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%)

- Probe nucleon charge radius:
  \[ G_E(Q^2) = 1 - \frac{1}{6} r_E^2 Q^2 + \cdots \]  
  (Q: four momentum transfer)

![Composition of the Universe Chart](image)

![Proton Radius Confusion Graph](image)
Nucleon Electromagnetic Form Factor (NEFF)

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

- 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: \( G_E(q^2) = F_1(q^2) + \tau\kappa F_2(q^2) \)
  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

\[
\overline{p}p \rightarrow e^+ e^- \quad 0
\]
Measurement techniques for baryon FF

<table>
<thead>
<tr>
<th></th>
<th>Energy Scan</th>
<th>Initial State Radiation</th>
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<tbody>
<tr>
<td>$E_{beam}$</td>
<td>discrete</td>
<td>fixed</td>
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<tr>
<td>$\mathcal{L}$</td>
<td>low at each beam energy</td>
<td>high at one beam energy</td>
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<tr>
<td>$\sigma$</td>
<td>$\frac{d\sigma_{p\bar{p}}}{d(cos \theta)} = \frac{\pi \alpha^2 \beta C}{2q^2} [</td>
<td>G_M</td>
</tr>
<tr>
<td>$q^2$</td>
<td>single at each beam energy</td>
<td>from threshold to $s$</td>
</tr>
</tbody>
</table>

Both techniques, energy scan and initial state radiation, can be used at BESIII.
Status on proton FFs

• Still mystery on proton cross section line-shape

\[ \sigma_{\text{point}} = \frac{\pi \alpha^2}{3m^2\tau} \left[ 1 + \frac{1}{2\tau} \right] \]


• Point-like cross section near threshold,

• The \( e^+e^- \rightarrow p\overline{p} \) 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

- pQCD prediction$^{[1]}$: $\left| \frac{G_M^n}{G_M^p} \right|^2 \approx \left( \frac{q_d}{q_u} \right)^2 = 0.25$

- VMD prediction$^{[2]}$: $\left| \frac{G_M^n}{G_M^p} \right|^2 \approx 1$

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Beijing Electron Positron Collider (BEPCII)

$E_{\text{beam}}$: 1.0-2.3 GeV
$\sigma_F$: $5.16 \times 10^{-4}$
$L$: $1.0 \times 10^{33}$ cm$^{-2}$s$^{-1}$ @3.773 GeV
BESIII detector

**Main Drift Chamber**
Small cell, 43 layer
\( \sigma_{xy} = 130 \, \mu m, \, dE/dx \approx 6\% \)
\( \sigma_p/p = 0.5\% \) at 1 GeV

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

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

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

Scan technique

ISR technique

R scan 1.3 fb⁻¹ (130 points)
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.

arxiv:1905.09001 (submit to PRL)
Oscillation structures?

• Oscillating structures observed in the EFF minus modified dipole parameterization in Babar.
  • Rescattering process in final state
  • Independent resonant structure

\[ G \sim A e^{-Bp} \]
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.

![Graph showing neutron form factors vs. momentum](image)
Neutron form factors at BESIII

Analysis Challenges: Insufficient MC simulation

- Corrections need to be applied for MC efficiency:
  - $C_{\text{data/MC}}$: correction due to data/MC difference
  - $C_{\text{trg}}$: trigger efficiency correction (in dependence of total deposition energy)
Neutron form factors at BESIII

$$\sigma_{NN}^{\text{Born}}(q^2) = \frac{N_{\text{data}}}{\epsilon_{MC} \times \epsilon_{\text{cor}} \times \mathcal{L}_{\text{int}} \times (1+\delta)}$$

$$\epsilon_{\text{cor}} = \frac{C_{\text{data}}}{MC} \times C_{\text{trg}}$$
Comparison with Space-Like Results

- pQCD predicted asymptotic behavior of FFs

Figures from Prof. Vanderhaeghen
Status on hyperon FFs

• Rare experimental results on Hyperon FF


• diquark correlation evidence
• favor spin–isospin singlet
Relative phase of baryon

• 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:
  • $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_A P_y \cdot \hat{q}$
  • $\alpha_A$: 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 $e^+ e^- \rightarrow \Lambda(\rightarrow p\pi^-)\overline{\Lambda}(\rightarrow \overline{p}\pi^+)$ is specified by the five dimensional vector $\xi = (\theta, \Omega_1, \Omega_2)$, the differential cross section is:

$$
\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \eta \mathcal{T}_5(\xi) \\
- \alpha_\Lambda^2 \left( \mathcal{T}_1(\xi) + \sqrt{1 - \eta^2} \cos(\Delta\Phi) \mathcal{T}_2(\xi) + \eta \mathcal{T}_6(\xi) \right) \\
+ \alpha_\Lambda \sqrt{1 - \eta^2} \sin(\Delta\Phi) \left( \mathcal{T}_3(\xi) - \mathcal{T}_4(\xi) \right).
$$

Fit data by Maximum Log Likelihood

$$
\begin{align*}
|G_E| &= 0.96 \pm 0.14\,(\text{stat.}) \pm 0.02\,(\text{sys.}) \\
|G_M| &= 0.96 \pm 0.14\,(\text{stat.}) \pm 0.02\,(\text{sys.}) \\
\Delta\Phi &= 37^\circ \pm 12^\circ\,(\text{stat.}) \pm 6^\circ\,(\text{sys.})
\end{align*}
$$


arXiv: 1903.09421 (submit to PRL)
Threshold effect

- Hyperon pair production:
  - Possibility to reconstruct hyperon pair production much close to threshold than the proton

Energy scan in 2014-2015 at BESIII
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 $\Lambda \rightarrow \bar{n}\pi^0$

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

- Recalling the baryon pair production cross section:
  \[
  \sigma_{BB}(q) = \frac{4\pi\alpha^2 C}{3q^2} \left[ |G_M(q)|^2 + \frac{1}{2\pi} |G_E(q)|^2 \right]
  \]
- The Coulomb correction factor $C = \frac{\pi\alpha}{\beta} \frac{1}{1 - \exp(-\frac{\pi\alpha}{\beta})}(Q)$, 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 $\Lambda \bar{\Lambda}$ threshold in $e^+e^- \to KKKK$ cross section
  • Mass=2232±3.5 MeV, width=20 MeV
$e^+ e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$ near kinematic threshold

Ten modes of $\Lambda_c^+$ ($\bar{\Lambda}_c^-$) 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)

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
  - Test on threshold effect
  - Complete determination of $G_E$ and $G_M$

Energy scan in 2014-2015 at BESIII
Thank you for your attention!