Nucleon structure from high-energy polarized proton-proton collisions

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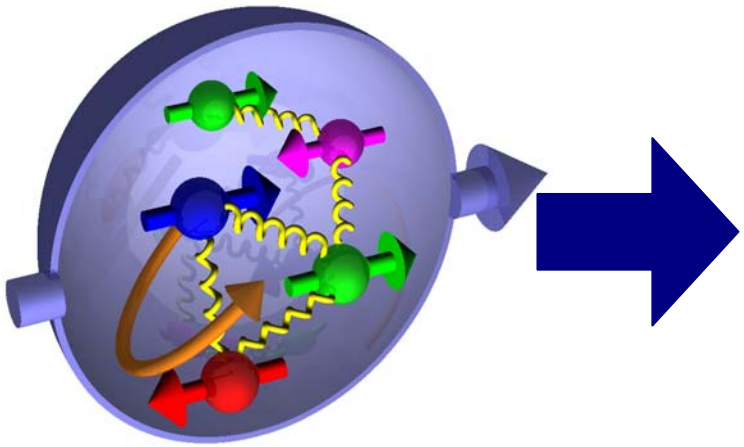
Contents

- Proton Structure
- RHIC facility and detectors
- Accessing Spin Structure
  - Transverse Spin
  - Gluon Helicity Distribution (ΔG)
  - Flavor-dependent Sea Quark Helicity Distributions

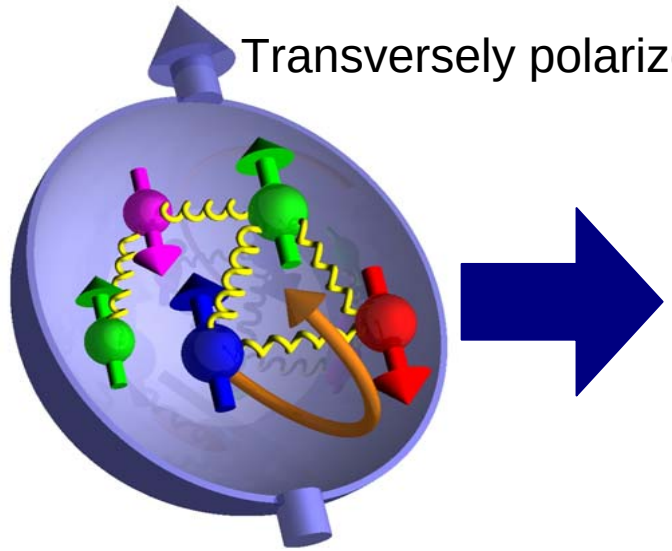
Nucleon Structure

- Magnetic moment of nucleons indicated there was substructure
  - This has turned out to be quite rich.
- Charge of the nucleon
  - From the quarks, as the gluons are chargeless.
- Momentum
  - Gluons carry about 50%
- Studies of the spin structure has also lead to a rich understanding of the nucleon.

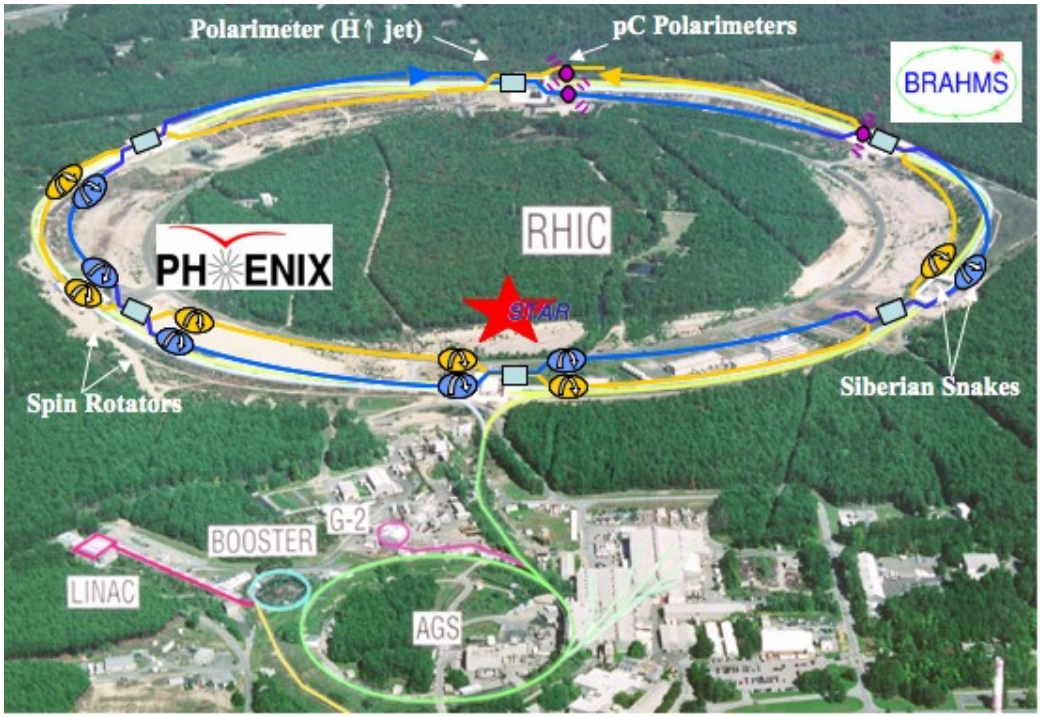
Longitudinally polarized



Transversely polarized

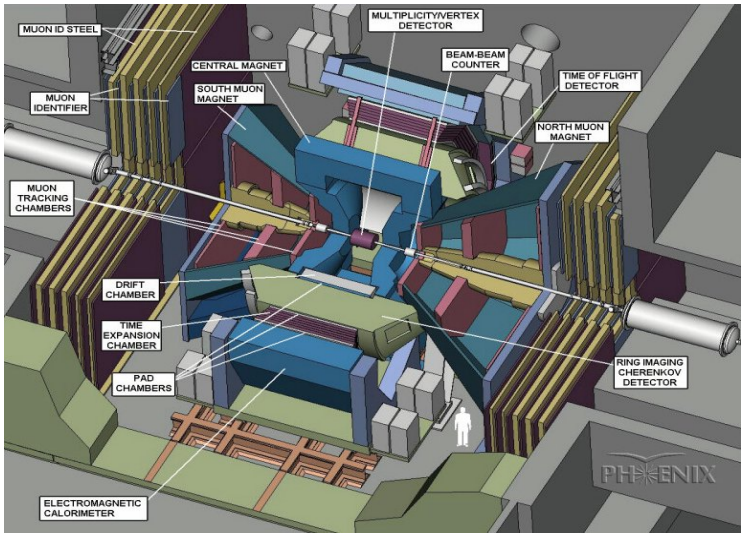


RHIC facility



- √s=62.4–500 GeV
  - Most data at 200 GeV
  - Short 62.4 GeV run in 2006
  - First 500 GeV data earlier this year
- Polarization
  - 57% at 200 GeV
  - ~35% at 500 GeV
- STAR and PHENIX
  - can select transversely or longitudinally polarized beams
- BRAHMS
  - only Transverse
  - was decomissioned after 2006.

Experiments

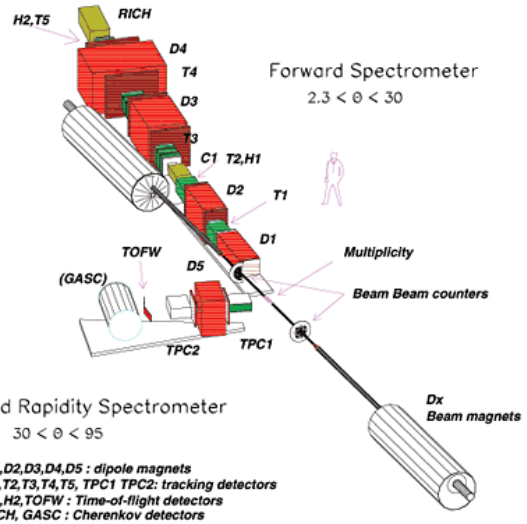


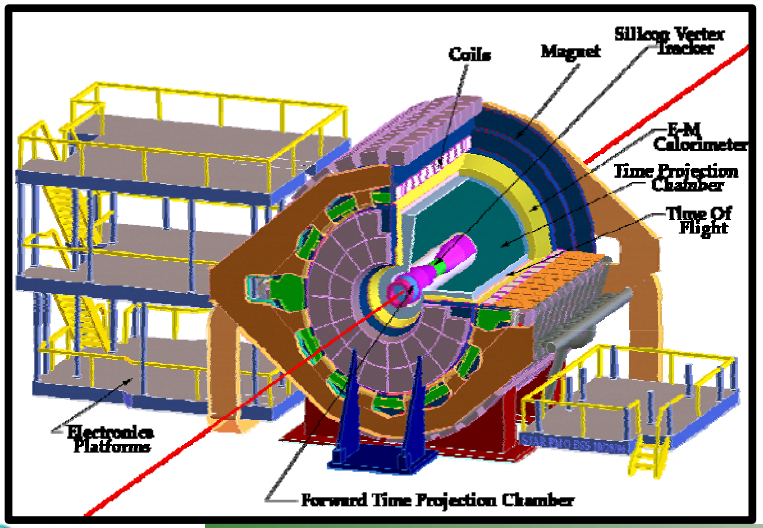
PHENIX

High rate capability
Limited acceptance
High p_T photon trigger

BRAHMS

Forward spectrometer
charge hadron id





STAR

Large acceptance
Azimuthal symmetry
Jet patch trigger

RHIC Performance

Year	√s [GeV]	L [pb^{-1}]	% Long./Trans.	P [%]	FoM (P^4L)	FoM (P^2L)
2002	200	0.15	0/100	15		0.0034
2003	200	0.35	100/0	27	0.0019	
2004	200	0.12	100/0	40	0.0031	
2005	200	3.6	95/5	49	0.20	0.035
2006	200	10	75/25	55	0.79	0.7
2006	62.4	0.1	80/20	48	0.0042	0.0046
2008	200	5.2	0/100	46		1.1
2009	500	~10	100/0	~35	~0.150	~1.2
2009	200	14	100/0	~55	~1.3	

- From PHENIX. Similar numbers for STAR.
- Significant longitudinal data sets in 2005 and 2006 (and now in 2009)
- Significant transverse data sets in 2006 and 2008
- First 500 GeV run in 2009.

Transverse Spin Structure

C. Aidala gave an overview of transverse spin results from RHIC in the TMD workshop.

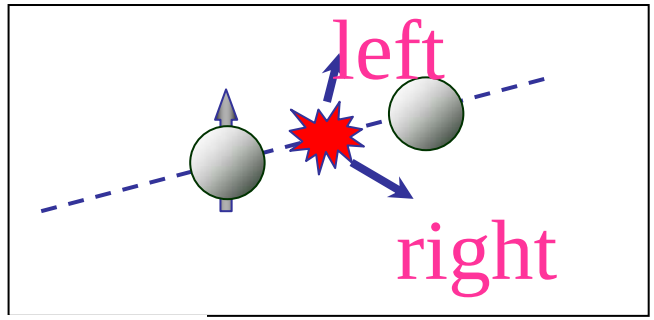
Here I just point out a few highlights and recent results.

Transverse Single Spin Asymmetries

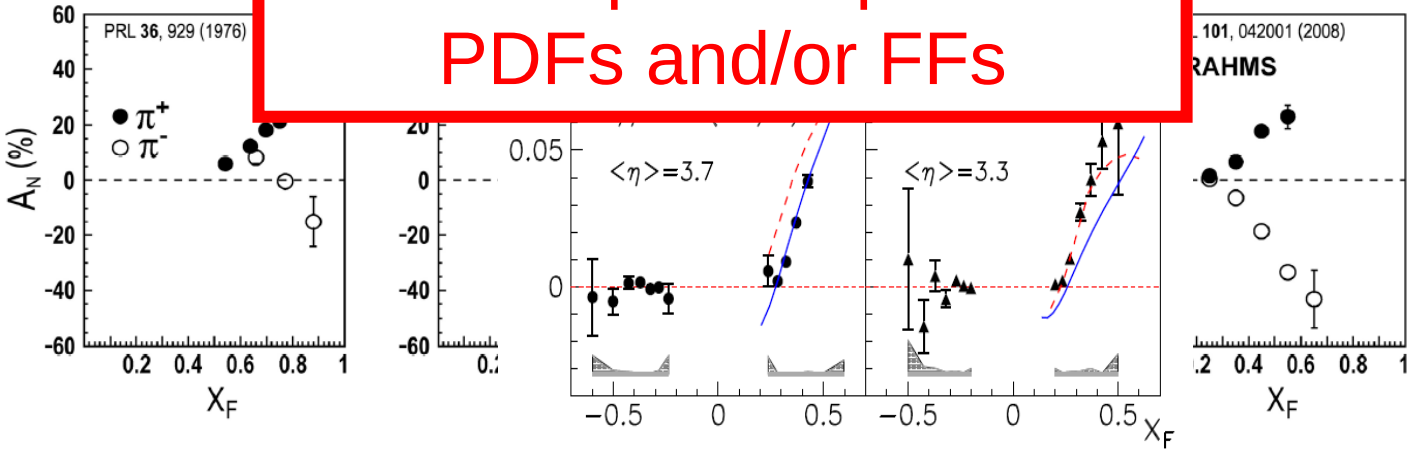
- Large single spin transverse spin (~40%) found at low energies

→ soft physics effect.

- Remain even at √s=62.4 and 200 GeV



Can use pQCD framework to interpret as part of PDFs and/or FFs

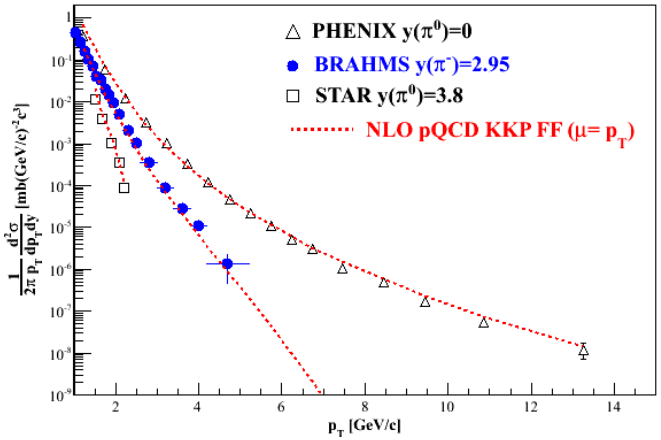


$$x_F = 2p_{long}/\sqrt{s}$$

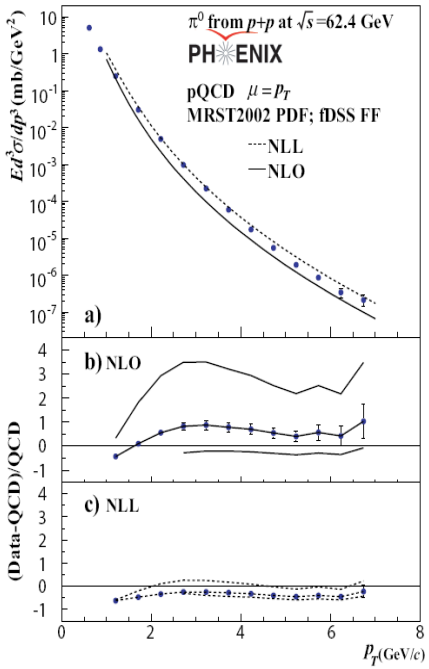
pQCD Framework Reasonable?

- At 200 GeV
  - Pion cross sections at both mid and forward rapidities described by NLO pQCD calculation.
- At 62.4 GeV
  - pions are reasonably well described at both mid and forward rapidities
  - NLL may be important

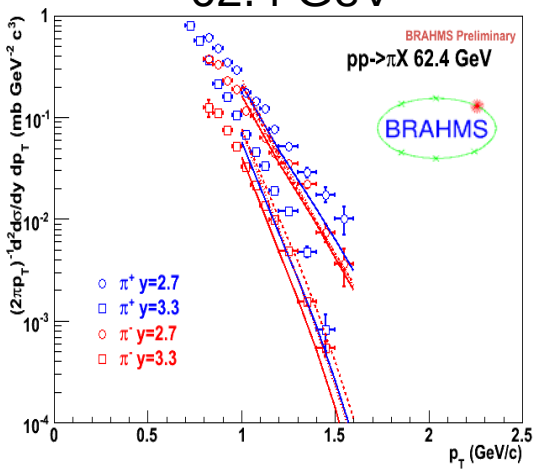
200 GeV



62.4 GeV



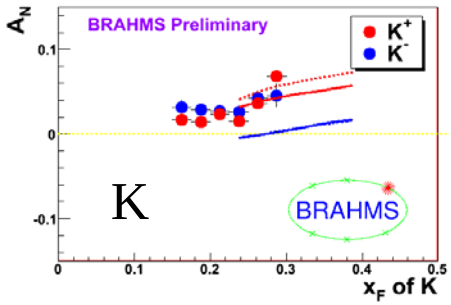
62.4 GeV



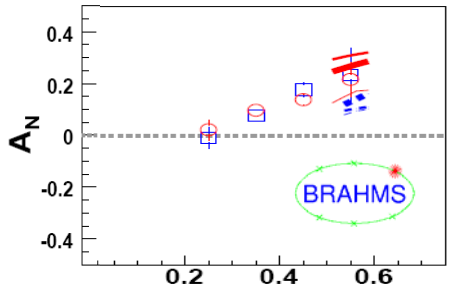
Some (Recent) Surprises

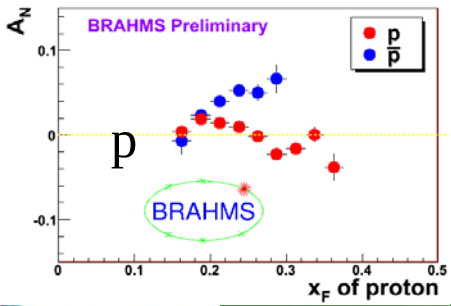
- Large pions asymmetries showed that they do not disappear at large √s
- Measurements of other hadrons have lead to more surprises
  - Large antiproton asymmetry from BRAHMS, but no proton asym.
  - Eta Asymmetry larger than π^0
  - Rising p_T dependence instead of drop

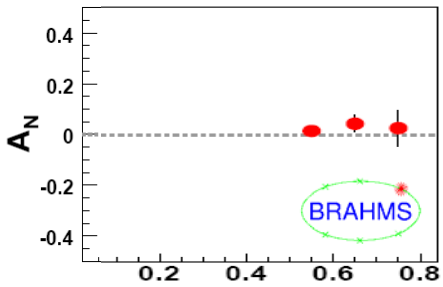
200 GeV

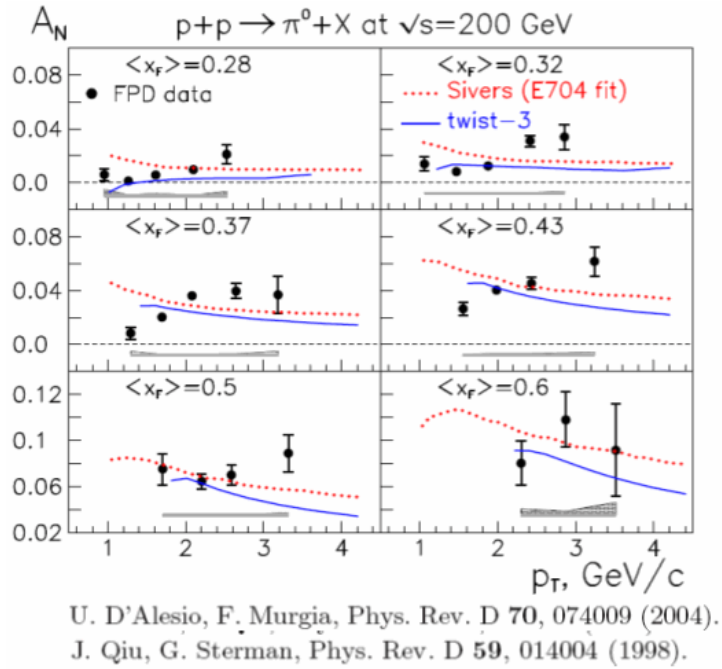


62.4 GeV



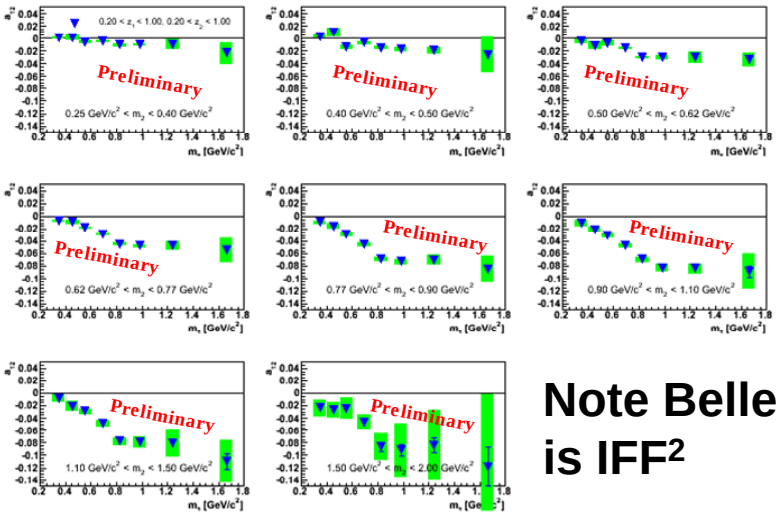






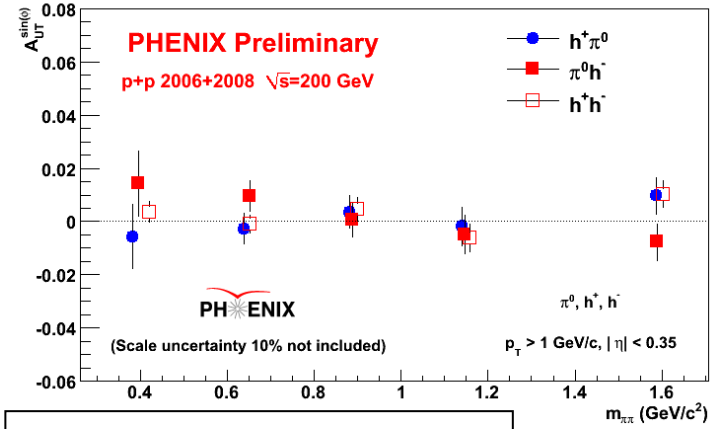
U. D'Alesio, F. Murgia, Phys. Rev. D **70**, 074009 (2004).
J. Qiu, G. Sterman, Phys. Rev. D **59**, 014004 (1998).

Correlation Measurements



8x8 m_1 m_2 binning

Note Belle is IFF²



Midrapidity.
Invariant mass dependence

IFF

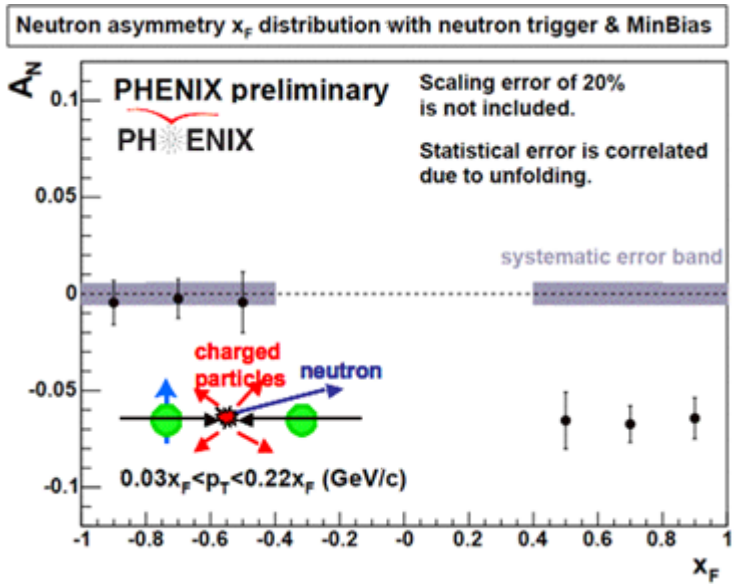
- Recent Interference Fragmentation Functions (IFF) data from BELLE shows large asymmetries
- BELLE measures IFF², so IFF is **large** effect

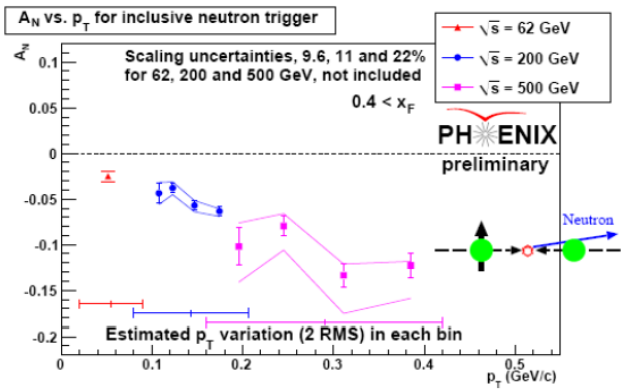
IFF and Transversity

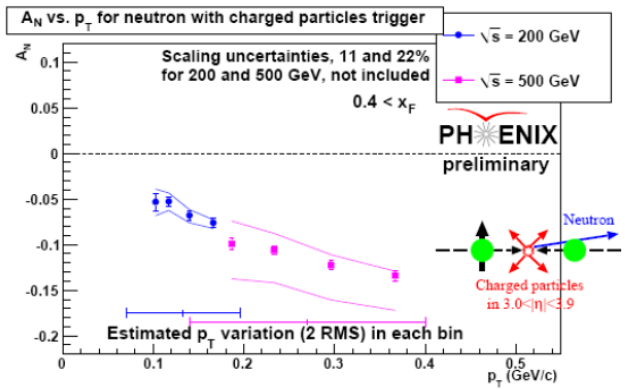
- Transversity must be coupled with another function, such as a FF.
- At PHENIX, due to limited acceptance, IFF is a better choice than Collins FF.
- With current statistical precision, PHENIX results are consistent with zero.

Very Forward Neutron Asymmetry

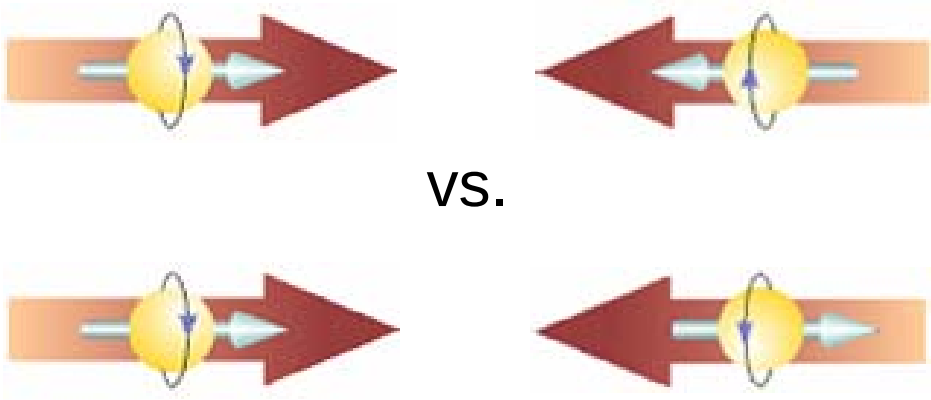
- Large very forward neutron asymmetry found at RHIC.
- Large when coincidence with less forward charged particles ("minbias")
- p_T dependence
- Not understood how it arrises
  - Challenge to Theorist to explain
- Used to monitor beam polarization direction







Gluon Helicity Distribution (ΔG)



Helicity Structure

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_0^1 dx \Delta q(x)$$
$$= \sum_{q,\bar{q}} \int_0^1 dx [q^+(x) - q^-(x)]$$

From polarized DIS, $\Delta\Sigma$ is well measured. Global fits find

$\Delta\Sigma \sim 0.24$

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{z,q} + L_{g,z}$$

$$\Delta G = \int_0^1 dx \Delta g(x)$$
$$= \int_0^1 dx [g^+(x) - g^-(x)]$$

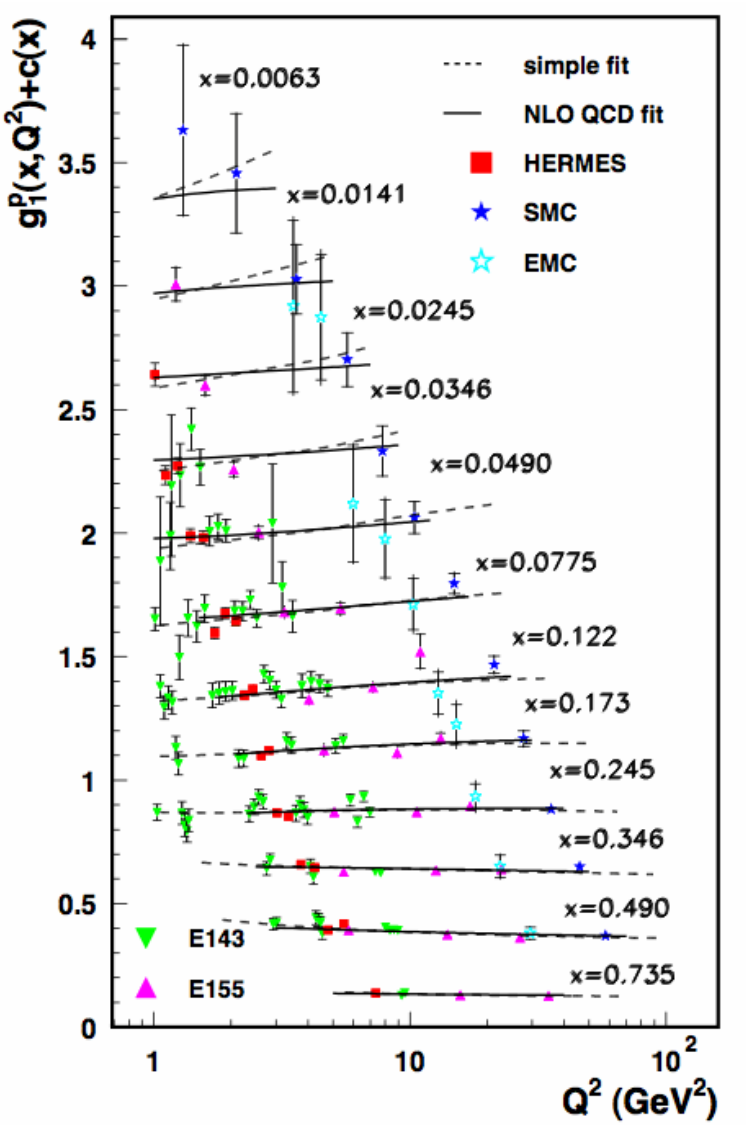
Does ΔG carry the remainder of the missing spin (or even more)?

Not clear how to measure

ΔG from DIS

- Unpolarized gluon info came from large Q^2 and x coverage of DIS measurements (HERA).
- Extract gluon distribution from DGLAP evolution in global fits.
- Polarized DIS measurements currently limited, so constraint from evolution is much weaker.
- How do we get gluon helicity info?

→ Go to polarized p+p collider



Accessing ΔG in p+p Collisions

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

From ep (&pp) (HERA mostly)

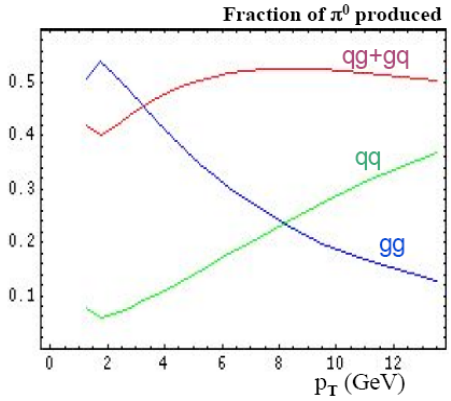
NLO pQCD

From e+e- (& SIDIS,pp)

- If $\Delta f = \Delta q$, then we have this from pDIS
- So roughly, we have

$$A_{LL} \cong a_{gg}\Delta g^2 + b_{gq}\Delta g\Delta q + c_{qq}\Delta q^2$$

- where the coefficients a, b and c are dependent on final state observable and event kinematics (η,p_T).



+- =

++ =

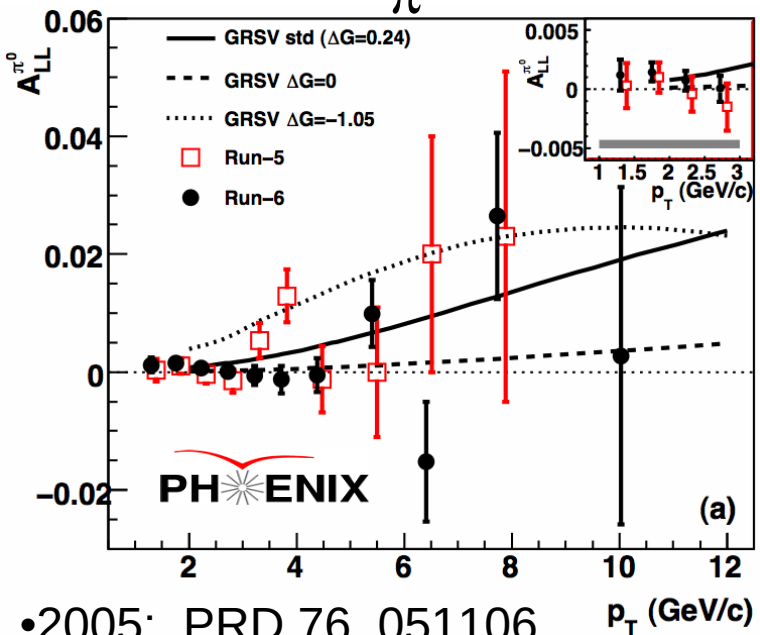
A_{LL} Results

- Many final state probes are studied at RHIC
  - Jets, π^0, $\pi^{\pm}$, η, Direct photon, etc.
- Due to abundant statistics and specialized triggers, the most significant constraints currently come from π^0s (PHENIX) and Jets (STAR).

$$A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

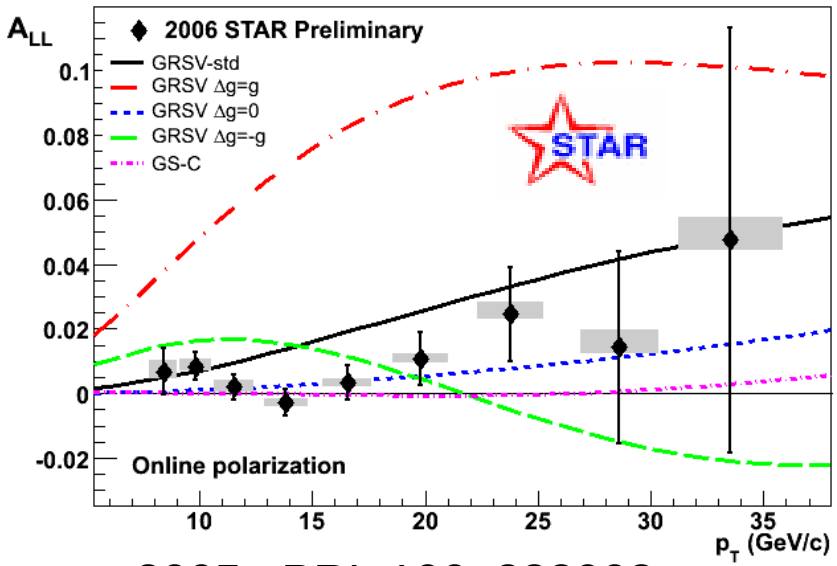
$$R = \frac{L_{++}}{L_{+-}}$$

π^0



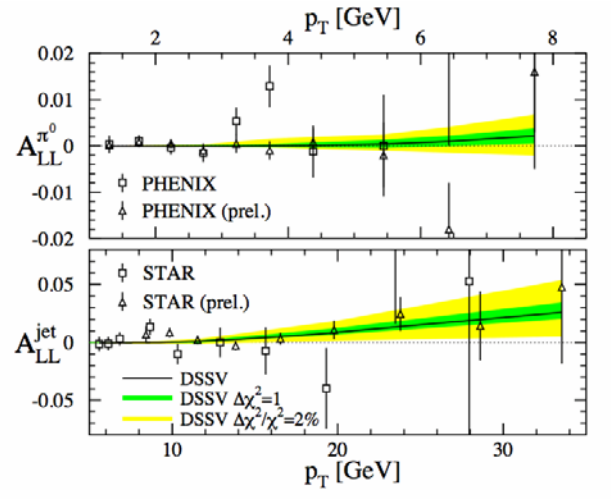
- 2005: PRD 76, 051106
- 2006: PRL 103, 012003

Jet

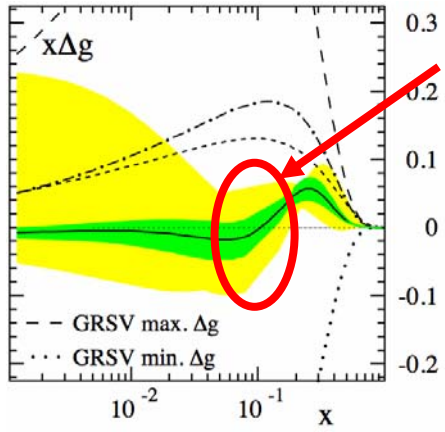


- 2005: PRL 100, 232003
- 2006: Preliminary

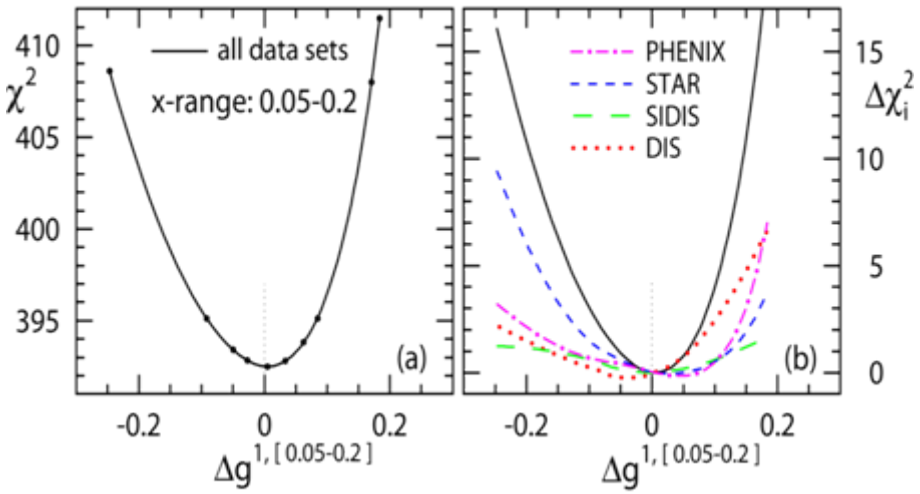
Constraining ΔG



DSSV, PRL **101**, 072001(2008)



RHIC region

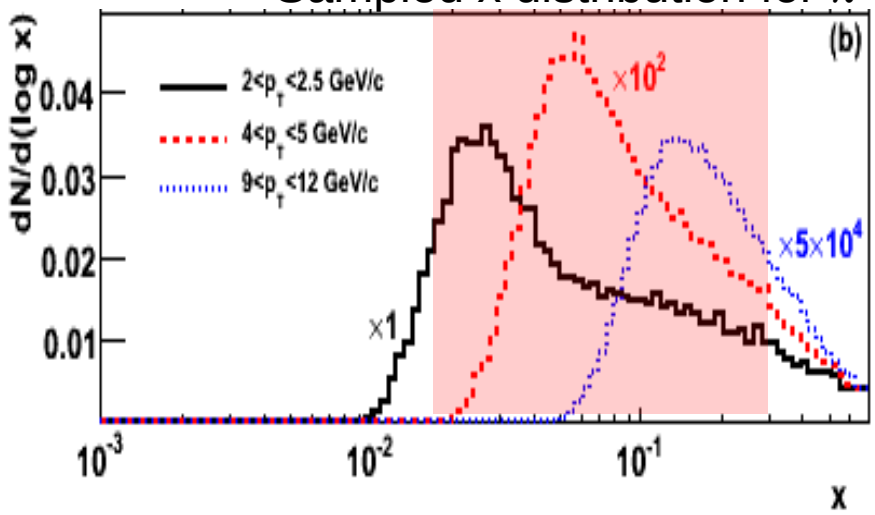


- DSSV fit world date including p+p for first time.
  - PRL101:072001,2008
  - arXiv:0904.3821
- RHIC data offer significant constraint at 0.05<x<0.2.
- Large uncertainty remains below RHIC x range.
- Understanding full uncertainties are important.

Extending the constraint

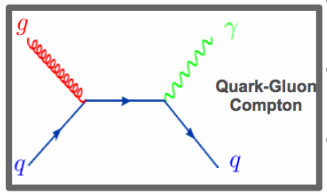
- Obviously, remeasure π^0 and jet A_{LL} with higher statistics
- Other processes
  - relevant with more luminosity
  - different sensitivity to ΔG, such as direct photon production
- Extending x range
- Narrow the sensitivity to $\Delta G(x)$
  - Correlation measurements

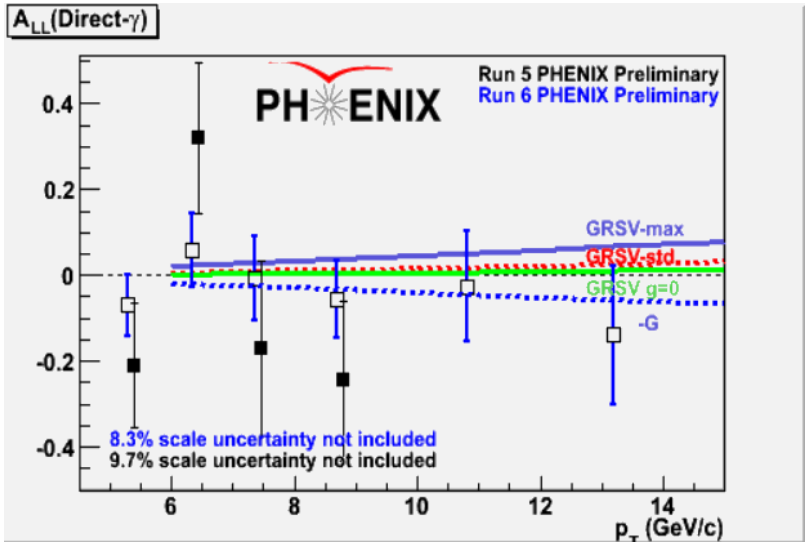
Sampled x distribution for π^0



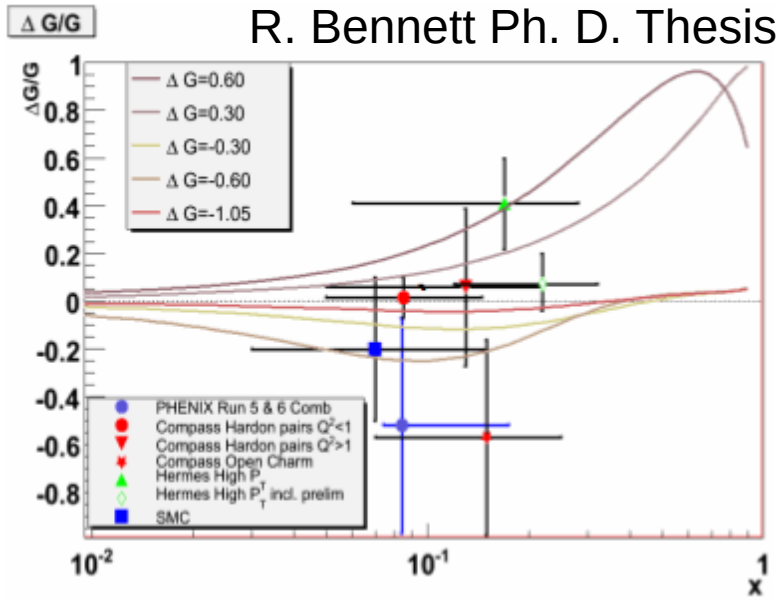
Direct Photon

- Example of a process with a different constraint on ΔG
  - Direct photon
    - Quark-Gluon Compton scattering dominates (~80%)
    - $A^{direct\ \gamma}_{LL}$ is essentially linear in ΔG.
    - Can give leading order constraint of ΔG/G
      - (R. Bennett's thesis, using PHENIX date from 2005 and 2006.)



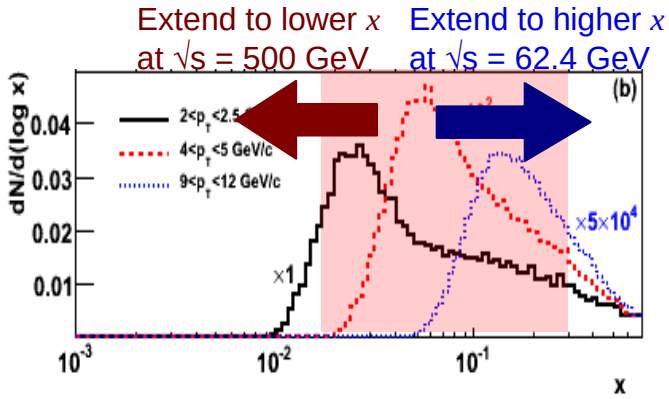


R. Bennett Ph. D. Thesis

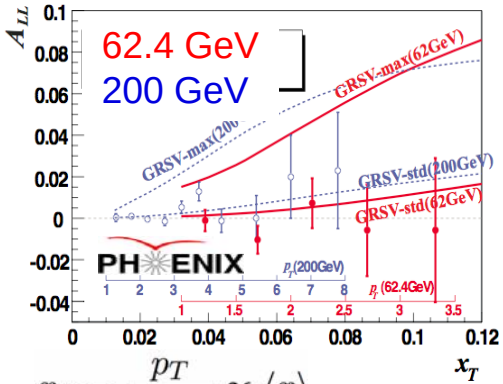


Extending x range

- Current measurements constrain ΔG in the x range [0.02,0.3]
- Need to constrain ΔG over wide x range
  - → Expand the x range
    - √s=62.4 GeV → higher x (short run in 2006)
    - √s=500 GeV → lower x (first run earlier this year)
    - Forward rapidity → lower x

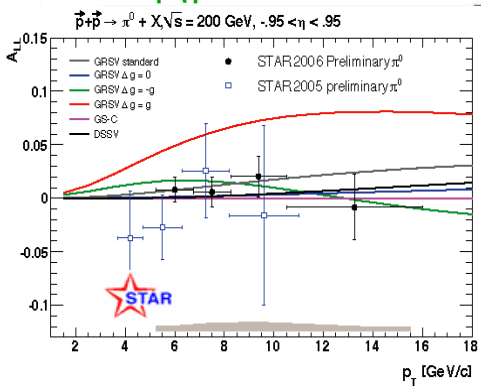


PRD 79, 012003 (2009)

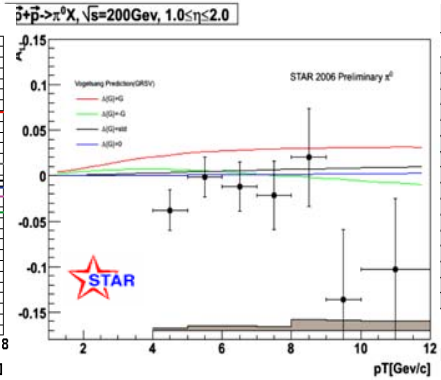


$$x_T = \frac{p_T}{\sqrt{s}/2} \propto \langle x \rangle$$

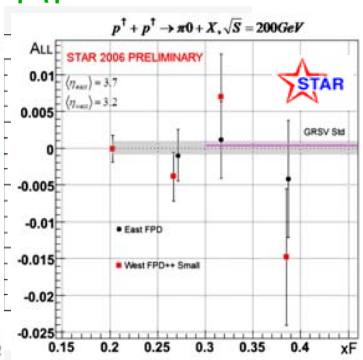
|η| <0.95



1<|η|<2

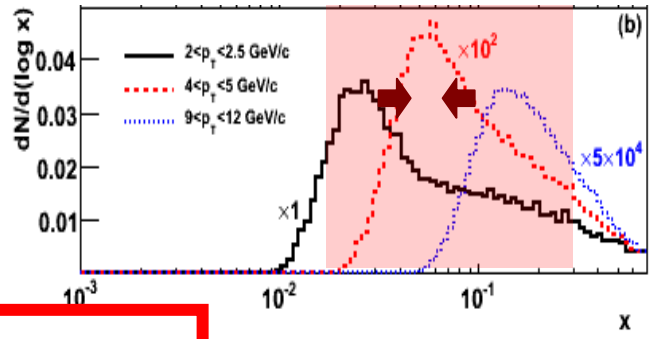


|η|=3.3,3.7



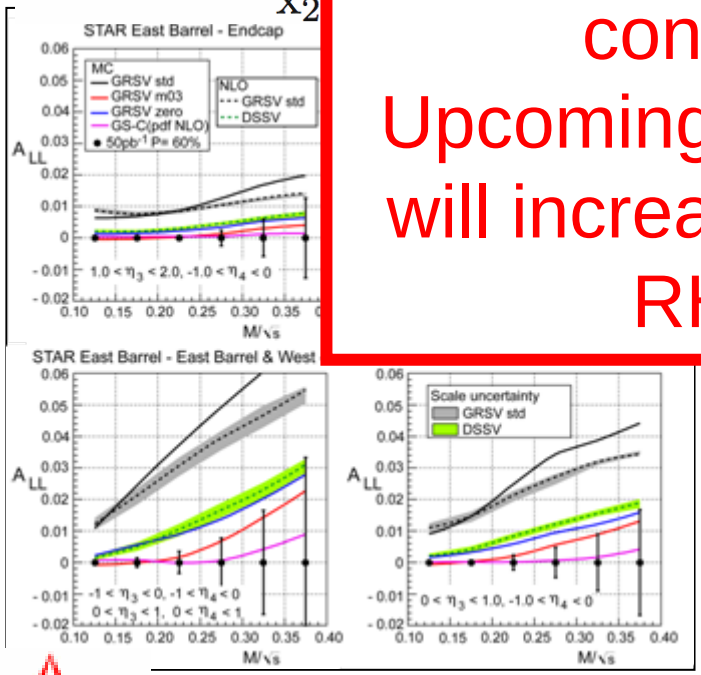
Narrowing x Sensitivity

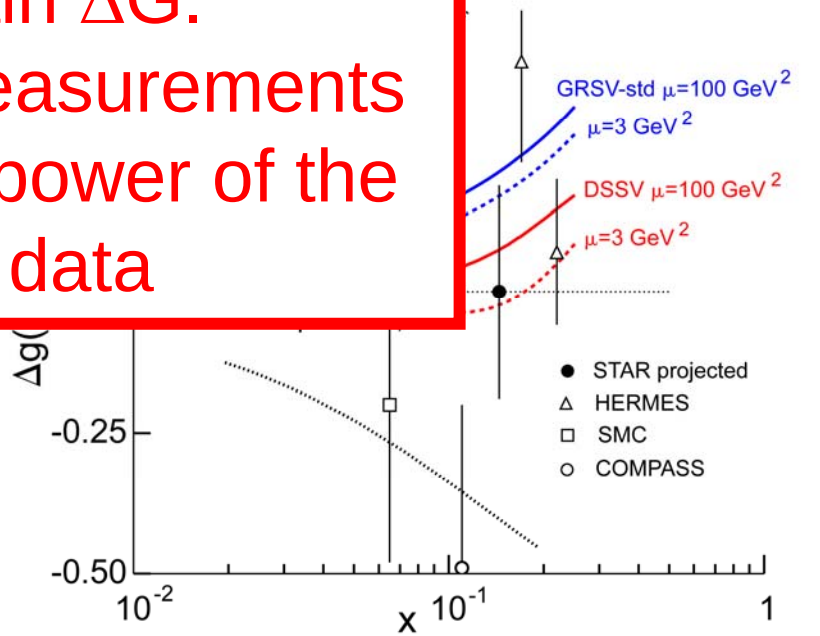
- Another option, get x from data.
- Upcoming measurements
  - Better constrain x (need more luminosity)
    - Two jet (or particle) correlations
    - Gamma-jet



$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$

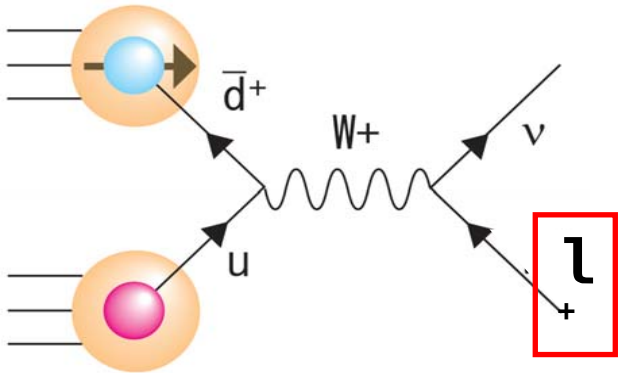
RHIC data significantly constrain ΔG.
Upcoming measurements will increase power of the RHIC data





STAR projection: L=50 pb^{-1},P=60%

Sea Quark Helicity Structure: Measuring A_L of W bosons

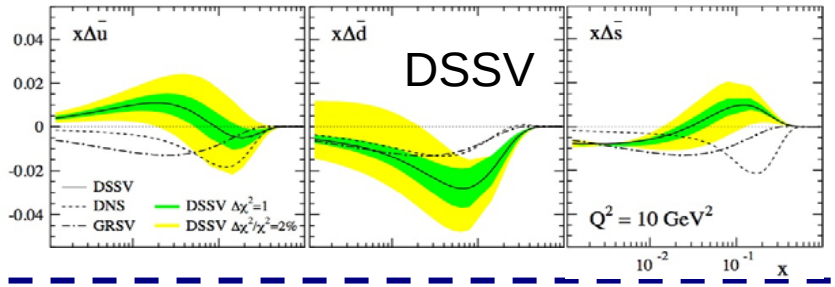


Helicity Structure

$$\Delta\Sigma = \sum_{q,\bar{q}} \int_0^1 dx \Delta q(x)$$
$$= \sum_{q,\bar{q}} \int_0^1 dx [q^+(x) - q^-(x)]$$

From polarized DIS, $\Delta\Sigma$ is well measured. Many global fits find $\Delta\Sigma \sim 0.24$

While $\Delta\Sigma$ is well constrainted from pDIS, Δq for the different quarks are less well know, especially in the case of sea quarks:



$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{z,q} + L_{g,z}$$

$$\Delta G = \int_0^1 dx \Delta g(x)$$
$$= \int_0^1 dx [g^+(x) - g^-(x)]$$

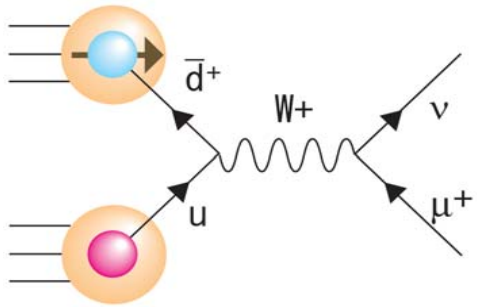
Does ΔG carry the remainder of the missing spin (or even more)?

Not clear how to measure

Sea Quark Helicity Distributions

- How can we get flavor dependent sea quark info?
  - SIDIS
    - Current constraints come from SIDIS
    - Relies on the favored fragmentation of the struck quark
  - At RHIC, W boson production in polarized p+p collisions is sensitive to specific combinations of quarks.
    - $u\bar{d} \rightarrow W^+$, $\bar{u}d \rightarrow W^-$
    - W boson production via V-A coupling

    → Perfect spin separation



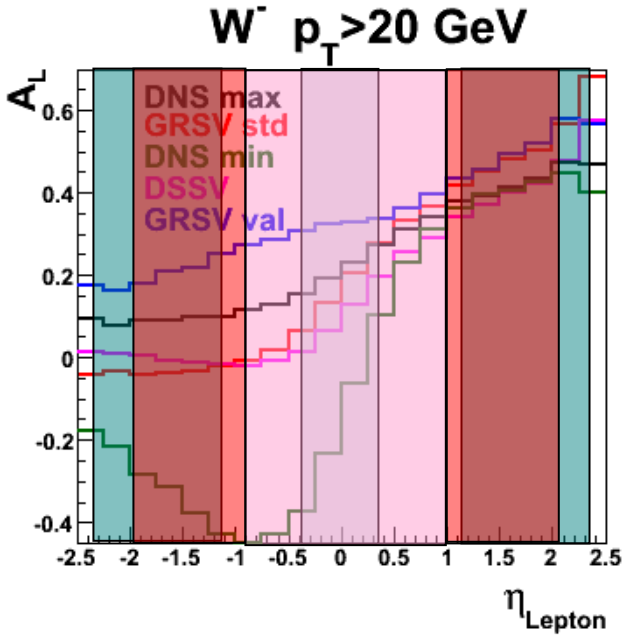
- Measure parity violating asymmetry in W boson production
  - Maximal violation of parity in W production can lead to large asymmetries.

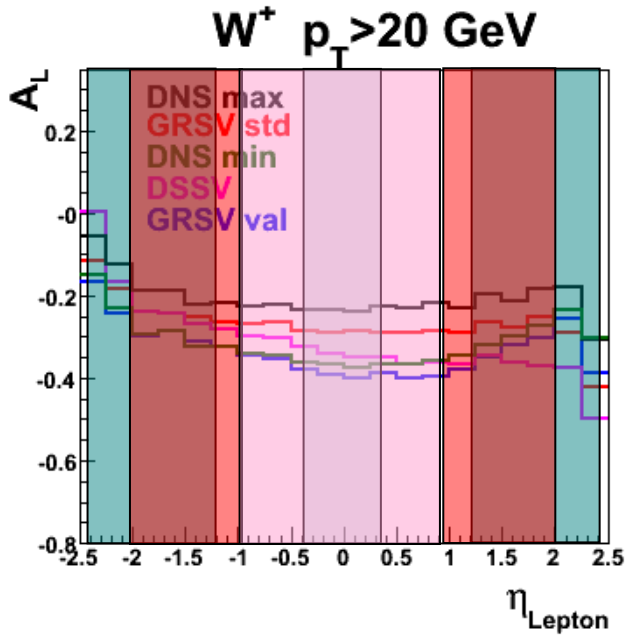
$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \propto \frac{\Delta\bar{d}(x_1)u(x_2) - \Delta u(x_1)\bar{d}(x_2)}{\Delta\bar{d}(x_1)u(x_2) + \Delta u(x_1)\bar{d}(x_2)}$$

- Similar case for W^- with d and $\bar{u}$.

Coverage of Lepton Rapidity

- Sensitivity to sea quark distributions vary with η of the measured lepton.
- Lepton decay kinematics reduce some sensitivity.





PHENIX Central Arms $e^{\pm}$

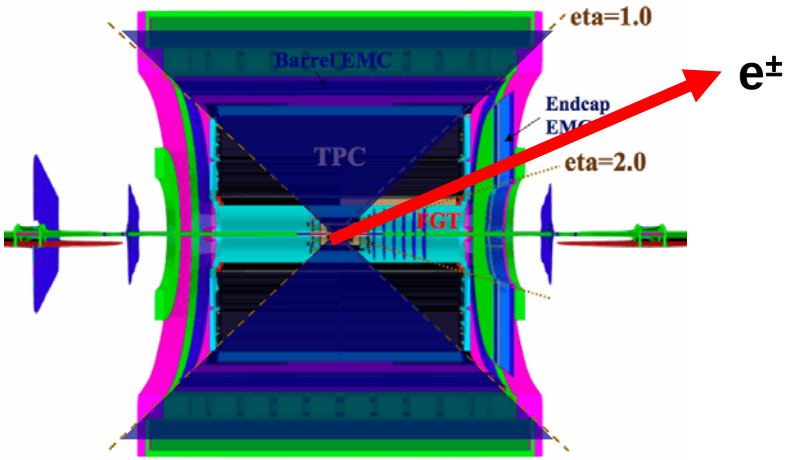
STAR Central Barrel $e^{\pm}$

PHENIX Muon Arms $\mu^{\pm}$

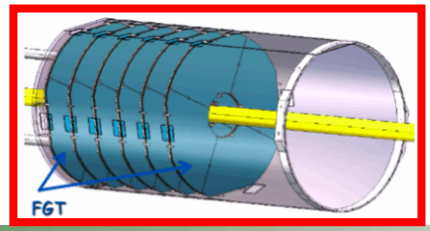
STAR Forward $e^{\pm}$

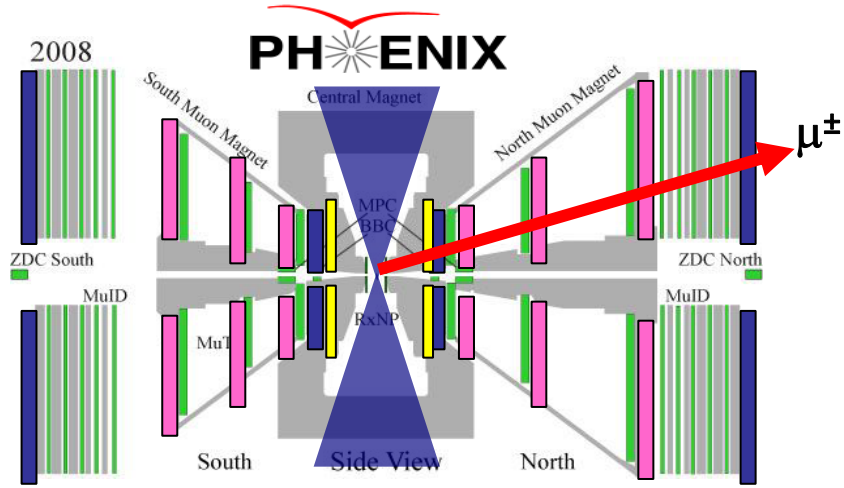
Upgrades for W Physics

- Both STAR and PHENIX can measure W->e near midrapidity
  - Analysis of first 500 GeV data in 2009 is underway!
- What about larger rapidities?
  - Both detectors are currently working on upgrades.



End Cap EMCal can tag electron.
TPC does not give enough points for charge sign measurement
→Forward GEM Tracker





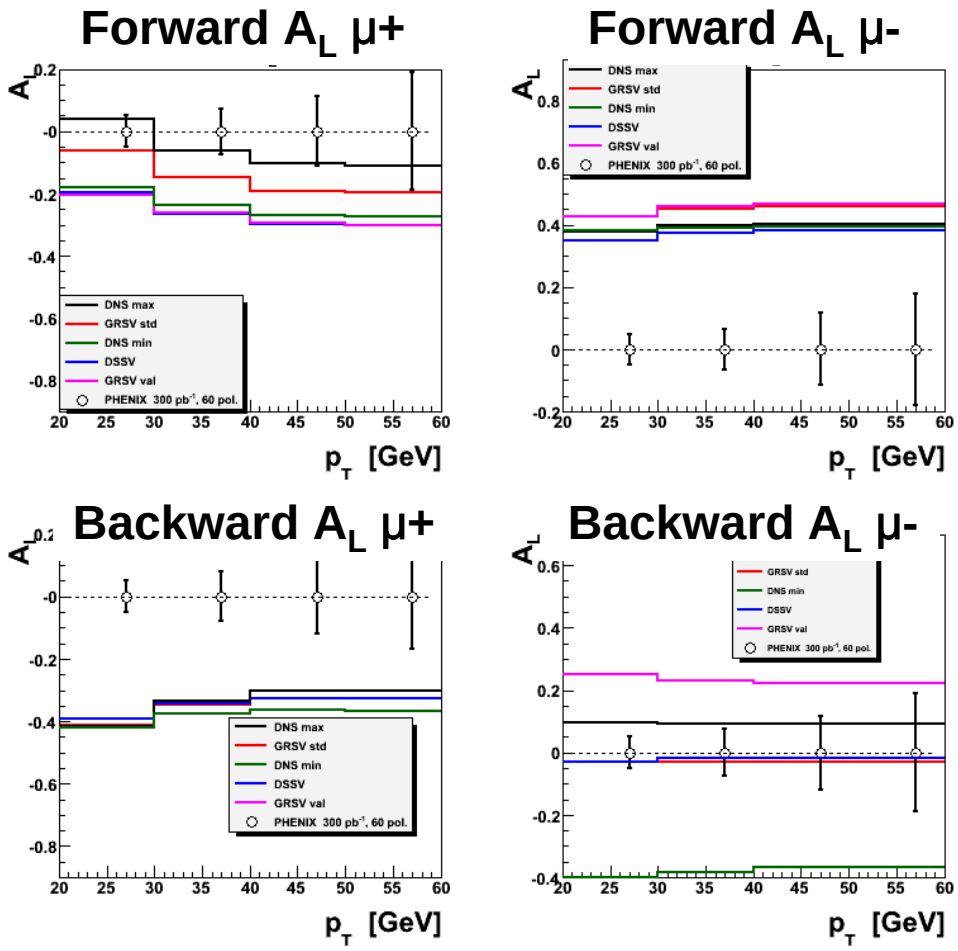
Identification from MUID and charge sign/ momentum from MUTr.
BUT, trigger is dominated by low momentum particles
→ Resistive Plate Chambers
→ 5% of MUTr signal into trigger circuit
Use bend in track to trigger high mom. muon

Conclusions

- The RHIC spin program is increasing our knowledge of the spin structure of the nucleon.
- Transverse Spin Distributions
  - Results from RHIC show that the unexpectedly large transverse spin asymmetries seen at lower $\sqrt{s}$ remain at 62.4 and 200 GeV.
  - Many of these results are a challenge to theory.
- Gluon Helicity Distribution
  - Measurements of A_{LL} at RHIC offer a significant constraint of ΔG in the range $0.02<x<0.3$, indicating a small contribution in this region.
  - Due to the limited x range, and the smearing of x in the current measurements, it is still too early to state $\Delta G=0$.
  - Measurements at $\sqrt{s}$=500 GeV will push towards lower x.
  - Jet and particle correlations will reduce smearing in x between p_T bins.
- Sea Quark Helicity Distributions
  - First 500 GeV run is complete, and analysis of W cross section and A_L is underway.
  - Upgrades will expand the sensitivity to these distributions.

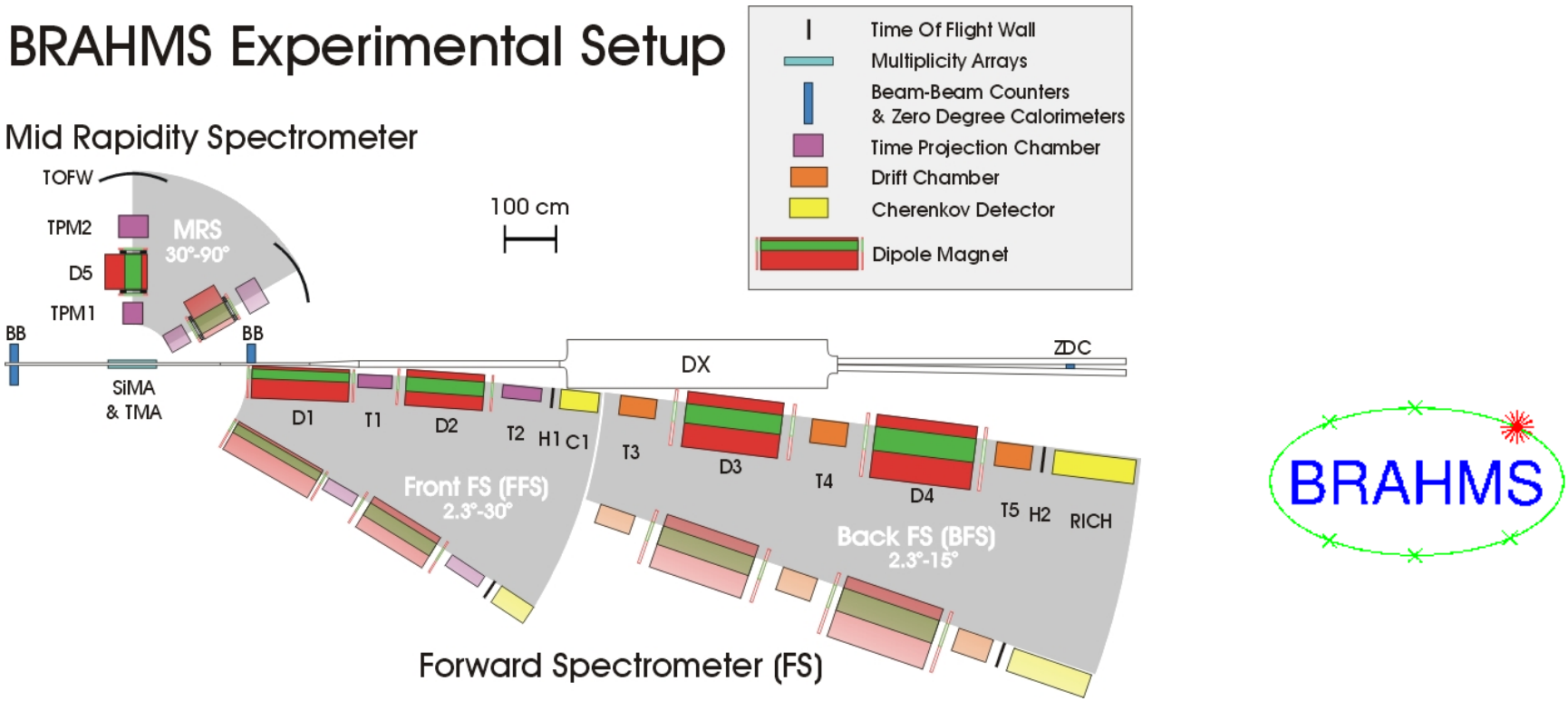
BACKUPS

Sensitivity for A_L^W



- 300 pb^{-1}, 60% pol

BRAHMS detector

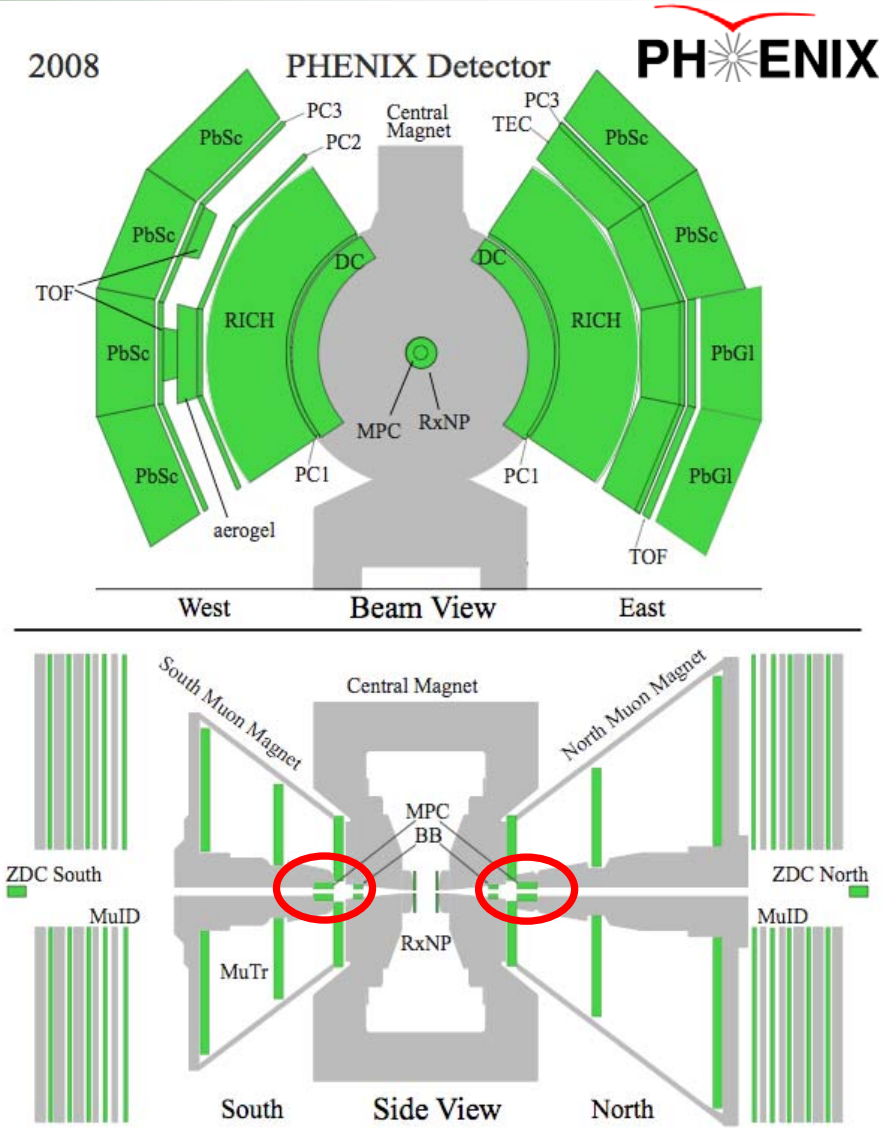


BRAHMS

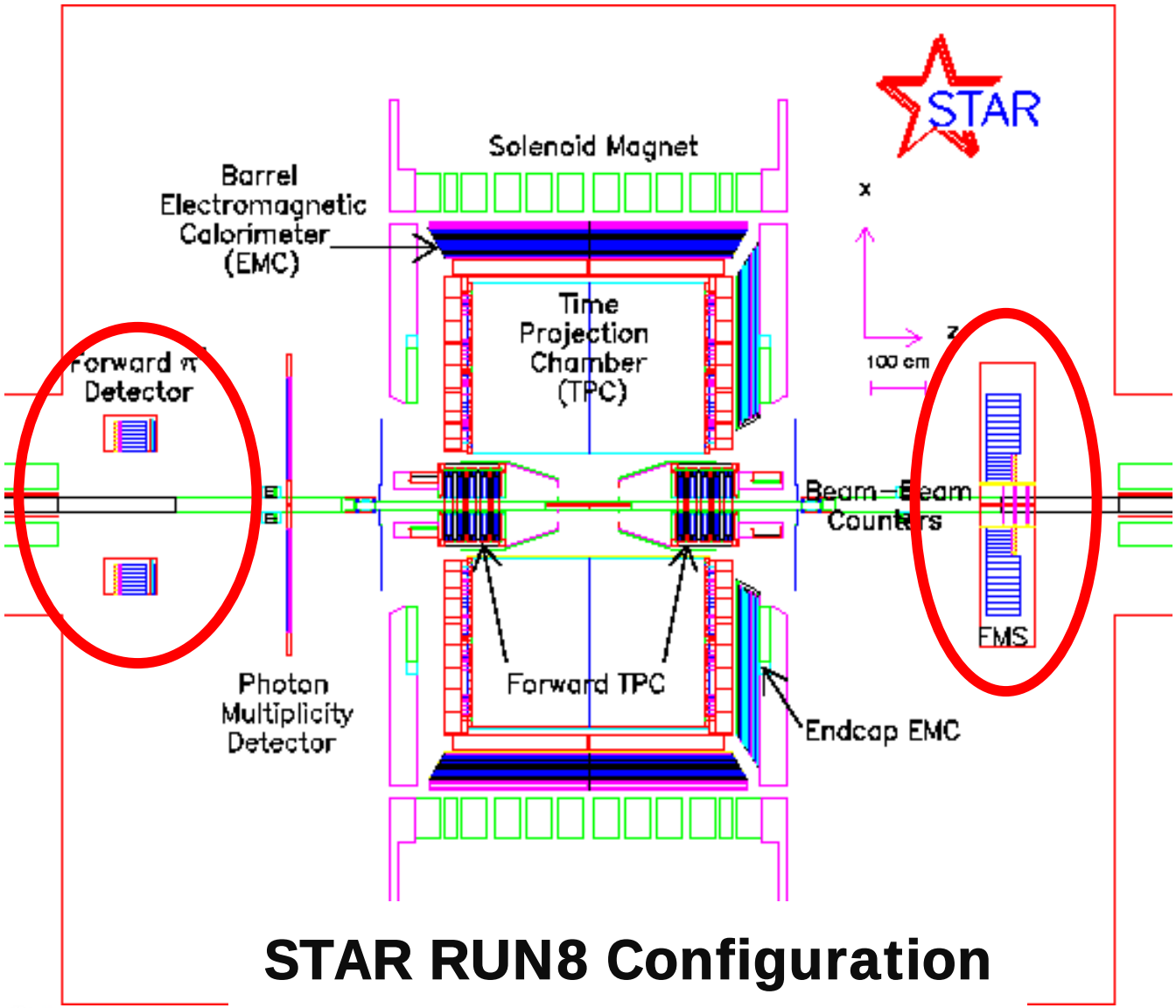
PHENIX detector

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes
- 2 forward muon spectrometers
  - Identify and track muons
- 2 forward calorimeters (as of 2007)
  - Measure forward pions, etas

Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



STAR detector



STAR RUN8 Configuration

TPC: -1.0 < h < 1.0

FTPC: 2.8 < |h| < 3.8

BBC : 2.2 < |h| < 5.0

EEMC: 1 < h < 2

BEMC: -1 < h < 1

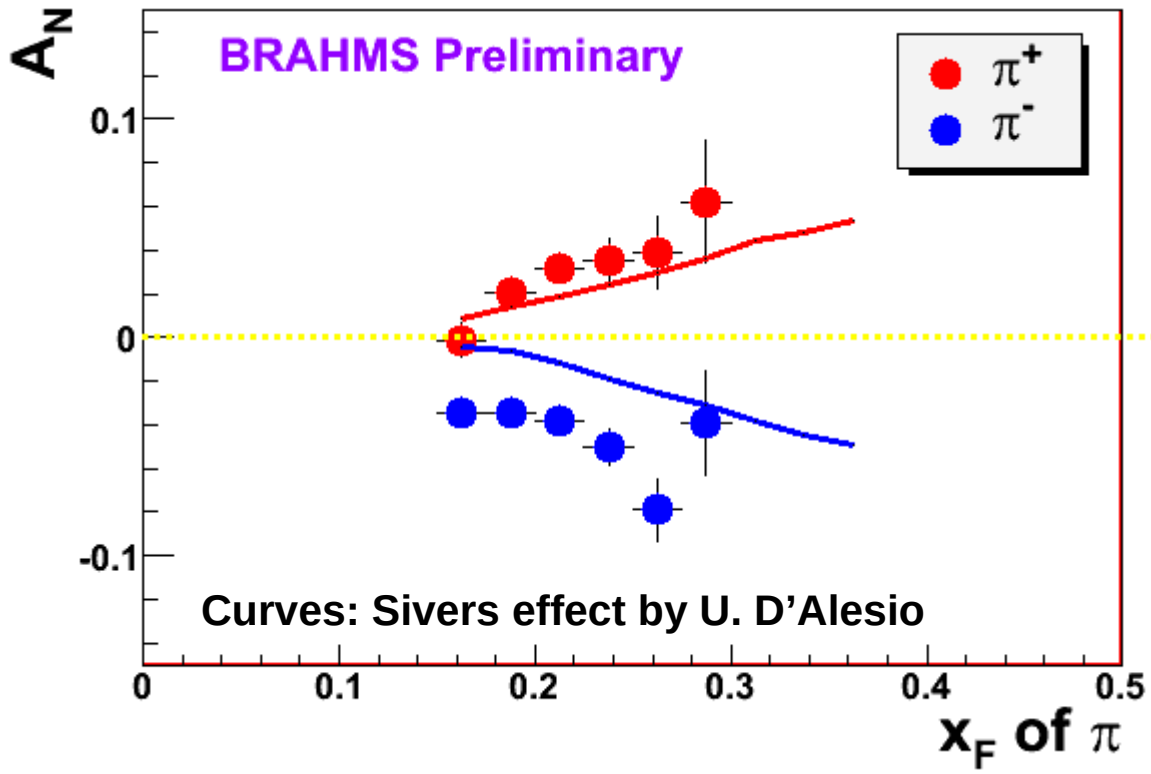
FPD/FPD++:

h ~ 3.3 – 4.1

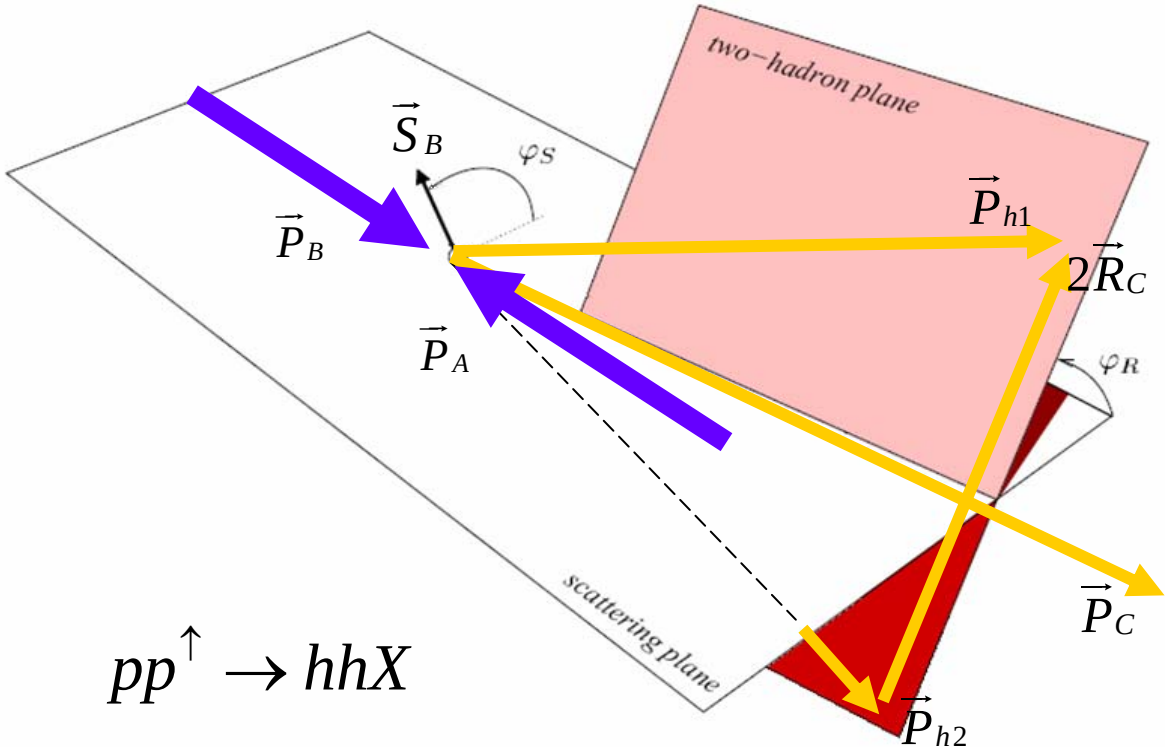
As of 2008

FMS : 2.5 < h<4.1

$A_N(\pi)$ at 4 deg. at 200 GeV



IFF: Definition of Vectors and Angles



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

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

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

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

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

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

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

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

$$A = A^{\sin\phi} \sin(\phi_R - \phi_S)$$

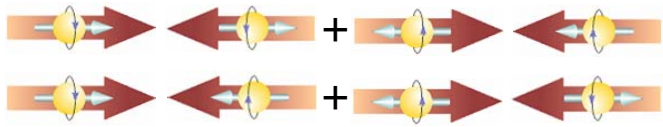
Bacchetta and Radici, PRD70, 094032 (2004)

Measuring A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}$$

+ - = Opposite helicity =

++ = Same helicity =



- Helicity Dependent Particle Yields
  - π^0, π^+, π^-, γ, η, etc
- (Local) Polarimetry
- Relative Luminosity ($R=L_{++}/L_{+-}$)
- A_{LL}