Measurement of the Proton Form Factor in $e^+e^-\text{ Annihilation at } BaBar$

Concetta Cartaro
SLAC
On Behalf of the $BaBar$ Collaboration

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**BaBar Dataset**

Data used for the analyses presented:
- On $\Upsilon(4S)$ resonance (10.58 GeV): 424 fb$^{-1}$
- Off $\Upsilon(4S)$ resonance (10.54 GeV): 45 fb$^{-1}$

**Graph:**
PEP II Delivered Luminosity: 553.48 fb
BaBar Recorded Luminosity: 531.43 fb
BaBar Recorded $\Upsilon(4S)$: 432.80 fb
BaBar Recorded $\Upsilon(3s)$: 30.23 fb
BaBar Recorded $\Upsilon(2s)$: 14.45 fb
Off Peak Luminosity: 53.85 fb

$\Upsilon(15)$ decays accessed via $\Upsilon(25,35) \rightarrow \Upsilon(15) \pi^+\pi^-$

**Diagram:**
- 1.5T Solenoid
- EMC
- DIRC
- SVT
- DCH
- IFR
- e$^+$ (3.1 GeV)
- e$^-$ (9 GeV)
**Nucleons Form Factors**

Space-like

\[ q^2 < 0 \]

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

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

- Dirac (F_1) and Pauli (F_2) FF
  \[ F_1^p(0) = 1 \quad F_2^p(0) = k_p \]
  \[ F_1^n(0) = 0 \quad F_2^n(0) = k_n \]
  \[ k_n = \text{nucleon anomalous magnetic moment} \]

- Notable points:
  \[ G_E(0) = 1 ; \quad G_M(0) = 2.79 \]
  \[ |G_E(4m_p^2)| = |G_M(4m_p^2)| \quad (p\bar{p} \text{ production threshold}) \]

Time-like

\[ q^2 = s > 0 \]

- Sachs FF: Electric (G_E) and Magnetic (G_M)
  \[ G_E(q^2) \equiv F_1(q^2) + \frac{q^2}{4M^2} F_2(q^2) \]
  \[ G_M(q^2) \equiv F_1(q^2) + F_2(q^2) \]
\[ e^+ e^- \rightarrow p \bar{p} \text{ CROSS SECTION} \]

- Cross section of the annihilation process:

\[ \sigma(s) = \frac{4\pi\alpha^2\beta C(s)}{3s} \left( |G_M(s)|^2 + \frac{2m_p^2}{s} |G_E(s)|^2 \right) \]

\[ \sqrt{s} = 2E_{\text{beam}}^* \]

\[ C \text{ is the Coulomb factor} \rightarrow \text{The cross section is non-zero at the threshold} \]

- The ratio \(|G_E/G_M|\) can be determined from the analysis of the polar angle distribution of the proton:

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

- From the measured cross section we define an effective form factor:

\[ |F_p(s)| = \sqrt{\frac{|G_M(s)|^2 + (2m_p^2/s) |G_E(s)|^2}{1 + 2m_p^2/s}} \]

- At high energies \(G_E\) is suppressed as \(1/E^2\) and \(|F_p| \sim |G_M|\).
Below 3.2 GeV:

- Statistical accuracy of these measurements is (20-30)%.
- Limited statistics does not allow to extract the $G_E/G_M$ ratio from the analysis of the angular distribution.
Near threshold data were obtained at the PS170 experiment at the antiproton storage ring LEAR (CERN):

- Steep growth of the form factor near threshold.
- The ratio $|G_E/G_M|$, measured with 30% accuracy in five energy points, agrees with unity

Measurements above 3GeV were performed at FNAL (E835 and E760)

The very precise points marked “NU” (Phys. Rev. Lett. 110 (2013) 022002) were obtained using CLEO data (~1/fb) collected at 3.77 and 4.17 GeV
The ISR Method (1/2)

- The $p\bar{p}$ mass spectrum in $e^+e^-\rightarrow \gamma p\bar{p}$ is related to the cross section for the non radiative process $e^+e^-\rightarrow p\bar{p}$.

- $W(s,x,\theta)$ is calculated from QED and describes angular ($1/\sin^2\theta$ at $\theta >> m_e/\sqrt{s}$) and energy ($1/x$) distributions of the ISR photon.

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

\[
x = \frac{2E_{\gamma}}{\sqrt{s}} = 1 - \frac{m^2}{s}
\]
The ISR Method (2/2)

- The ISR photon is emitted predominantly along the beam axis. The produced hadronic system is boosted against the ISR photon. Due to limited detector acceptance the mass region below 3 GeV can only be studied with detected photons (about 10% of ISR events).
- The statistics can be significantly increased above 3 GeV by using small-angle ISR.

From now on:
LA = Large angle
SA = Small angle
ADVANTAGES OF THE ISR METHOD

- A wide energy region is studied in a single experiment.
  - The effective ISR luminosity (pb\(^{-1}\)/GeV) increases with mass, partly compensating a decrease of the measured cross section.

- Low dependence of the detection efficiency on the hadronic invariant mass.
  - Measurement near and above threshold with the same selection criteria.

- Low dependence of the detection efficiency on hadron angular distributions (in the hadron rest frame).
  - For protons this significantly increases sensitivity for measurements of the \(G_E/G_M\) ratio.
**LA EVENT SELECTION**

- The LA analysis is published in:

- 2 tracks of opposite charge originating from the IP and identified as protons ($25.8^\circ < \theta < 137.5^\circ$).
- A photon with $E_{CM} > 3$ GeV ($20.0^\circ < \theta < 137.5^\circ$).
- Kinematic fit to $e^+e^- \rightarrow \gamma h^+h^-$ ($h=p,K$) requiring $p$ and $E$ conservation.
- $e^+e^- \rightarrow \gamma \pi^+\pi^-$, $\gamma \mu^+\mu^-$, $\gamma K^+K^-$ backgrounds suppressed by PID requirements and $\chi^2$ cuts.
**Backgrounds for LA Selection**

- Main background from \(e^+e^- \rightarrow p\bar{p}\pi^0\)
  - Undetected low-energy photon or merged photons from the \(\pi^0\) decay.
  - Estimated from data using a control sample of \(e^+e^- \rightarrow p\bar{p}\pi^0\) events.
    - Increases from 5% at \(M_{pp} < 2.5\) GeV to 50% at 4 GeV.
  - All data events observed above 4.5 GeV are explained by this background.

<table>
<thead>
<tr>
<th>Data</th>
<th>pp(\gamma)</th>
<th>pp(\pi^0)</th>
<th>ISR and (e^+e^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8298</td>
<td>7741±113</td>
<td>448±42</td>
<td>109±30</td>
</tr>
</tbody>
</table>

Reconstructed pp mass spectrum

Data: 8298 events

- \(J/\psi\)
- \(\psi(2S)\)
SA Event Selection

- 2 tracks of opposite charge originating from the IP and identified as protons \(25.8^\circ < \theta < 137.5^\circ\)
- \(P_T < 0.15 \text{ GeV}/c\)
- \(|M_{\text{rec}}^2| < 1 \text{GeV}^2/c^4\)

\[e^+e^- \rightarrow \gamma p\bar{p} \text{ (MC)}\]

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SA analysis is a preliminary result:

No requirement on the ISR photon!
The dominant background process is \( e^+e^- \rightarrow \gamma p \bar{p} \pi^0 \).

The main background in our large-angle ISR analysis from \( e^+e^- \rightarrow p \bar{p} \pi^0 \) is found to be negligible.

Selected events: 845.

Non resonant events: 149.

No events are observed with mass above 6 GeV/c^2.
LA ANGULAR DISTRIBUTION

$\theta_p$ is the angle between the proton momentum in the $pp$ rest frame and the momentum of $pp$ system in the $e^+e^-$ c.m. frame.

The distribution is fitted by a sum of histograms from two simulated samples, one with $G_E=0$ (dashed) and other with $G_M=0$ (dot-dashed).
**LA ANGULAR DISTRIBUTION ASYMMETRY**

- The asymmetry is absent in lowest order ($\gamma^* \rightarrow p\bar{p}$). It arises from higher-order contributions (soft extra ISR and FSR interference, two-photon exchange). By measuring the asymmetry we control the higher-order contributions.

- We analyze the difference between the measured and fitted distributions.
  - The slope is $-0.041\pm0.026\pm0.005$
  - The integral asymmetry:
    \[ A = \frac{\sigma(\cos \theta_p > 0) - \sigma(\cos \theta_p < 0)}{\sigma(\cos \theta_p > 0) + \sigma(\cos \theta_p < 0)} = -0.025\pm0.014\pm0.003 \]
**MEASURED CROSS SECTION**

\[ \sigma_{ee \rightarrow p\bar{p}}(m) = \frac{dN/dm}{\varepsilon RD/dm} \]

- Mass-independent systematic uncertainty is 4-5% for LA ISR. For SA ISR it decreases from 16% at 3 GeV to 6% at 4.5 GeV.
- In the mass region under study the cross section changes by about six orders of magnitude.
- Our data are in reasonable agreement with previous measurements.
- We improve accuracy and extend the mass region of measurements.
**Effective Proton Form Factor**

- A steep fall off and $G_E/G_M \neq 1$ near threshold are explained by nucleons’ final state interaction.
- A complex step-like behavior far off threshold (steps at 2.2, 2.55, 3 GeV/c²) is not described by existing models.
QCD MOTIVATED FIT

- All the data above 3 GeV except the two "NU" points are well described by this function.
- Adding the "NU" points change the fit $\chi^2/\nu$ from 17/24 to 54/26.
- Our data shows that the form factor decreases in agreement with the asymptotic QCD prediction or even faster above 4.5 GeV.

$$G_M \sim \frac{\alpha_s^2(m^2)}{m^4} \sim \frac{1}{m^4 \ln^2(m^2 / \Lambda^2)}$$
The points “SLAC 1993” represent data on the space-like magnetic form factor measured in \(ep\) scattering as a function of \(\sqrt{-q^2}\).

- The asymptotic values of the space- and time-like form factors are expected to be the same.
- In the mass region from 3 to 4.5 GeV the time-like form factor is about two times larger than the space-like one.

Our two points above 4.5 GeV may give an indication that the difference between the time- and space-like form factors begins to decrease.
**J/ψ AND ψ(2S) DECAYS**

- **B(J/ψ→p̅p) x 10^{-3}**
  - SA: $2.33±0.08±0.09$
  - LA: $2.04±0.07±0.07$
  - PDG: $2.17±0.07$

- **B(ψ(2S)→p̅p) x 10^{-4}**
  - SA: $3.14±0.28±0.18$
  - LA: $2.86±0.51±0.09$
  - PDG: $2.76±0.12$

- **LA ISR**
- **SA ISR**
SUMMARY

• The $e^+e^-\rightarrow p\bar{p}$ cross section and the proton effective form factor have been measured from threshold up to 6.5 GeV using the full BaBar data sample.

• The form factor shows a complex mass dependence. There are a near-threshold steep fall off and a step-like behavior at higher masses.

• The $|G_E/G_M|$ ratio has been measured from threshold up to 3 GeV/$c^2$. A large deviation of this ratio from unity is observed below 2.2 GeV/$c^2$.

• Asymmetry in the proton angular distribution has been measured.

• At masses above 3 GeV the observed decrease of the form factor agrees with the asymptotic dependence $\alpha_s^2(m)/m^4$ predicted by QCD.

• New measurements expected: VEPP2000, BES, FAIR,...
**ISR CROSS SECTION**

Born approximation

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

$$x = \frac{2E^*_\gamma}{\sqrt{s}}$$
$$m^2_{\bar{p}p} = q^2 = s (1-x)$$
$$\theta^*_\gamma: \text{ISR angle in } e^+e^- \text{ c.m.}$$

Radiator function:

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

$$e^+e^- \rightarrow \bar{p}p \quad \text{cross section}$$

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

- **reconstruction efficiency**
- **radiative corrections**

ISR differential luminosity

$$\frac{dL}{dM} = \frac{2m}{s} \frac{\alpha}{\pi \cdot x} \left[ (2-2x+x^2) \log \frac{1+C}{1-C} - \frac{x^2C}{2} \right] L_{ee} \cos \theta^*_{\text{min}}$$

- Obtained from integration of the radiator function over $\theta^*_\gamma$
- Known at 1% level (from MC simulation)
- $20^\circ < \theta^*_\gamma < 160^\circ \rightarrow \text{acceptance for ISR photon } \sim 10-15\% \text{ in BABAR}
**CROSS SECTION**

- **LA ISR** ($20^\circ < \theta_{\gamma^*} < 160^\circ$)

- **SA ISR** (Preliminary)

\[
\sigma_{ee \rightarrow p\bar{p}}(m) = \frac{dN/dm}{\varepsilon R dL/dm}
\]