Baryon time-like form factors at

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(on behalf of the BESIII Collaboration)

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BARYON FORM FACTORS

• Fundamental properties of Baryons
• Characterize the internal structure
• Connected to charge and magnetization distributions
• Playground for **theory** and **experiment**:
  • at low $q^2$ probe the size of the hadron
  • at high $q^2$ test QCD scaling

By a global analysis of scattering and annihilation experiments Form Factors can be extracted
OUTLINE

- BEPCII and BESIII
- Electromagnetic form factors (FFs) formalism
- Measurement of the proton electromagnetic FFs with:
  - energy scan technique: $e^+e^- \rightarrow B\bar{B}_\text{bar}$
  - Initial state radiation (ISR) technique: $e^+e^- \rightarrow B\bar{B}_\text{bar}\gamma$
- Measurement of hyperon FFs: $e^+e^- \rightarrow \Lambda_c\Lambda_{c,\text{bar}}, \Lambda\Lambda_{\text{bar}}$
- Ongoing analysis on the measurement of baryon FFs at BESIII
- Summary
BEPCII and BESIII

**Beijing Electron Positron Collider**

- Symmetric $e^+e^-$ collider
- Beam energy: 1.0 - 2.3 GeV
- Optimum energy: 1.89 GeV
- Design luminosity: $10^{33}$ cm$^{-2}$ s$^{-1}$
- Crossing angle: 22 mrad

**Electromagnetic Calorimeter**

$\sigma_E/\sqrt{E}$(%) = 2.5% (1 GeV),
(Csl) $\sigma_{z\phi}$(cm) = 0.5--0.7 cm/$\sqrt{E}$

**Time Of Flight**

$\sigma_T$(barrel) = 90 ps
$\sigma_T$(endcap) = 110 ps

**Main drift chamber**

$\sigma_{xy}$ = 130$\mu$m, $dE/dx \approx$ 6%
$\sigma_{p/p}$ = 0.5% at 1 GeV

**Muon Counter**

$\sigma_{xy}$ < 2 cm

**1 Tesla**

SC solenoid

**c.m. energy range:** 2 GeV - 4.6 GeV.
ELECTROMAGNETIC FORM FACTORS (FF)

- Spin ½ Baryons: two e.m. FFs

The vertex $\Gamma_\mu$ contains the unknown structure, parametrized by $F_1$ and $F_2$:

$$\Gamma_\mu = \gamma F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2)$$

- Sachs FFs:

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$
$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4M} F_2(q^2)$$

$$\left\{
\begin{array}{l}
F_1(0) = Q, F_2(0) = k \\
G_M(0) = \mu, G_E(0) = Q
\end{array}\right.$$

- Analyticity: $G_{E,M}(-\infty) = G_{E,M}(+\infty) \approx (q^2)^{-2}$ real FFs

$$G_E(4M^2) = G_M(4M^2)$$
**EXPERIMENTAL ACCESS IN TIME-LIKE REGION**

- **Energy scan (direct annihilation):** fixed $q^2$

\[
\frac{d\sigma^{\text{Born},1\gamma}}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} [(1 + \cos^2 \theta) |G_M|^2 + \frac{4M^2}{q^2} \sin^2 \theta |G_E|^2]
\]

\[
\sigma^{\text{Born}}(q^2) = \frac{4\pi \alpha^2 \beta C}{3q^2} [||G_M(q^2)||^2 + \frac{2M^2}{q^2} |G_E(q^2)|^2]
\]

\[
C = \begin{cases} \frac{\pi \alpha}{\beta} \frac{1}{1 - \exp(\pi \alpha / \beta)} & \text{charged B} \\ 1 & \text{neutral B} \end{cases}
\]

\[
k = \frac{g - 2}{2}, g = \frac{\mu}{J}
\]

- **Initial State Radiation:**

\[
\frac{d^2\sigma^{\text{ISR}}}{dx d\theta_\gamma} = W(s, x, \theta_\gamma) \sigma^{\text{Born}}(q^2)
\]

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

\[
x = 1 - \frac{q^2}{s} = \frac{2E_\gamma}{\sqrt{s}}
\]

Both techniques can be used at BESIII.
EXPERIMENTAL ACCESS IN TIME-LIKE REGION

- Energy scan (direct annihilation): fixed $q^2$

\[
\frac{d\sigma^{\text{Born},1\gamma}}{d\Omega} = \frac{\alpha^2 \beta C}{4q^2} [(1 + \cos^2 \theta)|G_M|^2 + \frac{4M^2}{q^2} \sin^2 \theta |G_E|^2]
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\[
\sigma^{\text{Born}}(q^2) = \frac{4\pi \alpha^2 \beta C}{3q^2} [||G_M(q^2)||^2 + \frac{2M^2}{q^2} |G_E(q^2)|^2]
\]

Effective FF: $|G| = \sqrt{\frac{\sigma^{\text{Born}}(q^2)}{(1 + \frac{2M^2}{q^2})(\frac{4\pi \alpha^2 \beta C}{3q^2})}}$

- Initial State Radiation:

\[
\frac{d^2\sigma^{\text{ISR}}}{dx d\theta_\gamma} = -W(s, x, \theta_\gamma) \sigma^{\text{Born}}(q^2)
\]

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

\[x = 1 - q^2 / s = 2E_\gamma / \sqrt{s}\]

both techniques can be used at BESIII
BESIII DATA SAMPLE

the world’s largest dataset directly produced at e+e-
J/ψ, ψ(2S), ψ(3770), ψ(4180), Y(4260)
R-QCD studies, XYZ states

M. BERTANI
BOLOGNA, EUNPC 2018
PROTON FORM FACTORS
PROTON SPACE-LIKE & TIME-LIKE FFs

Flat cross section near threshold followed by a step

\[ \sigma_{pp}(4M_p^2) = \frac{\pi^2 \alpha^3}{2M_p^2} \frac{\beta_p}{\beta_p} |G^p(4M_p^2)|^2 = 850 |G^p(4M_p^2)|^2 \text{ pb} \Rightarrow |G^p(4M_p^2)| = 1 \]

as point-like fermion pairs!

[EPJA39,315]
BESIII PRELIMINARY RESULTS

- Scan technique (black and red points):
  - 2012 data, 156.9 pb\(^{-1}\) [ PRD 91, 112004 (2015) ]
  - 2015 data, 688.5 pb\(^{-1}\): preliminary results, improved precitions

- ISR technique (light brown points):
  - tagged (7.4 pb\(^{-1}\) above 3.773 GeV), under reviewing
  - untagged (7.4 pb\(^{-1}\) above 3.773 GeV): preliminary results

Results compatible with BABAR
G_E AND G_M RATIO

Extraction of the ratio $R = |G_E|/|G_M|$ ratio from proton angular distribution

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}|G_M|^2[(1 + \cos^2\theta) + \frac{|G_E|^2}{|G_M|^2} \cdot \frac{4M^2}{q^2}\sin^2\theta]$$

- Discrepancy between BaBar and PS170
GE AND GM RATIO

Extraction of the ratio $R=|GE|/|GM|$ ratio from proton angular distribution

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

- Discrepancy between BaBar and PS170
- Tension with $R=|G_E|/|G_M| = 1$ expectation
PRELIMINARY MEASUREMENT OF $G_M$

Extraction of the magnetic FF $G_M$:

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

- few separate previous determinations of $|G_M|$
- great improvement with BESIII!

Uncertainty: 1.8%\textasciitilde3.6%
OSCILLATIONS IN PROTON FFs


Periodic interference in $F_p (e^+e^- \rightarrow pp_{\text{bar}})$ first seen in BaBar data, confirmed in BESIII!

Oscillations due to re-scattering of $p$ and $p_{\text{bar}}$ at $\sim 1$fm distance $\rightarrow$ large Imaginary part close to threshold

$p$=proton momentum in $p$ rest frame

$D = F_{\text{osc}} = |G_{\text{eff}}| - F_0$

see Egle’s talk!
$e^+e^- \rightarrow \Lambda_c\bar{\Lambda}_c$
MEASUREMENT OF $e^+e^- \rightarrow \Lambda_c \overline{\Lambda}_c$

Thanks to $\Lambda_c$ weak decay $e^+e^- \rightarrow \Lambda_c \overline{\Lambda}_c$ can be detected with good efficiency even exactly at threshold

BELLE measurement has significant uncertainties:

- $\Upsilon(4660) \rightarrow \Lambda_c \Lambda_{c\bar{c}}$ may be consistent with a hidden charm tetraquark (charmed baryonium)?
  

BESIII data set close to production threshold ($+1.6\text{MeV}$):

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Integrated lum. (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5745</td>
<td>47.67</td>
</tr>
<tr>
<td>4.5800</td>
<td>8.54</td>
</tr>
<tr>
<td>4.5900</td>
<td>8.16</td>
</tr>
<tr>
<td>4.5995</td>
<td>566.93</td>
</tr>
</tbody>
</table>
BESIII MEASUREMENT OF $e^+e^- \rightarrow \Lambda_c \bar{\Lambda}_c$

**Analysis method**

Single Tag method:

- Only one of the baryon is reconstructed
- Energy difference:
  \[ \Delta E = E_{\text{cand.}} - E_{\text{beam}} \]

beam-constraint mass

\[ M_{BC} = (E_{\text{beam}}^2 - p_{\text{cand.}}^2)^{1/2} \]

are used to extract the signals

- 10 Cabibbo-favored decay modes as well as corresponding charge-conjugate decay modes of $\Lambda_c^+$ are employed

[(PRL120 (2018) 132001)]
BESIII MEASUREMENT OF $e^+e^- \rightarrow \Lambda_c^+\Lambda_c^-$

**Polar angle distribution**

- Studied in center-of-mass system of $\Lambda_c^+\Lambda_c^-$
- Angle distribution is fitted by $1 + \alpha_{\Lambda_c} \cos^2 \theta$
- $|G_E/G_M|$ can be extracted from equation

$$|G_E/G_M|^2 (1 - \beta^2) = (1 - \alpha_{\Lambda_c})/(1 + \alpha_{\Lambda_c})$$

| Energy (GeV) | $|G_E/G_M|$ |
|--------------|-------------|
| 4.5745       | 1.14 ± 0.14 ± 0.07 |
| 4.5995       | 1.23 ± 0.05 ± 0.03 |

[(PRL120 (2018) 132001)]

$|G_E/G_M|$ measured for the first time by BESIII
CROSS SECTION OF $e^+e^- \to \Lambda_c \bar{\Lambda}_c$

- $\sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)$ behaviour similar to $\sigma(e^+ e^- \to pp)$:
  - Strong enhancement at threshold followed by a plateau
  - $\sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)$ close to the point-like value, once Coulomb factor is taken into account:
    \[
    \sigma(e^+ e^- \to \Lambda_c \bar{\Lambda}_c)_{\text{point}} \approx \frac{\pi^2 \alpha^3}{2M_B} \approx 145 \text{pb}
    \]

- Some tension between BELLE and BESIII at threshold, more data is needed at threshold and above 4.6 GeV

4.5729 GeV
NEUTRAL BARYONS FORM FACTORS
NEUTRAL BARYONS ENERGY BEHAVIOUR AT THRESHOLD

\[
\sigma_{B^0\overline{B}^0}(q^2) = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{2M^2}{q^2}|G_E(q^2)|^2\right] \quad \text{as} \quad q^2 \rightarrow 4M^2 \quad \pi\alpha^2\beta \frac{|G|^2}{3q^2} \rightarrow 0
\]

- NO Coulomb correction at hadronic level: \( C = 1 \)
- \( \sigma \rightarrow 0 \) if \( \beta \rightarrow 0 \)
- yet experimentally non zero \( \sigma \) are found
LAMBDA FORM FACTOR

- Only few measurements of $\sigma (e^+e^- \rightarrow \Lambda\Lambda)$ and Lambda Effective f.f.:
  - BaBar, DM2, very recently BESIII:

\[
\text{(a)} \quad \text{Cross section (pb)}
\]

\[
\text{(b)} \quad \text{Effective FF}
\]

- Threshold enhancement: BESIII point only 1 MeV over threshold $M_{\Lambda\Lambda} = 2.2324$ GeV:
  $\sigma(e^+e^- \rightarrow \Lambda\Lambda\text{bar}) = (305+/-45+66-36)$ pb, not zero!

- Away from threshold agreement between BESIII and BaBar points
LAMBDAA FORM FACTOR

Based on 40.5 pb$^{-1}$ collected in 4 scan points between 2.2324 – 3.08 GeV in 2012

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2324</td>
<td>$\Lambda \to p\pi^-, \Lambda \to \bar{p}\pi^+$</td>
</tr>
<tr>
<td></td>
<td>$\bar{\Lambda} \to \bar{n}\pi^0$ combined</td>
</tr>
<tr>
<td>2.4000</td>
<td>$\Lambda \to p\pi^-, \Lambda \to \bar{p}\pi^+$</td>
</tr>
<tr>
<td>2.8000</td>
<td>$\Lambda \to p\pi^-, \Lambda \to \bar{p}\pi^+$</td>
</tr>
<tr>
<td>3.0800</td>
<td>$\Lambda \to p\pi^-, \Lambda \to \bar{p}\pi^+$</td>
</tr>
</tbody>
</table>

The Born cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ is determined from:

$$\sigma^B = \frac{N_{obs}}{L_{int} \cdot \varepsilon \cdot (1 + \delta) \cdot B}$$

The effective FF is defined by

$$|G| = \sqrt{\frac{|G_M|^2 + 1/2\tau|G_E|^2}{1 + 1/2\tau}} \cdot \frac{3s\sigma^B}{4\pi a^2 \beta} \cdot \frac{1}{1 + 1/2\tau}$$

| $\sqrt{s}$ (GeV) | $L_{int}$ (pb$^{-1}$) | $N_{obs}$ | $\epsilon(1 + \delta)$ (%) | $\sigma^B$ (pb) | $|G|$ ($\times 10^{-2}$) |
|-----------------|-----------------------|-----------|----------------------------|-----------------|-------------------------|
| 2.2324$^1$      | 2.63                  | 43 ± 7    | 12.9                       | 312 ± 51$^{+72}_{-45}$ | 61.9 ± 4.6$^{+18.1}_{-9.0}$ |
| 2.2324$^2$      | 2.63                  | 22 ± 6    | 8.25                       | 288 ± 96$^{+64}_{-36}$ | 12.7 ± 0.9 ± 0.9         |
| 2.2324$^3$      | 3.42                  | 45 ± 7    | 25.3                       | 305 ± 45$^{+66}_{-36}$ | 4.10 ± 0.72 ± 0.26       |
| 2.4000          | 3.42                  | 45 ± 7    | 25.3                       | 128 ± 19 ± 18      | 2.90 ± 0.33 ± 0.14       |
| 2.8000          | 3.75                  | 8 ± 3     | 36.1                       | 14.8 ± 5.2 ± 1.9   | 2.90 ± 0.33 ± 0.14       |
| 3.0800          | 30.73                 | 13 ± 4    | 24.5                       | 4.2 ± 1.2 ± 0.5    | 2.90 ± 0.33 ± 0.14       |
LAMBDA FORM FACTOR

- Interactions in the final state of $\Lambda\bar{\Lambda}$ well reproduce BaBar data but not the first BESIII point near threshold.
LAMBDAA POLARIZATION OBSERVABLES

- With hyperons, polarization is experimentally observable by their weak Parity violating decay, polarization effects can be observed even if the initial $e^+e^-$ state is unpolarized.

- Complex FFs and relative phase:
  - $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$, $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$
  - $\Delta \Phi = \Phi_E - \Phi_M$

- $\Delta \Phi$ can be obtained from angular distribution of daughter baryon from $\Lambda$ weak decay

- 2015 scan data sample: $E_{cm} = 2.369$, 66.9 pb$^{-1}$

- Multidimensional formalism developed * to extract $G_E$ and $G_M$ from the decay distribution

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \mathbf{P}_y \cdot \hat{q},$$

$\alpha_\Lambda$: asymmetry parameter,
$\hat{q}$: unit vector along daughter baryon

- Until now, no conclusive phase measurement exists!

*PLB 772 (2017) 16.
RELATIVE PHASE MEASUREMENT

- Result:
  - $R = 0.94 \pm 0.16 \pm 0.03$ (±0.02 $\alpha_\Lambda$)
  - $\Delta \Phi = 42^\circ \pm 16^\circ \pm 8^\circ$ (±6$^\circ$ $\alpha_\Lambda$)

- Most precise result on $R$
  (BaBar: $R = 1.73^{+0.99}_{-0.57}$ in $2.23 < q < 2.40$ GeV*)

- First conclusive result on $\Delta \Phi$
  (BaBar: $-0.76 < \sin \Delta \Phi < 0.98$ in $2.23 < q < 2.80$ GeV*)

First time measurement of $\Delta \Phi$ for any baryon!
LAMBDA POLARIZATION MEASUREMENT
[arXiv:1808.08917v1 ]

- Using a large data of $J/\psi$ collected by BESIII:
  - $J/\psi \rightarrow \Lambda\bar{\Lambda}$
  - $\alpha_\Lambda = 0.75$ instead of 0.64 (PDG): $5\sigma$ deviations, affecting $\Delta \phi$ results!

- $\Delta \phi$ result at $J/\psi$ is consistent and improves $2.369 \text{MeV}$ finding:

$$\Delta \Phi = 42.3^\circ \pm 0.6^\circ \pm 0.5^\circ$$

First time measurement of $\Delta \Phi$ for any baryon!
**NEUTRON F.F.**

- Only two direct measurements of $\sigma (e^+e^- \rightarrow n\overline{n})$ and neutron Effective f.f.
- Large errors (30%)

- No measurement of $R=|G_E/G_M|$ or $|G_E|$ and $|G_M|$.
- $q<2$GeV $\sigma (e^+e^- \rightarrow n\overline{n}) \approx \sigma (e^+e^- \rightarrow p\overline{p})$.
- Non vanishing cross section at threshold?
- $|G_n| > |G_p|$ as $q$ increases (pQCD: $|G_p| \approx |G_n|$)

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BESIII has new, precise results, under internal review, stay tuned!
CONCLUSIONS AND PERSPECTIVES

✓ BESIII is an excellent laboratory for Baryon FFs measurement in the time-like region
✓ Present theory is missing something
✓ Proton FFs extracted with energy scan data and ISR analysis at resonances
✓ $\Lambda, \Lambda_C$ FFs close to threshold, intriguing enhancement observed
✓ First measurement ever of the relative phase between Electric and Magnetic FFs
✓ More data on tape is being analyzed
✓ Neutron FFs results will soon be public
✓ Possibly higher energy data in the future

Thank you!