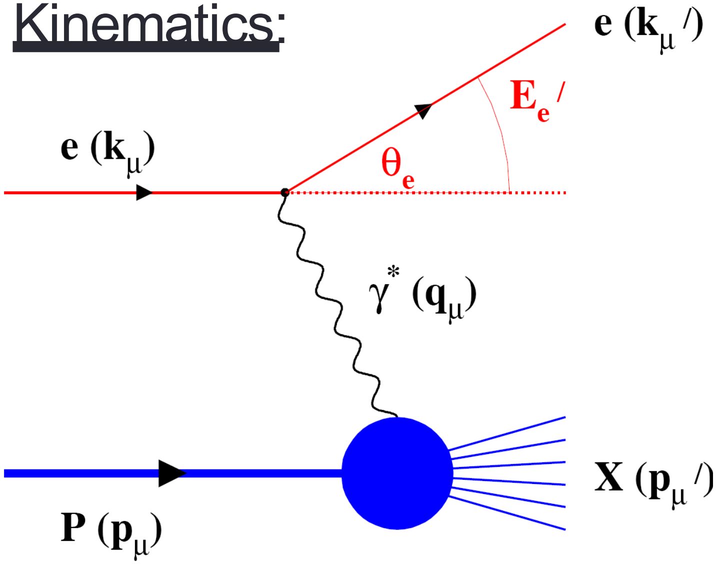
RHIC And EIC Physics

Deep Inelastic Scattering: Discovery of Spin Crisis

June 26, 2018
Asia Pacific Center for Theoretical Physics
Lecture 1 B

Deep Inelastic Scattering

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

Measure of resolution power

$$Q^2 = 2E_e E'_e (1 - \cos\Theta_{e'})$$

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

***Hadron* :**

$$z = \frac{E_h}{\nu}; p_t^{\text{with respect to } \gamma}$$

Inclusive events:

e+p/A → e'+X

detect only the scattered lepton in the detector

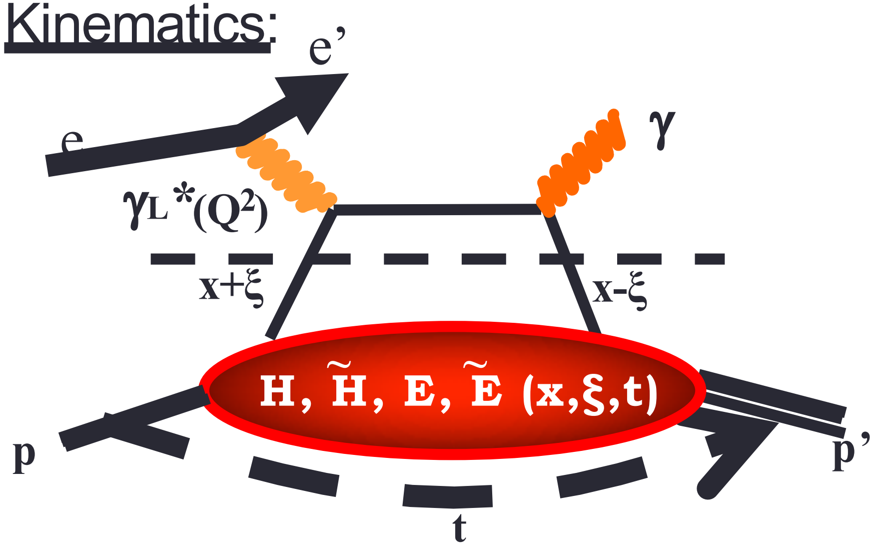
Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets in the detector

Deep Inelastic Scattering

Kinematics:



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Measure of resolution power

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$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x_B = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

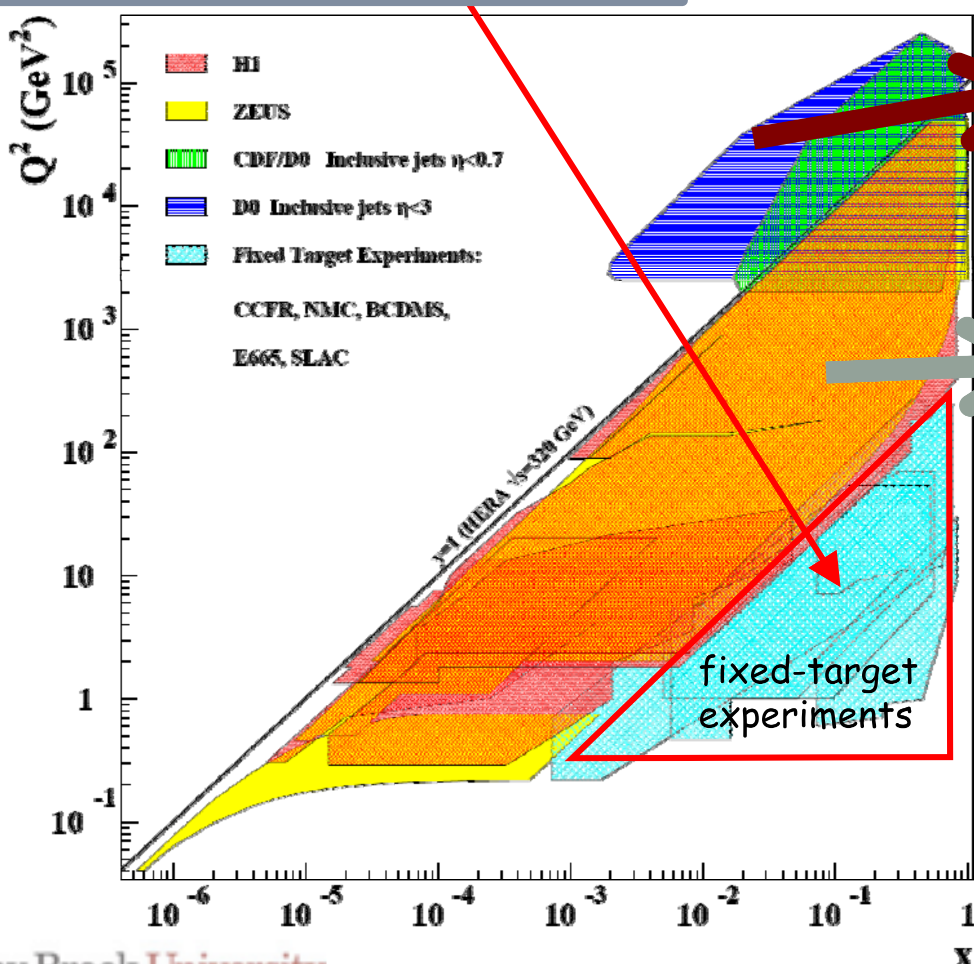
$$t = (p - p')^2, \xi = \frac{x_B}{2 - x_B}$$

Exclusive events:
e + **(p/A)** → e'+ **(p'/A')**+ γ / J/ψ / ρ / ϕ
detect **all** event products in the detector

Special sub-event category rapidity gap events
e + **(p/A)** → e' + γ / J/ψ / ρ / ϕ / jet
Don't detect **(p'/A') in final state**

Perspective on x,Q^2, Center of Mass

Fixed target e-N experiments
(center of mass < 30 GeV)



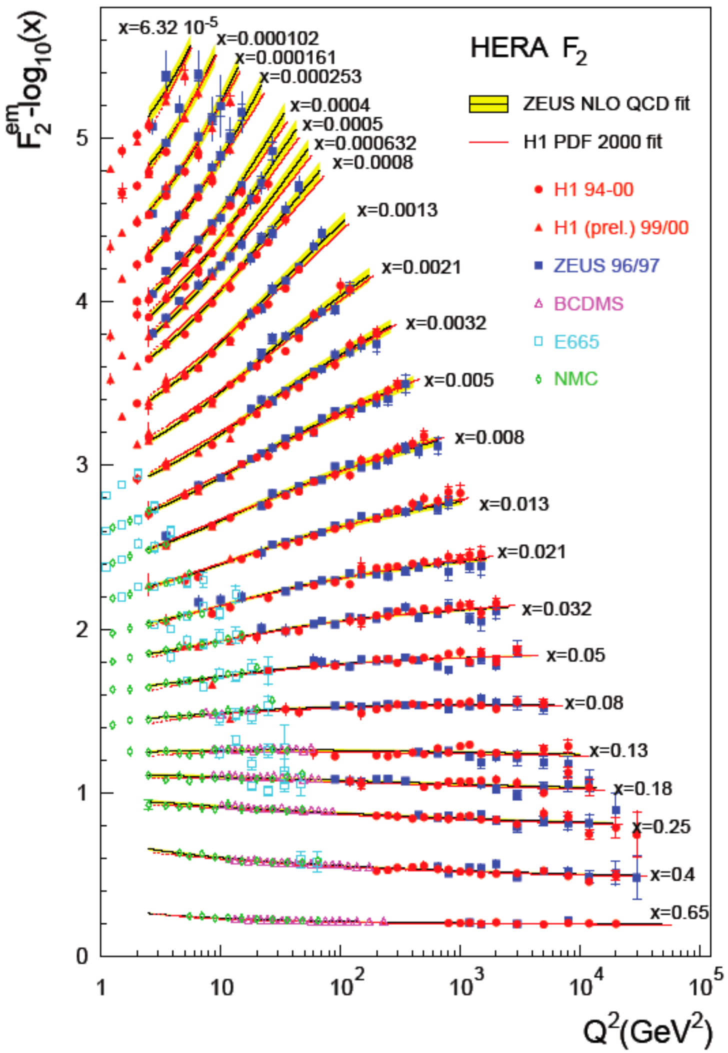
Hadron-Hadron
Collider: CM ~2 TeV

Typically accessible
By e-N collider experiments
CM ~ 300 GeV

$$Q^2 = S x y$$

Remember:
Meaning of x, Q^2, and y?

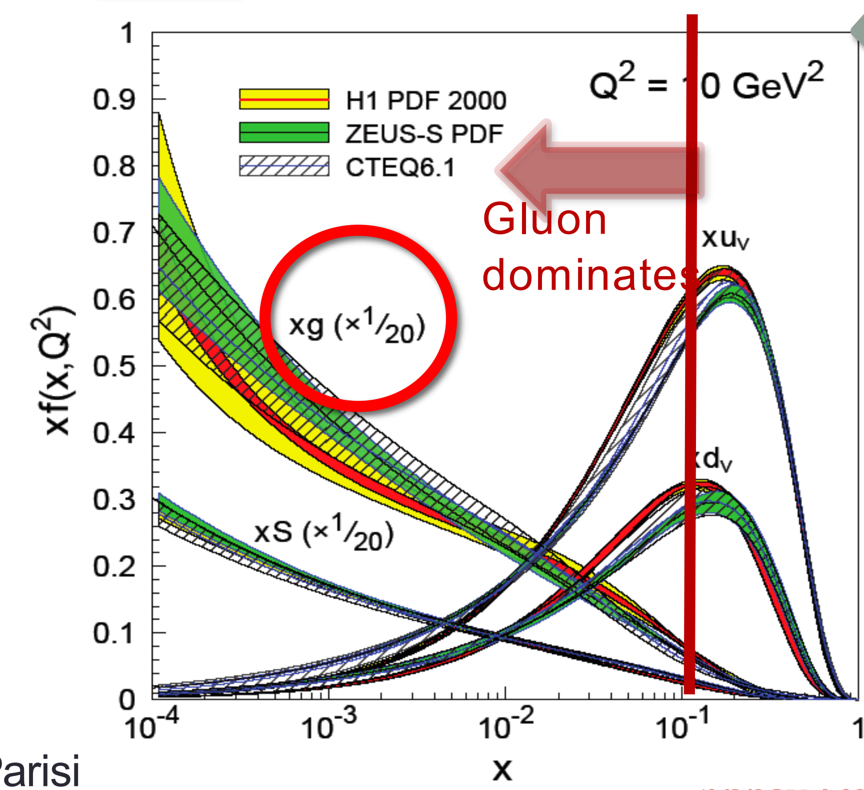
Measurement of Glue at HERA



- Scaling violations of $F_2(x,Q^2)$

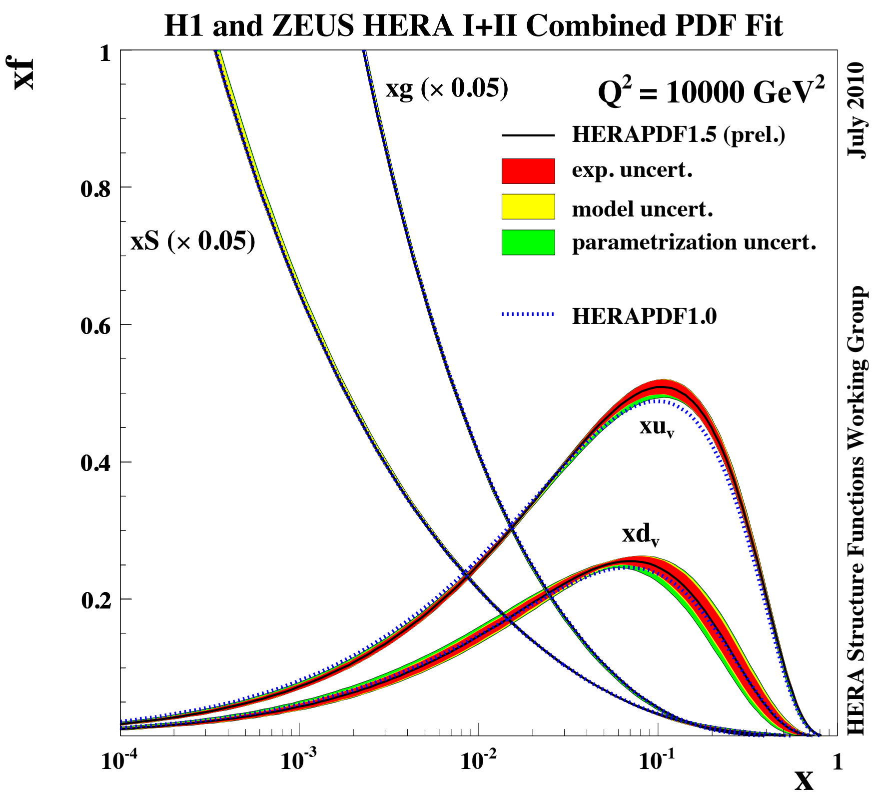
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

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



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Measurement of Gluons at HERA



- Inclusive e-p scattering at 300 GeV center of mass
- Low x gluon distribution measured up to x = 10^{-4}
- Evolved to a high value of Q^2 using the Altarelli Parisi equation
- Gluon distribution keeps on rising: "the Low x singularity"

Method of extraction standard based on the fact that quarks radiate gluons

What this means to our understanding of QCD? Infinite Rise? – Physics for EIC

Some equations…

Assume only γ^* 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 (S)

Lepton spin (s)

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

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

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

Lepton-nucleon Cross Section

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

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

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

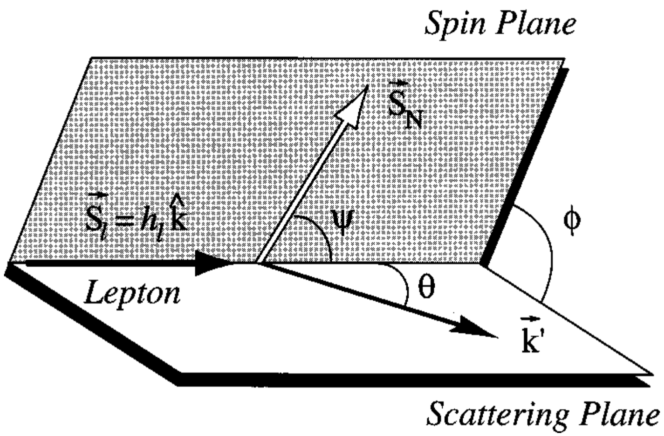
lepton helicity $h_l = \pm 1$

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 γ is small

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

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

Cross section asymmetries….

- $\Delta\sigma_{||}$ = anti-parallel – parallel spin cross sections
- $\Delta\sigma_{perp}$= lepton-nucleon spins orthogonal
- Instead of measuring cross sections, it is prudent to measure the differences: Asymmetries in which many measurement imperfections might cancel:

$$A_{||} = \frac{\Delta\sigma_{||}}{2\overline{\sigma}}, \quad A_{\perp} = \frac{\Delta\sigma_{\perp}}{2\overline{\sigma}},$$

which are related to virtual photon-proton asymmetries A_1,A_2:

$$A_{||} = D(A_1 + \eta A_2), \quad A_{\perp} = d(A_2 - \xi A_1)$$

$$A_1 = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}$$

$$A_2 = \frac{2\sigma^{TL}}{\sigma_{1/2} + \sigma_{3/2}} = \gamma\frac{g_1 + g_2}{F_1}$$

$$d = \frac{\sqrt{1 - y - \gamma^2 y^2/4}}{1 - y/2} D,$$

$$\eta = \frac{\gamma(1 - y - \gamma^2 y^2/4)}{(1 - y/2)(1 + \gamma^2 y/2)},$$

$$\xi = \frac{\gamma(1 - y/2)}{1 + \gamma^2 y/2}.$$

d, η, ξ are kinematic factors

D = Depolarization factor: how much polarization of the incoming electron is taken by the virtual photon, calculable in QED

$$D = \frac{y(2 - y)(1 + \gamma^2 y/2)}{y^2(1 + \gamma^2)(1 - 2m_l^2/Q^2) + 2(1 - y - \gamma^2 y^2/4)(1 + R)}$$

- $A_{||}$ could be written down in terms of spin structure function g_1, and A_2 along with kinematic factors:

$$\frac{A_{||}}{D} = (1+\gamma^2)\frac{g_1}{F_1} + (\eta - \gamma)A_2$$

Where A_1 is bounded by 1, and A_2 by sqrt($R=\sigma_T/\sigma_L$), when terms related A_2 can be neglected, and γ is small,

$$A_1 \simeq \frac{A_{||}}{D}, \quad \frac{g_1}{F_1} \simeq \frac{1}{1+\gamma^2}\frac{A_{||}}{D}$$

- Where: $F_1 = \frac{1+\gamma^2}{2x(1+R)} F_2$ and $A_2 = \frac{1}{1+\eta\xi}\left(\frac{A_\perp}{d} + \xi\frac{A_{||}}{D}\right)$

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 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

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

In this equation:

t = $\ln(Q^2/\Lambda^2)$

α_S = strong interaction constant

S & NS stand for flavor singlet & flavor non-singlet

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

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

Composition & Q^2 or t dependence of Structure Functions

$$\frac{d}{dt}\Delta\Sigma(x,t)=\frac{\alpha_s(t)}{2\pi}\int_x^1\frac{dy}{y}\left[P_{qq}^{S}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t)\right.$$
$$\left.+2n_f P_{qg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right],$$

Singlet quark distribution
And its t dependence

$$\frac{d}{dt}\Delta g(x,t)=\frac{\alpha_s(t)}{2\pi}\int_x^1\frac{dy}{y}\left[P_{gq}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t)\right.$$
$$\left.+P_{gg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right],$$

(Singlet) Gluon distribution
And its t dependence

Non-Singlet quark distribution
And its t dependence

$$\frac{d}{dt}\Delta q^{NS}(x,t)=\frac{\alpha_s(t)}{2\pi}\int_x^1\frac{dy}{y}P_{qq}^{NS}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q^{NS}(y,t).$$

At leading order g_1 decouples with ΔG

$$C_q^{0,\mathrm{S}}\left(\frac{x}{y},\alpha_s\right) = C_q^{0,\mathrm{NS}}\left(\frac{x}{y},\alpha_s\right) = \delta\left(1-\frac{x}{y}\right),$$

$$C_g^{0}\left(\frac{x}{y},\alpha_s\right) = 0.$$

Whenever you hear Analysis done at "Leading order"
--This means quark-gluon interactions are **dropped** from consideration

Beyond the leading order coefficient & splitting functions are not uniquely defined: There are some favorite schemes of theorists, each with distinct calculation advantage.

- Most are now available at α_S^2
- More comments on this in various theory talks

Life was easy in the Quark Parton Model (QPM)

Until first spin experiments were done!

Understanding the proton structure:

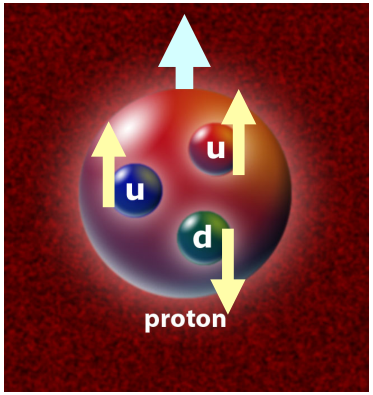
Friedman, Kendall, Taylor: 1960's SLAC Experiment

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)

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

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

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

New: we know only now

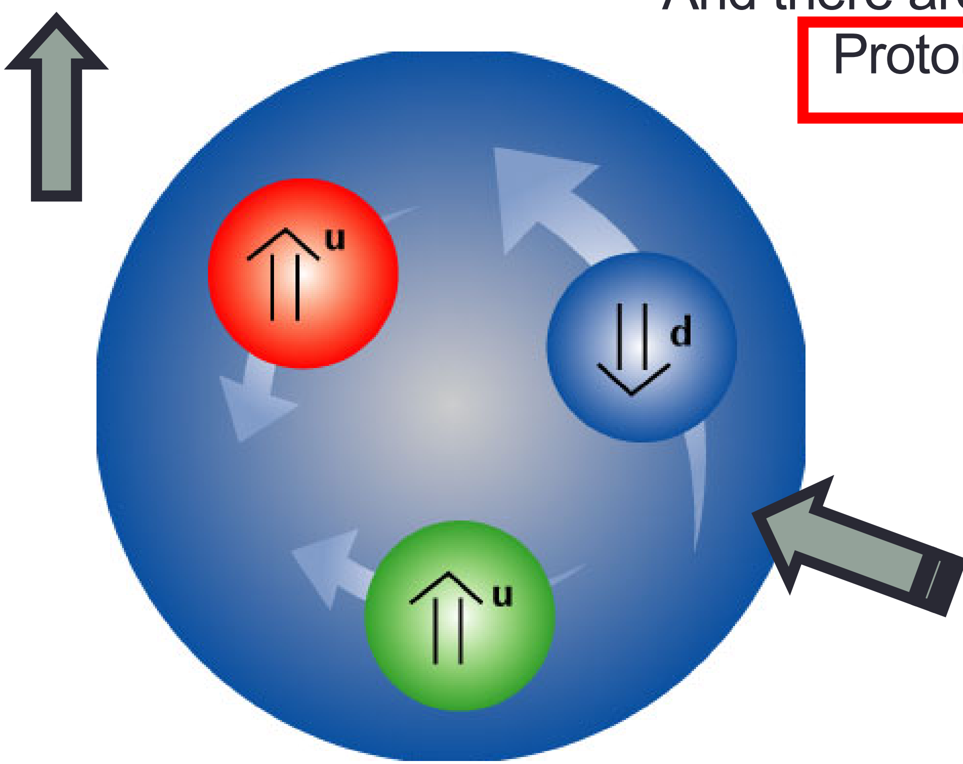
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects… my 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!

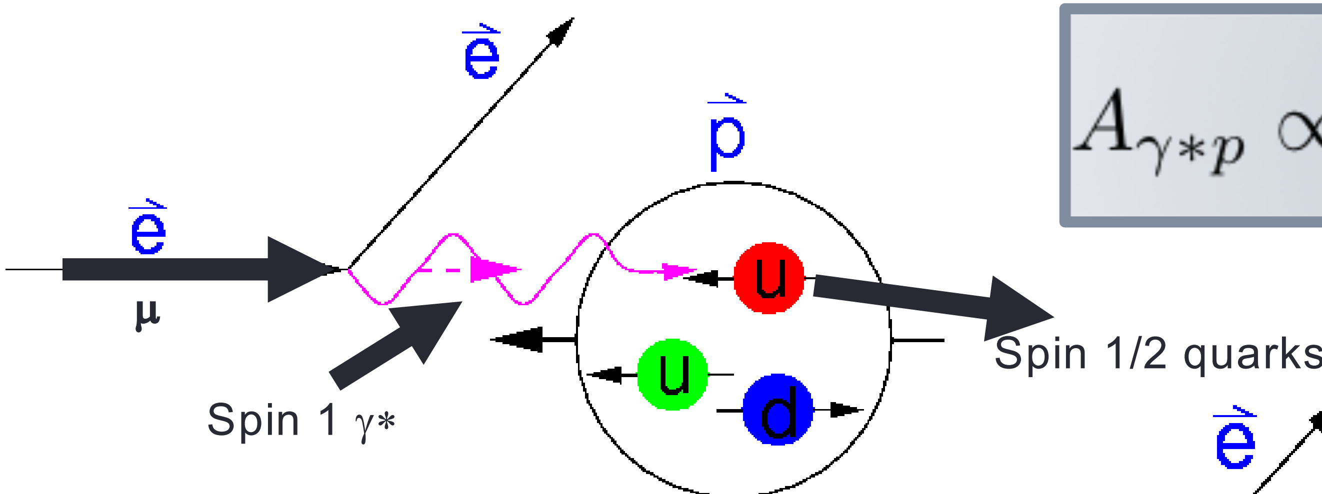
$$1/2 \stackrel{?}{=} 1/2 + 1/2 + 1/2$$

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

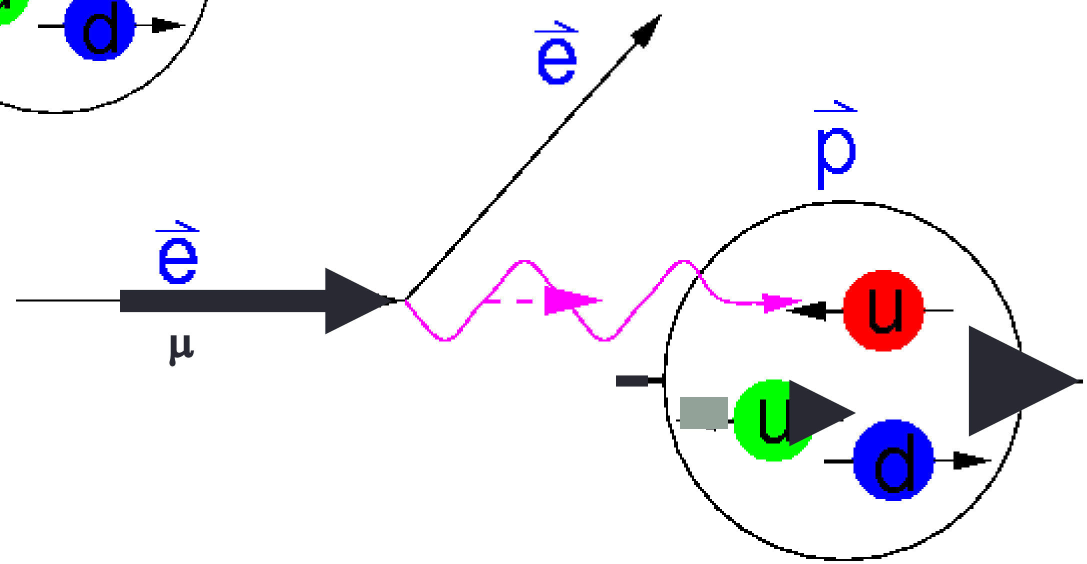
How was the Quark Spin measured?

- 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 (^3He: 2p+n)
- Polarized beams: electron,muon used in DIS experiments

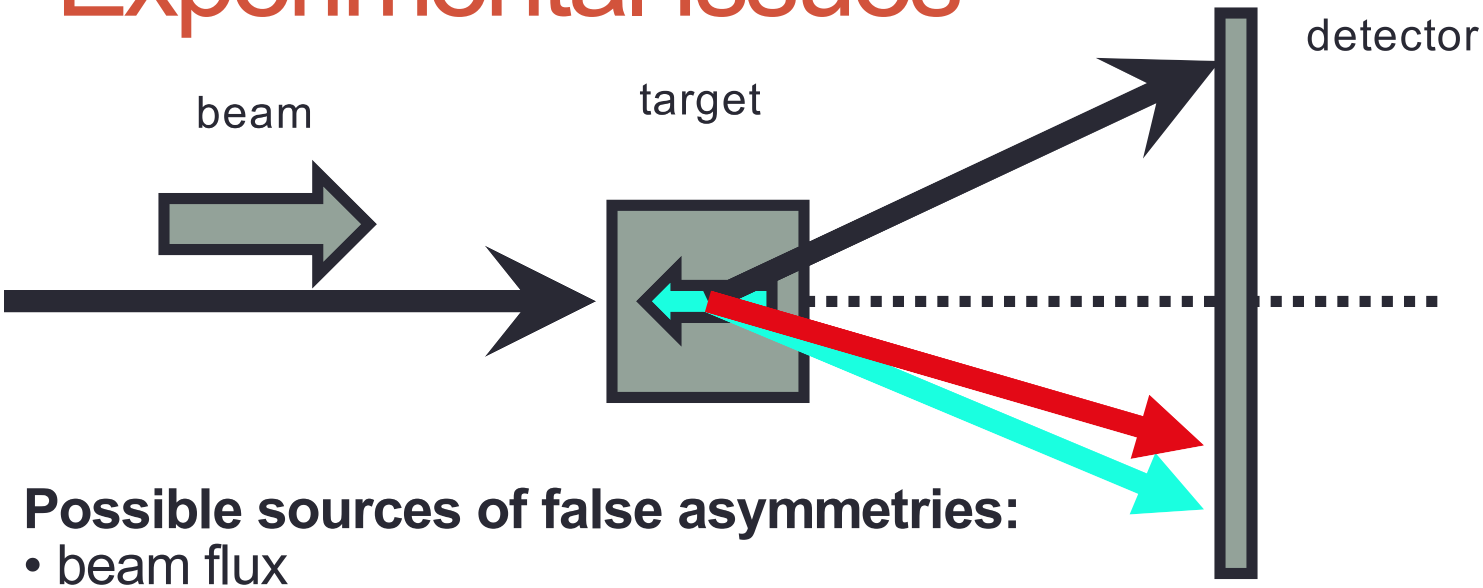
Determine the kinematics: measure with high accuracy:

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

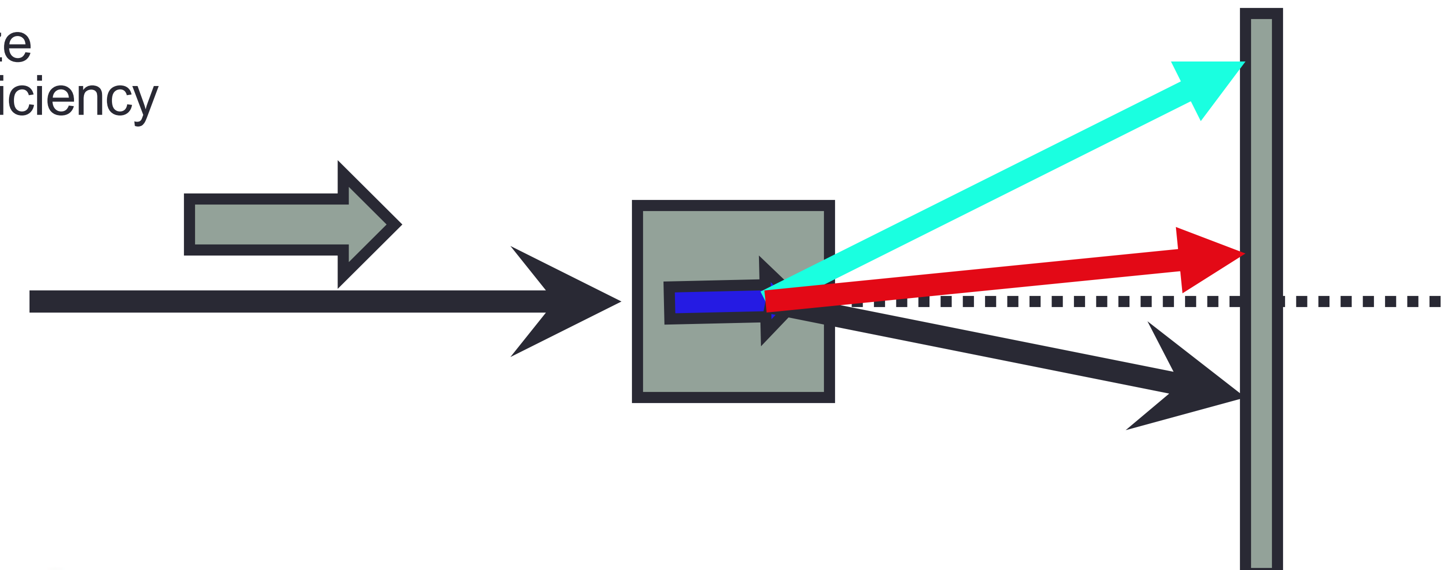
Control of false asymmetries:

- 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

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

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

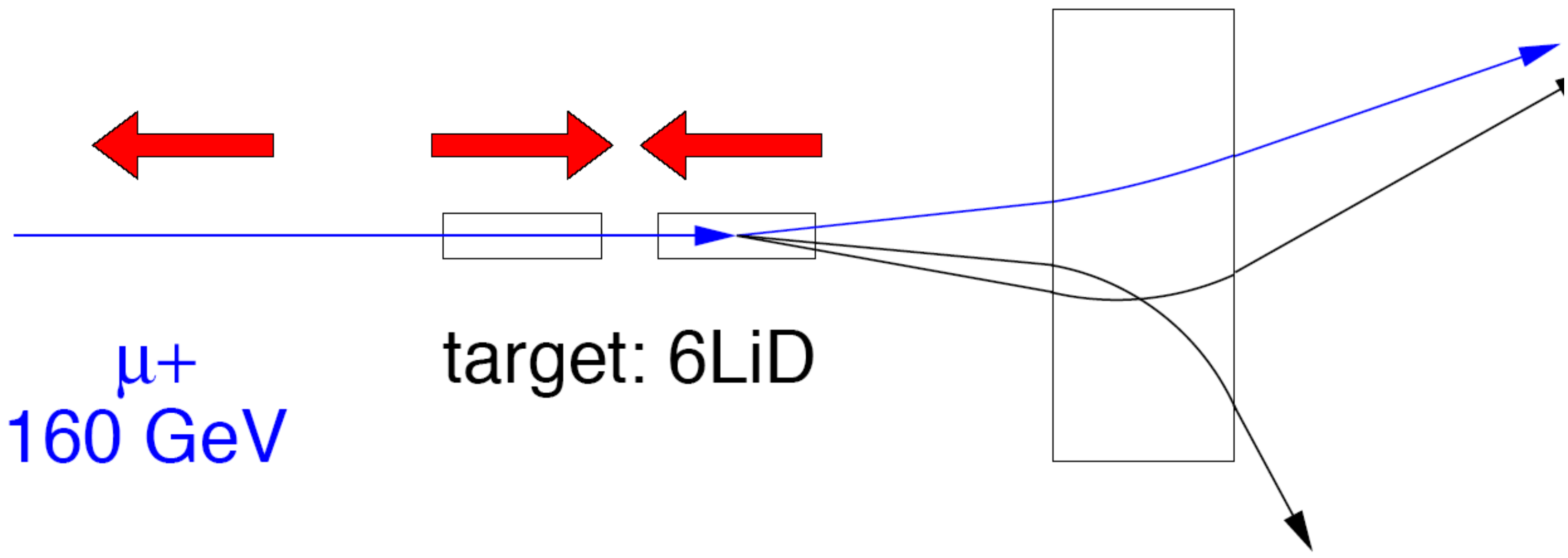
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

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 $$\Delta q = \int_0^1 \Delta q(x) dx$$

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

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

$$= \frac{1}{12}(\Delta u - \Delta d) + \frac{1}{36}(\Delta u + \Delta d - 2\Delta s) + \frac{1}{9}(\Delta u + \Delta d + \Delta s)$$

$a_3 = g_a$ — 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: $\Gamma_1^p = 0.170 \pm 0.004$

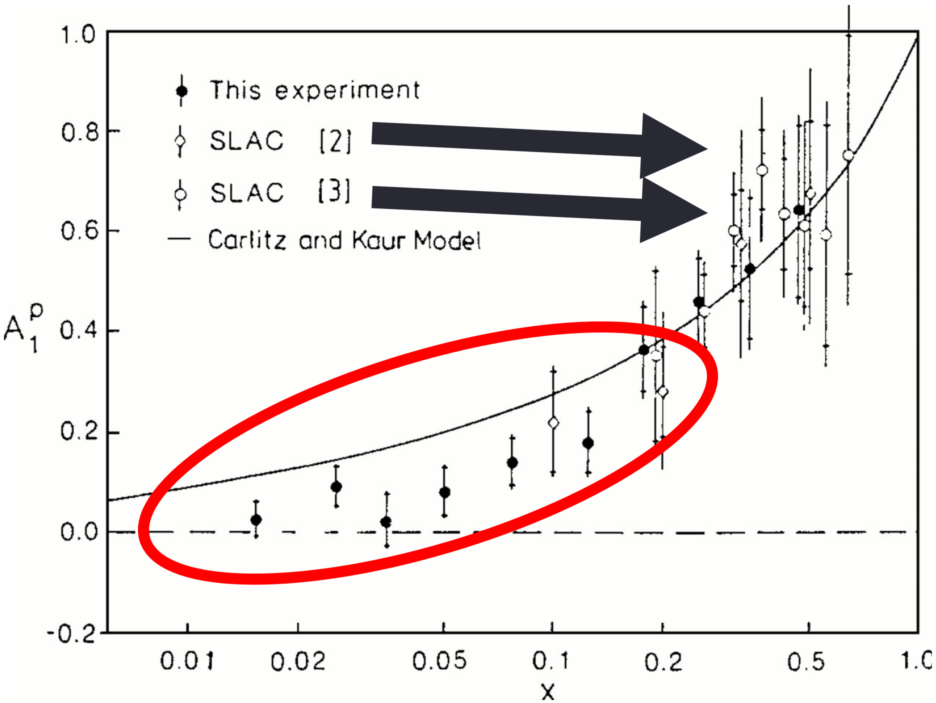
Measurements were done at SLAC (E80, E130) Experiments:

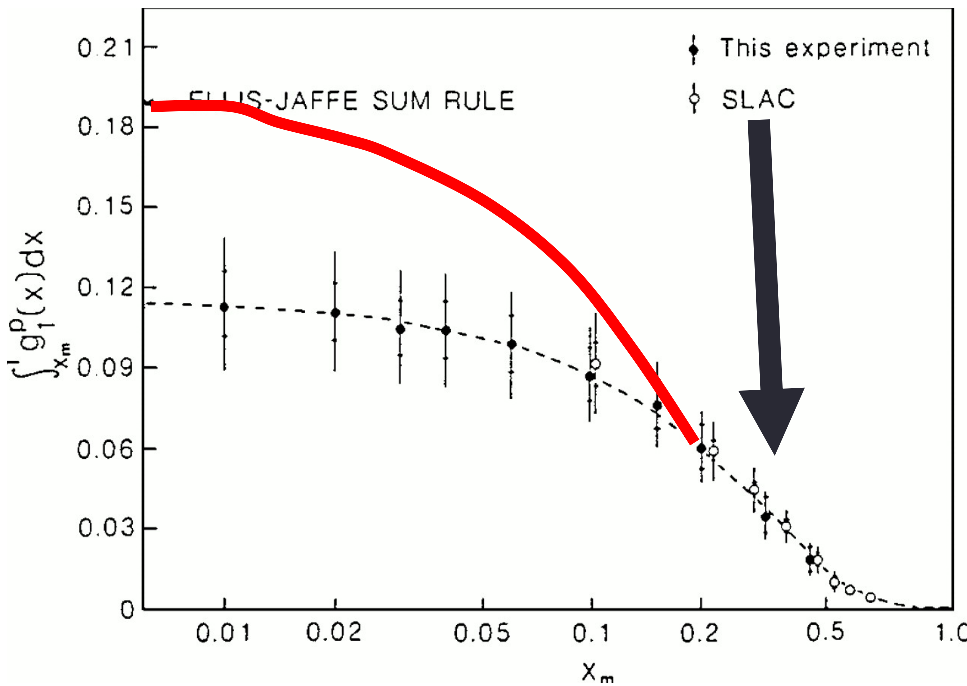
- Low 8-20 GeV electron beam on fixed target
- Did not reach low enough x → $x_{min} \sim 10^{-2}$
- Found consistency of data and E-J sum rule above

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)

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

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

Low x behavior of g_1

- Regge models (mostly used until mid 1990s):

$$Q^2 << 2M\nu, \text{ i.e. }, x \to 0, \; g_1^p \pm g_1^n \to x^{-\alpha} \qquad -0.5 < \alpha < 0.5$$

Where α is the intercept of the lowest contributing Regge trajectories

- Other model dependent expectations (non-QCD based):

$$g_1(x) \propto [2 \ln(1/x) - 1] \qquad g_1(x) \propto (x \ln^2 x)^{-1}$$

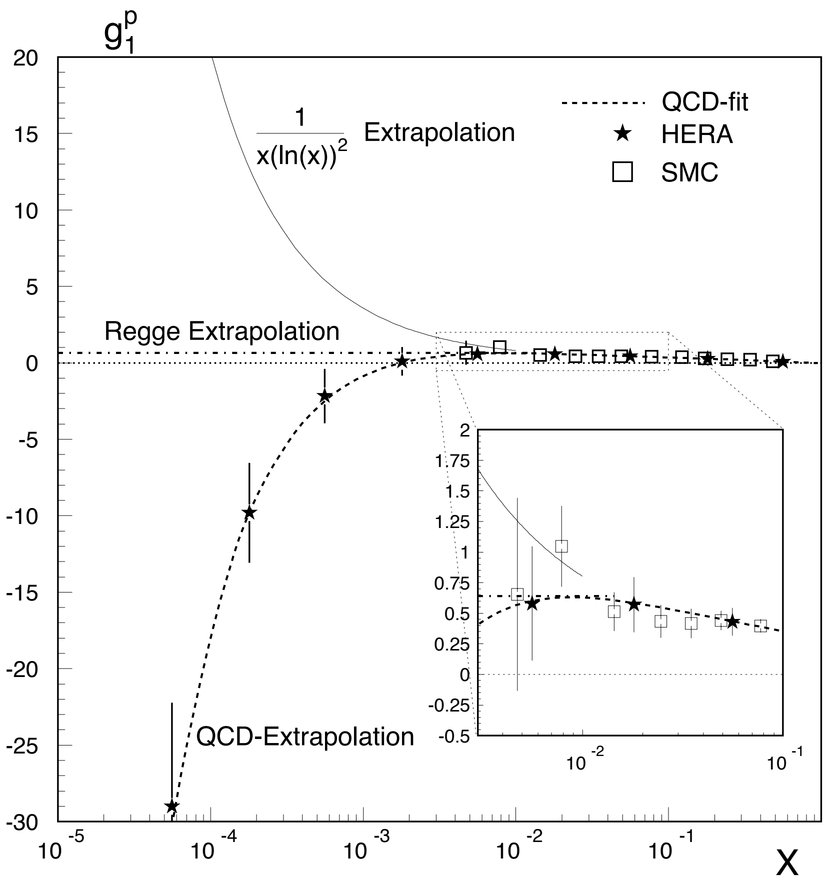
- QCD based calculations:

Resummation of AP: $g_1(x,Q^2) \sim \exp A \sqrt{\ln[\alpha_s(Q_0^2)/\alpha_s(Q^2)]\ln(1/x)}$

Resum of leading power of ln(1/x) gives:

$$g_1^{NS}(x,Q^2) \sim x^{-w_{NS}}, \quad w_{NS} \sim 0.4 \qquad g_1^{S}(x,Q^2) \sim x^{-w_S}, \quad w_S \sim 3 w_{NS}$$

A collection of low x behaviors:

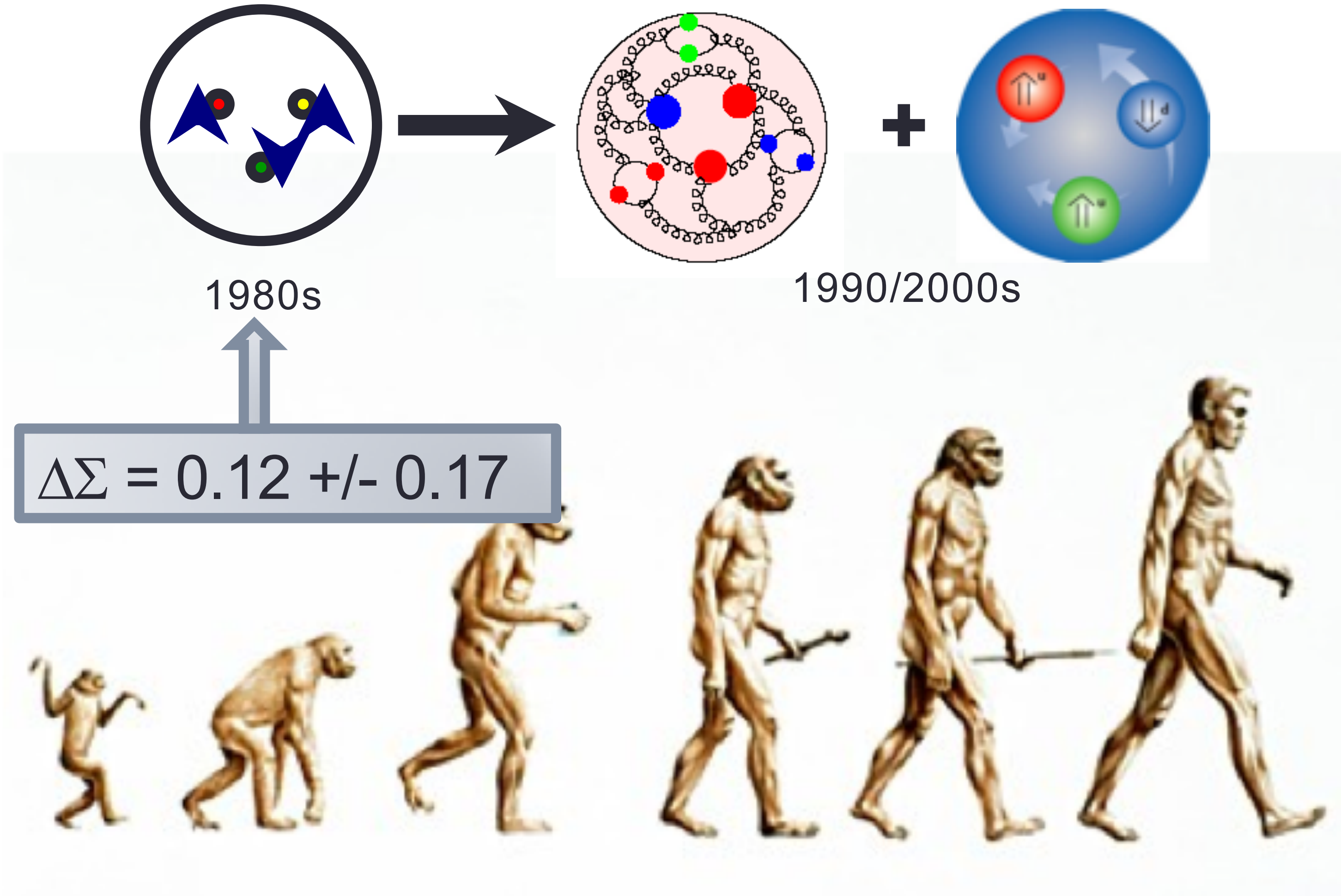


1996-1999 Serious of Future HERA Physics Workshop
Deshpande, Hughes, Lichtenstadt, HERA low x WS (1999)

Simulated data for polarized e-p scattering shown in the figure. Polarized HERA was not realize!

- Low x behavior all over the place
- No theoretical guidance for which one is correct
- Only logical path is though measurements.
  - Not easy
  - But planned in future
  - See lectures on EIC later in the week.

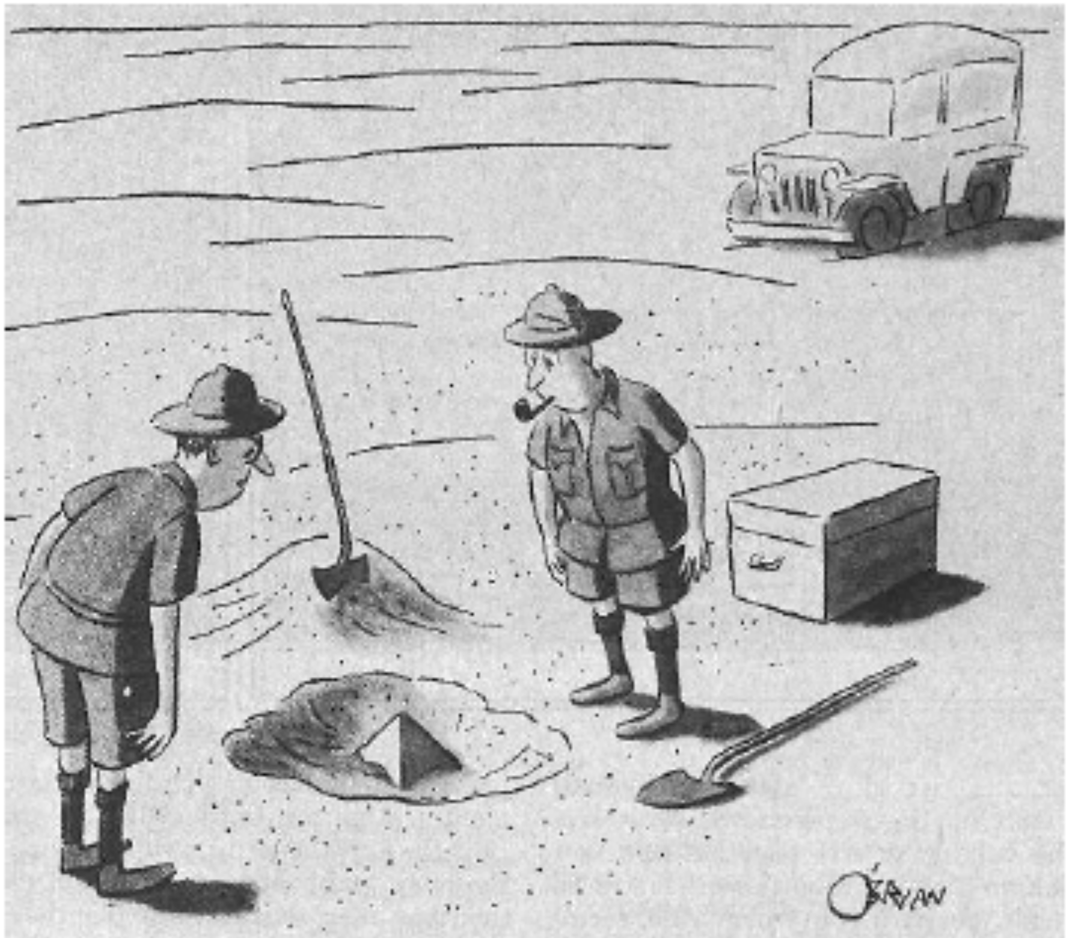
Evolution: Our Understanding of Nucleon Spin



$\Delta\Sigma = 0.12 +/- 0.17$

We have come a long way, but do we understand nucleon spin?

How significant is this?



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

RHIC and EC Physics

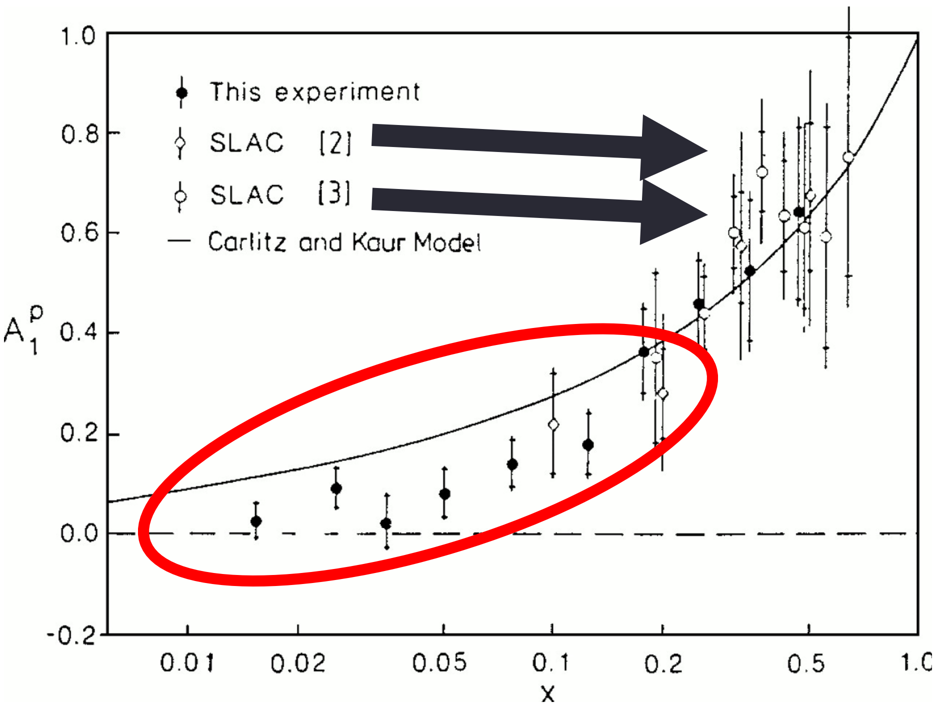
From Fixed Target Deep Inelastic Scattering to the Relativistic Heavy Ion Collider

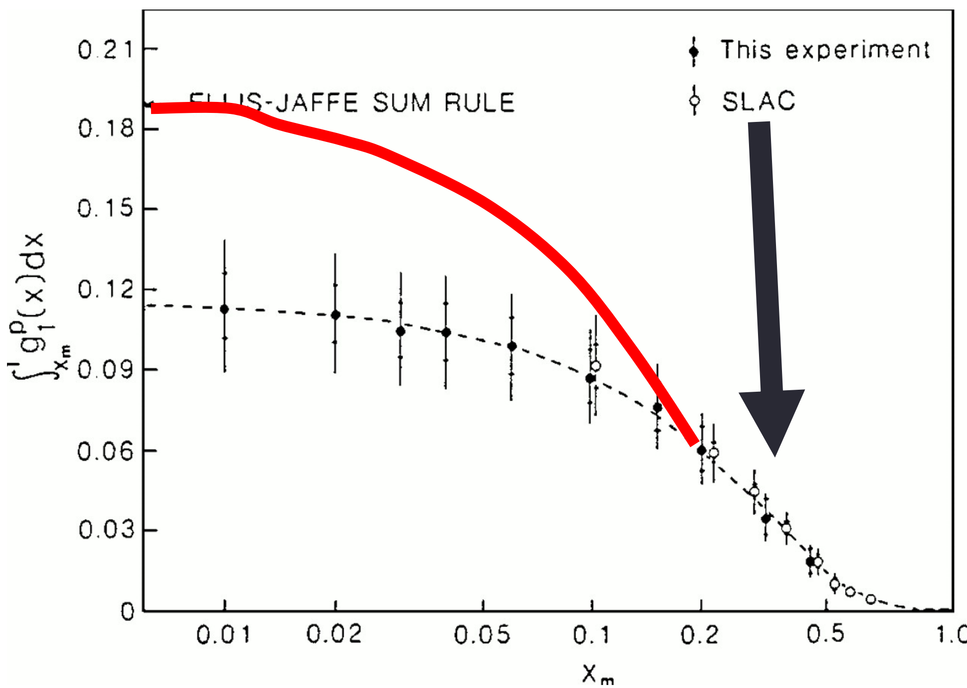
June 26, 2018

Asia Pacific Center for Theoretical Physics, Pohang

Lecture 1 C

Proton Spin Crisis (1989)!





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

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

Aftermath of the EMC Spin "Crisis"

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

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:

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

Altarelli, Ross
Carlitz, Collins
Mueller et al.

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

Jaffe, Manohar
Ji et al

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

Other spin rule(s) and tests of QCD:

- Bjorken spin sum rule (1966): Strong test of QCD

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

Where

$$C_1^{NS} = 1 - c_1^{NS}\left(\frac{\alpha_s(Q^2)}{\pi}\right) - c_2^{NS}\left(\frac{\alpha_s(Q^2)}{\pi}\right)^2 - c_3^{NS}\left(\frac{\alpha_s(Q^2)}{\pi}\right)^3 - O(c_4^{NS})\left(\frac{\alpha_s(Q^2)}{\pi}\right)^4$$

- Efremov, Leader, Teryaev sum rule:

$$\int_0^1 dx\, x \left[g_1^{\text{valence}}(x) + 2g_2^{\text{valence}}(x)\right] = 0$$

- Burkhardt Cottingham Sum rule $$\int_0^1 dx\ g_2(x) = 0$$

- Understanding higher twist corrections at low Q^2…..

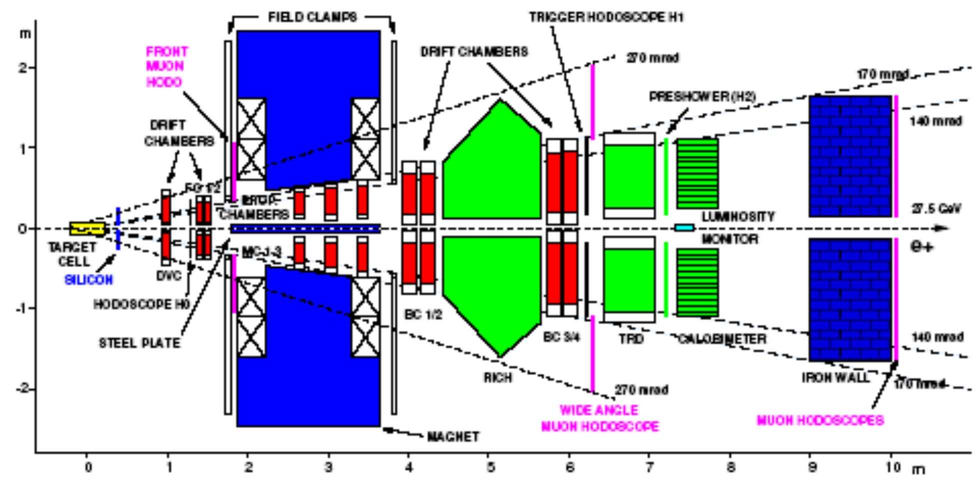
See review by S. E. Kuhn, J.-P Chen, E. Leader, arXiv:0812.3535v2 [hep-ph] 11 Feb 2009

Improved precision on $\Delta\Sigma$ and flavor separation:

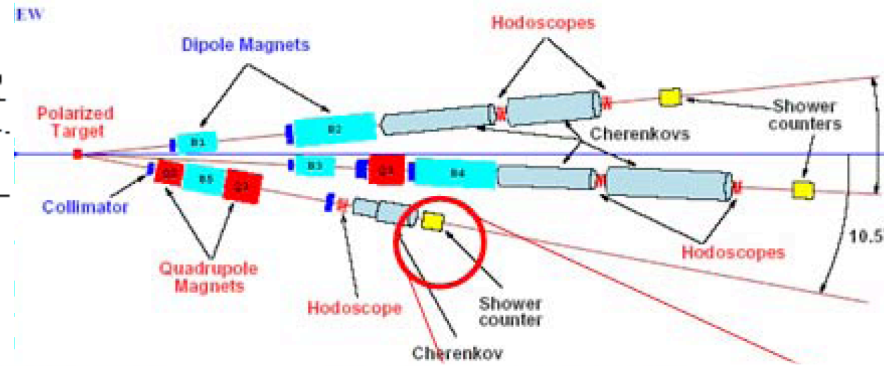
SMC and COMPASS experiments at CERN
E142-E155 experiments at SLAC
HERMES experiment at DESY
Hall A, B, C at Jefferson Laboratory

Mostly tried to reach pQCD region, Inclusive, no particle ID
Mostly Semi-Inclusive, with good particle ID
Mostly lower beam energies, precision mostly in the non-pQCD regime

Experiments

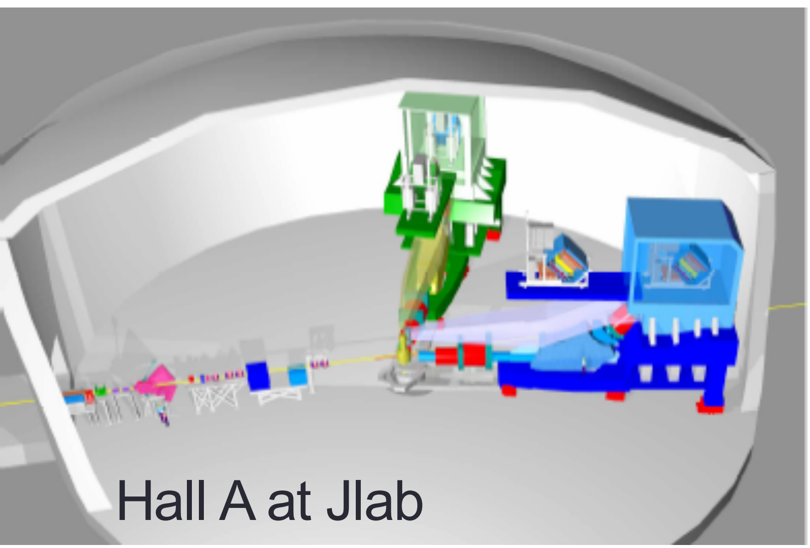


HERMES at DESY

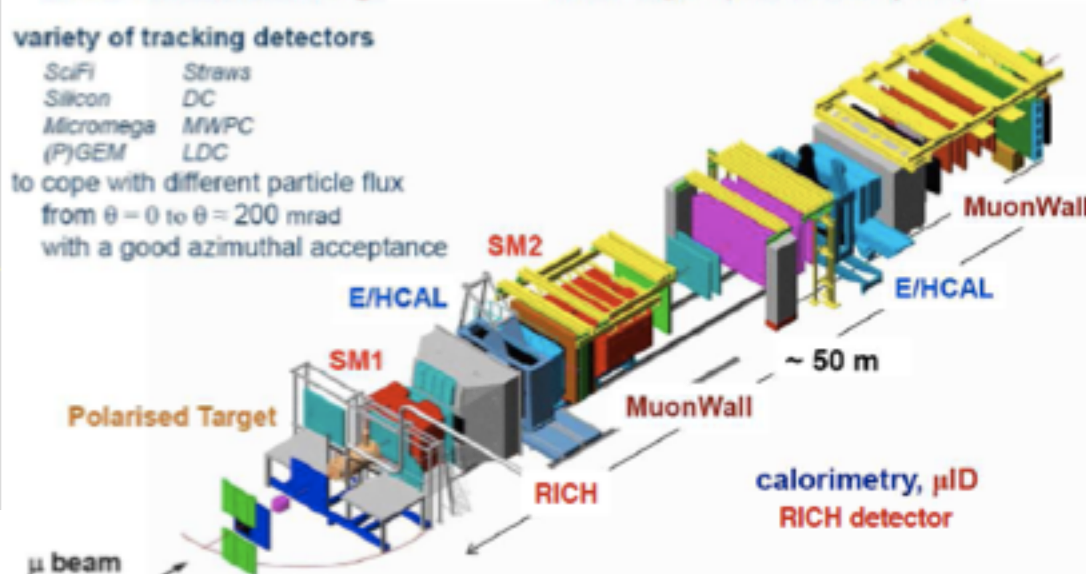


- high energy beams
- large angular acceptance
- broad kinematical range

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



Hall A at Jlab



SMC,COMPASS at CERN

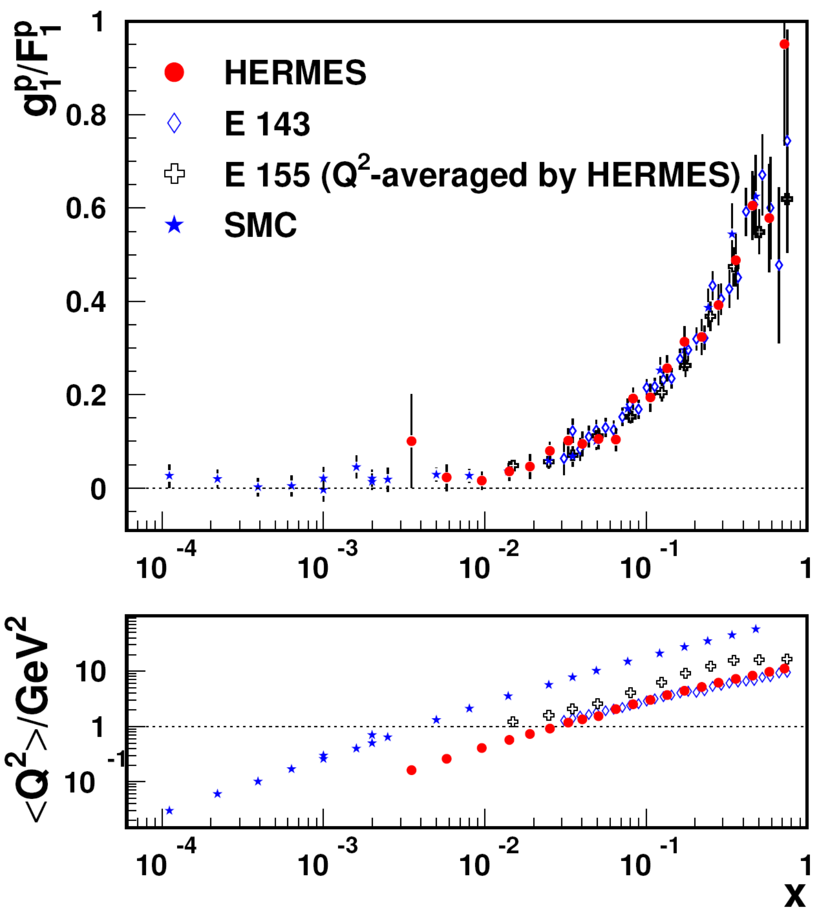
Comparison: fixed target experiments

exp	E_b (GeV)	x	Q^2 (GeV^2)	P_b
HERMES	27.6 $e^{\pm}$	0.02-0.6	1 - 15	$\pm$0.55
COMPASS	160 μ	0.003 - 0.6	1 - 100	-0.76
JLAB	<6 e^{-}	0.1 - 0.7	1 - 4.5	$\pm$0.7

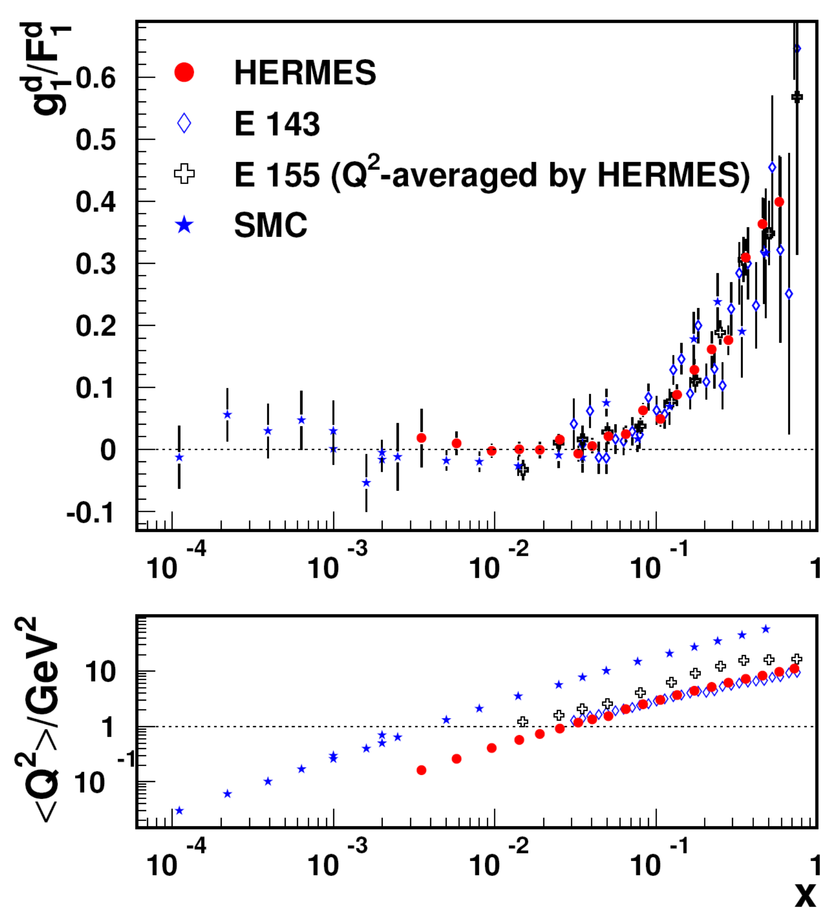
exp	P_t	target	$\mathcal{L}$ (cm^{-2}s^{-1})
HERMES	0.85	$\vec{\mathrm{H}}, \vec{\mathrm{D}}$	10^{31}
COMPASS	0.50	$\vec{\mathrm{Li}}\vec{\mathrm{D}}$	$5 \cdot 10^{32}$
Hall A	0.35	$^3\vec{\mathrm{He}}$	10^{36}
CLAS	0.8 (0.3)	NH_3 (ND_3)	10^{34}

Measurements:

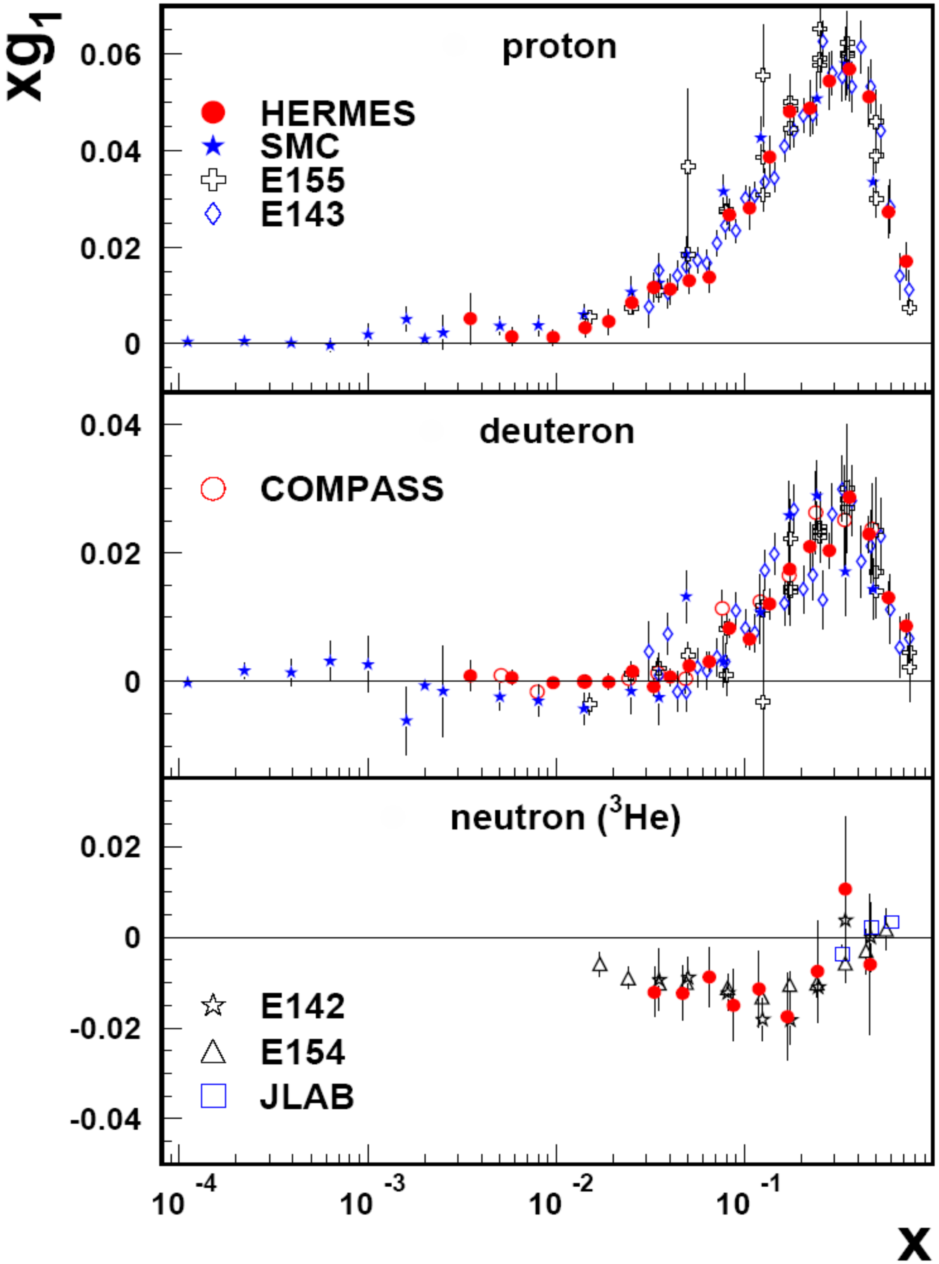
Proton Target

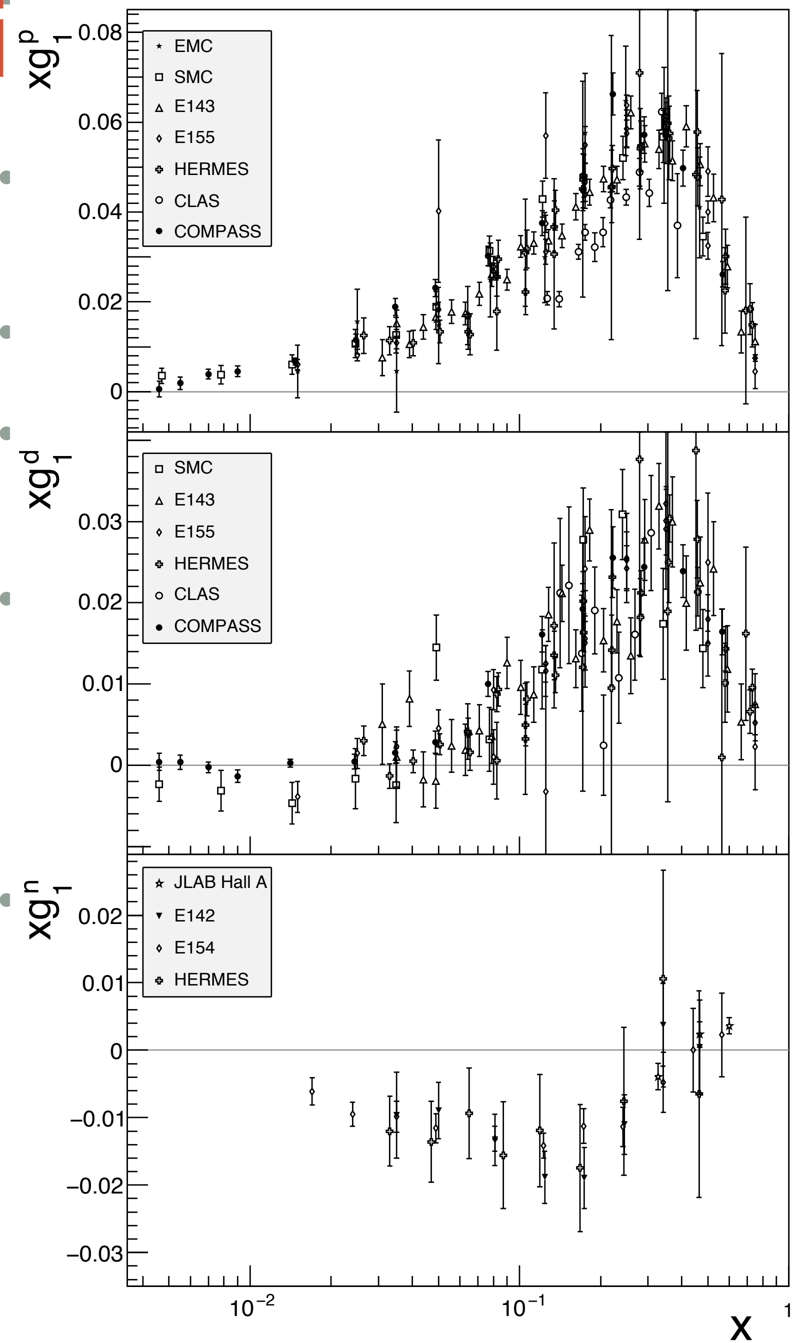


Deuteron Target



Spin structure Functi



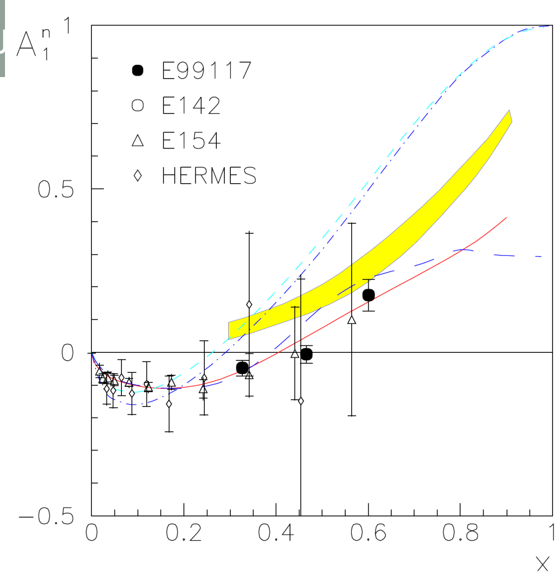


nde

Some fundamental tests of QCD?

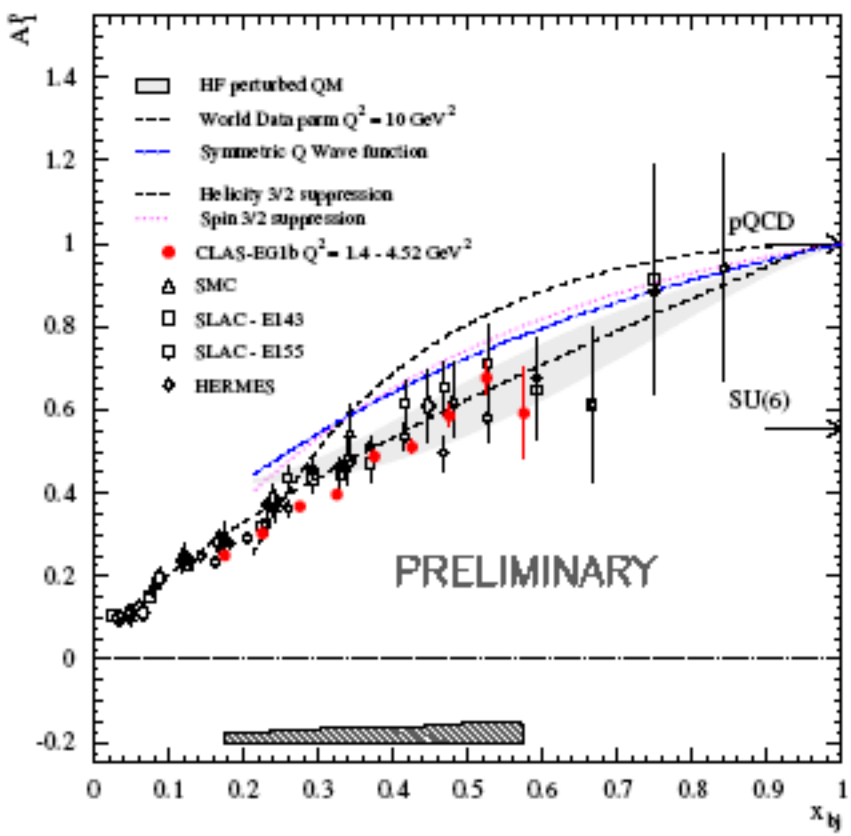
- So far we have focused only about:
  - Low x behavior of spin structure function
  - Its Q^2 evolution
  - Because those were needed to check various high energy sum rules

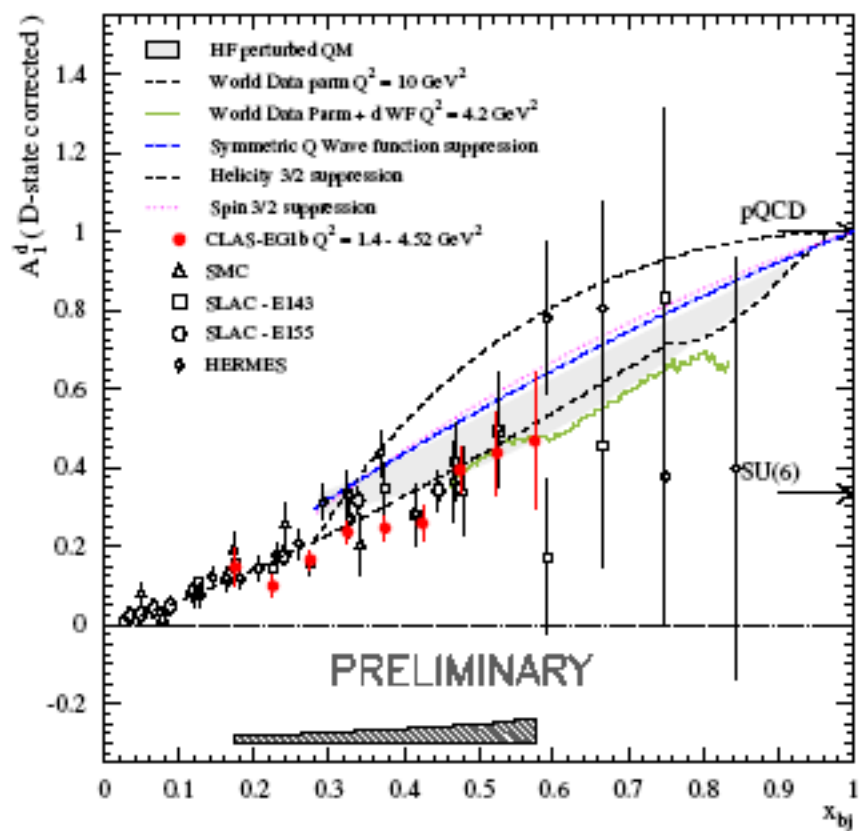
- ***What about high x?***
  - A region were we know gluons do NOT play a dominant role
  - Should we not test the predictions of structure functions and their behavior in this region?
  - Motivation for Jefferson Laboratory Physics



High x measurements

- Jlab focused on high x measurements: ***Luminosity Crucial!***
- A_1 of proton, neutron and deuteron
- pQCD predicts A_1=1 when x=1



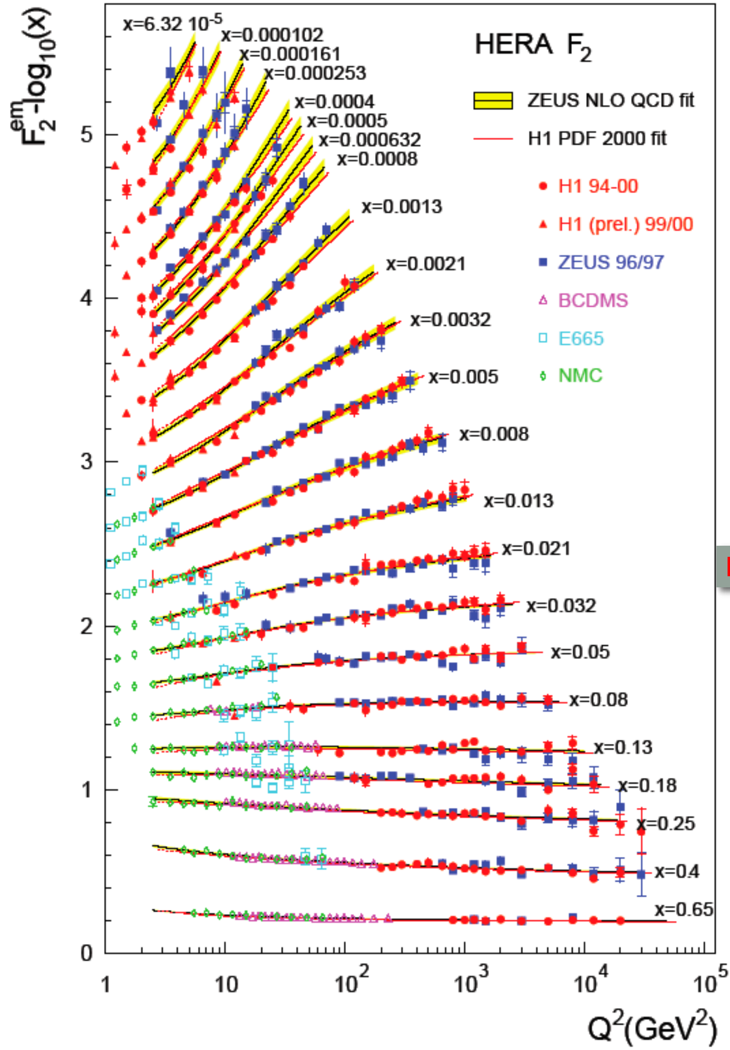


GET POLARIZED PARTON DISTRIBUTIONS

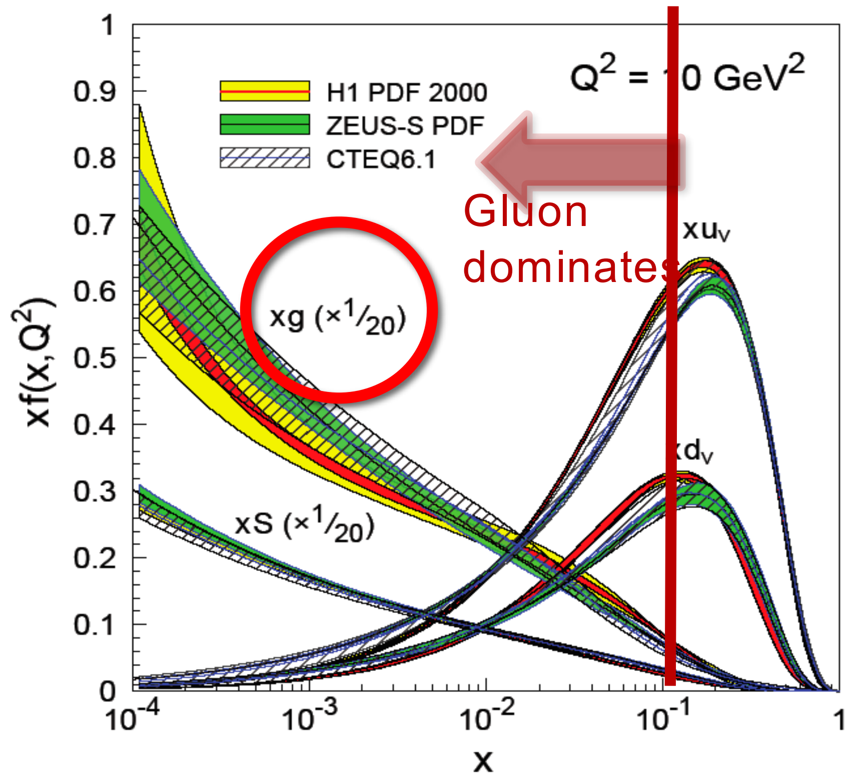
Next-to-Leading Order Perturbative QCD with DGLAP equation

SIMILAR IN SPIRIT TO WHAT IS DONE IN UNPOALRIZED PDFS…. CTEQ, MRST…

Similar to extraction of PDFs at HERA (RECALL)



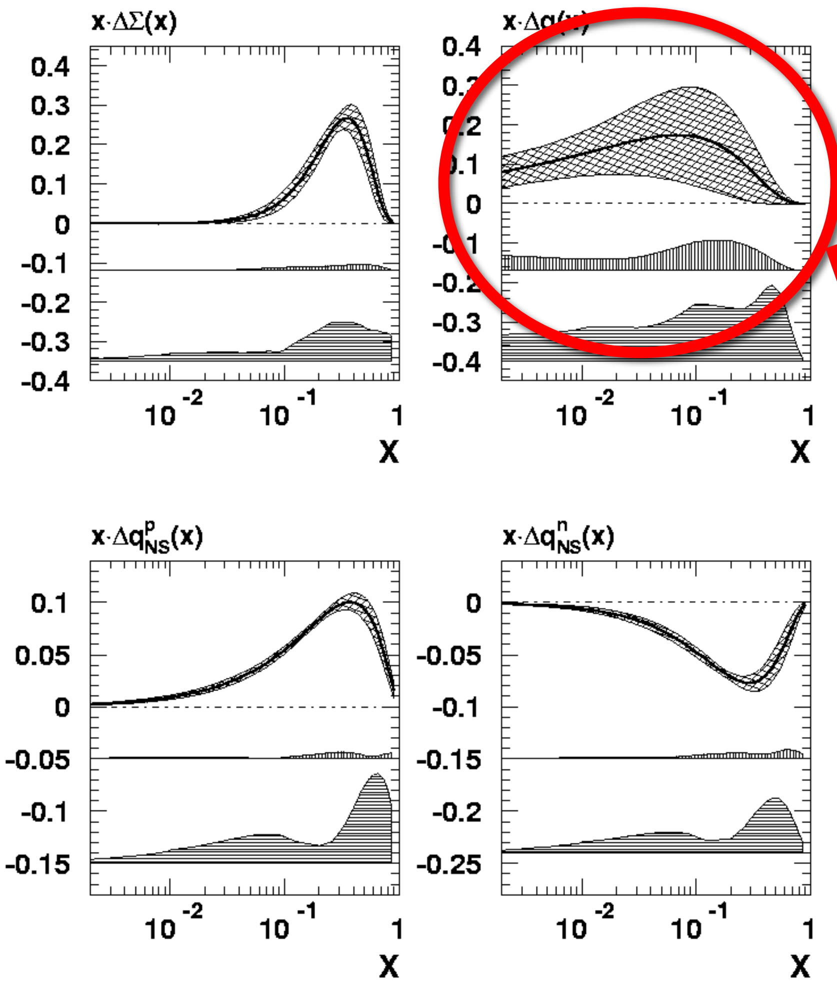
NLO pQCD analyses: fits with **linear** DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Global analysis of Spin SF

ABFR analysis method by SMC PRD 58 112002 (1998)



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

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

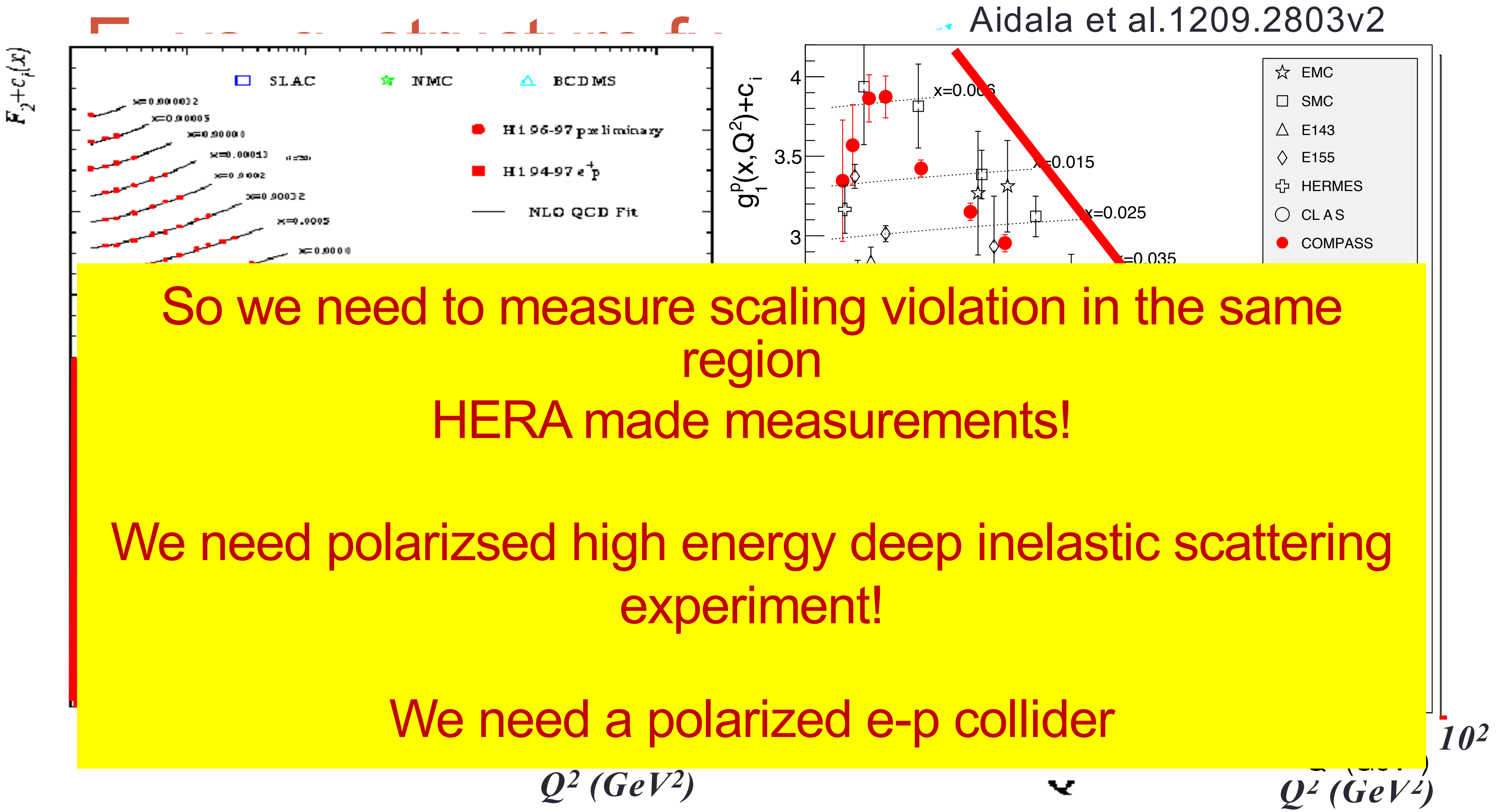
- Quark distributions fairly well determined, with small uncertainty
  - $\Delta\Sigma$ = 0.23 +/- 0.04
- Polarized Gluon distribution has largest uncertainties
  - ΔG = 1 +/- 1.5

Consequence:

- Quark + Anti-Quark contribution to nucleon spin is definitely small: Ellis-Jaffe sum violation confirmed

$$\Delta\Sigma = 0.23 \pm 0.03$$

- Is this small ness due to some cancellation between quark+anti-quark polarization: Semi-Inclusive data could address this.
- The gluon's contribution seemed to be large! $\Delta G = 1 \pm 1.5$
- While I am only presenting one global analysis result: Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
  - Anomaly scenario gained weight
  - Direct measurement of gluon spin with other probes warranted. Seeded the RHIC Spin program



So we need to measure scaling violation in the same region

HERA made measurements!

We need polarizsed high energy deep inelastic scattering experiment!

We need a polarized e-p collider

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

Natural questions about Nucleon's Spin

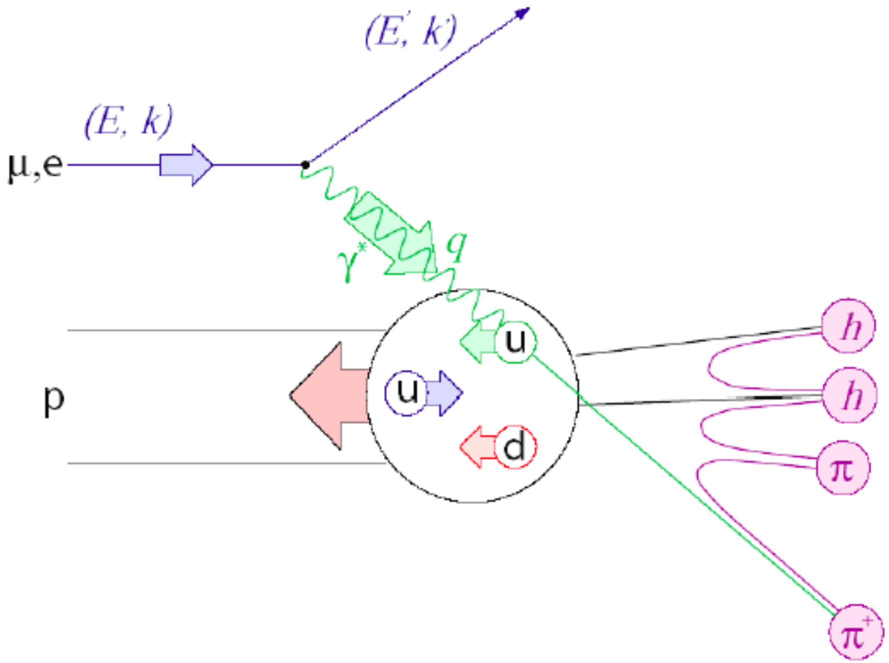
Do the quarks & anti-quarks really carry so little a spin of the proton?: ➔ A better precision on $\Delta\Sigma$ measurement highly needed.

$\Delta\Sigma$ contains quark as well as anti-Quark spin ➔Photons do not distinguish between them! Do the quarks and anti-Quarks cancel each others spin? i.e. are they anti-aligned for some reason?

Is the gluon's contribution to nucleon spin large? ➔ Is the "anomaly" scenario true? How would we do a direct determination of gluon's spin?

Is there an orbital motion of the quarks and gluons contributing to the nucleon spin?

Flavor tagging: semi-inclusive DIS



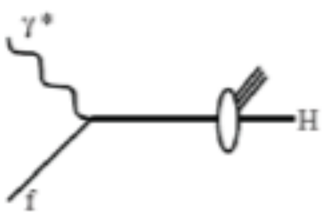
Method led
By HERMES
Now COMPASS
Jlab Experiments

- Inclusive DIS + *detect additional beam/target fragments*
- Selectively tagging *pions, kaons* separates the flavors involved in interactions, needs Particle ID
- Purity and efficiency of tagging studied extensively using MC simulations to overcome our ignorance in fragmentation process.

Significance of SIDIS

- In addition to scattered lepton, a hadron is observed and tagged, some times even identified.
- Probability to find a hadron H with fractional momentum z of the parton which evolved in to that hadron H: $D_f^H(z,Q^2)$
- pQCD predicts the Q^2 dependence identical to that of PDFs
- We get frag. functions from e+e- collisions (LEP, NOW BELLE)
- The reason we learn from the SIDIS data:

at LO:

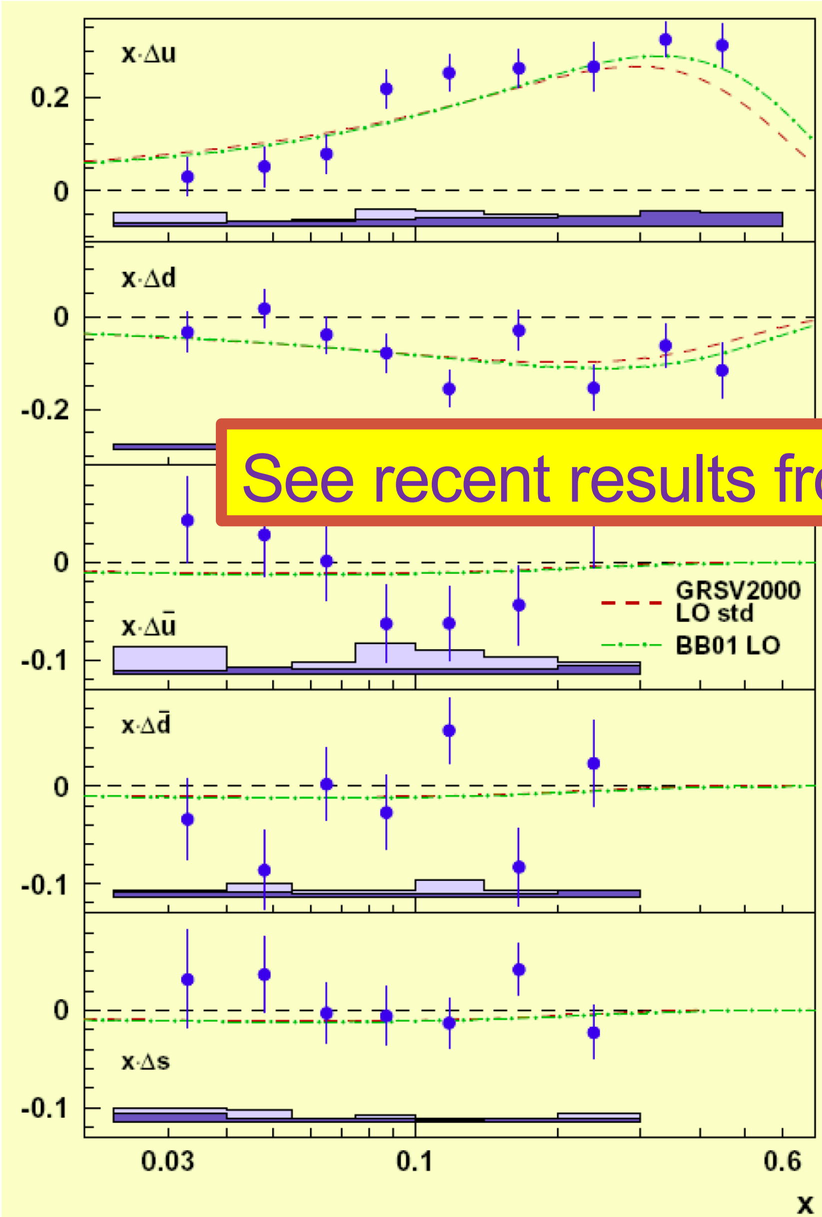


$$d\Delta\sigma \sim \sum_{q=u,\bar{u},\ldots,\bar{s}} \Delta q(x,Q^2) D_q^H(z,Q^2)$$

extra weight for each quark

breaks the $\Delta q + \Delta\bar{q}$ deadlock of DIS plus better flavor separation

Flavor Separation



$$A_1^h(x,Q^2) = \frac{\int dz \sum_f e_f^2 \Delta q_f(x,Q^2)\cdot D_f^h(z,Q^2)}{\int dz \sum_f e_f^2\, q_f(x,Q^2)\cdot D_f^h(z,Q^2)}$$

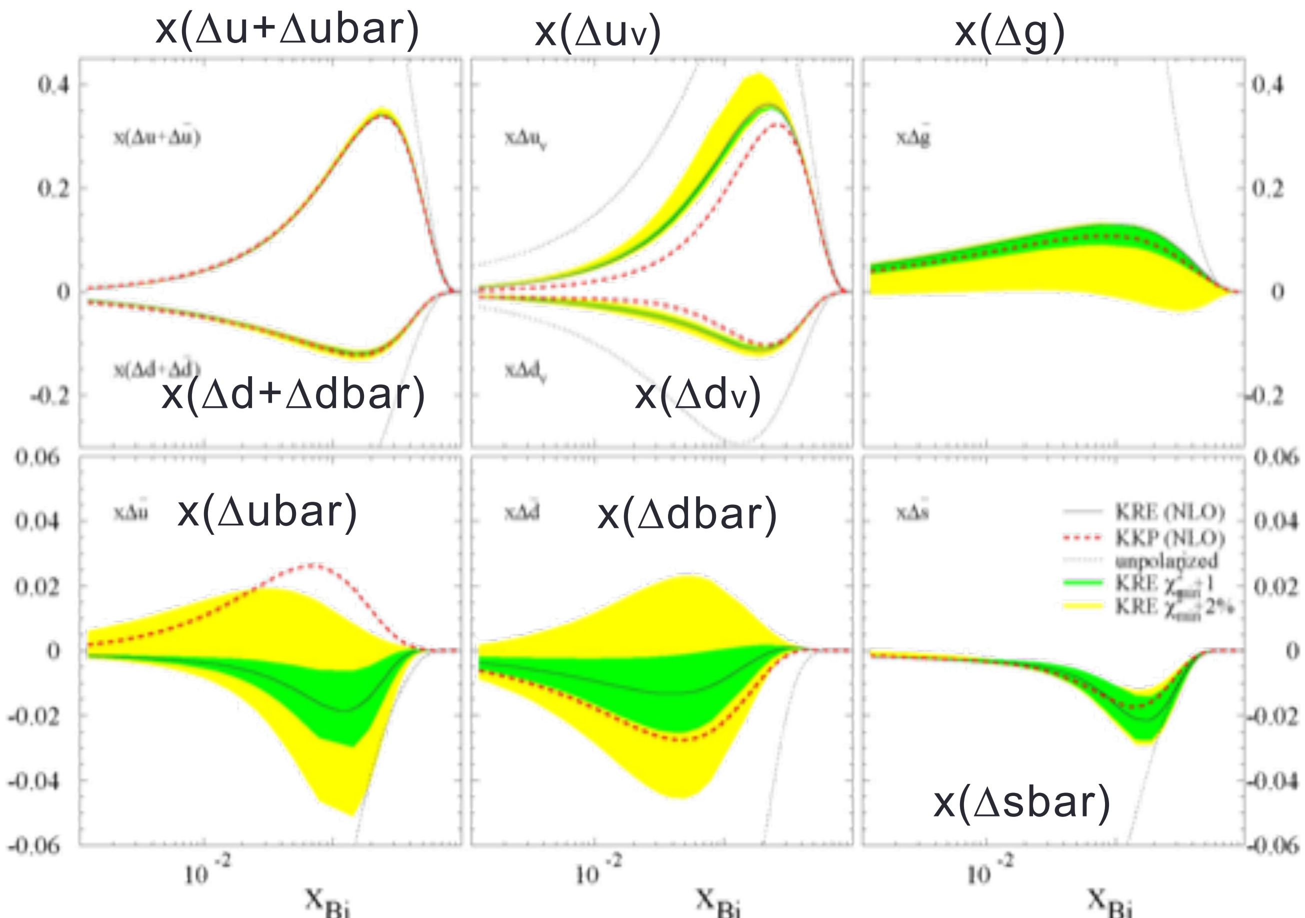
- Early 2000

See recent results from COMPASS collaboration

- Un-polarized fragmentation functions from LEP
- Evolution a la Altarelli Parisi
- Limited information of s, sbar due to lack of data on kaons
- LO extraction, MC used for purity and efficiency studies

Semi-Inclusive DIS Data & NLO pQCD

~2007, R. Sassot et al

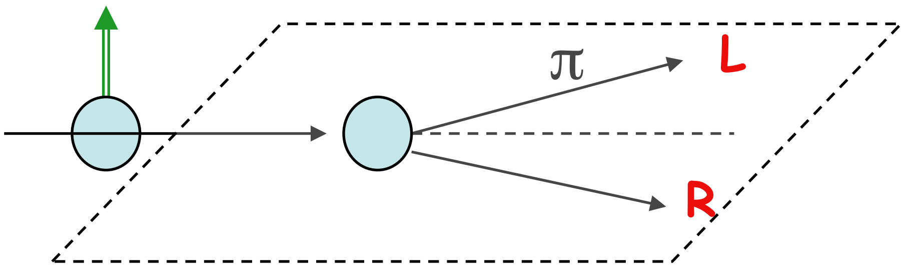


- **Sassot et al. NLO calculations/fits for inclusive+semi-inclusive data**
- Largest uncertainties in **polarized gluon & flavor separated anti-quark**

Transverse Spin Puzzle

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

Transverse spin introduction



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

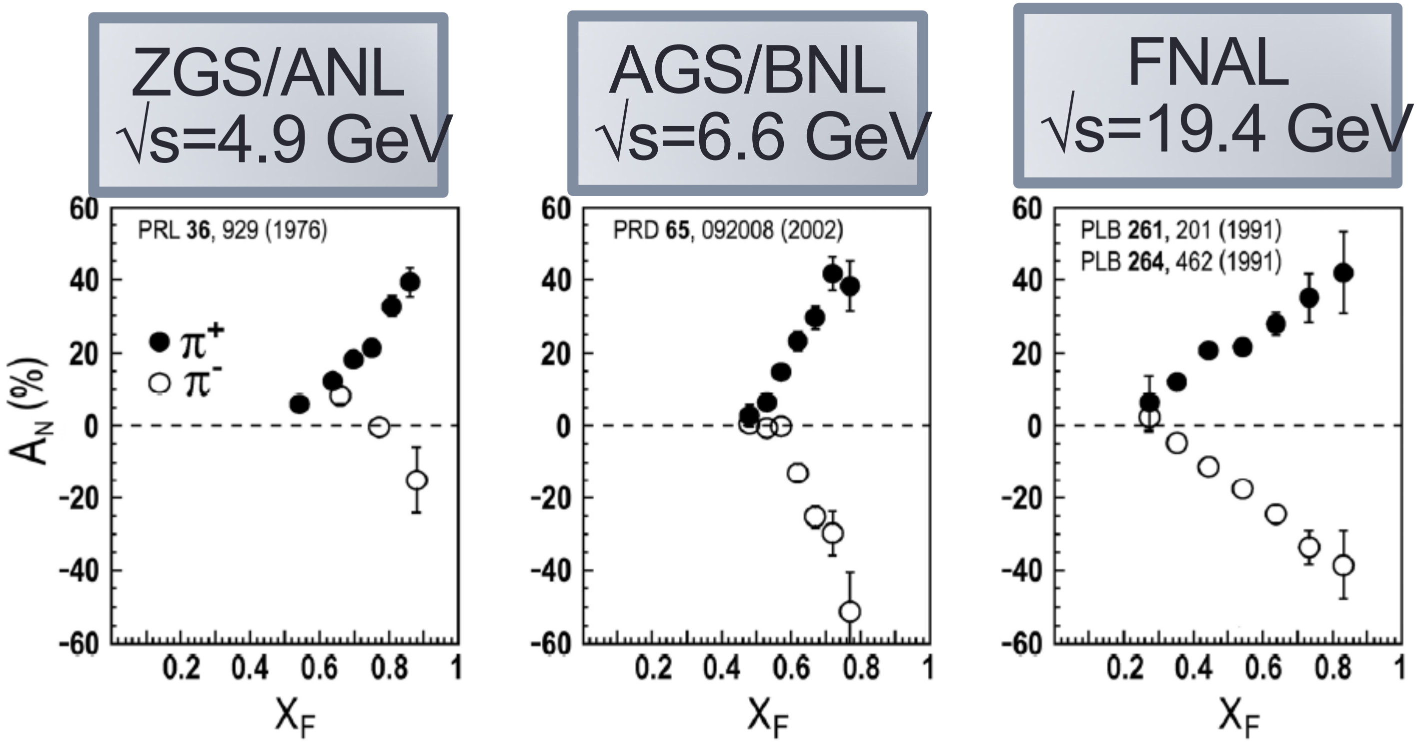
$$A_N \sim \frac{m_q}{p_T} \alpha_S$$

Kane, Pumplin, Repko 1978

- 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: single transverse spin asymmetries!

$$x_F = P_L / P_L^{\max} = 2P_L/\sqrt{s}$$



Results/Conclusions

By the time the fixed target polarized DIS experiments were over we learnt conclusively that:

- The quark+anti-quarks, $\Delta\Sigma$, indeed contribute very little

  $\Delta\Sigma$ = 0.3 +/- **0.03** (recall: 0.12 +/-**0.17** of EMC)
  The new results were calculated at Next-to-Leading Order pQCD.
  Low x extrapolations were consistent with pQCD

Ellis Jaffe spin sum rule was still violated

Bjorken Spin rule was found to be correct, other rules are continuously being updated, none have been found to be violated.

Polarized **gluon** distribution was found to be LARGE, but with large uncertainties

Dependence of results on Anti-Quark/Quark separation on non-perturbative objects such as *Fragmentation functions was a reason for concern….*

Seeds for RHIC Spin program:

Hadrons are almost full of gluons…. 95% of the mass of the hadrons comes from self interaction of gluons!

So if one wants to study gluons and their spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton collisions?***

A very nice measurement of anti-quark polarization was suggested, which did not require fragmentation functions

Curious and bothersome transverse spin asymmetries in p-p scattering persistent in every experiment performed…. US physicists heavily involved… decided to investigate further

Technical know-how of polarizing proton beams at high energy became available!