The Electron Ion Collider

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Day 2 : Lectures 3 and 4

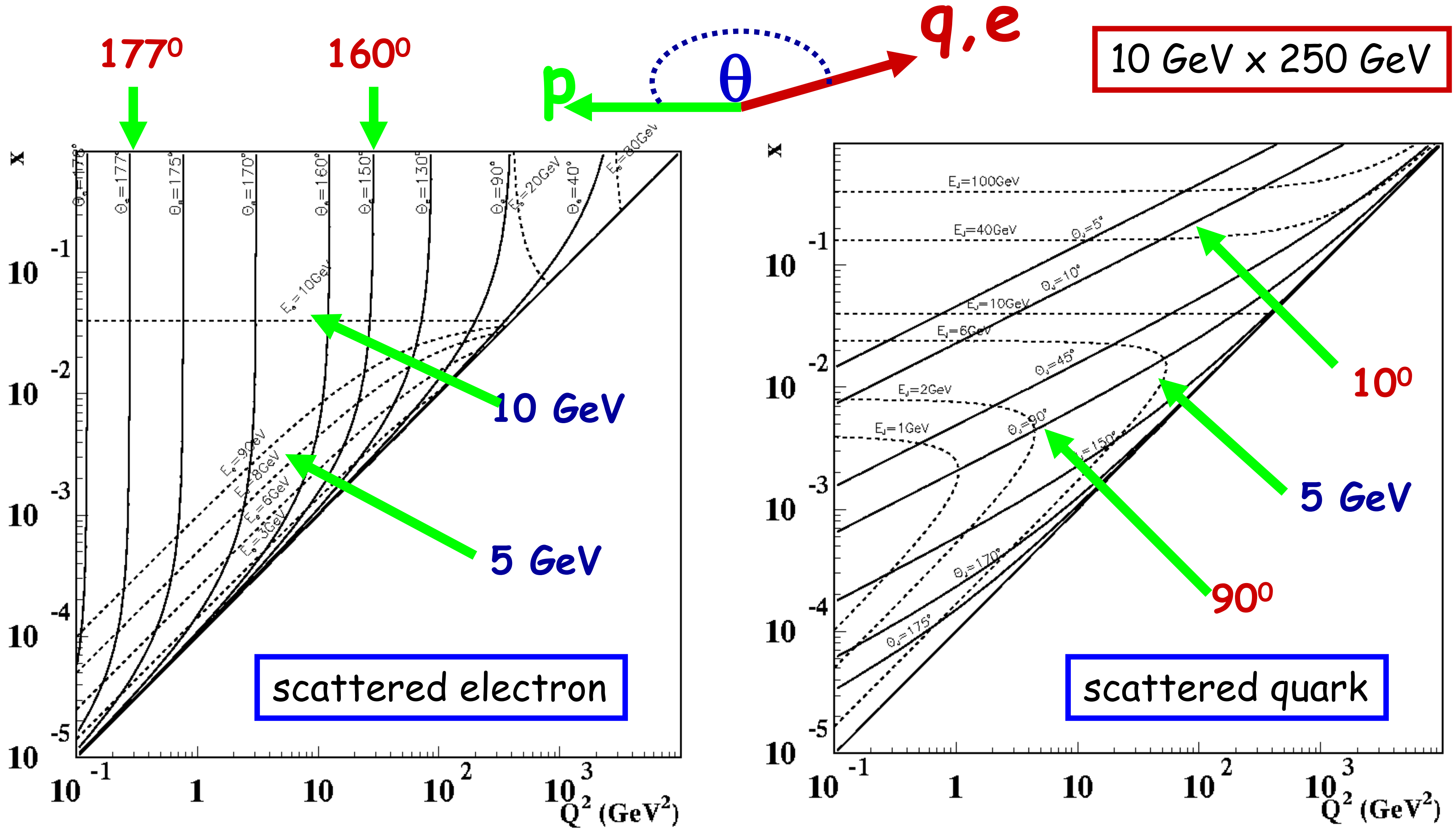
Today on the menu…

- Homework: Was every one able to calculate the angle correlations in x-Q2 plane for 10 GeV e x 250 GeV proton collisions?
  - Can scattered electron have an energy larger than the initial energy of the electron in a collider?

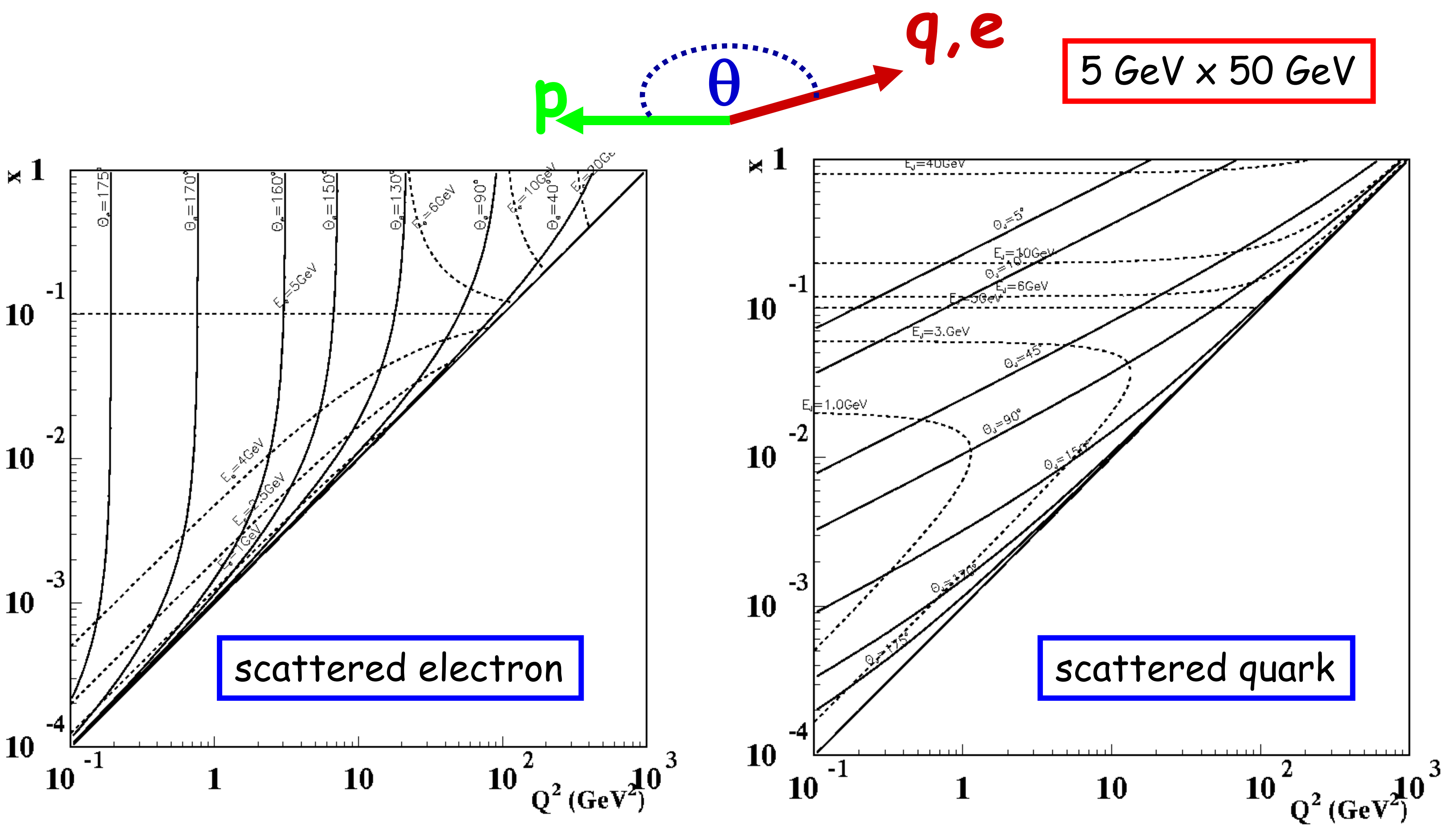
- Polarized/Unpolarized deep inelastic scattering, methods, tools, spin crisis history and status, inclusive and semi-inclusive DIS
- Results of fixed target experiments, limitations of the fixed target experiments
- DIS on Nuclei

Home Work: Where do electrons and quarks go?

Angles measured w.r.t. proton direction



Electron, Quark Kinematics



Levitating top

Despite understanding gravity, and rotational motion individually, when combined it produces unexpected, unusual and interesting results.

In nature, we observe such things and try to understand the physics behind it.

“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!

- 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)

20^{th} 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"

Lets get in to details of e-p scattering: what do we learn?

Lepton Nucleon Cross section

Assume only γ^* exchange

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

Nucleon spin

Lepton spin

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

$$W^{\mu\nu}(P,q,S) = -\left(g^{\mu\nu} - \frac{q^\mu q^\nu}{q^2}\right)F_1(x,Q^2) + \left(p^\mu - \frac{P\cdot q}{q^2}q^\mu\right)\left(p^\nu - \frac{P\cdot q}{q^2}q^\nu\right)\frac{1}{P\cdot q}F_2(x,Q^2)$$
$$-i\epsilon^{\mu\nu\lambda\sigma}q_\lambda\left[\frac{MS_\sigma}{P\cdot q}\left(g_1(x,Q^2) + g_2(x,Q^2)\right) - \frac{M(S\cdot q)P_\sigma}{P\cdot q}g_2(x,Q^2)\right]$$

What can unpolarized e-p scattering teach us?

Inclusive Cross-Section:

$$\frac{d^2\sigma^{eA\to eX}}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2) - \frac{y^2}{2}F_L(x,Q^2)\right]$$

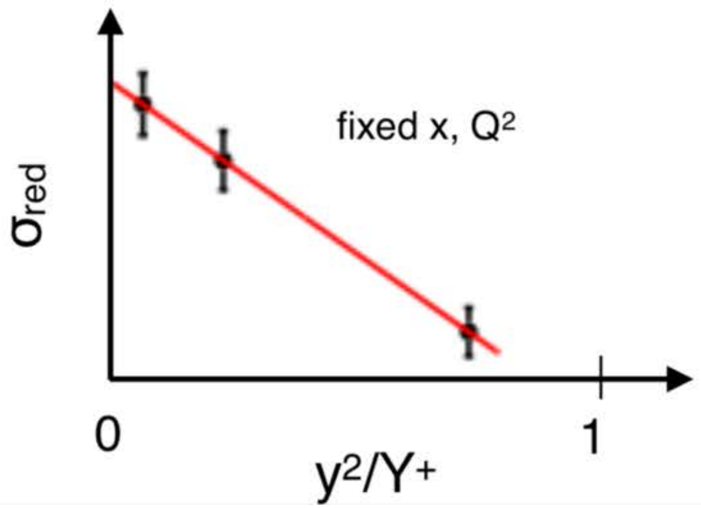
Reduced Cross-Section:

$$\sigma_r = \left(\frac{d^2\sigma}{dxdQ^2}\right)\frac{xQ^4}{2\pi\alpha^2[1+(1-y)^2]} = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2}F_L(x,Q^2)$$

$$\sigma_r(x,Q^2) = F_2^A(x,Q^2) - \frac{y^2}{Y^+}F_L^A(x,Q^2)$$

Rosenbluth Separation:

- Recall $Q^2 = x\,y\,s$
- Measure at different $\sqrt{s}$
- Plot σ_{red} versus $y2/Y^+$ for fixed x, Q^2
- F_2 is σ_{red} at $y2/Y^+ = 0$
- F_L = Slope of $y2/Y^+$



Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).
In LO: Probability to find parton with x, Q^2 in proton

PDF: Connecting experiment (e.g. pp) with theory

Jets, Drell-Yan, etc.: $\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to o}$

Observable

Parton Distribution Function (PDF)

Theoretical Calculations

Hadron Production: $\sigma_o = f_{i\to a} \otimes \hat{\sigma}_{a\to b} \otimes D_{b\to o}$

Fragmentation Functions

Structure functions allows us to extract the quark $q(x,Q^2)$ and gluon $g(x,Q^2)$ distributions (PDFs).
In LO: Probability to find parton with x, Q^2 in proton

What is Needed:

- Good data
  - Best: F_2 (ep), jets, Drell-Yan (pp)
  - Bad: Hadrons
- pQCD Calculation of the processes
  - LO, NLO, NNLO
- QCD Evolution Equations
  - DGLAP: Evolution in Q^2 (small to large) at fixed x (integro-differential equations)
  - BFKL: Evolution in x at fixed Q^2

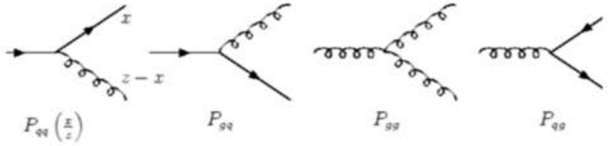
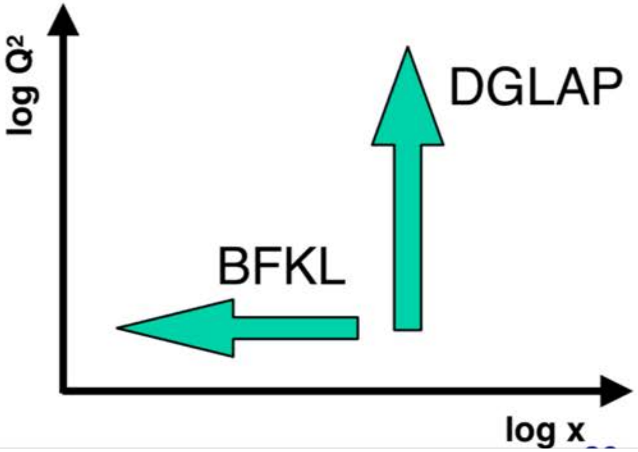
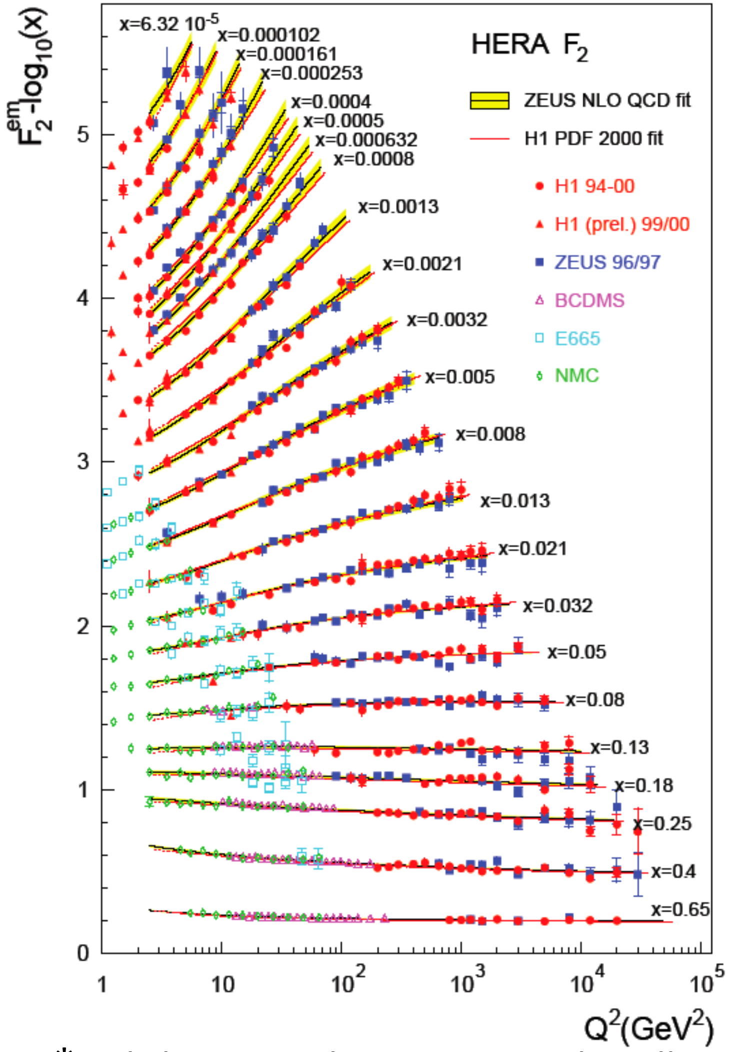


Figure 1.1: *The processes related to the lowest order QCD splitting functions. Each splitting function $P_{p'p}(x/z)$ gives the probability that a parton of type p converts into a parton of type p', carrying fraction x/z of the momentum of parton p*



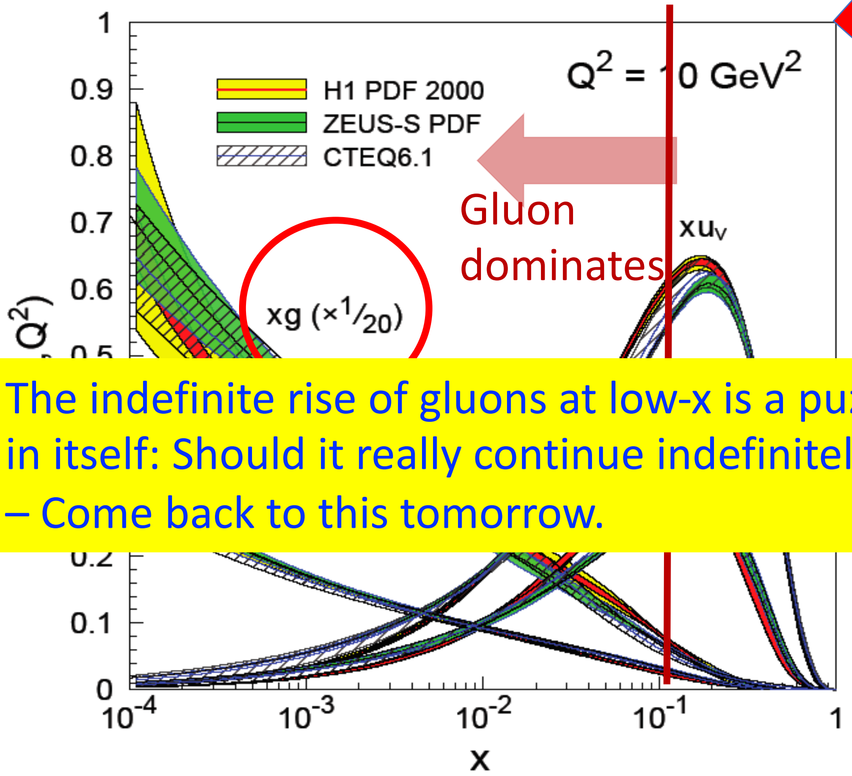
Measurement of Glue at HERA



- 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:

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Nucleon spin

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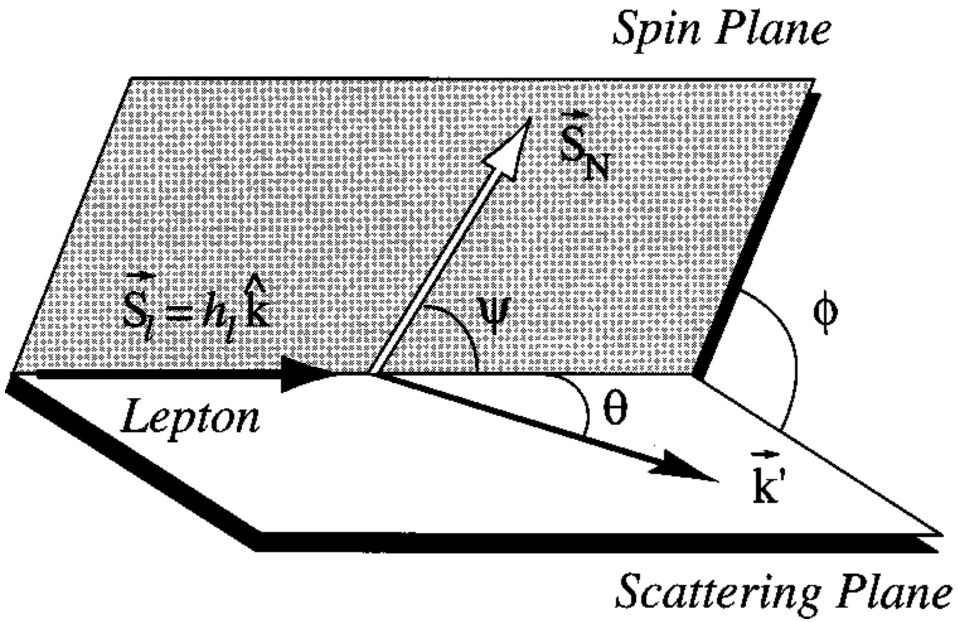
$$-i\epsilon^{\mu\nu\lambda\sigma} q_\lambda \left[\frac{M S_\sigma}{P\cdot q} (g_1(x,Q^2) + g_2(x,Q^2)) - \frac{M(S\cdot q)P_\sigma}{P\cdot q} g_2(x,Q^2) \right]$$

Lepton-nucleon cross section…*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

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

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

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:

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

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:

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

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,

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

$$F_1 = \frac{1+\gamma^2}{2x(1+R)}\,F_2 \qquad A_2 = \frac{1}{1+\eta\xi}\left(\frac{A_{\perp}}{d} + \xi\,\frac{A_{\parallel}}{D}\right)$$

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

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

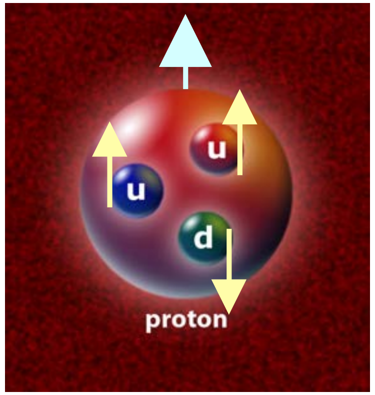
1990 Nobel Prize: *"for their pioneering investigations concerning **deep inelastic scattering of electrons on protons and bound neutrons**, which have been of essential importance for the development of the **quark model** in particle physics".*

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

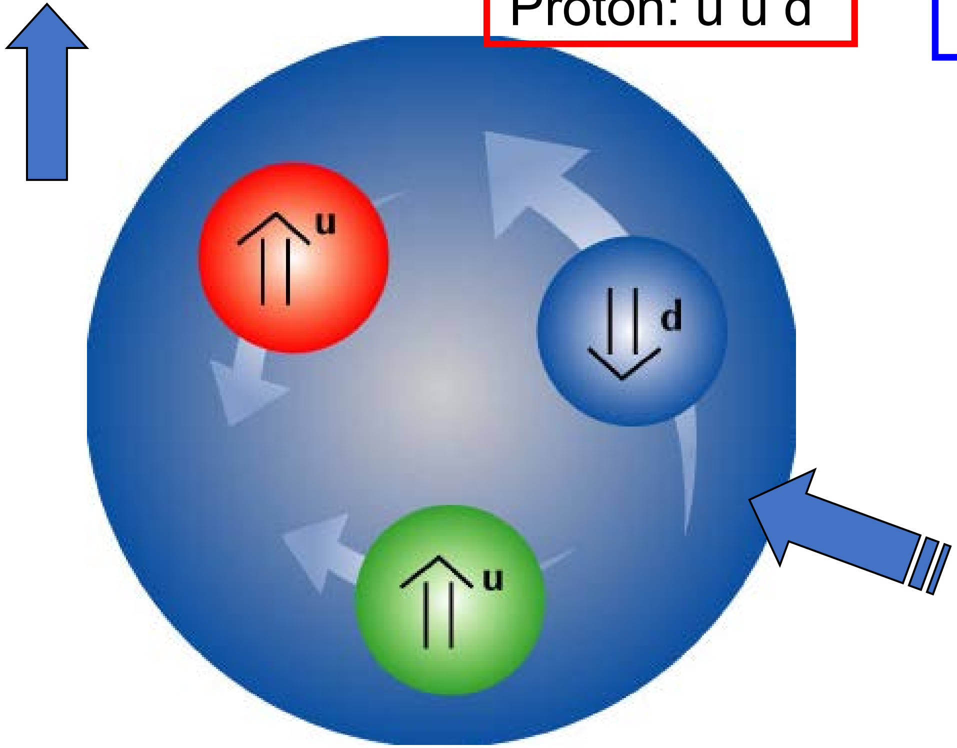
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

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



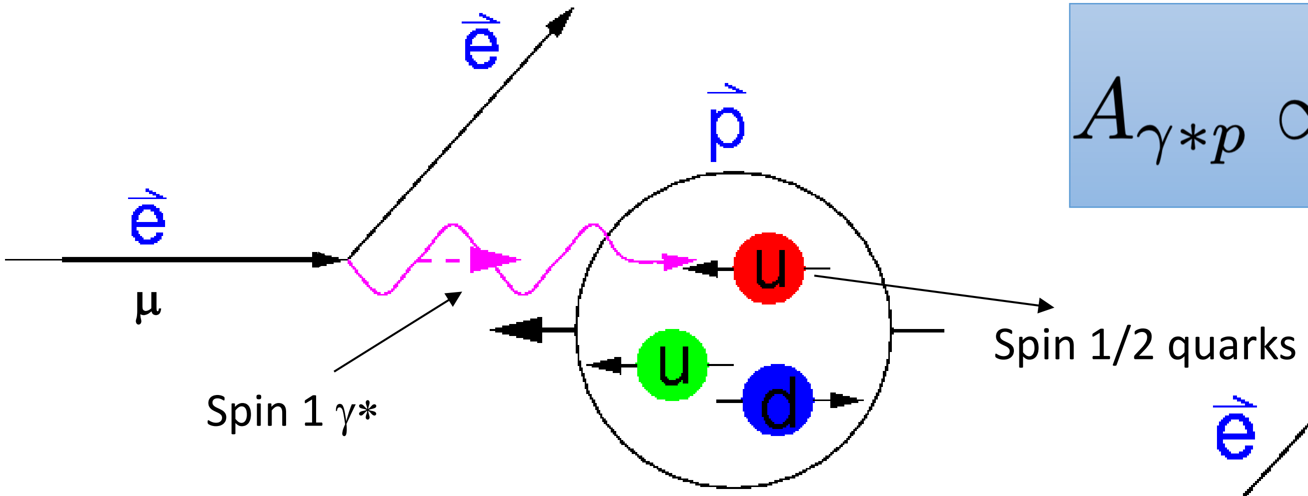
S_{proton} = Sum of all quark spins!

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

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

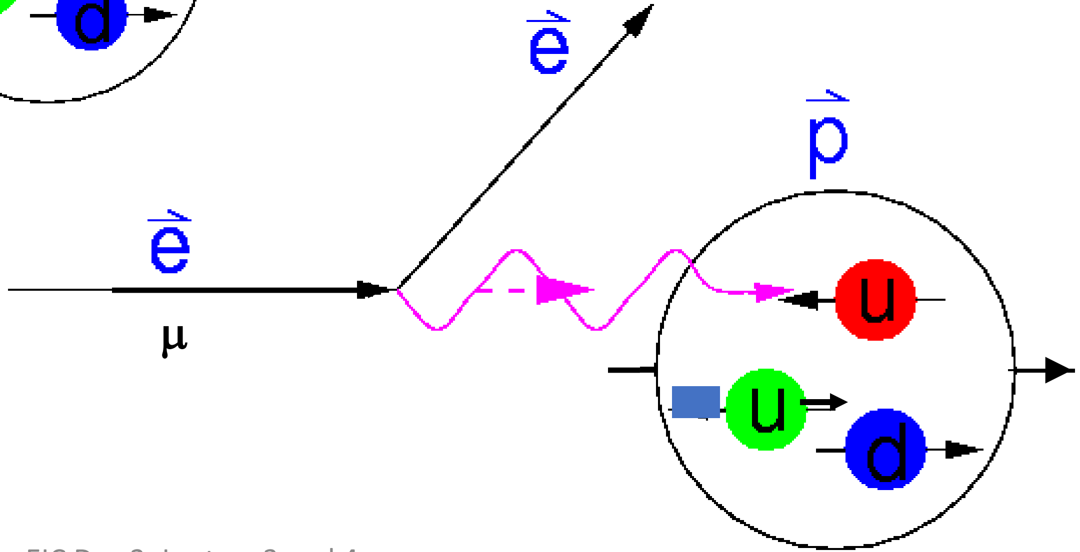
How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering



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

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



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

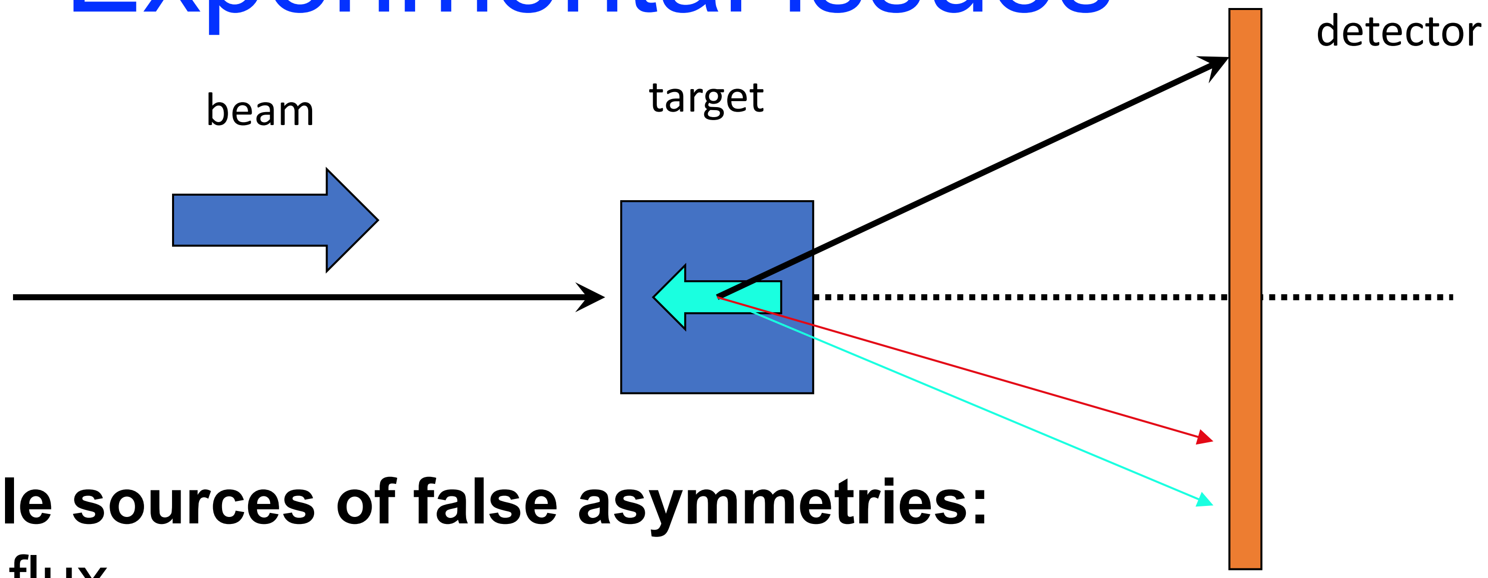
Determine the kinematics: measure with high accuracy:

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

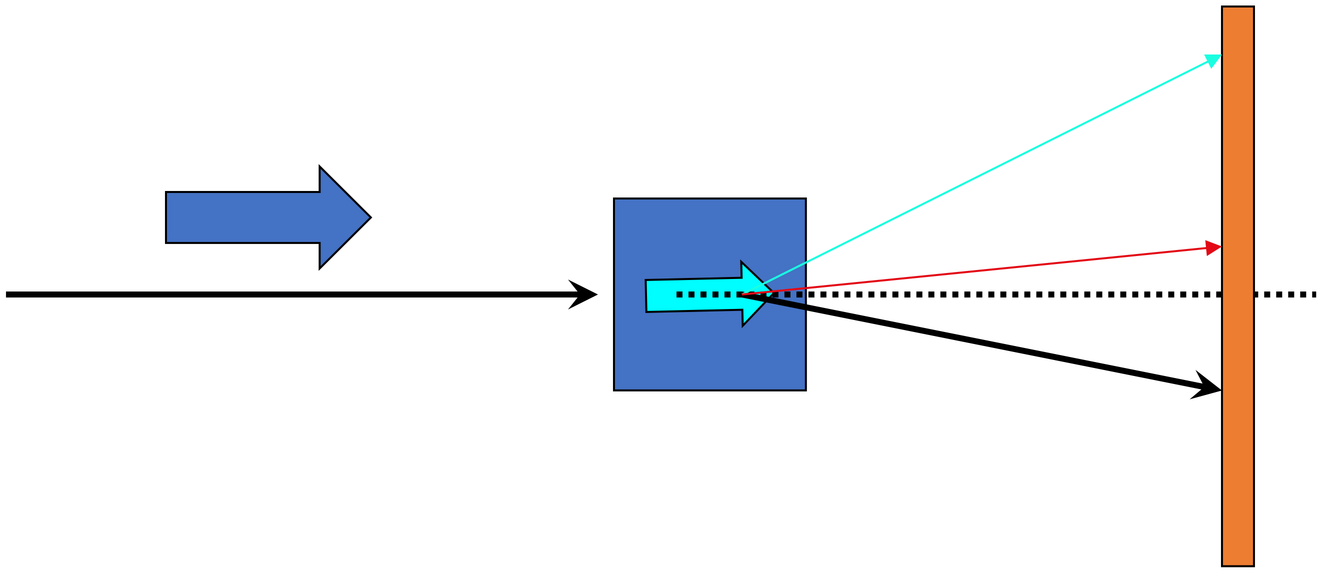
Control of false asymmetries:

- 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

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

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

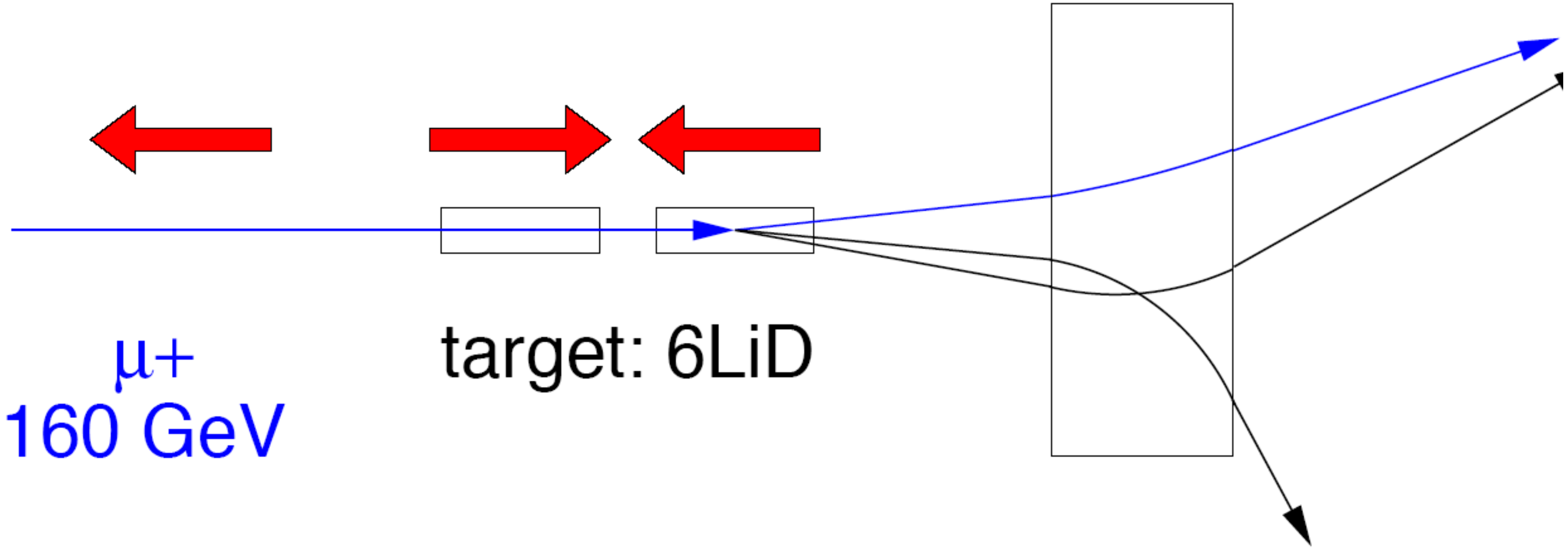
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

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

- Experiment setup (EMC, SMC, COMPASS@CERN)



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

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

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

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

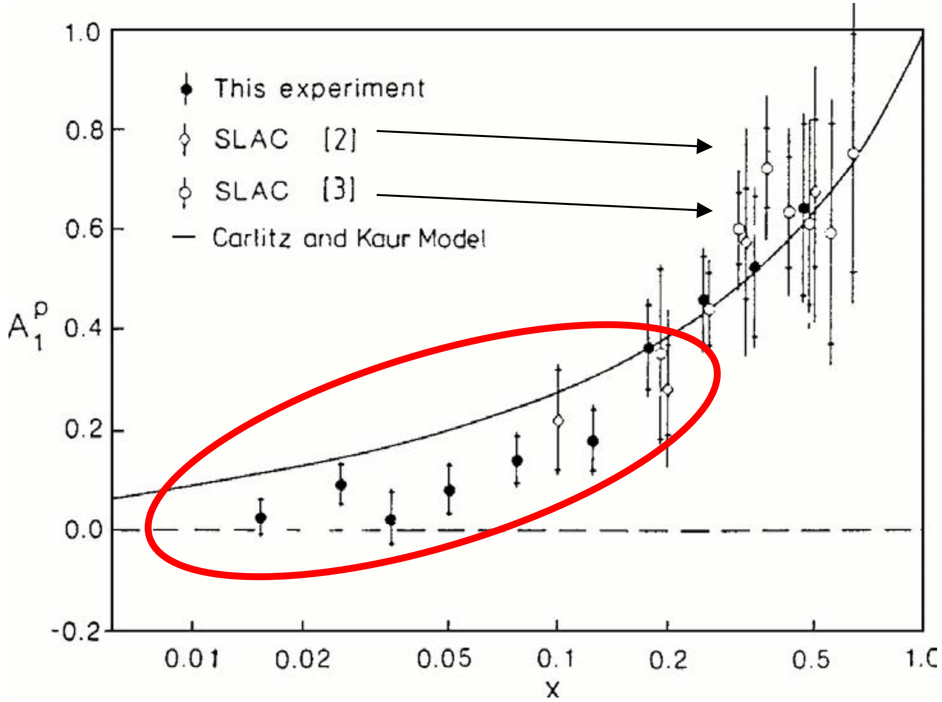
$a_3=g_a$ — Neutron decay

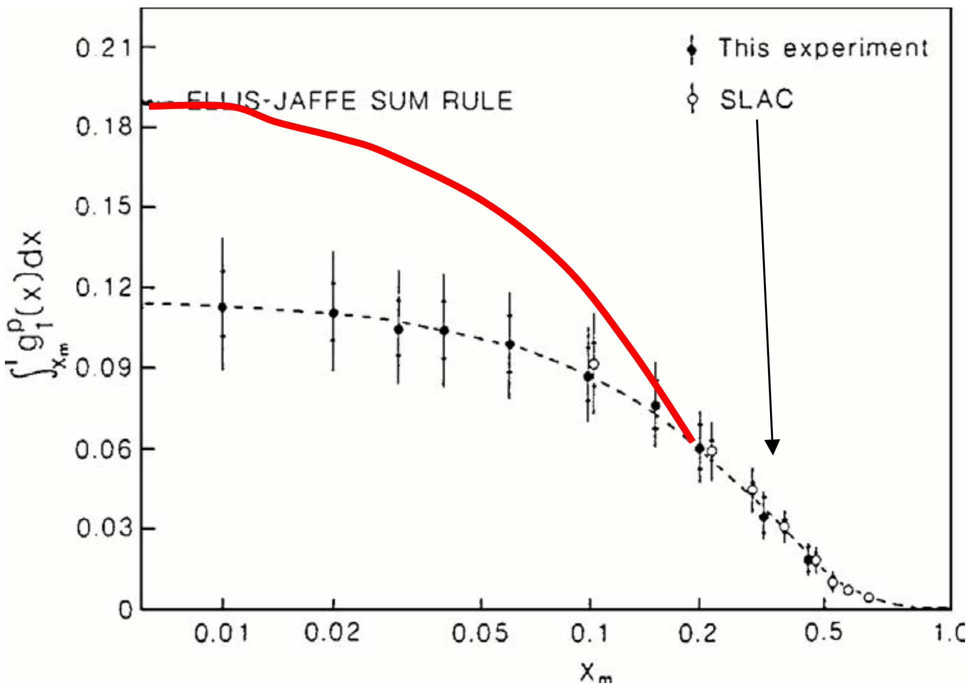
a_8 — (3F-D)/3 Hyperon Decay

a_0 — $\Delta\Sigma$

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

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):

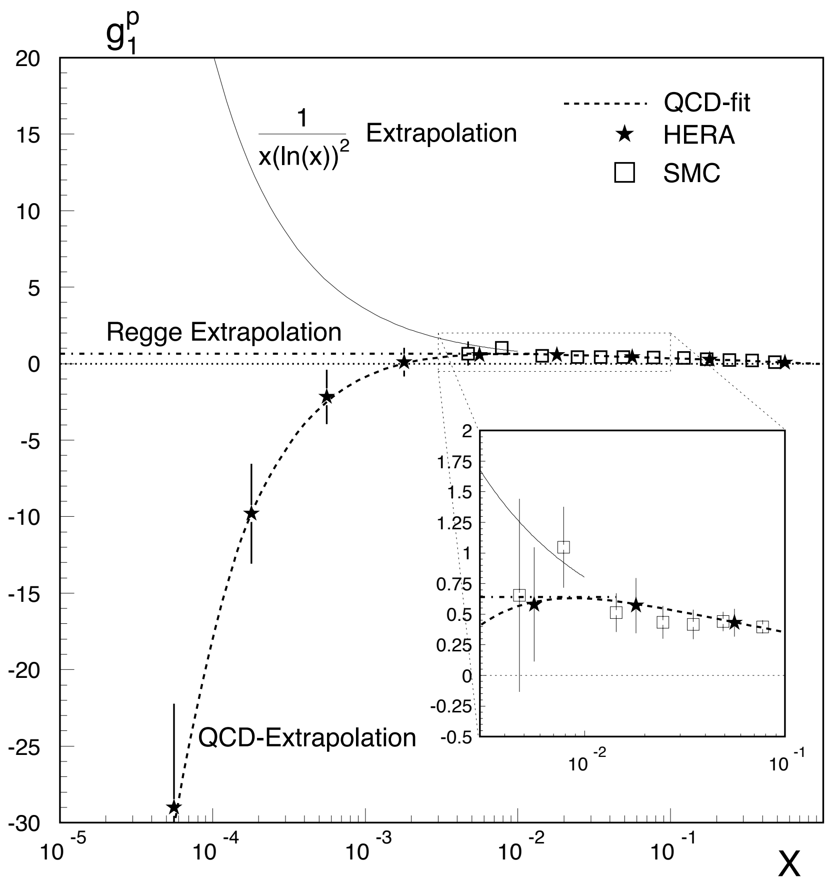
$$g_1(x) \propto [2\ln(1/x) - 1] \qquad g_1(x) \propto (x\ln^2 x)^{-1}$$

- QCD based calculations:
  Resummation of AP:
  Resum of leading power of ln(1/x) gives:

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

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

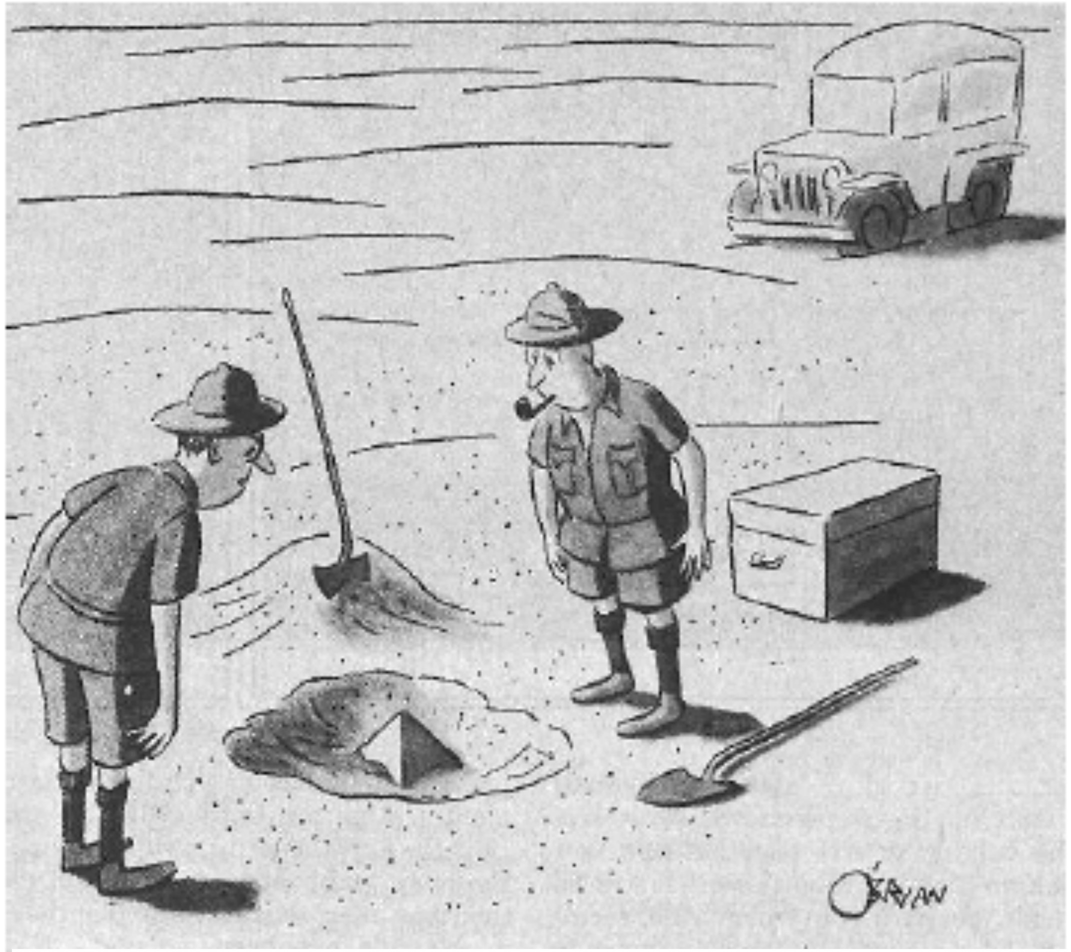
A collection of low x behaviors:



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 realized

- 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.

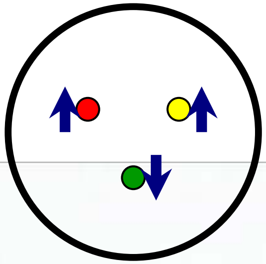
How significant is this?



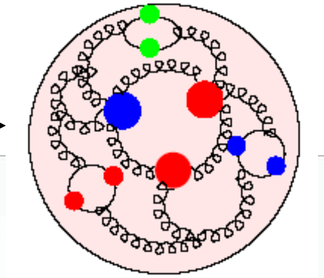
of course, on how far down it goes.

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

Evolution: Our Understanding of Nucleon Spin



1980s



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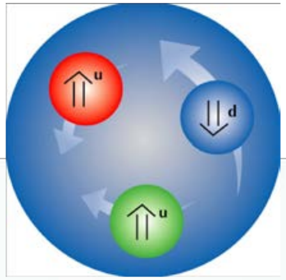
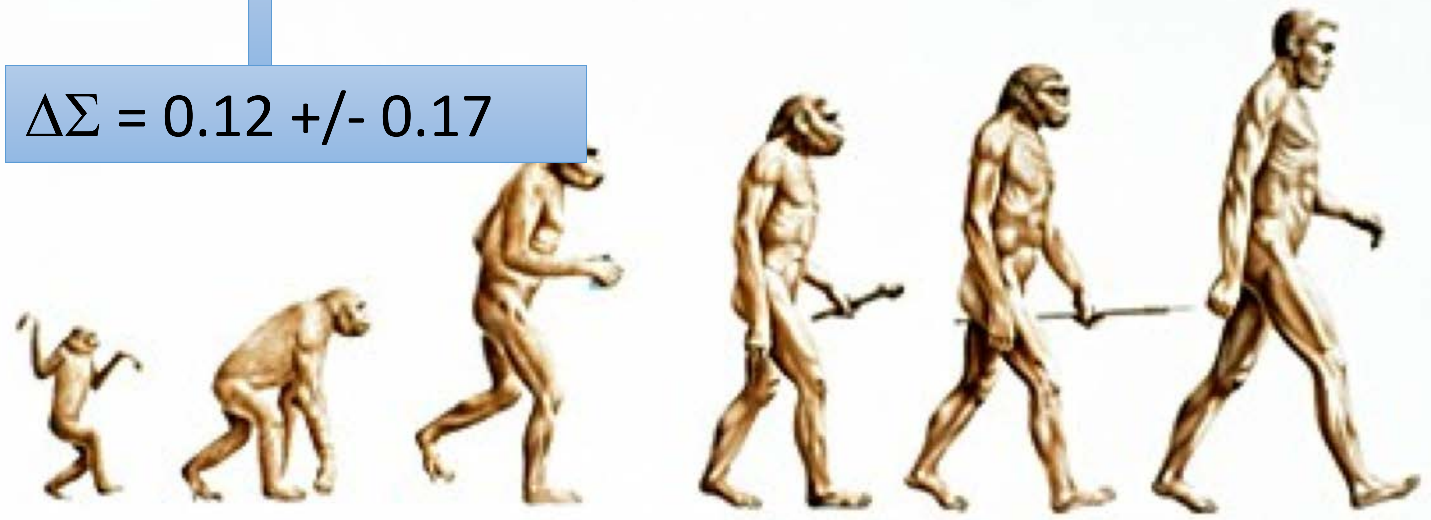


1990/2000s

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



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

Lesson:

- Every time we explored a physical observable with "spin" as one of the experimental variable, we have learnt something new about nature….

- **But was this really a " spin crisis"?**
  - Experimental uncertainties too large
  - The assumptions: naïve (constituent) quark model
  - ***We needed to examine and improve on both fronts!***

This is precisely what was done in the following decade….

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

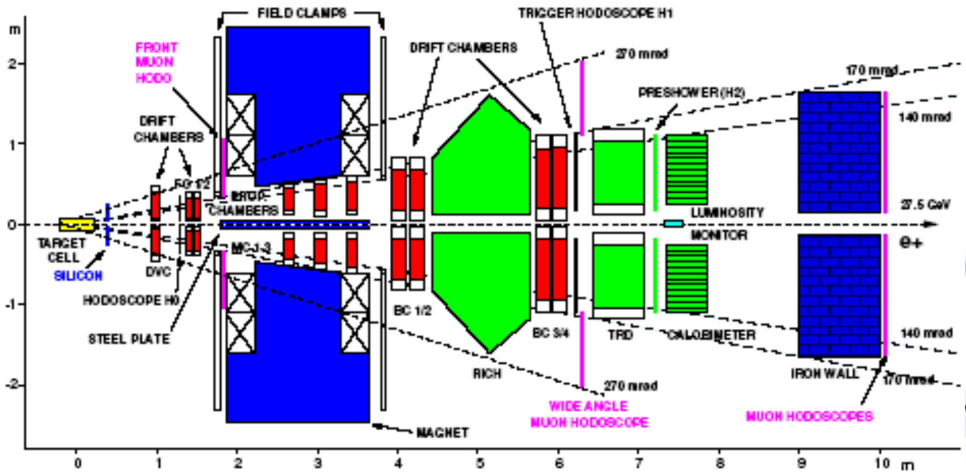
Mostly tried to reach pQCD region, Inclusive, no particle ID
Mostly Semi-Inclusive, with good particle ID
Mostly lower beam energies, precision mostly in the non-pQCD regime

Experimental Essentials

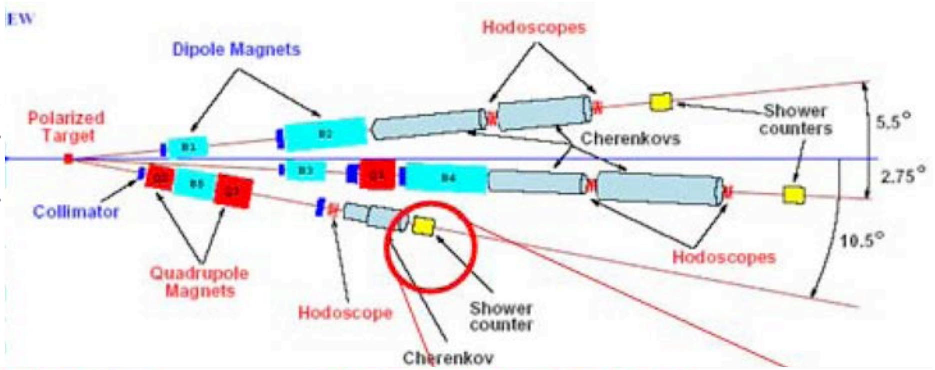
Facility & Beam Energy	Target types	Lepton beam	Minimum x_{Bj} reached
SLAC & JLab 9-49 GeV	solid/gas	Polarized e source	Xmin ~ 0.01
DESY 27 GeV	Internal (DESY) gas	Sokolov Ternov effect, e+/-	Xmin ~ 0.02
CERN 100-190 GeV	solid	Muons(+) from pion decay	Xmin ~ 0.003

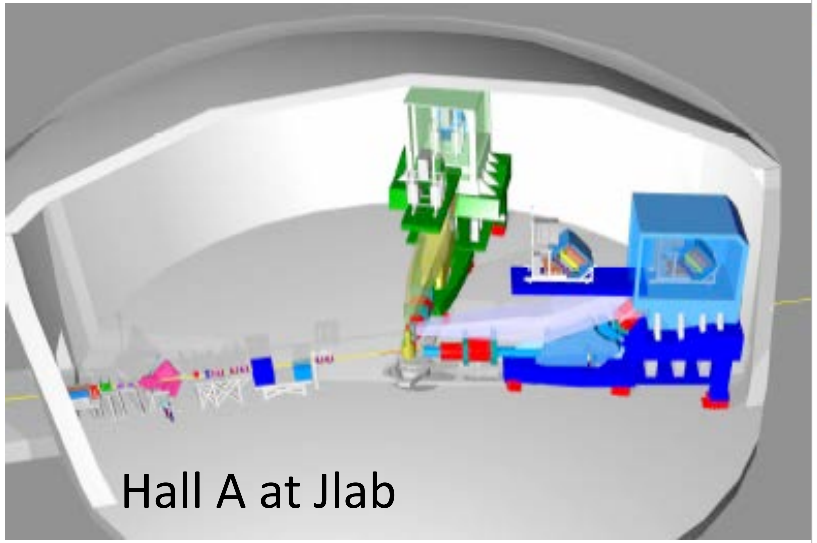
- False asymmetries were controlled by:
  - Rapid variation of beam polarization (SLAC & JLab)
  - Rapid variation of target polarization (HERMES@DESY)
  - Simultaneous measurement of two oppositely polarized targets in the same beam (SMC & COMPASS@CERN)

Experiments

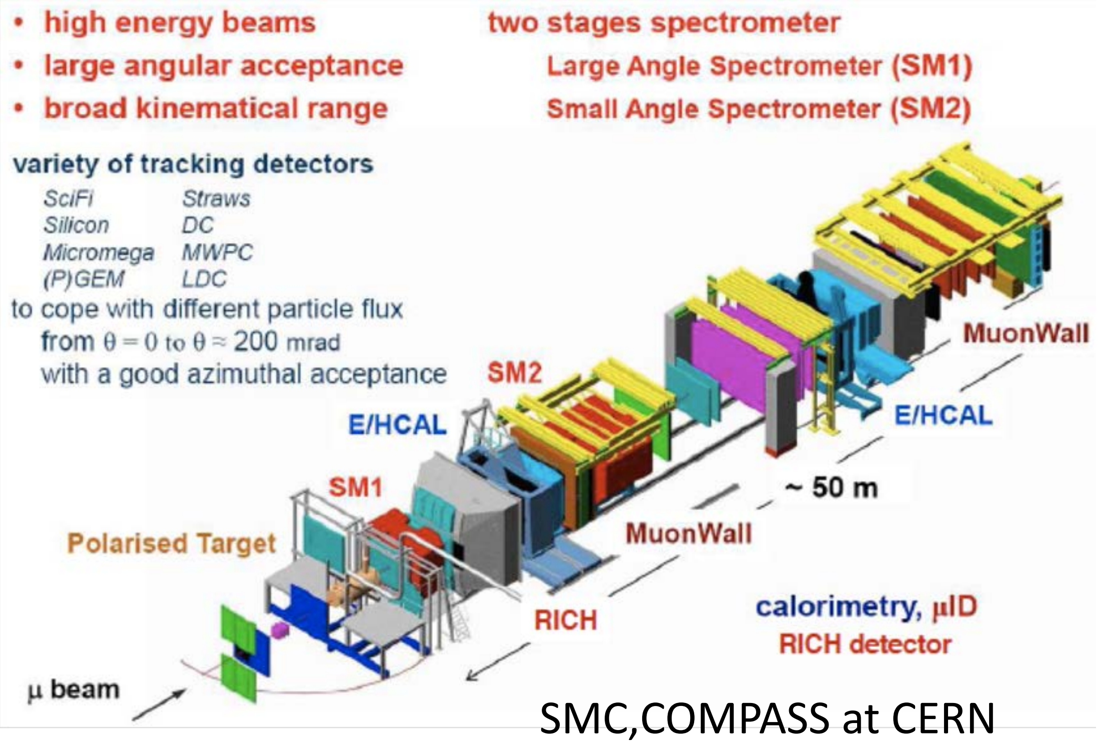


HERMES at DESY





Hall A at Jlab



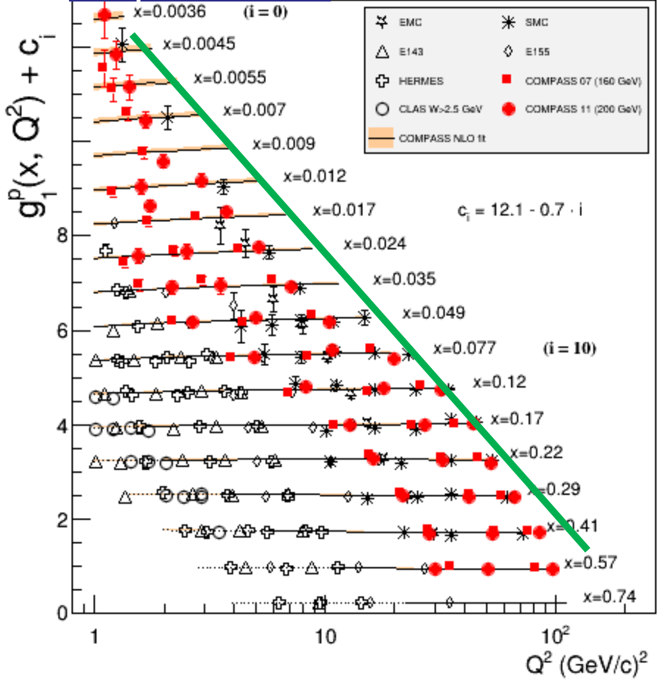
SMC,COMPASS at CERN

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

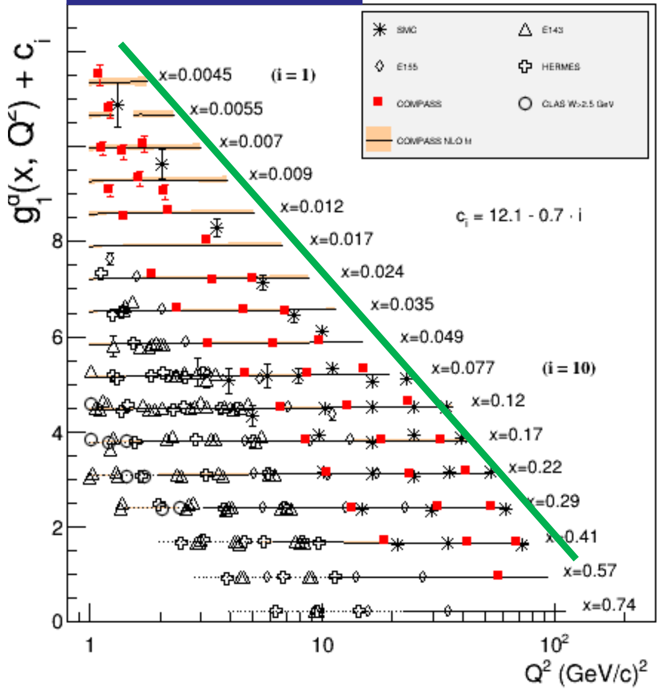
→ $g_1(x, Q^2)$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

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

proton



deuteron

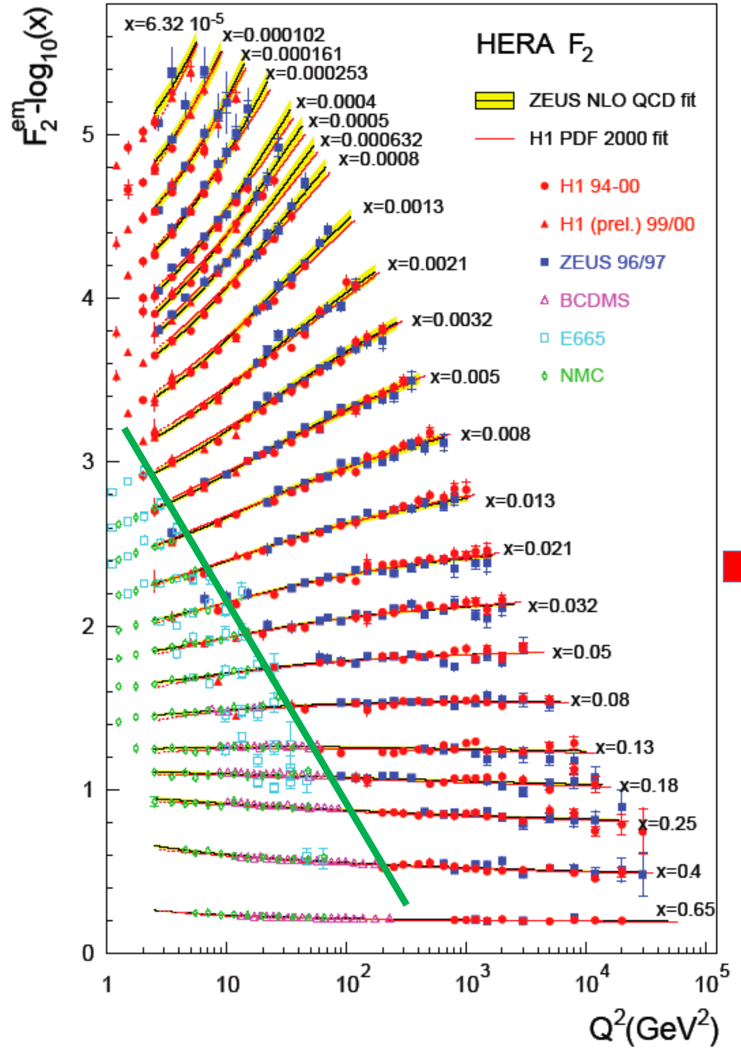


x and Q^2 coverage not yet sufficient for precise Δg

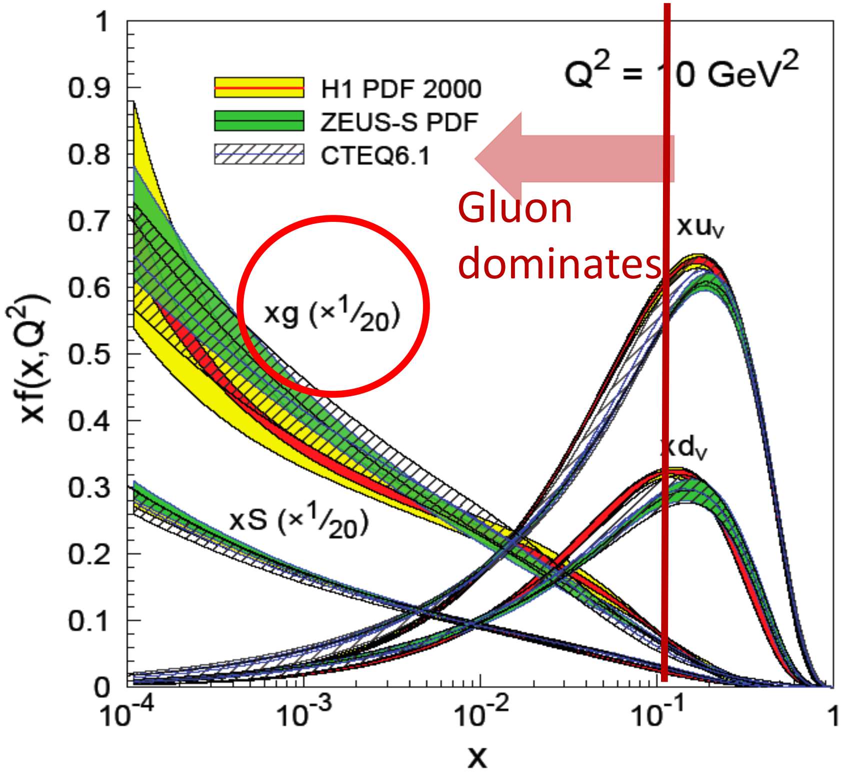
Can be improved by constraining from pp data (as DSSV, NNPDF…)

PLB753 (2016) 18

Similar to extraction of PDFs at HERA
(RECALL)



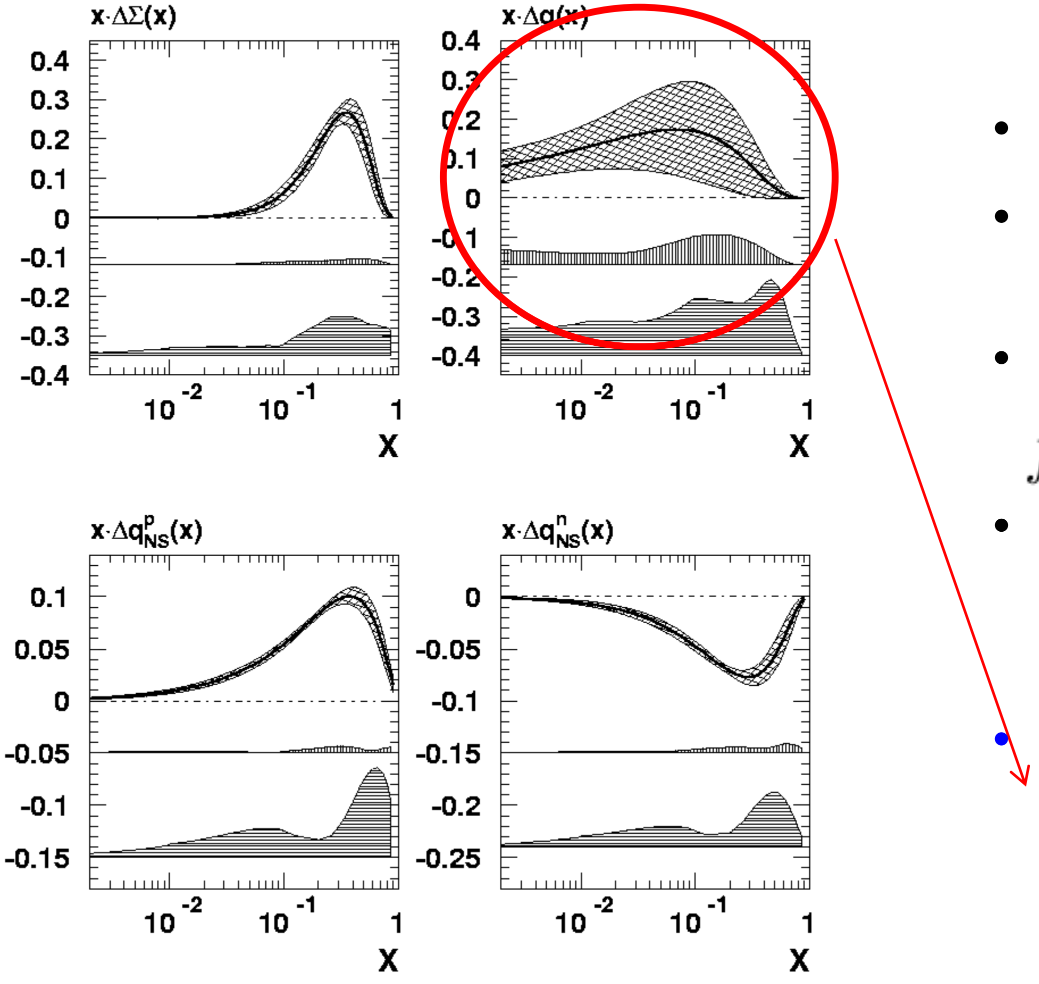
NLO pQCD analyses: fits with **linear** DGLAP* equations



*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

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

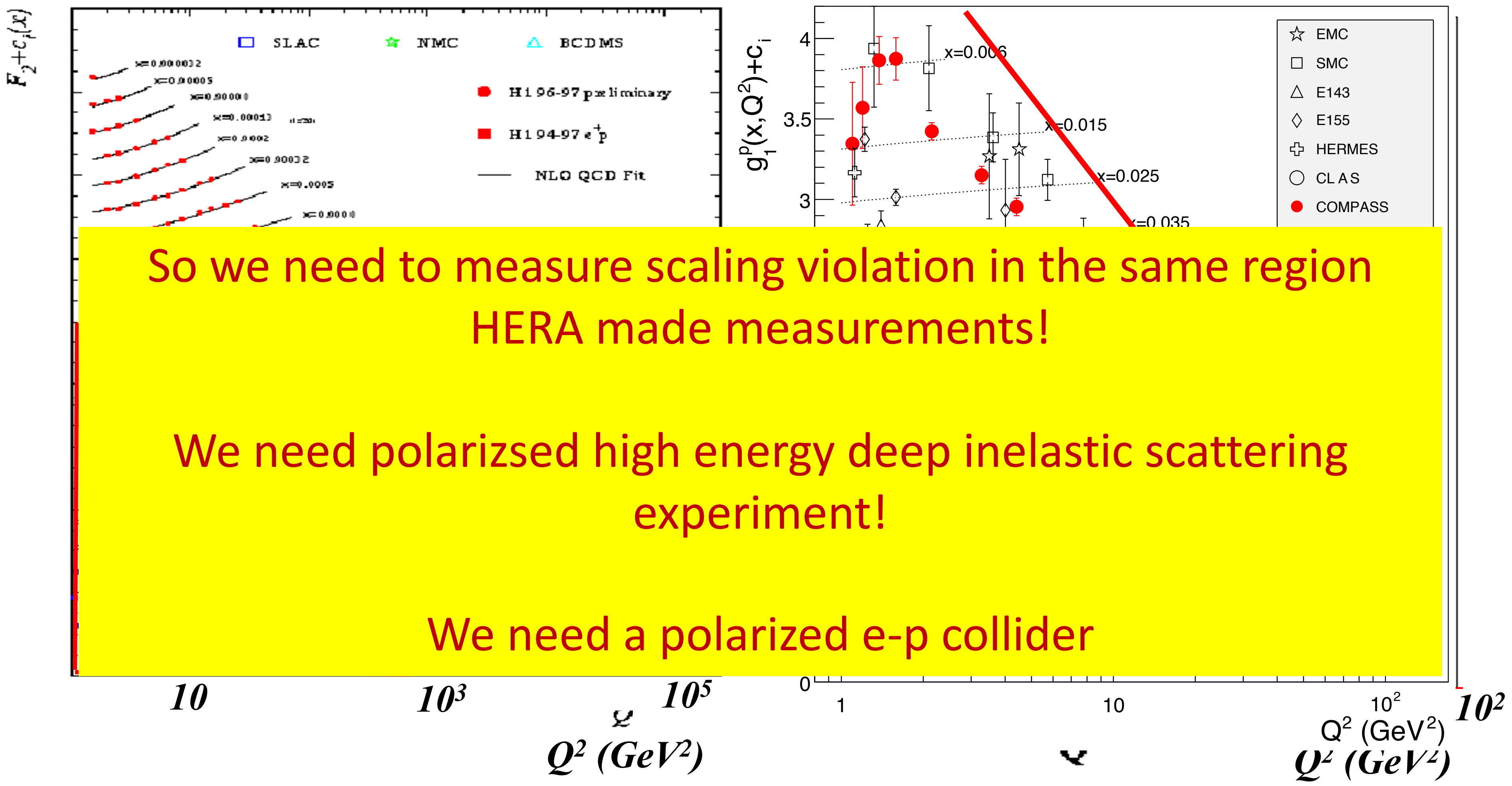
- Is this smallness due to some cancellation between quark+anti-quark polarization

- 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

F_2 vs. g_1 structure function measurements



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

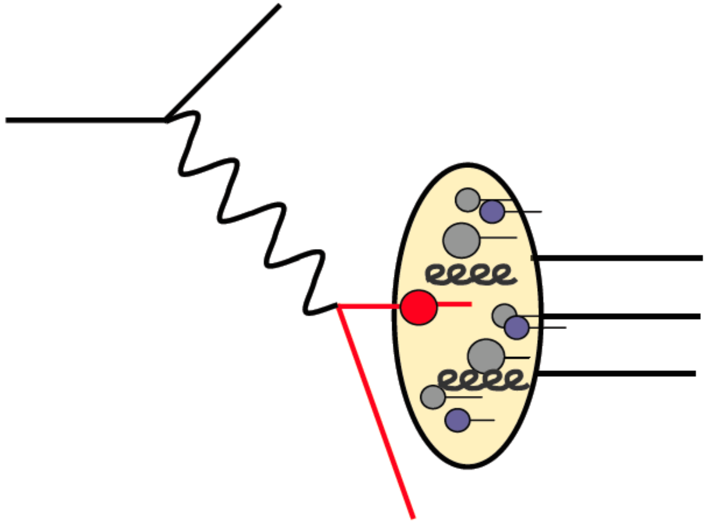
Large amount of polarized data since 1998… but not in NEW kinematic region!

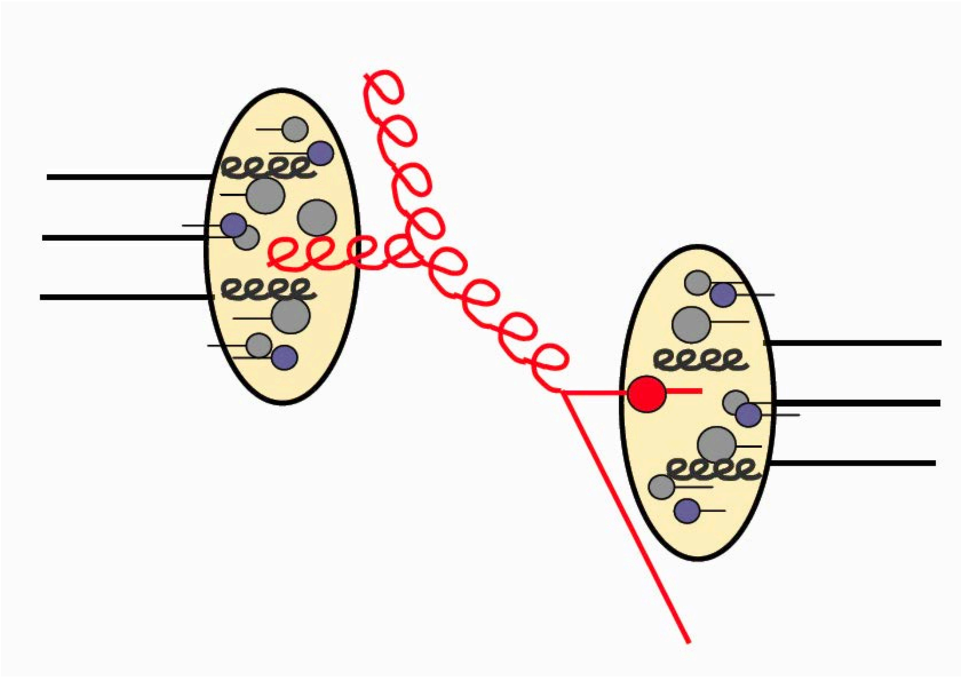
Large uncertainty in gluon polarization (+/-1.5) results from lack of wide Q^2 arm

RHIC Spin program and the Transverse Spin puzzle

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

Complementary techniques



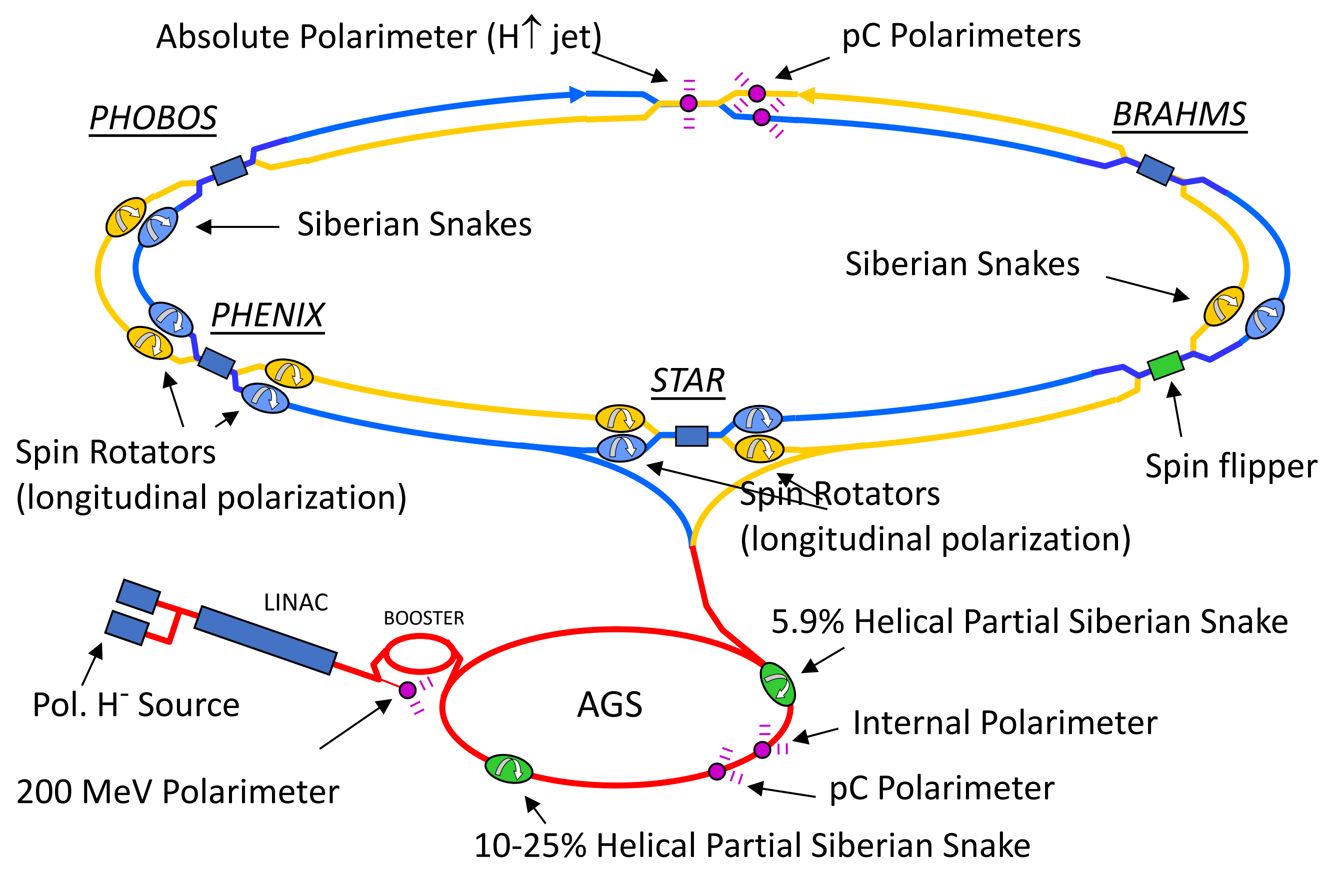


Photons colorless: forced to interact at NLO with gluons

Can't distinguish between quarks and anti-quarks either

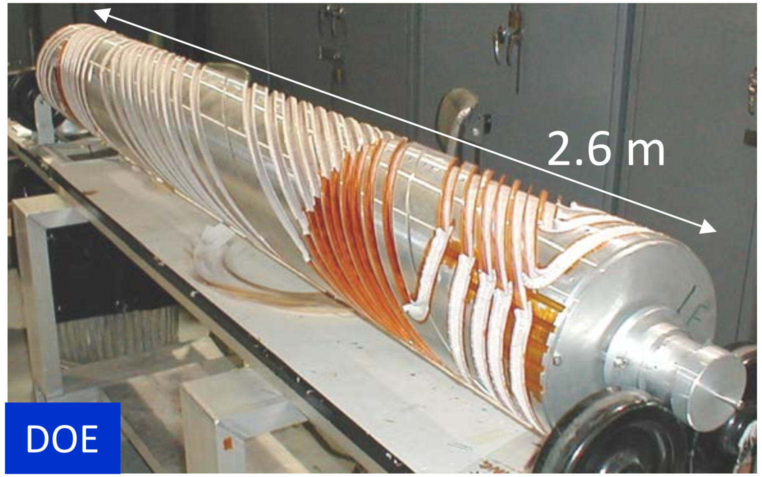
Why not use polarized quarks and gluons abundantly available in protons as probes ?

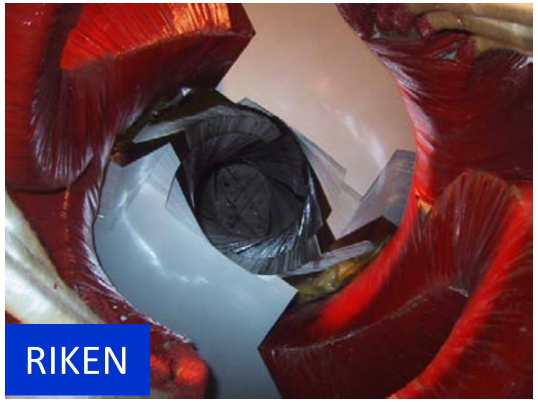
RHIC as a Polarized Proton Collider



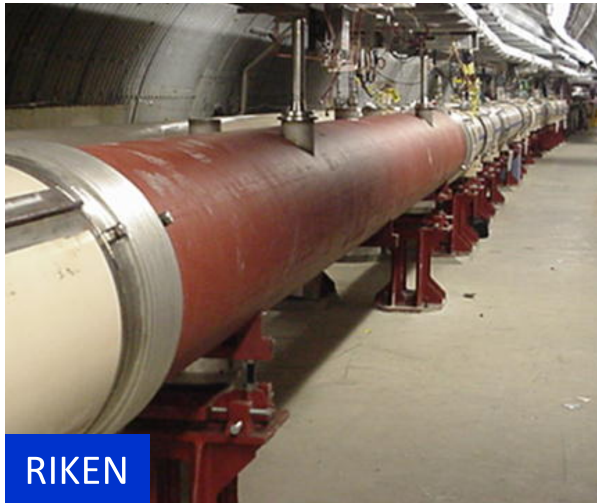
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

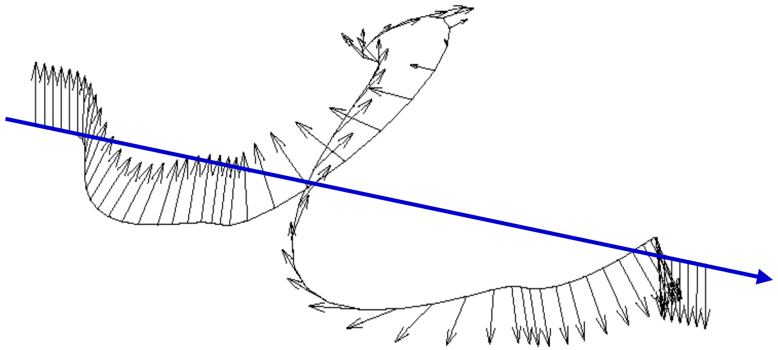
Siberian Snakes



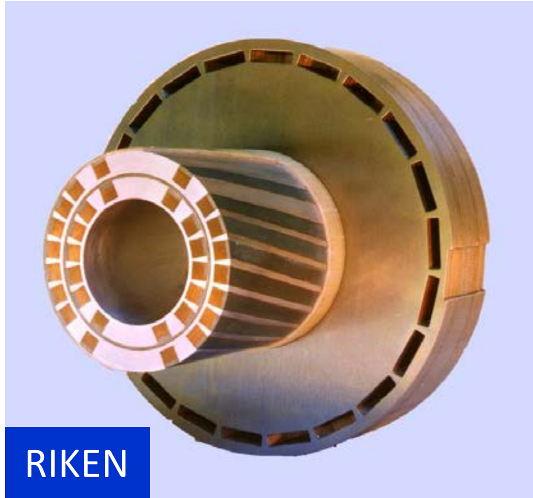


- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist

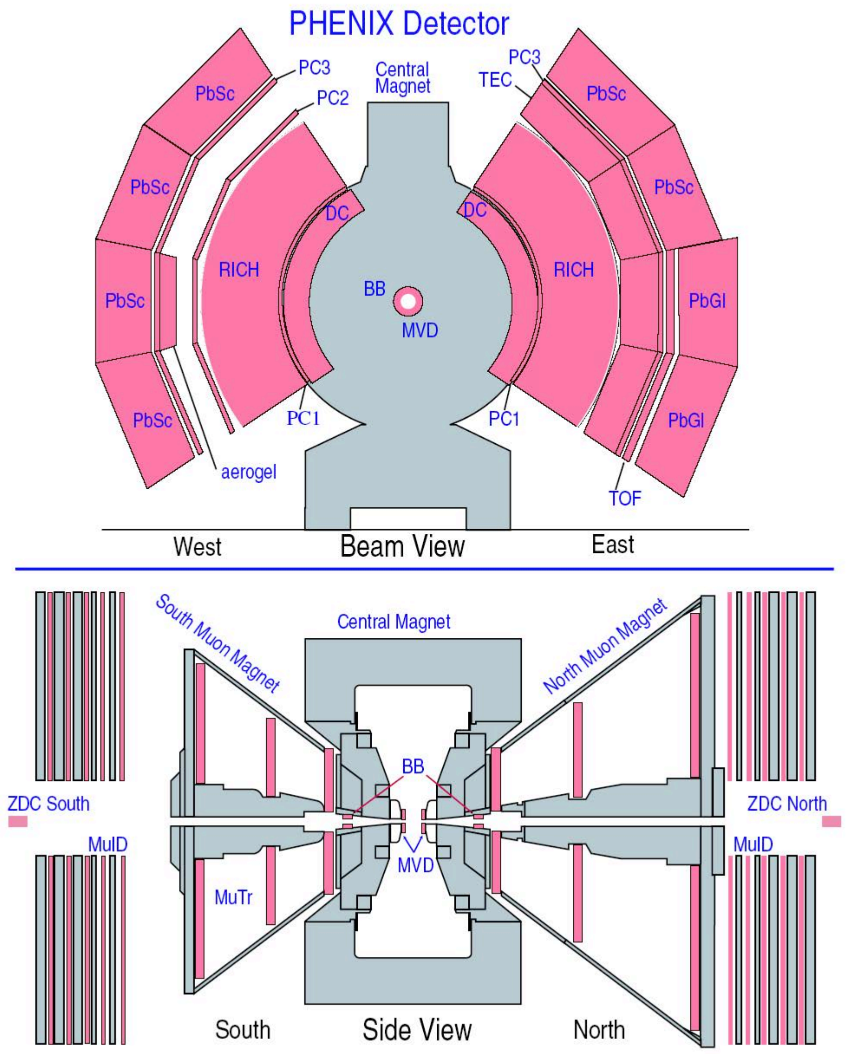




Courtesy of A. Luccio



PHENIX Detector at RHIC

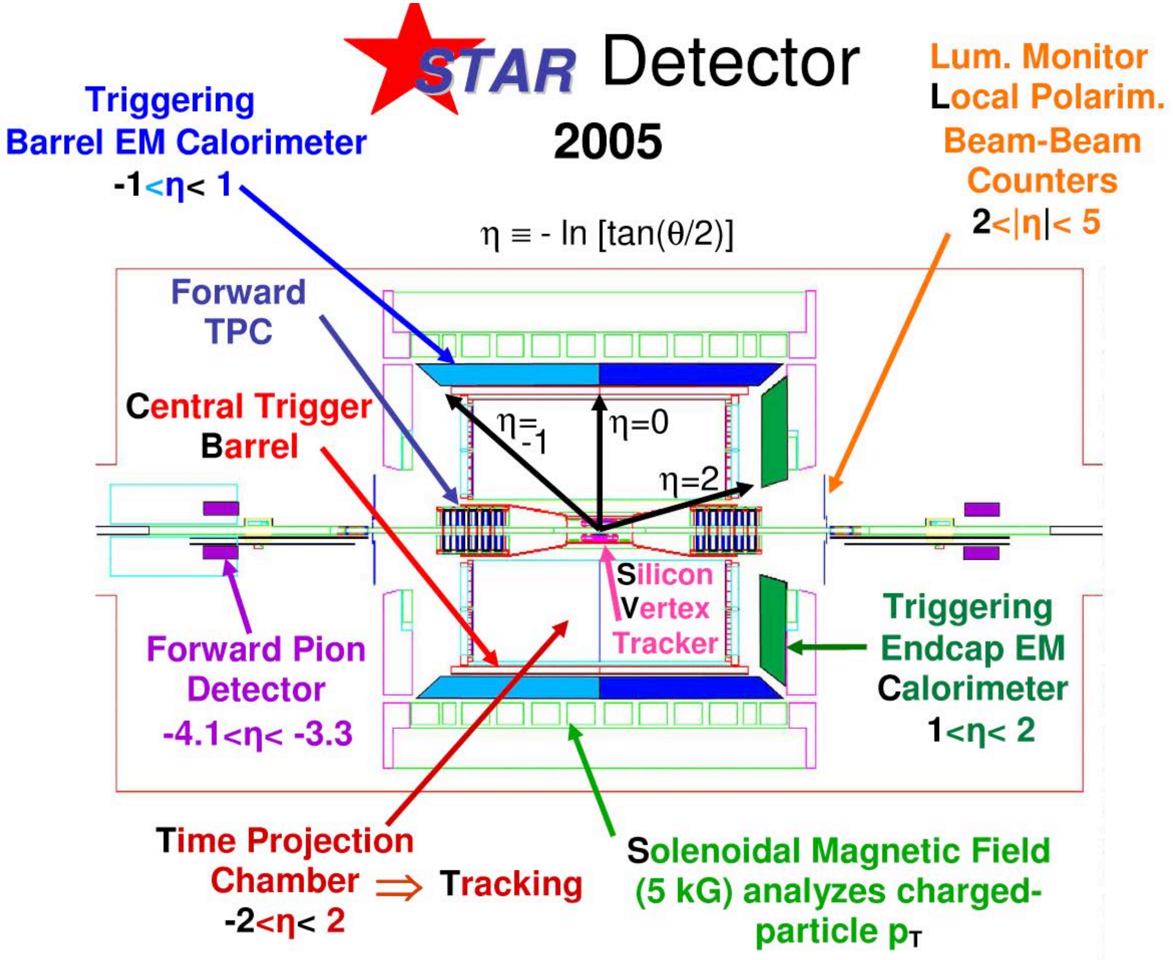


- ***Design philosophy:***
  - ***High resolution limited acceptance***
  - ***High rate capability DAQ***
  - ***Excellent triggers for rare events***
- Central arm
  - Tracking: Drift chambers, pad chambers, time expansion chamber
  - Superb EM Calorimetry PbGl, PbSc

    $\Delta\phi x \Delta\eta \sim 0.01 \text{ x } 0.01$

    π^0 to 2γ resolved up to 25 GeV pT
  - Particle Identification: RICH, TOF
- Forward Muon Arms:
  - Muon tracker, muon identifiers
- Global detectors:
  - Beam beam collision (BBC) counter, Zero Degree Calorimeters (ZDCs)
- Online monitoring, calibration and production

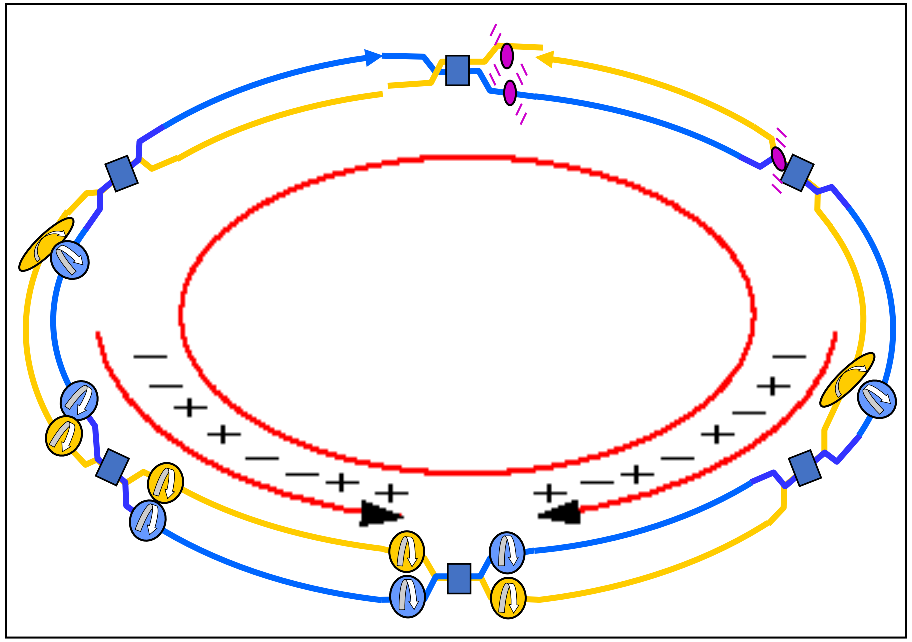
STAR Detector at RHIC



- *Design Philosophy:*
  - *Maximize acceptance*
  - *lower resolution*
- Subsystems:
  - f = 2p acceptance in EM calorimetry
    Barrel and EndCap
    Total: -1 < h < 2
  - Time Projection Chamber
  - Separate Forward pion detector
  - Silicon vertex tracker
  - Beam-Beam Counters
  - Zero Degree Calorimeter

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

Accessing ΔG in p+p Collisions at RHIC

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

From ep (&pp) (HERA mostly)

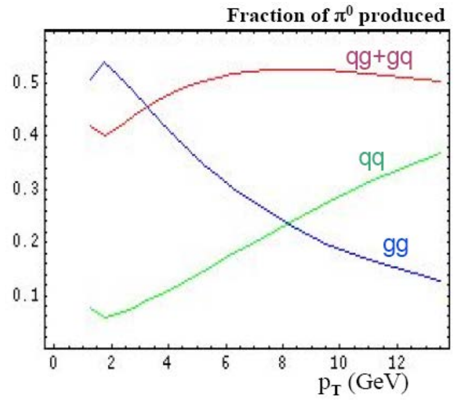
NLO pQCD

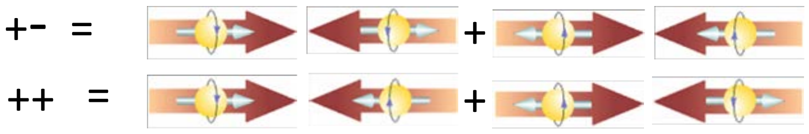
From e+e- (& SIDIS,pp)

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

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

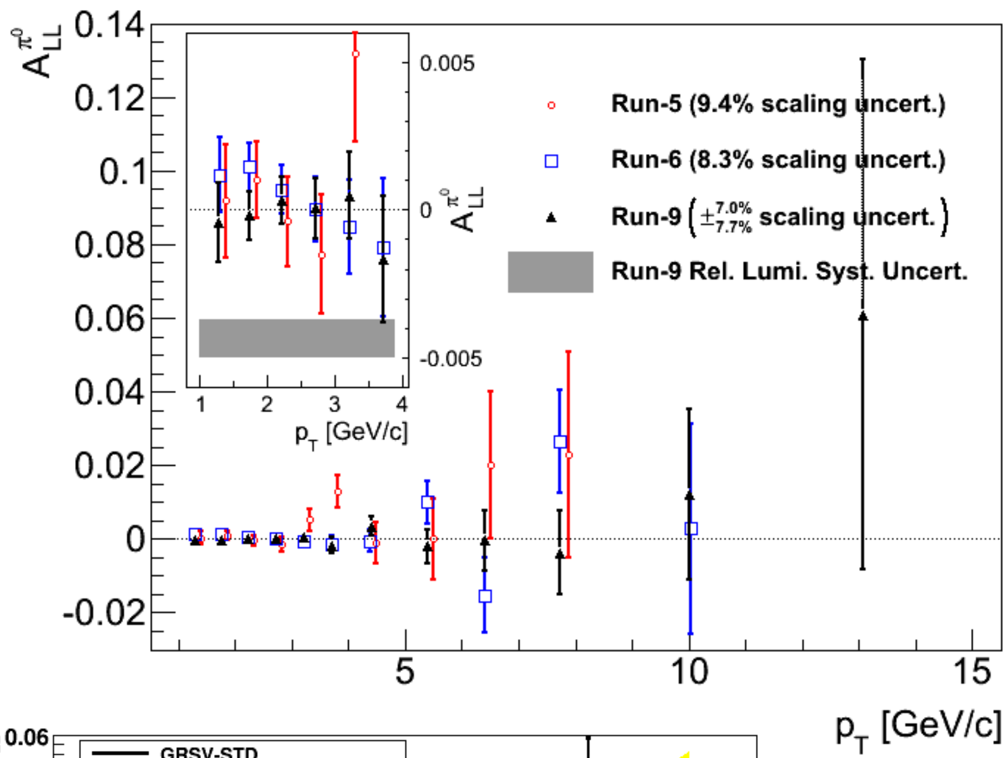
where the coefficients a, b and c depend on final state observable and event kinematics (η,p_T).

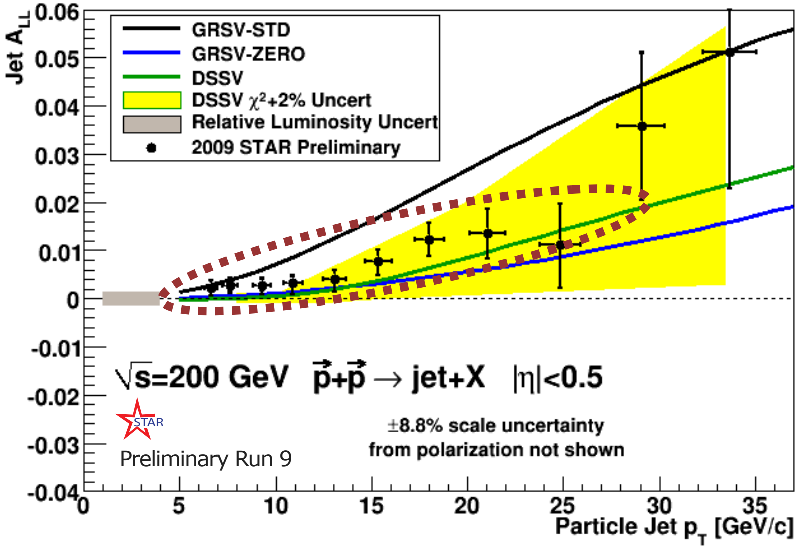


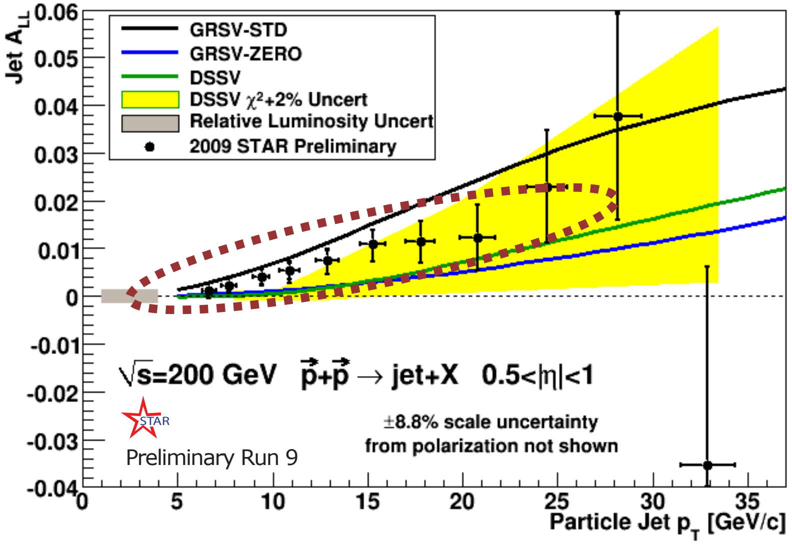


Most impactful results: on ΔG

- 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



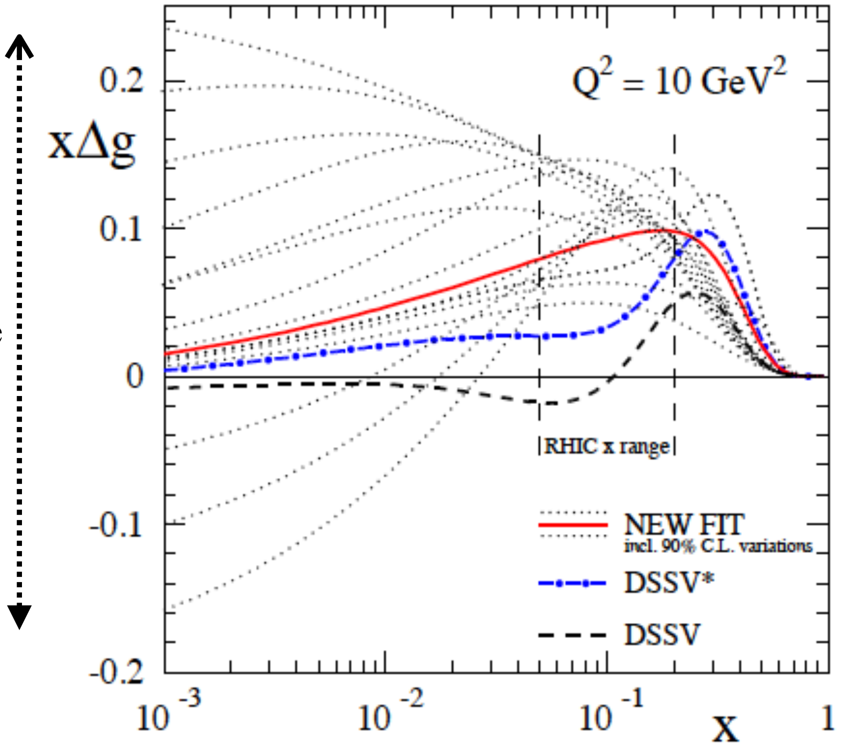




Recent global analysis: DSSV

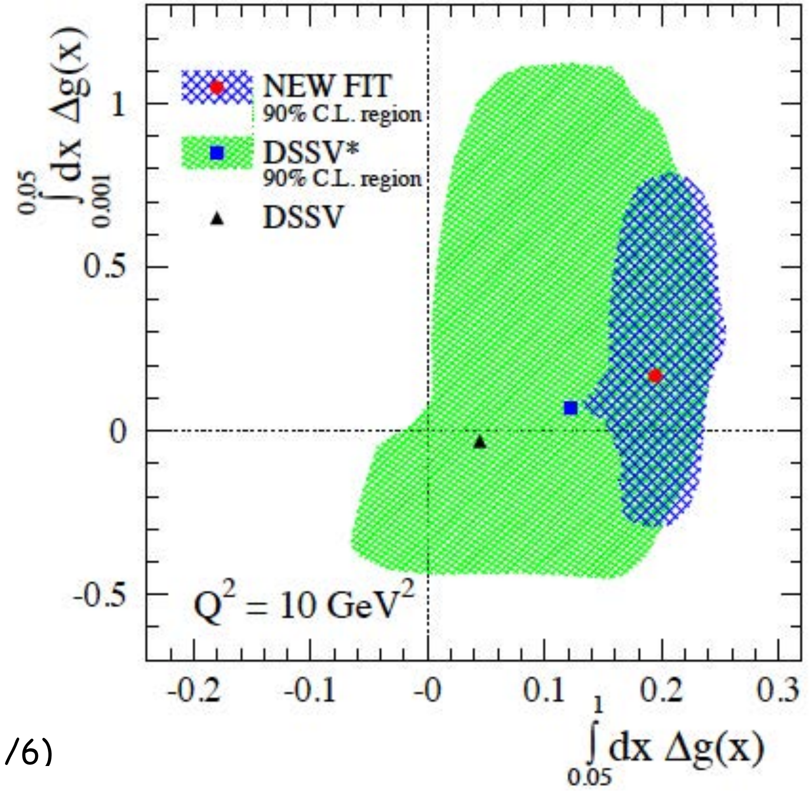
D. deFlorian et al., arXiv:1404.4293

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



/6)

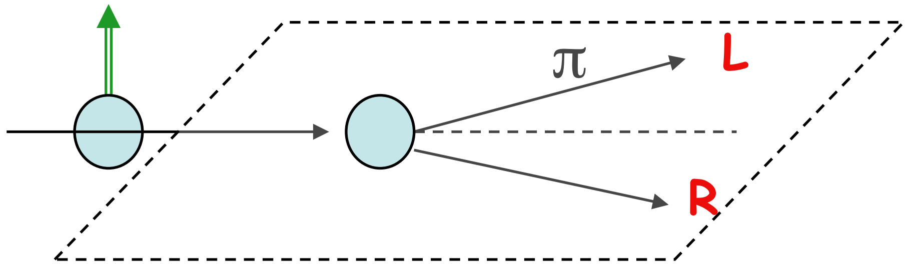
$\Delta G = 0.2$ +/- 0.02 +/- 0.5



While RHIC made a huge impact on ΔG

large uncertainties to remain in the low-x unmeasured region!

Transverse spin introduction



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

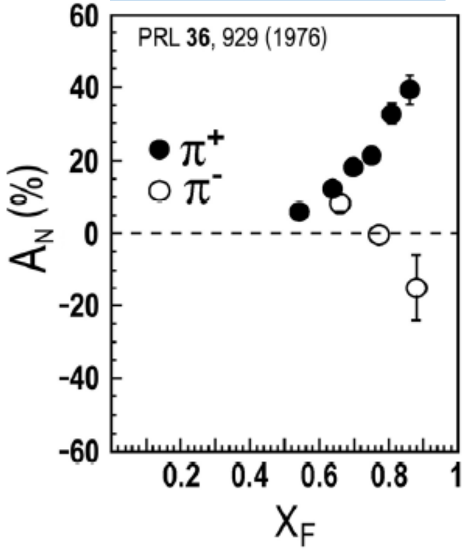
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

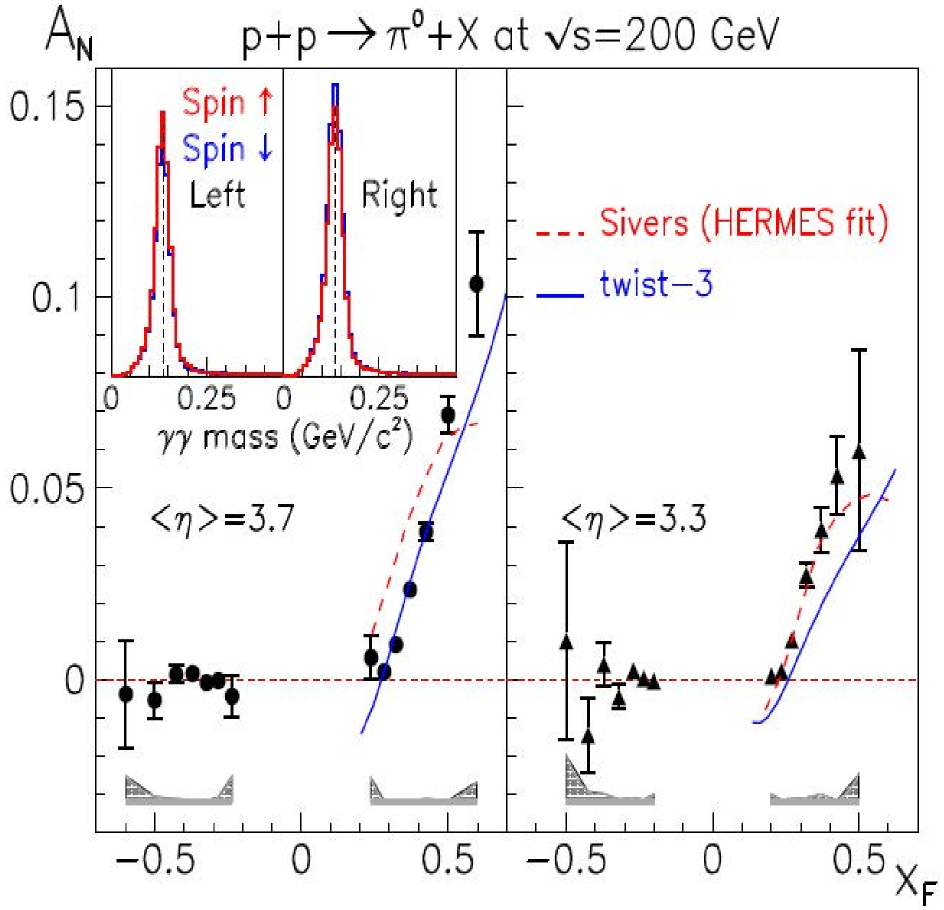
Kane, Pumplin and Repko
PRL 41 1689 (1978)

- 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….

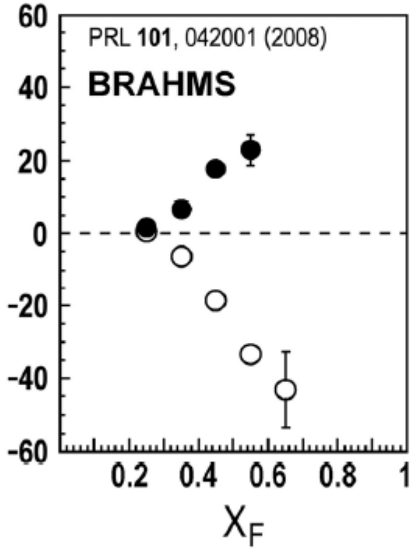
Pion asymmetries: at most CM energies!

ZGS/ANL
√s=4.9 GeV





RHIC
√s=62.4 GeV

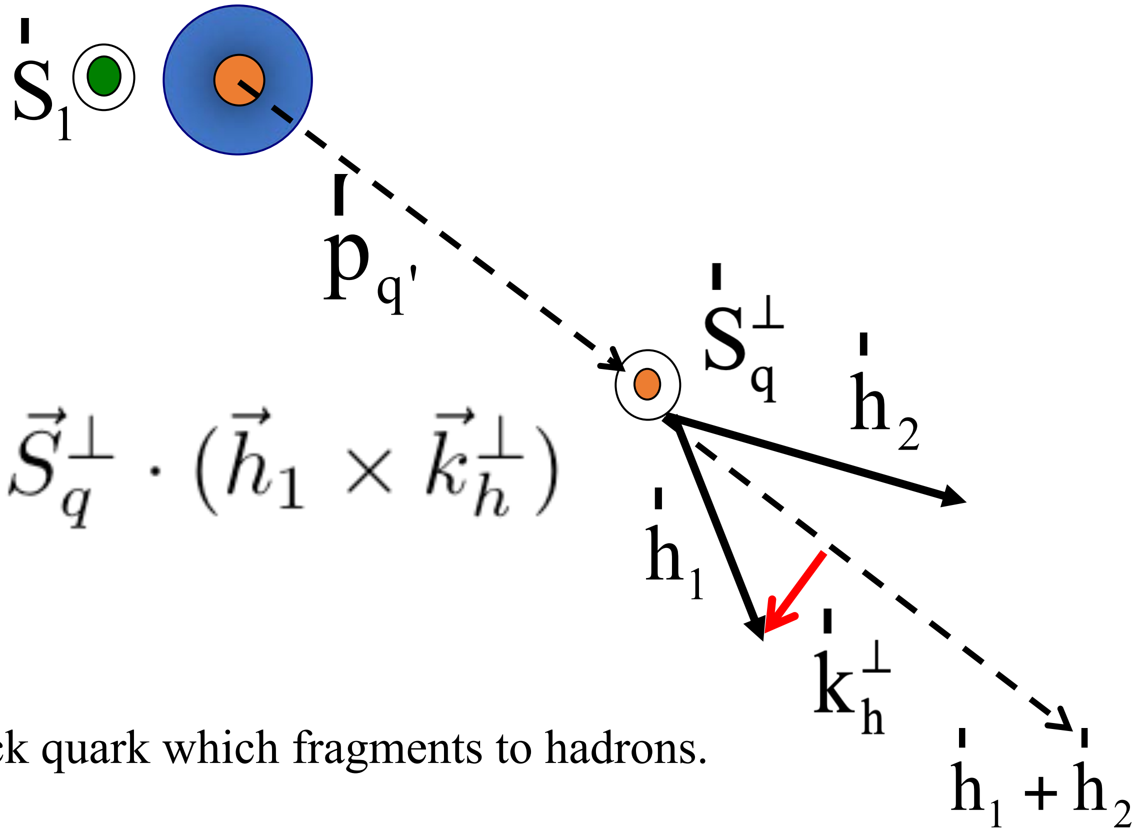


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well

Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

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

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

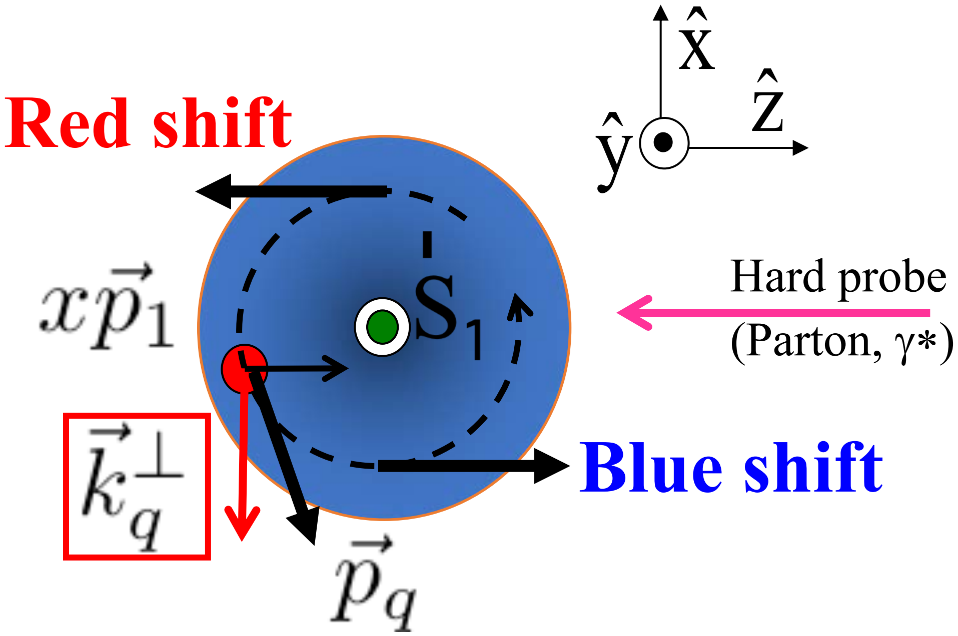


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

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 Functions

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)

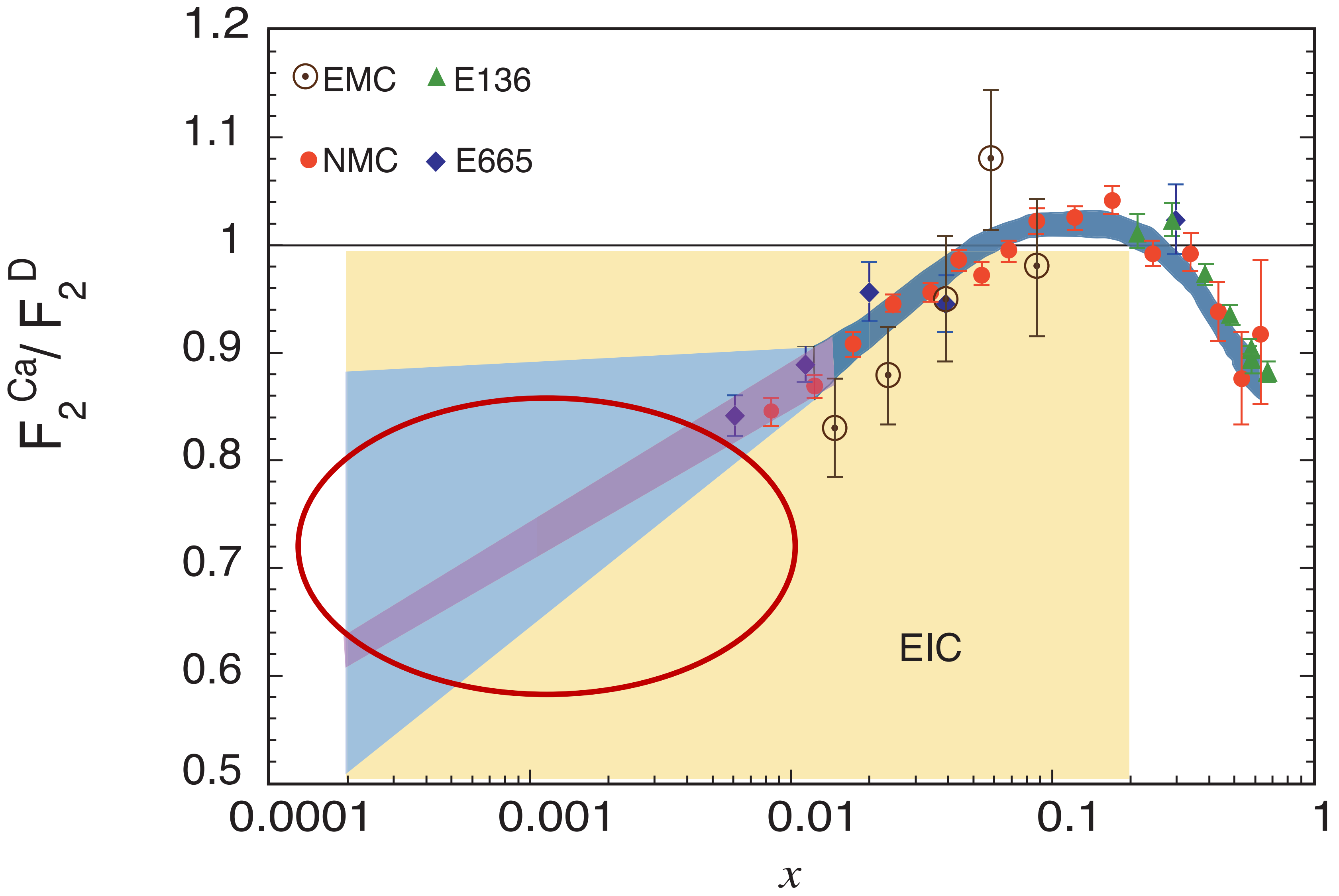
- e-p more precise in p-p as it directly probes the glue, with more experimental control.

- Low-x behavior of gluons in proton intriguing; Precise measurements of gluons critical.

We need a new polarized collider….

Nuclear Structure: A known unkown…

PDFs in nuclei are different than in protons!



Since 1980's we know the ratio of F_2's of nuclei to that of Deuteron (or proton) are different.

Nuclear medium modifies the PDF's.

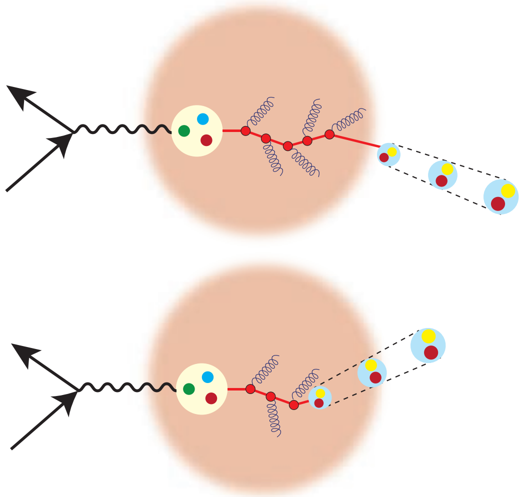
Fair understanding of what goes on, in the x > 0.01.

However, what happens at low x?

Does this ratio saturate? Or keep on going? – Physics would be very different depending on what is observed.

Date needed at low-x

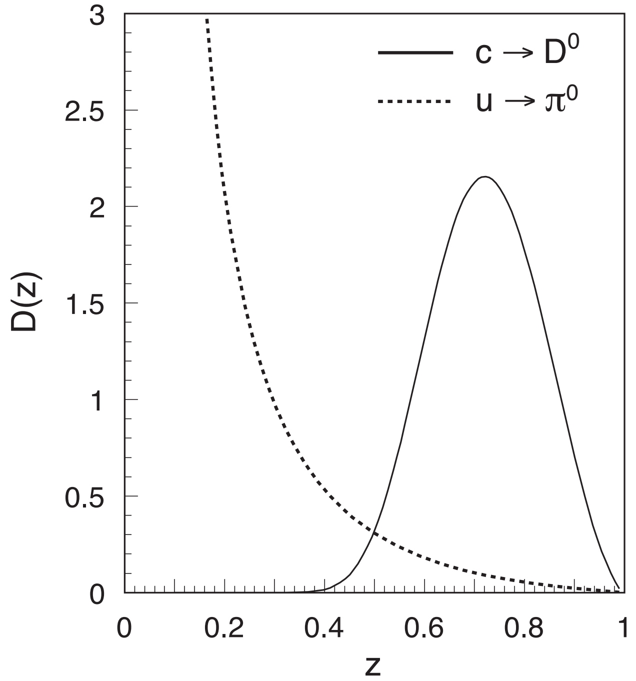
Nucleus as a femtometer detector



Interactions of partons moving through cold nuclear matter when a hadron is formed outside or inside the nucleus. Color neutralization, Fragmentation, inverse of confinement, clues? What really happens?

Need an e-A collider affording precision and control

Fragmentation functions models for heavy vs. light quarks. Very different shapes, and hence should be distinguishable in experiments.



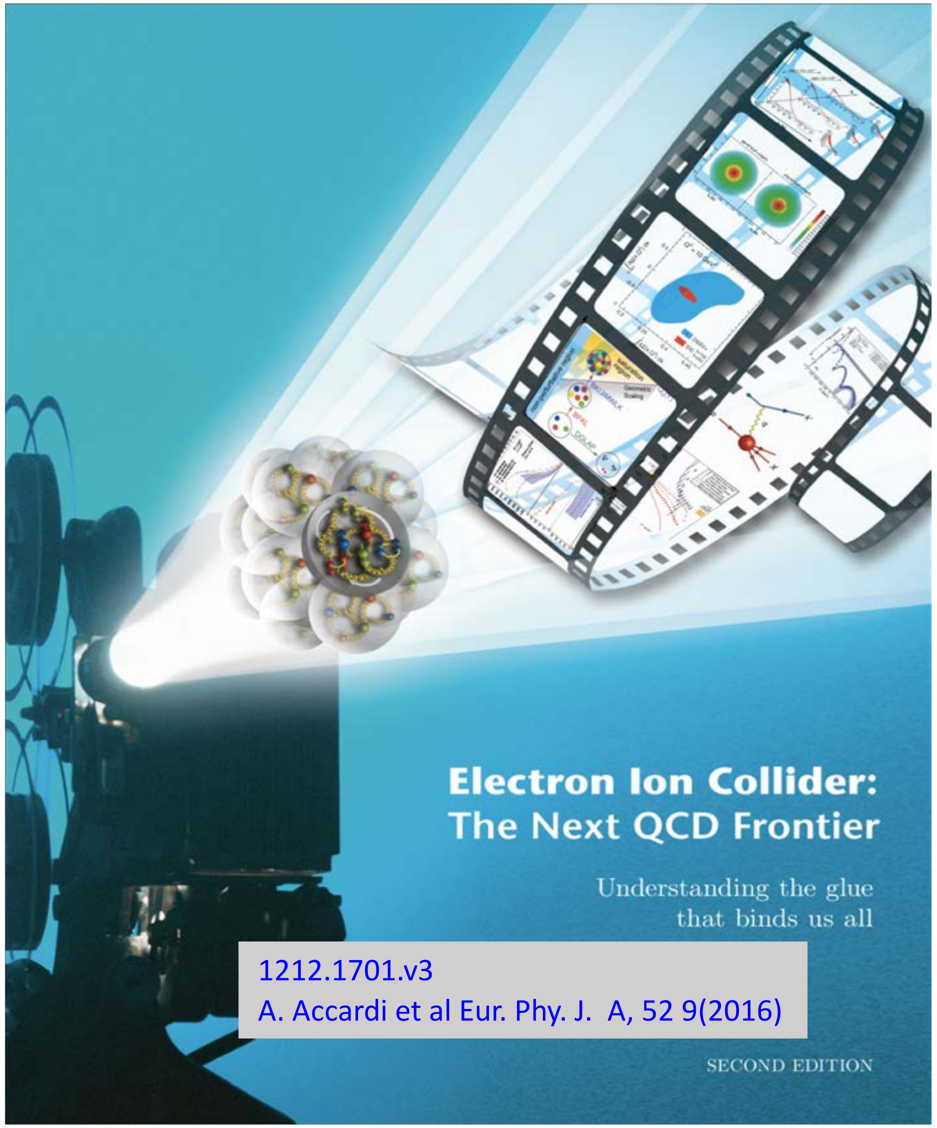
That Collider Is The Electron Ion Collider

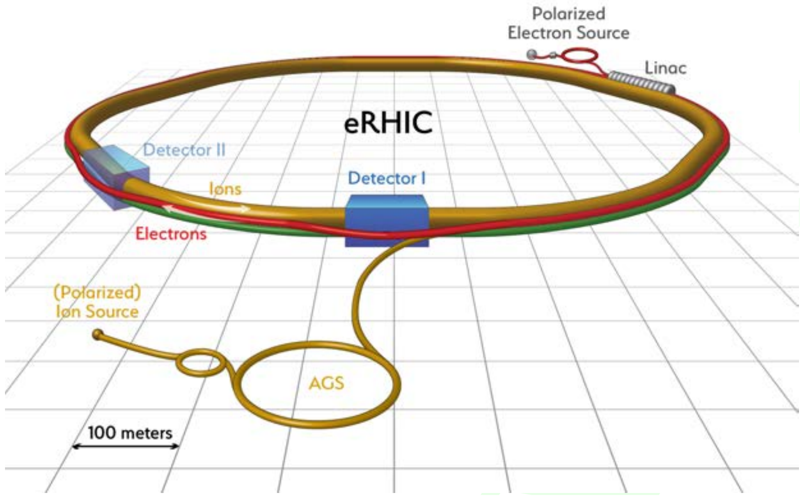
About which we will learn on Day 3

Thank you.

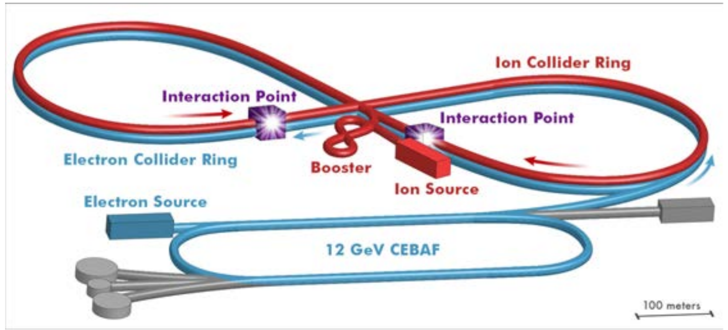
The Electron Ion Collider

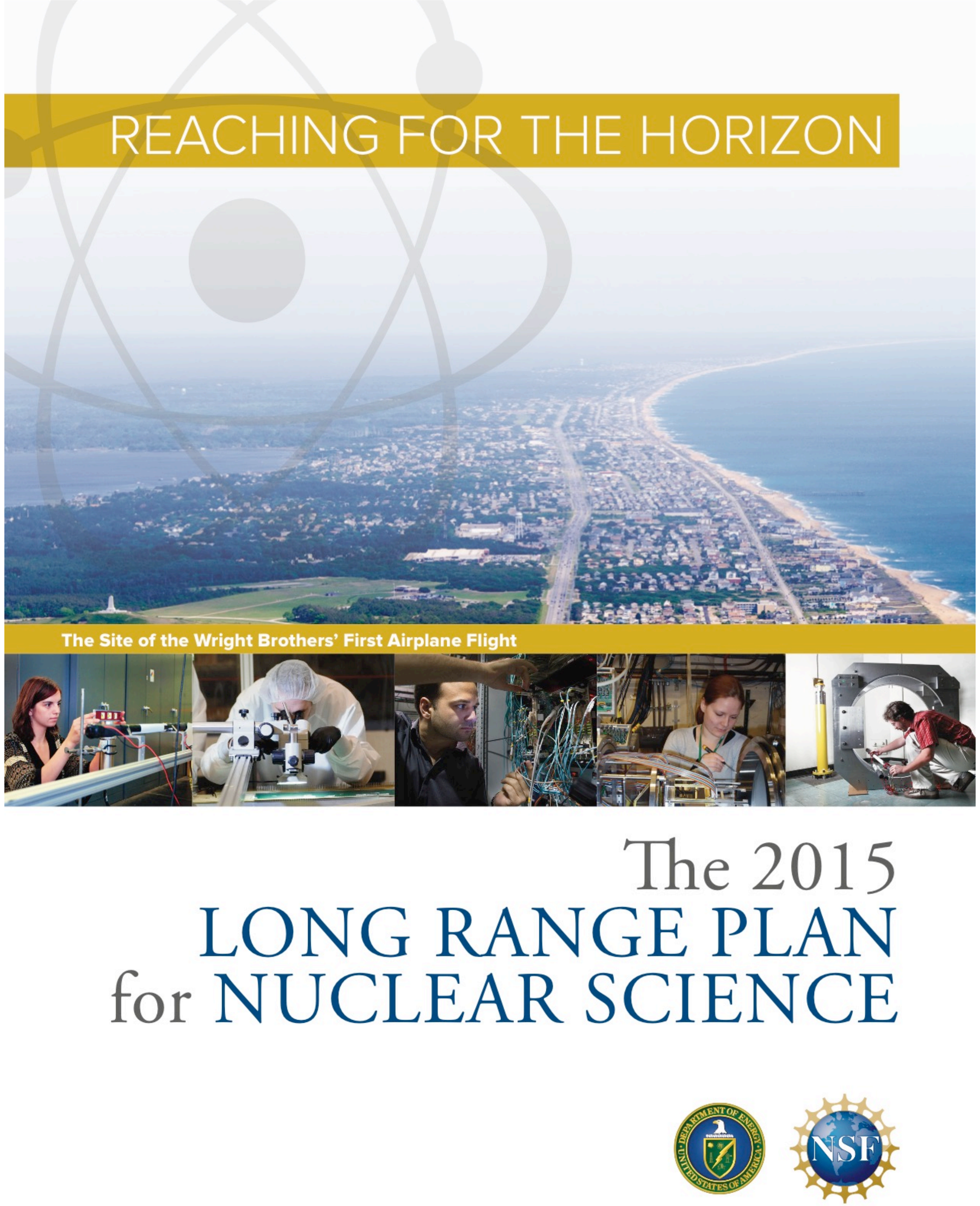
Two options of realization!





Not to scale





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

RECOMMENDATION:

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

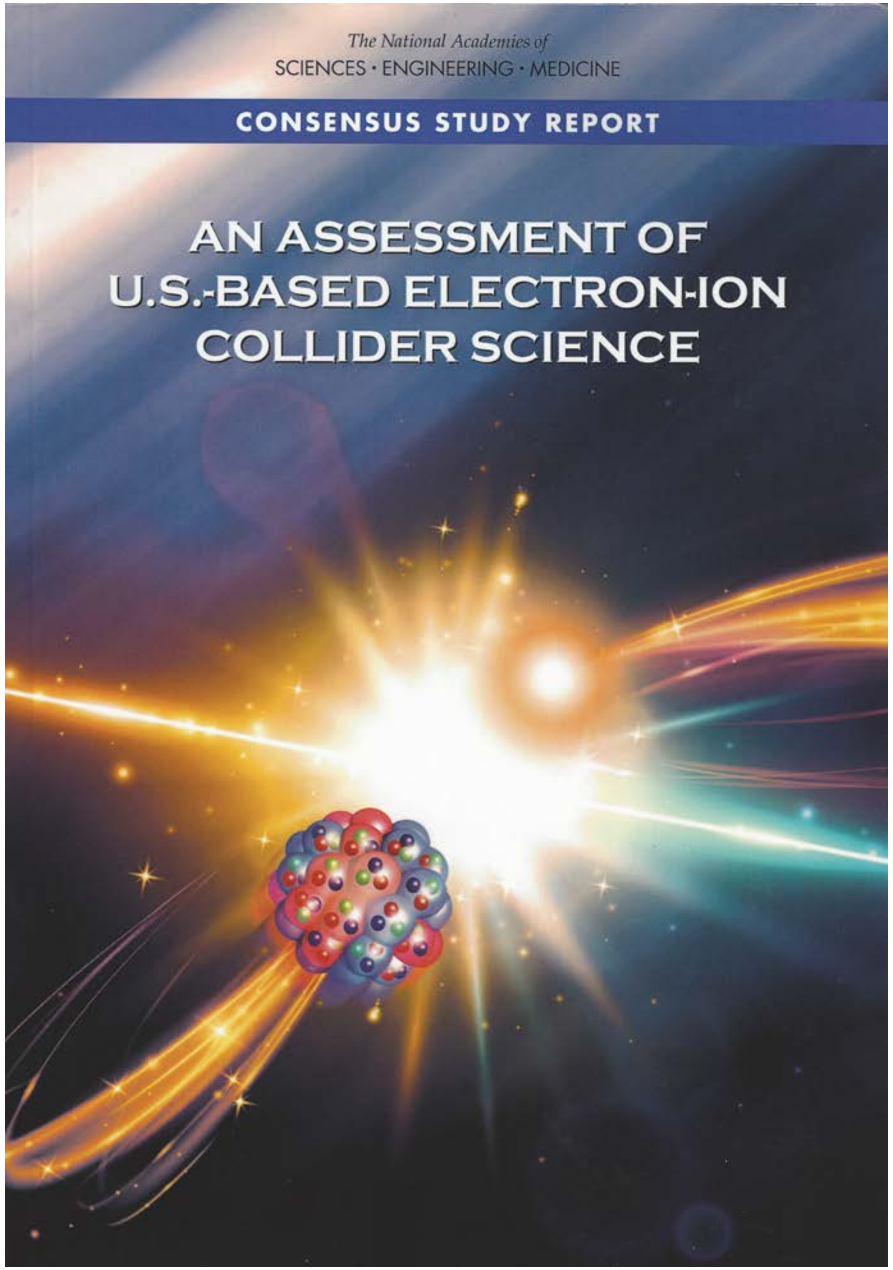
Initiatives:

Theory

Detector & Accelerator R&D

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

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



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.