The proton spin : facts and fancies

FACTS

1) Data : Proton Spin Crisis!
2) Mundane explanations

FANCIES

3) Naive Quark Models
   No Proton Spin Crisis!
4) Gluonic contributions via the axial anomaly
5) Angular momentum sum rule
   Where is the spin of the proton?
6) Chiral Models
   - Skyrme
   - Hybrid Bag
   - Cheshire cat principle
7) Conclusions

1.) The Data

* EMC Collaboration :
J. Ashman et al. Phys. Lett. B206, 364 (1988)

$$A_1 = \frac{\sigma(\mu\uparrow p\uparrow) - \sigma(\mu\uparrow p\downarrow)}{\sigma(\mu\uparrow p\uparrow) + \sigma(\mu\uparrow p\downarrow)}$$

$\uparrow\downarrow$ Polarization along the beam direction

Extended SLAC $\begin{cases} Q^2 \text{ up to } 70\ \mathrm{GeV}^2 \\ x \text{ down to } 0.01 \end{cases}$

data are consistent in the region of overlap

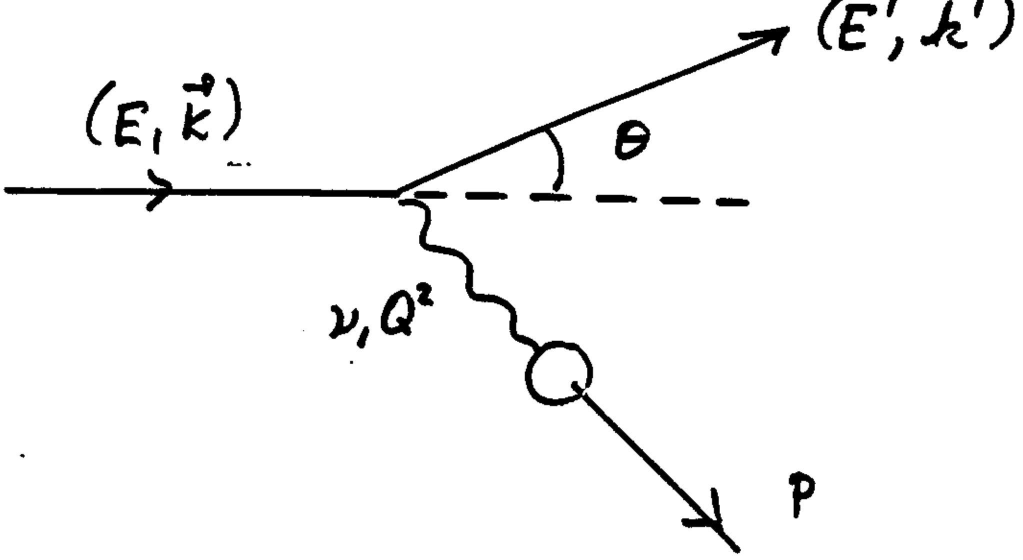
$$g_1 \simeq A_1 \frac{F_1}{1+R}. \qquad W_1(x,Q^2) \xrightarrow[Bj]{} F_1 \qquad R = \frac{\sigma_L}{\sigma_T} \to 0$$

The asymmetry directly yields information of the spin structure function

$$\int_0^1 dx\ g_1^p(x) = 0.114 \pm 0.012 \pm 0.026$$

Caveat : small evolution effects and small x extrapolations

Review (One photon approximation)



$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{\alpha^2}{Q^2} L_{\mu\nu} W^{\mu\nu}$$

$$L^{\pm}_{\mu\nu} = \frac{1}{2}\left(L^{S}_{\mu\nu} + L^{\pm A}_{\mu\nu}\right)$$

$$W_{\mu\nu} = W^{S}_{\mu\nu} + W^{A}_{\mu\nu}$$

$$L^{S}_{\mu\nu} = 2\left[k'_\mu k_\nu + k_\mu k'_\nu - g_{\mu\nu}(k\cdot k' - m^2)\right]$$

$$L^{\pm A}_{\mu\nu} = \mp i \varepsilon_{\mu\nu\lambda\sigma} k^\lambda k'^\sigma$$

$$W^{S}_{\mu\nu} = W_1(\nu, Q^2)\left(-g_{\mu\nu} - \frac{q_\mu q_\nu}{Q^2}\right) + \frac{W_2(\nu, Q^2)}{M^2}\left(p_\mu + \frac{p\cdot q}{Q^2} q_\mu\right)(p_\nu + \frac{p\cdot q}{Q^2}$$

$$W^{A}_{\mu\nu} = i \varepsilon_{\mu\nu\lambda\sigma} q^\lambda \Big(s^\sigma g_1(\nu, Q^2) + \frac{p\cdot q}{M} g_2(\nu, Q^2) - - s\cdot p\, p^\sigma \frac{g_2(\nu, Q^2)}{M}\Big)$$

$\Big\{$ S^μ proton spin
± helicities

Let us define

$$\langle p | \bar{q}_i \gamma_\mu \gamma_5 q_i | p \rangle =$$

$$G_A^{(i)}(q^2)\, \bar{P} \gamma_\mu \gamma_5 P + G_P^{(i)}(q^2)\, q_\mu \bar{P} \gamma_5 P$$

$i = u, d, s$ $\qquad$ q = momentum carried by the axial current

$$\int_0^1 dx\, g_1^p(x) = \frac{1}{18}\left(4 G_A^u + G_A^d + G_A^s\right) = 0.114$$

Now neutron and hyperon decays measure (SU(3))

$$g_A = G_A^{(3)} = G_A^u - G_A^d = F + D$$

$$G_A^{(8)} = G_A^u + G_A^d - 2 G_A^s = 3F - D$$

where

$F = 0.477 \pm 0.011$

$D = 0.755 \pm 0.011$

M. Bourkin et al.
Z. Phys. C21, 27
(1983

$\frac{F}{D} = 0.63$

All these equations imply

$$\boxed{G_A^{(1)} = G_A^u + G_A^d + G_A^s = 0.00 \pm 0.24}$$

$\uparrow$

$\langle p |$ Flavor Singlet Axial Current $| p \rangle$

FSAC

$G_A^u = 0.74 \pm 0.08 \quad G_A^d = -0.51 \pm 0.08$

$$\boxed{G_A^s = -0.23 \pm 0.08}$$

Recently more data from EMC

J. Ashman et al.. CERN-EP-89-73

$$\int_0^1 dx\, g_1^p(x) = 0.126 \pm 0.010 \pm 0.015$$

and new analyses of decays

Kaplan and Manohar N.P. <u>B310</u>, 527 (1988)

Jaffe and Manohar CTP-1706 (1989)

$F = 0.47 \pm 0.04 \quad D = 0.81 \pm 0.03 \qquad \frac{F}{D} = 0.58$

$G_A^{(3)} = 1.28 \qquad G_A^{(8)} = 0.60$

$$\boxed{G_A^{(0)} = \begin{matrix} 0.01 \\ 0.14 \end{matrix}}$$

$G_A^u = \begin{matrix} 0.74 \\ 0.77 \end{matrix} \qquad G_A^d = \begin{matrix} -0.53 \\ -0.49 \end{matrix} \qquad \boxed{G_A^s = \begin{matrix} -[illegible] \\ -[illegible] \end{matrix}}$

* EMC data are consistent with low energy $\nu p \to \nu p$ scattering L.A. Ahren et al PR<u>D35</u> 785 (1987)

* Different sets of F and D are not consistent with each other: result vary though no more than 20%.

Conclusion :

$$G_A^{s} = \text{non-negligible}$$

$$G_A^{(1)} \quad \text{suppressed}$$

The fact that $G_A^{(1)} \approx 0$ has named the matter :

Proton spin crisis!

Interpretation :

In the simple parton model

$$G_A^{(i)} = \Delta q^{(i)}$$

$$\Delta q = \int_0^1 dx \left[q^{+}(x) - q^{-}(x) + \bar{q}^{+}(x) - \bar{q}^{-}(x) \right]$$

i.e.. polarized quark density

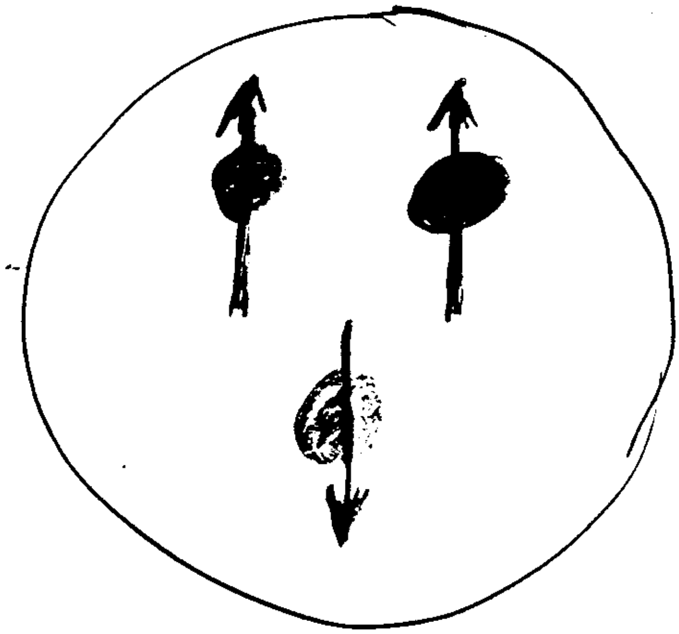
$$G_A^{(1)} = \Delta u + \Delta d + \Delta s = 0$$

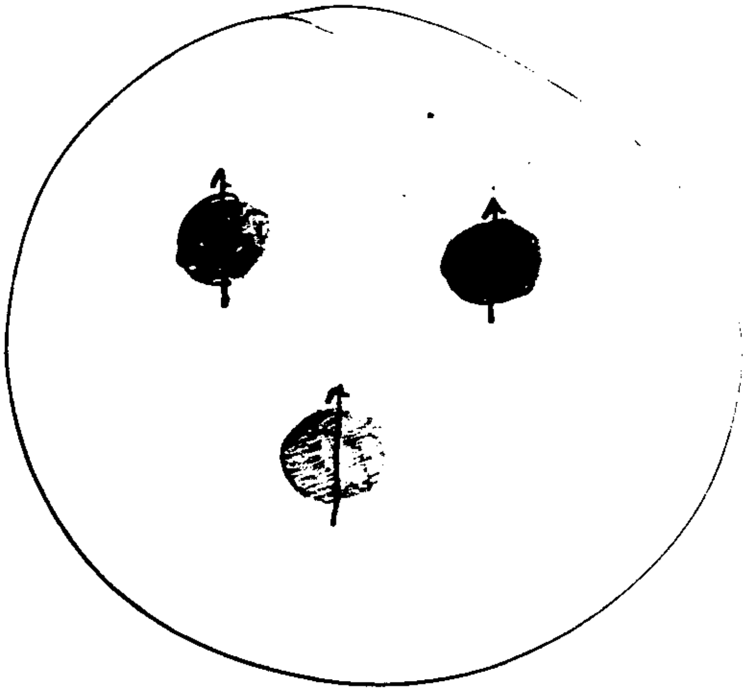
crisis

in the NRQM $\Delta s = 0 \quad \Delta u + \Delta d = 1$

This argument is very naive : more sophisticated leads to Ellis-Jaffe sum rule

Naive interpretation.





$$\Delta u + \Delta d = 0.23 \pm 0.08$$

Where is the spin?

$$\int_0^1 dx\, g_1^p(x) = \frac{1}{18}\left(4\Delta u + \Delta d + \Delta s\right)$$

$$\simeq \frac{1}{18}\left(\frac{5}{2} G_A^{(8)} + \frac{3}{2} G_A^{(3)} + 6\Delta s\right)$$

$$= \frac{1}{18}\left(9F + D + 6\Delta s\right)$$

Ellis + Jaffe $\Delta s = 0$ (certainly naive since $\Delta s ($q

$$\int_0^1 dx\, g_1^p(x) = 0.175 \pm 0.018 \quad !$$

$$\Longrightarrow ? \quad \boxed{G_A^{(1)} = \Delta u + \Delta d = \Sigma = 0.60 \pm 0.12}$$

Thus **EMC** more than two standard deviations away from traditional physics

Moreover $\boxed{\Delta s \neq 0}$ proton: strangeness content $\neq 0$

2. Mundane explanations

i) Data not in the scaling region

M. Anselmino, B.L. Ioffe and E. Leader
NSF-ITP-88-94

No viable option: no Q^2 dependence is visible in the data

ii) Unreliable extrapolation to $x = 0$

F.E. Close and R.G. Roberts
Phys. Rev. Lett. 60, 1471 (1988)

Regge theory + no Pomeron - Pomeron singularity
$\Longrightarrow$ No singular behavior is to be expected

Because one might easily conclude [illegible] [illegible] are singular would be to explain the data.

It would be useful to have an independent determination o G_A'. A dedicated high statistics low energy $\nu p \to \nu p$ scattering could provide a better measurement (A. White)

iii) Large SU(3) breakings

Axial charges are not protected from large breakings by the Ademollo-Gallo the

* SU(3) violations are known to be significant (~20%) for magnetic moments

* However SU(3) symmetry works remarkably well for the axial charge Jaffe + Manohar

* the baryon axial charges are not sensitive to large SU(3) breaking in the baryon wave function

H.J. Lipkin Phys. Lett. B230, 135 (1989)

Conclusion:

EMC data seem to imply new physics

We develop:

- Large OZI violations
- [illegible] contributions via axial anomaly
- Orbital angular momentum instead of spin angular momentum

3. Naive Quark Models

i) NRQM

The proton is constructed in terms of constituent quarks U, D, S not in terms of current quarks of the QCD lagrangian

[illegible] $$\bar{u}\gamma_\mu\gamma_5 d \longrightarrow g_A^{8}\,\bar{U}\gamma_\mu\gamma_5 D + \text{higher derivatives}$$

$\nearrow$ unknown renormalization

$$\left.\begin{aligned} F &= \tfrac{2}{3}\, g_A^{(8)} \\ D &= g_A^{(8)} \end{aligned}\right\} \qquad \frac{F}{D} = \frac{2}{3} \quad \text{close to exp} \left\{\begin{matrix} 0.63 \\ 0.58 \end{matrix}\right.$$

From the values of F and D $\quad g_A^{(8)} \approx 0.75 \pm 0.$

singlet current

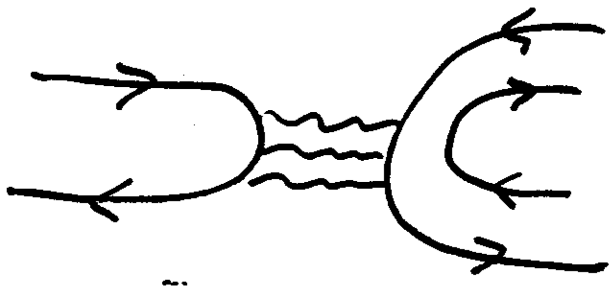
$$\bar{u}\gamma_\mu\gamma_5 u + \bar{d}\gamma_\mu\gamma_5 d + \bar{s}\gamma_\mu\gamma_5 s \Longrightarrow$$

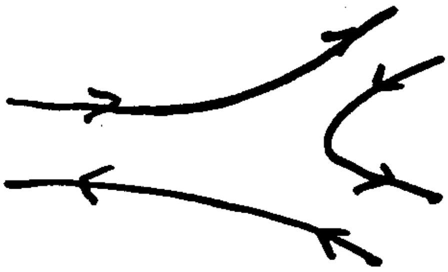
$$g_A^{(1)}\left[\bar{U}\gamma_\mu\gamma_5 U + \bar{D}\gamma_\mu\gamma_5 D + \bar{S}\gamma_\mu\gamma_5 S + \ldots\right.$$

$g_A^{(8)}$ and $g_A^{(1)}$ are independent

Their difference measures the importance of OZI rule violations since only the singlet current can mix with the gluons.

Recall OZI





Disconnected diagrams are suppressed

$\phi \to \pi \rho$ $\qquad\qquad$ $\phi \to K\bar{K}$

$\psi'' \to$ uncharmed $\qquad\qquad$ $\psi'' \to D\bar{D}$

Since proton has no S quarks

$$G_A^1 = g_A^{(1)} \underbrace{\left(G_A^U + G_A^D \right)}_{1} = 0$$

$$\left.\begin{aligned} &\Rightarrow \quad g_A^{(1)} \approx 0 \\ \text{Since} \quad &g_A^{1} = 0.75 \end{aligned}\right\} \text{large OZI violations in the axial sector}$$

If $g_A^8 = g_A^1 \Rightarrow$ no s (current) ~~quarks~~ quarks in the proton, i.e. $G_A^{(1)} = 0.75$ basically the Ellis-Jaffe analysis

Recall: $G_A^{(1)} = 1$ only if constituent quarks are the same as current quarks (wrong)

$F = \frac{2}{3}$ $\quad D = 1$ $\quad$ etc..

(ii) MIT Bag Models

- current quarks
- orbital angular momentum

$$\sim \begin{pmatrix} f \\ r\cdot\hat{r}\, g \end{pmatrix}$$

$$\left.\begin{aligned} F &= \frac{2}{3}\int\left(f^2 - \frac{1}{3}g^2\right) \\ D &= \underbrace{\int\left(f^2 - \frac{1}{3}g^2\right)}_{\text{orbital angular momentum}} \end{aligned}\right\} g_A \Rightarrow \quad D \simeq .75$$

In relativistic models $G_A^{(1)} < 1$ merely because the quark carries orbital angular momentum. Here OZI type effects (quark-annihilation [illegible] [illegible])

(25-40% effects)

Conclusion:

i) $G_A^{(1)} = 1$ makes no sense

(ii) EMC data may be easily accomodated if
  a) OZI violations
  b) angular momentum is carried by the quarks

4. Gluonic contributions via the Axial Anomaly

- We know from DIS that gluons carry half of the proton momentum

- Gluons do not contribute to additive quantum numbers like electric charge, strangeness but there is no reason to expect gluon contribution to spin and orbital angular momentum

partonic
- Altarelli + Ross Phys. Lett. B193, 391 (1988)
- Efremov + Terayev Dubna Report E3-88-287
- Carlitz, Collins, Mueller Phys. Lett. B214, 229 (1988)

The FSAC is anomalous

$$\partial^\alpha A_\alpha^5 = \frac{\alpha_s N_f}{8\pi} F^{\mu\nu a} F_{\mu\nu}^{a*}$$

Define

$$k_\alpha = \frac{\alpha_s N_f}{2\pi} \varepsilon^{\mu\nu\rho\sigma} A_\nu^a \left(\partial_\rho A_\sigma^a - \frac{g}{3} f_{abc} A_\rho^b A_\sigma^c \right)$$

$$\tilde{A}_\alpha^5 = A_\alpha^5 - k_\alpha$$

$$\partial^\alpha \tilde{A}_\alpha^5 = 0$$

Non anomalous and has no anomalous dimension (does not evolve) current approach ~ $\left\{ \begin{array}{l} \text{T. P. Cheng – Ling Fong Li} \\ \text{D.P.F meeting (1990)} \end{array} \right.$

$$\left.\begin{array}{ll} \langle p | \partial^\alpha \tilde{A}^5_\alpha | p \rangle \sim \Delta q^{①} & \text{(valence quark)} \\ \langle p | \partial^\alpha k_\alpha | p \rangle \sim \Delta g^{①} & \text{(gluon contribution)} \end{array}\right\}$$

$\downarrow$ [illegible]

$$\langle p | A^5_\alpha | p \rangle \sim S_\alpha \left(\Delta q' - \frac{\alpha_s}{2\pi} \Delta g' \right)$$

$$G_A^{(1)} = \Delta u + \Delta d + \Delta s - \frac{3\alpha_s}{2\pi} \Delta g =$$
$$= G_A^{(u)} + G_A^{(d)} + G_A^{(s)}$$

The anomaly in the singlet sector induces a gluon contribution.

The gluon term if large might explain the difference between parton and constituent quark

→ current matrix elements

naive. A+R, etc... $\quad G_A^{(1)} \simeq 0 \Rightarrow \Delta u + \Delta d + \Delta s = \frac{3\alpha_s}{2\pi} \Delta g$

T.P. Cheng, L.F. Li $\Big\}$ $\quad G_A^{(i)} = \tilde{G}_A^{(i)} + {}_k G_A^{(i)}$ $\quad$ Current Algebra type relations

5. Angular momentum sum rule

Where is the spin of the proton ?

Jaffe + Manohar

$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta g + \langle L_z \rangle_q + \langle L_z \rangle_g$$

$$\Delta q = \int_0^1 dx \left[q^+(x) - q^-(x) + \bar{q}^+(x) - \bar{q}^-(x) \right]$$

$$\Delta g = \int_0^1 dx \left[g^+(x) - g^-(x) \right]$$

We have seen this sum rule in action at the level of NRQM and MIT Bag Model

Gluonic School $\frac{1}{2} = \frac{1}{2}\Delta q + \Delta g$ incomplete

Cheng - Li $\frac{1}{2} = \frac{1}{2}\Delta q' + \Delta g'$

$$\Delta q' = \Delta q + \boxed{\sigma_q}$$

non perturbative

$$\Delta g' = \Delta g + \boxed{\sigma_g}$$

$$G_A^i = \Delta q' - \frac{\alpha_s}{2\pi}\Delta g' = \Delta q - \frac{\alpha_s}{2\pi}\Delta g$$

$$\sigma_q - \frac{\alpha_s}{2\pi}\sigma_g = 0$$

$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta g + \frac{1}{2}\sigma_q + \sigma_g$$

Jaffe + Manohar $\Delta g = 0$ gluons have been taken into account in the anomalous dimension

$$\frac{1}{2} = \frac{1}{2}\Delta q + \langle L_z \rangle_q$$

There might be a problem of double counting.

We have possible realizations of QCD at low energy, namely MODELS.

What do they have to say?

6. Chiral Models

Skyrme Model

Brodsky, Ellis and Karliner
Phys. Lett. B206, 309 (1988)

$$\mathcal{L} = \frac{f_\pi^2}{4} \mathrm{Tr}\,(\partial_\mu U)\,\partial^\mu U + \frac{1}{32e^2} \mathrm{Tr}\left[U^\dagger \partial_\mu U, U^\dagger \partial_\nu U\right]$$

$$+ N_c \; \mathcal{L}_{WZ}$$

$$U \sim e^{i\lambda^a \cdot \pi^a/2}$$

Certainly $\Delta q = 0$, $\Delta g = 0$ $\Longrightarrow$ everything angular momentum $\langle L_z \rangle =$

moreover $\langle p | FSAC | p \rangle = 0$

Add gluonium $\chi = g\bar{g}$ if one take:
into account the anomaly $\Delta g = 0$ also

Again spin comes from angular momentum
$\langle L_z \rangle = \langle L_z \rangle_q + \langle L_z \rangle_g$

Conclusion:

All the spin corresponds to angular momentum of the rotating skyrmion

Hybrid Models

Dreiner + Ellis + Flores Phys. Lett. B221, 169 (1989)

Since Δq might be small not zero $\Rightarrow$

One needs a bag singularity $\Rightarrow$ Chiral Bag

Hybrid Models interpolate between Skyrme and MIT Bag Model (naïve)

$$0 \leq G_A^{01} \leq 0.6$$

The value of the FSAC is a measure of the size of the quark core

$$\boxed{\text{D+E+F get} \quad R < 0.5\,\text{fm}}$$

Caveat: Since the pion does not contribute to the isosinglet current we have to incorporate an η' outside to restore $U_A(1)$ broken by the boundary condition.

D+E+F

Their work implies that the FSAC is extremely dependent on the size of the core

Cheshire cat principle

B.-Y. Park, V.V, M. Rho and G.E. Brown
N.P. A504, 829 (1989)

B.-Y. Park and V.V, FTUV89-23

The result of Dreiner, Ellis and Flores contradicts the phenomenological Ccp :

If $\frac{1}{N_c}$ dominance is an approximate statement in 3+1 dimensions : Observables should not depend on the radius of the core.

Ccp depends on Casimir effects of the cavity : due to the vacuum of the cavity ($\neq$ free vacuum) flavor flux flows from the interior to the exterior of the bag (charge fractionation). Only color is confined

We incorporate gluons to the calculation

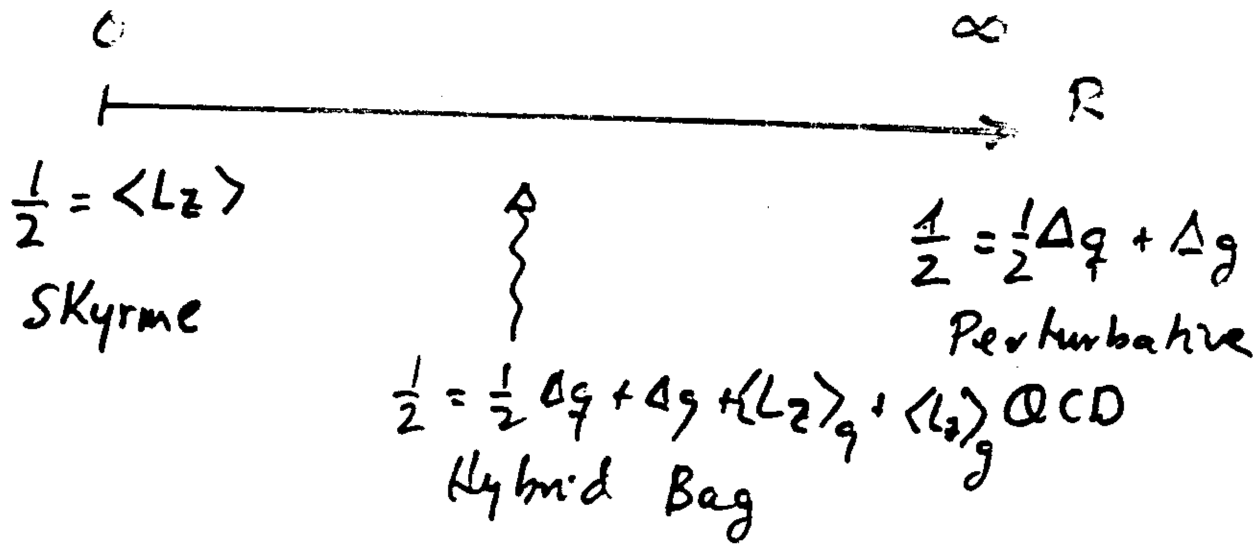
The Axial anomaly is important: similar to Altarelli + Ross here

$$\boxed{\alpha_s \Delta g \quad \text{is not small}}$$

Therefore the contribution of the anomaly is comparable to the rest

Caveat: result depends very strongly on the confinement mechanism

In the most favorable case



$\langle p | FSAC | p \rangle \simeq 0.1$

7. Conclusions

FACTS : well established

- * EMC measures FSAC
- * The data on g_1 are in the scaling region
- * the extrapolation to $x=0$ seems reliable
- * SU(3) appears to be in this context a good symmetry

Therefore

$$G_A^{(s)} \neq 0$$

$$G_A^{(1)} \text{ suppressed}$$

FANCIES

Quark and gluon distributions

* partonic description $G_A^{(1)} = \Delta u + \Delta d + \Delta s - \frac{3\alpha_s}{2\pi}\Delta g$

* current matrix description

$$G_A^{(1)} = \Delta u' + \Delta d' + \Delta s' - \frac{3\alpha_s}{2\pi}\Delta g' \approx \frac{F_2'}{2M} g_{\eta' NN}$$

a la Veneziano CERN-TH-5450-8

* OZI violations a la Jaffe + Manohar

They may be connected

Spin content of the proton

discussion as to how the sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta q + \Delta g + \langle L_z\rangle_q + \langle L_z\rangle_g$$

is realized

The ⟨FSAC⟩ seems to favor models of hadron structure with a Skyrmion cloud :

The Chiral Bag Model

Gluons and η' due to the axial anomaly have to be incorporated in the spin. Gluon confinement is crucial to understand the data but not is yet fully understood.

New experimental investigation

- scattering on neutrons : Bjorken sum rule
- strange quark content of the nucleon
  - πN, KN, ... hadronic reactions
  - μN, νN, ... semileptonic reactions
- $G_A^{(1)}$
  - dedicated low energy νp-scattering

The flavor content of hadrons is a very important fact to understand non-perturbative QCD

Theoretical implications

- Consequences of $G_A^s \neq 0$ in Nuclear Physics, Heavy Ion physics etc... should be addressed

To conclude:

The proton might not be look as naive as we initially thought for certain probes. Gluons seem to play an important role in the FSAC.

More data is needed and more theoretical work to understand the overlap between perturbative and non-perturbative degrees of freedom