Baryon Electromagnetic Form Factor at BESIII

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OUTLINE

✓ INTRODUCTION:
  • The BESIII experiment and data sets
  • Electromagnetic Form Factors formalism

✓ Baryon Form Factors at BESIII
  • Proton Form Factor
    • $|G_E|/|G_M|$ measurements
    • ISR: taggend and untagged analysis
  • $\Lambda$ Form Factors
    • Phase information (preliminary result)
  • $\Lambda_C$ Form Factors

✓ Summary and Conclusions
2004: started BEPCII/BESIII construction
✓ Double rings
✓ Beam energy: 1-2.3 GeV
✓ Designed luminosity: $1 \times 10^{33}$ cm$^{-2}$s$^{-1}$
2008: test run
2009 – today: BESIII physics runs
The BESIII Detector


Electromagnetic CsI(Tl) Calorimeter
- $\sigma_{E/E} < 2.5\%$ @ 1 GeV (barrel)
- $\sigma_{E/E} < 5\%$ @ 1 GeV (end caps)
- $\sigma_{xy} \sim (6 \text{ mm})/E^{1/2}$ @ 1 GeV

RPC: 9 layers

Muon Detector
- $\Delta\Omega/4\pi = 93\%$

Drift Chamber
- $\sigma_{r/\phi} \sim 130 \mu m$ (single wire)
- $\sigma_{pt}/p_t \sim 0.5\%$ @ 1 GeV

ToF
- $\sigma_t \sim 90\text{ ps}$ (barrel)
- $\sigma_t \sim 120\text{ ps}$ (end caps)

ToF
The BESIII data set

- Charm physics
- Charmonium spectroscopy
- Light hadrons
- Search for new physics
- $\tau$ and QCD physics
- ...

World largest data sample for $J/\psi$, $\psi(2S)$ and $\psi(3770)$

Electromagnetic form factors

Hadrons are not point-like particles
- Internal structure
- Internal dynamic \( \rightarrow M_{\text{hadron}} \neq \sum m_q \)-valence

Form Factors (FFs) used to parametrize the structure and internal dynamics: 2 FFs involved for \( s=1/2 \) baryons

**SPACE-LIKE FF**
(Real functions)

**TIME-LIKE FF**
(Complex functions)

Electron scattering \( q^2 < 0 \)

Annihilation processes \( q^2 > 0 \)

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

**Dirac FF:**
related to the charge

**Pauli FF:**
related to the magnetization

0 \quad 4M_N^2 \quad q^2
Time-like Electromagnetic FFs

- Sachs parameterization:

\[ G_E(q^2) = F_1(q^2) + \frac{q^2}{4M_B} F_2(q^2) \quad G_M(q^2) = F_1(q^2) + F_2(q^2) \]

  Electric FF  Magnetic FF

- Differential cross section:

\[ \left[ \frac{d\sigma}{d\Omega_{CM}} \right] = \frac{\alpha^2 \beta^2 C}{4q^2} \left[ (1 + \cos^2 \theta) |G_M|^2 + \frac{1}{\tau} \sin^2 \theta_B |G_E|^2 \right] \]

\[ \beta = \sqrt{1 - \frac{1}{\tau}}, \quad \tau = \frac{q^2}{4M^2}, \quad C = \frac{y}{(1 - \exp(-y))}, \quad y = \frac{\alpha \pi}{\beta} \]

- Total cross section:

\[ \sigma(q^2) = \frac{2\pi \alpha^2 \beta C}{3q^2 \tau} \left( 2\tau |G_M|^2 + |G_E|^2 \right) \]

- The measurement of the differential cross section at fixed energy allows the determination of the ratio \(|G_E|/|G_M|\). From the total cross section the effective FF can be measured:

\[ |G_{\text{eff}}| = \sqrt{\frac{2\tau |G_M|^2 + |G_E|^2}{2\tau + 1}} \]

\[ \Rightarrow \text{equivalent to } |G_M| \text{ under the assumption } |G_E| = |G_M| \]
Proton FF in TL region - Scan data 2012

- Direct production channel $e^+e^- \rightarrow pp$
- R-scan data @ 12 points ($\mathcal{L} = 157 \text{ pb}^{-1}$) collected between 2.22 to 3.67 GeV in 2012
- Event selection:
  - Two charged tracks
  - PID for proton and antiproton
  - Kinematic fit constraints
  - Background subtracted
- Cross section and effective FF measurements:

$$\sigma_{\text{Born}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{L \cdot \epsilon \cdot (1 + \delta)} \quad |G| = \sqrt{\frac{\sigma_{\text{Born}}}{86.83 \cdot \beta / s (1 + \frac{2m_p^2}{s})}},$$

- Good agreement with previous measurements
- Overall improvement of the uncertainties by $\sim 30\%$
Extraction of $|G_E|/|G_M|$ ratio from the study of the proton polar angle distribution at those points with largest statistics

- Detection efficiency correction vs. $\cos\theta_p$ are applied

- $\sqrt{s}=2.2324$ GeV
- $\sqrt{s}=2.4$ GeV
- $\sqrt{s}=(3.05-3.08)$ GeV

- $|G_E|/|G_M|$ ratio consistent with 1
- Agreement with BaBar data (PRD87,092005)
- BESIII limited statistic: new scan data?
Using the Initial State Radiation (ISR)

\( e^+e^- \) annihilation is mostly accompanied by emission of one or several photons from the initial state \( \rightarrow \) events with ISR photons have a lower c.m. energies

- Continuous \( q^2 \) range
- Complementary approach to the energy scan technique

Two complementary methods:
- ISR-Tagged
- ISR-Untagged

MC simulation (PHOKHARA 9.1)

- Low statistics
- Large bkg

- High statistics
- \( \sqrt{s'} > 1 \text{GeV} \)
- Low bkg
Proton FF from ISR

- 7.4 fb\(^{-1}\) at c.m. energies between 3.773 GeV and 4.6 GeV
- ISR-Tagged and Untagged analysis exploited

**TAGGED ANALYSIS: LARGE ANGLE (LA)**
- Two tracks, one cluster in EMC
- Kinematic constraints applied (4C fit)
- 5C veto fit with additional \(\gamma\)

**UNTAGGED ANALYSIS: SMALL ANGLE (SA)**
- Two tracks, PID by dE/dx and TOF
- Polar angle of missing momentum and missing mass squared distributions to identify non-detected ISR \(\gamma\)
Cross section and $|G_{eff}|$ measurements
- LA: 31 intervals in $1.877 \leq \sqrt{s} \leq 3.0$ GeV
- SA: 30 intervals in $2 \leq \sqrt{s} \leq 3.8$ GeV
Consistent with previous measurements
Total relative uncertainties on the cross section is between 8% and 37%
SA results competitive in statistic with BaBar (PRD88,072009; PRD87,092005)
Proton FF from ISR: $R=|G_E|/|G_M|$ extraction

- $R=|G_E|/|G_M|$ measurements can be extracted from the analysis of the $\theta_p$ distribution, the angle between the proton momentum in the ppbar rest frame and the momentum of the ppbar system in the $e^+e^-$ c.m. frame
  - LA: 6 intervals in $1.877 \leq \sqrt{s} \leq 3.0$ GeV
  - SA: 3 intervals in $2 \leq \sqrt{s} \leq 3.8$ GeV

\[
\frac{d\sigma}{d\cos \theta_p} = A[H_M(\cos \theta_p, M_{p\bar{p}})] + \frac{R}{T} H_E(\cos \theta_p, M_{p\bar{p}})
\]

- From MC under the hypothesis $|G_E| = 0$
- From MC under the hypothesis $|G_M| = 0$

They are the equivalent forms of $1+\cos^2\theta_p$ and $\sin^2\theta_p$ in the case of $e^+e^-\rightarrow p\bar{p}$

- Competitive accuracy
- Total uncertainty dominated by statistical uncertainty
- Agreement with BaBar and BESIII scan data
Effective proton FF as a function of the 3-momentum ($p$) of the relative motion of the $p\bar{p}$ pair: damped oscillatory behaviour observed by BaBar and then confirmed in BESIII.

Due to a possible interference effect involving rescattering processes at moderate kinetic energies of the outgoing hadrons (when the center-of-mass of the produced hadrons are separated by $\sim 1$ fm)
Measurement of $\Lambda \text{FF}$ at BESIII

- $e^+e^-\rightarrow \Lambda \bar{\Lambda}$, $\Lambda\rightarrow p\pi$, $\bar{\Lambda}\rightarrow \bar{p}\pi^+$ ($\bar{\Lambda}\rightarrow \bar{n}\pi^0$, $\Lambda\rightarrow X$, with $X$=inclusive decays)
- Indirect search for the antiproton (search for mono-energetic $\pi^0$)
- 4 energy scan points: 2.2324 GeV, 2.4 GeV, 2.8 GeV and 3.08 GeV
- 1 MeV above the $\Lambda \bar{\Lambda}$ mass threshold
- Cross section and effective electromagnetic FF determined

- Good agreement with BaBar and DM2 data
- The observed threshold enhancement underlying a more complicated physics scenario
- These results could help to understand the mechanism of baryon production and test theory hypotheses based on threshold enhancement effect

BESIII (PRD97)
BaBar (PRD76,092006)
DM2 (Z. Phys. C. 48,23)
pQCD prediction
No Coulomb effect for neutral baryons BUT
unexpected rise at the threshold
Multidimensional analysis needed for a complete decomposition of \( G_E \) and \( G_M \)
- 66.9 pb\(^{-1} \) @ \( \sqrt{s} = 2.396 \) GeV
- Complex form of FF:
  - \( G_E = |G_E|e^{i\phi_E} \), \( G_M = |G_M|e^{i\phi_M} \)
- First measurement of the relative phase \( \Delta \phi = \phi_E - \phi_M \)

\[ \Delta \phi \neq 0 \Rightarrow \text{polarization effect on the final state even for unpolarized initial state} \]

Polarization and spin-correlation parameters determined \( \Rightarrow \) they allow to determine the relative phase between \( G_E \) and \( G_M \)

\[ R = 0.94 \pm 0.16_{\text{stat}} \pm 0.03_{\text{syst}} \pm 0.02 \alpha_\Lambda \]
\[ |\Delta \Phi| = 42^\circ \pm 12^\circ_{\text{stat}} \pm 8^\circ_{\text{syst}} \pm 6^\circ \alpha_\Lambda \]
Λ polarization measurement

- $J/\psi \rightarrow \Lambda \bar{\Lambda}$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ and $\Lambda \rightarrow \bar{\pi}\pi^0$
- With hyperons, the polarization is experimentally observable by their weak parity violating decay → extracted from the angular distributions of its decay products
- The magnitude of the polarization depends on $\theta_\Lambda$
- $\Delta \phi = (42.4 \pm 0.6 \pm 0.5)^\circ$ : consistent and more precise than $\sqrt{s}=2.396$ GeV analysis

\begin{itemize}
  \item $\mu(\cos \theta_\Lambda) \sim 1 - \alpha_\psi 2\alpha_\pi \sin \Delta \Phi \cos \theta_\Lambda \sin \theta_\Lambda$ ⇒ clear polarization effect observed
  \item **Asymmetry parameter for the $\Lambda \rightarrow p\pi^-$ decay mode $\alpha_-$ : 5σ deviation from the PDG value**
    \begin{itemize}
      \item This means that all published results on $\Lambda$ polarization, determined from the product of $\alpha_-$ and and the polarization, are 17(3)% too large
    \end{itemize}
\end{itemize}
Measurement of $\Lambda_c$ FF at BESIII

- 4 c.m. energies: 4.5745, 4.5800, 4.5900, 4.5995 GeV (631.3 pb^{-1})
- 10 Cabibbo-favored + c.c. hadronic decay modes considered
- Total cross section: weighted average over all the 20 decay modes
  - Very high precision achieved (1.3% @ 4.6 GeV)
- Polarization and spin-correlation parameters determined ⇒ they allow to determine the relative phase between $G_E$ and $G_M$
- **Step at threshold + plateau region**: indicate the complexity of production behaviour of the $\Lambda_c$
- $|G_E/G_M|$ measured for the first time

\[
|G_E/G_M|^2 = (1 - \alpha)/(\frac{4m_{\Lambda_c}^2}{s} - \alpha + \frac{4m_{\Lambda_c}^2}{s})
\]

| $\sqrt{s}$ (MeV) | $\alpha_{\Lambda_c}$ | $|G_E/G_M|$ |
|------------------|----------------------|------------------|
| 4574.5           | -0.13 ± 0.12 ± 0.08  | 1.14 ± 0.14 ± 0.07 |
| 4599.5           | -0.20 ± 0.04 ± 0.02  | 1.23 ± 0.05 ± 0.03  |

$p(\theta) \propto 1 + \alpha_{\Lambda_c} \cos^2 \theta$

$\sqrt{s} = 4.5745$ GeV

$\sqrt{s} = 4.5995$ GeV
Conclusions

- BESIII provides an ideal environment to measure baryon FFs.
- Two complementary approaches can be used
  - Energy scan
  - ISR technique
- $p$, $\Lambda$, $\Lambda_c$ cross sections and FFs measured with very high precision
  - Intriguing enhancement observed at threshold
  - Oscillating behaviour of proton FF
  - First measurement of the relative phase of EM FFs for $\Lambda$
    (preliminary result)
Near future:

- Present theory is missing something
- $e^+e^-\rightarrow p\bar{p}$: more data from BESIII and CMD3
- $e^+e^-\rightarrow \Lambda\bar{\Lambda}$: more data at threshold
- $e^+e^-\rightarrow \Lambda_c\bar{\Lambda}_c$: more data at threshold and above by BESIII
- $e^+e^-\rightarrow n\bar{n}$: more data from SND and CMD3; BESIII preliminary soon available
- $\text{BR}(J/\psi\rightarrow \gamma n\bar{n})$: BESIII preliminary soon available
- $|G_E|/|G_M|$ phase: more data from BESIII
Back-up slides
The **BES III** Collaboration

**USA**
- Carnegie Mellon University
- Indiana University
- University of Hawaii
- University of Minnesota
- University of Rochester

**EUROPE**
- Bochum University
- Budker Institute of Nuclear Physics, **Ferrara University**
- GSI Darmstadt
- Helmholtz Institute Mainz, **INFN, Laboratori Nazionali di Frascati**
- Johannes Gutenberg University of Mainz
- Joint Institute for Nuclear Research (JINR), KVI/University of Groningen
- Turkish Accelerator Center Particle Factory Group (TAC-PF), Universitaet Giessen
- University of Münster, **University of Turin**
- Uppsala University

**CHINA**
- IHEP, CCAST, UCAS, Beijing Institute of Petro-chemical Technology
- Beihang Univ.
- Guangxi Normal Univ.
- Guangxi Univ.
- Hangzhou Normal Univ.
- Henan Normal Univ.
- Henan Univ. of Science and Technology
- Huazhong Normal Univ.
- Huangshan College
- Hunan Univ.
- Lanzhou Univ.
- Liaoning Univ.
- Nanjing Normal Univ.
- Nanjing Univ.
- Nankai Univ.
- Peking Univ.
- Shanxi Univ.
- Sichuan Univ.
- Shandong Univ.
- Shanghai Jiaotong Univ.
- Soochow Univ.
- Southeast Uny.
- Sun Yat-sen Univ.
- Tsinghua Univ.
- Univ. of Jinan
- Univ. of Science and Technology of China
- Univ. of Science and Technology Liaoning
- Univ. of South China
- Wuhan Univ.
- Zhejiang Univ.
- Zhengzhou Univ.

**OTHER IN ASIA**
- COMSATS Institute of Information Technology (CIIT), Institute of Physics and Technology
- Mongolia
- Tokyo University
- Seoul National University
- University of the Punjab

~350 members
66 institutions from
14 countries

http://bes3.ihep.ac.cn
BESIII physics programme

Light hadron physics
- Meson and baryon spectroscopy
- Multiquark states
- Threshold effects
- Glueballs and hybrids
- Two-photon physics
- Form factors

QCD and \( \tau \)
- Precision R measurement
- \( \tau \) decay

Charmonium physics
- Precision spectroscopy
- Transitions and decays

XYZ meson physics
- \( Y(4260), Y(4360) \) properties
- \( Z_c(3900)^+, \ldots \)

Charm physics
- Semi-leptonic form factors
- Decay constants \( f_D \) and \( f_{D_s} \)
- CKM matrix: \( |V_{cd}| \) and \( |V_{cs}| \)
- \( D^0 - \bar{D}^0 \) mixing, CPV
- Strong phases

Precision mass measurements
- \( \tau \) mass
- \( D, D^* \) mass
\[
\frac{d^2 \sigma_{e^+e^- \to \bar{p}p\gamma}(q^2)}{dq^2 d \cos \theta^*_\gamma} = \frac{1}{s} W(s, x, \theta^*_\gamma) \sigma_{\bar{p}p}(q^2),
\]

\[
W(s, x, \theta^*_\gamma) = \frac{\alpha}{\pi x} \left( \frac{2 - 2x + x^2}{\sin^2 \theta^*_\gamma} - \frac{x^2}{2} \right), \quad x = \frac{2E^*_\gamma}{\sqrt{s}} = 1 - \frac{q^2}{s}
\]
Proton FF Oscillation

PRL114,232301 - PRC93,035201
Final State interaction [NPA 929, 102]
FSI expect a sharp rise but not a jump on thr and no relationship with the pointlike FF

**Final State interaction** [A. Milstein, PhiPsi2017, Maitz]

Predictions for the cross section of $e^+e^- \to N\bar{N}$ near the threshold


$J/\psi, \psi(2S) \to p\bar{p}\gamma$ decay

The invariant mass spectra in $J/\psi(\psi(2S) \to p\bar{p}\gamma)$ decays:

Left: $J/\psi \to p\bar{p}\gamma$ decay. Right: $\psi(2S) \to p\bar{p}\gamma$ decay.
$J/\psi, \psi(2S) \rightarrow B\bar{B}$

\[ \alpha_\psi = 0.469 \pm 0.026 \]
\[ \text{BF} = (19.43 \pm 0.03) \times 10^{-4} \]

$J/\psi \rightarrow \Lambda\bar{\Lambda}$

$\psi(2S) \rightarrow \Lambda\bar{\Lambda}$

$J/\psi \rightarrow \Sigma^0\bar{\Sigma}^0$

$\psi(2S) \rightarrow \Sigma^0\bar{\Sigma}^0$

\[ \text{BES}III, \text{PRD 95, 052003 (2017)} \]
Inclusive angular distributions

\[ e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)\bar{\Lambda} \]

\[ d\Gamma \propto \left( 1 + \alpha_\psi \cos^2 \theta_\Lambda \right) \{1 + \alpha_1 P_\Lambda(\theta_\Lambda) \sin \theta_1 \sin \phi_1\} \]

\[ \Lambda \rightarrow p\pi^-: \Omega_1 = (\cos \theta_1, \phi_1) : \alpha_1 \rightarrow \alpha_- \]

Hyperon polarization determined from angular distribution of the nucleon from the weak decay

Exclusive angular distributions

Two decay modes for \( \bar{\Lambda} \):

\[ e^+e^- \rightarrow (\Lambda \rightarrow p\pi^-)(\bar{\Lambda} \rightarrow \bar{p}\pi^+) \]

\[ \bar{\Lambda} \rightarrow \bar{p}\pi^+ (or \bar{n}\pi^0): \Omega_2 = (\cos \theta_2, \phi_2) \]

\[ \Lambda \rightarrow p\pi^-: \Omega_1 = (\cos \theta_1, \phi_1) : \alpha_1 \rightarrow \alpha_- \]

\[ d\Gamma \propto \mathcal{W}(\xi)d\xi = \mathcal{W}(\xi)d\cos \theta_\Lambda d\Omega_1 d\Omega_2 \]

\[ \xi : (\cos \theta_\Lambda, \Omega_1, \Omega_2) \quad 5D \text{ PhSp} \]

\[ \mathcal{W}(\xi) = 1 + \alpha_\psi \cos^2 \theta_\Lambda \]

\[ + \alpha_1 \alpha_2 \left( \sin^2 \theta_\Lambda \sin \theta_1 \sin \theta_2 \cos \phi_1 \cos \phi_2 + \cos^2 \theta_\Lambda \cos \theta_1 \cos \phi_2 \right) \]

\[ + \alpha_1 \alpha_2 \sqrt{1 - \alpha_\psi^2} \cos(\Delta \Phi) \{\sin \theta_\Lambda \cos \theta_1 \sin \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2\} \]

\[ + \alpha_1 \alpha_2 \alpha_\psi (\cos \theta_1 \cos \theta_2 - \sin^2 \theta_\Lambda \sin \theta_1 \sin \theta_2 \sin \phi_1 \sin \phi_2) \]

\[ + \sqrt{1 - \alpha_\psi^2} \sin(\Delta \Phi) \sin \theta_\Lambda \cos \theta_1 (\alpha_1 \sin \theta_1 \sin \phi_1 + \alpha_2 \sin \theta_1 \sin \phi_2) \]

\[ \Delta \Phi \neq 0 \Rightarrow \text{independent determination of } \alpha_1 \text{ and } \alpha_2! \]
Summary of the $J/\psi \to \Lambda \bar{\Lambda}$ analysis

$\Lambda \to p\pi^-$: $\alpha_\gamma = 0.750 \pm 0.009 \pm 0.004$

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

$\Rightarrow$ Polarization: max 20%

17(3)% larger than PDG average

$> 5\sigma$ difference

CP test:

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$$

$A_{CP} = -0.006 \pm 0.012 \pm 0.007$

Previous result (using $\alpha P$ product):

$A_{CP} = 0.013 \pm 0.021$

PS185 PRC54(96)1877

CKM $A_{CP} \sim 10^{-4}$
PREDICTION FOR $\Delta \phi$

Predictions for $\Delta \Phi$

Haidenbauer, Meißner, PRL761 (‘16) 456