Proton Form Factors measurements in the Time-like Region

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7th European Research Conference on
Electromagnetic Interactions with Nucleons and Nuclei
EINN 2007
September 10-16, 2007  Milos
Outline:

- BABAR measurement of $e^+e^- \rightarrow p\bar{p}$ by means of ISR events
  - analysis strategy
  - cross section and BF of charmonium states

- Form Factors:
  - definitions and main properties
  - measurement of the ratio $|G_E/G_M|$
  - review of $|G_M|$ measurements
  - asymptotic behavior $\rightarrow$ fit to pQCD predictions
  - puzzling behavior at $p\bar{p}$ threshold
  - $\Lambda$ and neutron time-like form factors

- Conclusions and perspectives
Initial State Radiation: motivations

 ISR studies at the $\Upsilon(4S)$ can yield the same observables as the low energy $e^+e^-$ experiments

- precise measurements of $e^+e^-$ cross sections at low c.m. energy
- hadron spectroscopy for $1 < \sqrt{s} < 5$ GeV
- form factors (this talk)
- new states discovery (e.g. $Y(4260)$)

- measurement of the ratio 
  \[ R(s) = \frac{\sigma_{e^+e^-\rightarrow\text{hadrons}}(s)}{\sigma_{e^+e^-\rightarrow\mu^+\mu^-}(s)} \]
ISR cross section

Born approximation

\[
\frac{d\sigma_{e^+e^-\rightarrow p\bar{p}\gamma}}{dm \, d\cos\theta^*_\gamma} = \frac{2m}{s} W(s, x, \theta^*_\gamma) \cdot \sigma_{e^+e^-\rightarrow p\bar{p}}(m_{p\bar{p}})
\]

\[
x = \frac{2E^*_\gamma}{\sqrt{s}} \quad m^2_{p\bar{p}} = q^2 = s(1 - x)
\]

\[\theta^*_\gamma: \text{ISR angle in } e^+e^-\text{ c.m.}\]

Radiator function:

\[
W(s, x, \theta^*_\gamma) = \frac{\alpha}{\pi \cdot x} \left( \frac{2 - 2x + x^2}{\sin^2\theta^*_\gamma} - \frac{x^2}{2} \right)
\]

\[e^+e^- \rightarrow p\bar{p} \text{ cross section}\]

\[
\sigma_{p\bar{p}}(m) = \frac{(dN / dm)}{\varepsilon (1 + \delta_{\text{rad}})(dM / dm)}
\]

reconstruction efficiency
radiative corrections

ISR differential luminosity

\[
\frac{dM}{dM} = \frac{2m}{s} \frac{\alpha}{\pi \cdot x} \cdot \left( 2 - 2x + x^2 \right) \log \frac{1+C}{1-C} - x^2 C \right) L_{ee}
\]

- obtained from integration of the radiator function over \(\theta^*_\gamma\)
- known at 1% level (from MC simulation)
- \(20^\circ < \theta^*_\gamma < 160^\circ \implies\) acceptance for ISR photon \(~15\%\) in BABAR
ISR in **BABAR**

- uniform data quality all-over the energy range
  - no systematics from point-to-point normalization
- statistically very competitive sample
  - largest sample of $e^+e^- \rightarrow p\bar{p}$ events collected up to now
- c.m. boost
  - at threshold $\varepsilon \neq 0$
- hard photon detected:
  - event tagging $\Rightarrow$ loose hadron selection
  - hadronic system at wide angle (in LAB ref)
    - large geometric acceptance
    - full $p\bar{p}$ angular coverage (in $p\bar{p}$ c.m.)
- higher background

**BABAR** $L_{ee} = 89.3$ fb$^{-1}$

**DM/dm** (nb$^{-1}$/0.1 GeV)
Analysis strategy

Events selection:

- require “hard” $\gamma + 2$ tracks of opposite charge identified as protons
- $\pi/K/p$ discrimination using $dE/dx$ and Cherenkov angle
- kinematic fit requiring $p$ and $E$ conservation ,
- select signal according to fit $\chi^2$

Monte Carlo simulations used for detector acceptances, selection efficiencies and estimates of different background sources:

- ISR generators based on:
- multiple ISR soft photons:
  - M.Caffo et al, N. C. 110A(1997)515
- final state radiation: (PHOTOS)

4025 events selected in 232 fb$^{-1}$ of data

- $\sim$6% residual background, dominated by non ISR $e^+e^- \rightarrow p\bar{p} \pi^0$
**$e^+e^- \rightarrow p\bar{p}\gamma$: efficiency**

- Determined by MC simulation and corrected by Data/MC differences
- Corrections for:
  - $\chi^2$ shape
  - Nuclear interactions with detector material
  - Particle-ID
  - Photon detection (use $e^+e^- \rightarrow \mu^+\mu^-\gamma$ data)
  - Dependence on $G_E$ and $G_M$
  - Triggering

**efficiency vs $m_{p\bar{p}}$**

- $m_{pp} < 3\text{GeV} / c^2$
- $3 < m_{pp} < 4.5\text{GeV} / c^2$

**efficiency vs $\cos\theta_p$**

- Maximum deviation from mean value < 10%
$e^+e^- \rightarrow p\bar{p}\gamma$: cross section

$\sigma(e^+e^- \rightarrow pp)$

**PRD 73, 012005 (2006)**

**Mode** | **BaBar BF** | **PDG 06**
--- | --- | ---
$J/\psi \rightarrow p\bar{p}$! | $(2.22 \pm 0.16) \times 10^{-3}$ | $(2.17 \pm 0.08) \times 10^{-3}$
$\psi(2S) \rightarrow p\bar{p}$! | $(3.3 \pm 0.9) \times 10^{-4}$ | $(2.65 \pm 0.22) \times 10^{-4}$
**FF: Space-like and Time-like region**

**Space-like**

\[ q^2 < 0 \]

\[ \gamma^*(q) \]

\[ \Gamma^\mu(q) \]

**Time-like**

\[ q^2 = s > 0 \]

\[ \gamma^*(q) \]

\[ \Gamma^\mu(q) \]

\[ \Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}}{2M_N} q_\nu F_2(q^2) \]

- **Dirac (F_1) and Pauli (F_2) F.F.**
  \[ F_1^p(0) = 1 \quad F_2^p(0) = 1 \]
  \[ F_1^n(0) = 0 \quad F_2^n(0) = 1 \]

- **Sachs FF:**
  - **Electric (G_E):**
    \[ G_E(q^2) \equiv F_1(q^2) + \frac{q^2}{4M^2} F_2(q^2) \]
  - **Magnetic (G_M):**
    \[ G_M(q^2) \equiv F_1(q^2) + F_2(q^2) \]
**FF: Space-like and Time-like region**

- **Elastic scattering**

\[
\frac{d\sigma}{d\Omega}(q^2, \theta) = \sigma_M \left[ G_E^2 - \tau \left( 1 + 2(1 - \tau) \tan^2 \frac{\theta}{2} \right) G_M^2 \right]
\]

\[
\sigma_M = \frac{\alpha^2 E^2 \cos^2 (\theta / 2)}{4E^3 \sin^4 (\theta / 2)} \quad \quad \tau \equiv \frac{q^2}{4M^2}
\]

- **Annihilation**

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

\[
\beta = \sqrt{1 - \frac{1}{\tau}} \quad \quad C = \frac{y}{1 - e^{-y}} \quad \quad y = \frac{\pi \alpha M_p}{\beta q}
\]

C: correction for Coulomb interaction at threshold.
Not present in \( e^+e^- \rightarrow n\bar{A}, \Lambda\bar{\Lambda} \)
FF properties: analyticity and asymptotic behavior

- by definition, at threshold: \( G_E(4m_p^2) = G_M(4m_p^2) \)
- perturbative QCD constrains the FF asymptotic behavior
- \( q^2 \rightarrow -\infty \quad G_{E,M} \rightarrow \frac{\text{constant}}{q^4 \ln \left( \frac{q^2}{\Lambda_{QCD}^2} \right)^2} \)
- \( q^2 \rightarrow \pm \infty \quad G_{E,M}(q^2) = G_{E,M}(-q^2) \)
Measurement of the proton FF

- The moduli of the FF in the time-like region can be derived from measurements of the cross sections of \( e^+e^- \leftrightarrow p\bar{p} \) processes.
- Many measurements both from \( e^+e^- \rightarrow p\bar{p} \) and \( p\bar{p} \rightarrow e^+e^- \) experiments.
- Most experiments collected very low statistics \( \Rightarrow \) impossible to disentangle \( |G_E| \) and \( |G_M| \).

**Extract \( |G_M| \) from the total cross section under the arbitrary assumption \( |G_M| = |G_E| \)**

\[
\sigma = \frac{4\pi\alpha^2 \beta C}{3m_{p\bar{p}}^2} |F|^2, \quad |F| = \sqrt{|G_M|^2 + \frac{1}{2\tau}|G_E|^2}
\]

**Quantitative information on \( |G_E| \)**

only by PS170 and BABAR

(by measuring the ratio \( |G_E|/|G_M| \) from angular distributions)

\[
\frac{d\sigma}{d\cos\theta} \propto \left(1 + \cos^2\theta\right) + \tau \left|\frac{G_E}{G_M}\right|^2 \sin^2\theta
\]
Time-like $|G_E/G_M|$ measurements

- **BABAR** measured angular distribution from threshold up to $\sim 3$ GeV/$c^2$
- Observed maximum at $m \approx 2$ GeV/$c^2$ ($G_E$ dominance after threshold)
- Inconsistent with PS170 measurements at LEAR
- Strong point in favour of ISR method: very weak angular dependence of detection efficiency

\[
\frac{d\sigma(G_M)}{d\cos\theta} \sim 1 + \cos^2 \theta_p
\]
\[
\frac{d\sigma(G_E)}{d\cos\theta} \sim \sin^2 \theta_p
\]
**History of $|G_M|$ measurements**

**First successful measurements:**

- **1973** $p p \bar{p} @ ADONE$ (Frascati)
  - $e^+ e^- \rightarrow p \bar{A}$
  - 25 events in 0.2 pb$^{-1}$ of data at 4.4 GeV$^2$
History of $|G_M|$ measurements

First successful measurements:
- **1973 ppbar @ ADONE (Frascati)**
  - $e^+e^- \rightarrow p\bar{A}$
  - 25 events in 0.2 pb$^{-1}$ of data at 4.4 GeV$^2$

70’s and 80’s:
- **ELPAR exp. (CERN)**
  - $p\bar{A}$ annihilations at rest
- **DM1, DM2 @ DCI (Orsay)**
  - $e^+e^- \rightarrow p\bar{A}$
  - 0.7 pb$^{-1}$ of data collected
  - first attempts to measure angular distributions
History of $|G_M|$ measurements

Experiments in the 90’s:

- **FENICE @ ADONE**
  - Mainly devoted to neutron FF measurement
  - 69 $e^+e^- \rightarrow p\bar{p}$ events in 4 $q^2$ bins

- **PS170 @ LEAR (CERN)**
  - First high statistics experiments
  - $\bar{p}$ beam stopped in a liquid $H$ target
  - 3667 $p\bar{p} \rightarrow e^+e^-$ events in 9 $q^2$ bins
  - Angular distribution measured compatible with $|GE| = |GM|

- **E760 and E835 (FNAL)**
  - $p\bar{p} \rightarrow e^+e^-$ (fixed target)
  - First measurements of FF at high $q^2$
History of $|G_M|$ measurements

New $e^+e^-$ colliders

- **CLEO @ CESR (2005)**
  - Only 14 events

- **BES @ BEPC (2005)**
  - 9 $q^2$ bins from 4 GeV$^2$ up to 9 GeV$^2$ (~200 events total)
  - No angular measurements
  - Assume $|G_E| = |G_M|$ 

- **BaBar @ PEP-II (2006)**
  - ISR events
  - ~4000 events divided in ~40 $q^2$ bins
  - Results presented assuming $|G_E| = |G_M|$
Closer look at the results:

Fit to the pQCD prediction (assuming $\Lambda = 0.3$ GeV):

Asymptotic behavior holds already for $m_{pA} > 3$ GeV/$c^2$
Closer look at the results:

Steep rise of the FF at threshold seen by PS170 and BABAR.

Sharp drops at $m_{pA} \sim 2.2$ and 3.0 GeV,
- no interpretations yet
- seen also in cross section distribution

Steep rise of the FF at threshold seen by PS170 and BABAR.
Why the rise of FF at threshold?

- Similar behavior observed in the $p\bar{A}$ mass spectrum in processes with different dynamics:

  Mass spectrum of the $p\bar{A}$ system in several $B$ decays compared to FF distribution:

  \begin{itemize}
  \item \textbf{BABAR} $\cdot B^0 \rightarrow D^{(s)} \bar{p} p(\pi)$ avg.
  \item FF $e^+ e^- \rightarrow \bar{p} p$ (via ISR)
  \item $B^+ \rightarrow \bar{p} p K^+$
  \end{itemize}

  \textbf{BABAR} measurement of $J/\psi \rightarrow p\bar{A} \gamma$

  Sharp peak of $m_{p\bar{A}}$ at threshold opposite C-parity

  Fits consistent with a sub-threshold resonant structure with $J^{PC} = 0^{++}$
  \((m \sim 1860 \text{ MeV}/c^2, \Gamma < 30\text{MeV})\), inconsistent with known states

  \textbf{BES} measurement of $J/\psi \rightarrow p\bar{A} \gamma$

  Similar results on $B$ decays published by \textbf{Belle}:

  \textbf{PRL} \textbf{89}, \textbf{151802} (2002)

  \textbf{PRD} \textbf{72}, \textbf{051101} (2005)
  \textbf{PRD} \textbf{74}, \textbf{051101} (2006)
A possible explanation

- The rise is the tail of a narrow resonance below threshold $\Rightarrow$ Baryonium

- This hypothesis can be tested:
  - A meson $V_0$, with vanishing coupling to $e^+e^-$, which decays through a $\rho/\omega$ recurrence ($V_1$), should show up as a dip in several hadronic cross sections

\[
A \propto \frac{1}{s - M_1^2} \left( 1 + a \frac{1}{s - M_0^2} a \frac{1}{s - M_1^2} + \ldots \right)
\]

\[
A = \frac{s - M_0^2}{(s - M_1^2)(s - M_0^2) - a^2}
\]

P.J. Franzini and F.J. Gilman (1985)
Example: observed dip in $6\pi$ production

$e^+e^- \rightarrow 3\pi^+3\pi^-$

$e^+e^- \rightarrow 2\pi^+2\pi^-2\pi^0$

<table>
<thead>
<tr>
<th>$V_0$</th>
<th>$M(\text{MeV}/c^2)$</th>
<th>$\Gamma(\text{MeV})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>hadrons</td>
<td>$\sim 1870$</td>
<td>10±20</td>
</tr>
<tr>
<td>DM2</td>
<td>1930(30)</td>
<td>35(20)</td>
</tr>
<tr>
<td>FOCUS</td>
<td>1910(10)</td>
<td>37(13)</td>
</tr>
<tr>
<td>BABAR</td>
<td>1880(50)</td>
<td>130(30)</td>
</tr>
<tr>
<td>BABAR ($\pi^0$)</td>
<td>1860(20)</td>
<td>160(20)</td>
</tr>
</tbody>
</table>

DM2

FOCUS diffractive photoproduction

$e^+e^- \rightarrow 3\pi^+3\pi^-$

PL B514, 240 (2001)
Neutron Form Factor

- Measurements only from FENICE and DM2 experiments
- No Coulomb correction at threshold $\Rightarrow \sigma(s=4m_n^2) = 0$

Need to be clarified with new neutron FF measurements

| $|G_M^n|/|G_M^p|$ | DM2 extr. from $G^A$ |
|-----------------|------------------|
| data            | $\sim 1.5$       |
| naively         | $\sim |Q_d/Q_u| = 0.5$ |
| pQCD            | $< 1$            |
Measurement of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ cross section and $\Lambda$ FF

- $e^+e^- \rightarrow \gamma\Lambda\bar{\Lambda}$ recently measured at BABAR (presented at LP2007, submitted to PRD)

NEW BABAR RESULT!

- $\sigma(e^+e^- \rightarrow \Lambda\bar{\Lambda})$

$$\begin{array}{c}
\text{Cross section (pb)}
\end{array}$$

- $|G_M^\Lambda| \text{ vs } m_{\Lambda\bar{\Lambda}}$

$$\begin{array}{c}
\text{Form factor}
\end{array}$$

Analyzed: 232 fb$^{-1}$
Signal: 204 ± 19
Background: 15 ± 3
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$ angular distributions

- Extract $|G_E/G_M|$ from angular distributions:

| $m_{\Lambda\bar{\Lambda}}$, GeV/$c^2$ | N   | $N_{bkg}$ | $|G_E/G_M|$       |
|----------------------------------|-----|-----------|------------------|
| 2.23-2.40                        | 120 | 3 ± 5     | $1.73^{+0.99}_{-0.57}$ |
| 2.40-2.80                        | 96  | 10 ± 6    | $0.71^{+0.66}_{-0.71}$ |

- Compatible with $|G_E/G_M|=1$, but also with results from proton FF
If the relative phase $\phi$ between $G_E$ and $G_M$ is different from zero, the outgoing baryons are polarized in the direction normal to the scattering plane


Polarization measured using correlation between the directions of the $\Lambda$ polarization vector and the momentum of decay proton in $\Lambda$ rest frame

$$\frac{dN}{d \cos \theta_{p\bar{\xi}}} = A(1 + \alpha_\Lambda \zeta_f \cos \theta_{p\bar{\xi}}), \quad \alpha_\Lambda = 0.642 \pm 0.013$$

with the polarization $\zeta_f \propto \sin \phi$

- Slope in data is $0.020 \pm 0.097$ for $M_{\Lambda\Lambda} < 2.8$ GeV
  $$-0.22 < \zeta_f < 0.28 \quad (90\% \ CL)$$

- Under $|G_E| = |G_M|$ assumption
  $$-0.76 < \sin \phi < 0.98$$
Baryons FF measurement in BABAR

![Graph showing |G_M| versus m(GeV/c^2) for different baryons.](image)

- **Λ**
- **Σ^0**
- **ΛΣ^0**
Summary

- Time-like Proton FF have been measured at several $e^+e^-$ and $p\bar{p}$ facilities for the last ~30 years, most of them statistically limited.

Precise results from BABAR obtained via ISR:
- most accurate measurements of $\sigma(e^+e^-\rightarrow p\bar{p})$ and proton FF
- FF measured from threshold up to $q^2 \sim 20 \text{ GeV}^2$
- drops in the cross section and FF observed at $q^2 \sim 4.4$ and $9 \text{ GeV}^2$
- enhancement at threshold of the FF confirmed
- $|G_E/G_M|$ measured via angular distribution for $q^2 < 9 \text{ GeV}^2$
  - $|G_E/G_M| > 1$ just above threshold (disagreement with previous results).

- Other open questions in Nucleon FF measurements:
  - $|G_M^n| > |G_M^p|$ contrary to expectations
  - JLab results on space-like proton FF

New results from BABAR on $\Lambda$ Form Factors:
- $\sigma(e^+e^-\rightarrow \Lambda\Lambda)$ and $\Lambda$ FF measured from threshold up to $3 \text{ GeV}$
- Angular distribution and polarization measurements ==> first attempts to determine $|G_E/G_M|$ and relative phase between $G_E$ and $G_M$
Perspectives

- **BABAR**:  
  - will have 4X data by 2008 ==> increase the precision on $p\bar{A}$ and $\Lambda\bar{\Lambda}$  
  - expected new results from Belle in a near future

- $\tau$/charm factory at Beijing can use ISR, too

- **VEPP-2000 (BINP)**:  
  - near threshold $e^+e^- \rightarrow p\bar{A}$

- **PANDA @ GSI**:  
  - $p\bar{A} \rightarrow e^+e^-$ up to 20 GeV$^2$

- ? **DANAE (Frascati)** $e^+e^- \rightarrow n\bar{A}$, $e^+e^- \rightarrow p\bar{A}$

- ? **Super-B factory**
PEP-II and \textit{BABAR}
\( e^+e^- \rightarrow p\bar{A}\gamma \): background

- 4025 events selected in 232 fb\(^{-1}\) of data
- \( \sim 6\% \) residual background, dominated by non ISR \( e^+e^- \rightarrow p\bar{A}\pi^0 \)

### Background Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>( \pi^+\pi^-\gamma )</th>
<th>( K^+K^-\gamma )</th>
<th>( pp\pi^0 )</th>
<th>( pp\pi^0\gamma )</th>
<th>( uds )</th>
<th>( p\bar{p}\gamma )</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_1 )</td>
<td>5.9 ( \pm 2.5 )</td>
<td>2.5 ( \pm 1.0 )</td>
<td>229 ( \pm 32 )</td>
<td>13 ( \pm 3 )</td>
<td>26 ( \pm 4 )</td>
<td>3737 ( \pm 75 )</td>
<td>4025</td>
</tr>
</tbody>
</table>

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Space-like $G_E/G_M$ measurements

- Scaling law predicts:
  \[ G_E(q^2) \approx G_M(q^2)/\mu_p \]

Jlab measurement polarization method

\[
\frac{G_E(q^2)}{G_M(q^2)} = -\sqrt{\frac{-2\epsilon}{\tau(1+\tau)}} \frac{P_\parallel}{P_\perp} \\
\frac{1}{\epsilon} = 1 + 2(1-\tau)\tan^2\left(\frac{\theta}{2}\right)
\]

2γ + GPD correction
Dispersive analysis of $G_E/G_M$

$|G_E(q^2)/G_M(q^2)|$

$pQCD$ prediction

$B\overline{B}AR$ – PS170 comparison

Comparison of baryon FF measured by BABAR

\[ \text{Form factor} \]

\[ Q \text{ (GeV)} \]

\[ \begin{array}{c}
\Delta p \\
\bullet \Lambda \\
\circ \Sigma^0 \\
\triangledown \Lambda \Sigma^0 \\
\end{array} \]