Symposium to honor the career and accomplishments of
Professor Alan Krisch

Experimental Challenges in Spin Physics

Present & Future

Abhay Deshpande
Stony Brook University

A century of "spin surprises"

- Stern & Gerlach (1921):
  - Space quantization associated with direction
- Goudsmit and Uhlenbeck (1927):
  - Atomic fine structure and electron spin magnetic moment
- Stern (1933):
  - Proton anomalous magnetic moment (2.79)
- Experiments with spin have a high discovery potential
- Prescott et al., Yale-SLAC (1978) :
  - E-W interference in polarized e-d DIS, parity non-conservation
- European Muon Collaboration's "Spin Crisis" (1989)
  - Valence quarks do not carry much of proton's spin

Spin experiments lead to precision

- World's most precise measurement of Weinberg angle:

$$\sin^2\theta_W^{\text{eff}} = 0.23061 \pm 0.00047$$

from SLD, with polarized electron beams a factor of 25 improvement compared to un-polarized beams

Experiments with Spin enable precision!

- LEP collider, the most precise information about the beam energy comes from the resonant depolarization of the beams

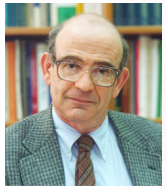
Quotes from wise physicists:

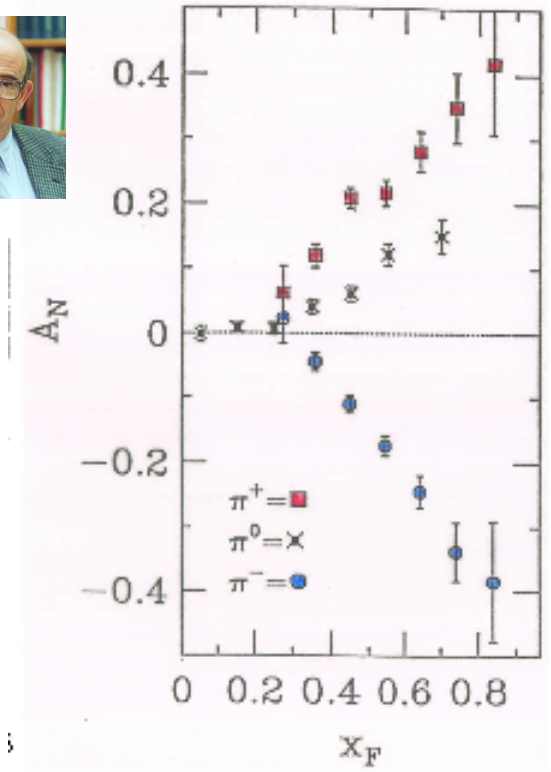
"Experiments with *spin* have killed more theories than any other single physical property …"

"If theorists had their way, they would have banned all experiments with spin"

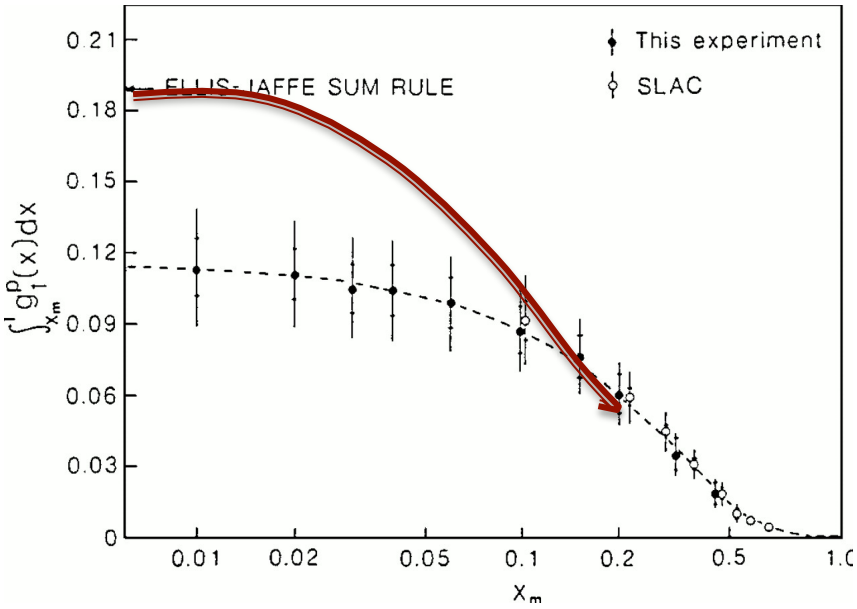
Early indicators of the "unusual" with spin at high energy

ZGS/ANL 1960'S





EMC/CERN 1980'S



Nucleon Spin Puzzle

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

- $\Delta\Sigma$: The [q+qbar] contribution to the nucleon spin
- ΔG : The gluon's contribution to the nucleon spin
- L_{Q+G} : The orbital contribution from quarks and gluons
  - There are many theoretical issues with definitions, model dependencies, and measurability of these quantities

While we resolve the theoretical issues, the best way to "address" the nucleon puzzle is to measure as precisely as we can the $\Delta\Sigma$ and ΔG

G. Altarelli, DIS2009

Plan of my talk

- Proton's structure with *violent* collisions of polarized protons: The RHIC Spin program
  - Resent results & their limitations, experimental techniques, near future challenges
  - Gluon Spin, Anti-Quark Spin & transverse spin measurements

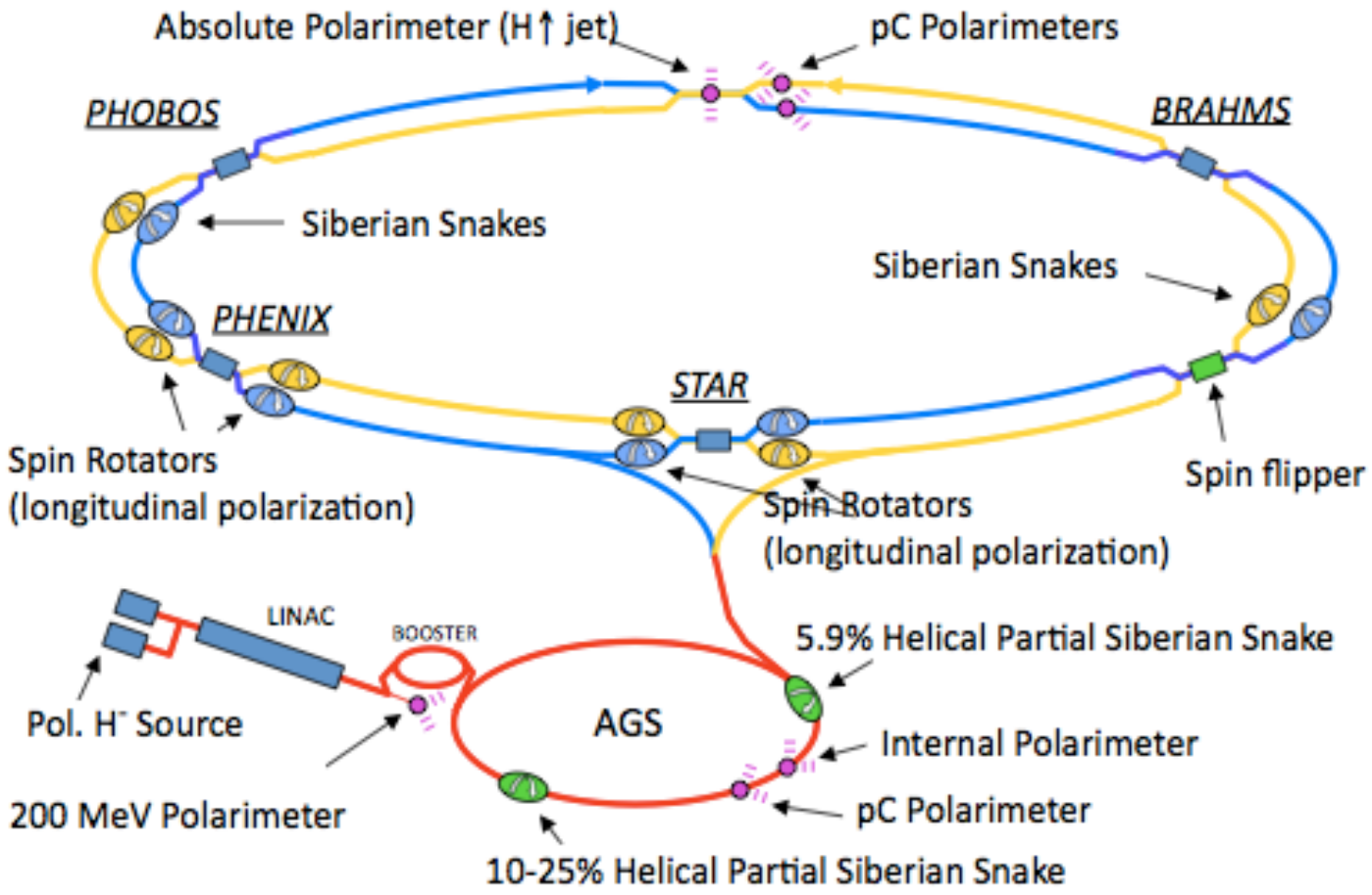
Spin in the context of the Electron Ion Collider

R. Milner's talk

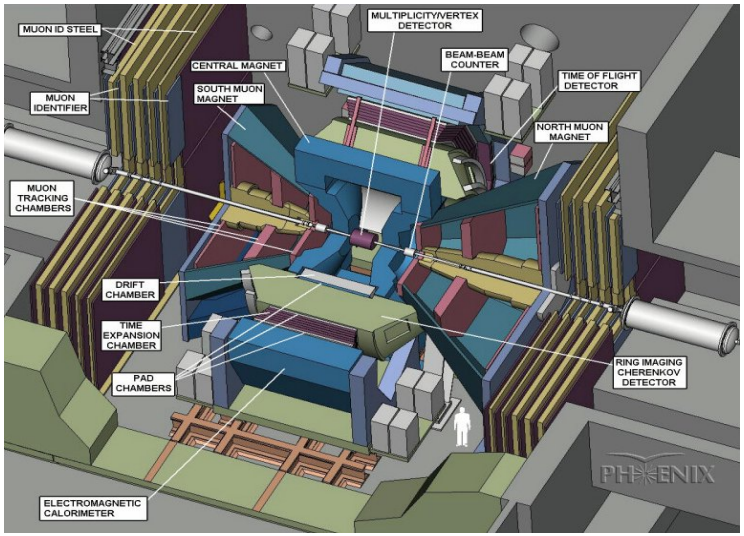
- Proton's spin structure through *non-violent* collisions (3D spatial structure of the proton)
- Spin for *precision* measurements in QCD & EW physics

Polarized protons in RHIC

T. Roser's talk



Experiments @ RHIC

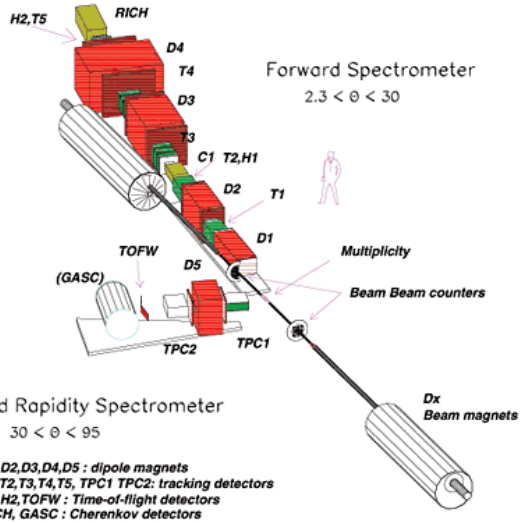


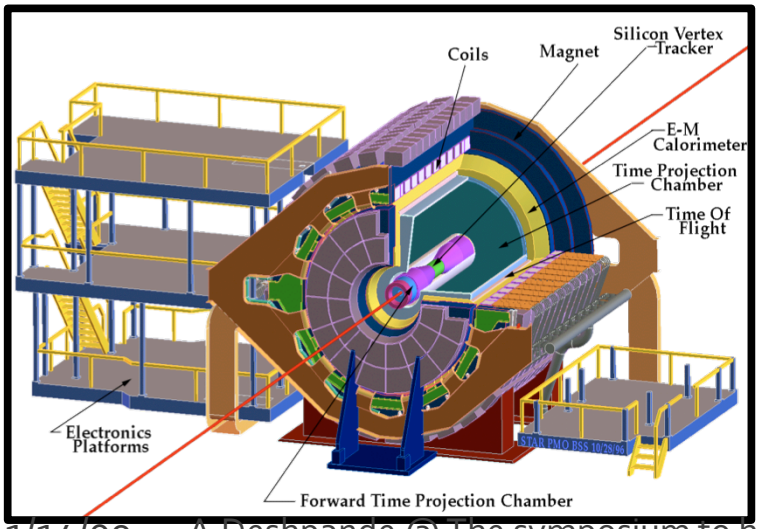
PHENIX

High rate capability
Limited acceptance
High p_T photon trigger

BRAHMS

Forward spectrometer
charge hadron id





STAR

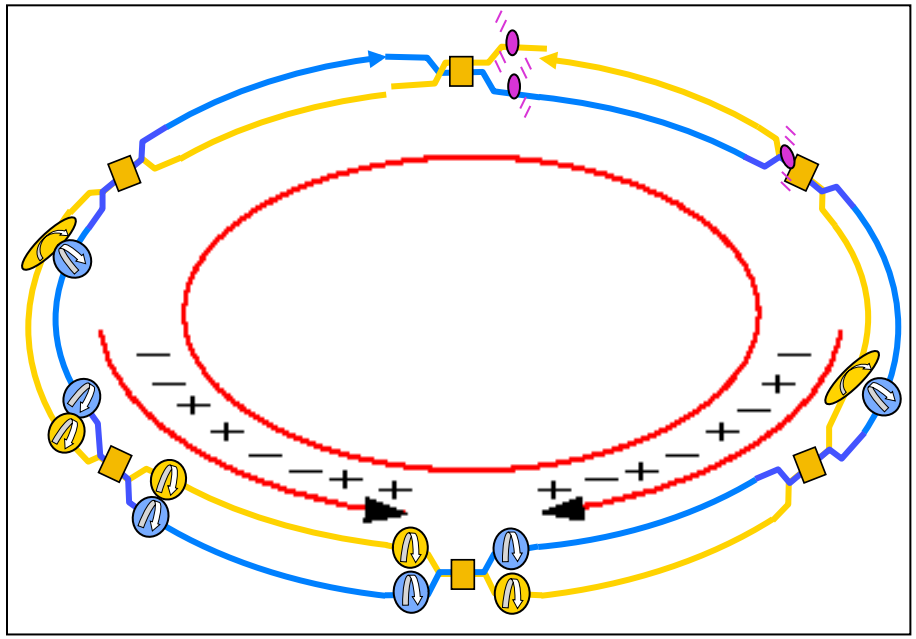
Large acceptance
Azimuthal symmetry
Jet patch trigger

RHIC Spin program

- Direct measurement of polarized gluon employing multiple complementary measurements
  - Inclusive and semi-inclusive pion, photon, jet production
  - Double **longitudinal** helicity asymmetry A_{LL}
- Direct measurement of anti-quark polarization via maximally PV production & decay of $W^{+/-}$
  - Single **longitudinal** asymmetry A_L
- Systematic study of transverse spin phenomena
  - Explore fundamental aspects of QCD & transverse spin structure of the nucleon through **transverse** spin collisions

N. Makin's talk

Asymmetry measurements at Colliders



Effective spin reversal every 106 ns between collisions & availability of all spin combination in a single fill allows exquisite control of systematic uncertainties

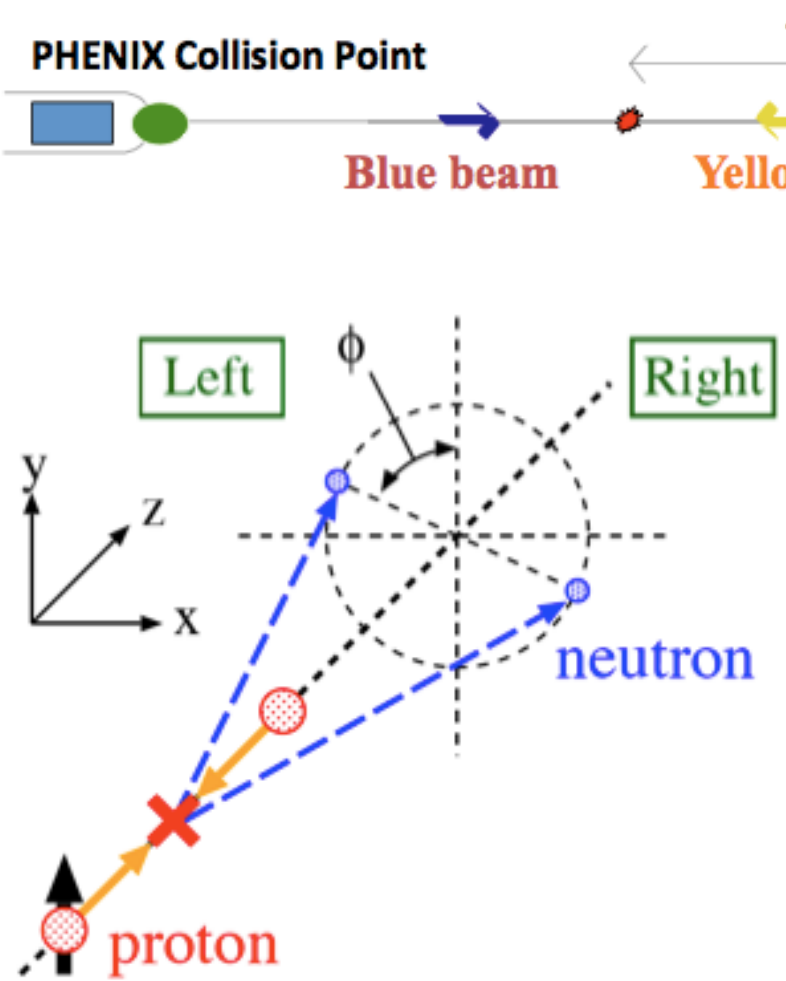
Spin rotators determine the collisions' spin orientation transverse or longitudinal

$$A_{LL} = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} = \frac{1}{|P_1 P_2|} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}}; \quad R = \frac{L_{++}}{L_{+-}}$$

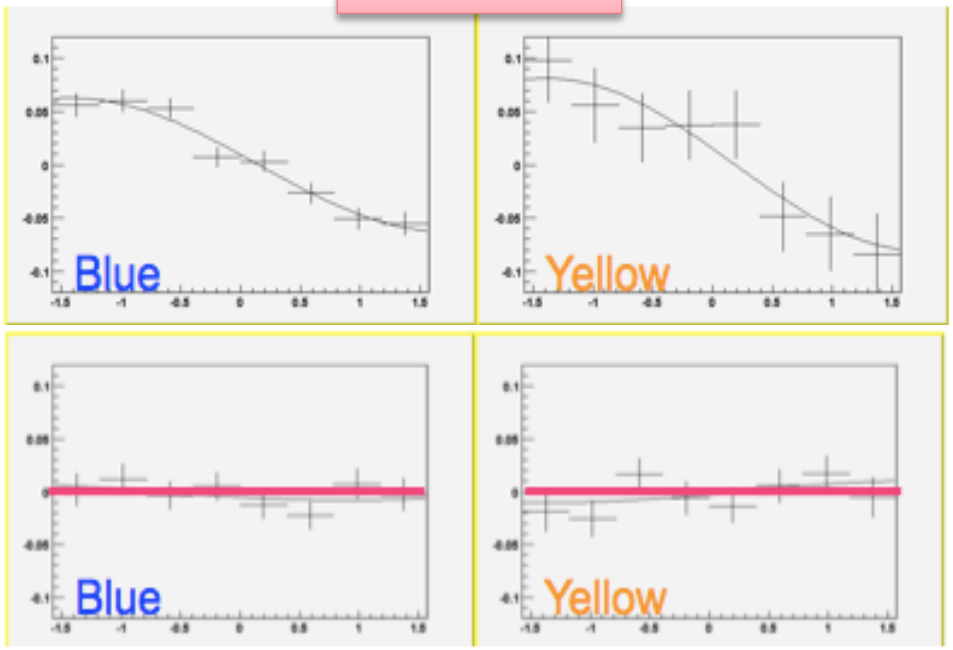
For A_{LL} & A_L measurements: Can we confirm that protons are longitudinal?

Assuring longitudinal collisions for A_{LL} and A_L measurements

Discovery!



CM 200 GeV



Understanding the proton $\Delta\Sigma$ and ΔG is an experimental challenge:
Theoretical issues understood, mostly…

ΔG & Anti-Quark Measurements from RHIC & future…

Accessing ΔG in p+p Collisions at RHIC

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

From ep (&pp) (HERA mostly)

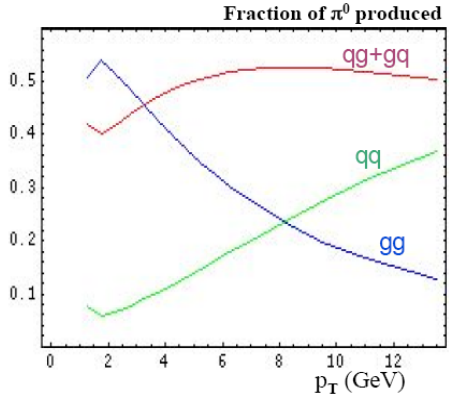
NLO pQCD

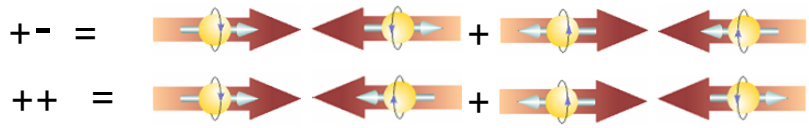
From e+e- (& SIDIS,pp)

- If 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 depend on final state observable and event kinematics (η,p_T).

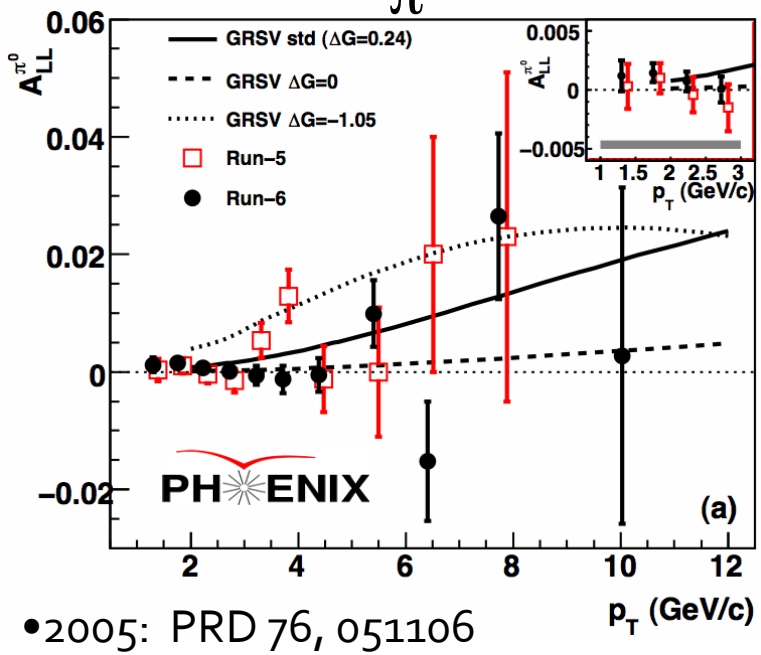




A_{LL} Results

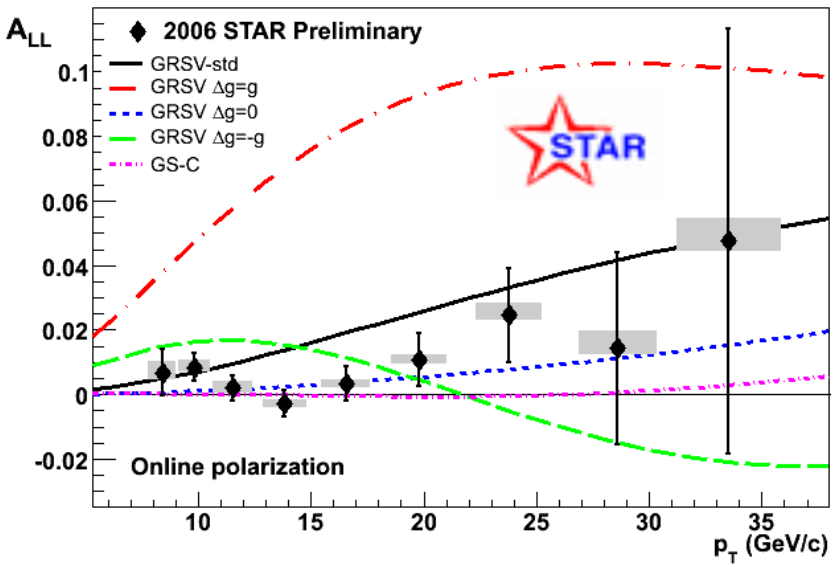
$$\frac{\Delta G}{G} \propto A_{LL} = \frac{1}{P_B P_Y} \frac{N_{++} - R N_{+-}}{N_{++} + R N_{+-}} \quad R = \frac{L_{++}}{L_{+-}}$$

π^0



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

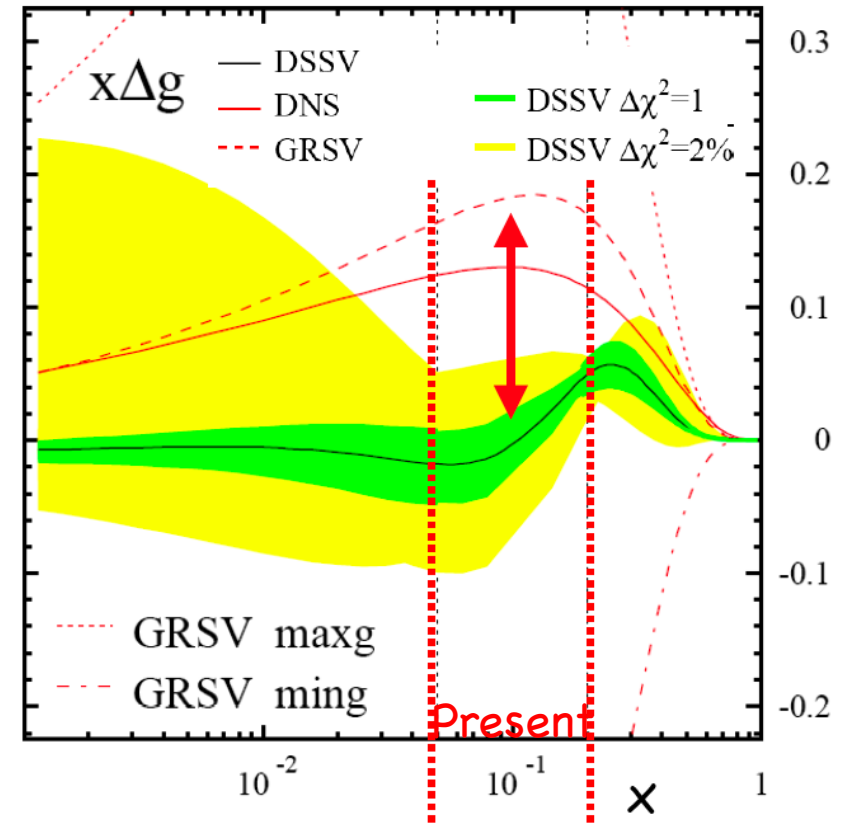
Jet



- 2005: PRL 100, 232003
- 2006: Preliminary (unpublished)

$\Delta G(x)$ @ Q^2=10 GeV^2

de Florian, Sassot, Stratmann & Vogelsang

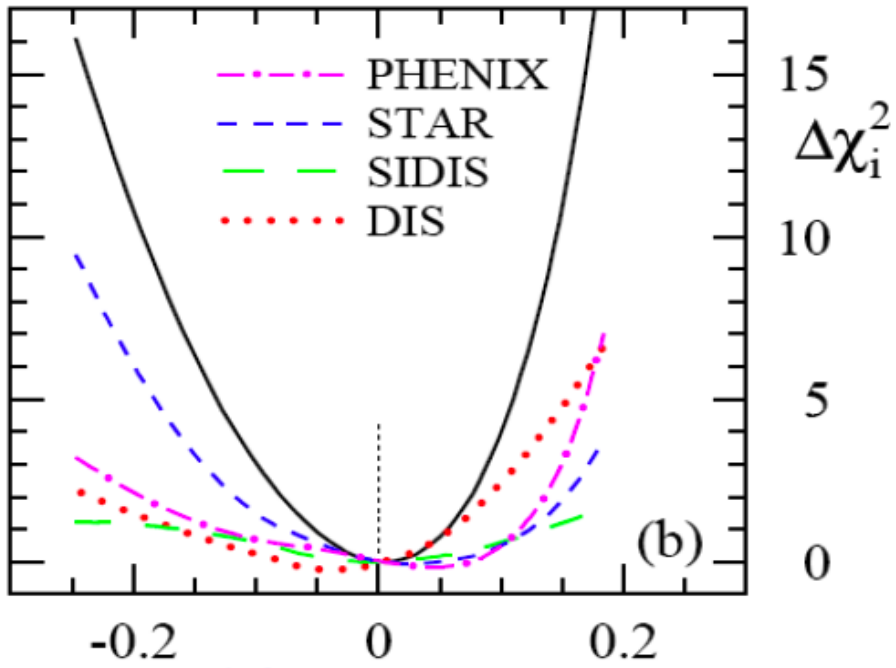


small-x
$0.001 \leq x \leq 0.05$

RHIC range
$0.05 \leq x \leq 0.2$

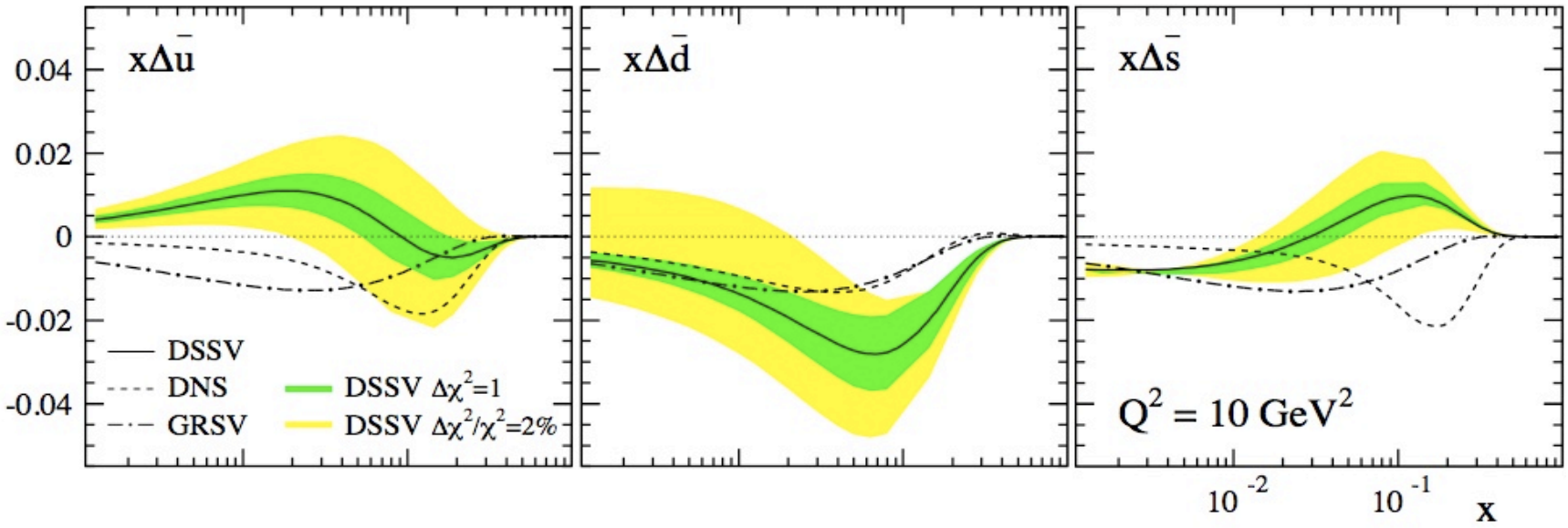
large-x
$x \geq 0.2$

- **Global analysis: DIS, SIDIS, RHIC-Spin**
- **Uncertainly on ΔG large: Need more low-x measurements!**



$$\delta g \equiv \int_{0.05}^{0.2} \Delta g(x, 10\,\mathrm{GeV}^2)\,dx$$

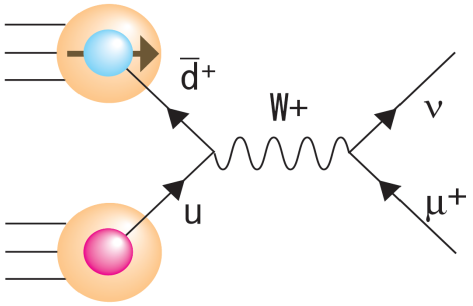
What about the anti-quark polarization?



- DIS probe (γ^*) doesn't distinguish q from qbar
  - Has to take measure semi-inclusive (π, K production)
  - Uncertainties in fragmentation functions
- High energy p-p collisions enable probing q,qbar through $W^{+/-}$ production –> Plan at RHIC

Sea Quark Helicity Distributions

- How can we get flavor dependent sea quark info?
  - At RHIC, W boson production in polarized p+p collisions is sensitive to specific combinations of quarks: u-dbar (W^+), ubar-d (W^-)



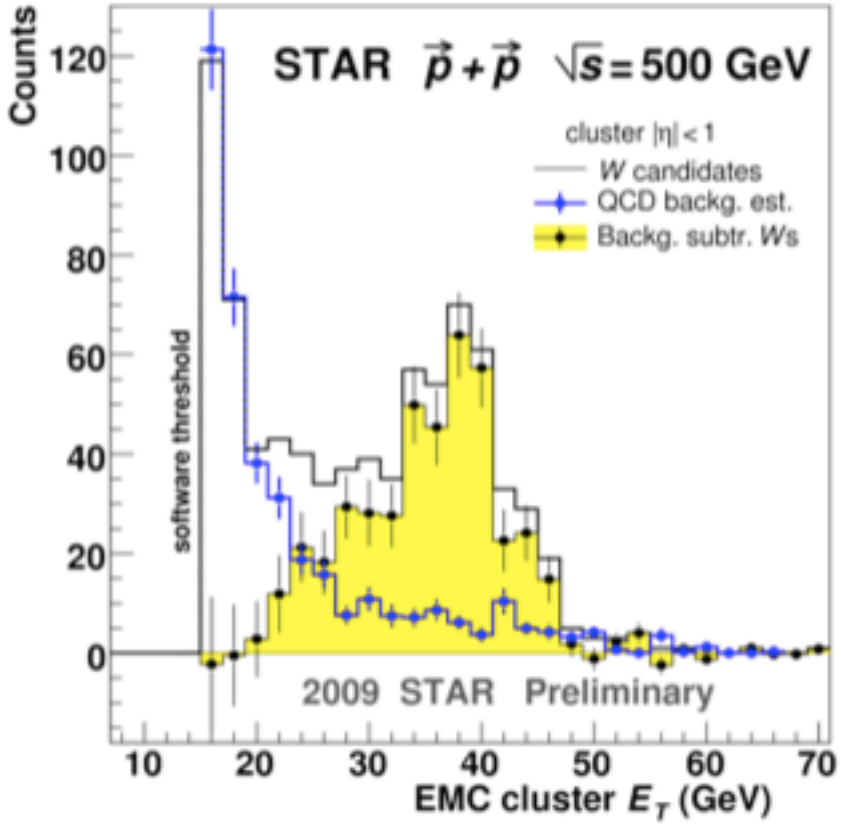
- Measure parity violating asymmetry in W boson production

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

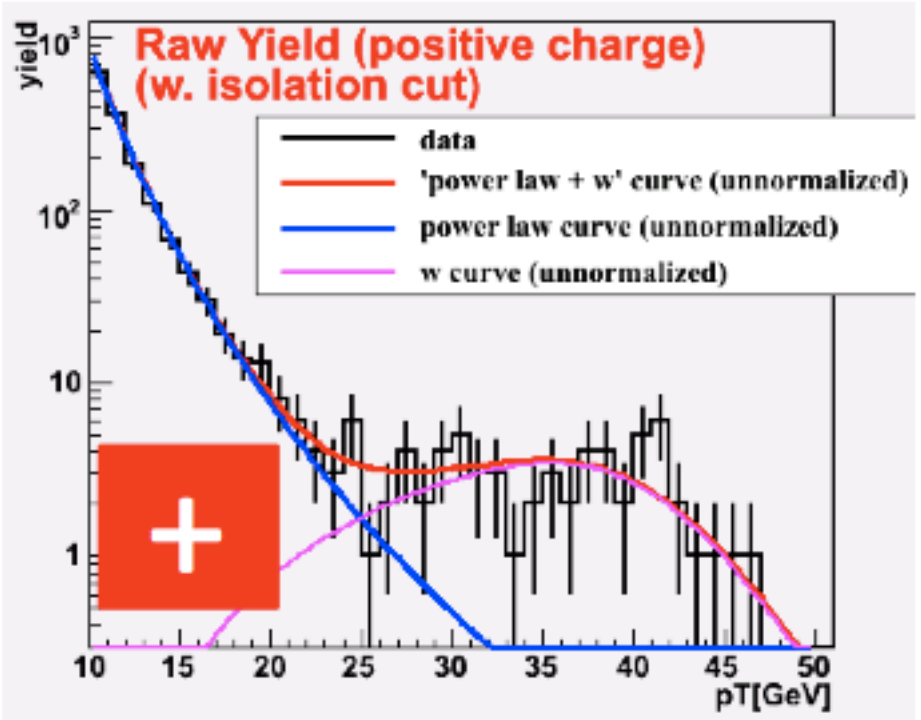
- Similar case for W^- with d and u.
- W's decay in to leptons: Plan to measure them precisely in the high η (forward) directions

First Observation of W's at RHIC
Exciting few years ahead…

STAR: J. Seele, DNP09

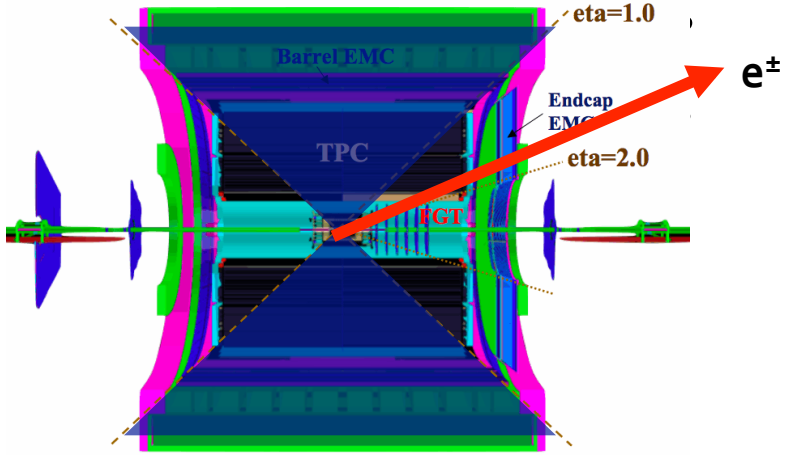


PHENIX, K. Okada, DNP09

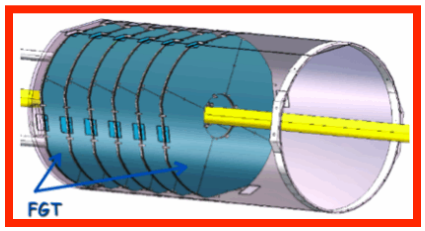


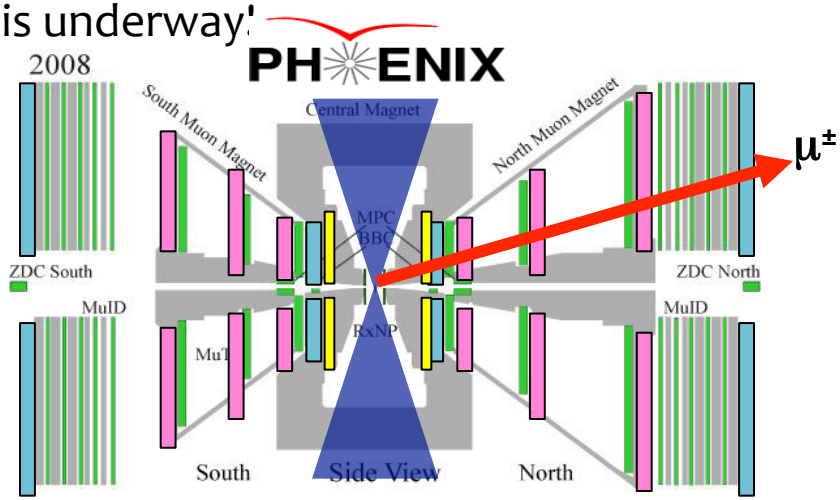
Upgrades for W Physics

- Both STAR and PHENIX can measure W->e near midrapidity
  - Analysis of first 500 GeV data in 2009 is underway!



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





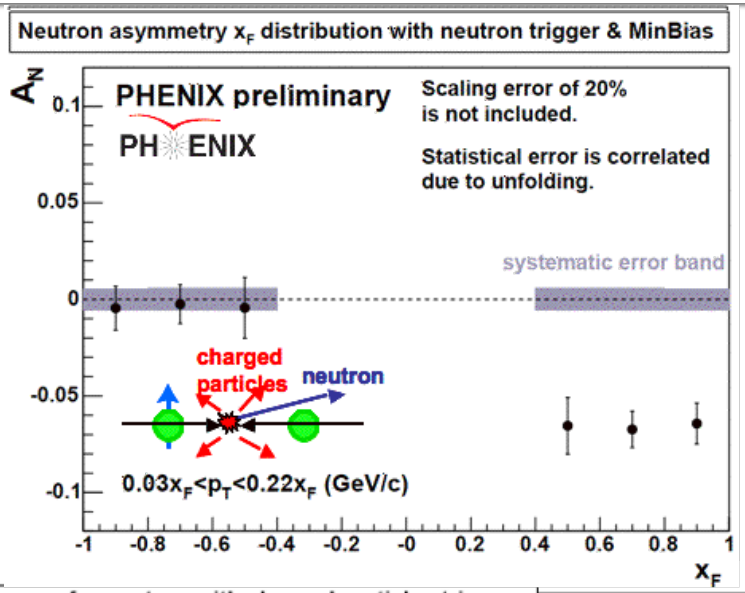
Identification from MUID and charge sign/ momentum from MUTr.
BUT, trigger is dominated by low momentum particles
→ Resistive Plate Chambers
→ 5% of MUTr signal into trigger circuit
Use bend in track to trigger high mom. muon

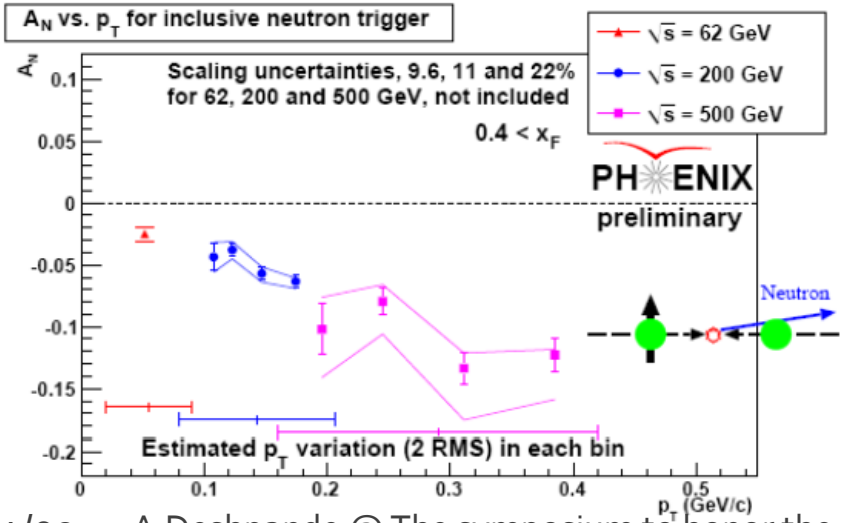
Understanding the subtleties of transverse spin effects is significantly more difficult, the framework for understanding them is only now being developed….

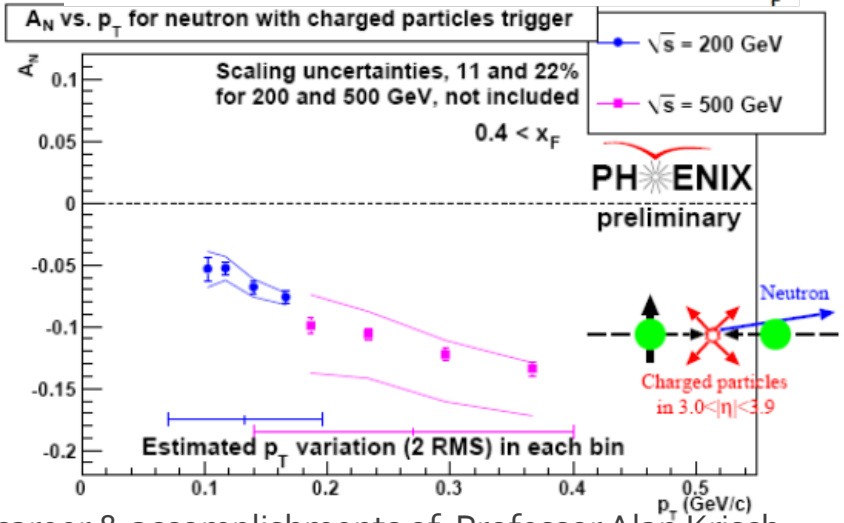
Transverse spin effects

Unexpected discovery… needs theoretical guidance

- Large very forward neutron asymmetry found at RHIC.
- Center of Mass & p_T dependence studied
- Not understood how it arises: a challenge to theorist

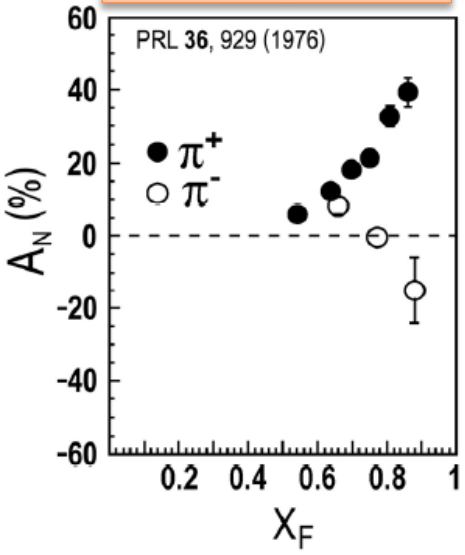


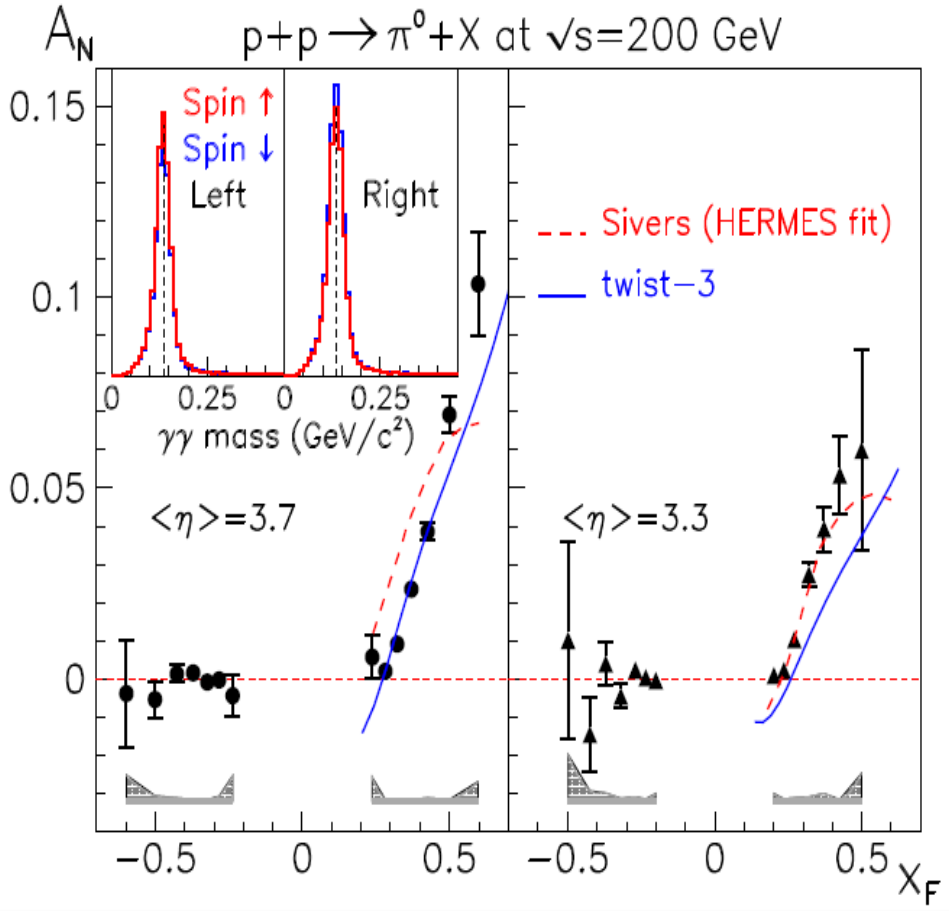




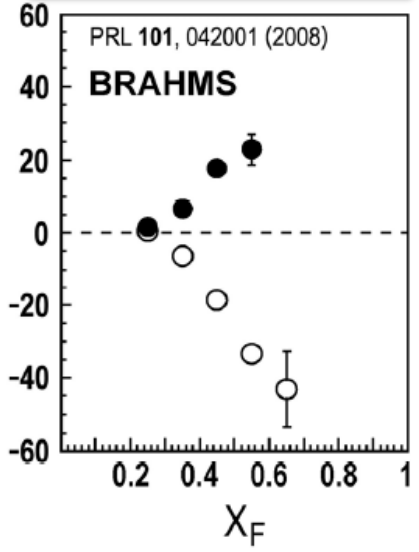
Pion asymmetries since ADK's

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

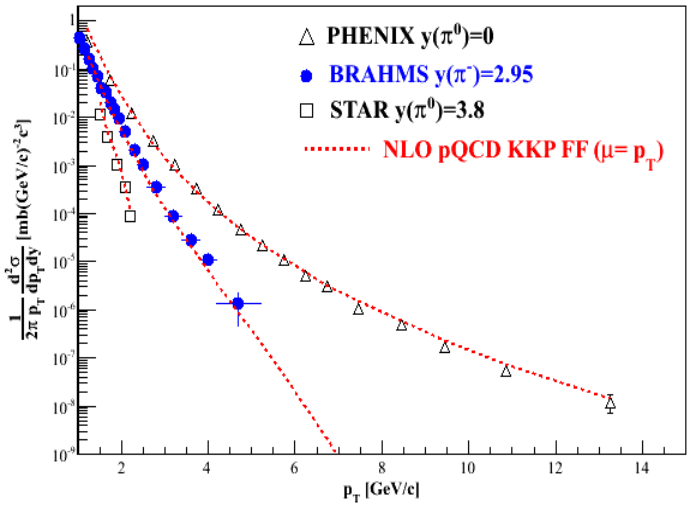


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

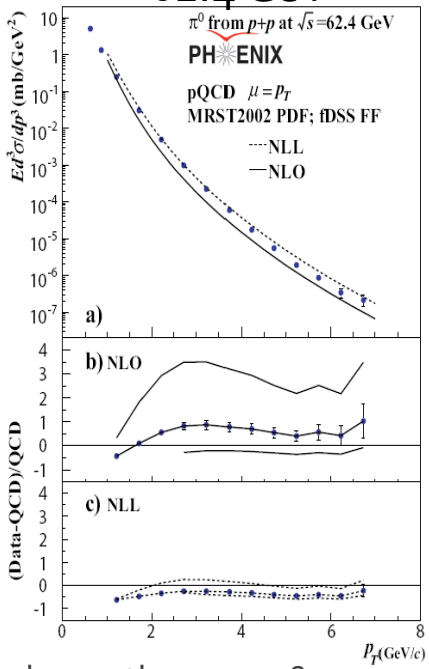
New at RHIC: pQCD Framework

- 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

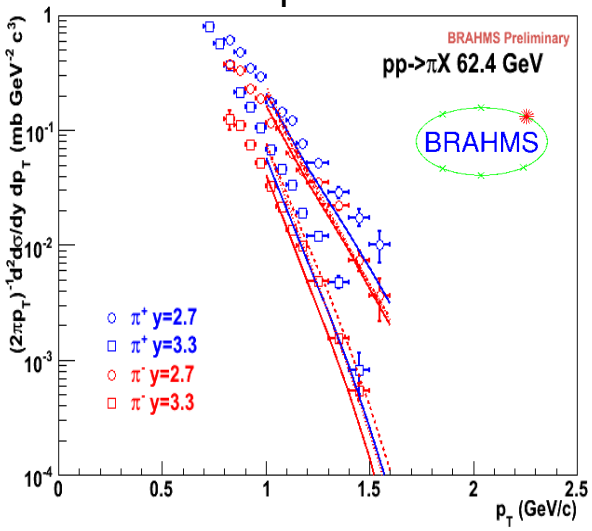
200 GeV



62.4 GeV



62.4 GeV



STONY BROOK UNIVERSITY

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

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

$\eta \rightarrow$ Further evidence against a valence quark effect!

Larger than the neutral pion!

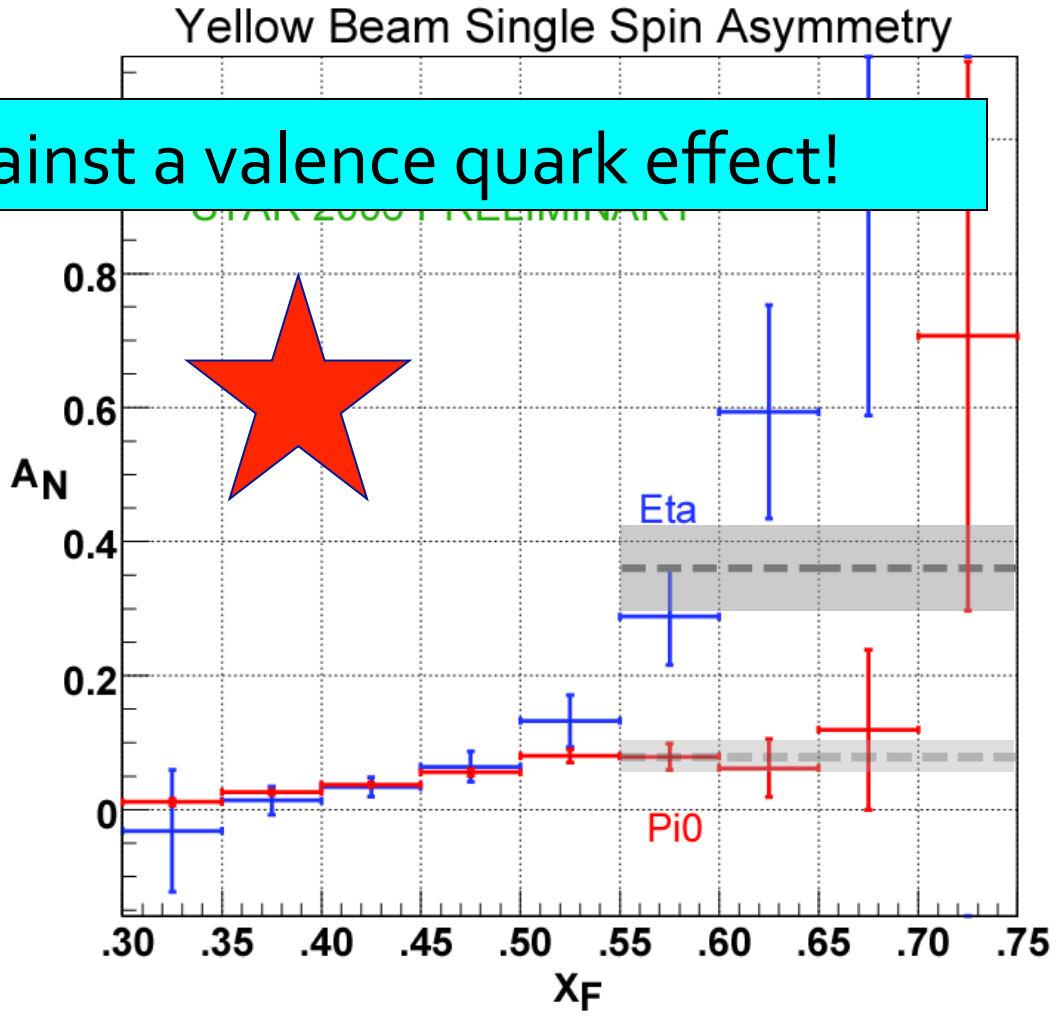
$$.55 < X_F < .75$$

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

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

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

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

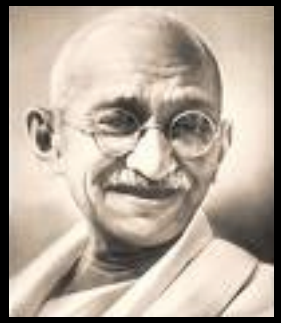


Challenge: Understanding the Transverse Spin effects…

- Possibilities: Moving beyond inclusive probes to start to examine various correlation measurements

- Challenges: Theoretical framework to relate the measurements to DIS & gain insight in to the transverse spin dynamics & possible connection to OAM?

N. Makin's talk

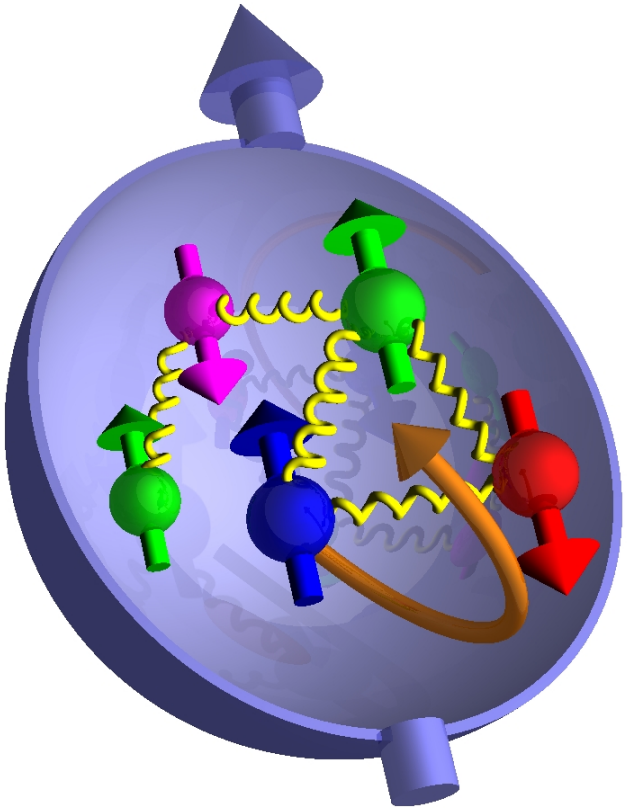


Non-violent investigations of nucleon spin…

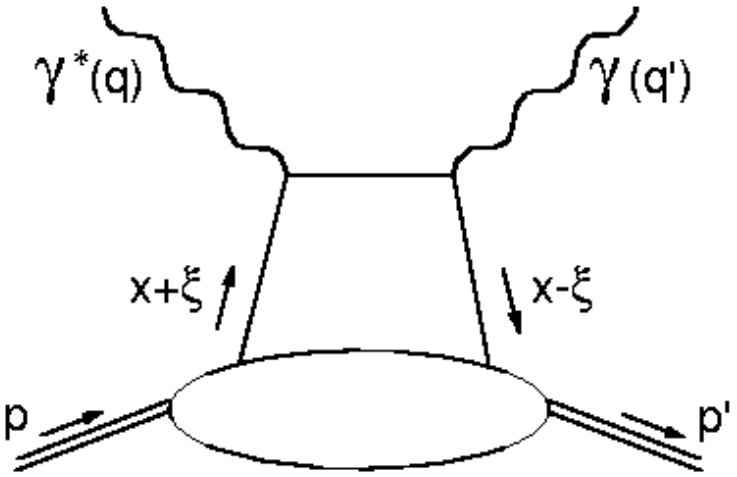
Selected measurements at the future Electron Ion Collider

Generalized Parton Distributions & orbital motion [??]

Quarks, Gluons and their orbital motion



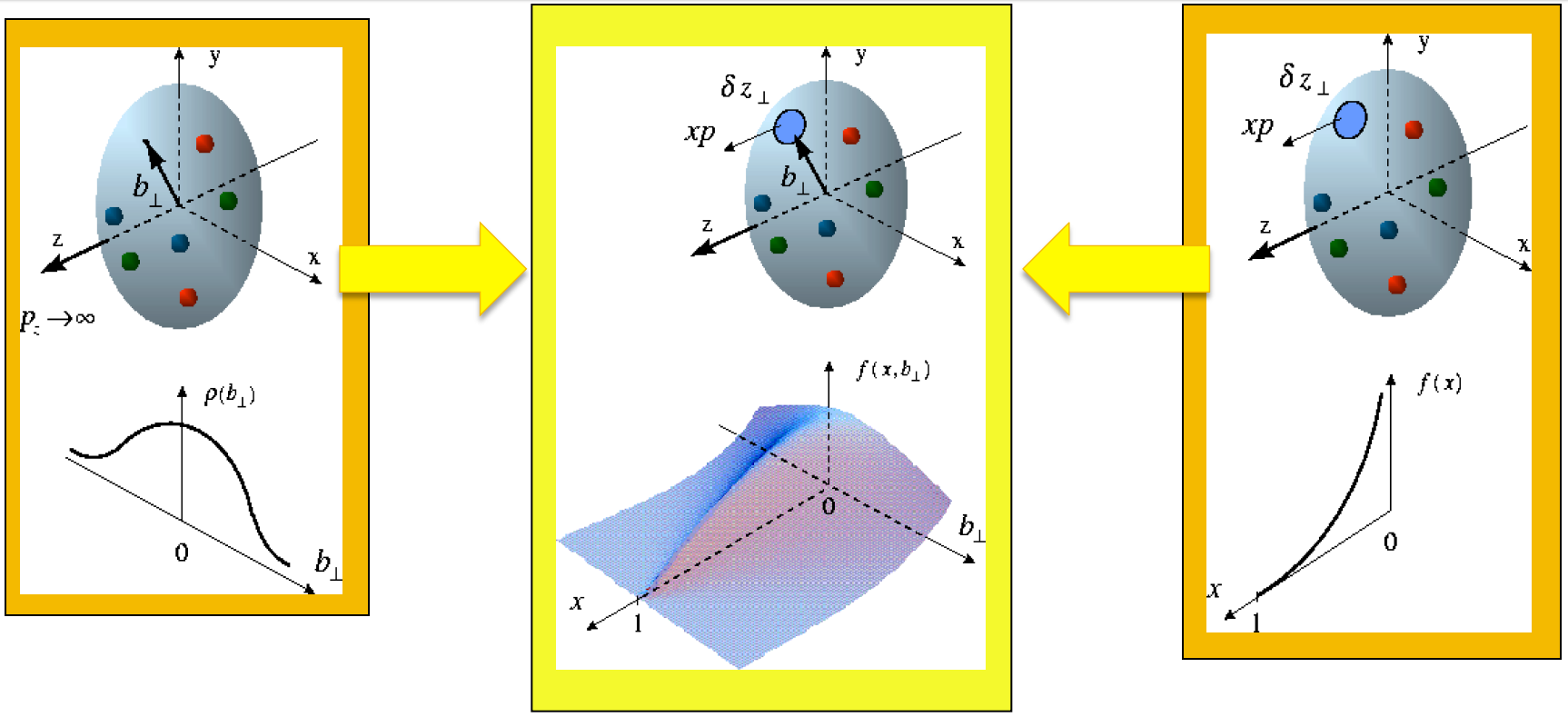
Lets not break the proton to explore it!
Deeply Virtual Compton Scattering (DVCS)



Beyond form factors and quark distributions

Generalized Parton Distributions

X. Ji, D. Mueller, A. Radyushkin (1994-1997)

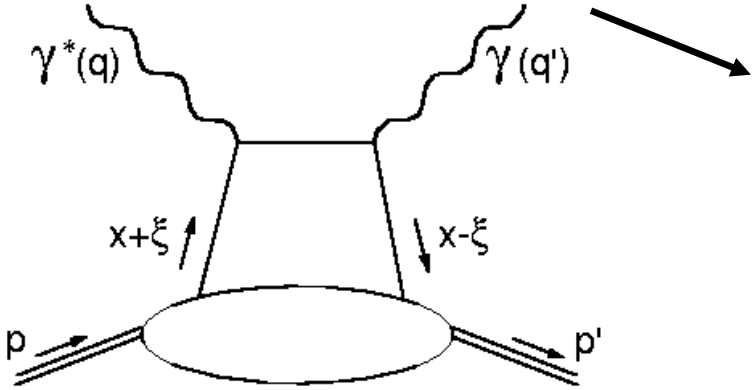


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

DVCS/Vector Meson Production: Generalized Parton Distributions



- Hard Exclusive DIS process
- γ (default) but also **vector mesons**
- Remove a parton & put another back in!

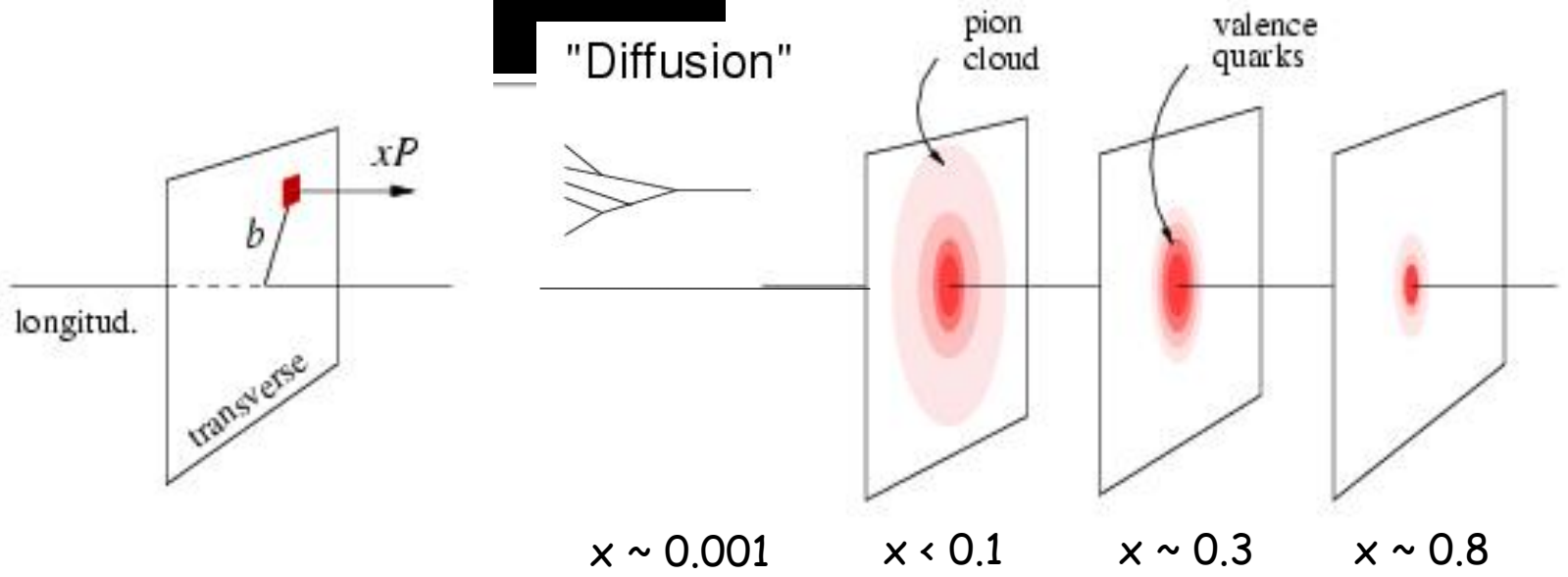
- Claim: possible access to --> Generalized parton distributions with theoretically clean connections to partonic orbital angular momentum!

$$\int x dx [H(x,t,\xi) + E(x,t,\xi)] = 2J_{quark} = \Sigma + 2L_q$$

0 0 --> $-Q^2$

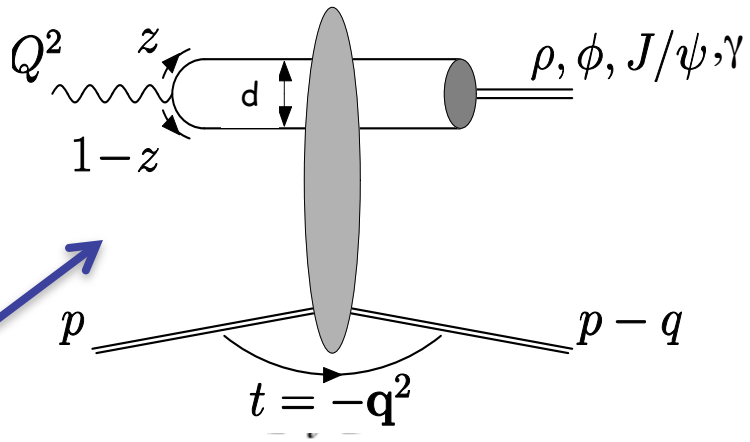
Experimental effort just beginning…To fully explore this physics

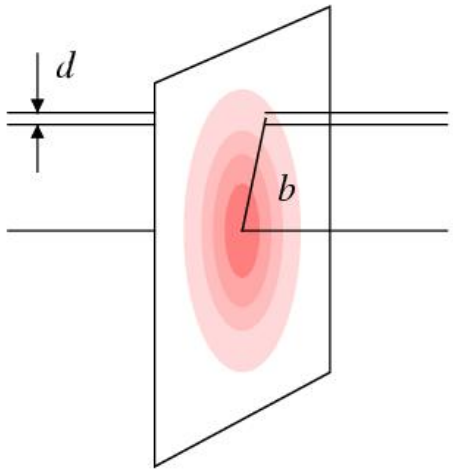
GPDs and Transverse Parton Imaging



gives *transverse size of quark* (parton) with longitud. momentum fraction x

EIC:
1) x < 0.1: gluons!
2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.





Spin allows precision…

Towards precision studies…

Bj Sum Rule & Determination of α_s

"g-2"-Like precision measurement in QCD (?)

$\alpha_s(M_Z)$ has been determined from Bj spin sum rule by many groups:

1. J. Ellis & M. Karliner, Phys. Lett. B341, 387 (1995)
2. G. Altarelli et al., Nucl. Phys. B496, 337 (1997)
3. B. Adeva et al. SMC Collaboration, Phys. Rev. D58 (1998) 112002
4. ……. Recent one from Jlab as well, but at very low Q^2

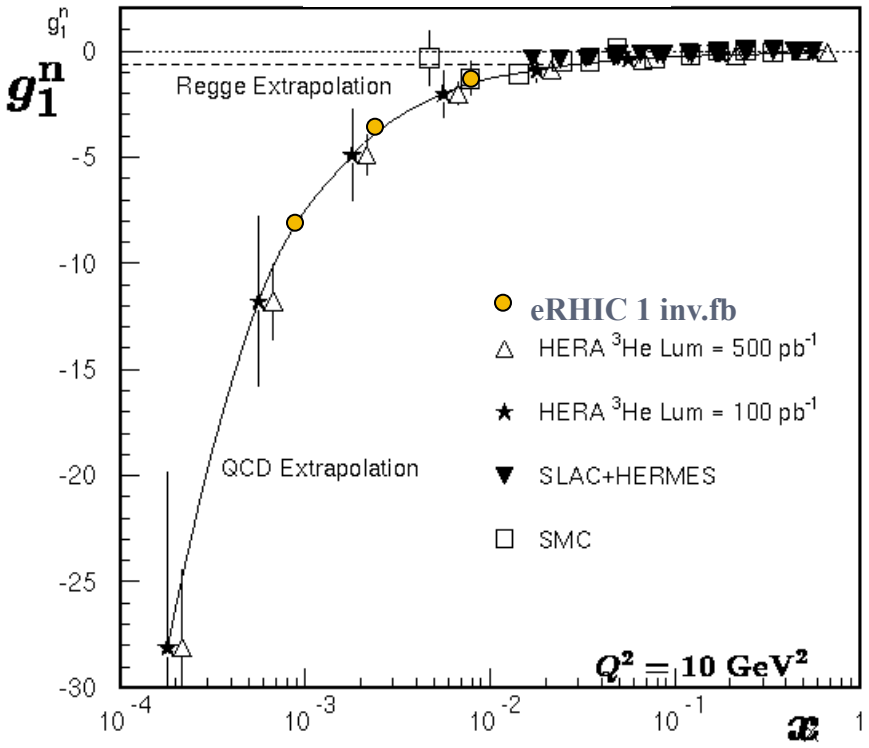
Largest uncertainties from low-x extrapolations!

$$\Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right| C_1^{NS}(Q^2)$$

Particle Data Book (2002, 2004,2006,2008). Extended version:

"Theoretically, this sum rule is better for determining α_s because perturbative QCD result is known to higher order ($o(\alpha_s^4)$), and these terms are important at low Q^2…… **Should data at lower x become available**, so that the low x extrapolation is more tightly constrained, the ***Bj sum rule method could give the best determination of α_s***"

A challenge: Spin Structure of Neutron @ low x



At EIC

- With polarized D or He^{+3} to be stored and accelerated
- ~ 2 months of data at EIC allows the measurement shown on left

Nuclear corrections need to be revisited(?)

Challenges:

1. Intense polarized He^{+3} and D sources
2. Precision polarimetry (for high energy e/h beams) needed

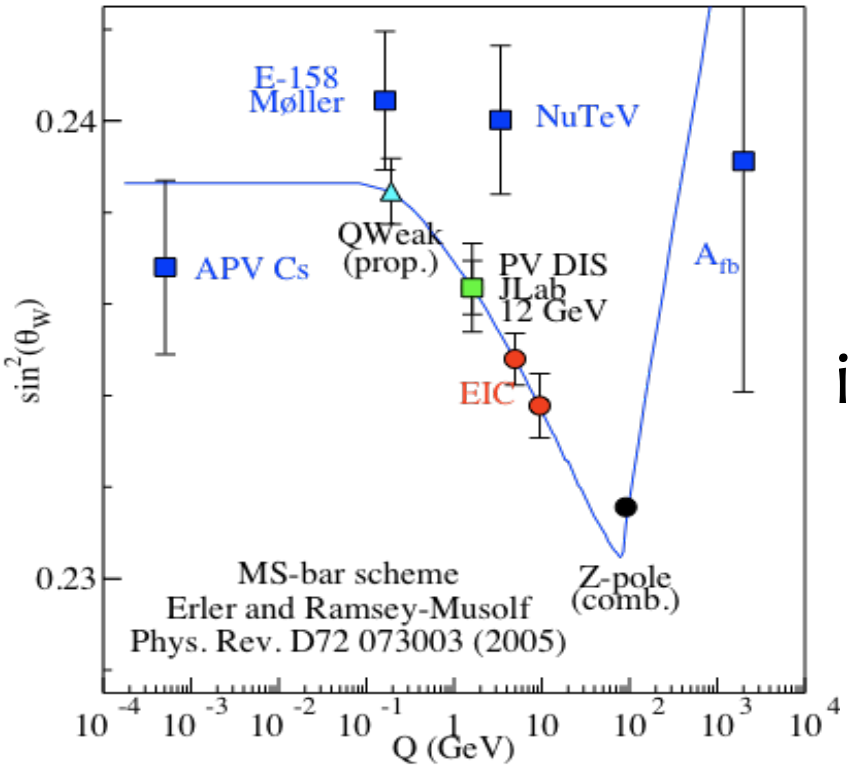
Some measurements considered so far for the EIC:

- Push the luminosity requirements > 10^{34} $cm^{-2}s^{-1}$
- Push the polarimetry and beam quality (stability, uniformity) requirements to the extreme:
  - (dPol/Pol) ~ 1%
  - Ultra low beam divergence for DVCS/Diffraction…

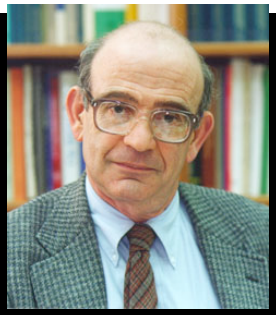
Why not consider using this machine for precision EW-Physics measurements?

EW Physics topics under consideration*:

- High energy collisions of polarized electrons and protons and nuclei afford a unique opportunity to study
  - Contributions from W and Z couplings with quarks and a
    - Polarized protons (g_5 spir there nuclear modificatio
- Parity violating DIS: a prol ics
  - Measurements of $Sin^2\theta_W$ at
- New window for physics b
  - Lepton flavor violation sear



*Initiated through discussions with: M. R. Musolf, K. Kumar
Being pursued by: W. Marciano, K. Kumar, M. Savastio, W. Vogelsang, AD



Thank you

- 500+ physicists around the world doing forefront research using "spin" as a variable
- Spin is now an accepted tool for high energy physics: *This was not the case when Alan started*
- I have no doubt that it will play as prominent a role in understanding the various physics frontiers in this century as it did in the last
- Development of "spin" as a tool has had enormous consequence to the development of physics – *Alan has played a highly visible & pivotal role in this over the last 40+ years!*