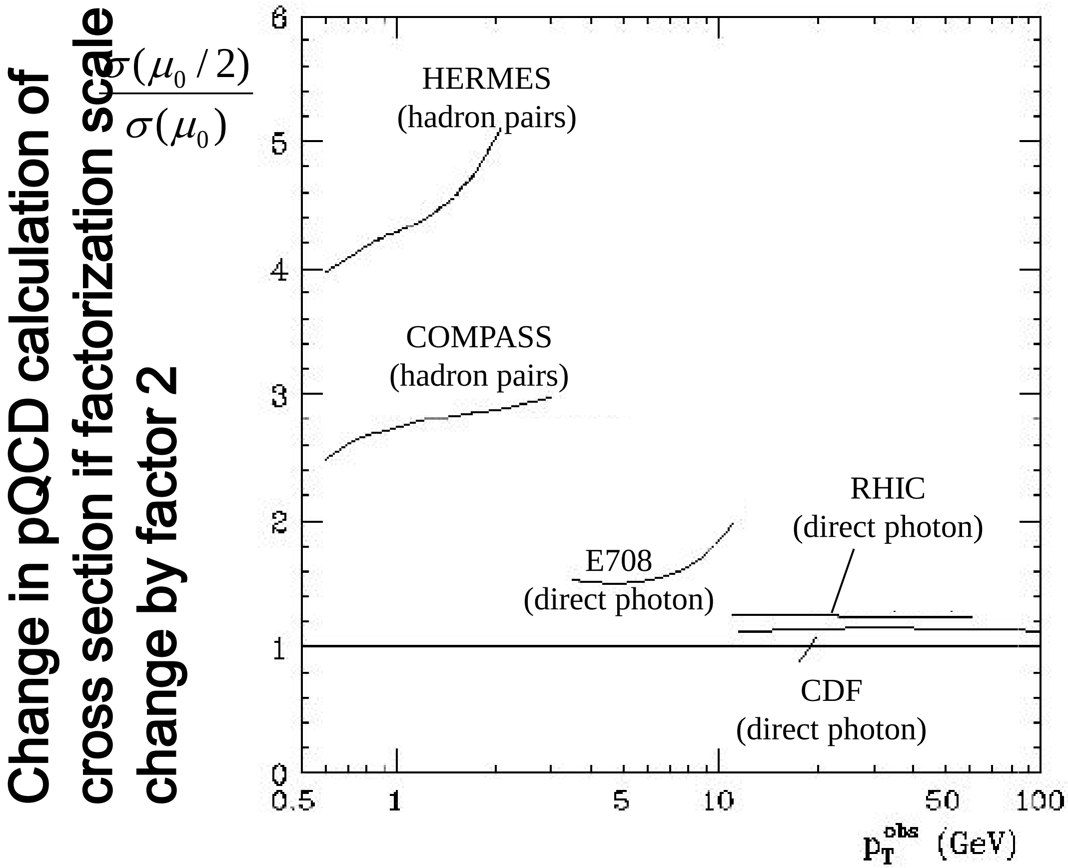
With new PHENIX data—stronger constraints on negative values

Jet Reconstruction

- Midpoint Cone Algorithm with Split-Merge
  - Cone Radius: 0.7
  - Seed 0.5 GeV
- Dijet Cuts
  - Asymmetric p_T cut
    - $\max(p_{T1}, p_{T2}) > 10$
    - $\min(p_{T1}, p_{T2}) > 7$
  - Back-to-back in ϕ



pQCD Scale Dependence at RHIC vs. Spin-Dependent DIS



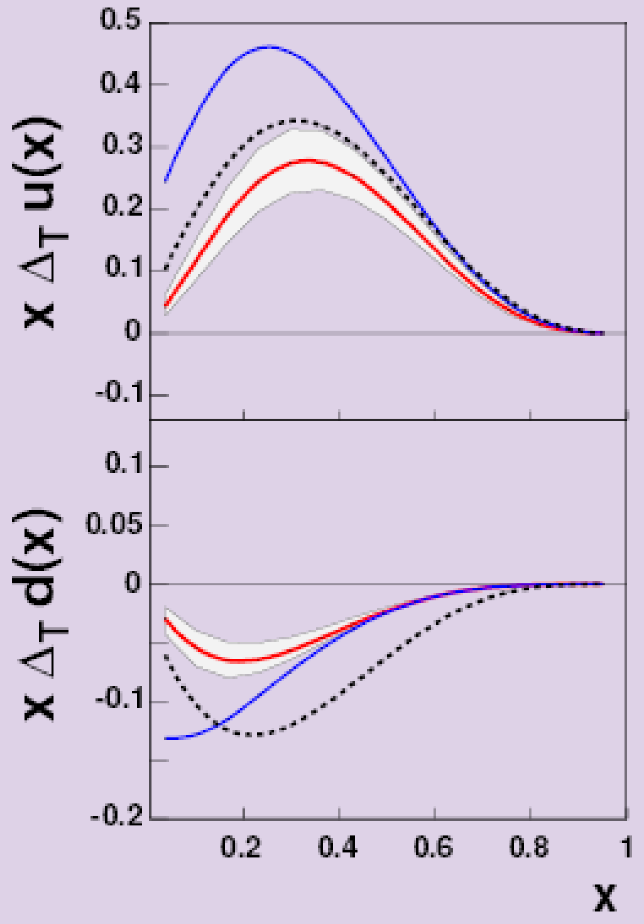
Scale dependence benchmark:

Tevatron ~ 1.2
RHIC ~ 1.3
COMPASS ~ 2.5 – 3
HERMES ~ 4 – 5

➔ Scale dependence at RHIC is significantly reduced compared to fixed-target polarized DIS.

Transversity vs. helicity

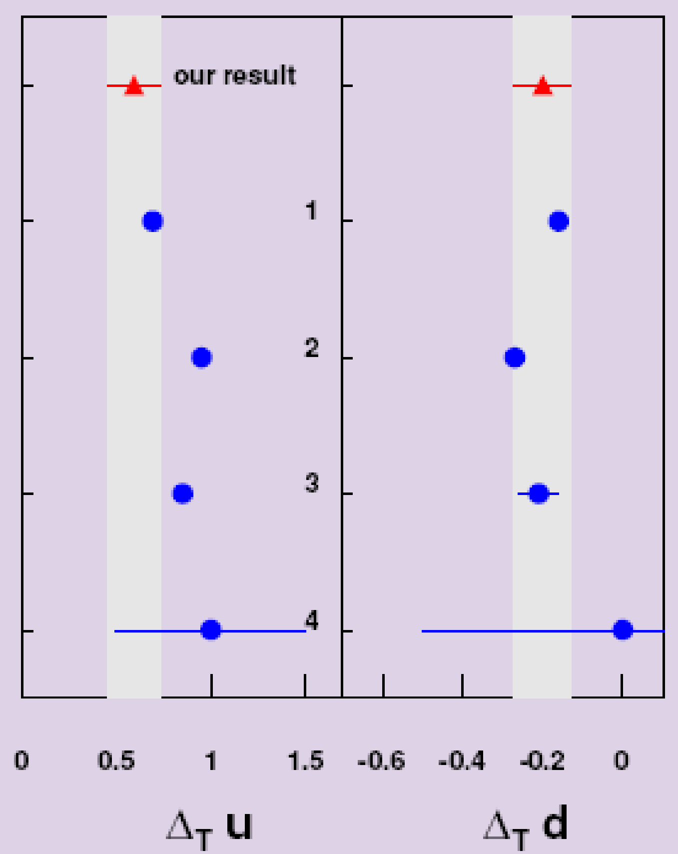
Prokudin et al. at Ferrara



1. Solid red line – transversity distribution
$$\Delta_T q(x)$$
this analysis at $Q^2 = 2.4$ 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

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

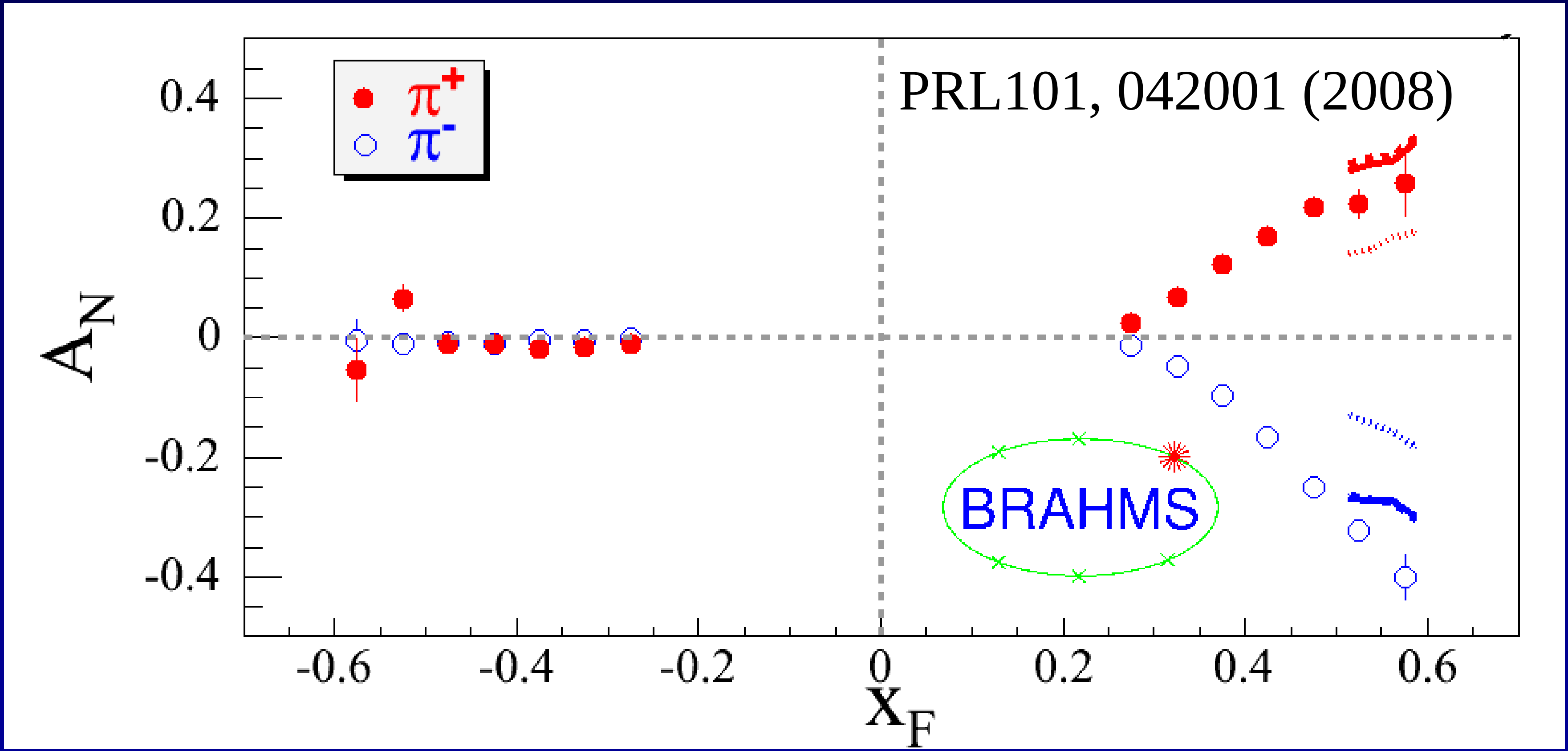


Prokudin et al. at Ferrara

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

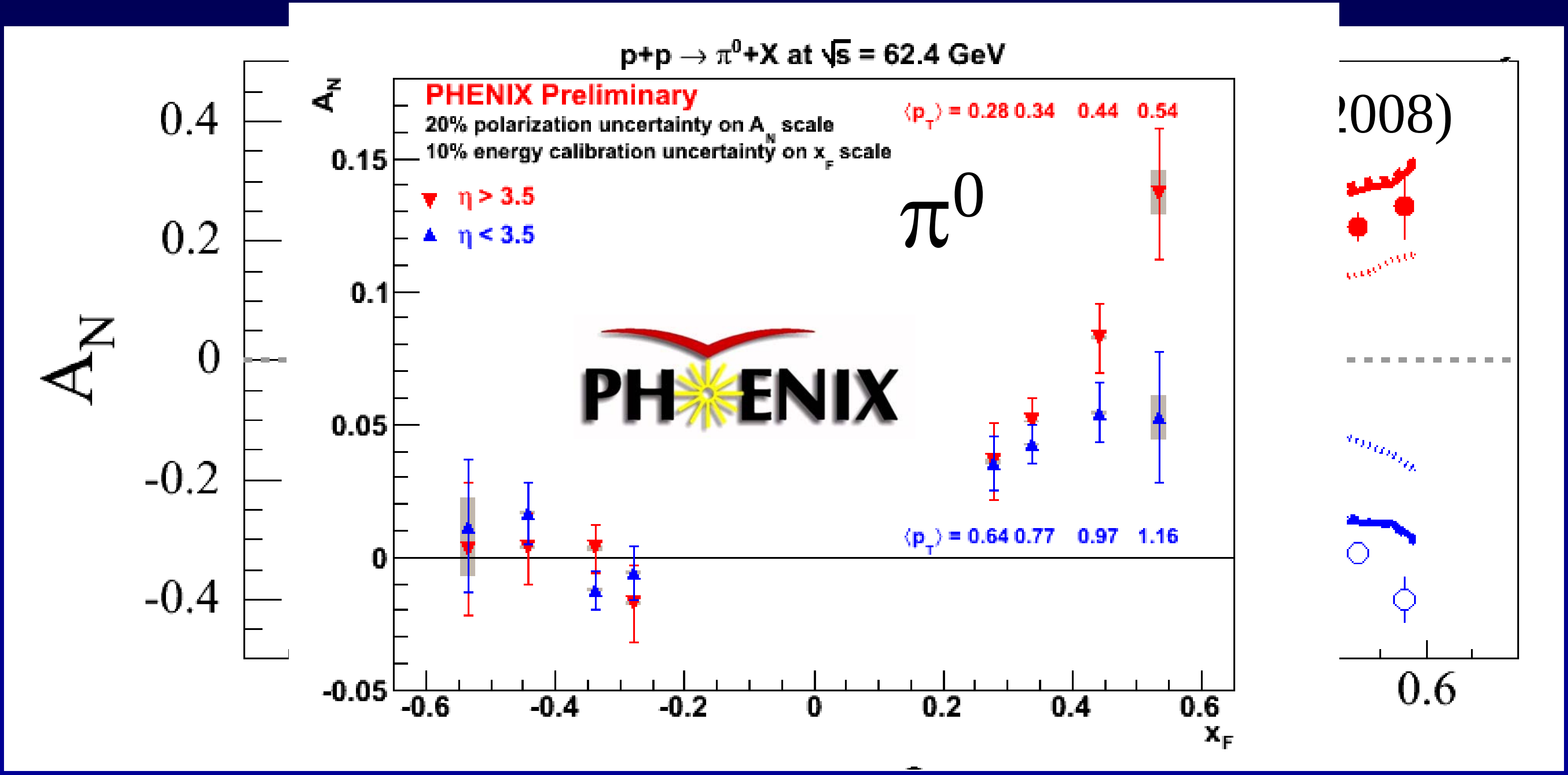
Transverse SSA's Persist up to RHIC Energies!

$\sqrt{s}$ = 62.4 GeV

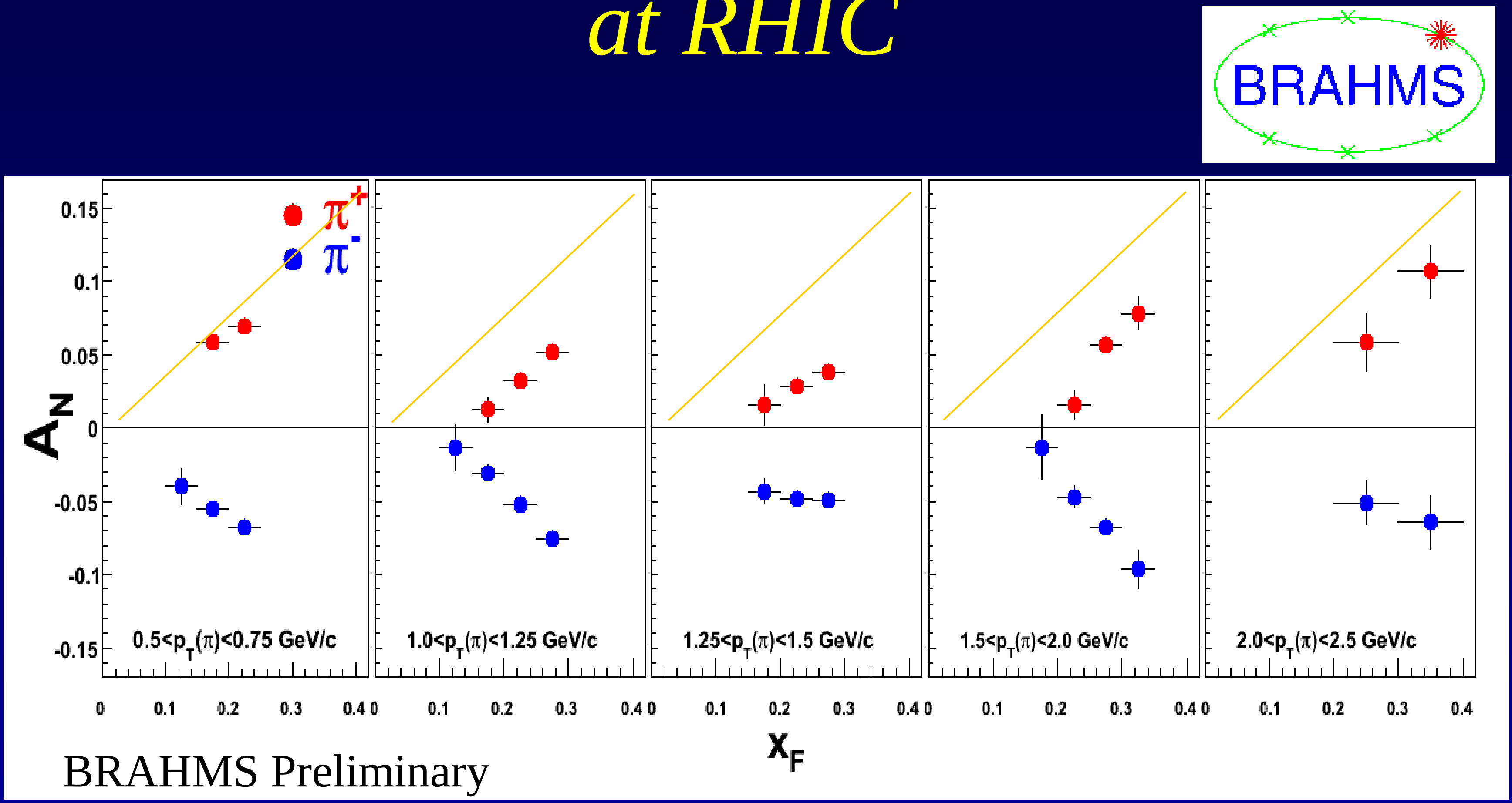


Transverse SSA's Persist up to RHIC Energies!

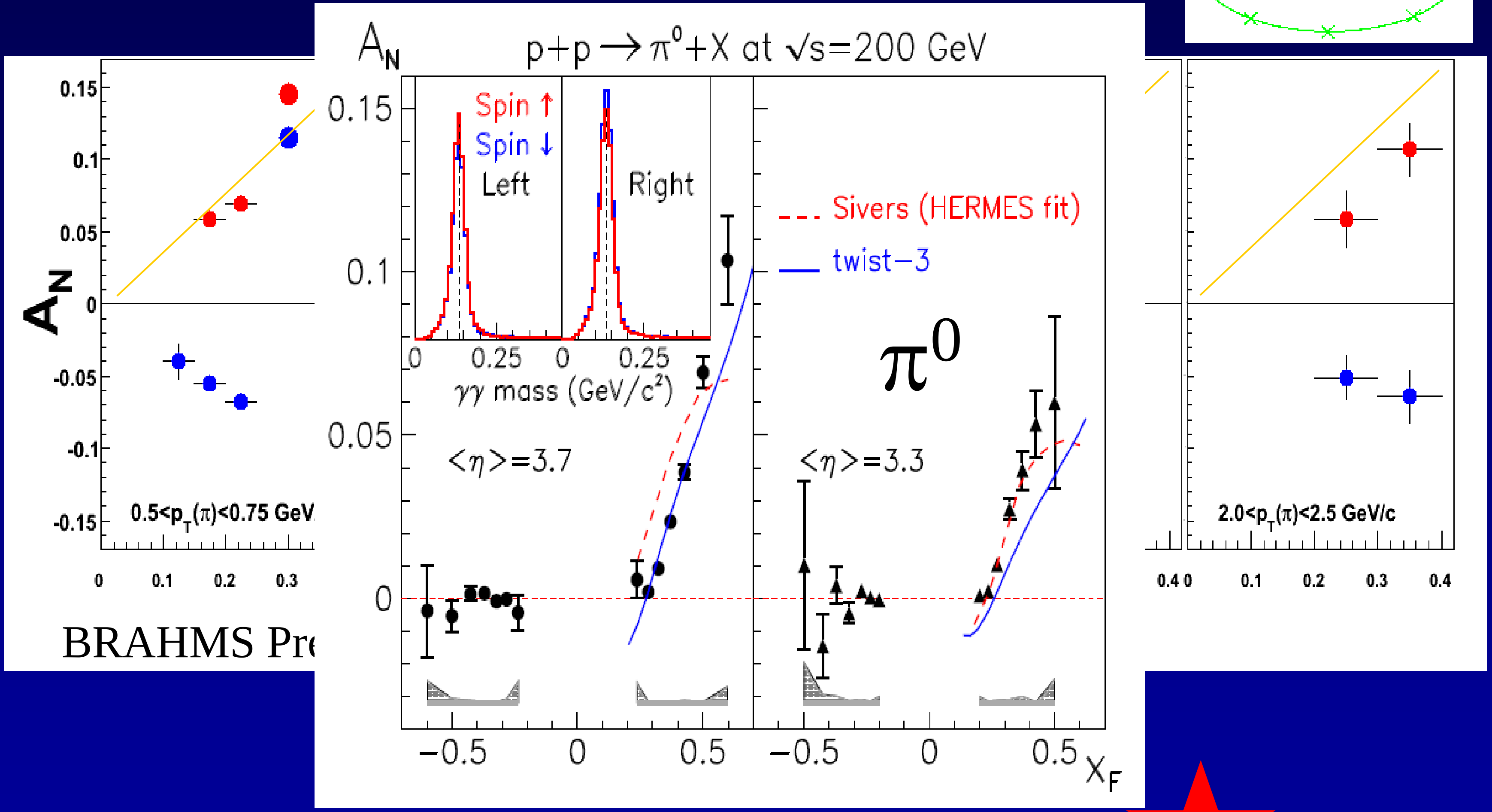
$\sqrt{s}$ = 62.4 GeV



Transverse SSA's at $\sqrt{s}$ = 200 GeV at RHIC

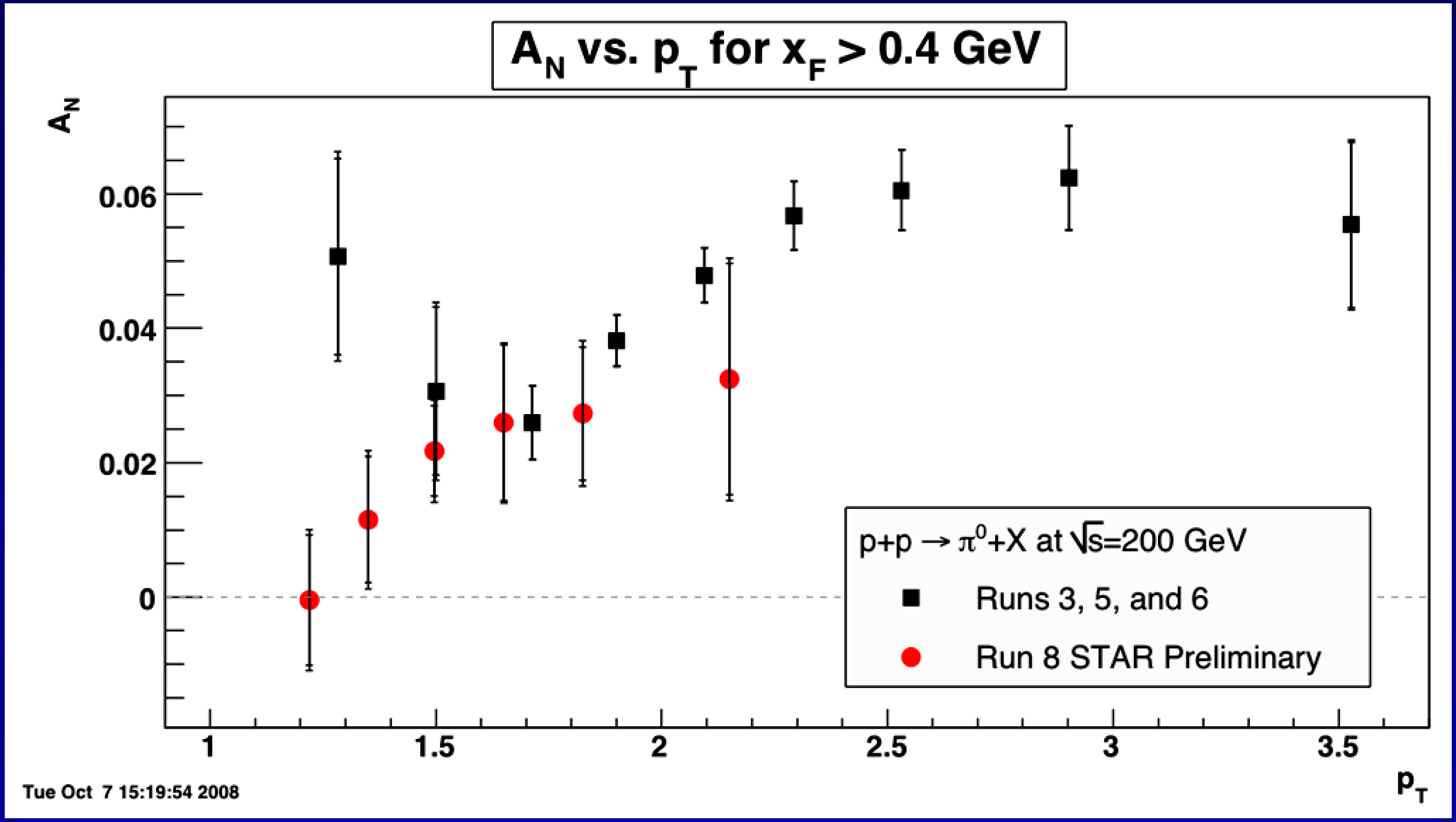


Transverse SSA's at √s = 200 GeV at RHIC



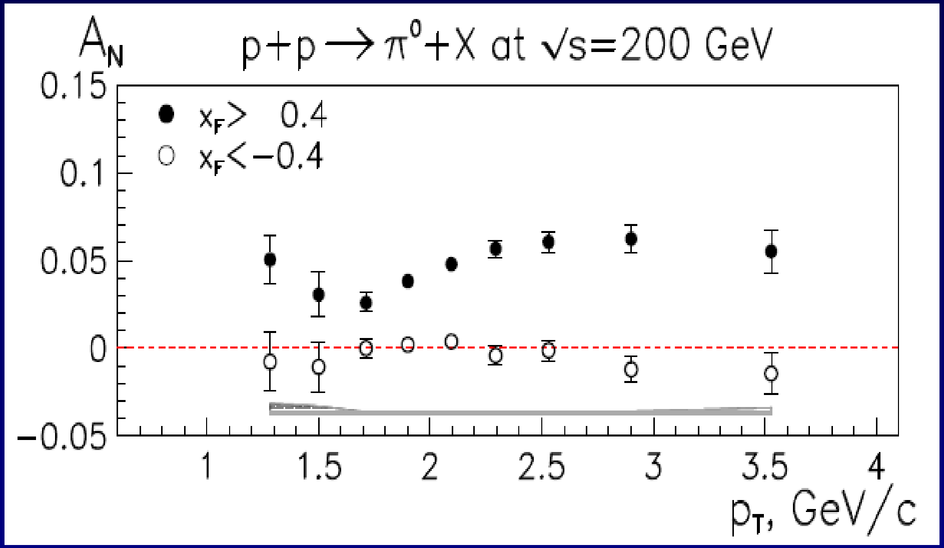
PRL101, 222001 (2008)

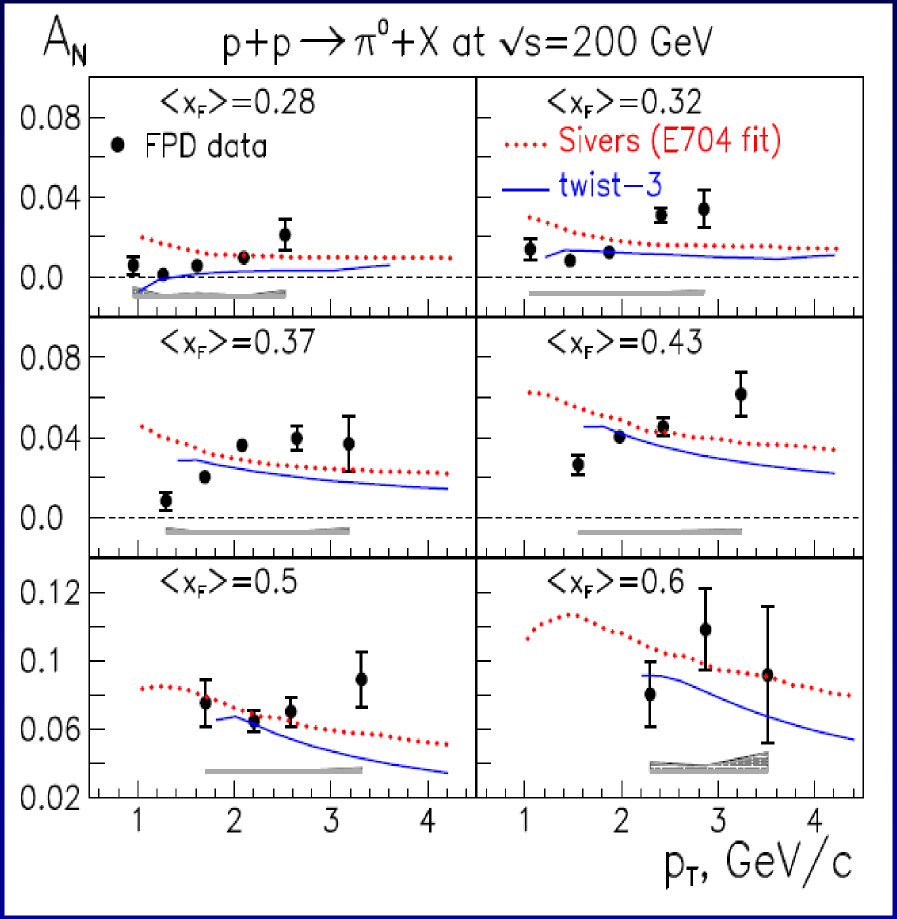
Neutral Pion Transverse SSA: Decrease at Low pT Now Observed



Black points: Phys. Rev. Lett. 101, 222001 (2008)

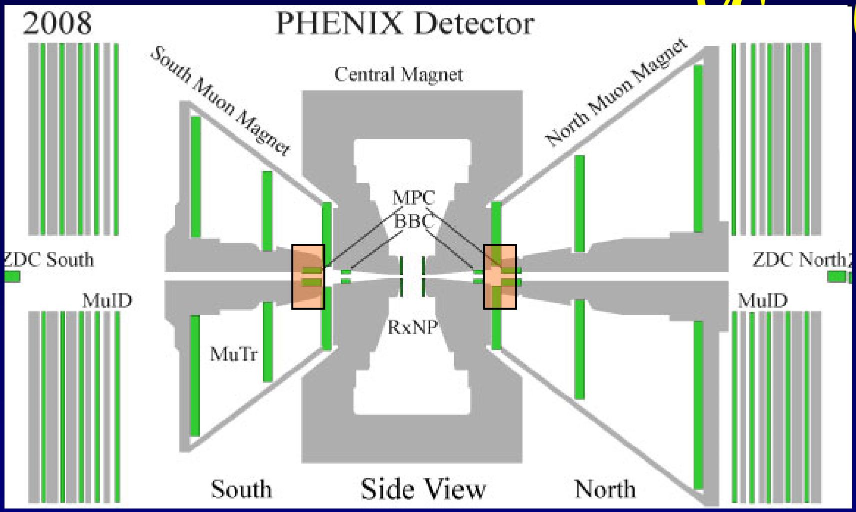
Forward π^0 A_N at 200 GeV: p_T dependence

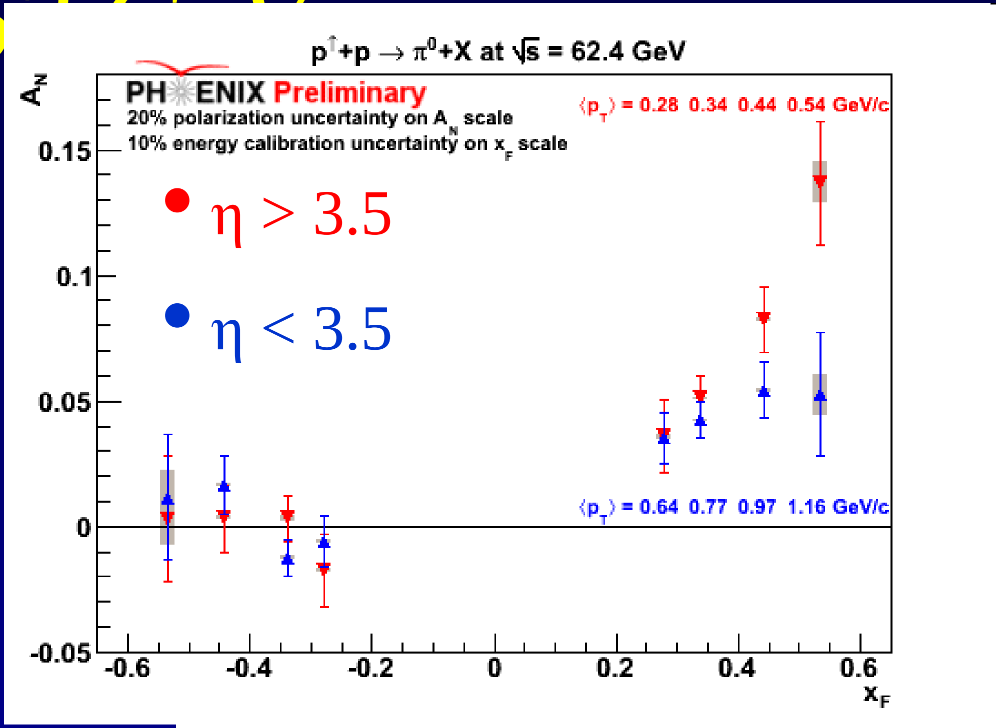




arXiv:0801.2990
Accepted by PRL

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

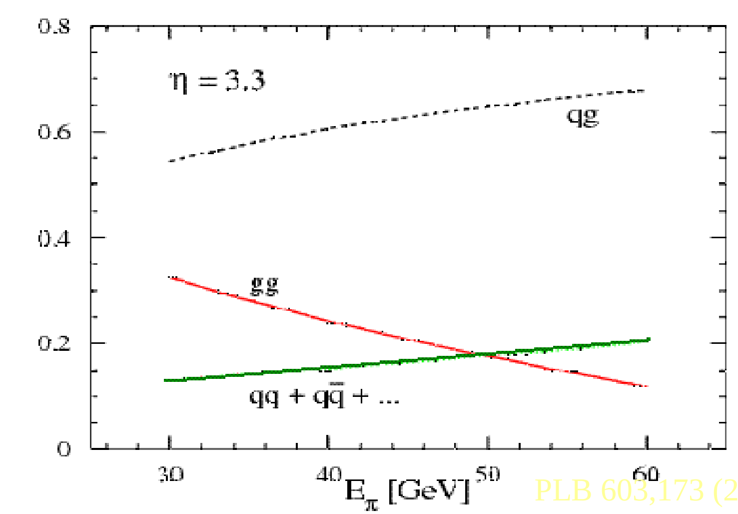




PHENIX π^0 results available for $\sqrt{s}$=62 GeV

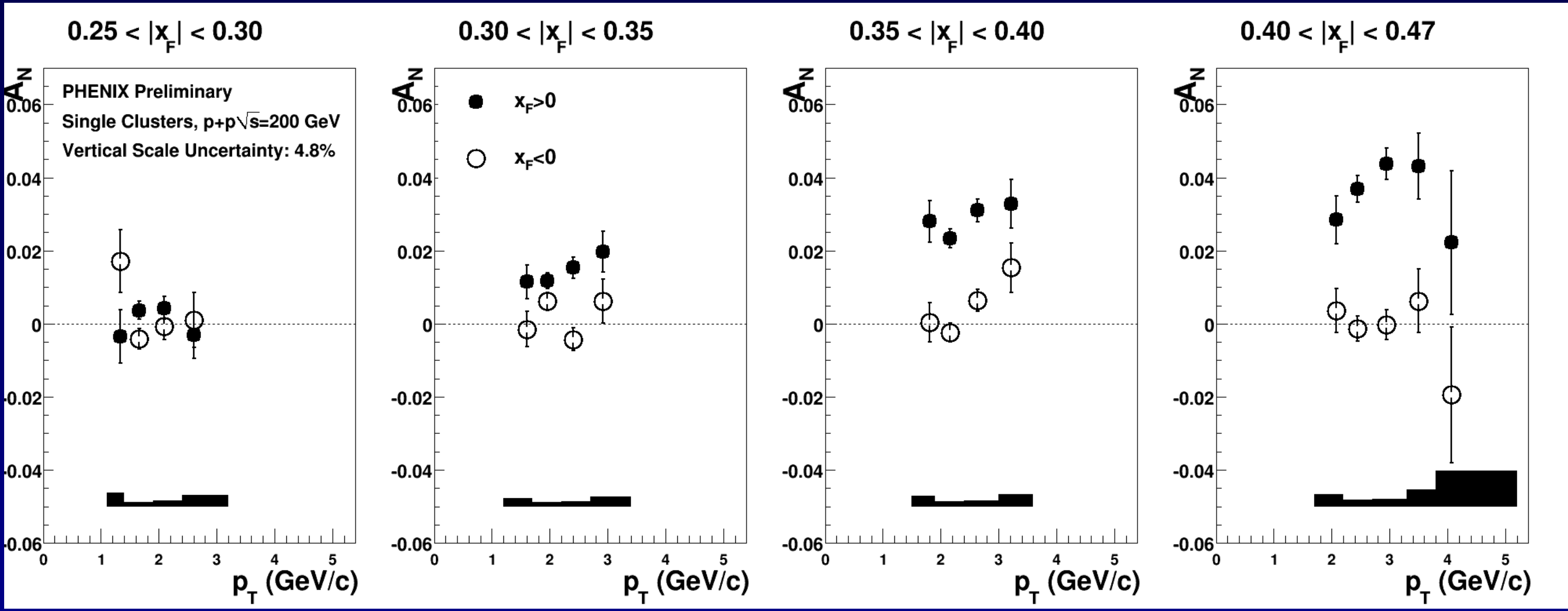
- Production dominated by quark-gluon
- Similar x_F scaling to higher and lower center of masses
- Asymmetries could enter a global analysis on transverse spin asymmetries

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

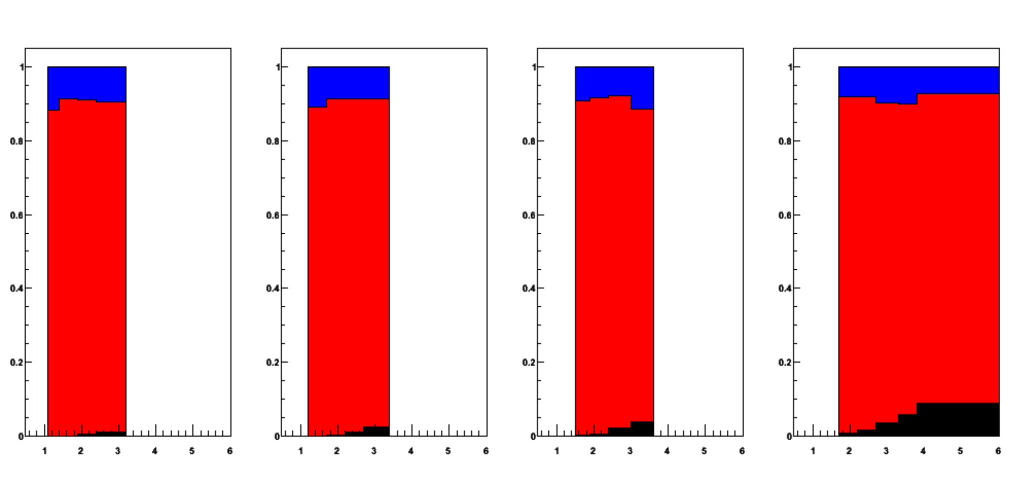


PLB 603,173 (2004)

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



Fraction of clusters



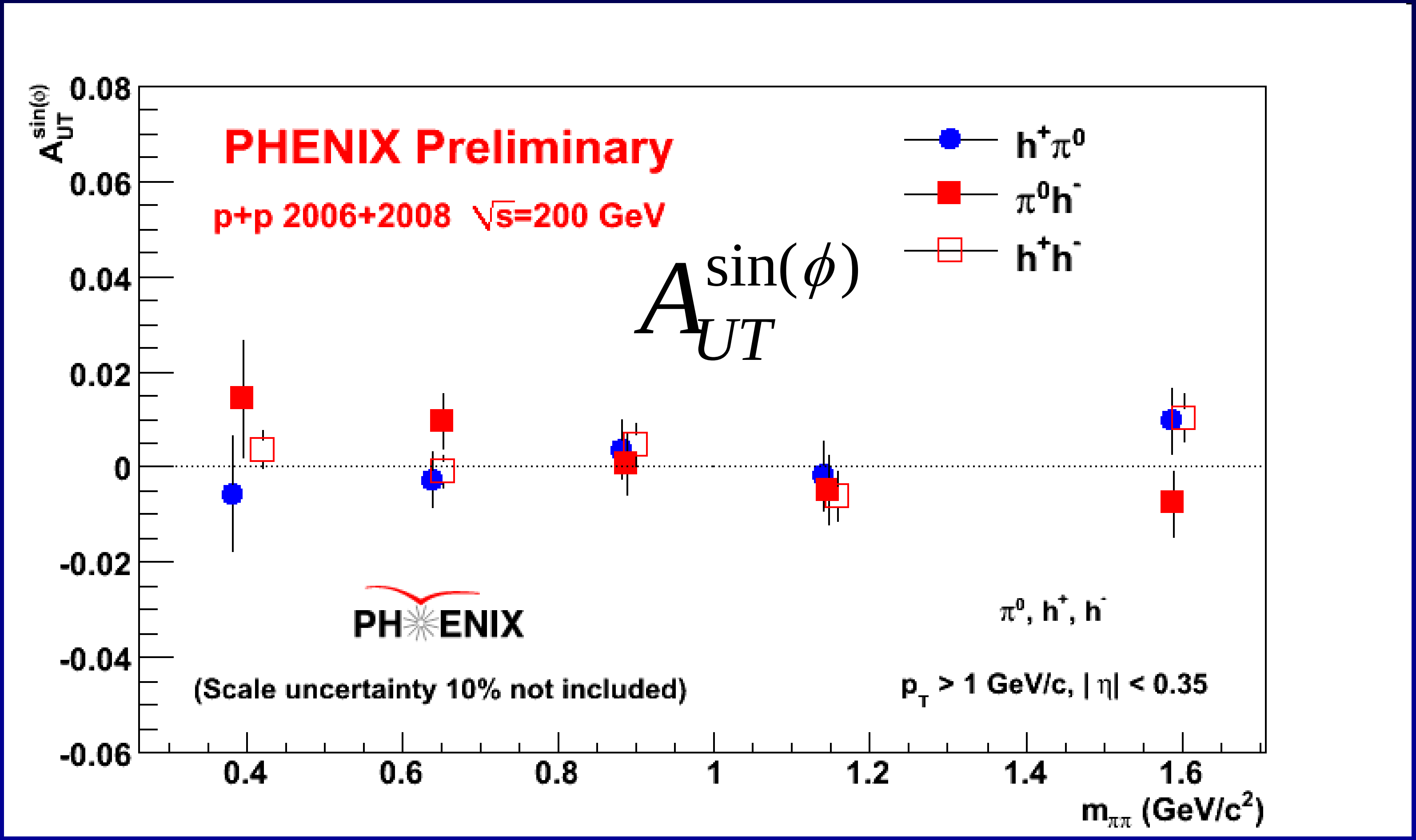
Decay photon

π^0

Direct photon

p_T (GeV/c)

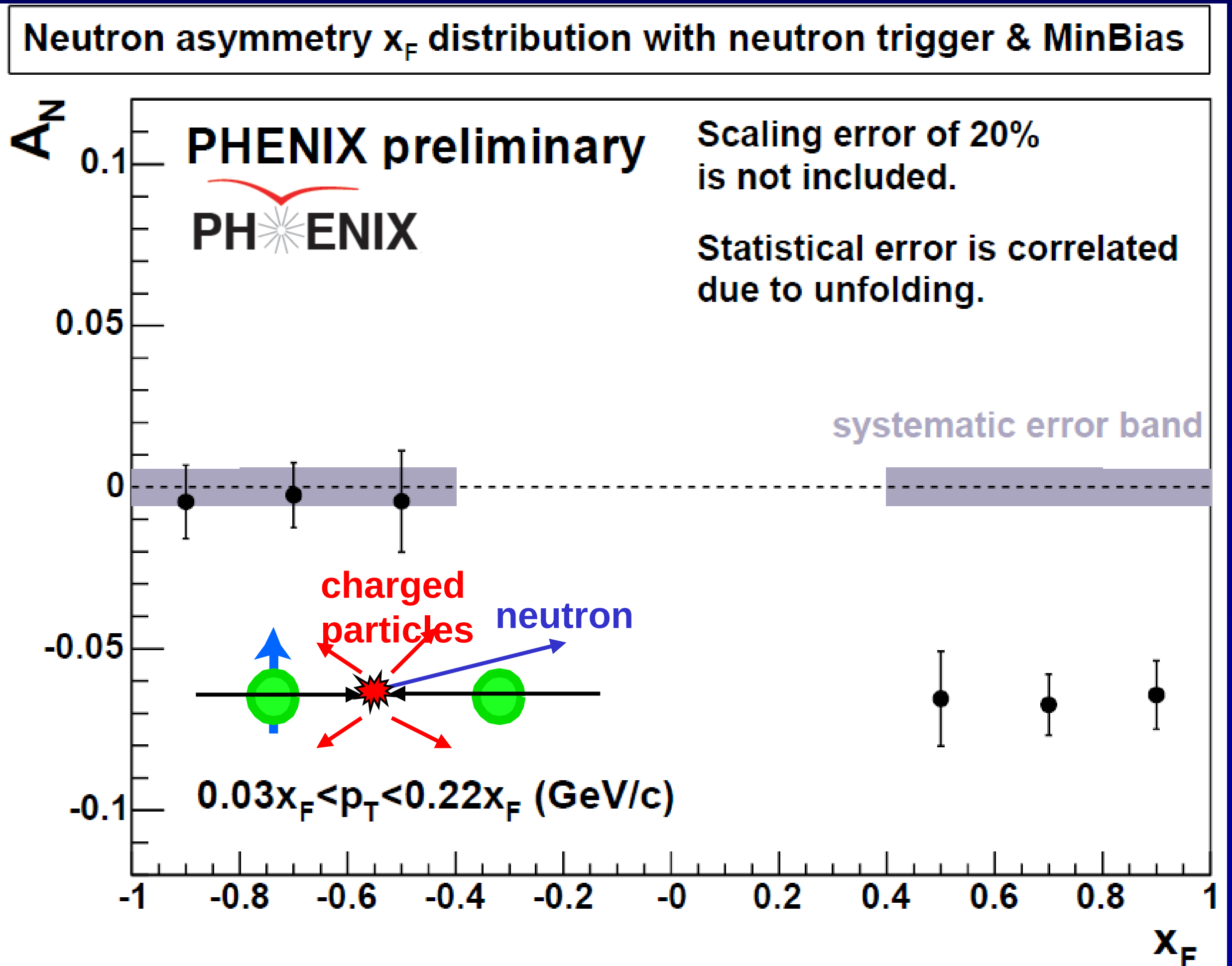
Interference Fragmentation Function to Probe Transversity



Added statistics from 2008 running. No significant asymmetries seen at mid-rapidity.

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.)

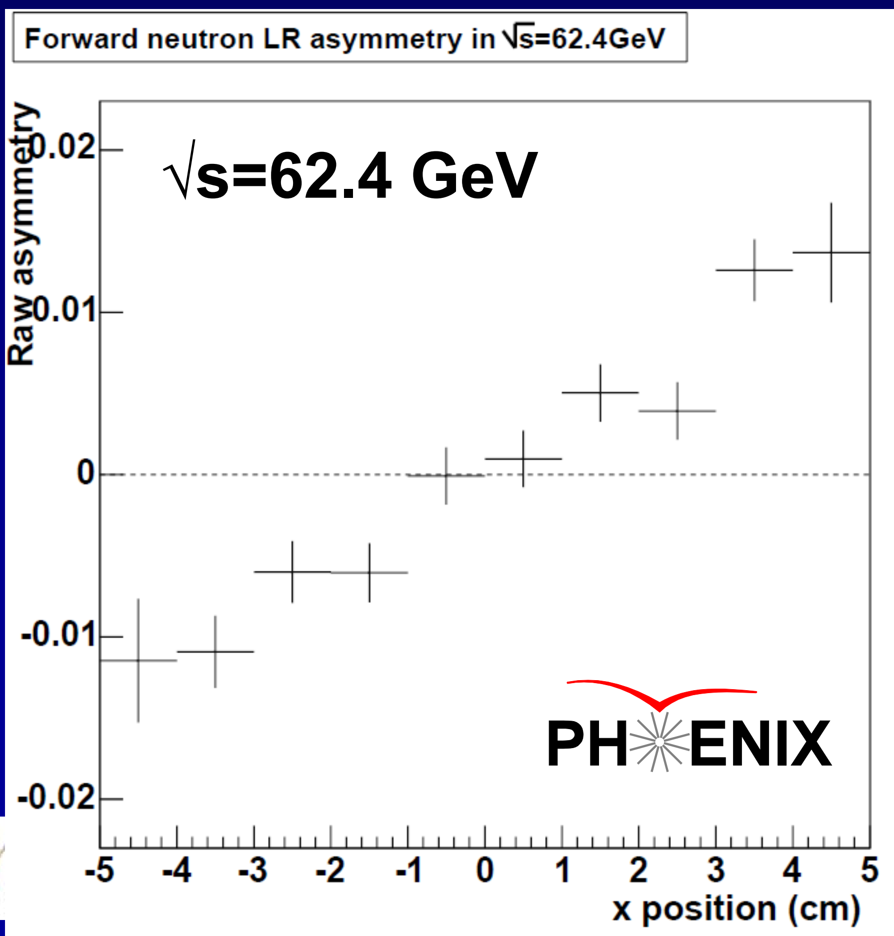
$0.4<|x_F|<0.6$ 0.088 GeV/c
$0.6<|x_F|<0.8$ 0.118 GeV/c
$0.8<|x_F|<1.0$ 0.144 GeV/c

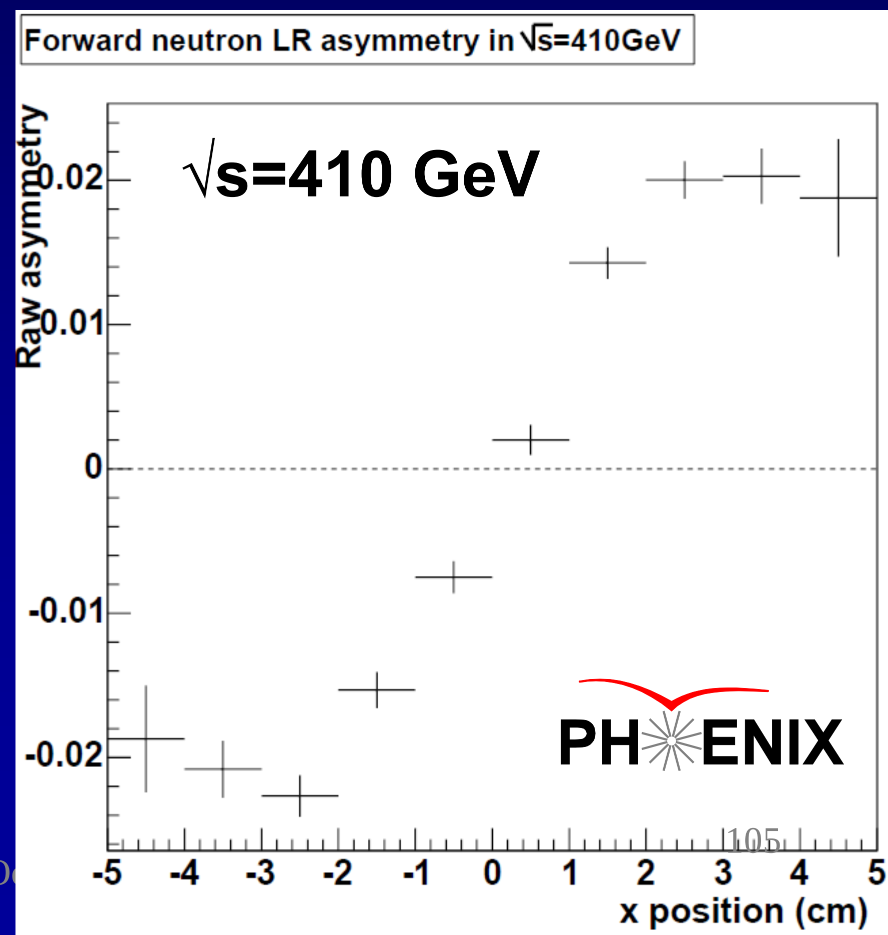
preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

Forward neutrons at other energies

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

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



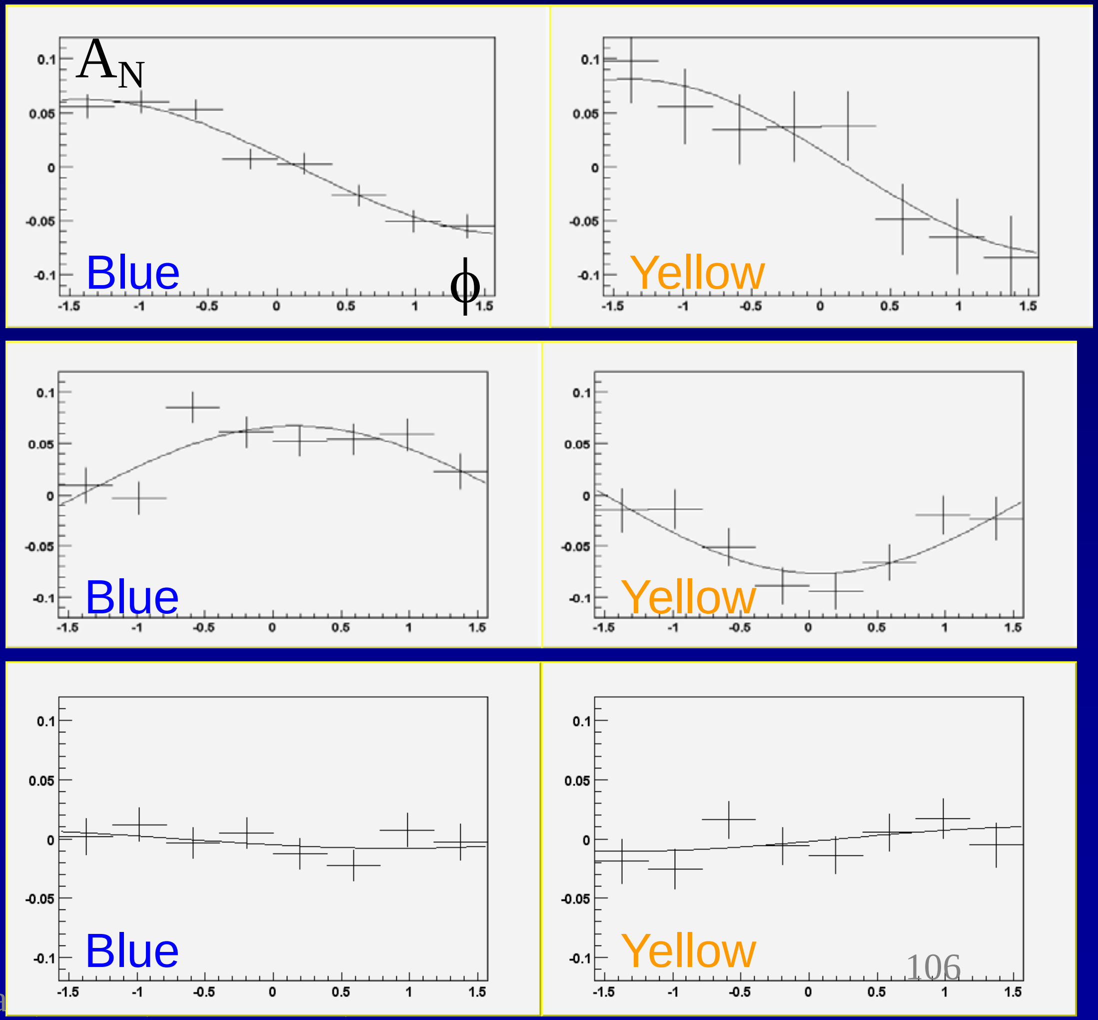


Single-Spin Asymmetries for Local Polarimetry: Confirmation of Longitudinal Polarization

Spin Rotators OFF
Vertical polarization

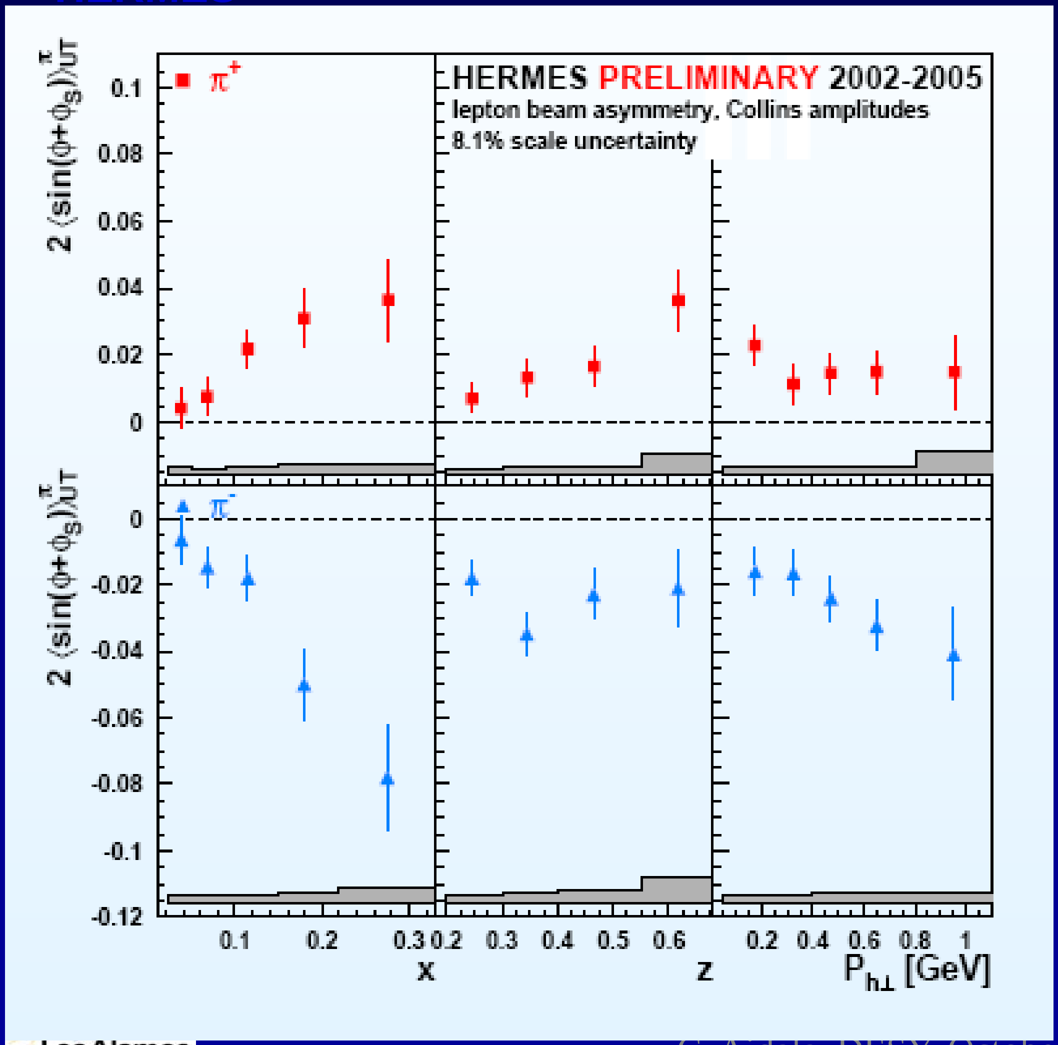
Spin Rotators ON
Current Reversed!
Radial polarization

Spin Rotators ON
Correct Current
Longitudinal polarization!



First Observation of the Collins Effect in Polarized Deep Inelastic Electron-Proton Scattering

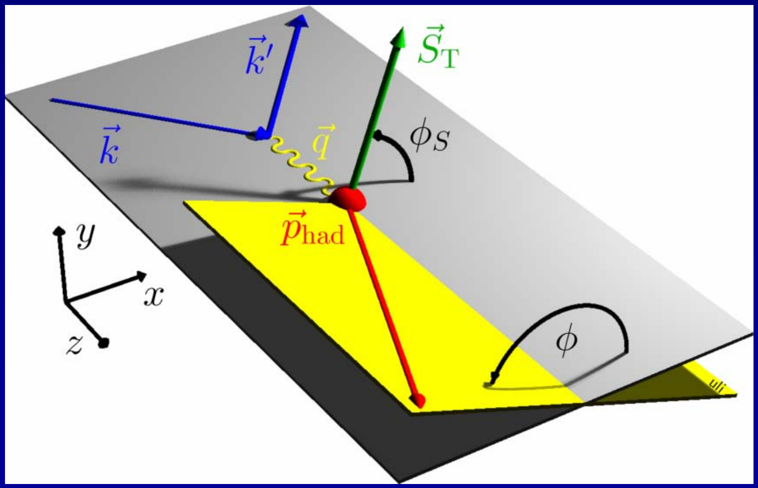
HERMES



Collins Asymmetries in semi-inclusive deep inelastic scattering

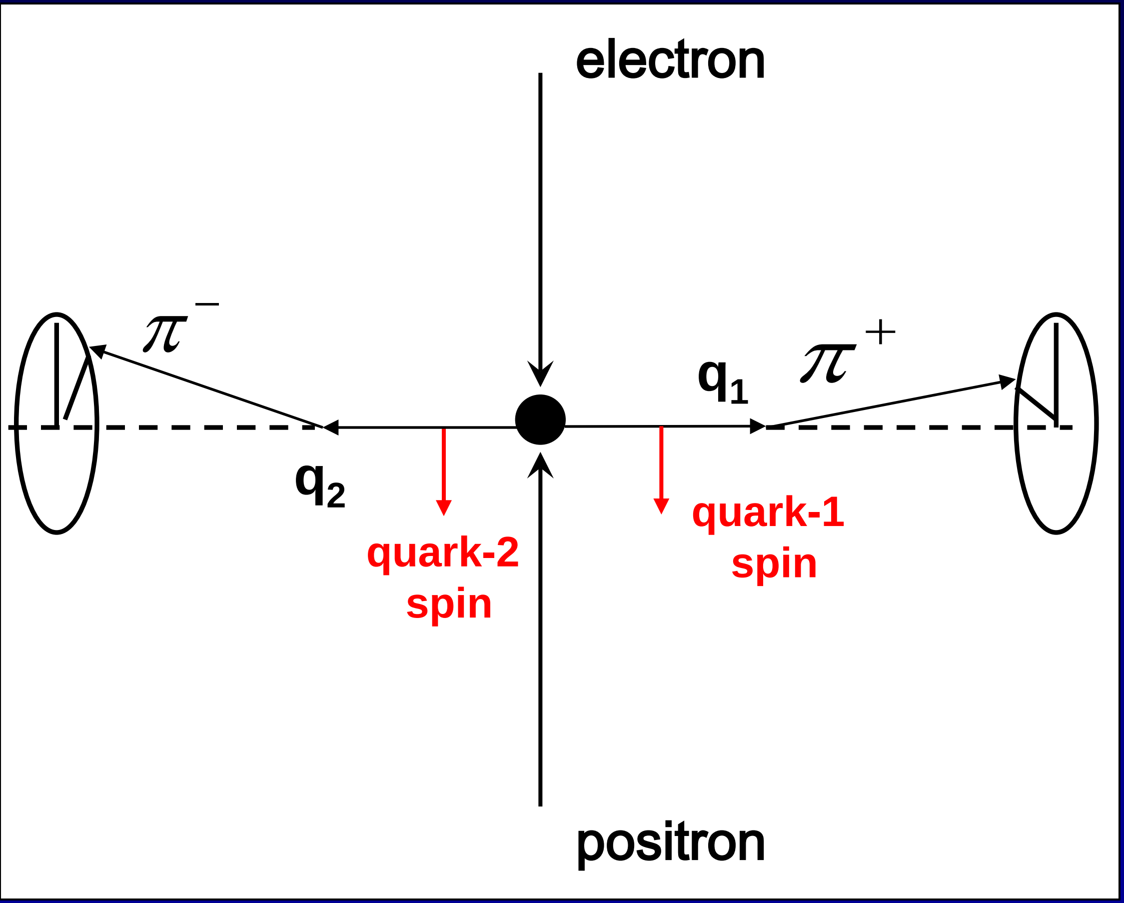
$e+p \rightarrow e+\pi+X$

~ Transversity (x) x Collins(z)



$A_{UT}\sin(\phi+\phi_s)$

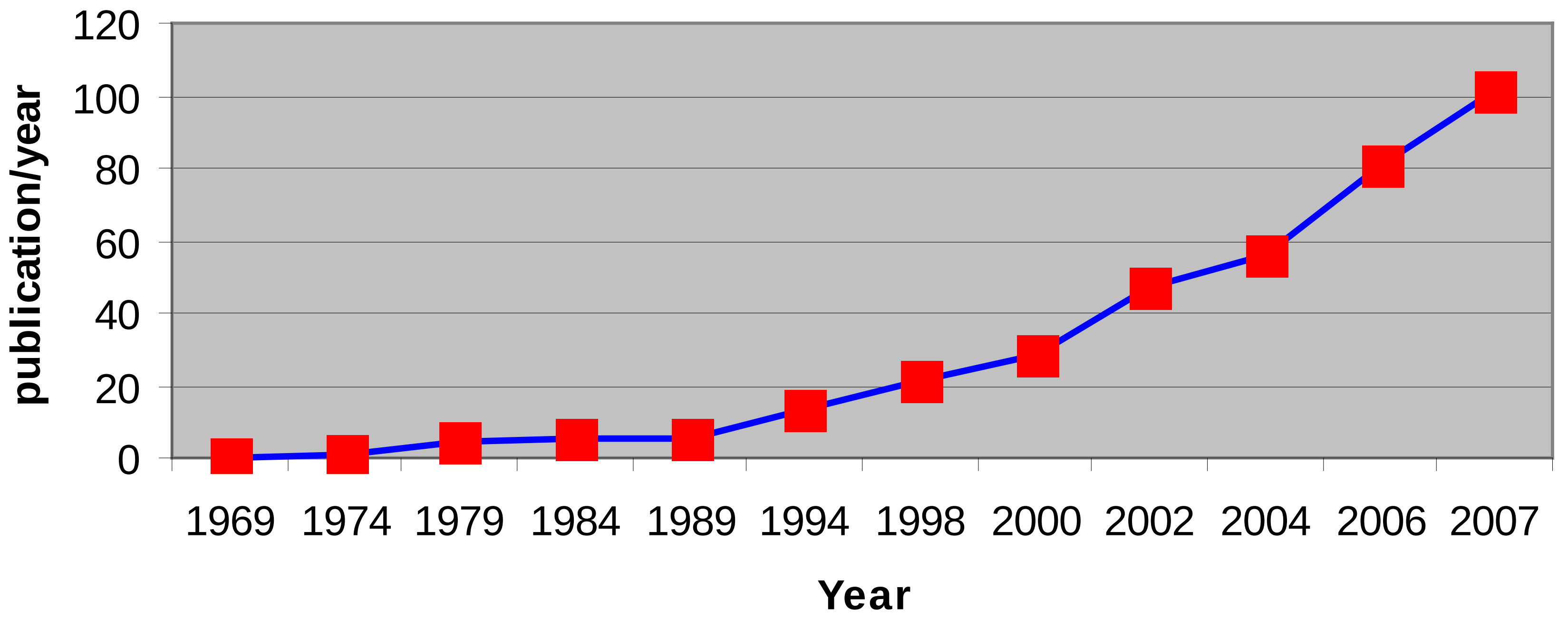
The Collins Effect Must be Present In e^+e^- Annihilation into Quarks!



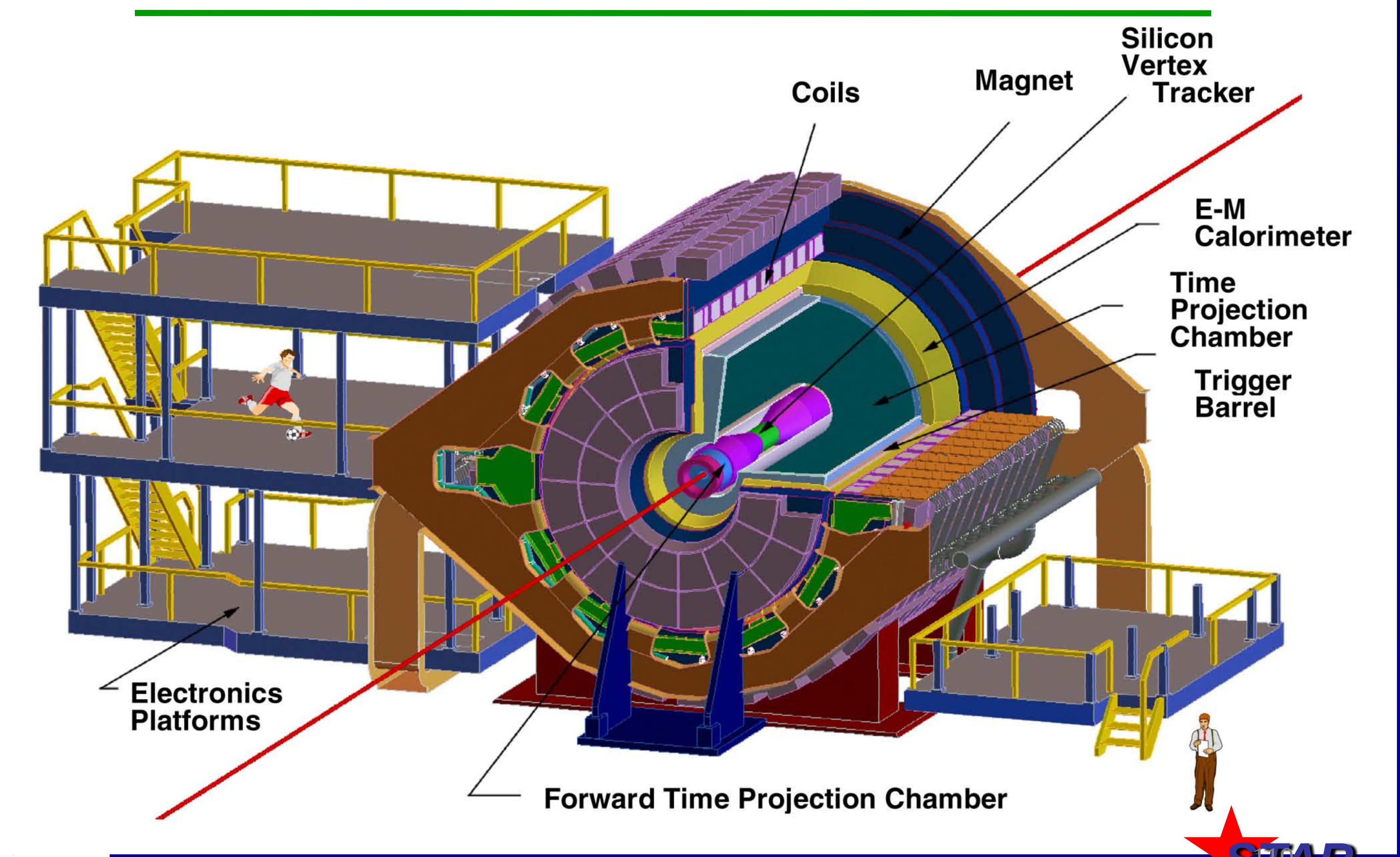
Collins effect in e+e-
Quark fragmentation
will lead to effects
in di-hadron correlation
measurements!

Fundamental Theoretical Work: Sivers Effect and Questions of Universality and Factorization

Annual number of publications on transverse spin in SPIRES vs time. The total number of pulications is about ~750, about 15% are experimental.



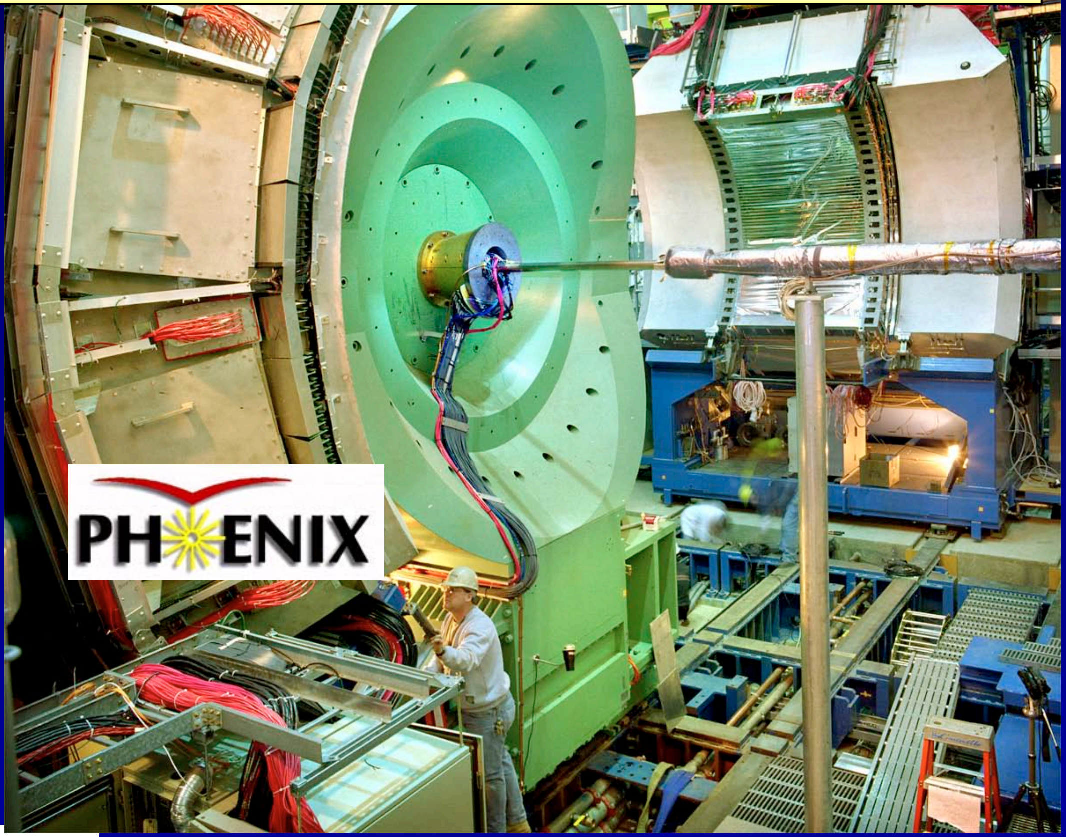
The STAR Detector at RHIC



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

$|\eta| < 0.35$

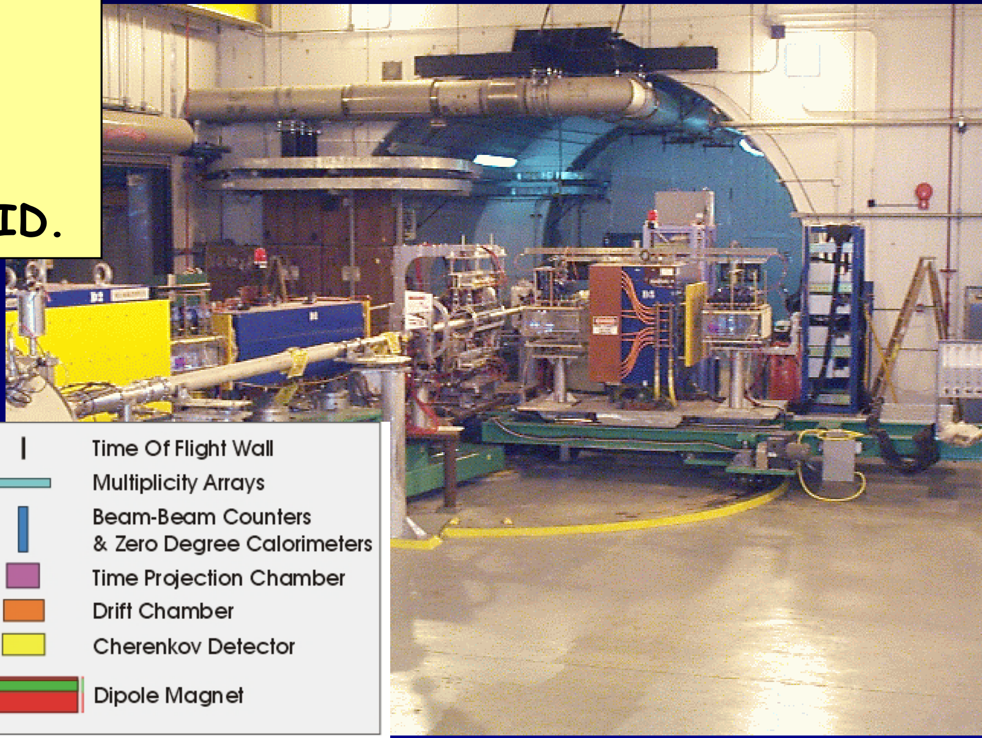
2 forward spectrometers

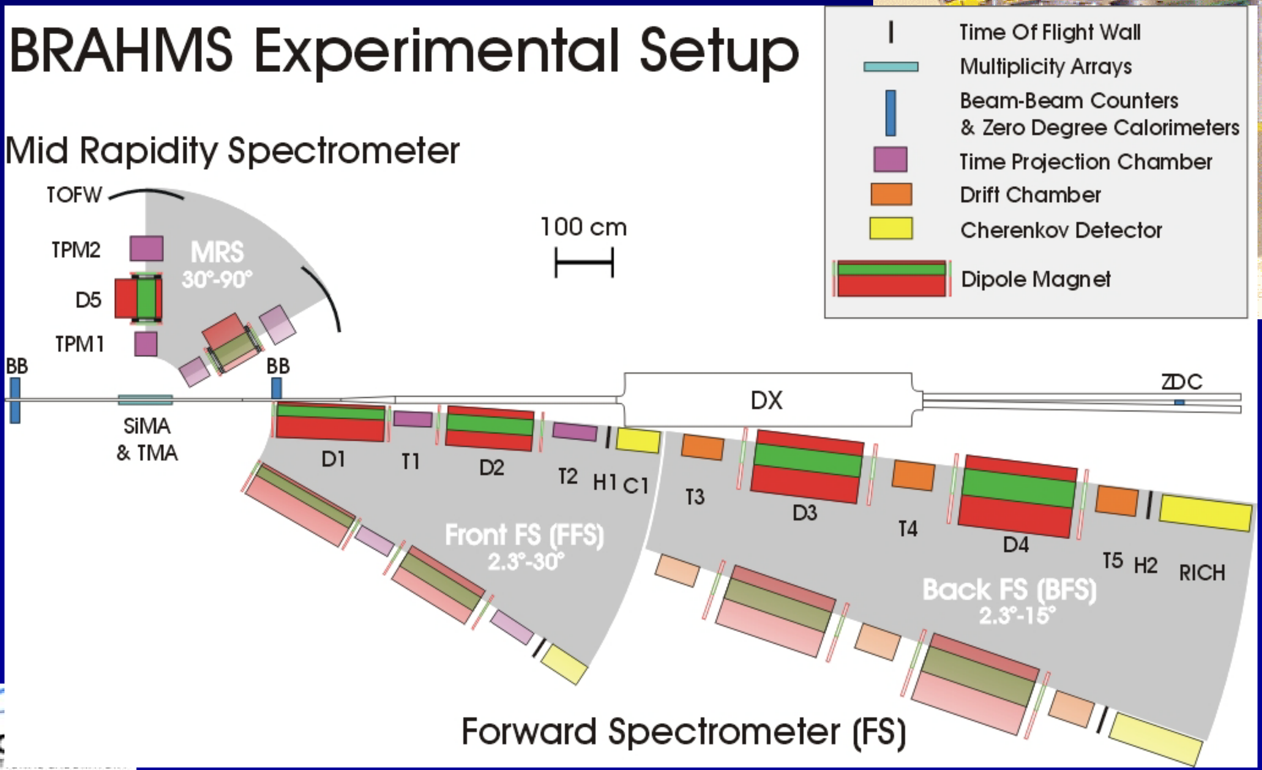
- Identify and track muons

BRAHMS detector

Philosophy:

Small acceptance spectrometer arms designed with good charged particle ID.





Helicity Flip Amplitudes

Elastic proton-quark scattering

(related to inelastic scattering through optical theorem)

Three independent pdf's corresponding to following helicity states:

$$
\begin{array}{ccccc}
\frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\
\frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2}
\end{array}
$$

Take linear combinations to form:

$$q \longleftrightarrow \left(\frac{1}{2} \;\; \frac{1}{2} \to \frac{1}{2} \;\; \frac{1}{2}\right) + \left(\frac{1}{2} \;\; -\frac{1}{2} \to \frac{1}{2} \;\; -\frac{1}{2}\right)$$ Helicity average

$$\Delta q \longleftrightarrow \left(\frac{1}{2} \;\; \frac{1}{2} \to \frac{1}{2} \;\; \frac{1}{2}\right) - \left(\frac{1}{2} \;\; -\frac{1}{2} \to \frac{1}{2} \;\; -\frac{1}{2}\right)$$ Helicity difference

$$\boxed{\delta q \longleftrightarrow \left(\frac{1}{2} \;\; -\frac{1}{2} \to -\frac{1}{2} \;\; \frac{1}{2}\right)}$$ Helicity flip

Helicity Flip Amplitudes

Elastic proton-quark scattering
(related to inelastic scattering t

Three independent pdf's corres

$$\begin{array}{cccccc} \frac{1}{2} & \frac{1}{2} & \longrightarrow & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \longrightarrow & \frac{1}{2} & -\frac{1}{2} \\ \frac{1}{2} & -\frac{1}{2} & \longrightarrow & -\frac{1}{2} & \frac{1}{2} \end{array}$$

Take linear combinations to fo

Helicity flip distribution also called the "transversity" distribution.

Corresponds to the difference in probability of scattering off of a transversely polarized quark within a transversely polarized proton with the quark spin parallel vs. antiparallel to the proton's.

$$q \longleftrightarrow \left(\tfrac{1}{2}\ \tfrac{1}{2} \rightarrow \tfrac{1}{2}\ \tfrac{1}{2}\right) + \left(\tfrac{1}{2}\ -\tfrac{1}{2} \rightarrow \tfrac{1}{2}\ -\tfrac{1}{2}\right)$$ Helicity average

$$\Delta q \longleftrightarrow \left(\tfrac{1}{2}\ \tfrac{1}{2} \rightarrow \tfrac{1}{2}\ \tfrac{1}{2}\right) - \left(\tfrac{1}{2}\ -\tfrac{1}{2} \rightarrow \tfrac{1}{2}\ -\tfrac{1}{2}\right)$$ Helicity difference

$$\boxed{\delta q \longleftrightarrow \left(\tfrac{1}{2}\ -\tfrac{1}{2} \rightarrow -\tfrac{1}{2}\ \tfrac{1}{2}\right)}$$ Helicity flip

Helicity Flip Amplitudes

Elastic proton-quark scatterin

(related to inelastic scattering t

Chiral-odd! But chirality conserved in QCD processes . . . Can transversity exist and produce observable effects?

$$\frac{1}{2} \quad -\frac{1}{2} \quad \longrightarrow \quad -\frac{1}{2} \quad \frac{1}{2}$$

Helicity flip distribution also called the "…sversity" distribution.

…esponds to the difference in …bility of scattering off of a …sversely polarized quark within a transversely polarized proton with the quark spin parallel vs. antiparallel to the proton's.

Take linear combinations to fo

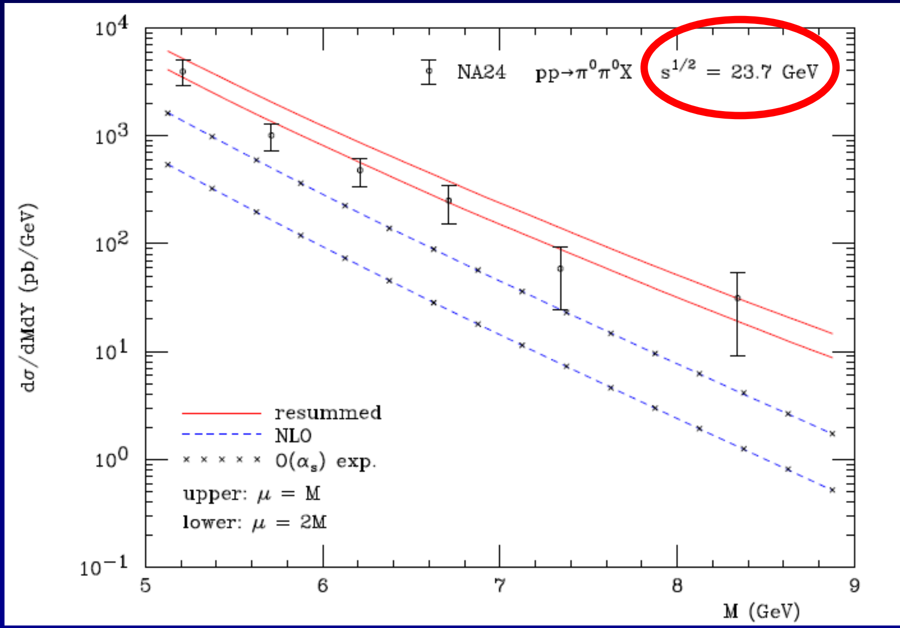
$$q \longleftrightarrow \left(\frac{1}{2} \quad \frac{1}{2} \rightarrow \frac{1}{2} \quad \frac{1}{2}\right) + \left(\frac{1}{2} \quad -\frac{1}{2} \rightarrow \frac{1}{2} \quad -\frac{1}{2}\right)$$ Helicity average

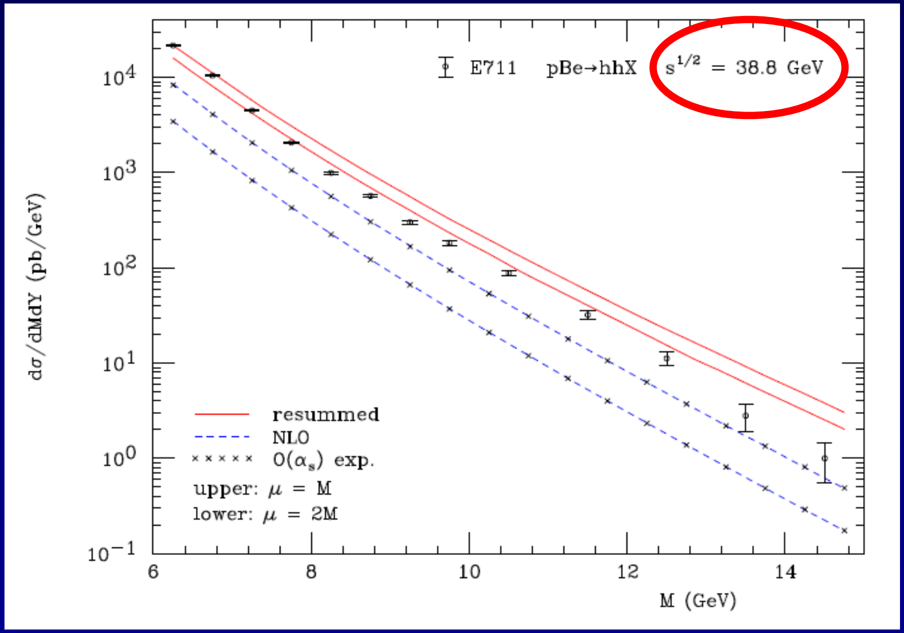
$$\Delta q \longleftrightarrow \left(\frac{1}{2} \quad \frac{1}{2} \rightarrow \frac{1}{2} \quad \frac{1}{2}\right) - \left(\frac{1}{2} \quad -\frac{1}{2} \rightarrow \frac{1}{2} \quad -\frac{1}{2}\right)$$ Helicity difference

$$\boxed{\delta q \longleftrightarrow \left(\frac{1}{2} \quad -\frac{1}{2} \rightarrow -\frac{1}{2} \quad \frac{1}{2}\right)}$$ Helicity flip

Progress in pQCD Calculational Techniques

23.7 GeV! 38.8 GeV!





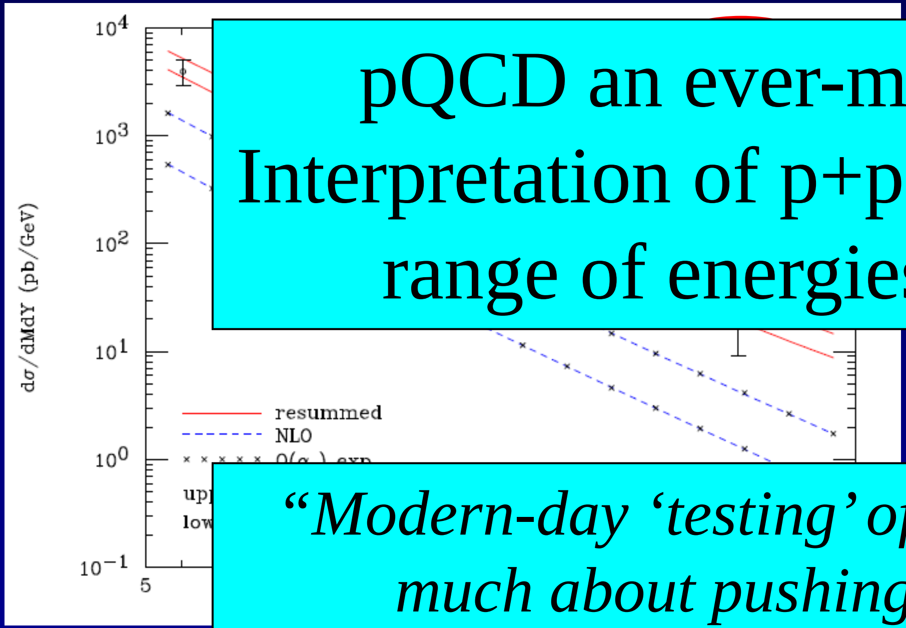
One recent example:

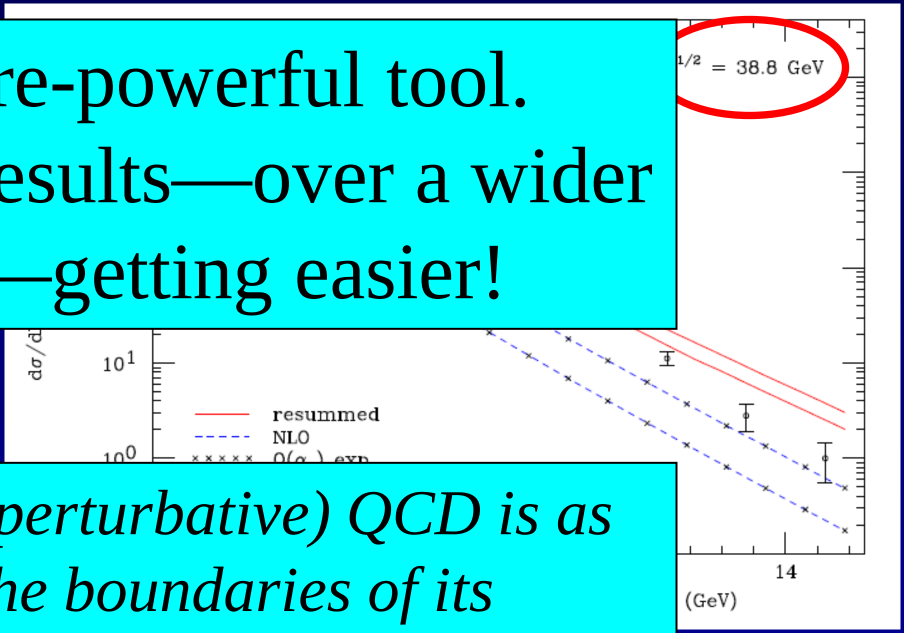
Almeida, Sterman, Vogelsang, PRD80, 074016 (2009)

Cross section for di-hadron production vs. invariant mass using threshold resummation (rigorous method for implementing p_T and rapidity cuts on hadrons to match experiment)

Progress in pQCD calculational techniques

23.7 GeV! 38.8 GeV!





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

"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)

One r... Alme... Cross... d resummation (rigorous method for implementing p_T and rapidity cuts on hadrons to match experiment)

Los Alamos NATIONAL LABORATORY EST. 1943