Nucleon Spin

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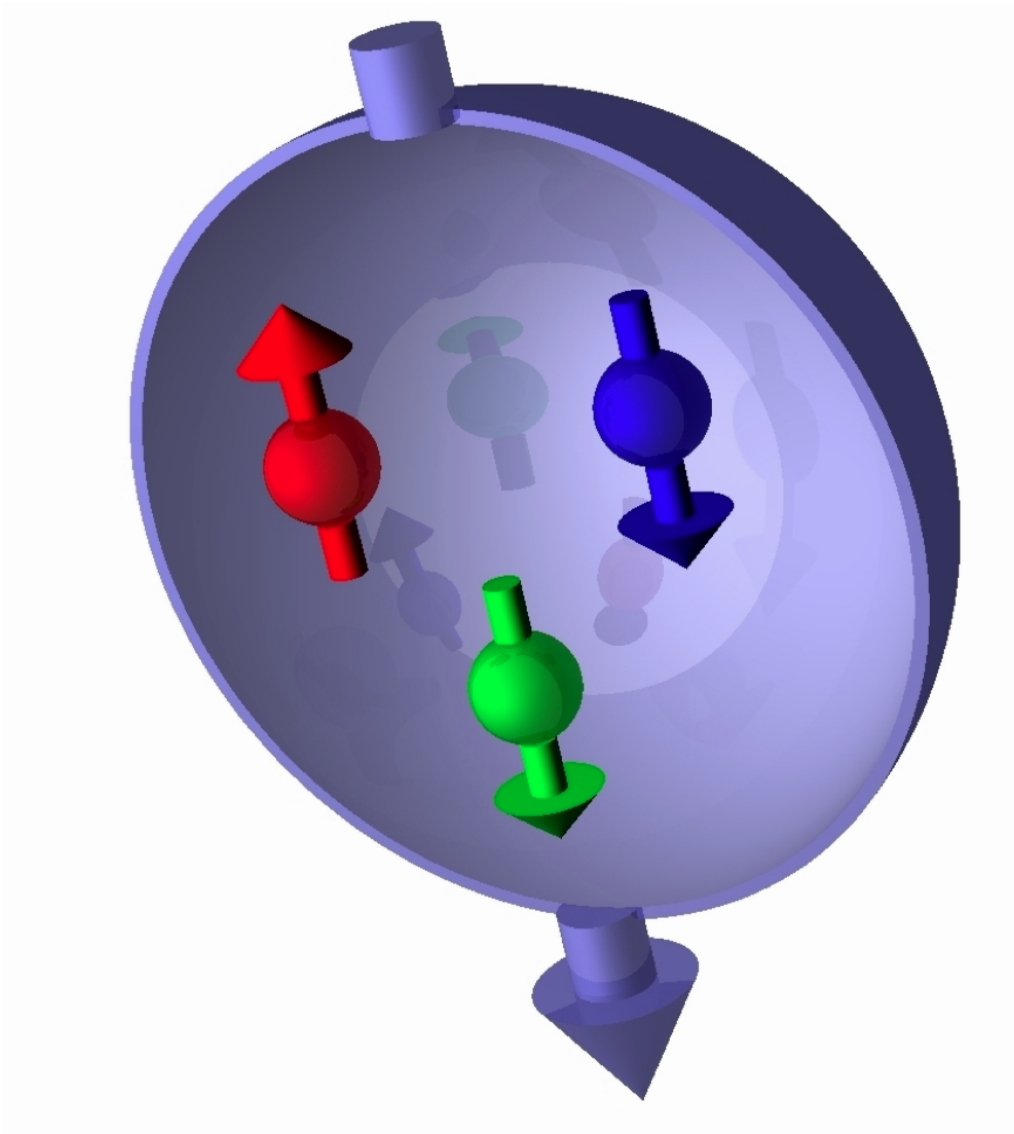
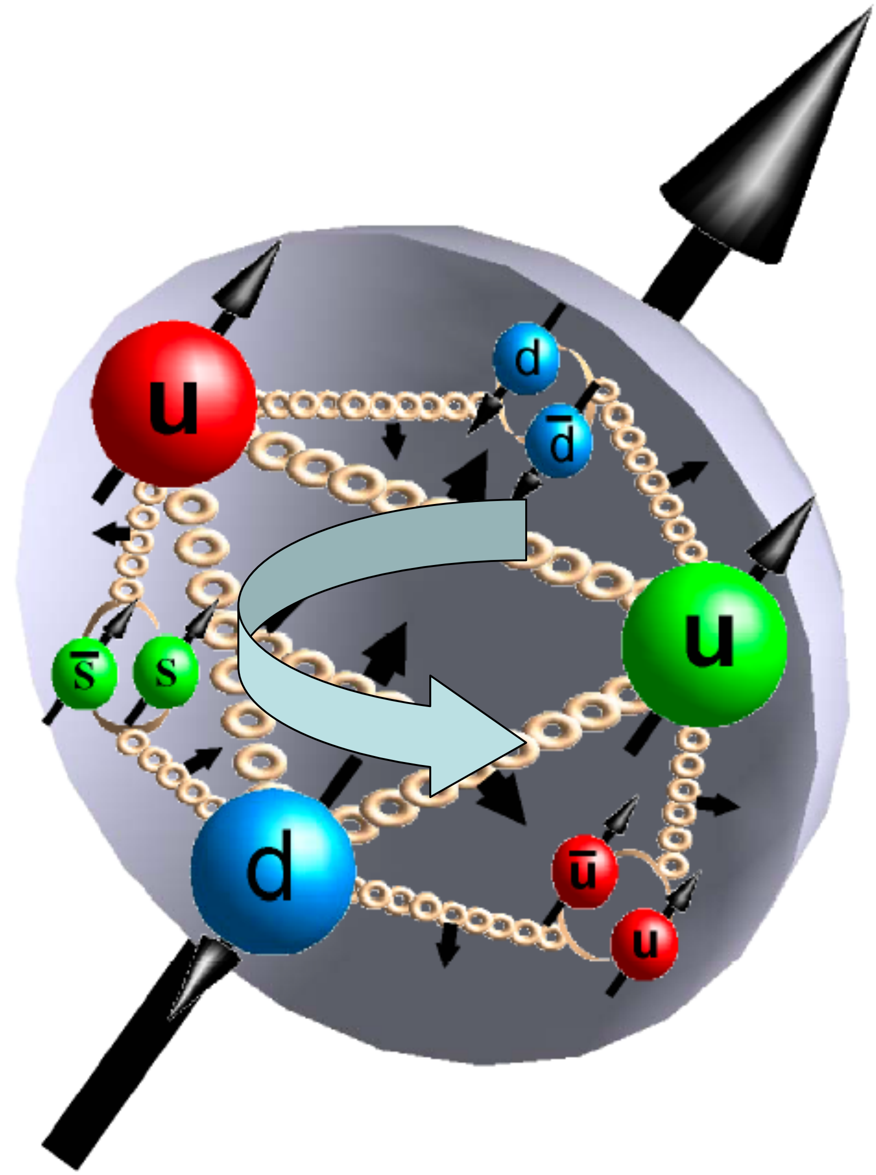
Abstract: In 1988 the European Muon Collaboration showed that the quark contribution to spin only accounts for 20-30 percent of the nucleon spin; The "naive quark parton model" predicted the quarks would make up 60 percent of the proton spin. This discrepancy has lead to 22 years of experiment trying to extract the spin composition of the proton and neutron, and in effect the underlying structure of these hadrons. This talk will begin with a brief discussion of the early experimental projects, the underlying physics of how they work, and their conclusions, and will conclude with a discussion of the future of spin physics at RHIC.



$\frac{1}{2} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2}$ $\qquad$ $\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L(z)$

Context

1960's :

Feynman's Parton model and Bjorken Scaling result in QCD/quarks and gluons

Late 1970s/Early 1980s :

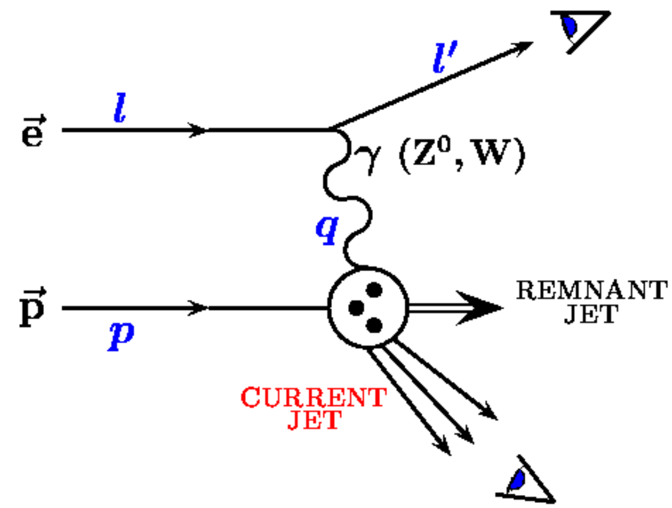
SLAC appears to show proton spin is carried by quark spins

1988 :

EMC increases range of fractional momentum of quark data, in particular the lower range, and uses its data in tandem with SLAC's to show that little if any of the proton spin is due to quarks

Deep Inelastic Scattering

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



Where s,S are lepton and nucleon spin

$L_{\mu\nu}$ controls the QED related kinematics

$W^{\mu\nu}$ nucleon structure/QCD tensor

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

g1 and g2 are polarized structure functions/spin distributions over x, the fractional momentum of the quark, since g2 tends to be smaller, we will neglect it for most of this talk.

What are F_i and g_i?

F_1 and F_2 are momentum distributions

g_1 and g_2 are the spin distributions

In the simple parton model,

$F_2(x) = 2xF_1$

$g_2 = 0$

Which give:

$$F_1(x) = \tfrac{1}{2}\sum_f e_f^2\left\{q_f^+(x) + q_f^-(x)\right\} = \tfrac{1}{2}\sum_f e_f^2 q_f(x)$$

$$g_1(x) = \tfrac{1}{2}\sum_f e_f^2\left\{q_f^+(x) - q_f^-(x)\right\} = \tfrac{1}{2}\sum_f e_f^2 \Delta q_f(x)$$

Where: $q = q^+ + q^-$

$$\Delta q = q^+ - q^-$$

g_1 vs spin

How do we relate g_1 and the nucleon spin? Or in particular what does g_1 tell us about the quark contribution to the spin?

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s$$

We make the following substitution into $g_1(x)$ (because of their transformation properties under SU(3) flavor group):

$$\Delta q_3 = (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d})$$

$$\Delta q_8 = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s})$$

$$\Delta\Sigma = (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s})$$

Integrating $g_1(x)$ (for the proton) gives the first moment:

$$\Gamma_1^p = \int_0^1 g_1(x)dx = \tfrac{1}{9}\left(\tfrac{3}{4}a_3 + \tfrac{1}{4}a_8 + a_0\right)$$

Where the a's are just:

$$a_3 = \int_0^1 dx\Delta q_3 \qquad a_8 = \int_0^1 dx\Delta q_8(x) \qquad a_0 = \Delta\Sigma = \int_0^1 dx\Delta\Sigma(x)$$

a_3 and a_8 are known quantities from β-decays.

Spin Crisis

In the simple parton model we can get the expression for:

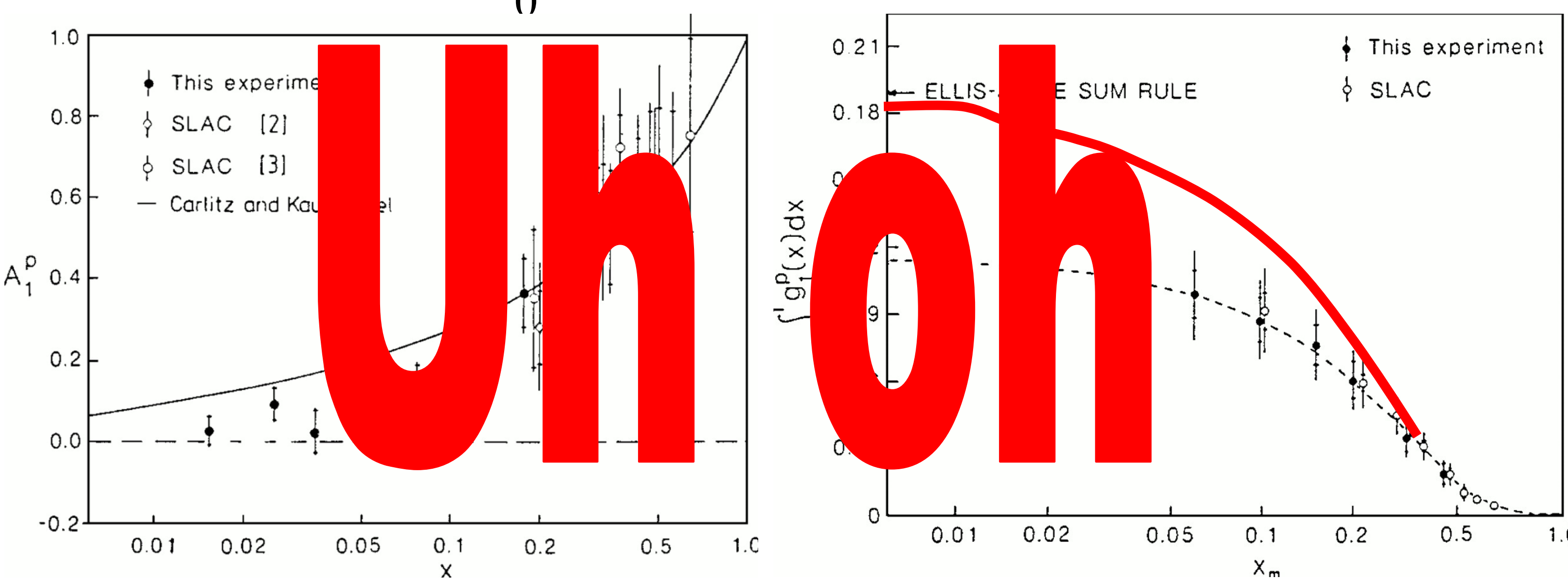
$$a_0 = \Delta\Sigma = a_8 + 3(\Delta s + \Delta\bar{s})$$

In 1974 Ellis and Jaffe suggested that the strange quark contribution was negligible:

$$a_0 \approx a_8 \approx 0.59$$

Which contradicts the EMC measurement.

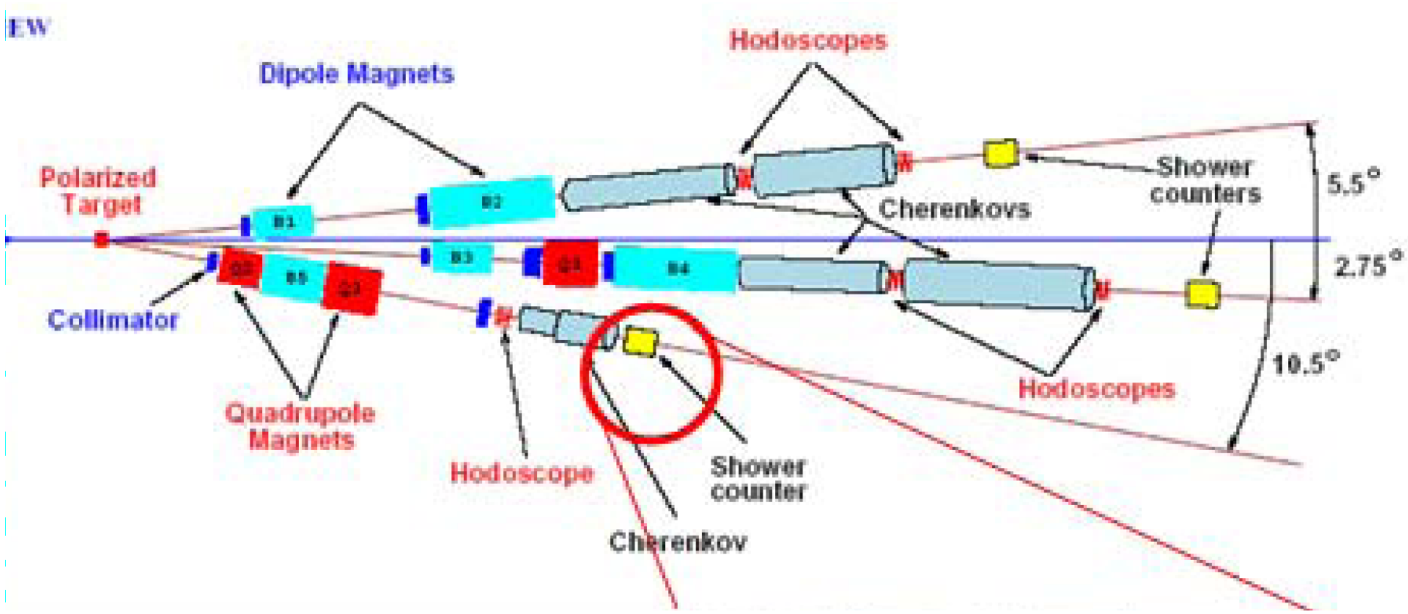
$$a_0^{EMC} = .14 \pm .19$$



SLAC

SLAC

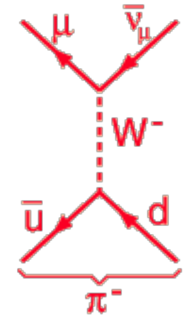
- Polarized e^- on polarized p target
- Initial data gave the impression that the ‘naïve quark parton model’ was accurate.
- Later in collaboration with EMC and SMC results showed that Bjorken Sum rule appeared to be valid.



EMC/SMC/COMPASS

Naturally polarized μ beam at CERN on a polarized p target

Data suggest gluon contribution may be large



European Muon Collaboration

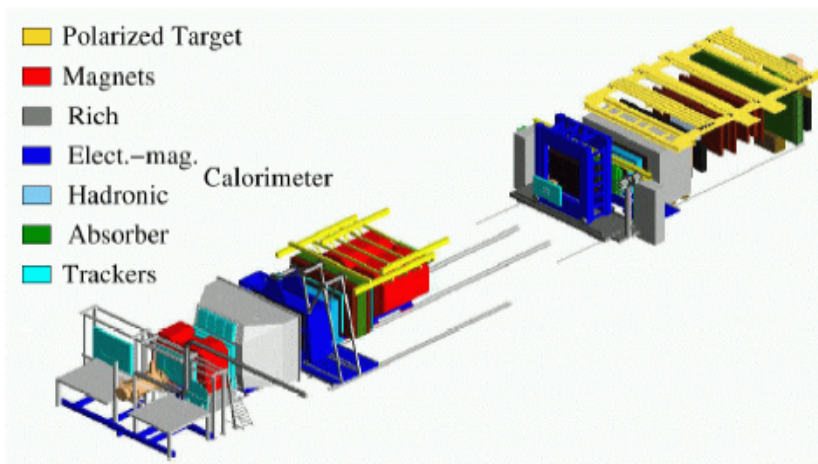
- 1988 - Shows 'naïve quark parton model' is inaccurate
- Gives result of small contribution of quarks to spin of p

Spin Muon Collaboration

- Semi-inclusive data gives further information on the various flavor contribution
- Measured the whole range of momentum transfer data available for a fixed target

COmmon Muon and Proton Apparatus for Structure and Spectroscopy

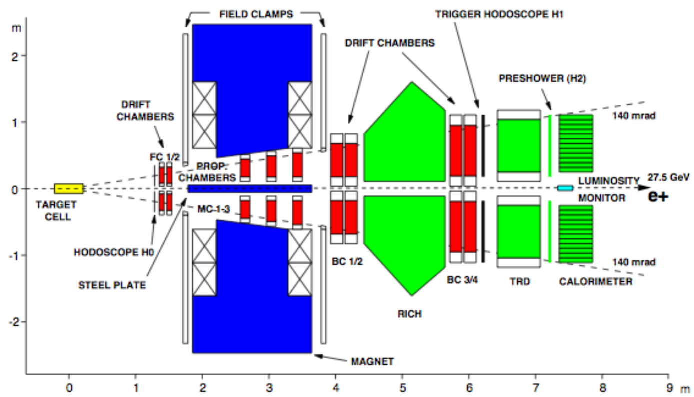
- Purpose is to look at gluon polarization



HERMES & JLab

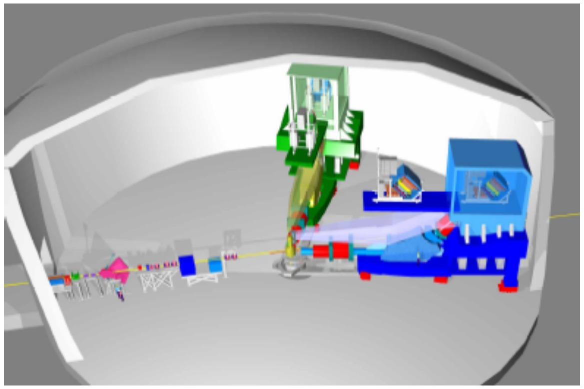
HERMES

- e^+/e^- hit low density gas targets fed directly from atomic beam sources
- Targets are polarized using radio-frequency fields and Stern-Gerlach type separation
- Beam is polarized by the Sokolov-Ternov effect
- Semi-Inclusive data



Jefferson Lab

- Electron (Polarization >85%) scattering experiments
- Three targets - ^{3}He d p
- Able to do longitudinal or transverse polarization to beam direction gives more direct extraction of g_1 and g_2



Results to Date

Nucleon Spin = $\frac{1}{2}\Delta\Sigma + \Delta G + L(z)$

Net quarks contribution ➔ 30-35%

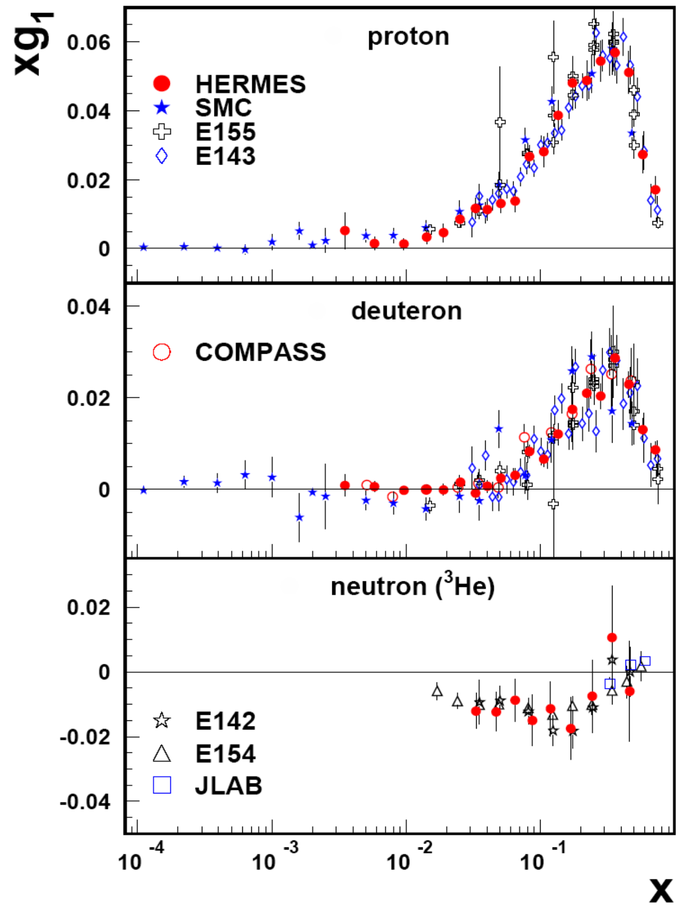
Restrictions on the gluon contribution ➔ low

Exact magnitude is not yet known

Appears the orbital angular momentum will account for the remainder

Not directly measurable

➔ Semi inclusive measurements help deduce

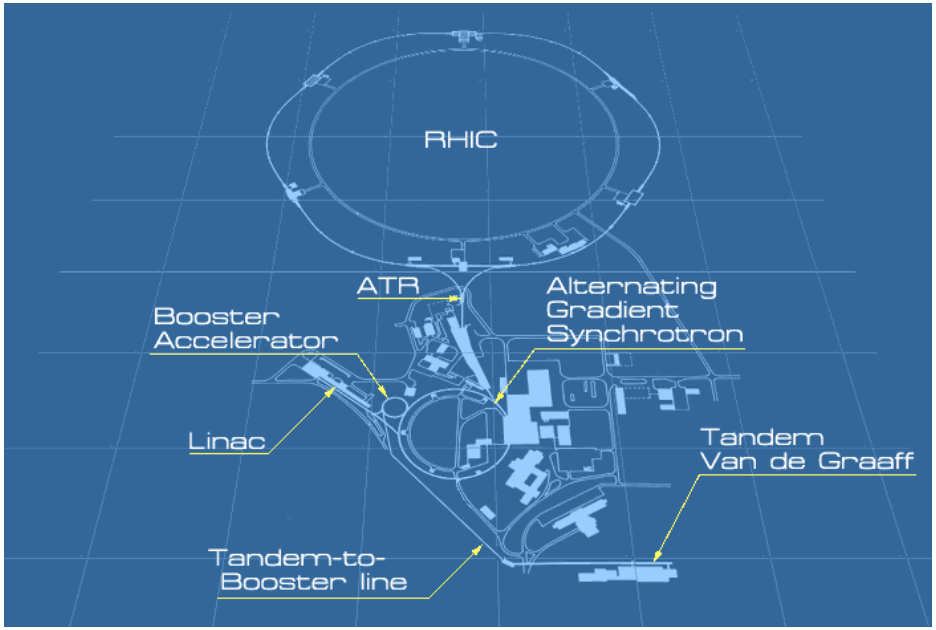


RHIC

We need a specialized way to probe gluons, since they have no charge they wont directly interact with photons, so we can't use leptons.

We need a specialized way to probe quark anti-quark contributions to nucleon spin, but since photons don't distinguish between quarks and antiquarks, we need something else.

RHIC's solution is p + p collisions.



Basics

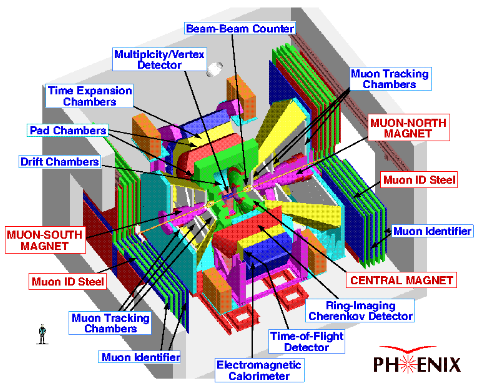
Basics:

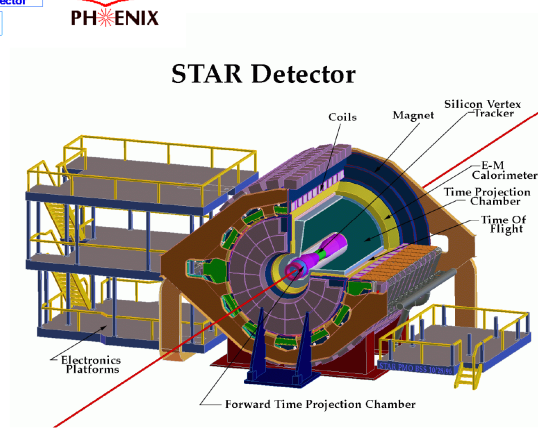
A chain of accelerators are fed by an H- source

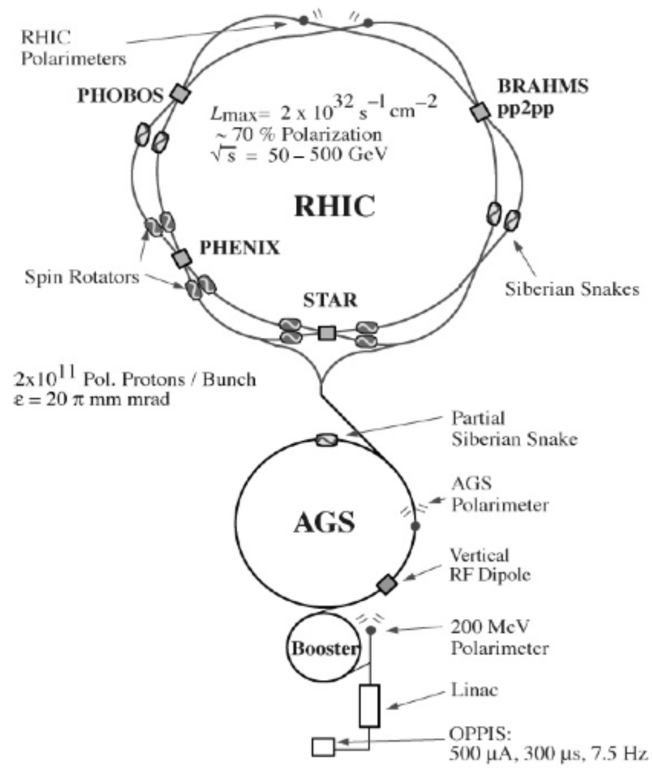
Groups of $2 \cdot 10^{11}$ p with 70% polarization are transferred to RHIC rings at 22 GeV

This is repeated 120 times for each ring

The protons are accelerated to 250 GeV max







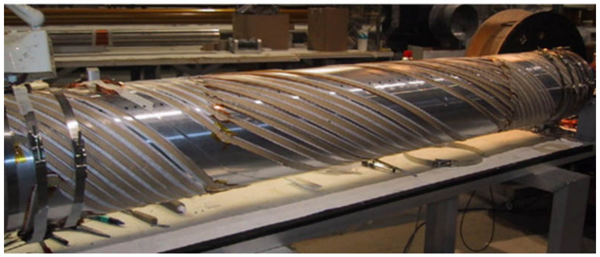
Maintaining the Spin

2 factors affect maintenance of the polarization of the accelerated protons:

- Its magnetic moment makes it sensitive to anomalies in the B field
- Spin resonances that occur approximately every 500 MeV of acceleration in the Accelerating Gradient Synchrotron

The main system for preventing depolarization:

- By rotating the spin by π about a selected axis in horizontal plane each pass
- Using 4 siberian snakes, 2 in each ring



Warm (top) and superconducting Siberian Snakes

ΔG and measurement

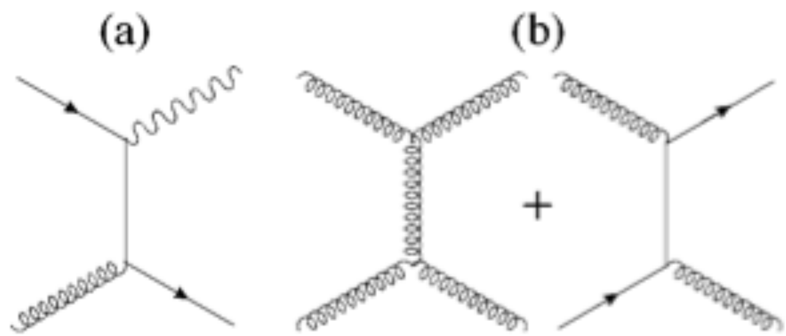
RHIC measures over a large range of x, using high momentum transfer to ensure pQCD is available. The two main measurement methods:

a) Prompt photon production, $\vec{p}\vec{p} \rightarrow \gamma X$

And primarily:

b) π/Jet Production, $\vec{p}\vec{p} \rightarrow \pi^{\pm,0} X, jetX$

To First order the diagrams are as follows:

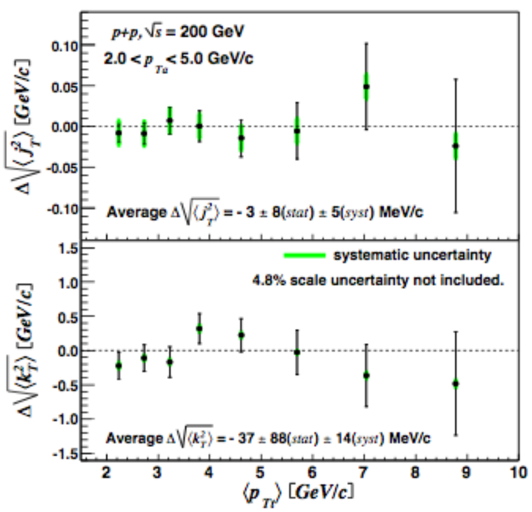


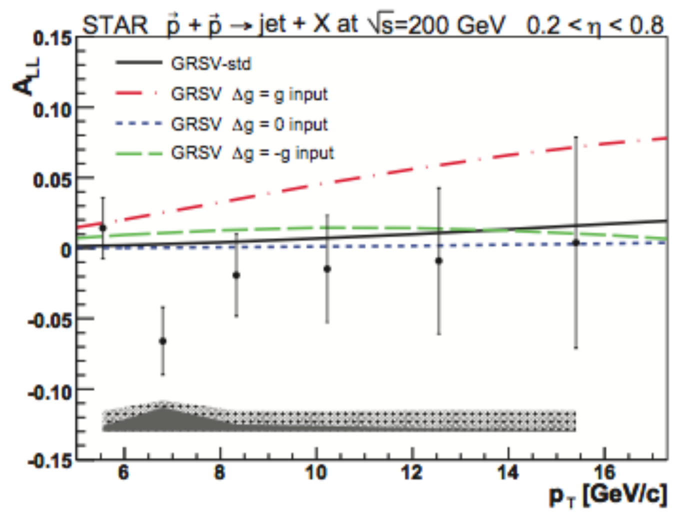
π and Jet Production

$\vec{p}\vec{p} \rightarrow \pi^{\pm,0} X, jetX$ is the main system for measuring Δg at RHIC.

Well structured jets occur at the higher energy end of RHIC, $\sqrt{s} \approx 500 \;\; GeV$, the observables show strong sensitivity to Δg because of the subprocesses (gg, qg)

STAR is the only appropriate detector for the jets, as PHENIX's angular resolution is too small for looking at jet production. However, PHENIX can look at π production through the same subprocesses.





PHENIX and STAR data are consistent with Δg = 0

Prompt Photon Production

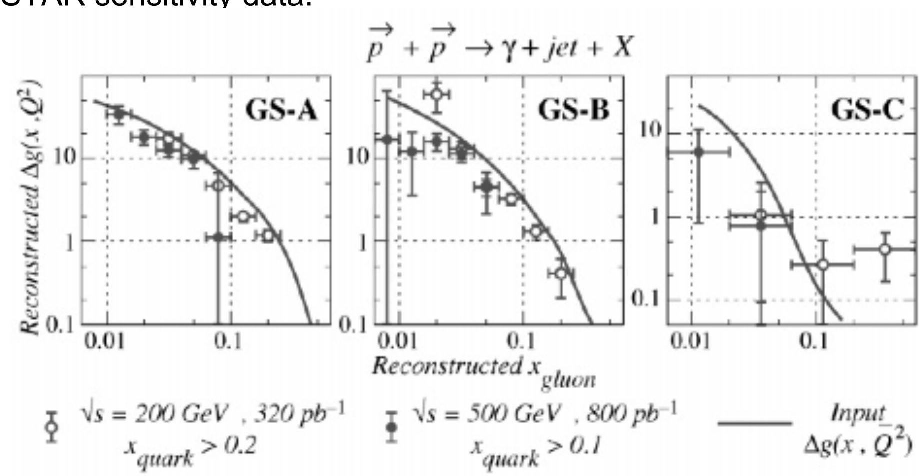
Prompt photon production, $\vec{p}\vec{p} \rightarrow \gamma X$ is the simplest of the two processes.

A photon is produced by the above mechanism. This is in theory the most straightforward method of measuring gluon polarization.

It is simpler than the other methods as there is the distinct signal of a photon, without local jet debris.

PHENIX and STAR are using this procedure for leading order determination of Δg.

STAR sensitivity data:



Weak Boson Probing of Δq

The main mechanism of W's is: $u\bar{d} \rightarrow W^{+}$

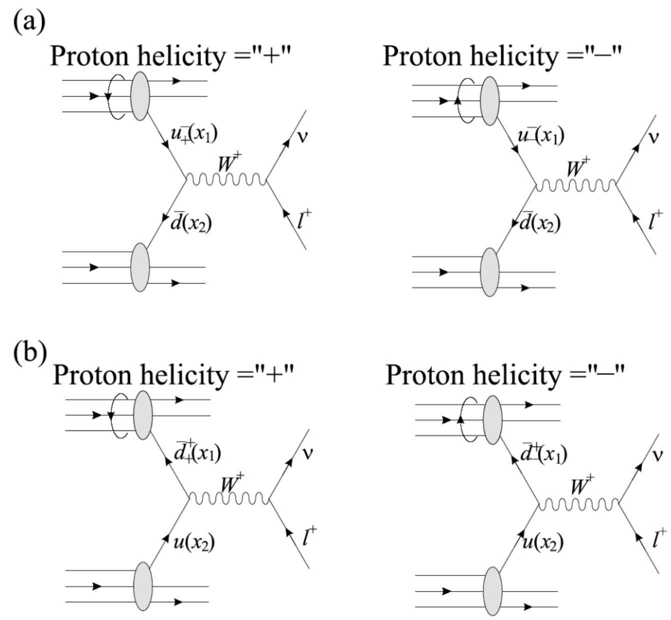
The parity violating asymmetry is measured as:

$$A_L^W = \frac{1}{P}\frac{N_-(W) - N_+(W)}{N_-(W) + N_+(W)}$$

The production of the weak bosons violates parity maximally, so for (a) and (b) below, the parity violating asymmetry is equal to the longitudinal polarization asymmetry of the quarks as follows:

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

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



The asymmetry for W^- is given by interchanging u and d

Conclusion

The nucleon spin question is not answered!

- Although values for the quark contribution is getting more and more accurate, the composition among the various flavors is still being analyzed, and the first probes into quark anti-quark composition are under way.
- There are restrictions on the gluon polarization, but the actual value is still open, and could be a non-negligible contribution.
- New experiments at RHIC are going to help get more accurate measurements.

But why do we care? What do we learn other than 'why' the spin is 1/2?

- The composition gives us insight into the underlying structure, and dynamics (i.e. the orbital contribution) of the constituents of the nucleons
- Learning about the gluon polarization will give insight into the dynamics of gluons that is not yet known
- We get a better picture of the power of pQCD and the accuracy of QCD models, and therefore higher precision QCD

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5) Abelev et al. “Longitudinal double-spin asymmetry and cross section for inclusive neutral pion production at midrapidity in polarized proton collisions at $\sqrt{s} = 200$ GeV” arxiv.org 0911.2773.

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Extra: Targets

Jlab - $^{15}NH_3$ and $^{15}ND_3$

SMC - Butanol, C_4H_9OH

COMPASS - ^{6}LiD

In general H or D rich compounds, i.e. alcohols/ammonia

Extra: Target Polarization

Polarized H/D target

- Subtract out pure proton results
  - Requires us to account for the “Deuteron D - State”
- Polarize H/D rich compounds with several T Magnetic field and cool to <1K
  - Unpaired e^- are nearly 100% polarized, and transfer polarization to H/D nuclei via Dynamic Nuclear Polarization.
    - Gives protons ~80-90% polarized
    - Gives neutrons ~30-50% polarized

^{3}He target

- Can be considered (to first order) a proton pair w/ anti-aligned spins, therefore leaving a polarized neutron target.
- Advantage of not needing to subtract out the proton contribution, and can stand larger beam currents
- Polarization by spin exchange with alkali atom vapor
  - 50+% polarization (increases in laser and vapor technologies has increased this significantly, up to ~70%)

Extra: Bjorken SR and W consts

Rigorous derivation, with only the assumption of isospin invariance:

$$\Gamma^{p-n}(Q^2) = \int_0^1 \left(g_1^p(x) - g_1^n(x) \right) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| (1 - \Delta B_j)$$

$a_3 = g_A = 1.267 \pm .0035$

$a_8 = .585 \pm .025$