The Curse of Spin: Lurching from One Crisis to the Next

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Thus the path of spin is strewn with the wreckage of discarded theories. The positive aspect is that better (hopefully) theories arise from the debris.

Contents

THE ANCIENT WORLD

An example: Electroweak Theory

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Role of spin in comparing rates for $\pi \to e\bar{\nu}$ and $\pi \to \mu\bar{\nu}$ was crucial. Measurement of the Helicity of the neutrino was also a vital experiment in confirming this.

fig

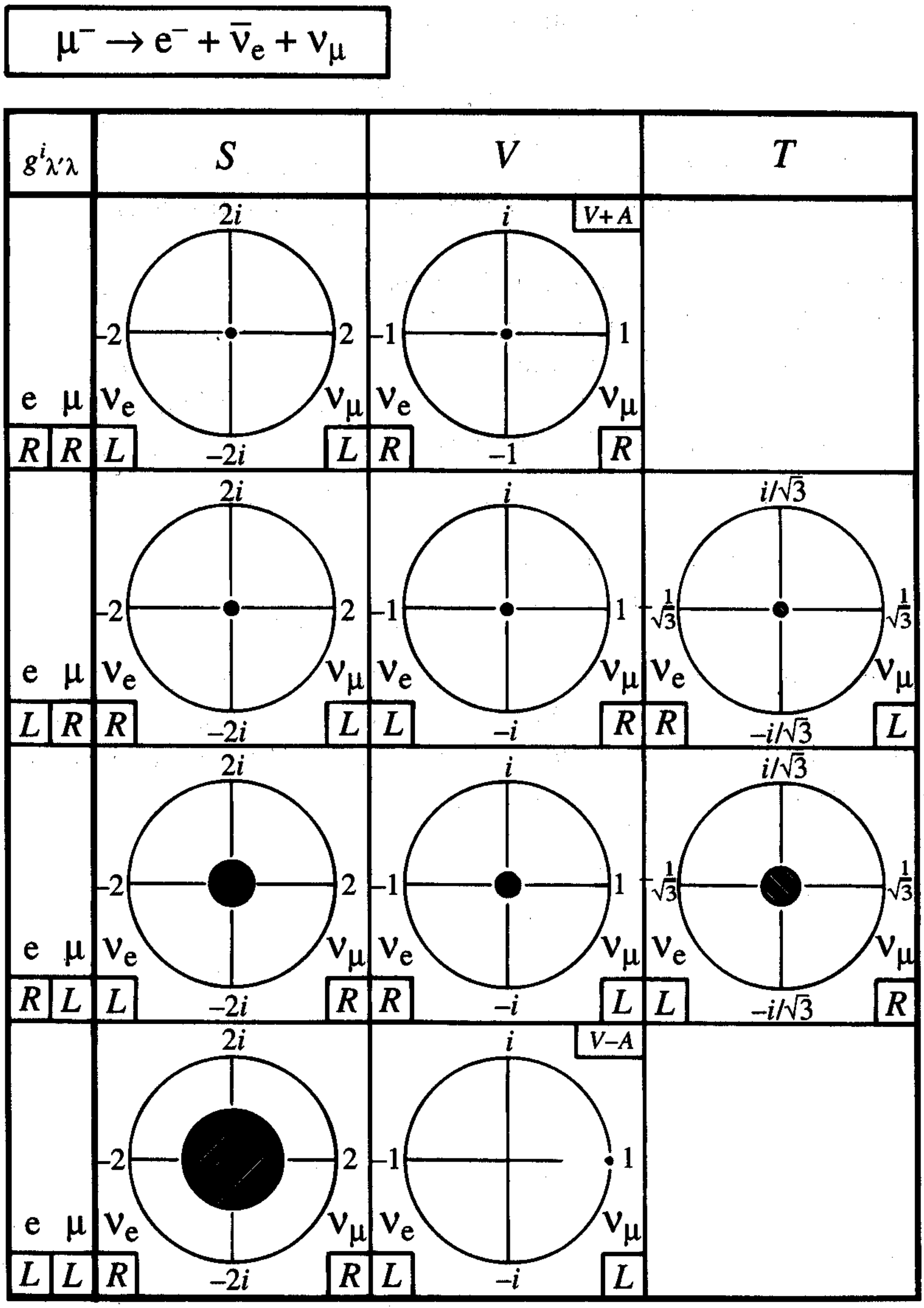


Fig. 1.8. 90% confidence level limits on the coupling constants $g^i_{\lambda'\lambda}$ from the SIN experiments.

Without this unification of Weak and Electromagnetic interactions would have been impossible!

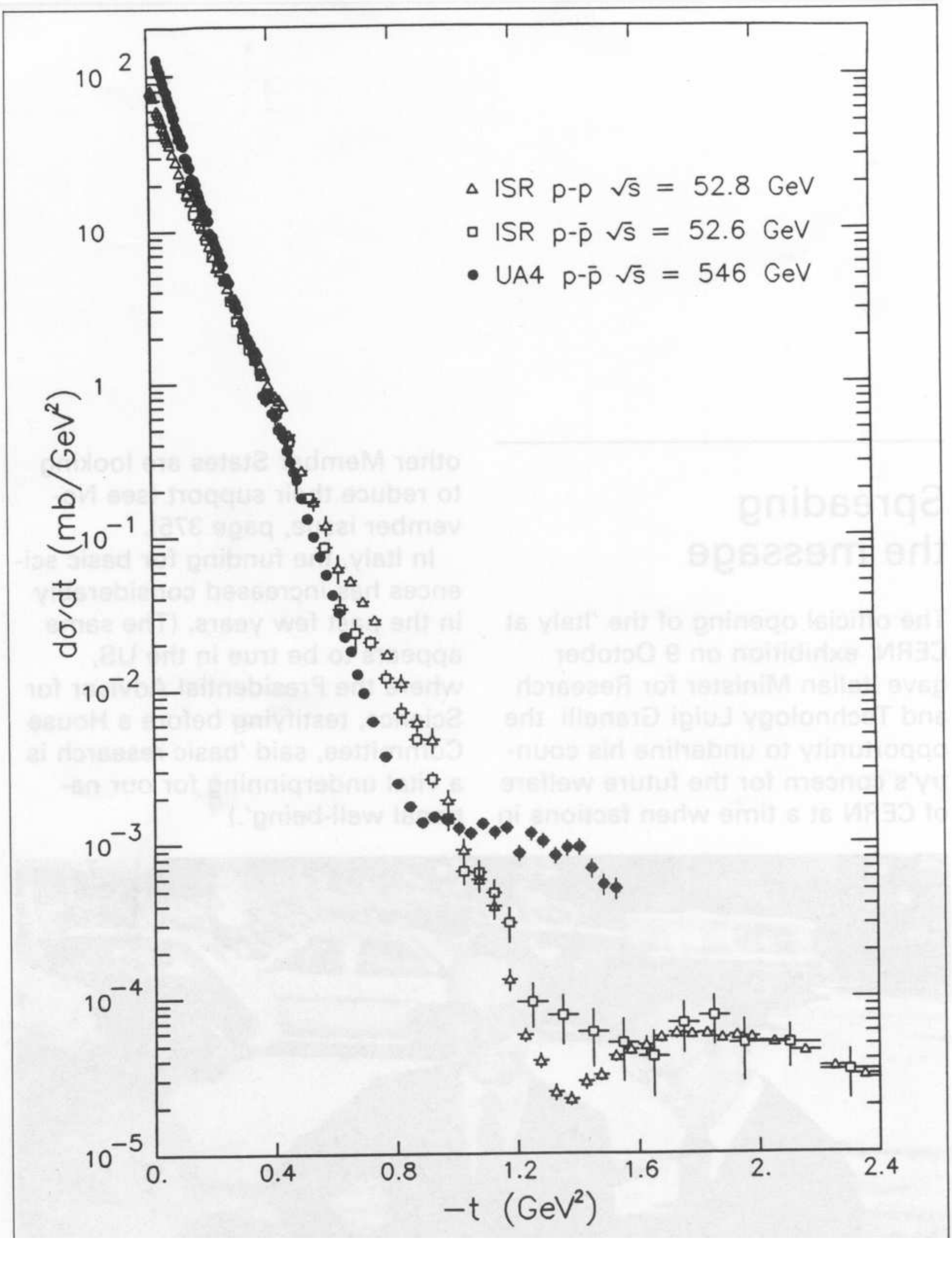
Another example: Regge Poles

Totally unexpected SHRINKING of diffraction peaks in $\frac{d\sigma}{dt}$ for elastic cross-sections

$$A(p_1) + B(p_2) \to A(p_3) + B(p_4)$$

$t = (p_1 - p_3)^2$

fig



ISR p-p √s = 52.8 GeV
ISR p-p̄ √s = 52.6 GeV
UA4 p-p̄ √s = 546 GeV
dσ/dt (mb/GeV²)
10²
10
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
0.
0.4
0.8
1.2
1.6
2.
2.4
−t (GeV²)

Beautiful explanation by Theory of Complex Angular Momentum: simplest version: Regge Poles—————————BUT

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Total failure to predict POLARIZATIONS

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2) Pedagogical-psychological:

Spin had a difficult birth: fine structure of hydrogen (spin-orbit coupling); Stern-Gerlach experiment; “mysterious effects too complicated to explain in an undergraduate text” etc etc

slides

19.1 THE FINE STRUCTURE OF HYDROGEN

$$H_{\text{magn}} = \frac{1}{m^2c^2}\frac{1}{r}\frac{dV}{dr}\mathbf{L}\cdot\mathbf{S} \tag{18.100}$$

When the actual calculation is made with the proper Lorentz transformations for the fields, it is found that owing to purely kinematic effects we must add a term to the energy, which has the same form as (18.100) but a different coefficient. Known as the *Thomas term*, this contribution to the Hamiltonian is

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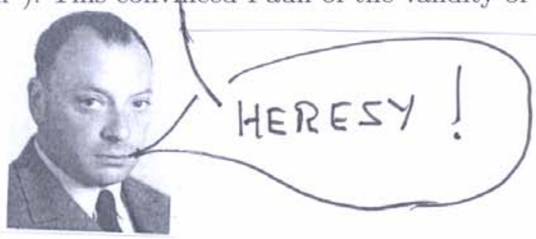
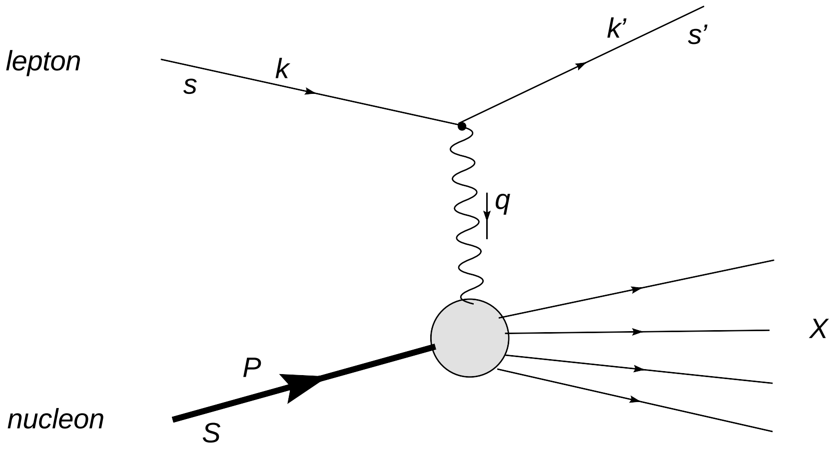
Note that a direct calculation of the spin–orbit coupling, with the usual formulations of special relativity, gives a value *twice* as large as (13.22), and therefore a fine-structure splitting twice too large. This is why Pauli, at the end of 1925, did not believe in the idea of spin, and called it a "Irrleher" in a letter to Niels Bohr. However, in March 1926, L.H. Thomas remarked that the rest frame of the electron is not an inertial frame, and that a correct calculation introduces a factor of 1/2 in the formula (the Thomas precession[2]). This convinced Pauli of the validity of the spin-1/2 concept.



THE RENAISSANCE

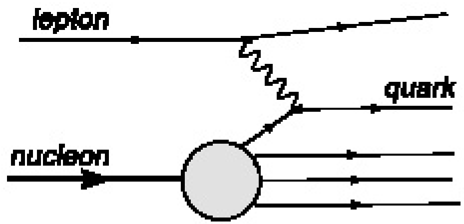
Deep Inelastic Scattering: a reminder

slide


lepton
s
k
k'
s'
q
X
P
nucleon
S

Deep Inelastic Scattering in the parton model

fig


lepton
quark
nucleon

Deep Inelastic Scattering in the parton model

$$Q^2 \equiv -q^2 = -(k - k')^2 \qquad \nu \equiv E_{Lab} - E'_{Lab}$$

$$x \equiv x_{Bjorken} = \frac{Q^2}{2M\nu}$$

The cross-sections are expressed in terms of two (unpolarized) STRUCTURE FUNCTIONS:$F_{1,2}$

In simple Parton Model: $F_{1,2}(x)$

Including some aspects of QCD:$F_{1,2}(x, Q^2)$

Slow evolution in Q^2

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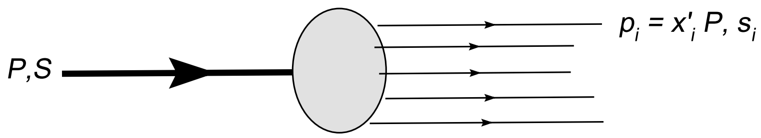
$$F_1(x,Q^2) = \frac{1}{2} \sum_{flav} e_j^2 [q_j(x,Q^2) + \bar{q}_j(x,Q^2)]$$

A key ingredient: the UNPOLARIZED parton number density $q(x)$

fig


P,S
p_i = x'_i P, s_i

Quite analogously, POLARIZED cross-section expressed in terms of two spin-dependent STRUCTURE FUNCTIONS: $g_{1,2}$

$$g_1(x, Q^2) = \frac{1}{2} \sum_{flav} e_j^2 [\Delta q_j(x, Q^2) + \Delta \bar{q}_j(x, Q^2)]$$

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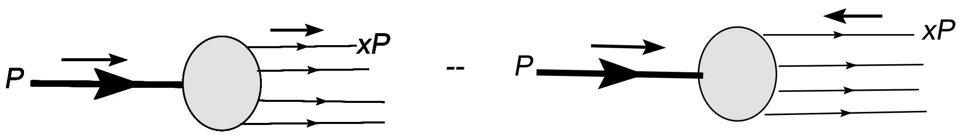
The key ingredient here is the polarized quark density

fig


P
xP
--
P
xP

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$$\Delta q = \int dx \Delta q(x)$$

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Important flavour combinations :

$$a_3 = \Delta u + \Delta \bar{u} - \Delta d - \Delta \bar{d}$$

$= 1.267 \pm 0.0035$

$$a_8 = \Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} - 2(\Delta s + \Delta \bar{s})$$

$= 0.585 \pm 0.025$

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

Ellis -Jaffe Theory: safe to ignore $\Delta s + \Delta\bar{s}$

$$\Longrightarrow \Delta\Sigma \simeq a_8 \simeq 0.59$$

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Now EMC measurement of

$$\Gamma_1^p = \int dx g_1^p(x)$$

$$= \frac{1}{12}\left[a_3 + \frac{1}{3}(a_8 + 4a_0)\right]$$

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Moreover, since

$$\Delta\Sigma = 2S_z^{quarks}$$

EMC seems to imply $S_z^{quarks} = 0$

and there appears to be 'A crisis in the parton model: where, oh where, is the proton's spin?' [Anselmino and L, Z.Phys. C**41**,(1988) 239]

Resolution (??)of the crisis : The Anomalous Gluon Contribution

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The Operator Product Expansion has no gluon operator contributing to the first moment of g_1, but Feynman diagram approach yields result:

$$a_0 = \Delta\Sigma - \frac{3\alpha_s(Q^2)}{2\pi}\Delta G(Q^2) \qquad (2)$$

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Is this acceptable? What do we know about ΔG?

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ATTEMPTS TO MEASURE ΔG

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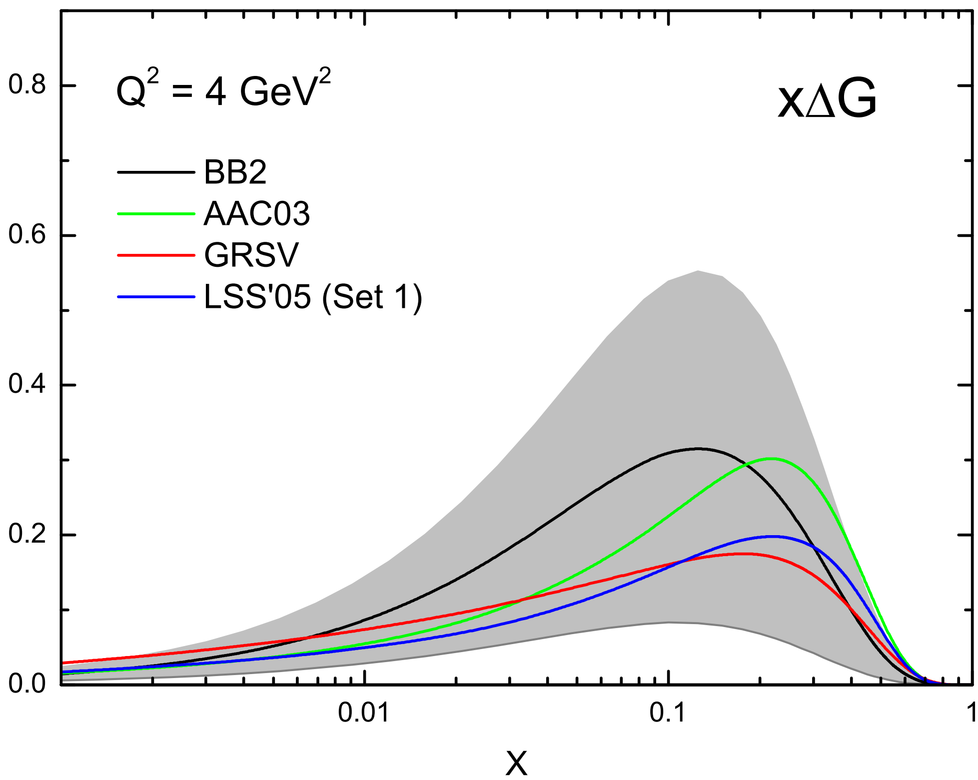
fig world results on $\Delta G(x)$



This is a test.

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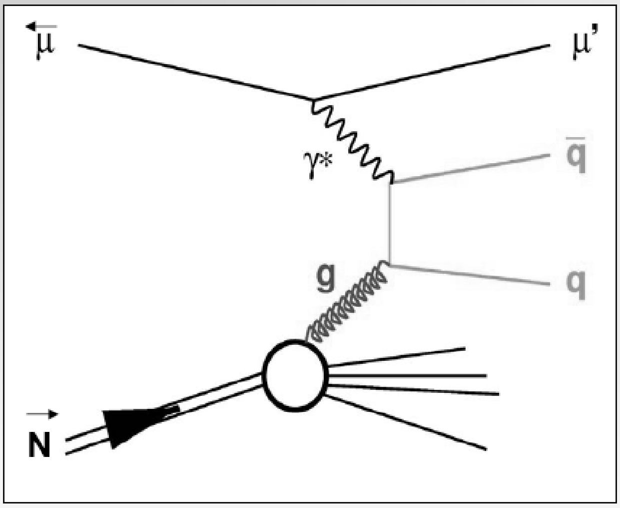
(2) $c\bar{c}$ production in DIS. Requires high energy lepton beam: COMPASS at CERN.

Given that the nucleon has no INTRINSIC charm, the $c\bar{c}$ are produced via 'gluon-photon fusion'.
fig

Photon-Gluon fusion



q = c

"OPEN CHARM"
cross section difference
in **charmed meson** production
→ *theory well understood*
→ *experiment challenging*

q = u,d,s

"HIGH p_T HADRON PAIRS"
cross section difference in 2+1 jet production in COMPASS:
events with **2 hadrons with high p_T**
→ *experiment "easy"*
→ *theory more difficult*

Detecting BOTH charmed particles would be an absolutely clean signal for the mechanism!

But the intensity is too low—-factor of 30 in rate lost in detecting second charmed meson—- so rely on single charm production. Also on back-to-back jets—much less clean.

Figure shows some of the COMPASS results

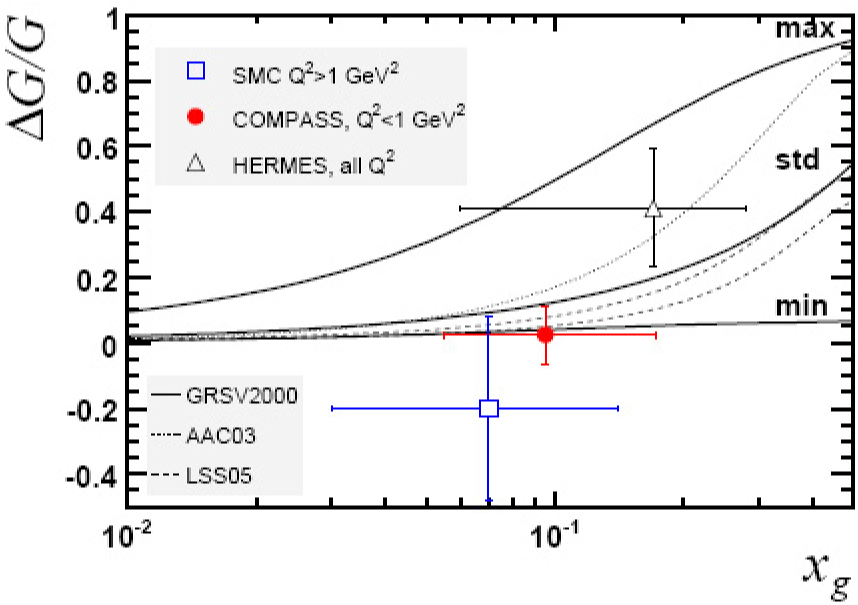


Figure 3: Comparison of the $\Delta G/G$ measurements from COMPASS (present work), SMC [14], and HERMES [23]. The horizontal bar on each point represents the range in x_g. The curves show various parametrizations from NLO fits in the $\overline{\mathrm{MS}}$ scheme at $\mu^2 = 3$ (GeV/c)^2: GRSV2000 [20] (3 curves, please see text for details), AAC03 [24], and LSS05 sets 1 and 2 [25].

Suggests very small ΔG compatible with result quoted above

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(3) A_{LL} with polarized protons: uniquely at RHIC.

Several reactions:

$\vec{p} + \vec{p} \longrightarrow \pi^0 + X$ (needs Fragmentation Functions)

$\vec{p} + \vec{p} \longrightarrow Jet + X$

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Dominant partonic reactions:

$\vec{g} + \vec{g} \longrightarrow g + g$: dominates at smaller p_T^2

$\vec{g} + \vec{q} \longrightarrow g + q$: dominates at larger p_T^2

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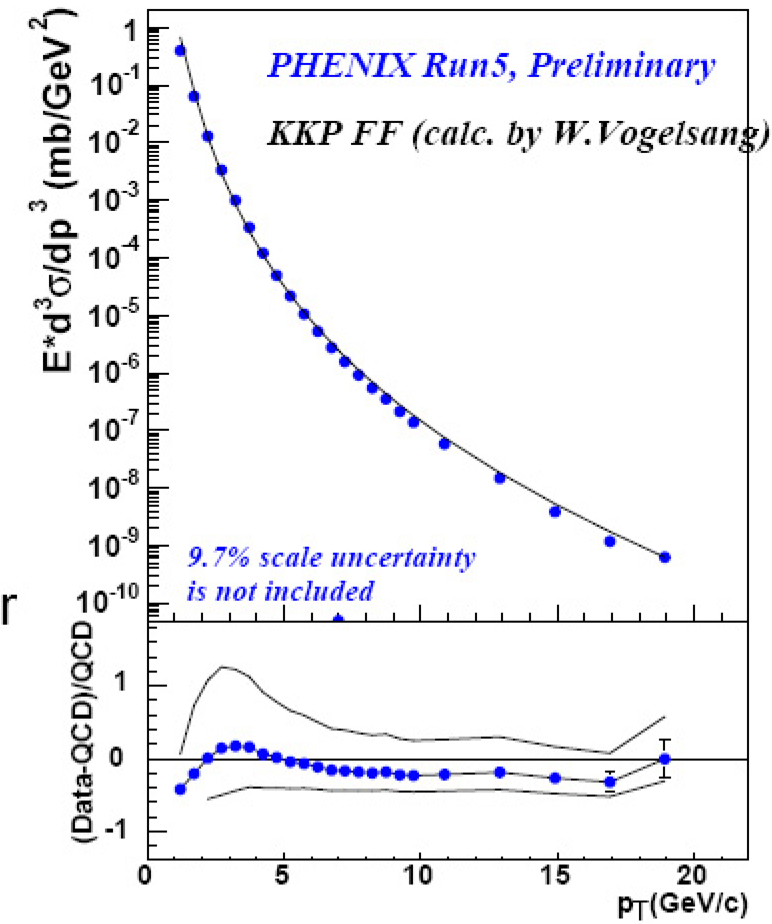
Nice test: PQCD describes cross-sections quite well. Fig

π° Cross Section

> Data points extend from 1 to 20 GeV/c in pT.

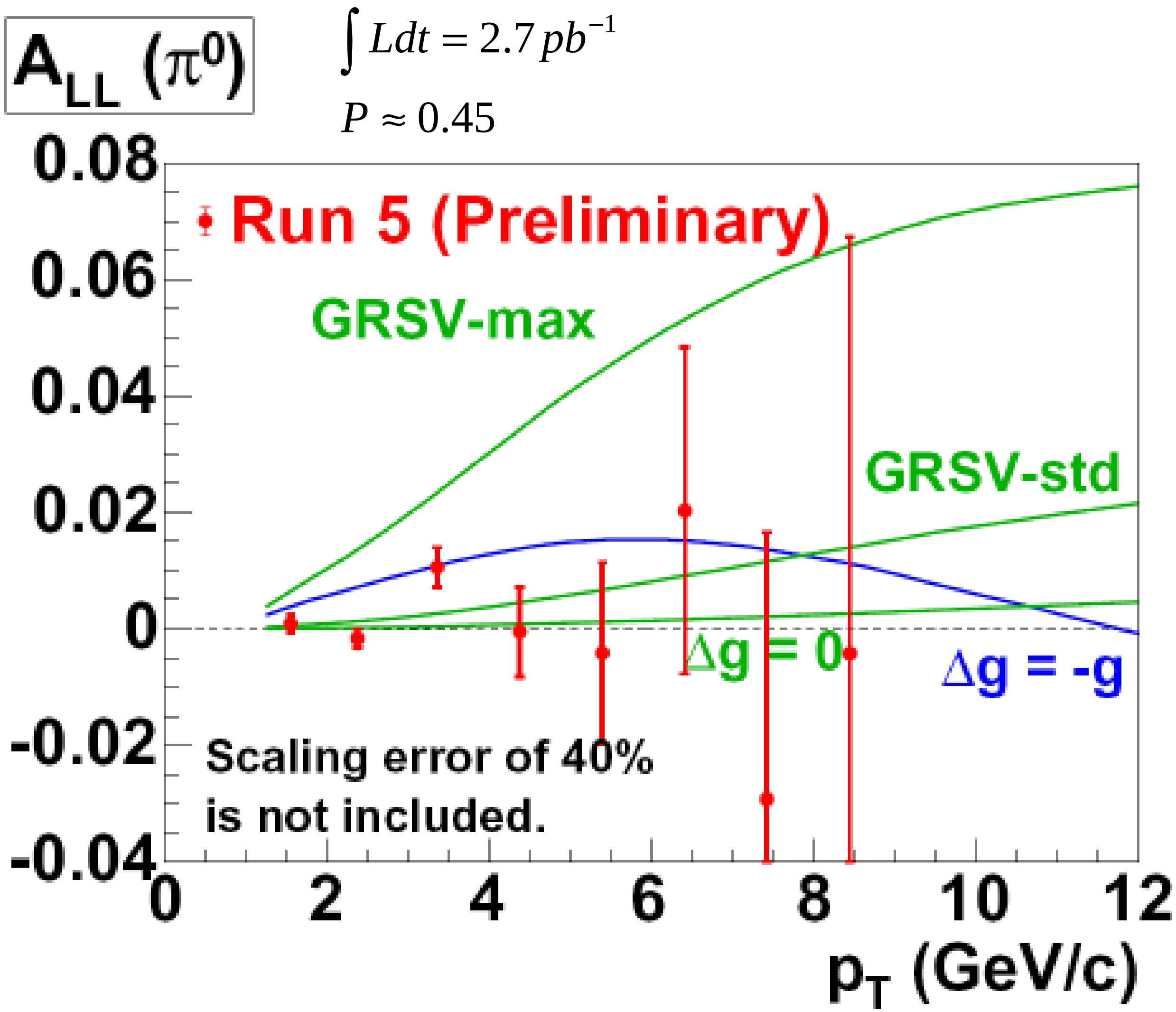
> pQCD calculation with KKP FF describes the data well over all measured pT region. (range of 10^9)

> The cross section of other channel, for example charged pion, is also useful to test pQCD.



Results: A_{LL} is SMALL!

Fig



A_{LL} (π^0)
$\int Ldt = 2.7\,pb^{-1}$
$P \approx 0.45$
Run 5 (Preliminary)
GRSV-max
GRSV-std
Δg = 0
Δg = -g
Scaling error of 40%
is not included.
0.08
0.06
0.04
0.02
0
-0.02
-0.04
0
2
4
6
8
10
12
p_T (GeV/c)

..

Consistent with ZERO gluon polarization

Consistent with ZERO gluon polarization

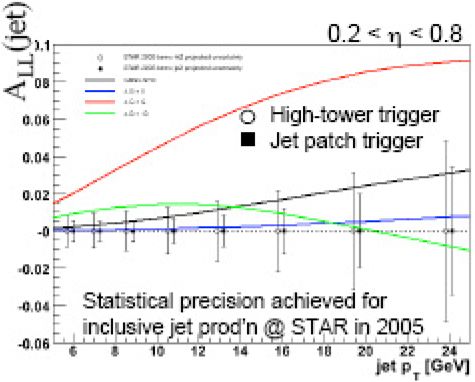
THE SPIN CRISIS

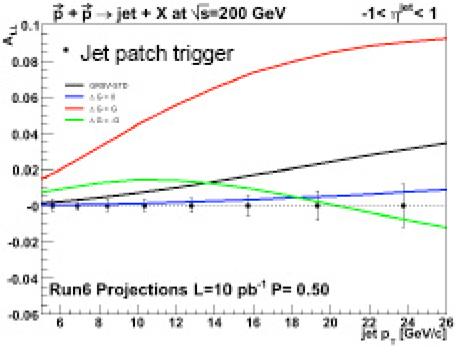
IS STILL WITH US !

Expect more definite statement on A_{LL} very soon: much improved accuracy

fig

Prospects for Run5 (first long pp run) and Run6(ongoing)





Run5 improvements:
- P_b~45% (~40% in Run4) L= 3/pb (0.3/pb in Run4)
  FoM (Run5)/FoM(Run4) = 16

- Acceptance: 3/4 BEMC complete (1/2 in Run4)
- Two complementary jet triggers permit assessment of trigger bias due to q vs. g jet differences in shape, multiplicity, hardness in z.

Potential to discriminate between several A_{LL} predictions based on DIS parametrizations

TRANSVERSE SINGLE-SPIN ASYMMETRIES

Hadronic reactions like

$$p^{\uparrow} + p \to \pi + X$$

$p^{\uparrow}$: transversely polarized proton

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Asymmetry under reversal of direction of polarisation

$$A_N \equiv \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

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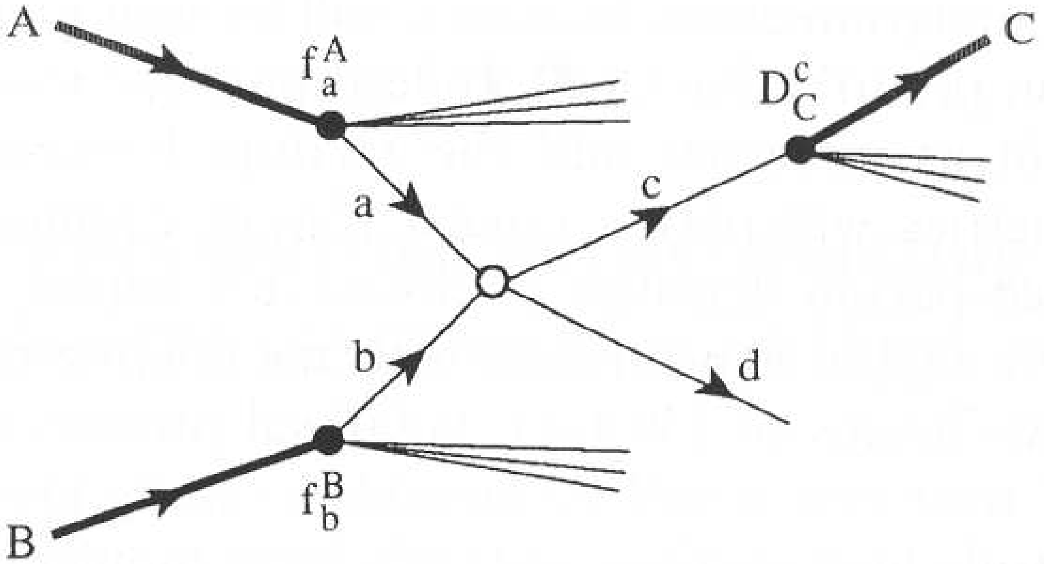
Partonic mechanism:

fig



A
B
C
f_a^A
f_b^B
D_C^c
a
b
c
d

In collinear Parton Model $A_N \approx 0$

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$$\hat{a}_N = \alpha_s \frac{m_q}{\sqrt{s}} f(\theta^*)$$

where $f(\theta^*)$ is of order 1

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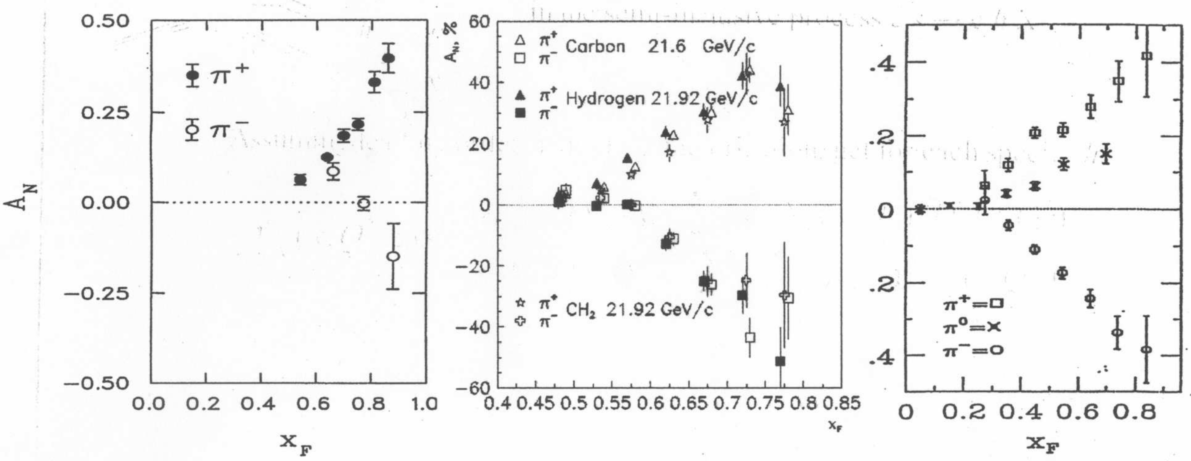
THE DATA STRONGLY CONTRADICT THIS!

fig

Asymmetry in pion production at large X_F

ZGS (12 GeV) AGS (22 GeV) FNAL (200 GeV)



Phys.Rev.D65:092008,2002

Phys. Lett. B261(1991)201
Phys. Lett. B264(1991)462

BROOKHAVEN NATIONAL LABORATORY

Large asymmetry in pion production
Asymmetry persists to high energy
No asymmetry in proton production at the AGS (not shown)

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2) Invent new SOFT mechanisms—-beyond the parton model

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Number density of hadrons with momentum $\boldsymbol{P}_h = \frac{1}{z}\boldsymbol{p} + \boldsymbol{k}_T$ depends on polarization $\mathscr{P}$ of fragmenting quark.

$$D(z, \boldsymbol{P}_h) = A + B_C \;\; \mathscr{P} \cdot (\boldsymbol{p} \times \boldsymbol{P}_h)$$

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Moreover, can't calculate B_S or B_C so need to introduce new functions phenomenologically, for each flavour of quark and antiquark. Ugly!

THE LATEST PROBLEM

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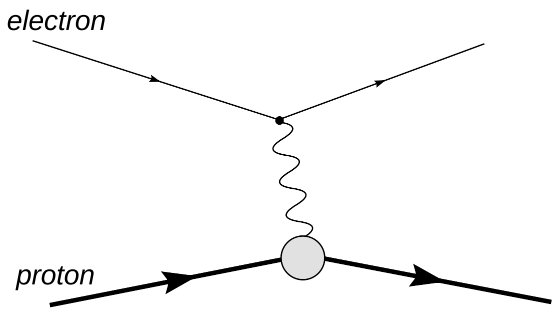
As always, assume ONE PHOTON Exchange

fig


electron
proton

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$$\bar{u}(p')[\gamma_\mu F_1^{em}(Q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2M}\kappa F_2^{em}(Q^2)]u(p)$$

$q = p' - p$ κ = anomalous magnetic moment
$Q^2 = -q^2$

$F_{1,2}$ Dirac em form factors. Sachs more convenient: $G_E = F_1 - \kappa\tau F_2$ $G_M = F_1 + \kappa F_2$

$\tau = \frac{Q^2}{4M^2}$

$$\begin{aligned} G_E(0) &= 1 \\ G_M(0) &= \text{total magnetic moment}(\mu) = 2.79 \end{aligned}$$

Diff. cross-section in the LAB: ROSENBLUTH

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)'_{Mott} \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2)\right]$$

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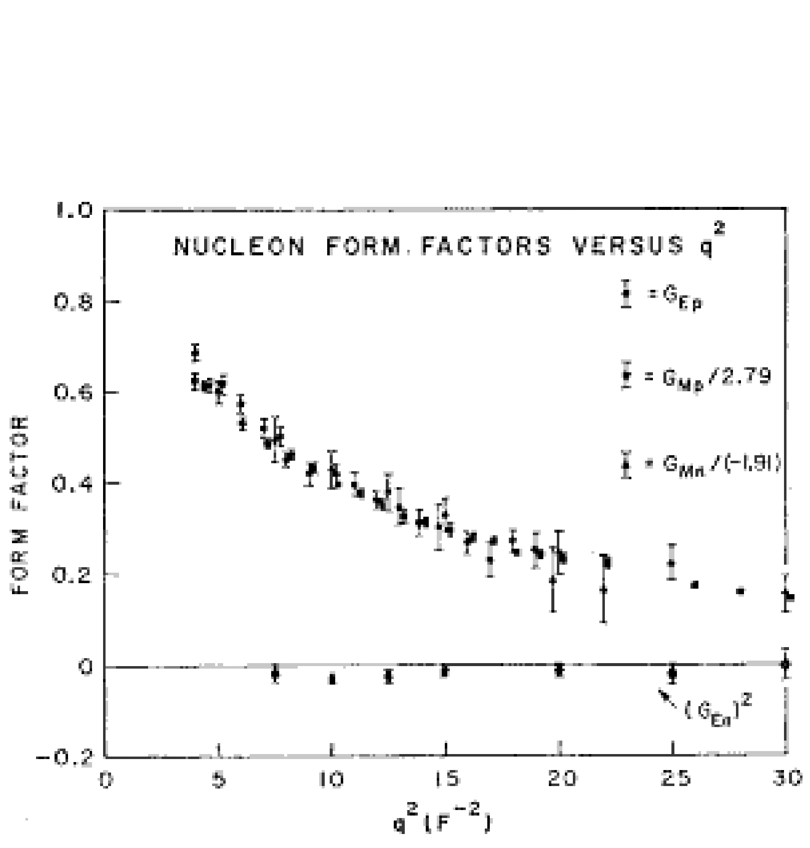
Both G_E and G_M drop with increasing Q^2

Long standing experimental assertion that

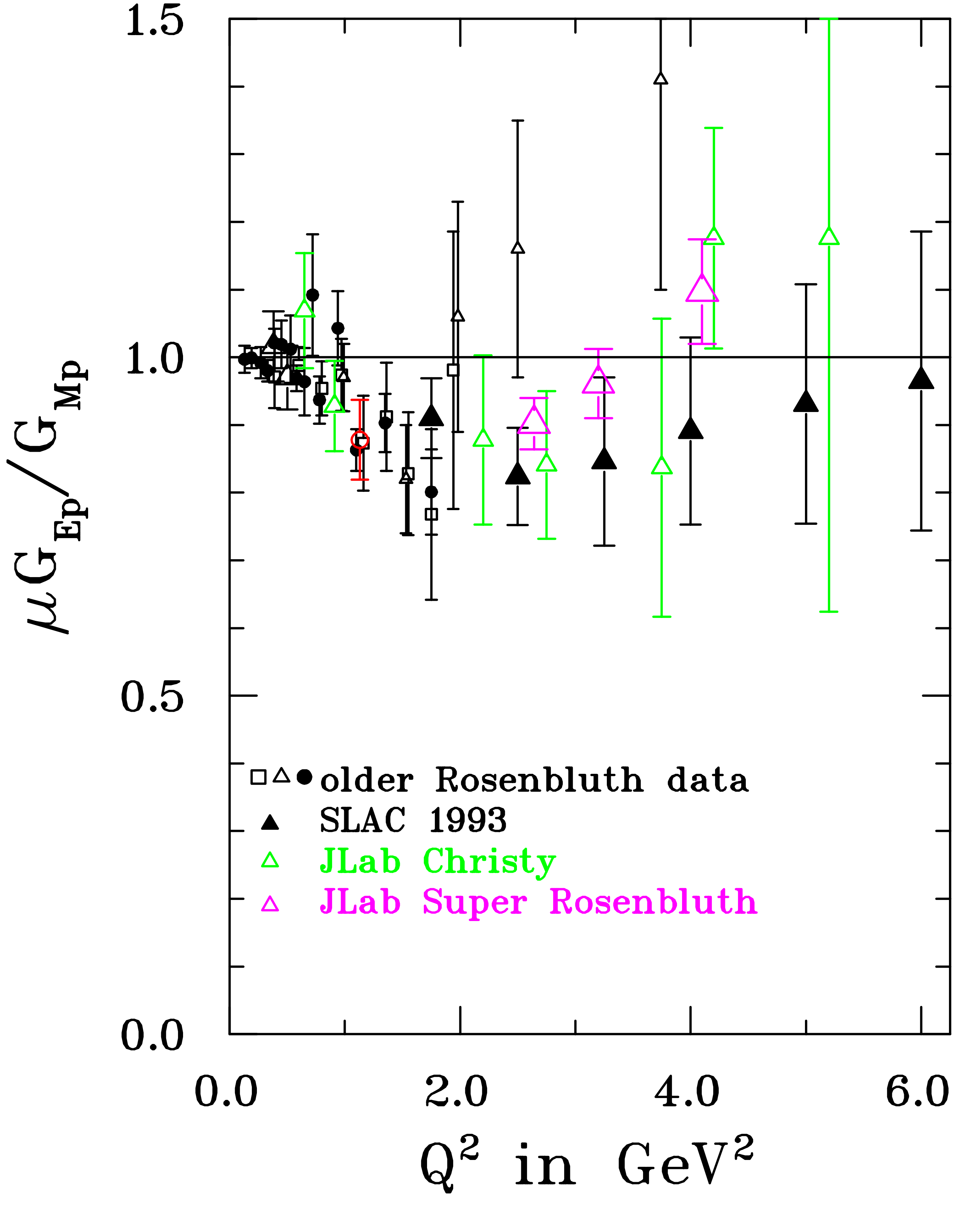
$$G_M(Q^2) \approx \mu G_E(Q^2)$$

fig


NUCLEON FORM FACTORS VERSUS q^2
= G_{Ep}
= $G_{Mp}/2.79$
= $G_{Mn}/(-1.91)$
$(G_{En})^2$
FORM FACTOR
$q^2\,(F^{-2})$
1.0
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30

New cross-section measurements are consistent with this:

fig



1.5
1.0
0.5
0.0
$\mu G_{Ep}/G_{Mp}$
0.0
2.0
4.0
6.0
Q^2 in GeV^2
older Rosenbluth data
SLAC 1993
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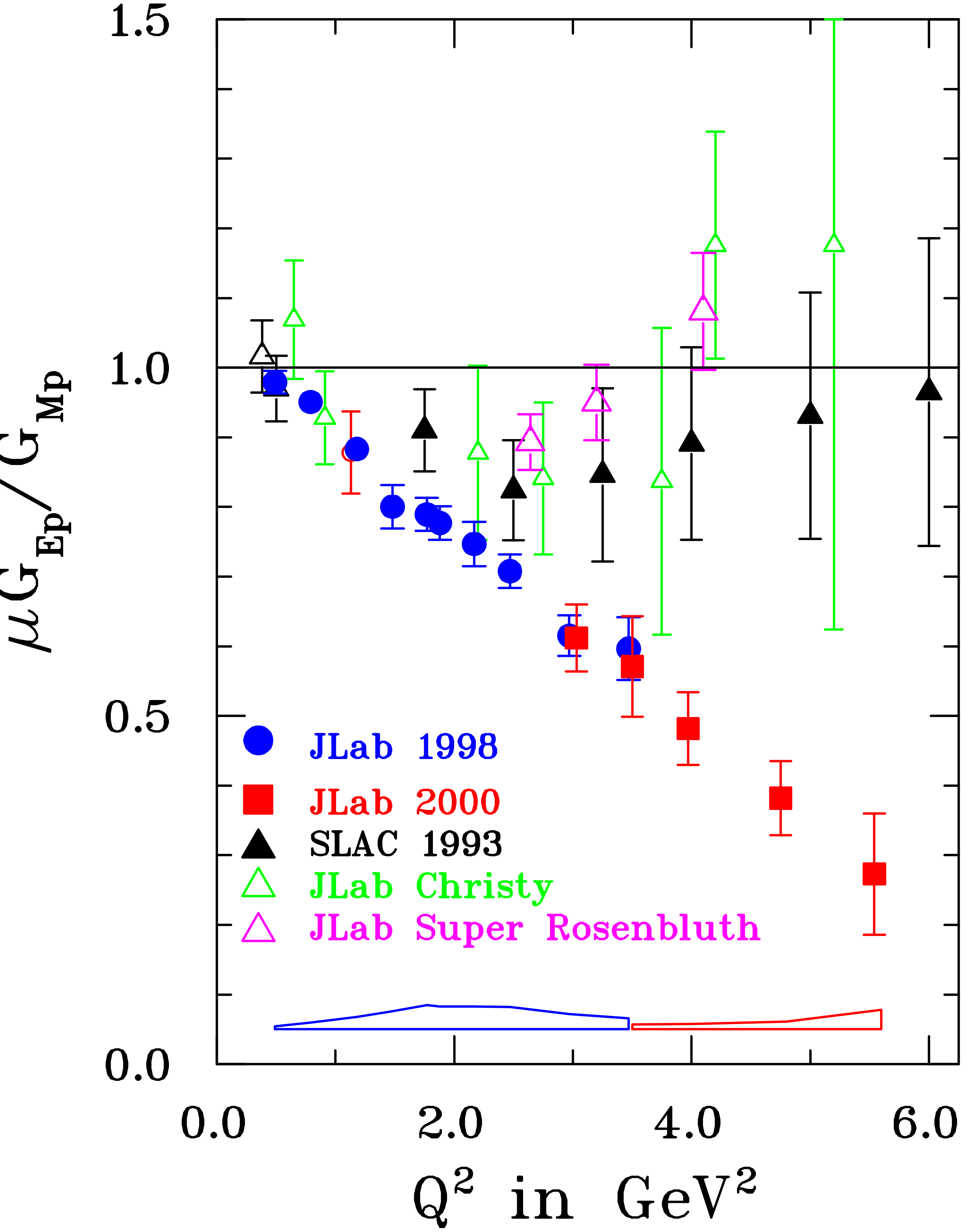
TRANSVERSE (in scattering plane) polarization of the recoil proton:

$$\mathscr{P}_T \propto -2\sqrt{\tau(1+\tau)}\, G_E G_M \tan(\theta/2)$$

fig



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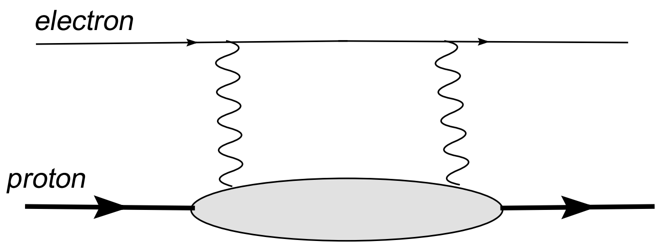
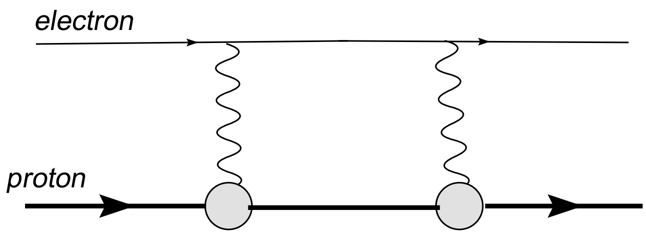
Exact calculation would require evaluation of Feynman graph:

fig


electron
proton

Not possible. Can do approximate calculation of simplest two photon graph:

fig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What about famous prediction of perturbative QCD:

$$G_E/G_M \rightarrow \text{constant as } Q^2 \rightarrow \infty \quad ?????$$

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(c) We are facing the realization that what is arguably the best-understood of all reactions i.e. electron-proton elastic scattering, has, in fact, been significantly misunderstood