• Ratio of proton to Delta trajectories: ratio of zeroes of Bessel functions.

• One scale $\Lambda_{\text{QCD}}$ determines hadron spectrum (slightly different for mesons and baryons)

• Only quark-antiquark, $qqq$, and $gg$ hadrons appear at classical level

• Covariant version of bag model: confinement + conformal symmetry
New Perspectives in QCD from AdS/CFT

• Need to understand QCD at the Amplitude Level: hadron wavefunctions!

• Remarkable new insights from AdS/CFT, the duality between conformal field theory and Anti-de Sitter Space

• Impact of ISI and FSI: Single Spin Asymmetries, Diffractive Deep Inelastic Scattering, Shadowing, Antishadowing
Rosenbluth extractions of $G_E$ and $G_M$

In the Born approximation:

\[ \sigma_R = \frac{d\sigma}{d\Omega} \frac{\varepsilon(1+\tau)}{\sigma_{\text{Mott}}} = \tau G_M^2(Q^2) + \varepsilon G_E^2(Q^2) \]

\[ \tau = \frac{Q^2}{(2M)^2} \]

Initial Rosenbluth measurements consistent with form factor scaling

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

For large $Q^2$ values, $\tau G_M^2$ dominates and $G_E^2$ becomes difficult to extract

Janssens et al., 1966

$Q^2 = 0.39 \text{ GeV}^2$

$\mu_p G_E / G_M = 1.061 \pm 0.058$
**Definitive test:** Positron-proton scattering vs. electron-proton scattering

\[
R \equiv \frac{\sigma_{e^+}}{\sigma_{e^-}} = \frac{(A_{1\gamma} + A_{2\gamma})^2}{(A_{1\gamma} - A_{2\gamma})^2} \approx 1 + 4 \text{Re}(A_{2\gamma}/A_{1\gamma})
\]

- **e+/e-**
  \[
  \langle R \rangle = 1.003 +/- 0.005
  \]
  *J. Mar et al., PRL 21, 482(1968)*
  and refs therein

- **µ+/µ-**
  \[
  \langle R \rangle = 0.993 +/- 0.006
  \]
  *L. Camilleri et al., PRL 23, 149 (1969)*
  \((Q^2 < 1 \text{ GeV}^2)\)

**One-photon approximation assumed to be good to ~1%**

**However:** Low luminosity of secondary e+/µ beams meant that precise limits were only available for low \(Q^2\) and/or small scattering angles.
**G_E/G_M from Polarization Transfer**

Use polarized electron beam, unpolarized proton target, measure the polarization transferred to the struck proton

\[
P_L = M_p^{-1} (E+E') \sqrt{\frac{1}{1+\tau}} \frac{G_M^2 \tan^2(\theta_e/2)}{}
\]

\[
P_T = 2 \sqrt{\frac{1}{1+\tau}} G_E G_M \tan(\theta_e/2)
\]

\[
P_N = 0
\]

\[
\frac{G_E}{G_M} = \frac{P_T (E+E') \tan(\theta_e/2)}{P_L \frac{2M_p}{2M_p}}
\]

G_E/G_M goes like ratio of two components
--- insensitive to absolute polarization, analyzing power
--- less sensitive to radiative corrections

Comparison of different electron polarizations
--- cancellation of false asymmetries

Also useful for neutron (where G_E << G_M, so L-T very difficult)

--- N. Dombey, Rev. Mod. Phys. 41, 236 (1969)
$G_E/G_M$ from Polarization Transfer

MIT-Bates:
B. D. Milbrath, et. al., PRL 82 (1999) 2221(E)

Jefferson Lab:
M. K. Jones, et. al., PRL 84 (2000) 1398
O. Gayou, et. al., PRC 64 (2001) 038202
O. Gayou, et. al., PRL 88 (2002) 092301

Mainz:
Th. Pospischil, et. al., EPJA 12, (2001) 125
(low $Q^2$ - not shown in figure)

$\mu_p G_E/G_M \sim 1 - 0.13 (Q^2 - 0.04)$

Surprising result: $\mu_p G_E \neq G_M$ at large $Q^2$
- Renewed interest in nucleon form factors, nucleon structure
- New examination of long-standing pQCD predictions
- Highlighted the role of relativity, angular momentum
- Generated interest outside of the field

Articles in Science News, Physics Today, New York Times, USA Today, etc...

Predicted by Iachello!

Frascati Nucleon05
10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC
Proton $G_E/G_M$ Ratio

Rosenbluth (Longitudinal-Transverse) Separation

Polarization Transfer

LT

$$\sigma_R = G_M^2(Q^2) + \frac{\varepsilon}{\tau} G_E^2(Q^2)$$

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

$$\varepsilon = [1 + 2(1 + \tau) \tan^2 \theta/2]^{-1}$$

$$G_E/G_M$$ from slope in $\varepsilon$ plot

PT

$$\frac{G_E}{G_M} = -\sqrt{\frac{\tau(1 + \varepsilon)}{2\varepsilon}} \frac{P_T}{P_L}$$

$P_{T,L}$ polarization of recoil proton

Wally Melnitchouk
• Polarization transfer Jlab measurement of space-like form factor: \( \frac{G_E}{G_M} \) decreasing; revolution!

• Time-like data from Babar: \( \frac{G_E}{G_M} \) increasing

• Rosenbluth unreliable

• \( G_E - G_M \) scaling wrong

• Possible problem for PQCD

• Two-Photon exchange to the rescue. Resonance model vs. parton handbag -- need both even to get Thomson limit, LET
- Improved calculation of box diagrams, (unexcited intermediate state only)

- GPD based model, γ-q coupling
- Not valid at low $Q^2$ or $ε$ values

A. Afanasev, private communication
- Axial-VMD model
- Provides $ε$-dependence (arbitrary magnitude)
- Out of date, included for completeness

My summary:
1) Calculations differ in magnitude and $ε$-dependence, but rapidly improving
2) All show small effects at large $ε$
   All show decrease at low $ε$
   All show weak $Q^2$-dependence
   ➡️ Consistent with e+/e- ratios and observed form factor discrepancy

- Generalized formalism for elastic scattering beyond Born approximation

M. Rekalo and E. Tomasi-Gustafsson, EPJ A22, (2004);
- Model-independent properties, connection of time-like and space-like regimes

Arrington
Two-photon exchange in elastic e scattering

Wally Melnitchouk
Jefferson Lab

Workshop on Nucleon Form Factors
Frascati, October 12-14, 2005

+ J. Tjon (Maryland/JLab), P. Blunden, S. Kondratyuk (Manitoba)

Two-photon exchange amplitude with $\Delta$ intermediate state

But: Cannot use Dirac/Feynman propagator
Contains Delta Delta Delta Delta intermediate state with full strength
Afanasev, Carlson, Chen, Vanderhaeghen, sjb

Interference of one-photon and two-photon exchange

\[ \sigma(e^-p \rightarrow e^-p) \]
\[ \sigma(e^+p \rightarrow e^+p) \]

Afanasev, Carlson, Chen, Vanderhaeghen, sjb

Predictions for the electron-proton/positron-proton asymmetry

Interference of one-photon and two-photon exchange

Rosenbluth w/2-\(\gamma\) corrections vs. Polarization data

Pol.: Gayou et al.

One may comment on the growth of the error bars at higher Q^2. The calculation with

- Pol.: Jones et al.
- Pol.: Gayou et al.
- Pol.: Gayou et al. fit
- Rosenbluth, Mo-Tsai corr. only
- Rosenbluth, incl. 2\(\gamma\) corr. w/gauss. GPD
Interference of one-photon and two-photon exchange

Frascati Nucleono5 10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC
JLab E05-017 (Hall C): Improved Rosenbluth data

Proton detection can give factor of 2-3 improvement over world’s L-T data on $G_E/G_M$
(as demonstrated by E01-001)


LT-PT comparisons provide $\Delta \sigma^{\text{TPE}}$
with 50-100% uncertainty

Reduce to 20-30% for $Q^2 > 1-2$

At lower $Q^2$, positron-electron comparisons will determine the size of $\Delta \sigma^{\text{TPE}}$

Reduce TPE uncertainties on $G_M$ by factor of 2-3 for all $Q^2$,

\textit{at or below the experimental uncertainties} (if $\varepsilon$-dependence known)

Final step: better knowledge of $\varepsilon$-dependence of amplitudes
On another planet: Measure $G_E/G_M$ using Rosenbluth with positron-proton scattering.

Find $G_E^2 < 0$!!
On another planet: Measure $G_E/G_M$ using Rosenbluth with positron-proton scattering

Would find square of $G_E$ negative!
• BaBar $|G_E/G_M|$ measurements vs previous ones and dispersion relation prediction (yellow) based on JLab space-like $G_E/G_M$ and analyticity

Baldini
The "inverse problem"

Two photon contribution to $e^+e^- \rightarrow \ldots$

Simone Pacetti

$$\text{Ratio } |G^p_E(q^2)/G^p_M(q^2)| \text{ and dispersion relations}$$

$$R(q^2) = \mu_p \frac{G_E(q^2)}{G_M(q^2)}$$
Asymptotic behaviour of $R$ and comparison with some existing models

Simone Pacetti

Ratio $|G_E^p(q^2)/G_M^p(q^2)|$ and dispersion relations
Asymptotic value and space-like zero

Real asymptotic values for $R$

\[
R_{\text{BaBar}}(\infty) = 2.65 \pm 0.55 = (0.95 \pm 0.20) \mu_p \\
R_{\text{Lear}}(\infty) = 6.4 \pm 1.9 = (2.3 \pm 0.7) \mu_p
\]

BaBar in agreement with the scaling law $|G_E| \approx |G_M|$ but with opposite sign

Asymptotic behaviour of $F_2/F_1$

\[
\lim_{s \to \infty} \frac{s}{4M_N^2} \frac{F_2}{F_1} = \frac{R(\infty)}{\mu_p} - 1 = \begin{cases} 
-0.05 \pm 0.20 & \text{BaBar} \\
1.3 \pm 0.7 & \text{Lear}
\end{cases}
\]

$F_2/F_1$ decreases like $(1/s)$ (Lear) or faster (BaBar) as $s$ diverges

Space-like zero

The analysis foresees, in a model-independent way, the presence of a space-like zero $t_0$ for $R$

\[
t_0^{\text{BaBar}} = (-10 \pm 1) \text{ GeV}^2 \\
t_0^{\text{Lear}} = (-7.9 \pm 0.7) \text{ GeV}^2
\]

BaBar only!

In spite of this the asymptotic scaling law seems preserved

Simone Pacetti

Ratio $|G_E^p(q^2)/G_M^p(q^2)|$ and dispersion relations

Frascati Nucleon 2005

10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC

59
Remarks on two-photon correction

Need to check input against all data on Compton amplitude

\[ \gamma p \rightarrow \gamma p, \ \gamma \gamma \rightarrow p\bar{p}, \]
including large \( s, t \)

DVCS:
\[ \gamma^* p \rightarrow \gamma p \]
\[ \gamma^* \gamma^* \rightarrow p\bar{p} \]
\[ \gamma^* \rightarrow p\bar{p}\gamma \]

Difference of hfs in hydrogen \((e^- p)\)
and muonium \((e^- \mu^+)\).

Measure \( e^\pm p \) Charge asymmetry

Need to combine parton-based and hadron-based models

Cannot use Feynman propagator for composite spin-1/2 systems
e.g. \( He^+ (e^- \alpha) \)

Mechanism for low energy theorem for composite systems

Hiller, Carlson, Huang, sjb

Primack, sjb
Study of $\gamma\gamma \rightarrow p\bar{p}$
Production at Belle

Chen-Cheng Kuo (Belle Collaboration)

- General theory of hard exclusive process in QCD:
  \[ \frac{d\sigma}{dt} \propto s^{2-n_c} f(\theta^*) \]
  (as $s \rightarrow \infty$; $s \equiv W_{\gamma\gamma}^2$)
  if $n_c = 8$, then $\sigma \propto W_{\gamma\gamma}^{-10}$

Three-quark picture using proton wave function based on QCD sum rules:
\[ \frac{d\sigma(\gamma\gamma \rightarrow B\bar{B})}{d|\cos \theta^*|} \propto \frac{W_{\gamma\gamma}^{-10} f'(\theta^*)}{1-\cos^2 \theta^*} \]
**Measured Cross Sections for $\gamma\gamma \rightarrow p\bar{p}$**

![Graph showing cross sections for $\gamma\gamma \rightarrow p\bar{p}$](image)

- **Complete diquark**
- **Diquark, only helicity conserved amplitudes**
- **Three-quark**

<table>
<thead>
<tr>
<th>fitted $n$</th>
<th>range of $W_{\gamma\gamma}$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1$^{+0.8}_{-1.1}$</td>
<td>2.5–2.9</td>
</tr>
<tr>
<td>12.4$^{+2.4}_{-2.3}$</td>
<td>3.2–4.0</td>
</tr>
</tbody>
</table>

- Steeper fall in $W_{\gamma\gamma}$ than pQCD $n = 10$ ($n = 10$ not rejected for $W_{\gamma\gamma} > 3.2$ GeV)
- Decreasing $n$ in $W_{\gamma\gamma}$ (indication of a transition to asymptotic predictions)

$(\eta_c$ contribution included)
Angular Distribution at Higher Energies and Predictions

\[ 2.5 < W_{\gamma\gamma} < 3.0 \text{ GeV} \]

- **Belle** ◊ OPAL (2.55–2.95 GeV)
- CLEO △ L3
- diquark (complete)
- diquark (only HCAs)
- three-quark handbag ($R_V \sim 0$)

\[ 3 < W_{\gamma\gamma} < 4 \text{ GeV} \]

- **Belle** △ L3 (3.0–4.5 GeV)
- diquark (complete)
- diquark (only HCAs)
- three-quark handbag ($R_V \sim 0$)

- **Ascending trend** is a general feature of pQCD due to the hard scattering amplitude:
  \[
  \frac{d\sigma}{d|\cos \theta^*|} \propto \frac{1}{tu} \propto \frac{1}{1 - \cos^2 \theta^*}
  \]

- **Handbag contribution with $R_V^P$ neglected**:
  \[
  \frac{d\sigma}{d|\cos \theta^*|} \propto \frac{1}{1 - \cos^2 \theta^*}
  \]

- **Steeper enhancement of data at higher $|\cos \theta^*|$ must be explained**

Baryon Regge exchange
\[ s \gg -t, -u \]

---

Frascati Nucleon05 10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC
Crucial test: neutral suppression

\[
\frac{d\sigma}{dt}(\gamma\gamma\rightarrow\pi^+\pi^-) \sim \frac{4 | F_\pi(s) |^2}{1 - \cos^4 \theta_{c.m.}}
\]
Fig. 5. Cross section for (a) $\gamma \gamma \rightarrow \pi^+\pi^-$, (b) $\gamma \gamma \rightarrow K^+K^-$ in the c.m. angular region $|\cos \theta^*| < 0.6$ together with a $W^{-6}$ dependence line derived from the fit of $s|R_M|$. (c) shows the cross section ratio. The solid line is the result of the fit for the data above 3 GeV. The errors indicated by short ticks are statistical only.

Two Photon Reactions

Hard Exclusive Processes: Fixed angle

PQCD, AdS/CFT:

$\Delta \sigma(\gamma\gamma \rightarrow \pi^+\pi^-, K^+K^-) \sim 1/W^6$

$|\cos(\theta_{CM})| < 0.6$

Frascati Nucleono5 10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC
PQCD: \[
\frac{d\sigma}{d|\cos \theta^*|} (\gamma \gamma \rightarrow M^+ M^-) \approx \frac{16\pi\alpha^2}{s} \frac{|F_M(s)|^2}{\sin^4 \theta^*},
\]

Angular dependence of the cross section, \(\sigma_0^{-1}d\sigma/d|\cos \theta^*|\), for the \(\pi^+\pi^-(\text{closed circles})\) and \(K^+K^-\)(open circles) processes. The curves are \(1.227 \times \sin^{-4} \theta^*\). The errors are statistical only.

**Measurement of the** \(\gamma \gamma \rightarrow \pi^+\pi^-\) **and** \(\gamma \gamma \rightarrow K^+K^-\) **processes**  
**at energies of** 2.4–4.1 GeV

**Crucial test:** neutral suppression

Frascati Nucleono05  
Belle Collaboration  
New Perspectives on the Nucleon in QCD  
Stan Brodsky, SLAC
FIG. 5: Nucleon analyzing power, which is equal to normal recoil polarization. The elastic contribution (nucleon intermediate state in the two-photon exchange box diagram) is shown by the dotted curve [27]. The GPD calculation for the inelastic contribution is shown by the dashed curve for the gaussian GPD, and by the solid curve for the modified Regge GPD. The GPD calculation is cut off in the backward direction at $-u = M^2$. In the forward direction the modified Regge GPD result goes down to $Q^2 = 2 \text{ GeV}^2$ and the gaussian GPD result to $Q^2 = M^2$.

Afanasev, Carlson, Chen, Vanderhaeghen, sjb
Comparison of $A_{\perp}$ with Model Calculations

- Single-Spin-Asymmetries: $e^-$ Spin transverse

- Transverse Beam Spin Asymmetry (Imaginary Part, only in 2-Photon)

Intermediate State: Proton, $\pi N$ States (MAID) (B. Pasquini)

Data: Mainz

Frascati Nucleon05 10-14-05

New Perspectives on the Nucleon in QCD

Stan Brodsky, SLAC
Timelike proton form factor data

Historical ref: Zichichi, Berman, Cabibbo

ISR technique
Kuhn et al

Historical ref: Zichichi, Berman, Cabibbo
Fig. 5. Total cross section $e^+e^- \rightarrow p\bar{p}$ as measured in two different energy regions.
BaBar measurement very near threshold confirms steep rise of Form Factor

Steep behavior at threshold also seen in other processes
Threshold Enhancement observed by BES

BESII $J/\psi \rightarrow \gamma p\bar{p}$

$M=1859^{+10}_{-25}$ MeV/c$^2$

$\Gamma < 30$ MeV (90% CL)

$\chi^2$/dof=56/56

3-body phase space

acceptance weighted BW

fitted peak location

Diego Bettoni

Timelike Form Factors
• Negative step at \( w \sim 2.2 \) GeV (!?)

Speculations:
• Strong resonances interference?
• A new (inelastic) amplitude:
  opening of baryonic excitations?
Possible Explanations

- Tail of a narrow resonance below threshold (baryonium ?).
- Dominance of $\pi$ exchange in $\bar{p}p$ final state interaction.
- Underestimation of the Coulomb correction factor.

Possible test for baryonium: a vector meson with very small coupling to $e^+e^-$ (and relatively small hadronic width), lying on top of a $\rho/\omega$ recurrence, should show up as a dip in some hadronic cross section.
The dip in the total multihadronic cross section and the steep variation of the proton form factor near threshold may be fitted with a narrow vector meson resonance, with a mass $M \sim 1.87$ GeV and a width $\Gamma \sim 10-20$ MeV, consistent with an $N\bar{N}$ bound state.
• Dip observed in $6\pi$ diffractive photoproduction by E687 at Fermilab
• New results from Babar expected soon
E. Solodov
BINP Novosibirsk
Representing BaBar collaboration

$$\frac{d\sigma(s,x)}{dx d(cos \theta)} = W(s,x,\theta) \cdot \sigma_0(s(1-x)),$$

$$W(s,x,\theta) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2 \theta} - \frac{x^2}{2} \right), \quad x = \frac{2E_\gamma}{\sqrt{s}}$$
Cross section fit for 3(π⁺π⁻), 2(π⁺π⁻)π⁰π⁰

Cross section is described as:
(N.N.Achasov, hep-ph/9609216)

\[
\sigma(e^+e^- \rightarrow V_1 + V_2) = \frac{4\pi\alpha^2}{s^{3/2}} \left( \frac{gm_1^2 e^{i\varphi}}{m_1^2 - s - i\sqrt{s}\Gamma_1} + A_{V_1}(s) \right)^2
\]

\[A_{V_1}(s) = c_0 + c_1 \frac{-\beta}{e^{\sqrt{s-m_0}}} \frac{1}{(\sqrt{s-m_0})^{2-\alpha}}\]

\[\sigma_0 = 0.12 \pm 0.03 \text{ nb} \]
\[m_1 = 1.88 \pm 0.05 \text{ GeV/c}^2\]
\[\Gamma_1 = 0.13 \pm 0.03 \text{ GeV}\]
\[\varphi_1 = 21 \pm 40 \text{ deg.}\]

\[\sigma_0 = 0.46 \pm 0.10 \text{ nb} \]
\[m_1 = 1.86 \pm 0.02 \text{ GeV/c}^2\]
\[\Gamma_1 = 0.16 \pm 0.02 \text{ GeV}\]
\[\varphi_1 = -3 \pm 15 \text{ deg.}\]

The dip is not well described by single BW!

October 14, 2005
E.Solodov Workshop on NFF
The neutron form factor is bigger than that of the proton !!!
\[
\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta}{4s} C D = \frac{\alpha^2 \beta}{4s} C \left[ |G_M|^2 (1 + \cos^2 \theta) + \frac{1}{\tau} |G_E|^2 \sin^2 \theta \right]
\]

\[
\beta = \sqrt{1 - 4M^2/s} \quad \tau = s/4M^2
\]

\[
C = \frac{y}{1 - \exp(-y)} \quad y = \pi \alpha M / \beta \sqrt{s}
\]

Coulomb Correction

Sommerfeld, Schwinger
C is the Coulomb correction factor, taking into account the QED coulomb interaction. Important at threshold.

\[ C = \frac{1}{1 - e^{-y}} \]

\[ y = \frac{\pi \alpha M_N}{\beta \sqrt{s}} \]

\[ C \left( \frac{s}{4M_N^2} \right)^{\frac{1}{\beta}} \rightarrow \sigma \text{ finite} \]

\[ \sigma \left( 4M_N^2 \right) = \frac{\pi^2 \alpha^3}{4M_N^2} \left| G_E(4M_N^2) \right|^2 \approx 0.1 \text{ nb} \]

There is no Coulomb correction in the neutron case.