Center for Frontiers in Nuclear Science

EIC : Why a collider? Why polarized?

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Lecture 2 of 3

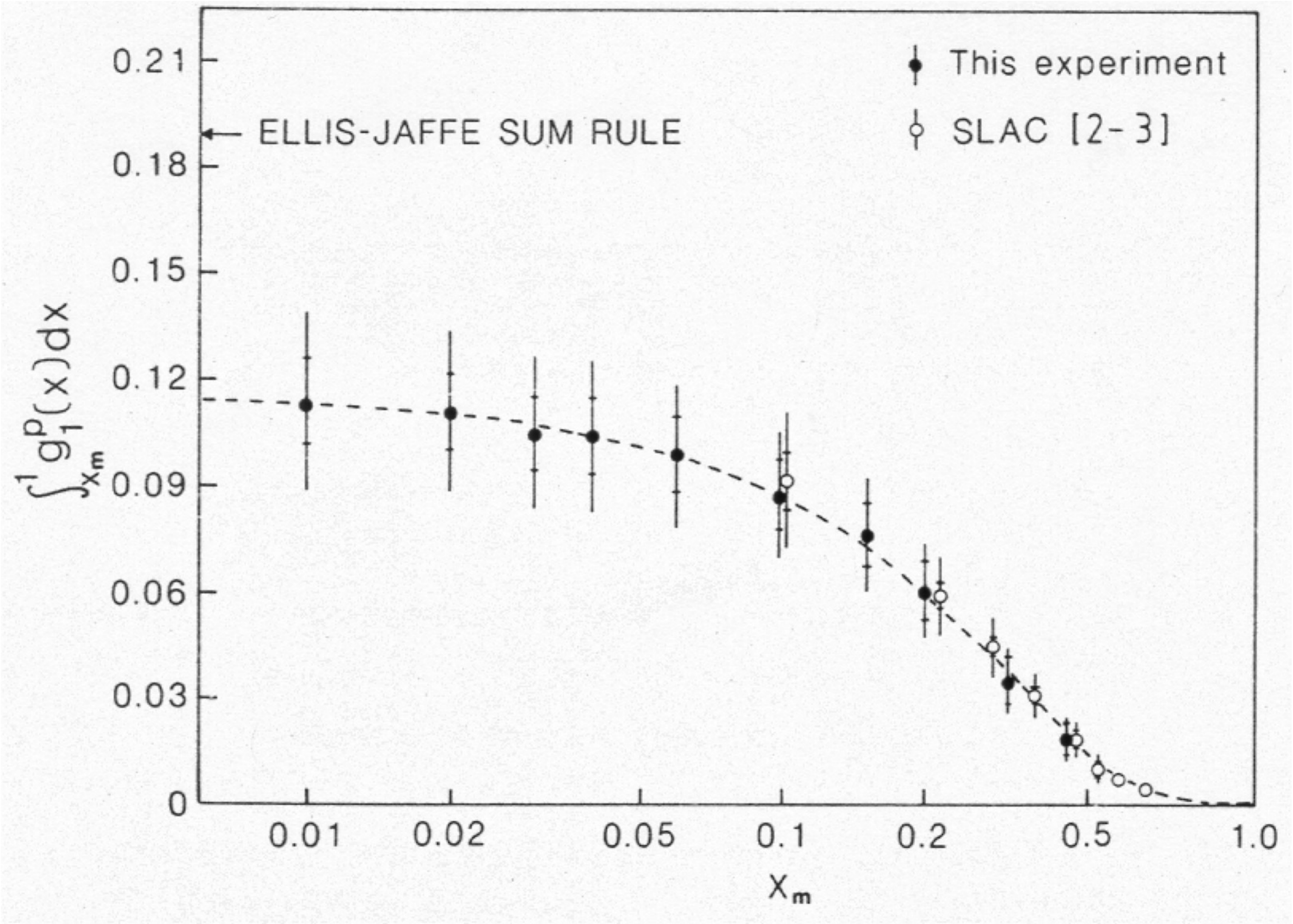
NNPSS 2023 at UC Riverside

Stony Brook University

July 10, 11, 12, 2023

Brookhaven National Laboratory

But first re-visit how to make measurements with polarized observables

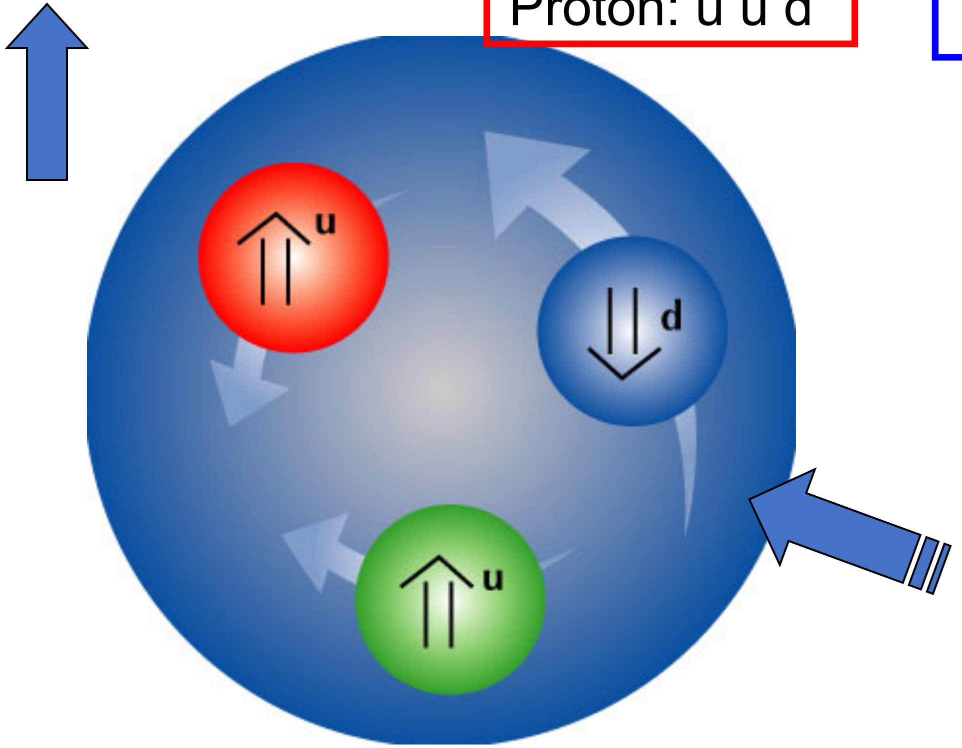


Nucleon's Spin: Naïve Quark Parton Model (ignoring relativistic effects… now, illustration only, but historically taken seriously)

- 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!

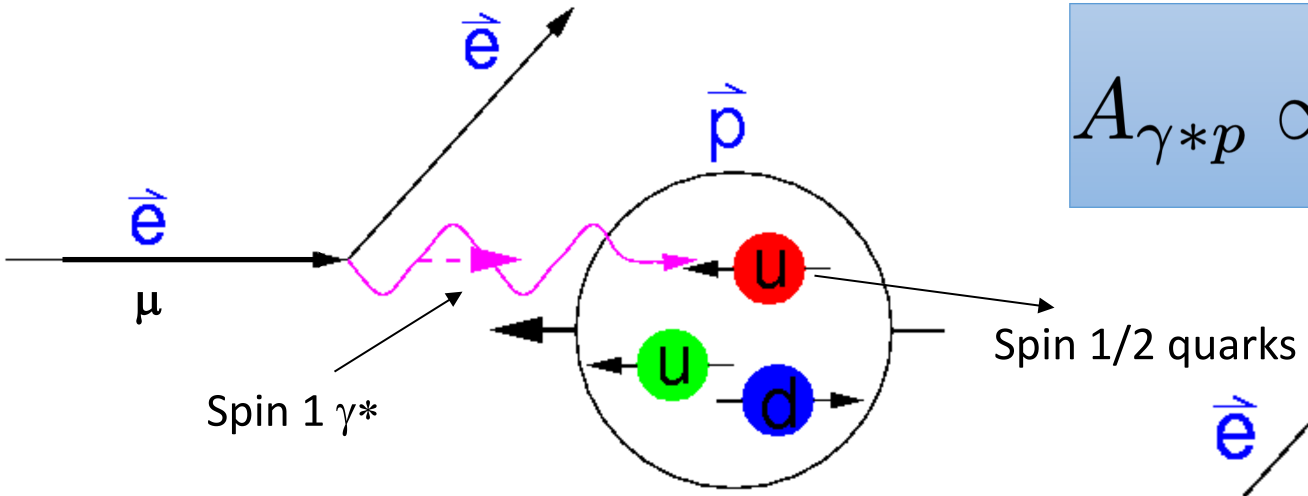
$$1/2 \overset{?}{=} 1/2 + 1/2 + 1/2$$

$$\boxed{1/2 = 1/2 - 1/2 + 1/2}$$

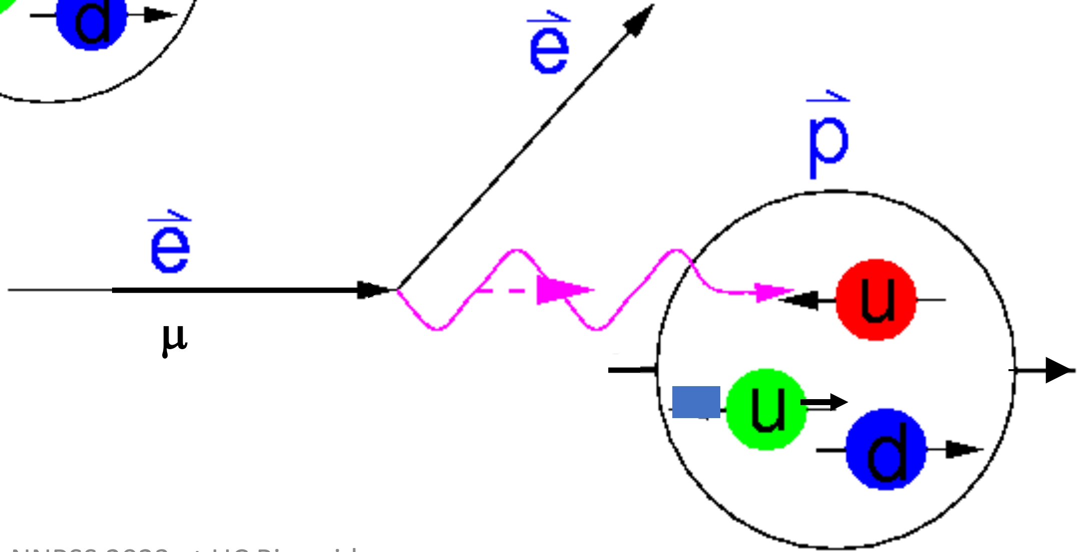
How was the Quark Spin measured?

- Deep Inelastic polarized electron or muon scattering

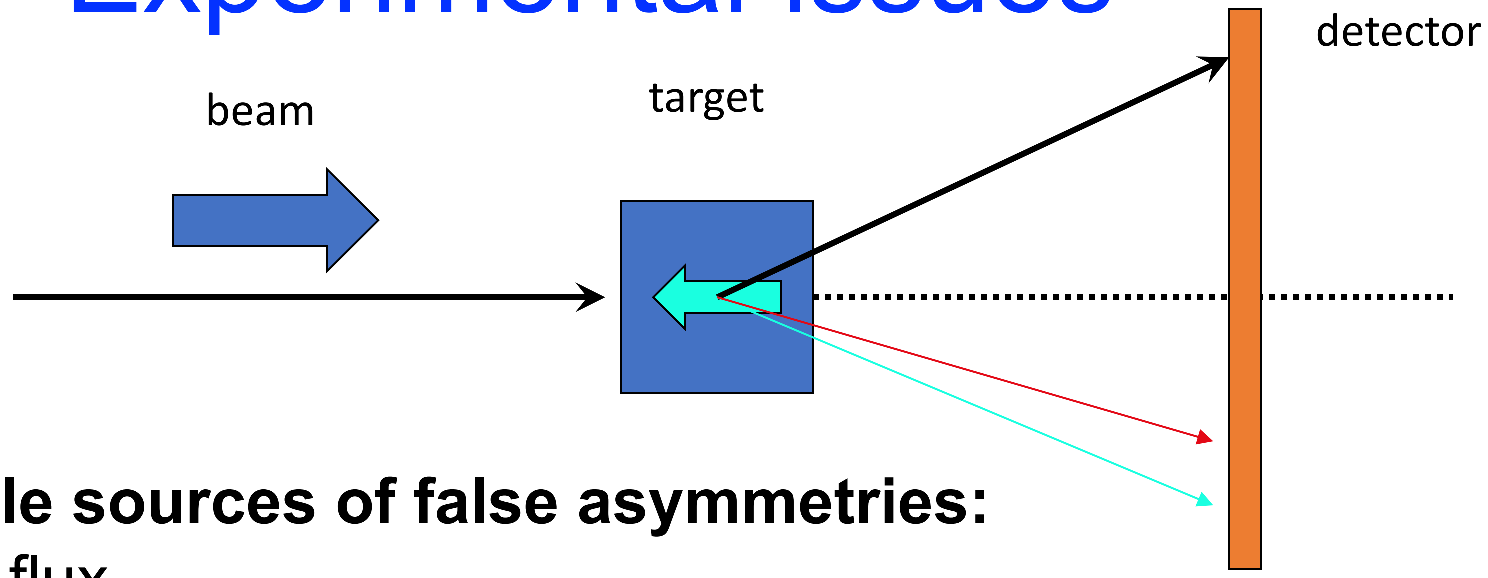
$$A_{\gamma * p} \propto \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}}$$



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

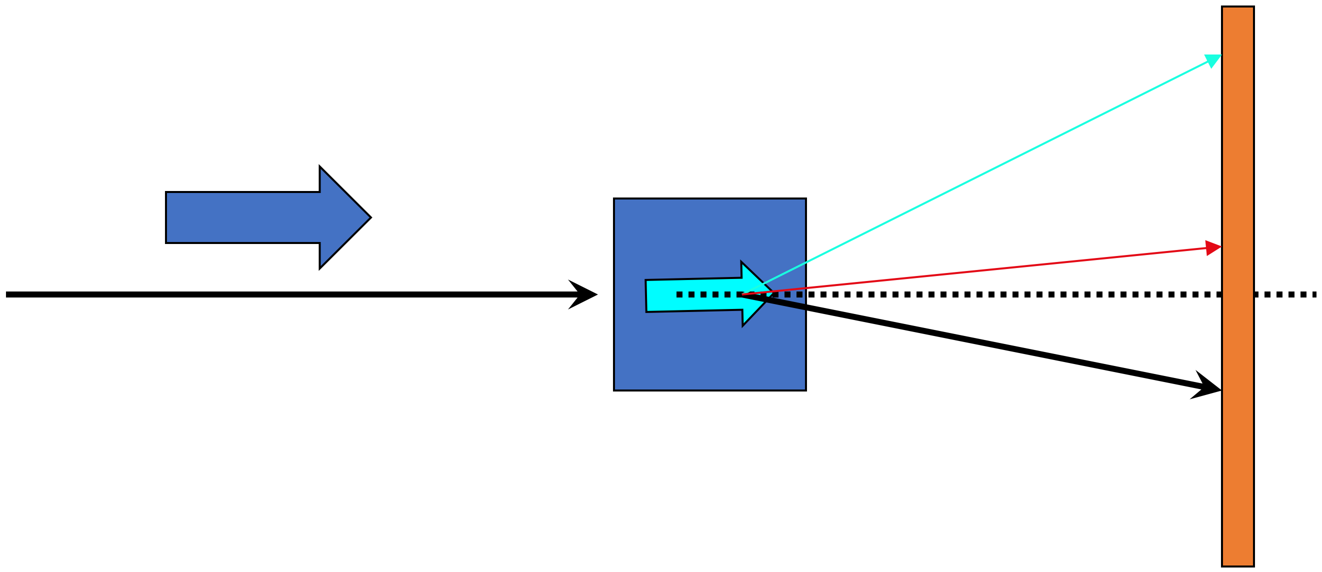


Experimental issues



Possible sources of false asymmetries:

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



$A_{measured} = A_{LL}$
Double Longitudinal Spin asymmetry

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

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

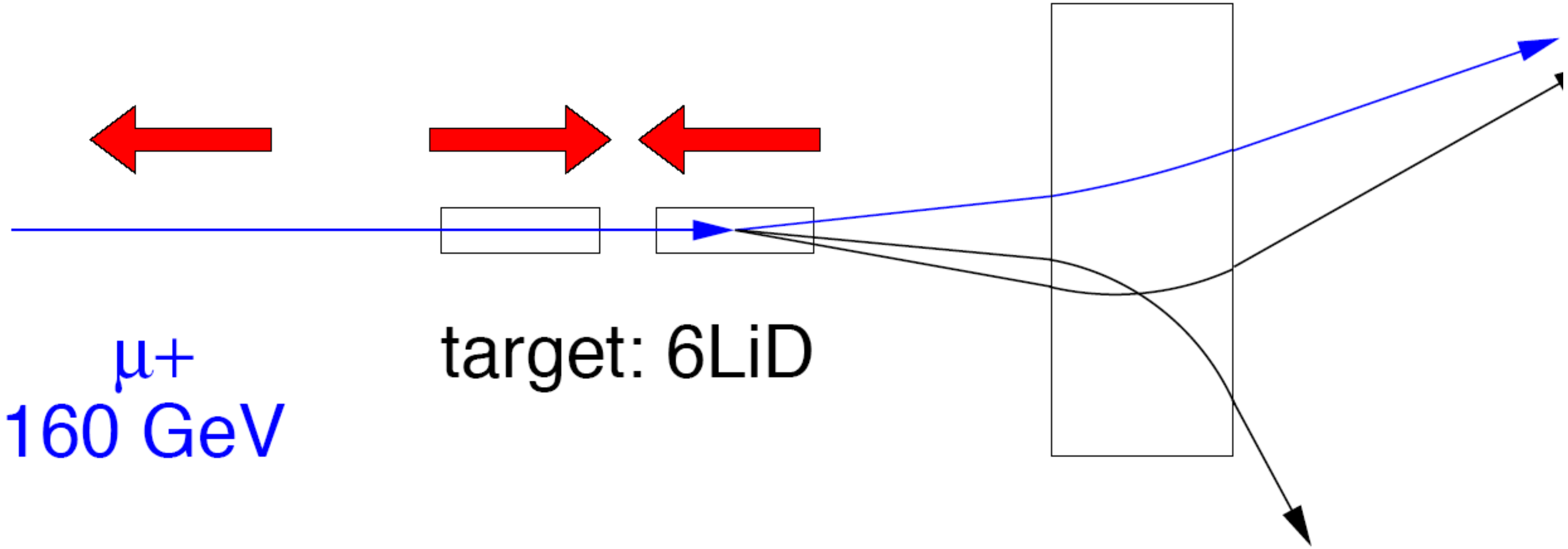
$$N^{\rightarrow\rightarrow} = N_b \cdot N_t \cdot \sigma^{\rightarrow\rightarrow} \cdot D_{acc} \cdot D_{eff}$$

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

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

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

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

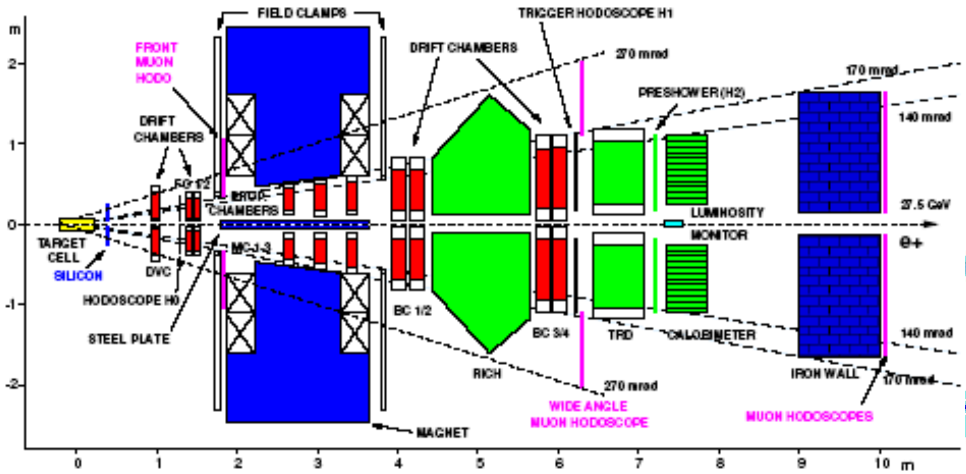
Determine the kinematics: measure with high accuracy:

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

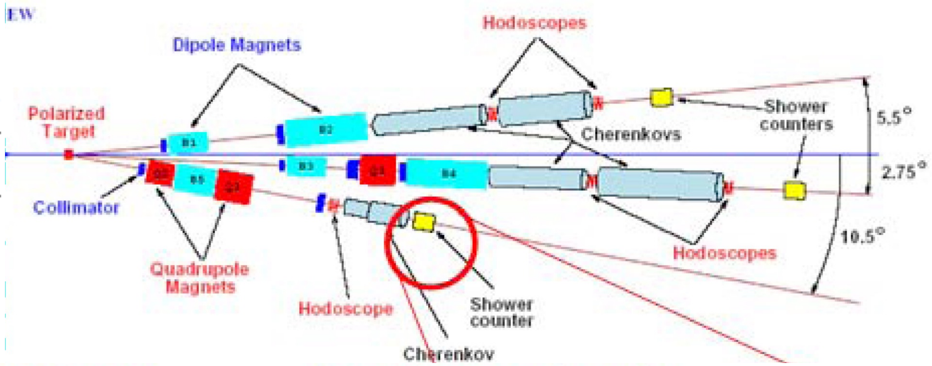
Control of false asymmetries:

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

Experiments

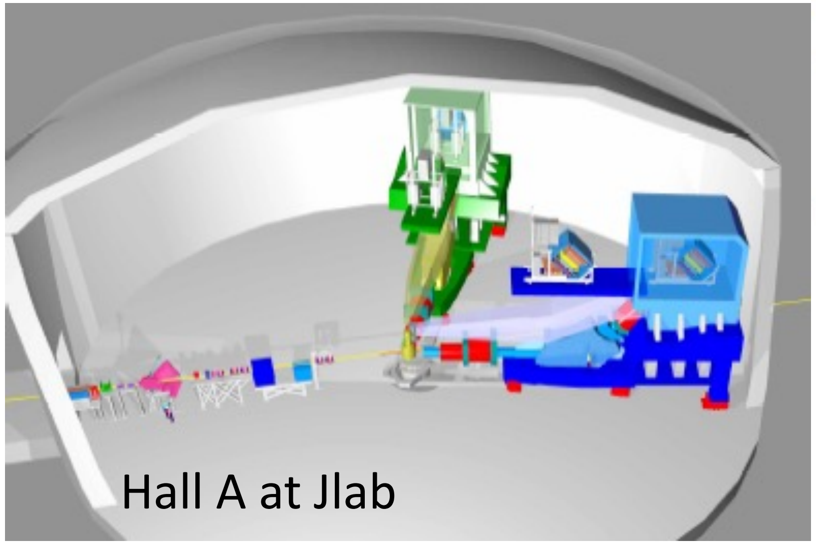


HERMES at DESY



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

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

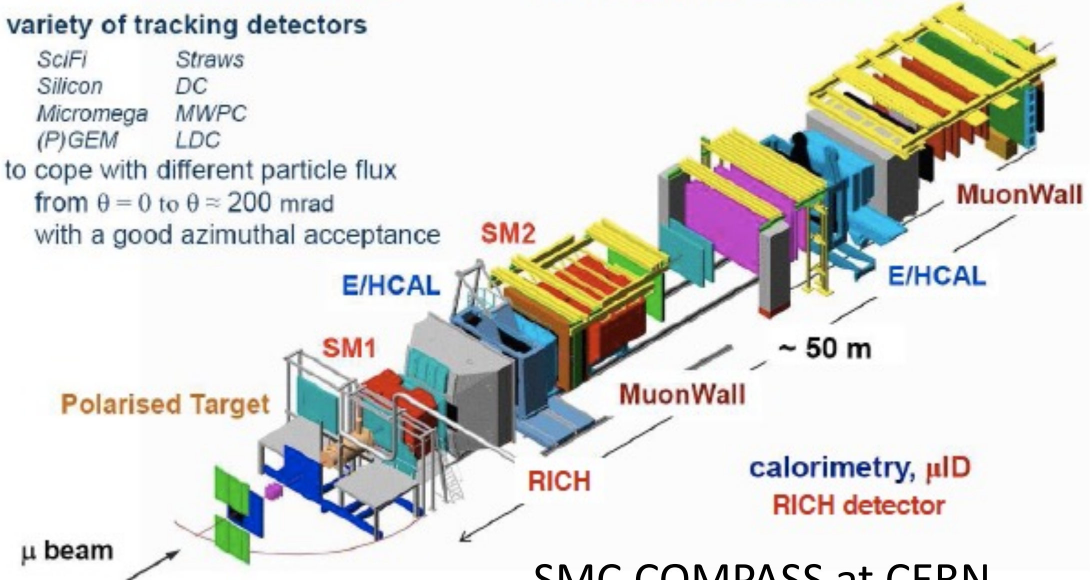


Hall A at Jlab

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

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

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

$$a_3 = \frac{g_A}{g_V} = F + D = 1.2601 \pm 0.0025 \qquad a_8 = 3F - D \Longrightarrow F/D = 0.575 \pm 0.016$$

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

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

First Moments of SPIN SFs

$$\Delta q = \int_0^1 \Delta q(x)dx \qquad g_1(x) = \frac{1}{2}\Sigma_f e_f^2\{q_f^+(x) - q_f^-(x)\} = \frac{1}{2}\Sigma_f e_f^2 \Delta q_f(x)$$

$$\Gamma_1^p = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right] = \frac{1}{12}\underbrace{(\Delta u - \Delta d)}_{a_3=g_a} + \frac{1}{36}\underbrace{(\Delta u + \Delta d - 2\Delta s)}_{a_8} + \frac{1}{9}\underbrace{(\Delta u + \Delta d + \Delta s)}_{a_0}$$

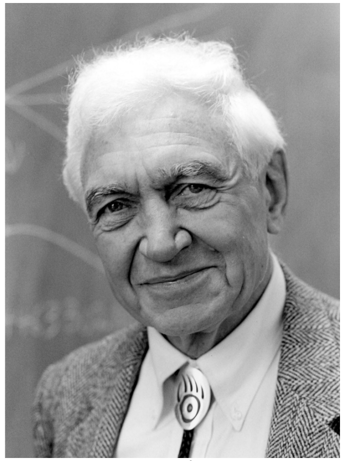
$\Delta\Sigma$

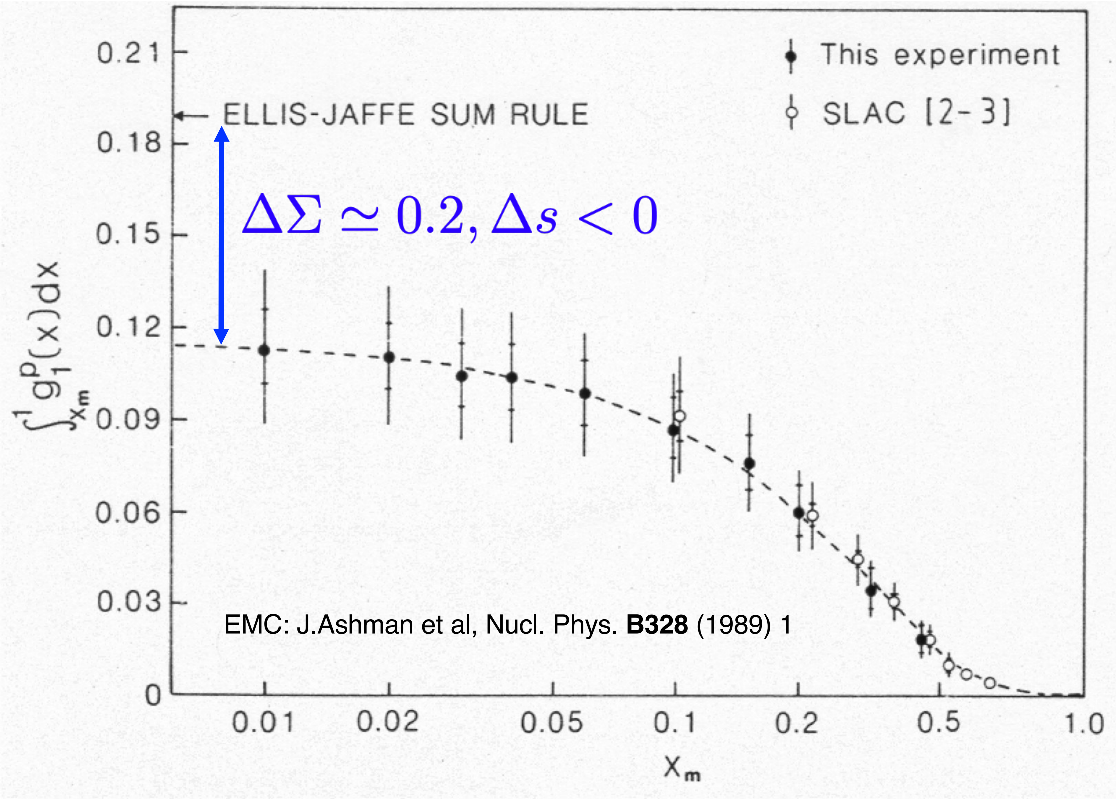
Neutron decay

(3F-D)/3
Hyperon Decay

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

Polarized Deep-Inelastic Scattering


V.W. Hughes (1921-2003)

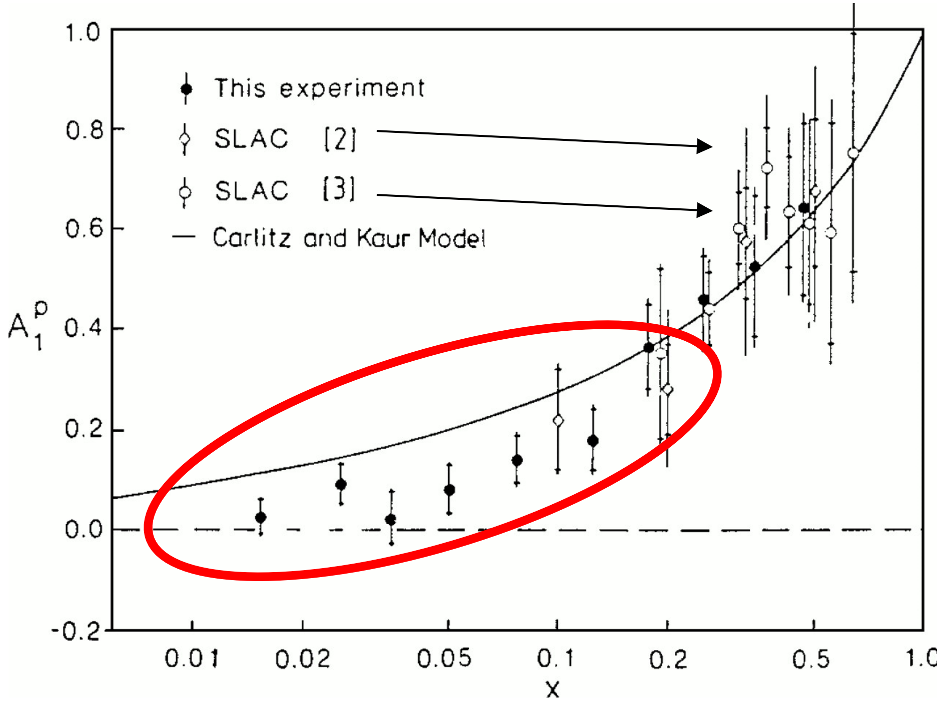


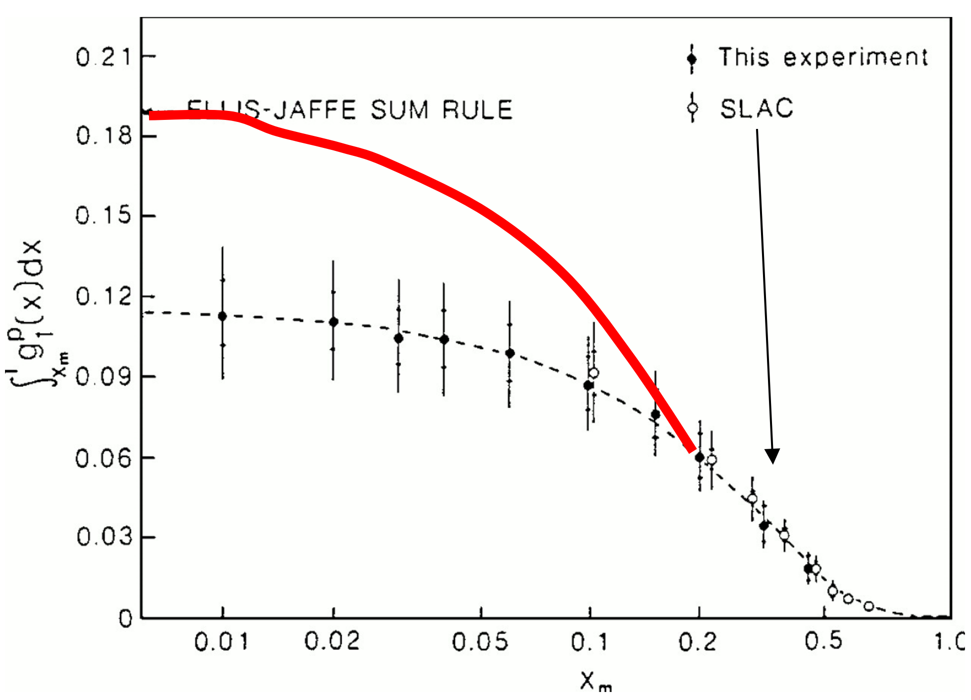
EMC: J.Ashman et al, Nucl. Phys. **B328** (1989) 1

" The sum of quark and anti-quark spins contribute little to the proton spin, and strange quarks are negatively polarized. "

Proton Spin Crisis (1989)!

EMC experiment at CERN: high energy muon beam – reached lower x





$\Delta\Sigma/2$ = (0.12) +/- (0.17) (EMC, 1989)

$\Delta\Sigma/2$ = 0.58 expected from E-J sum rule….

If the quarks did not carry the nucleon's spin, what did? → Gluons?

Consequence:

- Quark (+anti-quark) contribution to nucleon spin is definitely small:

$$\text{Quark's contribution to nucleon spin} \rightarrow \frac{1}{2}\Delta\Sigma = 0.15 \pm 0.03$$

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

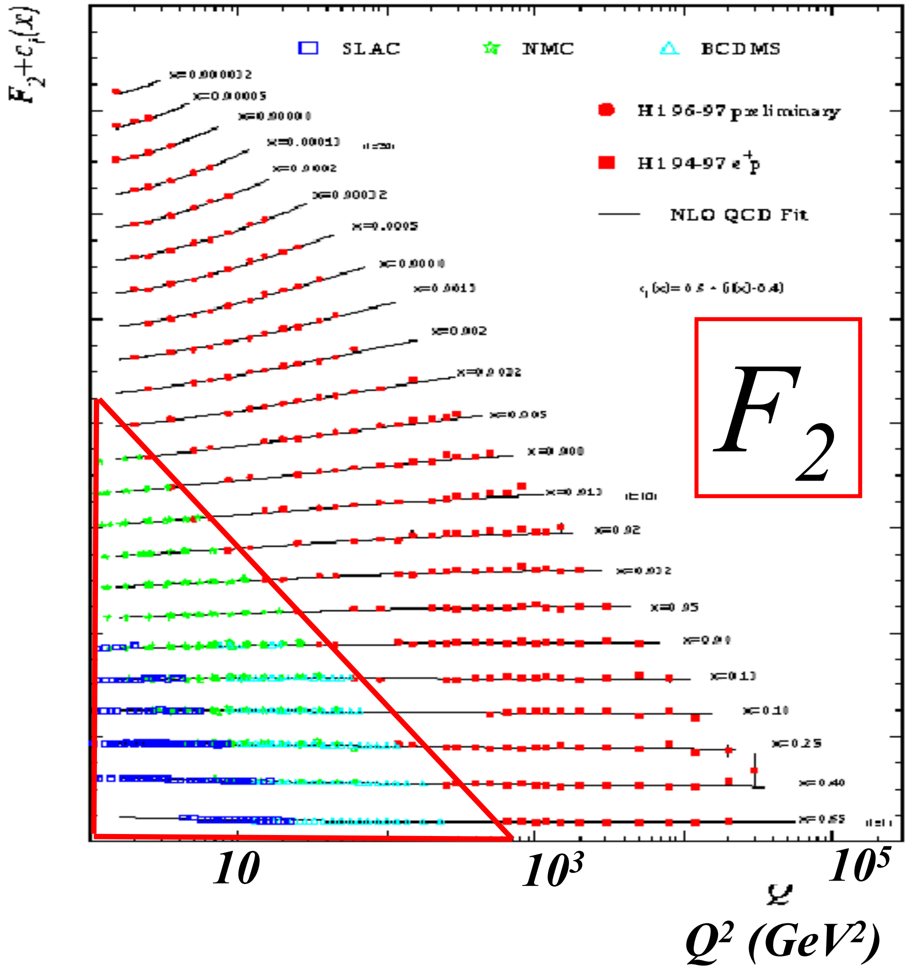
- Or does glue make a very large contribution? $\Delta G = 1 \pm 1.5$

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

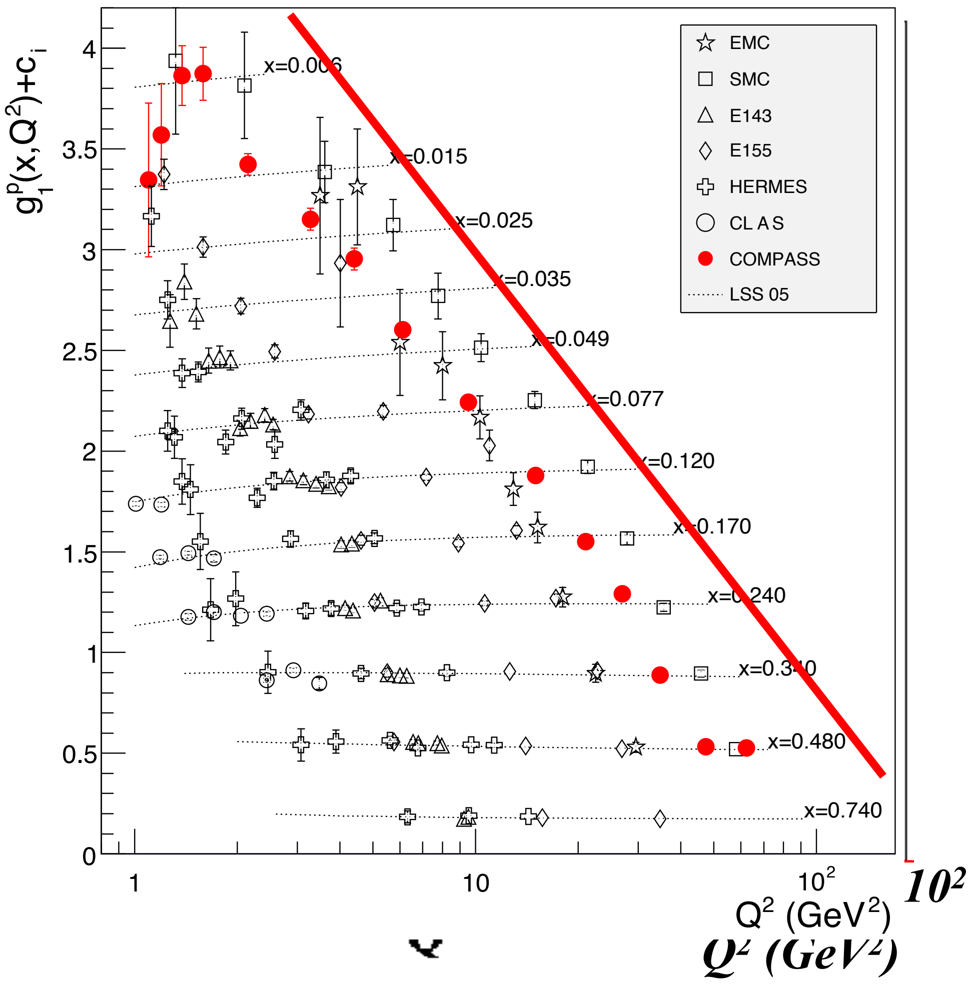
Can one do the same thing for spin structure function g_1?

Spin contribution of the gluon to the proton from scaling violation g_1 spin structure function?

F_2 vs. g_1 structure function measurements



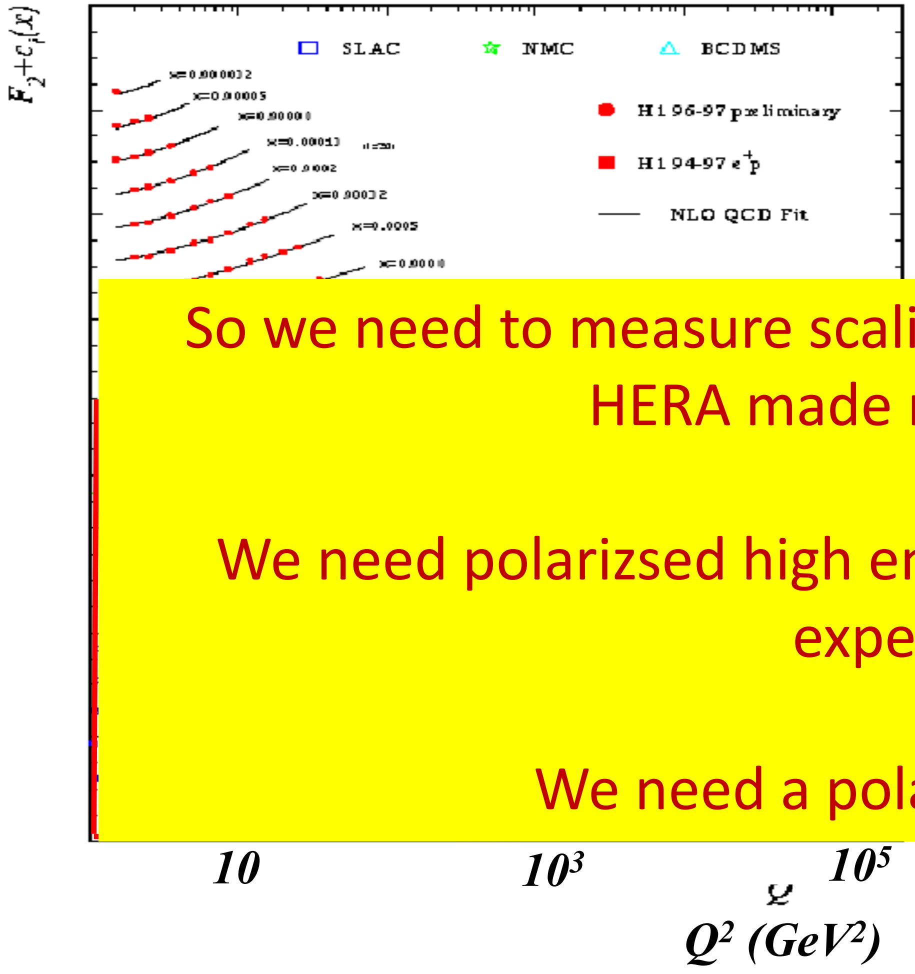
Aidala et al.1209.2803v2

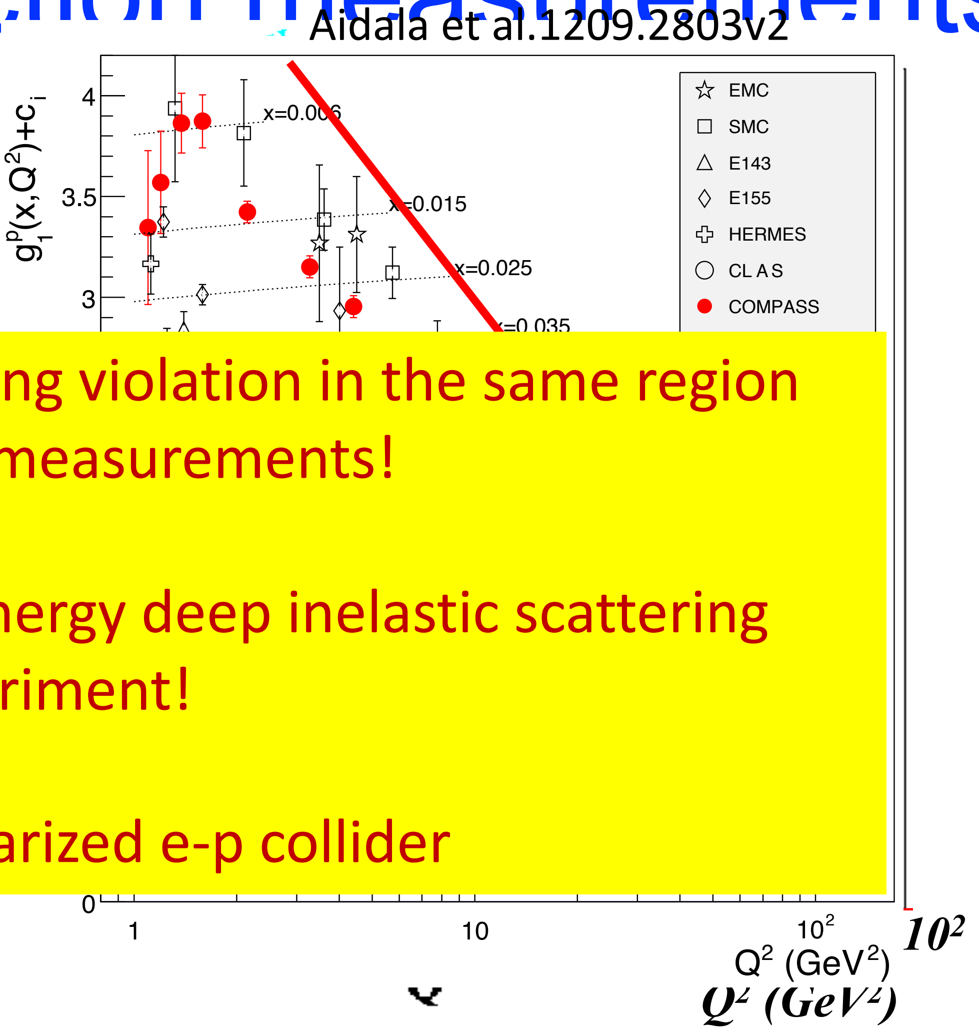


Large amount of polarized data since 1998… but not in NEW kinematic region!

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

F_2 vs. g_1 structure function measurements





So we need to measure scaling violation in the same region HERA made measurements!

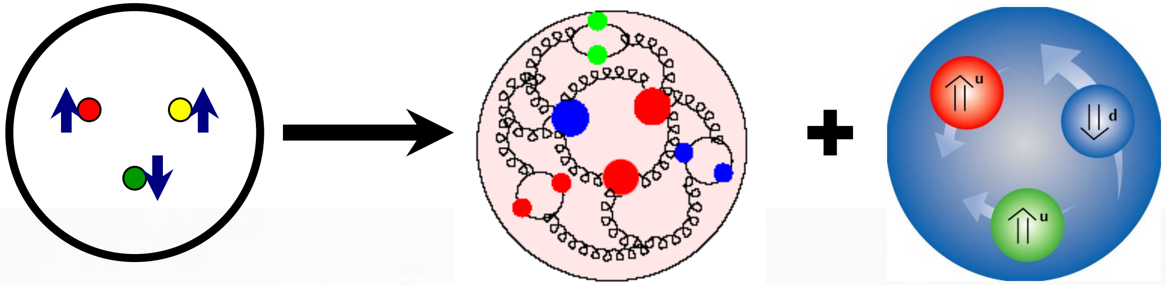
We need polarizsed high energy deep inelastic scattering experiment!

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

Our Understanding of Nucleon Spin Puzzle

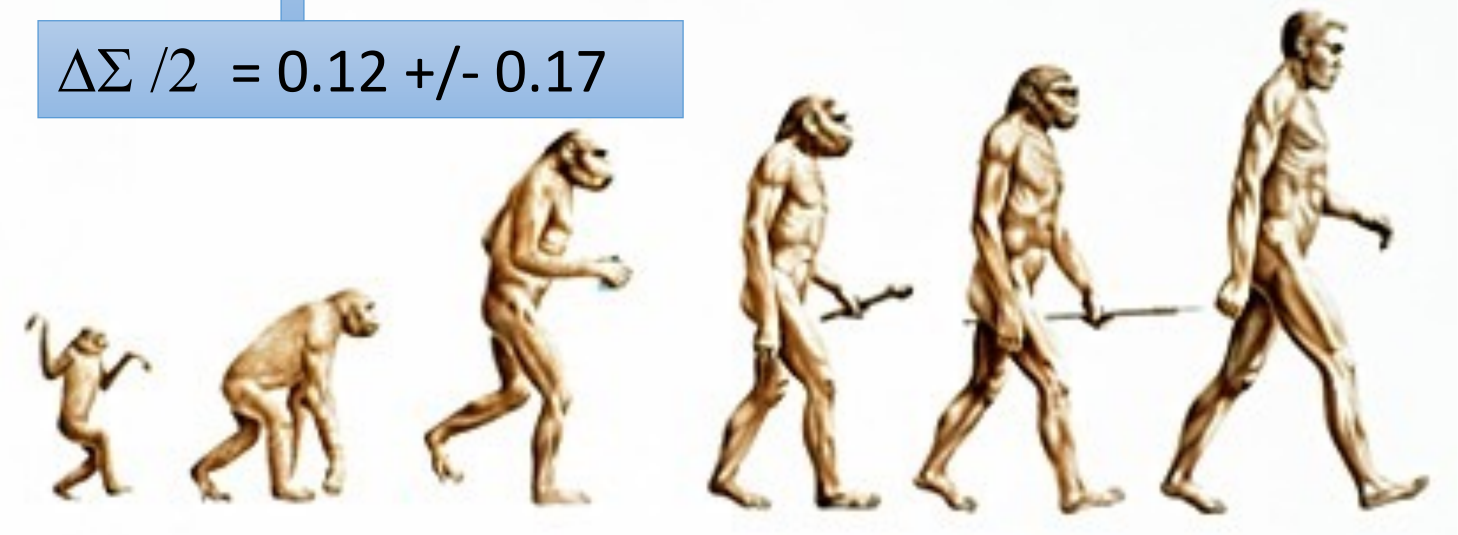


1980s

1990/2000s

$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + [\Delta g + L_G]$$

$\Delta\Sigma /2 = 0.12 +/- 0.17$



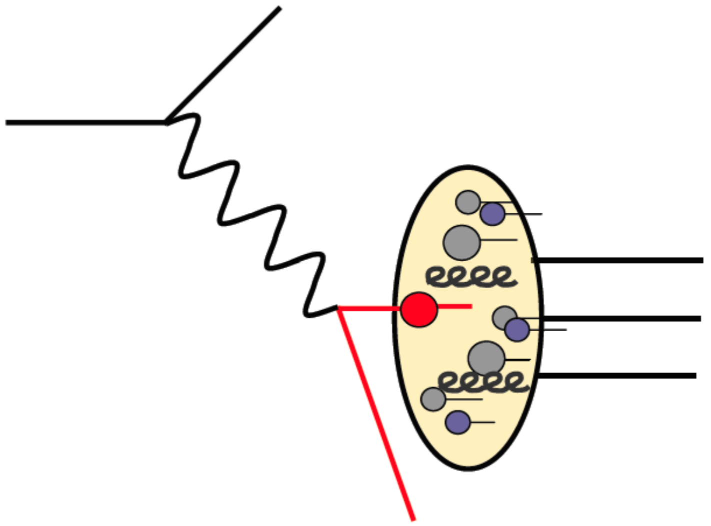
Need information about transverse dimensions of the proton

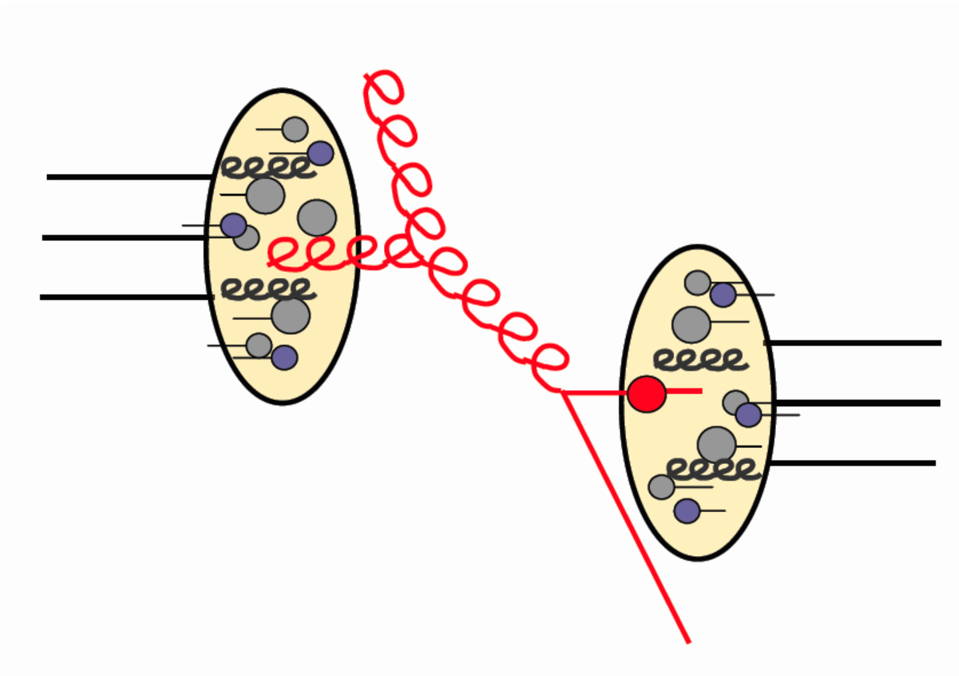
Spin discovered a problem…. What now? Need precision and investigations of gluons….

RHIC Spin program and the Transverse Spin puzzle

Pre-cursor to a polarized e-p collider

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 ?

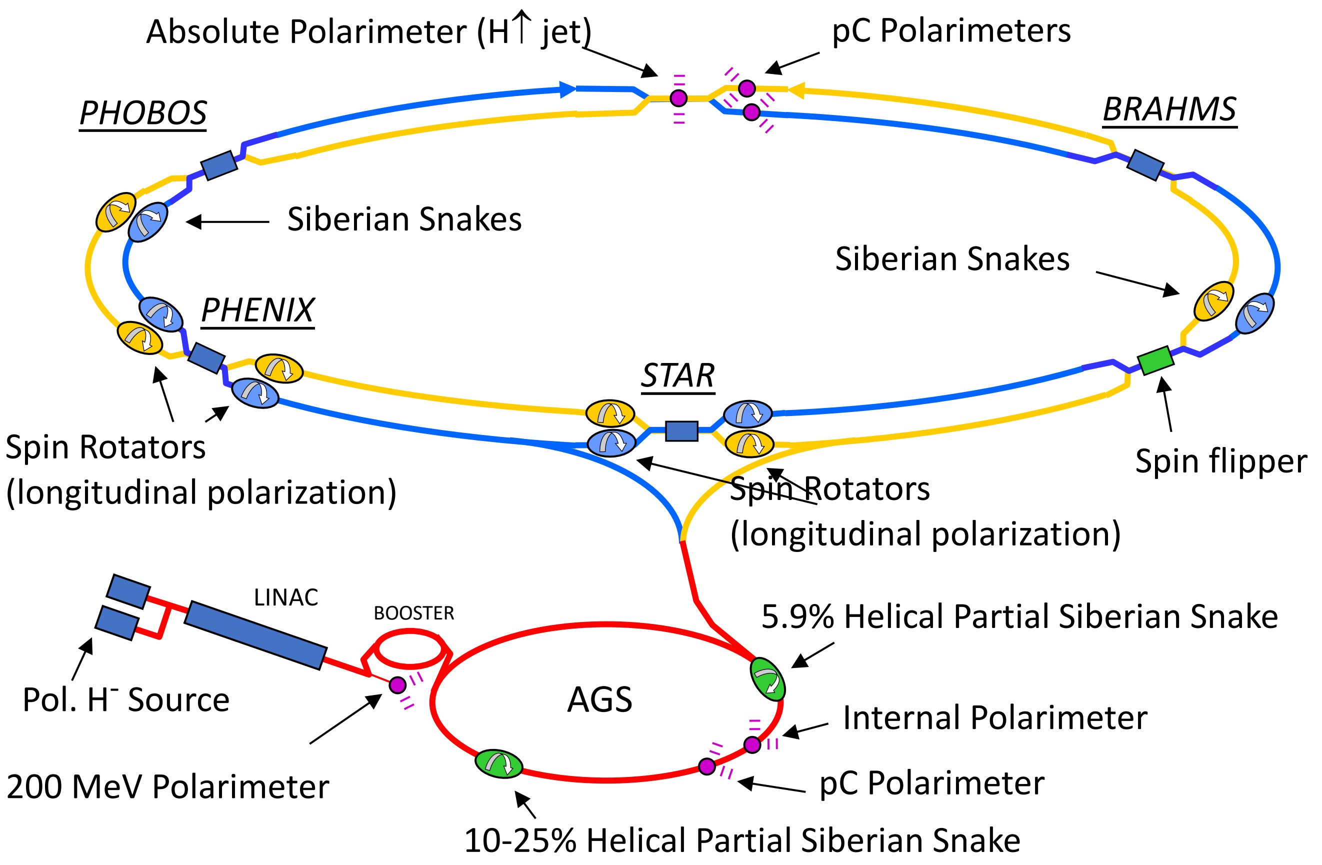
Seeds for RHIC Spin program:

If one wants to study gluon's spin contribution to proton's spin, ***why not directly explore the gluon spin with polarized proton p-p collisions?***

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

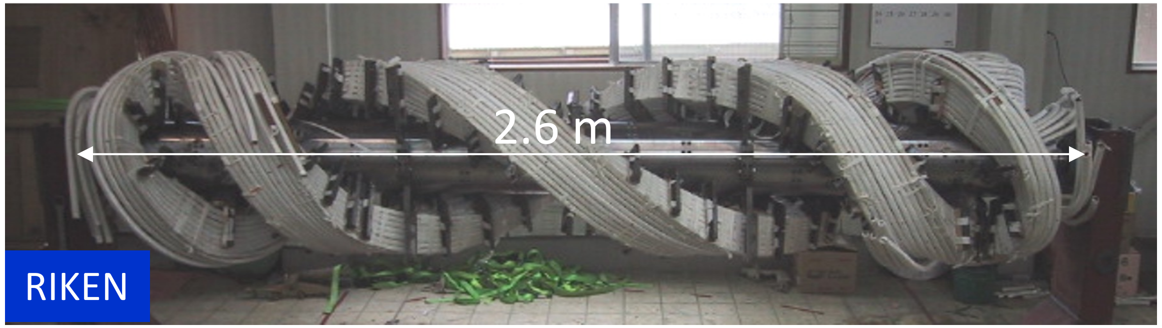
Technical know-how of polarizing proton beams at high energy became available in the mid-late 1990's

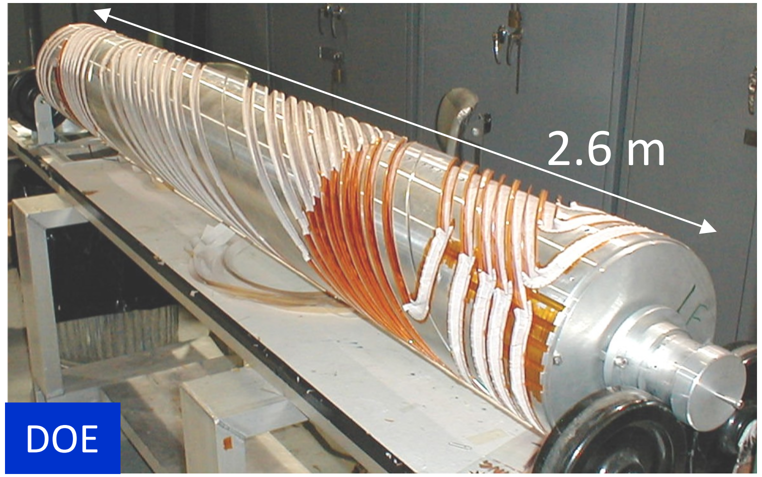
RHIC as a Polarized Proton Collider



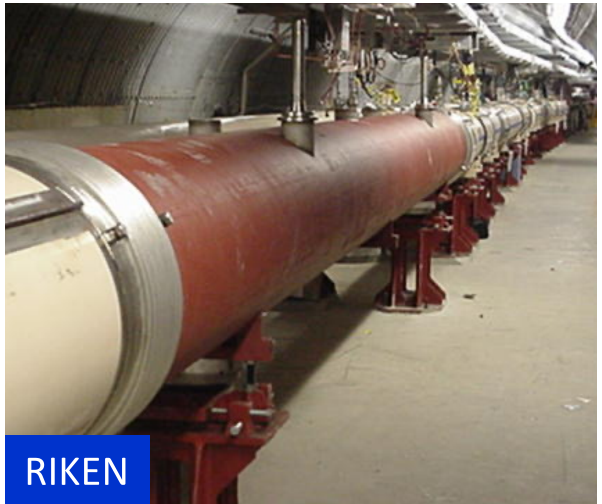
Without Siberian snakes: $\nu_{sp} = G\gamma = 1.79\ E/m \rightarrow$ ~1000 depolarizing resonances
With Siberian snakes (local 180° spin rotators): $\nu_{sp} = ½ \rightarrow$ no first order resonances
Two partial Siberian snakes (11° and 27° spin rotators) in AGS

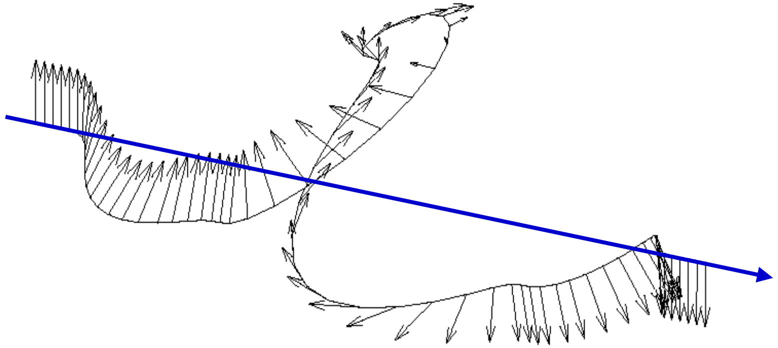
Siberian Snakes



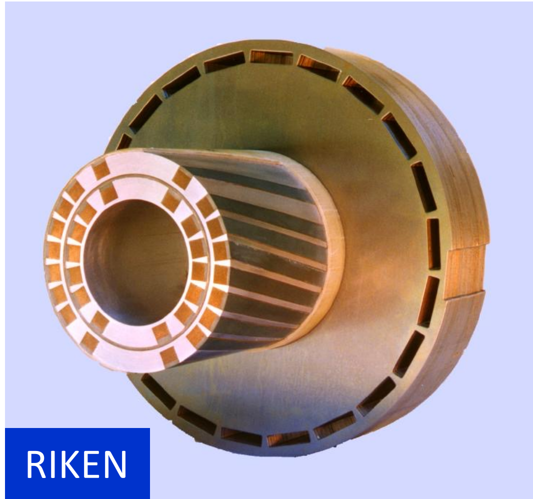


- AGS Siberian Snakes: variable twist helical dipoles, 1.5 T (RT) and 3 T (SC), 2.6 m long
- RHIC Siberian Snakes: 4 SC helical dipoles, 4 T, each 2.4 m long and full 360° twist





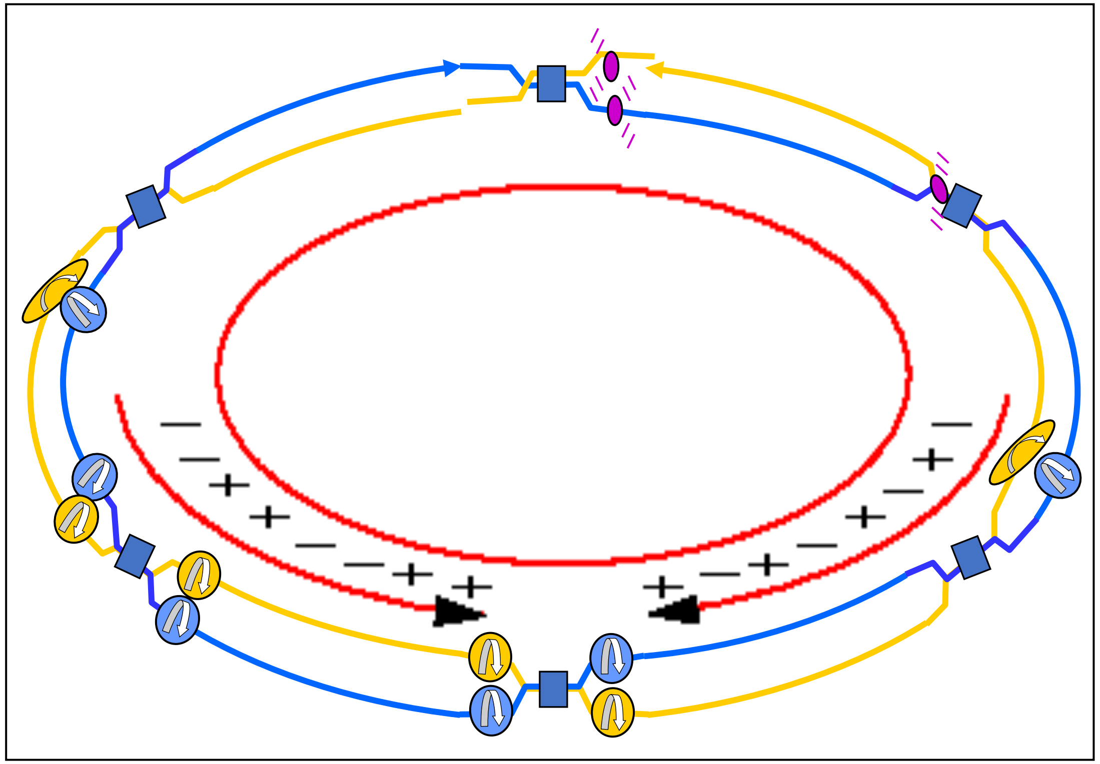
Courtesy of A. Luccio



Measuring A_{LL}

Longitudinal Spin Asymmetry using polarized proton bunches in the RHIC ring

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



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

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

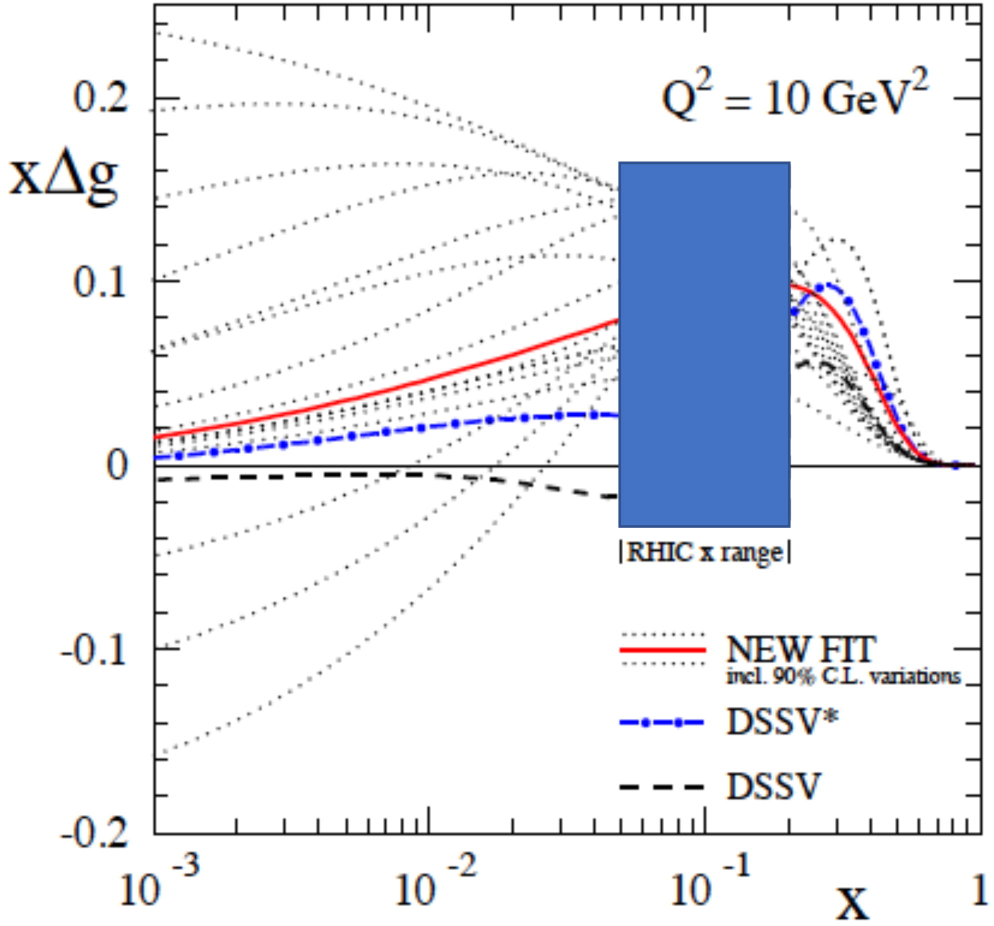
✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time
⇒ Possibility for false asymmetries are greatly reduced

Recent global analysis: DSSV

D. deFlorian et al., arXiv:1404.4293

$\Delta G = 0.2 \pm 0.02 \pm 0.5$

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



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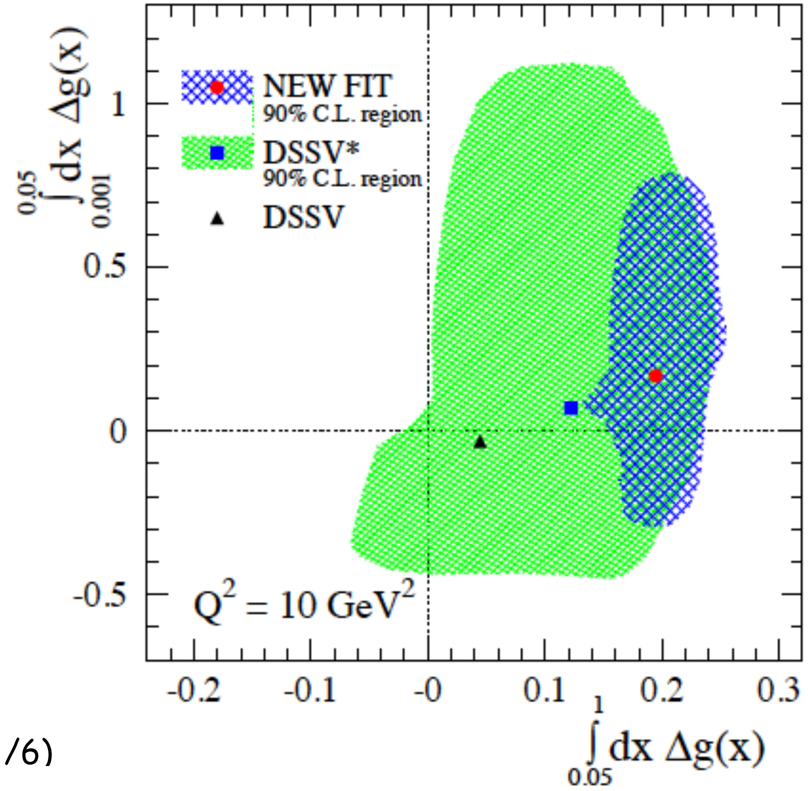
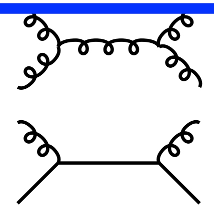


While RHIC made a huge impact on ΔG

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

2009 RHIC data established non-zero ΔG

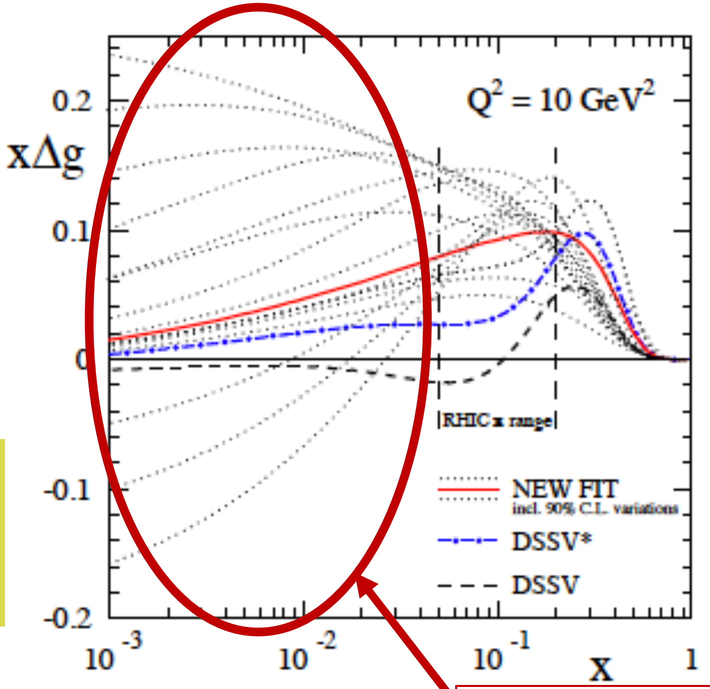
Reaction	Dom. partonic process	probes	LO Feynman diagram
$\vec{p}\vec{p} \to \pi + X$ [61, 62]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	
$\vec{p}\vec{p} \to \text{jet(s)} + X$ [71, 72]	$\vec{g}\vec{g} \to gg$ $\vec{q}\vec{g} \to qg$	Δg	(as above)

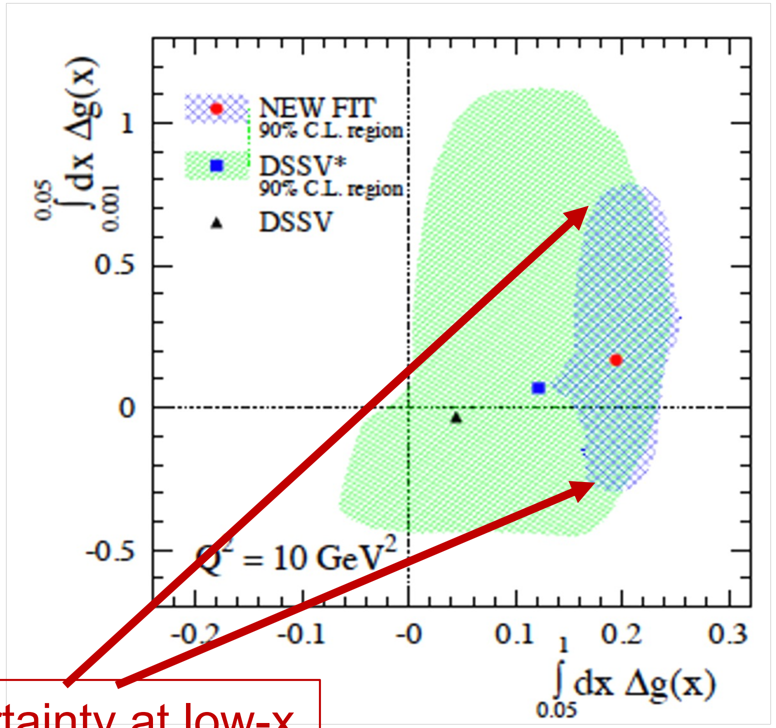
-- PHENIX 2005-9, PRD 90, 12007 (2014)

-- STAR 2009, PRL 115 (2015) 92002

-- DSSV PRL (113) 12001 (2014)

$$\int_{0.05}^{1.0} dx \Delta g \sim 0.2 \pm^{0.06}_{0.07} @ \ 10 \ \mathrm{GeV}^2$$





Large uncertainty at low-x

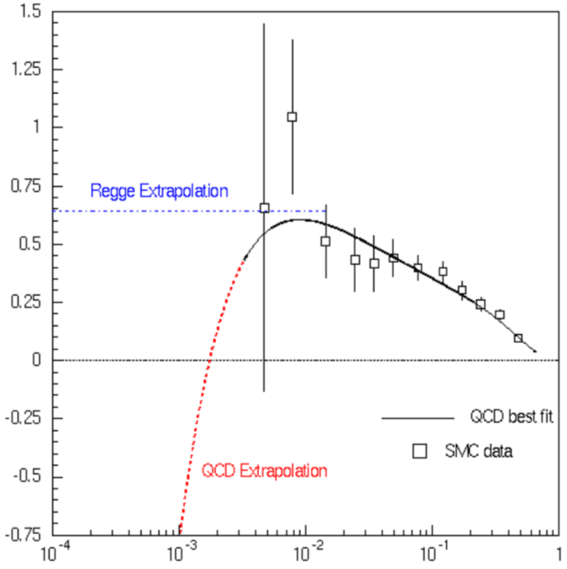
Recall a historical fact and plot….

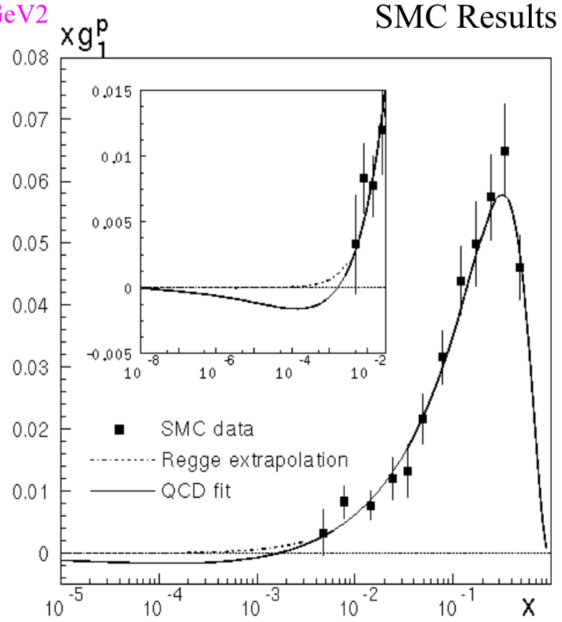
Recall from “EIC A Dream to Reality” on Day 1

Lack of low x data… consequences

Q2 = 10 GeV2

SMC Results





- Regge extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = 0.002 \pm 0.002$$

- QCD fit extrapolation:

$$\int_0^{0.003} g_1^p(x, Q_0^2)dx = -0.011 \pm 0.011$$

$$g_1(x \to 0) \propto x^{\alpha} \quad \text{as } 0 < \alpha < 0.5$$

Regge/QCD

In these discussions, while many focused on the low-x Extrapolations.

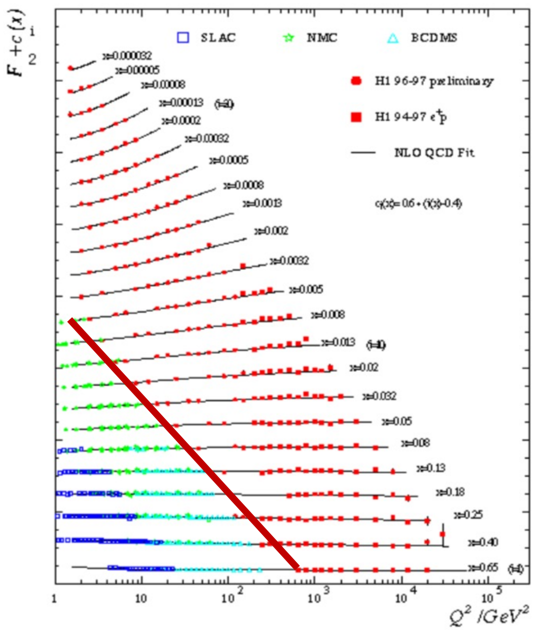
SMC PRD98 (112002) 1998

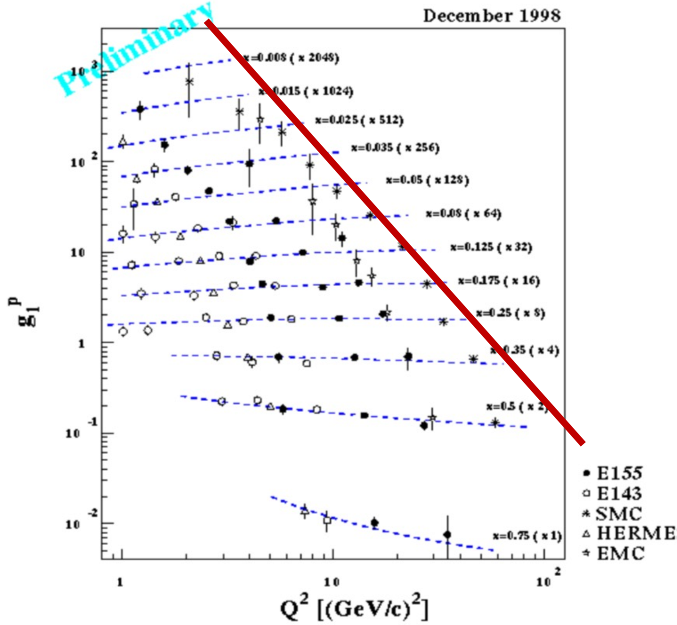
Seeds for a **polarized collider**

How far does polarized DIS have to go!

World data on F_1^p

World data on g_1^p

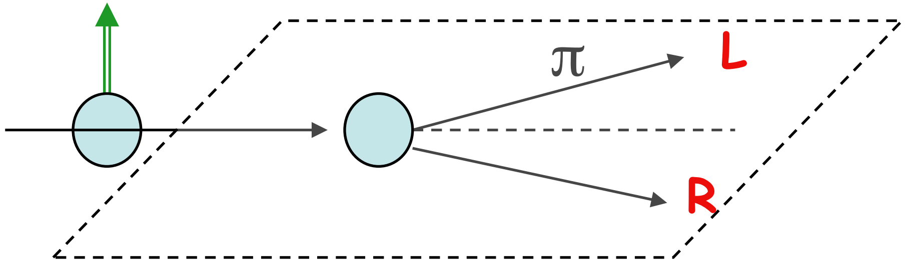




Transverse Spin effects in p-p observed but ignored for 40+ years

Recent developments and state of the art in Marco Radici's lecture

Transverse spin introduction



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

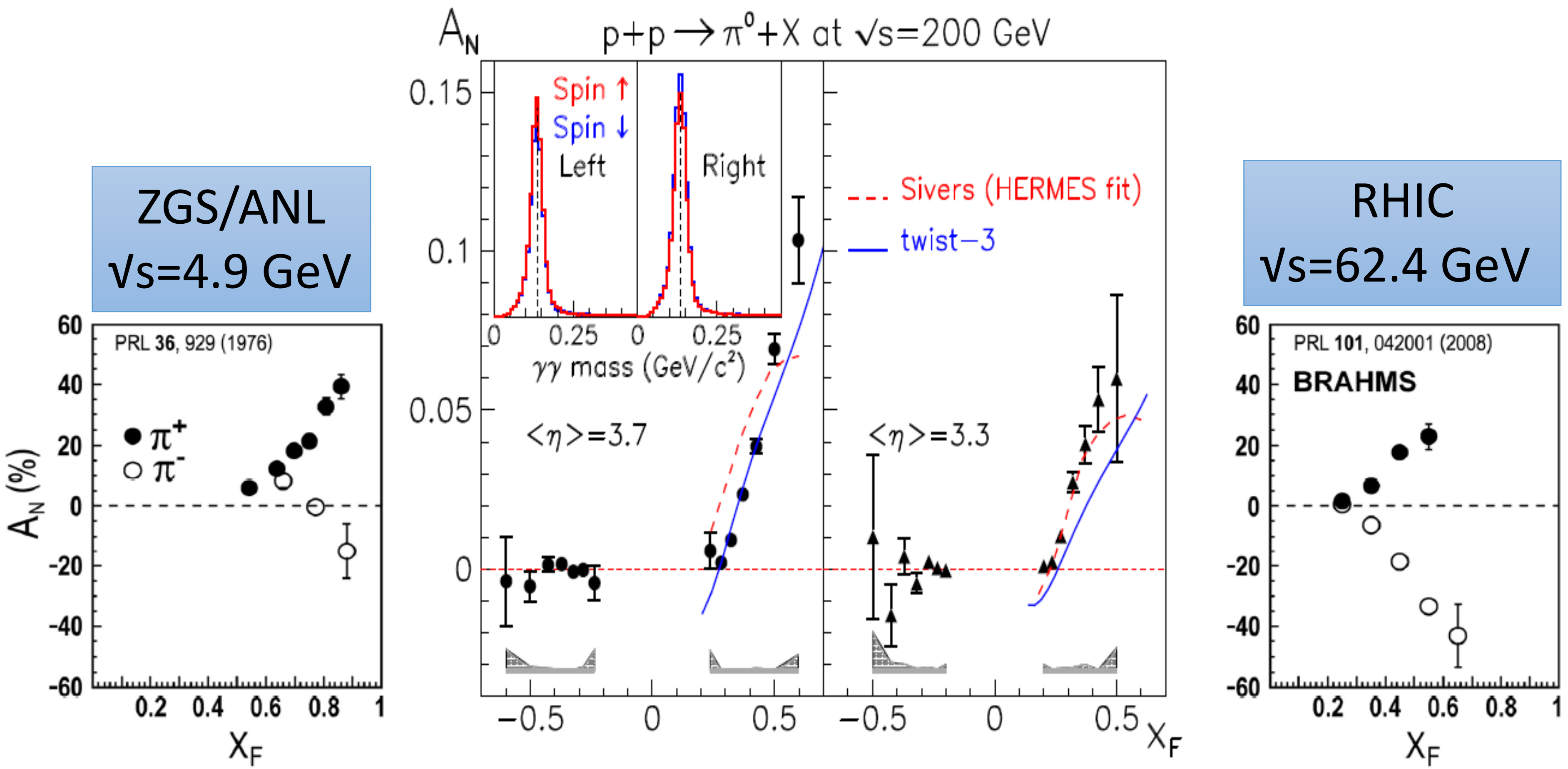
$$A_N \sim \frac{m_q}{p_T} \cdot \alpha_S \sim 0.001$$

Kane, Pumplin and Repko
PRL 41 1689 (1978)

- Since people focused at high p_T to interpret them in pQCD frameworks, this (expected small effect) was “neglected However….

- Pion production in single transverse spin collisions showed us something different….

Pion asymmetries: at broad range in CM energies!

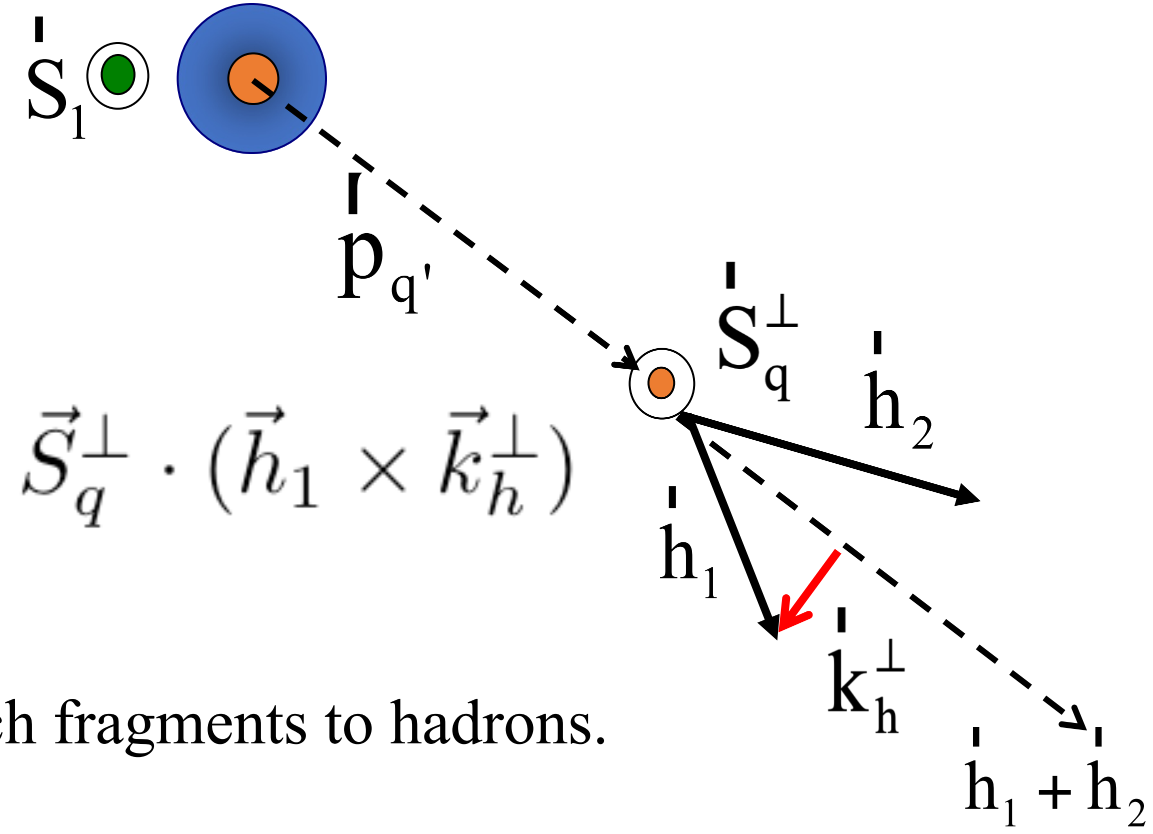


Suspect soft QCD effects at low scales, but they seem to remain relevant to perturbative regimes as well ➔ **0.001 expected 0.2-0.6 observed at all Center of Mass Energies**

What could be the origin of such effect?
Collins (Heppelmann) effect: Asymmetry in the fragmentation hadrons

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

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

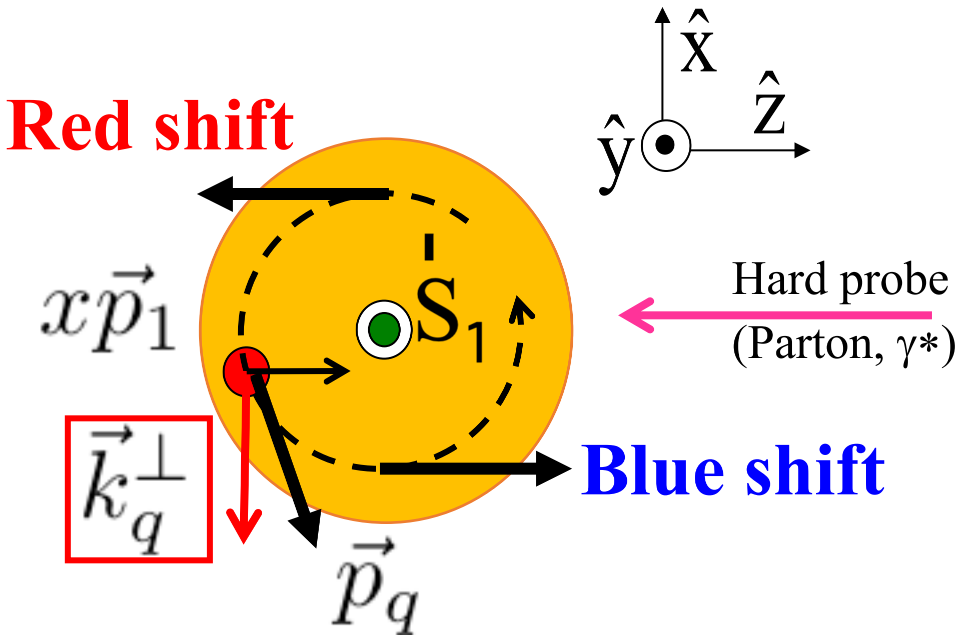


$$SSA_{Collins} \propto \vec{S}_q^{\perp} \cdot (\vec{h}_1 \times \vec{k}_h^{\perp})$$

Polarization of struck quark which fragments to hadrons.

Other possibility: 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

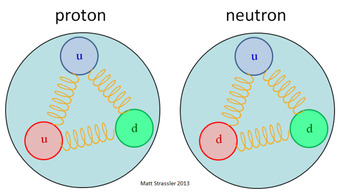
Generalized **P**arton **D**istribution Functions

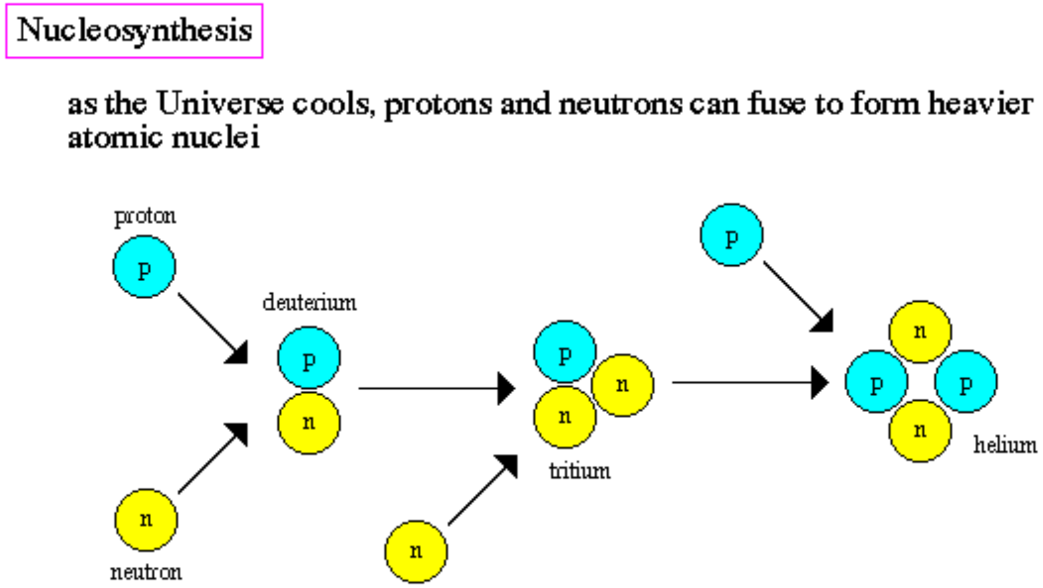
PRD59 (1999) 014013

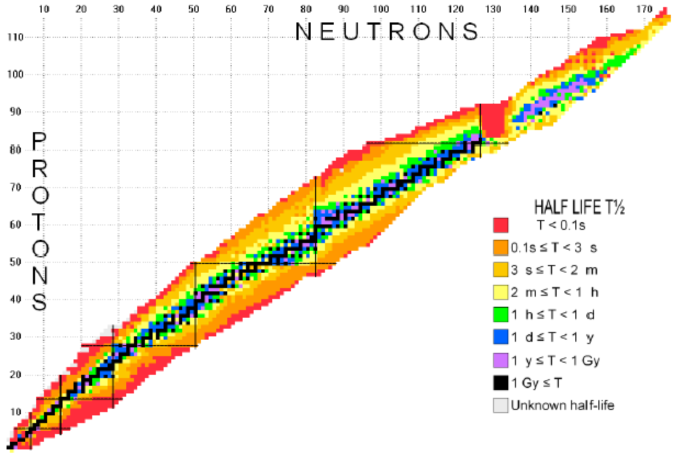
Lepton nucleus scattering for understanding the nuclear structure and dynamics:

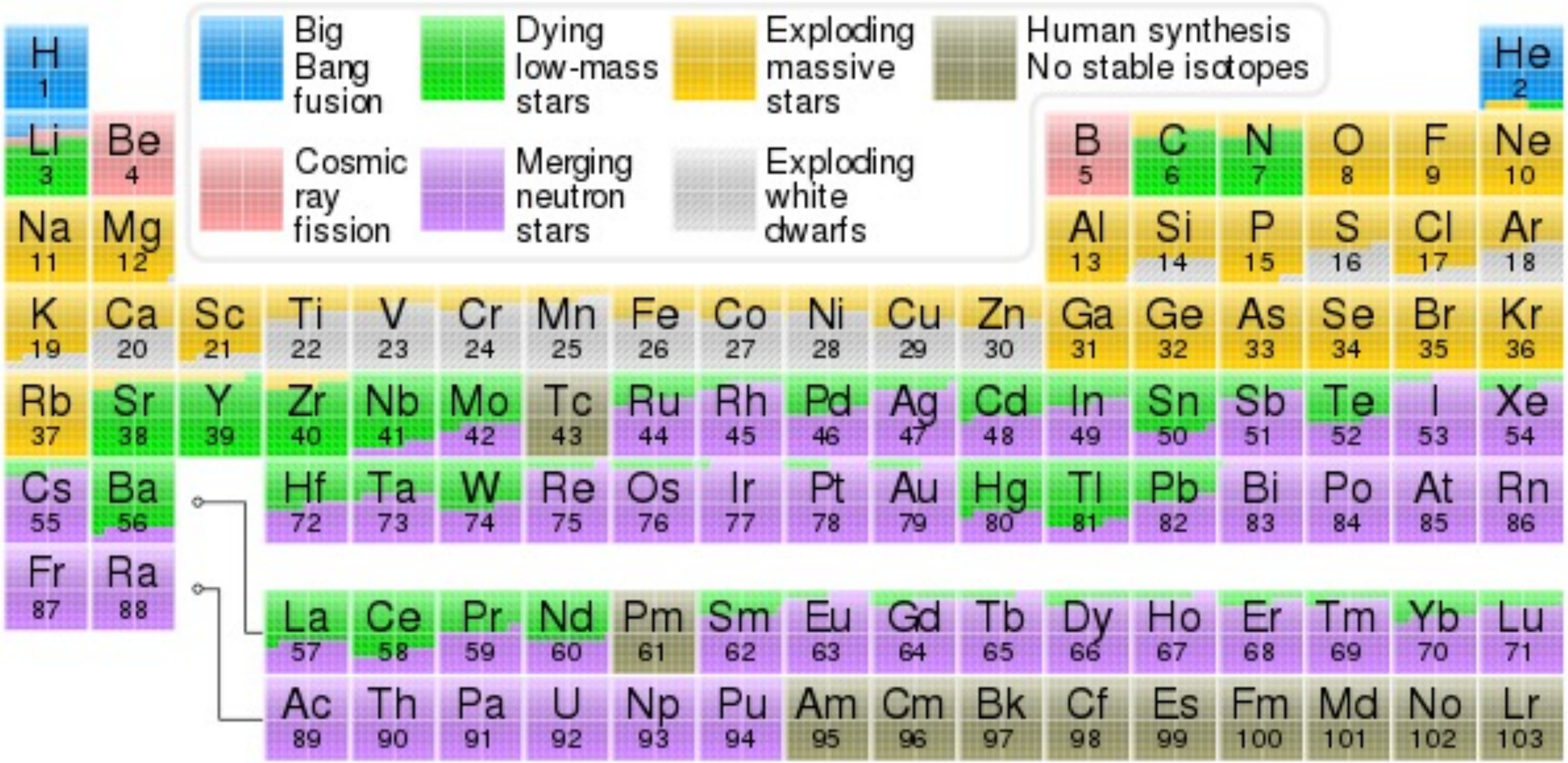
Nuclear structure a known unknown….

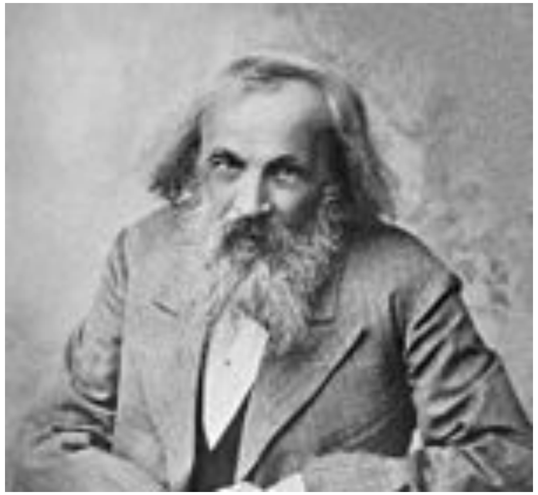
From protons/neutrons to visible nuclei
We know what happened
but don't fully understand why







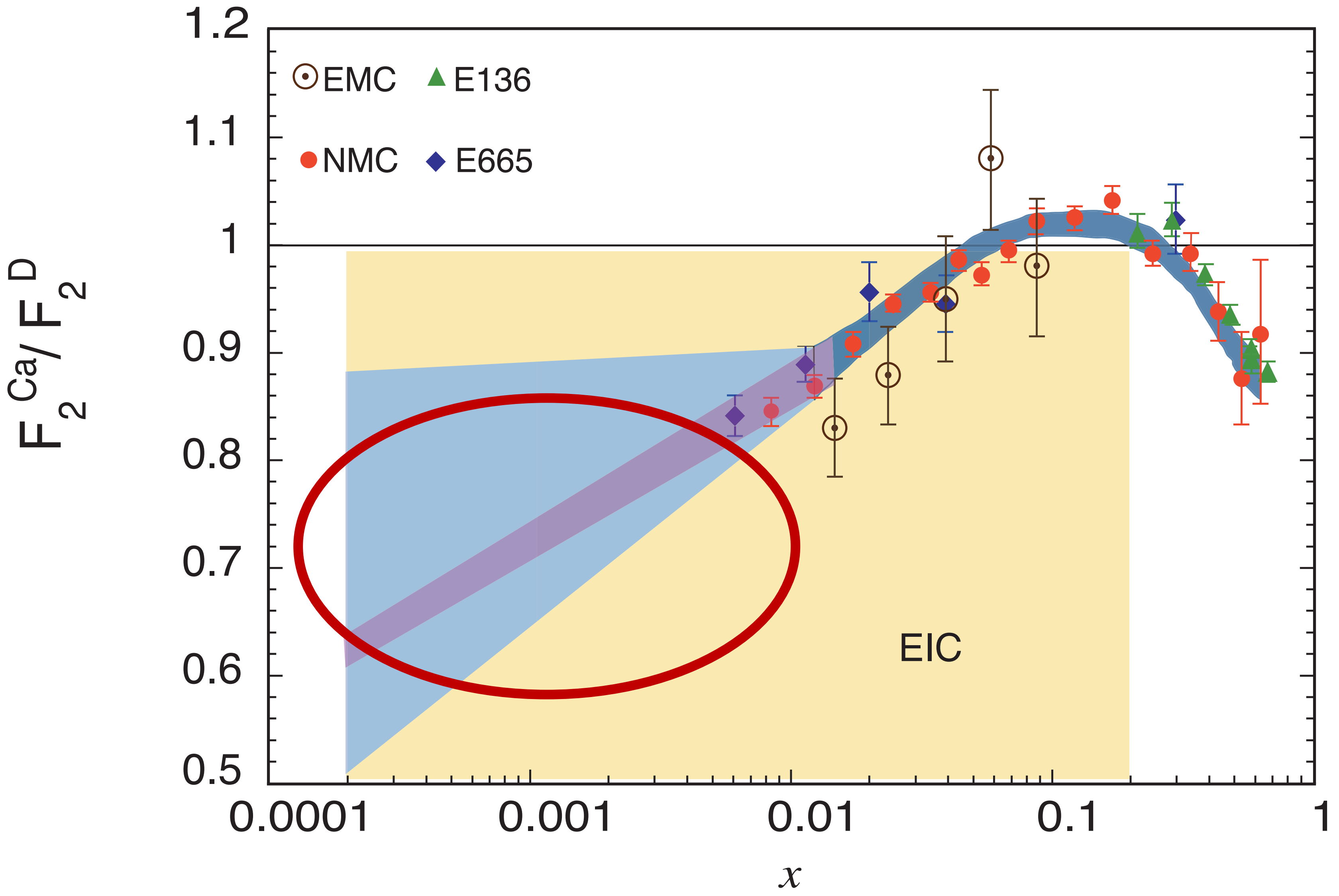




Dmitri Ivanovich Mendeleev

the periodic table of elements

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.

Data needed at low-x

Lessons learned:

- Proton and neutrons spin not just alignment of quarks and gluons….
    - Proton's spin is complex: alignment of quarks, **gluons and orbital motion**
- To fully understand proton structure (including the partonic dynamics) one needs to explore over a **broader x-Q2 range (not in fixed target but in collider experiment)**
- **Low-x behavior of gluons in proton:** Precise measurements of gluons critical.
- Low x behavior of partons in Nuclei essential to complete our understanding of structure of matter…

We need a new high-luminosity polarized **e-p/A** collider….