Baryon Form Factors with BESIII

Cui Li (Uppsala University)
on behalf of the BESIII Collaboration

14-19 February, FAIRNESS 2016
Outline

- Motivation
- BEPCII and BESIII
- Nucleon Electromagnetic Form Factors
- Hyperon Electromagnetic Form Factors
- Summary
Motivation
Electromagnetic Form Factors

- The nucleons are the fundamental building blocks of matter

- Clearly understanding nucleons structure is critical to the understanding of the world

- EM FFs are key ingredients to describe the internal structure

- EM FFs provide the most direct access to the spatial charge and magnetization distributions
Baryon electromagnetic form factors

could be studied in:

- **Space-like:**
  - elastic scattering $e^- B \rightarrow e^- B$
  - momentum transfer squared $q^2 < 0$
  - FFs are real as function of $q^2$

- **Time-like:**
  - $e^+ e^- \leftrightarrow B \bar{B}$
  - momentum transfer squared $q^2 > 0$
  - FFs are complex as function of $q^2$

We can measure baryon time-like EM FFs in BESIII
Two methods

<table>
<thead>
<tr>
<th>Energy Scan</th>
<th>Initial State Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data sample</td>
<td>one $\sqrt{s}$</td>
</tr>
<tr>
<td>$q^2$ range</td>
<td>from threshold to $\sqrt{s}$</td>
</tr>
<tr>
<td>Integrated Lum.</td>
<td>high at one energy beam energy</td>
</tr>
<tr>
<td></td>
<td>in progress</td>
</tr>
<tr>
<td>A series of $\sqrt{s}$</td>
<td></td>
</tr>
<tr>
<td>single at each beam energy</td>
<td></td>
</tr>
<tr>
<td>low at each beam energy</td>
<td></td>
</tr>
<tr>
<td>this talk</td>
<td></td>
</tr>
</tbody>
</table>
Measurement of TL EM FFs

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

- Born cross section:
  \[
  \sigma(q^2) = \frac{4\alpha^2 \beta C}{3q^2} \left[ |G_M(q^2)|^2 + \frac{1}{2\tau} |G_E(q^2)|^2 \right]
  \]

- Effective FFs:
  \[
  |G(q^2)| = \sqrt{\frac{\sigma}{4\alpha^2 \beta C \left( 1 + \frac{1}{2\tau} \right)}}
  \]

  \( \tau = \frac{q^2}{(4m_B^2)} \),  \( \theta \) is the polar angle of baryon in the CM

\[ R = \left| \frac{G_E}{G_M} \right| \] measurement

- Angular dependence:
  \[
  \frac{d\sigma}{d\cos \theta} = N \left[ (1 + \cos^2 \theta) + \frac{R^2}{\tau} (1 - \cos^2 \theta) \right]
  \]
  \( N \) is the overall normalization.

- All the formulas are valid
  - for the baryons with spin=1/2
  - assuming one photon exchange domination
Hyperon electromagnetic form factors

- Hyperons unstable → cannot serve as target
- Only Time-Like hyperon EM FFs are experimentally accessible.
- $e^+e^-$-collisions are currently the best way to study hyperon structure.
- Difference between nucleon and hyperon EM FFs provides a powerful test of SU(3) symmetry
Polarization effect in the 
\[ e^+ e^- \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^- \bar{p}\pi^+ \]

In the time-like region:
- \[ G_E(q^2) = |G_E(q^2)| e^{i\Phi_E} \]
- \[ G_M(q^2) = |G_M(q^2)| e^{i\Phi_M} \]
- Relative phase:
  \[ \Delta\Phi = \Phi_M - \Phi_E \]

A nonzero relative phase leads to polarization \( P_n \) of the outgoing baryons.

- \[ P_n = \frac{\sin 2\theta \text{Im}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+\cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 \sin^2\theta} \quad \Rightarrow \text{gives modulus of } \Delta\Phi \]
- \[ C_{lm} = \frac{\sin 2\theta \text{Re}[G_E(q^2)G_M^*(q^2)]/\sqrt{\tau}}{|G_M(q^2)|^2(1+\cos^2\theta)+\frac{1}{\tau}|G_E(q^2)|^2 \sin^2\theta} \quad \Rightarrow \text{gives sign of } \Delta\Phi \]

- The \( n \) is the normal to the production plane, \( \hat{n} = \hat{e}_e \times \hat{e}_{\bar{\Lambda}} \)
- \( \hat{l} \) is \( \Lambda(\bar{\Lambda}) \) momenta direction in c.m. frame
- \( \hat{m} = \hat{n} \times \hat{l} \)
Measure the $\Lambda$ polarization

- The differential cross section of the decay proton angle:
  \[ \frac{d\sigma}{d\cos\theta_p} = \frac{1}{2} (1 + \alpha_\Lambda P_n \cos\theta_p) \]
  
- The polarization can be extracted by:
  \[ P_n = \frac{3}{\alpha_\Lambda} < \cos\theta_p > \]

- The spin correlation of the $\Lambda$ and $\bar{\Lambda}$:
  \[ C_{lm} = \left( \frac{9}{\alpha \bar{\alpha}} \right) < \cos\theta_{pl} \cos\theta_{\bar{p}m} > \]

- $\alpha$ is the asymmetry parameter,
  $\alpha_\Lambda = 0.64, \alpha_{\bar{\Lambda}} = -0.64$

Hence, the phase between the form factors would be known.
BEPCII and BESIII
BEPCII and BESIII

Bird view of Beijing Electron Positron Collider (BEPCII)

- Storage ring
- LINAC

BESIII at BEPCII

2004: start BEPCII&BESIII construction
2009-now: data taking
BEPCII storage rings

Double-ring $e^+ e^-$ collider:
- Beam energy: 1.0-2.3 GeV
- Crossing angle: $\pm 11$ mrad
- Design
  - Luminosity: $1 \times 10^{33} cm^{-2} s^{-1}$
  - Achieved: $8.5 \times 10^{32} cm^{-2} s^{-1}$
  - Energy spread: $5.16 \times 10^{-4}$
  - Optimum energy: 1.89 GeV
BESIII detector

BESIII detector:
- MDC: main drift chamber (40% He + 60% propane)
- TOF: time of flight (two layers plastic scintillators)
- EMC: electromagnetic calorimeter (CsI(Tl))
- MUC: muon system (resistive plate chambers)

Performance:

<table>
<thead>
<tr>
<th>Expt.</th>
<th>MDC Wire resolution</th>
<th>MDC $dE/dx$ resolution</th>
<th>EMC Energy resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>110 $\mu$m</td>
<td>5%</td>
<td>2.2 – 2.4%</td>
</tr>
<tr>
<td>BABAR</td>
<td>125 $\mu$m</td>
<td>7%</td>
<td>2.67%</td>
</tr>
<tr>
<td>Belle</td>
<td>130 $\mu$m</td>
<td>5.6%</td>
<td>2.2%</td>
</tr>
<tr>
<td>BESIII</td>
<td>115 $\mu$m</td>
<td>&lt; 5%</td>
<td>2.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Expt.</th>
<th>TOF time resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>100 ps</td>
</tr>
<tr>
<td>Belle</td>
<td>90 ps</td>
</tr>
<tr>
<td>BESIII</td>
<td>68 ps (Barrel)</td>
</tr>
<tr>
<td>BESIII</td>
<td>100 ps (ETOF)</td>
</tr>
</tbody>
</table>
The BESIII data sample

- \( J/\psi \) \( 1.3 \times 10^9 \)
- \( \psi'0.5 \times 10^9 \)
- \( \psi(3770) \) \( 2.9 \text{ fb}^{-1} \)
- \( \psi(4040) \) \( 0.5 \text{ fb}^{-1} \)
- \( \psi(4420) \) \( 1 \text{ fb}^{-1} \)
- \( \psi(4600) \) \( 0.5 \text{ fb}^{-1} \)
- \( Y(4230+4260) \) \( 1.9 \text{ fb}^{-1} \)
- \( Y(4360) \) \( 0.5 \text{ fb}^{-1} \)

\( \sim 130 \) scan points (\( \sim 1.3 \text{ fb}^{-1} \))
The small and big scan
Mentioned in this talk.

Small scan at 2011/2012. \( \sim 157 \text{pb}^{-1} \)

Big scan at 2014/2015. \( \sim 525 \text{pb}^{-1} \)

<table>
<thead>
<tr>
<th>( E_{\text{cm}} (GeV) )</th>
<th>Luminosity (pb(^{-1}))</th>
<th>Used for</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2324</td>
<td>2.6</td>
<td>Proton FFs, ( \Lambda ) FFs</td>
</tr>
<tr>
<td>2.4</td>
<td>3.4</td>
<td>Proton FFs, ( \Lambda ) FFs</td>
</tr>
<tr>
<td>2.8</td>
<td>3.8</td>
<td>Proton FFs, ( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.05</td>
<td>14.9</td>
<td>Proton FFs</td>
</tr>
<tr>
<td>3.06</td>
<td>15.1</td>
<td>Proton FFs</td>
</tr>
<tr>
<td>3.08</td>
<td>30.7</td>
<td>Proton FFs, ( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.4</td>
<td>1.7</td>
<td>( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.5</td>
<td>3.6</td>
<td>( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.542</td>
<td>18.2</td>
<td>( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.6</td>
<td>9.6</td>
<td>( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.65</td>
<td>48.8</td>
<td>( \Lambda ) FFs</td>
</tr>
<tr>
<td>3.671</td>
<td>4.6</td>
<td>( \Lambda ) FFs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( E_{\text{cm}} (GeV) )</th>
<th>Luminosity (pb(^{-1}))</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>9.3</td>
<td>Nucleon FFs</td>
</tr>
<tr>
<td>2.1</td>
<td>11.3</td>
<td>Nucleon FFs</td>
</tr>
<tr>
<td>2.15</td>
<td>2.8</td>
<td>( Y(2175) )</td>
</tr>
<tr>
<td>2.175</td>
<td>10.1</td>
<td>( Y(2175) )</td>
</tr>
<tr>
<td>2.2</td>
<td>13.0</td>
<td>Nucleon FFs &amp; ( Y(2175) )</td>
</tr>
<tr>
<td>2.2324</td>
<td>11.2</td>
<td>Hyp Threshold (( \Lambda \Lambda ))</td>
</tr>
<tr>
<td>2.3094</td>
<td>20.5</td>
<td>Nucleon &amp; Hyp FFs</td>
</tr>
<tr>
<td>2.3864</td>
<td>22.1</td>
<td>Hyp Threshold (( \Sigma^0 \Lambda ))</td>
</tr>
<tr>
<td>2.396</td>
<td>64.8</td>
<td>Nucleon &amp; Hyp FFs</td>
</tr>
<tr>
<td>2.5</td>
<td>1.0</td>
<td>Hyp Threshold (( \Sigma^- \Sigma^+ ))</td>
</tr>
<tr>
<td>2.6444</td>
<td>66.3</td>
<td>Nucleon &amp; Hyp FFs</td>
</tr>
<tr>
<td>2.7</td>
<td>1.0</td>
<td>Hyp Threshold (( \Xi^- \Xi^+ ))</td>
</tr>
<tr>
<td>2.8</td>
<td>1.0</td>
<td>Hyp &amp; R scan</td>
</tr>
<tr>
<td>2.9</td>
<td>102.1</td>
<td>Nucleon &amp; Hyp FFs</td>
</tr>
<tr>
<td>2.95</td>
<td>15.7</td>
<td>( m_{pp} ) step</td>
</tr>
<tr>
<td>2.981</td>
<td>15.4</td>
<td>( \eta_c, m_{pp} ) step</td>
</tr>
<tr>
<td>3.0</td>
<td>15.3</td>
<td>( m_{pp} ) step</td>
</tr>
<tr>
<td>3.02</td>
<td>16.6</td>
<td>( m_{pp} ) step</td>
</tr>
<tr>
<td>3.08</td>
<td>123.0</td>
<td>Nucleon FFs</td>
</tr>
</tbody>
</table>
Nucleon Electromagnetic FFs
Experimental status of proton EM FFs

- EM FFs
  - Steep rise towards threshold
  - Two rapid decreases

- FFs ratio
  - Only two experiments, BaBar and PS170
  - Inconsistent results
  - Poor precision and limited energy range
Proton FFs from 2012 scan

- Uncertainty in effective FFs improved by 30%
- The $R = |G_E/G_M|$ ratio are close to unity
- Consistent with BaBar results in the same $q^2$ region
Proton FFs: prospects from 2015 scan

From proposal

<table>
<thead>
<tr>
<th>$E_{cm}$ (GeV)</th>
<th>Luminosity (pb$^{-1}$)</th>
<th>$\delta R_{em}/R_{em}$</th>
<th>$\delta G_M/G_M$</th>
<th>$\delta G_E/G_E$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>8.95</td>
<td>9.2%</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>2.1</td>
<td>10.8</td>
<td>10%</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>2.2</td>
<td>13</td>
<td>9.5%</td>
<td>3%</td>
<td>11%</td>
</tr>
<tr>
<td>2.3084</td>
<td>20</td>
<td>9.7%</td>
<td>3%</td>
<td>10%</td>
</tr>
<tr>
<td>2.3950</td>
<td>35</td>
<td>8.8%</td>
<td>3%</td>
<td>9%</td>
</tr>
<tr>
<td>2.644</td>
<td>65</td>
<td>14.6%</td>
<td>5%</td>
<td>16%</td>
</tr>
<tr>
<td>2.9</td>
<td>100</td>
<td>24%</td>
<td>6%</td>
<td>25%</td>
</tr>
<tr>
<td>3.1</td>
<td>150</td>
<td>$\sim$ 35%</td>
<td>8.5%</td>
<td>35%</td>
</tr>
</tbody>
</table>

- Expected statistical accuracies for $R$ between the 9% and 35%.
- Combination of the last three energy points would lead to 15% accuracy in $R$.
- Expected statistical accuracies for $|G_M|$ between 3 to 9%, 9 to 35% for $|G_E|$.
Neutron EM FFs

Two measurements

- FENICE with $74 \, e^+ e^- \rightarrow n \bar{n}$ events
- recently confirmed by SND
- from $n \bar{n}$ threshold up to 2GeV
- Compare with proton FFs (BaBar)
  - both increase near threshold
  - close to each other

BESIII: Based on the new scan data in 2-3.1GeV:

- Extract EM FFs in wide $q^2$ region
- Measure $R$ for the first time
Hyperon Electromagnetic FFs
Experimental status

- Babar Collaboration: $e^+ e^- \rightarrow \gamma \Lambda \bar{\Lambda}$
  - Based on very little data.
  - Total error on the $G_E/G_M$ ratio 33-100%.
  - $\Lambda \bar{\Lambda}$: $\sim$200 events
  - $\Lambda$ polarization: $-0.22 < P_n < 0.28$
  - Relative phase: $-0.76 < \sin \phi < 0.98$

- CLEO-c: $\Lambda \bar{\Lambda}$ @3.773GeV: $\sim$ 105 events
e^+ e^- \rightarrow \Lambda\bar{\Lambda} \text{ from 2012 scan}

- Cross section does not vanish at threshold
- Suggested explanation Coulomb interaction at quark level
- Data sample is too small to extract angular distributions
  - model dependent efficiencies → the biggest contribution to the systematic uncertainty
Hyperon FFs: expectation from 2015 scan

For $\Lambda\bar{\Lambda}$, we could give angular distribution
→ model dependence of efficiencies gone
→ get rid of the biggest source of systematic uncertainties

We shall also be able to measure $e^+e^- \rightarrow \Lambda\bar{\Sigma}^0, \Sigma^0\bar{\Sigma}^0, \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \ldots$:

- Determine FFs, $R$ and polarization at single energy points
- Measure effective FFs with possible energy points
Summary

- **2012 scan**:  
  - The proton form factors and their ratio have been measured.  
  - Preliminary results of $\Lambda$ just released.

- **2015 scan**:  
  - Proton FFs will be significantly improved  
  - BESIII’s first result of neutron FFs will come  
  - Possible to measure relative phase of $\Lambda$  
  - More and better measurements of baryon FFs will come

- Measurements by ISR also in progress

Thank you!
backups
\[ e^+ e^- \rightarrow \Lambda \bar{\Lambda} \text{ at } \sqrt{s} = 2232.4 \text{ MeV} \]

BESIII has collected data at \( \sqrt{s} = 2232.4 \) MeV, which is only 1.0 MeV above \( \Lambda \bar{\Lambda} \) threshold. Two separate analyses:

- Reconstruct \( \Lambda \rightarrow p \pi^- \) and \( \bar{\Lambda} \rightarrow \bar{p} \pi^+ \)
  - The momentum of final states are too low to leave a message in the detector.
  - Antiproton interacting on the beam pipe will produce secondary particles, whose vertex is around 3 cm.
  - \( N_{\Lambda\bar{\Lambda}} = 43 \pm 7 \)

- Reconstruct \( \bar{\Lambda} \rightarrow \bar{n} \pi^0 \)
  - The final states of \( \pi^0 \) has a mono-momentum around 105 MeV.
  - \( N_{\Lambda\bar{\Lambda}} = 22 \pm 6 \)
Results of cross section

- Data at $\sqrt{s} = 2400.0$, 2800.0 and 3080.0 MeV are also used to study $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$, with $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. 

| $\sqrt{s}$ (MeV) | Reconstruction | $\sigma_{\text{Born}}$ (pb) | $|G|$ ($\times 10^{-2}$) |
|------------------|----------------|-----------------------------|--------------------------|
| 2232.4           | $\Lambda \rightarrow p\pi^-$, $\Lambda \rightarrow \bar{p}\pi^+$, $\bar{\Lambda} \rightarrow \bar{p}\pi^0$, combined | $325 \pm 53 \pm 46$     | $63.4 \pm 5.7$            |
| 2400.0           |                | $300 \pm 100 \pm 40$       | $133 \pm 20 \pm 19$      | $12.93 \pm 0.97 \pm 0.92$ |
| 2800.0           |                | $320 \pm 58$               | $15.3 \pm 5.4 \pm 2.0$   | $4.16 \pm 0.73 \pm 0.27$  |
| 3080.0           |                | $3.9 \pm 1.1 \pm 0.5$      | $2.21 \pm 0.31 \pm 0.14$ |