Spin Physics at RHIC

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RIKEN BNL Research Center

Outine

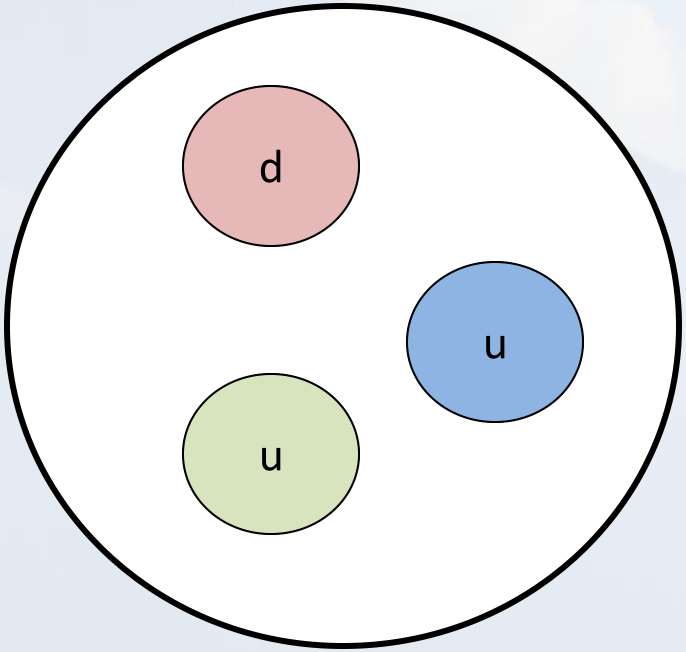
- Proton structure
  - Overview
  - Spin: helicity and transverse
- RHIC and the experiments
- Helicity:
  - Helicity sum rule
  - Knowledge of ΔG prior to RHIC
  - Accessing ΔG in p+p collisions: A_{LL}
    - Results
    - Impact in global analysis
  - Future plans
- Transverse:
  - Motivation: large Single Spin Asymmetries (SSA) in p+p
  - Theory: Transversity and k_T dependent functions
  - Measurements at RHIC and in DIS
  - Future plans
- Conclusions

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
  - Quark Content: $2 = u_{valence} = \int_0^1 dx[u(x) - \bar{u}(x)]$

$$1 = d_{valence} = \int_0^1 dx[d(x) - \bar{d}(x)]$$

$$0 = s_{valence} = \int_0^1 dx[s(x) - \bar{s}(x)]$$



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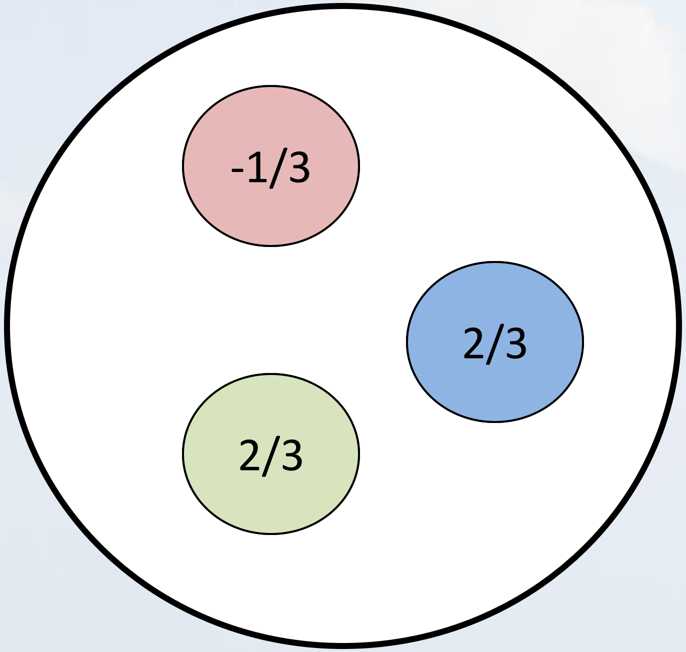
$$1 = d_{valence} = \int_0^1 dx[d(x) - \bar{d}(x)]$$

$$0 = s_{valence} = \int_0^1 dx[s(x) - \bar{s}(x)]$$

  - Charge: $+1 = e_u \int_0^1 dx[u(x) - \bar{u}(x)]$

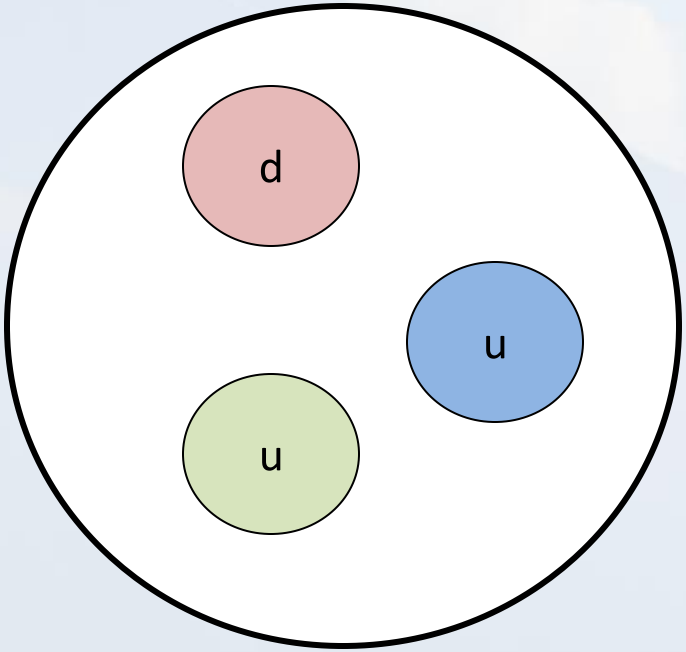
$$+ e_d \int_0^1 dx[d(x) - \bar{d}(x)]$$

$$+ e_s \int_0^1 dx[s(x) - \bar{s}(x)] + ...$$



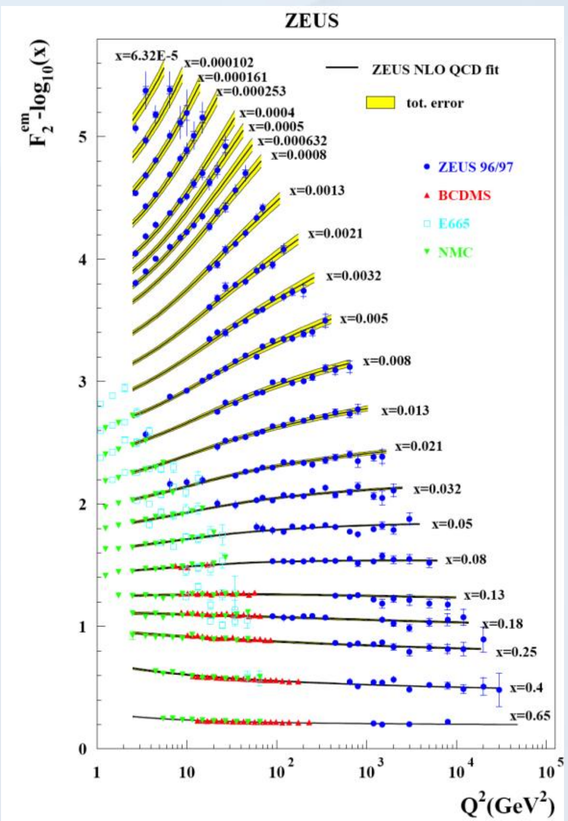
Structure of the Nucleon

- Properties of the proton arise from properties of the constituents
  - Momentum: $$1 \neq \sum_q \int_0^1 x dx [q(x) + \bar{q}(x)]$$

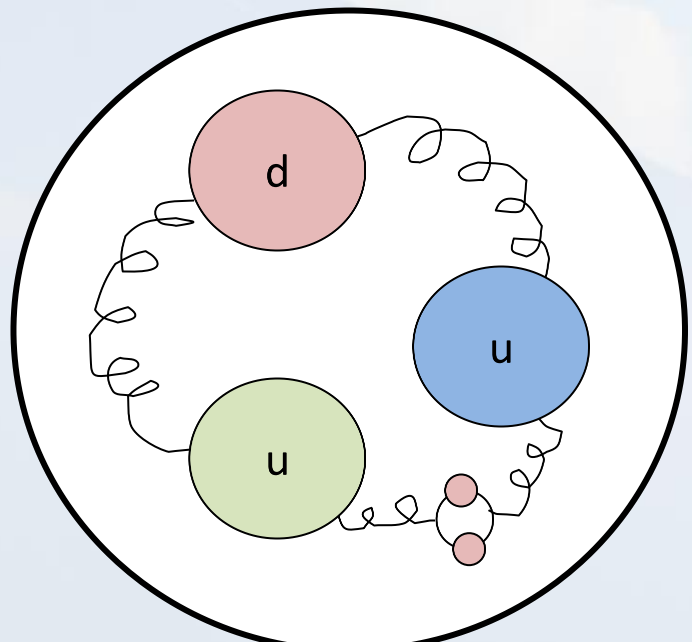


Structure of the Nucleon

- Properties of the proton arise from properties of the constituents
  - Momentum: $$1 = \sum_q \int_0^1 x dx [q(x) + \bar{q}(x)] + \int_0^1 x dx g(x)$$



- Knowledge of the gluon PDF comes primarily from scaling violation in DIS measurements, accessible due to large range of x and Q^2



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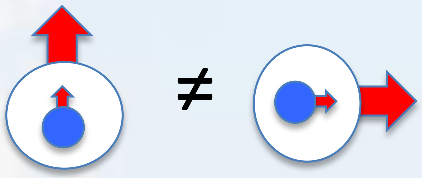
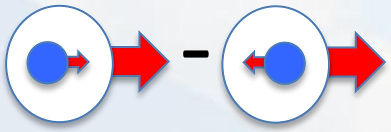
Spin Structure

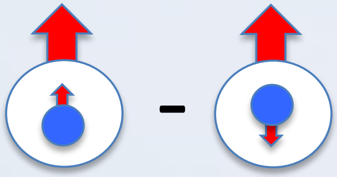
- How correlated are the parton spins with parent nuclei?
  - As boosts and rotations do not commute, we must answer this for the helicity and transverse spin cases independently



- <u>Helicity:</u>
  - Initially expected quarks to be highly correlated, carrying ~60% of proton spin
  - From polarized DIS results, quarks only carry ~30%.
  - Is the rest carried by gluons? Or OAM?

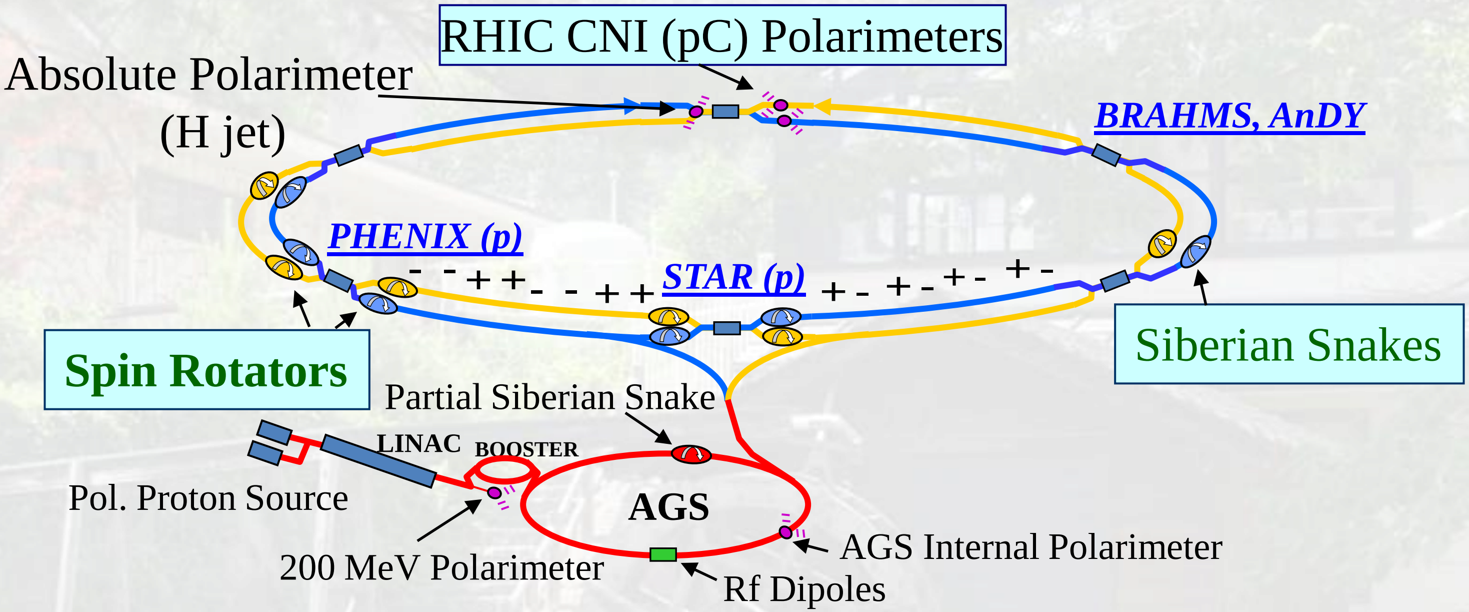


- <u>Transverse:</u>
  - pQCD hard scattering asymmetries are small, and so assumed small transverse spin asymmetries
  - Instead found very large (~60%) single spin asymmetries (SSA) at low $\sqrt{s}$
  - What is the source? Correlations with partonic tranverse momentum (k_T)? Initial state or final state effects?



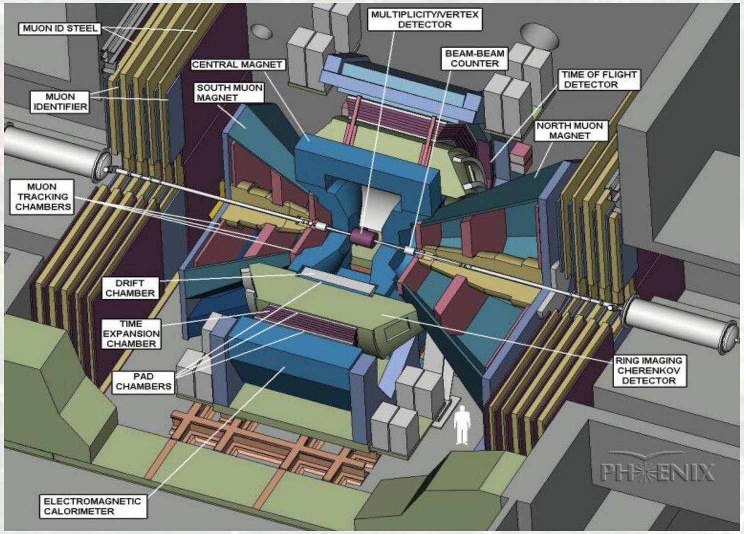
THE EXPERIMENTS

RHIC



- Collides polarized protons at $\sqrt{s}$=62.4, 200 and 500 GeV
- Stable spin orientation is vertical
  - Only transversely polarized p+p at BRAHMS, AnDY
  - Spin rotators at PHENIX and STAR allow longitudinally polarized p+p
- Achieved 60% (45%) polarization at $\sqrt{s}$=200 (500) GeV

Experiments

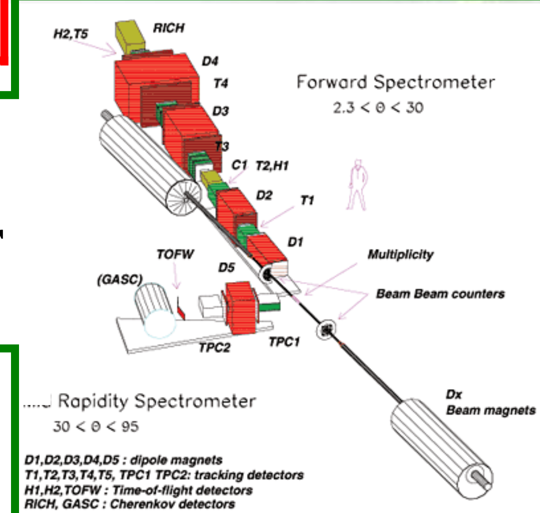


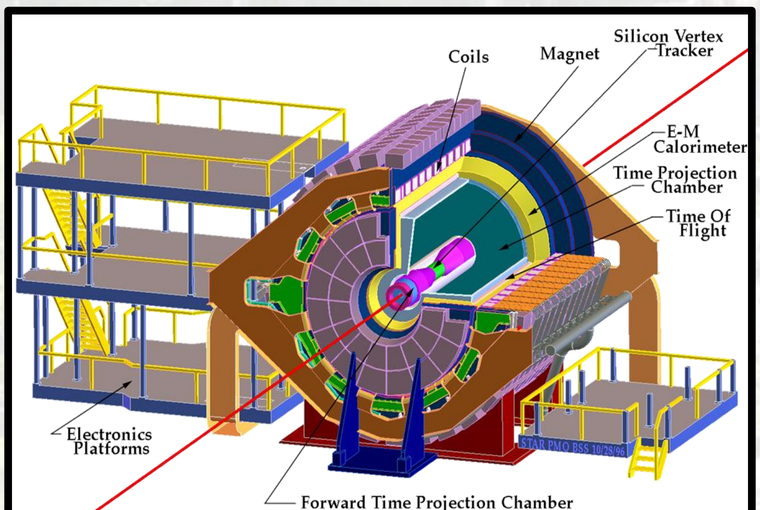
PHENIX

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

BRAHMS

Forward spectrometer
charge hadron id





STAR

Large acceptance
Azimuthal symmetry
Jet patch trigger
Forward EMcal

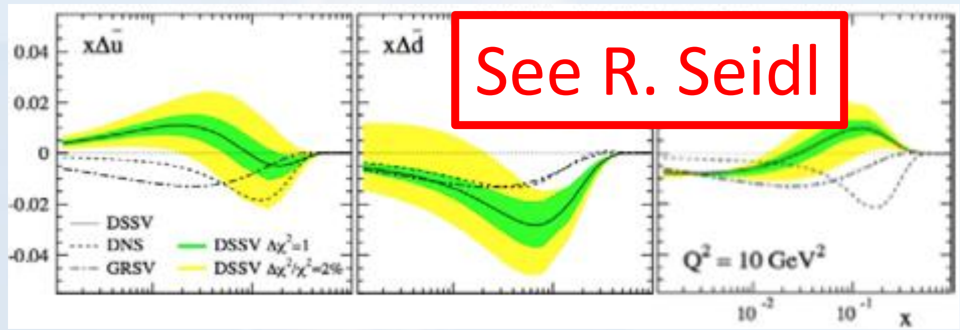
HELICITY STRUCTURE

Helicity Sum Rule*

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

From polarized DIS, ΔΣ is well measured. Global fits find ΔΣ ~ 0.3

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



See R. Seidl

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

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

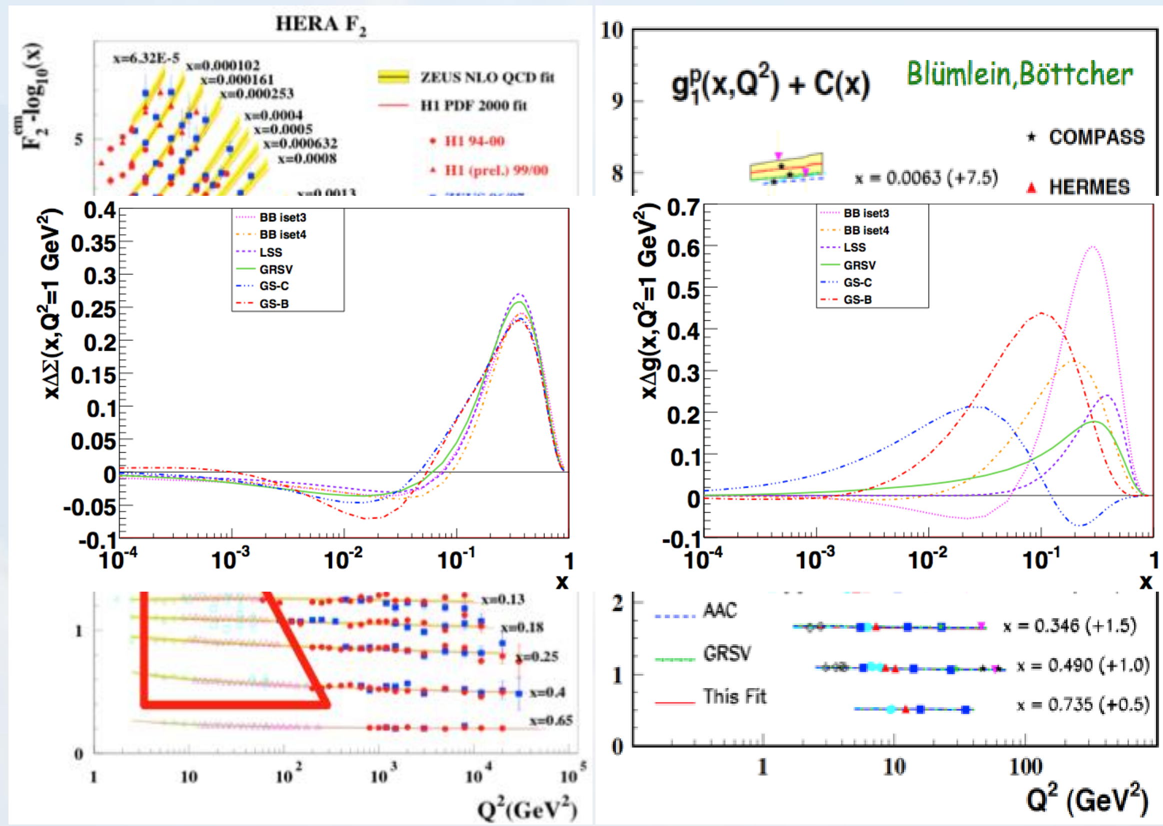
Does ΔG carry the remainder of the missing spin?

Not clear how to measure

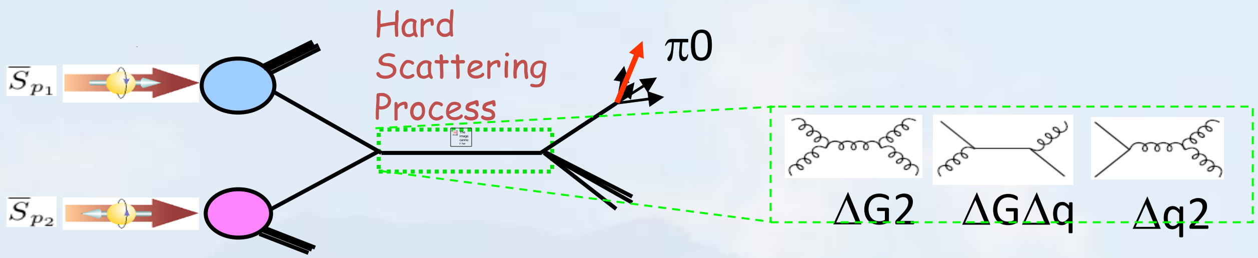
*Jaffe-Manohar definition

Helicity Structure of the Nucleon

- As in unpolarized case, use DIS to understand the quark structure
  → $\Delta\Sigma$
- For $G(x)$, using scaling violations
  - Requires large x and Q^2 coverage
- For the gluon spin constribution, ΔG, current fixed target data are not enough



Accessing ΔG in p+p: A_{LL}



- Collide longitudinally polarized protons
  - Probe gluon at LO in α_s
- Procedure:
  1. Check that unpolarized cross section is described by pQCD
  2. Measure production asymmetry, A_{LL}, in specified final state
     - Ex: π^0, $\pi^{\pm}$, Jets, dijets (di-hadrons), direct photons
  3. Extract ΔG in global analysis of polarized DIS, Semi Inclusive DIS (SIDIS) and p+p data

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$$

Why A_{LL}?

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

From ep (&pp)
(HERA mostly)

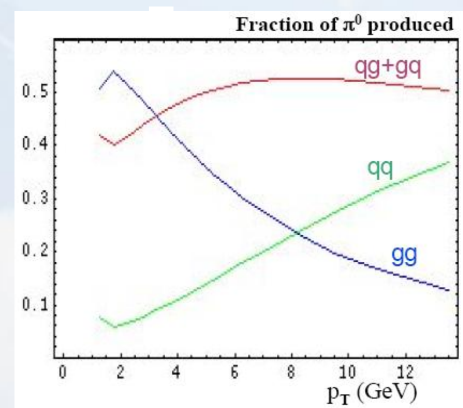
pQCD NLO

From e^+e^-
(& SIDIS,pp)

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

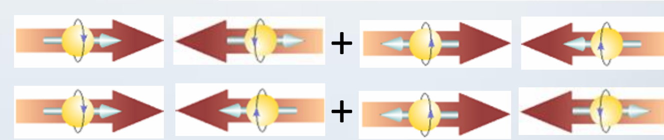
$$A_{LL} \cong a_{gg}\Delta g^2 + b_{gq}\Delta g \Delta q + c_{qq}\Delta q^2$$

where a, b, c depend on kinematics and probe



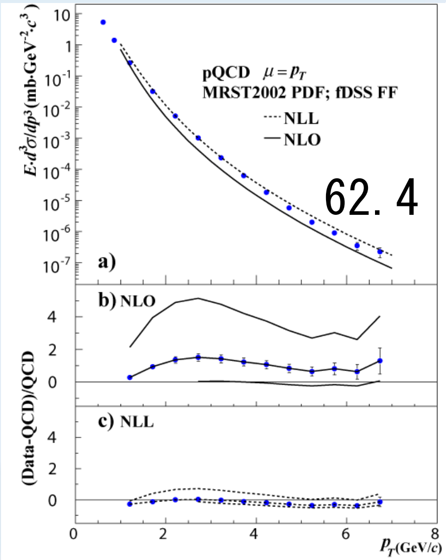
+- =

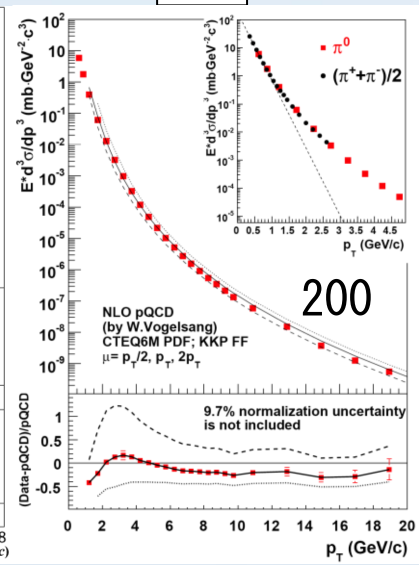
++ =

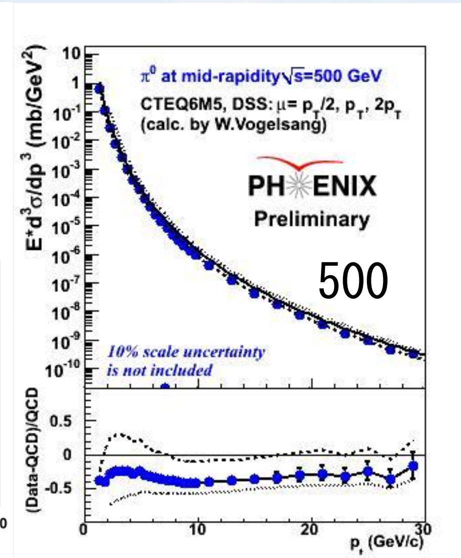


Step One: pQCD Describes Data

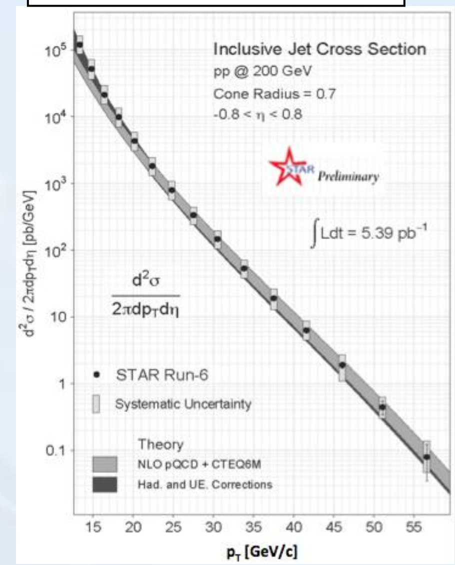
π0



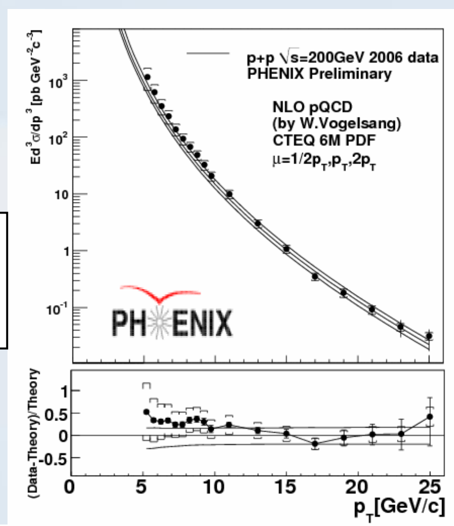




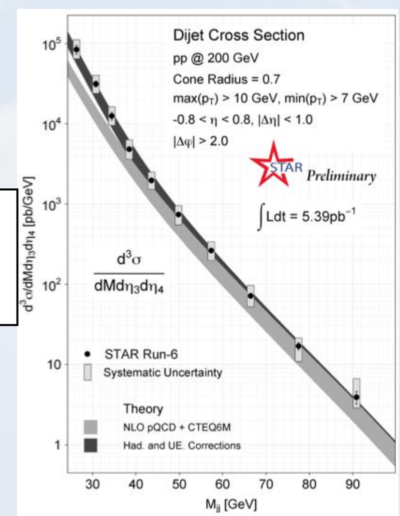
Jet @ 200 GeV



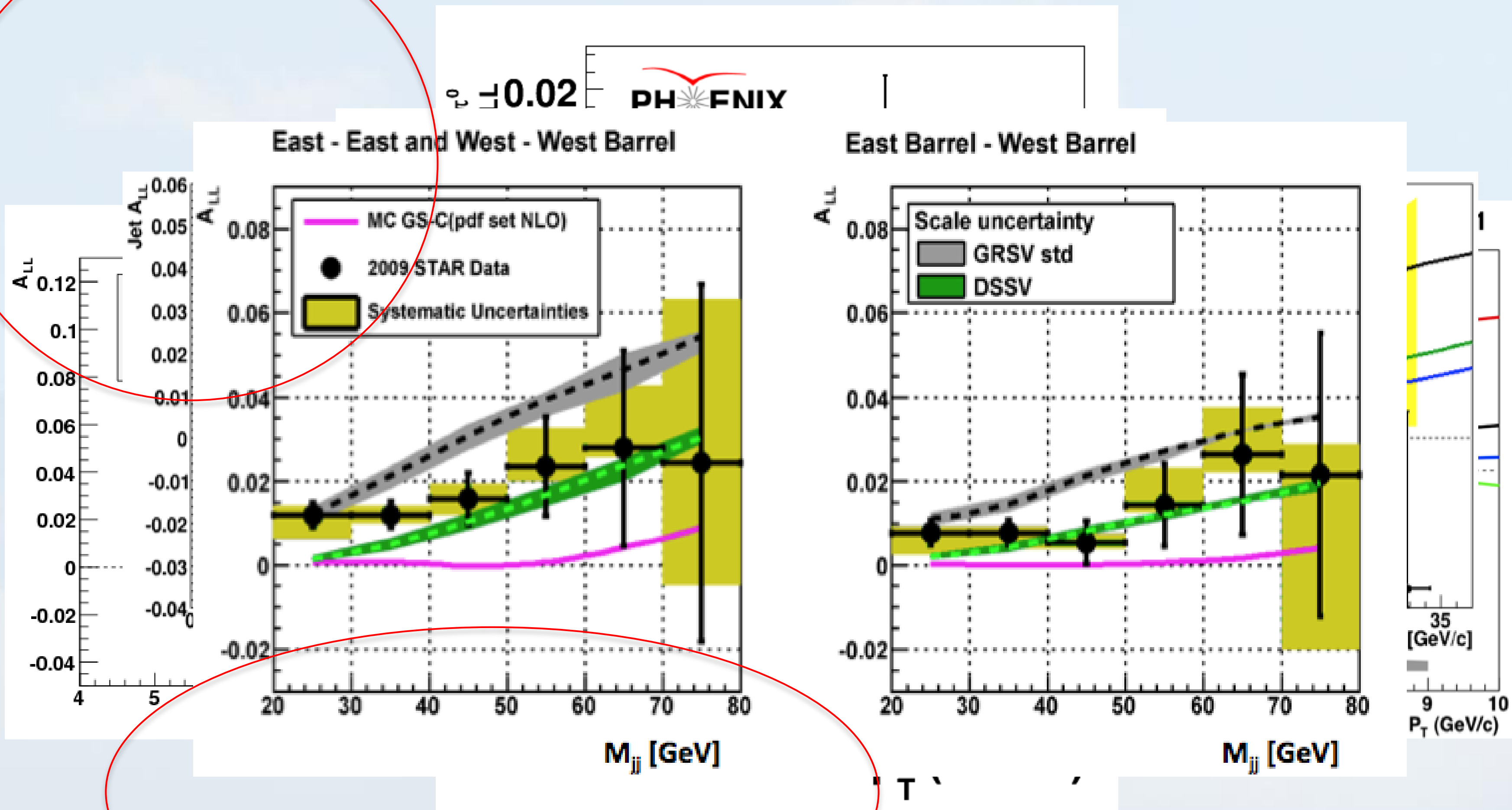
Direct γ @ 200 GeV



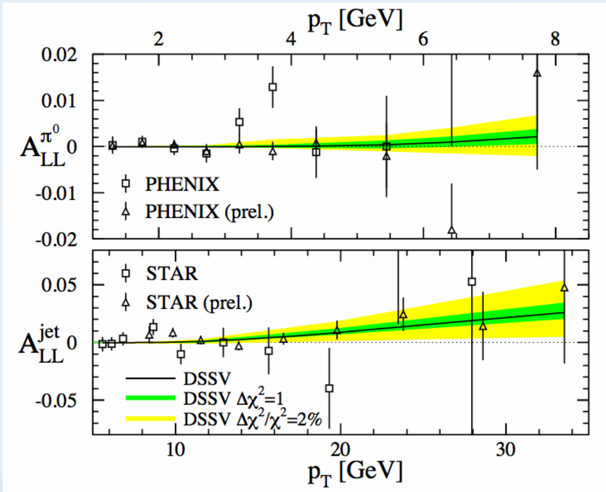
Dijet @ 200 GeV



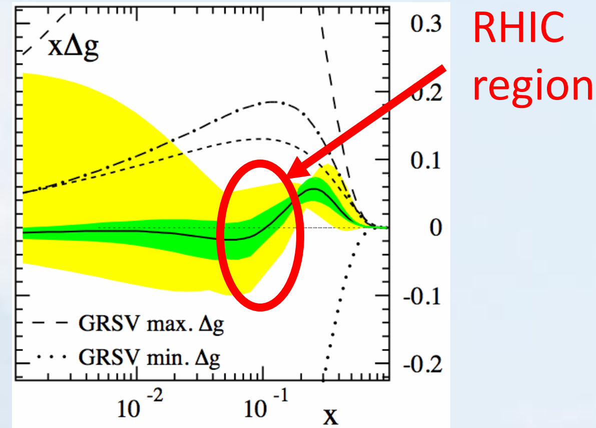
Step Two: Measure A_{LL}

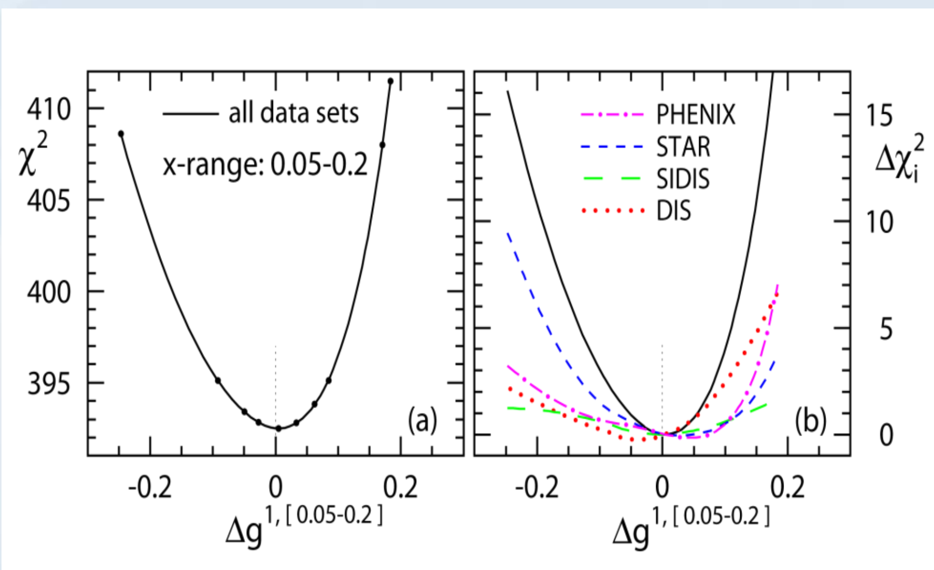


Step Three: Constraining ΔG



+DIS
+SIDIS

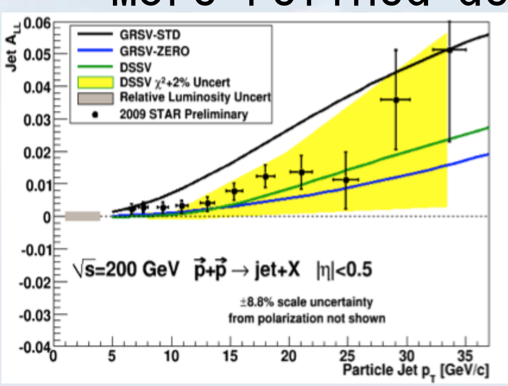


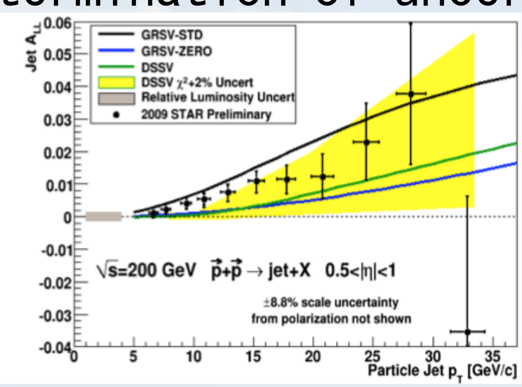


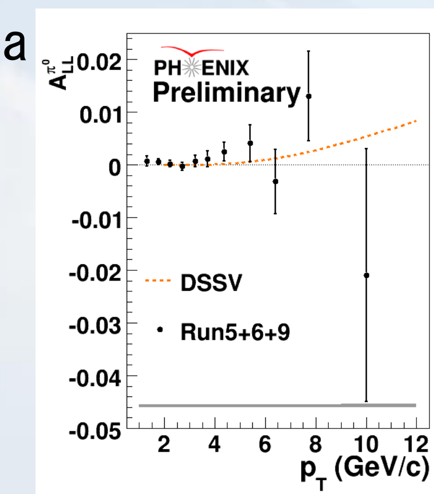
- DSSV fit world date including p+p for first time.
- PRL101:072001, 2008
- PRD 80:034030, 2009
- RHIC data offer significant constraint at 0.05<x<0.2.
- Large uncertainty remains below RHIC x range.
- 1.5 times more data from 2009.

Better Determination of ΔG

- Extention of DSSV underway:
  - Theorists (D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang)
  - Experimentalist (C. Gal, S. Taneja, KB, A. Deshpande)
  - Inclusion of Run 9 π^0 and jet A_{LL}
  - Inclusion of dijet and other hadron A_{LL} and W A_L data
  - Proper treatment of all experimental systematic uncertainties
  - More refined determination of uncerta … zed
-







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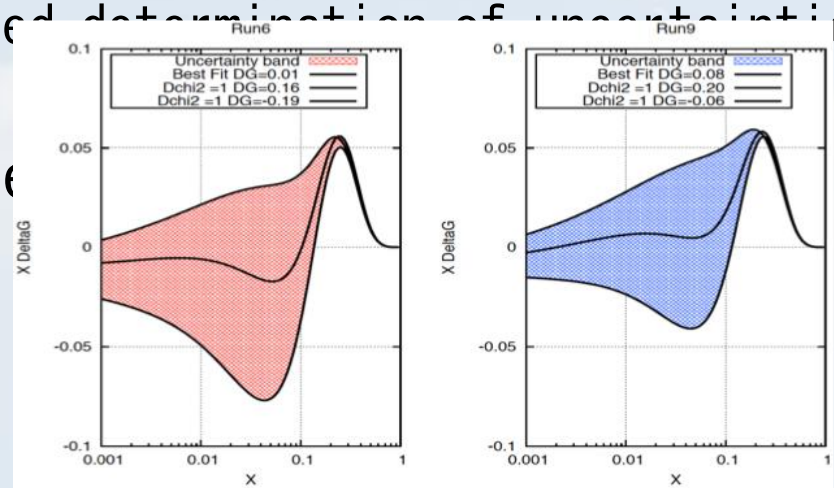
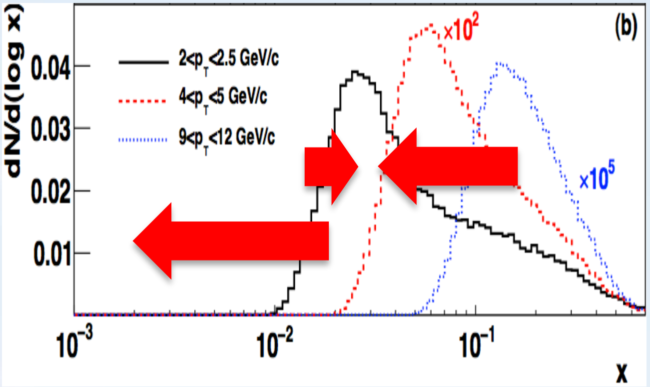
  - Proper treatment of all experimental systematic uncertainties
  - More refined determination of uncertainties on polarized PDFs
- Impact or ne

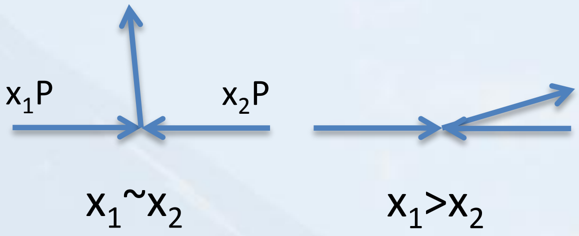


Recently released STAR jet result is also being added. Both Run9 data sets indicate larger ΔG

Limitations of Current Data

- Current mid-rapidity inclusive measurements (π^0, jet, etc.) at $\sqrt{s}$=200 GeV have two draw backs
  - They cover a limited range in x (approx. 0.02<x<0.3)
  - Each p_T bin integrates over a wide range in x
- We can extend x range by
  - Measuring at larger rapidity (low x gluon)
  - Measuring at larger $\sqrt{s}$ (smaller x at same p_T)
- We can more precisely determine x through correlation measurements
- And we can do both





$$x_1 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{\eta_3} + p_{T4}e^{\eta_4}\right)$$

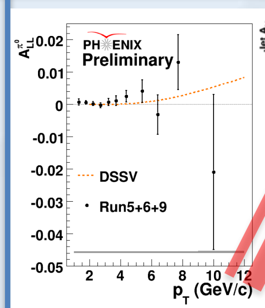
$$x_2 = \frac{1}{\sqrt{s}}\left(p_{T3}e^{-\eta_3} + p_{T4}e^{-\eta_4}\right)$$

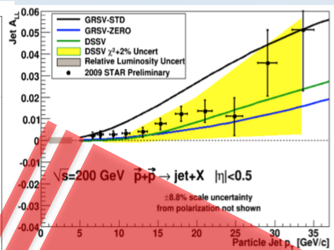
Future plans

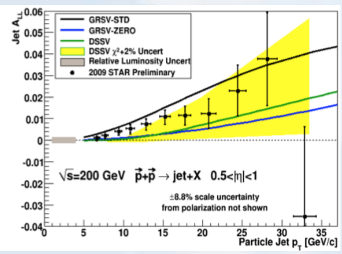
- More precise determination of $\Delta G(x)$ over wider range in x

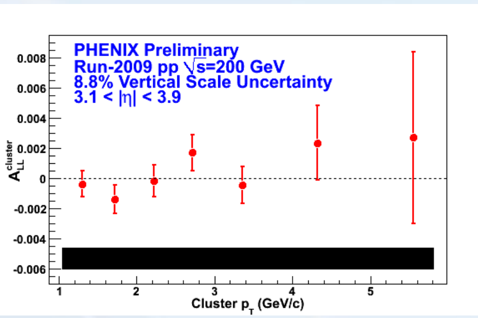
Higher x   Central   Forward   Lower x

Single particle

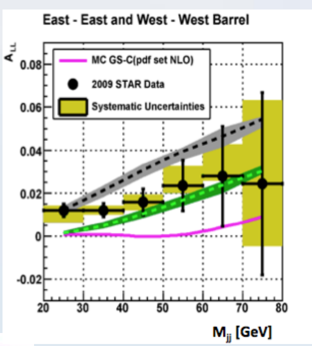


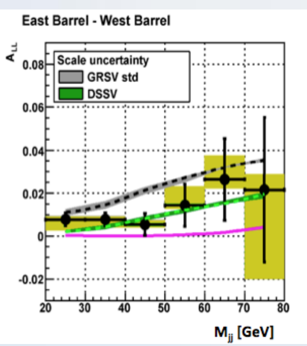






Correlations





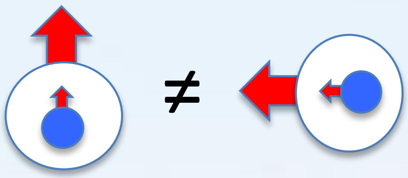
Better x determination

Forward-Central correlation measurements at both STAR and PHENIX

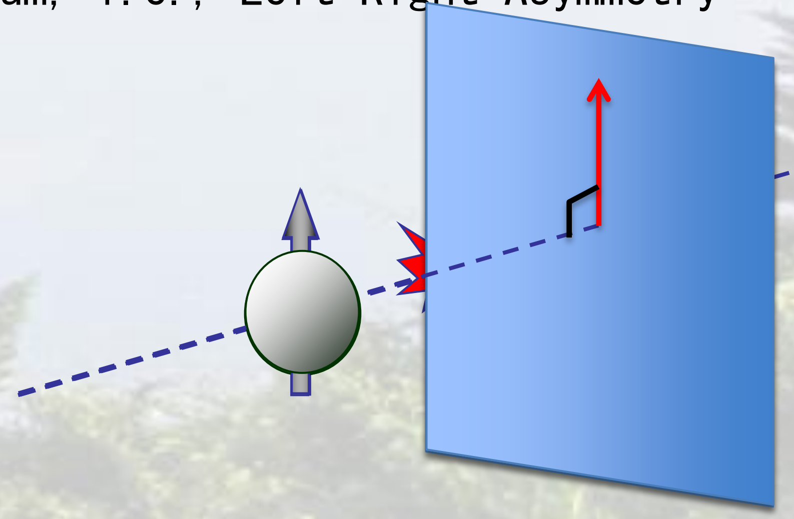
TRANSVERSE SPIN

Basic Idea of Measurements

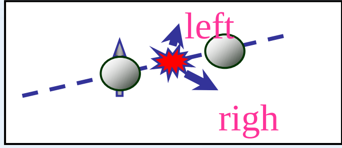
- Recall:



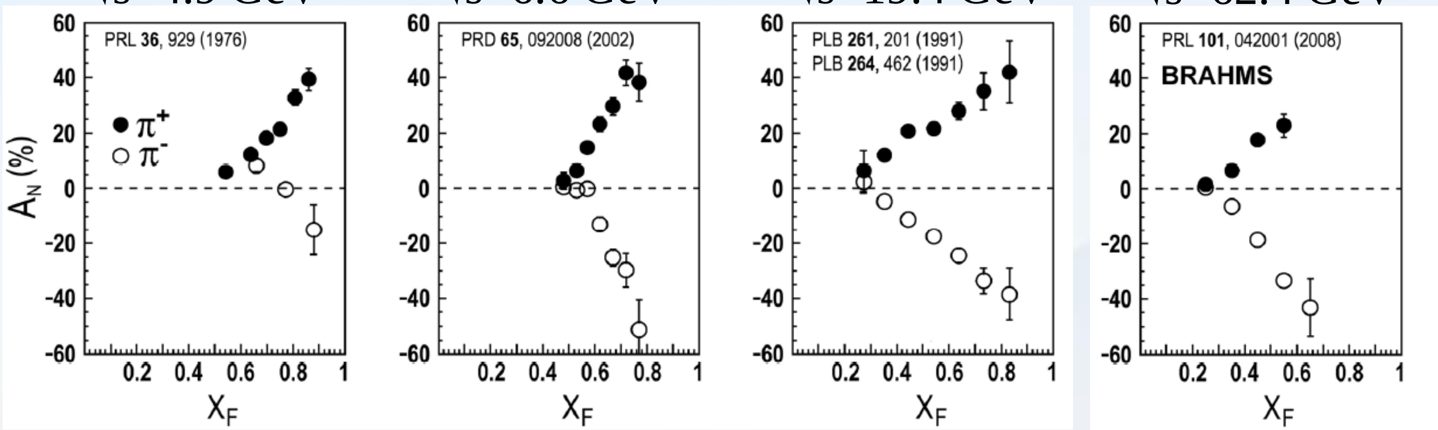
- Measure angular production dependence
  - Angle in a specific plane with respect to a specific vector
  - Easy examples:
    - ϕ dependent particle production in plane transverse to proton momentum, i.e., Left-Right Asymmetry



$p^{\Uparrow}$+p → $h^{\pm}$ SSA



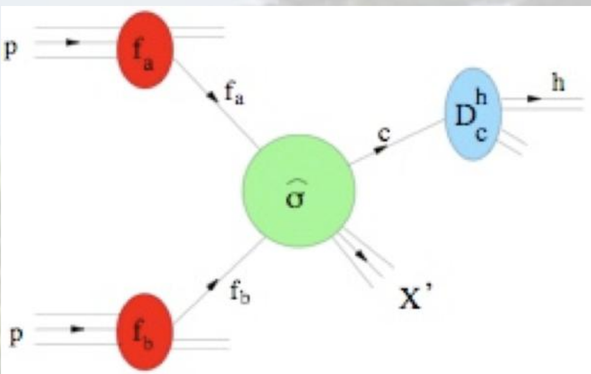
ANL $\sqrt{s}$=4.9 GeV | BNL $\sqrt{s}$=6.6 GeV | FNAL $\sqrt{s}$=19.4 GeV | RHIC $\sqrt{s}$=62.4 GeV

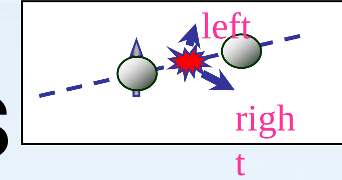


$$x_F = \frac{p_L}{\sqrt{s}/2}$$

- Large asymmetries seen over large range in $\sqrt{s}$, including RHIC energies
- Hard scattering process expected to only have very small asymmetries

➔ Effect is initial or final state effect

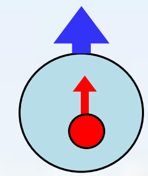




Possible explanations

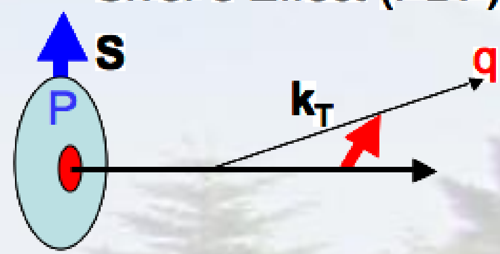
- Initial State:
  - Transversity
    - Correlation between proton and quark spin
    - Chiral-Odd, so must couple with another Chiral-Odd function
    - *Does not generate L-R asymmetries by itself*
  - Sivers
    - Correlation between proton spin and parton k_T.
    - *Could generate L-R asymmetries*
- Final State
  - Collins
    - Correlation between scattered quark spin and fragmenting hadron k_T.
    - Chiral-Odd
    - *Coupled with transversity could generate L-R asymmetries*

Transversity (PDF)



Proton spin and quark spin correlation

Siver's Effect (PDF)



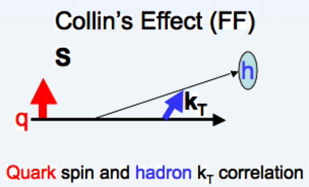
Proton spin and quark k_T correlation

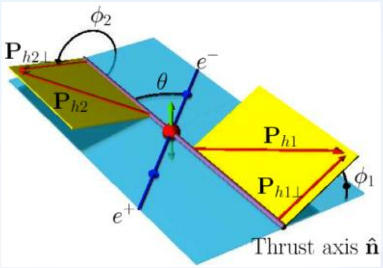
Collin's Effect (FF)

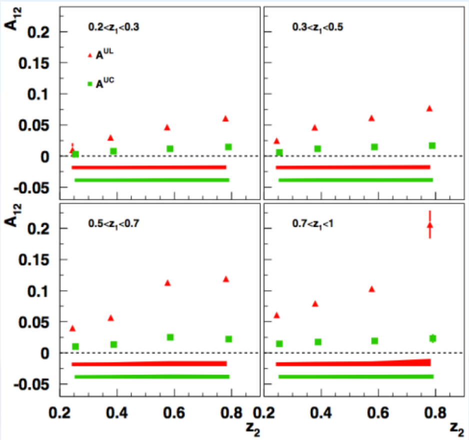
Quark spin and hadron k_T correlation

Methods to extract each

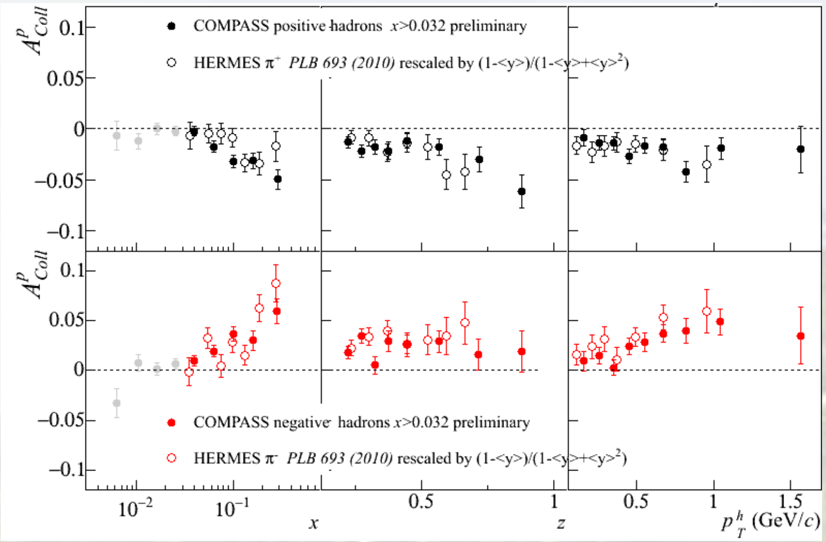
- Collins FF from e^+e^- (Belle)
  - M. Gross-Perdekamp, R. Seidl and other

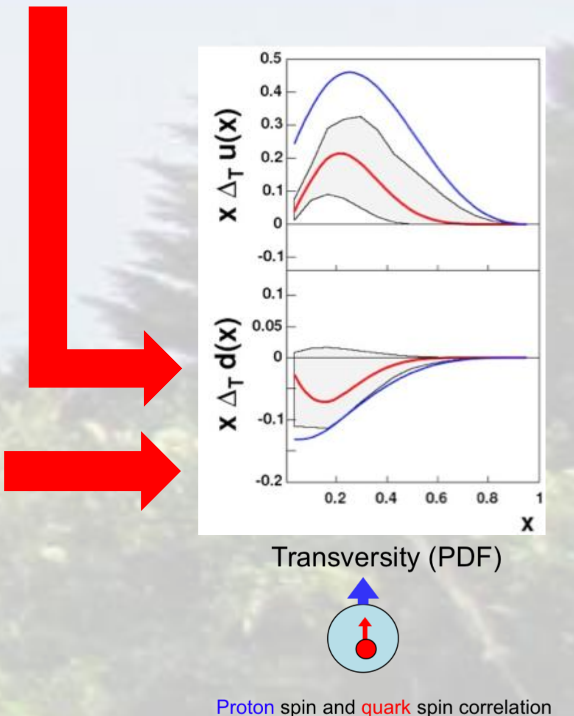




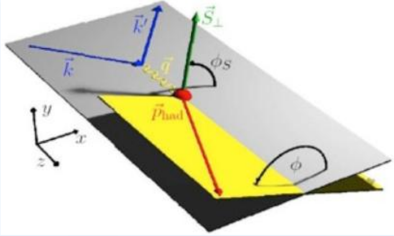


- Collins × transversity from SIDIS (Hermes, Compass)

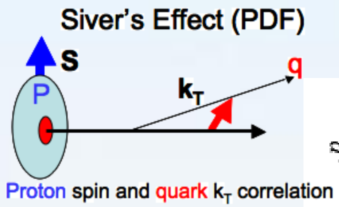


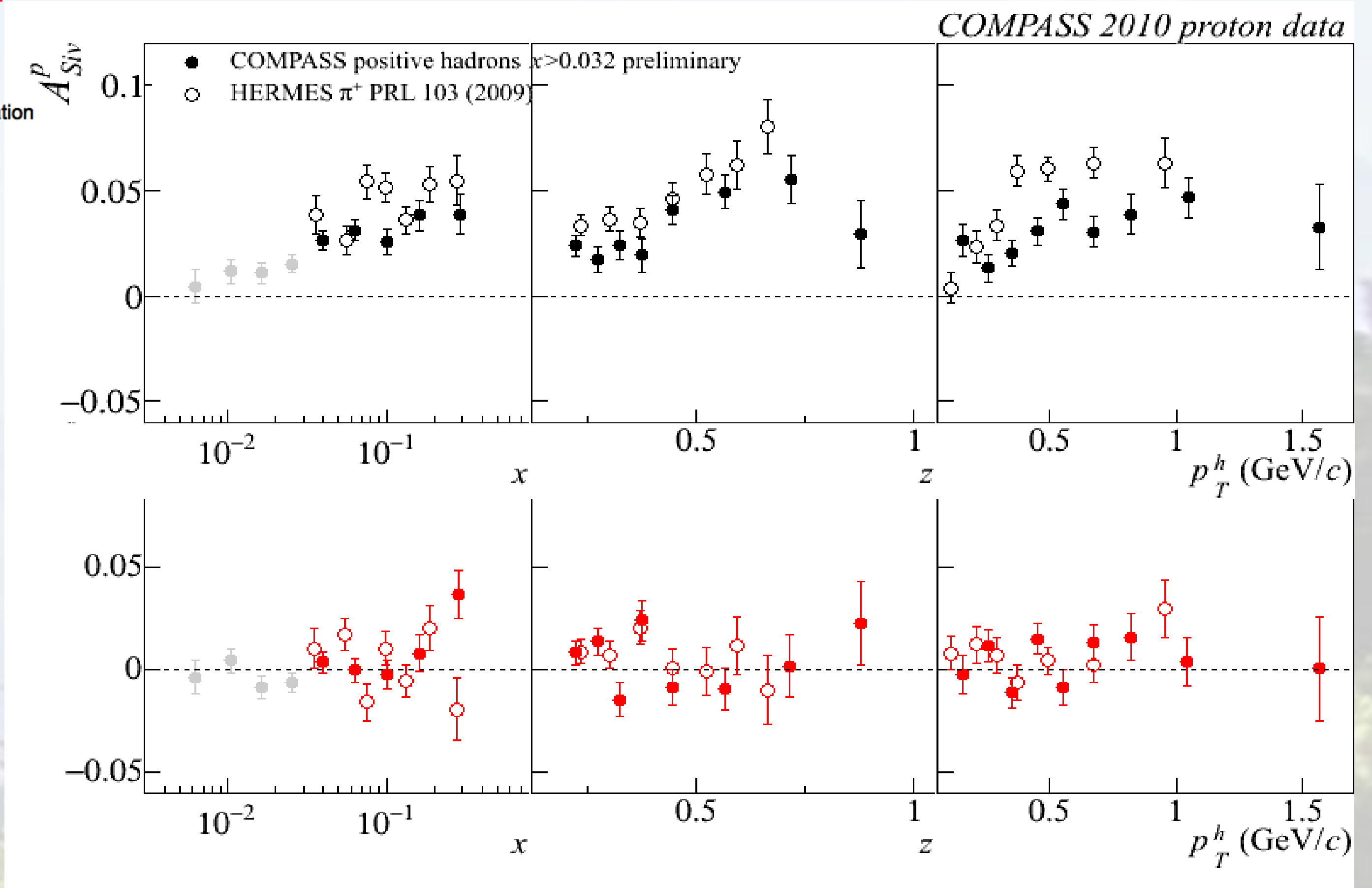


Methods to extract each

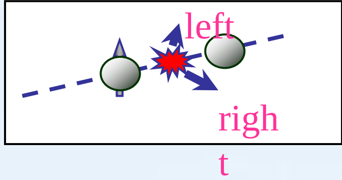


- Sivers function from SIDIS (Hermes, Compass)

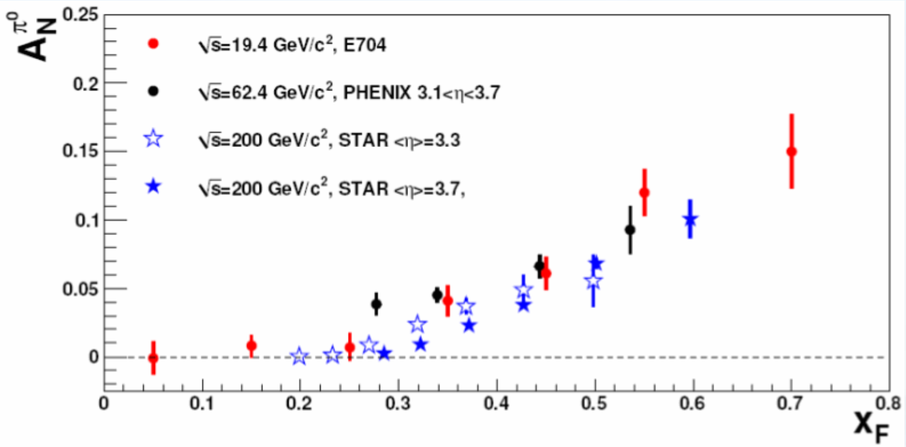




Back to RHIC

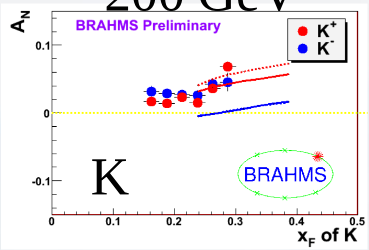


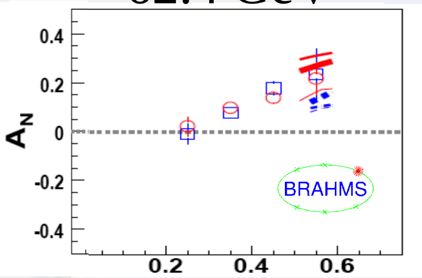
- At RHIC, we have measured forward SSA for many hadrons
  - π^0, $\pi^\pm$, K, p, η

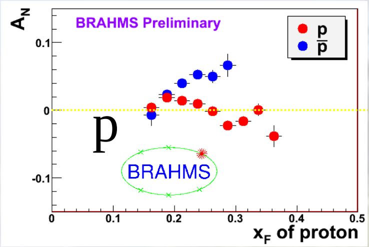


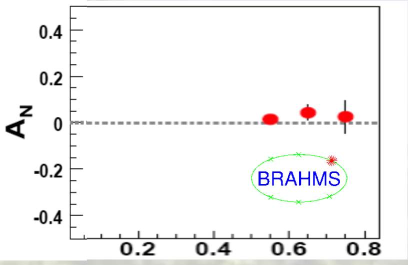
200 GeV

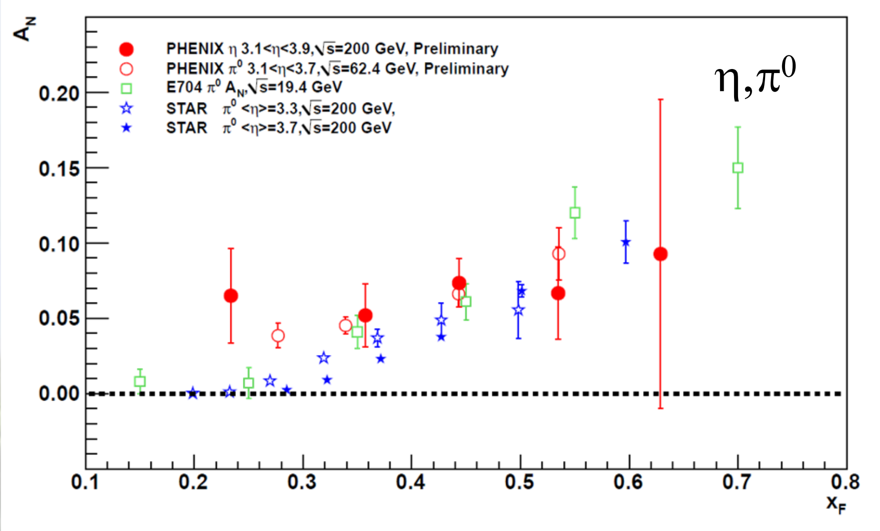
62.4 GeV





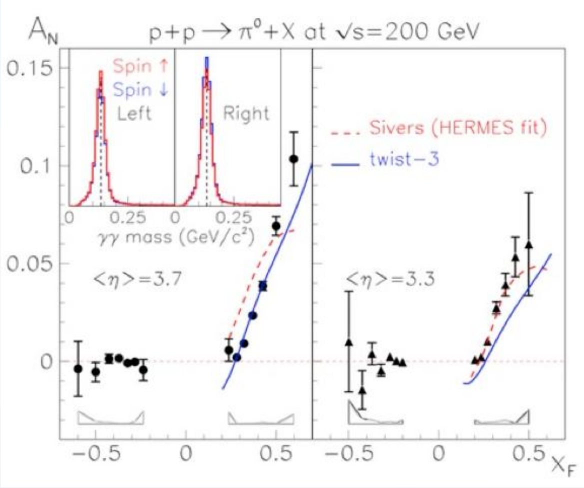


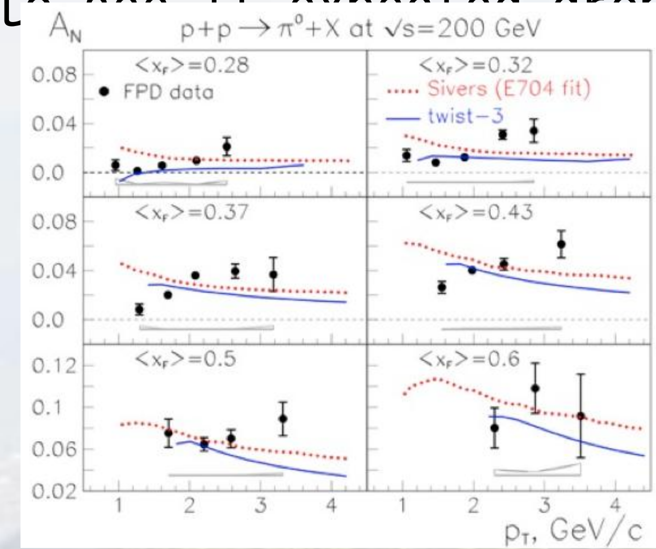


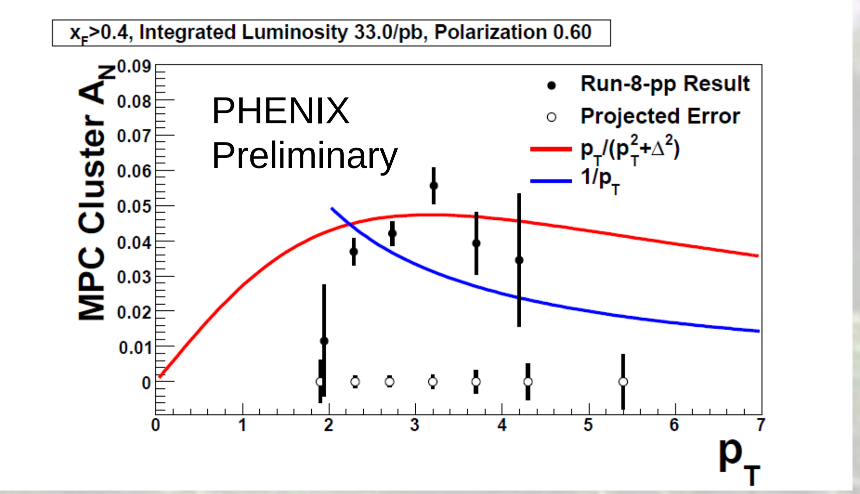


Understanding p_T Dependence

- Trend in A_N data described by theory,
- But when look deeper, indications that all is not well understood
  - Expected fall off at high p_T not yet seen
- STAR and PHENIX pushing to high p_T to see if expected drop off occurs

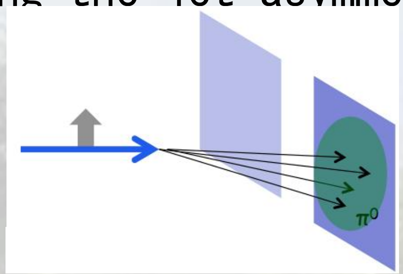


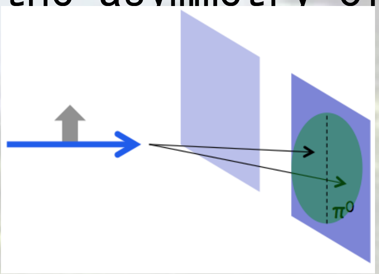




Future plans

- Several short and long term approaches to understand transverse spin phenomena in p+p
  - *Near term (R. Seidl)*
    - Plan to understand these different effects with the current PHENIX detector (and smaller upgrades) over the next few years
  - *Longer term (I. Nakagawa)*
    - Plans for the sPHENIX upgrade and how Drell-Yan measurements at RHIC can help us understand universality of TMDs
    - The sPHENIX detector can also be used to finally understand the mechanism generating the large A_N by seperately measuring the jet asymmetry and the asymmetry of a hadron in a jet





Conclusions

- The nucleon spin structure is a rich subject to study
- Helicity
  - Measurements of the double helicity asymmetry A_{LL} directly access the gluon helicity
  - RHIC measurements have significantly constrained the ΔG
  - Over next few years,
    - Extend knowledge of ΔG to lower x by measuring a $\sqrt{s}$=500 GeV and at large η
    - Better determination of $\Delta G(x)$ through correlation measurements
- Transverse
  - Initial measurements in p+p saw surprisingly large asymmetries
  - Measurements at RICH and in SIDIS are trying to disentangle the source
  - Planning to make measurements at RHIC to measure Sivers and Collins separately
- Much more about future plans from R. Seidl and I. Nakagawa


Thank
You

BACKUPS

Another Route to Transversity

- Interference Fragmentation Function (IFF)
  - Measured at BELLE
  - Collinear (no k_T dependence)
  - Correlates quark spin with produced hadron pair angular momentum
- At PHENIX, couples with transversity
  - Initial data do not have needed sensitivity
  - Expected data in next few year will be precise enough