Recent results of Baryon electromagnetic form factors at BESIII

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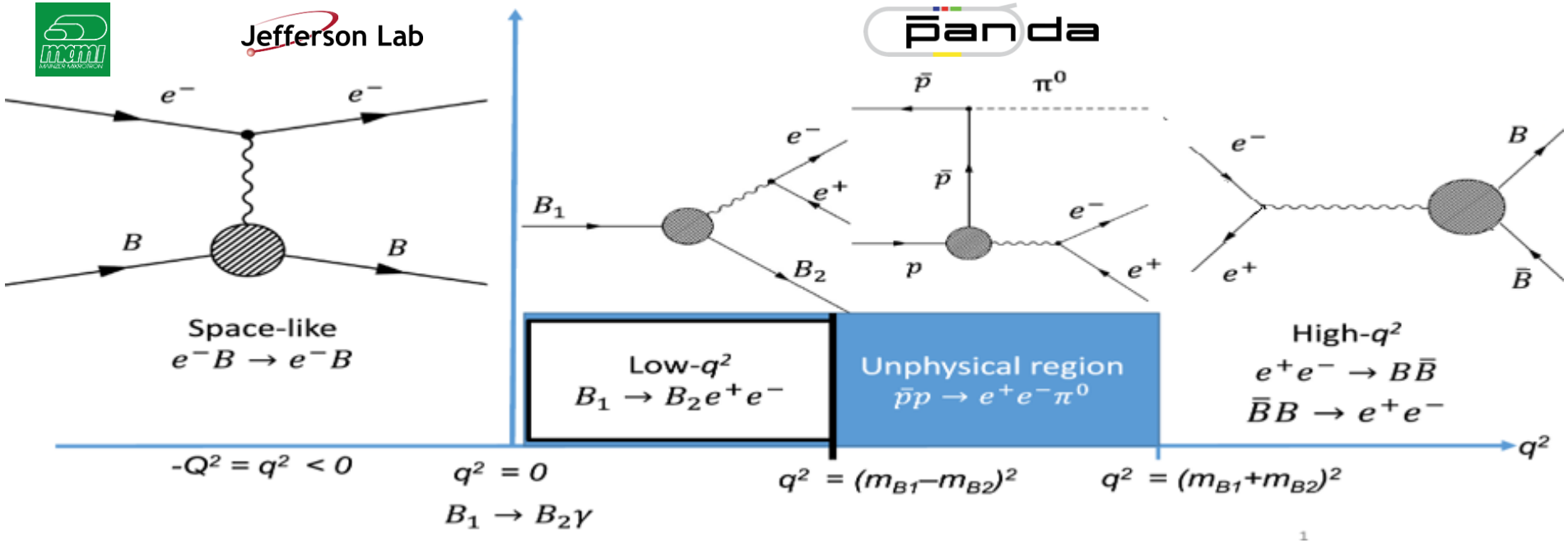
(On behalf of BESIII Collaboration)

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

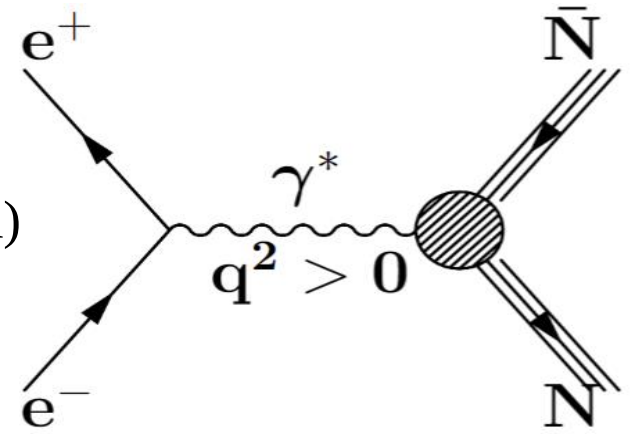
1961, first paper by N. Cabibbo and R. Gatto *Phys.Rev.* 124 (1961) 1577-1595

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

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

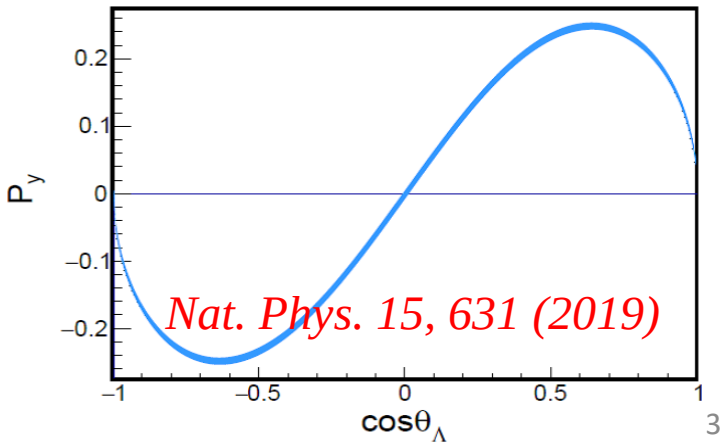
Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ (Born cross section)

$$\xrightarrow{|G_E|=|G_M|} \sigma_{B\bar{B}} = \frac{2\pi\alpha^2 C\beta}{q^2}|G_{\text{eff}}|^2$$



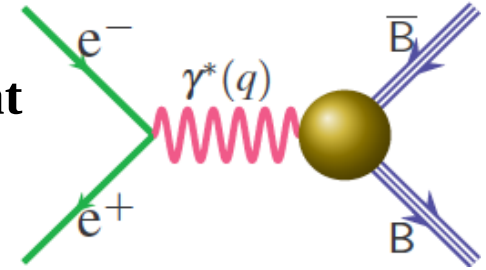
- The complex feature of TLFF leads to transversely polarized baryon even the beams are unpolarized. *Nuov Cim A* **109**, 241–256 (1996)

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



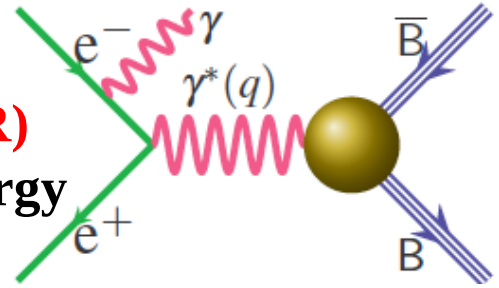
Time-like EMFFs: experiment review

- **Energy scan method at discrete c.m.energies**



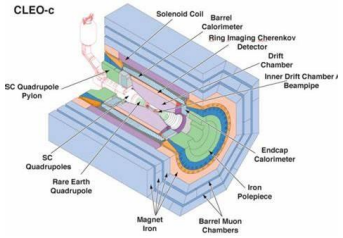
  - Well-defined c.m.energy, low background
  - Very good energy resolution
  - Discrete values, leaving gaps without information

- **Initial state radiation (ISR) method at a fixed c.m.energy**

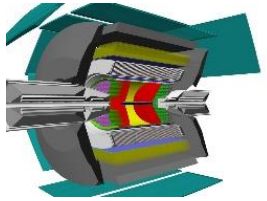


  - At a fixed c.m.energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
  - Systematic uncertainty in a coherent way
  - Large luminosity needed
  - Higher background

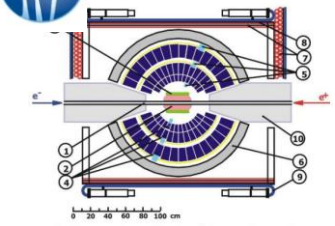
CLEO-c



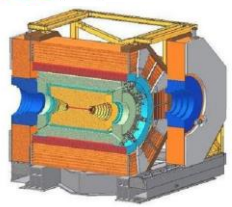
CMD-3



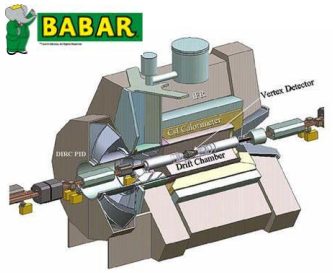
SND

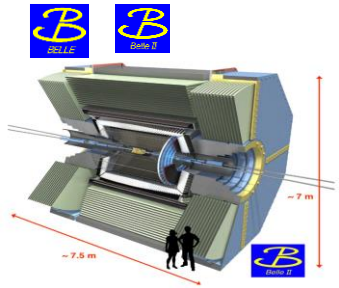


BESIII

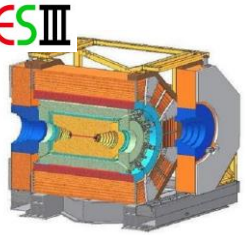


BABAR



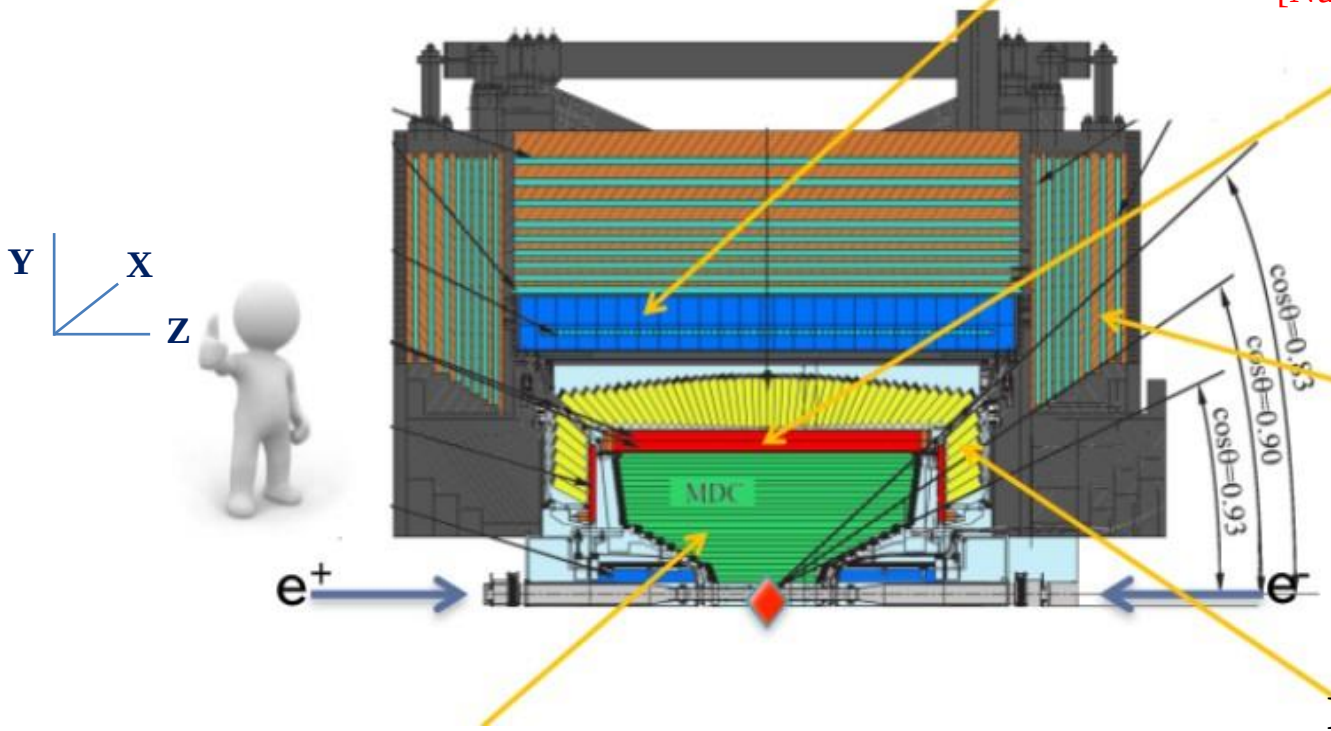


BESIII



BESIII Experiment

BESIII experiment is based on a symmetric electron positron collider running at the tau-charm region (2.00-4.95 GeV).



Super conducting magnet

✓ **1 Tesla**

[Nucl. Instrum. Meth. A614, 345-399 (2010)]

Time of Flight (TOF)

- **2 layer plastic scintillators**
- **$\sigma_T \approx 68$ ps (barrel)**
- **$\sigma_T \approx 110$ ps (endcap) (~65 ps after upgrade of MRPC)**
- **Particle id**

Muon system

- **9 layers of RPC**
- **P > 400 MeV/c**
- **$\delta R\phi \approx 1.4 – 1.7$ cm**

Multilayer drift chamber (MDC)

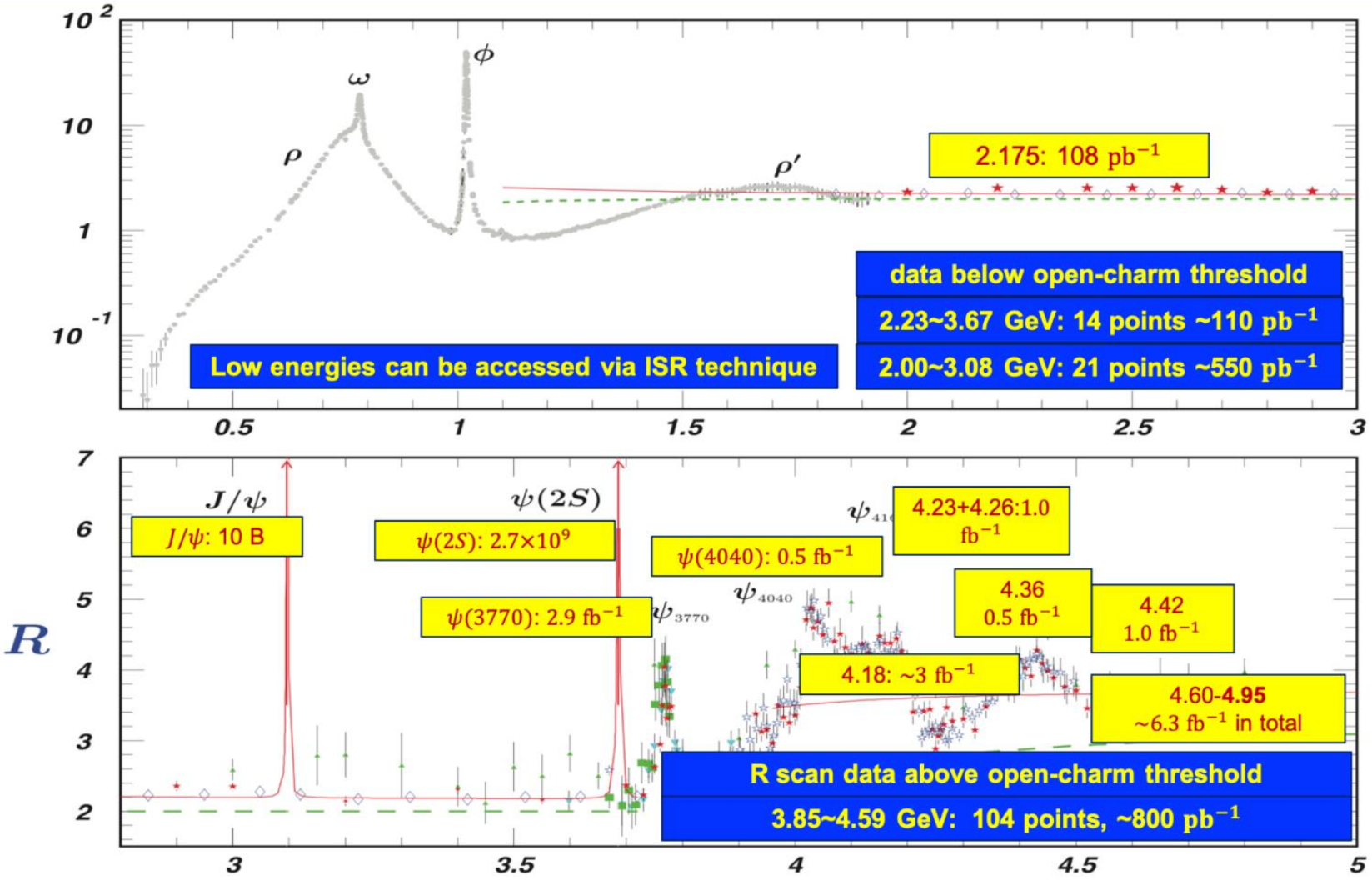
- **He/C_3H_8 (60/40)**
- **43 layers**
- **Momentum resolution $\sigma_p/p \approx 0.5\%$ @ 1 GeV**
- **Spatial resolution $\sigma_{xy} \approx 130$ μm.**

Electromagnetic calorimeter (EMC) (CsI(Tl))

→ 6240 crystals overall

- **$\sigma(E)/E \approx 2.5\%$**
- **$\sigma_{Z,\phi}(E) \approx 0.5 – 0.7$ cm**

BESIII Dataset

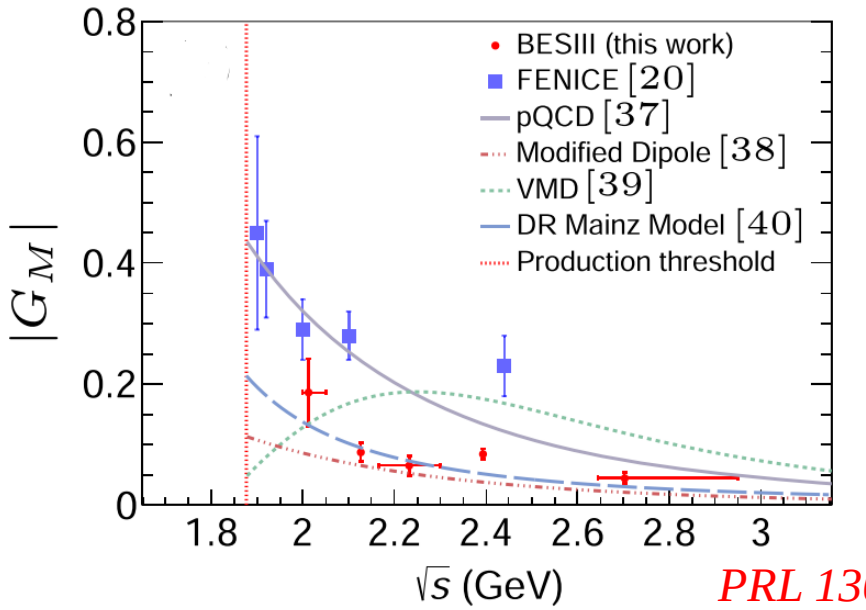


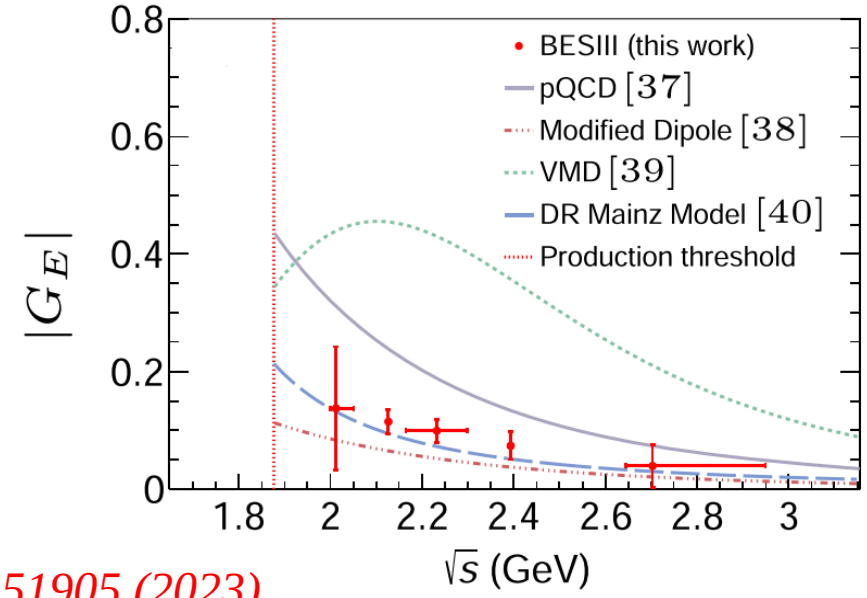
World largest data in tau-charm region

- ✓ Charmonium spectroscopy
- ✓ Charm physics
- ✓ Light hadrons
- ✓ New physics search
- ✓ **Ideal ground to study the Baryon EMFFs with both energy scan and ISR methods!**

Recent results of neutron EMFFs

- $|G_E|$, $|G_M|$ of neutron are measured separately at $\sqrt{s}$ = 2.0-2.95 GeV.
- Compared with the FENICE results, the values for $|G_M|$ from this work are smaller by a factor of 2-3. *Nucl. Phys. B517, 3 (1998)*
- Results are compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR), and DR model gives good consistency.





PRL 130, 151905 (2023)

Measurement of Hyperons FFs

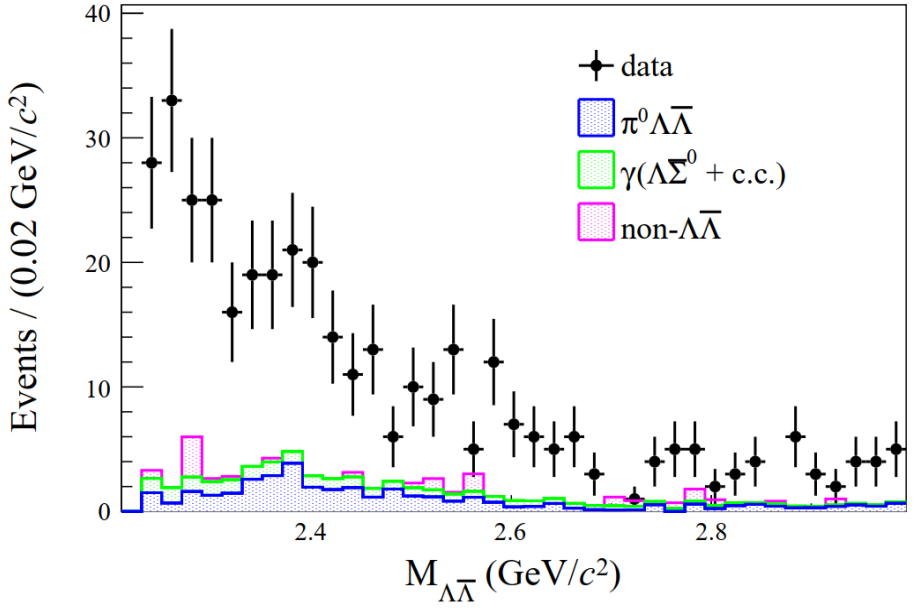
- It is difficult to study EMFFs of hyperons in space-like due to the difficulty in stable and high-quality hyperon beams.
- The hyperons can be produced in e^+e^- annihilation above their production threshold.
- The angular distribution of daughter baryon from Hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega}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

Advantages:

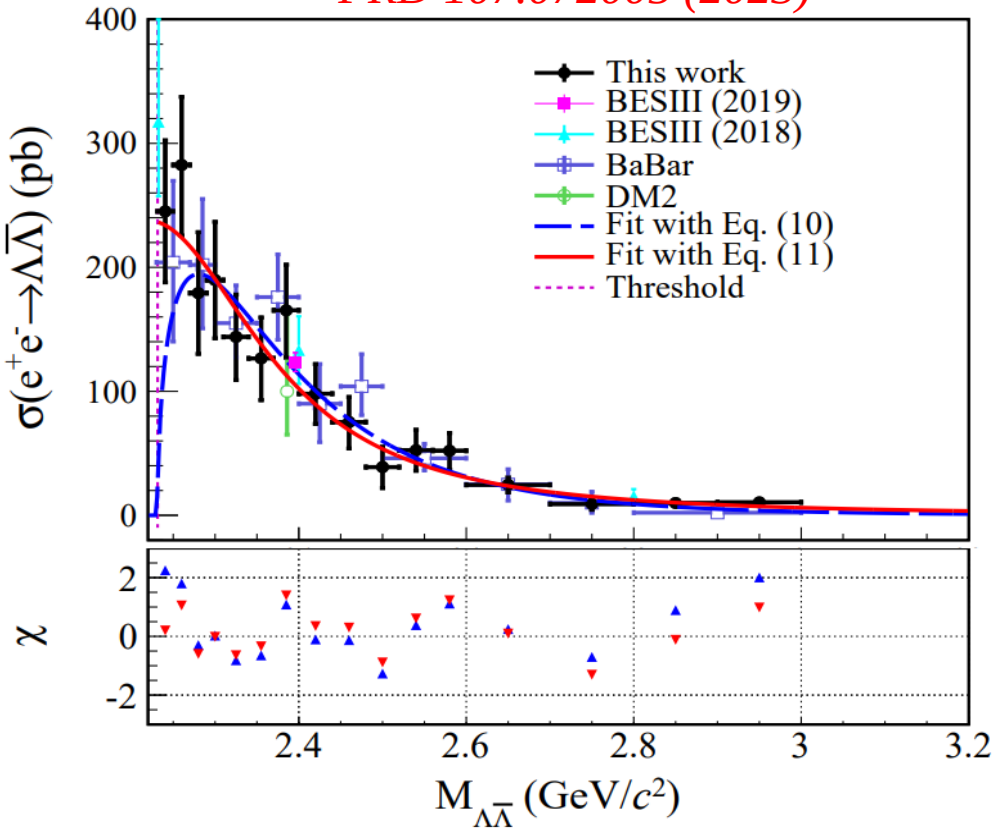
- Cross section can be obtained very close to threshold with finite PHSP of final state.
- With hyperon weak decay to B+P, the polarization of hyperon can be measured, so does the relative phase between G_E and G_M! (Of course, enough statistics needed)

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

- Cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ is measured with 11.9 fb^{-1} data collected at $\sqrt{s} = 3.773$ to 4.258 GeV by ISR method.
- The non-zero cross section near threshold is consistent with previous measurement.



PRD 107.072005 (2023)



BESIII scan: $312 \pm 45^{+66}_{-36}$ 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

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

- A study of the cross section line shape to search for the source of the non-zero cross section has been performed.

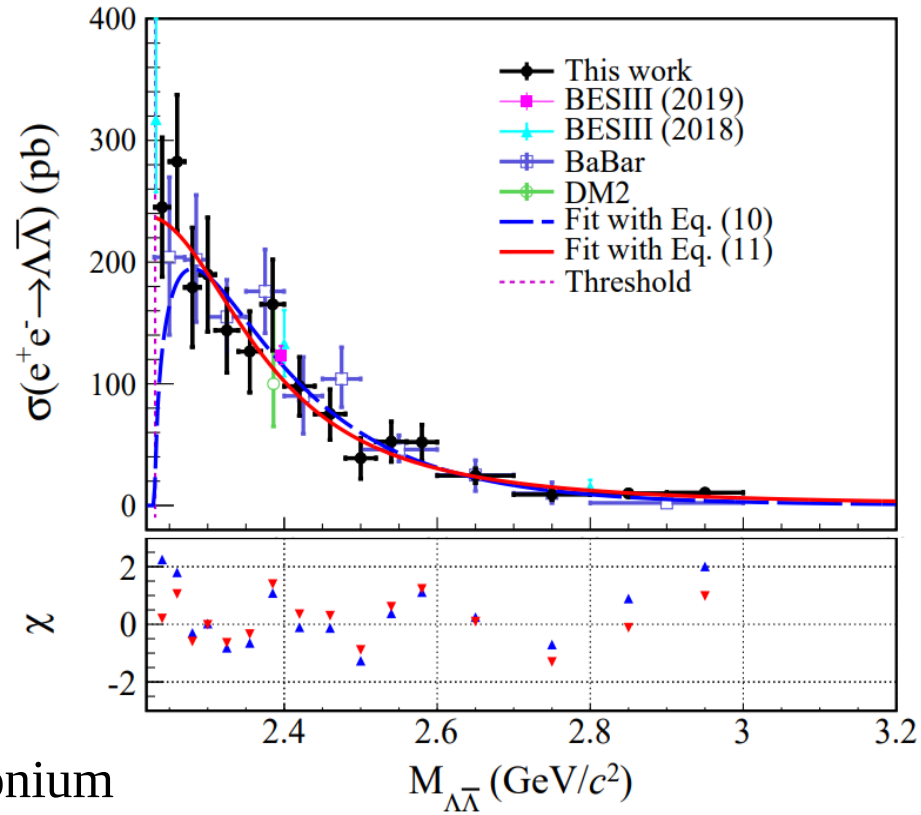
PRD 107.072005 (2023)

- A model inspired by the perturbative QCD has been tried (blue dashed line in figure): *Phys. Rep. 550.1 (2015)*

$$\sigma(s) = \frac{c_0 \cdot \beta(s) \cdot C}{(\sqrt{s} - c_1)^{10}}$$

- A model assuming a step exists near the threshold has been tried too (red solid line in figure): *PRL 124. 042001 (2020)*

$$\sigma(s) = \frac{e^{a_0}\pi^2\alpha^3}{s[1 - e^{-\pi\alpha_s/\beta}]\left[1 + \left(\frac{\sqrt{s} - 2m_\Lambda}{a_1}\right)^{a_2}\right]}$$

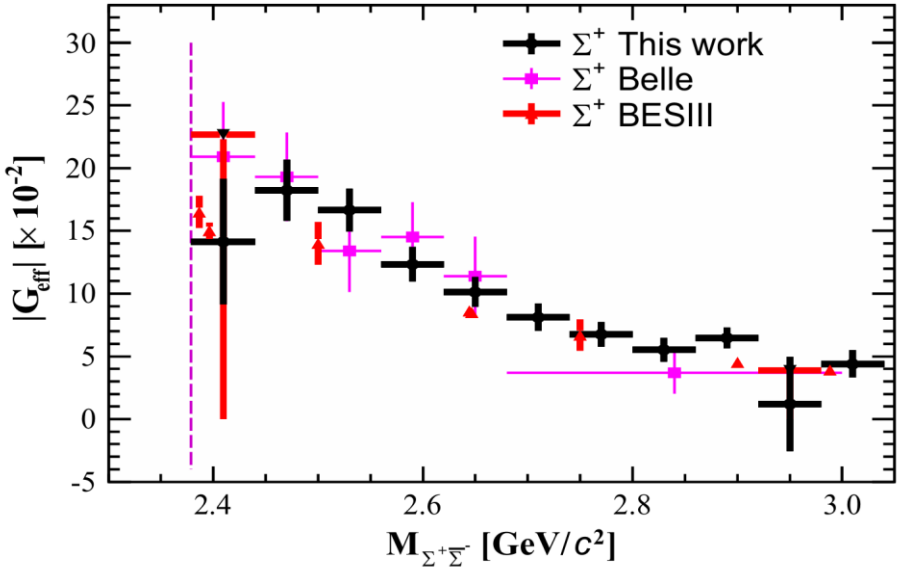


- The latter gives a better description of the cross section.
- Some theorists think there are contributions of higher strangeonium decays ($\phi(4S)$, $\phi(3D)$) to the $\Lambda\bar{\Lambda}$ pair around 2.4-2.6 GeV.

PRD 108. 094036 (2023)

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

- Cross section and effective FF are measured with 11.9 fb^{-1} data collected at $\sqrt{s} = 3.773$ to 4.258 GeV by ISR method.
- The non-zero cross section near threshold is consistent with previous measurement.

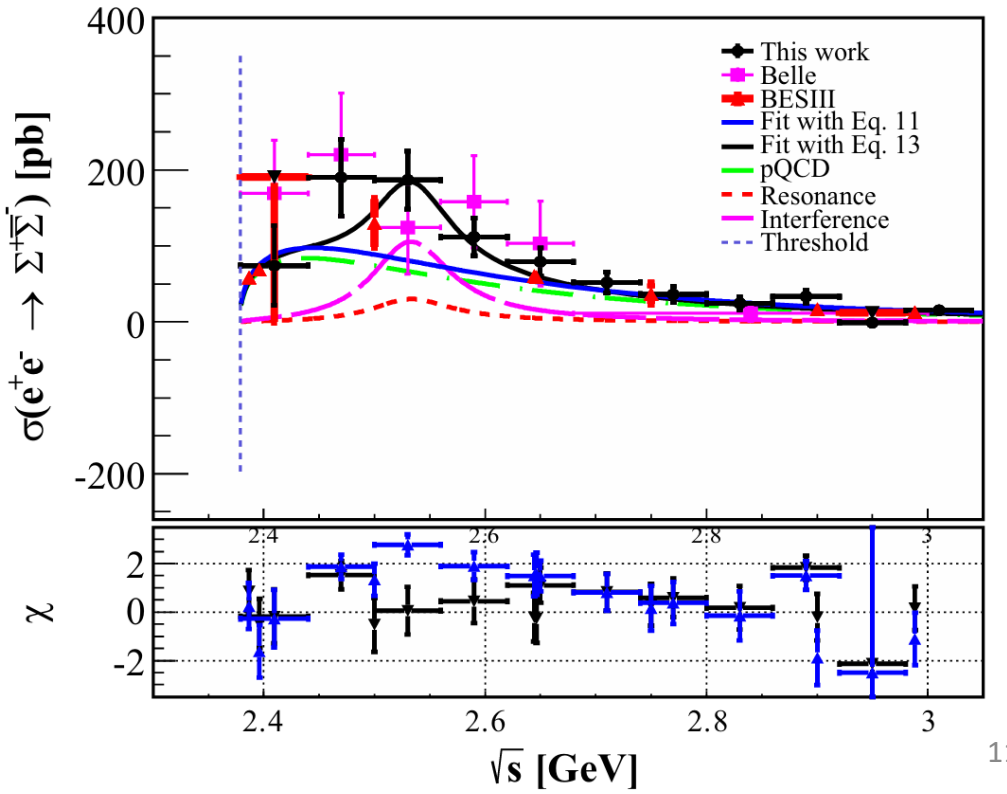


BESIII scan: $58 \pm 6^{+2.8}_{-2.6}$ pb at 2.3864 GeV (~1 MeV above threshold)

Belle ISR: $169 \pm 64 \pm 27$pb in [2.379, 2.440] GeV

BESIII ISR: $74^{+50}_{-52} \pm 5$ pb in [2.379, 2.440] GeV

PRD 109, 034029 (2024)



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

- A study of the cross section line shape has been performed.

- A model inspired by the perturbative QCD has been tried (blue line in figure): *Phys. Rep. 550.1 (2015)*

$$\sigma(s) = \frac{c_0 \cdot \beta(s) \cdot C}{(\sqrt{s} - c_1)^{10}}$$

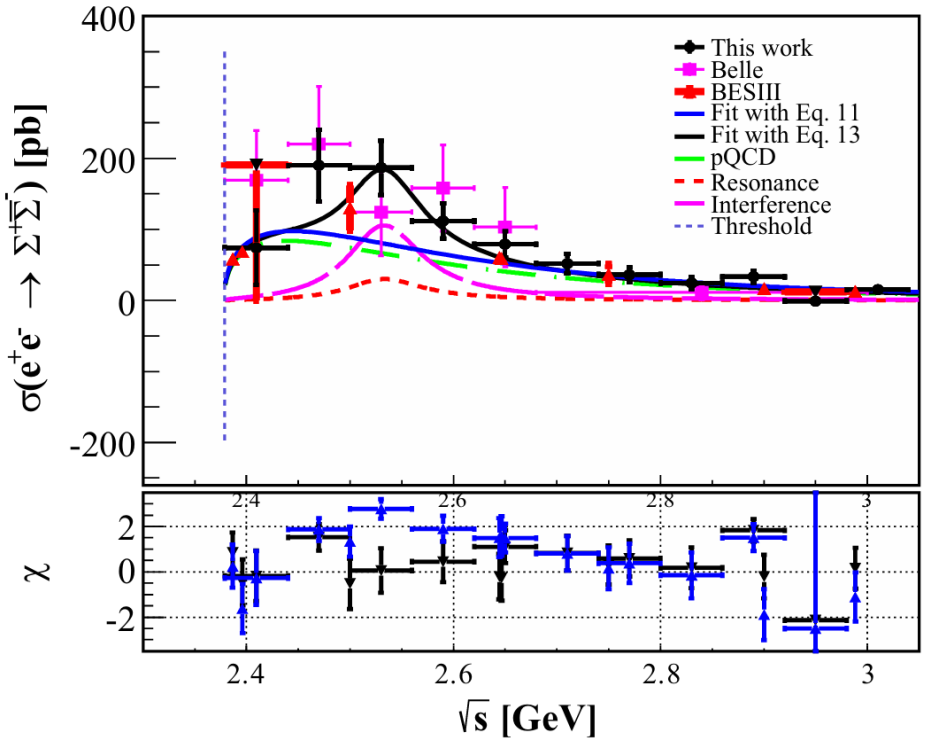
- A model assuming a resonance exists based on the pQCD is tried (black line in figure):

$$\sigma(s) = \left| \sqrt{\frac{c_0 \cdot \beta(s) \cdot C}{(\sqrt{s} - c_1)^{10}}} + e^{i\phi} BW(s) \sqrt{\frac{P(s)}{P(M)}} \right|^2,$$

where $BW(s) = \frac{\sqrt{12\pi\Gamma^{ee}\mathrm{B}\Gamma}}{s^2 - M^2 + iM}$

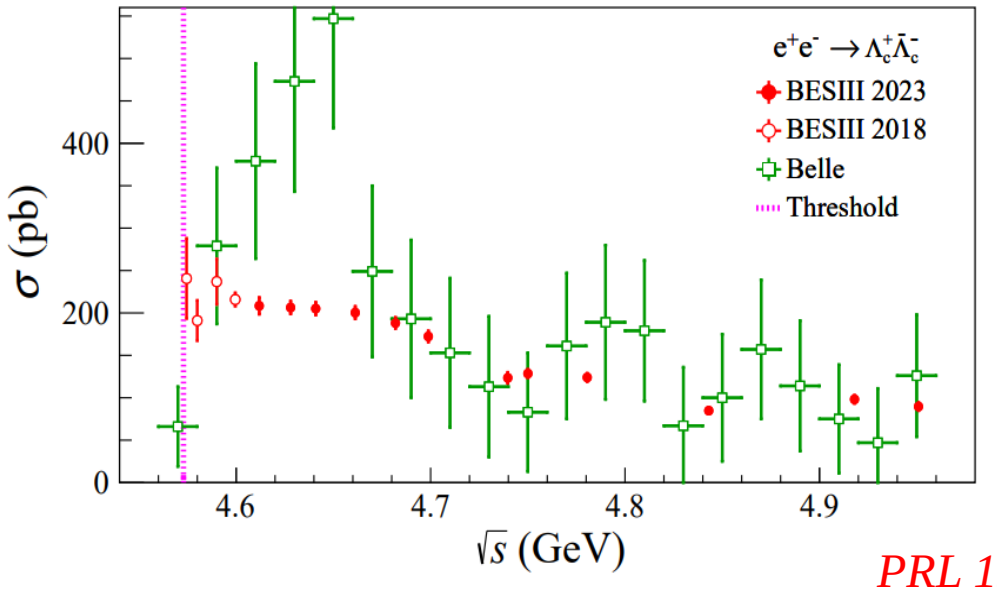
- The latter gives a better description of the cross section, a resonance state is proved to exist at around 2.5 GeV with a significance of 3.4σ.

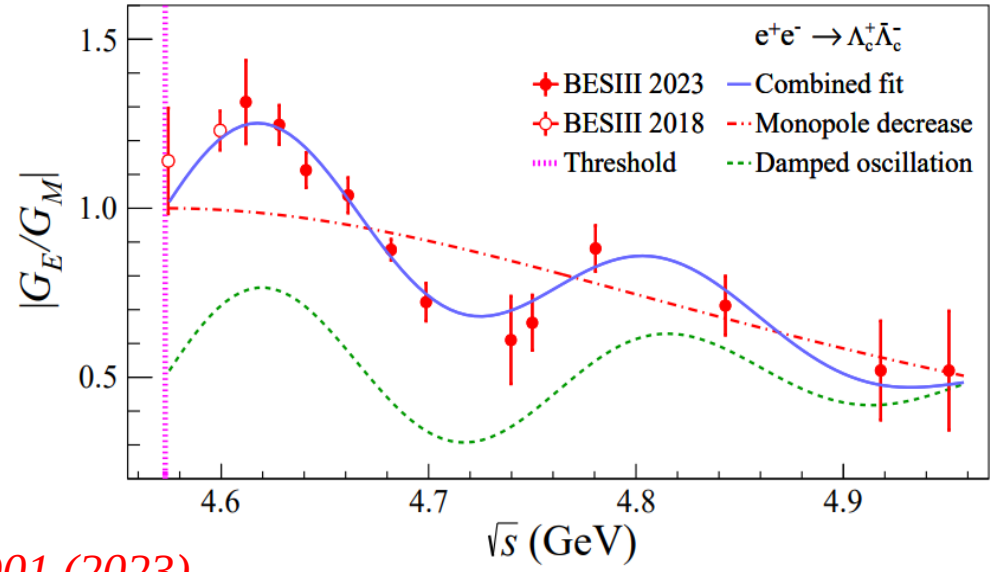
PRD 109, 034029 (2024)



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

- Measurements of cross section, $|G_E|$, $|G_M|$, and their ratio are performed at $\sqrt{s}$ = 4.64-4.95 GeV.
- Flat cross sections around 4.63 GeV are obtained and no indication of the resonant structure Y (4630), as reported by Belle, is found.
- An oscillation behavior is observed in the energy dependence of $|G_E|/|G_M|$, for the first time.

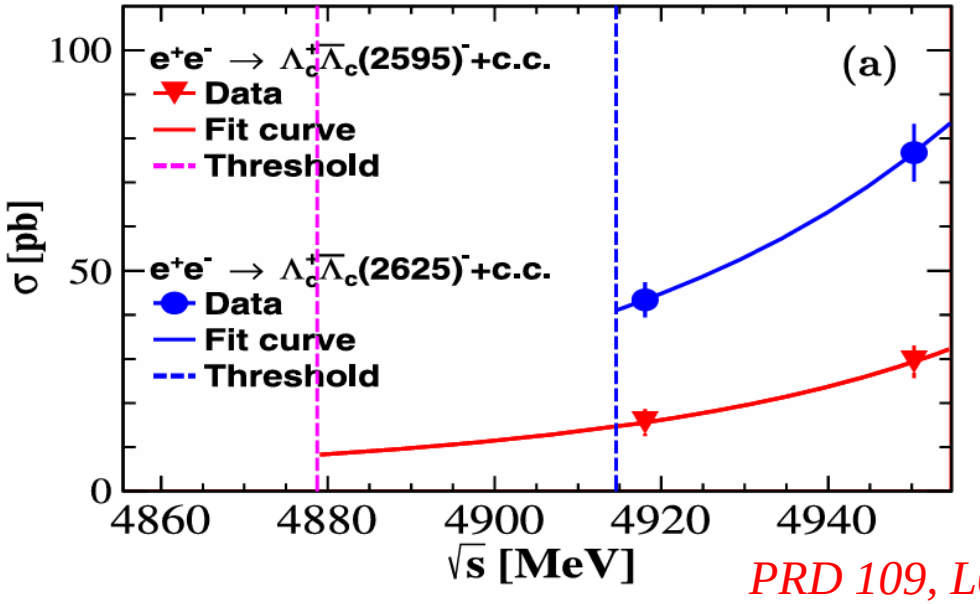


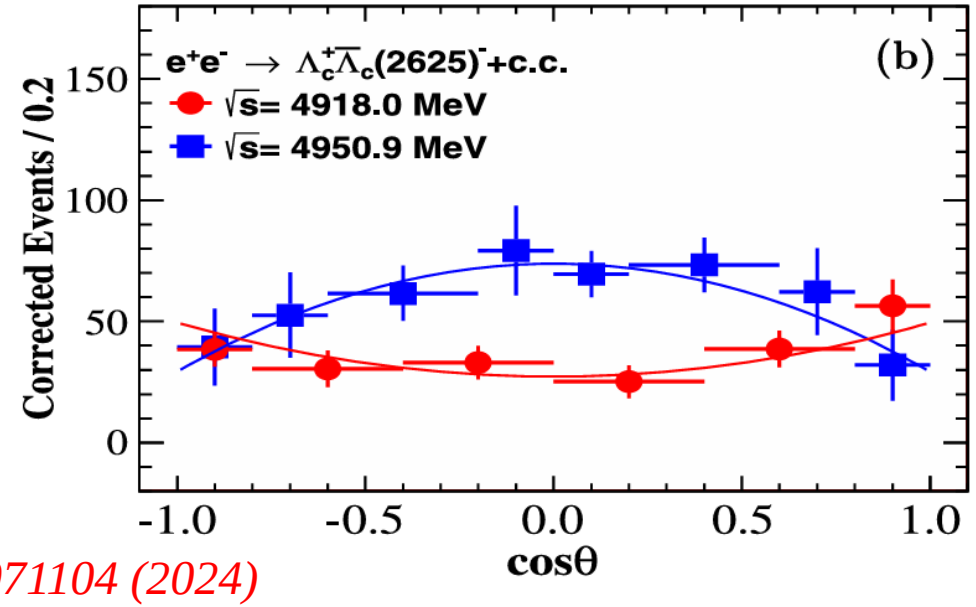


PRL 131, 191901 (2023)

Cross section of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^{-*} + \text{c.c.}$

- Cross sections of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c(2595)^- + c.\text{c.}$ and $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c(2625)^- + c.\text{c.}$ are measured for the first time at 4.92 and 4.95 GeV.
- The angular distribution parameter α_{Λ_c} and FF ratio $\sqrt{|G_E|^2 + |G_M|^2}/|G_C|$ for $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c(2625)^- + c.\text{c.}$ are extracted for the first time by studying the angular distributions of baryon in final state. *PRD 16, 2165 (1977)*
- The non-zero cross sections are observed close to threshold and are fitted by pQCD model.





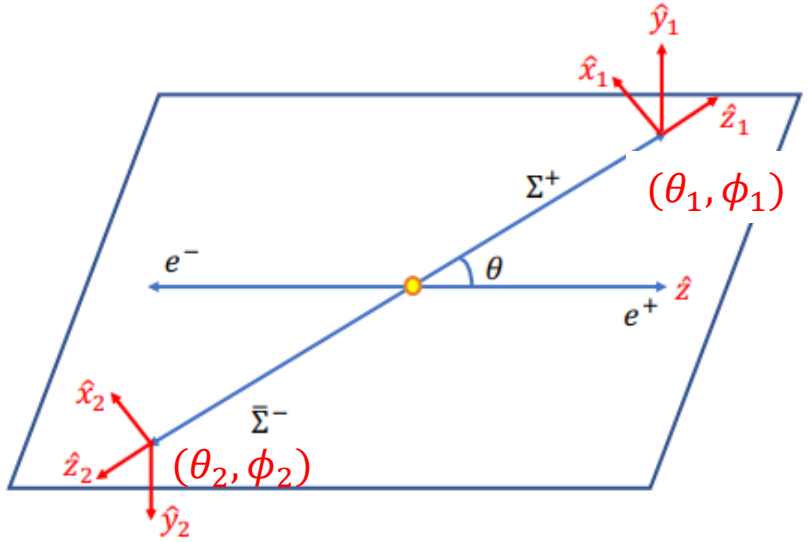
PRD 109, L071104 (2024)

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:

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

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

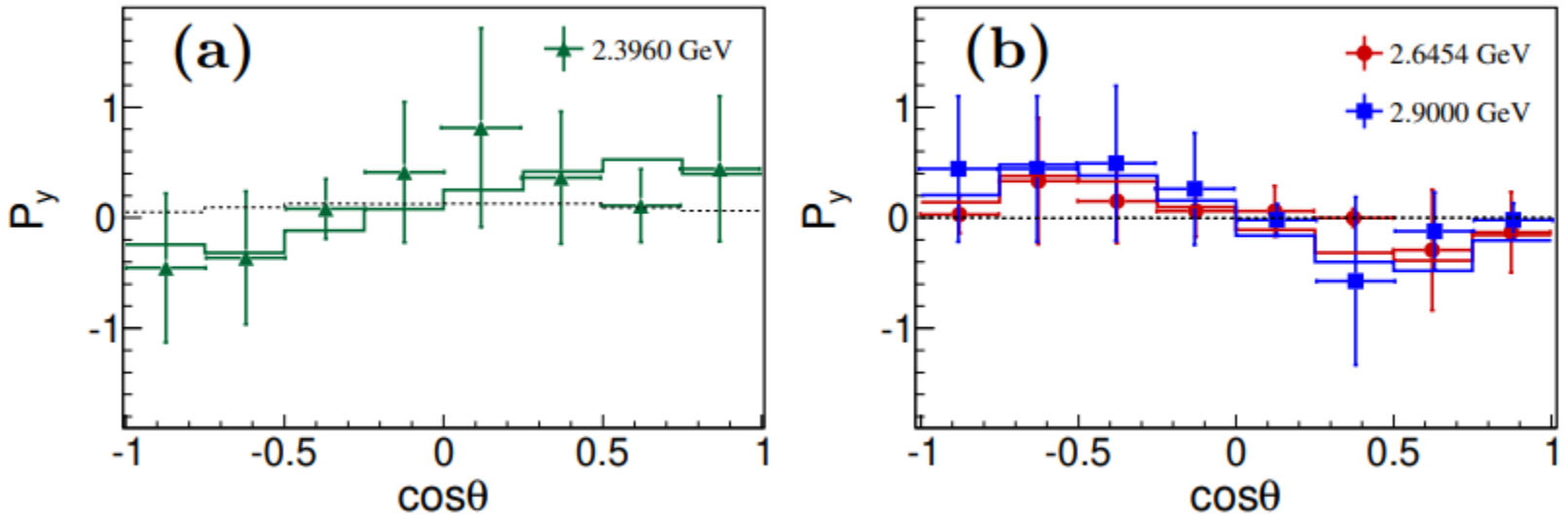


- A nonzero relative phase leads to polarization p_y of the out going baryons:

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

Complete measurement of Σ^+ EMFFs

- Polarization is observed at $\sqrt{s}$ =2.396, 2.645 and 2.900 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.

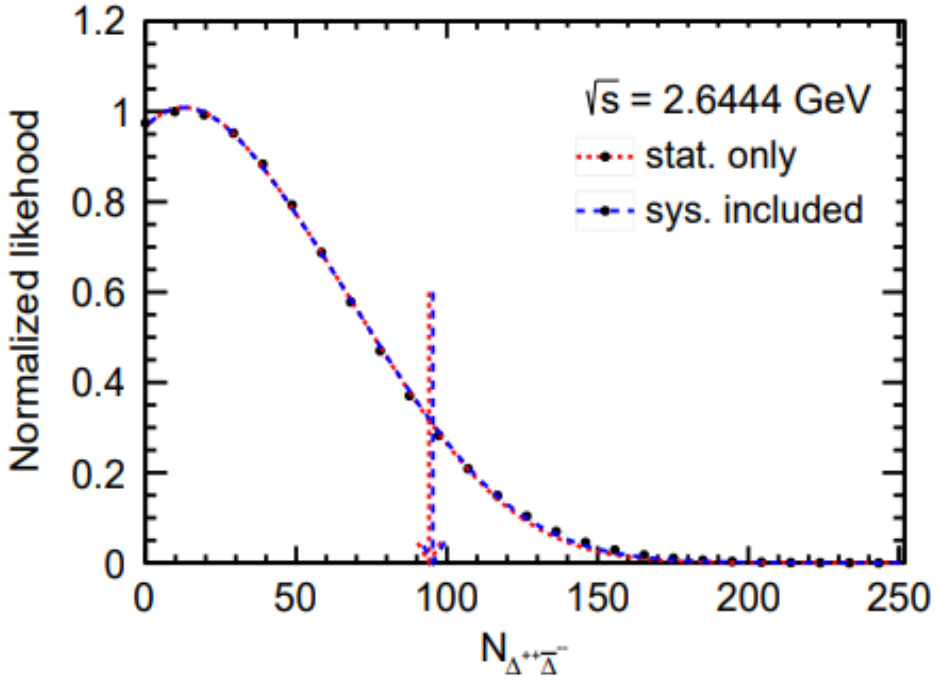


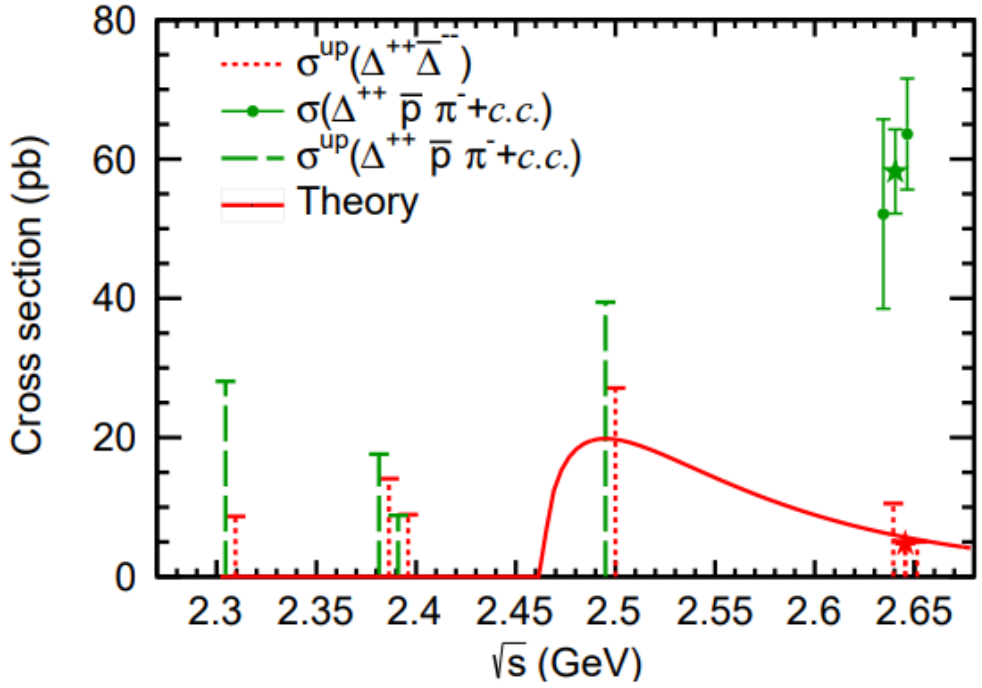
PRL 132, 081904 (2024)

Study of the spin 3/2 baryons: $e^+e^- \to \Delta\bar{\Delta}$

- $e^+e^- \to \Delta^{++}\bar{\Delta}^{--}$ is searched at $\sqrt{s} = 2.3094$-2.6464 GeV.

➢ No significant signal observed, but signal for $e^+e^- \to \Delta^{++}p\pi^-$ observed.

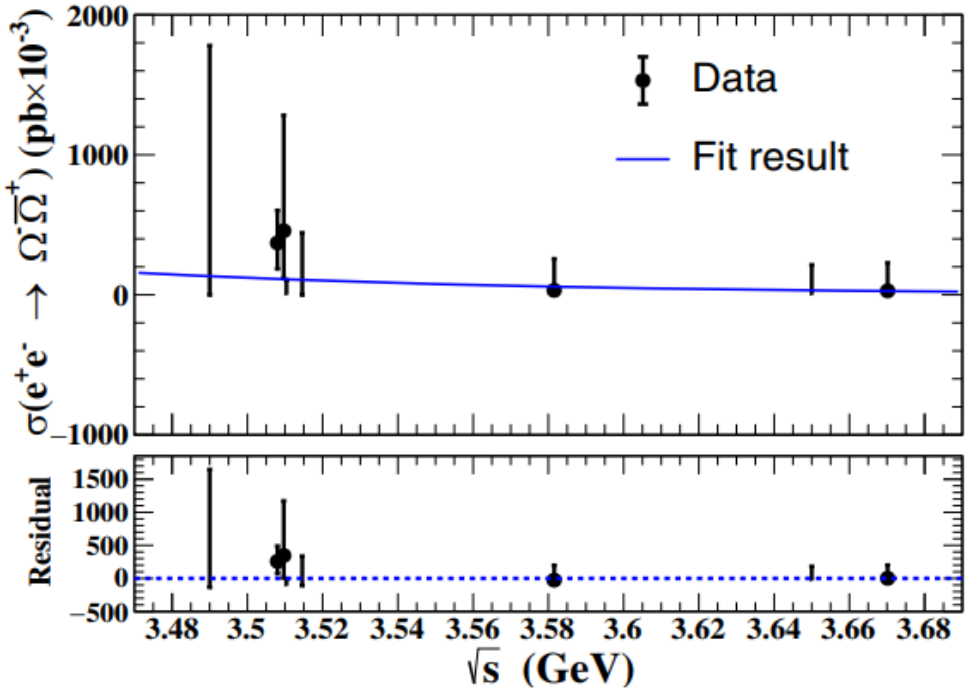


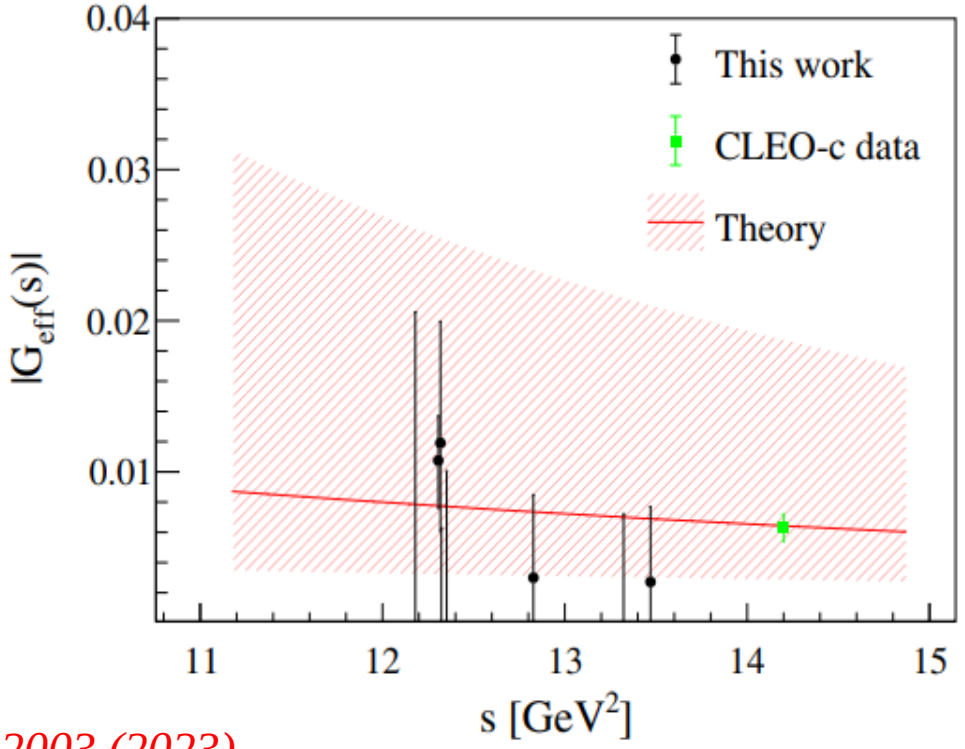


PRD 108, 072010 (2023)

Study of the spin 3/2 baryons: $e^+e^- \to \Omega\bar{\Omega}$

- Born cross sections and effective FF of $e^+e^- \to \Omega^-\bar{\Omega}^+$ are measured at 8 energy points between $\sqrt{s} = 3.49$ and 3.67 GeV.
  - No significant signal observed.
  - Upper limit of effective FF is consistent with pQCD driven prediction.





PRD 107, 052003 (2023)

Summary

- Fruitful physics results of EMFFs are obtained 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.

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Thank you!