Hadron Form Factors at BESIII
(focused on Baryon)

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ON BEHALF OF BESIII
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Hadron Form Factors

All **hadronic structure** and **strong interactions** in form factors but subject to QED corrections. Hadronic vector current: \((2s+1)\) form factors. For baryons with \(\frac{1}{2}\) spin, two electromagnetic FFs.

Form Factor real cross section (Rosenbluth)  
no single spin observables  
double spin observables

Form Factor complex cross section (angular Distr.)  
single spin observables \((P_\gamma)\)  
double spin observables

\[
q^2 < 0 \\
\text{space like}
\]

\[
q^2 > 0 \\
\text{time like}
\]

unphysical region

\[
4M_p^2
\]

\[
q^2[(\text{GeV}/c)^2]
\]
Fundamental properties of hadrons
- Contain information on charge, magnetization distribution
- Crucial testing ground for models of hadron internal structure
- Necessary input for experiments probing hadronic structure, or trying to understand modification of hadronic structure in hadronic medium

Driving renewed activity on theory side:
- Models trying to explain all four EM FFs of Nucleons
- Trying to explain data at both low and high $q^2$
- Progress on QCD based calculations
Rossenbluth separation on Space-like data

Fit angular distr. of Time-like data

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

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

time like EM form factor: badly known

PRD 87, 092005 (2013)
Outline

- BESIII detector at BEPC;
- Proton FFs;
- Neutron FFs;
- $^\Lambda$ FFs;
- $^\Lambda_c$ FFs;
- Other hyperons FFs;
- Summary.
Data Samples at BESIII

e+e- collider

~130 points for R Scan (~1.3 fb⁻¹)
**BESIII DETECTOR**

**Drift Chamber (MDC)**
- $\sigma_{p/p}^{(0)/0} = 0.5\% (1\text{ GeV})$
- $\sigma_{dE/dx}^{(0)/0} = 6\%$

**Time Of Flight (TOF)**
- $\sigma_{T}^{+}$: 90 ps Barrel
- 110 ps endcap

**Super-conducting magnet (1.0 Tesla)**

**$\mu$ Counter**
- 8-9 layers RPC
- $\delta R \Phi = 1.4 \text{ cm} \sim 1.7 \text{ cm}$

**EMC:**
- $\sigma_E / \sqrt{E^{(0)/0}} = 2.5\% (1\text{ GeV})$
- (Csl) $\sigma_{z,\phi}(\text{cm}) = 0.5 - 0.7 \text{ cm/} \sqrt{E}$
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 (assume \(|G_E| = |G_M|\))**:

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

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

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

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

\[ \frac{\pi\alpha}{\beta \left(1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)\right)}, \text{at threshold} \quad \frac{\pi\alpha}{\beta} \quad \text{a jump at} \]

\[ C = \begin{cases} 
1, & \text{for a neutral } B\bar{B} \text{ pair, } \sigma \rightarrow 0 \\
\text{assuming coulomb acts after } B\bar{B} \text{ pair are built and they are as point-like particles.} 
\end{cases} \]
Proton Form Factors with data 2012

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

Analysis features:
- $p$ and $p$ from vertex, in time, back to back, $E_{p,p} = E_{CM}/2$
- Efficiencies 60% (2.23 GeV) ... 3% (~4 GeV)
- Radiative corrections from ConExc (NLO in ISR)
- Normalization to $e^+e^-\rightarrow e^+e^-$, $e^+e^-\rightarrow \gamma\gamma$ (Babayaga 3.5)

$$\sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \varepsilon \cdot (1 + \delta)}$$

$$|G_E| = |G_M| = |G| = \sqrt{\frac{\sigma_{\text{born}}}{(1 + \frac{1}{2}\tau)\left(\frac{4\pi\alpha^2\beta C}{3E_{CM}^2}\right)}}$$

- $N_{\text{obs}}$: observed signal events
- $L$: integrated luminosity
- $N_{\text{bkg}}$: estimated background (from MC)
- $\varepsilon$: detection efficiency (from MC)
- $1 + \delta$: radiative factor (from MC)

- No steps observed in cross section.
- Overall uncertainty improvement by 30%.
- Effective FF consistent with Babar.
Angular analysis to extract the em FFs:

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

\[ R_{em} = \frac{G_E(q^2)}{G_M(q^2)} \]

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

Fit function:

\[ \frac{dN}{d\cos \theta_p} = N_{\text{norm}} \left[ (1 + \cos^2 \theta_p) + R_{em}^2 \frac{1}{\tau} \sin^2 \theta_p \right] \]

\[ N_{\text{norm}} = \frac{2\pi \alpha^2 \beta L}{4s} \left[ 1.94 + 5.04 \frac{m_p^2}{s} R^2 \right] G_M(s)^2 \text{ is the overall normalization} \]
- $R_{em}$ consistent with BaBar and $R=1$.
- $|G_M|$ extracted for first time!

**fitting method and momentum method**

\[
\langle \cos^2 \theta_p \rangle = \frac{1}{N_{\text{norm}}} \int \frac{2\pi \alpha^2 \beta C}{4s} \cos^2 \theta_p [(1 + \cos^2 \theta_p)|G_M|^2 \\
+ \frac{4m_p^2}{s} (1 - \cos^2 \theta_p) |R^2|G_M|^2] d\cos \theta_p.
\]

| $\sqrt{s}$ (MeV) | $|G_E/G_M|$ | $|G_M|$ ($\times 10^{-2}$) |
|------------------|----------------|-----------------|
| 2232.4           | 0.87 ± 0.24 ± 0.05 | 18.42 ± 5.09 ± 0.98 |
| 2400.0           | 0.91 ± 0.38 ± 0.12 | 11.30 ± 4.73 ± 1.53 |
| (3050.0, 3080.0) | 0.95 ± 0.45 ± 0.21 | 3.61 ± 1.71 ± 0.82 |

Fit on $\cos \theta_p$

**Method of moments**

| $\sqrt{s}$ (MeV) | $|G_E/G_M|$ | $|G_M|$ ($\times 10^{-2}$) |
|------------------|----------------|-----------------|
| 2232.4           | 0.83 ± 0.24 | 18.60 ± 5.38 |
| 2400.0           | 0.85 ± 0.37 | 11.52 ± 5.01 |
| (3050.0, 3080.0) | 0.88 ± 0.46 | 3.34 ± 1.72 |
Prospects for $e^+e^- \rightarrow p\bar{p}$

- Expected statistical accuracies or $R_{em}=|G_E|/|G_M|=1$ between 9% and 35% (similar to space-like region for the same $q^2$-region)
- Expected accuracies for $|G_M|$ between 3 to 9%, 9 to 35% for $|G_E|$
Prospects of $e^+e^- \rightarrow p\bar{p}\gamma_{ISR}$

- Continuous $q^2$-range available: $m_{th}^2 < q^2 < s$
- Full angular distribution in hadronic center-of-mass
- Detection efficiency independent of $q^2$ and hadronic angular distribution
- Acceptance at threshold $\neq 0$

Data samples (ECM): $\psi(3770), \psi(4040), Y(4230), Y(4260), Y(4360), Y(4420), Y(4600)$. Total: 7.4 fb$^{-1}$

Analysis for each $E_{CM}$ and $q$, then combine statistics
- ISR kinematics: photon and pp-system with small opposite polar angles
- Efficiencies: ~20% $\gamma$-untagged, ~6% $\gamma$-tagged analysis
- From 2.0 GeV up untagged-photon analysis possible

Final statistics competitive with BaBar
Prospects for $e^+e^- \rightarrow n\bar{n}/n\bar{n}\gamma_{ISR}$

Only two direct measurements of neutron effective FF

Very challenging: energies of $n, \bar{n}$ are not fully deposited in EMC, bkg from $\gamma, K_L^0$, beam, ...

**EMC calorimeter**

CsI(Tl): $15X_0$, $\lambda_I = 171.5\text{ g/cm}^2$, $\rho = 4.53\text{ g/cm}^3$

$\rightarrow$ 52% $n, \bar{n}$ interact in EMC

**MUC: Iron + resistive plates (under study)**

$\lambda_I = 132.1\text{ g/cm}^2$, $\rho = 7.874\text{ g/cm}^3$, 56 cm Fe thickness in barrel  $\rightarrow$  ~96 % $n, \bar{n}$ interact in MUC

Expect the first measurement of $R_{EM}$ with BESIII unprecedented statistics
Prospects for $e^+ e^- \rightarrow n\bar{n}/n\bar{n}\gamma_{ISR}$

**Strategy:**
- First identification of $\bar{n}$ and $\gamma_{ISR}$:
- EMC shower information (for $e^+ e^- \rightarrow n\bar{n}\gamma_{ISR}$ Neural Network) for neutron identification
- Event kinematics (geometry)

$e^+ e^- \rightarrow n\bar{n}$
- $n/\bar{n}$ detection efficiencies of ~20/30% (efficiencies up to % level)
- Main background from beam background processes
  - Unprecedented statistics above 2.0 GeV (~300 evts at 2.4 GeV)

$e^+ e^- \rightarrow n\bar{n}/n\bar{n}\gamma_{ISR}$
- Only tagged analysis possible (efficiencies at per mil level)
- Increase detection efficiency using TOF, MUC
- Main background from $e^+ e^- \rightarrow n\bar{n}\pi^0$ and $e^+ e^- \rightarrow \gamma\gamma\gamma$
“What happens with the baryon structure when a light quark is replaced by a heavier one?”
\[ e^+ e^- \rightarrow \Lambda\bar{\Lambda} \text{ FFs from 2012 data} \]

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

Coulomb factor \( C = 1 \) for neutral \( B\bar{B} \) pair assuming coulomb acts after \( B\bar{B} \) pair are built and they are as neutral point-like particles.

- Expected to increase with the velocity near the threshold starting from ZERO.
- From Babar, \( e^+ e^- \rightarrow \Lambda\bar{\Lambda} \) measured from threshold to 2.27 GeV, non-zero cross section( 204 ± 60 ± 20 pb).

\[
G_E = |G_E(q)| e^{i\Phi_E}, G_M = |G_M(q)| e^{i\Phi_M}, \text{ relative phase } \Phi = \Phi_M - \Phi_E \text{ can be extracted from } \Lambda/\bar{\Lambda} \text{ polarization.} \]
$e^+e^- \rightarrow \Lambda\bar{\Lambda}$ FFs from 2012 data

Data $\sqrt{s} = 2232.4$ MeV, 1.0 MeV above $\Lambda\bar{\Lambda}$ threshold.

**Strategy for** $e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$

i) The momentum of final states are too low to leave message in the detector.
ii) Antiproton interacting on the beam pipe will produce secondary particles, whose vertex is around 3 cm.
iii) The yield of $\Lambda\bar{\Lambda}$ events is $43 \pm 7$.

**Strategy for** $e^+e^- \rightarrow \Lambda\bar{\Lambda}, \Lambda \rightarrow \bar{n}\pi^0$.

i) Multiply Variable Analysis tool (Boosted Decision Tree) is applied to separated from large background.
ii) The final states of $\pi^0$ has a mono-momentum around 105 MeV.
iii) The yield of $\Lambda\bar{\Lambda}$ events is $22 \pm 6$. 
$e^+ e^- \rightarrow \Lambda\bar{\Lambda}$ FFs from 2012 data

\begin{table}
\begin{tabular}{|c|c|c|c|}
\hline
$\sqrt{s}$ (MeV) & Reconstruction & $\sigma_{\text{Born}}$ (pb) & $|G|$ ($\times 10^{-2}$) \\
\hline
2232.4 & $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$  & $325 \pm 53 \pm 46$ & $63.4 \pm 5.7$ \\
& $\bar{\Lambda} \rightarrow \bar{\pi}\pi^0$ & $(3.0 \pm 1.0 \pm 0.4) \times 10^2$ &  \\
& combined & $320 \pm 58$ &  \\
\hline
2400.0 & & 133 $\pm 20 \pm 19$ & \\
2800.0 & & 15.3 $\pm 5.4 \pm 2.0$ & \\
3080.0 & & 3.9 $\pm 1.1 \pm 0.5$ & \\
\hline
\end{tabular}
\end{table}

Surprisingly, large cross section near threshold!

Cross section does not vanish at threshold $\rightarrow$ Coulomb interaction at quark level?

Will be clarified with more data of 2015?
Prospects of $\Lambda\bar{\Lambda}$ FFs

From BESIII 2015 data: 15 points above $\Lambda\bar{\Lambda}$ threshold!

Parity violating decay: $\Lambda \to p\pi$, emission of proton depends on $\Lambda$-polarisation

$$\frac{dN}{d \cos \theta_p} \propto 1 + \alpha_\Lambda P_n \cos \theta_p$$

Imaginary part of FFs leads to polarization observables:

$$P_n = -\frac{\sin 2\theta \sin \Delta \phi / \tau}{R \sin^2 \theta_\Lambda / \tau + (1 + \cos^2 \theta_p) / R} = \frac{3}{\alpha_\Lambda} \langle \cos \theta_p \rangle$$

Expected statistical accuracies for $P_n$ between 6 and 17%

Expected statistical accuracies for $R = |G_E|/|G_M| = 1$ between 14 and 29%

**Complete determination of TL FFs possible!!**
Prospects for $\Lambda_c \bar{\Lambda}_c$ at threshold

$G_E$ and $G_M$ in S/D wave form: $\forall \tau \; G_E = G_S - 2G_D, \; G_M = G_S + G_D$

At threshold, only S wave in principle.

---

Belle ISR process with $\Lambda_c \rightarrow pK_S, pK^-\pi^+,\Lambda\pi^+$

$\sigma_{M_0} = 0.15 \; nb \rightarrow no \; D \; wave$?

- Assuming the same total number of events, the statistical error in retrieving $|G_E/G_M|^2$, from the angular distribution depends almost linearly on $|G_E/G_M|^2$

- $W=4.575 GeV$ at BESIII,
  - $L=42 \; pb^{-1} \rightarrow dR/R \sim 23\%$ (done)
  - $L=200 \; pb^{-1} \rightarrow dR/R \sim 10\%$

*Proposal have been made to collect more $L_{int}$*

\[ e^+e^- \rightarrow \Lambda \Sigma^0, \Sigma^0 \Sigma^0 \text{ previously measured by BaBar, no } R_{em} \text{ extraction possible} \]

\[ e^+e^- \rightarrow \Lambda \Sigma^0, \Sigma^0 \Sigma^0, \Sigma^- \Sigma^+, \Sigma^+ \Sigma^-, \Xi^0 \Xi^0, \Xi^+ \Xi^-, \Omega^+ \Omega^- : \]

measurements of effective FF and \( R_{em} \) and \( P_n \) at single energy points possible

\[ e^+e^- \rightarrow \Lambda_c^- \Lambda_c^+ : \]

measurements of effective FF, \( R_{em} \) and \( |G_M| \) at threshold possible

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
E_{e^+e^-} (GeV) & L (pb^{-1}) & \epsilon_{\Lambda \Sigma^0} (%) & \sigma_{\Lambda \Sigma^0} (pb) & N_{\Lambda \Sigma^0} & \epsilon_{\Sigma^0 \Xi^-} (%) & \sigma_{\Sigma^0 \Xi^-} (pb) & N_{\Sigma^0 \Xi^-} \\
\hline
2.309 & 20 & 4 & 374 & 123 & 4 & 351 & 115 \\
2.386 & 20 & 8 & 40 & 26 & 7 & 100 & 158 \\
2.395 & 55 & 8 & 40 & 72 & 15 & 25 & 100 \\
2.644 & 65 & 15 & 6 & 24 & 15 & 25 & 100 \\
2.9 & 100 & 17 & 2 & 14 & 17 & 3.4 & 24 \\
2.981 & 15 & 17 & 1.5 & 1.6 & 17 & 3.0 & 3 \\
\hline
\end{array}
\]

10 fold more events of the world data could be get!!!
Summary

- BESIII excellent laboratory for hadron form factor measurements: scan data + ISR technique.
- Proton Form Factors and their ratio have been measured using a small amount of data.
- Results on $\Lambda\bar{\Lambda}$ just released.
- New high statistics data between 2.0 and 3.1 GeV will significantly improve FFs measurements for $p, n, \Lambda, \Xi, \Omega, \Sigma, \Lambda_c$. Also from ISR measurements exciting results for nucleon FFs expected.
- ISR technique allows access to energies below 2 GeV: the first result is the charged pion (see Y.Q. Wang’s report).
- Other related topics being studied (not reviewed here):
  - Space-like transition FFs of mesons (di-$\gamma$ contributions to $(g_\mu-2)$)
THANKS FOR YOUR ATTENTION!
Time-like FFs at BESIII

Data collected at BESIII

<table>
<thead>
<tr>
<th>Data sample</th>
<th>Lint</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi$</td>
<td>$\sim 0.45$ fb$^{-1}$</td>
<td>3.097</td>
</tr>
<tr>
<td>$\psi'$</td>
<td>$\sim 0.8$ fb</td>
<td>3.686</td>
</tr>
<tr>
<td>$\psi''$</td>
<td>2.9 fb$^{-1}$</td>
<td>3.773</td>
</tr>
<tr>
<td>xyz</td>
<td>$(0.5+1.9+0.5+1.0+0.5)$ fb$^{-1}$</td>
<td>$(4.2-4.6)$</td>
</tr>
<tr>
<td>scan</td>
<td>$\sim 12$ pb$^{-1}$</td>
<td>2.23, 2.4, (3.05-3.08)</td>
</tr>
<tr>
<td></td>
<td>0.85 fb$^{-1}$</td>
<td>(3.85-4.60)</td>
</tr>
<tr>
<td></td>
<td>525.5 pb$^{-1}$</td>
<td>2.00-3.08</td>
</tr>
</tbody>
</table>
Prospects of $e^+e^- \rightarrow p\bar{p}\gamma_{ISR}$

- Continuous $q^2$-range available: $m^2_{th} < q^2 < s$
- Full angular distribution in hadronic center-of-mass
- Detection efficiency independent of $q^2$ and hadronic angular distribution
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- Efficiencies: ~20% $\gamma$-untagged, ~6% $\gamma$-tagged analysis
- From 2.1 GeV up untagged-photon analysis possible

Final statistics competitive with BaBar

To get the same result as BaBar, the luminosity needed at BESIII:

<table>
<thead>
<tr>
<th>$E$ (MeV)</th>
<th>$L$ (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10579</td>
<td>450</td>
</tr>
<tr>
<td>4260</td>
<td>64.8</td>
</tr>
<tr>
<td>4040</td>
<td>56.6</td>
</tr>
<tr>
<td>3770</td>
<td>47.0</td>
</tr>
<tr>
<td>3686</td>
<td>44.1</td>
</tr>
<tr>
<td>3100</td>
<td>25.6</td>
</tr>
<tr>
<td>2232</td>
<td>4.8</td>
</tr>
</tbody>
</table>

To get the same result as BaBar, the luminosity needed at BESIII:

$E=10579$ MeV $L=450$ pb$^{-1}$
$E=4260$ MeV $L=64.8$ pb$^{-1}$
$E=4040$ MeV $L=56.6$ pb$^{-1}$
$E=3770$ MeV $L=47.0$ pb$^{-1}$
$E=3686$ MeV $L=44.1$ pb$^{-1}$
$E=3100$ MeV $L=25.6$ pb$^{-1}$
$E=2232$ MeV $L=4.8$ pb$^{-1}$