Electron Ion Collider Lecture 1

Why EIC? Development of the case for an EIC

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"Spin" is an interesting and fundamental property in nature

Always full of surprises!

1955
Bohr & Pauli
Trying to understand
The tippy top toy

1900's a Century of Spin Surprises!

Experiments that fundamentally changed the way we think about physics today!

- Stern Gerlach Experiment (1921)
  - Space quantization associated with direction
- Goudsmit and Uhlenbeck (1926)
  - Atomic fine structure and electron spin
- Stern (1933)
  - Proton's anomalous magnetic moment : 2.79 (proton not a point particle)
- Kusch (1947)
  - Electron's anomalous magnetic moment: 1.00119 (electron a point particle)
- Yale-SLAC Experiment (Prescott et a.)
  - Electroweak interference in polarizded e-D scattering
- European Muon Collaboration (EMC) (1988)
  - The Nucleon Spin Crisis (now – a puzzle)

20th Century could be called a "*Century of Spin Surprises!*"

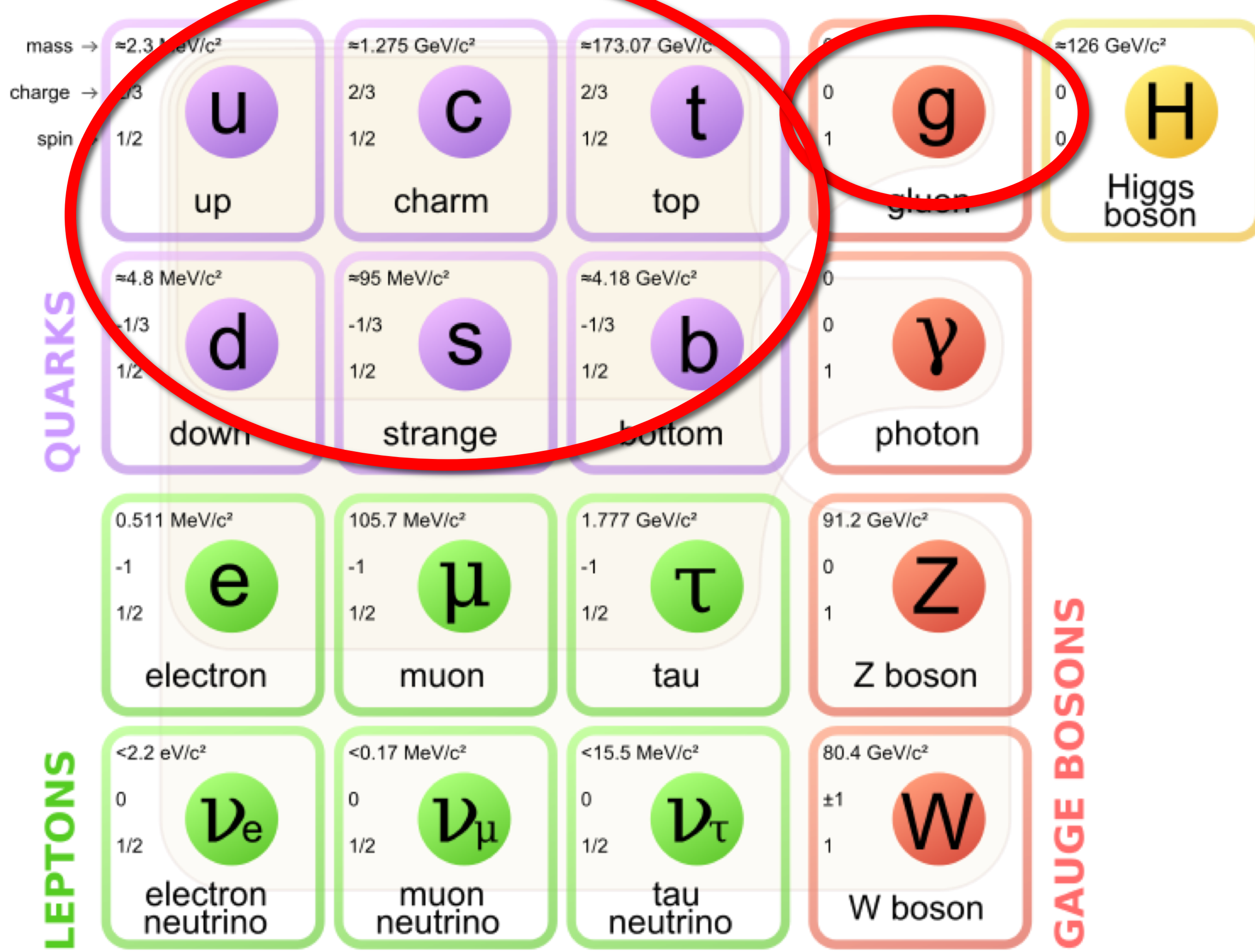
In fact, it has noted by :

Prof. Elliot Leader (University College London) that
"Experiments with spin have killed more theories in physics, than any other single physical variable"

Prof. James D. Bjorken (SLAC), jokingly, that
"If theorists had their way, they would ban all experiments involving spin"

The Standard Model of physics

Theory of *almost* everything



QED vs. QCD

- Quantum Electro-Dynamics (QED)
  - Electric charges : 2 types + & -
  - Electrons, protons carry electric charge
  - Interactions mediated by massless "photons" γ
  - Photons are electrically neutral → no electromagnetic charge!

Charge Carriers in QED is Chargeless!

- Quantum Chromo-Dynamics (QCD)
  - Color charges : 3 types → red, blue, green ➔ Never seen separately
  - Interactions between quarks mediated by massless "gluons" → "g"
  - Quarks carry electric AND color charge
  - Gluons are electrically neutral but carry color charge!

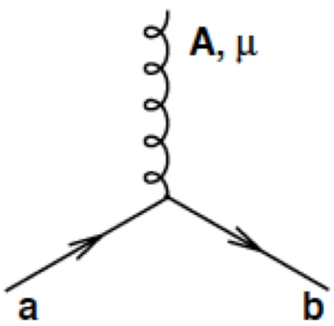
Charge Carrier in QCD is Charged!

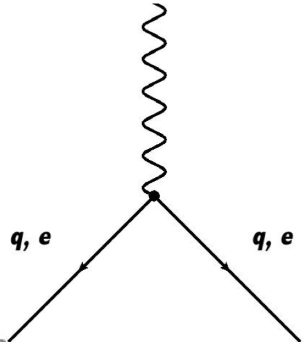
What distinguishes QCD from QED?

QED is mediated by photons (γ) which are charge-less

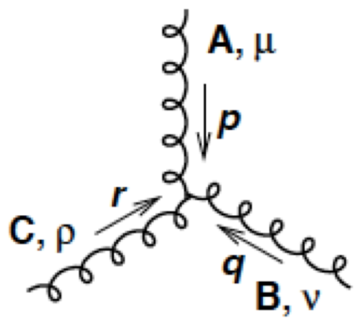
QCD is mediated by gluons (g), also charge-less but *are* colored!

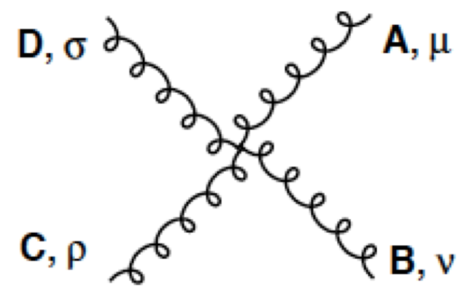
In QCD & g → γ in QED





Only in QCD

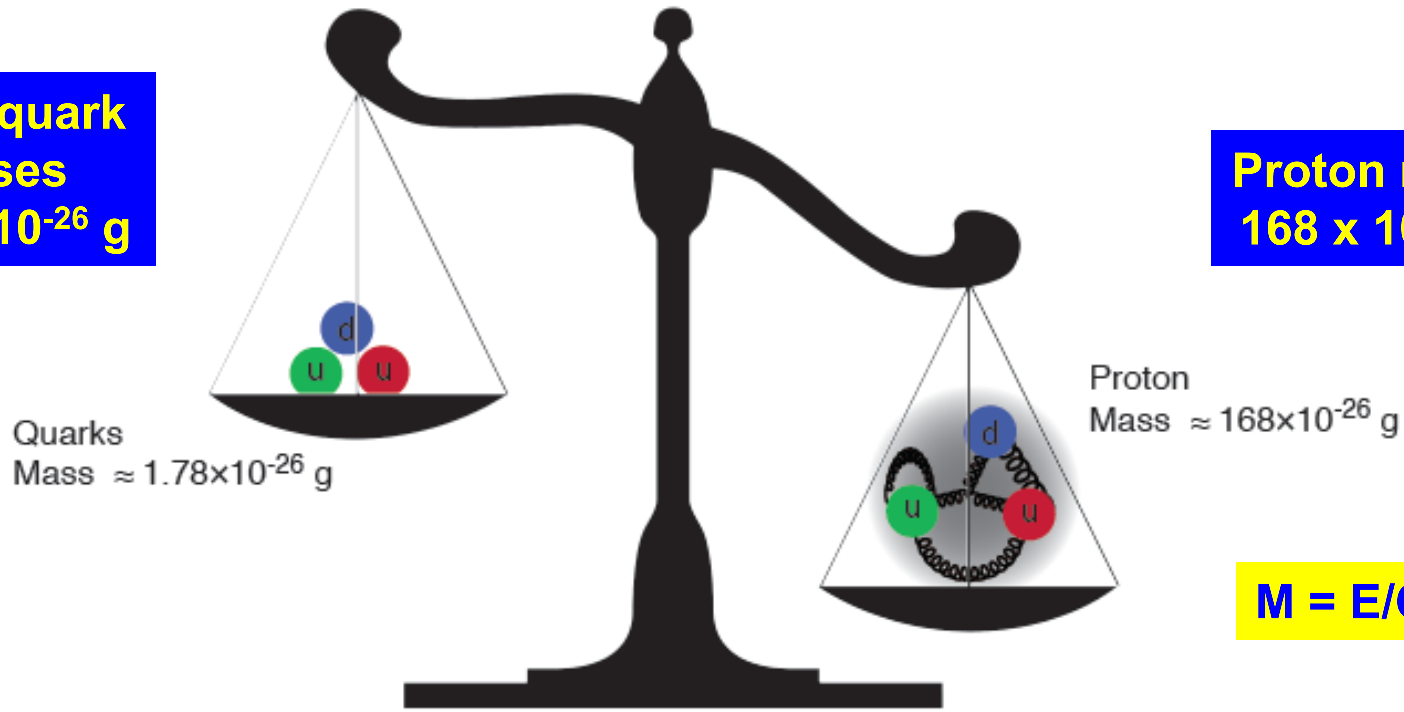




The Color-Interactions create mass!!!!

The mass miss-understanding

Sum of quark masses = 1.8 x 10^{-26} g



Proton mass 168 x 10^{-26} g

$M = E/C^2$

The **Higgs** ["God particle"] is responsible for **quark** masses ~ 1-2% of the proton mass.

Gluons are massless…yet their interaction are responsible for (nearly all) the **mass of visible matter in the universe**

Deep Inelastic Scattering

A most impressive investigative method in particle physics

If you wanted to look inside the hadrons….

Understanding the proton structure

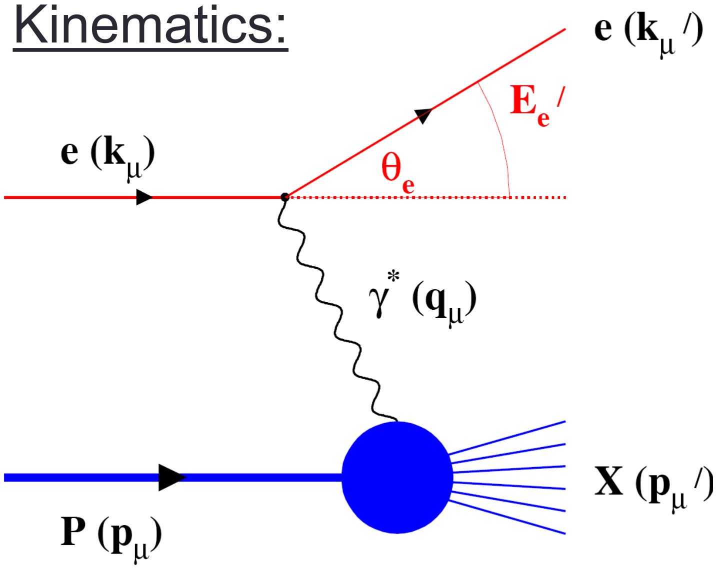
How would you do it?

Deep Inelastic Scattering (DIS)

- Discovered quarks inside the nucleons → birth of QCD → Nobel Prizes in 1990 and 2004, respectively…
- Discovered Nucleon Spin Crisis
- Discovered the quarks inside a proton in nucleus behave differently

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 :

$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ

Inclusive events:

e+p/A → e'+X

detect only the scattered lepton in the detector

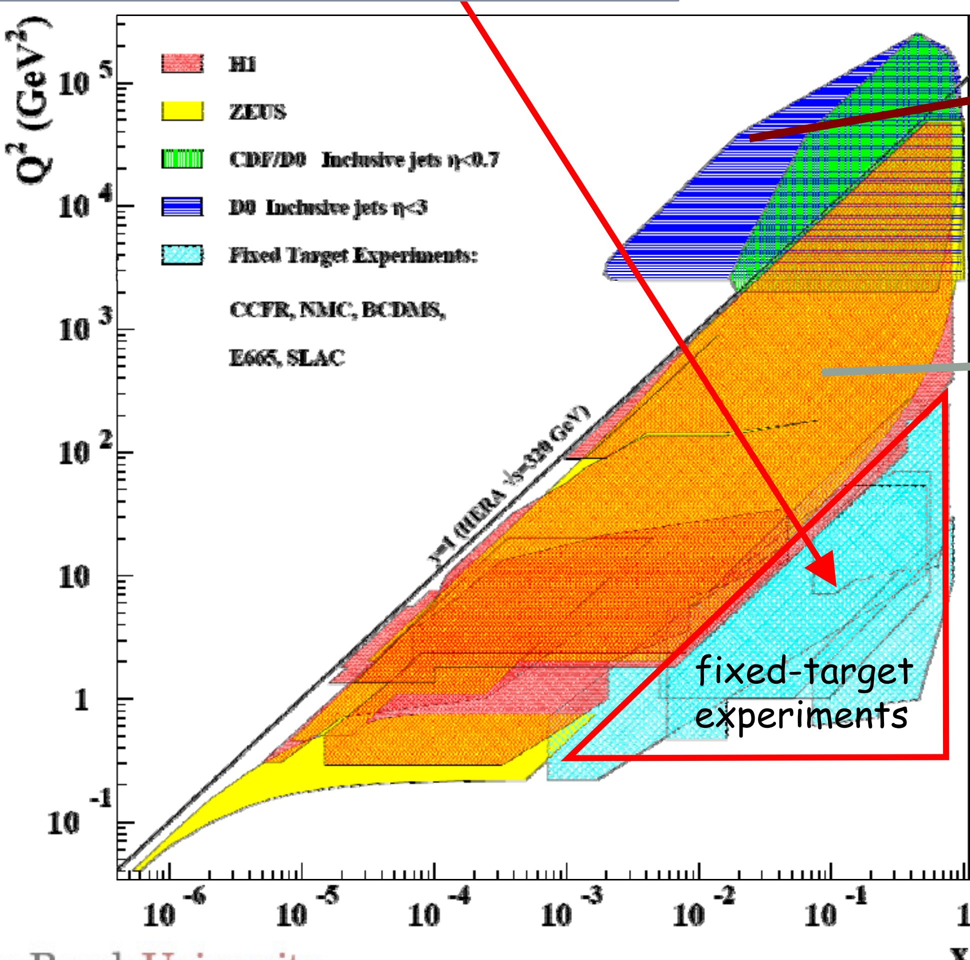
Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

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

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?

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)

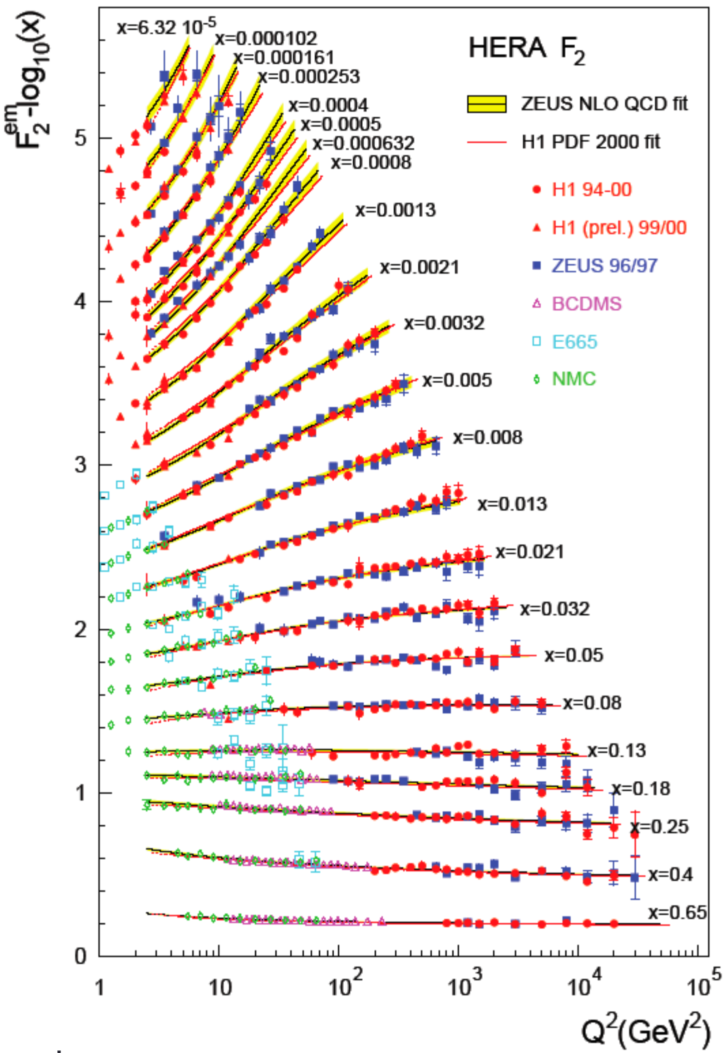
Lepton spin (s)

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

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

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

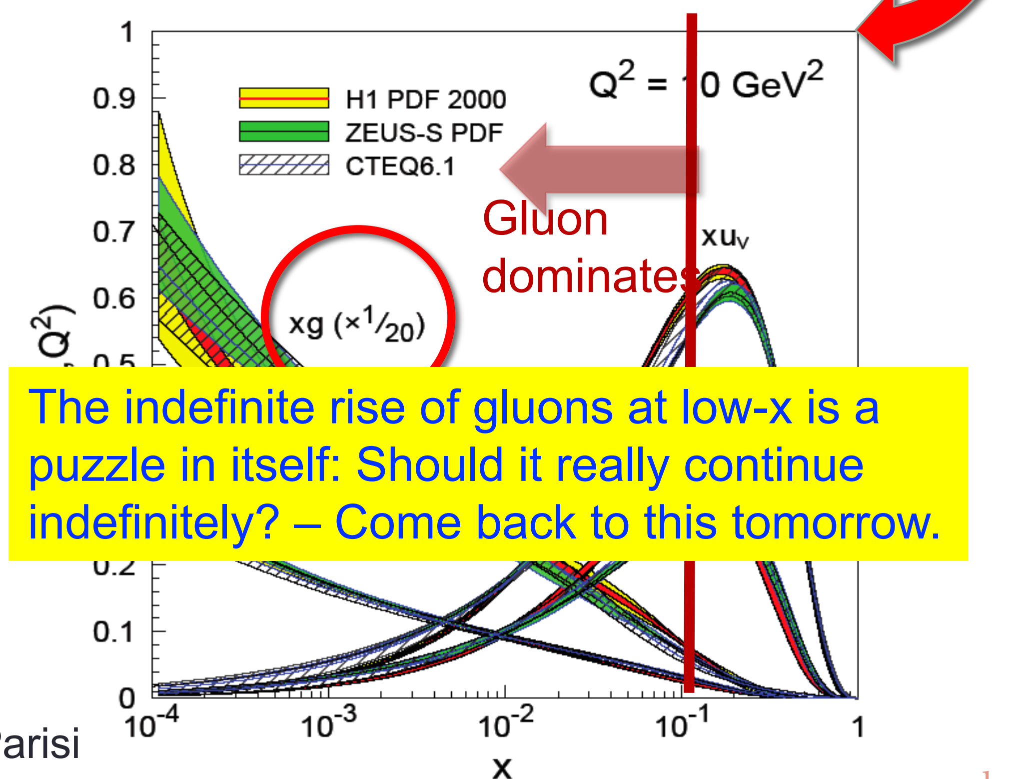
Measurement of Glue at HERA



- 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



The indefinite rise of gluons at low-x is a puzzle in itself: Should it really continue indefinitely? – Come back to this tomorrow.

*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

Lepton-nucleon Cross Section *without spin*

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

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

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

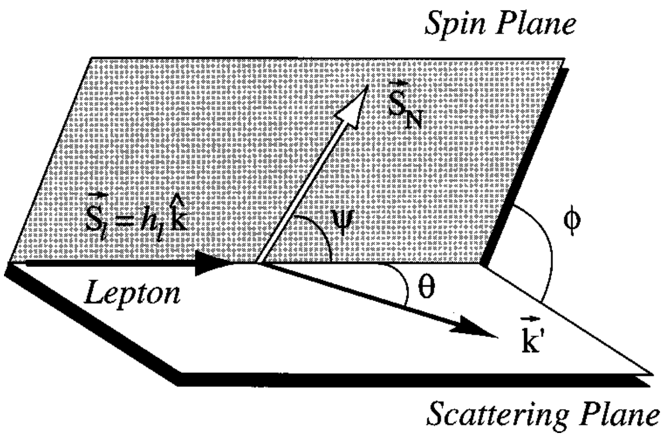
lepton helicity $h_l = \pm 1$

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

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

exchanged virtual photon energy $= \nu$

Lepton-nucleon cross section…*with spin*



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

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

For high energy scattering γ is small

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

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

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

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

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 & Q² or t dependence of Structure Functions

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

Singlet quark distribution
And its t dependence

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

(Singlet) Gluon distribution
And its t dependence

Non-Singlet quark distribution
And its t dependence

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

Spin Crisis

Life was easy in the Quark Parton Model until first spin experiments were done!

Understanding the proton spin structure:

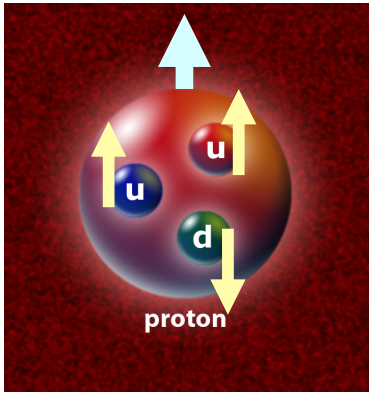
Friedman, Kendall, Taylor: 1960’s SLAC Experiment

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)

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

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

Experimental measurements with spin

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

We know from experiments in 1990s

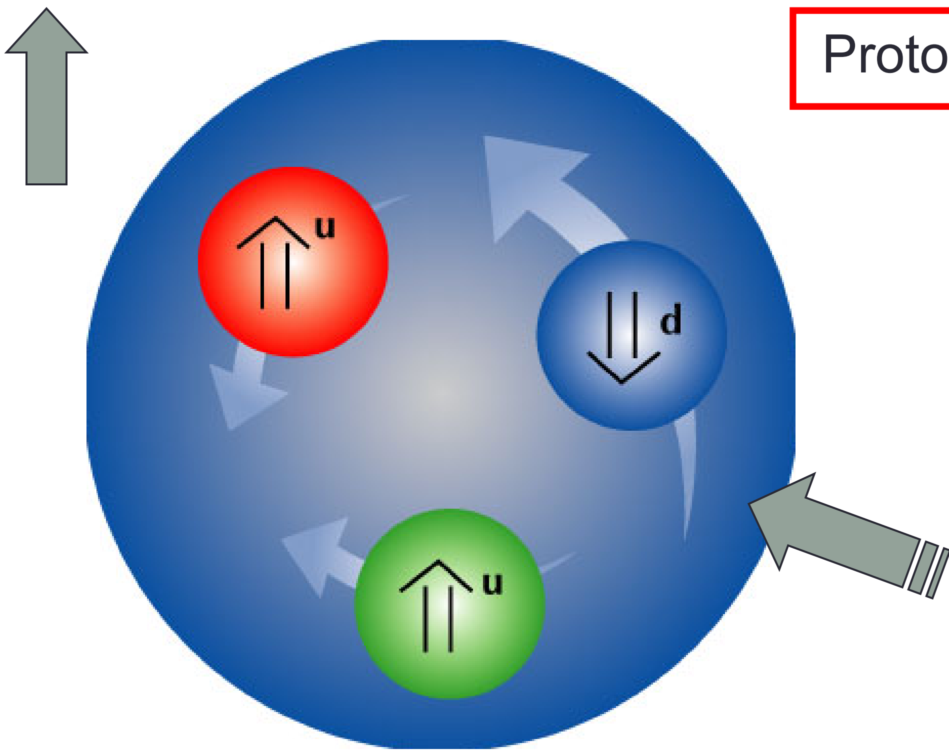
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects… now, illustration only, but historically taken seriously)

- 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!

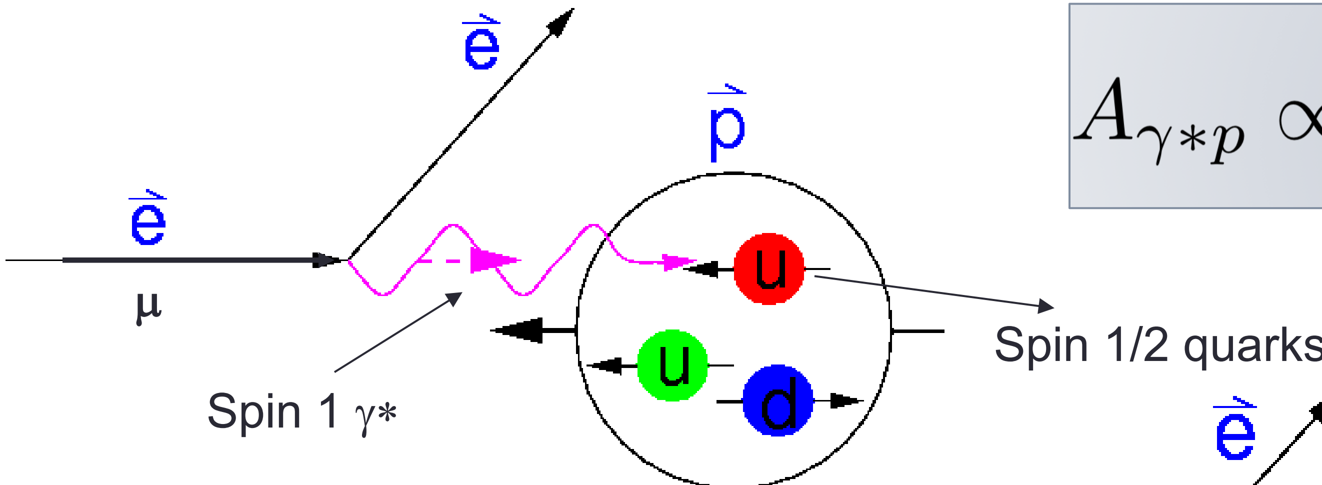
1/2 $\stackrel{?}{=}$ 1/2 + 1/2 + 1/2

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

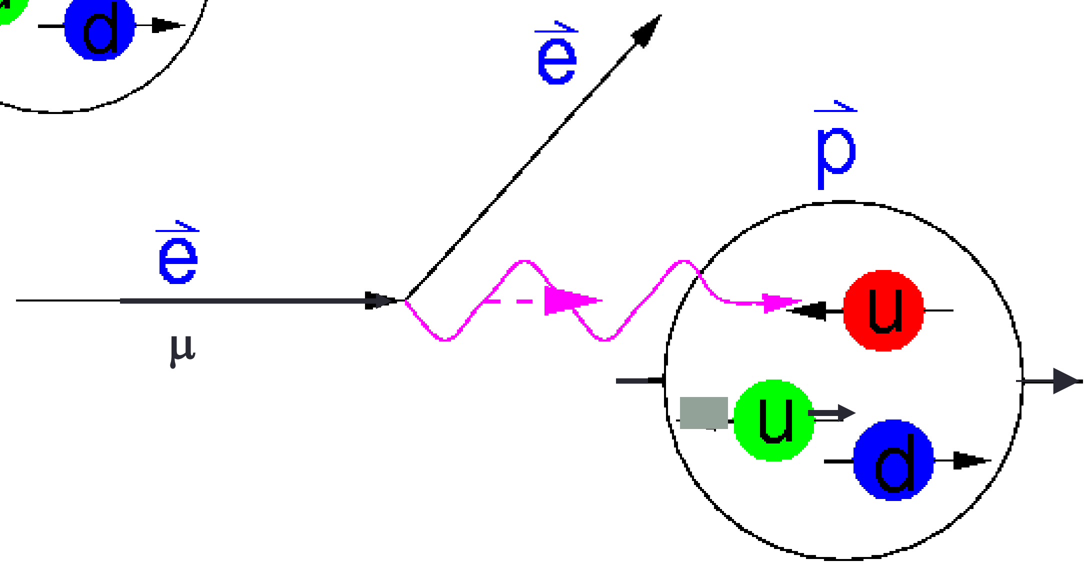
How was the Quark Spin measured?

- 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

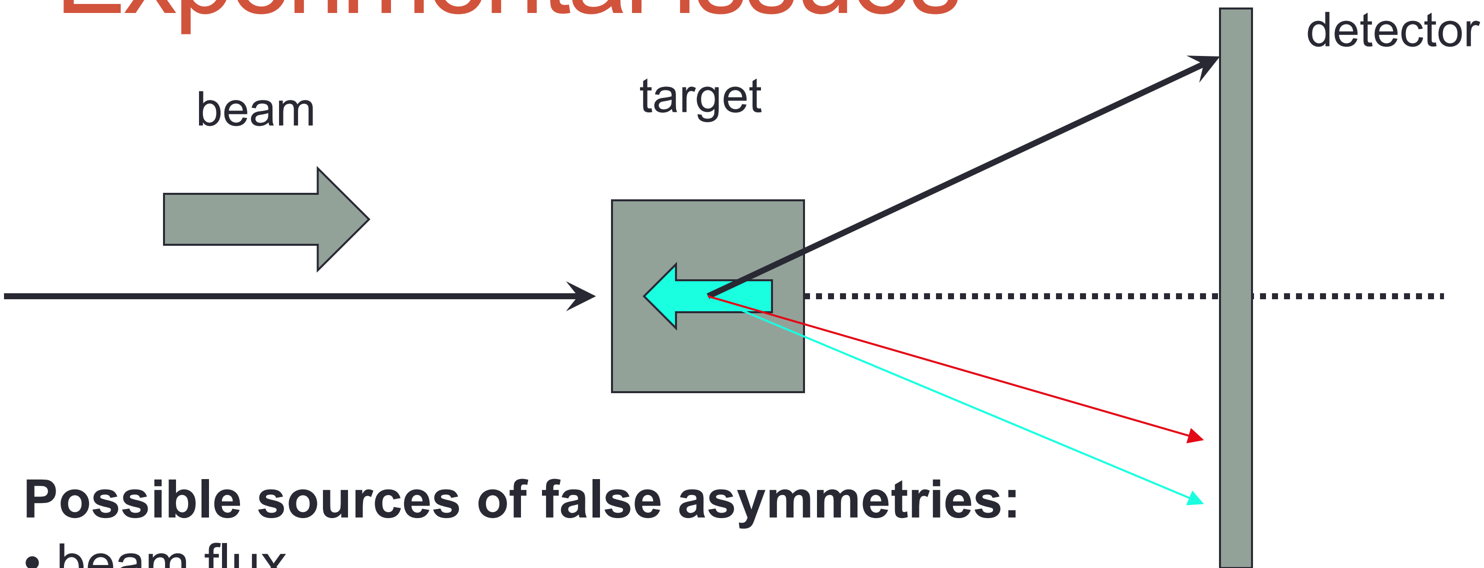
Determine the kinematics: measure with high accuracy:

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

Control of false asymmetries:

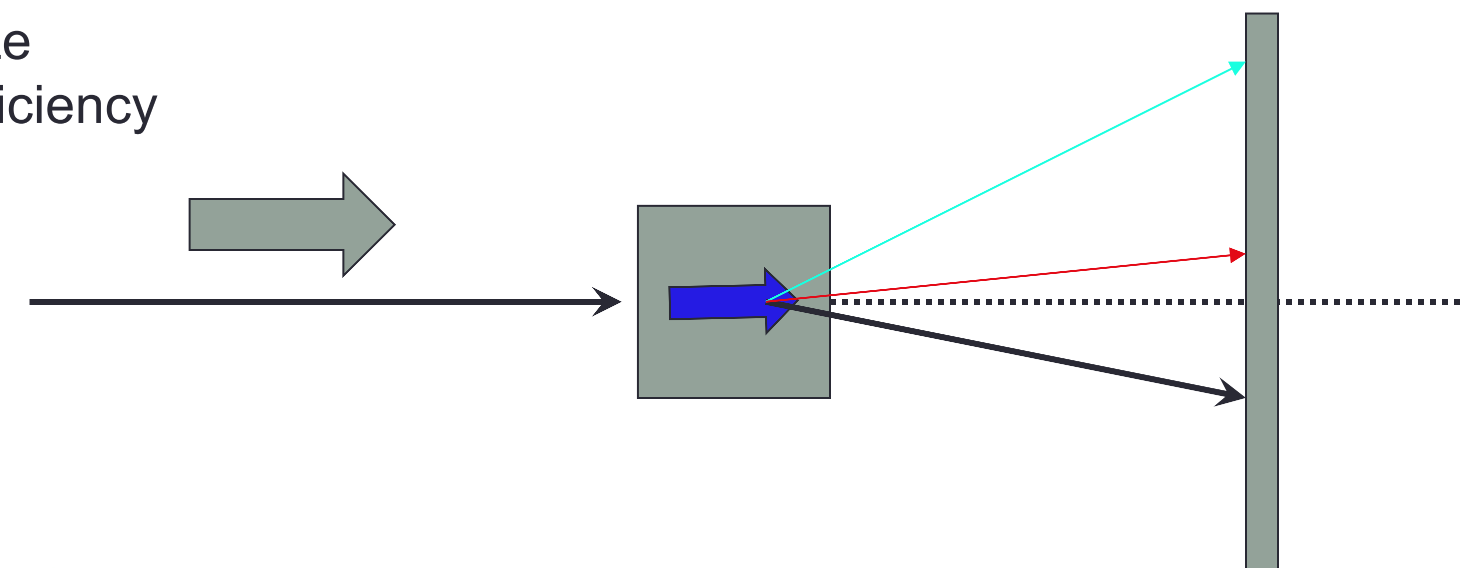
- Need excellent understanding and control of **false asymmetries** (time variation of the detector efficiency etc.)

Experimental issues



Possible sources of false asymmetries:

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



An Ideal Situation

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

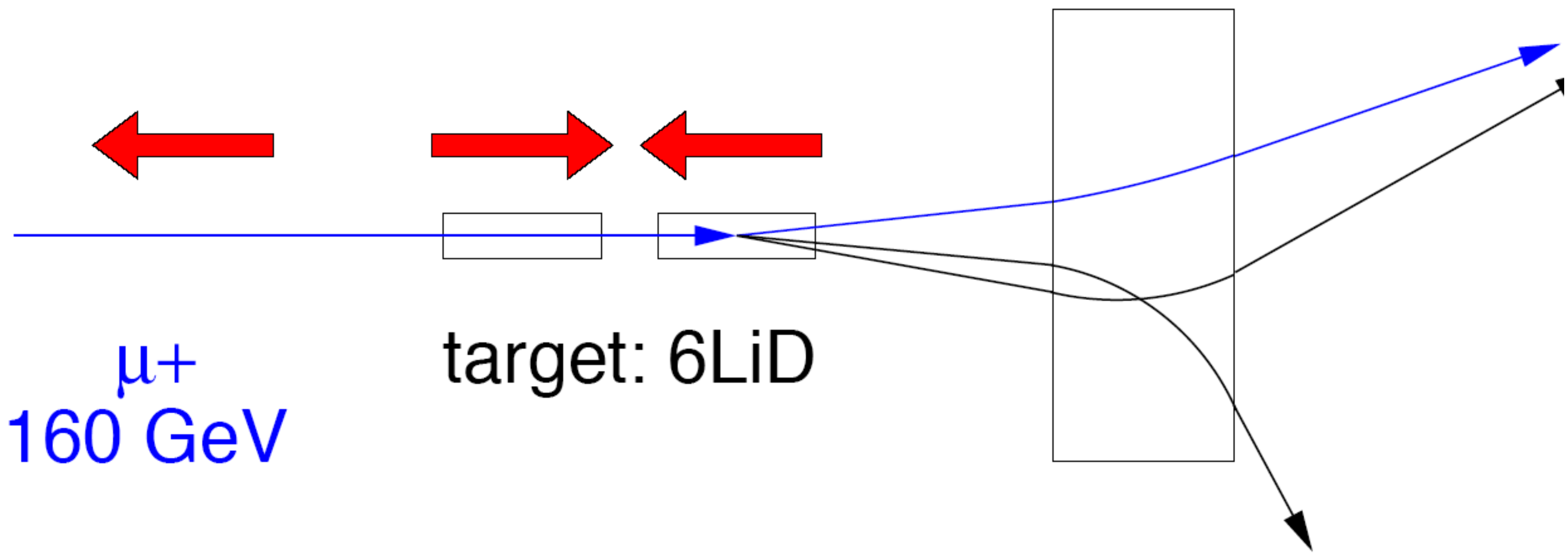
$$N^{\leftarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\leftarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

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

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

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

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

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

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

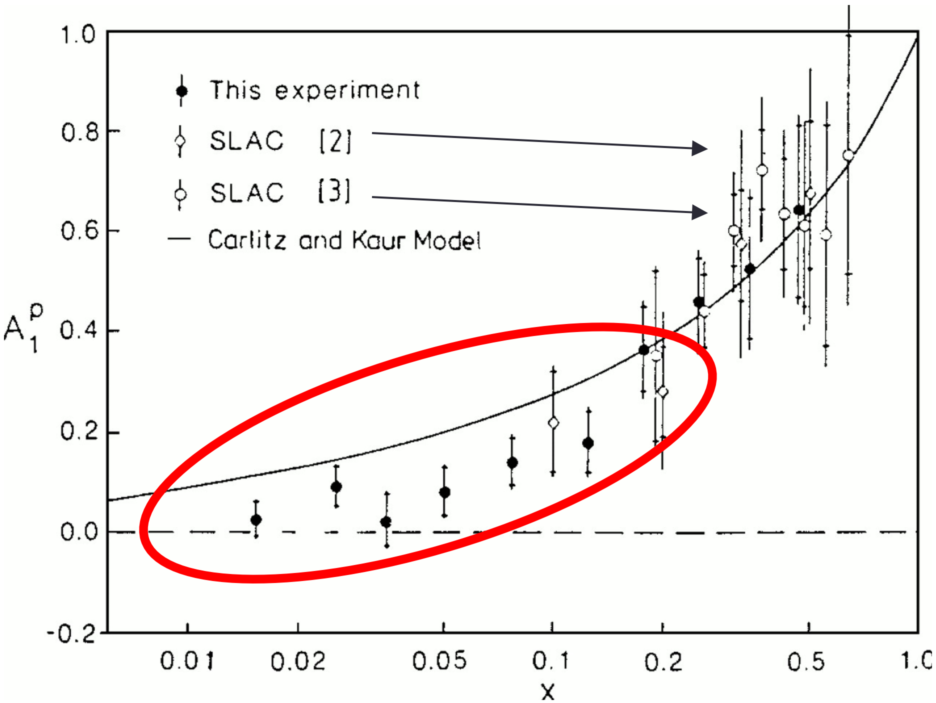
Measurements were done at SLAC (E80, E130) Experiments:

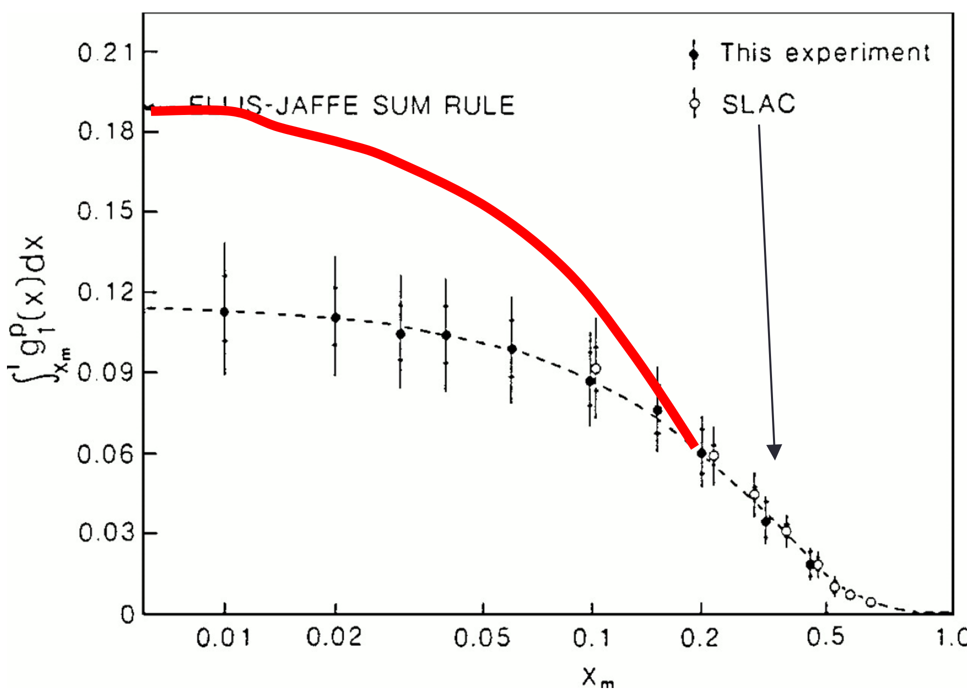
- Low 8-20 GeV electron beam on fixed target
- Did not reach low enough x → $x_{min} \sim 10^{-2}$
- Found consistency of data and E-J sum rule above

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)

$\Delta\Sigma$ = 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**.

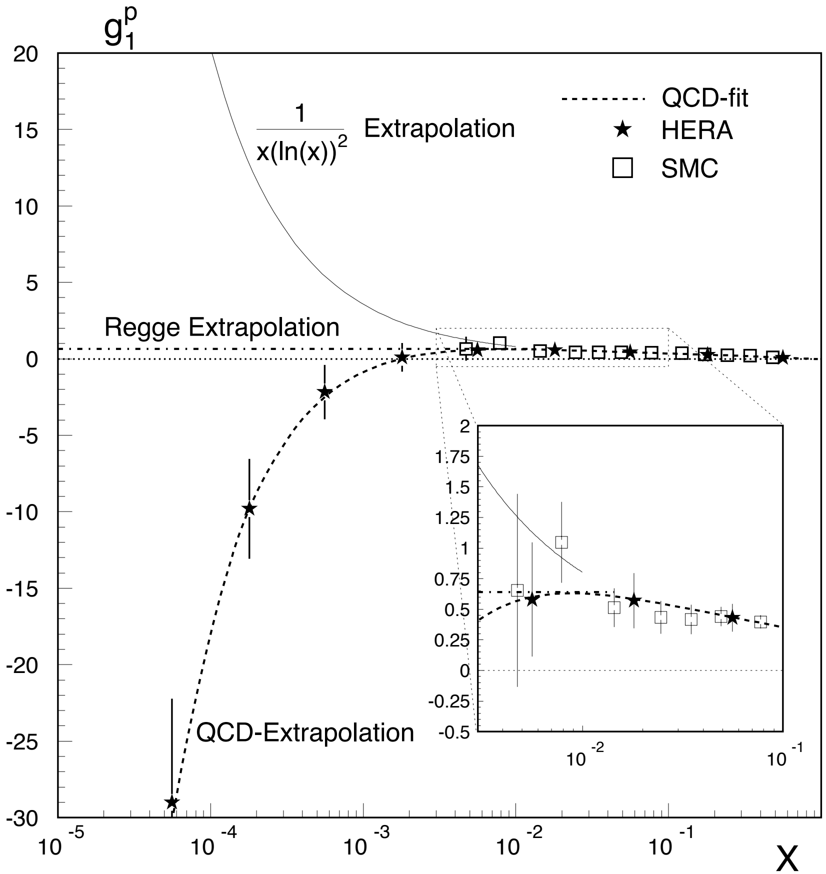
Extrapolations to x = 1, are *somewhat* less problematic:

$$|A_1| \leq 1$$

- 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

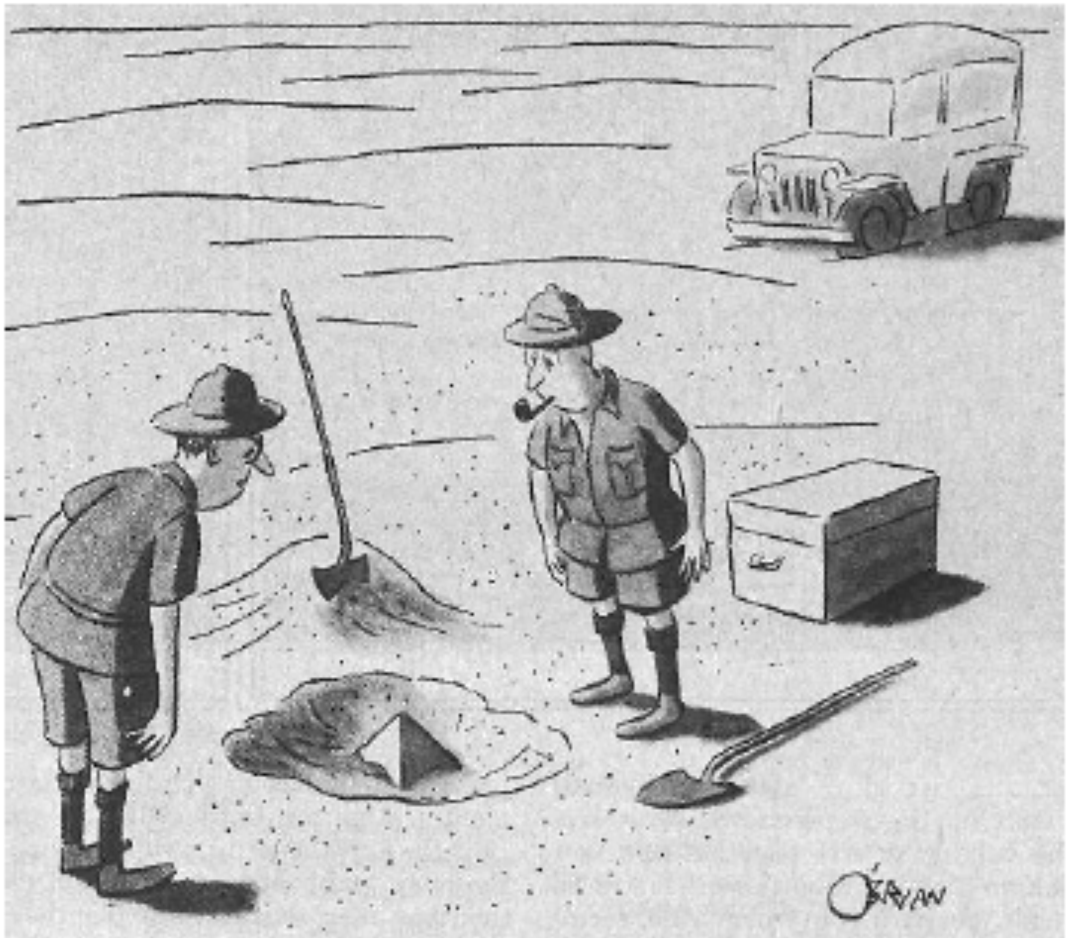
A collection of low x behaviors:



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.

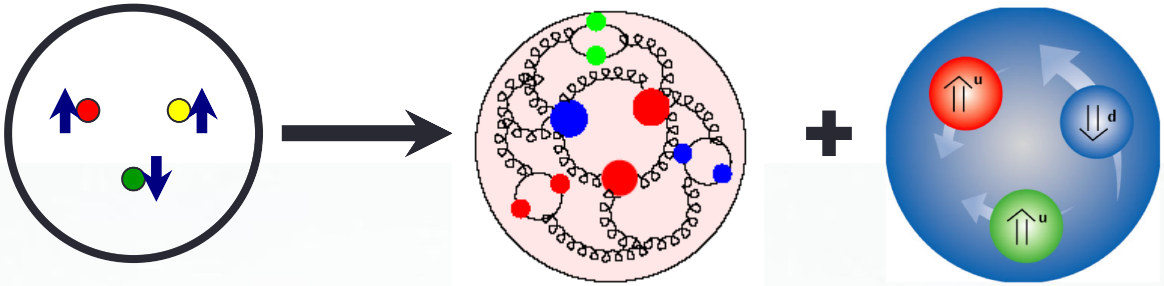
How significant is this?



of course, on how far down it goes.

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

Evolution: Our Understanding of Nucleon Spin



1980s

1990/2000s

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

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

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:

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

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

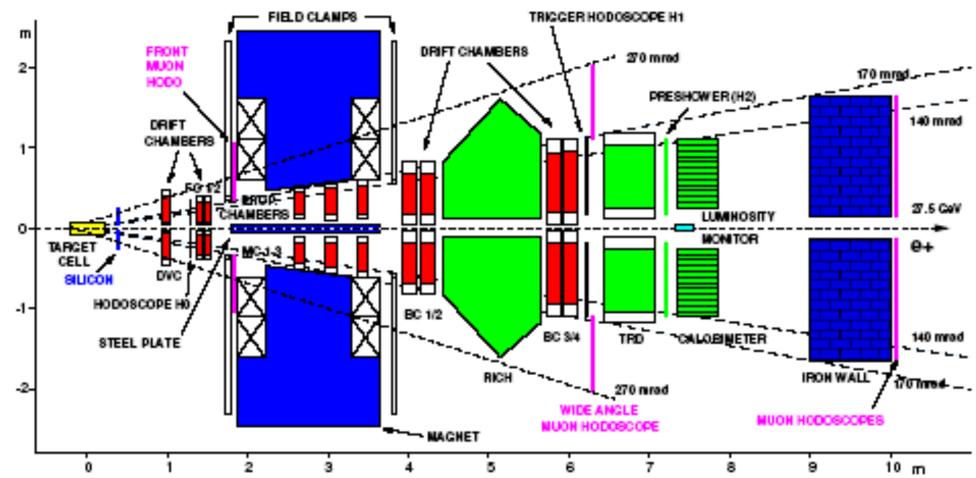
It became clear that precision measurements of nucleon spin constitution was needed!

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

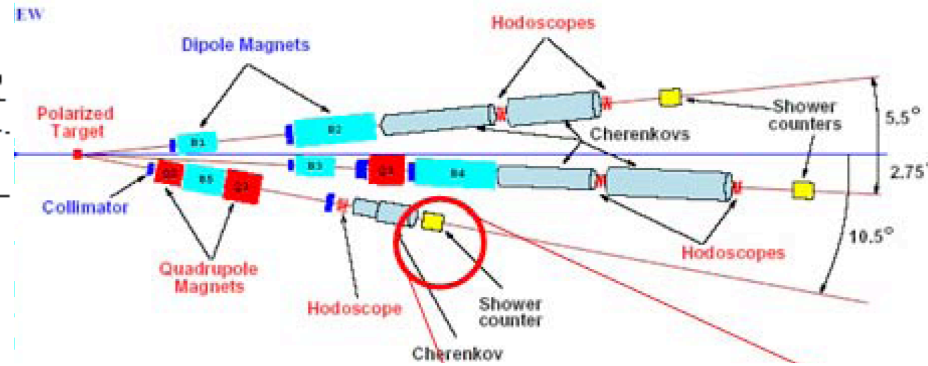
SMC and COMPASS experiments at CERN
E142-E155 experiments at SLAC
HERMES experiment at DESY
Hall A, B, C at Jefferson Laboratory

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

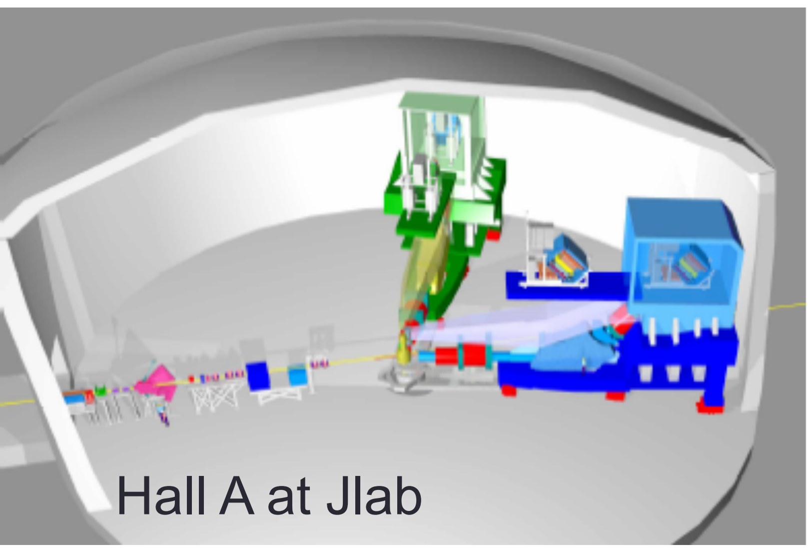


HERMES at DESY



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

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

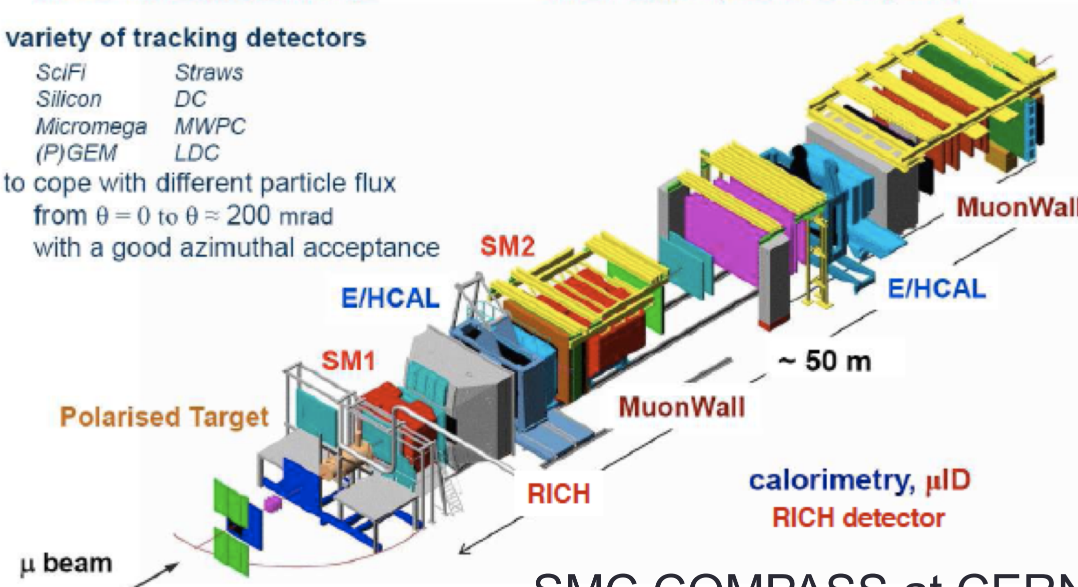


Hall A at Jlab

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

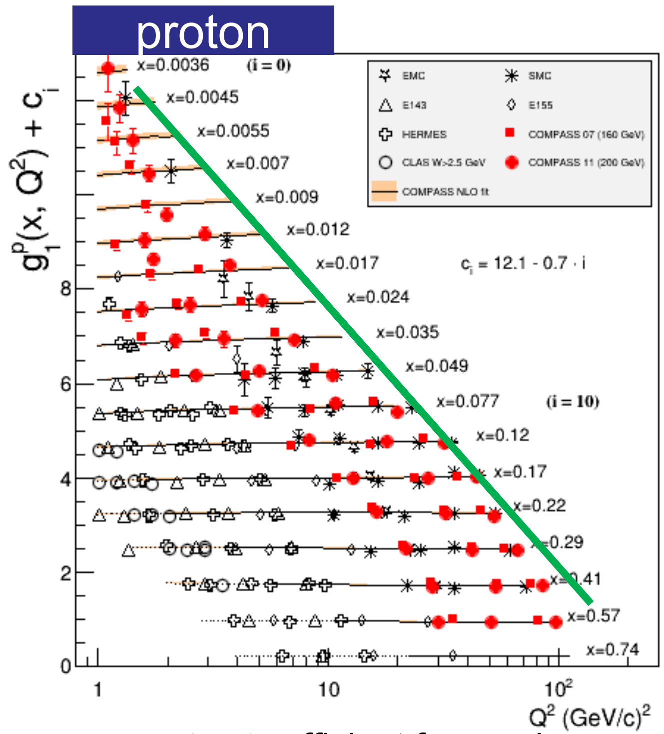


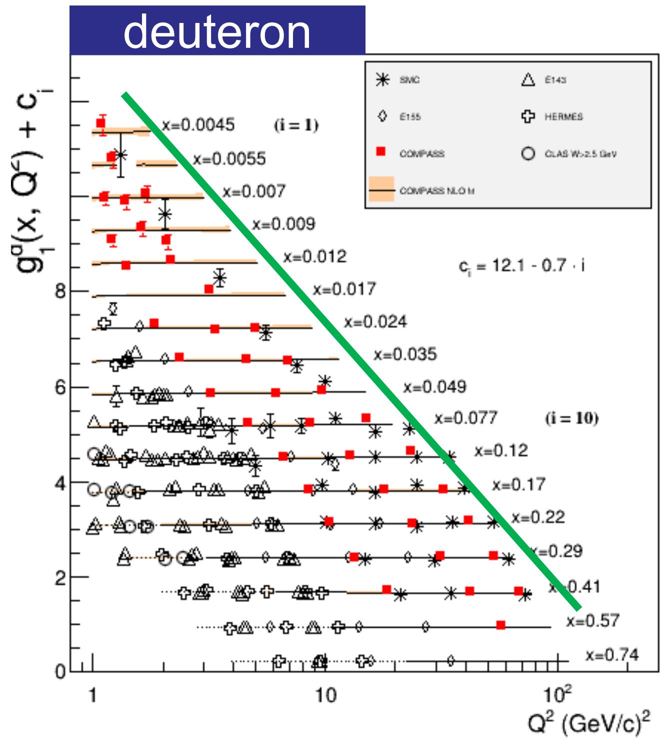
SMC,COMPASS at CERN

QCD fits- World data on g_1^p and g_1^d

→ $g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$$\frac{dg_1}{d\ln Q^2} \propto -\Delta g(x, Q^2)$$





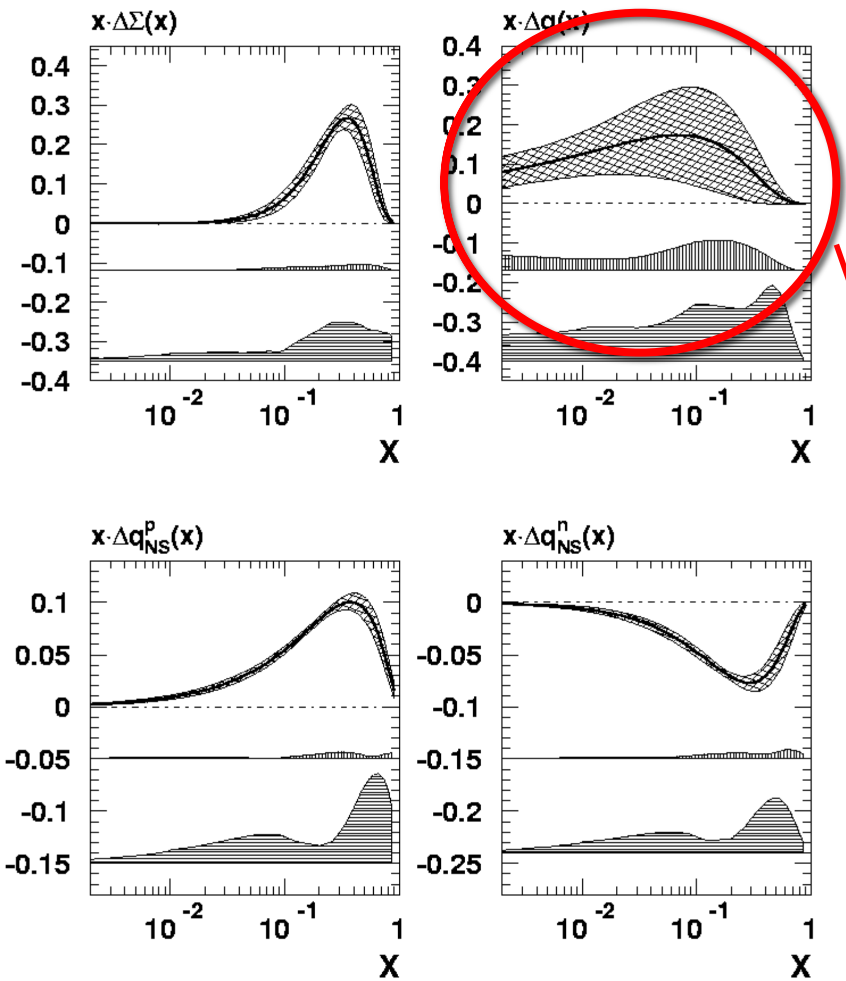
x and Q^2 coverage not yet sufficient for precise Δg

Can be improved by constraining from pp data (as DSSV, NNPDF…)

PLB753 (2016) 18

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

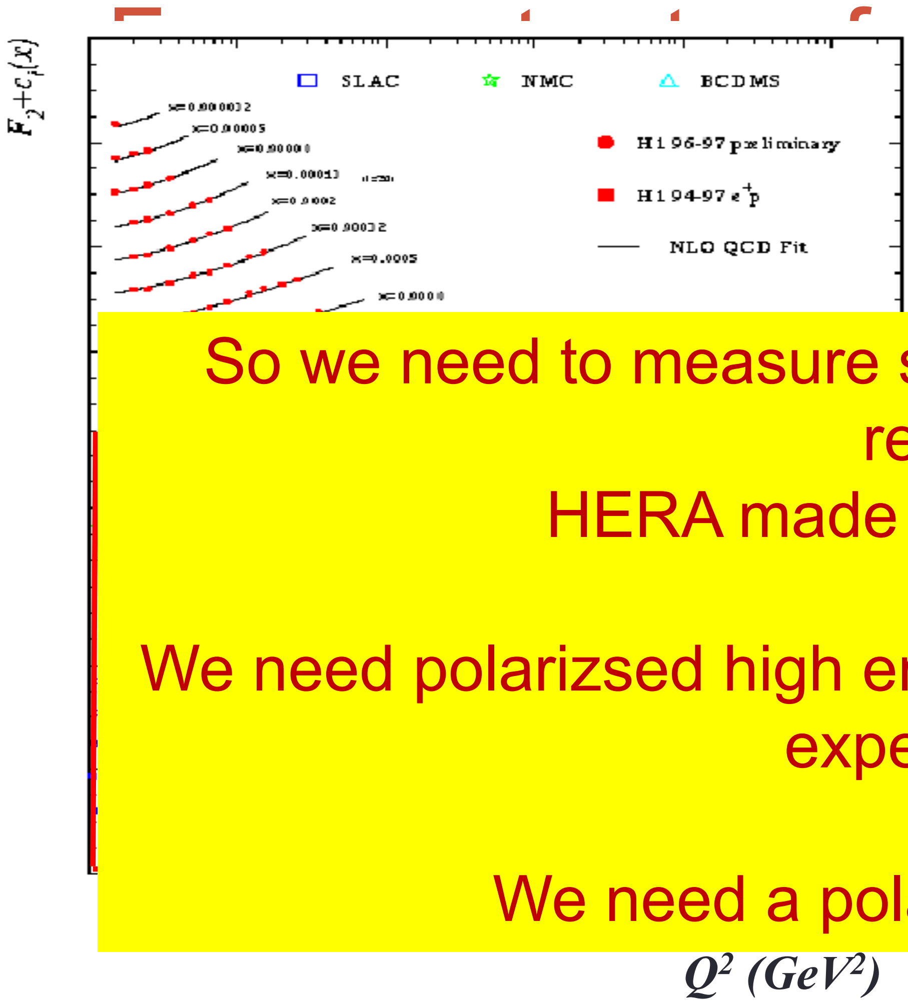
$$\Delta\Sigma = 0.30 \pm 0.05$$

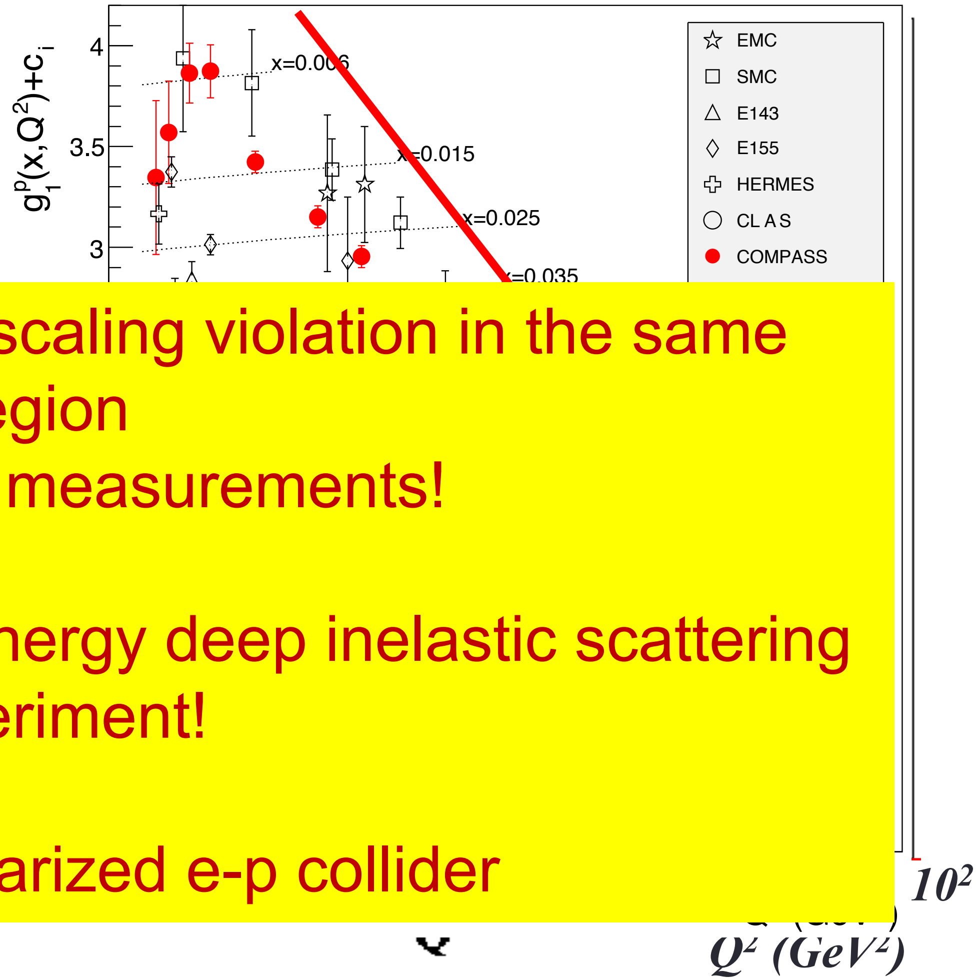
- Is this smallness due to some cancellation between quark+anti-quark polarization

- The gluon's contribution seemed to be large! $\Delta G = 1 \pm 1.5$

- Most NLO analyses by theoretical and experimental collaboration consistent with HIGH gluon contribution
  - Direct measurement of gluon spin with other probes warranted. Seeded the RHIC Spin program

Aidala et al.1209.2803v2





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?

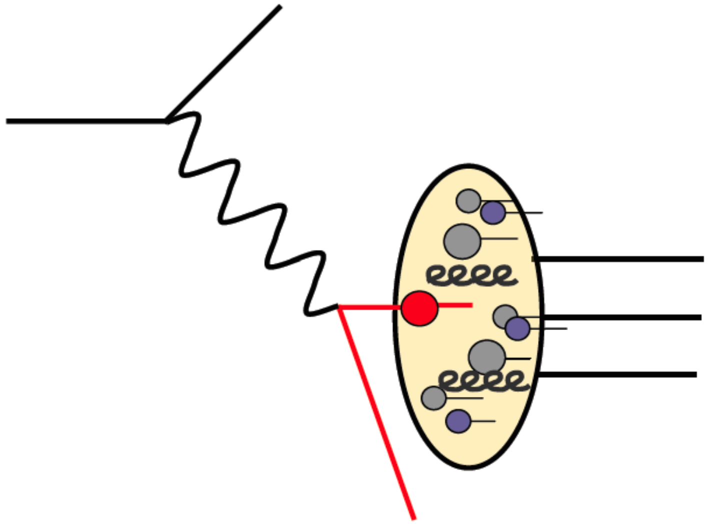
Is the gluon's contribution to nucleon spin large? ➔ Is the "anomaly" scenario true? How would we do a direct determination of gluon's spin?

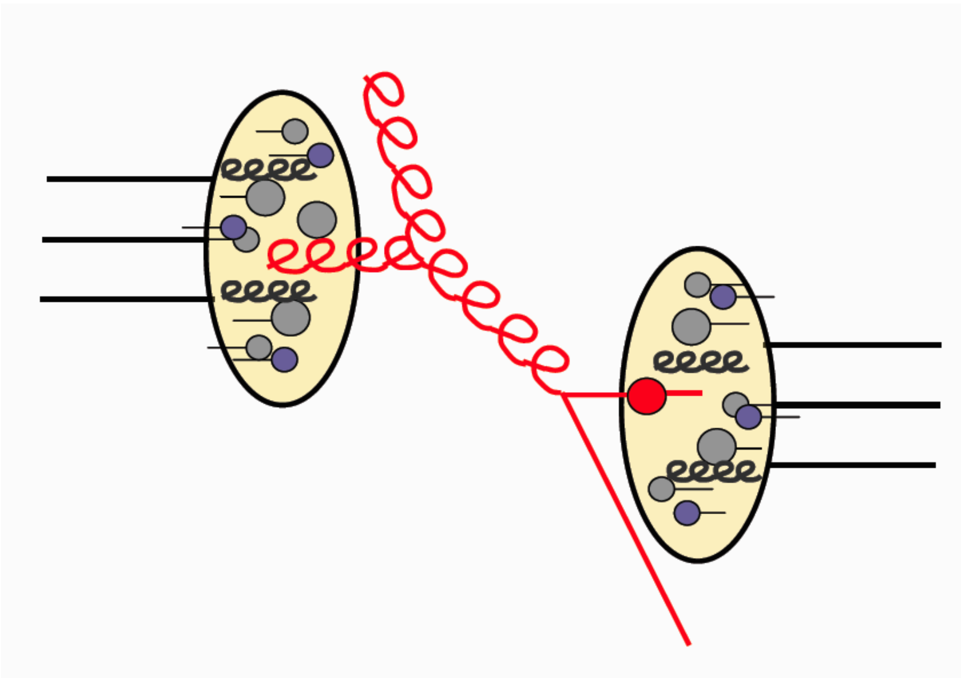
Is there an orbital motion of the quarks and gluons contributing to the nucleon spin?

RHIC Spin program and the Transverse Spin puzzle

Evidence for transverse spin had been observed but ***ignored*** for almost 3 decades…

Complementary techniques



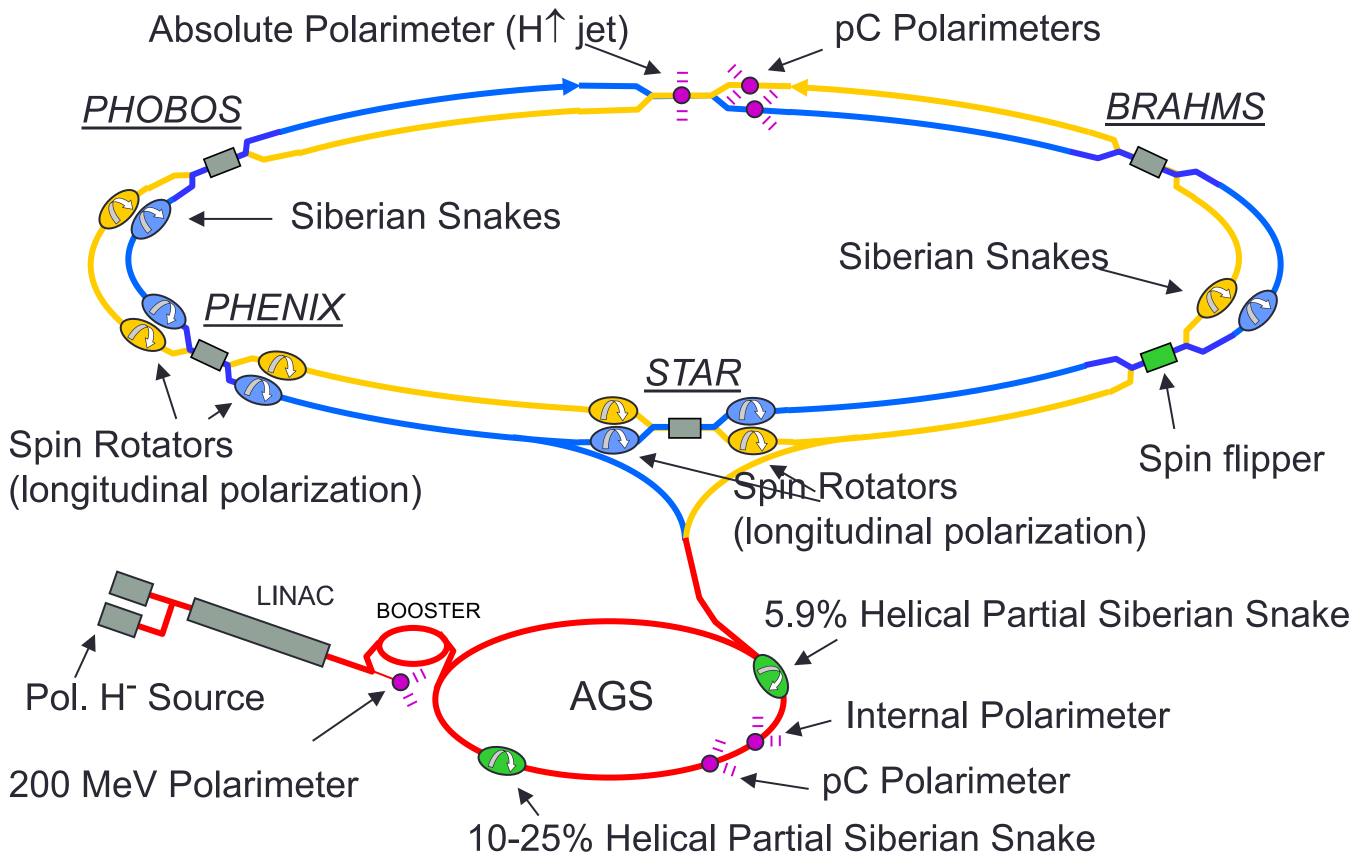


Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks either

Why not use polarized quarks and gluons abundantly available in protons as probes ?

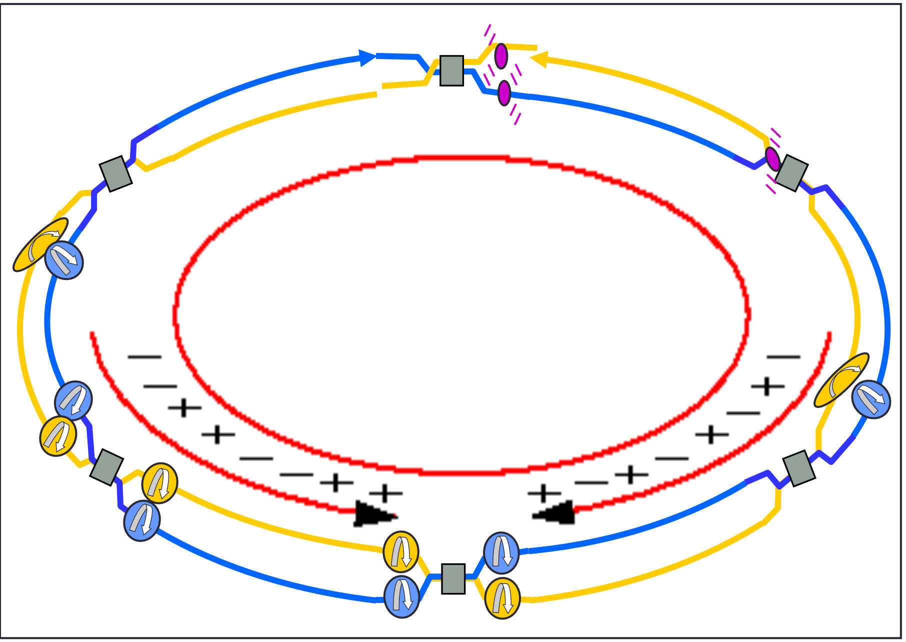
RHIC as a Polarized Proton Collider



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

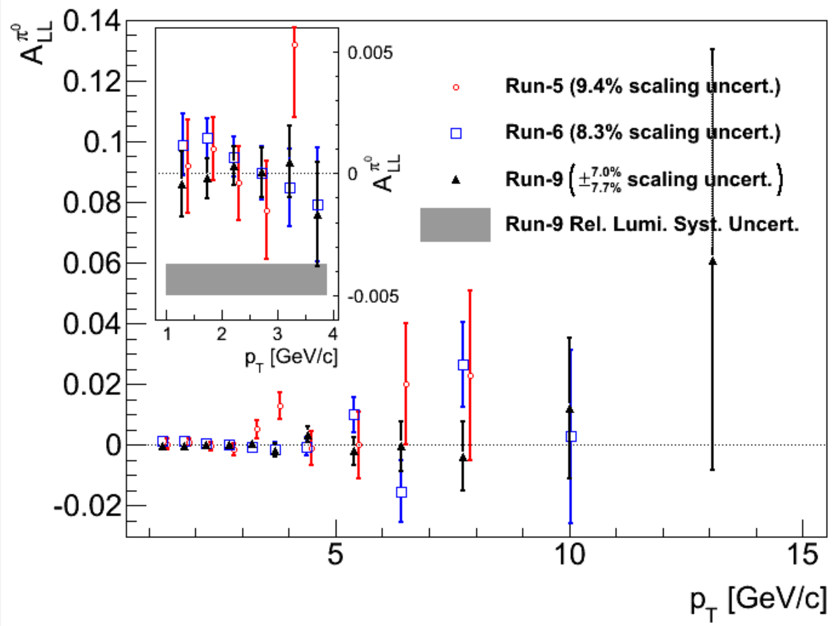
Exquisite control over false asymmetries due to ultra fast rotations of the target and probe spin.

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

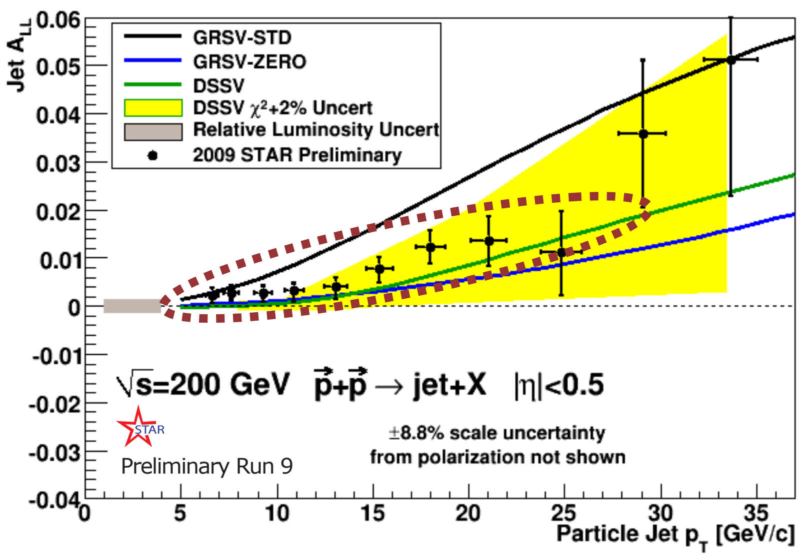
⇒ Possibility for false asymmetries are greatly reduced

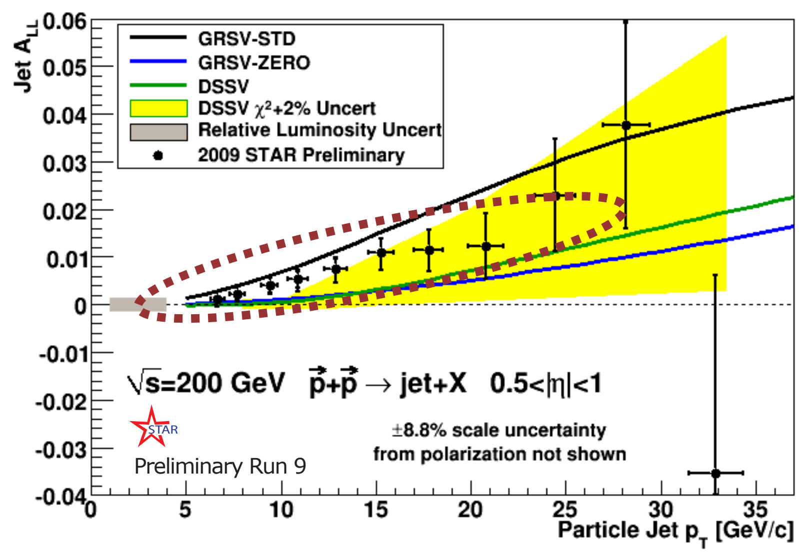
Most impactful results: on ΔG

- Inclusive probes
- Many others but highest impact with π^0 and jets
- Have been used in recent NLO pQCD analyses
- Experimental & theory systematic uncertainties have largely been downplayed.. This is an opportunity for near term improvement



A. Manion for PHENIX



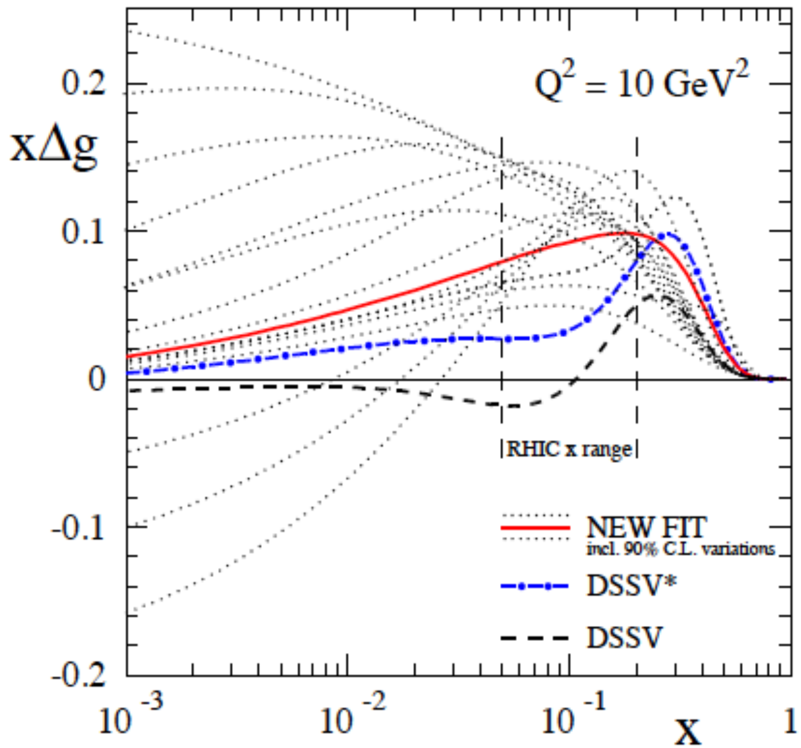


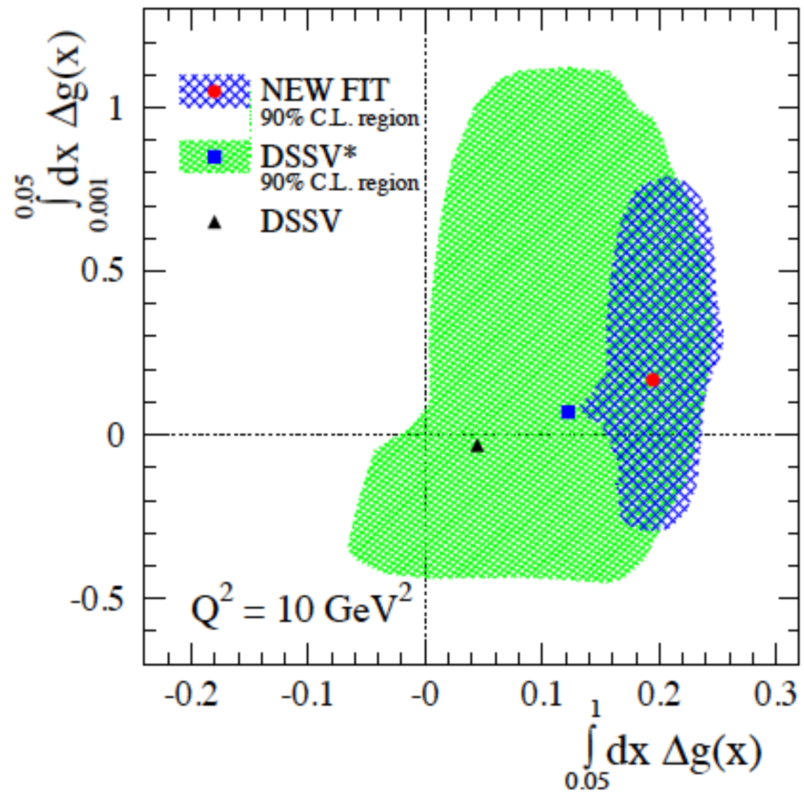
B. Surrow for STAR at DIS2014

Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

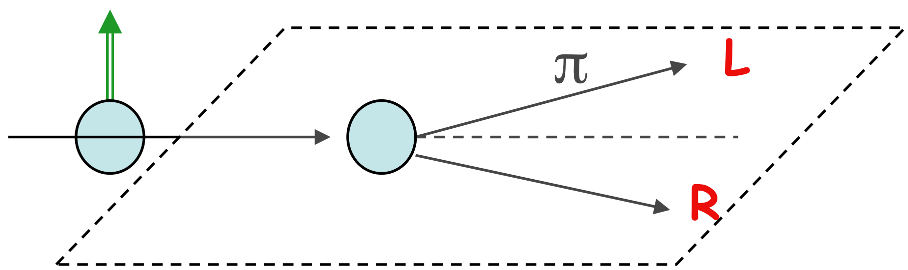
Wide spread at low x (x<0.05) of alternative fits consistent within 90% of C.L.





Dramatically makes the statement that, while we have made a huge impact, We are improving ΔG contributions only in a limited x-region, allowing large uncertainties to remain in the low-x unmeasured region!

Transverse spin introduction



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

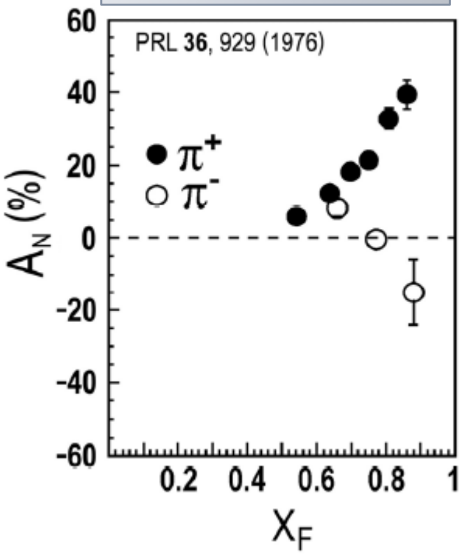
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

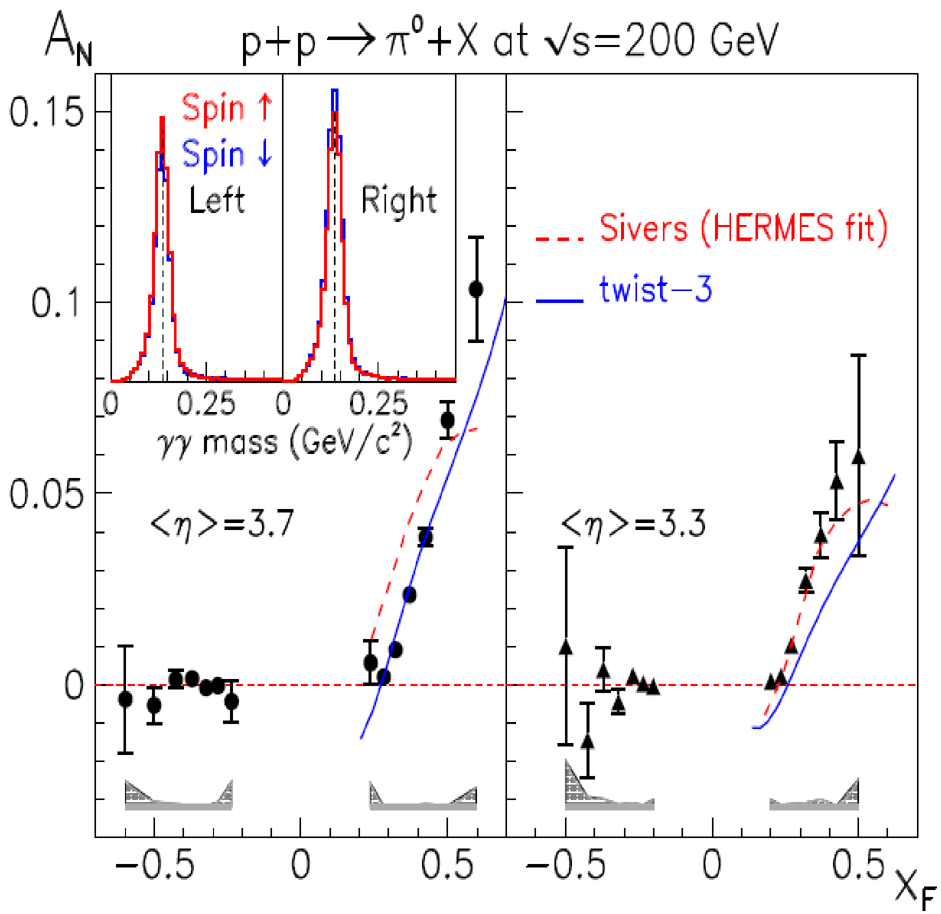
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- 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….

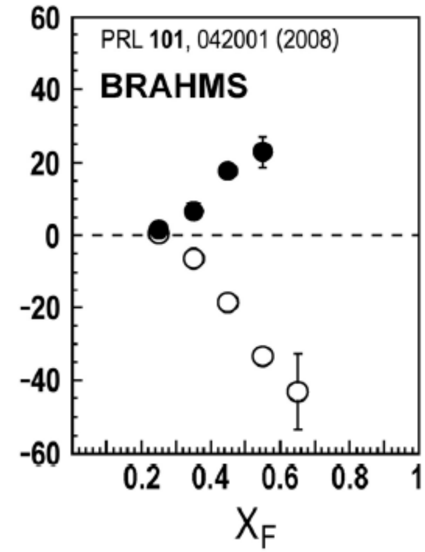
Pion asymmetries: at most CM energies!

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





RHIC
$\sqrt{s}$=62.4 GeV

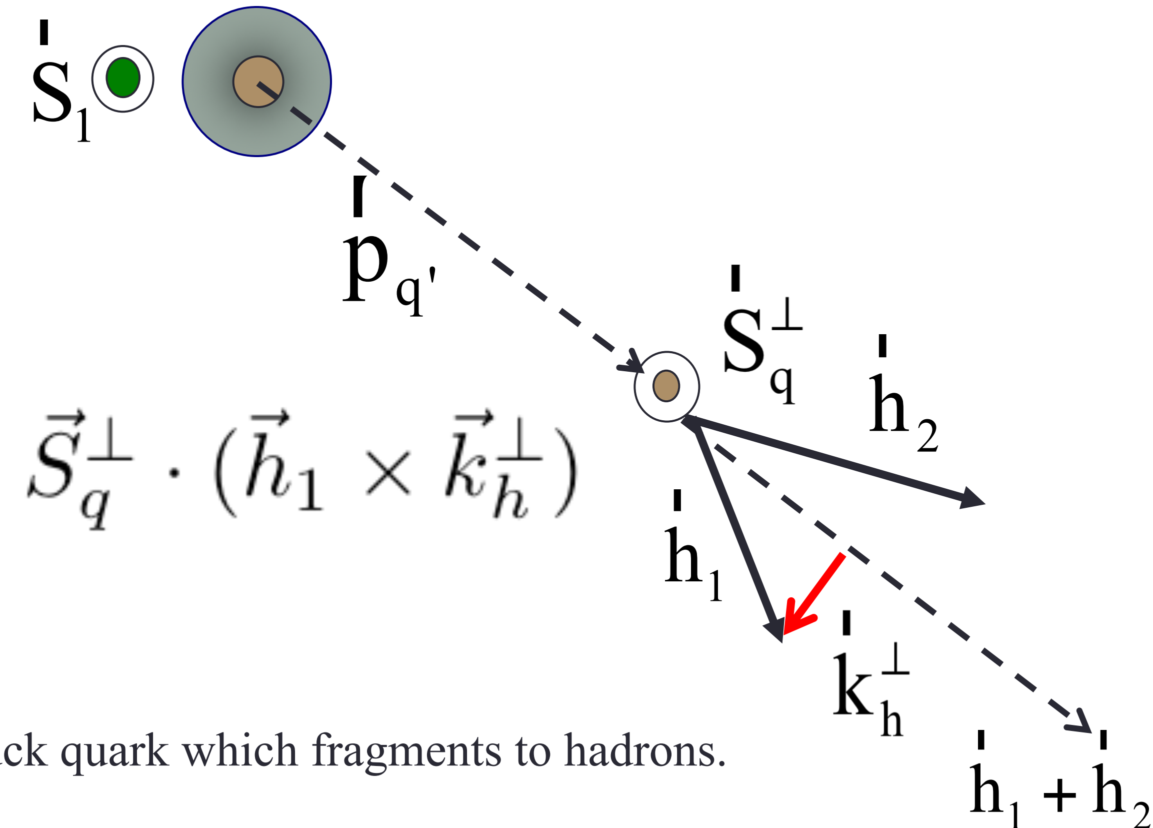


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

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

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

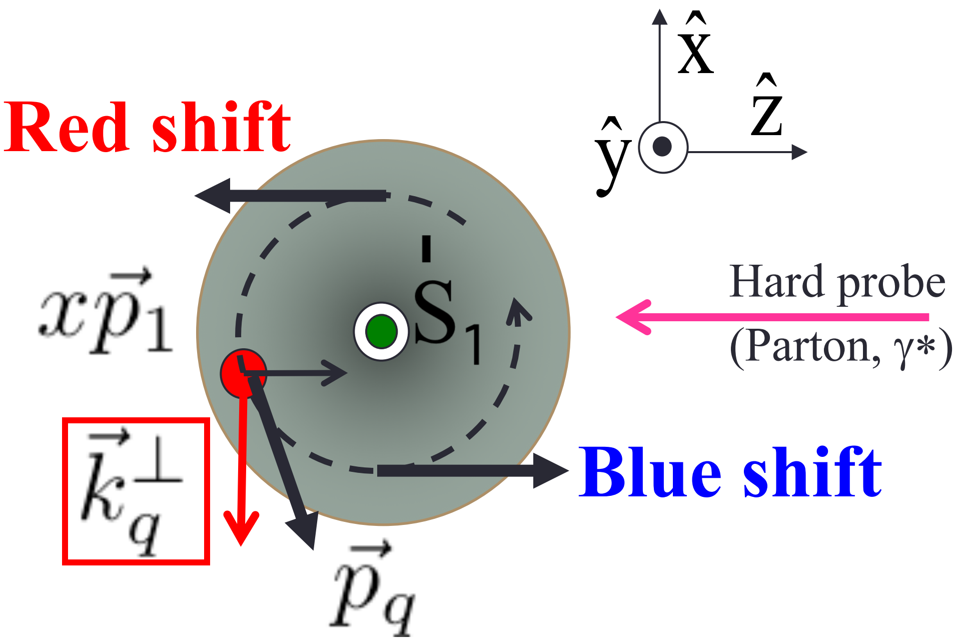


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

What does "Sivers effect" probe?

Top view, Breit frame



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

PRD66 (2002) 114005

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

Final **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

Generalized **P**arton **D**istribution **F**unctions

PRD59 (1999) 014013

Lessons learned:

- Proton and neutrons are not as easy to understand in terms of quarks, and gluons, as earlier anticipated:
  - Proton's spin is complex: alignment of quarks, gluons and possibly orbital motion
  - Proton mass: interactions amongst quarks and gluons, not discussed too much
- To fully understand proton structure (including the partonic dynamics) one needs to explore over a much broader x-Q2 range (not in fixed target but in collider experiment)
- e-p more precise in p-p as it directly probes the glue, with more experimental control.
- Low-x behavior of gluons in proton intriguing; Precise measurements of gluons critical.
- Nuclear binding amongst protons and neutrons? Residual color interactions? What is the role of gluons in binding the partons and nucleons in Nuclei : equally not clear… to study, -→ an electron-nucleus collider

That Collider Is The Electron Ion Collider

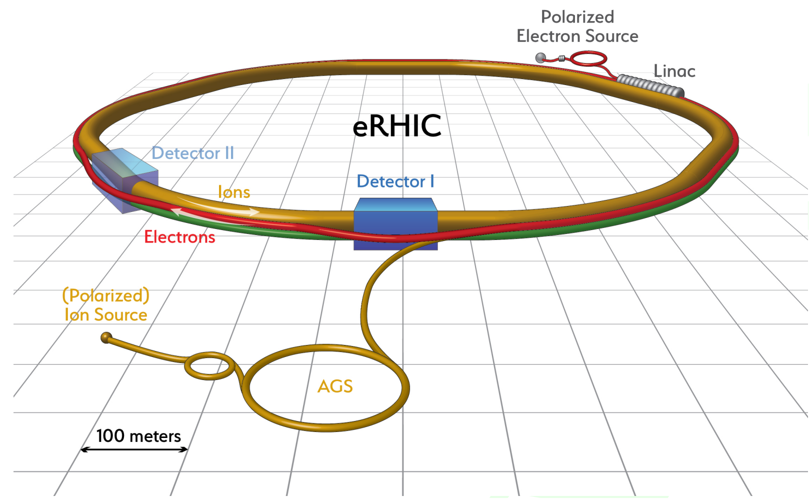
About which we will learn in Lecture 2

Thank you.

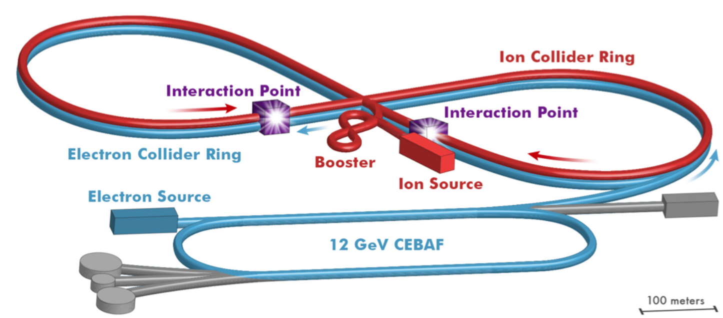
The Electron Ion Collider

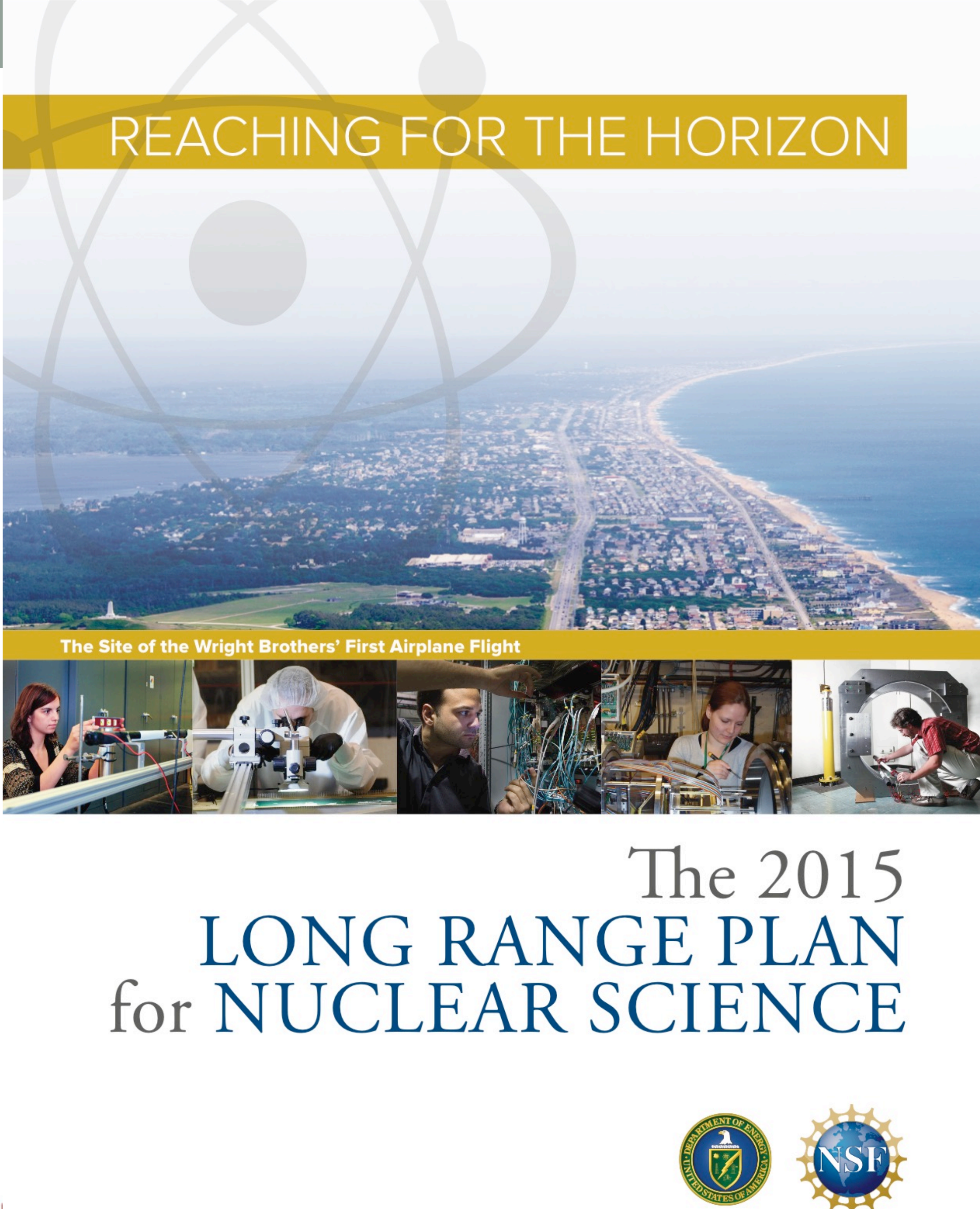
Two options of realization!

1212.1701.v3
A. Accardi et al Eur. Phy. J. A, 52 9(2016)



Not to scale





RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

$1.1M/year since 2011 for detector R&D

$7.5M/year since 2018 for accelerator realization R&D

http://science.energy.gov/np/reports

July 26, 2018

PREPUBLICATION COPY—SUBJECT TO FURTHER EDITORIAL CORRECTION

An Assessment of
U.S.-Based Electron-Ion Collider Science

Committee on U.S.-Based Electron-Ion Collider Science Assessment

Board on Physics and Astronomy

Division on Engineering and Physical Sciences

A Consensus Study Report of

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

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Washington, DC
www.nap.edu

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The committee concludes that the science questions regarding the building blocks of matter are **compelling** and that an EIC **is essential** to answering these questions.

Furthermore, the answers to these fundamental questions about the nature of the atoms will also have implications for particle physics and astrophysics and possibly other fields. Because an EIC will require significant advances and innovations in accelerator technologies, the impact of constructing an EIC will affect all accelerator-based sciences.

An EIC is **timely** and has the support of the nuclear science community. The science that it will achieve is unique and world leading and will ensure global U.S. leadership in nuclear science, as well as in accelerator science and the technology of colliders.