Recent result of nucleon time-like form factors at BESIII

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QNP2022 - The 9th International Conference on Quarks and Nuclear Physics
Sept. 5-9, 2022
The standard model of particle physics is a well-tested theoretical framework, however, the SM has a number of issues that need further investigation:

- The nature of quark confinement
- Matter-antimatter asymmetry of the Universe
- Gravity, dark matter, numbers of flavors, etc.

Nucleons are composite objects with inner structure. At low Q, perturbative QCD is not possible (expansion of coupling constant $\alpha_s$)

$\Rightarrow$ Nucleon structure must be measured in experiments!
Electromagnetic Form Factors

- Fundamental properties of the nucleon
  - Connected to charge, magnetization distribution
  - Crucial testing ground for models of the nucleon internal structure

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: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$, $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

Normalization of FF: $q^2 = 0$: $G_E = Z$, $G_M = \mu_N$

$q^2 = 4m_N^2$: $G_E = G_M$
Experimental Access of Time-like Form Factors

<table>
<thead>
<tr>
<th>$E_{beam}$</th>
<th>Energy Scan</th>
<th>Initial State Radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>discrete</td>
<td>fixed</td>
<td></td>
</tr>
<tr>
<td>low at each beam energy</td>
<td>high at one beam energy</td>
<td></td>
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</tbody>
</table>

\[
\frac{d\sigma_{pp}}{d(cos \theta)} = \frac{\pi \alpha^2 \beta C}{2 q^2} |G_M|^2 (1 + \cos^2 \theta) + \frac{4m_p^2}{q^2}|G_E|^2 \sin^2 \theta
\]

\[
\frac{d^2\sigma_{pp\gamma}}{dq^2 d\theta_{\gamma}} = \frac{1}{s} W(s, x, \theta_{\gamma}) \sigma_{pp}(q^2)
\]

\[
W(s, x, \theta_{\gamma}) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2 \theta_{\gamma}} - \frac{x^2}{2} \right)
\]

$q^2$ single at each beam energy

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

\[
\sim \frac{1}{400}
\]
BEPCII/BESIII: a $\tau$-charm factory

**Energy**
- $E_{cm} = 2.0 - 4.6$ GeV (2.0-4.95 GeV since 2019)
- Energy spread: $\Delta E \approx 5 \times 10^{-4}$
- Peak luminosity in continuously operation
  - @ $E_{cm} = 3.77$ GeV: $1.0 \times 10^{33}$ cm$^{-2}$s$^{-1}$

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

**Electromagnetic Calorimeter**
- CsI(Tl): $L = 28$ cm
- Barrel $\sigma_E = 2.5\%$
- Endcap $\sigma_E = 5.0\%$

**Muon Counter**
- RPC
  - Barrel: 9 layers
  - Endcap: 8 layers
  - $\sigma_{\text{spatial}} = 1.48$ cm

**Time Of Flight**
- Plastic scintillator
  - $\sigma_T$ (barrel): 80 ps
  - $\sigma_T$ (endcap): 110 ps
  - (update to 65 ps with MRPC)
Data Samples Collected at BESIII

Can cover 0-4.9 GeV from direct annihilation or ISR

Energy scan 526 pb⁻¹

Inclusive:

KEDR

BES

4.13, 4.16
4.19, 4.2, 4.21, 4.22,
4.236, 4.245, 4.27,
4.28, 4.29, 4.315, 4.34,
4.38, 4.4, 4.44
7.7 fb⁻¹

4.36
4.42
1 fb⁻¹

4.61, 4.62, 4.64,
4.66, 4.68, 4.70
3.7 fb⁻¹

About 25 fb⁻¹
The Born cross section for $e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$ ($B$ is spin 1/2 baryon):

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

At threshold: $G_M = G_E = G, \quad \tau = \frac{s}{4m_B^2} = 1$

The $\sigma_{B\bar{B}}(q)$ becomes:

$$\sigma_{B\bar{B}}(q) = \frac{2\pi\alpha^2 c\beta}{q^2} |G|^2 = \frac{2\pi\alpha^2 c\beta}{s} |G|^2$$

- C: **Coulomb Enhancement factor (CEF)**
- $\beta = \sqrt{1 - 4m_B^2/s}$ (vanish at threshold)
- G: form factor
Coulomb Enhancement Factor

- \( C = E \cdot R \) (for charged baryon)
  - \( E = \pi \alpha F / \beta \), \( R = \frac{1}{1 - e^{\frac{-\pi \alpha F}{\beta}}} \)
  - \( F = 1 + \beta^2 \) or \( \sqrt{1 - \beta^2} \)

- \( \sigma_{B\bar{B}}(q) = \frac{2\pi \alpha^2 C\beta}{s} |G|^2 \)

\( C \) will lead to a non-zero Born cross section at threshold
**Proton Form Factors at BESIII**

- **ISR method** with detected photon and undetected using 7.5 fb\(^{-1}\) integrated luminosity.

- From threshold to \(q^2=4.0\) GeV\(^2\), average cross section 840 pb

- **Point-like** cross section at threshold, \(\sigma_{\text{point}} = \frac{\pi \alpha^2}{3 m^2 \tau} \left[ 1 + \frac{1}{2\tau} \right] = 845\) pb
Proton Form Factors at BESIII

➢ Scan technique from 2.0 to 3.08 GeV, using 688.5 pb\(^{-1}\) integrated luminosity.

➢ \(|G_E/G_M|, |G_M|\) are determined with **high accuracy**, comparable to data in SL.

➢ \(|G_E|\) is measured for the first time.
Neutron Form Factors

- Measurements on Neutron FFs are rare. Data from the FENICE indicates
  \[
  \frac{\sigma(e^+e^→n\bar{n})}{\sigma(e^+e^-→p\bar{p})} > 1
  \]

- An intermediate coherent isovector state serving as an intermediary between \(e^+e^-\) and \(N\bar{N}\)

\[
f = \frac{\sigma(e^+e^- → p\bar{p})}{\sigma(e^+e^- → nn)} = \left| \frac{A_1 + e^{i\alpha}A_0}{A_1 - e^{i\alpha}A_0} \right|^2 = \left| \frac{1 + e^{i\alpha}\varepsilon}{1 - e^{i\alpha}\varepsilon} \right|^2
\]

\(A_1\) and \(A_0\) are I = 1 and 0 amplitudes, and dominated by single states \(\rho, \omega, \phi\)

\(\varepsilon = A_0/A_1\)

\(\varepsilon = 1/3\)

\(\varepsilon = 1/10\)


J. Ellis and M. Karliner hep-ph/0108259
Neutron Form Factors at BESIII

- **High luminosity** 18 data sets at center-of-mass energies between 2.0 and 3.08 GeV, 647.9 pb$^{-1}$
- **Pure neutral channel** $e^+e^- \rightarrow n\bar{n}$, only EMC and/or TOF information
- **Sophisticated background suppression**: $e^+e^- \rightarrow \gamma\gamma$, beam-associated

![Flowchart](image)

**Category A**: No charged tracks in the MDC, most energetic shower in EMC as anti-neutron candidate

**Category B**: TOF response associated with the anti-neutron

**Category C**: TOF response associated with the neutron

Nat. Phys. 17, 1200–1204 (2021)
Clarify the “puzzle” that photon-neutron coupling larger than photon-proton coupling existing over 20 years.

Oscillation of FF observed in neutron data, with same frequency, but orthogonal phase.
Results from three Methods

- Born cross section and effective form factor

\[ \sigma_B^i = \frac{N_i^s}{\mathcal{L}_{\text{int}} \epsilon_i (1 + \delta)}, \quad |G^i| = \sqrt{\frac{\sigma_B^i}{\frac{4\pi \alpha^2}{3q^2} (1 + \frac{1}{2r})}} \]

- Consistent results from three methods

\[ \sigma_B = \sum_i w_i \sigma_B^i, \quad \Delta \sigma_B = \sqrt{\frac{1}{\sum_i \sum_j W_{i,j}}} \quad w_i = \frac{\sum_j W_{i,j}}{\sum_i \sum_j W_{i,j}}, \quad W = [\Delta \sigma^T \rho \Delta \sigma]^{-1} \]
Combined Results

- $\Delta \sigma_B^{min} \sim 8\%$ @ 2.396 GeV, total No. of signal $\sim 2300$
- Deviated from FENICE results by $2\sigma$
- Using proton pair production as input $\Rightarrow \sigma_{Bp}^{\bar{p}p} / \sigma_{Bn}^{\bar{n}n} \in (1, 4)$
Oscillation in reduced $G_{\text{eff}}$

- Babar observed the oscillation in proton $G_{\text{eff}}$
- Similar oscillation structure in neutron $G_{\text{eff}}$ after subtracting the dipole structure

\begin{align*}
G_{\text{osc}}(q^2) &= |G_n| - G_D^* , \\
G_D^* &= G_D \cdot \frac{1}{1 + \frac{q^2}{m_a^2}} , \\
G_D &= \frac{A_n}{\left(1 - \frac{q^2}{0.71 \text{(GeV)}^2}\right)^2} , \\
F_{\text{osc}}^{n,p} &= A^{n,p} \cdot \exp(-B^{n,p} \cdot p) \cdot \cos(C \cdot p + D^{n,p}) , \\
p &= \sqrt{E^2 - m_{n,p}^2} , \\
E &= \frac{q^2}{2m_{n,p}} - m_{n,p}
\end{align*}

---

**BESIII**

- Fit with $G_0^\text{mod}$
  - $A_n = 3.5 \pm 0.1$
  - $m_a^2 = 47839146.0 \pm 1.4 \text{ GeV}^2$
  - $\chi^2/\text{ndf} = 64.3/16$

- Fit with $G_0$
  - $A_n = 3.5 \pm 0.1$
  - $\chi^2/\text{ndf} = 64.9/16$

**Null Hypothesis:**
- $P_0 = 0.00 \pm 0.00$
- $\chi^2/\text{ndf} = 64.3/17$

**Oscillation Hypothesis:**
- $P_0 = 0.00 \pm 0.00$
- $A = 0.08 \pm 0.03$
- $B = 1.01 \pm 0.24$
- $C = 5.28 \pm 0.36$
- $D = -3.77 \pm 0.55$
- $\chi^2/\text{ndf} = 11.8/13$
**Oscillation in reduced-\(G_{\text{eff}}\)**

- **Simultaneously fit** the oscillation structure for proton and neutron (share frequency \(C\))

\[
F_{\text{osc}}^{n,p} = A^{n,p} \cdot \exp(-B^{n,p} \cdot p) \cdot \cos(C \cdot p + D^{n,p}), \quad p \equiv \sqrt{E^2 - m_{n,p}^2}, \quad E \equiv \frac{q^2}{2m_{n,p}} - m_{n,p}
\]

\[
C = (5.55 \pm 0.28) \text{ GeV}^{-1}
\]

\[
\Delta D = |D_p - D_n| = (125 \pm 12)^\circ
\]
Abnormal threshold effects observed in various baryon pair production: \( p\bar{p}, \Lambda\bar{\Lambda}, \Lambda_c^+\bar{\Lambda}_c^- \) …

Oscillation structures observed in \( p\bar{p}, n\bar{n} \)

\(|G_E/G_M|\) ratio significantly larger than 1 at low beta for \( p, \Lambda_c^+, \Sigma^+ \), indicating large D-wave near threshold

Relative phase angle of form factor \( \Delta\phi(\sin\Delta\phi) \) measured for \( \Lambda, \Lambda_c^+ \)

The neutron pair productions measured at BESIII with improved precision.

Interesting effects observed in the reduced effective form factors of nucleon.

More theoretical discussions are desirable.

Thank you!