# Recent results of baryon electromagnetic form factors at BESIII

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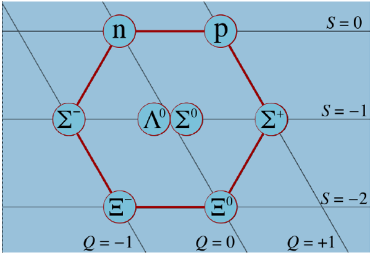
# Outline

# Introduction — The Standard Model and baryons

The Standard Model of particle physics is a well tested theory, but it is not the final theory, because, for example,

- it does not involve gravity,
- it can not explain the matter-antimatter asymmetry, dark matter, and dark energy,
- it lacks accurate prediction power for the strong interaction in the low energy region.

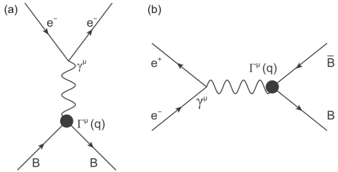



- Understanding the structure and the dynamics of baryons are crucial topics of modern particle physics.
- For example, the sizes, spins, magnetic moments, and masses of nucleons are not fully understood, even after 100 years of studies.

# Introduction — Electromagnetic form factors (EMFFs)

Electromagnetic form factors (EMFFs) are fundamental observables:

- accounting for non point-like structures of hadrons,
- describing electric and magnetic structures of hadrons,
- providing keys to understanding the strong interaction.




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

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

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

- $q^2 < 0$, space-like (SL) region:
  - $G_E(q^2)$ and $G_M(q^2)$ are real,
  - measured via $e^- N$ scattering.
- $q^2 > 0$, time-like (TL) region:
  - $G_E(q^2)$ and $G_M(q^2)$ are complex,
  - measured via $e^+e^-$ or $p\bar{p}$ annihilation.

# Introduction — Baryon pair production via $e^+e^-$ annihilation

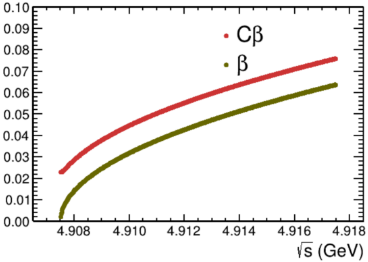
$$\frac{d\sigma^{\text{Born}}}{d\Omega}(q^2,\theta_B) = \frac{\alpha^2\beta C}{4q^2}\Bigg((1+\cos^2\theta_B)|G_M(q^2)|^2 + \frac{1}{\tau}\sin^2\theta_B|G_E(q^2)|^2\Bigg)$$

$$\sigma^{\text{Born}}(q^2)=\frac{4\pi\alpha^2\beta C}{3q^2}\left(|G_M(q^2)|^2+\frac{1}{2\tau}|G_E(q^2)|^2\right)$$

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

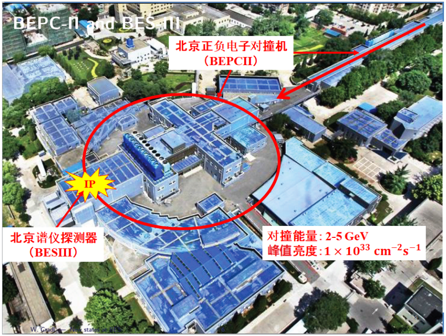
- $|G_{eff}|$ can be measured via total Born cross section,
- $G_E/G_M$, $G_E$ or $G_M$ should be measured via angular analysis.

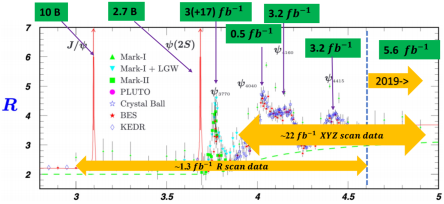
- $C \neq 1$ for charged baryon pairs.
- $C = 1$ for neutral baryon pairs.




- $\sigma^{Born}(4M_B^2) \neq 0$ for charged baryon pairs.
- $\sigma^{Born}(4M_B^2) = 0$ for neutral baryon pairs.

# Introduction — The BESIII experiment



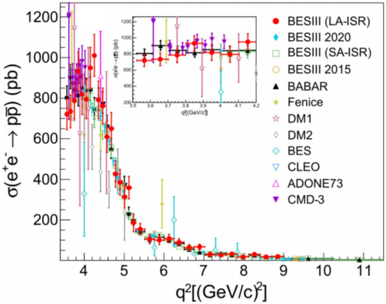

- 依托于中科院高能所内的北京正负电子对撞机 (BEPCII) 和北京谱仪探测器 (BESIII)。
- 运行在陶粲能区，在强子物理和粲味物理方面，有着丰富的研究课题。
- 自 2009 年以来，采集了世界上最大的陶粲能区数据样本，为本报告所涉及的重子形状因子研究打下了坚实的数据基础。

# Outline

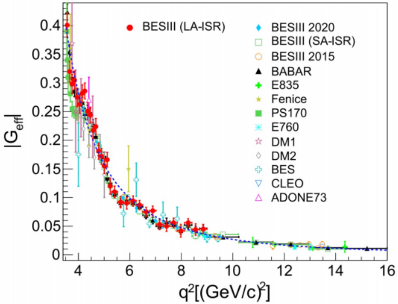
# EMFFs of nucleons — Proton EMFFs (I)

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

Born cross sections




Effective EMFFs

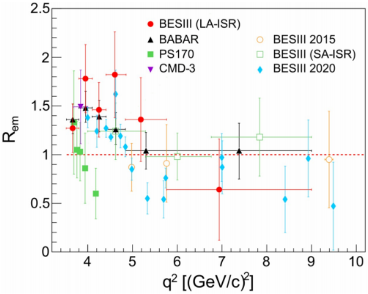



- BESIII measured the Born cross sections of $e^+e^- \to p\bar{p}$ and determined the proton effective EMFFs, using both energy scan and ISR methods.
- Best precision was achieved, and in addition the EFFs of proton are measured for the first time.

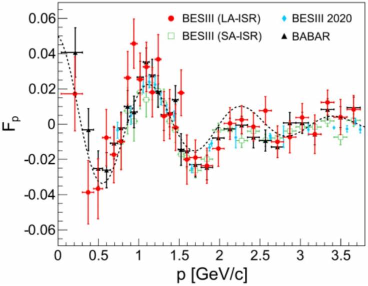
# EMFFs of nucleons — Proton EMFFs (II)

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

$|G_E/G_M|$



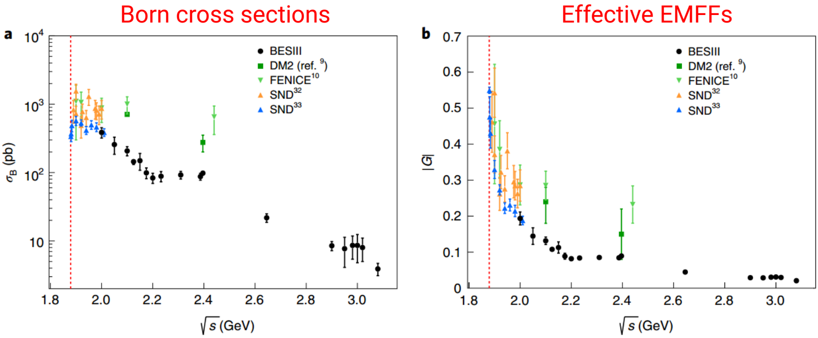

Effective EMFFs residual




- BESIII produced the most accurate $|G_E/G_M|$ ratios using energy scan method, which favor BaBar over PS170 and thus help clarify the puzzle.
- BESIII confirmed the oscillation in the effetive EMFFs residual first seen by BaBar.
  - Interference effect involving rescattering processes in the final state, or independent resonant structures?

# EMFFs of nucleons — Neutron EMFFs (I)

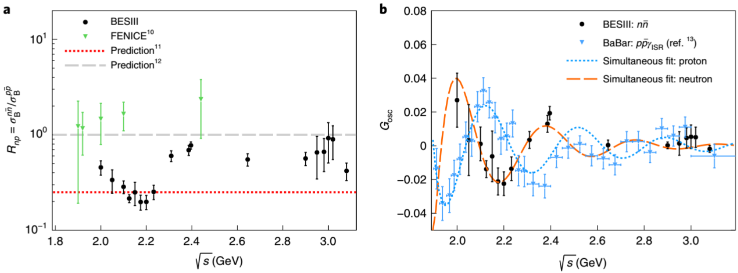
Nature Physics 17 (2021) 11, 1200-1204




- BESIII measured the Born cross sections of $e^+e^- \to n\bar{n}$ and determined the neutron effective EMFFs, at 18 center-of-mass (CM) energies between 2.00 and 3.08 GeV, with unprecedented precision.
- This is a challenging measurement because neutron and anti-neutron are difficult to detect.

# EMFFs of nucleons — Neutron EMFFs (II)

Nature Physics 17 (2021) 11, 1200-1204

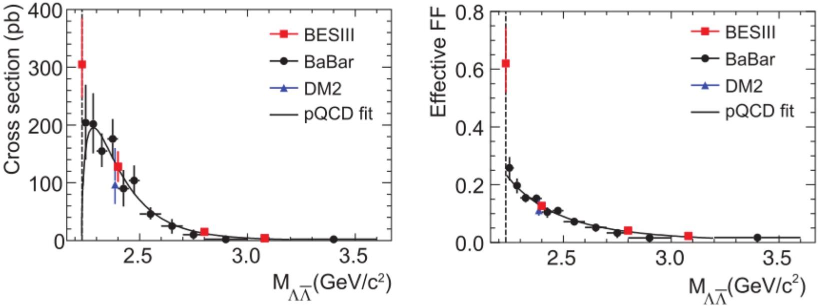



- From BESIII measurements, the cross section for $e^+e^- \to p\bar{p}$ are larger than that of $e^+e^- \to n\bar{n}$ in general.
  - more compatible with the QCD-motivated model predictions than FENICE measurements.
  - Photon-proton interaction is stronger than photon-neutron interaction, clarifing the long-standing puzzle on the photon-nucleon interactions.
- BESIII discovered the oscillation in the effetive EMFFs residual of neutron, similar to that of proton, but with different phase.

# Outline

# EMFFs of strange hyperons — $\Lambda$ EMFFs (I)

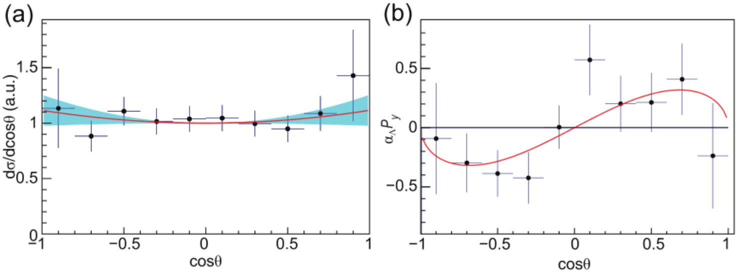
PRD 97 (2018) 032013




- BESIII measured the Born cross sections of $e^+e^- \to \Lambda\bar{\Lambda}$ and determined the $\Lambda$ effective EMFFs, at 4 CM energy points between 2.2324 and 3.0800 GeV.
- A cross-section enhancement is observed near the $\Lambda\bar{\Lambda}$ production threshold.

# EMFFs of strange hyperons — $\Lambda$ EMFFs (II)

PRL 123 (2019) 122003




- The first complete measurement of the $\Lambda$ EMFFs with a multidimensional analysis.

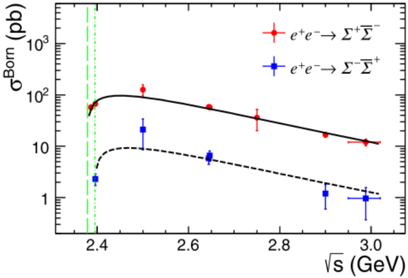
$$R = 0.96 \pm 0.14(\mathrm{stat}) \pm 0.02(\mathrm{syst}) \quad \sigma = 118.7 \pm 5.3(\mathrm{stat}) \pm 5.1(\mathrm{syst})\ \mathrm{pb}$$

$$\Delta\Phi = 37^\circ \pm 12^\circ(\mathrm{stat}) \pm 6^\circ(\mathrm{syst}) \quad |G| = 0.123 \pm 0.003(\mathrm{stat}) \pm 0.003(\mathrm{syst})$$

A milestone of hyperon EMFFs measurements!

# EMFFs of strange hyperons — $\Sigma^+/\Sigma^-$ EMFFs

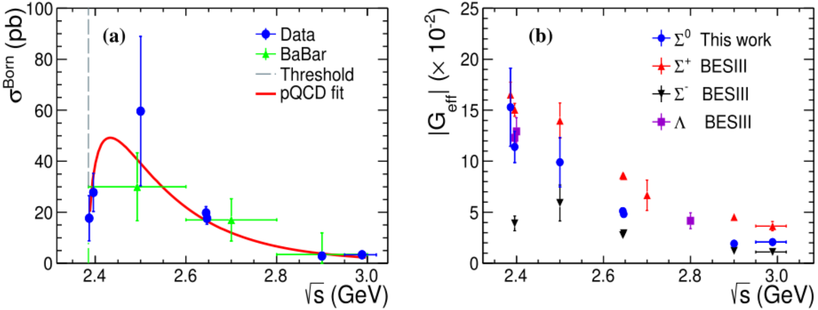
PLB 814 (2021) 136110




- First measurements of $e^+e^- \to \Sigma^\pm\Sigma^\mp$ cross sections in the off-resonance region.
- Well described by pQCD motivated functions, and no cross-section enhancements are observed near the production thresholds.
- The ratio of $\sigma^{Born}(e^+e^- \to \Sigma^+\bar{\Sigma}^-)$ to $\sigma^{Born}(e^+e^- \to \Sigma^-\bar{\Sigma}^+)$ is determined to be $9.7 \pm 1.3$, which is inconsistent with predictions from various models.

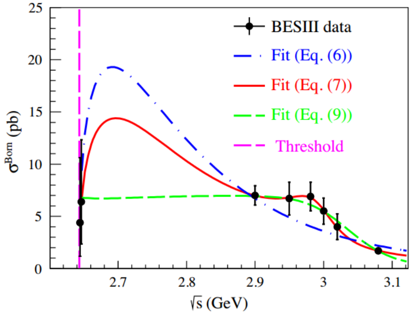
# EMFFs of strange hyperons — $\Sigma^0$ EMFFs

PLB 831 (2022) 137187



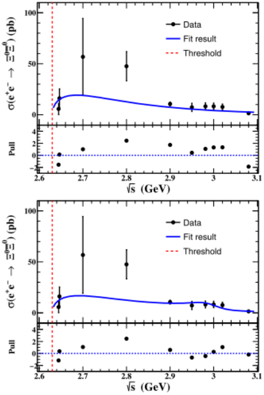

- BESIII measured the Born cross sections of $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ and determined the $\Sigma^0$ effective EMFFs, at CM energy points between 2.644 and 3.080 GeV.
- Well described by pQCD motivated functions, and no cross-section enhancements are observed near the production thresholds.

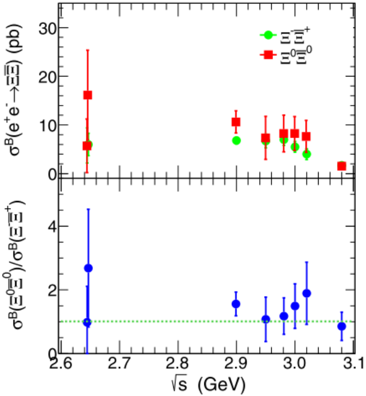
PRD 103 (2021) 012005




- BESIII measured the Born cross sections of $e^+e^- \to \Xi^-\bar{\Xi}^+$ and determined the $\Xi^-$ effective EMFFs, at 8 CM energy points between 2.644 and 3.080 GeV.
- After performing a fit to the Born cross section of $e^+e^- \to \Xi^-\bar{\Xi}^+$, no significant threshold effect is observed.

PLB 820 (2021) 136557



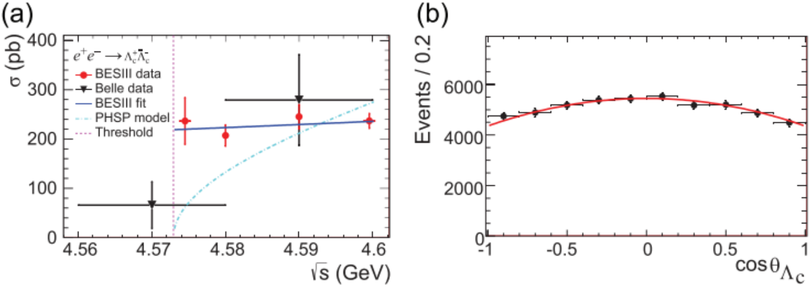




- BESIII measured the Born cross sections of $e^+e^- \to \Xi^0\bar{\Xi}^0$ and determined the $\Xi^0$ effective EMFFs, no significant threshold effect is observed.
- The calculated $\sigma^{Born}(e^+e^- \to \Xi^0\bar{\Xi}^0)/\sigma^{Born}(e^+e^- \to \Xi^-\bar{\Xi}^+)$ is compatible with isospin symmetry.

# Outline

# EMFFs of charmed baryons — $\Lambda_c^+$ EMFFs

PRL 120 (2018) 132001




- BESIII measured the Born cross sections of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ at $\sqrt{s} = 4.5745, 4.5809, 4.5900, 4.5995$ GeV, with unprecedented precision.
- Different cross-section lineshapes from Belle, and abnormal threshold behaviour is observed.
- $|G_E/G_M|$ of $\Lambda_c^+$ has been extracted for the first time.
  - $1.14 \pm 0.14$ (stat.) $\pm 0.07$ (sys.) at $\sqrt{s} = 4.5745$ GeV,
  - $1.23 \pm 0.05$ (stat.) $\pm 0.03$ (sys.) at $\sqrt{s} = 4.5995$ GeV.

# Outline

1. Introduction
   1. The Standard Model and baryons
   2. Electromagnetic form factors (EMFFs)
   3. Baryon pair production via $e^+e^-$ annihilation
   4. The BESIII experiment
2. EMFFs of nucleons
   1. Proton EMFFs
   2. Neutron EMFFs
3. EMFFs of strange hyperons
   1. $\Lambda$ EMFFs
   2. $\Sigma^+/\Sigma^-/\Sigma^0$ EMFFs
   3. $\Xi^-/\Xi^0$ EMFFs
4. EMFFs of charmed baryons
   1. $\Lambda_c^+$ EMFFs
5. **Summary and prospects**

# Summary

- Based on the world's largest $e^+e^-$ annihilation data samples in the $\tau$-Charm region collected with the BESIII detector, we studied the TL EMFFs of all the ground octet baryons and $\Lambda_c^+$, in a systematic way.
  - Measured many cross sections and EMFFs for the first time or with the best precision.
  - Clarified several long-standing puzzles.
  - Confirmed/Discovered the oscillating feature of proton/neutron.
  - Observed abnormal cross-section enhancements near the $\Lambda/\Lambda_c^+$ pair production thresholds.

- All these studies shed new light on the understandings of the structure and the dynamics of baryons.

- Review article on the topic: Guangshun Huang and Rinaldo Baldini Ferroli, National Science Review 8 (2021) 11, nwab187

# Prospects

- It will take a long time to ultimately unravel the structure and the dynamics of baryons.
- More studies on the baryon EMFF measurements are ongoing at BESIII.
- Further improvements in the baryon EMFF measurements will be the focus of future powerful colliders:
  - SuperKEKB/Belle II in Japan (TL region)
  - FAIR/Panda in Germany (TL region)
  - STCF in China (TL region)
  - SCTF in Russia (TL region)
  - EIC in America (SL region)
  - EICC in China (SL region)

*Thanks for your attention!*