Recent results of Baryon electromagnetic form factors at BESIII

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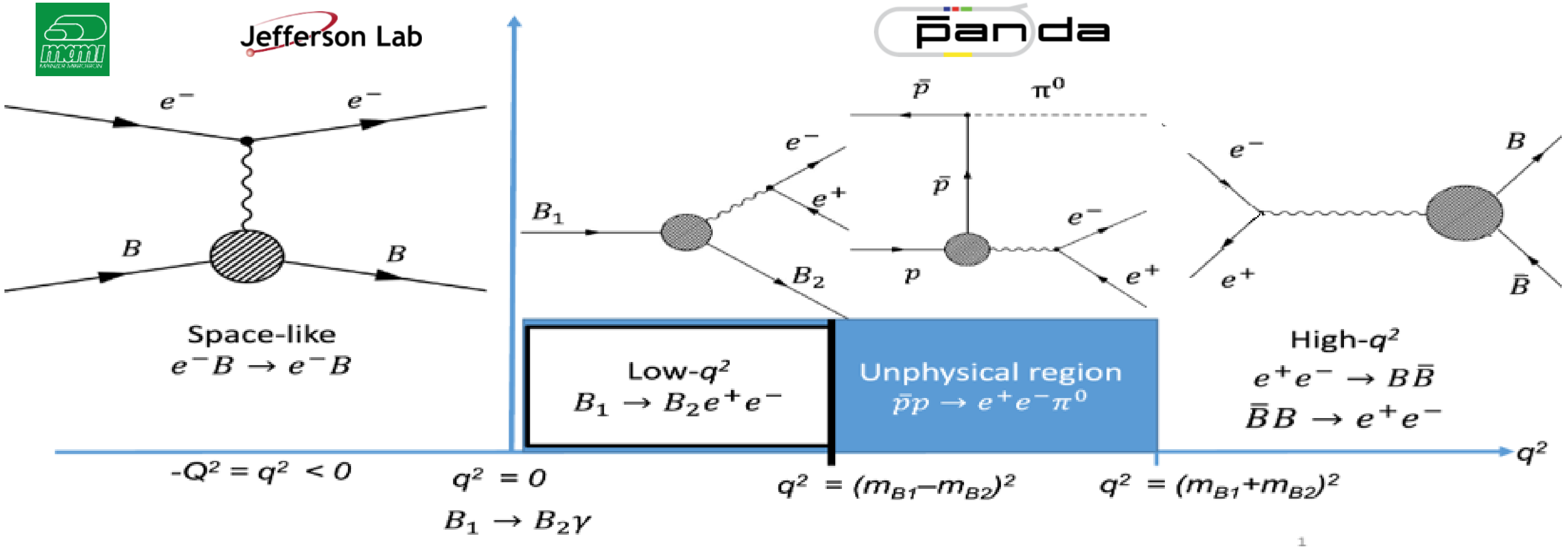
Outline

- Introduction
- BESIII Experiment
- Nucleon Form Factors at BESIII
- Hyperon Form Factors at BESIII
- 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 describing the hadron current:

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

$F_1(q^2)$: Dirac FF; $F_2(q^2)$: 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, Cabibbo and Gatto first proposed the time-like EMFFs can be studied in e^+e^- collisions

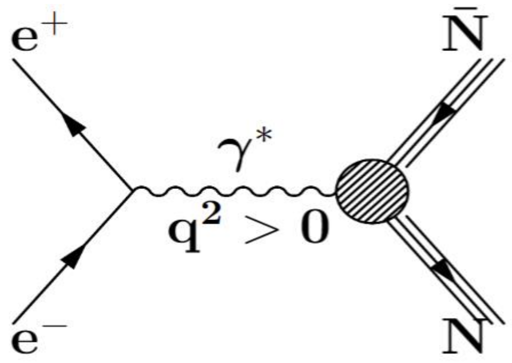
- The differential cross section of $e^+e^- \to B\bar{B}$ (1/2 baryon) is given:

Phys. Rev. 124, 1577-1595 (1961)

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

Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ (Born cross section)

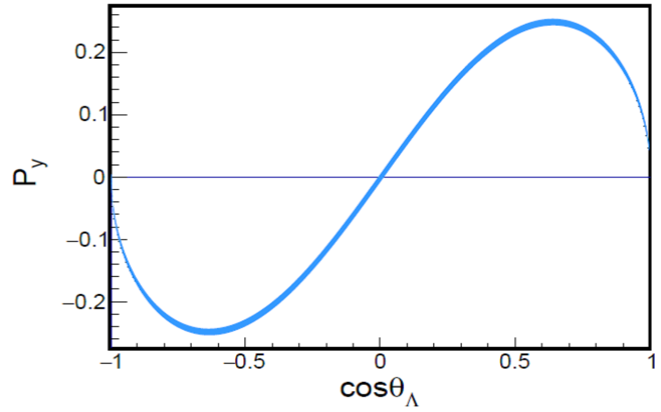
$$\xrightarrow{|G_E|=|G_M|} \sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left(1+\frac{1}{2\tau}\right)|G_{\text{eff}}|^2$$



- Complex form of TLFF leads to transversely polarized baryon even the beams are unpolarized

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

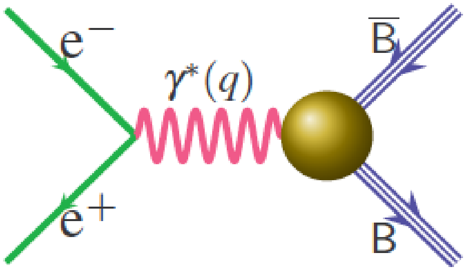
Nuov Cim A **109**, 241–256 (1996)



Nat. Phys. 15, 631 (2019)

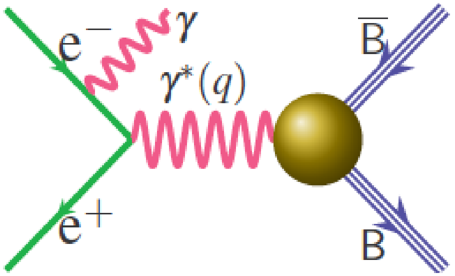
Time-like EMFFs: Experiment Review

- **Energy Scan Method at discrete c.m. energies**



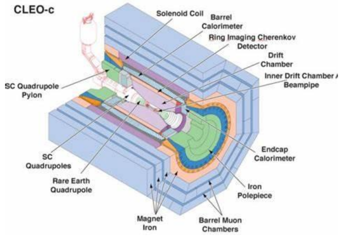
  - Well-defined c.m. energy, low background
  - Very good energy resolution
  - Discrete values, leaving gaps without information

- **Initial State Radiation (ISR) Method at a fixed c.m. energy**

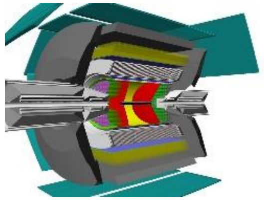


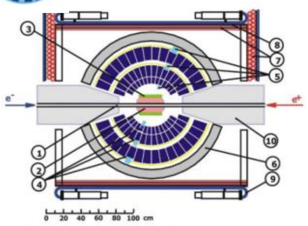
  - At a fixed c.m. energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
  - Systematic uncertainty in a coherent way
  - Large luminosity needed
  - Higher background

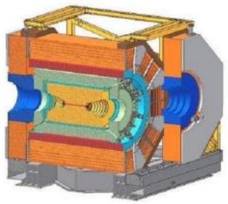
CLEO-c

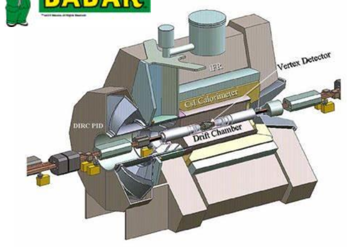


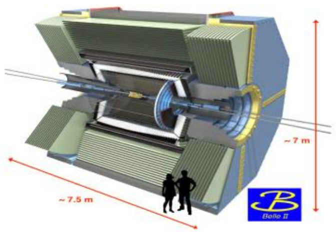
CMD-3

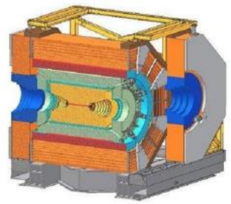










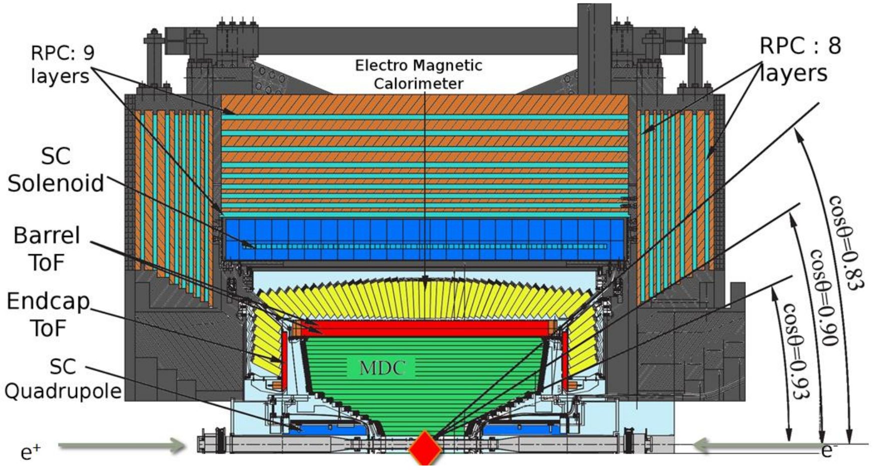


BESIII Experiment

BESIII detector records symmetric e^+e^- collisions in the tau-charm region $(1.84 - 4.95\ \text{GeV})$

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

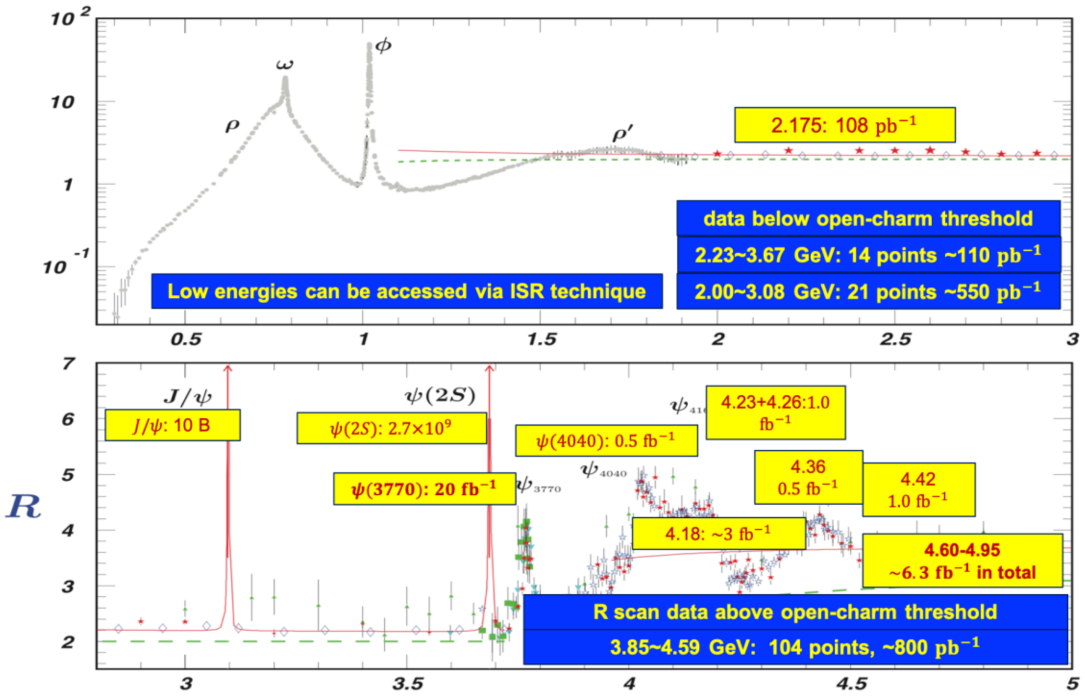


BESIII Detector

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

Time Of Flight
Plastic scintillator, 2 layer
- $\sigma_T(\text{barrel}) = 68$ ps
- $\sigma_T(\text{endcap}) = 110$ ps

(update to 60 ps with MRPC)



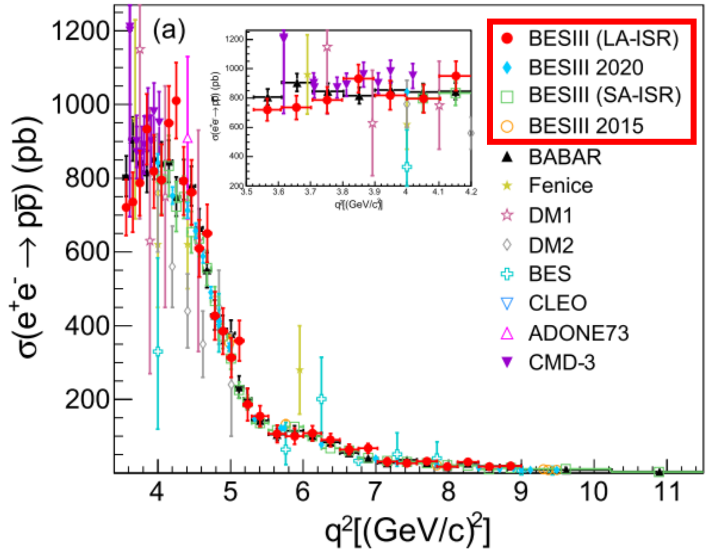
✓ **Ideal environment to study the Baryon EMFFs with both energy scan and ISR methods!**

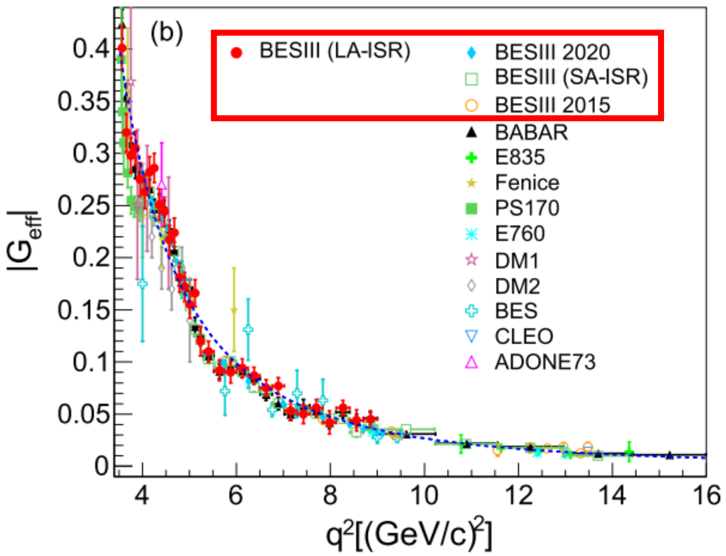
Nucl. Instrum. Meth. A 614, 345-399 (2010)

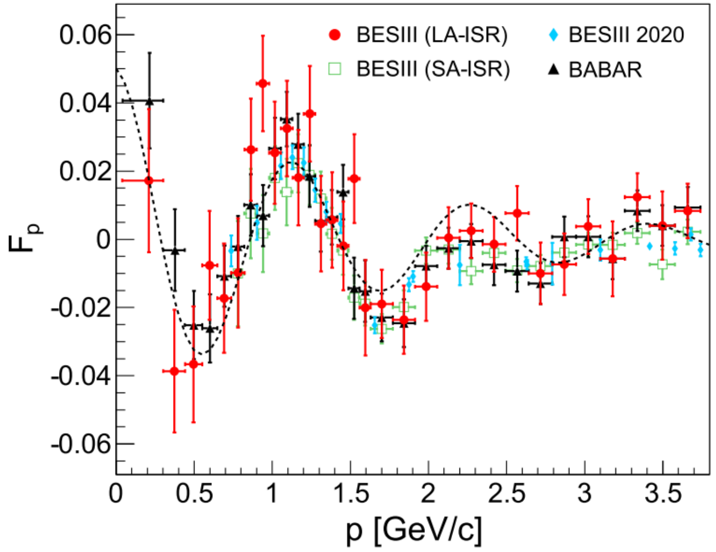
Proton EMFFs

- Born cross section ($\sigma_{p\bar{p}}$), $|G_{\text{eff}}|$ and $|G_E/G_M|$ of proton measured with high accuracy using two technique
  - ✓ 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)
  - ✓ ISR Method:
    - ➢ LA-ISR: threshold – 3.0 GeV/c^2, PLB 817, 136328 (2021)
    - ➢ SA-ISR: 2.0 – 3.8 GeV/c^2, PRD 99, 092002 (2019)
    - ➢ Data Sets: 3.773-4.600 GeV, 7.5 fb^{-1}
- Most precise measurement at 2.125 GeV with $\delta\sigma_{p\bar{p}} \sim 3.0\%$, $\delta|G_{\text{eff}}| \sim 1.5\%$
- Periodic oscillations distribution after subtracting the modified dipole contribution

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



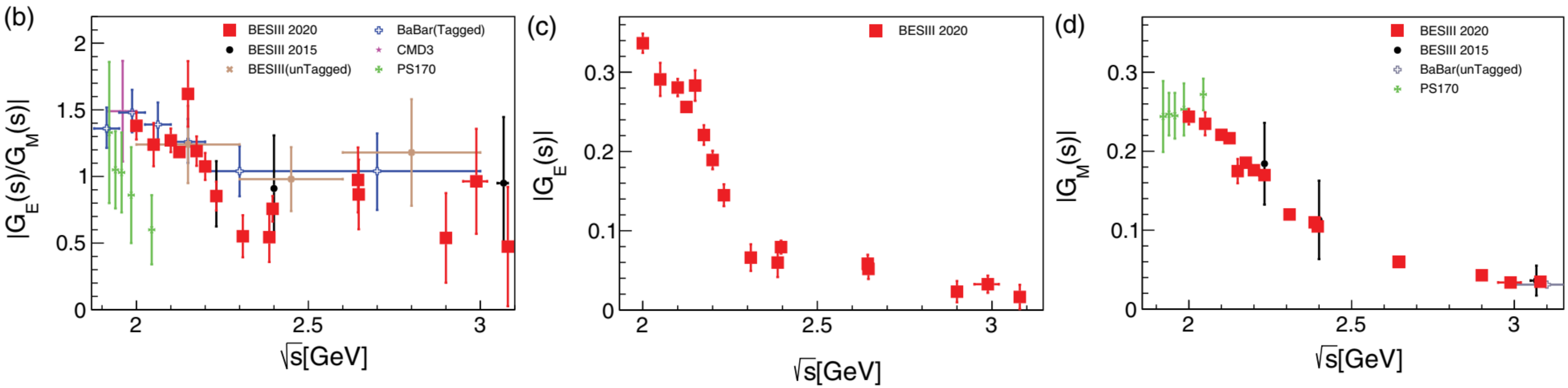




Proton EMFFs

- $|G_E/G_M|$ are determined with high accuracy, $\delta|G_E/G_M| \sim 3.5\%$ at 2.125 GeV (most precise)
- $|G_M|$ is measured for the first time over a wide range of energies with uncertainties of 1.6% to 3.9%
- $|G_E|$ is obtained for the first time

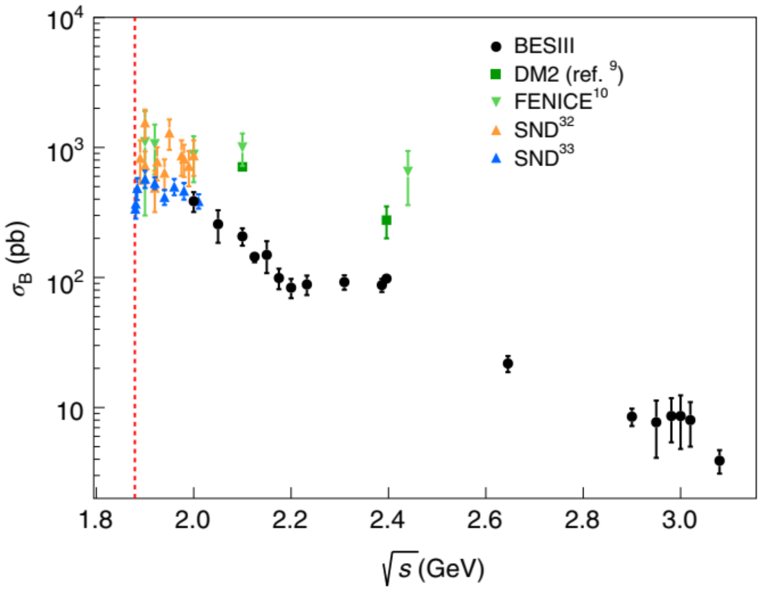
PRL 124, 042001 (2020)

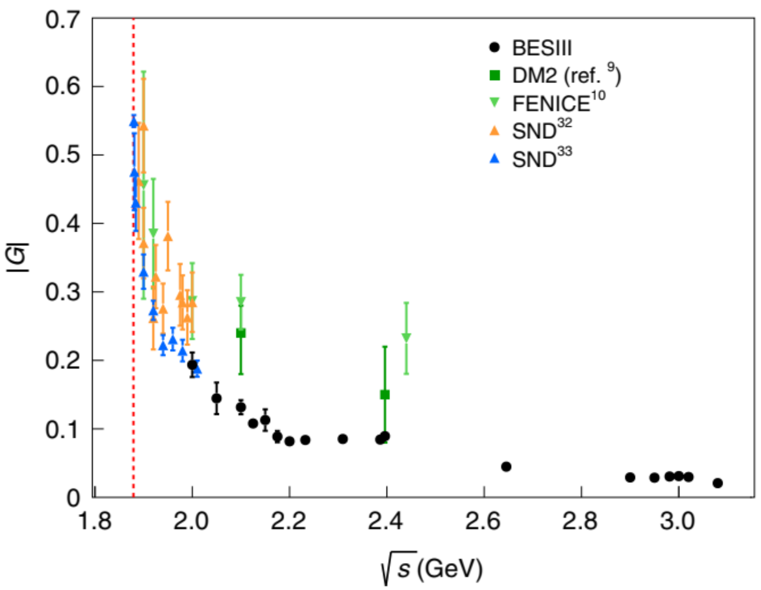


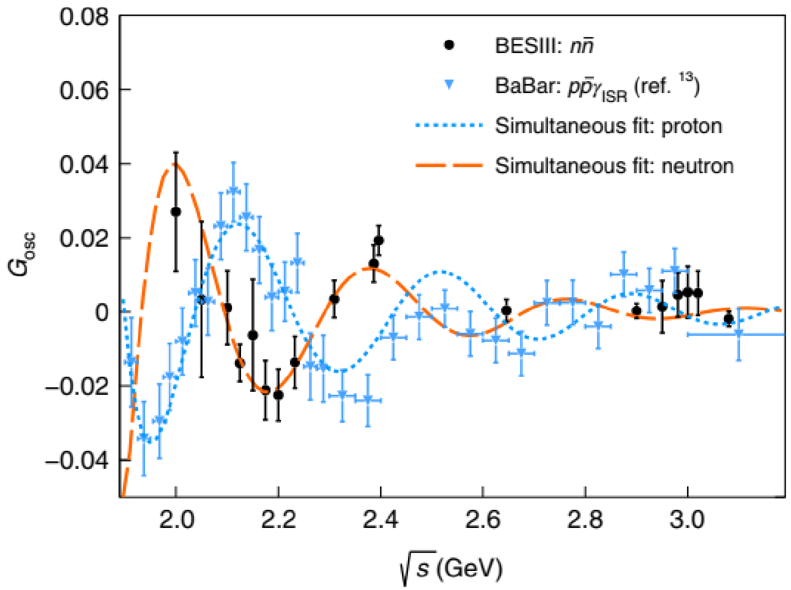
Neutron EMFFs

- Born cross section ($\sigma_{n\bar{n}}$) and $|G_{\rm eff}|$ of neutron, $2.00 - 3.08$ GeV, 647.9 $\rm pb^{-1}$
- Substantially improve the overall precision
- Oscillation of reduced-$|G_{\rm eff}|$ observed in neutron with a phase almost orthogonal to that of proton

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







Neutron EMFFs

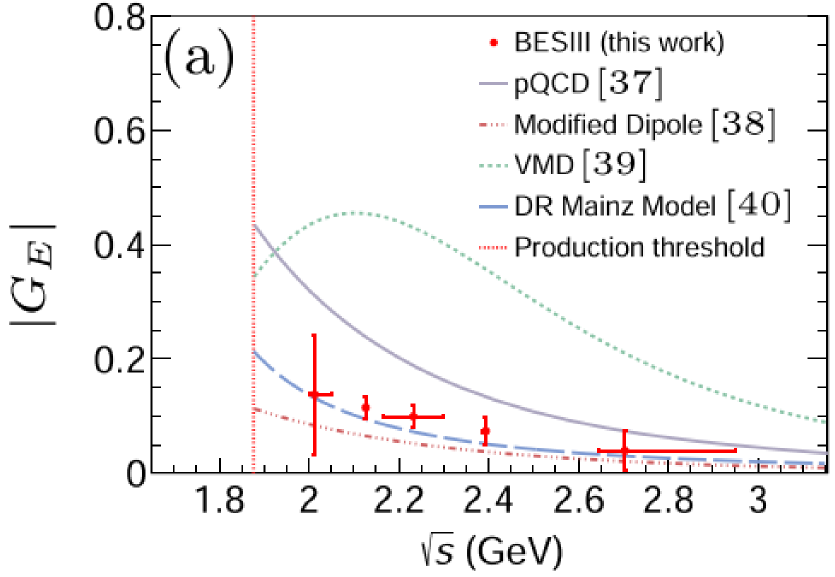
- $|G_E|$, $|G_M|$ of neutron, 2.0 − 2.95 GeV, 354.6 pb^{-1}

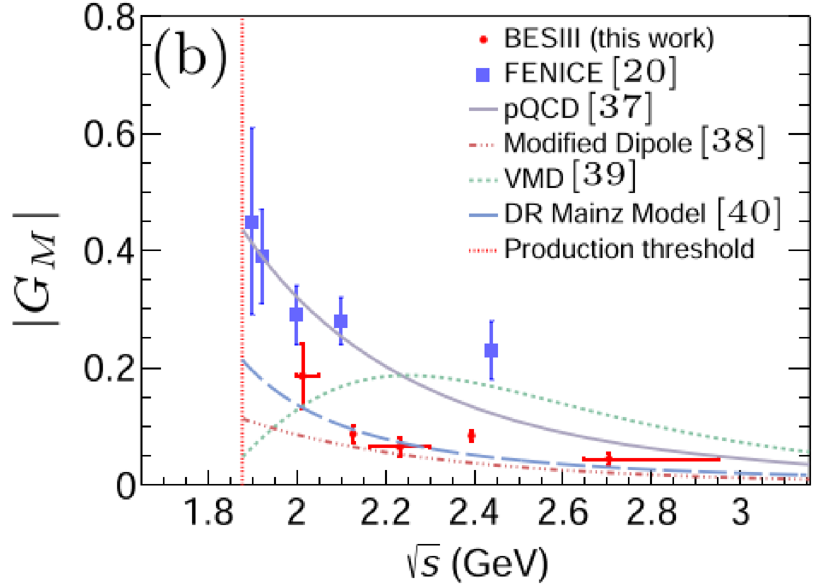
Nucl. Phys. B 517, 3 (1998)

- Compared with the FENICE results, the values for $|G_M|$ from this work are smaller by a factor of 2-3
- Results are compared with various models: pQCD, modified dipole, vector meson dominance (VMD) and dispersion relations (DR)

PRL 130, 151905 (2023)

- DR model gives good consistency





From Nucleon to Hyperon

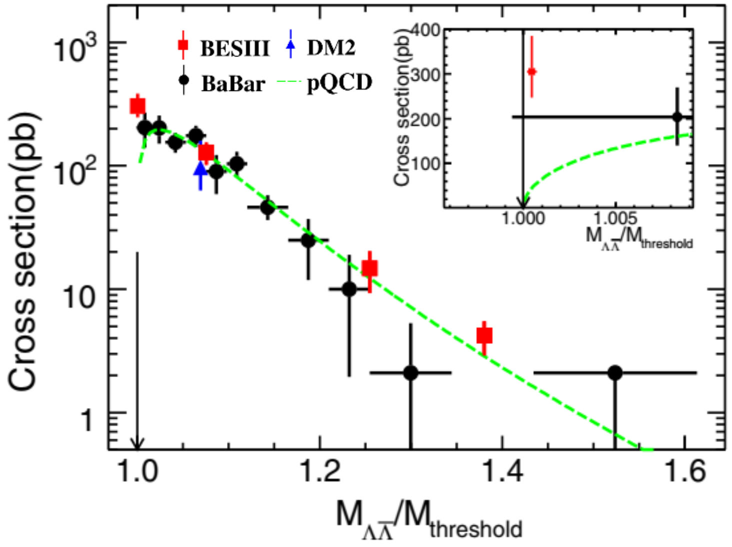
- It is difficult to study EMFFs of hyperons in space-like due to the difficulty in stable and high-quality hyperon beams
- The hyperons can be produced in e^+e^- annihilation above their production threshold
- The angular distribution of daughter baryon from Hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega}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

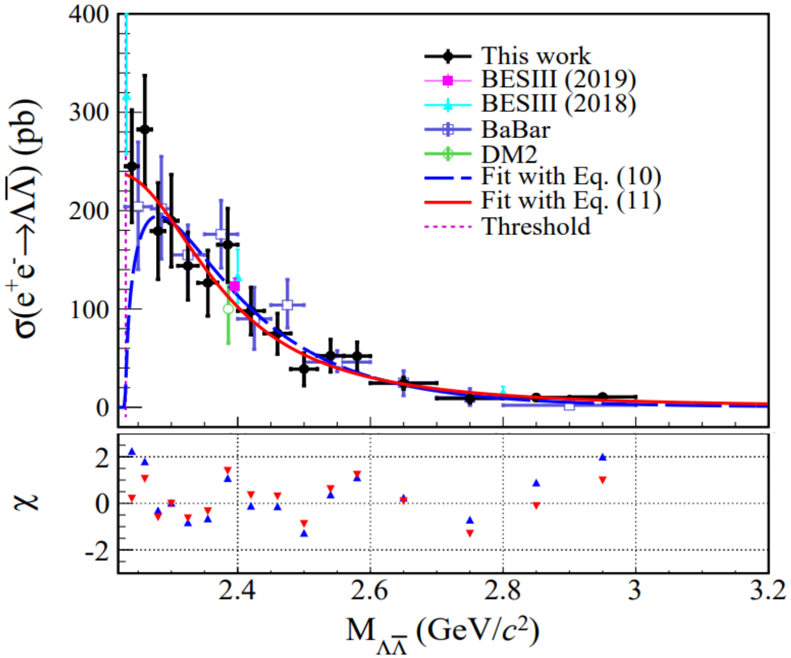
Advantages:

- Cross section can be 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)

Cross Section of $e^+e^- \to \Lambda\bar{\Lambda}$

- Energy Scan Method:
  - 2.2324, 2.400, 2.800 and 3.080 GeV, PRD 97, 032013 (2018)
- ISR Method:
  - LA-ISR: threshold – 3.00 GeV/c^2, PRD 107, 072005 (2023)
  - Data Sets: 3.773 – 4.258 GeV, 11.9 fb^{-1}
- Non-zero cross section near threshold, consistent with BaBar result





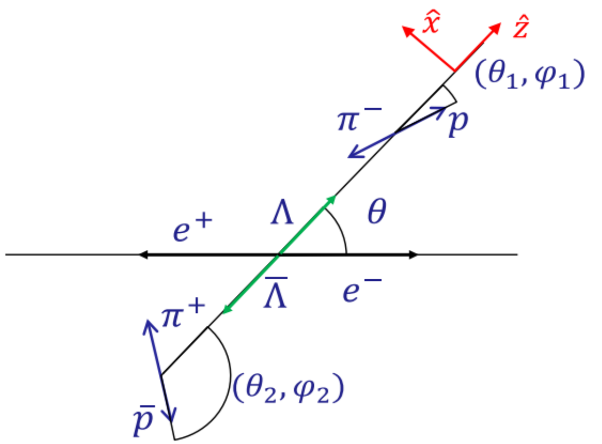
BESIII Scan: $305 \pm 45^{+66}_{-36}$ pb at 2.2324 GeV (~1 MeV above threshold)

BaBar ISR: $204^{+62}_{-60} \pm 22$ pb in [2.23, 2.27] GeV

BESIII ISR: $245 \pm 56 \pm 14$ pb in [2.231, 2.250] GeV

Complete Measurement of Λ EMFFs

- An event of the reaction $e^+e^- \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ is formalized by joint angular distribution:



$$W(\xi) = \mathcal{T}_0 + \eta\mathcal{T}_5$$ Unpolarized part

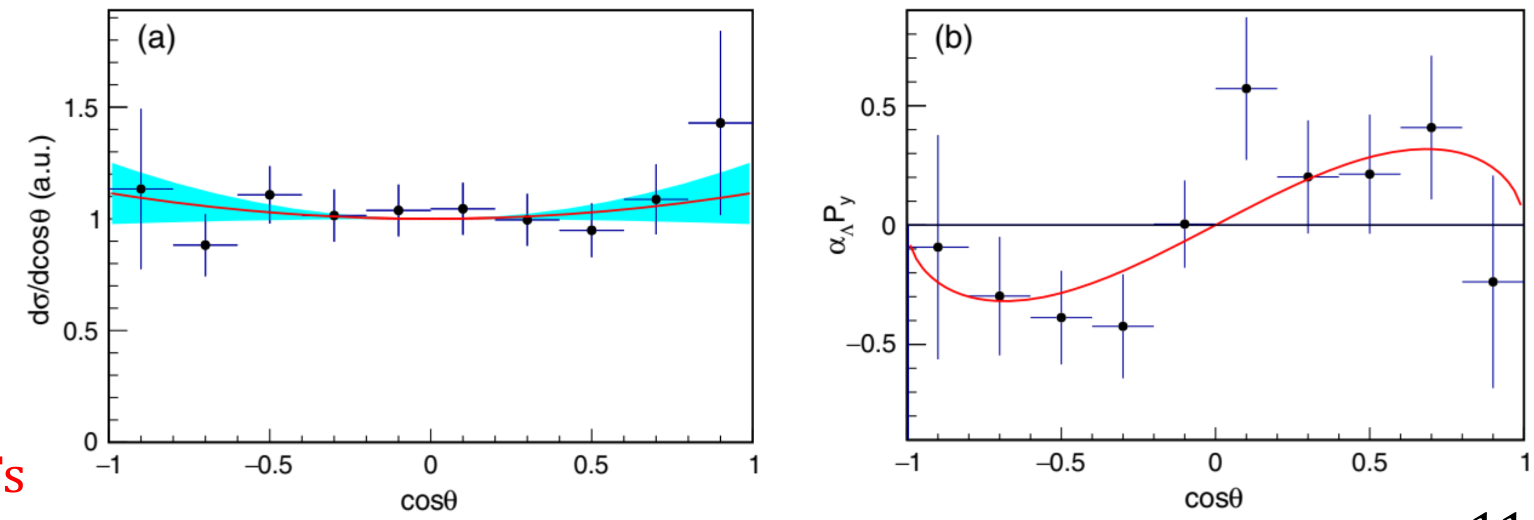
$$-\alpha_\Lambda^2\left[\mathcal{T}_1 + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,\mathcal{T}_2 + \eta\mathcal{T}_6\right]$$ Correlated part

$$+\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)(\mathcal{T}_3 - \mathcal{T}_4)$$ Polarized part

- A nonzero relative phase leads to polarization p_y of the out going baryons:

$$p_y = \frac{\sqrt{1-\eta^2}\sin\theta\cos\theta}{1+\eta\cos^2\theta}\sin(\Delta\Phi)$$

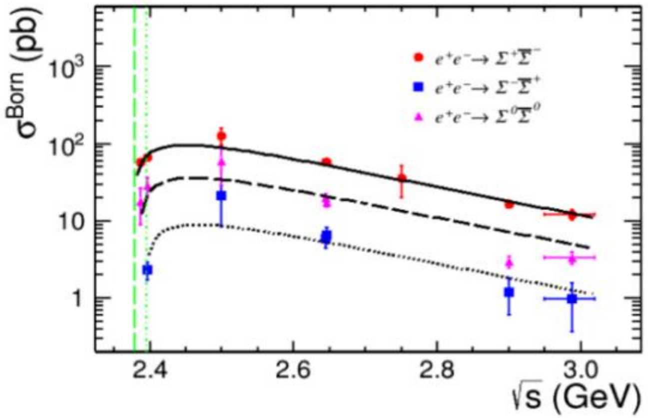
- Data Sets: 2.396 GeV, 66.9 pb^{-1}
- $\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14 \pm 0.02$
- $\Delta\Phi = 37° \pm 12° \pm 6°$
- Confirm the complex form of EMFFs

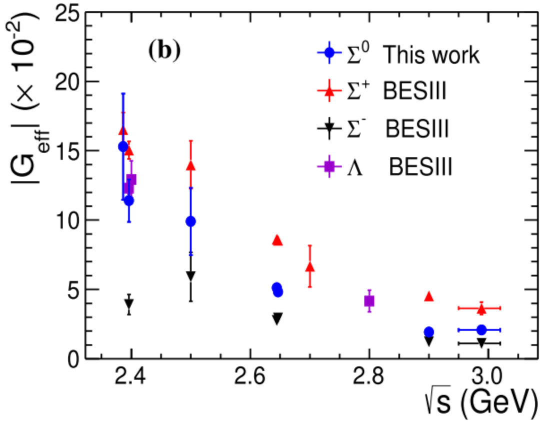


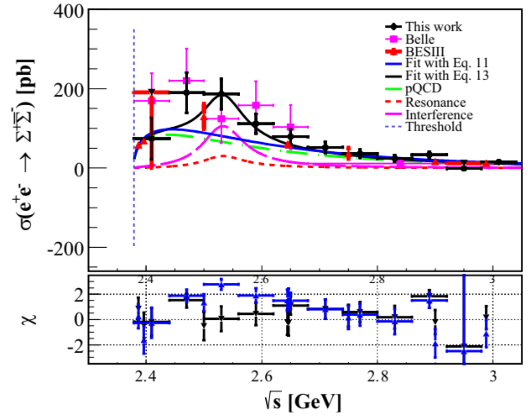
PRL 123, 122003 (2019)

Cross Section of $e^+e^- \to \Sigma\bar{\Sigma}$

- Energy Scan Method: $\Sigma^{\pm}\bar{\Sigma}^{\mp}$: PLB 814, 136110 (2021); $\Sigma^{0}\bar{\Sigma}^{0}$: PLB 831, 137187 (2022)
  - ➢ Born cross section of $e^+e^- \to \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \Sigma^0\bar{\Sigma}^0$ are measured from threshold to 3.02 GeV
  - ➢ The cross section can be well described by pQCD-motivated functions
  - ➢ An asymmetry in cross section for Σ isospin triplets: $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1 \Rightarrow$ related with valence quark?







- ISR Method:
  - ➢ SA-ISR: threshold – 3.04 GeV/c^2, $\Sigma^+\bar{\Sigma}^-$: PRD 109, 034029 (2024)
  - ➢ Data Sets: 3.773 – 4.258 GeV, 11.9 fb^{-1}
- No significant threshold effect is observed

BESIII Scan: $58.2 \pm 5.9^{+2.8}_{-2.6}$ pb at 2.3864 GeV (~1 MeV above threshold) for $\Sigma^+\bar{\Sigma}^-$; $2.3 \pm 0.5 \pm 0.3$ pb at 2.3960 GeV for $\Sigma^-\bar{\Sigma}^+$; $17.6 \pm 8.7 \pm 1.6$ (< 42.4) pb at 2.3864 GeV for $\Sigma^0\bar{\Sigma}^0$

BESIII ISR: $74^{+50}_{-52} \pm 5$ (<190) pb in [2.379, 2.440] GeV for $\Sigma^+\bar{\Sigma}^-$

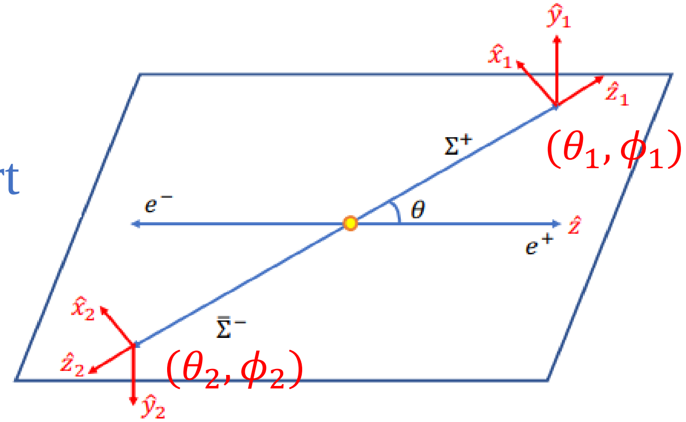
Complete Measurement of Σ^+ EMFFs

- An event of the reaction $e^+e^- \to \Sigma^+(\to p\pi^0)\bar{\Sigma}^-(\to \bar{p}\pi^0)$ is formalized by joint angular distribution:

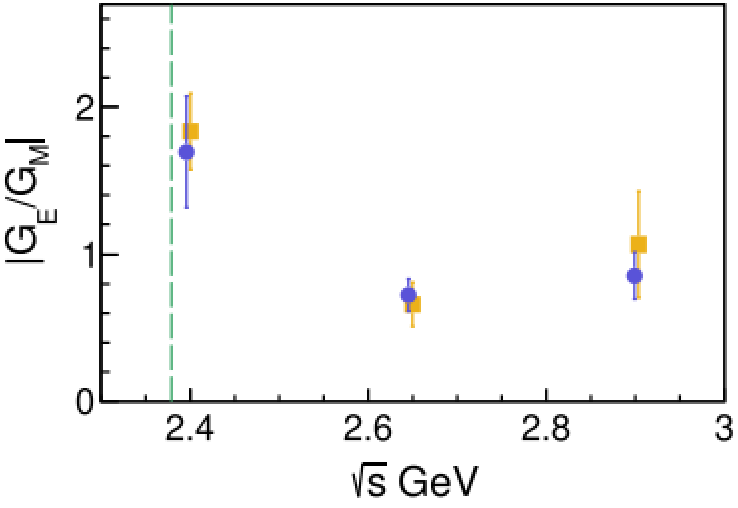
$$W(\xi) \propto \mathcal{F}_0(\xi) + \alpha\mathcal{F}_5(\xi)$$ Unpolarized part

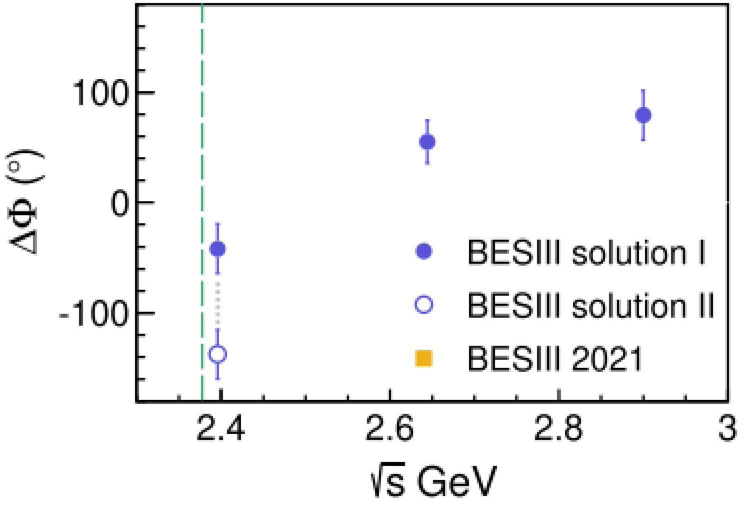
$$+\alpha_1\alpha_2\left[\mathcal{F}_1(\xi) + \sqrt{1-\alpha^2}\cos(\Delta\Phi)\,\mathcal{F}_2(\xi) + \alpha\mathcal{F}_6(\xi)\right]$$ Correlated part

$$+\sqrt{1-\alpha^2}\sin(\Delta\Phi)[-\alpha_1\mathcal{F}_3(\xi) + \alpha_2\mathcal{F}_4(\xi)]$$ Polarized part



- Polarization is observed at 2.3960, 2.6454 and 2.9000 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

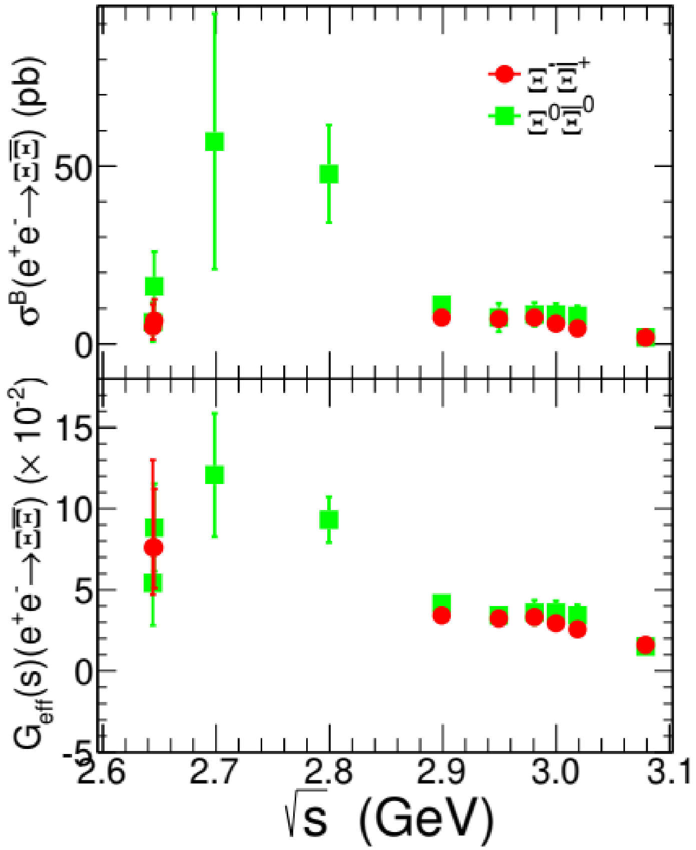


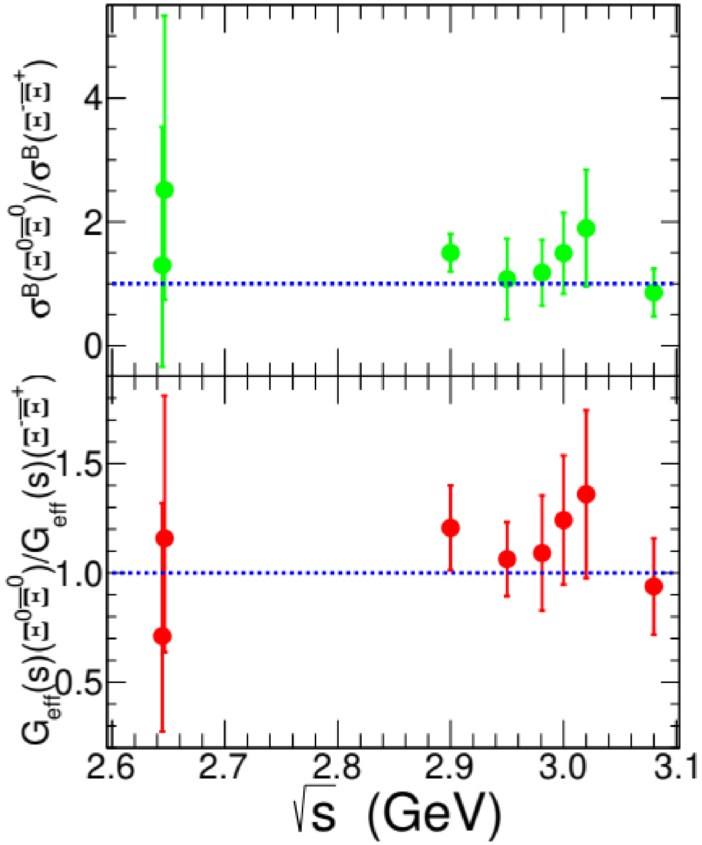


PRL 132, 081904 (2024)

Cross Section of $e^+e^- \to \Xi\bar{\Xi}$

- Born cross section of $e^+e^- \to \Xi^-\bar{\Xi}^+, \Xi^0\bar{\Xi}^0$ are measured from threshold to 3.08 GeV
  - ➢ No significant threshold effect is observed
  - ➢ The ratio of Born cross sections and $|G_{\rm eff}|$ for both modes are within 1σ of the expectation of isospin symmetry





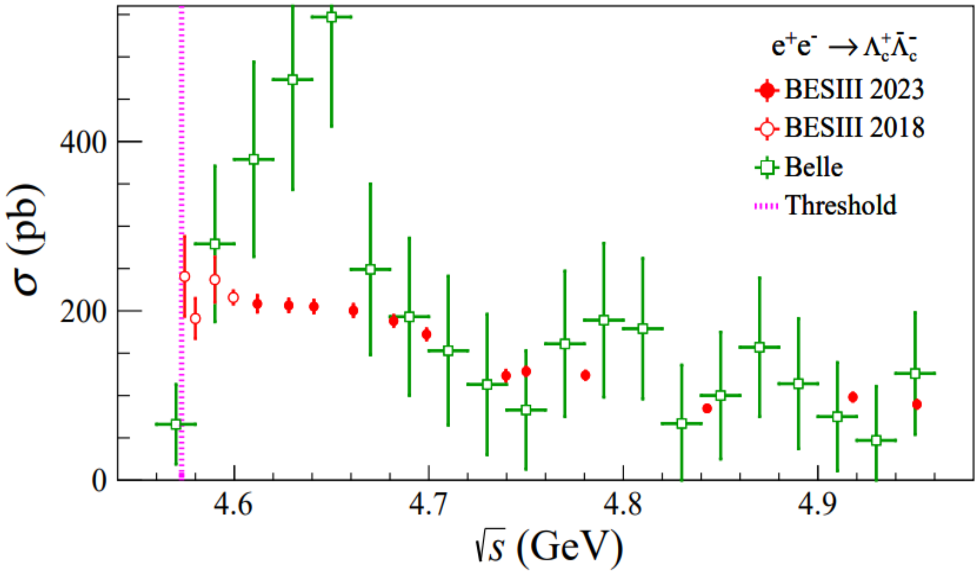
$\Xi^-\bar{\Xi}^+$: PRD 103, 012005 (2021)
$\Xi^0\bar{\Xi}^0$: PLB 820, 136557 (2021)

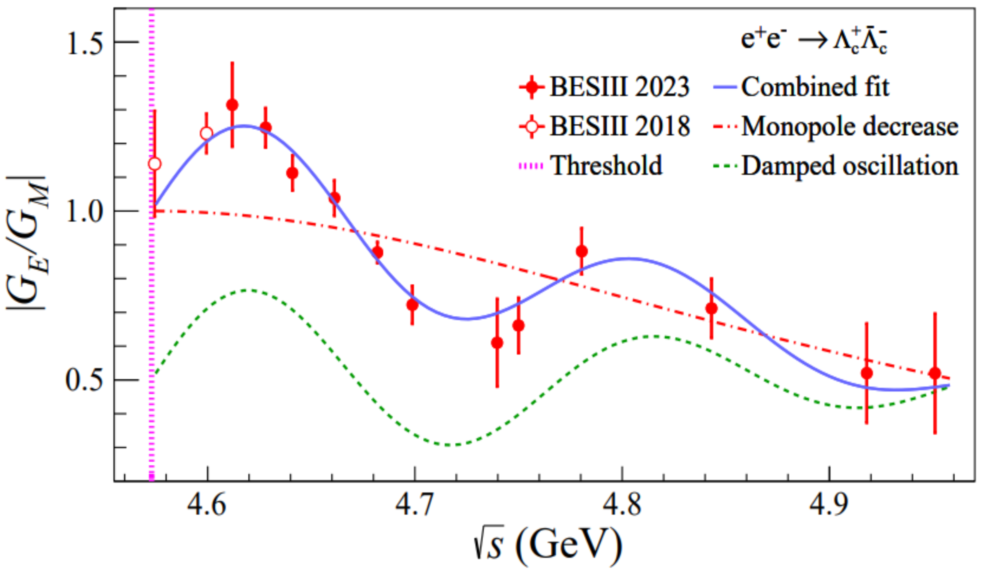
Cross Section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- Measurements of cross section and $|G_E/G_M|$ with high accuracy are performed, $4.5745 - 4.9509$ GeV
- Enhanced cross section near threshold: $236 \pm 11 \pm 46$ pb at 4.5745 GeV (1.6 MeV above threshold)
- Flat cross sections around 4.63 GeV are obtained ⇒ indicate no enhancement around the $Y(4630)$ resonance, which is different from Belle
- No oscillatory behavior is discerned in $|G_{\text{eff}}|$ spectrum of Λ_c^+, in contrast to the case for proton and neutron

PRL 131, 191901 (2023); PRL 120, 132001 (2018)

- An oscillation behavior is observed in the energy dependence of $|G_E/G_M|$

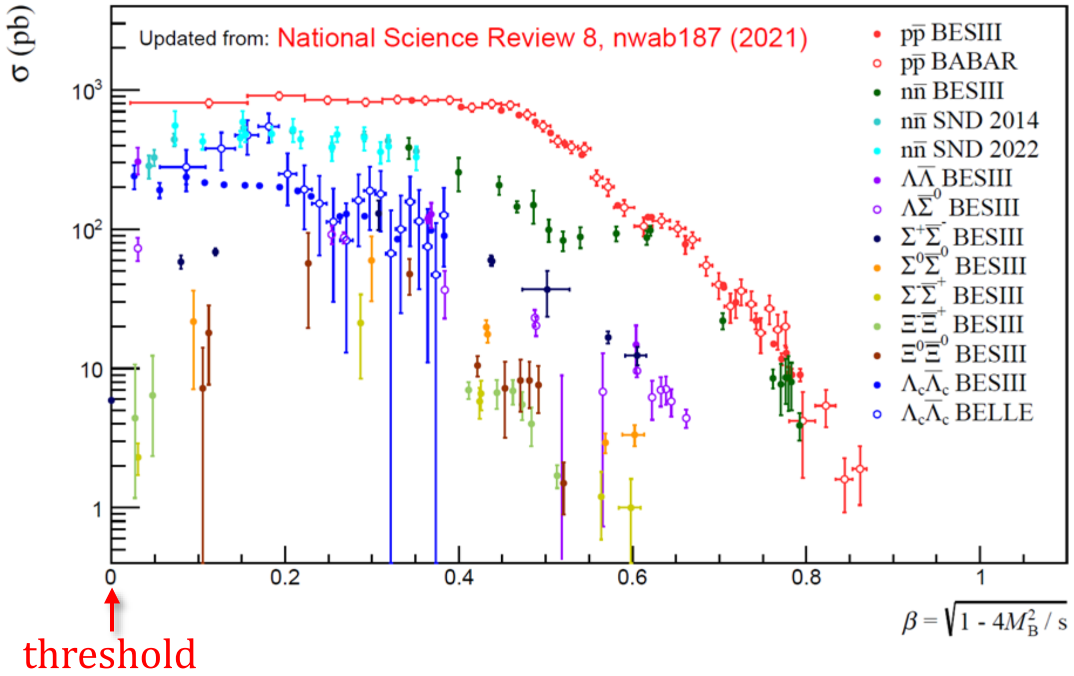




Summary

- Fruitful physics 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!



Back up

Neutron

$$G_{\rm osc}(q^2) = |G| - G_{\rm D}$$

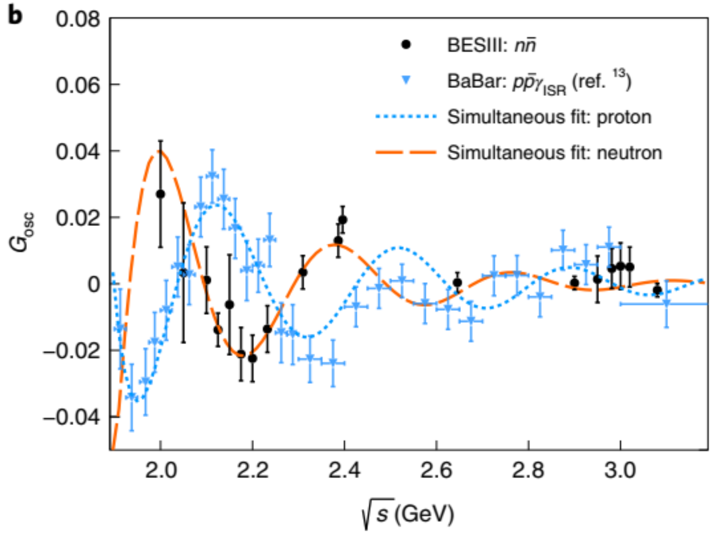
The well-established dipole formula $G_{\rm D}(q^2) \equiv G_{\rm D}$, $G_{\rm D}(q^2) = \frac{\mathcal{A}_n}{\left(1-\frac{q^2}{0.71(GeV^2)}\right)^2}$ with $\mathcal{A}_n = 3.5 \pm 0.1$, a normalization factor

The $G_{\rm osc}(q^2)$ values for both neutron and proton can be simultaneously fitted by the function $F_{\rm osc}$ of the relative momentum p with a common momentum frequency C.

$$F_{\rm osc}^{n,p} = A^{n,p} \exp(-B^{n,p} p) \cos(Cp + D^{n,p}), p \equiv \sqrt{E^2 - m_{n,p}^2}, E \equiv \frac{q^2}{2m_{n,p}} - m_{n,p}$$

Phys. Rev. Lett. 114, 232301 (2015)

$$\Delta D = |D_p - D_n| = (125 \pm 12)^\circ$$



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

- pQCD inspired model parametrization: $|G_E(q^2)| = |G_M(q^2)| = \frac{C}{q^4\left[\ln\left(\frac{q^4}{\Lambda^2_{QCD}}\right)+\pi^2\right]}$

Neutron

- DR model: Dispersion-theoretical approach denoted as the "Mainz model", based on the Vector-Meson Dominance (VMD), using isoscalar and isovector components of the nucleon form factors to decompose the neutron and proton FFs in their isospin components to distinguish the contributions from isoscalar and isovector vector mesons.

$$F_1(q^2) = F_1^V(q^2) + F_1^S(q^2)$$
$$F_2(q^2) = F_2^V(q^2) + F_2^S(q^2)$$

With this approach the Mainz model describes the electric and magnetic Sachs form factors as:

$$\mathrm{F}_i^{IS}(q^2) = \left[\sum_m \frac{a_{i,m}^{IS} L^{-1}(m_m^{IS})^2}{(m_m^{IS})^2 - q^2}\right] L(q^2)$$

$$\mathrm{F}_i^{IV}(q^2) = \left[F_i^{\rho}(q^2)L(q^2) + \sum_{m\neq\rho} \frac{a_{i,m}^{IV} L^{-1}(m_m^{IV})^2}{(m_m^{IV})^2 - q^2}\right] L(q^2)$$

with the function $L(q^2)$:

$$L(q^2) = \left[\ln\left(\frac{\Lambda^2 - q^2}{Q_0^2}\right)\right]^{-\gamma}$$

Modified Dipole prediction - Phys. Lett. B 504 (2001)
pQCD prediction - Phys. Rev. Lett. 79 (1997).
DR prediction from *Mainz Model* - Phys. Lett. B 385 (1996)
modified VMD IJL prediction - Phys. Rev. C 69 (2004)

- The modified VMD model: intrinsic FF $g(q^2) = \frac{1}{(1-\gamma e^{i\theta} q^2)^2}$

$$D_\rho^{-1}(q^2) = \frac{m_\rho^2 + 8\Gamma_\rho m_\pi/\pi}{m_\rho^2 - q^2 + (4m_\pi^2 - q^2)\Gamma_\rho \alpha(q^2)/m_\pi + i\Gamma_\rho 4m_\pi \beta(q^2)}$$

$$\alpha(q^2) = \frac{2}{\pi}\sqrt{\frac{q^2 - 4m_\pi^2}{q^2}} \ln\left[\frac{\sqrt{q^2 - 4m_\pi^2} + \sqrt{-q^2}}{2m_\pi}\right],$$

$$\beta(q^2) = \begin{cases} \left[\frac{\left(\frac{q^2}{4m_\pi^2}-1\right)^3}{\frac{q^2}{4m_\pi^2}}\right]^{1/2} & \text{for } q^2 \geq 4m_\pi^2 \\ 0 & \text{for } q^2 < 4m_\pi^2 \end{cases}$$

$$F_1^V(q^2) = \tfrac{1}{2}g(q^2)\left(1 - \beta_\rho + \frac{\beta_\rho}{D_\rho(q^2)}\right), \qquad F_2^V(q^2) = \tfrac{1}{2}g(q^2)\left(\frac{3.706}{D_\rho(q^2)}\right)$$

$$F_1^S(q^2) = \tfrac{1}{2}g(q^2)\left((1 - \beta_\omega - \beta_\phi) - \beta_\omega \frac{m_\omega^2}{m_\omega^2 + q^2} - \beta_\phi \frac{m_\phi^2}{m_\phi^2 + q^2}\right)$$

$$F_2^S(q^2) = \tfrac{1}{2}g(q^2)\left((-0.120 - \alpha_\phi)\frac{m_\omega^2}{m_\omega^2 + q^2} + \alpha_\phi \frac{m_\phi^2}{m_\phi^2 + q^2}\right)$$

Λ

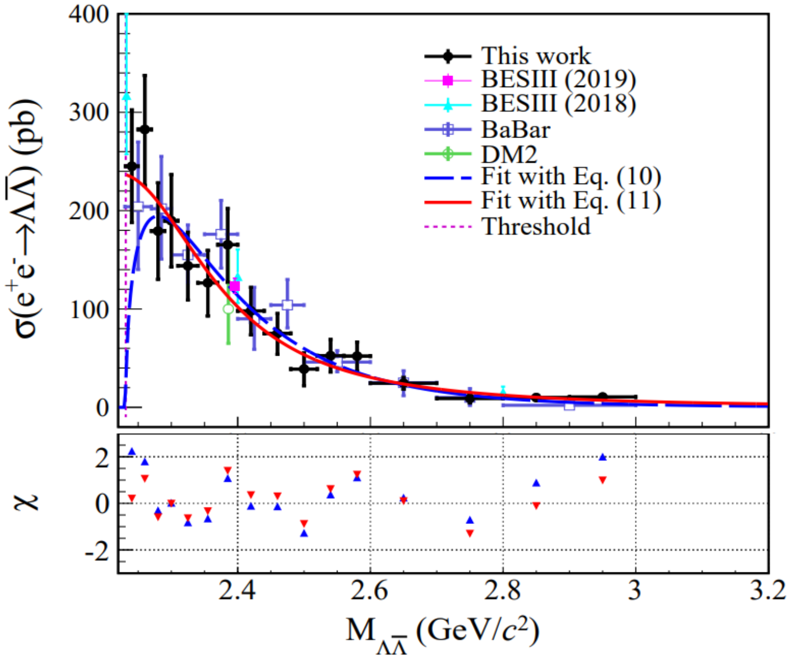
- A model inspired by the perturbative QCD has been tried (blue dashed line in figure): $$\sigma(s)=\frac{c_0\cdot\beta(s)\cdot C}{(\sqrt{s}-c_1)^{10}}$$ Phys. Rep. 550. 1 (2015)

- A model assuming a step exists near the threshold has been tried too (red solid line in figure): PRL 124. 042001 (2020) $$\sigma(s)=\frac{e^{a_0}\pi^2\alpha^3}{s[1-e^{-\pi\alpha_s/\beta}]\left[1+\left(\frac{\sqrt{s}-2m_\Lambda}{a_1}\right)^{a_2}\right]}$$

- joint angular distribution

The angular distribution parameter $\eta=\frac{\tau-R^2}{\tau+R^2}$ with $\tau=\frac{s}{4m_B^2}$

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



Σ

- pQCD-motivated functions (Eq. 11):

$$\sigma^{\mathrm{B}}(s) = \frac{\beta C}{s}\left(1 + \frac{2m_B^2}{s}\right)\frac{c_0}{(s-c_1)^4\left(\pi^2 + \ln^2\left(s/\Lambda_{\mathrm{QCD}}^2\right)\right)^2},$$

- pQCD-motivated as continuum contribution and a vector meson (Eq. 13):

$$\sigma_{Y\bar{Y}}(s) = \left|\sqrt{\frac{C\beta}{s}\left(1+\frac{2M_Y^2}{s}\right)\frac{c_0}{(s-c_1)^4[\pi^2+\ln^2(s/\Lambda_{\mathrm{QCD}}^2)]^2}} + e^{i\phi}BW(s)\sqrt{\frac{P(s)}{P(M)}}\right|^2. \qquad (13)$$

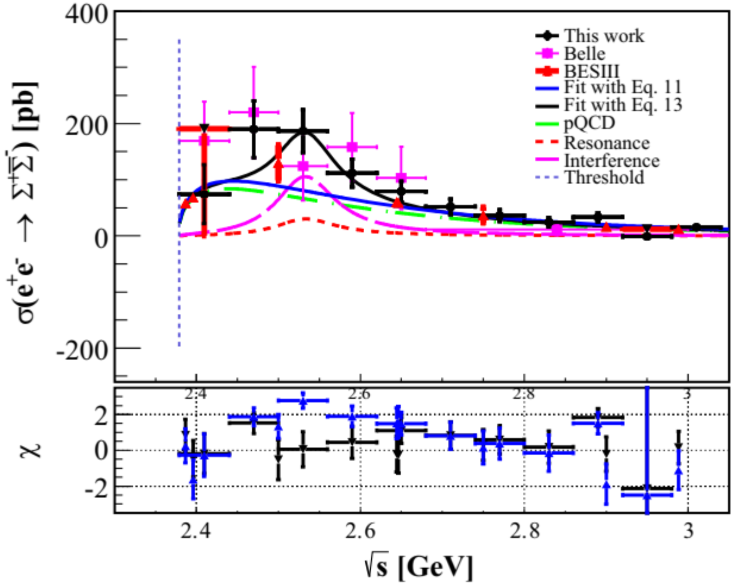
- joint angular distribution

The angular distribution parameter $\alpha = \frac{\tau - R^2}{\tau + R^2}$ with $\tau = \frac{s}{4m_B^2}$

α_1 and α_2 are the decay asymmetry parameters of the Σ^+ and $\bar{\Sigma}^-$

Owing to limited statistics, we assume CP to be conserved and $\alpha_1 = -\alpha_2 = -0.980$

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



- An asymmetry in results is observed for the Σ isospin triplet, with the Σ^+ results lying above the Σ^0 results which in turn are higher than the Σ^- results.

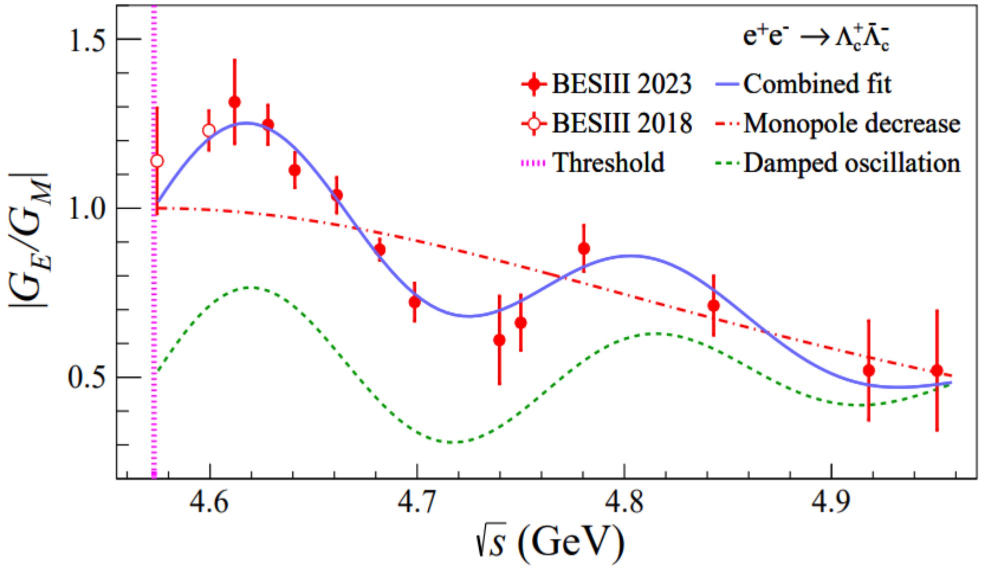
This behavior confirms the hypothesis that the effective FF is proportional to $\sum_q Q_q^2$ with $q = u, d, s$ quarks.

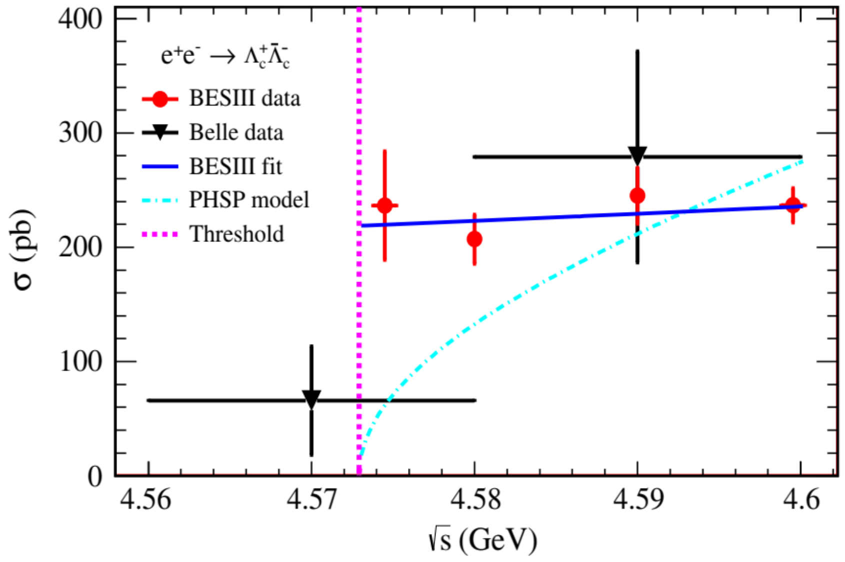
Λ_c

- Fitting with a function combining the monopole decrease with a damped oscillation

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

- The oscillation frequency is determined to be $r_3 = (32 \pm 1)\ \mathrm{GeV}^{-1}$, which is about 3.5 times greater than that measured for the proton





$$\sigma_{B\bar{B}}(s) = \frac{4\pi\alpha^2 C\beta}{3s}|G_M(s)|^2\left(1 + \frac{2m_B^2c^4}{s}\left|\frac{G_E(s)}{G_M(s)}\right|^2\right). \quad (1)$$

FIG. 2. Cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ obtained by BESIII (this work) and Belle. The blue solid curve represents the input line shape for KKMC when determining the $f_{\rm ISR}$. The dash-dotted cyan curve denotes the prediction of the phase-space (PHSP) model, which is parametrized by Eq. (1), but with $C = 1$ and flat $|G_M|$ with respect to $\sqrt{s}$.

- Interaction of final states, lead to a non-zero cross section for charged baryon at threshold (Andrei D Sakharov *Sov. Phys. Usp.* **34** 375(1991))