Proton Form Factors at BESIII

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Outline

- Introduction
- BESIII detector at BEPC;
- Proton FFs
  - with 2012 scan data
  - with \( \psi(3773) \) and XYZ data in ISR mode
  - MC simulated with 2014 scan data
- Summary.
Hadron Form Factors

Fundamental properties of hadrons about charge, magnetization distribution, internal structure. Necessary input for physics. Driving renewed activities on theory side.

Form Factor real

- Cross section (Rosenbluth)
- No single spin observables
- Double spin observables

Form Factor complex

- Cross section (angular Distr.)
- Single spin observables ($P_Y$)
- Double spin observables

$q^2 < 0$
- Space like

$q^2 > 0$
- Time like

$4M_p^2$

Unphysical region

$m_\ell \ll m_p$
Rossenbluth separation on Space-like data

- Fit angular distr. of Time-like data

\[ \mu_\text{p}_{\text{Br}} / G_{\text{M}_\text{p}} \]

\[ Q^2 \text{ (GeV}^2) \]

\( q^2 < 0 \): precision of order %

\( q^2 > 0 \): precision >20%

Time like EM form factor: badly known

PRD 87, 092005 (2013)
Periodic structures in TL proton FFs


oscillation behavior in $G_{\text{eff}}$

$F_{\text{osc}}(p) = A \exp(-Bp) \cos(Cp + D)$.

A possible presence of an imaginary part associated to rescattering processes.

A relative distance of 0.7–1.5 fm between the centers of the forming hadrons.

with world data mainly from Babar

$G_{\text{eff}}$
Beijing Electron Positron Collider (BEPC)

2004: start BEPCII construction
2008: test run of BEPCII
2009: Start of BESIII data taking

Beam energy: 1.0-2.3 GeV

Achieved Design Luminosity on Apr 5th, 2016 : $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
MDC

R inner: 63mm;
R outer: 810mm
Length: 2582 mm
Layers: 43
\[ \sigma_{xy} = 130 \, \mu m, \frac{dE}{dx} \sim 6 \]
\[ \sigma_p/p = 0.5\% \text{ at } 1 \text{ GeV} \]

CsI(Tl) EMC

Crystals: 28 cm(15 \(X_0\))
Barrel: \(|\cos \theta| < 0.83\)
Endcap:
\[ 0.85 < |\cos \theta| < 0.93 \]
Barrel \(\sigma_E \) 2.5\%, \(\sigma_l \) 6mm
Endcap \(\sigma_E \) 5.0\%, \(\sigma_l \) 9mm

RPC MUC

BMUC: 9 layers – 72 modules
EMUC: 8 layers – 64 modules
\[ \sigma_{\text{spatial}} = 1.48 \, \text{cm} \]

TOF

BTOF: two layers
ETOF: 48 crys. for each
\[ \sigma_T(\text{barrel}): 80 \, \text{ps} \]
\[ \sigma_T(\text{endcap}): 110 \, \text{ps} \]
Baryon EM FFs at BESIII

\[ \sigma_{BB}^{Born}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2} \left[ |G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2 \right] \]

**Effective form factor** \( \sigma \propto G(q^2) \)

\[ |G(q^2)| = \frac{\sigma_{BB}^{Born}(q^2)}{\sqrt{\left(1 + \frac{1}{2\tau}\right)\left(\frac{4\pi\alpha^2\beta C}{3q^2}\right)}} \]

Separation of \( |G_E| \) and \( |G_M| \) through angular analysis:

\[ \frac{d\sigma_{BB}^{Born}}{d\Omega_{CM}} = \frac{\alpha^2\beta C}{4q^2} \left[ (1 + \cos^2\theta_B^{CM})|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta_B^{CM} \right] \]

\[ \tau = \frac{q^2}{4M_B^2}, \beta = \sqrt{1 - 1/\tau}, \]

\[ C = \begin{cases} 1, & \text{for a neutral } B\bar{B} \text{ pair, } \sigma \to 0 \text{ assuming coulomb acts after } B\bar{B} \text{ pair are built and they are as point-like particles.} \\ \frac{\pi\alpha}{\beta} \frac{1}{1-\exp(-\pi\alpha/\beta)}, & \text{at threshold } \frac{\pi\alpha}{\beta} \text{ a jump at threshold for charged} \end{cases} \]
Comparison between scan and ISR

- $E_{\text{beam}}$ discrete $\rightarrow q^2$ fixed
  - $q$ very precise $\sim 0.1$ MeV, ideal for threshold studies
- ‘High’ cross section ($\sim$ pb)
  - Low integrated luminosity enough for high statistics
- High geometrical acceptance
  - High detection efficiency

- $E_{\text{beam}}$ fixed $\rightarrow$ Continuous $q^2$-range depends on the ISR
  - Acceptance at threshold $\neq 0$
  - $m^2_{\text{th}} < q^2 < s$
- ‘Small’ cross section ($\sim 10^{-3}$ pb)
  - High luminosities needed
- Small geometrical acceptance: ISR emitted at very large or very small polar angles

Red line is the luminosity of $p\bar{p}\gamma_{\text{ISR}}$ out of 7.4 fb$^{-1}$ dataset at high energy ($\psi(3773)$, XYZ)
Proton Form Factors with scan data 2012

Analysis based on 157 pb\(^{-1}\) collected at 12 scan points between 2.22 – 3.71 GeV in 2011 and 2012

Analysis features:
- \( p \) and \( \bar{p} \) from vertex, in time, back to back, \( E_{p,p} = E_{CM}/2 \)
- \( \varepsilon \times (1 + \delta) \sim 50\%-60\% \)
- Radiative corrections from ConExc (NLO in ISR)
- bkg normalized according to MC calculation

\[
|G| = \sqrt{\frac{\sigma_{\text{Born}}}{L \cdot \varepsilon \cdot (1 + \sigma)}}
\]

\[
\sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \varepsilon \cdot (1 + \sigma)}
\]

\( N_{\text{obs}} \): observed signal events
\( L \): integrated luminosity
\( N_{\text{bkg}} \): estimated background from MC (beam associated bkg, physical bkg, e.g., bhabha, dimu, \( pp \pi^0 \))
\( \varepsilon \): detection efficiency (from MC)
\( 1 + \delta \): radiative factor (from MC)

bkg level very low
- Effective FF consistent with Babar.
- Overall uncertainty improved by 30%.
- No steps observed in cross section.
Angular analysis to extract the EM FFs

Angular analysis to extract the EM FFs:

\[
\frac{d\sigma}{d\Omega} (q^2) = \frac{\alpha^2 \beta}{4s} |G_M(s)|^2 [(1 + cos^2 \theta_p) + R_{EM}^2 \frac{1}{\tau} sin^2 \theta_p]
\]

\[R_{EM} = |G_E(q^2)|/|G_M(q^2)|\]

\[\theta: \text{polar angle of the proton at the c.m. system}\]

Fit function:

\[
\frac{dN}{dcos\theta_p} = N_{norm}[(1 + cos^2 \theta_p) + R_{EM}^2 \frac{1}{\tau} sin^2 \theta_p]
\]

\[N_{norm} = \frac{2\pi \alpha^2 \beta L}{4s} [1.94 + 5.04 \frac{m_p^2}{s} R^2]G_M^2 (s) \text{ is the overall normalization in } |cos\theta_p| < 0.8\]
Method of Moment to extract the EM FFs

\[ R = \sqrt{T \frac{y_4 - y_2 < \cos^2 \theta >}{< \cos^2 \theta > y_1 - y_3} } \]

\[ G_M = \sqrt{\frac{N_{\text{norm}}}{N_1 (y_2 + \frac{R^2}{\tau} y_1) } } \]

\[ < \cos^2 \theta > = \frac{N_1}{N_{\text{norm}}} \int_{x_{\text{min}}}^{x_{\text{max}}} \cos^2 \theta \left\{ \left( 1 + \cos^2 \theta \right) |G_M|^2 + \frac{1}{\tau} (1 - \cos^2 \theta) R^2 \right\} d\cos \theta \]

\[ N_{\text{norm}} = \int_{x_{\text{min}}}^{x_{\text{max}}} \left\{ \left( 1 + \cos^2 \theta \right) |G_M|^2 + \frac{1}{\tau} (1 - \cos^2 \theta) R^2 |G_M|^2 \right\} d\cos \theta \]

\[ N_1 = \frac{L(1 + \delta) hc \pi \alpha^2 \beta C}{2s} \]

\[ y_1 = \int_{x_{\text{min}}}^{x_{\text{max}}} \left( x - \frac{x^3}{3} \right) dx, \quad y_2 = \int_{x_{\text{min}}}^{x_{\text{max}}} \left( x + \frac{x^3}{3} \right) dx, \quad y_3 = \int_{x_{\text{min}}}^{x_{\text{max}}} \left( \frac{x^3}{3} - \frac{x^5}{5} \right) dx, \quad y_4 = \int_{x_{\text{min}}}^{x_{\text{max}}} \left( \frac{x^3}{3} + \frac{x^5}{5} \right) dx \]

Both methods in essence use the angular distribution of proton.
- \( R_{EM} \) consistent with BaBar and \( R=1 \).
- \(|G_M|\) extracted for first time!
Two kinds of analysis:
- photon detected (tagged analysis, ~12% of events)
- photon outside detector (untagged analysis, ~41% of events)
FFs with $e^+ e^- \rightarrow p\bar{p}\gamma_{ISR}$ tagged

<table>
<thead>
<tr>
<th>$\psi''$</th>
<th>2.9 fb$^{-1}$</th>
<th>3.773</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi(4040)$</td>
<td>0.5 fb$^{-1}$</td>
<td>4.009</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>1.9 fb$^{-1}$</td>
<td>4.23 and 4.26</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>0.5 fb$^{-1}$</td>
<td>4.36</td>
</tr>
<tr>
<td>$Y(4420)$</td>
<td>1.0 fb$^{-1}$</td>
<td>4.42</td>
</tr>
<tr>
<td>$Y(4600)$</td>
<td>0.5 fb$^{-1}$</td>
<td>4.60</td>
</tr>
</tbody>
</table>

Analysis for each $E_{CM}$ and $q$, then combine statistics
- Two charged tracks in MDC.
- The photon with the highest energy in EMC tagged as ISR photon.
- ISR kinematics: photon and $p\bar{p}$-system with small opposite polar angles
- From 2.0 GeV up, ISR analysis possible
- Background studied and subtracted with data and MC

- Cross section ($G_{eff}$) in 31 mass intervals. Stat. $\sim$ 5% - 32%
- $R$ in 6 mass intervals. Stat. $\sim$ 16% - 34%
- Consistent result with previous results
- Final statistics competitive with BaBar
- Cross section at threshold
- Systematic error included
FFs with $e^+ e^- \rightarrow p \bar{p} \gamma_{ISR}$ tagged

- Two charged tracks from vertex and with opposite charge
- Identification of non-detected photon based on missing momentum and missing mass
- Background channels are almost suppressed
- Background evaluation and subtraction
- Signal efficiency $\sim 16$

The same datasets as ISR tagged are used

- Final statistics (7.4 fb$^{-1}$) are competitive with BaBar
- Results from data will be released soon
MC study of 2015 scan data

- Similar strategy as 2012 data is used:
- Two charged tracks in MDC with opposite charge
- PID to veto bkg from other two body decays
- EMC information used to veto bhabha: E/p
- Vertex fit to improve momentum resolution

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Totime</th>
<th>Luminosity (pb⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>123 : 01 : 09</td>
<td>10.074 ± 0.005 ± 0.067</td>
</tr>
<tr>
<td>2.05</td>
<td>42 : 25 : 51</td>
<td>3.343 ± 0.003 ± 0.027</td>
</tr>
<tr>
<td>2.1</td>
<td>104 : 54 : 20</td>
<td>12.167 ± 0.006 ± 0.085</td>
</tr>
<tr>
<td>2.12655</td>
<td>~ 21 days</td>
<td>108.49 ± 0.02 ± 0.97</td>
</tr>
<tr>
<td>2.15</td>
<td>28 : 23 : 23</td>
<td>2.841 ± 0.003 ± 0.024</td>
</tr>
<tr>
<td>2.175</td>
<td>102 : 12 : 30</td>
<td>10.625 ± 0.006 ± 0.091</td>
</tr>
<tr>
<td>2.2</td>
<td>113 : 49 : 35</td>
<td>13.699 ± 0.007 ± 0.092</td>
</tr>
<tr>
<td>2.2324</td>
<td>111 : 27 : 27</td>
<td>11.856 ± 0.007 ± 0.087</td>
</tr>
<tr>
<td>2.3094</td>
<td>137 : 27 : 51</td>
<td>21.089 ± 0.009 ± 0.143</td>
</tr>
<tr>
<td>2.3864</td>
<td>89 : 43 : 45</td>
<td>22.549 ± 0.010 ± 0.176</td>
</tr>
<tr>
<td>2.396</td>
<td>222 : 28 : 34</td>
<td>66.869 ± 0.017 ± 0.475</td>
</tr>
<tr>
<td>2.5</td>
<td>5 : 04 : 12</td>
<td>1.098 ± 0.002 ± 0.009</td>
</tr>
<tr>
<td>2.6444</td>
<td>115 : 24 : 39</td>
<td>33.722 ± 0.013 ± 0.216</td>
</tr>
<tr>
<td>2.6464</td>
<td>112 : 05 : 06</td>
<td>34.003 ± 0.013 ± 0.282</td>
</tr>
<tr>
<td>2.700</td>
<td>3 : 44 : 55</td>
<td>1.034 ± 0.002 ± 0.007</td>
</tr>
<tr>
<td>2.800</td>
<td>3 : 57 : 22</td>
<td>1.008 ± 0.002 ± 0.007</td>
</tr>
<tr>
<td>2.900</td>
<td>214 : 01 : 57</td>
<td>105.253 ± 0.025 ± 0.905</td>
</tr>
<tr>
<td>2.950</td>
<td>25 : 35 : 22</td>
<td>15.942 ± 0.010 ± 0.143</td>
</tr>
<tr>
<td>2.981</td>
<td>22 : 25 : 15</td>
<td>16.071 ± 0.010 ± 0.095</td>
</tr>
<tr>
<td>3.000</td>
<td>20 : 53 : 33</td>
<td>15.881 ± 0.010 ± 0.110</td>
</tr>
<tr>
<td>3.020</td>
<td>22 : 22 : 02</td>
<td>17.290 ± 0.011 ± 0.123</td>
</tr>
<tr>
<td>3.080</td>
<td>194 : 48 : 13</td>
<td>126.185 ± 0.029 ± 0.921</td>
</tr>
</tbody>
</table>

MC study with the same luminosity as 2014 data

- Count or fit momentum distribution to get \( N_{\text{obs}} \)
MC study with the same luminosity as 2015 data

Unprecedented accuracies above 2.0 GeV: 0.5% @ 2.125 GeV; 26% @ 2.8 GeV

MC study with the same luminosity as 2015 data

Assuming $R \sim 1$, then:

- precision expected for $R \sim 9\% - 35\%$, comparable as space-like region
- precision expected for $G_M \sim 1\% - 9\%$, for $G_E 3\% - 35\%$ (first time!).
- possible extraction of the forward-backward asymmetry ($2\gamma$–contribution,…)
- periodic structure of TL FFs?
Summary

- Proton FFs measurement with 2012 scan data at BESIII
  - Published

- Proton FFs measurement with $\psi(3773)$ and XYZ data at BESIII
  - ISR tagged in memo stage
  - ISR untagged in memo stage

- Proton FFs measurement with 2014 scan data at BESIII is going on
  - under working
Prospects on proton FFs

Hot topics in EM Form Factor research: $G_E/G_M$, charge radius, unphysical region, threshold behavior, radiative corrections, two-photon exchange, large $Q^2$, interference

- **at VEPP-2000**
  - $e^+e^-$ collider
  - $|G^N_e|/|G^N_M|, |G^N_{\text{eff}}|$ (scan)
  - $q^2 \leq (4.0 \text{ GeV})^2$

- **at BEPCII**
  - $e^+e^-$ collider
  - $|G^B_e|, |G^B_M|, G^A_e/G^A_M$ phase (scan and ISR)
  - $q^2 \leq (3.5 \text{ GeV})^2$

- **at FAIR**
  - $\bar{p}p$ collider
  - $|G^P_e|, |G^P_M|, G^P_e/G^P_M$ phase (?)
  - $(2.4 \text{ GeV})^2 \leq q^2 \leq (3.7 \text{ GeV})^2$

- **at SuperKEKB**
  - $e^+e^-$ collider
  - $q^2 \leq (4.5 \text{ GeV})^2$
A few words about other baryon pairs, similar to $p\bar{p}$

The cross section near threshold does not increase, but flat. Bayron FFs or a new Coulomb factor may interpret?
A few words about other baryon pairs, similar to $n\bar{n}$

Cross section at threshold is non-zero outside of error!

Bayron FFs or a new Coulomb factor (taking into account the quark effect) may interpret?
Thanks for your attention!