Study of Baryon form factors at BESIII

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Outline

• Introduction

• Baryon Form factors
  • Nucleon form factors
  • Hyperon form factors

• Summary and prospect
Composition of the Universe

- Nucleon is the dominant component of visible universe (>99%)

Prove nucleon charge radius:

\[ G_E(Q^2) = 1 - \frac{1}{6} r_E^2 Q^2 + \cdots \]  
(Q: four momentum transfer)
Nucleon Electromagnetic Form Factor (NEFF)

- Elastic scattering of electron and proton (Hofstadter, Nobel Prize 1961)
  - Theoretically, differential cross section is:
    \[ \left( \frac{d\sigma}{d\Omega} \right)_{\text{ep}} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left( 1 + 2\tau \tan^2 \frac{\theta}{2} \right) F(q^2) \]

- The nucleon electromagnetic vertex \( \Gamma_\mu \) describing the hadron current:
  \[
  \Gamma_\mu(p', p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)
  \]

- Sachs FFs:
  - Electric FF: \( G_E(q^2) = F_1(q^2) + \tau \kappa_F(q^2) \)
  - Magnetic FF: \( G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2) \)

\[
\tau = \frac{q^2}{4m^2}, \quad \kappa = \frac{g-2}{2}, \quad g = \frac{\mu}{J}
\]
Playground of EMFFs

- **In SL**, FFs are real.
  - Encode information about charge distribution of the nucleon
- **In TL**, FFs are complex, $|G_E/G_M|$ and $\Delta \Phi$.
  - Can be related to the time evolution of the EM charges within the nucleon
- **BESIII** has access to the FFs in TL
# Measurement techniques for baryon FF

<table>
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<tr>
<th>$E_{\text{beam}}$</th>
<th>Energy Scan</th>
<th>Initial State Radiation</th>
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<td>$\mathcal{L}$</td>
<td>low at each beam energy</td>
<td>high at one beam energy</td>
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| $\sigma$          | $\frac{d\sigma_{p\bar{p}}}{d(\cos \theta)} = \frac{\pi \alpha^2 \beta C}{2q^2} \left[ |G_M|^2 (1 + \cos^2 \theta) \right]$  
                      $+ \frac{4m_p^2}{q^2} |G_E|^2 \sin^2 \theta$ | $\frac{d^2\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s} W(s, x, \theta_\gamma) \sigma_{p\bar{p}}(q^2)$  
                      $W(s, x, \theta_\gamma) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2 \theta_\gamma} - \frac{x^2}{2} \right)$ |
| $q^2$             | single at each beam energy | from threshold to $s$ |

Both techniques, energy scan and initial state radiation, can be used at BESIII

$\sim \frac{1}{400}$
Status on proton FFs

• Still mystery on proton cross section line-shape


- Point-like cross section near threshold,
  - $\sigma_{\text{point}} = \frac{\pi \alpha^2}{3 m^2 \tau} \left[ 1 + \frac{1}{2 \tau} \right]$

- The $e^+e^- \rightarrow p\bar{p}$ cross section shows an exponential growth in 1 MeV interval above threshold.
Status on proton FFs

• Inconsistency on $|G_E/G_M|$ of proton & poor precision


• pQCD predicts a continuous transition and SL-TL equality at high $Q^2$
• SL best accuracy in $Q^2(0.5, 8.5)$ GeV$^2$: 1.7%
• TL accuracy before BESIII: exceeding 20%
Status on neutron FFs

• Poor precision, limited $q^2$ range in neutron FF

$$|\frac{G_M^n}{G_M^p}|^2 \approx \left(\frac{q_d}{q_u}\right)^2 = 0.25$$

• pQCD prediction\([1]\):

• VMD prediction\([2]\):

BESIII data samples

Scan technique

ISR technique

Energy scan 526 pb\(^{-1}\)

Inclusive:

KEDR

* BES
Proton FFs with ISR technique

- Combined seven data samples (7.4 fb$^{-1}$)

- Precision on $|G_{\text{eff}}|$ : 4.1%-28.7%(untagged)
- Precision $|G_E/G_M|$ ratio: 23.0%-31.4%(untagged)
- Confirm Babar’s result on $|G_E/G_M|$ above threshold

Proton FFs with scan technique

- Precise measurement of cross section $e^+e^- \rightarrow p\bar{p}$ at 22 points from 2.0 to 3.08 GeV, 688.5 pb$^{-1}$
- $|G_E/G_M|$, $|G_M|$ are determined with high accuracy, with uncertainty comparable to data in SL
- $|G_E|$ is measured for the first time

Best precision on $\sigma$: 3% (systematic dominant)
Best precision on $|G_E/G_M|$: 3.4% (statistical dominant)
Proton FFs with scan technique

- Hypothesis on other results: $|G_E| = |G_M|$
- First line-shape of $|G_M|$ without hypothesis, achieved by BESIII scan data.
Oscillation structures?

- Oscillating structures observed in the EFF minus modified dipole parameterization in Babar.
  - Rescattering process in final state
  - Independent resonant structure
Neutron form factors at BESIII

- Analysis Challenges: Reconstruction of $e^+ e^- \rightarrow n\bar{n}$
  - No MDC signal
  - Low EMC efficiency,
  - No TOF reconstruction

Prospects:
- BESIII new result ($s = 2.0$ to $3.08$ GeV) on Neutron Form Factor is foreseen with high precision (best accuracy < 10%).
- Measured $G_E/G_M$ ratio for the first time.
Neutron form factors at BESIII

- Event must be selected by only one of the three categories.

- Events in each of the three categories undergo a complete independent analysis:
  - Selection Criteria
  - Signal yield extraction
  - Efficiency determination
  - Corrections for efficiency
  - Cross section determination
Comparison with Space-Like Results

Neutron and Proton Magnetic Form Factors in the SL and TL regions:
- The pQCD predicts an asymptotic behavior of the form factors in the SL and TL regions.
- At high $q^2$, the pQCD predicts $G_M^{\text{SL}} = G_M^{\text{TL}}$ for neutron and proton form factors.
- The neutron and proton form factors in the TL region are larger than those in the SL region.
Angular Analysis for the Extraction of $R_{EM}$ and $|G_M|$ FFs

The $R_{EM}$ and $|G_M|$ form factors can be extracted by fitting the efficiency corrected angular distribution:

$$
\frac{d\sigma^{Born}_{n\bar{n}}}{d\cos\theta_{\bar{n}}} = \frac{d\mathcal{N}/d\cos\theta_{\bar{n}}}{\epsilon^{MC}_{n\bar{n}} \times \mathcal{C}_{dm} \times \mathcal{C}_{trg} \times (1 + \delta) \times \mathcal{L}_{Int}} = A \times |G_M|^2 \left[(1 + \cos^2\theta_{\bar{n}}) + R^2_{em} \frac{4M^2_{\bar{n}}}{s}(1 - \cos^2\theta_{\bar{n})}\right]
$$

- $R^2_{em} = |G_E/G_M|$ is the form factor ratio, $A = \frac{2\pi \alpha^2 \beta}{4s}$ is the normalisation factor.

Integration over bin width of the fit function is performed due to the large bin width:

$$
\left(\frac{d\sigma^{Born}_{n\bar{n}}}{d\cos\theta_{\bar{n}}}\right)_i = \sum_{bin=1}^{bin=n} \int_{bin} A_i \times |G_M|^2 \left[(1 + \cos^2\theta_{\bar{n}}) + R^2_{em} \frac{4M^2_{\bar{n}}}{s}(1 - \cos^2\theta_{\bar{n})}\right]
$$

- $i$ stands for the three categories, i.e A, B and C.

The neutron form factors are extracted by performing a simultaneous fit to the angular distributions from the three categories where the $R_{EM}$ is shared.
Results of Magnetic Form Factor of the Neutron

- Comparison of Magnetic Form Factor to the Theoretical Prediction:
  - The only existing results of $|G_M^n|$ are from Fenice, they were determined under the hypothesis $|G_E^n|=0$
  - A comparison of $|G_M^n|$ results from this analysis to the various theoretical predictions is performed
Status on hyperon FFs

• Rare experimental results on Hyperon FF


| $q^2$ = 14.2 GeV$^2$

- diquark correlation evidence
- favor spin–isospin singlet
Measurement of Hyperon FFs near threshold

- The Born cross section for $e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$, can be expressed in terms of electromagnetic form factor $G_E$ and $G_M$:
  \[
  \sigma_{BB}(q) = \frac{4\pi\alpha^2c\beta}{3q^2} \left[ |G_M(q)|^2 + \frac{1}{2\tau}|G_E(q)|^2 \right]
  \]
- The Coulomb factor $C = \frac{\pi\alpha}{\beta} \frac{1}{1 - \exp\left(-\frac{\pi\alpha}{\beta}\right)}$ for a charged $B\bar{B}$ pair, and equals to 1 for a neutral $B\bar{B}$ pair.
- Complex form of FFs: $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$; Relative phase: $\Delta\Phi = \Phi_E - \Phi_M$
Determination of the Relative phase of FFs

• Complex form of FFs:
  • $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$
  • Relative phase: $\Delta \Phi = \Phi_E - \Phi_M$

• A non-zero phase has polarization effect on the Baryons:
  • $P_y \propto \sin \Delta \Phi$

• The angular distribution of daughter baryon from Hyperon weak decay is:
  • $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}$
  • $\alpha_\Lambda$: asymmetry parameter
  • $\hat{q}$: unit vector along the daughter baryon in hyperon rest frame

With hyperon weak decay to B+P, the polarization of hyperon can be measurement, so does the relative phase between $G_E$ and $G_M$!
Complete measurement of $\Lambda$ EMFFs

- An event of the reaction $e^+ e^- \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ is specified by the five dimensional vector $\xi = (\theta, \Omega_1, \Omega_2)$, the differential cross section is:

$$\mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \eta \mathcal{F}_3(\xi) - \alpha_L^2 \left( \mathcal{F}_1(\xi) + \sqrt{1 - \eta^2 \cos(\Delta \Phi)} \mathcal{F}_2(\xi) + \eta \mathcal{F}_6(\xi) \right) + \alpha_A \sqrt{1 - \eta^2 \sin(\Delta \Phi)} \left( \mathcal{F}_3(\xi) - \mathcal{F}_4(\xi) \right).$$

Fit data by Maximum Log Likelihood

$|G_E| = 0.96 \pm 0.14 \text{(stat.)} \pm 0.02 \text{(sys.)}$

$\Delta \Phi = 37^\circ \pm 12^\circ \text{(stat.)} \pm 6^\circ \text{(sys.)}$
Measurement of $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ at $\sqrt{s} = 2.2324$ GeV


- Near threshold production ($2M_\Lambda + 1.0$ MeV) and small PHSP in $\Lambda/\bar{\Lambda}$ decays
- Indirect search for antiproton in $\Lambda \rightarrow p\pi^-, \bar{\Lambda} \rightarrow \bar{p}\pi^+$
- Search for mono-energetic $\pi^0$ in $\bar{\Lambda} \rightarrow \bar{n}\pi^0$

- The anomalous behavior differing from the pQCD prediction at threshold is observed.

Recalling the baryon pair production cross section:

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

- The Coulomb correction factor $C = \frac{\pi\alpha}{\beta} \left[ 1 - \exp\left(-\frac{\pi\alpha}{\beta}\right) \right]$ (Q), cancel the $\beta$ for a charged $BB$ pair, equals to 1 for a neutral $BB$ pair.
A possible resonance around $\Lambda\bar{\Lambda}$ resonance?

- A hint for resonance around $\Lambda\Lambda$ threshold in $e^+e^- \rightarrow KKKK$ cross section
  - Mass=$2232 \pm 3.5$ MeV, width$\approx$20 MeV

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$e^+ e^- \rightarrow \Lambda_c^+ \Lambda_c^-$ near kinematic threshold

- Ten modes of $\Lambda_c^+$ ( $\Lambda_c^-$ ) are reconstructed
- Measurement of the Born cross section at 4 energy points below 4.6 GeV with unprecedented statistical accuracy (~1.3% at 4.6 GeV)

\[ e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^- \] near kinematic threshold

- Angular distribution study

A summary of \(|R_{EM}|\) for measured Baryons
Summary and discussion

• Nucleon FFs is measured with scan and ISR techniques at BESIII
  • Answered the remaining questions on proton FFs
  • Precise measurement on neutron FFs is ongoing

• With the large data set, more precise results on Hyperon FFs are expected on BESIII.
  • More precise cross section line-shape
  • Search for resonant structure and test di-quark correlation
  • Test on threshold effect
  • Complete determination of $G_E$ and $G_M$

Energy scan in 2014-2015 at BESIII
Thank you for your attention!
Beijing Electron Positron Collider (BEPCII)

$E_{\text{beam}}$: 1.0-2.3 GeV
$\sigma_E$: $5.16 \times 10^{-4}$
$L$: $1.0 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @3.773 GeV
**Main Drift Chamber**
Small cell, 43 layer
\( \sigma_{xy}=130 \, \mu m, \, dE/dx\sim 6\% \)
\( \sigma_p/p = 0.5\% \) at 1 GeV

**Time Of Flight**
Plastic scintillator
\( \sigma_T \) (barrel): 80 ps
\( \sigma_T \) (endcap): 110 ps
(endcap update with MRPC \( \sigma_T : 65 \) ps)

**Electromagnetic Calorimeter**
CsI(Tl): \( L=28 \, cm \) (15X_0)
Energy range: 0.02-2 GeV
Barrel \( \sigma_E \) 2.5\%, \( \sigma_l \) 6mm
Endcap \( \sigma_E \) 5.0\%, \( \sigma_l \) 9mm

**Muon Counter**
Resistive plate chamber
Barrel: 9 layers
Endcaps: 8 layers
\( \sigma_{\text{spatial}} \) 1.48 cm