A Beautiful Spin

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The Origin of Spin?

- As an English word, it existed before 12th century.
- As a fundamental observable of subatomic particles, it was introduced by G. Uhlenbeck and S. Goudsmit in 1925. (Also Kronig, 1925)

''This is a good idea. Your idea may be wrong, but since both of you are so young without any reputation, you would not loose anything by making a stupid mistake."

P. Ehrenfest, upon receiving the paper by G. Uhlenbeck and S. Goudsmit, from "The story of spin",S. Tomonaga

Our Heroes

Uhlenbeck

Goudsmit

Klein

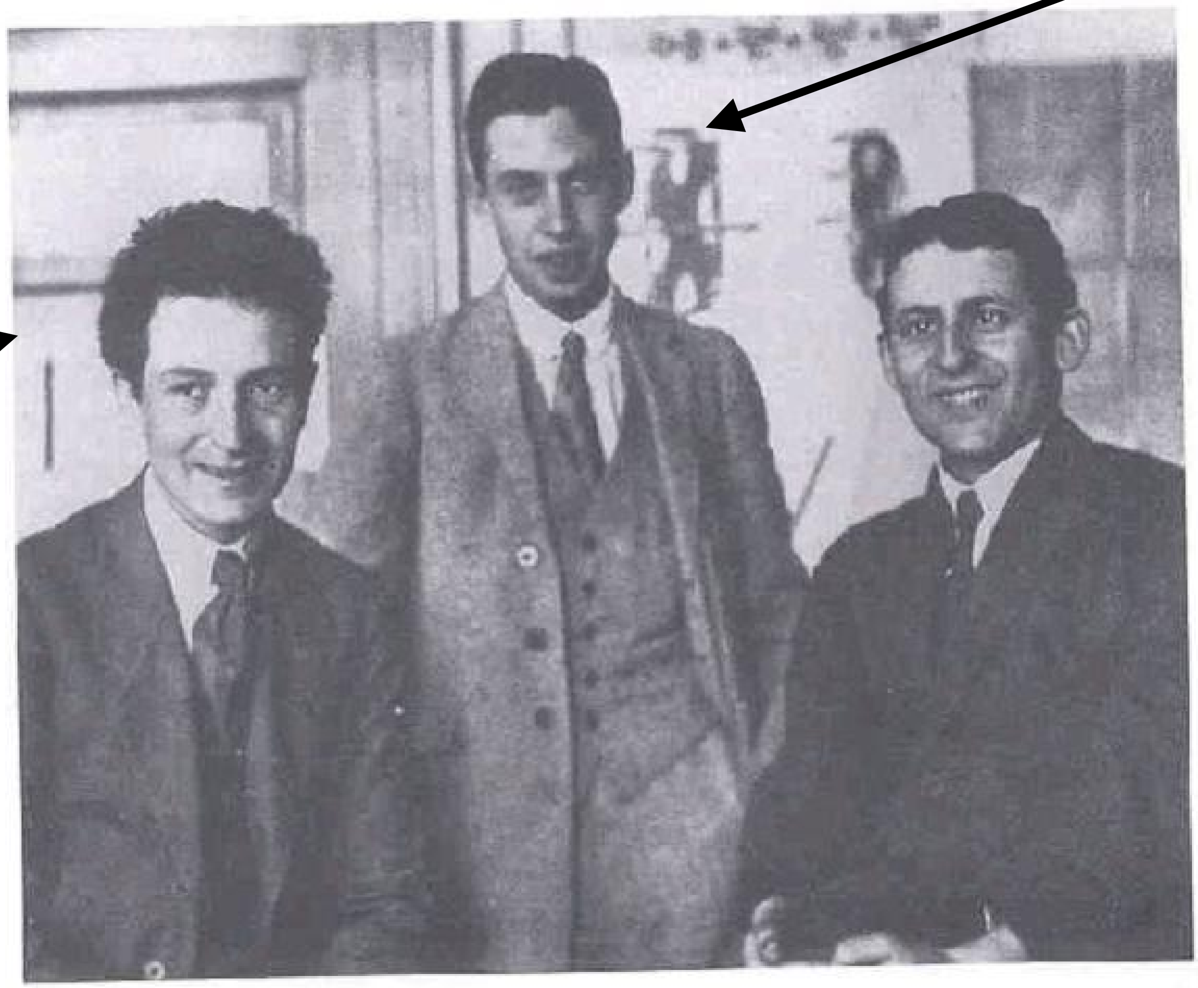


Figure 2.2 Oscar Klein (1894–1977), George E. Uhlenbeck (1900–1988), and Samuel A. Goudsmit (1902–1978), 1926. [Photograph by H. Knauss. Courtesy of AIP Emilio Segrè Visual Archives]

Goudsmit, Samuel Abraham (1902 - 1978)

Dutch-American physicist

Born in The Hague in the Netherlands, Goudsmit was educated at the universities of Amsterdam and Leiden, where he obtained his PhD in 1927. He emigrated to America shortly afterward, serving as professor of physics at the University of Michigan (1932-46) and North Western (1946-48). He then moved to the Brookhaven National Laboratory on Long Island, New York, where he remained until his retirement in 1970.

A Dictionary of Scientists, Oxford University Press, © Market House Books Ltd 1999

Celebrating Spin Physics at BNL

- 1957, the Cosmotron at BNL discovered the parity-violation in K-decay (!-! puzzle). Spin turns out be to a key element in many parity-violation experiments.
- In 1980s, a series of experiments were done at AGS measuring hadronic single-spin asymmetries and hyperon polarizations.
- Recently, the muon g-2 experiment achieved a precision better than 1 ppm for the first time.
- RHIC spin: A whole new and exciting program on QCD spin physics.
- EIC(?): A future machine with spin as its key feature.

The Spacetime Symmetry

- The 3+1 dimensional spacetime is symmetry under translations + rotations —> Poincare group (contracted SO(3,2))
- The group are generated by 10 generators

$$P_m, \; J_{mn} \quad (m, n = 0,1,2,3)$$

- Two Casimir operators define two ***universal*** observables

$$P_m P^m = m^2 \quad \longrightarrow \text{MASS}$$

$$W_m W^m = s(s+1), \quad W^m \sim e^{mabg} J_{ab} P_g \quad \longrightarrow \text{SPIN}$$

Pauli-Lubanski vector

More Revolutions in Spacetime?

- 3+1 spacetime is a result of ***classical*** and ***low-energy*** approximations.
- At higher-energy,
  - Spacetime might be 10- or 11-dimensional
    - How do we end up seeing only 3+1 ?

      Compatification or brane?
  - Strong gravitational fluctuations may exist in the spacetime curvature: the meaning of spacetime as we know it may cease to exist.

Spinning Spin

Spin is a beautiful concept that plays a central role in modern physics…

Theme I: As a useful lab to explore physics beyond the Standard Model.

Theme 2: As a powerful tool to measure physical observables that are hard to obtain otherwise.

Theme 3: As an effective approach to unravel non-perturbative QCD dynamics.

Theme I: Spin As a Useful Lab to Explore Physics Beyond Standard Model

A Partial List of Experiments…

- BNL: the muon g-2 experiment (Sichtermann)
- SLAC E148: Moller scattering (session)
- Jlab Qweak: eP elastic scattering (session)
- LANL: Neutron electric dipole moment
- TIUMF & IUCF: P-even/T-odd effect through charge symmetry violation in np scattering.
- COSY: P-even/T-odd interactions in pD scattering (session)
- PSI: Polarization of positron from mu-decay (session)
- RHIC spin: Parity-violation at high-energy
- …

Magnetic Moment

- The **spin** of a particle supports the notion of magnetic moment.

$$\vec{\mu} = g \frac{e\hbar}{2mc} \vec{s}$$

  - For a point-like particle without interactions, $g_D = 2$!
  - $a = (g-2)/2$ is a measure of ***underlying dynamics.***

- The latest result for muon: (Sichtermann)
  - the muon g-2 collaboration (hep-ex/0208001)

    $a_\mu^{BNL} = 11\ 659\ 204\ (7)(5) \times 10^{-10}$
  - World average:

    $a_\mu^{WORLD} = 11\ 659\ 208\ (8) \times 10^{-10}$

Muon Magnetic Moment From BNL (hep-ex/0208001)

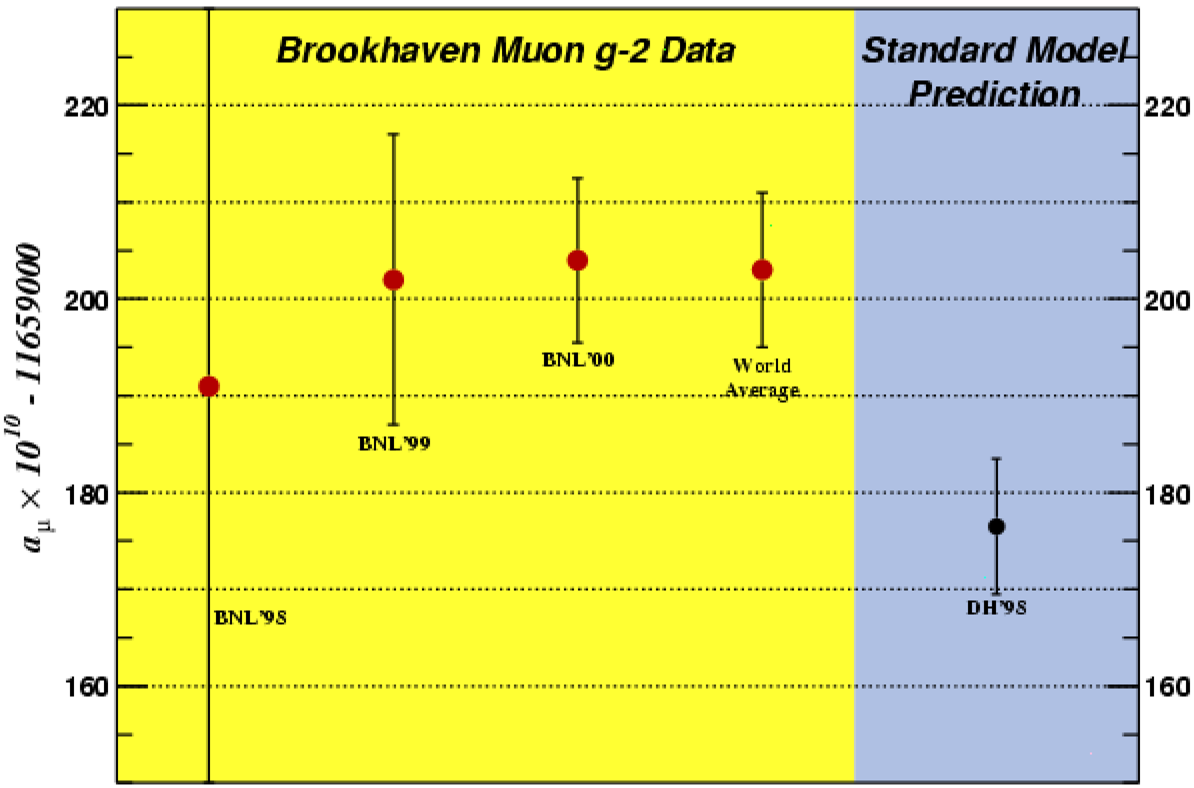


FIG. 4: Recent measurements of a_μ, together with the standard model prediction using the evaluation in Ref. [9] of $a_\mu(\text{had}, 1)$ from e^+e^- and τ decay data.

- The lastes theoretical number
  - Taking into account the infamous sign flip for light-light scattering contribution, and “averaging” over several latest hadronic calculations:

$$a_{!} = 11\ 659\ 182.1\ (7.2)\ !10^{-10}$$

- Discrepancy

$$!a_{!} = 21\ (11)\ !10^{-10},\ \sim 1.9!\ \text{deviation}$$

- Implication for SUSY (M. Byrne et al, hep-ph/0208067)
  1. There must be at least 2 *s*particles with mass less than 760 GeV (at 1! level).
  2. For models with gaugino mass unification, there must be one *s*particle with mass less than 580 GeV.
  3. There is no lower bound on tan!.

Electric Dipole Moment

- For a static particle, the only 3-vector present is the spin. Hence the EDM must be $\vec{d} = d\,\vec{s}$
  - EDM is T-odd, and CP-odd in field theory. In the SM, the CP violation in the CKM matrix leads to a neutron EDM ~ 10^{-31}e cm.
  - However, the ***baryon number asymmetry*** in the Universe requires additional sources of CP violation, which might contribute ***significantly*** to EDM.
- The current limit on the neutron EDM is 0.63×10^{-25} e cm. However, the weak-scale SUSY "naturally" predicts the electron EDM on the order of ($10^{-25} \sim 10^{-27}$) e cm.
- The EDM collaboration at LANL proposed to push the limit two orders of magnitude lower, i.e., 10^{-27} e cm.

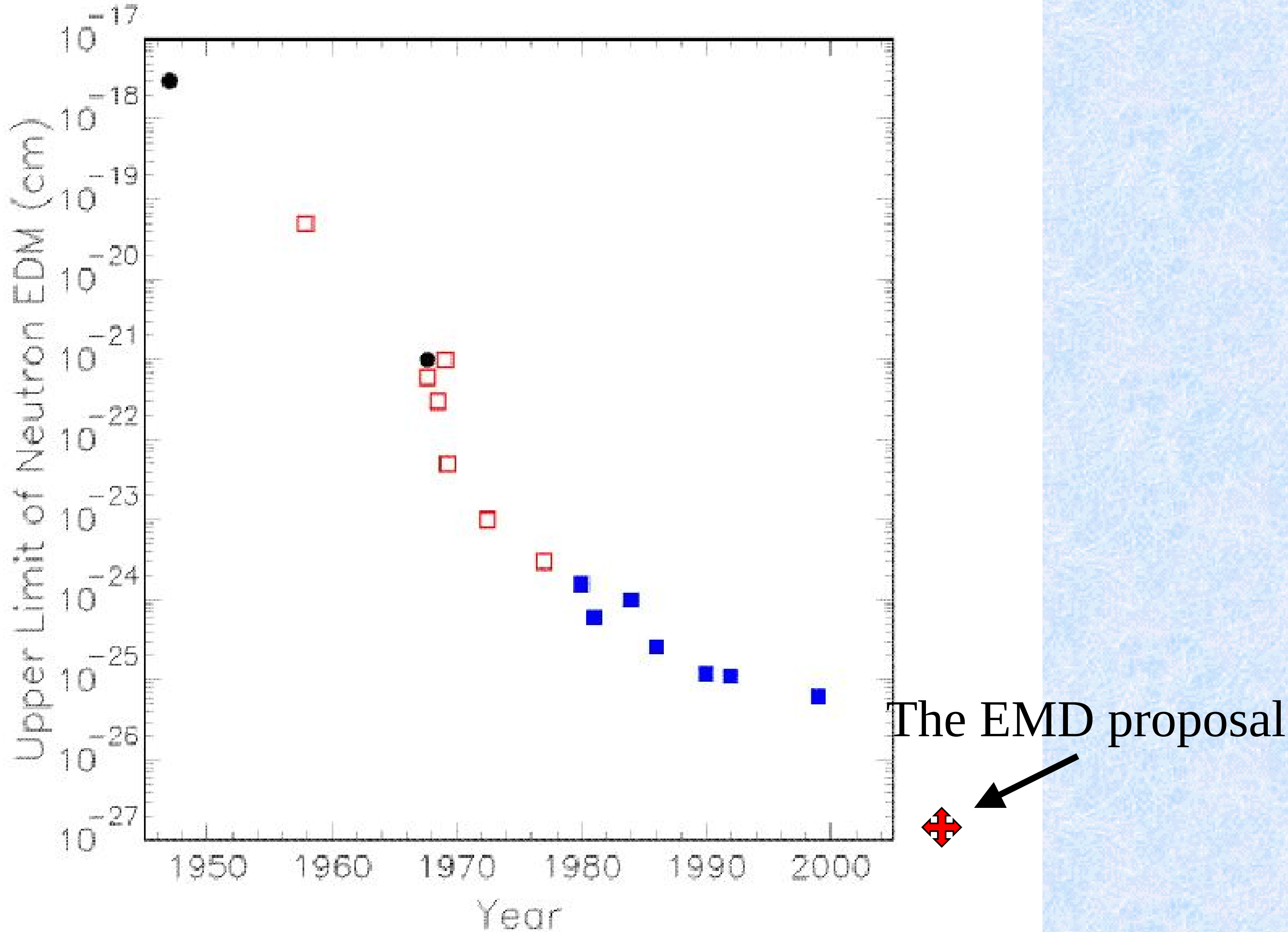


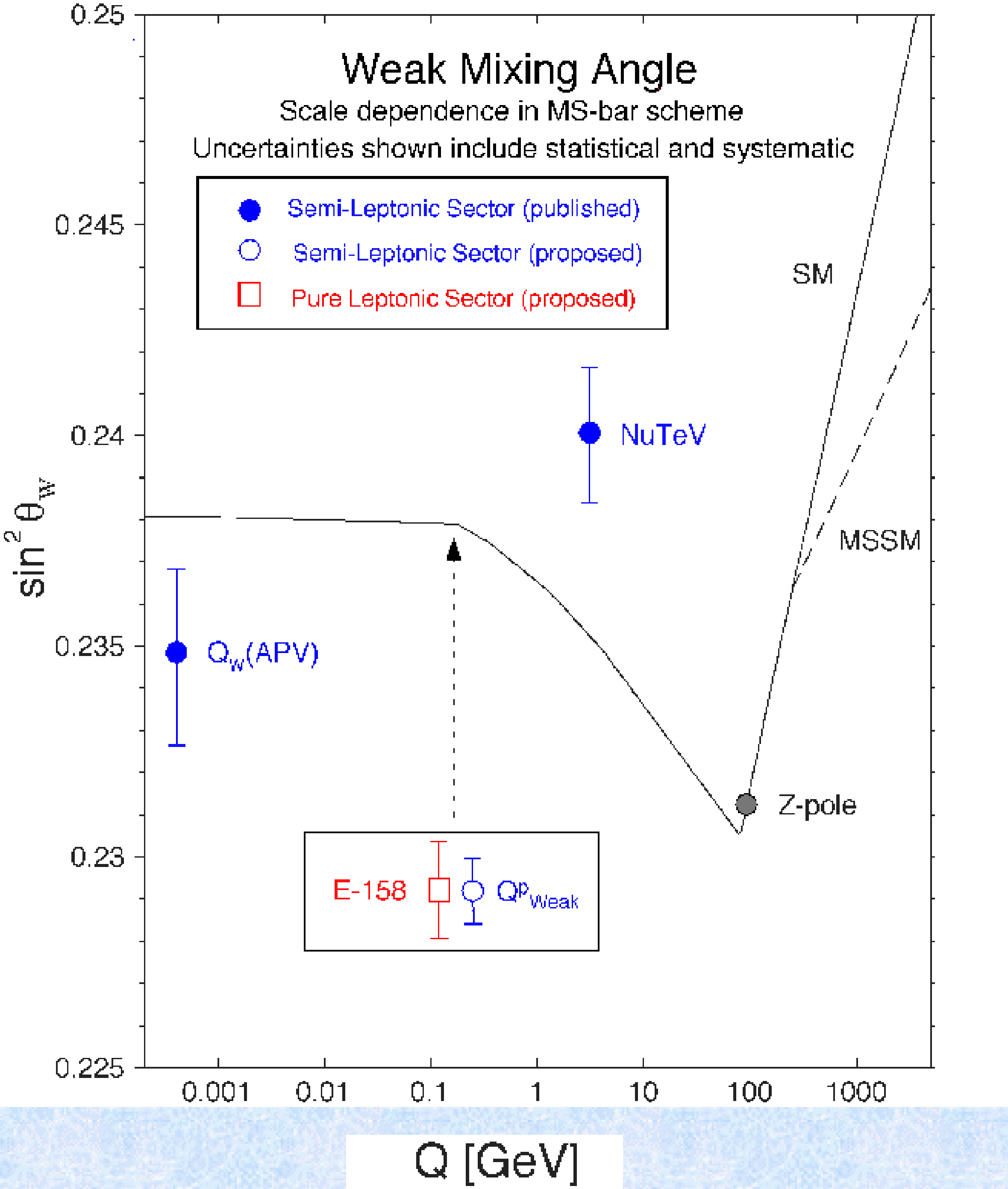
Fig. I-1. Upper limits of neutron EDM plotted as a function of year of publication. The solid circles correspond to neutron scattering experiments. The open squares represent in-flight magnetic resonance measurements, and the solid squares signify UCN magnetic resonance experiments.

Parity-Violating Asymmetry

- The spin of a particle can lead to simple correlations of type in the deca $\vec{s} \cdot \vec{p}$ and cross sections.
  - A natural place to look for parity violation! (C.S. Wu, 1957)
- Can be used for high precision measurement of weak charges of
  - Electron, $g_V^e = 1/4 - \sin^2 !_W$
  - Proton, $g_V^p = ¼ - \sin^2 !_W$

  And hence the $\sin^2 !_W$ itself!
- Like $!_{strong}(Q)$, $\sin^2 !_W$ runs with probing scale.

The Running of



- SLAC E148: Asymmetry in polarized Moller scattering: $e^- e^- \longrightarrow e^- e^-$
  - 6% measurement on the (vector) weak charge of the electron at Q^2=0.03 $(GeV/c)^2$.
- JLAB Qweak: Asymmetry in polarized ep elastic scattering
  - 4% measurement on the (vector) weak charge of the proton at Q^2=0.03 $(GeV/c)^2$ (0.3% on $\sin^2 !_W$)

- New Physics??
  - New Z-boson (mass range of 0.6 to 1 TeV)
  - New contact interactions from scalar Higgs (~ 10 GeV)
  - New physics in loops (!X~0.1, $!X^{World}$=0.38±0.51).

Theme II: Spin As a Powerful Tool to Measure Observables that are Hard to Obtain Otherwise.

Interesting Observables

- Strangeness content of the nucleon (Kumar)
- Form factors of the nucleon (Kelly)
- Parity-violating nucleon-nucleon interactions (Ramsay)
- Neutron density in a large nucleus through the Z interaction (session)
- ….

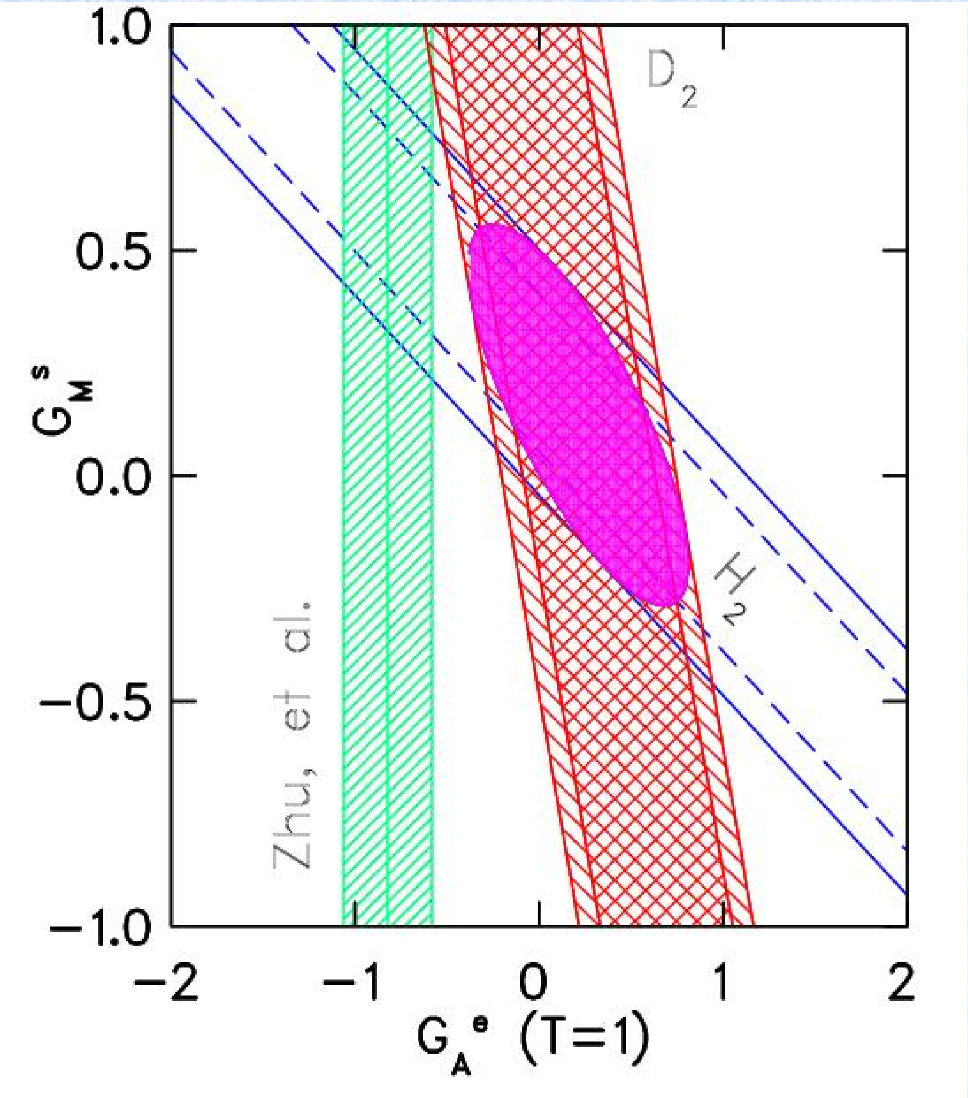
Strange content of the nucleon

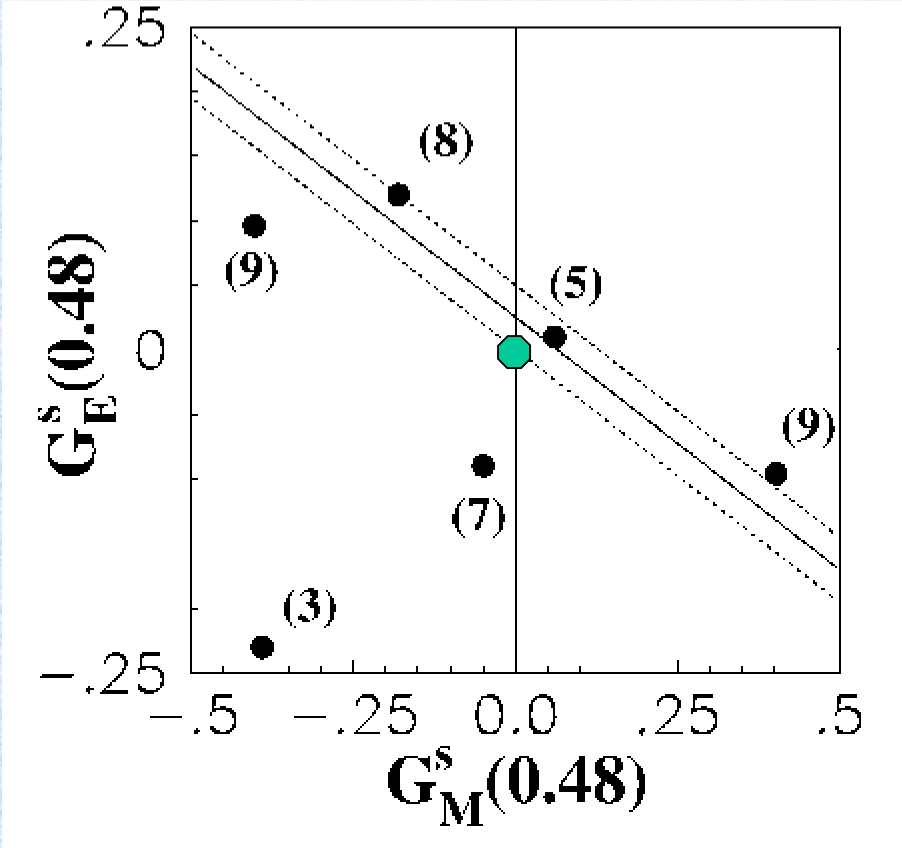
- Sizable strange effects may have been seen in various nucleon matrix elements: scalar charge, proton spin, momentum sum rule.
- Strange vector current defines form factors,

$$\left\langle P' \right| \bar{s} g^{m} s \left| P \right\rangle = \overline{U}(P') \left[F_1^{s}(Q^2) g^{m} + F_2^{s}(Q^2) \frac{i s^{mn} q_n}{2M} \right] U(P)$$

  – Strange magnetic moment $!_s = F_2(0)$.
  – Strange radius $! r_s^2 ! = - 6 dG_{Es} (Q^2)/dQ^2$

The form factors can be measured in polarized parity-violating electron-nucleon scattering in which the Z – exchange is probed. (R. McKeown)





SAMPLE results

HAPPEX results

Nucleon E&M Form Factors

- The neutron and proton form factors tell us much about the charge and current "distributions" in the nucleon, but are still not well measured!
- Polarization experiments are helping in a big way in their precision measurements! (Jlab)
- Example: polarization transfer in ep elastic scattering

  $\vec{e}p -> e\vec{p}$ gives the ratio of the form factors.

$$\frac{G_{E_p}}{G_{M_p}} = -\frac{P_t}{P_\ell}\frac{(E_e + E_{e'})}{2m}\tan\frac{\theta_e}{2} .$$

New data on

from Jlab.

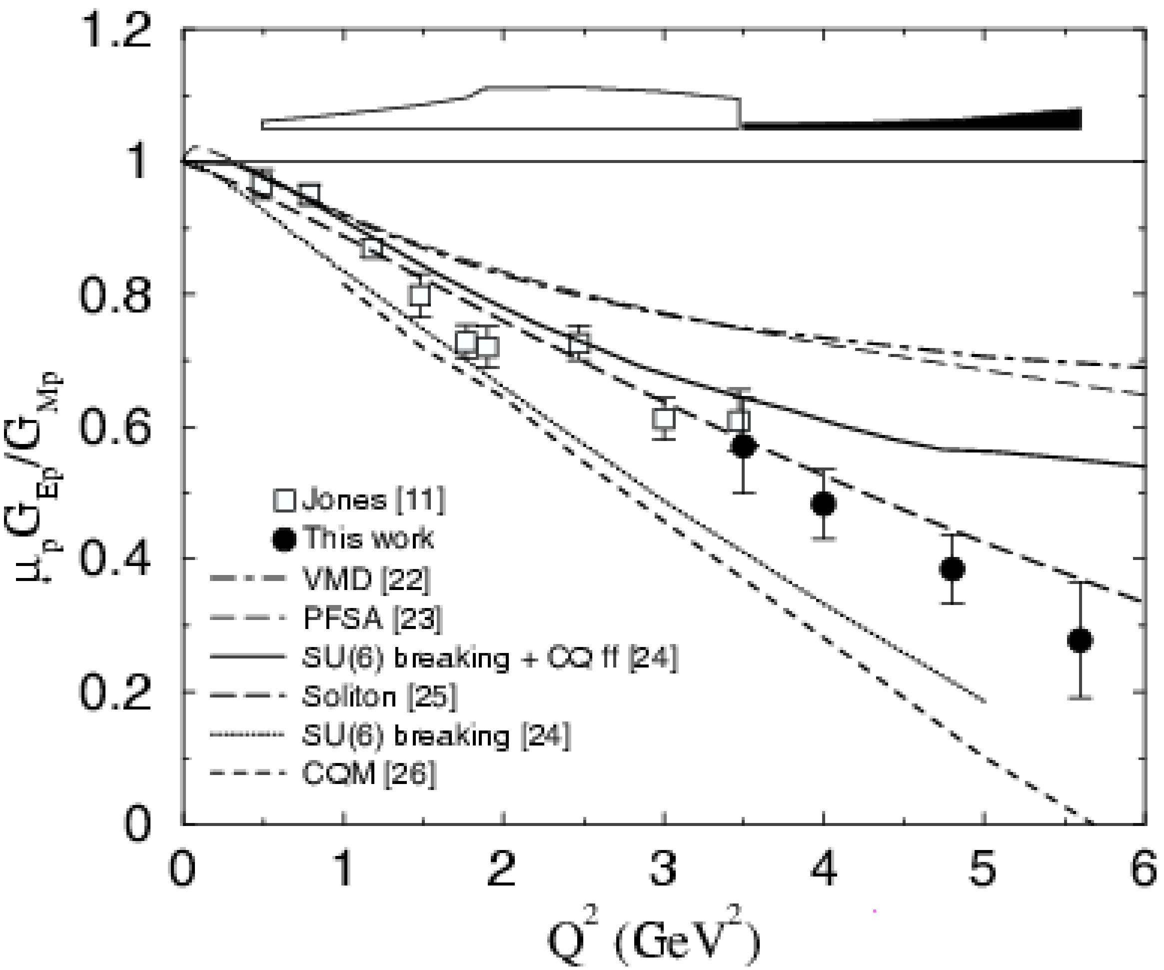


FIG. 2. The ratio $\mu_p G_{E_p}/G_{M_p}$ from this experiment and Jones *et al.* (Ref. [11]), compared with theoretical calculations. Systematic errors for both experiments are shown as a band at the top of the figure.

Parity-Violating NN Interactions

- Nucleon-nucleon interactions are parity-violating when taking into account the underlying weak boson exchanges.
  - These interactions have been summarized in terms of effective parity-odd meson-nucleon couplings (DDH).
  - Many of the couplings must be measured in spin-dependent processes. (Haeberli & Holstein, 1995)
- Experiments:
  - **Asymmetry** or **polarization** in E&M decay.
  - **Asymmetry** in P(pol) + P elastic scattering or thermal N(pol) + A scattering.
  - Neutron **spin rotation** through nuclei matter…

Constraints on P-odd NN! and NN! couping from elastic p(pol)p scattering

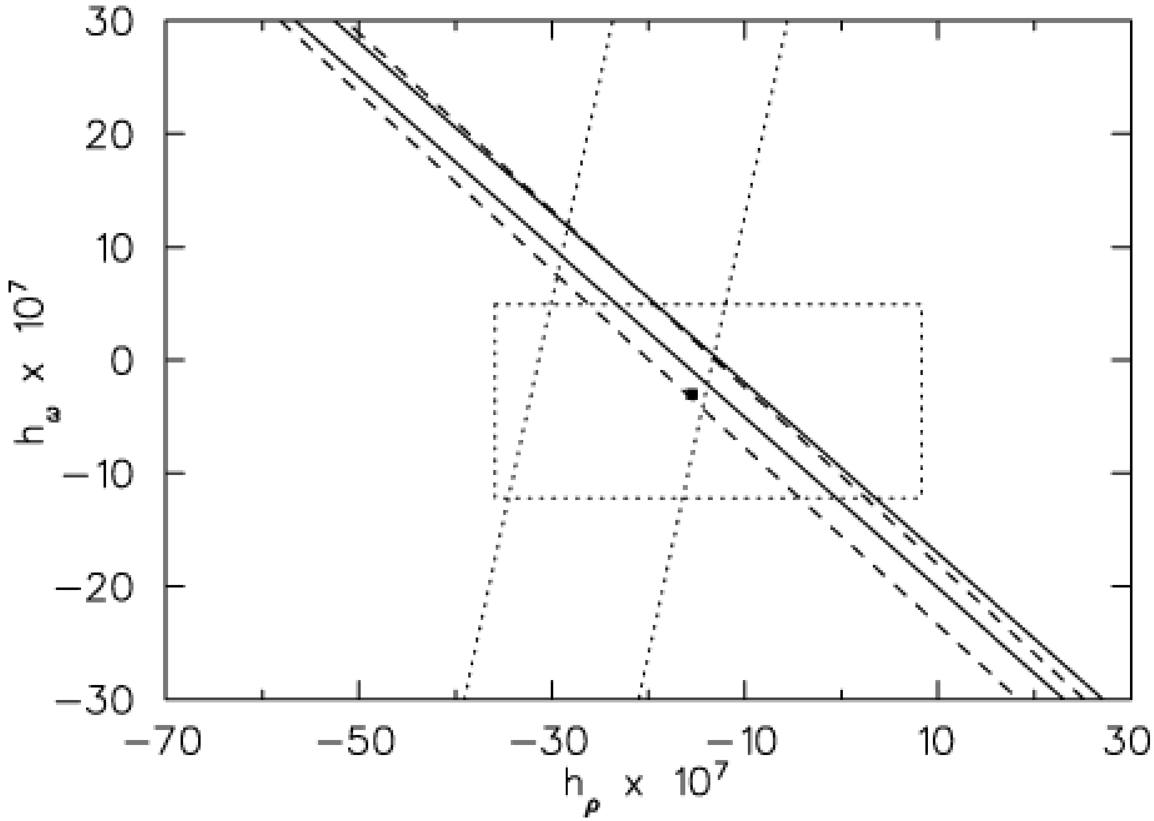


FIG. 3. Current constraints on the weak meson nucleon couplings based on experimental data and recent calculations [23]. The bands are the constraints imposed by different experiments (Bonn 13.6 MeV, dashed; PSI 45 MeV, solid; TRIUMF 221 MeV, dotted). The filled square and dotted rectangle are the DDH "best guess" and "reasonable range," respectively. Couplings are in units of 10^{-7}.

Theme III: Spin as an Effective Approach to Unravel Nonperturbative QCD Dynamics

QCD Spin Physics: A Vast Subject

- Spin structure functions of the nucleon (g1, g2) (Averett)
- Gluon polarizations in the proton (Bland, Stratmann)
- Transversity (Ratcliff)
- Single spin asymmetries (Ratcliff, Ukhanov)
- Generalized parton distributions (Vanderhaeghen)
- Semi-inclusive DIS (Miller)
- GDH sum rule & its generalizations (Helbing)
- …

All subjests are close to my heart!

Spin Structure of the Nucleon

§ According to QCD, we can write a decomposition of the nucleon spin

$$\frac{\mathbf{h}}{2} = \frac{1}{2}\Delta\Sigma\left(m^2\right) + L_q\left(m^2\right) + J_g\left(m^2\right)$$

- = ***u*** + ***d*** + ***s*** contributes about 30% of the nucleon spin, contrary to the naïve quark model.
- ***The total quark contribution J_q= 1/2 +L_q*** can be obtained from a sum rule of the generalized parton distribution.
- ***The gluon angular momentum J_g*** contains gluon helicity contribution D g, which can be measured in high-energy scattering.

Polarized sea quark distribution

- It has been speculated that the small size of D ! = D $!_v$ + D $!_s$ results from a cancellation between the valence and sea contribution.
- While inclusive DIS can’t separated the valence from the sea, semi-inclusive processes can.
- ***Surprise***: SMC & HERMES experiments didn’t find a large negatively polarized sea!
  - Better precision…
  - Validity of factorization…
  - Strange sea contribution D s (SU(3) flavor symmetry)
  - RHIC spin! (W-boson production)

Gluon polarization D g(x)

§ Well-defined theoretically (gauge invariant), just like the quark helicity distribution.

$$\Delta g(x) = \frac{i}{2x}\int \frac{d\lambda}{2\pi} e^{i\lambda x} \left\langle ps \right| F^{+\alpha}(0) L(0,\lambda n) \tilde{F}^{+}{}_{\alpha}(\lambda n) \left| ps \right\rangle$$

Ø Although its role in the spin decomposition is *not transparent*, D g(x) can be interpreted as the gluon helicity in the light-cone gauge.

§ Limited information has been obtained from

Ø NLO fit to the $g_1(x, Q^2)$ structure function data.

Ø Large p_t hadron production (HERMES collaboration)

Why does the gluon contribute so much to the spin of the nucleon?

Future measurements

High priority for future high-energy spin physics

- Direct photon production (RHIC)
- Jet & high-P_t hadron production (RHIC,COMPASS)
- Open charm & heavy quark production (SLAC,COMPASS,RHIC)
- Q^2 evolution (EIC, Milner's talk)
- …

Are the perturbative mechanisms clean?

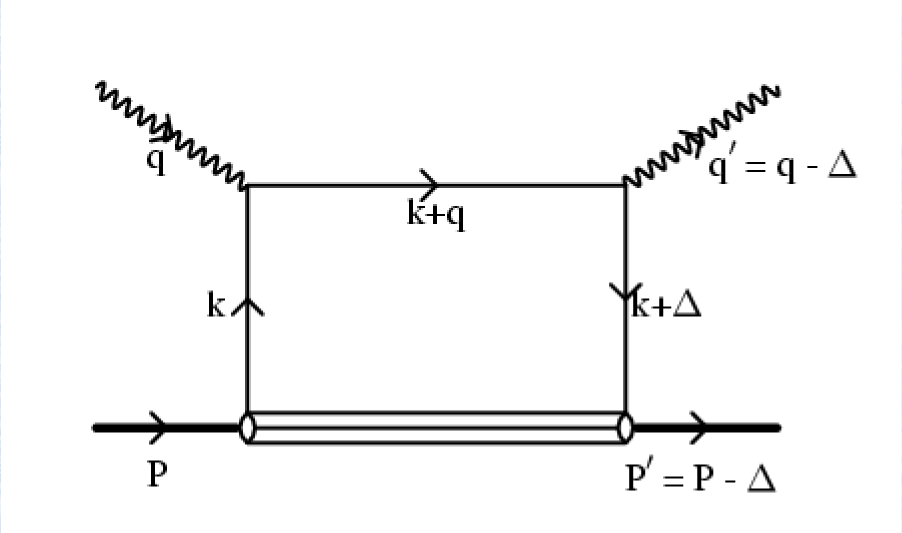
Are we going to get a good determination of the integral?

Generalized Parton Distributions

- ***Motivated by studying the nucleon spin physics!***
- A new type of parton "distributions" which contain much more information than any other nucleon observables that have been considered so far.
  - In various limits, they reduce to elastic form factors and Feynman parton distributions.
- They depends on three variables: x—the parton momentum fraction; $t=q^2$—the form factor resolution; !—the skewness.
- It can be measured in real expts!
  - Deeply-virtual Compton scattering & exclusive meson production

Deeply Virtual Compton Scattering

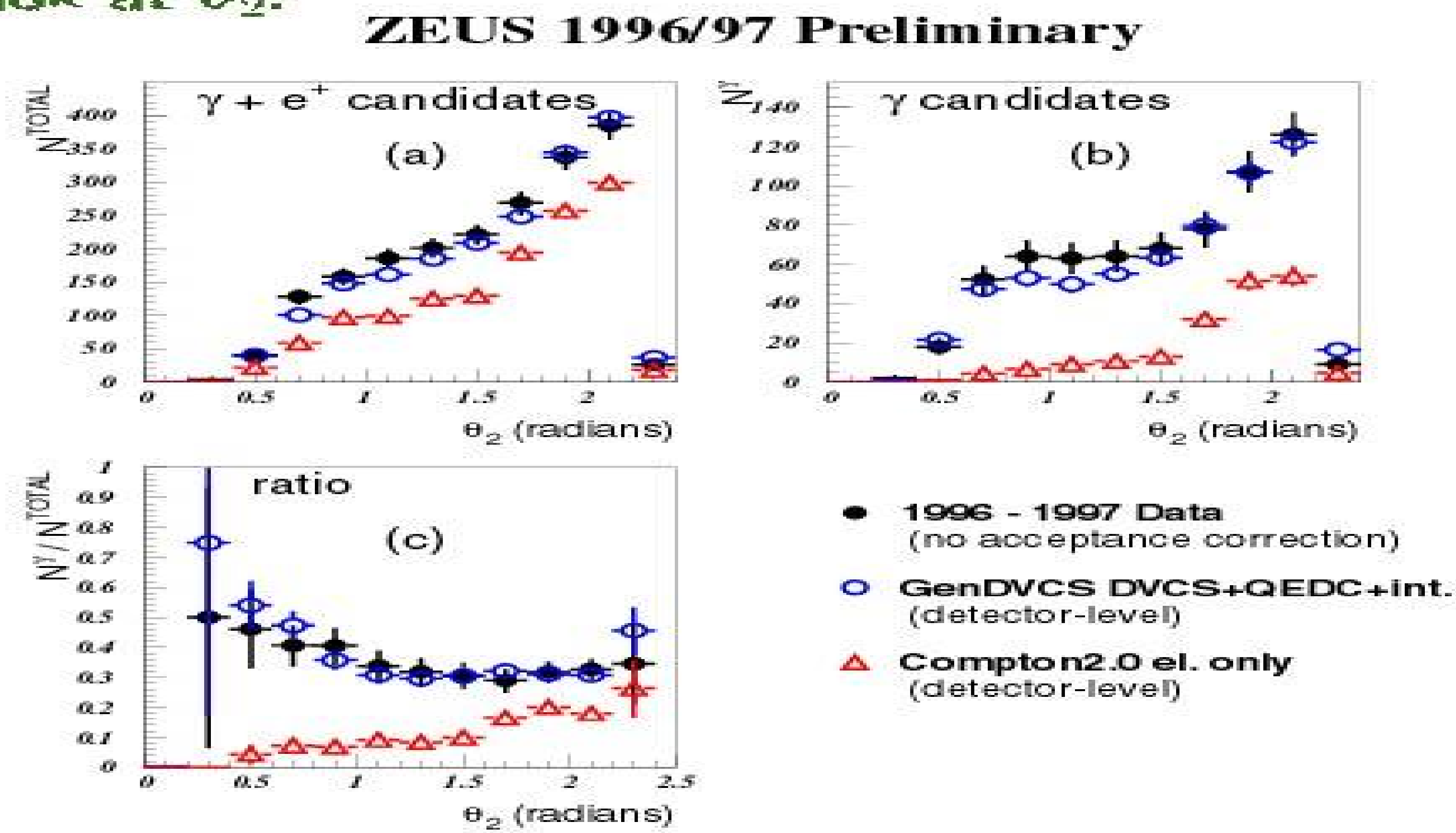
§ Exclusive production of high-energy photon in deep-inelastic scattering kinematics



– Single-quark scattering dominates! ! Compton scattering on a single quark
– Non-invasive surgery

ZEUS DVCS Data

Look at θ_2:



BUT, there may be π^0 etc background!

Photon Prod. Asy. From interference between DVCS & BH

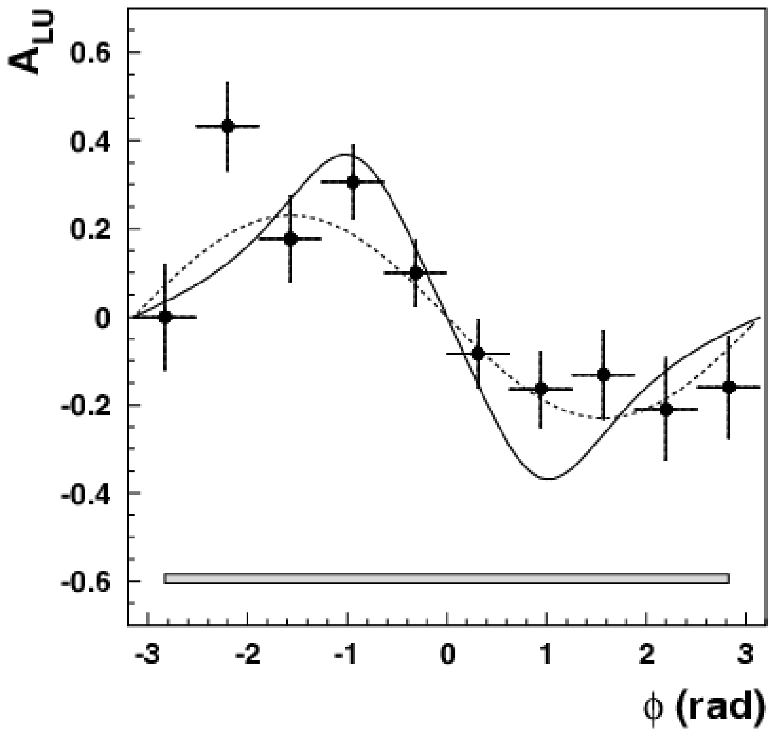


FIG. 3. Beam-spin asymmetry A_{LU} for hard electroproduction of photons as a function of the azimuthal angle ϕ. The data correspond to the missing-mass region between -1.5 and $+1.7$ GeV. The dashed curve represents a $\sin\phi$ dependence with an amplitude of 0.23, while the solid curve represents the result of a model calculation taken from Ref. [17]. The horizontal error bars represent the bin width, and the error band below represents the systematic uncertainty.

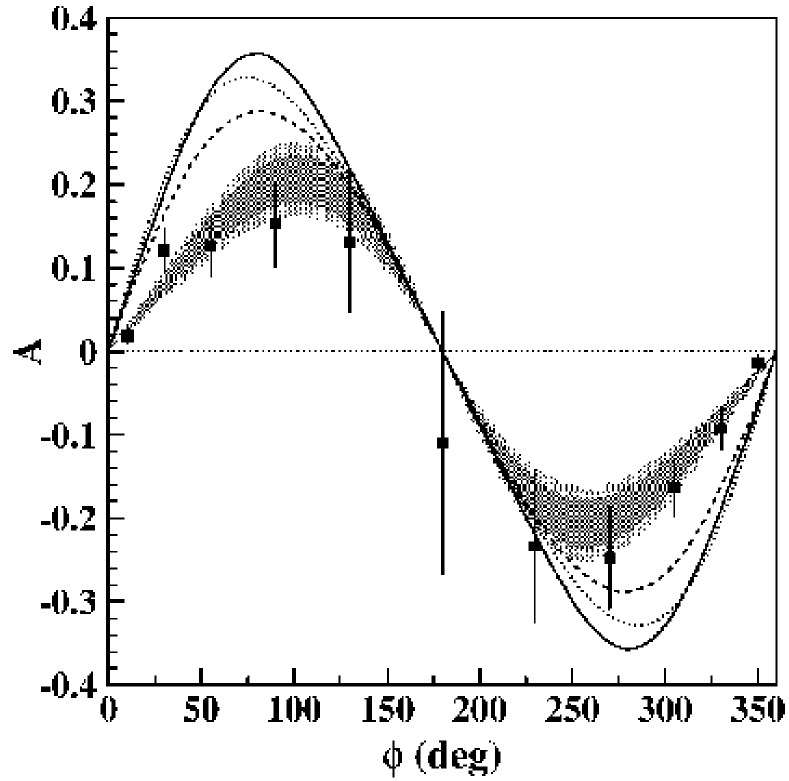


FIG. 4. ϕ dependence of the beam-spin asymmetry A. The dark shaded region is the range of the fitted function $A(\phi)$ defined by the statistical errors of parameters α and β, the light shaded region includes systematic uncertainties added linearly to the statistical uncertainties. The curves are model calculations according to Refs. [6,11] and are discussed in the text.

HERMES data

CLAS data

Transversity Distribution

- One of the three twist-two quark distributions describing the state of the quark beam in a nucleon beam (Ralston and Soper, ‘79)
  - Not a **transverse spin** distribution!
  - In non-relativistic quark model, however, the transversity distribution is the same as the helicity distribution and the quark can be in the transverse spin eigenstates.
- Allows access to the tensor charge of the nucleon (Jaffe and Ji, ’91) (which enters in calculations of the neutron EDM!)

How to measure !q(x)?

- DIFFICULT !
  - It is a chiral-odd quantity, requires another chiral-odd observable present in a hard process.
  - It vanishes asymptotically at a large resolution scale.
- Drell-Yan scattering with the transversely polarized protons (Ralston & Soper,'79, O. Martin et al'99)
- One can also consider inclusive jet production and direct-! production (For RHIC, see Soffer, Stratmann, and Vogelsang, hep-ph/0204058)
- !q(x) can be accessed through chiral-odd quark fragmentation functions…, in most cases, there are other competing processes.

(Transverse) Single-Spin Asymmetry

- A topics of much controversy and myriad speculations.
- It **only exists** when
  - There are initial and final state interaction **phases.**
  - There exist viable mechanisms from **helicity flips**.
    - Collins fragmentation functions
    - Sivers distributions
    - Twist-three correlations (Sterman & Qiu).
    - …
- ***Rich Phenomenology***
  - SSA for inclusive meson production in $P_{pol}P$ scattering.
  - Hyperon polarization in PP scattering.
  - SSA in inclusive meson production of eP_{pol} scattering.

The Story of Spin
--- S.Tomonaga

It is a mysterious beast, and yet its practical effect prevail the whole of science. The existence of spin, and the statistics associated with it, is the most subtle and ingenious design of Nature—without it the whole universe would collapse.

Preface by T. Oka

A World Without Spin…

10) Chemistry would have been messed up.

9) You can't get rid of the glare from the sunlight.

8) You can't have MRI if you've gotten brain cancer.

7) Quarks aren't compelled to have color.

6) Neutron stars would never be stable.

5) Weak interactions can't be chiral.

4) There wouldn't be any gauge theories.

3) You can't play around with supersymmetry. L

2) You would be stuck in 26-dimensions.

1) Spin doctors Washington DC would be jobless!

4^{th} Circum Pan Pacific Spin Symposium

Aug. 4-7, 2003
University of Washington
Seattle

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