Spin Physics @ RHIC

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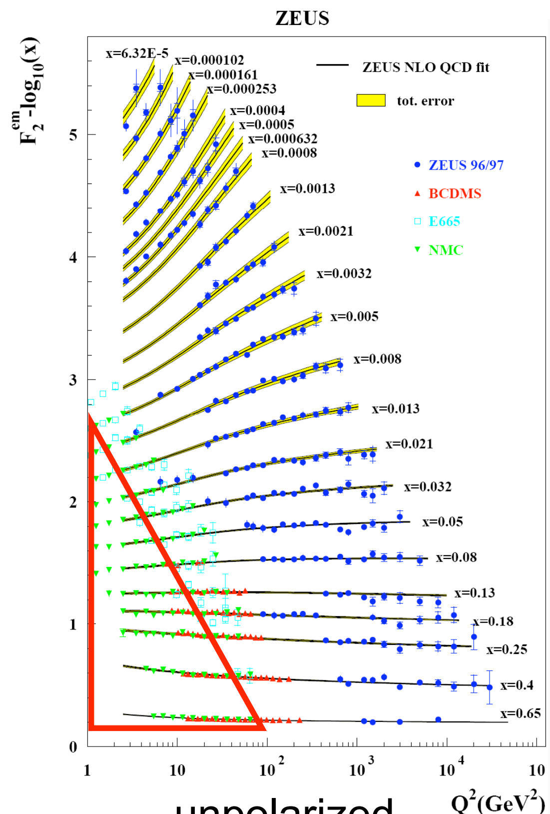
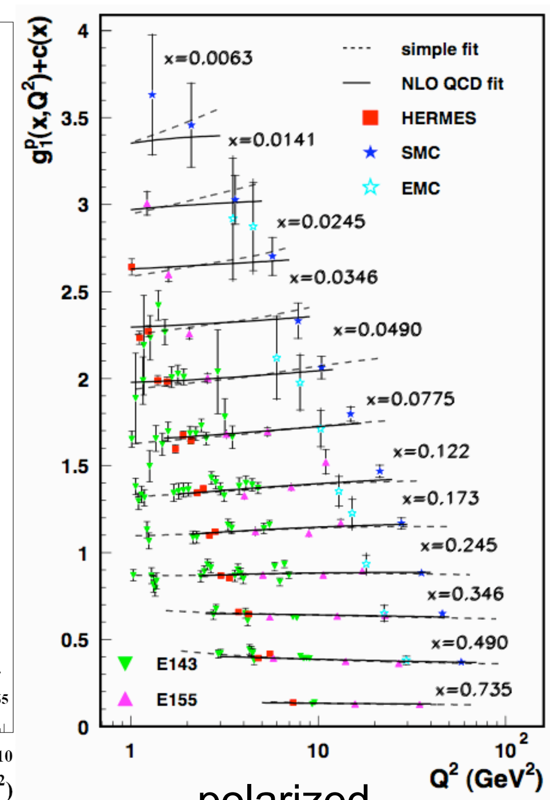
Structure of the Nucleon

- The nucleon is a composite particle, made up of quarks and gluons
- Properties of the proton arise from properties of the constituents
  - Charge
    - From quarks
  - Momentum
    - From quarks and gluons
  - Spin
    - Polarized DIS data limited in x and Q^2
    - Access with other methods



unpolarized

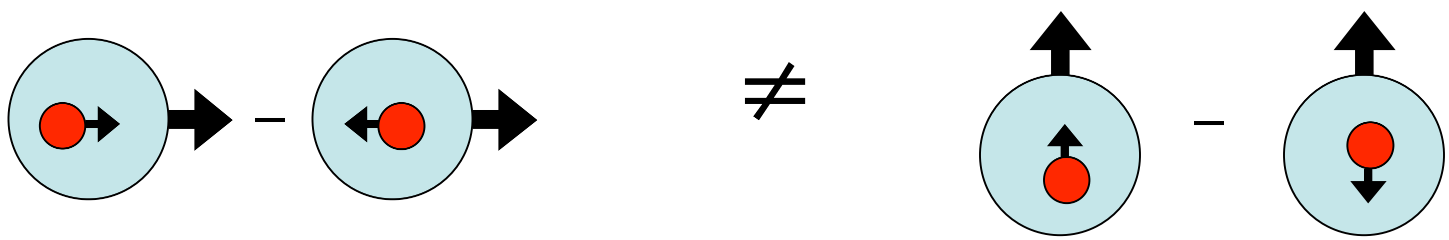


polarized

Spin Structure: Two ways

- As rotations and boosts don't commute, longitudinal and transverse spin structure are not the same

Helicity: $\Delta f(x)$ $\neq$ Transversity: $\delta f(x)$

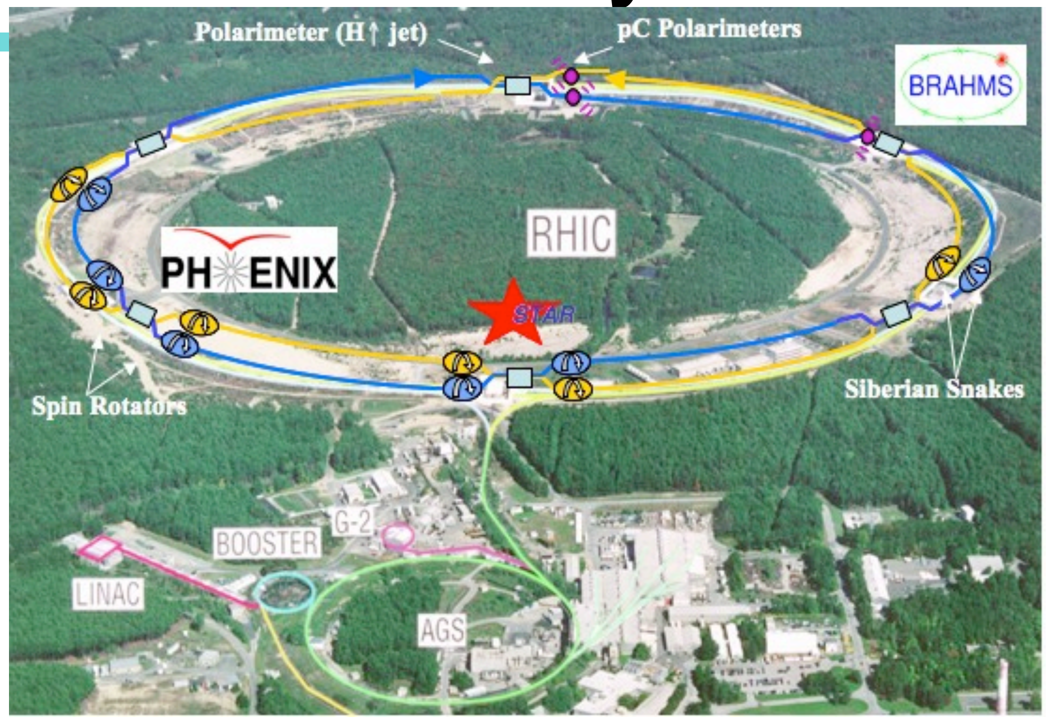


- At RHIC, we're interested in both.

<u>Outline</u>

- Gluon helicity
- Sea quark helicity
- Transverse spin

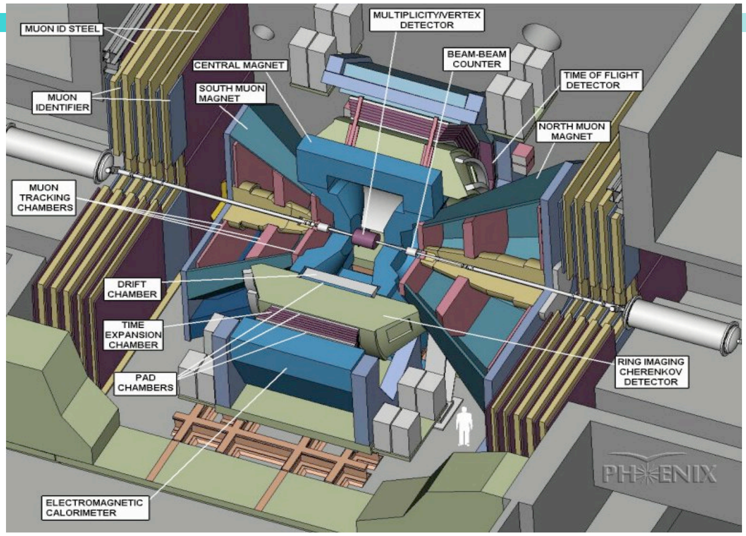
The RHIC Facility



- $\sqrt{s}$=62.4–500 GeV
  - Most data at 200 GeV
  - Short 62.4 GeV run in 2006
  - First long 500 GeV run now
- Polarization
  - 57% at 200 GeV
  - 45% at 500 GeV

- STAR and PHENIX
  - transverse or longitudinal polarization
- BRAHMS
  - only Transverse
  - was decomissioned after 2006.

Experiments

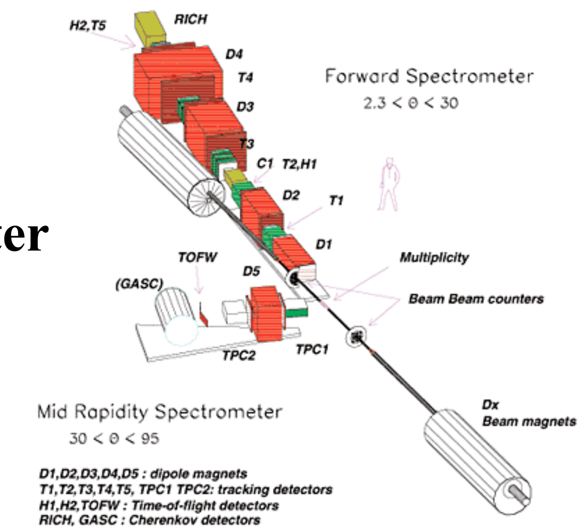


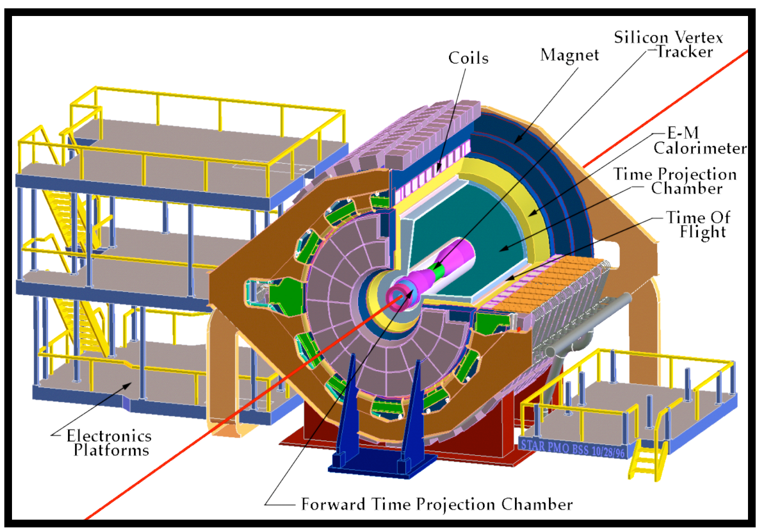
PHENIX

High rate capability
Limited acceptance
High p_T photon trigger
Forward muon arm

BRAHMS

Forward spectrometer
charge hadron id





STAR

Large acceptance
Azimuthal symmetry
Jet patch trigger
Forward EMcal

Helicity Structure

vs.

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 $\Delta\Sigma \sim 0.24$

Where is the missing spin?

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

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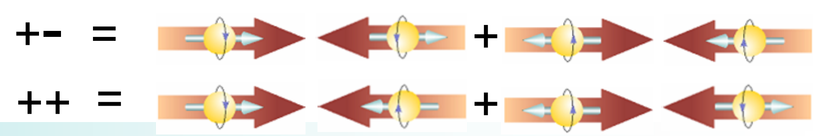
$$\Delta G = \int_0^1 dx \Delta g(x)$$
$$= \int_0^1 dx [g^+(x) - g^-(x)]$$

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

Not clear how to measure

Accessing ΔG in p+p Collisions

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



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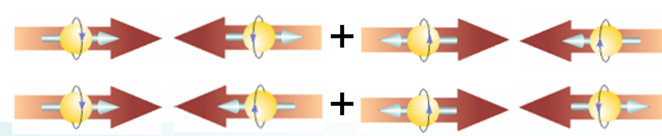
From ep (&pp) (HERA mostly)

NLO pQCD

From e+e- (& SIDIS,pp)

+- =

++ =



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From ep (&pp) (HERA mostly)

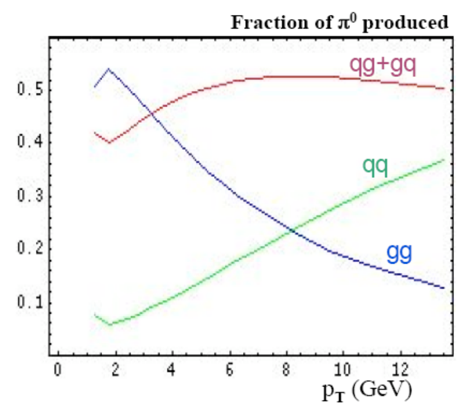
NLO pQCD

From e+e- (& SIDIS,pp)

- If Δf = Δq, 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).



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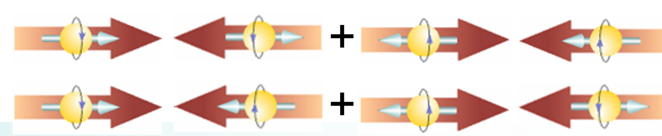


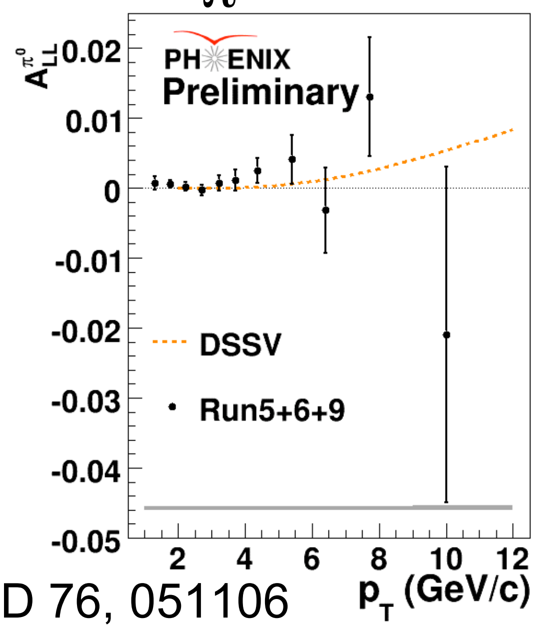
A_{LL} Results

- 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).

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

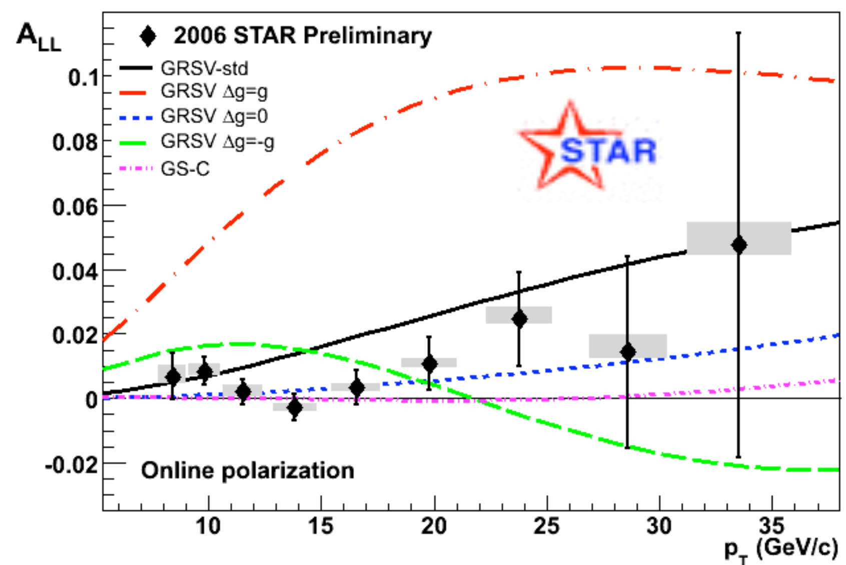
$$R = \frac{L_{++}}{L_{+-}}$$

π^0



- 2005: PRD 76, 051106
- 2006: PRL 103, 012003
- 2009: Preliminary

Jet



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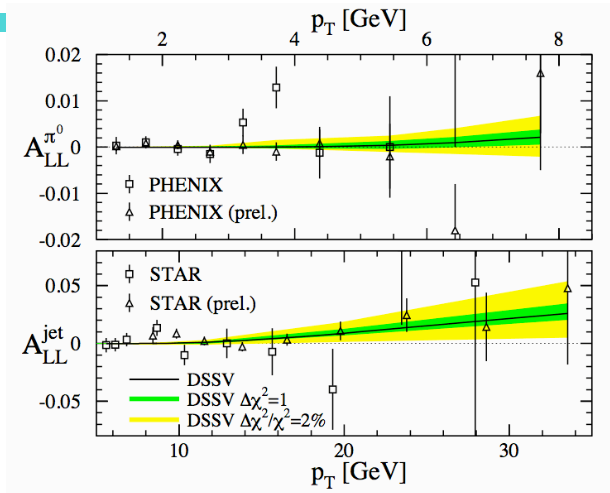
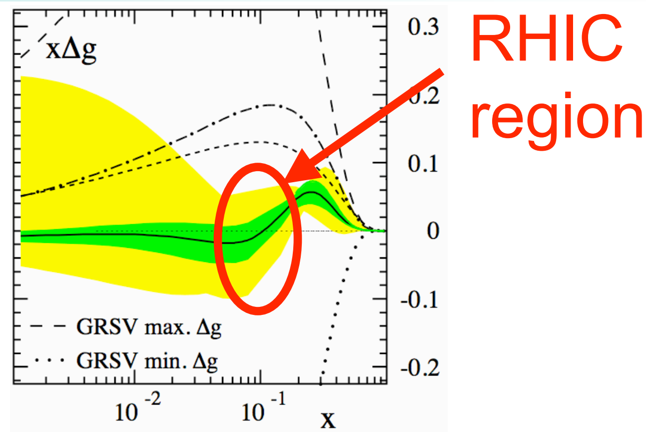
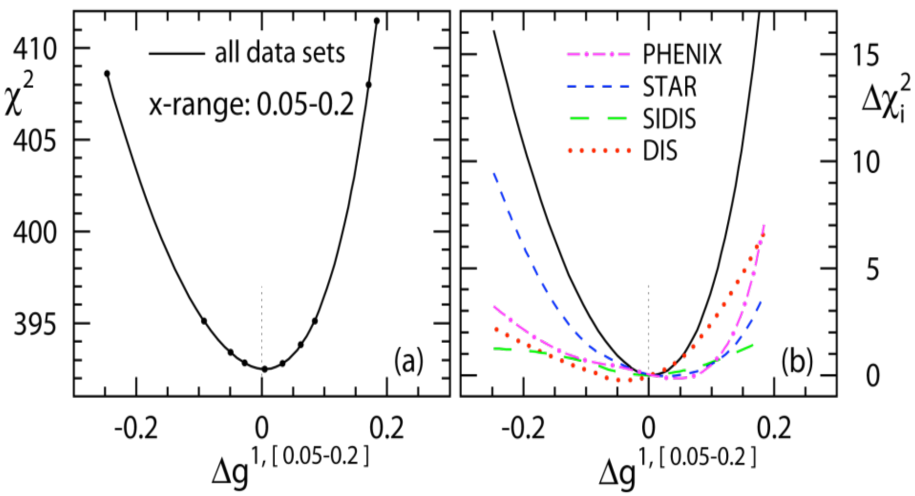
Constraining ΔG



+DIS
+SIDIS





- DSSV fit world date including p+p for first time.
  - PRL101:072001, 2008
  - PRD 80:034030, 2009
- RHIC data offer significant constraint at 0.05<x<0.2.
- Large uncertainty remains below RHIC x range.
- Joint Theory and Experimental group working to get more complete uncertainty.
- 1.5 times more data from 2009.

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)
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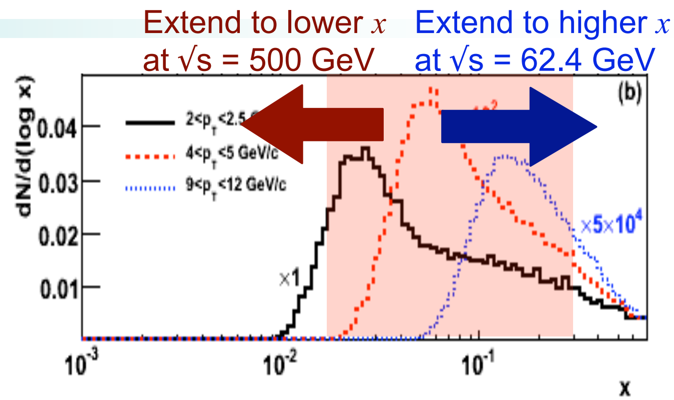
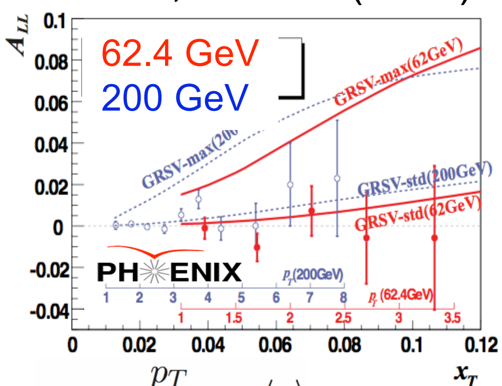
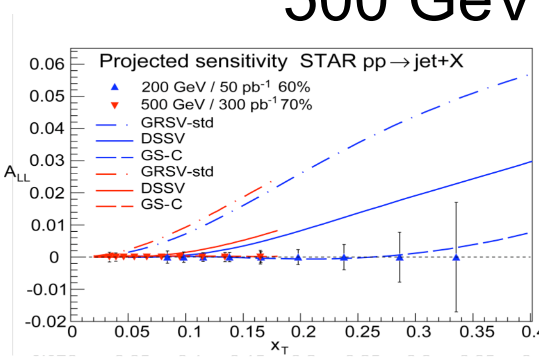


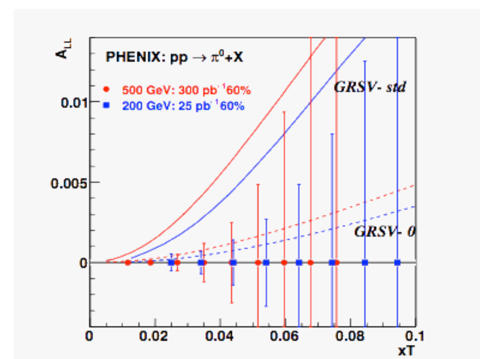
PRD 79, 012003 (2009)



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

500 GeV Expectations





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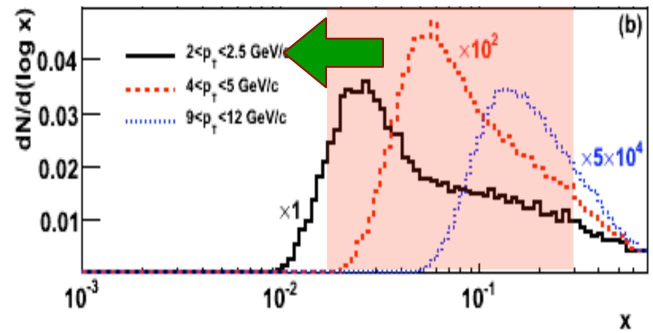
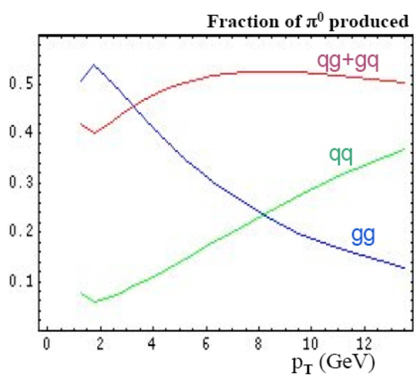
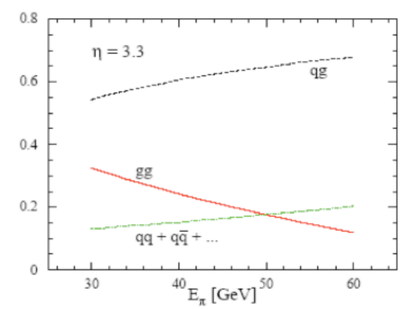


|η| <0.35 1<|η|<2 |η|=3.3,3.7





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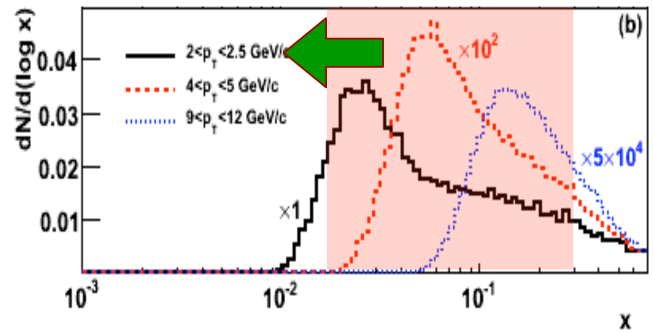

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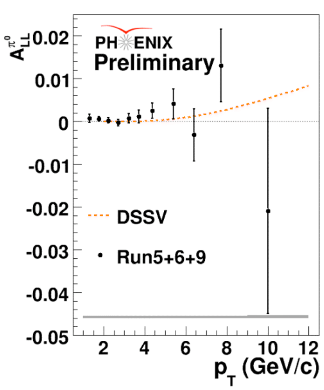

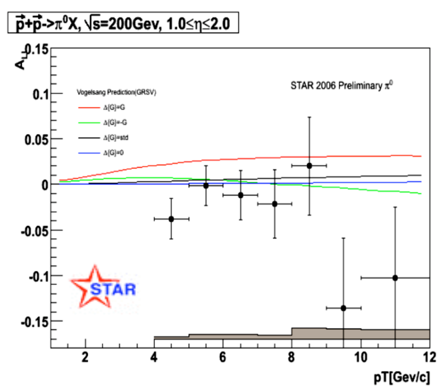

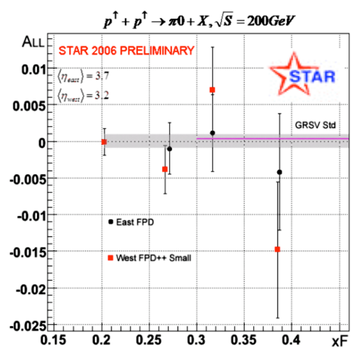

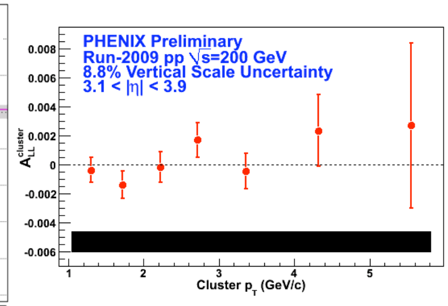

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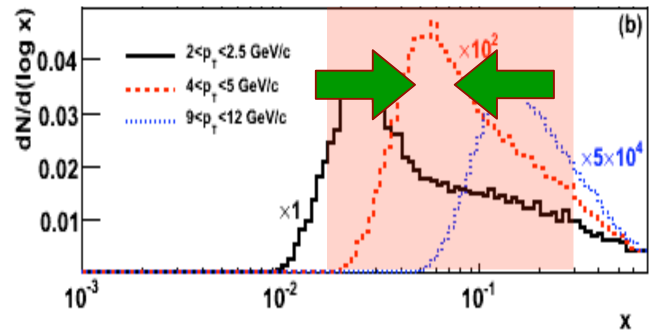
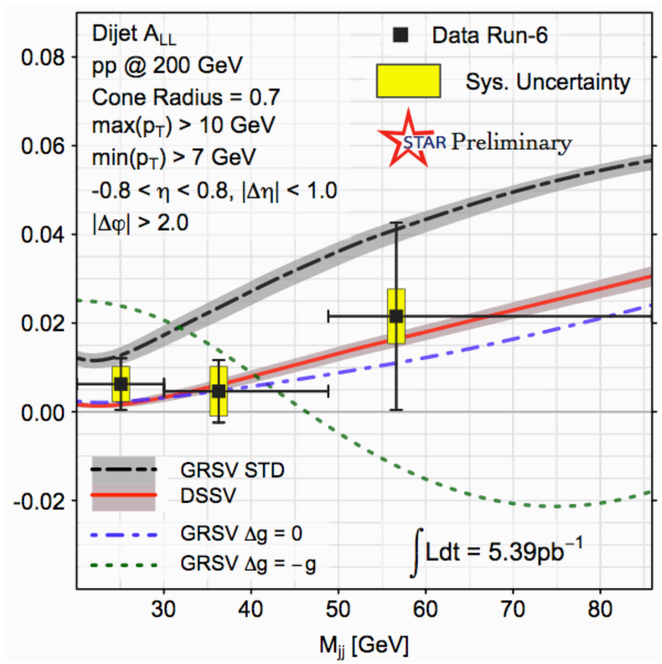
    - Forward rapidity → lower x
- Measure ΔG(x) through correlations
  - Inclusive measurements sample wide x range
  - Correlation measurements access ΔG as a function of x

$$x_1 = \frac{1}{\sqrt{s}}(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4})$$
$$x_2 = \frac{1}{\sqrt{s}}(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4})$$
$$M = \sqrt{x_1 x_2 s}$$
$$\eta_3 + \eta_4 = \ln\frac{x_1}{x_2}$$





Helicity Structure

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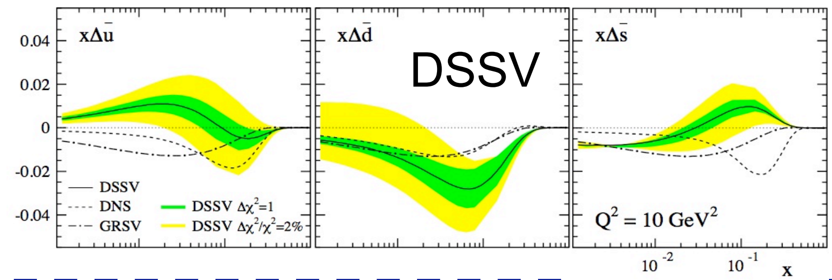
From polarized DIS, $\Delta\Sigma$ is well measured. Many global fits find $\Delta\Sigma \sim 0.24$

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



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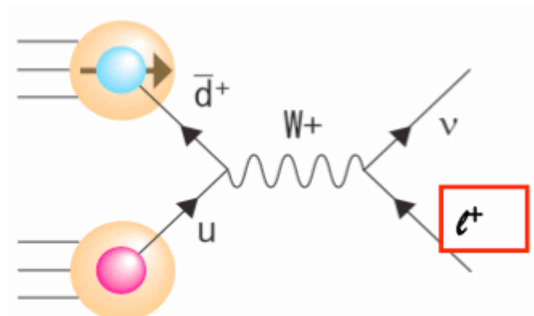
$$\Delta G = \int_0^1 dx \Delta g(x) = \int_0^1 dx [g^+(x) - g^-(x)]$$

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

Not clear how to measure

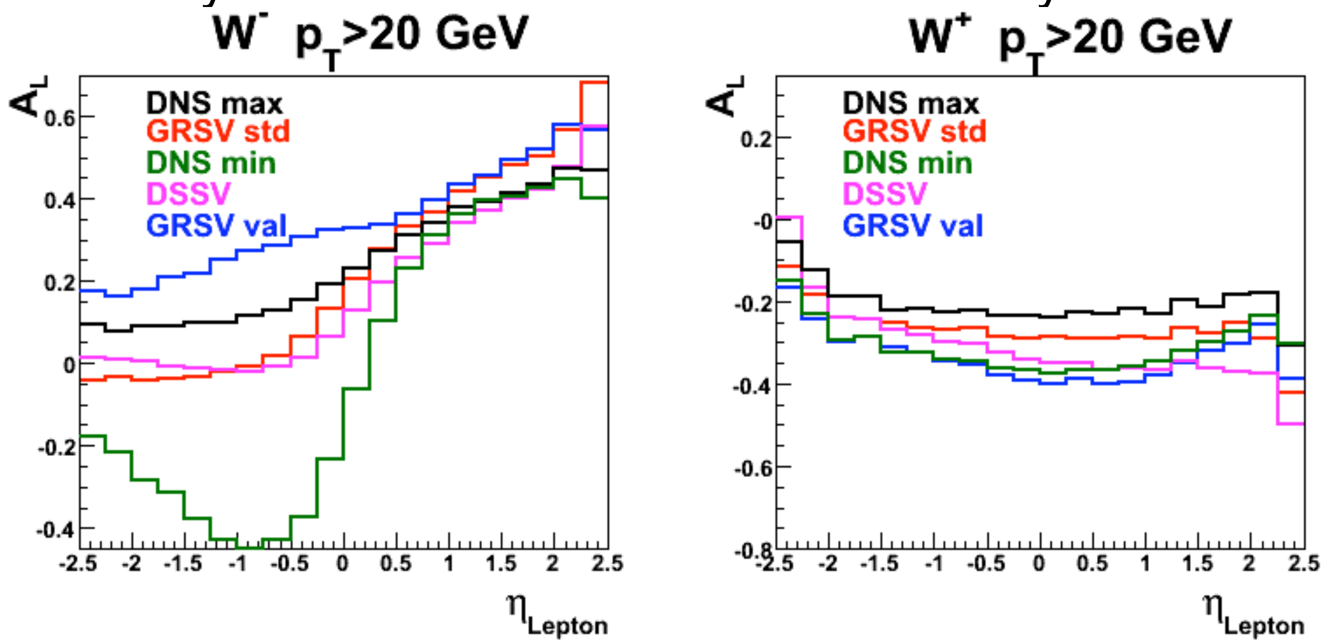
How to get flavor separation?

- 4 ways to get at flavor:
  - ℓ+p→ℓ+X vs. ℓ+n→ℓ+X
    - u and d separation, but not sea quarks.
  - ν+p→ℓ+X
    - Very small cross section→very large pol. target…not feasible
  - ℓ+p→ℓ+hadron+X (using favored fragmentation)
    - Small values of hard scale, source of current knowledge
  - p+p→W+X→ℓ+X
    - Hard scale ~m_W^2
    - Large asymmetries expected



Coverage of Lepton Rapidity

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



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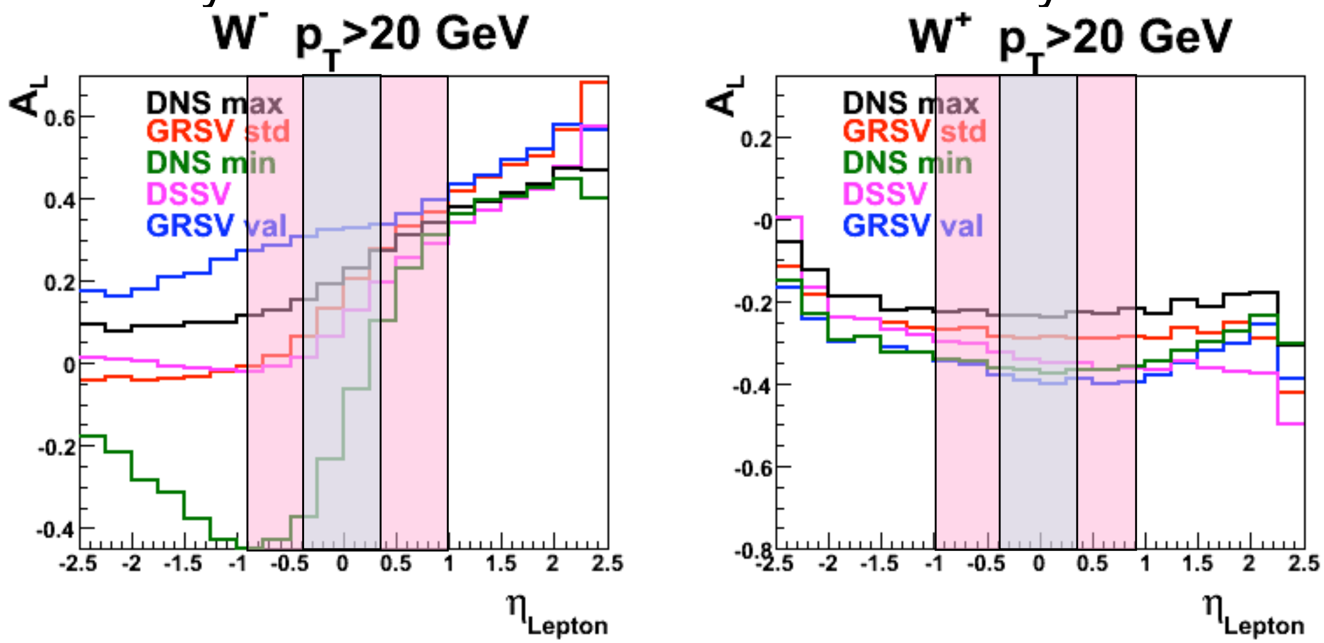

PHENIX Central Arms e±

STAR Central Barrel e±

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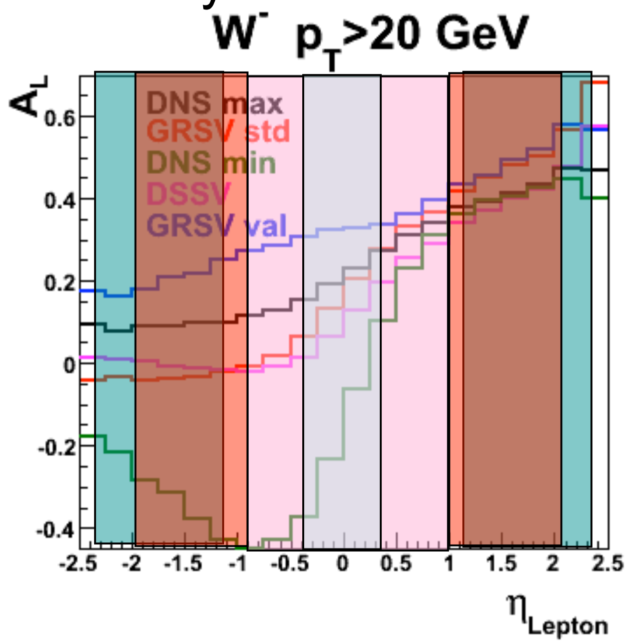
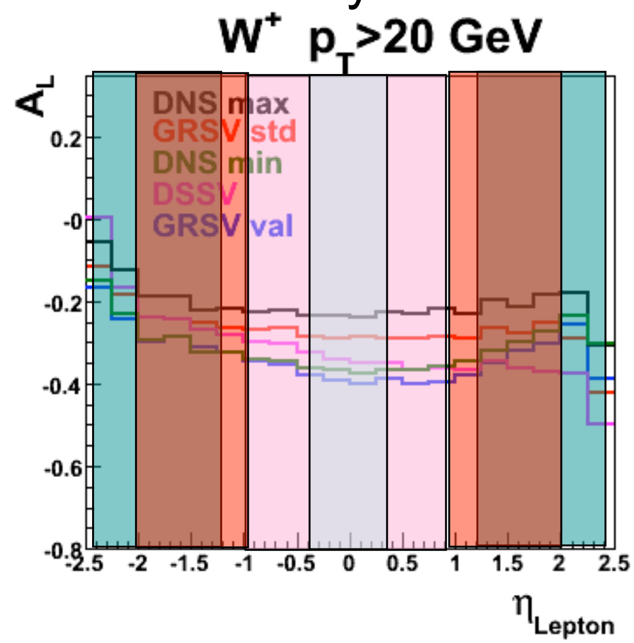




PHENIX Central Arms $e^\pm$

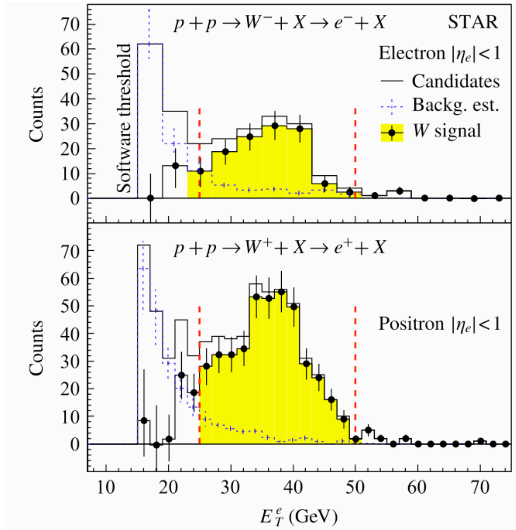
PHENIX Muon Arms $\mu^\pm$

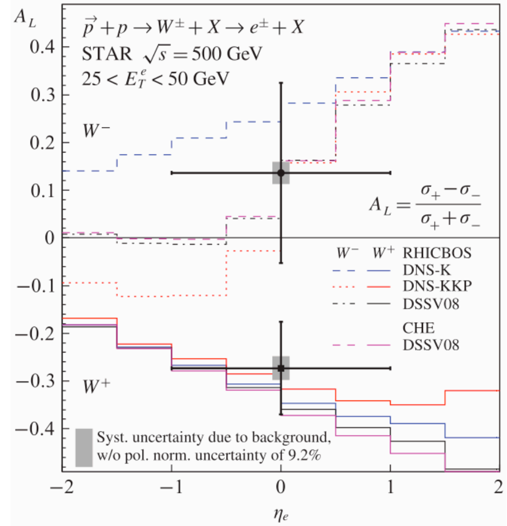
STAR Central Barrel $e^\pm$

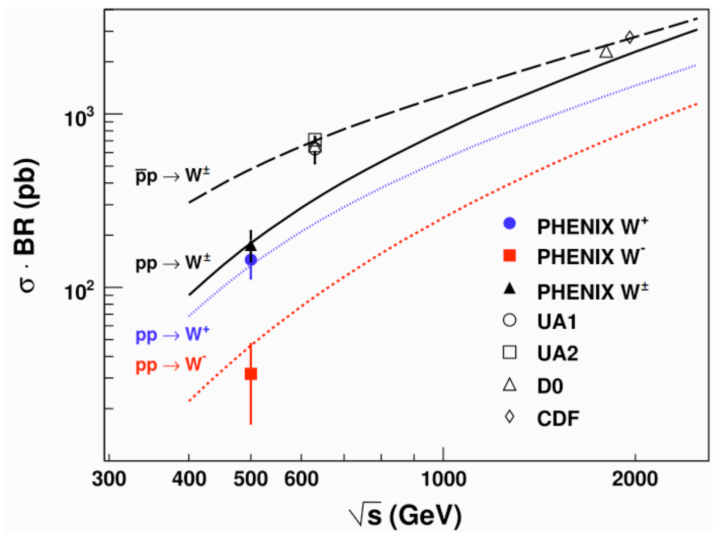
STAR Forward $e^\pm$

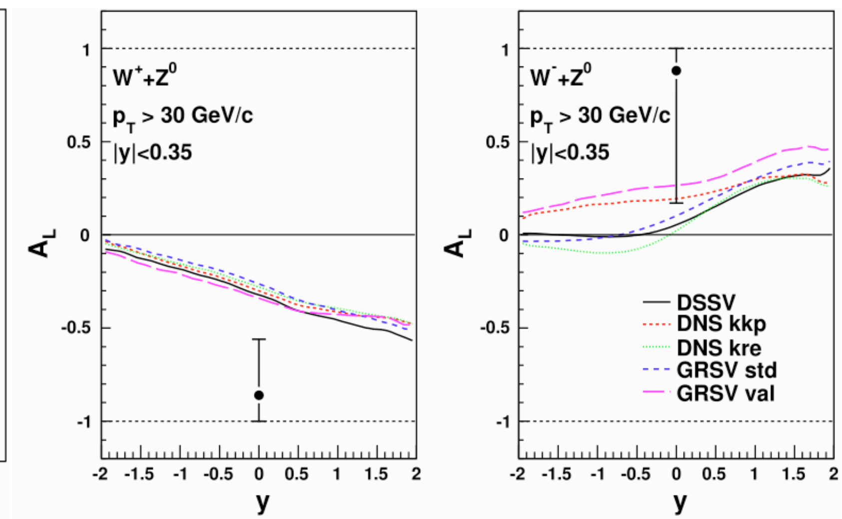
Results from First √s=500 Run: $W^{\pm}$ A_L

PHENIX
PRL 106:062001, 2011
STAR
PRL 106:062002, 2011



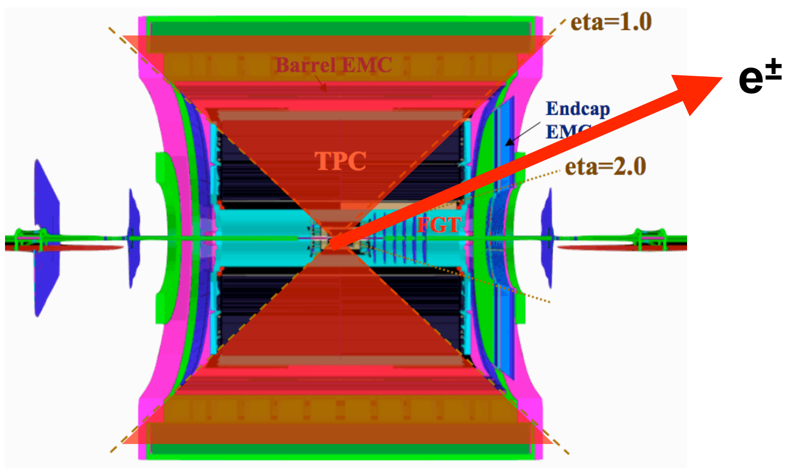


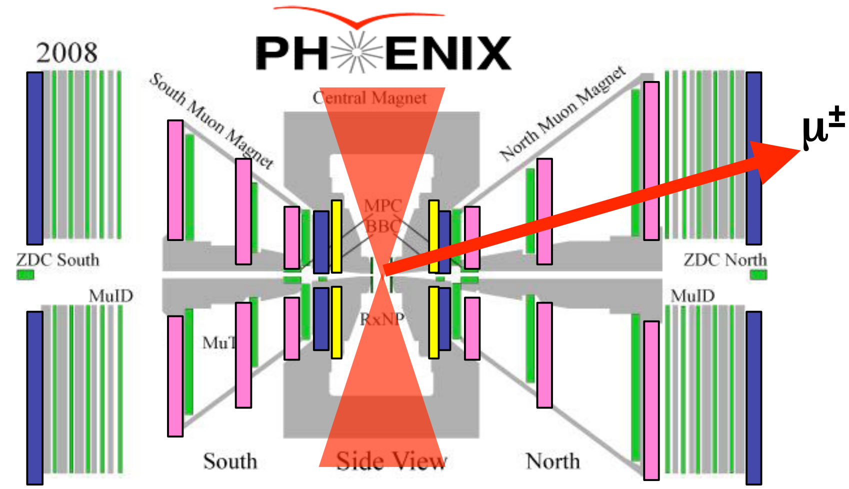




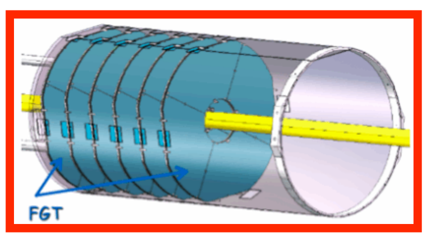
Upgrades for W Physics

- Accessing sea quarks by moving forward
  - Both STAR and PHENIX are currently working on upgrades.





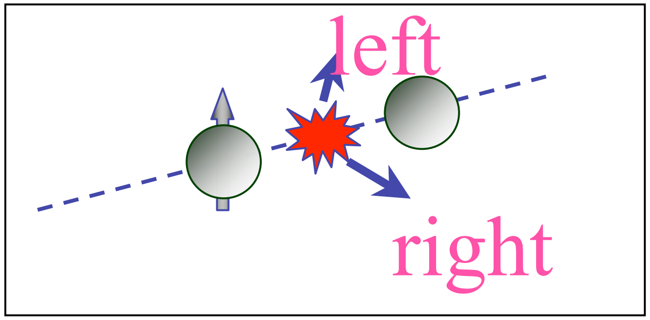
End Cap EMCal can tag electron. TPC does not give enough points for charge sign measurement
→Forward GEM Tracker
To be installed for next run



Identification from MUID and charge sign/ mom. from MUTr.
BUT, trigger is dominated by low mom. particles
→Resistive Plate Chambers
→Forward Tracker in trigger
Use bend in track to trigger on high mom.

INSTALLED and TAKING DATA now

Transverse Spin Structure



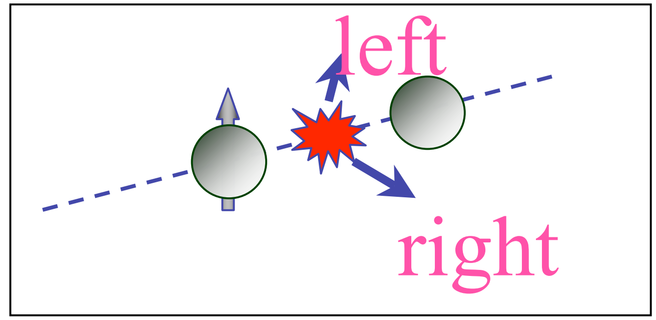
Transverse Single Spin Asymmetries

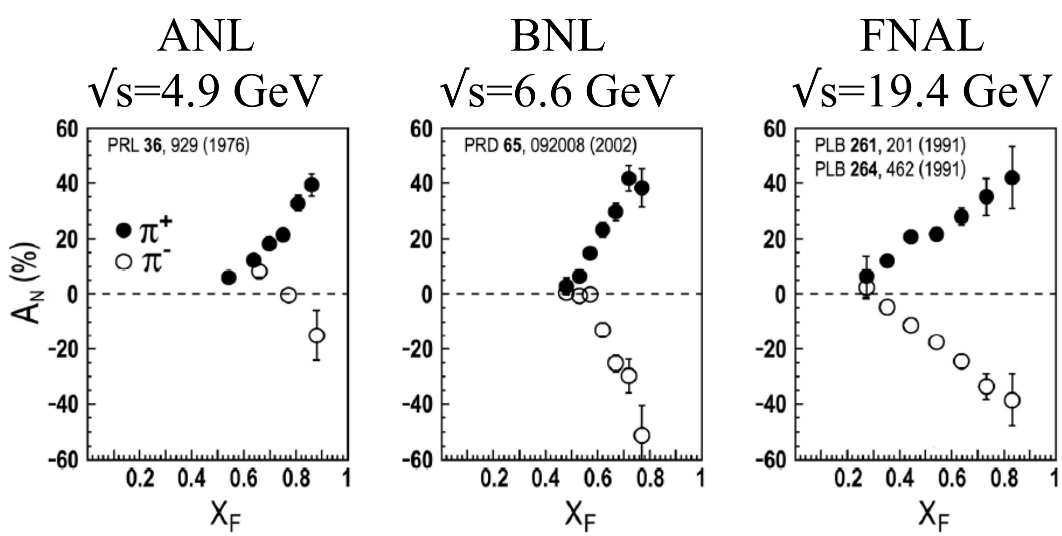
- Large single spin transverse spin (~40%) found at low energies

→ soft physics effect.

→ Generated theoretical work to find mechanism

  – Initial (Siver's) and Final (Collin's) state effects





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

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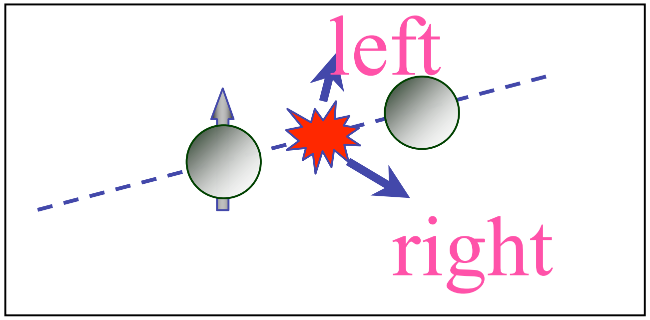
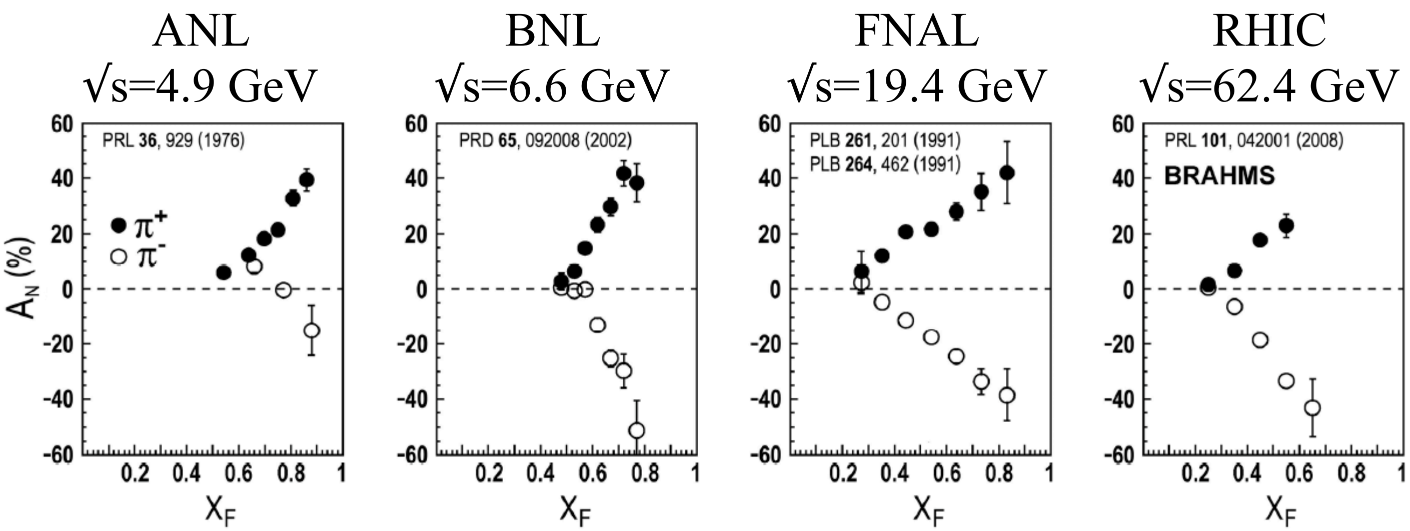
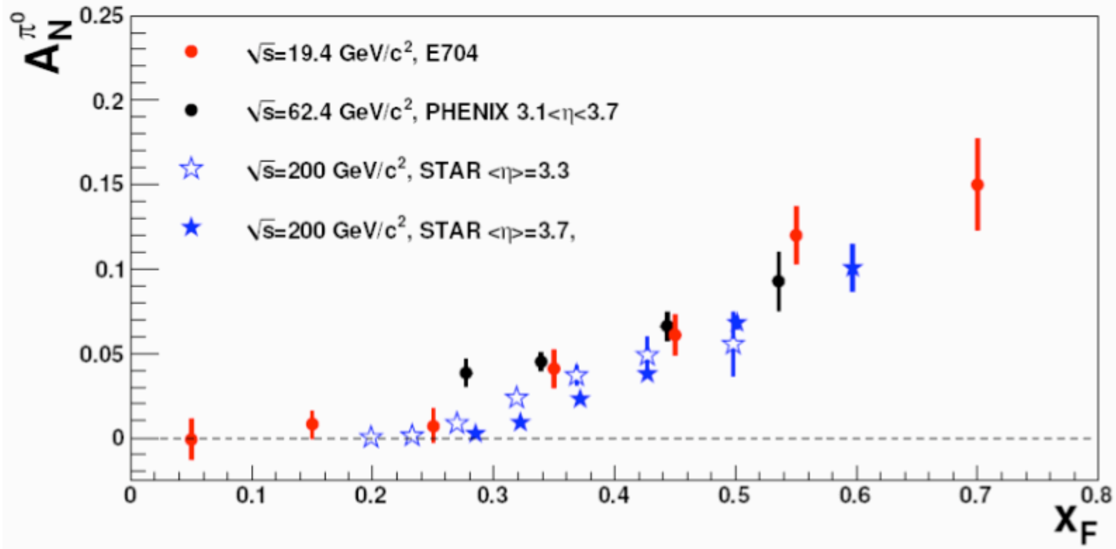




$$x_F = 2p_{long}/\sqrt{s}$$

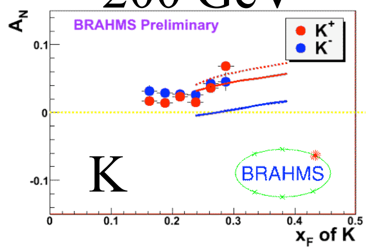
Possible Sources



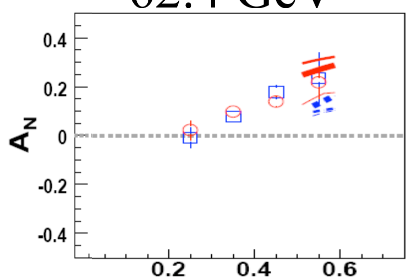
- Still theoretical work needed to understand:
  - Transversity: correlation between proton spin and quark spin
  - Siver's effect: correlation between proton spin and quark transverse motion (k_T) [measured in SIDIS]
  - Collin's effect: correlation between outgoing quark spin and k_T of fragmenting hadron [measured in e^+e^-]

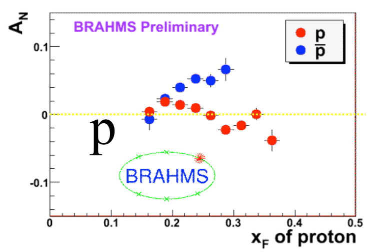
More transverse spin results (surprises)

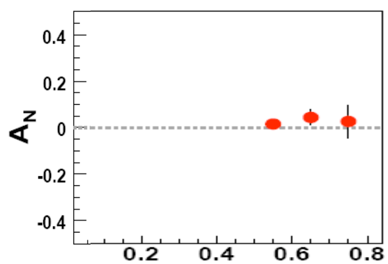
200 GeV

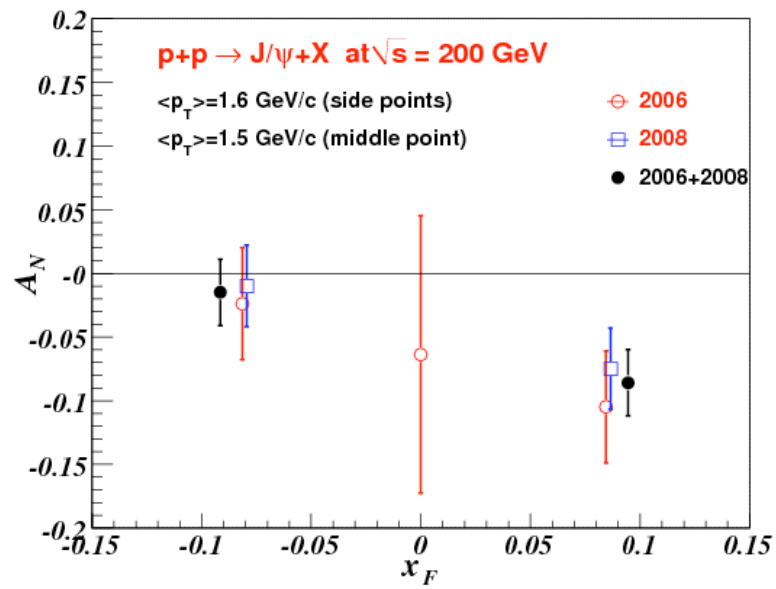


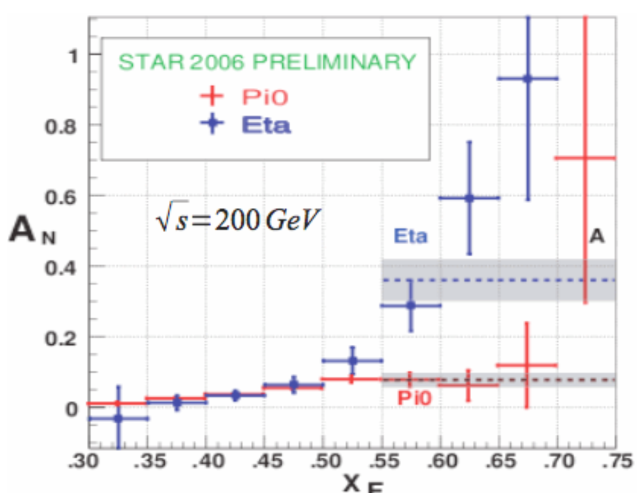
62.4 GeV

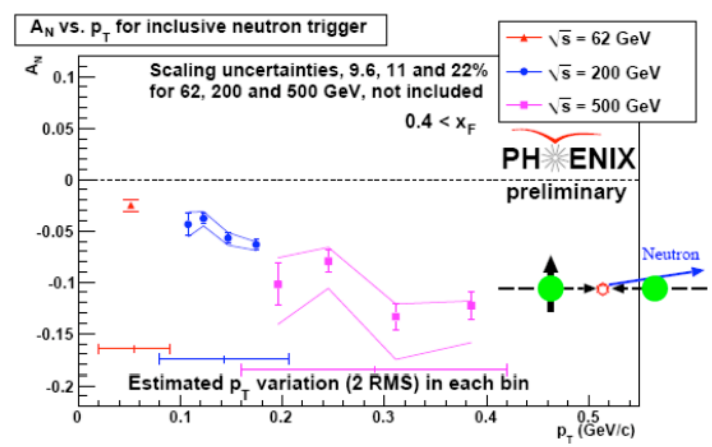






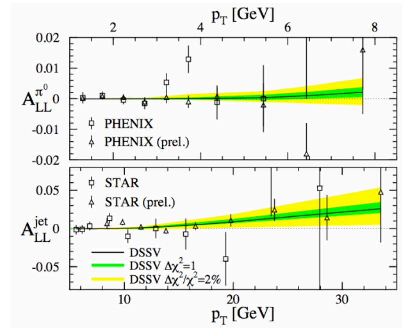


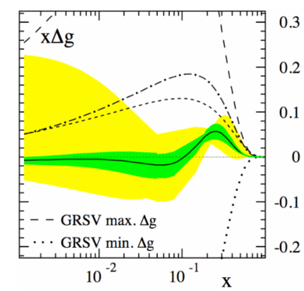




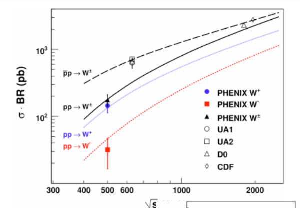
Conclusions

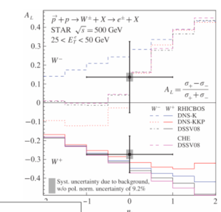
- The goal of RHIC spin is to understand the nucleon spin structure
- Results for A_{LL} significantly constrain the ΔG
  - Future measurement will extend x range

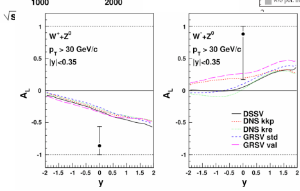




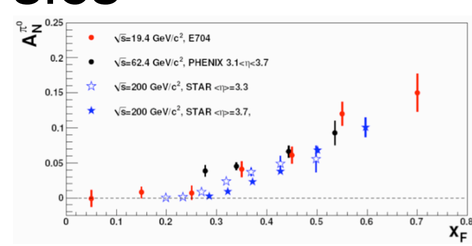
- W's have been measured at RHIC, with a first look at parity violating asymmetry A_L







- Many surprises in transverse spin physics



Backups

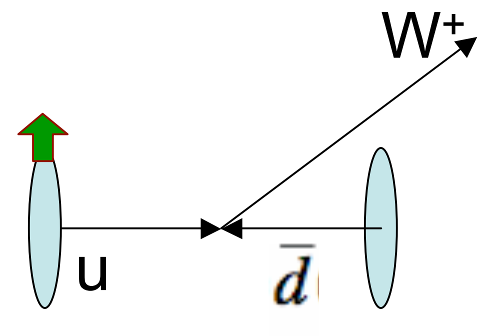
RHIC Performance

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	
2011	500	In Progress		~45		

- 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.

Kinematics

- Expect W produced in direction of high momentum (valence) quark
- However, leptonic decay smears this picture out in some cases.



$x_1 >> x_2$

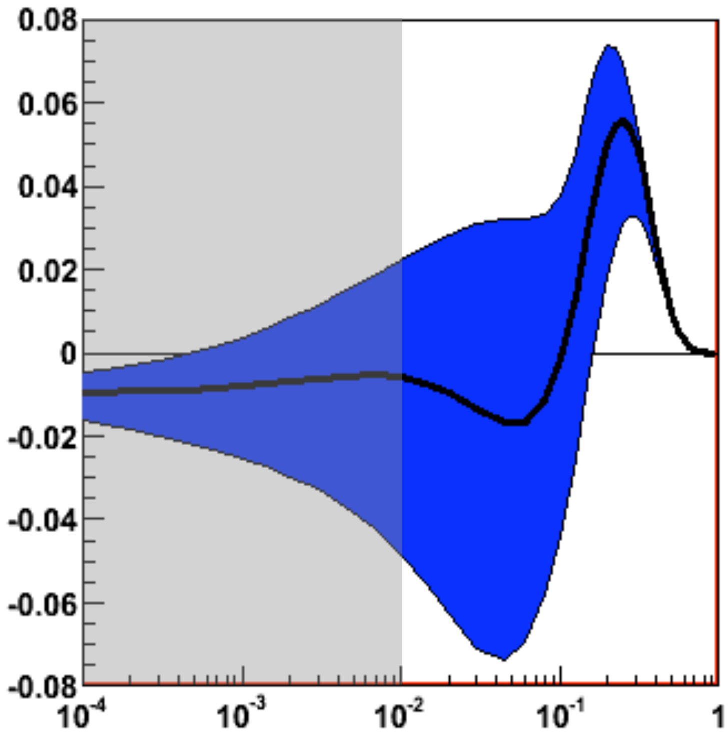
$$A_L^{l^-} = \frac{\Delta\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 - \Delta d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}{\bar{u}(x_1)d(x_2)(1-\cos\theta)^2 + d(x_1)\bar{u}(x_2)(1+\cos\theta)^2}$$

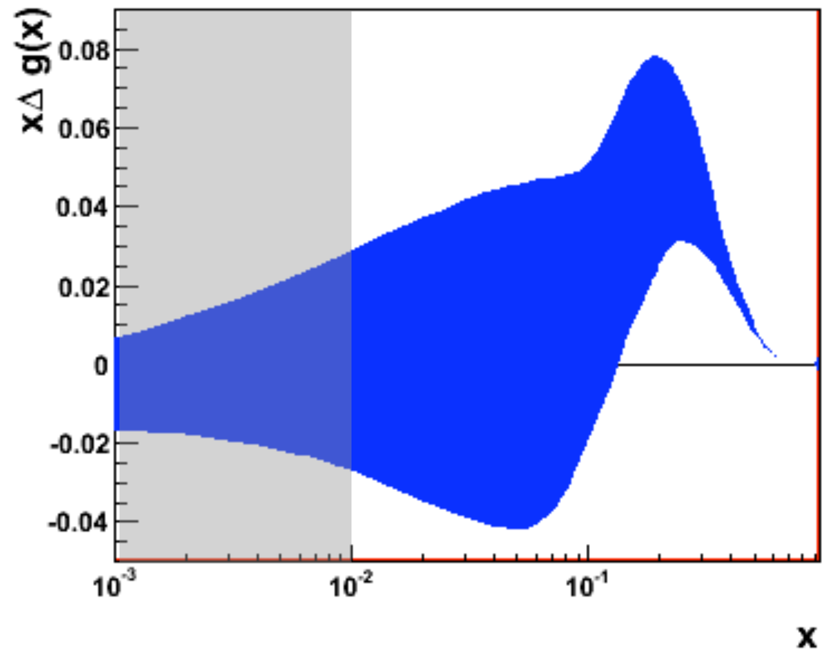
$$A_L^{l^+} = \frac{\Delta\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}{\bar{d}(x_1)u(x_2)(1+\cos\theta)^2 + u(x_1)\bar{d}(x_2)(1-\cos\theta)^2}$$

θ = lepton angle in partonic c.m.s.

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

- 2009 RHIC run was 1.5*more luminoisty.
  - Include new preliminary π0 A_{LL} data from PHENIX





KB, S. Taneja, C. Gal, A. Deshpande, D. deFlorian, R. Sassot, M Stratmann, W. Vogelsang