The 43rd International Symposium on Physics in Collision

# Recent Results of Baryon Electromagnetic Form Factors at BESIII

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# Outline



一尺之棰，日取其半，萬世不竭。

——莊周《莊子・天下》

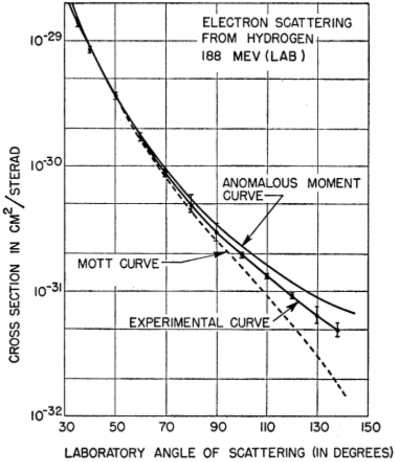
A chi-long stick, cut in half every day,

will never be exhausted in myriad ages.

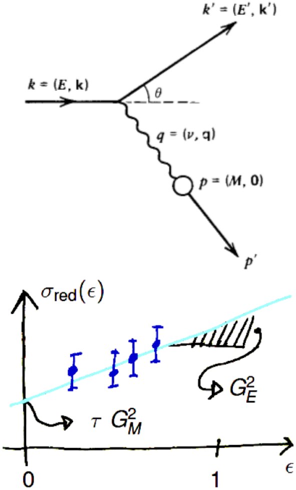
— "Chuang-Tzu · All-Under-Heaven"

by Chuang Chou

# Experiment of Electron Proton Scattering




☞ Phys. Rev. **98** (1955) 217.




**Robert Hofstadter**

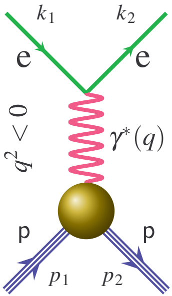
The **Nobel Prize** in Physics 1961

- The differential cross section of ep scattering indicates that **proton is not charged point-like particle**,
- The shape (or internal structure) of proton might be described by the form factors.

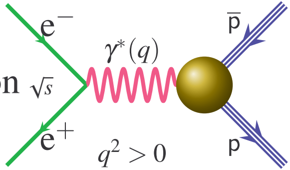
R. Hofstadter and R. McAllister, Phys. Rev. **98** (1955) 217; R .Hofstadter, Rev. Mod. Phys. **28** (1956) 214; R. Hofstadter, F. Bumiller and M. R. Yearian, Rev. Mod. Phys. **30** (1958) 482.

# Electromagnetic Form Factors of Proton

Elastic Scattering




Annihilation $\sqrt{s}$




- ☆ **Spin-$\frac{1}{2}$ baryons**: **two form factors**
- ☆ Assuming **one photon exchange**:

$$\mathcal{M} = -\frac{e^2}{q^2} j_{e\mu} j_p^\mu$$

- ☆ **Hadronic current:**

$$j_p^\mu = \bar{u}(p_2)\left[\gamma^\mu F_1(q^2) + \frac{i\kappa\sigma^{\mu\nu}q_\nu}{2m_p}F_2(q^2)\right]u(p_1)$$

- ☆ Sachs form factors:

$$G_{\rm E}(q^2) = F_1(q^2) + \frac{\kappa q^2}{4m_p^2}F_2(q^2)$$
$$G_{\rm M}(q^2) = F_1(q^2) + \kappa F_2(q^2)$$

- ☆ Elastic scattering: $e^-p \to e^-p$
  **Space-Like (SL) region**:

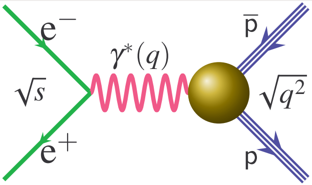
$$q^2 \simeq -2E_eE'_e(1-\cos\theta_e) < 0$$

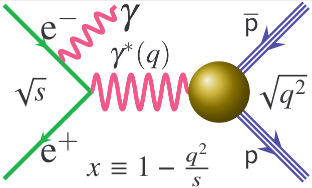
- ☆ Annihilation: $e^+e^- \leftrightarrow p\bar{p}$
  **Time-Like (TL) region**:

$$q^2 = s = M_{p\bar{p}}^2 > 0$$

$\kappa$ is the anomalous magnetic moment

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

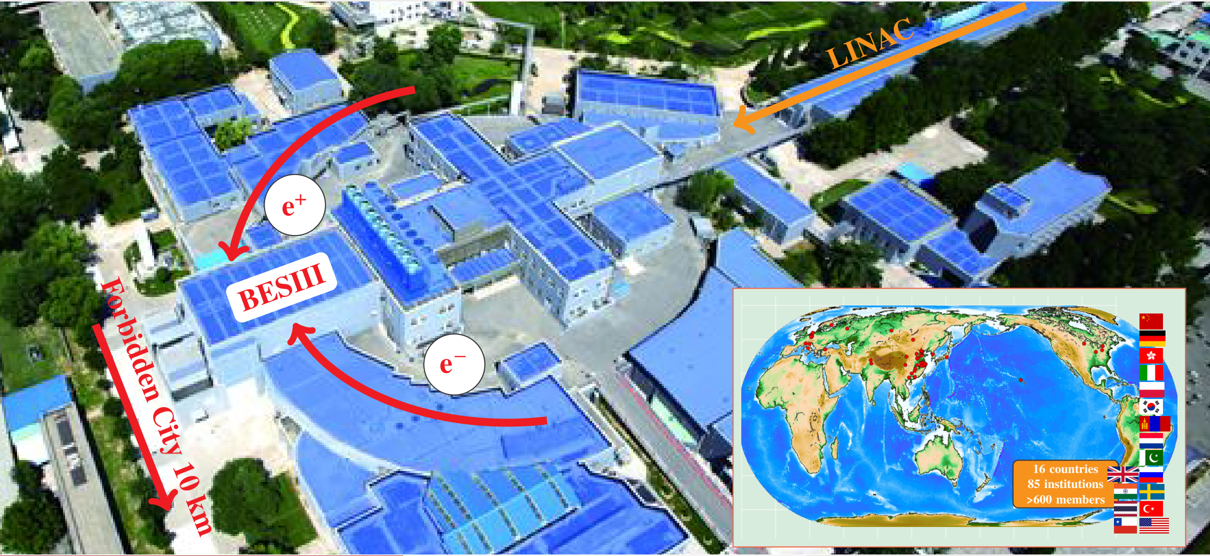


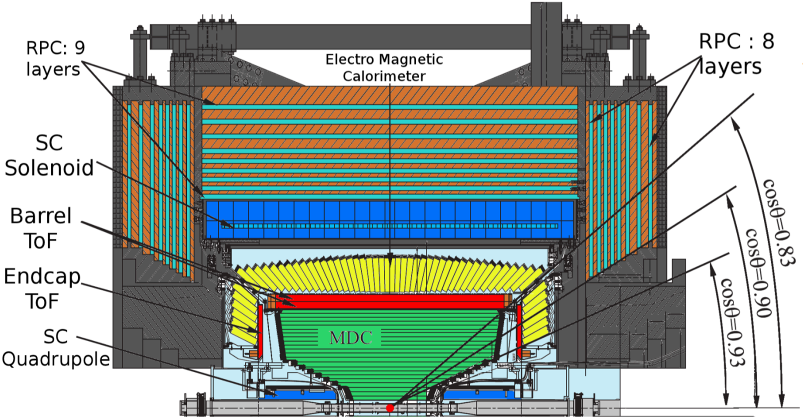

| | Energy Scan | Initial State Radiation |
|---|---|---|
| $\sqrt{s}$ | discrete | fixed |
| $\mathcal{L}$ | low at each beam energy | high at one beam energy |
| $\sigma$ | $\frac{d\sigma_{p\bar{p}}}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$ | $\frac{d\sigma_{p\bar{p}\gamma}}{dq^2} = \frac{1}{s}W(s,x)\sigma_{p\bar{p}}(q^2)$ $W(s,x) = \frac{\alpha}{\pi x}(\ln\frac{s}{m_e^2} - 1)(2 - 2x + x^2)$ |
| $q^2$ | single at each beam energy | from threshold to $s$ |
| | BESIII, CMD-3, ... | BaBar, BESIII, Belle, Belle-II, ... |

ISR suppression factor: $\frac{\alpha}{\pi} \sim \frac{1}{400}$

# Beijing Electron Positron Collider II (BEPCII)



# BESIII Spectrometer on BEPCII




BESIII detector: 93% coverage

$\sqrt{s}$ ~2.0 (1.8) - 4.965 GeV, $\mathcal{L}$ ~$1.0\times10^{33}$ $cm^{-2}s^{-1}$ (design)

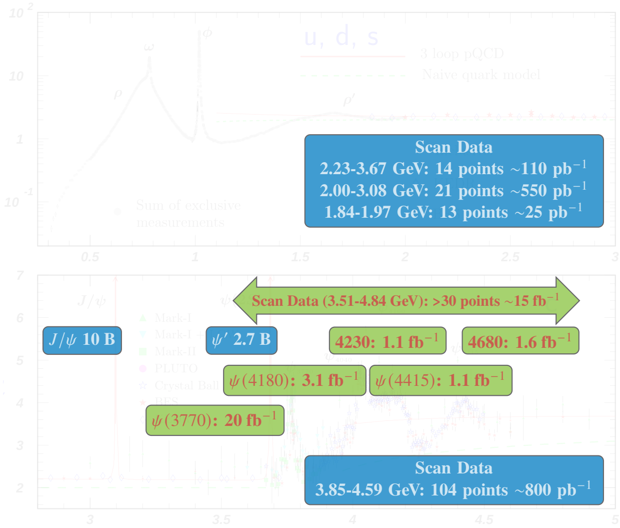
**MUC**
$\delta z \sim 5$ cm, $\delta r \sim 3$ cm

**EMC**
$\frac{\delta E}{E} < 2.5\%/\sqrt{E}$,
$\delta d \sim 0.6\sqrt{E}$ cm

**ToF**
$\delta t \sim 70$ ps (Barrel),
$\delta t \sim (110)60$ ps (Endcap)

**MDC**
$\frac{\delta p}{p} < 0.5\%$, $\frac{\delta(dE/dx)}{dE/dx} < 6\%$

# Electron Positron Annihilation Data at BESIII




## Physics Quantities Measured

- Differential cross section of $e^+e^- \longrightarrow B\bar{B}$ (spin-$\frac{1}{2}$):

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

- **Electromagnetic form factors** (EMFFs):
  $|G_E|$, $|G_M|$ and relateiv phase $\Delta\Phi$ $(\Im\mathfrak{m}\left[G_E G_M^*\right])$,

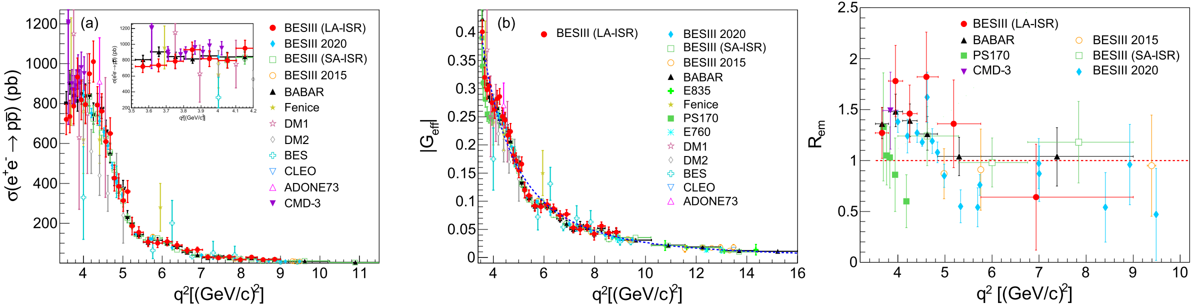
- Effective FF (total cross section):

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

- **Polarization** of hyperon is self-analyzing:

$$\mathcal{P}_y = -\frac{\sin 2\theta\,\Im\mathfrak{m}[G_E(s)G_M^*(s)]/\sqrt{\tau}}{|G_{E(s)}|^2\sin^2\theta/\tau+|G_{M(s)}|^2(1+\cos^2\theta)},$$

# Proton Electromagnetic Form Factors

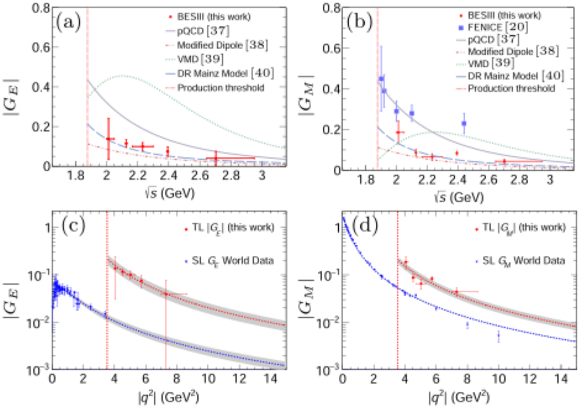



☞ Phys. Lett. B **817** (2021) 136328

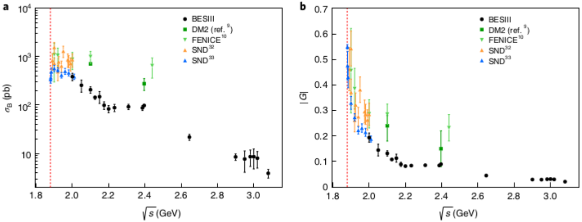
- Proton EMFFs have been measured through both direct annihilation and ISR return methods: PLB **817** (2021) 136328, PRL **124** (2020) 042001 and PRD 99 (2019) 092002,
- Wide $q^2$ region from the $p\bar{p}$ threshold up to 14 GeV$^2$,
- Most precise measurements on the ratio $\left(|\frac{G_E}{G_M}|\right)$ at 2.125 GeV with direct annihilation,
- Measurements of proton EMFFs below 4 GeV$^2$ through ISR-tagged method.

| |
|---|
| direct annihilation<br>2.00 - 3.08 GeV |
| ISR return<br>th. - 3.8 GeV<br>(by data at $\sqrt{s} \geq 3.773$ GeV) |

# Neutron Electromagnetic Form Factors




☞ Phys. Rev. Lett. **130** (2023) 151905

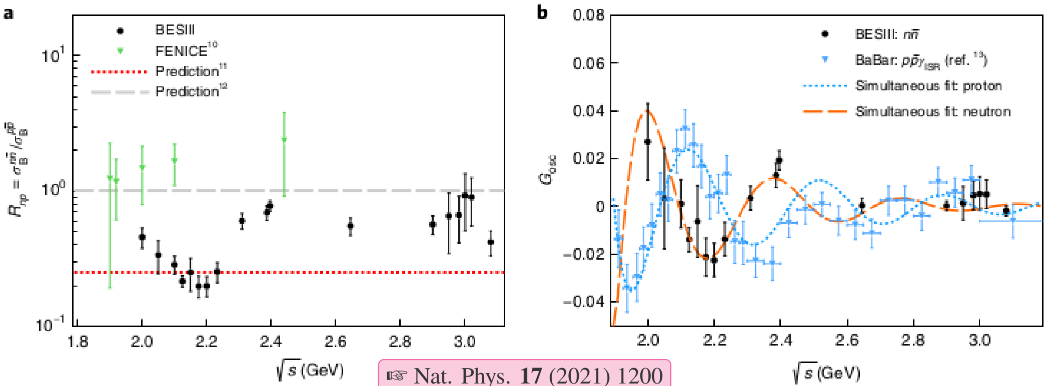



☞ Nat. Phys. **17** (2021) 1200

**First measurements for $|G_E|$ and $|G_M|$ of neutron in TL region**

- High precision of the neutron EMFFs measurements in a wide $q^2$ region,
- Very difficult to select the pure neutral final states,
- First time ever to extract the individual $|G_E|$ and $|G_M|$ of neutron in TL region,
- Direct annihilation with data at $\sqrt{s}$ = 2.0 - 3.08 GeV.

# Nucleon Pair Production through the $e^+e^-$ Annihilation




☞ Nat. Phys. **17** (2021) 1200

- The coupling strength of $\gamma^* p\bar{p}$ and $\gamma^* n\bar{n}$ is varied with different $\sqrt{s}$, which is differed from any naïve prediction models,
- Oscillation of residual $|G_{\rm eff}|$ observed in neutron with a phase orthogonal to that of proton.

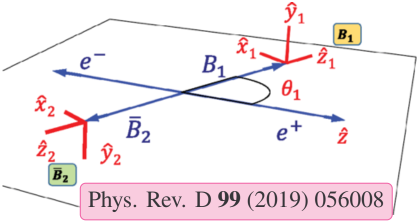
# From Nucleon to Hyperon

- Difficult to measure the hyperons EMFFs in the Space-Like region due to the unstable of hyperon either as target or beam,
- Access their EMFFs in the TL region via pair production of hyperons in the $e^+e^-$ annihilation,
- **Advantage**: self-analyzing of the polarization of hyperons,

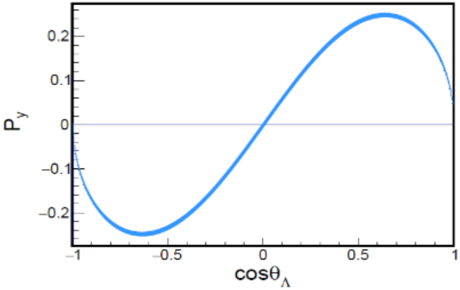
$$\mathcal{P}_y = -\frac{\sin 2\theta \Im\mathfrak{m}\left[G_E(s)G_M^*(s)\right]/\sqrt{\tau}}{|G_{E(s)}|^2 \sin^2\theta/\tau + |G_{M(s)}|^2(1+\cos^2\theta)},$$

- Extract the relative phase between $G_E$ and $G_M$ of the hyperons,
- The threshold is accessible benefited the decay of the hyperons.

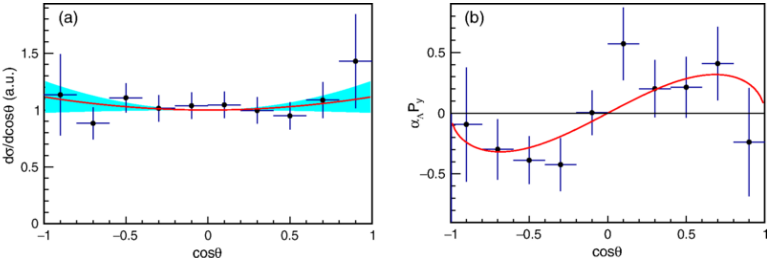
Nuov Cim A **109** (1996) 241

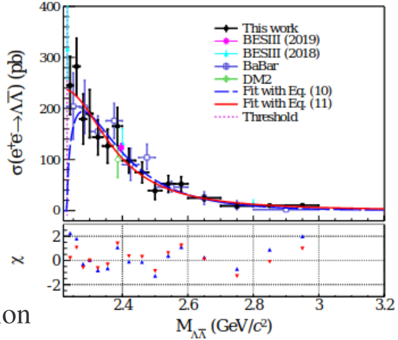



Phys. Rev. D **99** (2019) 056008



# EMFFs of Λ Hyperon at BESIII




- The EMFFs of Λ hyperon are studied through direct annihilation and ISR (tagged) methods at BESIII,
- The cross sections (effectiv FF) are measured in a wide $q^2$ range,
- The ratio and relative phase of Λ EMFFs at $\sqrt{s} = 2.396$ GeV:

$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14 \pm 0.02,\ \Delta\Phi = 37^\circ \pm 12^\circ \pm 6^\circ.$$

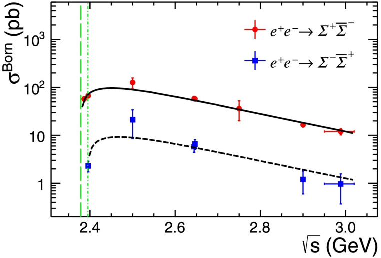
| |
|---|
| direct annihilation<br>2.2324 - 3.08 GeV |
| ISR (tagged) return<br>th. - 3.0 GeV<br>(by data at $\sqrt{s} \geq 3.773$ GeV) |

☞ Phys. Rev. D **97** (2018) 032013

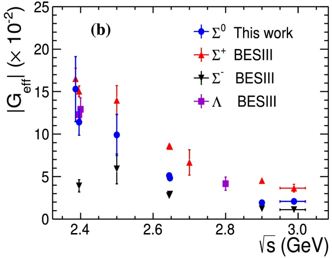
☞ Phys. Rev. Lett. **123** (2019) 122003

☞ Phys. Rev. D **107** (2023) 072005

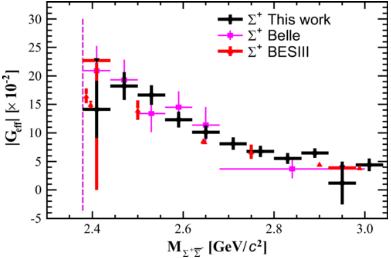
# EMFFs of Σ Hyperon at BESIII




☞ Phys. Lett. B **814** (2021) 136110




☞ Phys. Lett. B **831** (2022) 137187

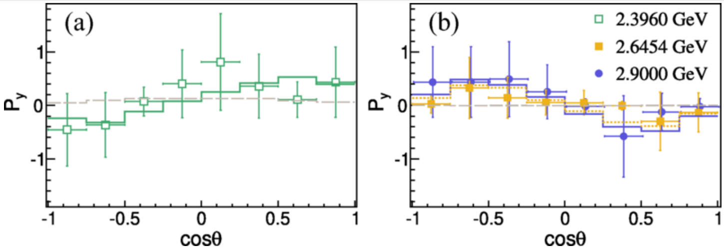


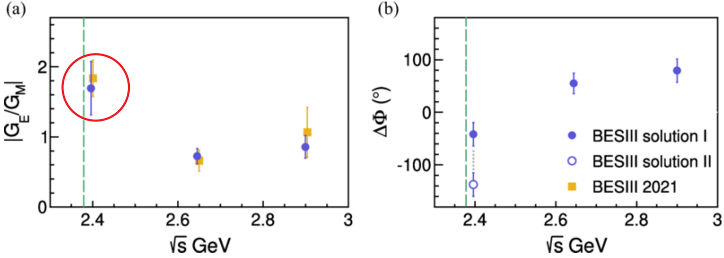

☞ Phys. Rev. D **109** (2023) 034029

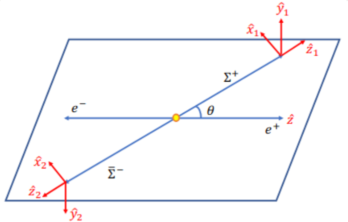
- Isospin triplet of strange hyperons: $\Sigma^-(dds)$, $\Sigma^+(uus)$ and $\Sigma^0(uds)$,
- EMFFs of all the three hyperons are measured via direct annihilation,
- An ISR measurement is also performed for the $\Sigma^+$ EMFFs study,
- Cross section for the isospin triplet roughly: $(9.7 \pm 1.3) : (3.3 \pm 0.7) : 1$.

| |
|---|
| direct annihilation for $\Sigma^\pm$ and $\Sigma^0$<br>2.3864 - 3.02 GeV |
| ISR (untagged) return for $\Sigma^+$<br>th. - 3.0 GeV<br>(by data at $\sqrt{s} \geq 3.773$ GeV) |

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



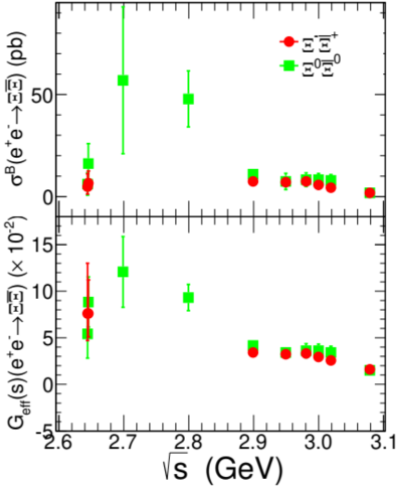



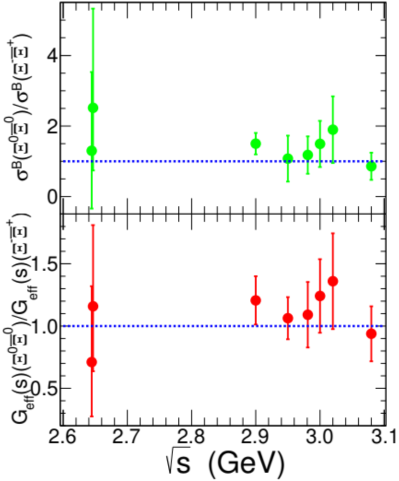

$$\mathcal{W}(\xi) \propto \mathcal{F}_0(\xi) + \alpha\mathcal{F}_5(\xi) + \alpha_1\alpha_2\left[\mathcal{F}_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \alpha F_6(\xi)\right] + \sqrt{1-\alpha^2}\sin(\Delta\Phi)\left[-\alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)\right]$$

- Joint angular distribution in the reaction of $e^+e^- \to \Sigma^+\bar{\Sigma}^-(\to p\pi^0\bar{p}\pi^0)$,
- **Unpolarized**, **correlated** and **polarized**,
- Determine the ratio and relative phase of $\Sigma^+$ EMFFs for the first time.

☞ Phys. Rev. Lett. **132** (2024) 081904

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



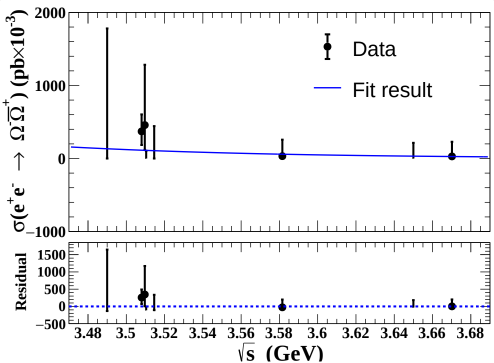



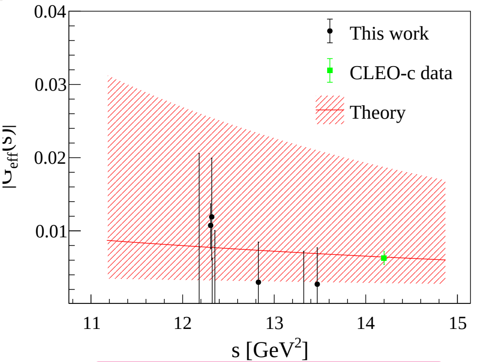

- Cross sections of $e^+e^- \to \Xi\bar{\Xi}$ are measured via direct annihilation with data at $\sqrt{s}$ = 2.644 - 3.08 GeV,
- Limited statistics for the points close to the threshold,
- The ratio of Born cross section and effective FF ($G_{eff}$) of the two channels are within $1\sigma$ of the expectation of isospin symmetry.

☞ Phys. Lett. B **820** (2021) 136557

☞ Phys. Rev. D **103** (2021) 012005

# EMFFs of Ω Hyperon – Three Valence *s*-Quarks



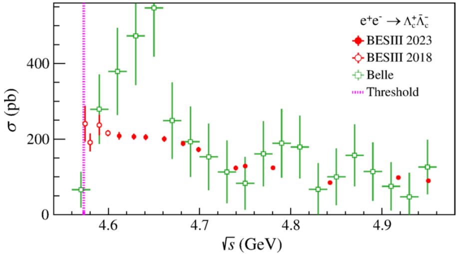



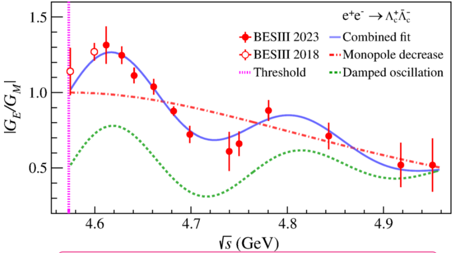

- Hyperon Ω: three valence *s*-quarks and spin-$\frac{3}{2}$ baryon,

☞ Phys. Rev. D **107** (2023) 052003

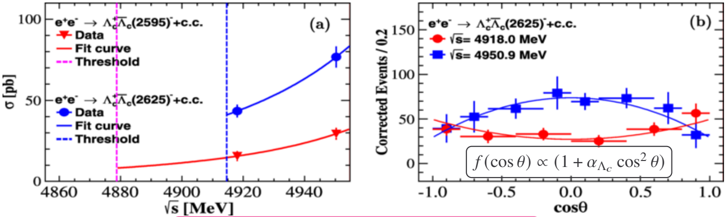
- Four FFs to describe the $\gamma^*\Omega^-\bar{\Omega}^+$ vertex, electric charge ($|G_{E0}|$), magnetic dipole ($|G_{M1}|$), electric quadrupole ($|G_{E2}|$), and magnetic octupole ($|G_{M3}|$),
- Upper limits of effective FF are obtained from the measurements of $e^+e^- \to \Omega^-\bar{\Omega}^+$ with data at $\sqrt{s}$=3.49 - 3.67 GeV.

# EMFFs of the Lightest Charmed Baryon $\Lambda_c$



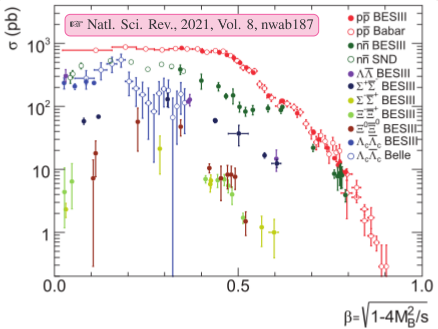

☞ Phys. Rev. Lett. **131** (2023) 191901




☞ Phys. Rev. D **109** (2024) L071104

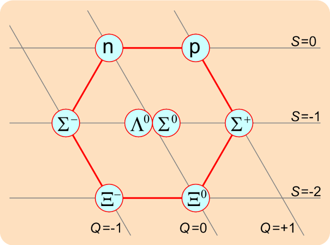
- Cross section, FFs ($|G_E|$, $|G_M|$) and their ratio ($\frac{G_E}{G_M}$) of charmed baryon $\Lambda_c$ are extracted with data at $\sqrt{s}$ = 4.64 - 4.95 GeV,
- Oscillation of energy-depended ratio is observed for the first time,
- Measurement on $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c(2595)^-$ $(\bar{\Lambda}_c(2625)^-) + c.c.$ is performed, final states have different spin combinations: $\frac{1}{2}\frac{1}{2}$ and $\frac{1}{2}\frac{3}{2}$,
- Sign of the angular parameter $\alpha_{\Lambda_c}$ is flipped between two very close energies for $\bar{\Lambda}_c(2625)^-$.

# The Status of the Baryons EMFFs




| 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 |

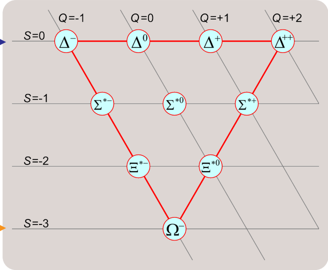
**Many measurements available**




**Difficult to measure**

**No data available**

**Upper limits only**



# Summary and Outlook

- BESIII is collecting the world largest $e^+e^-$ collision data in the $\tau - charm$ region,
- **Electromagnetic form factors** are studied for nucleons, hyperons, charmed-hyperon,
- Many fruitful physics results are obtained for the EMFFs through **direct annihilation and ISR return Methods**,
- Full picture of the hyperon EMFFs can be determined by the benefit of their self-analyzing **polarization** (relative phase of EMFFs),
- Results as strong inputs to understand the structure of baryons: threshold effect, coupling strength ($\gamma^* \mathrm{N\bar{N}}$, $\gamma^* \Sigma\bar{\Sigma}$) and oscillation behavior of residual effective FF,
- Current results are still limited by the low statistics for most of the measurements,
- More results from BESIII are expected soon, including low energy data (below 2 GeV) and 20 fb$^{-1}$ $\psi(3770)$ data for ISR analyses.


thank you
gracias
danke
merci
obrigado
teşekkür ederim
go raibh maith agat
mochchakkeram
ngiyabonga
謝謝
dziękuję
sukriya
kop khun krap
terima kasih
bedankt
спасибо
arigatô
dakujem
мерси
grazie
dank je
takk
sağolun
mauruuru
hvala
tapadh leat
감사합니다
ありがとう
рахмат
Баярлалаа
faafetai lava
kiitos
dankie
dhanyavad
köszönöm
blagodaram
misaotra
matondo
paldies
grazzi
mahalo
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obrigada
murakoze
trugarez
shukriya
mamnun
dhanyavadagalu
chnorakaloutioun
gratias ago
gràcies
tanemirt
rahmet
diolch
xièxie
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najis tuke
didi madloba
mèsi
sobodi
enkosi
děkuji
bayarlalaa
gracie
nandri
nanni
mersi
kia ora
barka
welalin
tack
spas
vinaka
спасибі
sulpáy
tau
djere dieuf
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manana
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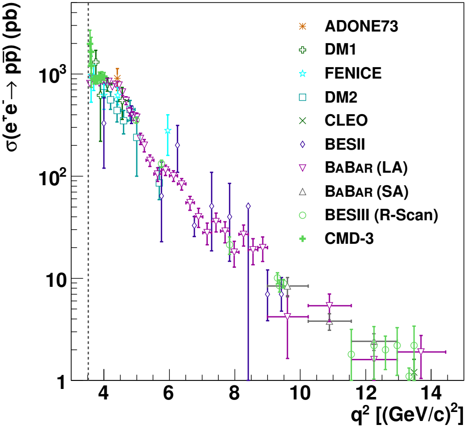
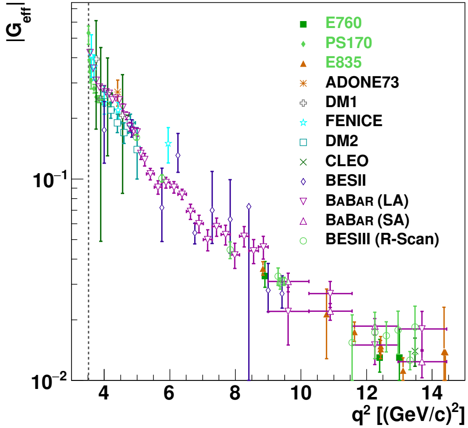
# Early Cross Section and Effective FF in Time-Like Region




Cross section of $e^+e^-\to p\bar{p}$

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

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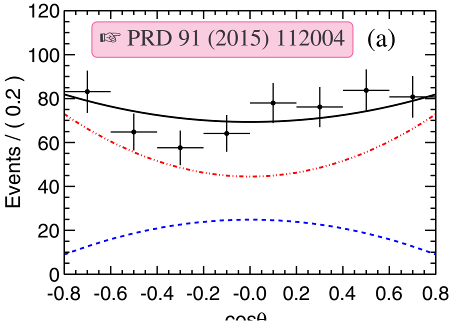
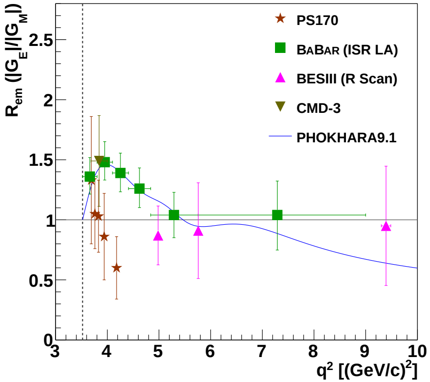
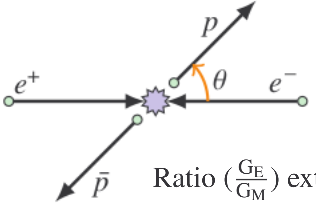
Effective FF of proton

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

# Early Measurements of the Proton FFs in Time-Like Region




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

Ratio $(\frac{G_E}{G_M})$ extracted by analyzing the angular distribution!