Recent results of Baryon electromagnetic form factors at BESIII

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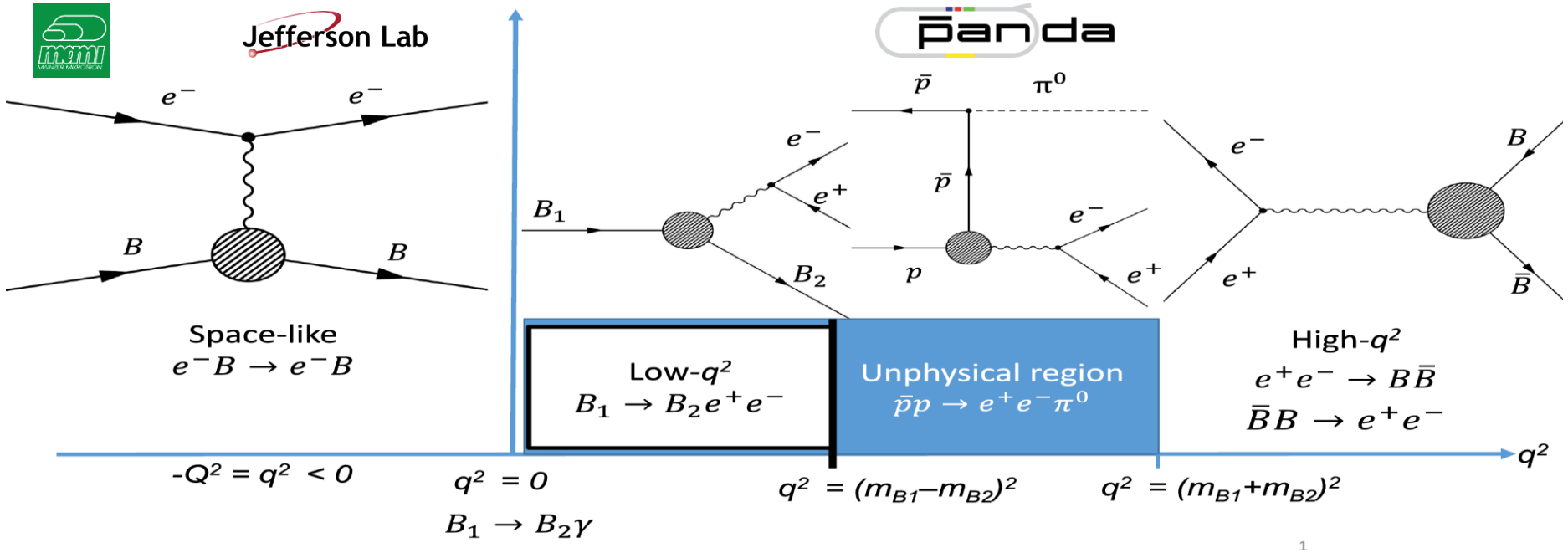
Electromagnetic Form Factors (EMFFs)

- 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

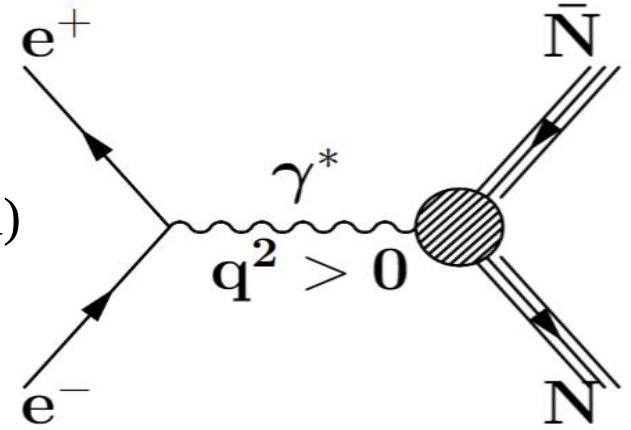
1961, first paper by N. Cabibbo and R. Gatto *Phys.Rev.* 124 (1961) 1577-1595

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

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

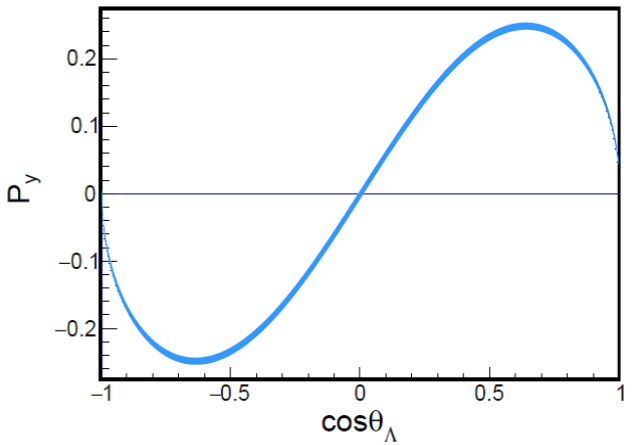
Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ (Born cross section)

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



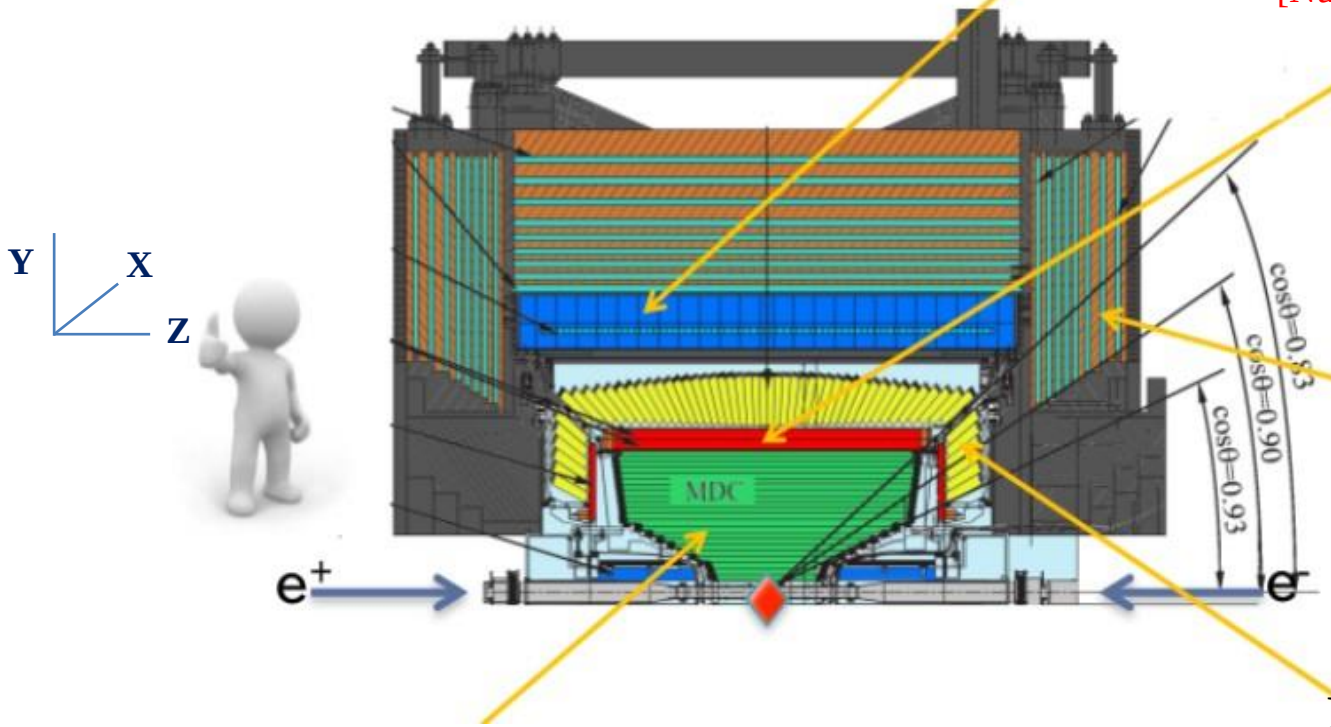
- The complex feature of TLFF leads to transversely polarized baryon even the beams are unpolarized. *Nuov Cim A* **109**, 241–256 (1996)

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



BESIII Experiment

BESIII experiment is 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 upgradation with 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)

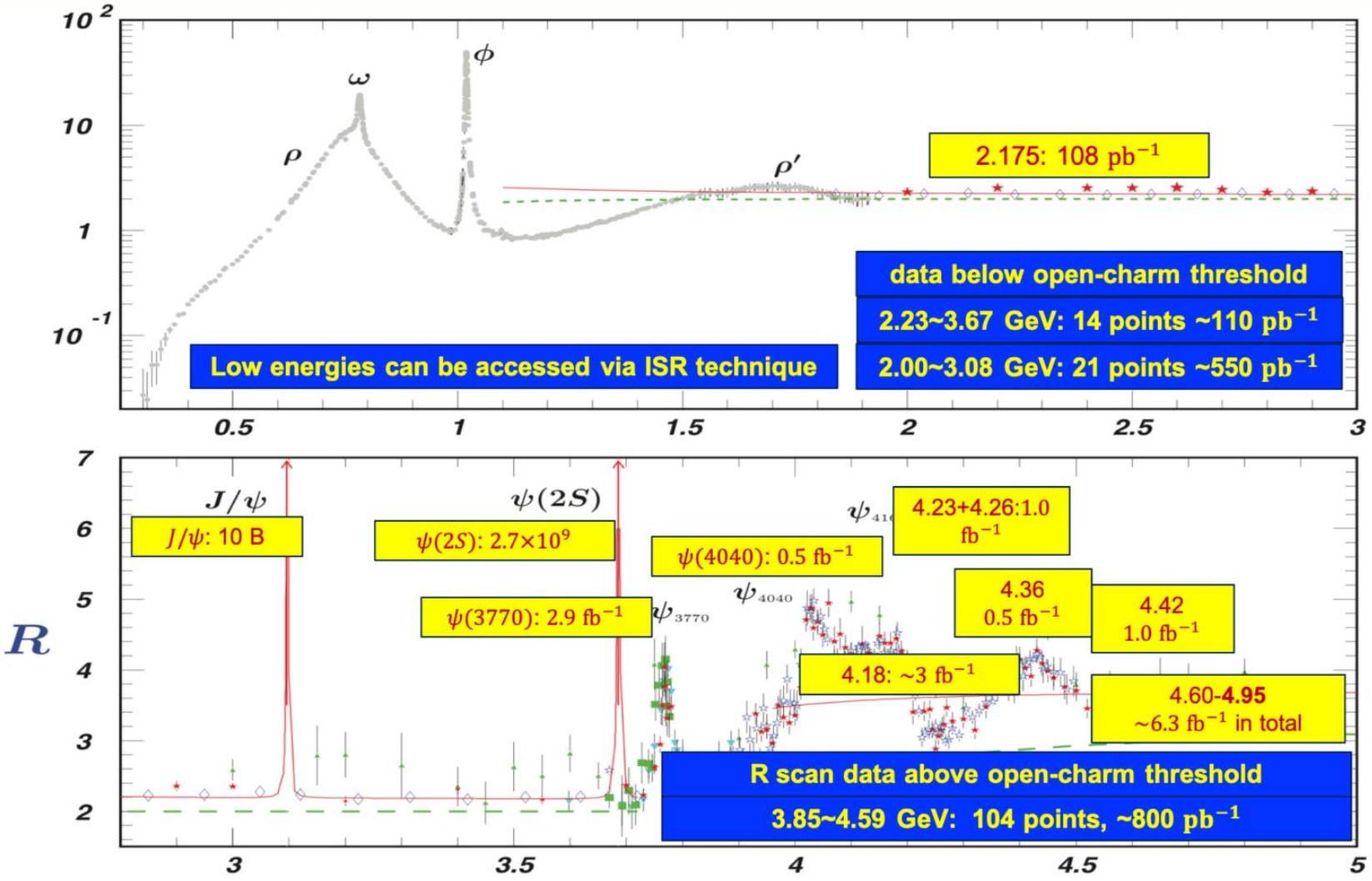
- **He/C_3H_8 (60/40)**
- **43 layers**
- **Momentum resolution $\sigma_p/p \approx 0.5\%$ @ 1 GeV**
- **Spatial resolution $\sigma_{xy} \approx 130$ μm.**

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

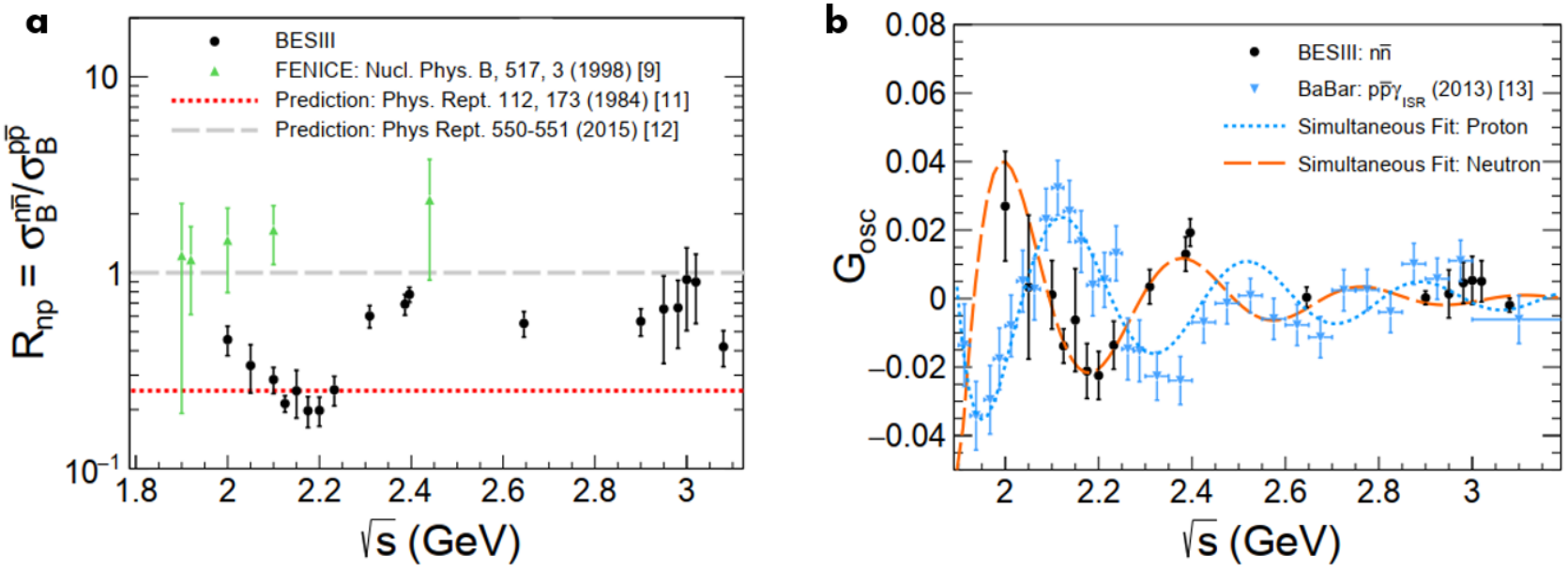


World largest data in tau-charm region

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

Recent results of neutron EMFFs

- Cross section and effective FF of $e^+e^- \to n\bar{n}$ measured from $\sqrt{s}$ = 2.0-3.08 GeV, 647.9 pb^{-1}.
- $\gamma - p$ coupling larger than $\gamma - n$ coupling => consistent with theoretical limits from VMD, Skyrme etc.
- Oscillation of reduced-|G| observed in neutron with a phase orthogonal to that of proton.

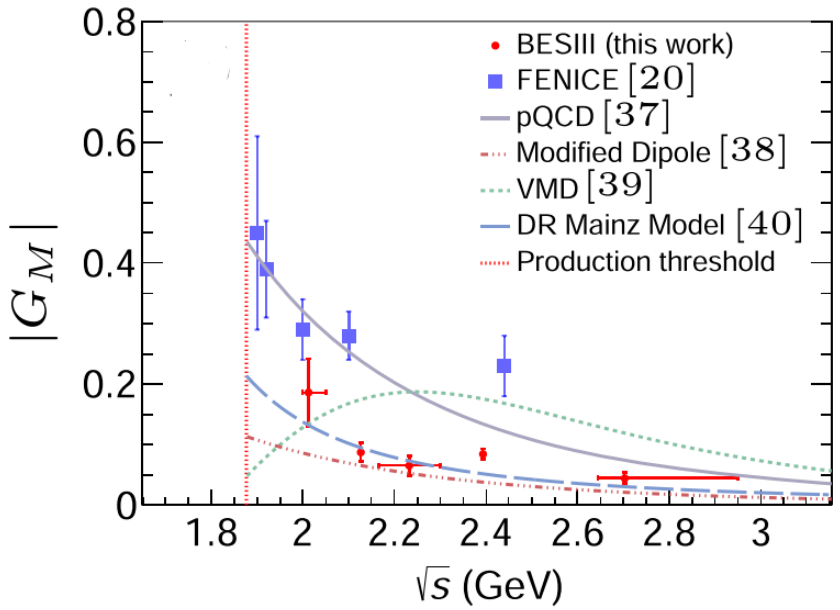


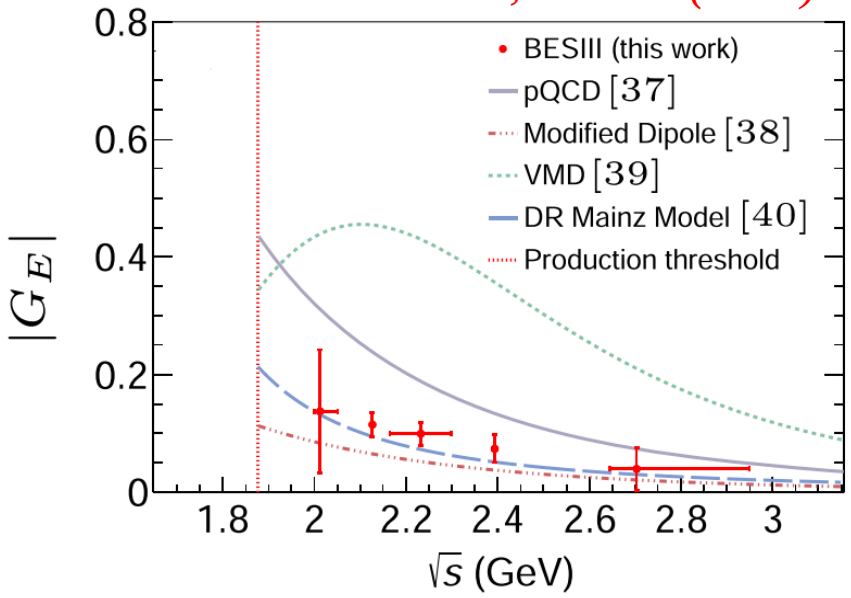
Nat. Phys. 17, 1200–1204 (2021)

Recent results of neutron EMFFs

- $|G_E|$, $|G_M|$ of neutron measured separately from $\sqrt{s}$ = 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.
- Results is 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

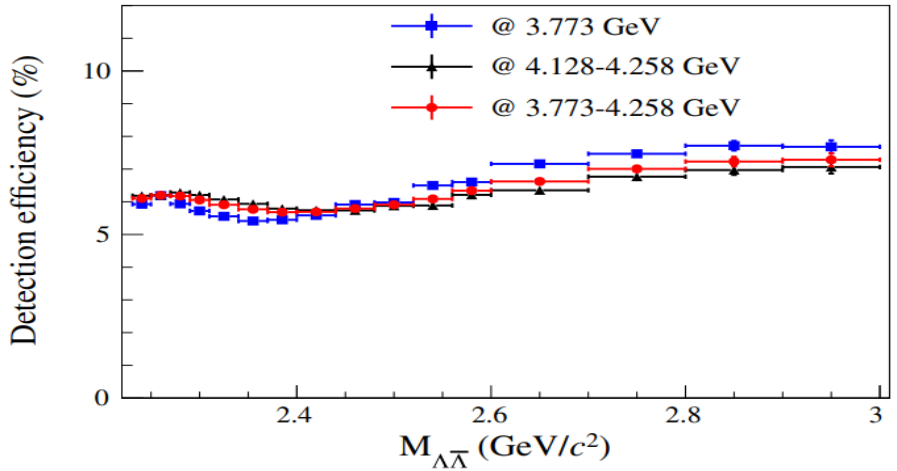
- It is difficult to study EMFFs of hyperons in space-like due to the difficulty in stable and high-quality hyperon beams.
- The hyperons can be produced in e^+e^- annihilation above their production threshold.
- The angular distribution of daughter baryon from Hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega}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

Advantages:

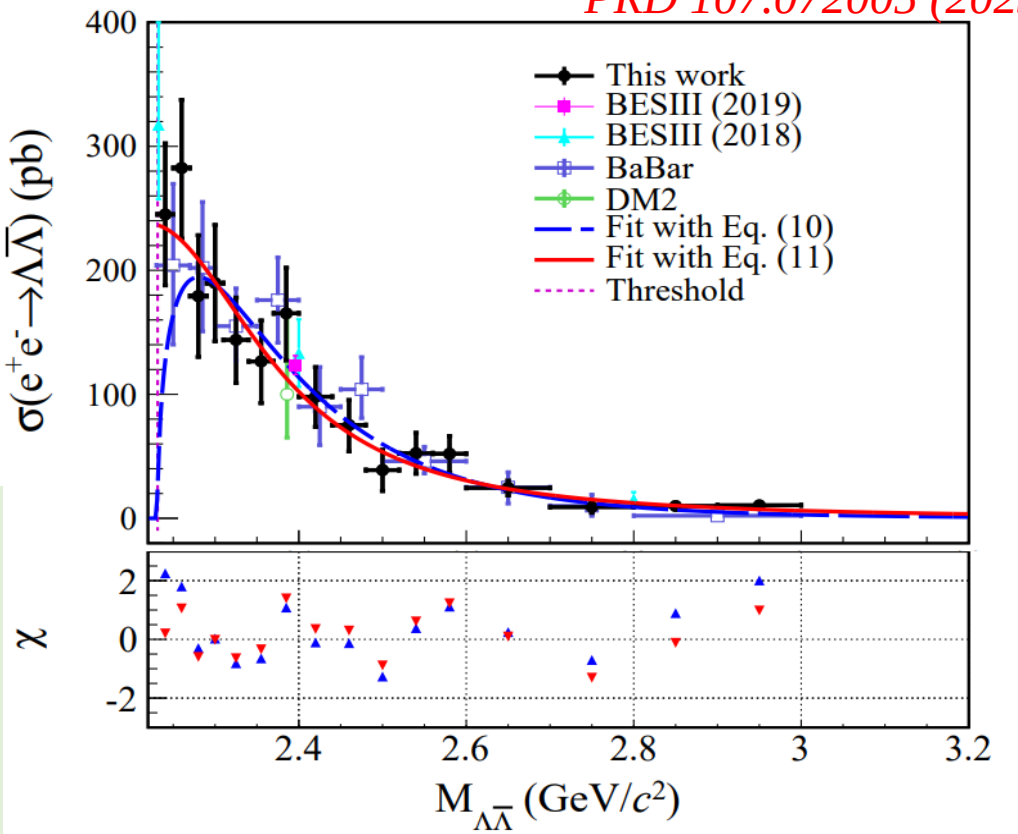
- Cross section can be obtained very close to threshold with finite PHSP of final state.
- With hyperon weak decay to B+P, the polarization of hyperon can be measured, so does the relative phase between G_E and G_M! (Of course, enough statistics needed)

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 from $\sqrt{s} = 3.773$ to 4.258 GeV by ISR method.
- The non-zero cross section 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, $283^{+53}_{-55} \pm 15$ pb in [2.25, 2.27] 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.
- A model inspired by the perturbative QCD has been tried (blue dashed line in figure): *Phys. Rep. 550.1 (2015)*

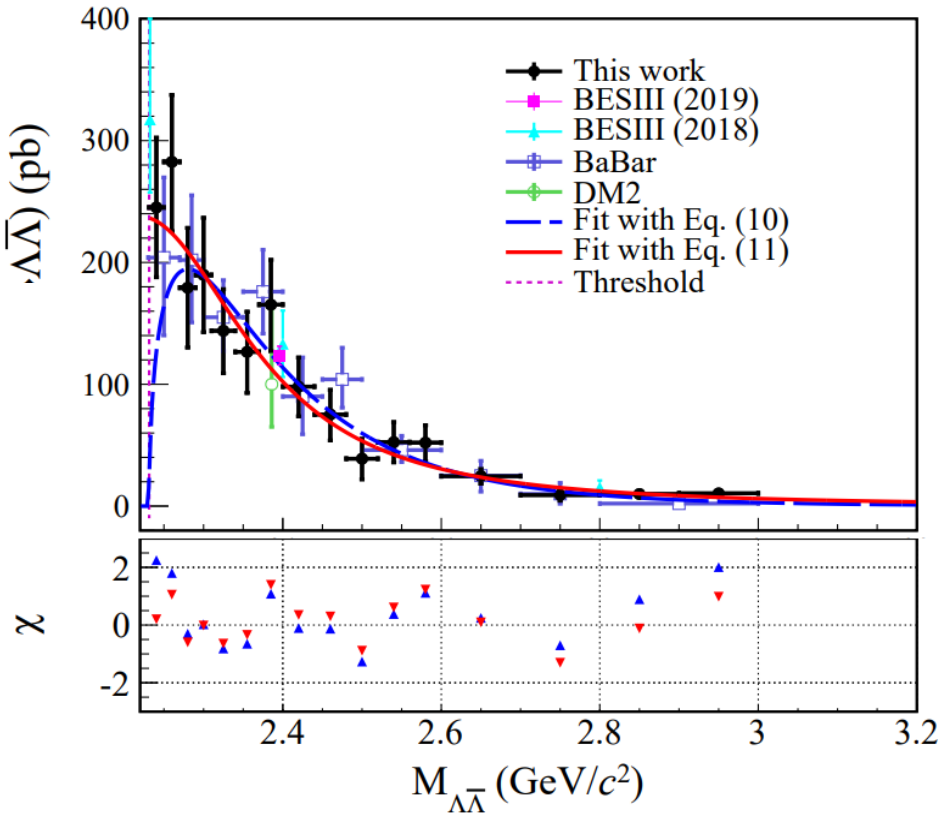
$$\sigma(s) = \frac{c_0 \cdot \beta(s) \cdot C}{(\sqrt{s} - c_1)^{10}}$$

- 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.

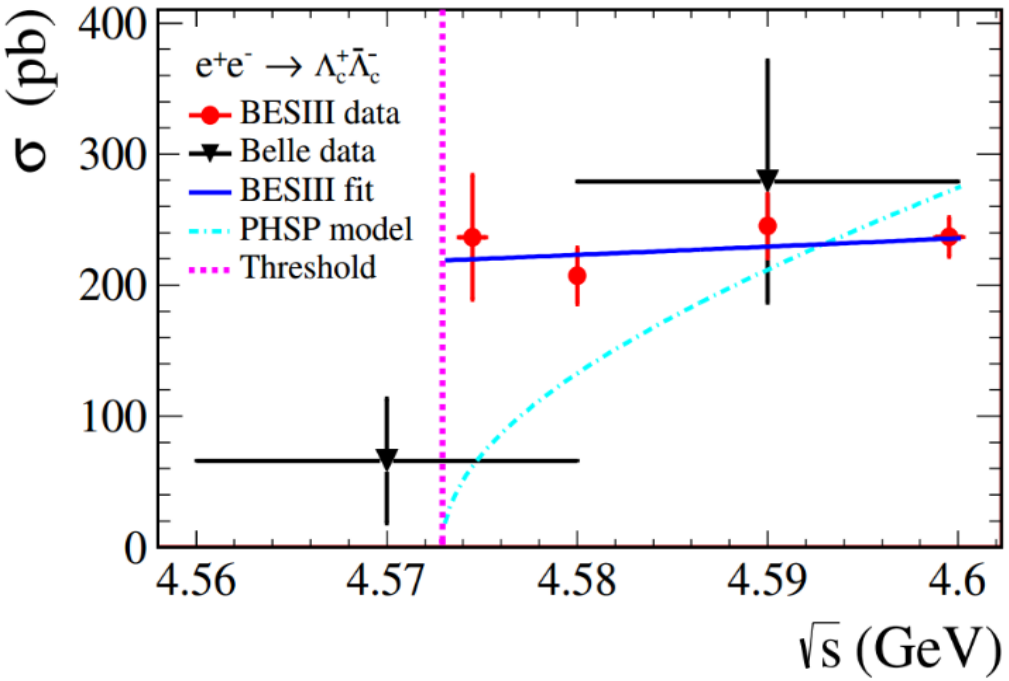
PRD 107.072005 (2023)

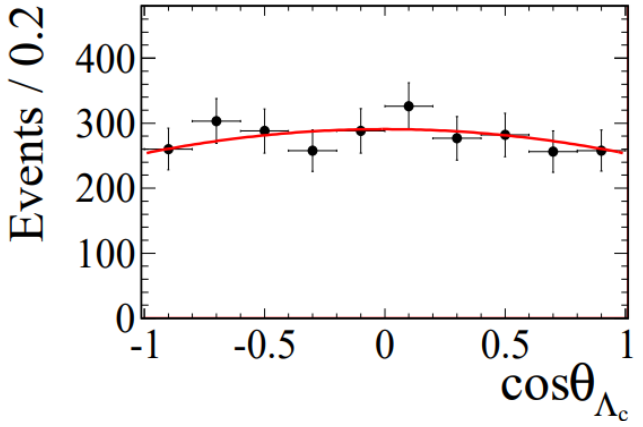


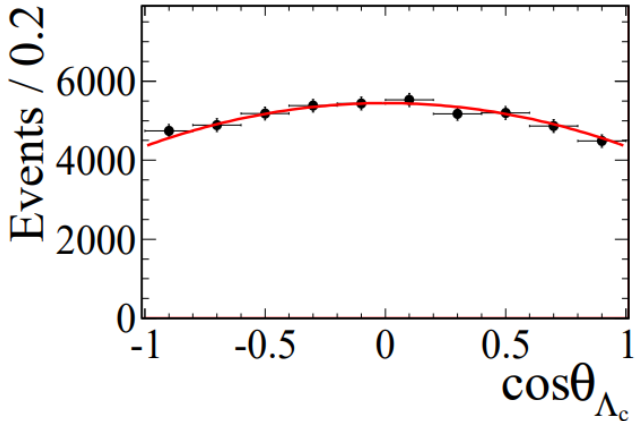
Cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- Cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ is measured at 4 c. m. e close to the threshold, and $|G_E|/|G_M|$ is measured at two of them with larger statistics.
- A step in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ cross section observed, similar to $e^+e^- \to p\bar{p}$, followed by a plateau.
- Cross section of first energy point (1.5 MeV above threshold) is $236 \pm 11 \pm 46$ pb.

PRL 120, 132001 (2018)





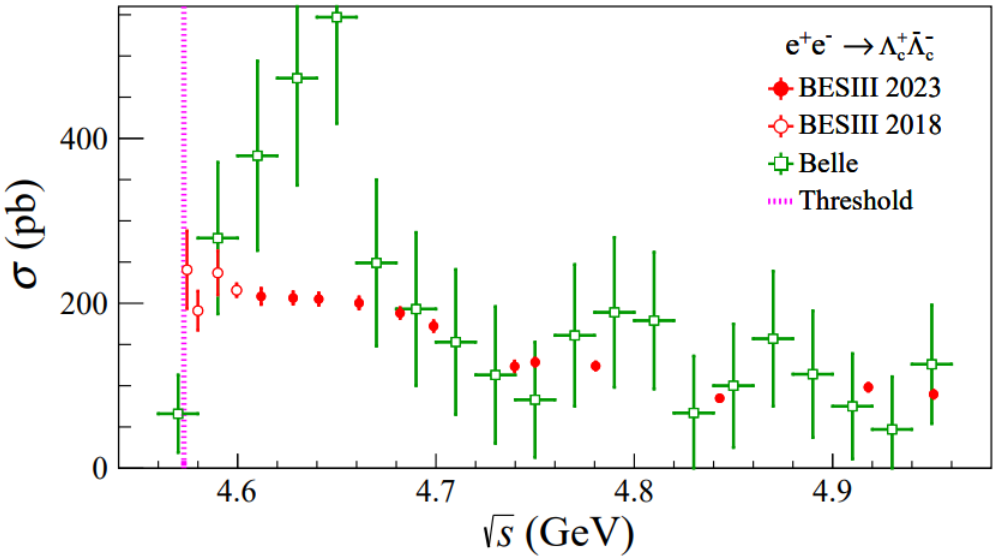


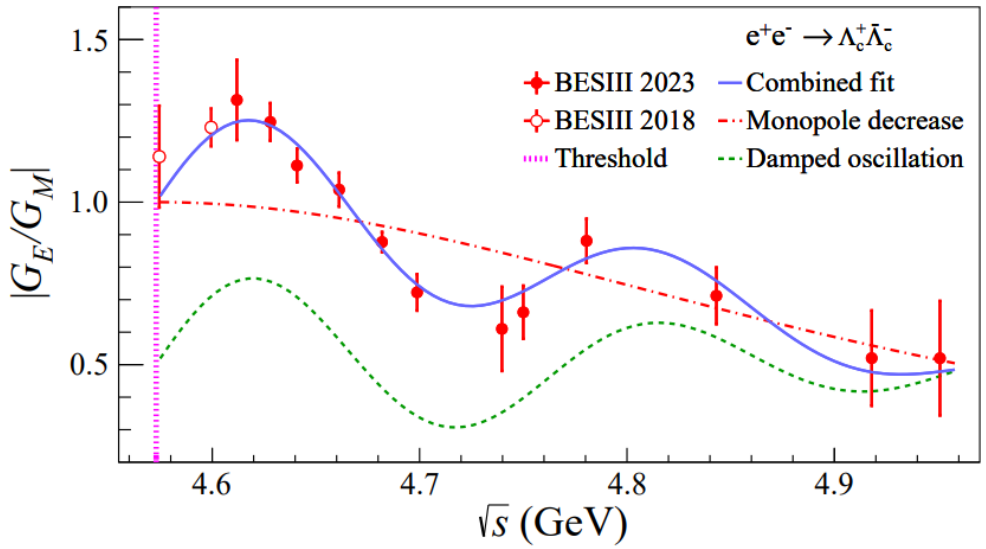
$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

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.

arXiv: 2307.07316





Complete measurement of Σ^+EMFFs

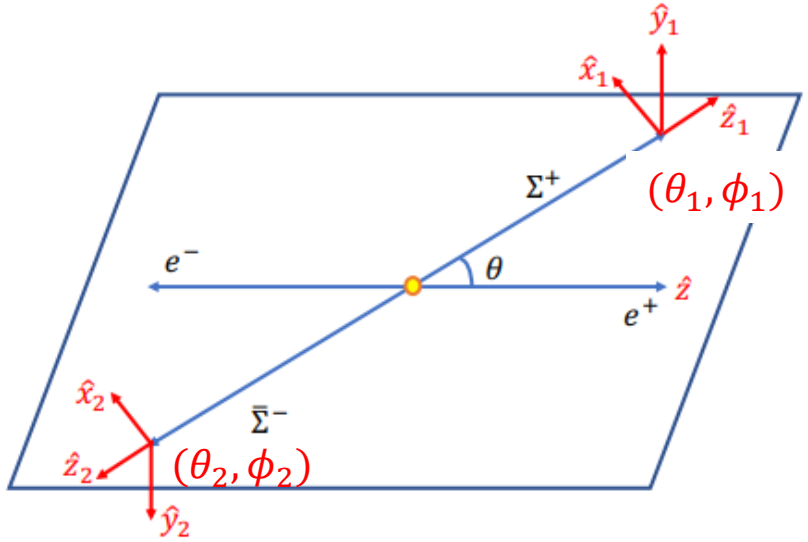
- An event of the reaction $e^+e^- \to \Sigma^+(\to p\pi^0)\bar{\Sigma}^-(\to \bar{p}\pi^0)$ is formalized by joint angular distribution:

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

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

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

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



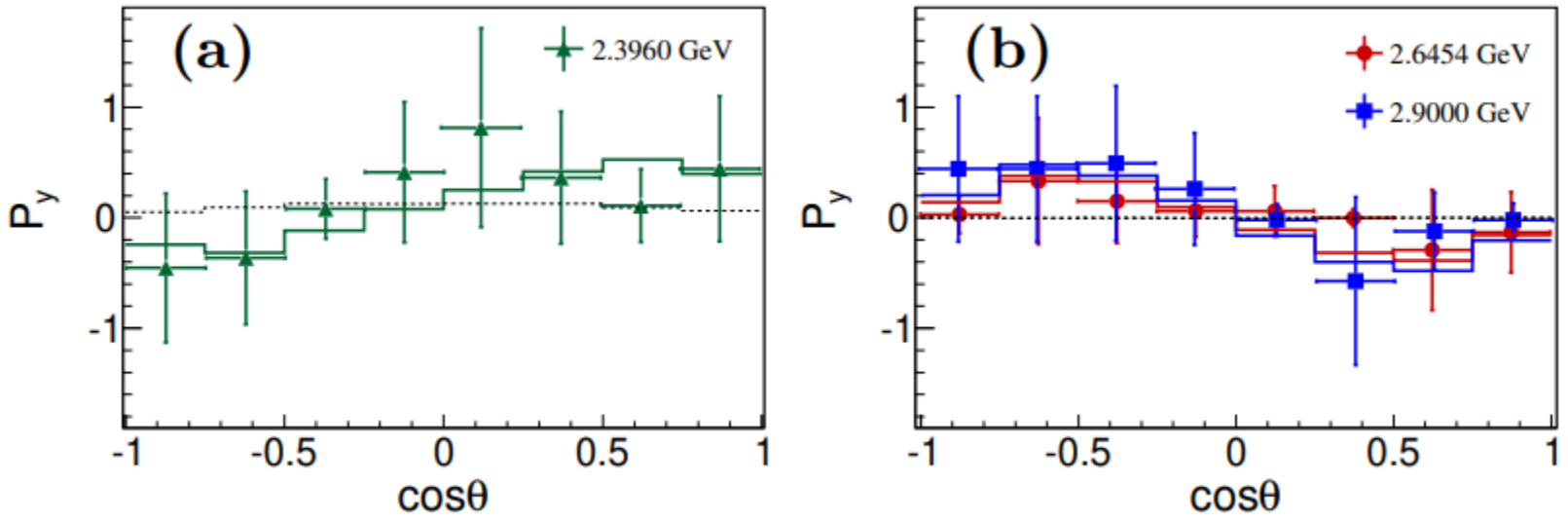
- A nonzero relative phase leads to polarization p_y of the out going baryons:

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

Complete measurement of Σ^+ EMFFs

- Polarization is observed at $\sqrt{s}$ =2.396, 2.644 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.

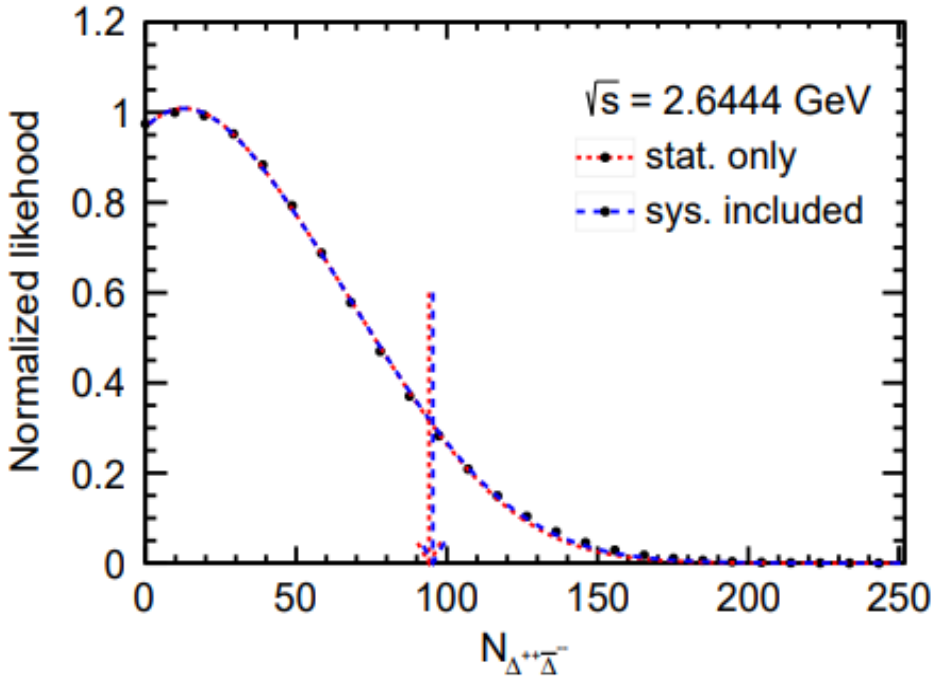
arXiv: 2307.15894

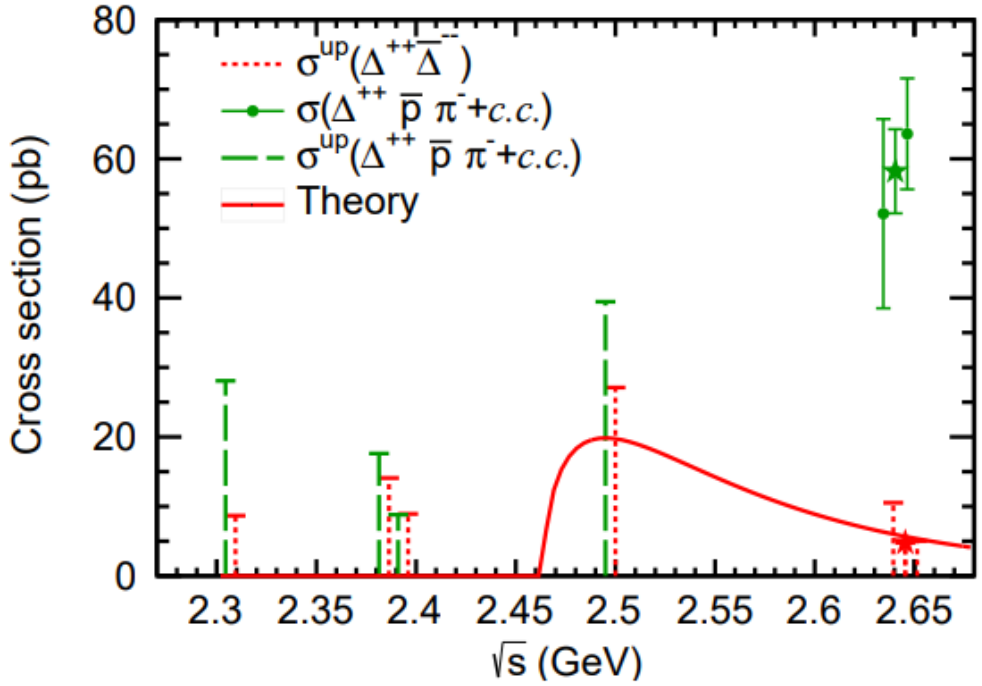


Study of the spin 3/2 baryons: $e^+e^- \to \Delta\bar{\Delta}$

- $e^+e^- \to \Delta^{++}\bar{\Delta}^{--}$ is searched with c.m.s in 2.3094 to 2.6464 GeV.
  - No significant signal observed, but signal for $e^+e^- \to \Delta^{++}p\pi^-$ observed.

arXiv: 2305.12166

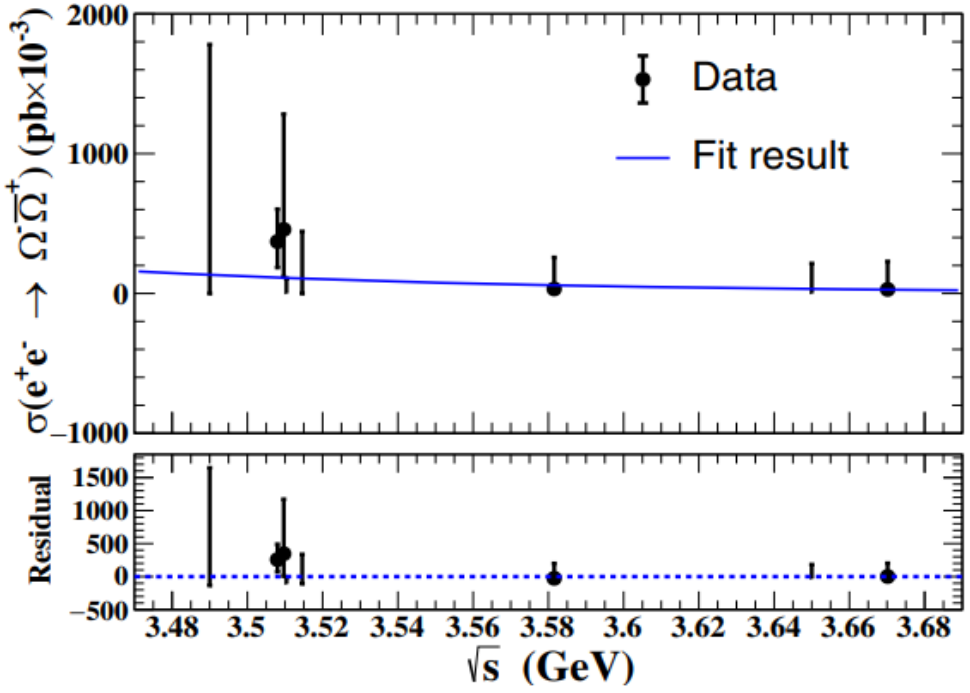


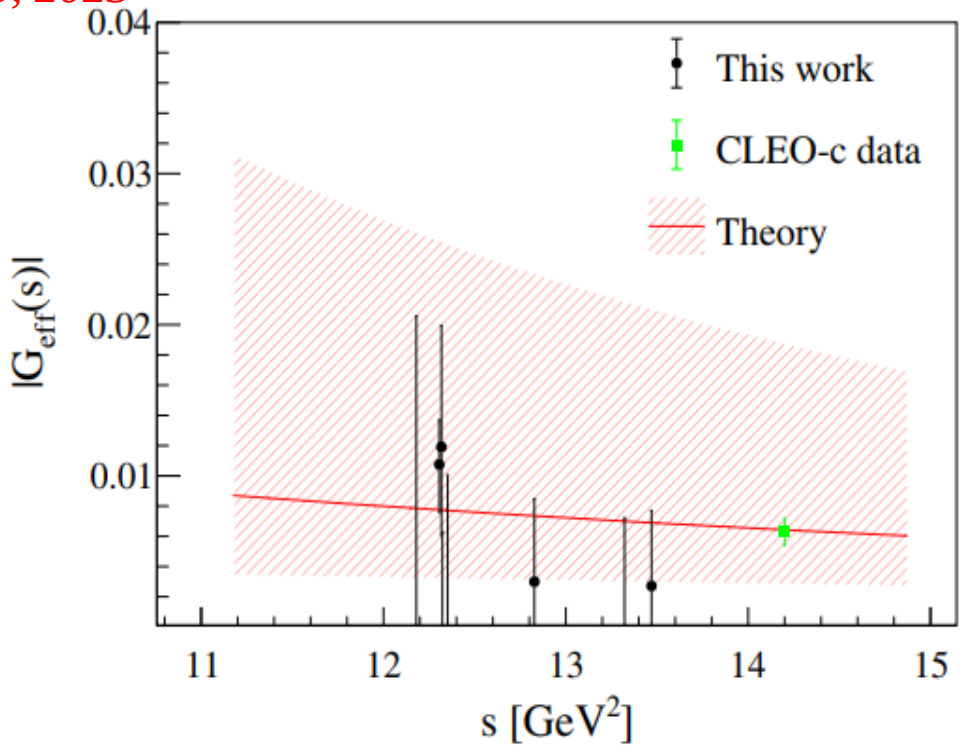


Study of the spin 3/2 baryons: $e^+e^- \to \Omega\bar{\Omega}$

- 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 from e^+e^- colliders, via energy scan and ISR methods.
- More results from BESIII are on the way.

Thank you!