

Baryon Electromagnetic Form Factors at BESIII

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**The International Conference on the Structure of
Baryons**

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BESIII

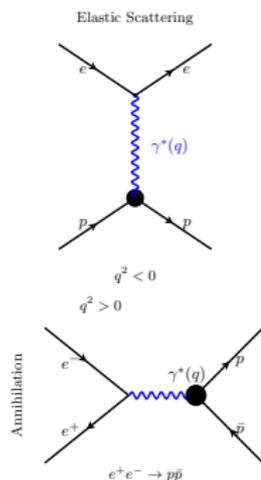


Outline

- 1 Introduction
- 2 BESIII Experiment
- 3 Nucleon Form Factors at BESIII
- 4 Hyperon Form Factors at BESIII
- 5 Summary and Outlook

Introduction: Electromagnetic Form Factors (EMFFs)

- Electromagnetic Form Factors (EMFFs) are fundamental properties of baryons.
- Connected to charge and current distributions.
- Serve as essential probes of baryon structure and dynamics, providing critical tests for theoretical models of hadron structure.



Hadronic vertex:

$$\Gamma^\mu(p', p) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2m_p} F_2(q^2)$$

Dirac and Pauli Form Factors:

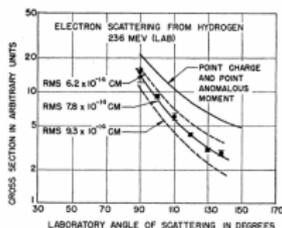
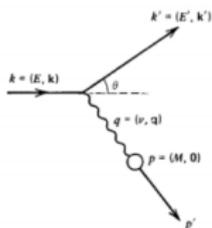
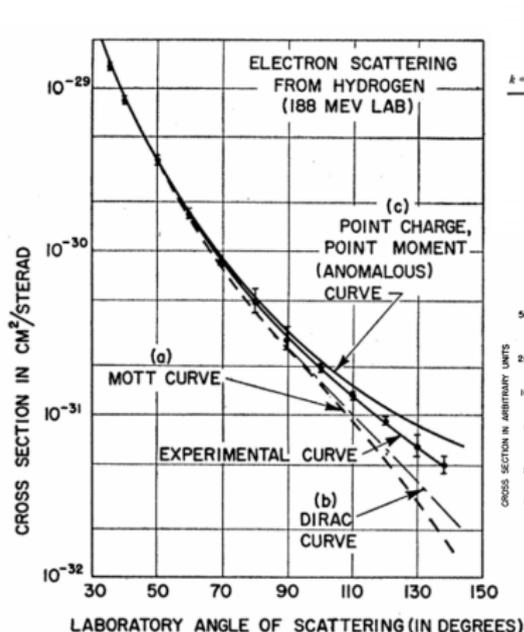
$F_1(q^2)$: Dirac FF $F_2(q^2)$: Pauli FF

Sachs Form Factors:

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

- **Elastic Scattering:** $e^- p \rightarrow e^- p$
Space-Like (SL) region: $q^2 \simeq -2E_e E_e'(1 - \cos \theta_e) < 0$
- **Annihilation:** $e^+ e^- \leftrightarrow p\bar{p}$
Time-Like (TL) region: $q^2 = s = M_{p\bar{p}}^2 > 0$

The “size” of the proton



- The differential cross section of ep scattering and subsequent measurements were found to be incompatible with the assumption of a charged point-like proton.
- The shape (or internal structure) of the proton might be described by the electromagnetic form factors.
- The best description of the data was obtained for $\sqrt{\langle r^2 \rangle} = 0.74 \pm 0.24$ fm.

R. Hofstadter and R. McAllister, *Phys. Rev.* **98** (1955) 217;

R. Hofstadter, *Rev. Mod. Phys.* **28** (1956) 214;

R. Hofstadter, F. Bumiller and M. R.

Yearian, *Rev. Mod. Phys.* **30** (1958) 482.

Phys. Rev. **98** (1955) 217

Time-like EMFFs: Theoretical Overview

Differential Cross Section:

$$\frac{d\sigma_{B\bar{B}}}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2} \left[|G_M|^2(1 + \cos^2\theta) + \frac{4m_B^2}{q^2} |G_E|^2 \sin^2\theta \right]$$

Integrated version (Born cross section):

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

Effective Form Factor (from total cross section):

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

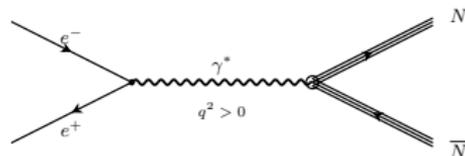
where $\tau = \frac{q^2}{4m_B^2}$, $\beta = \sqrt{1 - 4m_B^2/q^2}$, and C is the Coulomb correction factor.

Electromagnetic Form Factors (EMFFs)

- $|G_E|$ – Electric form factor
- $|G_M|$ – Magnetic form factor
- $\Delta\Phi = \arg(G_E) - \arg(G_M)$ – Relative phase

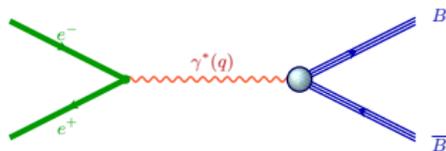
Polarization of hyperon (self-analyzing):

$$P_y = -\frac{\sin 2\theta \operatorname{Im}[G_E(s)G_M^*(s)]/\sqrt{\tau}}{|G_E(s)|^2 \sin^2\theta/\tau + |G_M(s)|^2(1 + \cos^2\theta)}$$



Time-like $e^+e^- \rightarrow N\bar{N}$ diagram.

Measure the Form Factors at an e^+e^- Collider

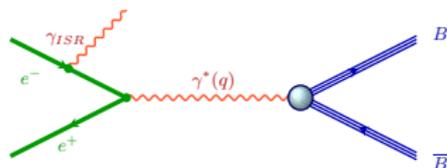


Energy Scan Method

- Well-defined center-of-mass energy.
- Low background.
- Very good energy resolution.
- Discrete values, leaving gaps without information.

Differential cross section:

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



ISR Method

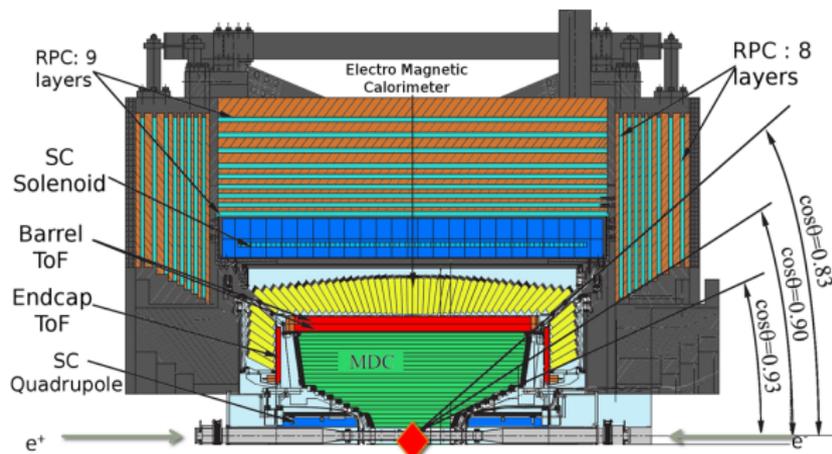
- At a fixed center-of-mass energy \sqrt{s} events are collected from threshold to \sqrt{s} .
- Systematic uncertainty can be evaluated coherently.
- Large integrated luminosity needed.
- Higher background.

Differential cross section with ISR:

$$\frac{d\sigma_{B\bar{B}\gamma}}{dq^2} = \frac{1}{s} W(s, x) \sigma_{p\bar{p}}(q^2),$$

$$W(s, x) = \frac{\pi\alpha}{x} \left(\ln \frac{s}{m_e^2} - 1 \right) (2 - 2x + x^2)$$

BESIII Spectrometer on BEPCII



Main Drift Chamber (MDC)

Small cell, 43 layers
 $\sigma_{xy} = 130 \mu\text{m}$
 $dE/dx \sim 6\%$
 $\sigma_p/p = 0.5\% @ 1 \text{ GeV}/c$

Time of Flight (TOF)

Plastic scintillator, 2 layers
 $\sigma_T(\text{barrel}) = 68 \text{ ps}$
 $\sigma_T(\text{endcap}) = 110 \text{ ps}$
 (Updated to 60 ps with MRPC)

Electromagnetic Calorimeter (EMC)

CsI(Tl): $L = 28 \text{ cm}$
 Barrel: $\sigma_E/E = 2.5\% @ 1 \text{ GeV}$
 Endcap: $\sigma_E/E = 5.0\% @ 1 \text{ GeV}$

Muon Counter (MUC)

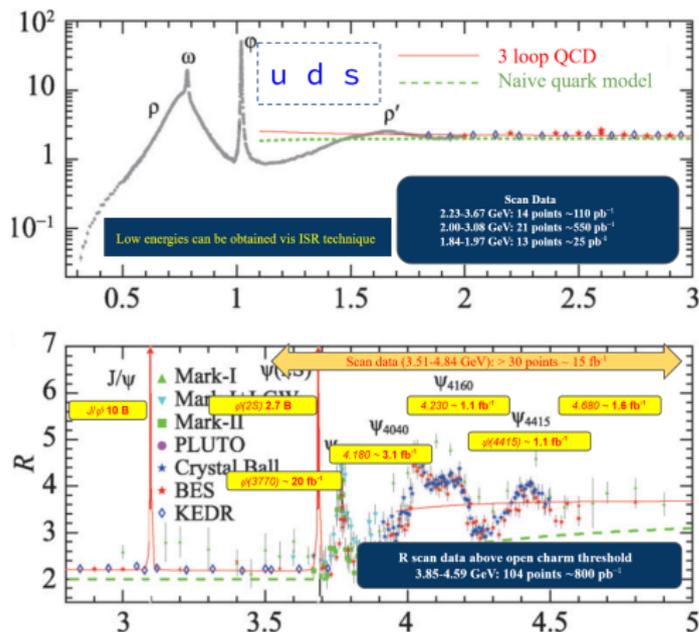
RPC technology
 Barrel: 9 layers
 Endcaps: 8 layers
 $\sigma_{\text{spatial}} = 1.48 \text{ cm}$

BESIII detector: 93% coverage

$\sqrt{s} \sim 2.0 (1.8) - 4.965 \text{ GeV}$, $L \sim 1.0 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ (design)

Nucl. Instrum. Meth. A **614**, 345–399 (2010)

Electron–Positron Annihilation Data at BESIII

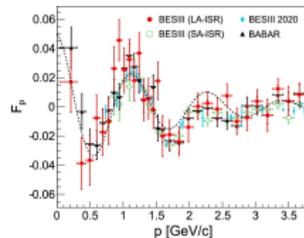
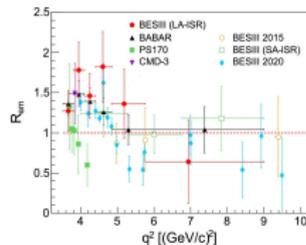
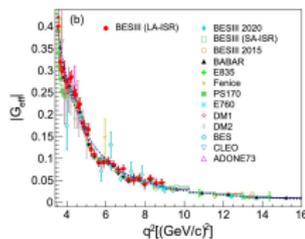
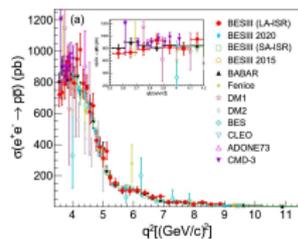


- World's largest data set in the τ -charm region
- Charmonium spectroscopy
- Charm physics
- Light hadrons and new physics searches

BESIII provides an ideal environment for studying baryon electromagnetic form factors (EMFFs) using both **energy-scan** and **initial-state radiation (ISR)** methods.

Proton Electromagnetic Form Factors

The proton EMFFs have been measured with high accuracy using two techniques: the **Energy Scan Method** and the **ISR Method**



LA-ISR: ISR photon emitted at large angle
SA-ISR: ISR photon emitted at small angle

Energy Scan Method:

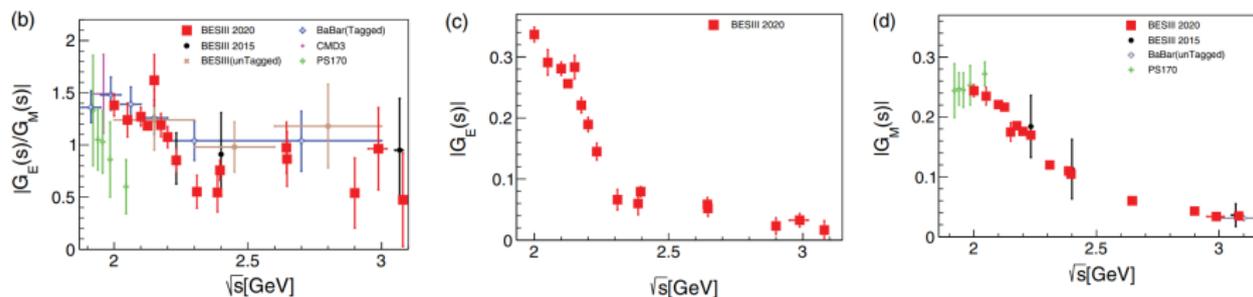
- 2.2324–3.6710 GeV, 156.9 pb^{-1} , *PRD 91, 112004 (2015)*
- 2.00–3.08 GeV, 688.5 pb^{-1} , *PRL 124, 042001 (2020)*
- Most precise measurement of the ratio $|G_E/G_M|$ at 2.125 GeV with direct annihilation.
- Wide q^2 region from the $p\bar{p}$ threshold up to 14 GeV^2 .
- Measurements of the proton EMFFs below 4 GeV^2 through ISR-tagged methods.

ISR Method:

- LA-ISR: threshold– $3.0 \text{ GeV}/c^2$, *PLB 817, 136328 (2021)*
- SA-ISR: $2.0\text{--}3.8 \text{ GeV}/c^2$, *PRD 99, 092002 (2019)*
- Data sets: $3.773\text{--}4.600 \text{ GeV}$, 7.5 fb^{-1}

Yadi Wang's talk

Proton Electromagnetic Form Factors (contd.)

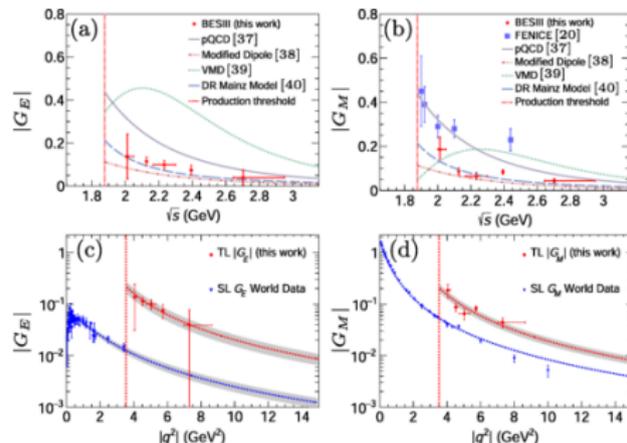


PRL 124, 042001 (2020)

- The ratio $|G_E/G_M|$ has been determined with high precision, reaching $\delta|G_E/G_M| \approx 3.5\%$ at 2.125 GeV - the most accurate to date.
- The magnetic form factor $|G_M|$ has been measured for the first time over a broad energy range, with uncertainties between 1.6% and 3.9%.
- The electric form factor $|G_E|$ has been extracted for the first time.

Yadi Wang's talk

Neutron Electromagnetic Form Factors



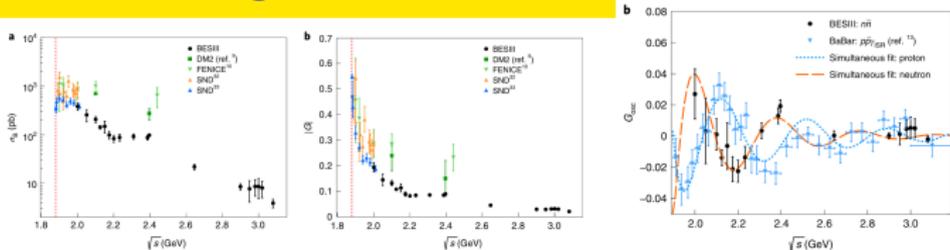
PRL 130, 151905 (2023)

First measurement of the $|G_E|$ and $|G_M|$ of neutron in the time-like region.

- The identification of purely neutral final states is experimentally challenging.
- The $|G_E|$ and $|G_M|$ of the neutron are measured separately in the energy range $\sqrt{s} = 2.0\text{--}2.95$ GeV.
- Compared to the FENICE results, the measured values $|G_M|$ are smaller by a factor of approximately 2–3.
- The results are compared with several theoretical models (pQCD, modified dipole, VMD, and dispersion relations), and the DR model shows the best overall consistency.

Yadi Wang's talk

Neutron Electromagnetic Form Factors (contd.)

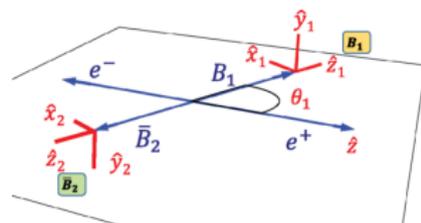


Nat. Phys. 17, 1200–1204 (2021)

- The Born cross section ($\sigma_{n\bar{n}}$) and the effective form factor $|G_{\text{eff}}|$ of the neutron have been measured in the range $\sqrt{s} = 2.00\text{--}3.08$ GeV, $\mathcal{L} \sim 647.9 \text{ pb}^{-1}$.
- These results substantially improve the overall measurement precision compared with earlier experiments.
- The coupling strengths of $\gamma^* p\bar{p}$ and $\gamma^* n\bar{n}$ vary with \sqrt{s} , deviating from the expectations of naïve prediction models.
- A clear oscillatory behavior is observed in the reduced $|G_{\text{eff}}|$ distribution, with a phase nearly orthogonal to that of the proton. **Yadi Wang's talk**

From Nucleon to Hyperon

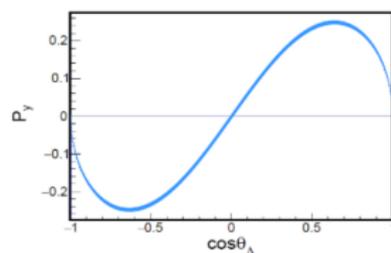
- Hard to study hyperon EMFFs in the **space-like region** due to the lack of stable hyperon beams.
- In the **time-like region**, hyperons are produced via e^+e^- annihilation above threshold.
- The angular distribution of decay baryons reveals the **polarization** of the parent hyperon.



Phys. Rev. D 99, (2019)

Advantages:

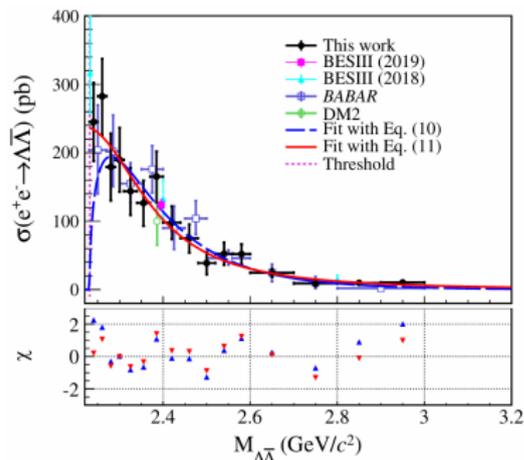
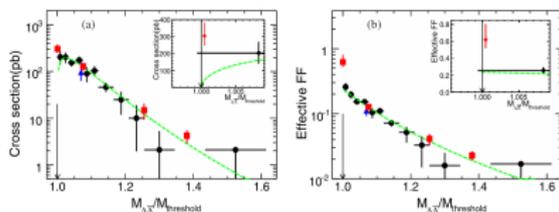
- Cross sections can be measured **close to threshold**.
- Weak decays ($Y \rightarrow B + P$) allow access to **polarization** and the relative phase of G_E and G_M .
- Hyperon weak decays are **self-analyzing**, enabling direct phase extraction.



$$P_y = - \frac{\sin 2\theta \operatorname{Im}[G_E(s)G_M^*(s)]/\sqrt{\tau}}{|G_E(s)|^2 \sin^2 \theta/\tau + |G_M(s)|^2(1 + \cos^2 \theta)}$$

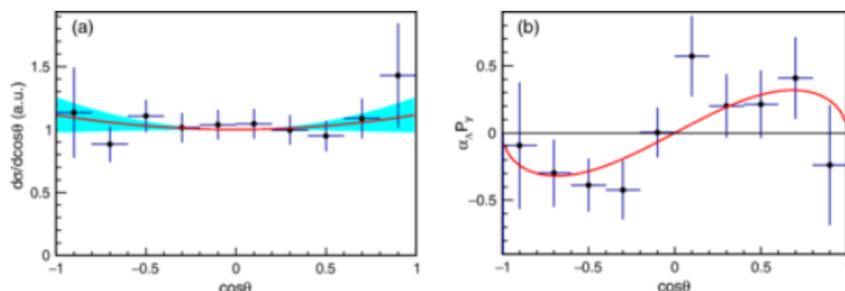
Nuov. Cim. A 109, 241 (1996)

Electromagnetic Form Factors of the Λ Hyperon at BESIII



BESIII Scan: $305 \pm 45^{+36}_{-66}$ pb at
 2.2324 GeV (1 MeV above threshold)
 BaBar ISR: $204^{+60}_{-62} \pm 22$ pb in [2.23,
 2.27] GeV
 BESIII ISR: $245 \pm 56 \pm 14$ pb in [2.231,
 2.250] GeV

- **Energy Scan Method:** Measurements at $\sqrt{s} = 2.2324, 2.400, 2.800,$ and 3.080 GeV. [PRD 97, 032013 \(2018\)](#)
- **ISR Method:** Large-Angle ISR (LA-ISR) from threshold up to 3.00 GeV/c^2 . [PRD 107, 072005 \(2023\)](#) **Data Sets:** 11.9 fb^{-1} at $\sqrt{s} = 3.773\text{--}4.258$ GeV.
- Non-zero cross section observed near threshold, consistent with BaBar.

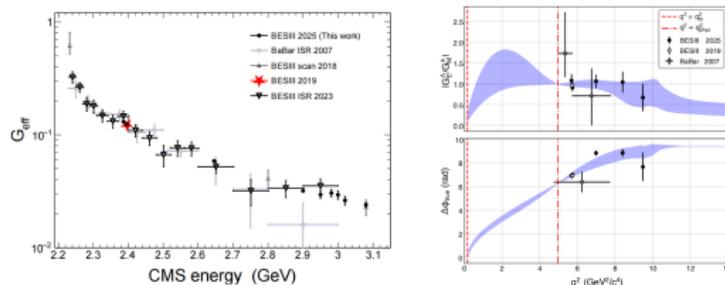
Measurement of Λ EMFFs

PRL 123, 122003 (2019)

- Events of the reaction $e^+e^- \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ are reconstructed to access the relative phase between G_E and G_M .
- A nonzero relative phase induces polarization of the outgoing baryons, given by $P_y = \frac{1-\eta}{2} \frac{\sin\theta \cos\theta}{1+\eta \cos^2\theta} \sin(\Delta\Phi)$.
- **Data sample:** $\sqrt{s} = 2.396$ GeV, 66.9 pb $^{-1}$.
- Extracted results: $|G_E/G_M| = 0.96 \pm 0.14 \pm 0.02$, $\Delta\Phi = (37^\circ \pm 12^\circ \pm 6^\circ)$.
- These results confirm the **complex nature of the electromagnetic form factors** of the Λ hyperon.

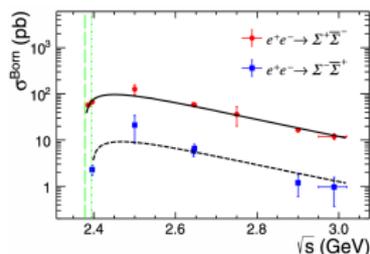
Recent measurement of Λ EMFFs

arXiv:2506.08072

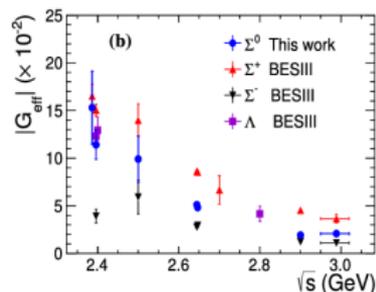


- First energy-dependent measurement of Λ EM form factors in the time-like region ($\sqrt{s} = 2.386\text{--}3.080$ GeV) using single- and double-tag $e^+e^- \rightarrow \Lambda\bar{\Lambda} \rightarrow p\pi^- \bar{p}\pi^+$ at BESIII.
- Ratio $R(q^2) = |G_E/G_M|$ nearly constant; relative phase $\Delta\Phi$ changes by $> 90^\circ$ between $\sqrt{s} = 2.396$ and 2.654 GeV.
- The dispersive fit gives an $\bar{r}_E^\Lambda = -0.076 \pm 0.043$ fm \Rightarrow negative charge radius \Rightarrow asymmetric ds quark distribution.

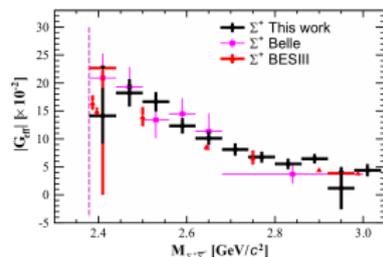
Electromagnetic Form Factors of the Σ Hyperon at BESIII



Phys. Lett. B 814
(2021) 136110



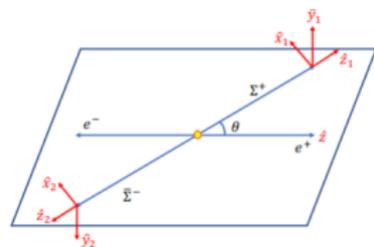
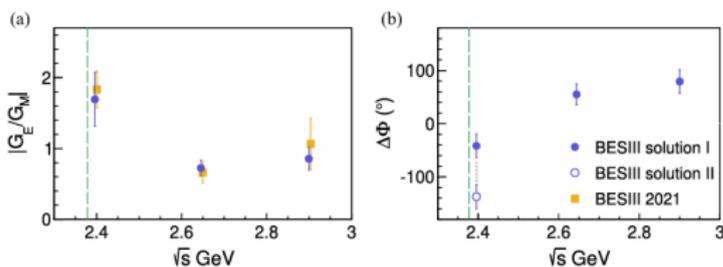
Phys. Lett. B 831
(2022) 137187



Phys. Rev. D 109
(2023) 034029

- The Σ hyperons form an isospin triplet: $\Sigma^- (dds)$, $\Sigma^0 (uds)$, and $\Sigma^+ (uus)$.
- Electromagnetic form factors of all three hyperons have been measured using direct e^+e^- annihilation.
- An ISR measurement has also been performed for the Σ^+ EMFFs study.
- The measured cross-section ratio for the isospin triplet is approximately $(9.7 \pm 1.3) : (3.3 \pm 0.7) : 1$.

Determine the $\Sigma^+(uus)$ EMFFs Completely



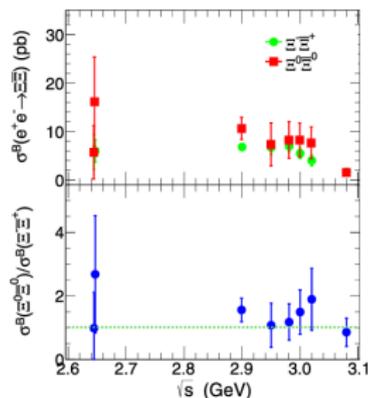
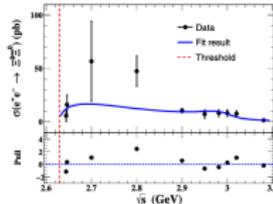
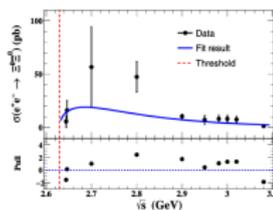
Phys. Rev. Lett. 132, 081904 (2024)

An event of the reaction $e^+e^- \rightarrow \Sigma^+(\rightarrow p\pi^0)\bar{\Sigma}^-(\rightarrow \bar{p}\pi^0)$ is reconstructed and analyzed through the joint angular distribution:

$$\begin{aligned}
 W(\xi) &\propto \mathcal{F}_0(\xi) + \alpha \mathcal{F}_5(\xi) \text{ (Unpolarized)} \\
 &+ \alpha_1\alpha_2\mathcal{F}_1(\xi) + (1 - \alpha_2 \cos \Delta\Phi)\mathcal{F}_2(\xi) + \alpha \mathcal{F}_6(\xi) \text{ (Correlated)} \\
 &+ (1 - \alpha_2 \sin \Delta\Phi)[- \alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)] \text{ (Polarized)}
 \end{aligned}$$

- Polarization signals observed at $\sqrt{s} = 2.3960, 2.6454, \text{ and } 2.9000$ GeV with statistical significances of $2.2\sigma, 3.6\sigma, \text{ and } 4.1\sigma$, respectively.
- The relative phase between G_E and G_M was determined for the first time in a broad q^2 region.

Cross Section and Effective FF of Ξ Hyperon – Two Valence s -Quarks



PRD 103, 012005 (2021):
 $\Xi-\Xi^+$ channel

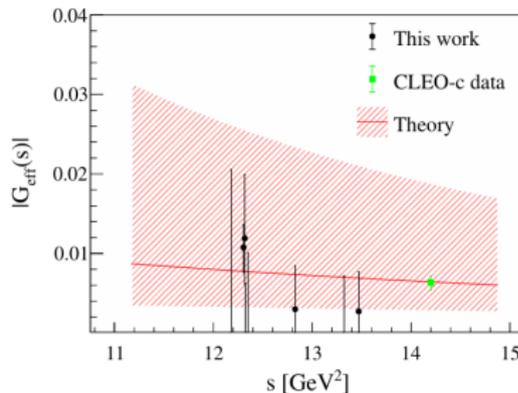
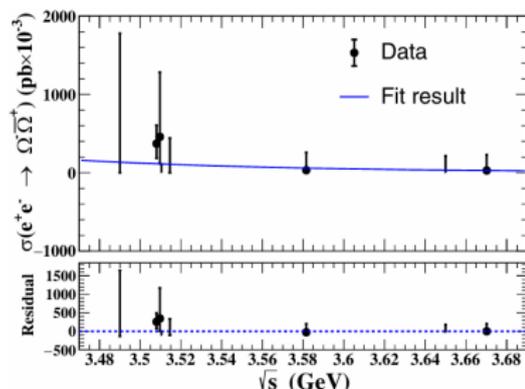
PLB 820, 136557 (2021):
 $\Xi^0-\Xi^0$ channel

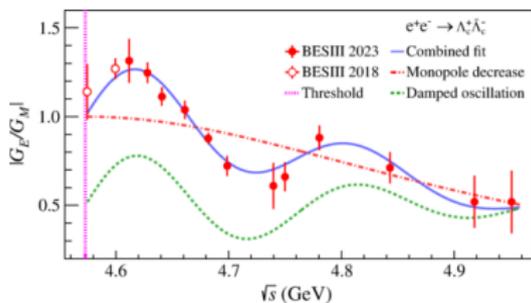
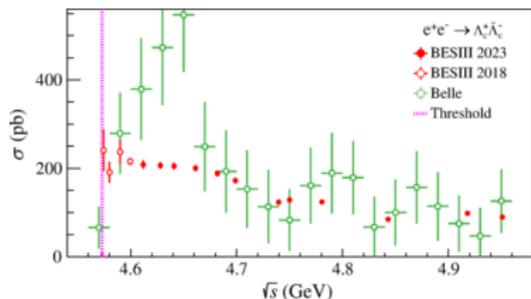
- Cross sections for $e^+e^- \rightarrow \Xi\Xi$ have been measured via direct annihilation in the energy range $\sqrt{s} = 2.644\text{--}3.080$ GeV.
- Limited statistics are available for data points close to the production threshold.
- The ratio of the Born cross section and the effective form factor $|G_{\text{eff}}|$ for the two channels agrees within 1σ with the expectations from isospin symmetry.

EMFFs of Ω Hyperon – Three Valence s -Quarks

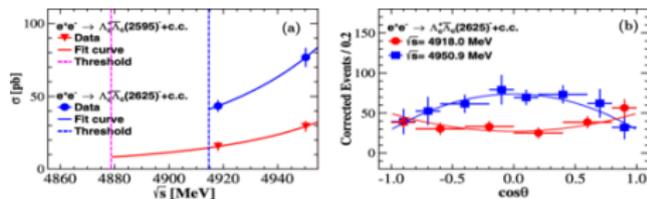
- The Ω^- hyperon: three valence s -quarks and a spin- $\frac{3}{2}$ baryon.
- Four form factors describe the $\gamma^* \Omega^- \bar{\Omega}^+$ vertex: electric charge ($|G_{E0}|$), magnetic dipole ($|G_{M1}|$), electric quadrupole ($|G_{E2}|$), and magnetic octupole ($|G_{M3}|$).
- Upper limits of the effective form factor are obtained from measurements of $e^+e^- \rightarrow \Omega^- \bar{\Omega}^+$ with data at $\sqrt{s} = 3.49\text{--}3.67$ GeV.

PRD 107, 052003 (2023)



EMFFs of the Lightest Charmed Baryon Λ_c 

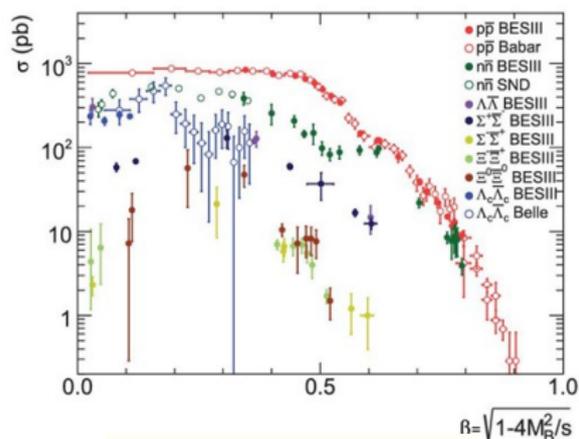
PRL 131, 191901 (2023)



Phys. Rev. D 109, L071104 (2024)

- Cross sections and form factors ($|G_E|$, $|G_M|$) of Λ_c are extracted using data at $\sqrt{s} = 4.64\text{--}4.95$ GeV.
- Flat cross sections around 4.63 GeV are obtained, and no indication of the resonant structure $Y(4630)$, as reported by Belle, is found.
- The energy-dependent ratio G_E/G_M shows oscillatory behavior — observed for the first time.
- The reaction $e^+e^- \rightarrow \Lambda_c^+ \bar{\Lambda}_c(2595)^-$ is also measured.

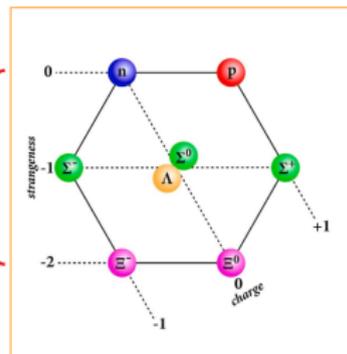
The Status of the Baryons EMFFs



Natl. Sci. Rev., 2021,
Vol. 8, nwab187

Channel	Status		Experiments
	Scan	ISR	
$p\bar{p}$	***	***	BESIII, BABAR, CMD-3
$n\bar{n}$	***	×	BESIII, SND
$\Lambda\bar{\Lambda}$	***	**	BESIII, BABAR, CLEO-c
$\Sigma\bar{\Sigma}$	**	**	BESIII, BABAR, CLEO-c
$\Xi\bar{\Xi}$	**	×	BESIII, CLEO-c
$\Omega\bar{\Omega}$	*	×	BESIII, CLEO-c
$\Lambda_c\bar{\Lambda}_c$	**	*	BESIII, Belle II

Many measurements available

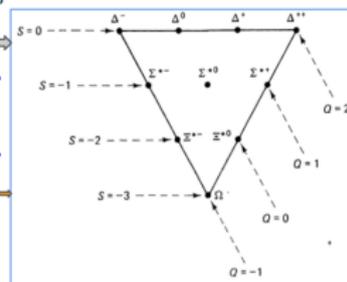


arXiv:2305.12166v2 [hep-ex], 2023

Difficult to measure

No data available

Upper limits only



Summary and Outlook

- BESIII has collected the world's largest e^+e^- collision data in the τ -charm region.
- Electromagnetic form factors have been studied for nucleons, hyperons, and charmed hyperons.
- Many fruitful results are obtained through direct annihilation and ISR methods.
- Hyperon EMFFs can be fully determined due to their self-analyzing polarization (phase of EMFFs).
- These results provide key insights into baryon structure: threshold effects, coupling strength, and oscillation patterns.
- Current precision is limited by statistics; new data (below 2 GeV and 20 fb^{-1} at $\psi(3770)$) will improve ISR analyses.

Thank You!