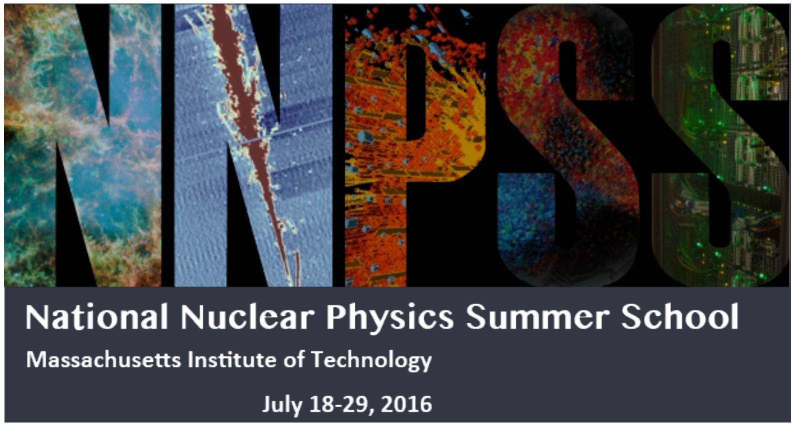



# The Electron Ion Collider (EIC)

Abhay Deshpande

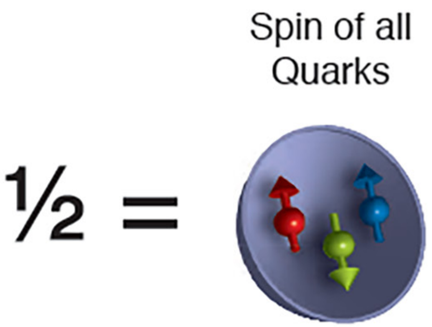
Lecture 2:

What do we need polarized beams?

Nucleon Spin Structure: What's the problem?

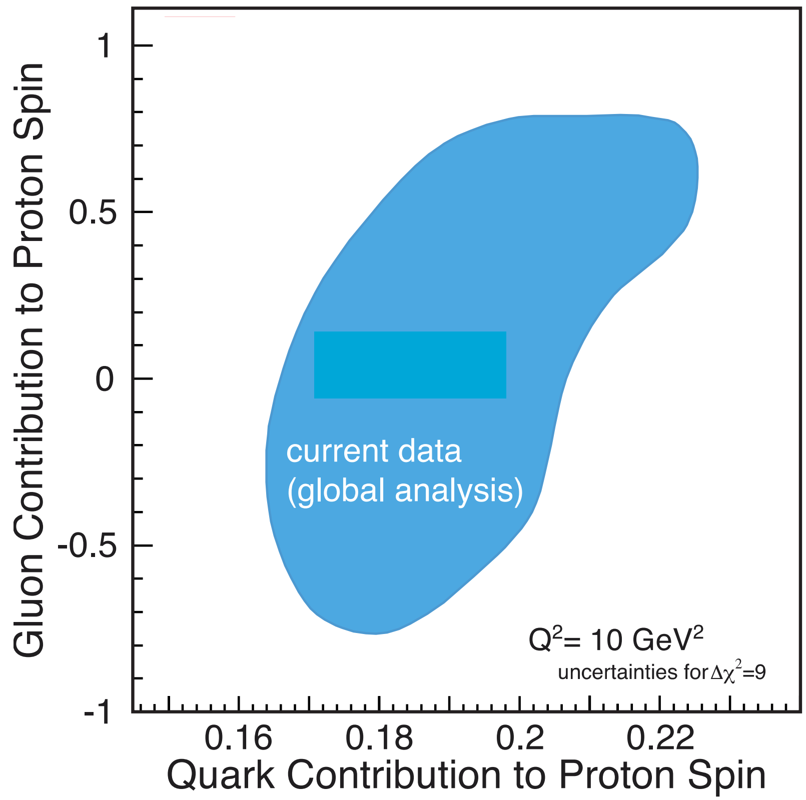
Stony Brook University

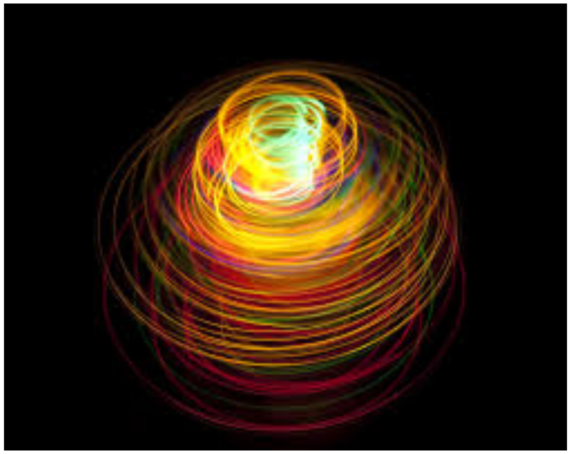
# The nucleon spin puzzle…. Since 1988..




$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G$$

? ?



# A brief history of nucleon spin: “Crisis” → “Puzzle”

# Some equations…

*Assume only $\gamma^*$ exchange*

- Lepton Nucleon Cross Section

$$\frac{d^3\sigma}{dx\,dy\,d\phi} = \frac{\alpha^2 y}{2Q^4} L_{\mu\nu}(k,q,s,)W^{\mu\nu}(P,q,S)$$

Nucleon spin

Lepton spin

- Lepton tensor $L_{\mu\nu}$ affects the kinematics (QED)
- Hadronic tensor $W^{\mu\nu}$ has information about the hadron structure

$$W^{\mu\nu}(P,q,S) = -(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2})F_1(x,Q^2) + (p^\mu - \frac{P\cdot q}{q^2}q^\mu)(p^\nu - \frac{P\cdot q}{q^2}q^\nu)\frac{1}{P\cdot q}F_2(x,Q^2)$$

$$-i\epsilon^{\mu\nu\lambda\sigma}q_\lambda\left[\frac{MS_\sigma}{P\cdot q}(g_1(x,Q^2)+g_2(x,Q^2)) - \frac{M(S\cdot q)P_\sigma}{P\cdot q}g_2(x,Q^2)\right]$$

# Lepton-nucleon Cross Section

$$\gamma = \frac{2Mx}{\sqrt{Q^2}} = \frac{\sqrt{Q^2}}{\nu}.$$

$$\sigma = \bar{\sigma} - \tfrac{1}{2} h_l \delta\sigma.$$

$$\frac{d^2\bar{\sigma}}{dx\,dQ^2} = \frac{4\pi\alpha^2}{Q^4 x}\left[ xy^2\left(1 - \frac{2m_l^2}{Q^2}\right) F_1(x,Q^2) + \left(1 - y - \frac{\gamma^2 y^2}{4}\right) F_2(x,Q^2)\right],$$

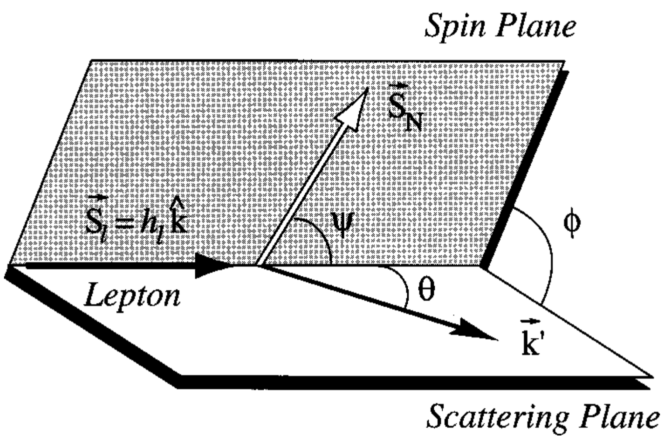
lepton helicity $h_l = \pm 1$

unpolarized structure functions $F_{1,2}(x, Q^2)$

scaling variable $x = Q^2/2M\nu$

exchanged virtual photon energy $= \nu$

# Polarized lepton-nucleon cross section…




$$\Delta\sigma = \cos\psi\Delta\sigma_{\parallel} + \sin\psi\cos\phi\Delta\sigma_{\perp}$$

$$\gamma = \frac{2Mx}{\sqrt{Q^2}} = \frac{\sqrt{Q^2}}{\nu}.$$

For high energy $\gamma$ is small

$$\frac{d^2\Delta\sigma_{\parallel}}{dxdQ^2} = \frac{16\pi\alpha^2 y}{Q^4}\left[\left(1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4}\right)g_1 - \frac{\gamma^2 y}{2}g_2\right]$$

$$\frac{d^3\Delta\sigma_T}{dxdQ^2d\phi} = -\cos\phi\,\frac{8\alpha^2 y}{Q^4}\,\gamma\sqrt{1 - y - \frac{\gamma^2 y^2}{4}}\left(\frac{y}{2}g_1 + g_2\right)$$

# Relation to spin structure function $g_1$

$$g_1(x) = \frac{1}{2}\sum_{i=1}^{n_f} e_i^2 \Delta q_i(x)$$

$$\Delta q_i(x) = q_i^+(x) - q_i^-(x) + \overline{q}_i^+(x) - \overline{q}_i^-(x)$$

$q_i^+ \ (\overline{q}_i^+)$ and $q_i^- \ (\overline{q}_i^-)$

Quark and anti-quark with spin orientation along and against the proton spin.

- In QCD quarks interact with each other through gluons, which gives rise to a weak $Q^2$ dependence of structure functions
- At any given $Q^2$ the spin structure function is related to polarized quark & gluon distributions by coefficients $C_q$ and $C_g$

# Composition & $Q^2$ or t dependence of Structure Functions

$$g_1(x,t) = \frac{1}{2}\sum_{k=1}^{n_f}\frac{e_k^2}{n_f}\int_x^1\frac{dy}{y}\left[C_q^{S}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t)\right.$$
$$+2n_f C_g\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)$$
$$\left.+C_q^{NS}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q^{NS}(y,t)\right].$$

In this equation:
t = ln($Q^2/\Lambda^2$)
$\alpha_S$ = strong interaction constant
S & NS stand for flavor singlet & flavor non-singlet

$$\Delta\Sigma(x,t) = \sum_{i=1}^{n_f}\Delta q_i(x,t),$$

$$\Delta q^{NS}(x,t) = \left[\sum_{i=1}^{n_f}\left(e_i^2 - \frac{1}{n_f}\sum_{k=1}^{n_f}e_k^2\right)\Big/\frac{1}{n_f}\sum_{k=1}^{n_f}e_k^2\right]\Delta q_i(x,t).$$

To study the $Q^2$ evolution experimentally: you need a wide $Q^2$ range in measurements

# Spin Crisis →Puzzle (1960-2000)

## Limitations of the Quark Parton Model (QPM) & lessons learnt

Early (fixed target) spin experiments and their limitations

*"If I had known this earlier,*
*I would have done Biology"*
*--W. Pauli*

@1960's # of hadrons > # of chemical elements

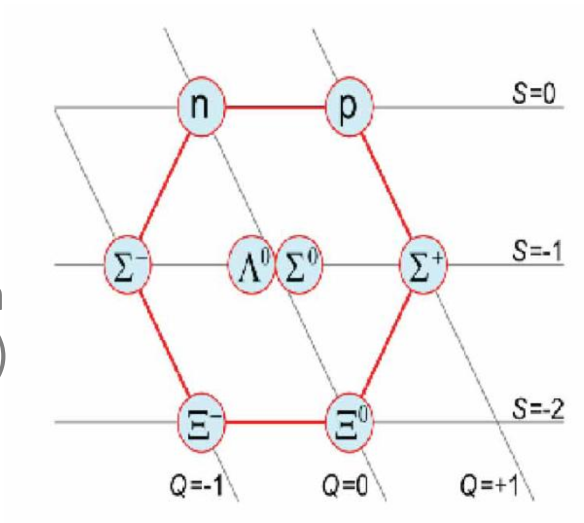
- baryons ( $J = n/2$ )$_{n=1,2,\ldots}$
- mesons: ( $J = n$ )$_{n=0,1,\ldots}$

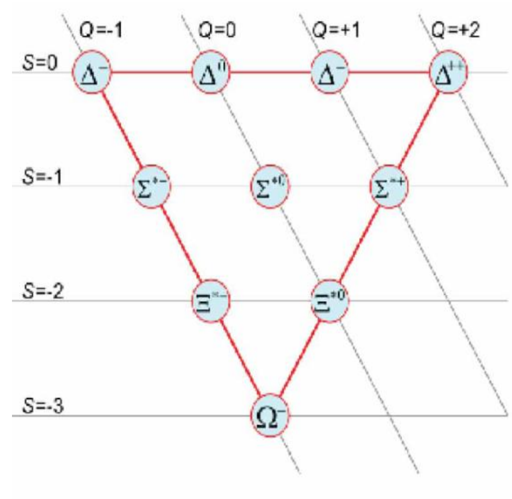
1961 'The Eightfold way' : all baryons and mesons grouped in multiplets definded by SU(3) symmetry

e.g., baryons:

$J^p = 1/2^+$

(same spin and parity)




$J^p = 3/2^+$

isolines of same charge and strangeness

# Understanding the proton structure:

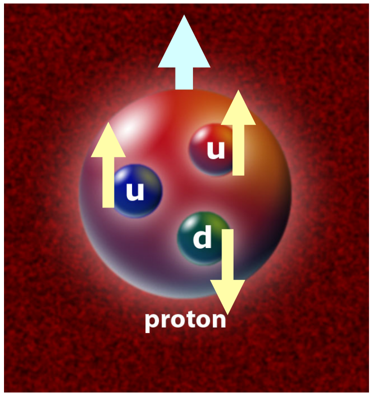
Friedman, Kendall, Taylor: 1960’s SLAC Experiment

***1990 Nobel Prize****: "for their pioneering investigations concerning* ***deep inelastic scattering of electrons on protons and bound neutrons****, which have been of essential importance for the development of the* ***quark model*** *in particle physics"*.

***Obvious next Question:***

Could we understand other properties of proton, e.g. SPIN, in the quark-parton model?

Proton Spin = ½, each quark is a spin ½ particle…



# Structure Functions & PDFs

- The $F_1$ and $F_2$ are unpolarized structure functions or momentum distributions
- The $g_1$ and $g_2$ are polarized structure functions or spin distributions
- In QPM
  - $F_2(x) = 2xF_1$ (Calan Gross relation)
  - $g_2 = 0$ (Twist 3 quark gluon correlations)

$$F_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) + q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 q_f(x)$$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

Remember this

# Nucleon spin & Quark Probabilities

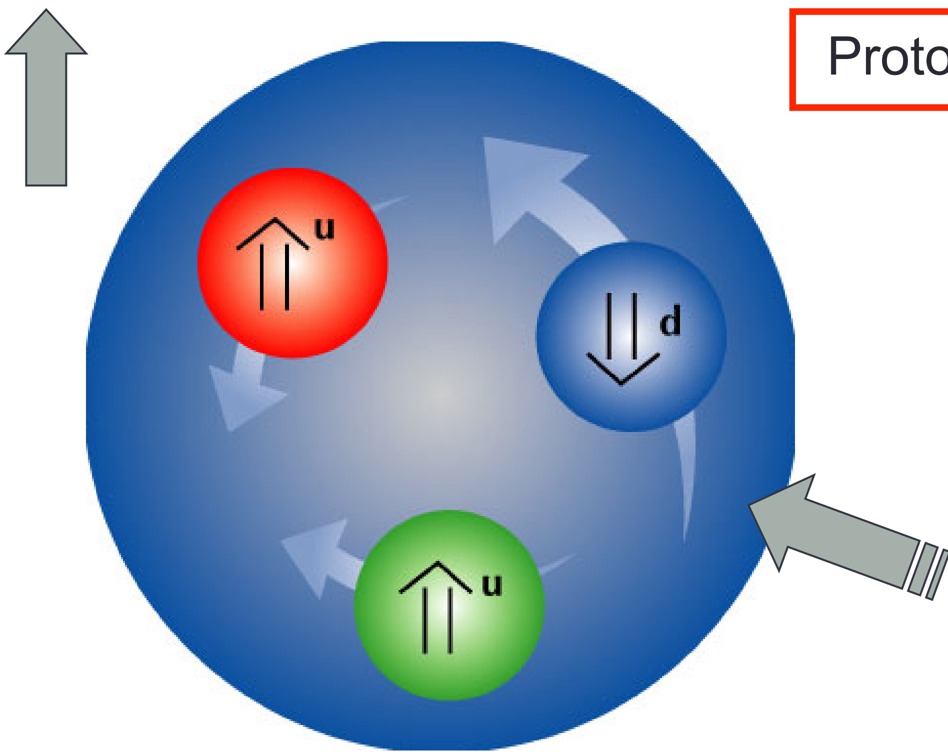
- Define
  $$\Delta q = q^+ - q^-$$
  - With $q^+$ and $q^-$ probabilities of quark & anti-quark with spin parallel and anti-parallel to the nucleon spin
- Total quark contribution then can be written as:
  $$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$
- The nucleon spin composition
  $$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

# Nucleon's Spin: Naïve Quark Parton Model

- Protons and Neutrons are spin 1/2 particles
- Quarks that constitute them are also spin 1/2 particles
  - And there are three of them in the

Proton: u u d

Neutron: u d d



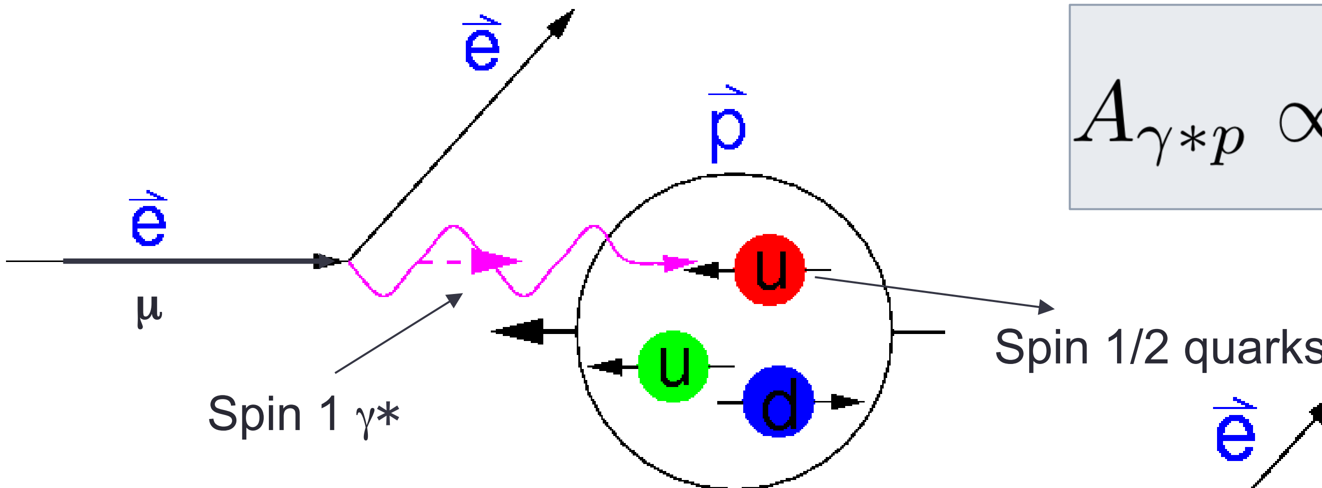

$S_{proton}$ = Sum of all quark spins!

$$1/2 \stackrel{?}{=} 1/2 + 1/2 + 1/2$$

$$1/2 = 1/2 - 1/2 + 1/2$$

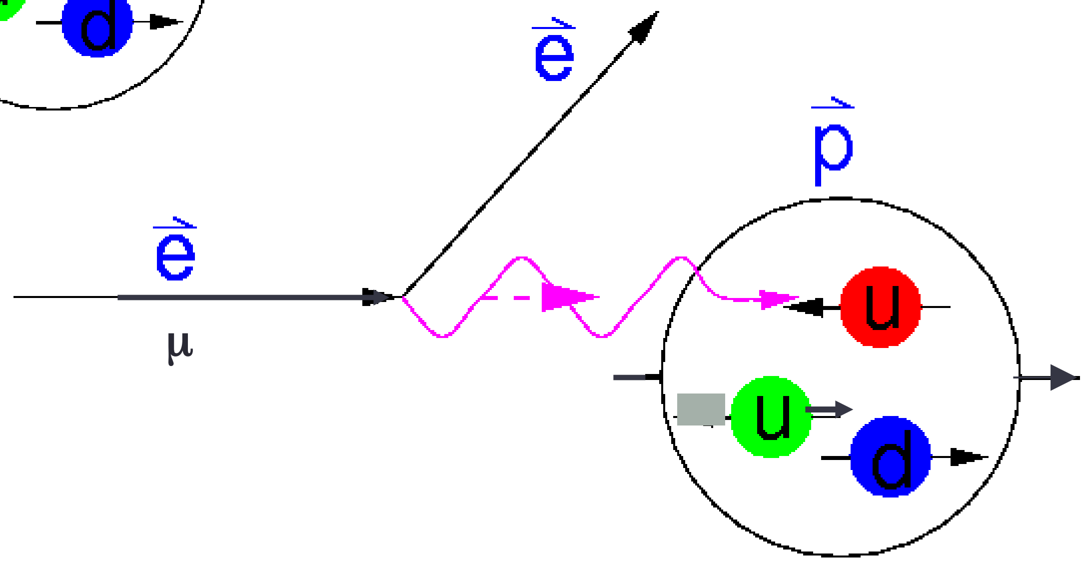
# How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering




$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$

$$\lambda = \frac{\text{Constant}}{p}$$



## Measurements of spin structure functions: What issues we need to worry about?

1) Design of experiments, operational issues
2) Calculations of spin structure functions

# Experimental Needs in DIS

**Polarized target, polarized beam**

- Polarized targets: hydrogen (p), deuteron (pn), helium ($^3$He: 2p+n)
- Polarized beams: electron,muon used in DIS experiments

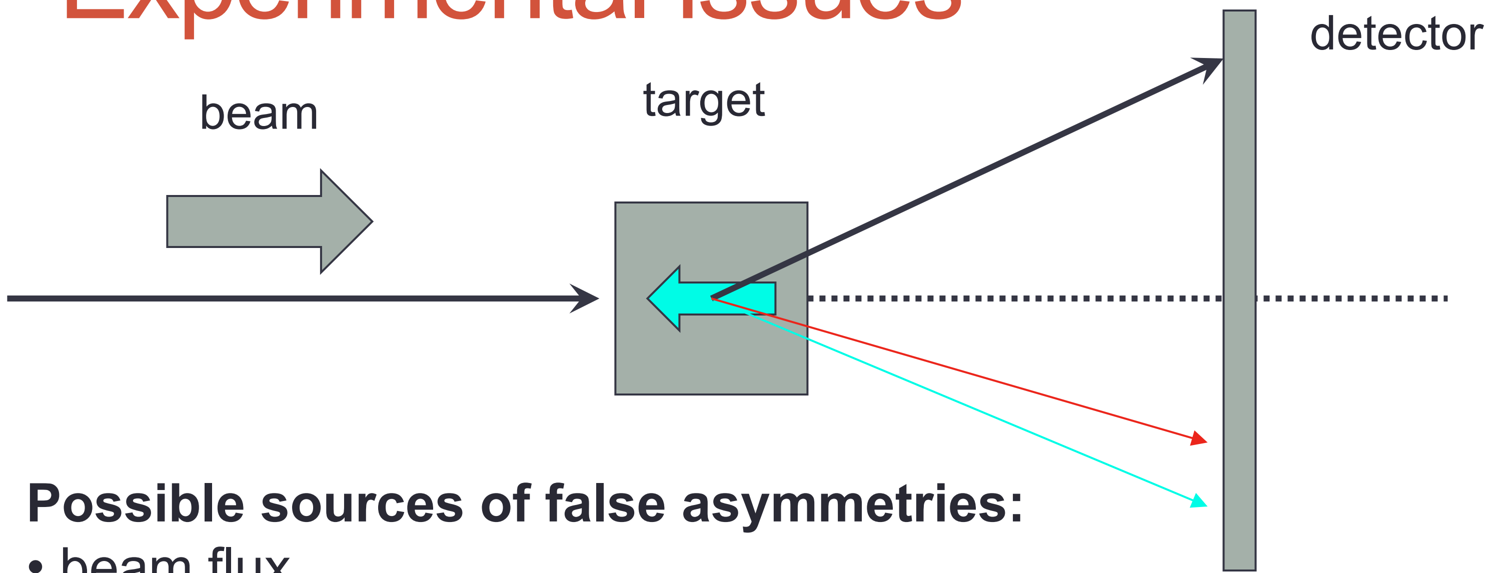
**Determine the kinematics: measure with high accuracy:**

- Energy of **incoming lepton**
- Energy, direction of **scattered lepton**: energy, direction
- Good identification of **scattered lepton**

**Control of false asymmetries:**

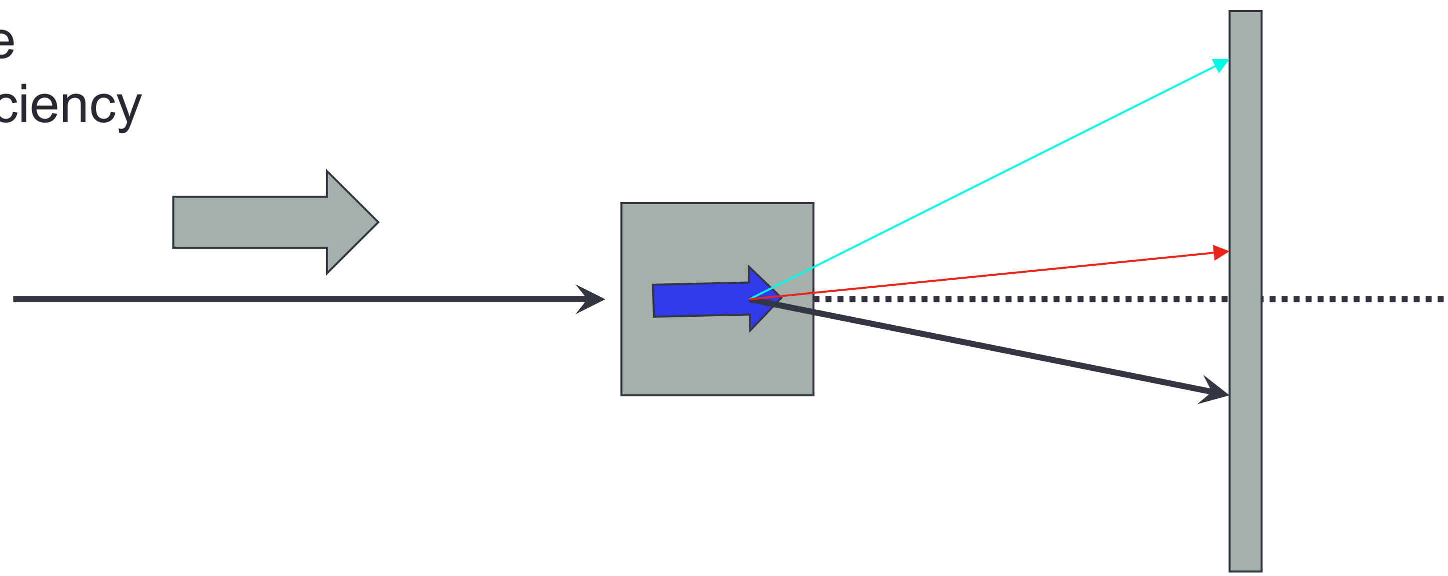
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

# Experimental issues




**Possible sources of false asymmetries:**

- beam flux
- target size
- detector size
- detector efficiency



# An Ideal Situation

$$A_{measured} = \frac{N^{\rightarrow\leftarrow} - N^{\rightarrow\rightarrow}}{N^{\rightarrow\leftarrow} + N^{\rightarrow\rightarrow}}$$

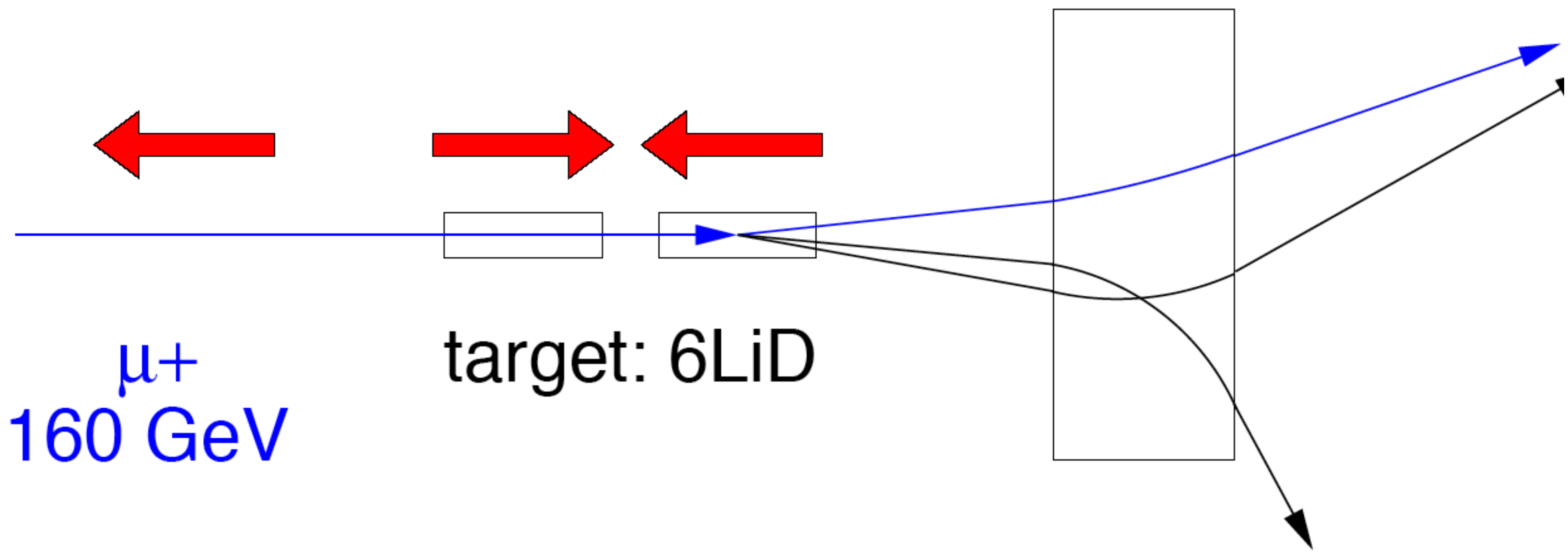
$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

If all other things are equal, they cancel in the ratio and….

$$A_{measured} = \frac{\sigma^{\rightarrow\leftarrow} - \sigma^{\rightarrow\rightarrow}}{\sigma^{\rightarrow\leftarrow} + \sigma^{\rightarrow\rightarrow}}$$

# A Typical Setup




- Target polarization direction reversed every 6-8 hrs
- Typically experiments try to limit false asymmetries to be about 10 times smaller than the physics asymmetry of interest

# Asymmetry Measurement

$$\frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} = A_{measured} = P_{beam} \cdot P_{target} \cdot f \cdot A_{||}$$

- f = dilution factor proportional to the polarizable nucleons of interest in the target "material" used, for example for $NH_3$, f=3/17

$$g_1 \approx \frac{A_{||}}{D} \cdot F_1 \approx \frac{A_{||}}{D} \frac{F_2}{2 \cdot x} \qquad \int_0^1 g_1^p(x, Q_0^2)dx = \Gamma_1^p(Q_0^2)$$

- D is the depolarization factor, kinematics, polarization transfer from polarized lepton to photon, D ~ $y^2$

# First Moments of SPIN SFs

- With $$\Delta q = \int \Delta q(x) dx$$

$$g_1(x) = \frac{1}{2}\Sigma_f e_f^2 \{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

$$= \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3 = g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

$a_3=g_a$: Neutron decay

$a_8$: (3F-D)/3 Hyperon Decay

$a_0$: $\Delta\Sigma$

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}} a_8\right] + \frac{1}{9} a_0$$

# First moment of $g_1^p(x)$ : Ellis-Jaffe SR

$$\Gamma_1^{p,n} = \frac{1}{12}\left[\pm a_3 + \frac{1}{\sqrt{3}}a_8\right] + \frac{1}{9}a_0$$

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025$$

$$a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

Assuming $SU(3)_f$ & $\Delta s = 0$ , Ellis & Jaffe: $\Gamma_1^p = 0.170 \pm 0.004$

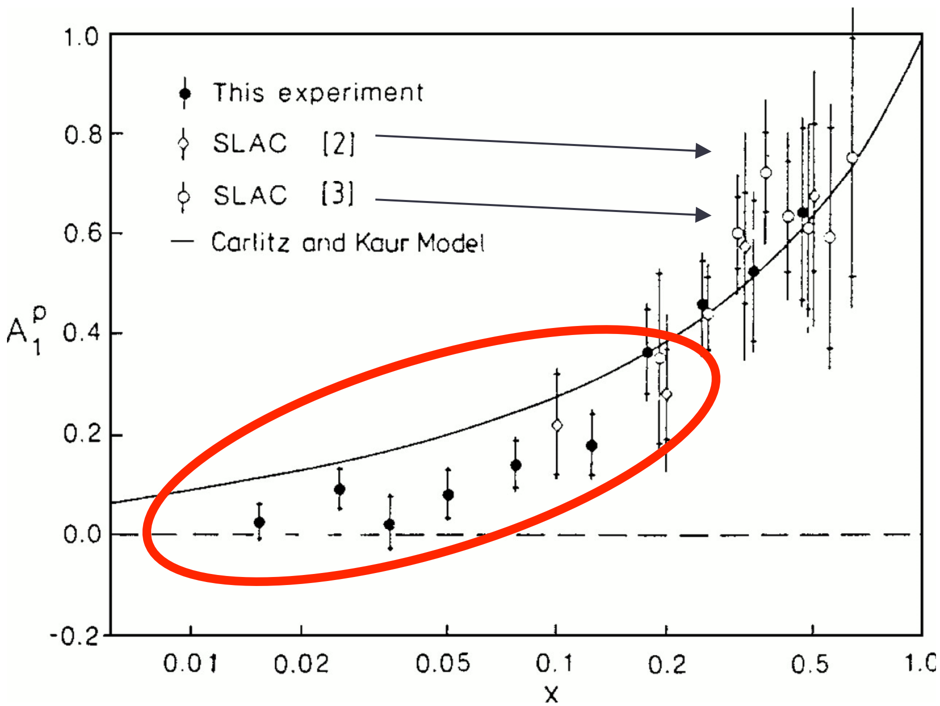
Measurements were done at SLAC (E80, E130) Experiments:

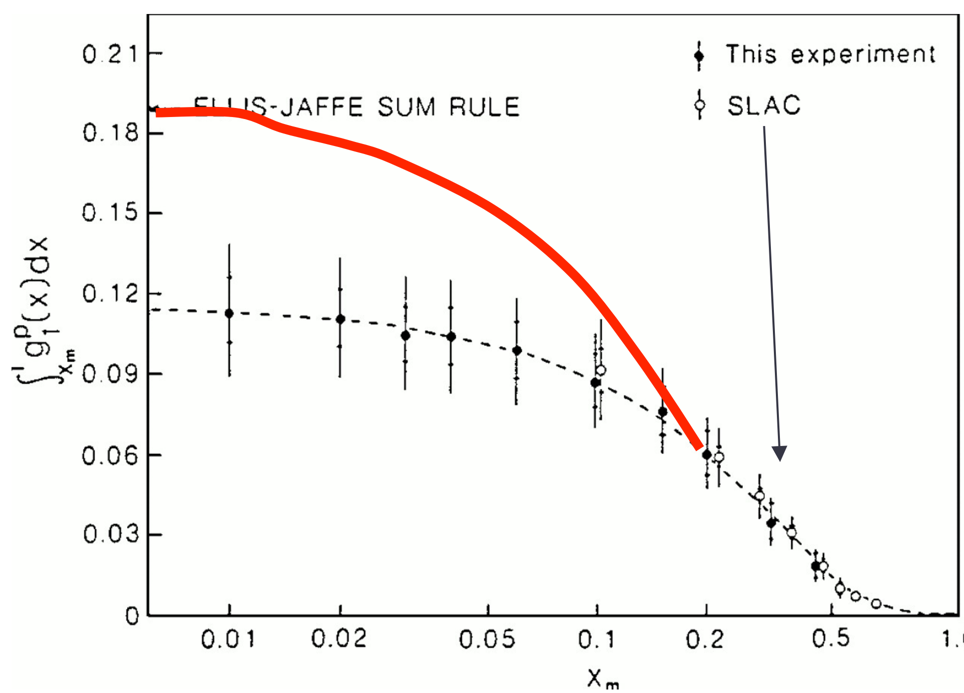
- Low 8-20 GeV electron beam on fixed target
- Did not reach low enough x → $x_{min} \sim 10^{-2}$
- Found consistency of data and E-J sum rule above

# European Muon Collaboration at CERN

- 160 GeV muon beam (lower intensity), but significantly higher energy
- Significantly LOWER X reach → $x_{min} \sim 10^{-3}$
- Polarized target
- Repeated experiment for $A_1$ and measured $g_1$ of the proton!

# Proton Spin Crisis (1989)!



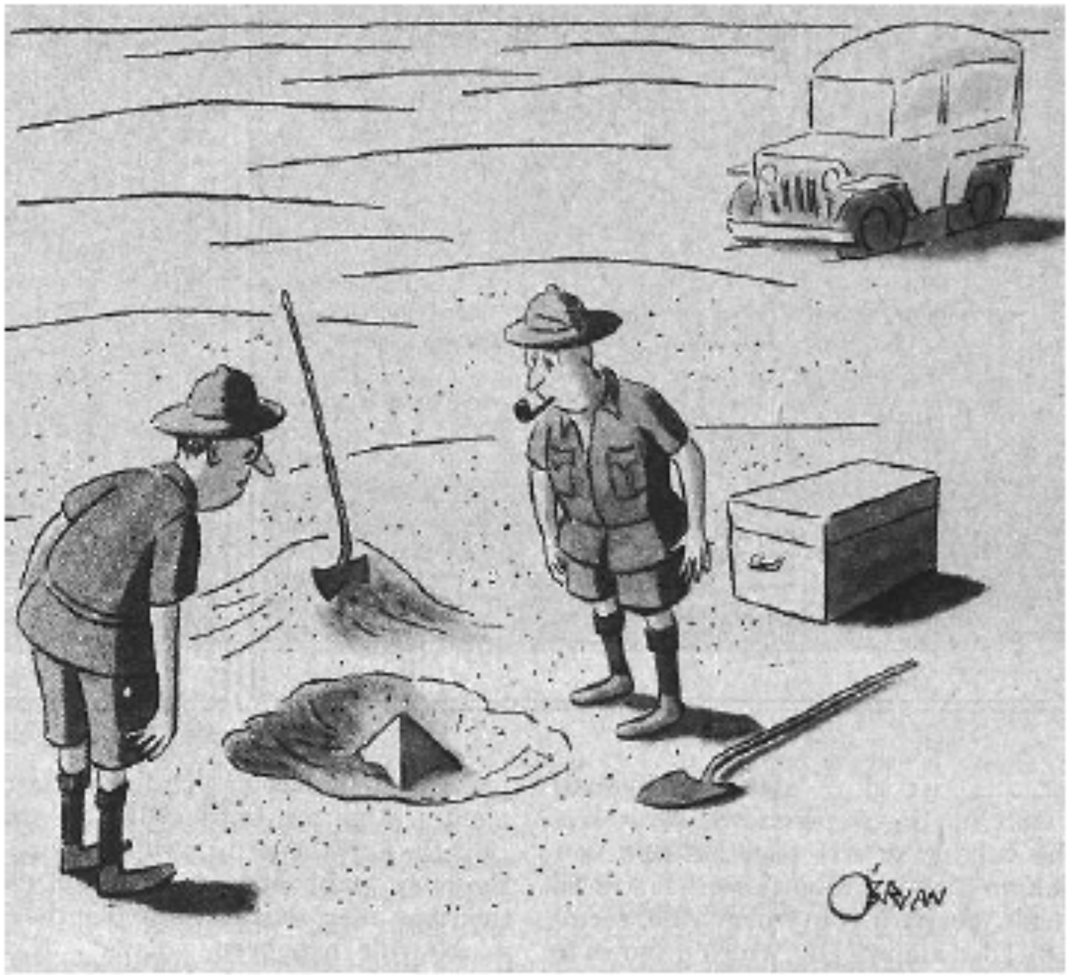




**$\Delta\Sigma$ = (0.12) +/- (0.17) (EMC, 1989)**

Ashman et al., EMC Collaboration, NPB 328 (1989) 1

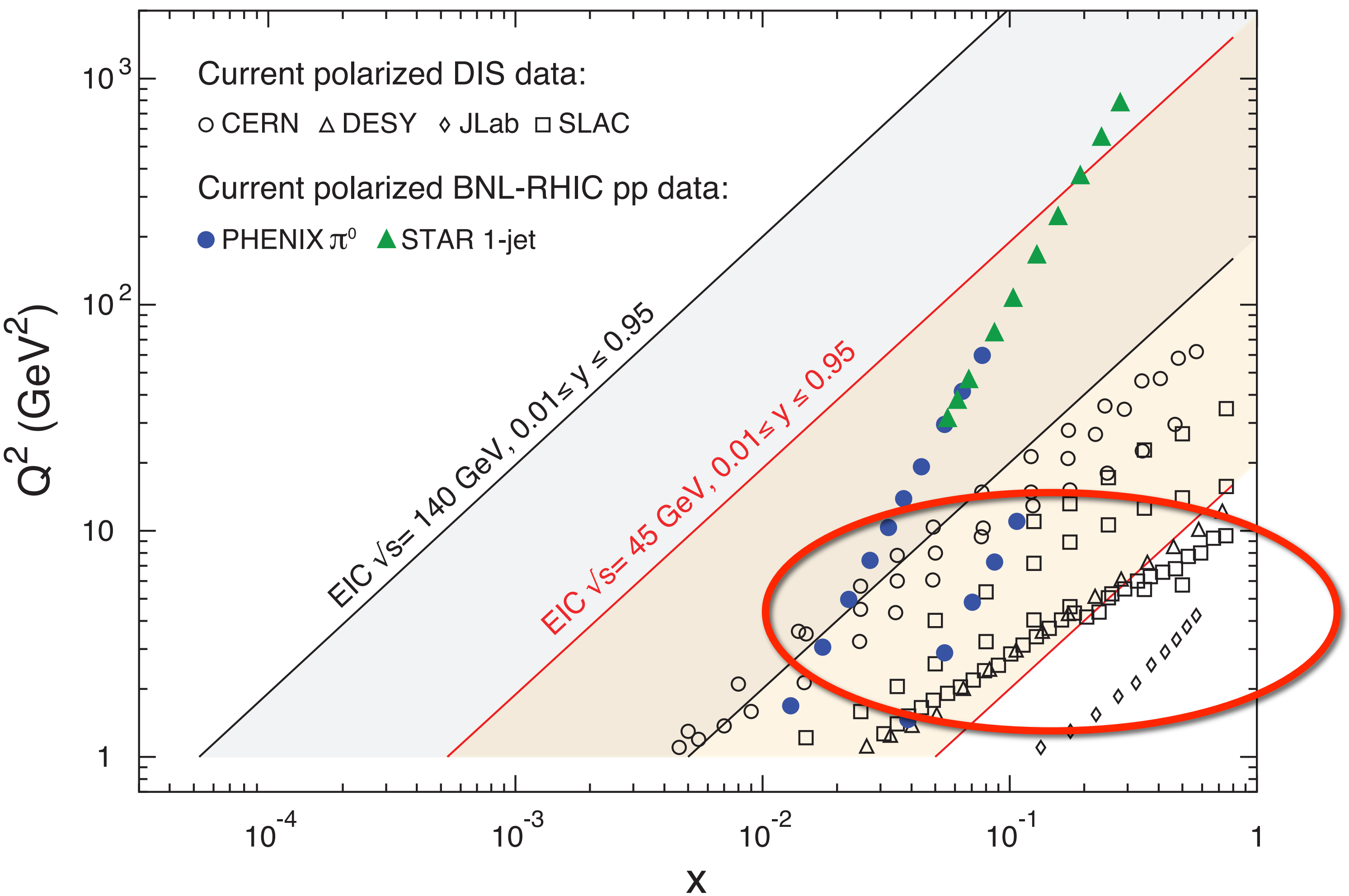
$\Delta\Sigma$ = 0.58 expected from E-J sum rule….

# How significant is this?



*"It could the discovery of the century. Depending, of course on how far below it goes…"*

# Fixed target experiments:



# Extrapolations!

The most simplistic but intuitive theoretical predictions for the polarized deep inelastic scattering are the **sum rules** for the nucleon structure function $g_1$.

$$\Gamma_1(Q^2) = \int_0^1 g_1(x, Q^2)\,dx$$

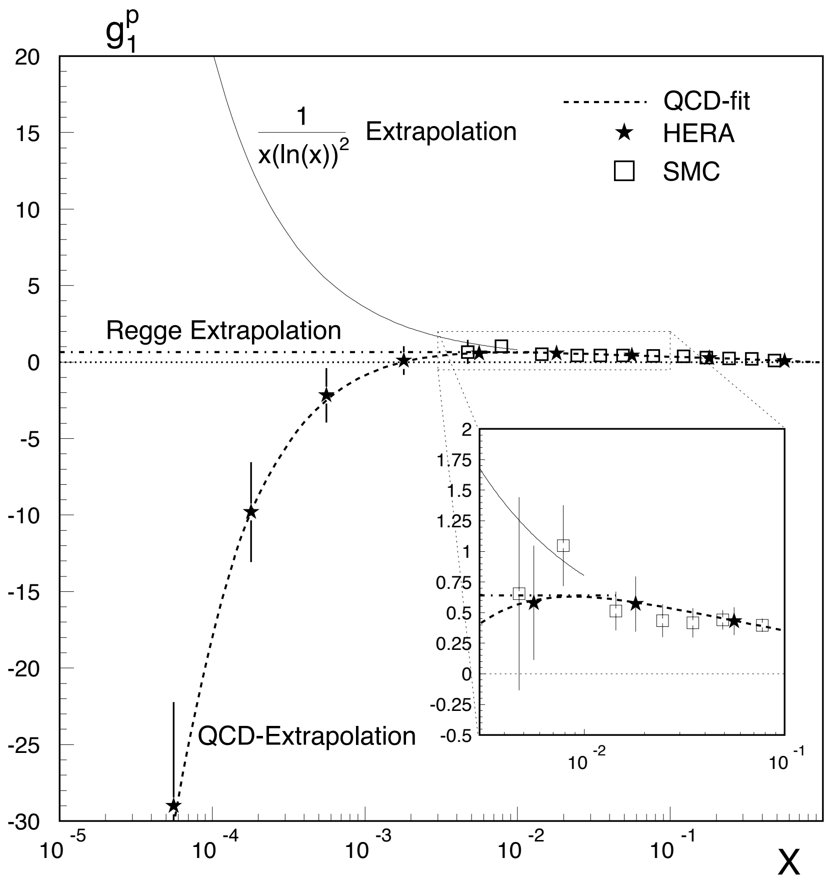
Due to experimental limitations, accessibility of x range is limited, and extrapolations to x= 0 and x = 1 are **unavoidable**.

Extrapolations to x = 1, are *somewhat* less problematic: $|A_1| \leq 1$

- Small contribution to the integral
- Future precisions studies at JLab 12GeV of great interest

Low x behavior of $g_1(x)$ is theoretically not well established hence of significant debate and excitement in the community

# A collection of low x behaviors:




Deshpande, Hughes, Lichtenstadt, HERA low x WS (1999)
Simulated data for polarized e-p scattering shown in the figure.

- Low x behavior all over the place
- No theoretical guidance for which one is correct
- Only logical path is though measurements.
  - Polarized HERA not easy
  - Now being considered in view of the Electron Ion Collider

A. De Roeck, A. Deshpande, V. Hughes, J. Lichtenstadt, G. Radel, EPJ, C6 (1999), 121

# Aftermath of the EMC Spin "Crisis"

Naïve quark model yields: $\Delta u = 4/3 \text{ and } \Delta d = -1/3 \Longrightarrow \Delta\Sigma = 1$

Relativistic effects included quark model: $\Delta\Sigma = 0.6$

After much discussions, arguments an idea that became emergent, although not without controversy: "gluon anomaly"

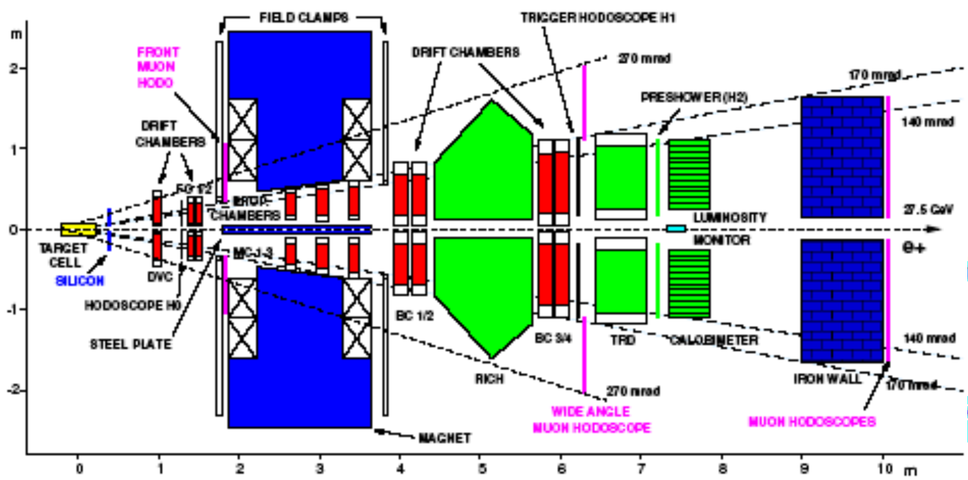
- True quark spin is screened by large gluon spin: Altarelli, Ross; Carlitz, Collins; Mueller et al.

$$\Delta\Sigma(Q^2) = \Delta\Sigma' - N_f \frac{\alpha_S(Q^2)}{2\pi} \Delta g(Q^2$$

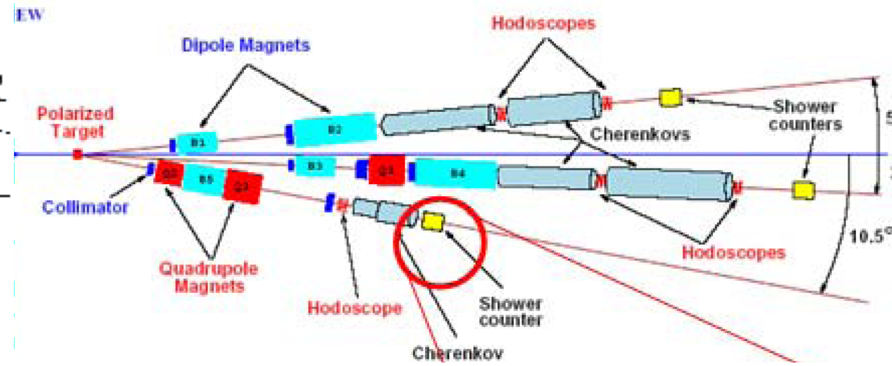
- But there were strong alternative scenarios proposed that blamed the remaining spin of the proton on: Jaffe, Manohar; Ji et al
  - Gluon spin (same as above)
  - Orbital motion of quarks and gluons (OAM)

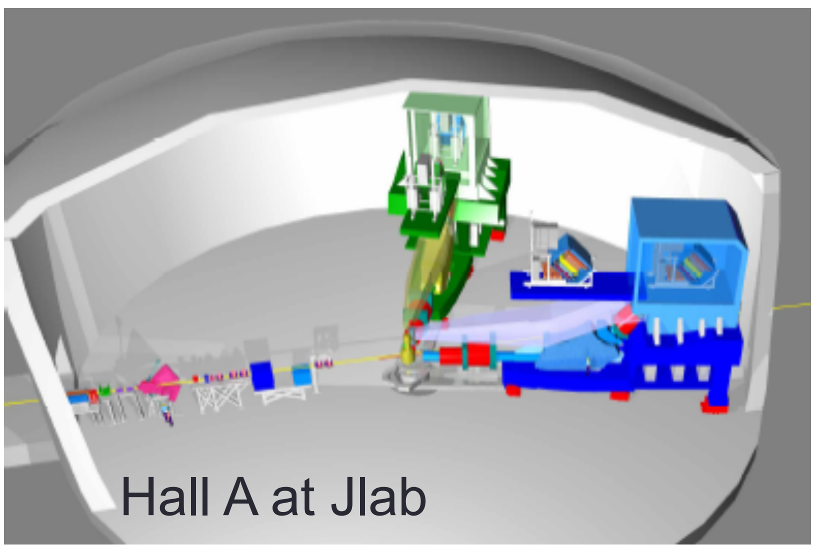
**It became clear that precision measurements of nucleon spin constitution was needed!**

# Experiments




HERMES at DESY



Hall A at Jlab

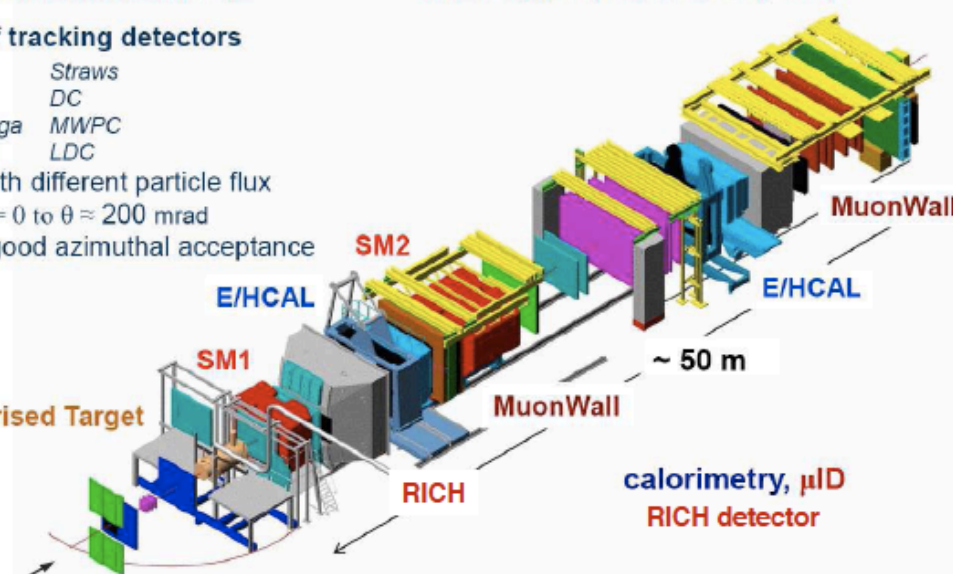
- high energy beams
- large angular acceptance
- broad kinematical range

two stages spectrometer
Large Angle Spectrometer (SM1)
Small Angle Spectrometer (SM2)

variety of tracking detectors

| | |
|---|---|
| *SciFi* | *Straws* |
| *Silicon* | *DC* |
| *Micromega* | *MWPC* |
| *(P)GEM* | *LDC* |

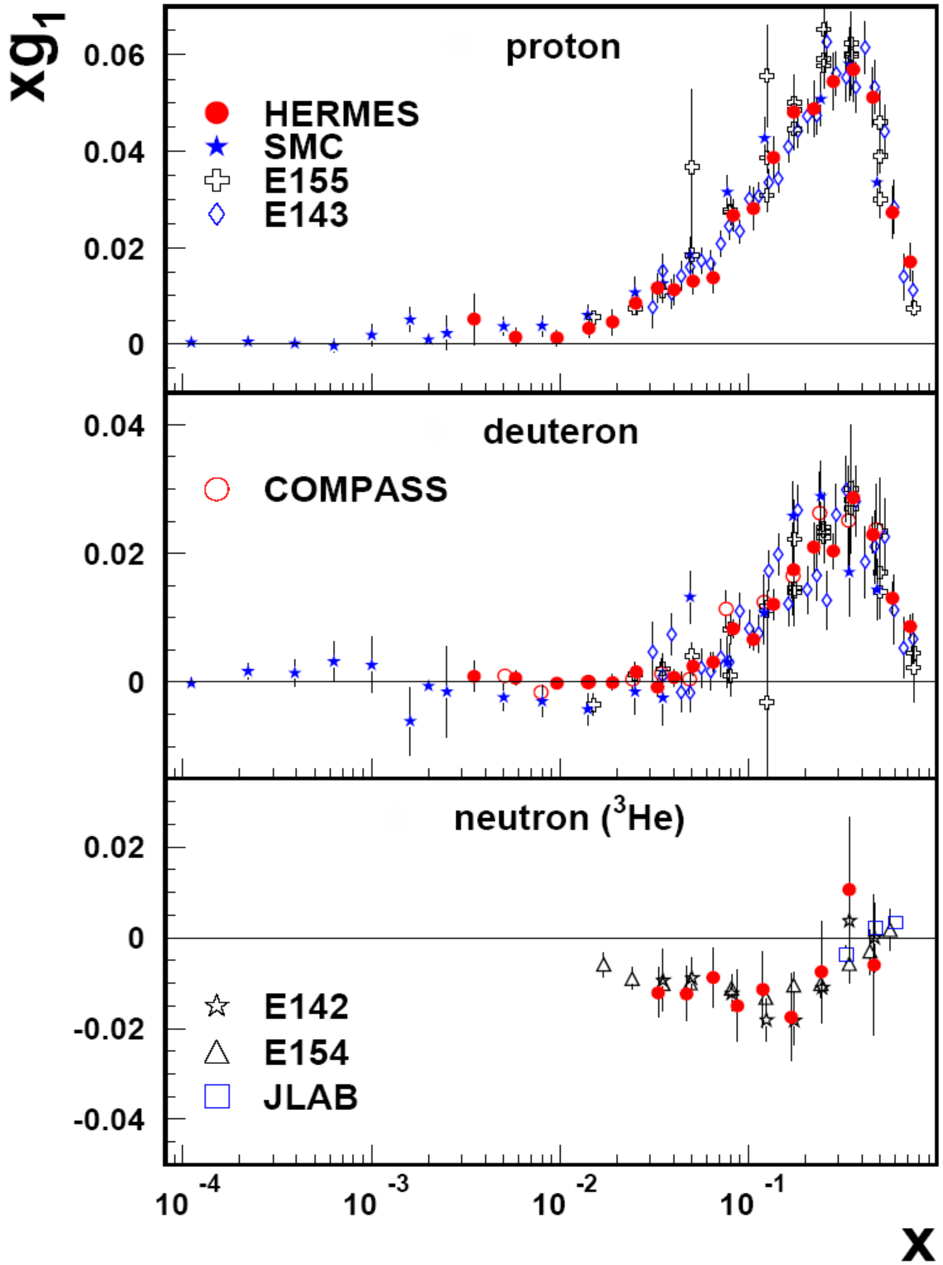
to cope with different particle flux
from $\theta = 0$ to $\theta \approx 200$ mrad
with a good azimuthal acceptance

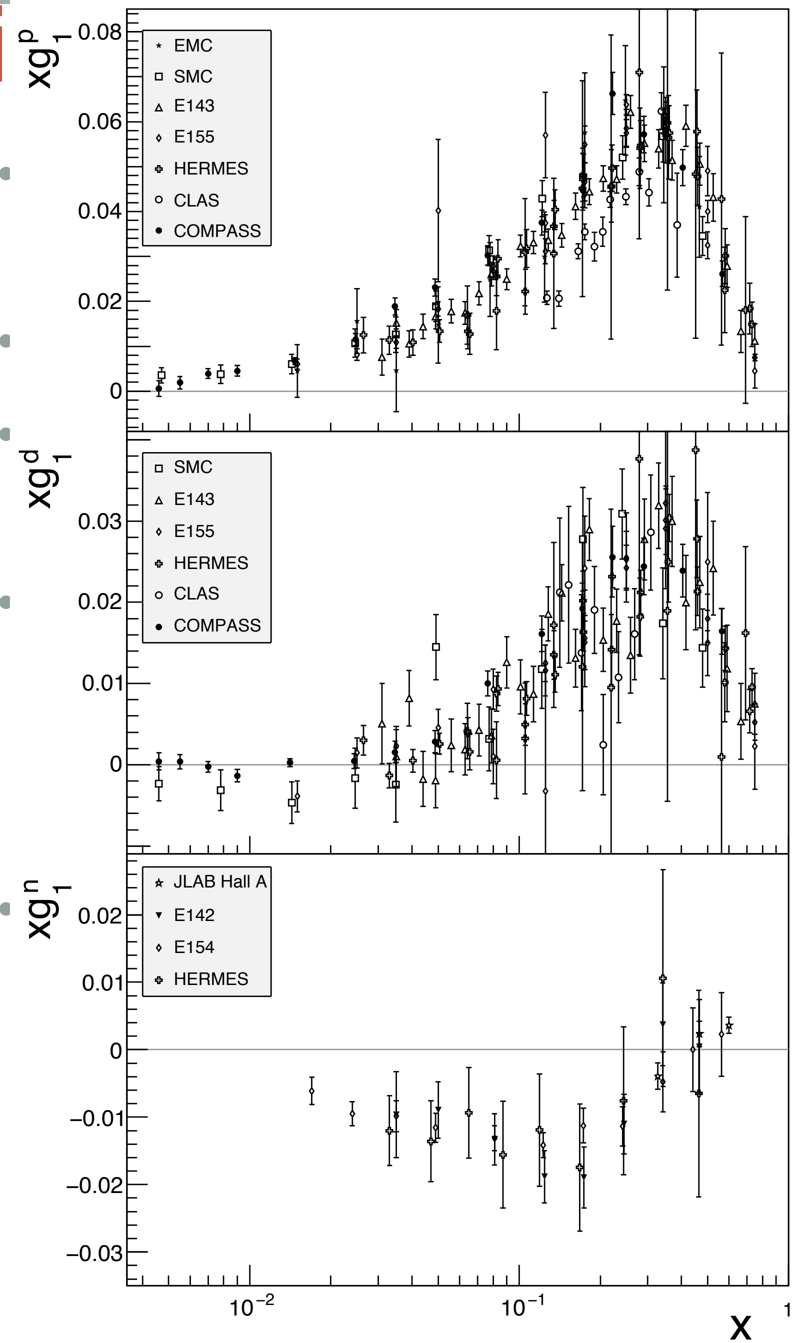



µ beam

SMC,COMPASS at CERN

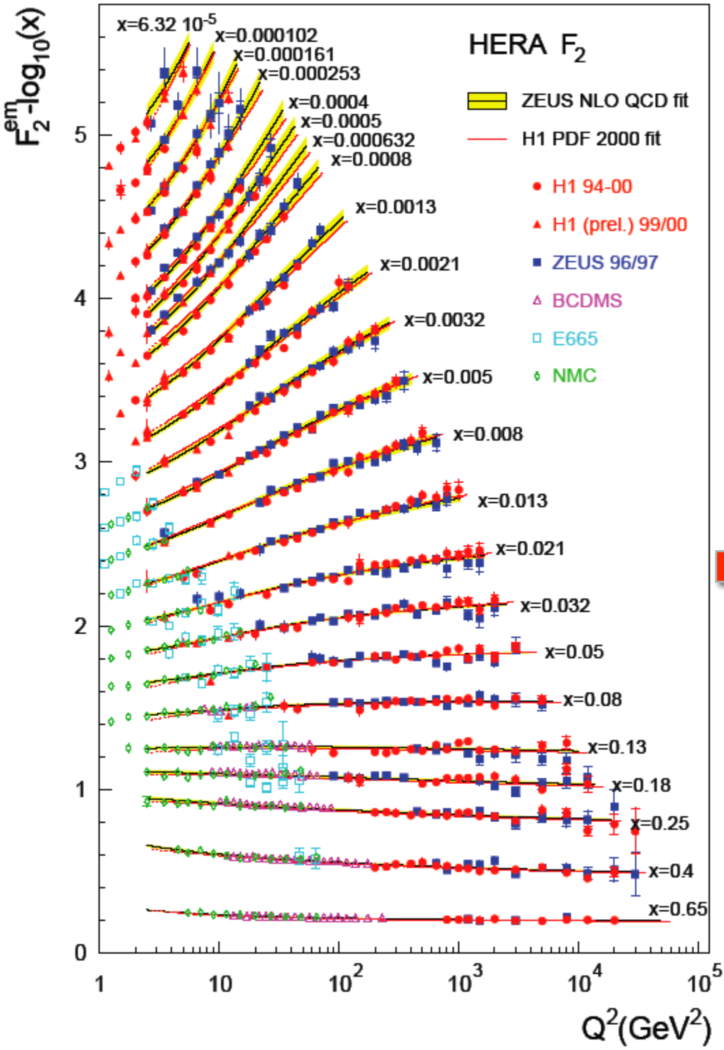
# Spin structure Functi



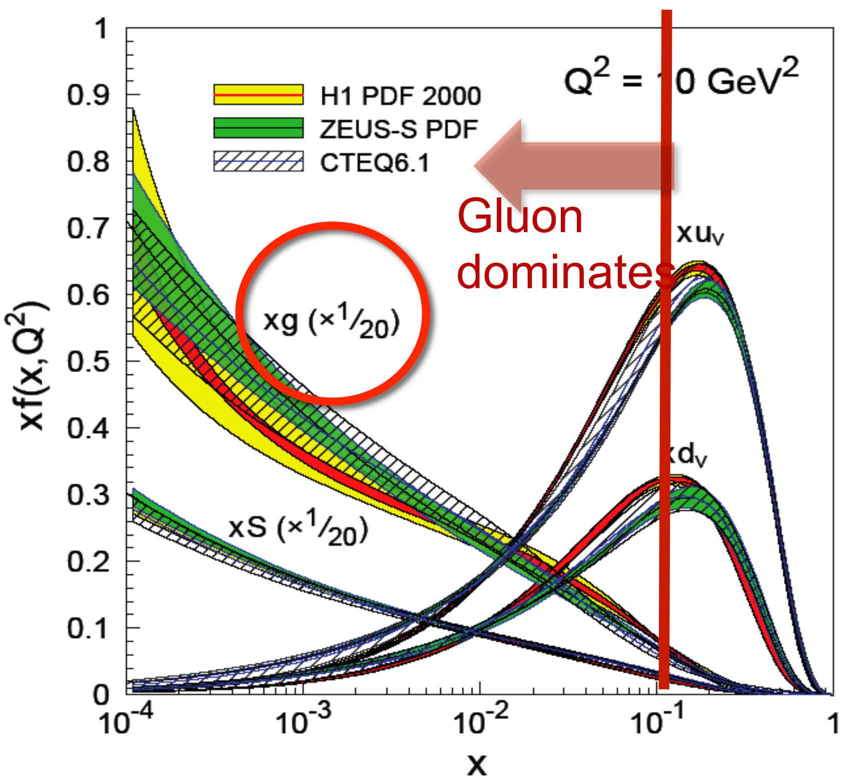



# How to extract the polarized gluon distribution?

# Similar to extraction of PDFs at HERA (RECALL)



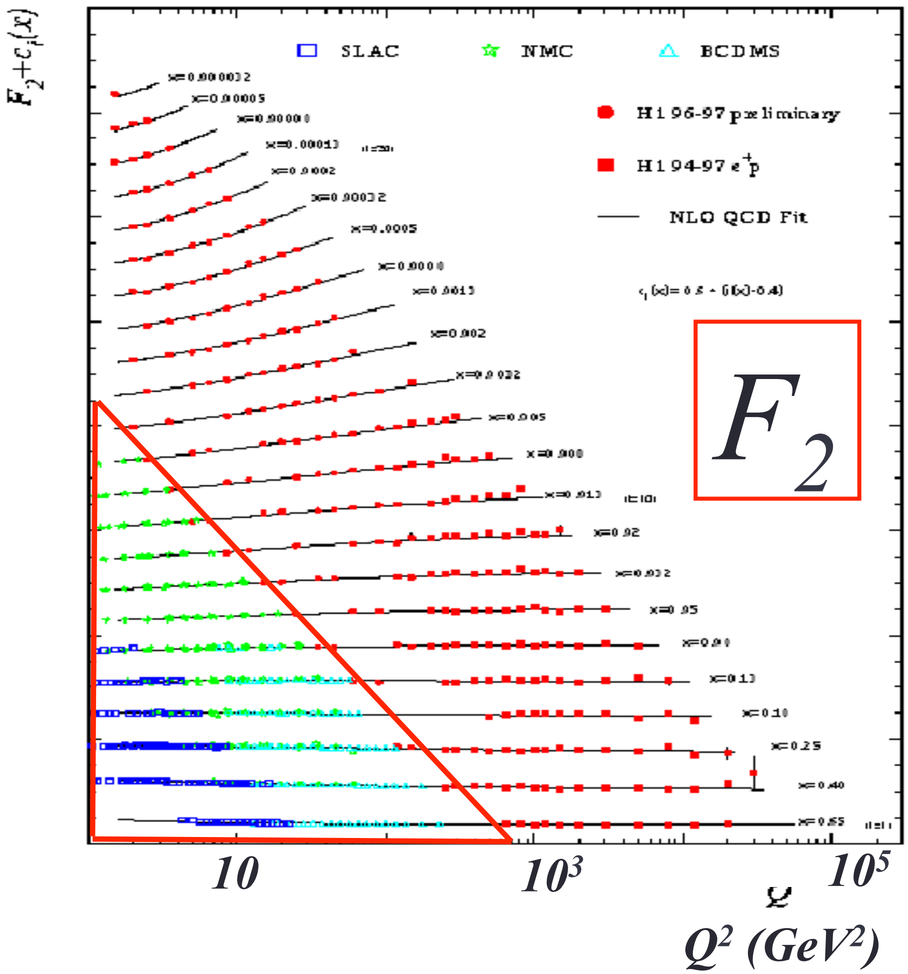

NLO pQCD analyses: fits with **linear** DGLAP* equations

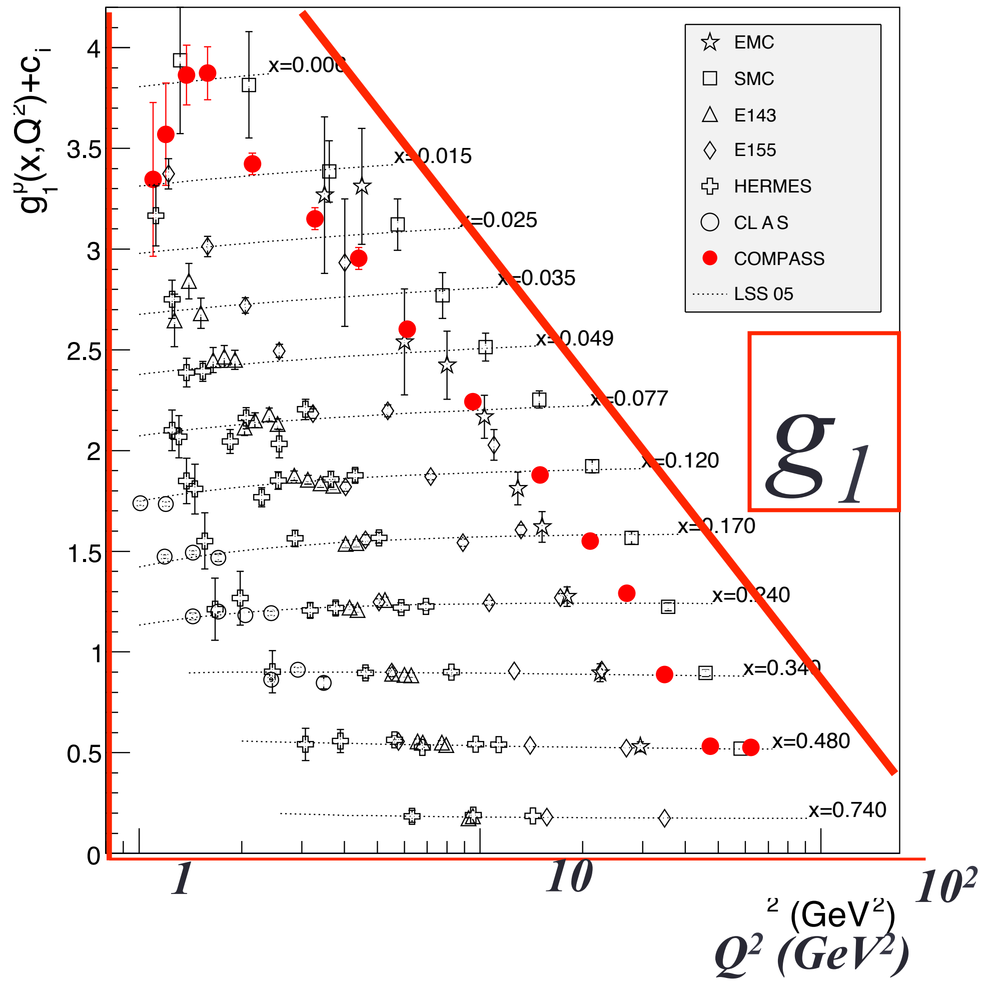



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

# $F_2$ vs. $g_1$ structure function measurements

Aidala et al.1209.2803v2

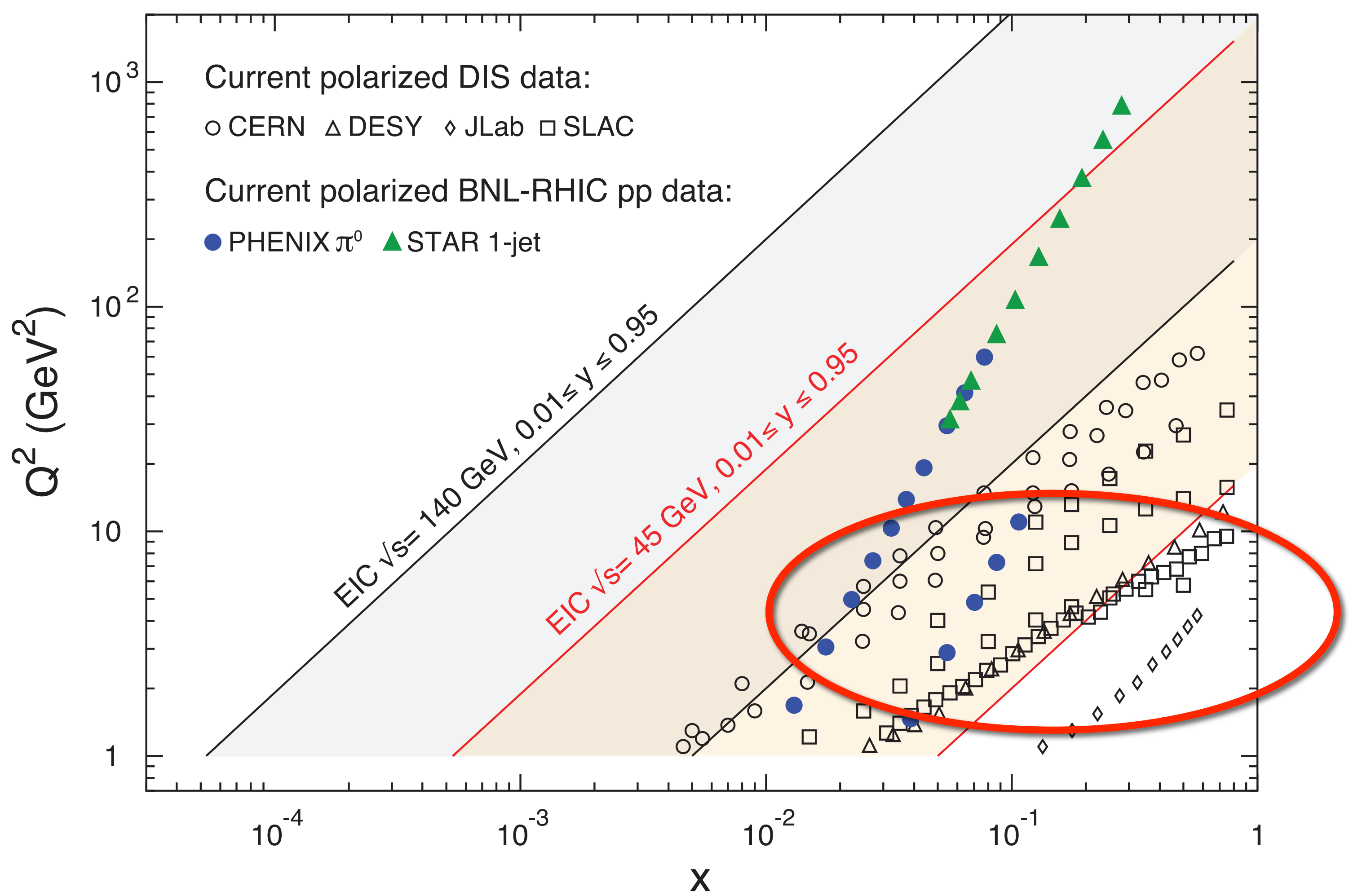



Large amount of polarized data since 1998… but not in NEW kinematic region!

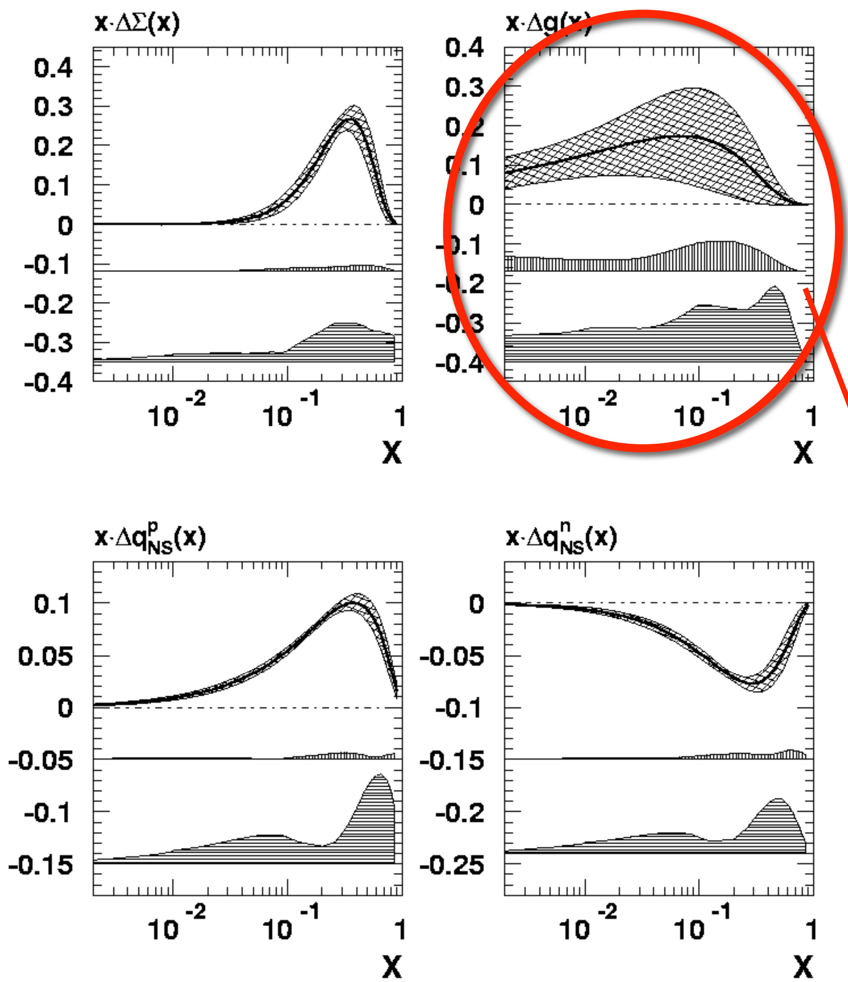
***Large uncertainty in gluon polarization (+/-1.5) results from lack of wide $Q^2$ arm***

# Fixed target experiments:



# Global analysis of Spin SF

SMC PRD 58 112002 (1998)

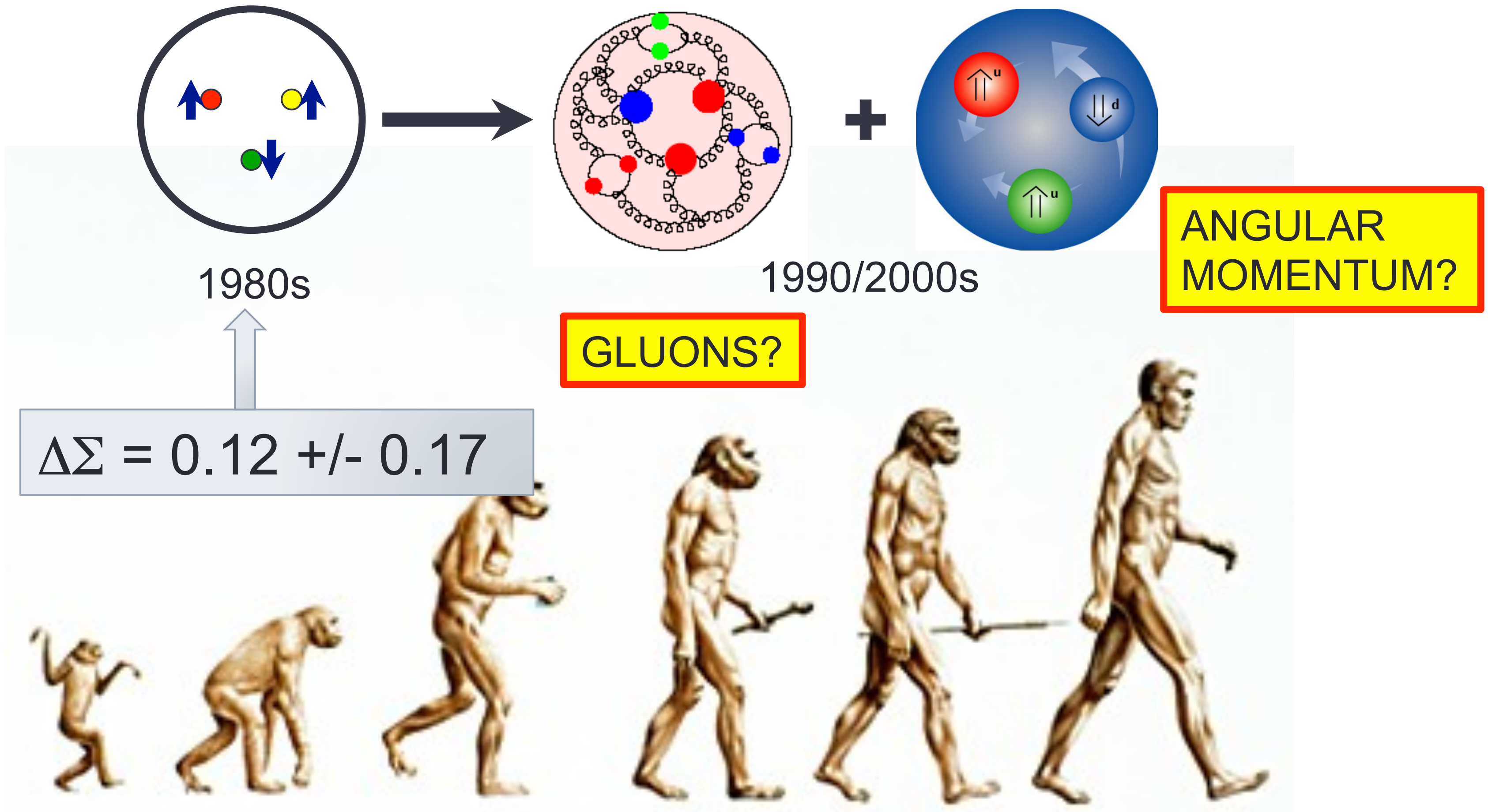



- World's all available $g_1$ data
- Coefficient and splitting functions in QCD at NLO
- Evolution equations: DGLAP

$$f(x) = x^{\alpha}(1-x)^{\beta}(1+ax+bx^2)$$

- Quark distributions fairly well determined, with small uncertainty
  - $\Delta\Sigma$ = 0.23 +/- 0.04
- Polarized Gluon distribution has largest uncertainties
  - $\Delta G$ = 1 +/- 1.5

# Evolution: Our Understanding of Nucleon Spin




Spin Crisis for the prevailing models …. But their limitations were quickly appreciated and discussed....

# Limitations of fixed target experiments:

- Kinematics of fixed target experiments: Does not allow exploration of low-x region
- Extraction of gluon polarization needed large $Q^2$ arm, and fixed target experiments did not allow that either….

- In 1990's ideas to achieve high energy polarized proton beams evolved… Siberian Snake Magnets
- High energy polarized proton beam polarimetry was developed as a future need…

- Ideally we needed a polarized e-p collider to overcome this, but non was under consideration! (although polarized HERA was proposed but failed)

NEED FOR A POLARIZED COLLIDER WAS UNDERSTOOD, TO MEASURE THE EXPECTED LARGE GLUON POLARIZATION

HOWEVER NO PLANS EXISTED FOR SUCH A COLLIDEER.

RHIC: RELATIVISTIC HEAVY ION COLLIDER WAS BEING PLANNED FOR THE INVESTIGATIONS OF QUARK GLUON PLASMA (AT BNL)

THE JAPANESE (RIKEN INSTITUTE) JUMPED IN WITH T.D. LEE AND DIR. SAMIOS, TO INSTALL SIBERIAN SNAKE MAGNETS AND SPIN ROTATOR MAGNETS TO ENABLE POLARIZED PROTON COLLISIONS IN RHIC.

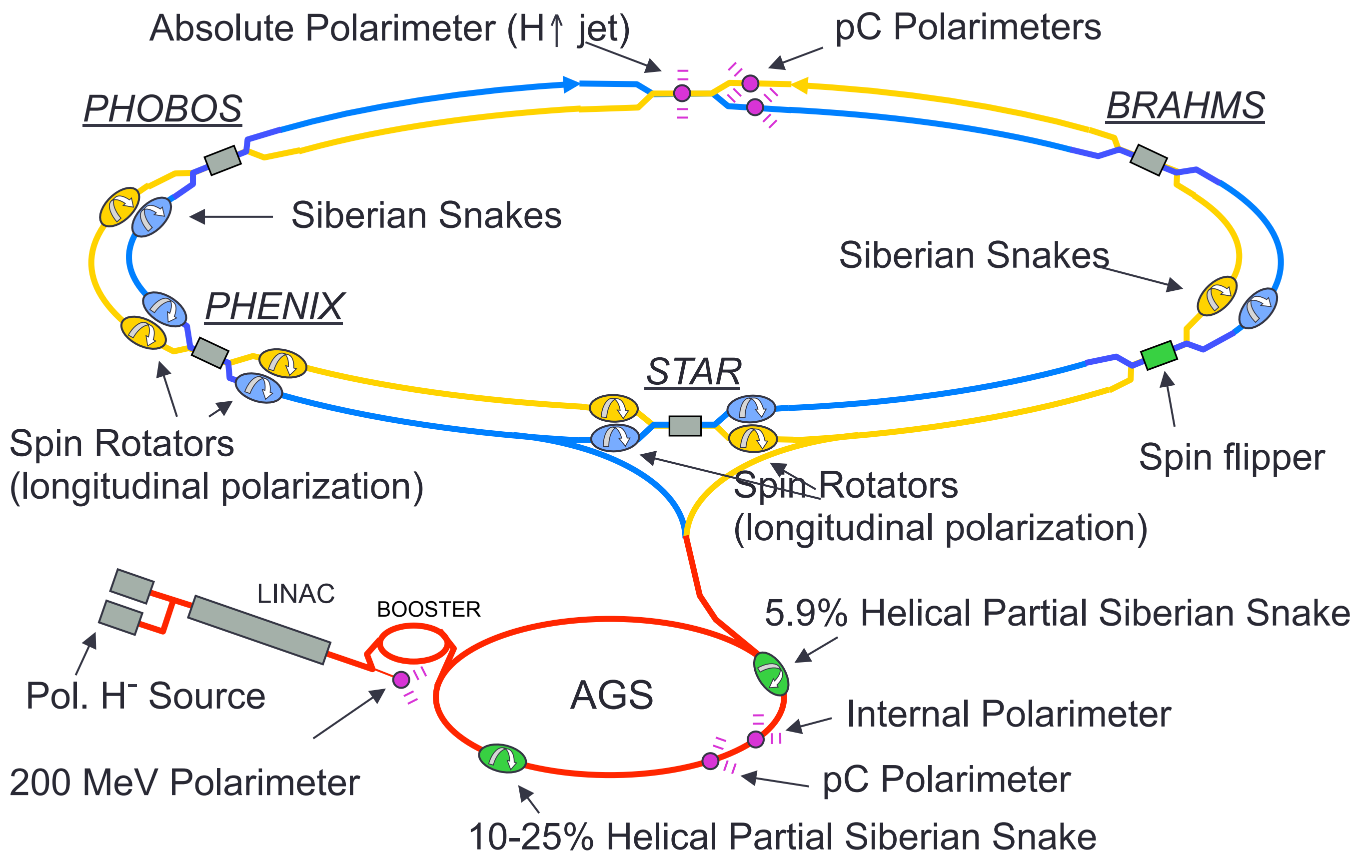
# Motivation for RHIC Spin:

- If gluons really carry the bulk of nucleon's spin, why not use polarized proton (known by then to be predominantly made of gluons!)?
  - Technical know-how (Siberian Snakes, Spin Rotators, polarimetry ideas) to do this at high energy evolved around the time (mid/late-1990s)

- Why $\Delta\Sigma$ (quark + anti-quark's spin) small? Are quark and anti-quark spins anti-aligned? Polarized *p*+p at high energy, through W+/- production could address this

- A severe need for investigations of the surprising transverse spin effects was naturally possible and needed with the proposed polarized p+p collider…

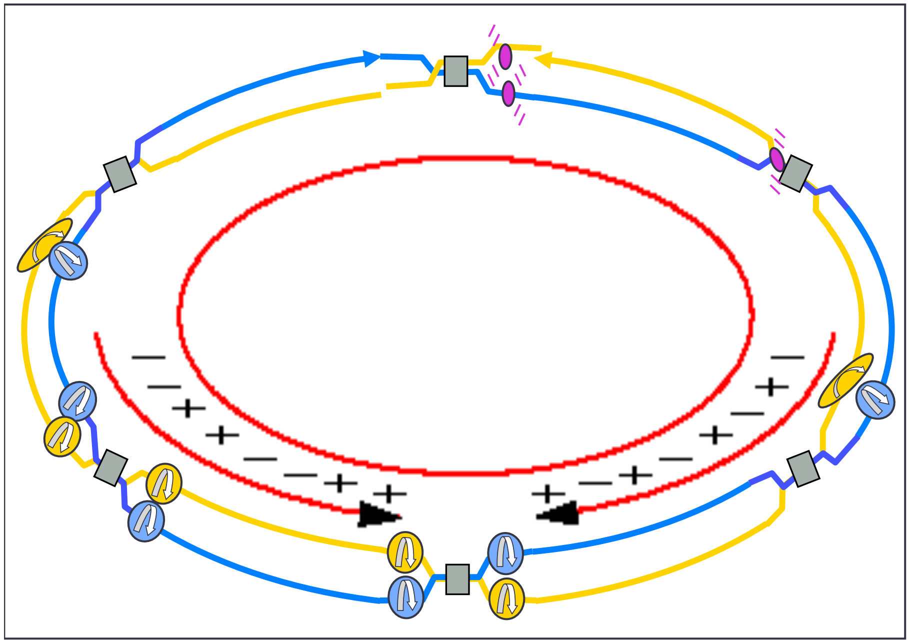
# RHIC as a Polarized Proton Collider




Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180$^{\circ}$ spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11$^{\circ}$ and 27$^{\circ}$ spin rotators) in AGS

# Measuring $A_{LL}$

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



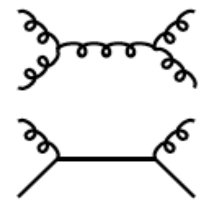
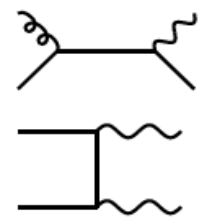
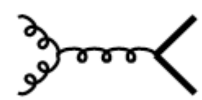
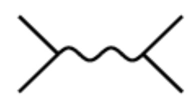
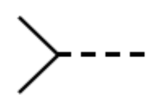
(N) Yield
(R) Relative Luminosity
(P) Polarization

Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

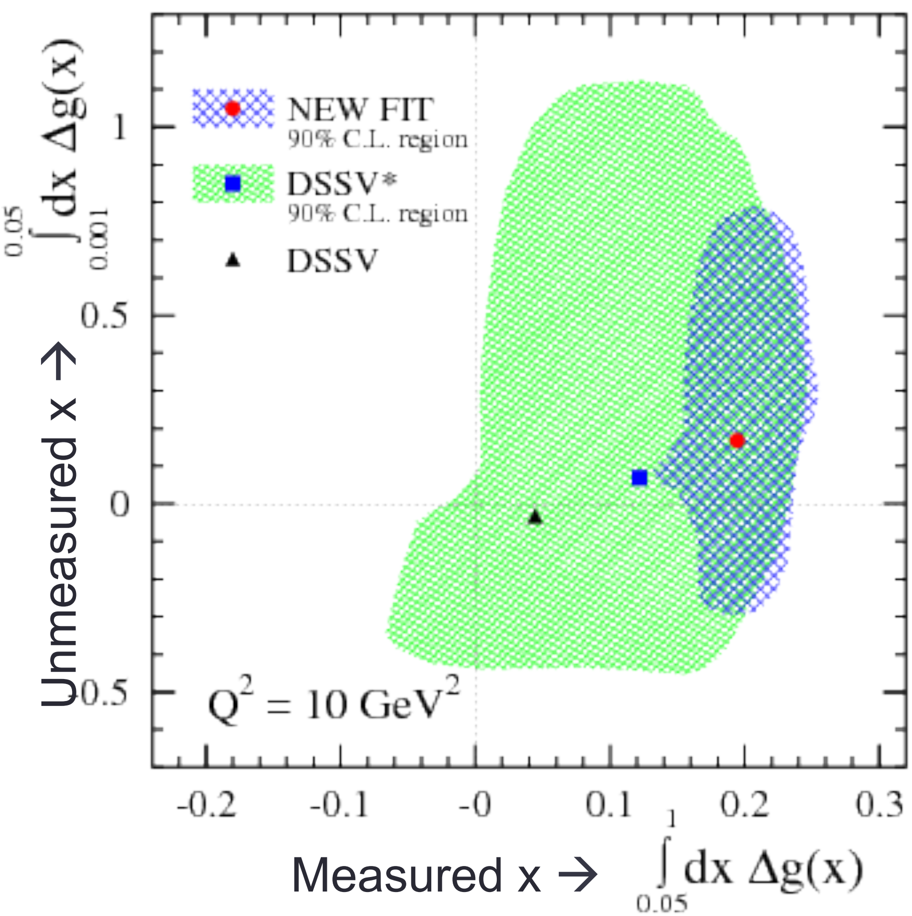
- ✓ Bunch spin configuration alternates every 106 ns
- ✓ Data for all bunch spin configurations are collected at the same time

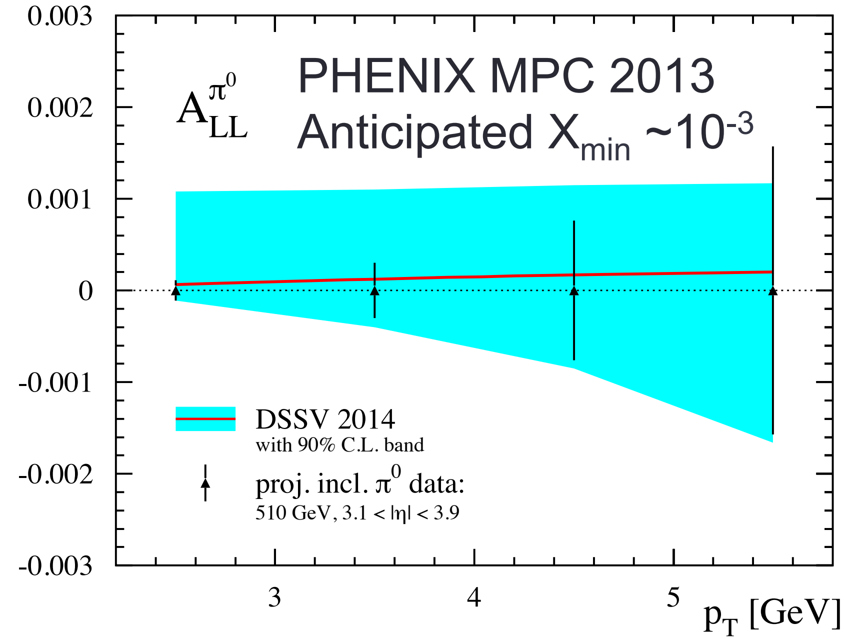
⇒ Possibility for false asymmetries are greatly reduced

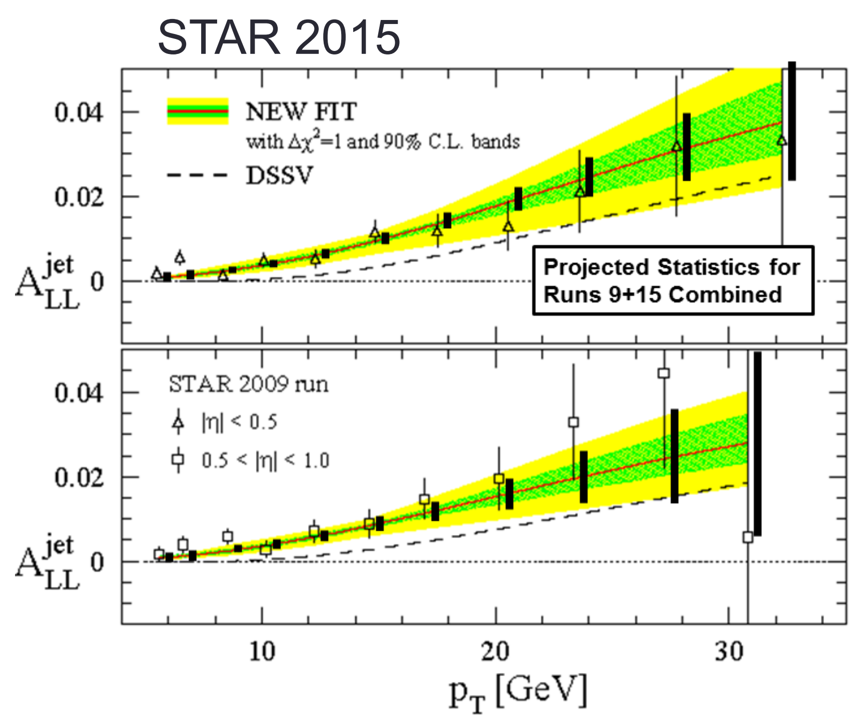
# The probes and techniques at RHIC

| Reaction | Dom. partonic process | probes | LO Feynman diagram |
|---|---|---|---|
| $\vec{p}\vec{p} \to \pi + X$ | $\vec{g}\vec{g} \to gg$<br>$\vec{q}\vec{g} \to qg$ | $\Delta g$ |  |
| $\vec{p}\vec{p} \to \text{jet(s)} + X$ | $\vec{g}\vec{g} \to gg$<br>$\vec{q}\vec{g} \to qg$ | $\Delta g$ | (as above) |
| $\vec{p}\vec{p} \to \gamma + X$<br>$\vec{p}\vec{p} \to \gamma + \text{jet} + X$<br>$\vec{p}\vec{p} \to \gamma\gamma + X$ | $\vec{q}\vec{g} \to \gamma q$<br>$\vec{q}\vec{g} \to \gamma q$<br>$\vec{q}\vec{\bar{q}} \to \gamma\gamma$ | $\Delta g$<br>$\Delta g$<br>$\Delta q, \Delta\bar{q}$ |  |
| $\vec{p}\vec{p} \to DX, BX$ | $\vec{g}\vec{g} \to c\bar{c}, b\bar{b}$ | $\Delta g$ |  |
| $\vec{p}\vec{p} \to \mu^+\mu^- X$<br>(Drell-Yan) | $\vec{q}\vec{\bar{q}} \to \gamma^* \to \mu^+\mu^-$ | $\Delta q, \Delta\bar{q}$ |  |
| $\vec{p}\vec{p} \to (Z^0, W^\pm)X$<br>$p\vec{p} \to (Z^0, W^\pm)X$ | $\vec{q}\vec{\bar{q}} \to Z^0,\ \vec{q}'\vec{\bar{q}} \to W^\pm$<br>$\vec{q}'\bar{q} \to W^\pm,\ q'\vec{\bar{q}} \to W^\pm$ | $\Delta q, \Delta\bar{q}$ |  |

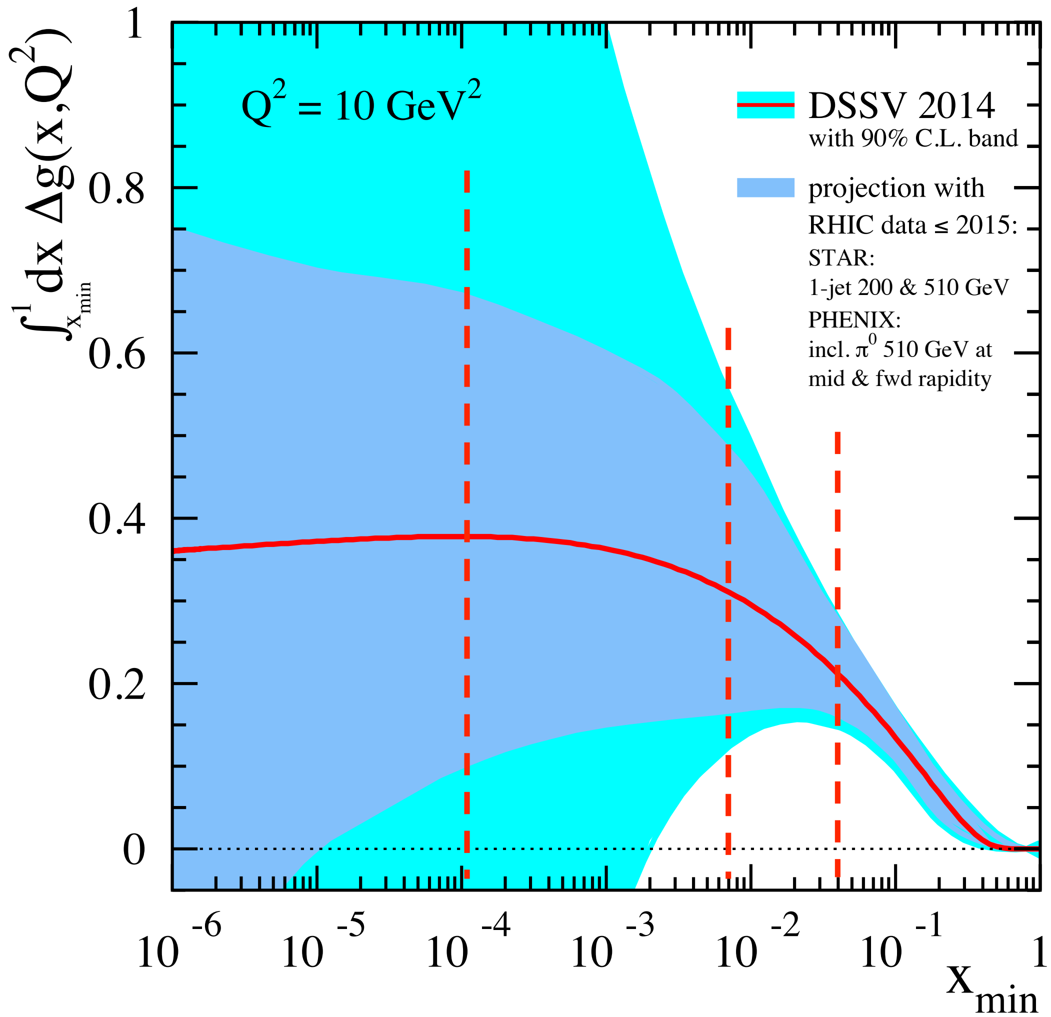
# Δg @ RHIC Current status: 0.05 < x < 0.2



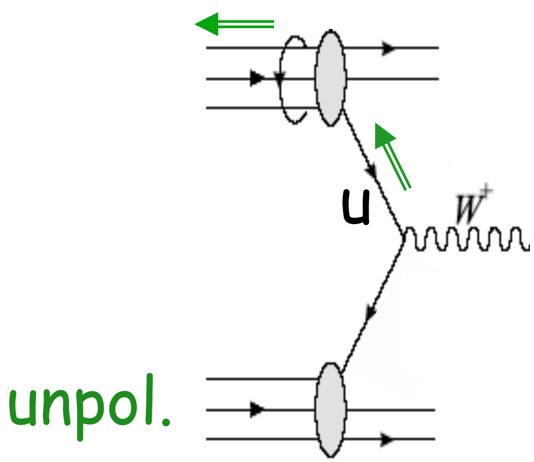



# RHIC's limit… no/limited handle on low-x




RHIC Spin
White Paper (2015)
For NSAC LRP

# Anti-Quark Polarization measurement via W production and decay



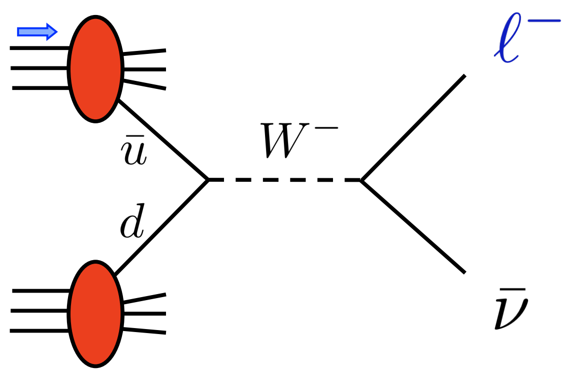

$$\sqrt{s} = 500 \text{ GeV}$$

- Large parity violating effect anticipated

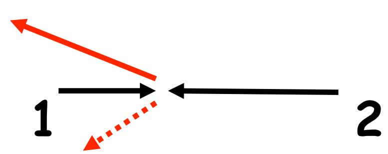
$$A_L = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \neq 0$$

- Measurement complimentary to SIDIS, but devoid of fragmentation function makes it cleaner!
- NLO analyses about now available

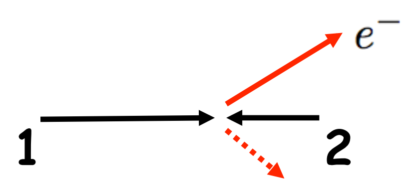
# Some insight in to what goes on….




$$\sigma^{W^-} \propto \bar{u}(x_1)\, d(x_2) \qquad + \; d(x_1)\, \bar{u}(x_2)$$



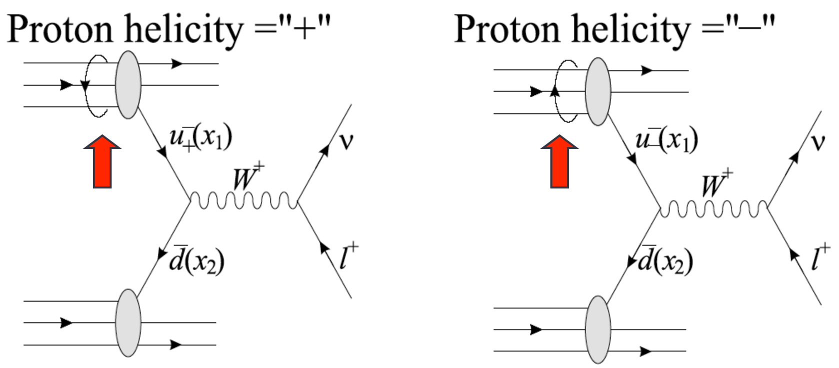

$\bar{u}(x_1)\, d(x_2)$



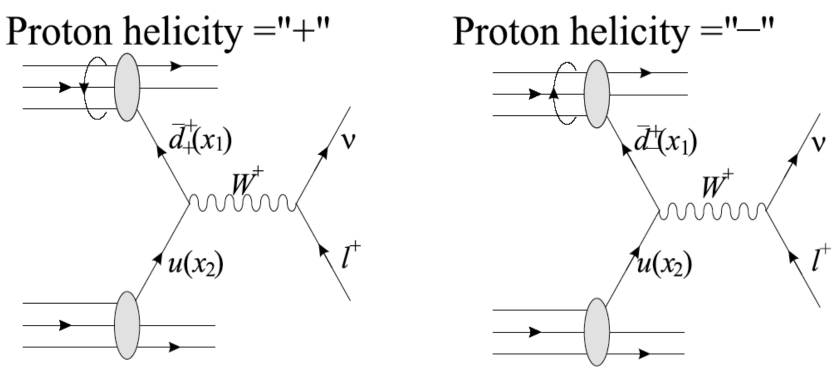

$d(x_1)\, \bar{u}(x_2)$

# W production @ RHIC

(a)



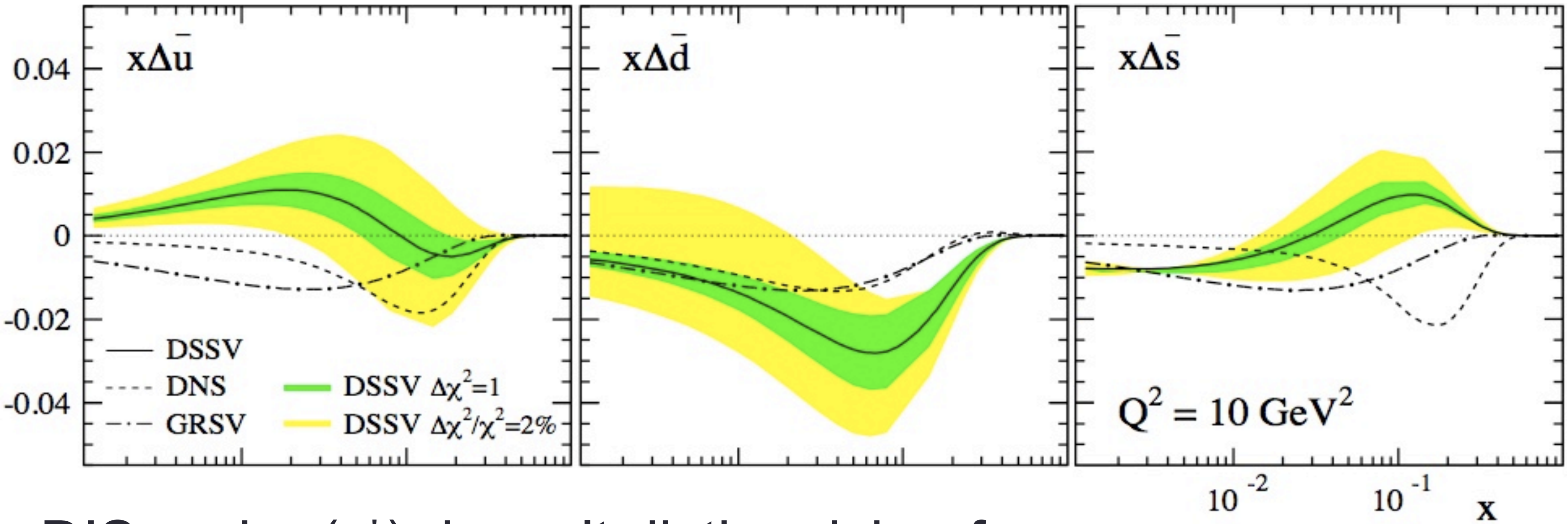

(b)




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

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

# What about the anti-quark polarization?

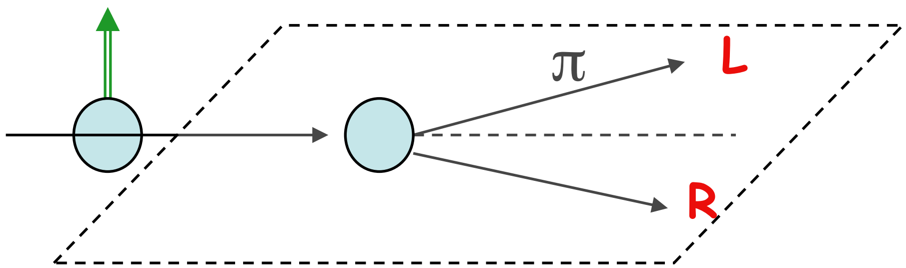



- DIS probe ($\gamma^*$) doesn't distinguish q from qbar
  - Has to take measure semi-inclusive ($\pi$, K production)
  - Uncertainties in fragmentation functions
- High energy p-p collisions enable probing q,qbar through $W^{+/-}$ production –> Plan at RHIC

# In parallel: The Transverse Spin Puzzle

Had been observed but ***ignored*** for almost 3 decades…

# Transverse spin introduction




$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

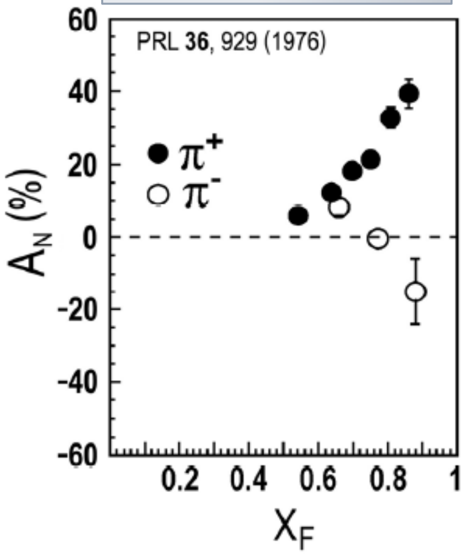
$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

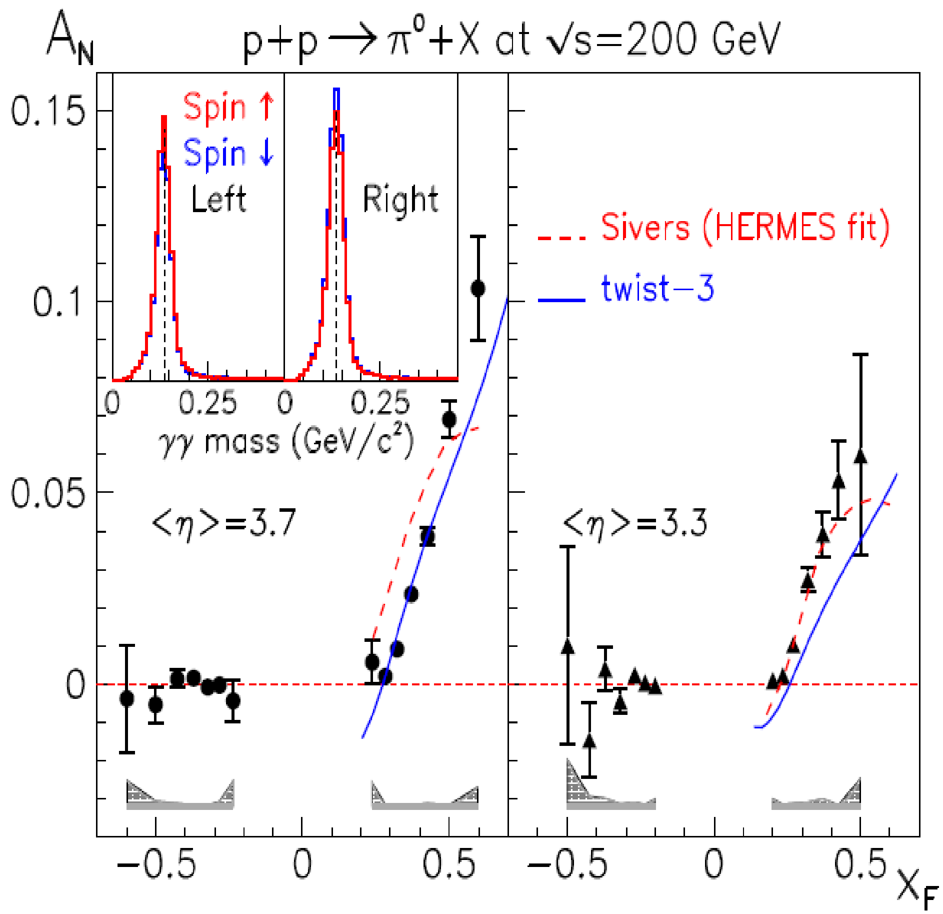
Kane, Pumplin, Repko 1978
PRL 41 1689 (1978)

- Since people starved to measure effects at high $p_T$ to interpret them in pQCD frameworks, this was "neglected" as it was expected to be small….. However….
- Pion production in single transverse spin collisions showed us something different….

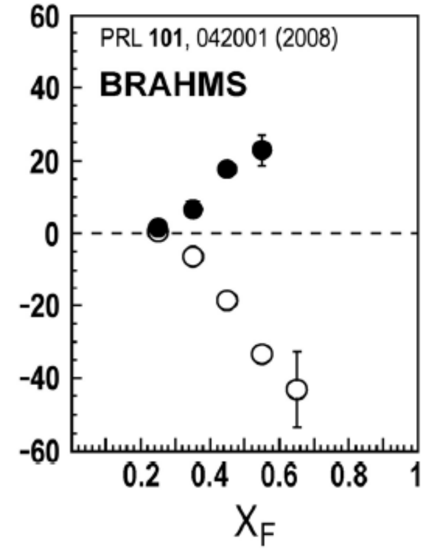
# Pion asymmetries: at most CM energies!

ZGS/ANL
$\sqrt{s}$=4.9 GeV




RHIC
$\sqrt{s}$=62.4 GeV

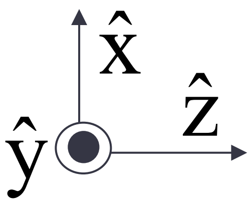



Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

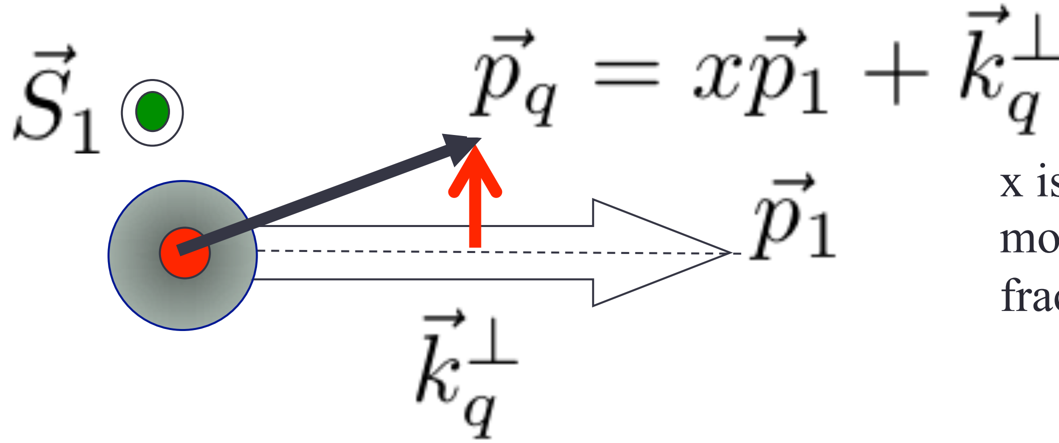
# Sivers effect: due to transverse motion of quarks in the nucleon: initial state effect

**Phys Rev D41 (1990) 83; Phys Rev D43 (1991) 261**

$$SSA_{Sivers} \propto \vec{S}_1 \cdot (\vec{p}_1 \times \vec{k}_q)$$

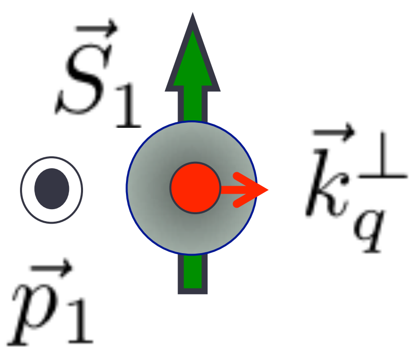



Top view




x is longitudinal momentum fraction.

Front view

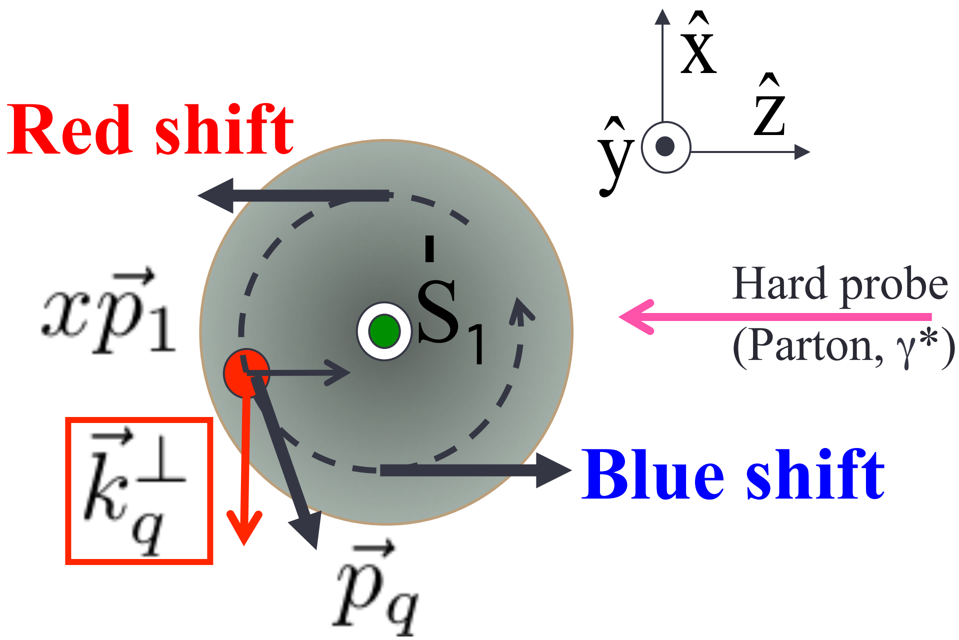



Quark transverse momentum in transversely polarized proton.

INITIAL STATE EFFECT: Orbital angular momentum?

# What does "Sivers effect" probe?

Top view, Breit frame




Quarks orbital motion adds/ subtracts longitudinal momentum for negative/positive $\hat{x}$ .

PRD66 (2002) 114005

**P**arton **D**istribution **F**unctions rapidly fall in longitudinal momentum fraction x.

**F**inal **S**tate **I**nteraction between outgoing quark and target spectator.

Sivers function

$$f_{1T}^{\perp}(x, \vec{k}_q^{\perp})$$

hep-ph/ 0703176

**Quark Orbital angular momentum**

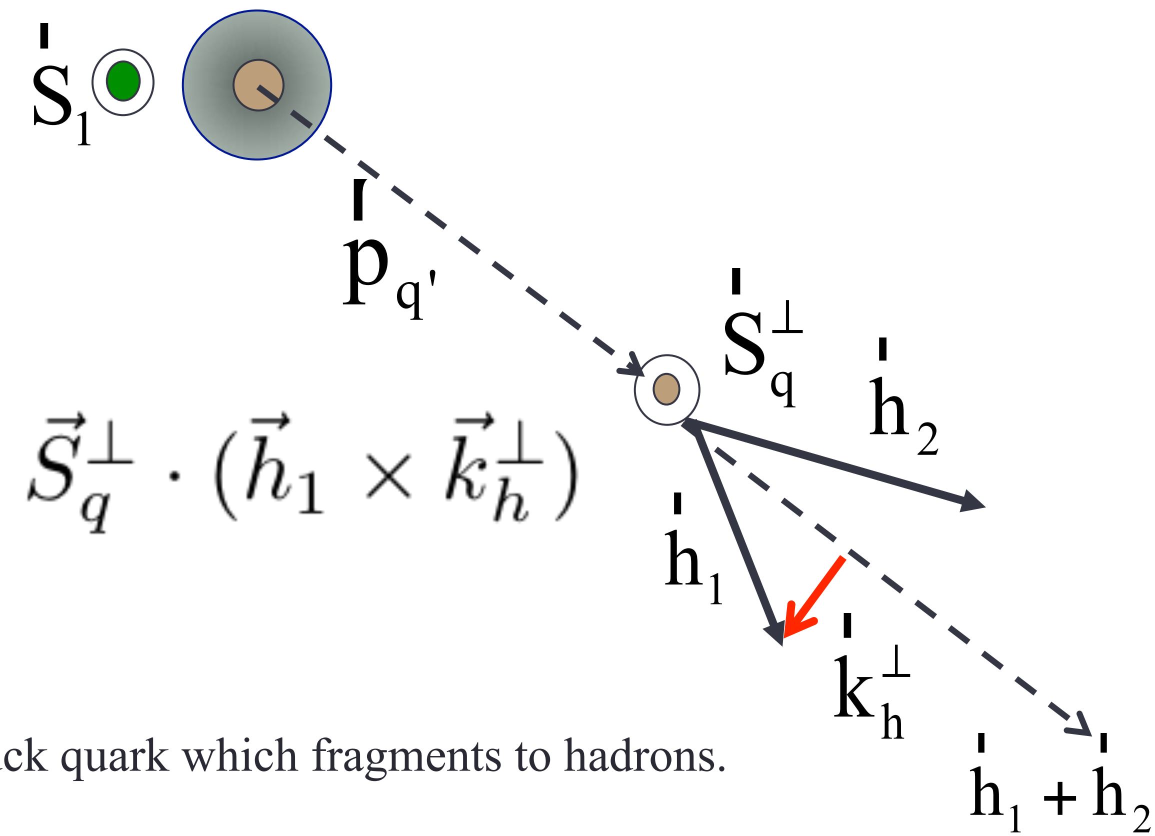
**G**eneralized **P**arton **D**istribution Functions

PRD59 (1999) 014013

# Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

Nucl Phys B396 (1993) 161,
Nucl Phys B420 (1994) 565

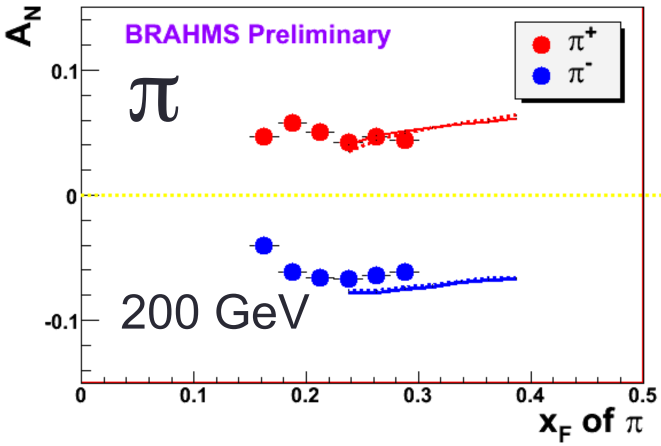
Example: $p^{\uparrow} + p \rightarrow h_1 + h_2 + X$

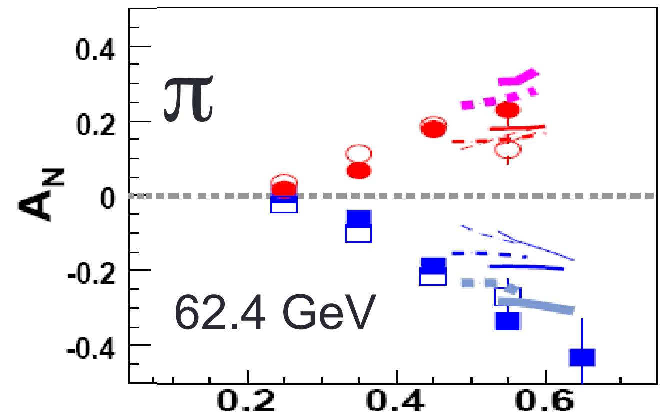


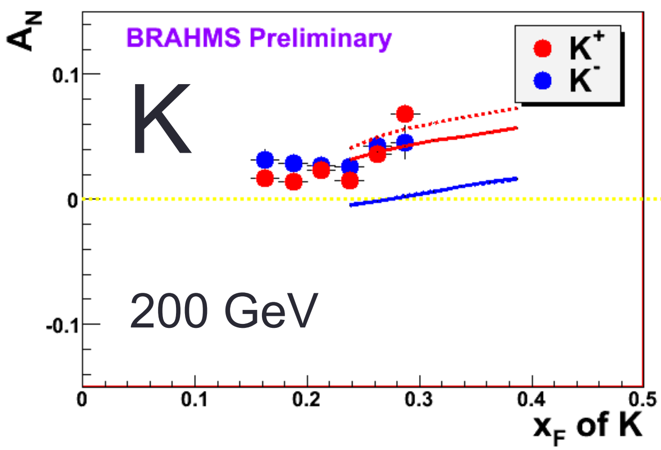

$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

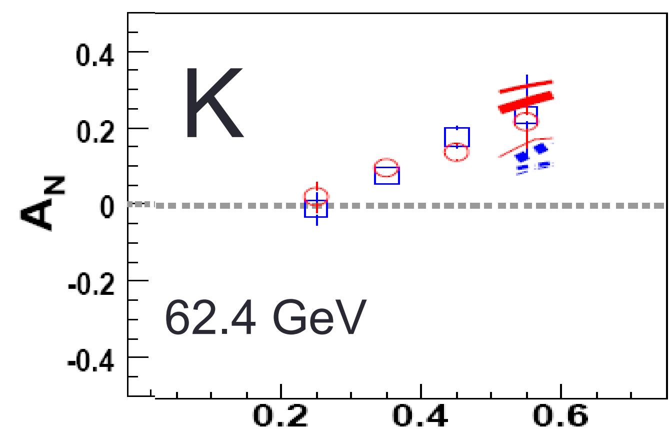
Polarization of struck quark which fragments to hadrons.

# $\pi$,K,p 200 & 62.4 GeV

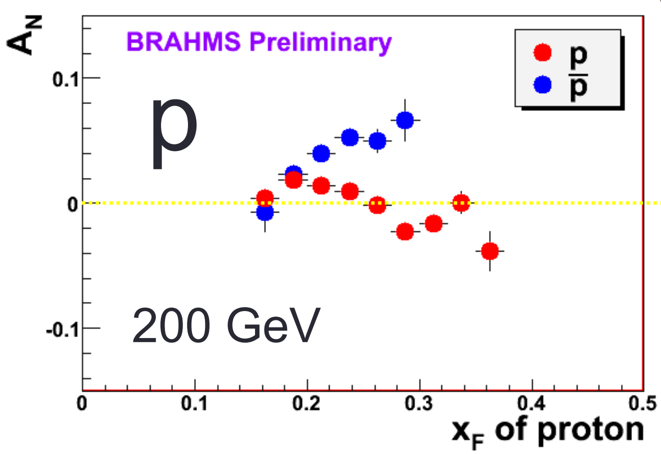


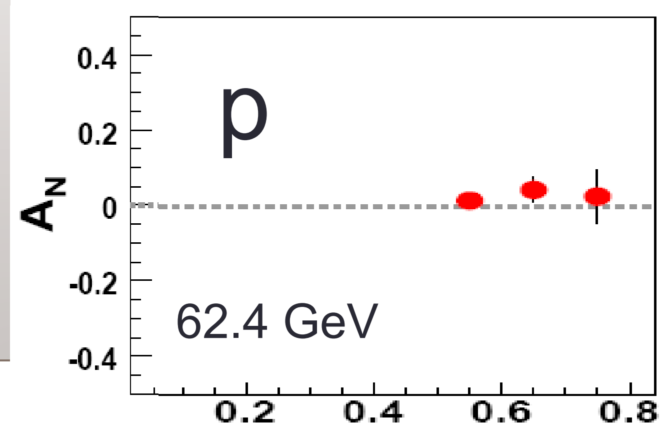




- Scales on plots different
- Kaon asymmetries not predicted
- Unfortunately no anti-proton measurement



Although not expected, at any observable level, 400+ times the expected values of asymmetries have been routinely seen experimentally: both in ep and pp systems.

- Transverse motion/momentum of partons (indirect evidence for orbital angular momentum of the quarks & gluons?)

- Asymmetry in fragmentation process (final state) or
- Both …. May be responsible.

# Summary

- RHIC Spin program made great strides in furthering our knowledge of nucleon, but we need something more to address some of the still open issues:

- **What remains?**
  - $\Delta$G at low x? Spin structure functions and its behavior at low x?
  - If orbital angular motion plays a role, what is the orbital contribution from Gluons?

  **Precision measurements at a future facility are essential…**

  **THE ELECTRON ION COLLIDER.... Can we do better?**

# Study of internal structure of a watermelon:

A-A (RHIC)

1) Violent collision of melons


2) Cutting the watermelon with a knife

Violent DIS e-A (EIC)

3) MRI of a watermelon

Non-Violent e-A (EIC)