Theoretical and experimental review
on
Nucleon Form Factors

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Agenda

Space-like region: definitions and data

Rosenbluth/Polarization conflict(?)

Time-like region: definitions, data and more

The ratio $G_E^p / G_M^p$

Proton form factor at threshold
Nucleon Form Factors definition

Space-like region \((q^2 < 0)\)

**Electromagnetic current** \((q = p' - p)\)

\[
J^\mu = \langle N(p')|j^\mu|N(p)\rangle = e\bar{u}(p')\left[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2)\right]u(p)
\]

**Dirac and Pauli form factors** \(F_1\) and \(F_2\) are real

**In the Breit frame**

\[
\begin{aligned}
\rho_q &= J^0 = e \left[ F_1 + \frac{q^2}{4M^2} F_2 \right] \\
\tilde{J}_q &= e \bar{u}(p')\gamma u(p) [F_1 + F_2]
\end{aligned}
\]

\[
2M\bar{u}(p')\gamma^\mu u(p) = \bar{u}(p')[\gamma^\mu + i\sigma^{\mu\nu}q_\nu]u(p)
\]

\[
\bar{u}(-\bar{p})u(\bar{p}) = E/M \\
u^\dagger(-\bar{p})u(\bar{p}) = 1
\]

**Sachs form factors**

\[
\begin{aligned}
G_E &= F_1 + \frac{q^2}{4M^2} F_2 \\
G_M &= F_1 + F_2
\end{aligned}
\]

**Normalizations**

\[
\begin{aligned}
F_1(0) &= Q_N \\
F_2(0) &= \kappa_N \\
G_E(0) &= Q_N \\
G_M(0) &= \mu_N
\end{aligned}
\]
\textbf{pQCD asymptotic behavior}

\textbf{Space-like region}

- \textbf{pQCD}: as $q^2 \rightarrow -\infty$, asymptotic behaviors of $F_1$ and $F_2$, and $G_E$ and $G_M$ must follow counting rules.

- Valence quarks exchange gluons to distribute the momentum transfer $q$.

\textbf{Non-helicity-flip current $J^{\lambda,\lambda}(q^2)$}

- $J^{\lambda,\lambda}(q^2) \propto G_M(q^2)$
- Two gluon propagators
- $G_M(q^2) \sim (q^2)^{-2}$ when $q^2 \rightarrow -\infty$.

\textbf{Helicity-flip $J^{\lambda,-\lambda}(q^2)$}

- $J^{\lambda,-\lambda}(q^2) \propto G_E(q^2)/\sqrt{-q^2}$
- Two gluon propagators / $\sqrt{-q^2}$
- $G_E(q^2) \sim (q^2)^{-2}$ when $q^2 \rightarrow -\infty$.

\textbf{Ratio of Sachs form factors}

- Ratio: $\frac{G_E}{G_M} \sim \text{constant}$ when $q^2 \rightarrow -\infty$.

\textbf{Dirac and Pauli form factors}

- $F_1(q^2) \sim (q^2)^{-2}$ when $q^2 \rightarrow -\infty$.
- $F_2(q^2) \sim (q^2)^{-3}$ when $q^2 \rightarrow -\infty$.
Space-like data
Rosenbluth separation

\[
\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{1}{1 - \tau} \left[ G_E^2 - \frac{\tau}{\epsilon} G_M^2 \right]
\]

\[ \tau = \frac{q^2}{4M_N^2} \]

- Mott pointlike cross section
  \[
  \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} = \frac{4\alpha^2}{(-q^2)^2} \frac{E_2^3}{E_1} \cos^2(\theta_e/2)
  \]

- Photon polarization
  \[
  \epsilon = \left[ 1 + 2(1 - \tau) \tan^2(\theta_e/2) \right]^{-1}
  \]

Rosenbluth plot

Reduced cross section

\[
\frac{d\sigma}{d\Omega}_{\text{red}} = \frac{\epsilon(\tau - 1)}{\tau} \left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = G_M^2 - \frac{\epsilon}{\tau} G_E^2
\]

- \((d\sigma/d\Omega)_{\text{red}}(\epsilon)\) slope \rightarrow G_E
- \((d\sigma/d\Omega)_{\text{red}}(\epsilon)\) intercept \rightarrow G_M

Dipole form:

\[
G_D(q^2) = \left(1 - \frac{q^2}{0.71\text{GeV}^2}\right)^{-2}
\]
$G_E^p$ and $G_M^p$ with Rosenbluth separation

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Nucleon Form Factors in Experiments and Theory
Elastic scattering of \textit{longitudinally polarized electrons} \((h = \pm 1)\) on nucleon target

Hadronic tensor:

\[
W_{\mu\nu} = W_{\mu\nu}(0) + W_{\mu\nu}(\vec{P}) + W_{\mu\nu}(\vec{P}') + W_{\mu\nu}(\vec{P}, \vec{P}')
\]

- no pol.
- ini. or fin. pol. of \(N\)
- ini. and fin. pol. of \(N\)

In case of \textit{polarized electrons} \((h = \pm 1)\) on \textit{unpolarized nucleon} target:

\[
P'_x = -\frac{2\sqrt{\tau(\tau-1)}}{G_E^2 - \frac{\tau}{\epsilon} G_M^2} G_E G_M \tan \left(\frac{\theta_e}{2}\right) \quad P'_z = \frac{(E_e + E'_e)\sqrt{\tau(\tau-1)}}{M \left(G_E^2 - \frac{\tau}{\epsilon} G_M^2\right)} G_M^2 \tan^2 \left(\frac{\theta_e}{2}\right)
\]

\[
\frac{P'_x}{P'_z} = \frac{2M \cot(\theta_e/2)}{E_e + E'_e} \frac{G_E}{G_M}
\]
$G_E^p / G_M^p$ in polarization transfer experiments

Polarization data do not agree with old Rosenbluth data (◇)

New Rosenbluth data (△, ○) from JLab still do not agree with polarization data

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Nucleon Form Factors in Experiments and Theory
Radiative corrections in Rosenbluth separation


Sachs form factors $G_E$ and $G_M$ are extracted from Born cross sections (one-$\gamma$ exchange)

The Born term is obtained from experimental cross sections correcting for radiative effects

$$\frac{d\sigma^{\text{exp}}}{d\Omega} = \left[ 1 + \delta(\epsilon) \right] \frac{d\sigma^{\text{Born}}}{d\Omega}$$

An example

Virtual Compton Scattering
PRC62,025501(00)

Two-photon with GPD
PRD72,013008(05)

Structure functions RC
PRC75,015207(07)

Polarization data

$G_E$ cont. in $\left( \frac{d\sigma^{\text{Born}}}{d\Omega} \right)^{\text{red}} < 1\%$

$\epsilon$: 

<table>
<thead>
<tr>
<th>$q^2$</th>
<th>Data</th>
<th>Born term</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-5.00$ GeV$^2$</td>
<td>○, ●</td>
<td>○, ●, ◇, ▲, □</td>
</tr>
<tr>
<td>$-3.25$ GeV$^2$</td>
<td>▲</td>
<td>○, ▲, □</td>
</tr>
<tr>
<td>$-1.75$ GeV$^2$</td>
<td>◇, □</td>
<td>○, ▲, □</td>
</tr>
</tbody>
</table>
$G_E^n$ and $G_M^n$ with different techniques

- Elastic $e$-$d$ cross section
- Polarization observables in electron scattering with $^2$H and $^3$He targets

- Quasi-elastic $e$-$d$ / elastic $e$-$p$ cross sections
- Polarization observables in electron scattering on a polarized $^3$He target

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Nucleon Form Factors in Experiments and Theory
Time-like region
Nucleon form factors
Time-like region \( (q^2 > 0) \)

- Crossing symmetry:
  \[ \langle N(p') | j^\mu | N(p) \rangle \rightarrow \langle \overline{N}(p') N(p) | j^\mu | 0 \rangle \]

- Form factors are complex functions of \( q^2 \)

Optical theorem

\[
\text{Im} \langle \overline{N}(p') N(p) | j^\mu | 0 \rangle \sim \sum_n \langle \overline{N}(p') N(p) | j^\mu | n \rangle \langle n | j^\mu | 0 \rangle \implies \left\{ \begin{array}{l}
\text{Im} F_{1,2} \neq 0 \\
\text{for } q^2 > 4M^2_\pi
\end{array} \right.
\]

\( |n\rangle \) are on-shell intermediate states: \( 2\pi, 3\pi, 4\pi, \ldots \)

Time-like asymptotic behavior

Phragmèn Lindelöf theorem:

If \( f(z) \rightarrow a \) as \( z \rightarrow \infty \) along a straight line, and \( f(z) \rightarrow b \) as \( z \rightarrow \infty \) along another straight line, and \( f(z) \) is regular and bounded in the angle between, then \( a = b \) and \( f(z) \rightarrow a \) uniformly in this angle.

\[
\lim_{q^2 \rightarrow -\infty} G_{E,M}(q^2) = \lim_{q^2 \rightarrow +\infty} G_{E,M}(q^2)
\]

\[ G_{E,M} \sim (q^2)^{-2} \quad \text{real} \]

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Cross section and analyticity

Annihilation cross section formula

\[ \frac{d\sigma}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} \left[ (1 + \cos^2 \theta) |G_M|^2 + \frac{1}{\tau} \sin^2 \theta |G_E|^2 \right] \]

- Outgoing nucleon velocity: \( \beta = \sqrt{1 - 1/\tau} \)
- Coulomb correction: \( C = \frac{\pi \alpha / \beta}{1 - \exp(-\pi \alpha / \beta)} \)

Space-like region
\( eN \rightarrow eN \)
FF’s are real

Time-like region
Unphysical region
No data
FF’s are complex

Hadronic helicity = \( \begin{cases} 1 & \Rightarrow G_E \\ 0 & \Rightarrow G_M \end{cases} \)

Only S-wave at threshold
\( G_E(4M_N^2) = G_M(4M_N^2) \)
Data obtained with $|G_M^p| = |G_E^p| \equiv |G_{\text{eff}}^p|$ (assumed true only at threshold)

$$|G_{\text{eff}}^p|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{16\pi\alpha^2C\cdot\frac{\sqrt{1-1/\tau}}{4q^2}\left(1 + \frac{1}{2\tau}\right)}$$
Time-like $|G_E^p / G_M^p|$ measurements

\[
\frac{d\sigma}{d\cos\theta} = \frac{\pi \alpha^2 \beta C}{2q^2} |G_M^p|^2 \left[ (1 + \cos^2\theta) + \frac{4M_p^2}{q^2 \mu_p^2} \sin^2\theta |R|^2 \right]
\]

\[
R(q^2) = \mu_p \frac{G_E^p(q^2)}{G_M^p(q^2)}
\]

\[
\sqrt{q^2} \ 	ext{(GeV)}
\]

Scaling

- **$\gamma\gamma$ exchange**
  - $C = +1$
  - Asymmetry in angular distributions
    - [E. Tomasi-Gustafsson, M.P. Rekalo, PLB504,291(01)]

- $\bar{p}p \rightarrow e^+ e^-$
  - **WIRE**
  - **FENICE+DM2**
  - **E835**

- **$\gamma\gamma$ exchange interferes with the Born term**

**Graph**

- **$|G_E^p(q^2) / G_M^p(q^2)|$**
- **$\sqrt{q^2}$**
$e^+e^- \rightarrow p\bar{p}\gamma$ BABAR 2013 data

**Integral asymmetry**

$$\langle A \rangle_{\cos \theta_p} = \frac{\sigma(\cos \theta_p > 0) - \sigma(\cos \theta_p < 0)}{\sigma(\cos \theta_p > 0) + \sigma(\cos \theta_p < 0)} = -0.025 \pm 0.014 \pm 0.003$$

$\sigma(\cos \theta_p \geq 0)$ is the cross section integrated with $W \leq 3$ GeV and $\cos \theta_p \geq 0$

**Integrated over the $p\bar{p}$-CM energy from threshold up to 3 GeV**

The MC-fit assumes **one-photon exchange**

**Slope** = $-0.041 \pm 0.026 \pm 0.005$
\( e^+ e^- \rightarrow n\bar{n} \)

A very large cross section also at threshold

Still room for \( \beta \) like rising

| Model                  | \( |G^n_M/G^p_M| \) |
|------------------------|---------------------|
| Data                   | \( \sim 1.5 \)       |
| Naively                | \( \sim |Q_d/Q_u| \) |
| pQCD                   | \( < 1 \)            |
| Soliton models         | \( \sim 1 \)         |
| VMD (Dubnicka)         | \( \gg 1 \)          |

FENICE (1988)
Phys. Lett. B 313, 283 (93)

SND (2011)
EPJ Web Conf. 37, 09020 (12)

Naively \( |Q_d/Q_u| \)
The ratio \( R = \mu_p G_E^p / G_M^p \)

- Dispersion relation for the imaginary part
- Model-independent approach
- First time-like \(|G_E| - |G_M|\) separation

\( \Rightarrow \) Ratio in the whole \( q^2 \) complex plane
Analytic $R(q^2)$

$$R(q^2) = R(0) + \frac{q^2}{\pi} \int_{4M^2}^{\infty} \frac{\text{Im}R(s)}{s(s - q^2)} ds$$

$R(q^2)$ space-like

$|R(q^2)|$ time-like

JLab+MIT-Bates

$B\overline{A}B\overline{A}R+DM2/FENICE+E835$

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Analytic $R(q^2)$

$$R(q^2) = R(0) + \frac{q^2}{\pi} \int_{4M^2}^{\infty} \frac{\text{Im}R(s)}{s(s - q^2)} ds$$

$R(q^2)$ space-like

$|R(q^2)|$ time-like

JLab+MIT-Bates

$\text{Babar} + \text{DM2/FENICE+E835}$

Nucleon Form Factors in Experiments and Theory
Analytic $R(q^2)$

$$R(q^2) = R(0) + \frac{q^2}{\pi} \int_{4M_n^2}^{\infty} \frac{\text{Im} R(s)}{s(s - q^2)} ds$$

$R(q^2)$ space-like

$|R(q^2)|$ time-like

Space-like zero $t_0 = (-10 \pm 1)$ GeV$^2$

JLab+MIT-Bates

BABAR+DM2/FENICE+E835

DR Approach

PRD69,054022(04)

1/Q

log$^2 Q^2/Q^2$

Impr. log$^2 Q^2/Q^2$

IJL
\[ R(q^2) = R(0) + \frac{q^2}{\pi} \int_{4M^2}^{\infty} \frac{\text{Im} R(s)}{s(s - q^2)} ds \]

- **Analytic** \( R(q^2) \)

- \( R(q^2) \) space-like

- \( |R(q^2)| \) time-like

- **JLab+MIT-Bates**

- **JLab 2010**
  - [PRL104,242301]

- **Space-like zero**
  - \( t_0 = (-10 \pm 1) \text{ GeV}^2 \)

- **B\(\Lambda\)B\(\Lambda\)R+DM2/FENICE+E835**

- **DR Approach**
  - \( 1/Q \), \( \log^2 Q^2/Q^2 \), \( \text{Impr. log}^2 Q^2/Q^2 \), \( \text{IJJL} \)

- **Nucleon Form Factors in Experiments and Theory**

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Asymptotic $G_E^p(q^2)/G_M^p(q^2)$ and phase

$pQCD$ prediction
\[
\frac{G_E^p(q^2)}{G_M^p(q^2)} \left| q^2 \right| \to \infty \rightarrow -1
\]

Phase from DR
\[
\phi(q^2) = -\frac{\sqrt{q^2 - s_{th}}}{\pi} \text{Pr} \int_{s_{th}}^{\infty} \frac{\ln |R(s)| ds}{\sqrt{s - s_{th}(s - q^2)}}
\]
\[ |G_E^p(q^2)| \text{ and } |G_M^p(q^2)| \text{ from } \sigma_{p\bar{p}} \text{ and DR} \]

\[ |G_{\text{eff}}^p(q^2)| \cdot q^4 \]

\[ |G_E^p(q^2)| = |G_M^p| \]

\[ |G_{\text{eff}}^p(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{4\pi\alpha^2\beta C} \left(1 + \frac{1}{2\tau}\right)^{-1} \]

- Usually what is extracted from the cross section \( \sigma(e^+ e^- \rightarrow p\bar{p}) \) is the effective time-like form factor \( |G_{\text{eff}}^p| \)
- obtained assuming \( |G_E^p| = |G_M^p| \)
- i.e. \( |R| = \mu_p \)

- Using our parametrization for \( R \) and the BABAR data on \( \sigma(e^+ e^- \rightarrow p\bar{p}) \), \( |G_E^p| \) and \( |G_M^p| \) may be disentangled
$|G_E^p(q^2)|$ and $|G_M^p(q^2)|$ from $\sigma_{pp}$ and DR

$$|G_M^p(q^2)|^2 = \frac{\sigma_{pp}(q^2)}{4\pi\alpha^2\beta C} \frac{1 + \frac{|R(q^2)|}{2\mu_p\tau}}{3s}^{-1}$$

- Usually what is extracted from the cross section $\sigma(e^+ e^- \rightarrow pp)$ is the effective time-like form factor $|G_{eff}^p|$ obtained assuming $|G_E^p| = |G_M^p|$ i.e. $|R| = \mu_p$

- Using our parametrization for $R$ and the $BABAR$ data on $\sigma(e^+ e^- \rightarrow pp)$, $|G_E^p|$ and $|G_M^p|$ may be disentangled

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Nucleon Form Factors in Experiments and Theory
Sommerfeld resummation factor needed?
The Coulomb Factor

\[ \sigma_{p\bar{p}} = \frac{4\pi\alpha^2\beta C}{3q^2} \left[ |G^p_M(q^2)|^2 + \frac{2M_p^2}{q^2} |G^p_E(q^2)|^2 \right] \]

\( C \) describes the \( p\bar{p} \) Coulomb interaction as FSI

[Sommerfeld, Sakharov, Schwinger, Fadin, Khoze]

**Distorted wave approximation**

\[ C = |\psi_{\text{Coul}}(0)|^2 \]

- **S-wave:** \( C = \frac{\pi \alpha}{\beta} \cdot \frac{\alpha}{\beta} \rightarrow 0 \)
- **Rel. corr.:** \( \beta \rightarrow \tilde{\beta} = \frac{\beta}{1 - \beta} \)
- **D-wave:** \( C = 1 \)

No Coulomb factor for boson pairs (P-wave)
Enhancement and Resummation Factors

Coulomb factor $c$ for S-wave only

- Partial wave FF $\cdots \cdots \cdots G_S = \frac{2G_M\sqrt{\tau} + G_E}{3}, \quad G_D = \frac{G_M\sqrt{\tau} - G_E}{3}$
- Cross section $\cdots \cdots \cdots \sigma(q^2) = 2\pi\alpha^2 \frac{\beta}{\tau q^2} \left[ c |G_S(q^2)|^2 + 2|G_D(q^2)|^2 \right]$
- Enhancement and Resummation factors $\cdots \cdots \cdots c = e \times r$

Enhancement factor

$e = \frac{\pi\alpha}{\beta}$

It is responsible for the one-photon exchange $p\bar{p}$ FSI
- dominates close to threshold: $c \sim e \quad \beta \sim 0$
- cancels the phase-space factor $\Rightarrow$ stepwise cross section at threshold

$\sigma_{pp}(4M_p^2) = \frac{\pi^2\alpha^3}{2M_p^2} \frac{\beta}{\tilde{\beta}} |G_S(4M_p^2)|^2 = 0.85 |G_S(4M_p^2)|^2 \text{ nb}$

Resummation factor

$r = \frac{1}{1 - e^{-\pi\alpha/\beta}}$

It is responsible for the multi-photon exchange $p\bar{p}$ FSI
- becomes ineffective few MeV above threshold: $r \sim 1 \quad \beta > 0$
- must account also for gluon exchange

$r \rightarrow r_s = \left[ 1 - \exp\left( -\pi\alpha_s/\tilde{\beta} \right) \right]^{-1}$

$\alpha_s \approx 0.5$

$\tilde{\beta} = \beta/(1-\beta)$
Step and plateau in \textit{BABAR} data . . . another possibility (Vladimir F. Dmitriev)

\[ \sigma_{p\bar{p}}(4M_p^2) = \frac{\pi^2 \alpha^3}{2M_p^2} |G_S^p(4M_p^2)|^2 \]

\[ \sigma_{pp}(4M_p^2) = 0.85 |G_S^p(4M_p^2)|^2 \text{ nb} \]

\[ |G_S^p(4M_p^2)| \equiv 1 \]

as pointlike fermion pairs!
Step and plateau in **BaBar** data

...another possibility (Vladimir F. Dmitriev)

**Expected cross section with**

\[ |G_S^p(4M_p^2)| = 1 \]

Assuming:

\[ G_E^p(q^2) = G_M^p(q^2) = 1 \]
\[ R = R_s \]
\[ \alpha_s = 0.5 \]

in the region \( q^2 \leq (2.1 \text{GeV})^2 \)

\[ \sigma_{p\bar{p}} = (850 \text{ pb}) \frac{1}{\tau} R_s \]

At threshold

\[ \sigma_{p\bar{p}}(4M_p^2) = \pi^2 \alpha^3 \frac{\beta_p}{\beta_{\bar{p}}} |G_S^p(4M_p^2)|^2 \]
\[ \sigma_{p\bar{p}}(4M_p^2) = 0.85 |G_S^p(4M_p^2)|^2 \text{ nb} \]

\[ |G_S^p(4M_p^2)| \equiv 1 \]

as pointlike fermion pairs!
BaBar: $G^p_{\text{eff}}$ including threshold effects

\[
|G^p_{\text{no corr}}(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\mathcal{E}\mathcal{R} \frac{16\pi\alpha^2}{3} \frac{\beta}{4q^2} (1 + \frac{1}{2\tau})}
\]

\[
|G^p_{\text{eff}}(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\mathcal{E}\mathcal{R}_s \frac{16\pi\alpha^2}{3} \frac{\beta}{4q^2} (1 + \frac{1}{2\tau})}
\]

BaBar [PRD73, 012005 (05)]

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\[ |G_{\text{no corr}}^p(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\mathcal{E} \mathcal{R} 16\pi \alpha^2 \frac{\beta}{4q^2} \left(1 + \frac{1}{2\tau}\right)} \]

\[ |G_{\text{eff}}^p(q^2)|^2 = \frac{\sigma_{p\bar{p}}(q^2)}{\mathcal{E} \mathcal{R}_s 16\pi \alpha^2 \frac{\beta}{4q^2} \left(1 + \frac{1}{2\tau}\right)} \]
Experiments: now and future

**Space-like region**

- **Mainz**
  - $G_E^n$ at $-q^2 = 1.5 \text{ GeV}^2$ (Pol. $^3\text{He}$)
  - $G_E^p$ and $G_M^p$ for $-q^2 \leq 2.0 \text{ GeV}^2$

**Jefferson Lab**

- [Hall A] $G_E^p / G_M^p$ up to $14 \text{ GeV}^2$
- [Hall A] $G_M^n$ (ratio) up to $18 \text{ GeV}^2$
- [Hall A] $G_E^n$ / $G_M^n$ up to $10.2 \text{ GeV}^2$
- [Hall B] $G_M^n$ (deuterium) up to $14 \text{ GeV}^2$
- [Hall C] $G_E^n$ up to $7 \text{ GeV}^2$

**Time-like region**

- **at VEPP-2000**
  - $e^+e^-$ collider
  - $|G_E^p|$, $|G_M^p|$ (scan)
  - $q^2 \leq (4 \text{ GeV})^2$

- **BESIII**
  - $e^+e^-$ collider
  - $|G_E^p|$, $|G_M^p|$, $|G_{eff}^n|$ (scan and ISR)
  - $q^2 \leq (3.5 \text{ GeV})^2$

- **at FAIR**
  - $p\bar{p}$ collider
  - $|G_E^p|$, $|G_M^p|$, $G_E^p / G_M^p$ phase ($\bar{p}$ polarization)
  - $(2.4 \text{ GeV})^2 \leq q^2 \leq (3.7 \text{ GeV})^2$

- **at SuperKEKB**
  - $e^+e^-$ collider
  - $|G_E^p|$, $|G_M^p|$, (ISR)
  - $q^2 \leq (4.5 \text{ GeV})^2$

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Nucleon Form Factors in Experiments and Theory
Radiative corrections

- Values of $G_E^p / G_M^p$ from Rosenbluth and polarization transfer techniques, that have different radiative corrections, do not agree.
- Form factor values are obtained from cross section at first order (Born approx.). $G_E$ and $G_M$ appear in the Born amplitude with different kinematical factors.
- Radiative corrections depending on relevant kinematical variables must be applied.

Models that reproduce proton and neutron, electric and magnetic form factors in space-like and time-like regions

- **Light-front constituent quark model** [G. Salmè et al.]
  Space-like and time-like nucleon form factors are determined in the framework of a relativistic quark model based on Bethe-Salpeter amplitudes and vector meson dominance.

- **Skyrme model with vector mesons** [U.-G. Meissner et al.]
  Space-like form factors, obtained as Fourier transforms of charge and magnetic moment distributions, can be analytically continued in the time-like region. Desired time-like imaginary parts are obtained even though they appear quite “unstable”. [See Simone Moretti poster].

- **VMD based models** [Gari, Krümpelmann, Iachello, Jackson, Landé,...]
  Nucleon form factors are parametrized using a mixture of VMD and pQCD. At low energy the coupling to the photons is described through VM exchange. At high energy “hadron/quark” form factors drive the transition to pQCD.
“To do” list

**Time-like** $|G_E| - |G_M|$ separation:
DR and data

**Understanding threshold effect(s):**

- Dispersive analyses: integral equation, sum rule, . . .
- Experimental observation in $p\bar{p} \rightarrow \pi^0 l^+ l^-$
  
  [PRC75,045205(07)]

**Asymptotic behavior:** DR and data for the phase

**Zeros ↔ phases:** DR and data

Roma - September 11th, 2013
Nucleon Form Factors in Experiments and Theory
"To do" list

Time-like $|G_E| - |G_M|$ separation:
DR and data

Understanding threshold effect(s):
Dispersive analyses: integral equation, sum rule, ...
Experimental observation in $p\bar{p} \rightarrow \pi^0 l^+ l^-$
[PRC75,045205(07)]

Asymptotic behavior: DR and data for the phase

Zeros ↔ phases: DR and data