26th International Symposium on Spin Physics

A Century of Spin

Recent Results of Baryon Electromagnetic Form Factors at BESIII

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(On behalf of BESIII Collaboration)

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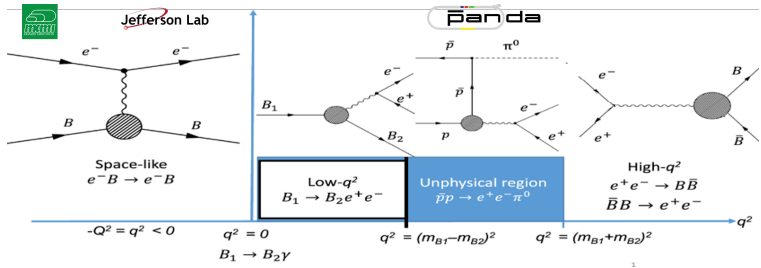
Outline

1. Introduction of EMFFs
2. BESIII Experiment
3. Nucleon Form Factors at BESIII
4. Hyperon Form Factors at BESIII
5. Summary

Electromagnetic Form Factors (EMFFs)

- **Electromagnetic Form Factors are fundamental properties of the Baryons**
  - Connected to charge, current distribution
  - Crucial testing ground for models of the baryons' internal structure and dynamics



- **The baryon electromagnetic vertex Γ_μ describes the hadron current:**

$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p}F_2(q^2), \quad F_1(q^2): \text{Dirac FF}, F_2(q^2): \text{Pauli FF}$$

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

Time-like EMFFs: Theoretic Review

1961, first paper by N. Cabibbo and R. Gatto: (Phys.Rev. 124 (1961) 1577-1595)

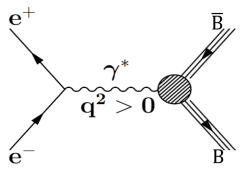
- **The production Born cross section of $e^+e^- \to B\bar{B}$ (1/2 baryon) is given by:**

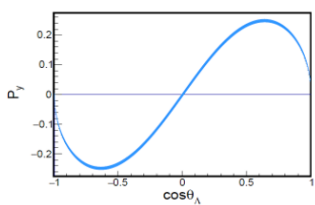
$$\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right],\ \tau = \frac{q^2}{4m_B^2}$$

Assuming $|G_E(q^2)| = |G_M(q^2)|$, $\sigma_{B\bar{B}} = \frac{2\pi\alpha^2 C\beta}{q^2}|G_{eff}(q^2)|^2$

- **The complex feature of TLFF leads to a polarization of the outgoing baryons even the beams are unpolarized.** (Nuov Cim A 109, 241–256 (1996))

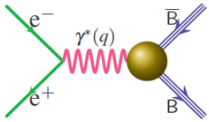
$$P_y = -\frac{\sin 2\theta\ \Im(G_E(q^2)G_M(q^2)^*)/\sqrt{\tau}}{|G_E(q^2)|^2 \sin^2\theta/\tau + |G_M(q^2)|^2(1+\cos^2\theta)}$$

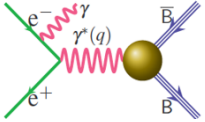




Nat. Phys. 15, 631 (2019)

Time-like EMFFs: Experiment Review



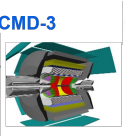


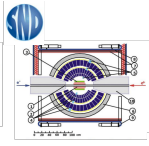
Energy scan method at discrete c.m.energies

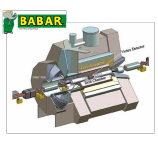
- Well-defined c.m.energy, low background
- Very good energy resolution
- Discrete values, leaving gaps without information

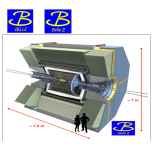
Initial state radiation method at a fixed c.m.energy

- At a fixed c.m.energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
- Systematic uncertainty in a coherent way
- Large luminosity needed
- Higher background









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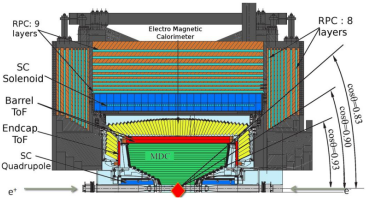
BESIII Expriment

BESIII detector records symmetric e^+e^- collisions in the τ-charm region(1.84-4.95 GeV).

Electromagnetic Calorimeter
CsI(Tl): L = 28 cm
- Barrel $\sigma_E/E = 2.5\%$ @1 GeV
- Endcap $\sigma_E/E = 5.0\%$ @1 GeV

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

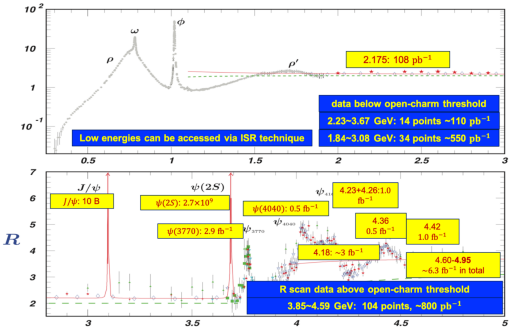


BESIII Detector

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

Time Of Flight
Plastic scintillator, 2 layer
- σ_T(barrel) = 68 ps
- σ_T(endcap) = 110 ps

(update to 60 ps with MRPC)



Ideal environment to study the Baryon EMFFs with both energy scan and ISR methods!

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

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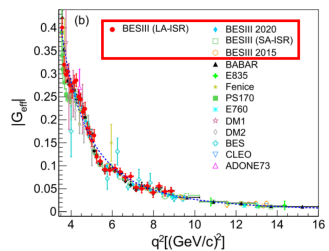
Effective EMFFs of Proton and Neutron

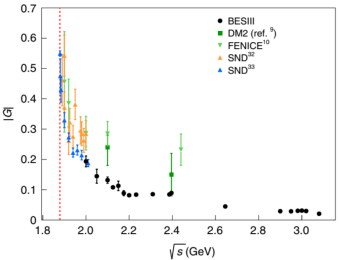
- $|G_{eff}|$ of proton is measured with high accuracy using both energy scan and ISR method.
- $|G_{eff}|$ of neutron is measured with energy scan method from 2.00-3.08 GeV.
- Oscillation of reduced-$|G_{eff}|$ (subtracting the modified dipole contribution) is observed in neutron with a phase orthogonal to that of proton.

PLB 817, 136328 (2021)



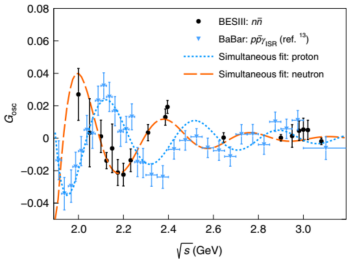
$|G_{eff}|$ of $p\bar{p}$

Nat.Phys.17,1200-1204 (2021)



$|G_{eff}|$ of $n\bar{n}$

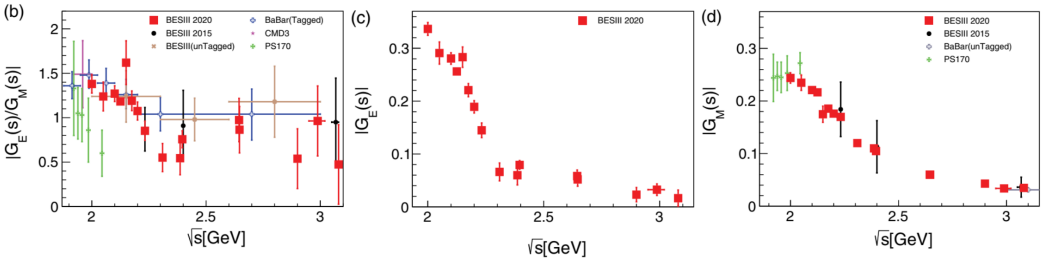
Nat.Phys.17,1200-1204 (2021)



reduced-$|G_{eff}|$

Recent Results of Proton EMFFs

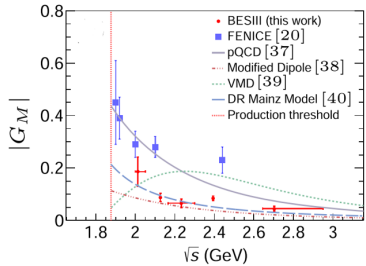
- $|G_E/G_M|$ is determined with high accuracy, $\delta|G_E/G_M| \sim 3.5\%$(most precise)
- $|G_E|$ and $|G_M|$ are measured for the first time over a wide range of energies.

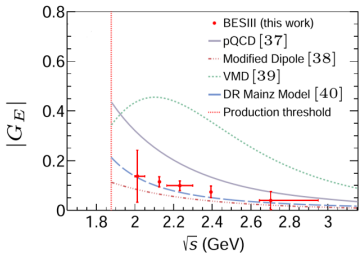


PRL 124, 042001 (2020)

Recent Results of Neutron EMFFs

- $|G_E|$, $|G_M|$ of neutron are measured separately from $\sqrt{s} = 2.0 - 2.95$ GeV[1].
- Compared with the FENICE results[2], the values for $|G_M|$ from this work are smaller by a factor of 2-3.
- Results is compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR), and DR model gives good consistency.





[1] PRL 130, 151905 (2023)
[2] Nucl. Phys. B517, 3 (1998)

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Measurement of Hyperons FFs

- It is difficult to study EMFFs of hyperons in space-like due to the difficulty in stable and high-quality hyperon beams.
- The hyperons can be produced in e^+e^- annihilation above their production threshold.
- The angular distribution of daughter baryon from Hyperon weak decay is:
  * $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}$
  * α_Λ: asymmetry parameter (P-violation)

Advantages:

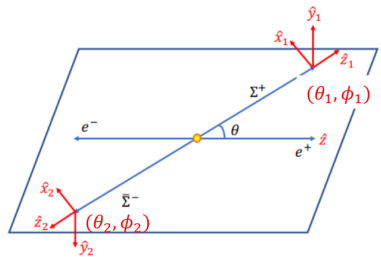
* Cross section is obtained very close to threshold with finite PHSP of final state.
* With hyperon weak decay to $B + P$, the polarization of hyperon can be measured, so does the relative phase between G_E and G_M! (Of course, enough statistics needed)

Complete Measurement of Σ^+ EMFFs

- The reaction $e^+e^- \to \Sigma^+(\to p\pi^0)\bar{\Sigma}^-(\to \bar{p}\pi^0)$ is formalized by joint angular distribution.
- The non-zero relative phase ($\Delta\Phi$) between G_E and G_M will lead to a P_y polarization of the outgoing baryons.

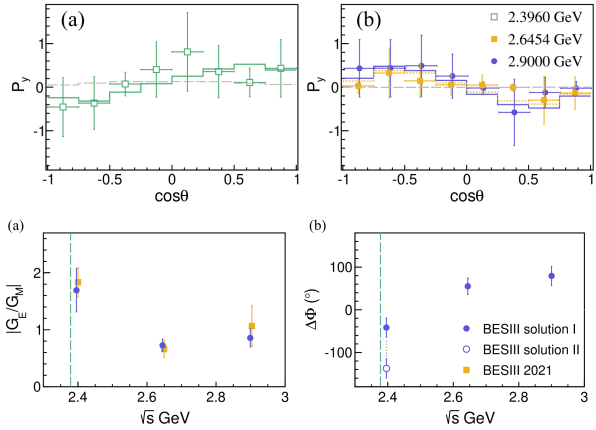
$$\mathcal{W}(\xi) \propto \mathcal{F}_0(\xi) + \alpha\mathcal{F}_5(\xi) \quad \text{Unpolarized part}$$
$$+ \alpha_1\alpha_2(\mathcal{F}_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha\mathcal{F}_6(\xi)) \quad \text{Spin correlated part}$$
$$+ \sqrt{1-\alpha^2}\sin(\Delta\Phi)(-\alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)) \quad \text{polarization part}$$

$$\mathcal{F}_0(\xi) = 1$$
$$\mathcal{F}_1(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\cos\phi_1\cos\phi_2 - \cos^2\theta\cos\theta_1\cos\theta_2$$
$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta(\sin\theta_1\cos\theta_2\cos\phi_1 - \cos\theta_1\sin\theta_2\cos\phi_2)$$
$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$
$$\mathcal{F}_5(\xi) = \cos^2\theta$$
$$\mathcal{F}_6(\xi) = \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2 - \cos\theta_1\cos\theta_2.$$



Complete Measurement of Σ^+ EMFFs

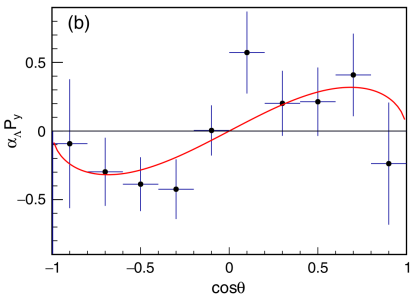
- Polarization is observed at $\sqrt{s} = 2.396$, 2.644 and 2.90 GeV with a significance of 2.2σ, 3.6σ and 4.1σ.[3]
- Relative phase $\Delta\Phi$ is determined for the first time in a wide q^2 range.

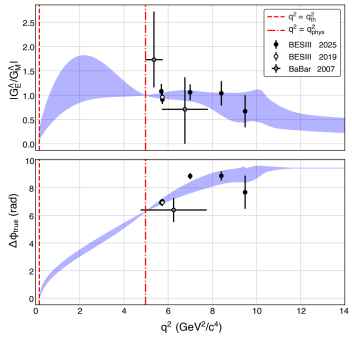


[3](PRL 132, 081904 (2024))

Complete Measurement of Λ EMFFs

- Clear P_y polarization can be observed in the first complete measurement of Λ EMFFs at 2.396 GeV.[4]
- A newest measurement of Λ EMFFs at 5 energy points from 2.3864 GeV to 3.0800 GeV is submitted to the arxiv.[5]A fit based on dispersion relations is performed to determine the complex form factor ratio as a function of q^2.





[4] PRL 123, 122003 (2019)

[5] https://arxiv.org/pdf/2506.08072

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Summary

- **Fruitful results of EMFFs from e^+e^- colliders via energy scan and ISR methods.**
- **Conventional parameterization of EMFFs is facing challenge from experimental observations (threshold effect, oscillation in reduced FFs and $|G_E/G_M|$ ratio).**
- **Relative phase of EMFFs gives rise to polarization of final baryons, and will play an important role in distinguishing various theoretical models.**
- **More results from BESIII are on the way.**

Thank You!