Recent Results of Baryon Electromagnetic Form Factors at BESIII

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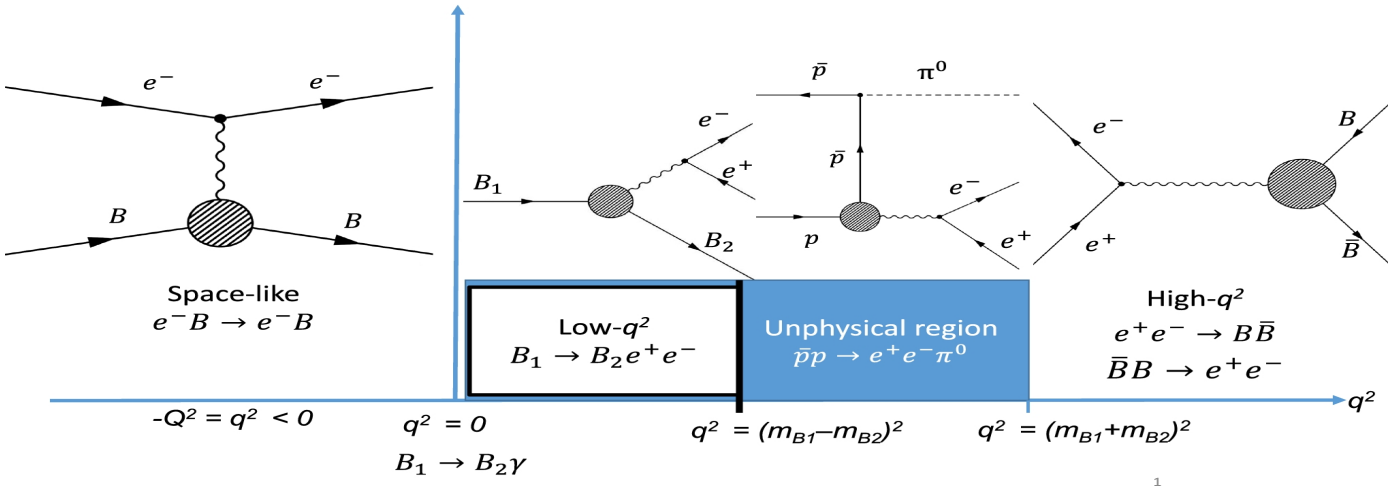
SCUOLA NORMALE SUPERIORE

Outline

- **Introduction of EMFFs**
- **BESIII Experiment**
- **Nucleon Form Factors at BESIII**
- **Hyperon Form Factors at BESIII**
- **Summary and Outlook**

Introduction of EMFFs

- Hadrons are not point-like particles.
- Electromagnetic Form Factors (EMFFs) are fundamental properties of baryons.
  - Connected to charge and current distributions.
  - Crucial testing ground for theoretical models of hadron structure.



Hardonic vertex:

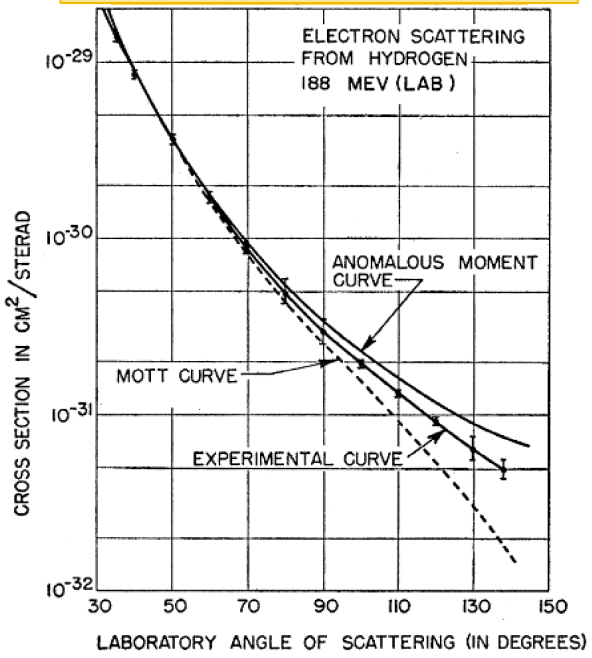
$$\Gamma^{\mu}(q) = \gamma_{\mu}F_1(q^2) + \frac{i\sigma_{\mu\nu}q^{\nu}}{2m_p}F_2(q^2)$$

F_1 and F_2 are the Dirac and Pauli FFs

Sachs FFs:

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

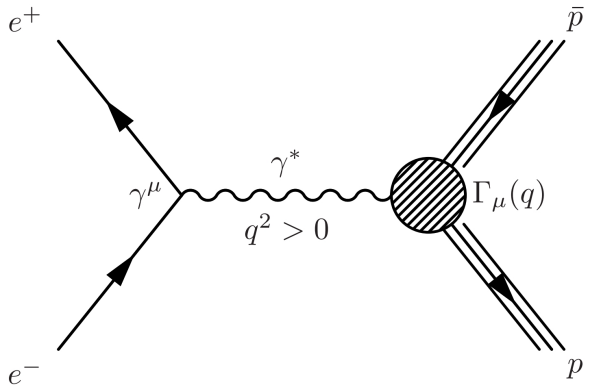
Nobel Prize in 1961
Rev. Mod. Phys. 30, 482 (1958)



Reveals the internal structure inside the nucleon

Time-like EMFFs: Theoretic Review

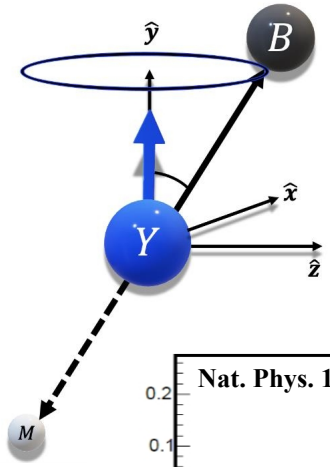
- Related to space-like EMFFs via dispersion relations.
- Time-like EMFFs are **complex**.
  - $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$, $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$.
  - $\Delta\Phi(q^2) = \Phi_M - \Phi_E$ = phase between G_E and G_M.



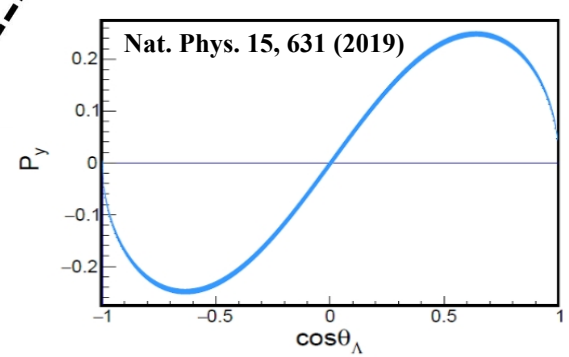
- $B\bar{B}$ production:

$$\frac{d\sigma_{B\bar{B}}}{d\Omega} = \frac{\alpha^2\beta C}{4s}[|G_M(s)|^2(1+\cos\theta^2) + \frac{1}{\tau}|G_E(s)|^2\sin\theta^2],$$
$$\tau = \frac{s}{4m_B^2}, C = \frac{y}{1-e^{-y}},\ y = \pi\alpha(1+\beta^2)/\beta$$

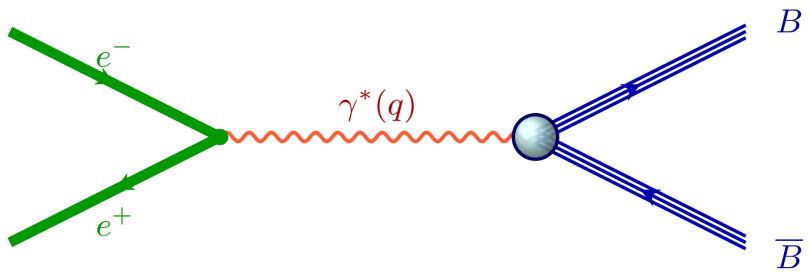
Integrated version: $\sigma(s) = \frac{4\pi\alpha^2\beta C}{3s}(1+\frac{1}{2\tau})|G_{\text{eff}}|^2$, $|G_{\text{eff}}|^2 = \frac{2\tau|G_M(s)|^2+|G_E(s)|^2}{2\tau+1}$



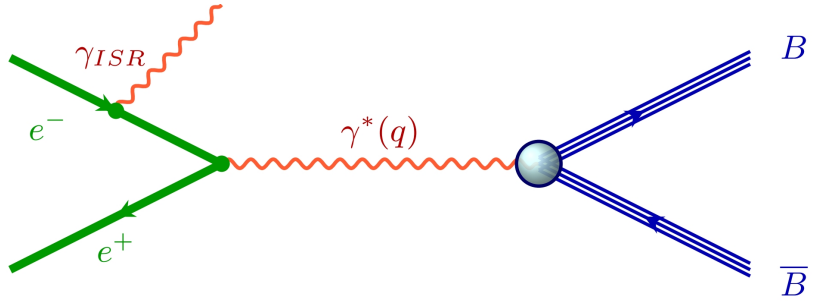
- Polarisation and self-analysis of hyperon weak decays:
  - ✓ $\Delta\Phi(q^2)$ polarises the produced baryons: $P_y = -\frac{\sin 2\theta\ \text{Im}[G_E G_M^*]/\sqrt{\tau}}{\frac{|G_E|^2\sin^2\theta}{\tau}+|G_M|^2(1+\cos^2\theta)}$.
  - ✓ Polarisation accessible: $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}$.



Time-like EMFFs: experimental review



- **Energy Scan Method**:
  - Well-defined c.m.energy
  - Very good energy resolution
  - low background
  - Discrete values, leaving gaps without information



- **Initial State Radiation(ISR) Method**:
  - 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

Path toward the baryon EMFFs: from **low** statistics to **high** statistics

Integrated cross section yielding the effective FFs

$$\sigma_{B\overline{B}} = \frac{2\pi\alpha^2 C\beta}{q^2}|G_{\text{eff}}|^2$$

→ One-dimensional angular analysis enabled the extraction of $|G_E/G_M|$:

$$\frac{\pi\alpha^2 C\beta}{2q^2}\left[(1+cos^2\theta)|G_M|^2+\frac{1}{\tau}|G_E|^2 sin^2\theta\right]$$

→ Full multi-dimensional angular analysis of the decay chain and yielding relative phase, $\Delta\Phi$

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- Hyperon Form Factors at BESIII
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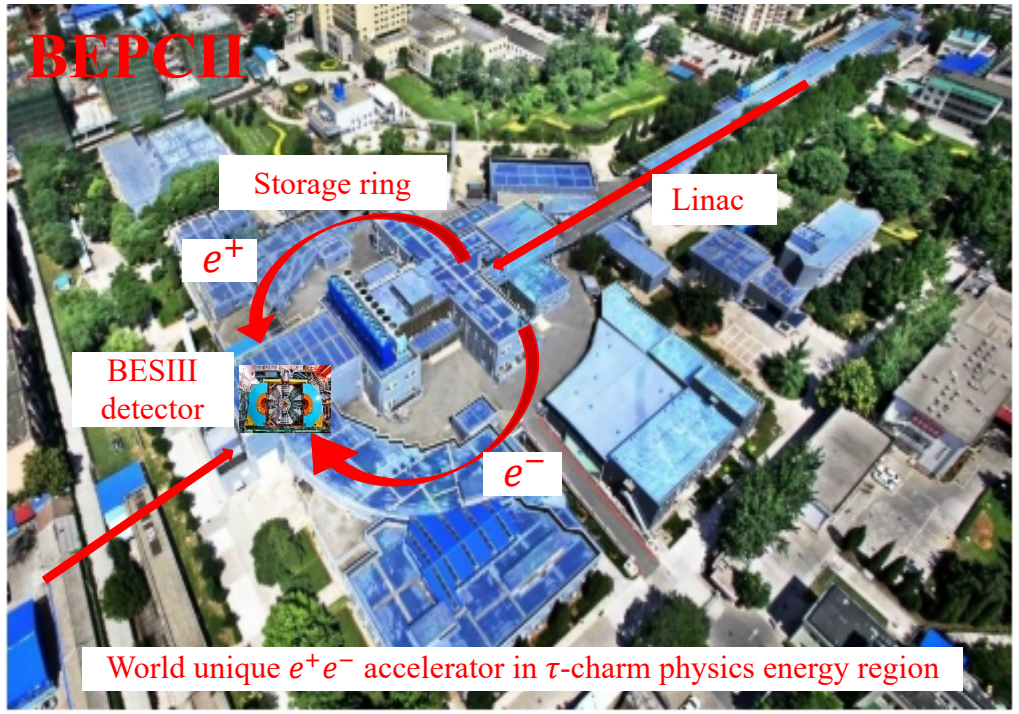
BESIII Experiment



Double rings

$E_{cm} = 1.84 - 4.95$ GeV

Peak luminosity @$E_{cm} = 3.773$ GeV:

1.1×10^{33} cm^{-2}s^{-1}

Circumference: 237.53 m

Crossing angle: 2×11 mrad

Electromagnetic Calorimeter

CsI(Tl): L=28 cm

Barrel σ_E=2.5%

Endcap σ_E=5.0%

Muon Counter

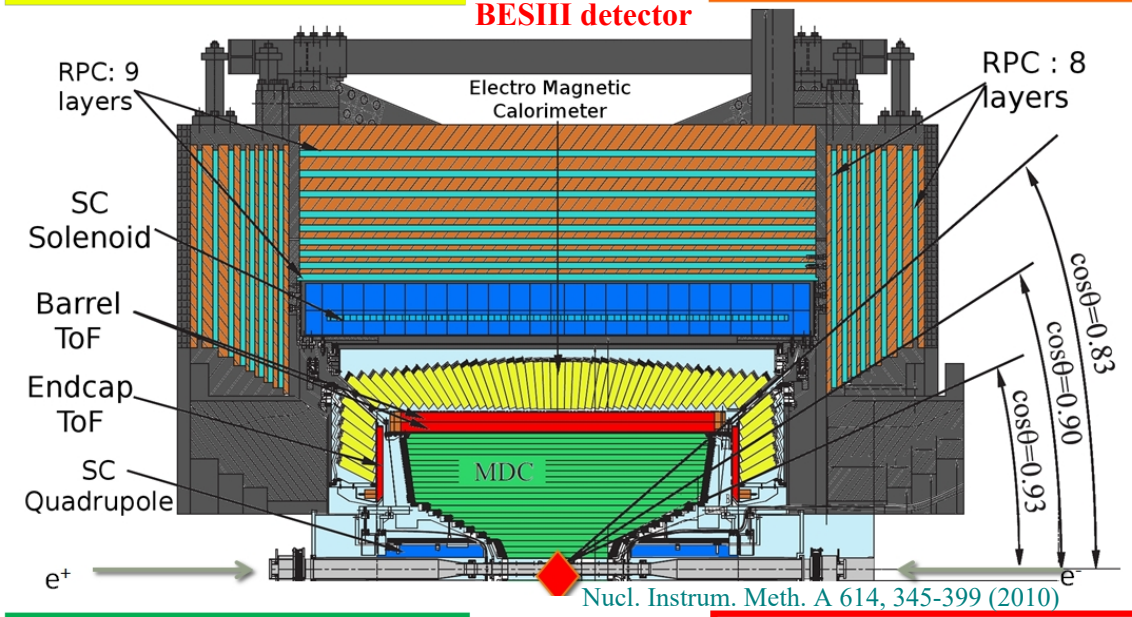
RPC

Barrel: 9 layers

Endcap: 8 layers

$\sigma_{spatial}$: 1.48 cm

BESIII detector



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

Main Drift Chamber

Small cell, 43 layer

σ_{xy}=130 μm

dE/dx~6%

σ_p/p= 0.5% at 1 GeV

Time Of Flight

Plastic scintillator

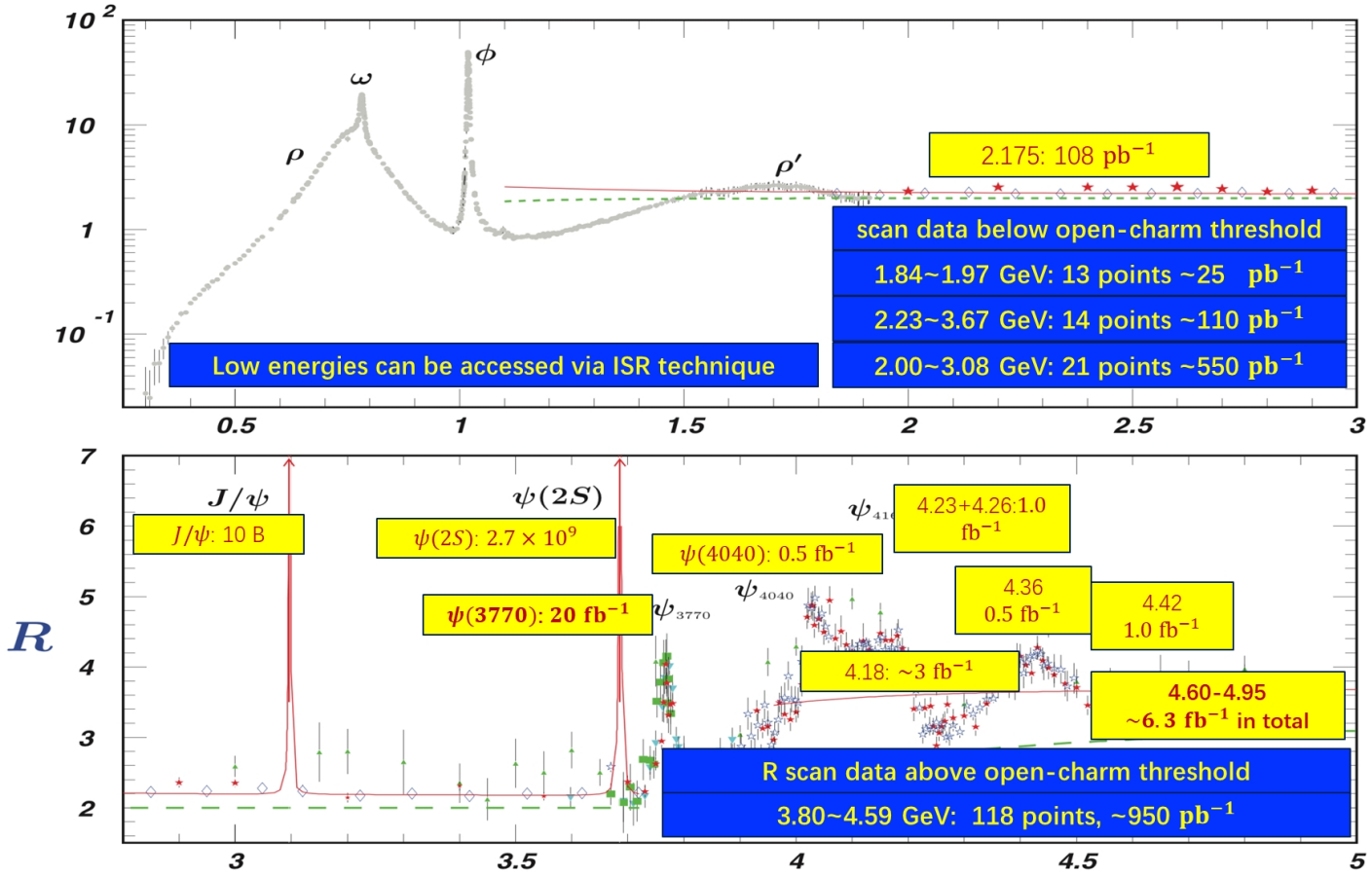
σ_T(barrel): 68 ps

σ_T(endcap): 110 ps

(update to 60 ps with MRPC)

Data Samples at BESIII

- **Over 40 fb^{-1}** data collected
- **Large Charmonium events**
  - 1×10^{10} J/ψ events
  - 2.7×10^{9} $\psi(3686)$ events
  - 20 fb^{-1} at 3.773 GeV ($D\overline{D}$ pair)
- **Unique scan data:**
  - Baryon pair threshold
  - Λ_c pair threshold
  - τ scan
  - χ_{c1} scan
  - R scan
  - XYZ scan



BESIII provides **an ideal environment** to study the baryon EMFFs with both **energy scan** and **ISR** methods!

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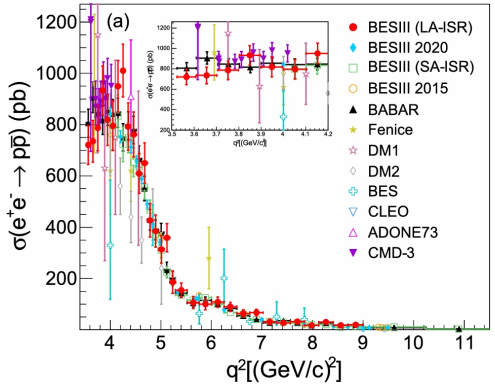
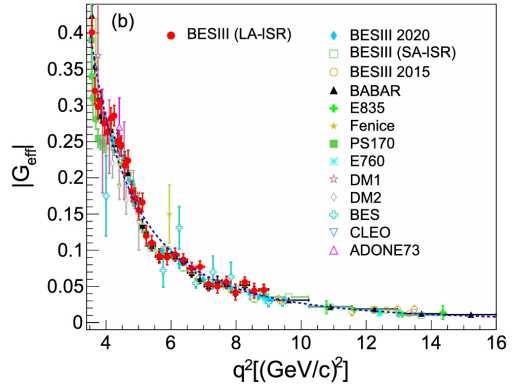
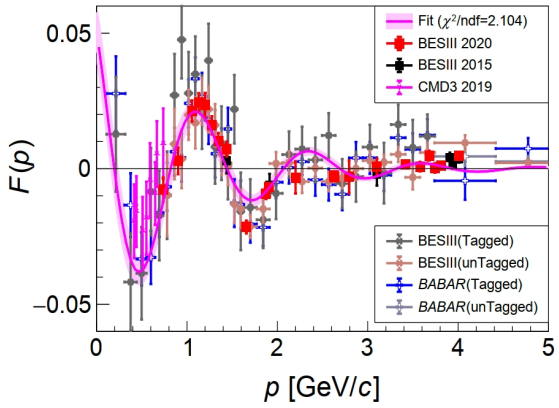
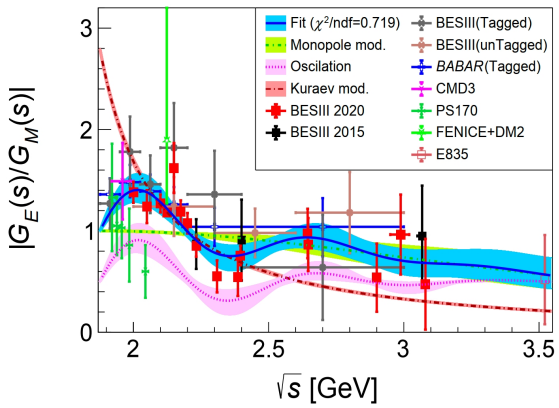
Nucleon Form Factors at BESIII

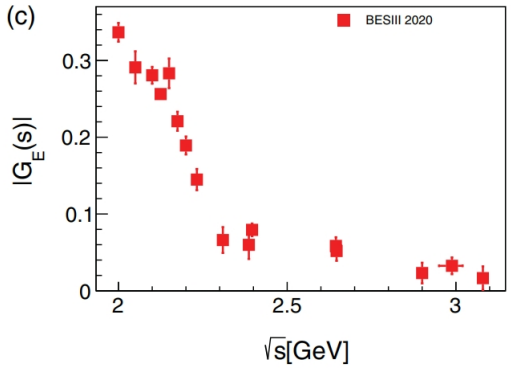
- The proton EMFFs have been measured with **high accuracy** by BESIII:

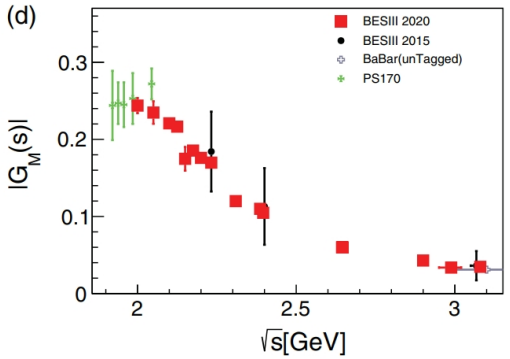










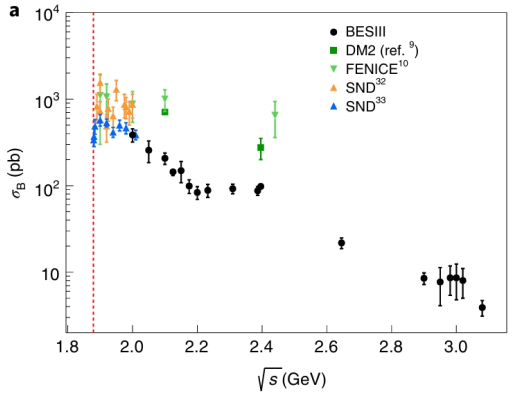


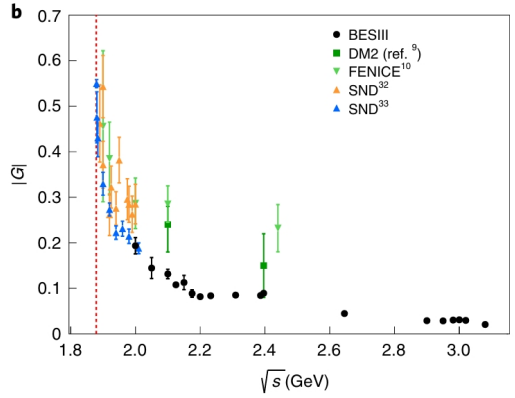
PRD 91, 112004 (2015) *PRD 99, 092002 (2019)*
PRL 124, 042001(2020) *PLB 817, 136328 (2021)*

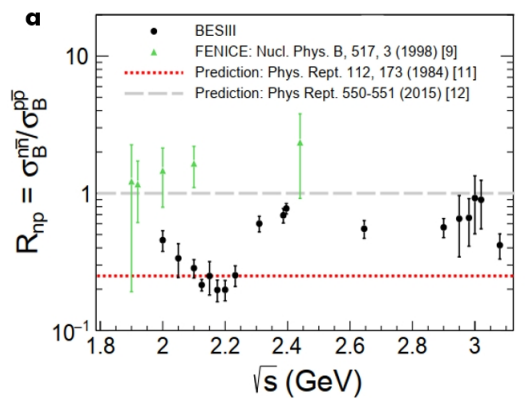
- ✓ **Wide q^2 region** from the $p\bar{p}$ threshold up to 14 GeV^2
- ✓ $|G_E/G_M|$, $|G_M|$ are determined with high accuracy.
- ✓ $|G_E|$ is measured for the first time.
- ✓ **Damped oscillation** distribution after subtracting the modified dipole.

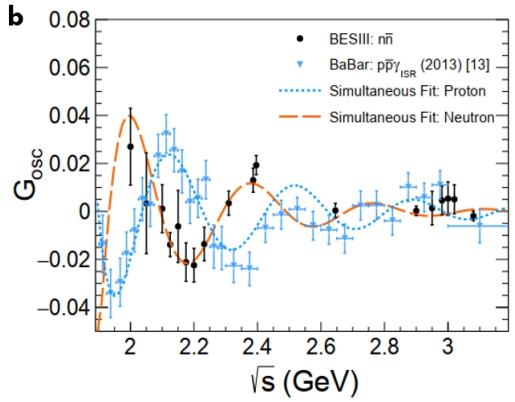
Nucleon Form Factors at BESIII

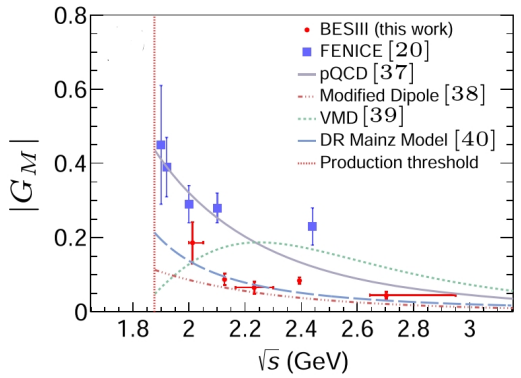
- The neutron EMFFs have been measured with **high accuracy** by BESIII:

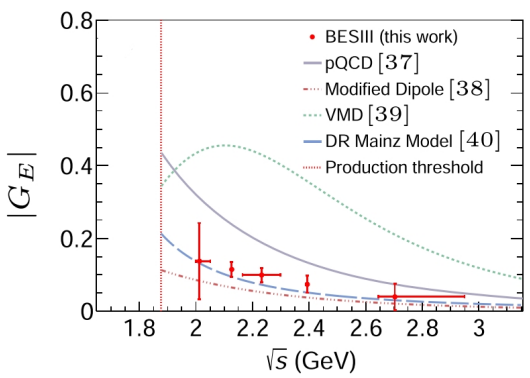












Nat.Phys.17, 1200-1204 (2021)
PRL 130, 151905 (2023)

- ✓ $\gamma - p$ coupling larger than $\gamma - n$ coupling.
- ✓ **Oscillation of reduced-|G|** observed in neutron with a phase **orthogonal** to that of proton.
- ✓ Compared with the FENICE results, the values for $|G_M|$ from this work are smaller by **a factor of 2-3**.
- ✓ Results perfer **dispersion relations (DR)** model.

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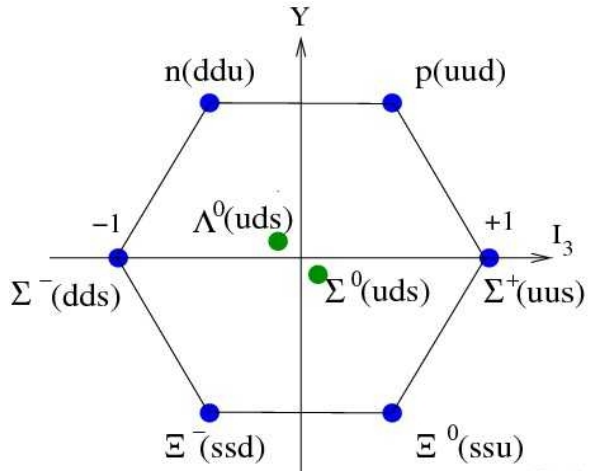
Hyperon Form Factors at BESIII

From Nucleon to Hyperon

- Hard to study hyperon EMFFs in the **space-like region** due to the lack of stable and high-quality hyperon beams.
- In the **time-like region**, the hyperon EMFFs can be approached by the study of **hyperon production** and **weak decay (self-analyzing)**.



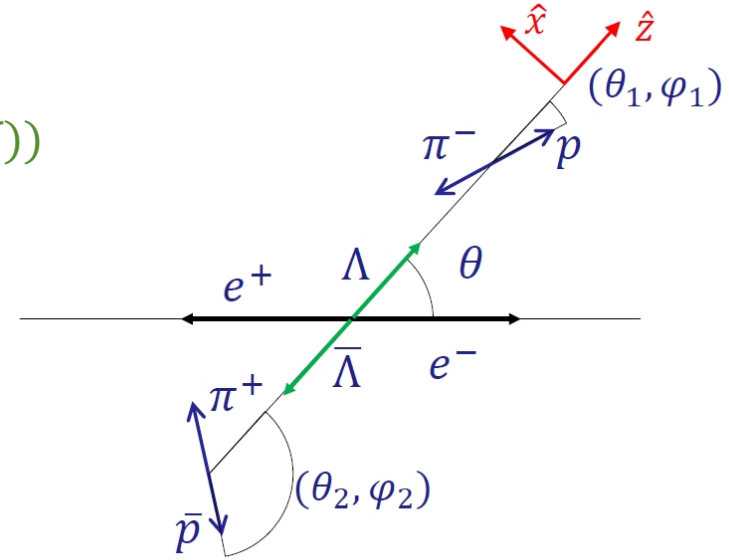
Complete Measurement of Hyperon EMFFs

Unpolarised part — Polarised part — Spin correlation part

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) + \alpha^2(F_1(\xi) + \sqrt{1-\eta^2}cos(\Delta\Phi)F_2(\xi) + \eta F_6(\xi)) + \alpha\sqrt{1-\eta^2}sin(\Delta\Phi)(F_3(\xi) + F_4(\xi))$$

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

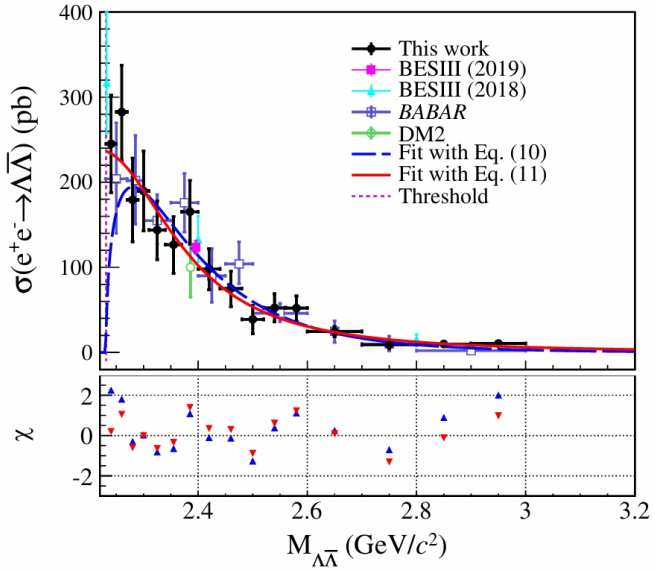
PLB 772 (2017) 16



Hyperon Form Factors at BESIII

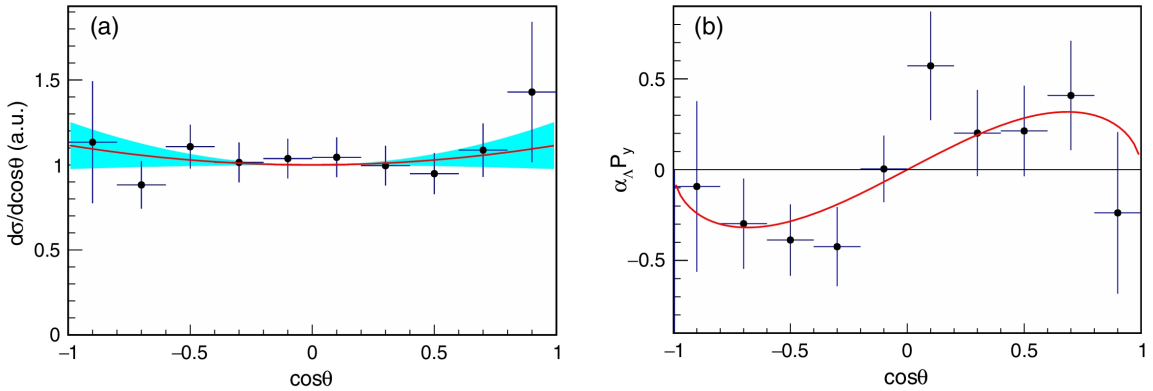
Λ EMFFs

- **Energy Scan Method**: Cross-section measurements at $\sqrt{s} = 2.2324$, 2.400, 2.800, and 3.080 GeV. *PRD 97, 032013 (2018)*
- **ISR Method**: Cross-section measurements from threshold up to 3.00 GeV/c^2. *PRD 107, 072005 (2023)*
- Non-zero cross section observed near threshold, consistent with BaBar.



- $\sqrt{s} = 2.2396$ GeV, 66.9 pb^{-1}. *PRL 123, 122003 (2019)*
  - Extracted results: $\left|\frac{G_E}{G_M}\right| = \mathbf{0.96 \pm 0.14 \pm 0.02}$

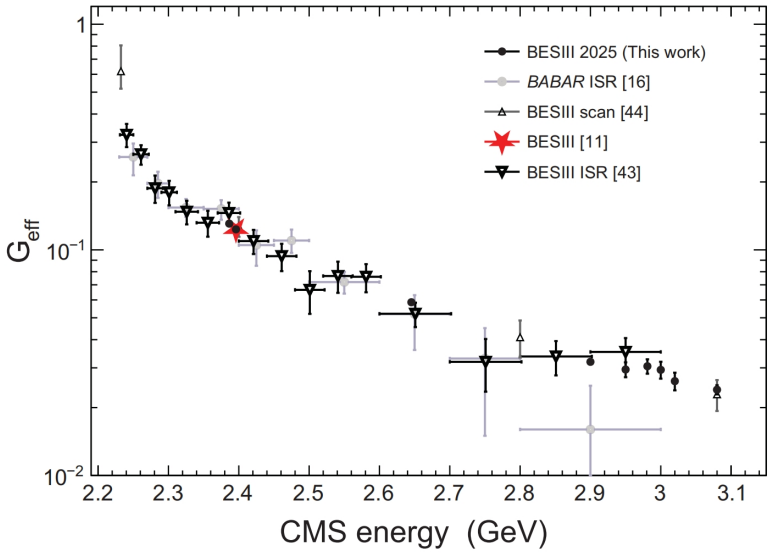
    $\Delta\boldsymbol{\Phi} = \mathbf{37^\circ \pm 12^\circ \pm 6^\circ}$
  - Confirm the complex nature of the EMFFs of the Λ hyperon.

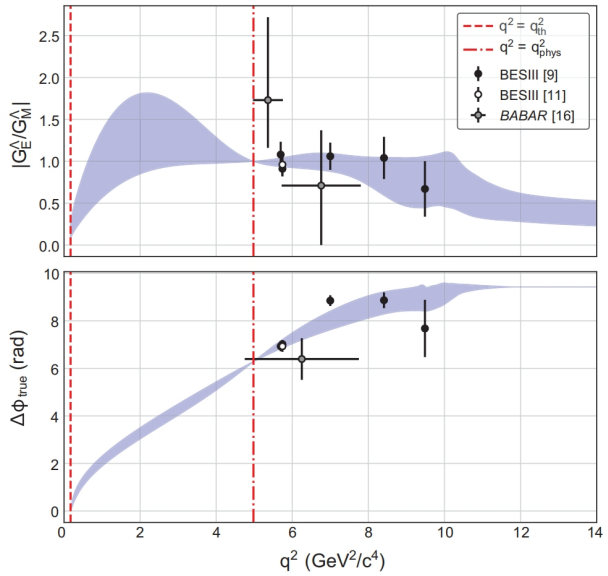


Hyperon Form Factors at BESIII

Λ EMFFs

- **A new complete measurement** of Λ EMFFs ($G_{\rm eff}, R, \Delta\Phi$) at five energies($\sqrt{s}$ = 2.386-3.08 GeV) using single- and double-tag method. *PRL 135, 191 902 (2025)*
- Ratio $R(q^2) = |G_E/G_M|$ nearly constant; relative phase $\Delta\Phi$ changes by $> 90°$ between $\sqrt{s}$ = 2.396 and 2.654 GeV.
- The dispersive fit gives an $\bar{r}_E^{\Lambda} = -0.076 \pm 0.043$ fm. ⇒ Asymmetric charge distribution

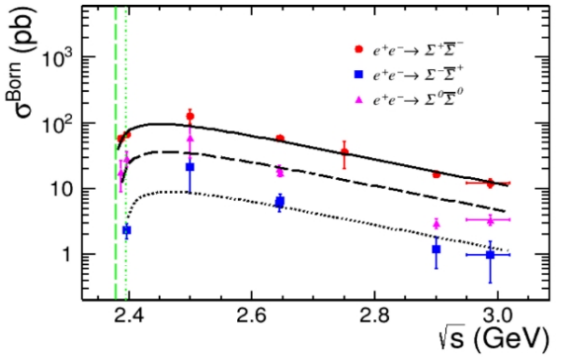




Hyperon Form Factors at BESIII

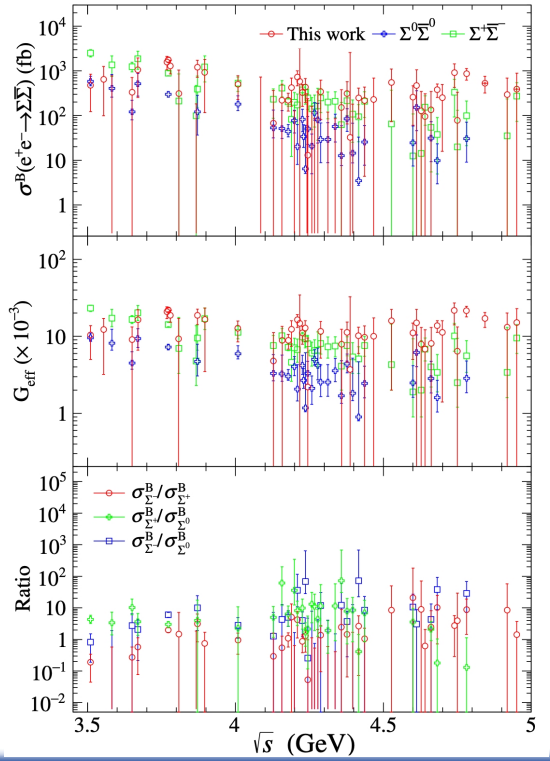
Σ EMFFs

- Born cross sections of $e^+e^- \to \Sigma^+\bar{\Sigma}^-, \Sigma^0\bar{\Sigma}^0, \Sigma^-\bar{\Sigma}^+$ are measured from threshold to 3.02 GeV.
- An asymmetry in cross sections for Σ isospin triplets: $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1$



$\Sigma^{\pm}\bar{\Sigma}^{\mp}$:PLB 814, 136110 (2021)
$\Sigma^0\bar{\Sigma}^0$:PLB 831, 137187 (2022)

- New measurements for Σ isospin triplets at higher energy regions (from 3.51 to 4.95 GeV).
  - ➢ Further test the vector-meson-dominance(VMD) model.

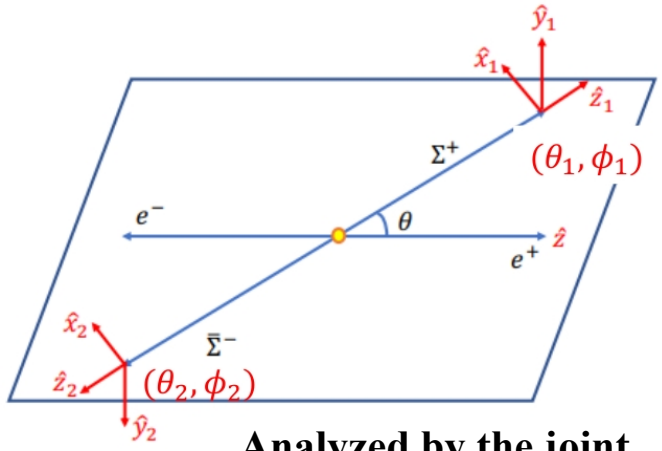


PRD 111, L051502 (2025)
JHEP 05, 022 (2024)
arXiv:2602.23835 (2026)

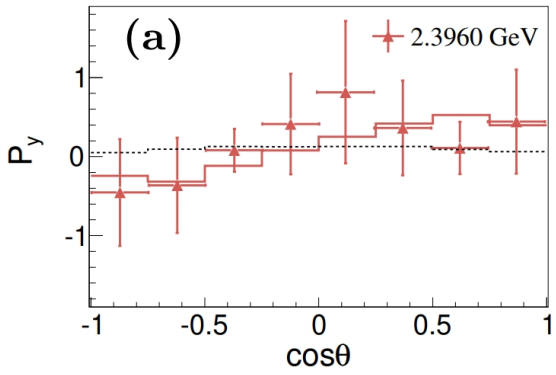
Hyperon Form Factors at BESIII

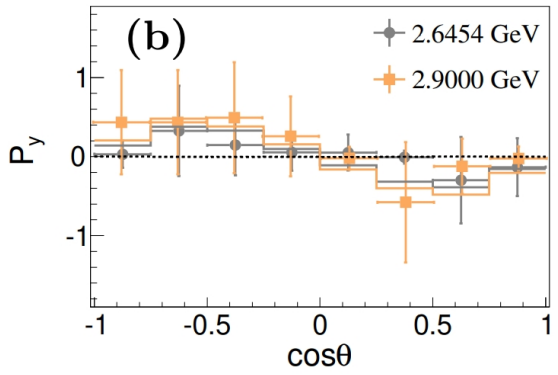
Σ EMFFs

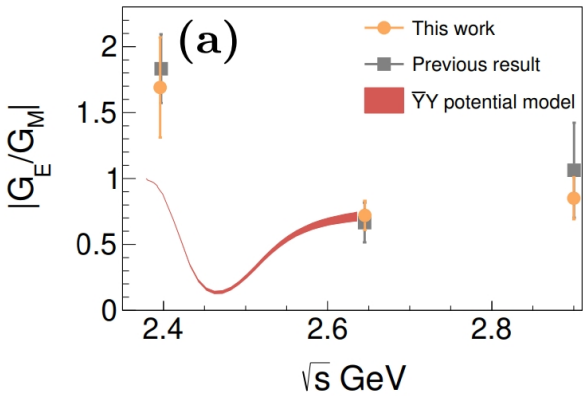
- **A new complete measurement** of Σ EMFFs ($G_{\rm eff}, R, \Delta\Phi$) at three energies. *PRL 132, 081904 (2024)*
- Polarization is observed at $\sqrt{s} = 2.396$, 2.644 and 2.90 GeV with a significance of 2.2σ, 3.6σ and 4.1σ.
- Relative phase is determined for the first time in a wide q^2 range.
- Compared with $\overline{Y}Y$ potential model[1], different tendency in $\Delta\Phi$.

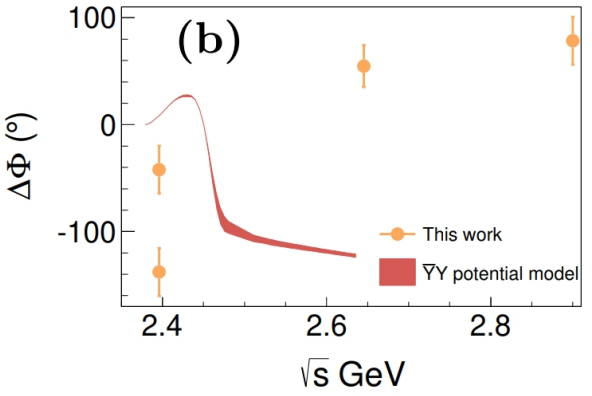


Analyzed by the joint angular distribution









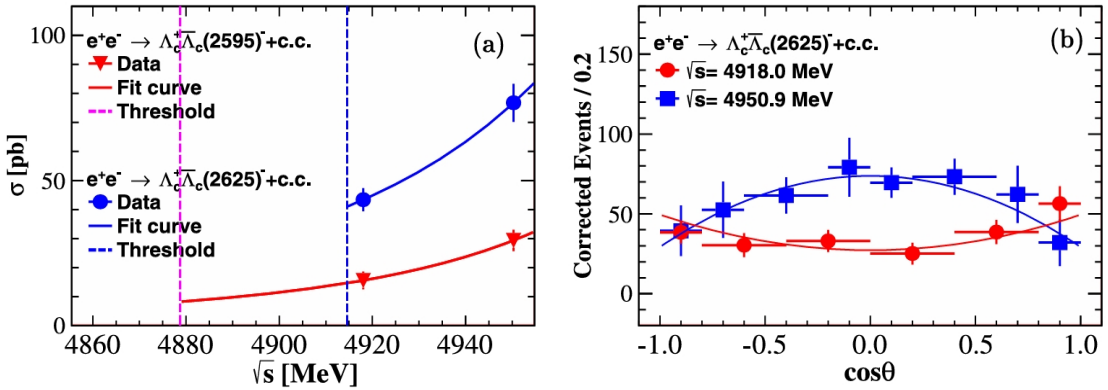
[1] *PRD 103, 014028 (2021)*

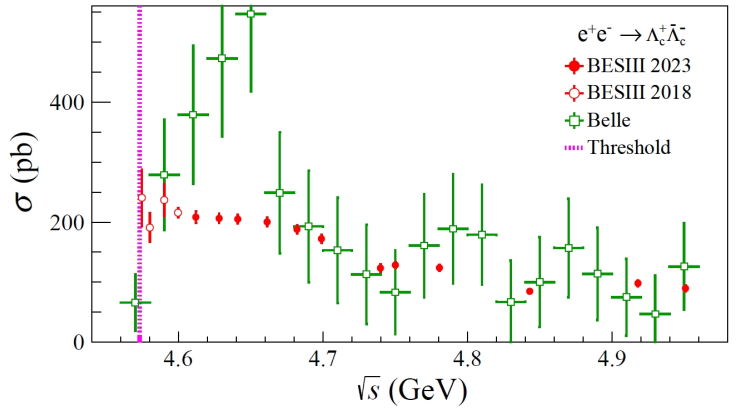
Hyperon Form Factors at BESIII

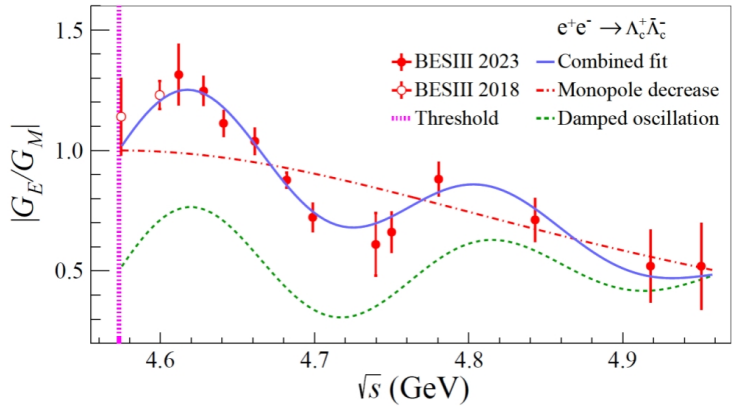
Λ_c EMFFs

- Λ_c EMFFs ($G_{\rm eff}, R$) are measured from threshold to 4.95 GeV.
  PRL 131, 191901 (2023); PRL 120, 132001 (2018)
- No indication of the resonant structure Y(4630), as reported by Belle, is found.
- Similar oscillation in $|G_E/G_M|$ distribution as proton observed.

- $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^- + c.c.$ and $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2625)^- + c.c.$ are measured for the first time at $\sqrt{s} = 4.918$ and 4.951 GeV. *PRD 109, L071104 (2024)*







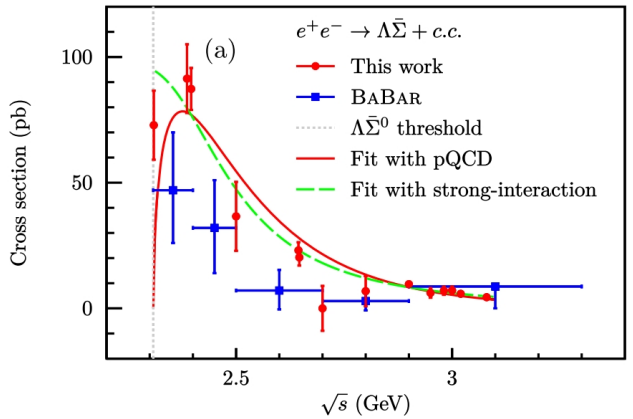
$$|G_E/G_M|(s) = \frac{1}{1+\omega^2/r_0}[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)],$$

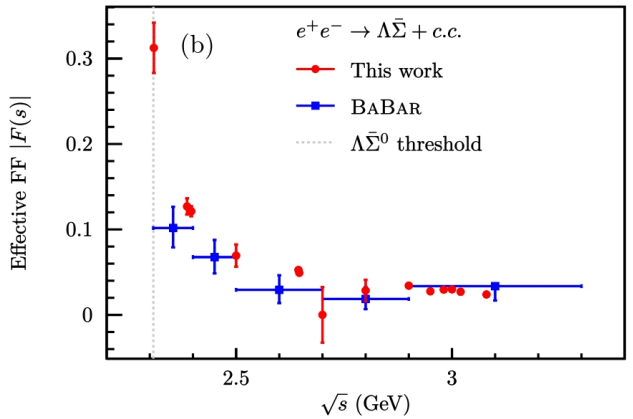
Hyperon Form Factors at BESIII

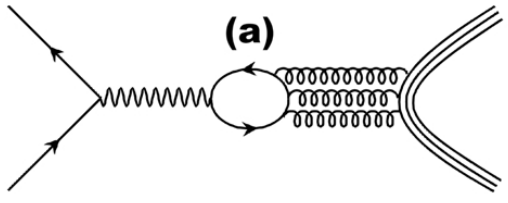
$\Sigma^0\Lambda$ EMFFs

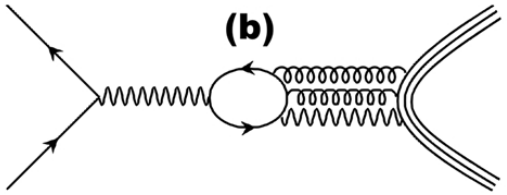
- **Cross-section line-shape** and G_{eff} are measured from threshold to 3.08 GeV using single-tag method. *PRD 109,012002(2024)*
- A **nonzero Born cross section** is observed near threshold.
- Failed to extract $|G_E/G_M|$ and $\Delta\Phi$ due to low statistics.

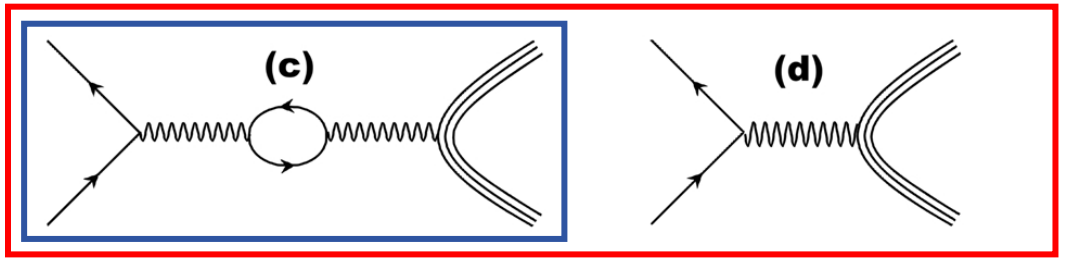
- **Particularity** at J/ψ mass: $e^+e^- \to \Lambda\bar{\Sigma} + c.c.$ predominantly **electromagnetic** (c,d). ⇒ **Access to EMFFs**
  - Isospin violation supress strong processes(a) by $\frac{m_d - m_u}{m_c} \sim \frac{1}{500}$
  - γgg process(b) is absent[1].
  - Enhanced by **vacuum polarization**. ⇒ **High precision!**









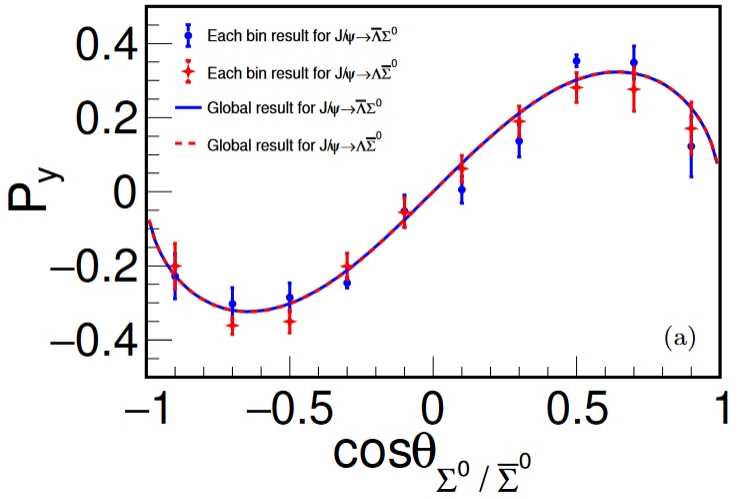


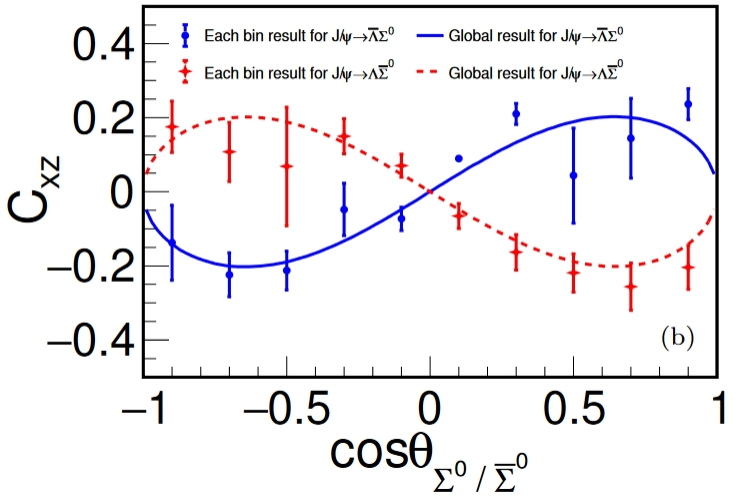
[1]*Eur. Phys. J. C 80, 903 (2020)*

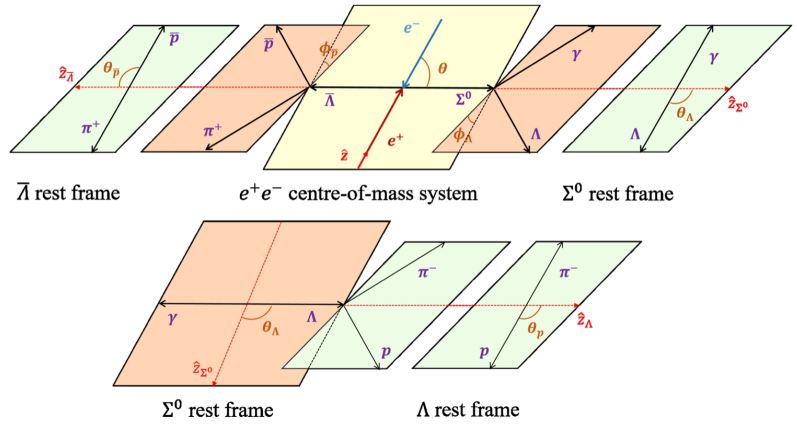
Hyperon Form Factors at BESIII

$\Sigma^0\Lambda$ EMFFs

- **First results** for **complete** $\Sigma^0\Lambda$ EMFFs measurement at J/ψ mass. *Nat. Commun. 15, 8812 (2024)*
  - ✓ $R = |G_E/G_M| = 0.860 \pm 0.029 \pm 0.010$
  - ✓ $\Delta\Phi_1(\bar{\Lambda}\Sigma^0) = 1.011 \pm 0.094 \pm 0.010$ rad
  - ✓ $\Delta\Phi_2(\Lambda\bar{\Sigma}^0) = 2.218 \pm 0.094 \pm 0.010$ rad
  - ✓ CP test: $\Delta\Phi_{CP} = |\pi - \Delta\Phi_1 - \Delta\Phi_2| = 0.003 \pm 0.133 \pm 0.014$ rad







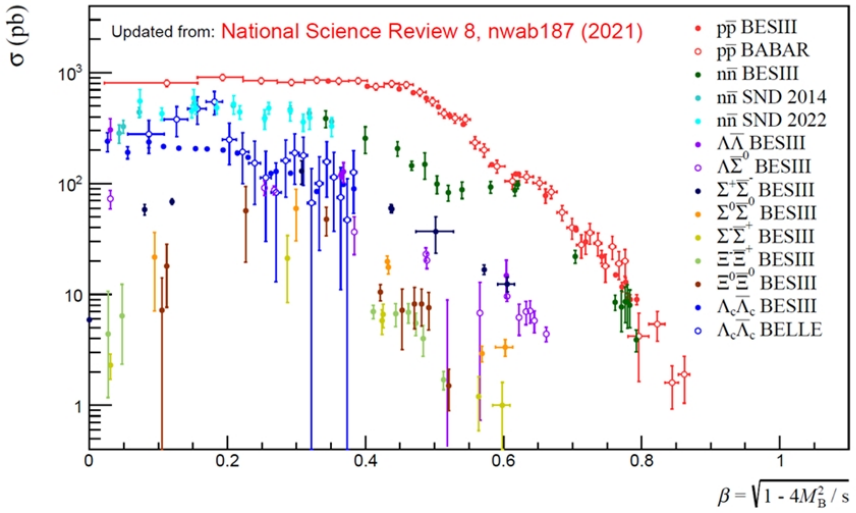
Outline

- Introduction of EMFFs
- BESIII Experiment
- Nucleon Form Factors at BESIII
- Hyperon Form Factors at BESIII
- **Summary and Outlook**

Summary and Outlook

- **Fruitful** physics results of baryon EMFFs from BESIII, via **energy scan** and **ISR** methods.
- Production cross section and EMFFs have been studied for nucleons, hyperons, and charmed baryons.
- Hyperon EMFFs can be **fully determined** due to their self-analyzing polarization ($\Delta\Phi$ can be extracted)
- These results provide **key insights into baryon structure**:

  threshold effects, coupling strength, and oscillation patterns.
- More results from BESIII are **on the way**.



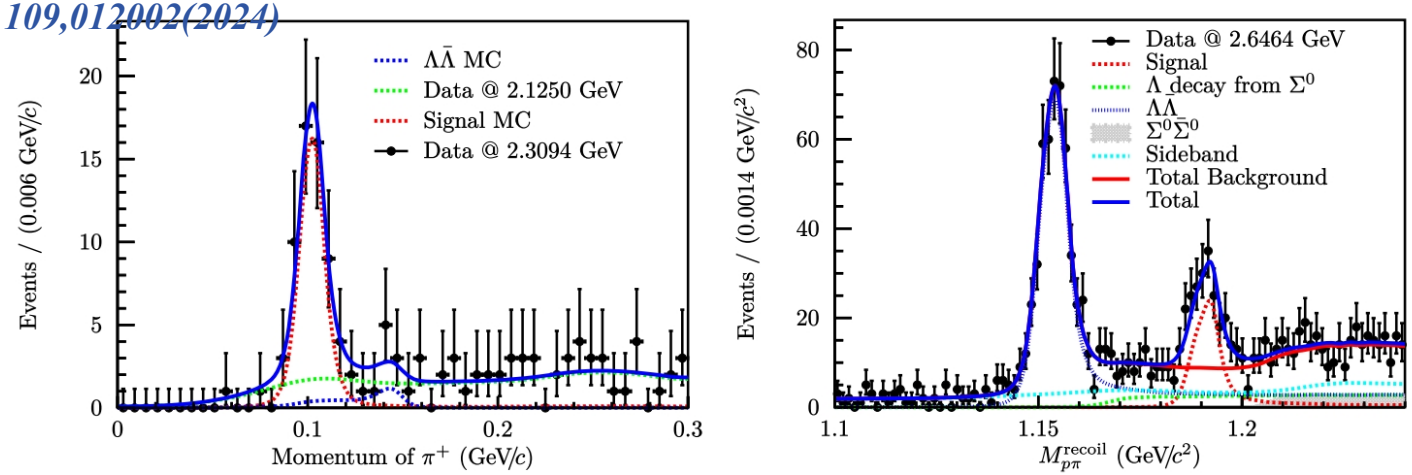
Thank you for your attention!!!

Q&A

Back Up:

PRD 109,012002(2024);PLB 772 (2017) 16

PRD 109,012002(2024)



PLB 772 (2017) 16

Production parameters of spin ½ baryons:

- Effective form factor, related to Born cross-section: $|G_{eff}| \propto \sqrt{\sigma_{Born}}$
- Angular distribution parameter $\eta = \frac{\tau - R^2}{\tau + R^2}$ where $\tau = q^2/4M^2_B$
- Phase $\Delta\Phi$

Decay parameter for 2-body decays: α

Hyperon Form Factors at BESIII

Ξ EMFFs

- Born cross sections of $e^+e^- \to \Xi^0\bar{\Xi}^0$ and $\Xi^-\bar{\Xi}^+$ are measured from threshold to 3.08 GeV.
- No significant threshold enhancement observed.
- The ratio of Born cross sections for both modes agrees with the expectation of isospin symmetry.

$\Xi^0\bar{\Xi}^0$:PLB 820, 136557 (2021)
$\Xi^-\bar{\Xi}^+$:PRD103, 012005(2021)