Electromagnetic Form Factors of baryon in Time-like

Xiaorong Zhou

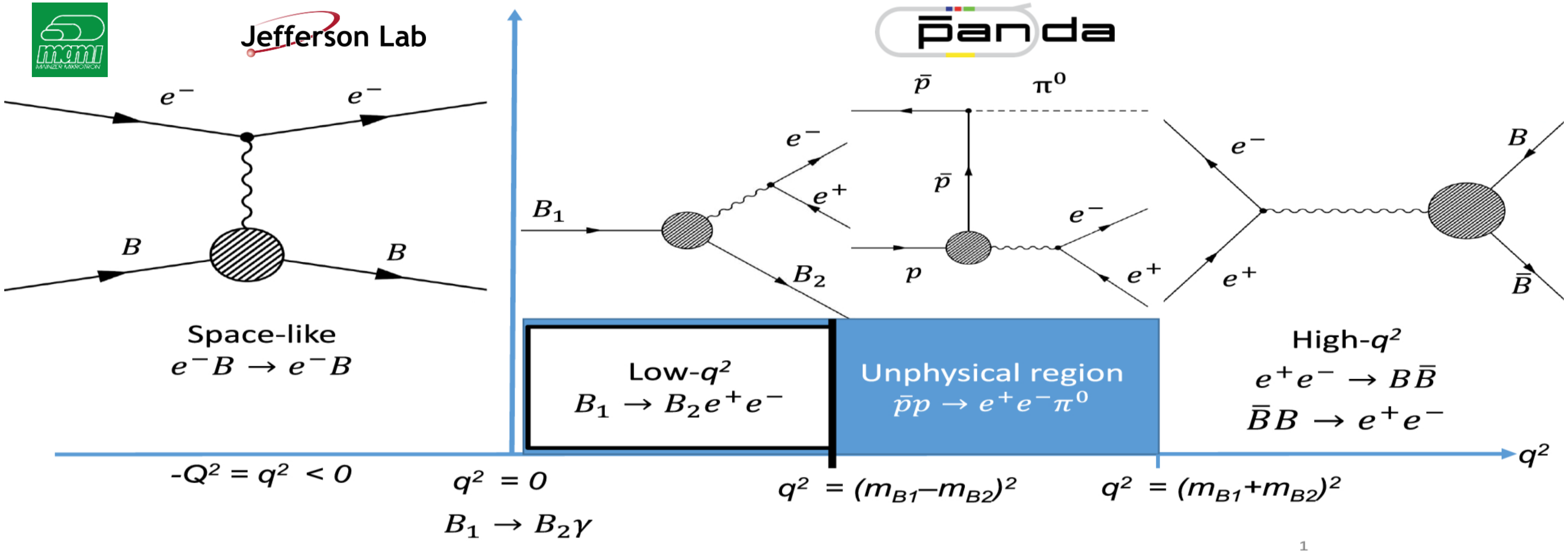
University of Science and Technology of China

The 20th International Conference on Hadron Spectroscopy and Structure

5–9 Jun 2023, Genova, Italy

Electromagnetic Form Factors (EMFFs)

- Electromagnetic Form Factors are fundamental properties of the nucleon
  - ➢ Connected to charge, current distribution
  - ➢ Crucial testing ground for models of the nucleon internal structure



The nucleon electromagnetic vertex Γ_μ describing the hadron current:

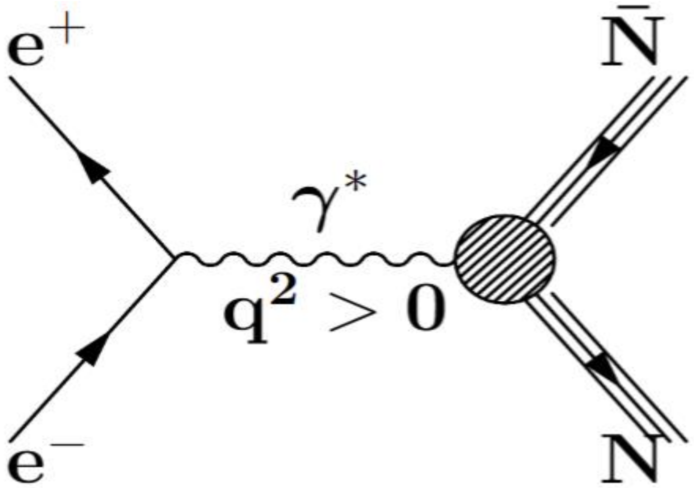
$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m_p} F_2(q^2)$$

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



PHYSICAL REVIEW VOLUME 124, NUMBER 5 DECEMBER 1, 1961

Electron-Positron Colliding Beam Experiments

N. Cabibbo and R. Gatto
Istituti di Fisica delle Università di Roma e di Cagliari, Italy and Laboratori Nazionali di Frascati del C.N.E.N., Frascati, Roma, Italy

(Received June 8, 1961)

Possible experiments with high-energy colliding beams of electrons and positrons are discussed. The role of the proposed two-pion resonance and of the three-pion resonance or bound state is investigated in connection with electron-positron annihilation into pions. The existence of a three-pion bound state would give rise to a very large cross section for annihilation into $\pi^0+\gamma$. A discussion of the possible resonances is given based on consideration of the relevant widths as compared to the experimental energy resolution. Annihilation into baryon-antibaryon pairs is investigated and polarization effects arising from the nonreal character of the form factors on the absorptive cut are examined. The density matrix for annihilation into pairs of vector mesons is calculated. A discussion of the limits from unitarity to the annihilation cross sections is given for processes going through the one-photon channel. The cross section for annihilation into pairs of spin-one mesons is rather large. The typical angular correlations at the vector-meson decay are discussed.

A neutral weakly interacting vector meson would give rise to a strong resonant peak if it is coupled with lepton pairs. Effects of the local weak interactions are also examined. The explicit relation between the e^2 corrections to the photon propagator due to strong interactions and the cross section for annihilation into strongly interacting particles is given.

- The production cross section of $e^+e^- \to B\bar{B}$ (1/2 baryon) is given.
- The complex feature of TLFF implies a polarization of baryon normal to the plane of production and proportional to sin(ΔΦ).

Time-like EMFFs: theoretic review

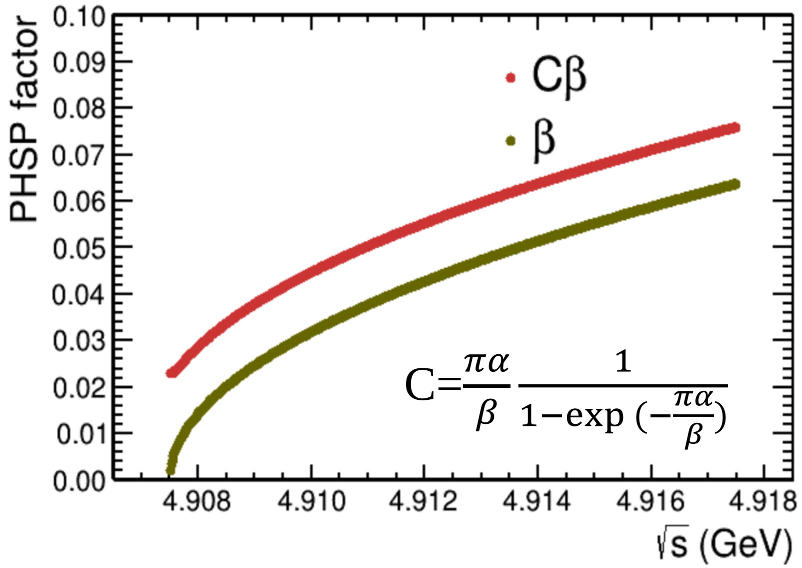
- Interaction of final states, lead to a non-zero cross section for charged baryon at threshold.

Sov. Phys. Usp. **34** 375(1991)

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

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

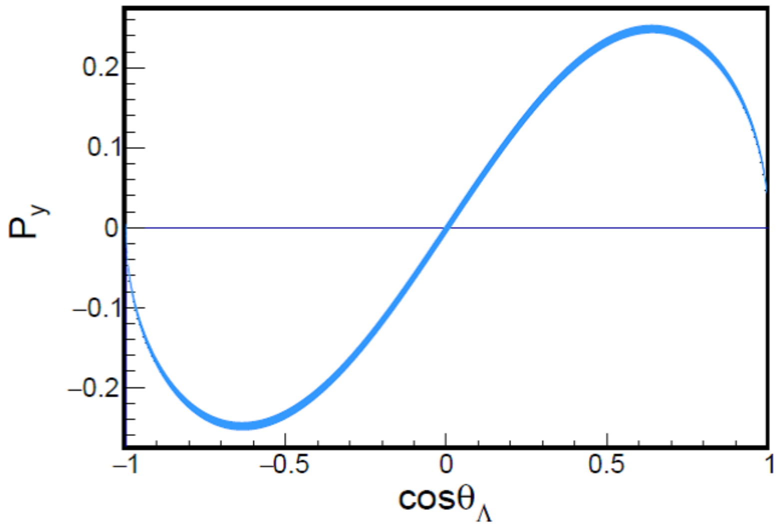
$$\xrightarrow{|G_E|=|G_M|} \sigma_{B\bar{B}} = \frac{2\pi\alpha^2 C\beta}{q^2}|G_{\mathrm{eff}}|^2$$



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

Nuov Cim A **109**, 241–256 (1996)

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

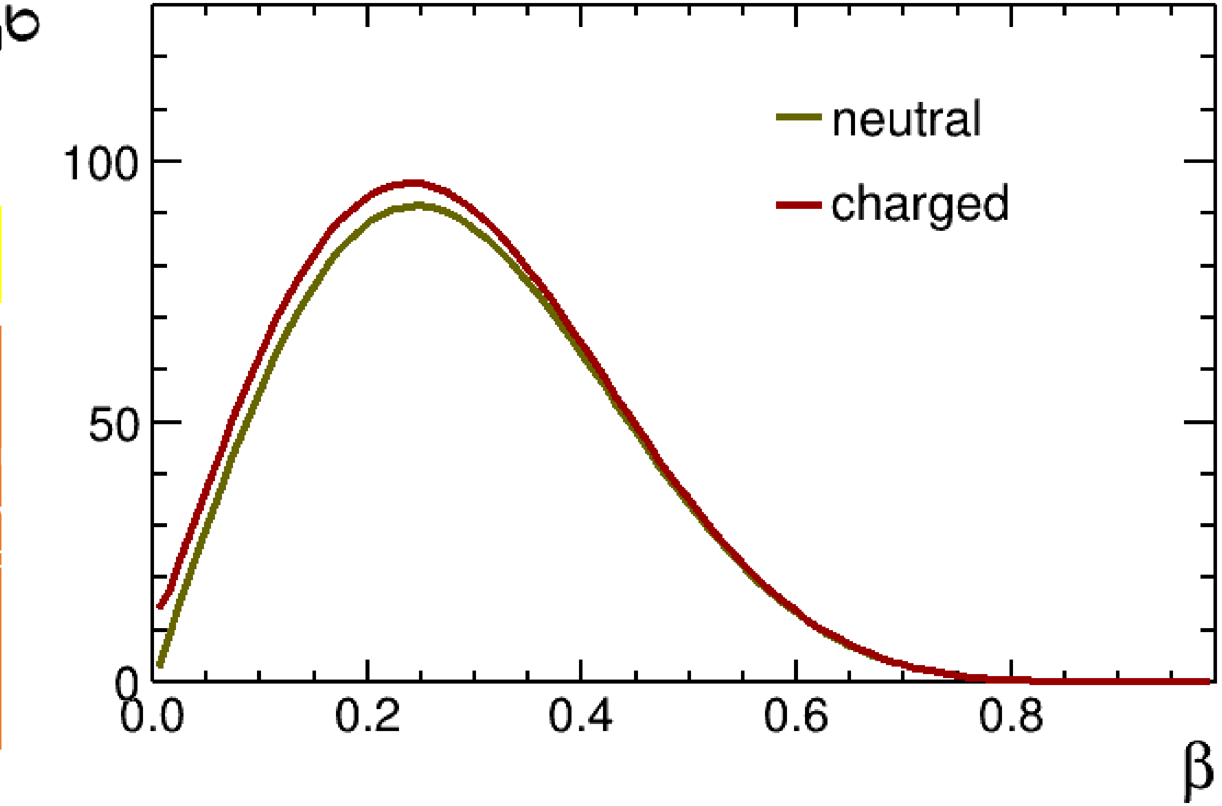


Time-like EMFFs: theoretic review

- Various theo irbative region: ChEFT, VM) etc.

Parametrization of

pQCD predicts contin transition at high q², the scaling behavior: F $q^{-4}, F_2 \propto q^{-6}$



VMD model described the effect of meson cloud

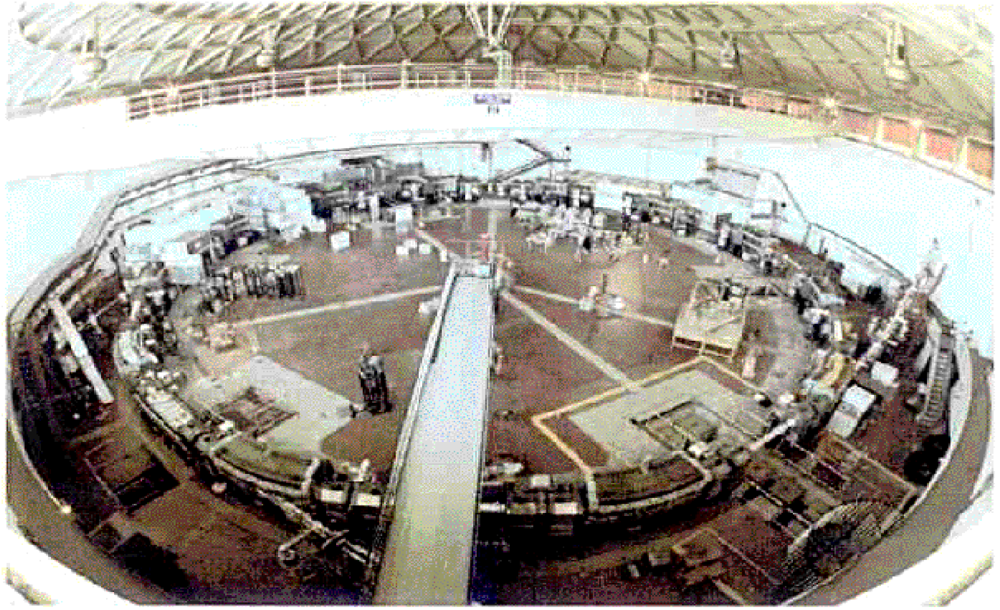
$$|G_{\mathrm{eff}}| = \frac{\mathcal{A}}{q^4\left[\ln^2\left(\frac{q^2}{\Lambda^2}\right)+\pi^2\right]}$$ or

$$|G_{\mathrm{eff}}| = \frac{\mathcal{A}}{\left(1+\frac{q^2}{m_a^2}\right)\left[1-q^2/q_0^2\right]^2}$$

- Dispersion theoretical analysis, provide a coherent framework for the joint interpretation of SL and TL EMFFs over the entire physical range of q².

Time-like EMFFs: experimental review

1972，first experiment (ADONE)



Nuovo Cim.A 14 (1973) 1-20

The Reaction $e^+e^- \to p\bar{p}$ at a Total Energy of 2.1 GeV.

M. Castellano, G. Di Giugno, J. W. Humphrey (*),
E. Sassi Palmieri, G. Troise, U. Troya and S. Vitale

Istituto Nazionale di Fisica Nucleare - Sezione di Napoli
Istituto di Fisica Sperimentale dell'Università - Napoli

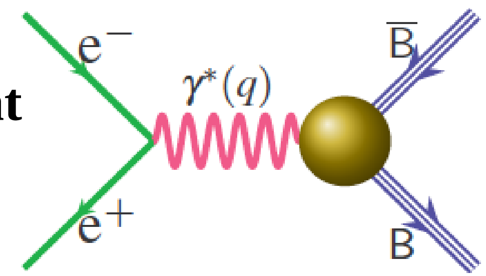
(ricevuto il 19 Settembre 1972)

Summary. — An optical spark-chamber counter experiment at Adone, the Italian colliding electron-positron ring, has succeeded in measuring the cross-section for the process $e^+e^- \to p\bar{p}$ near threshold ($E_{\text{c.m.}} = 2.1$ GeV). The result is $\sigma(e^+e^- \to p\bar{p}) = (0.91 \pm 0.22)$ nb.

- First experiment using spark-chamber counter performed at ADONE
- Integrated luminosity 0.19 pb^{-1}
- 25 signal events in 21901 photographs
- $\sigma(e^+e^- \to p\bar{p}) = (0.73 \pm 0.18)$ nb at c.m.e 2.1 GeV

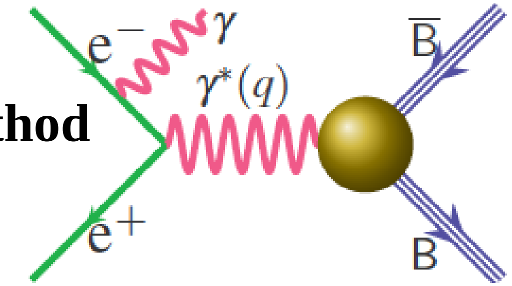
Time-like EMFFs: experiment review

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



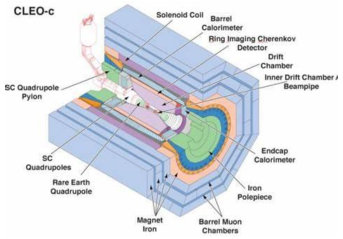
  - Well-defined c.m.energy, low background
  - Very good energy resolution
  - Discrete values, leaving gaps without information

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

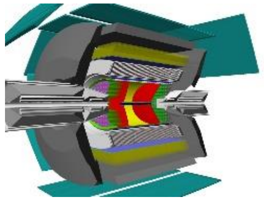


  - At a fixed c.m.energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
  - Systematic uncertainty in a coherent way
  - Large luminosity needed
  - Higher background

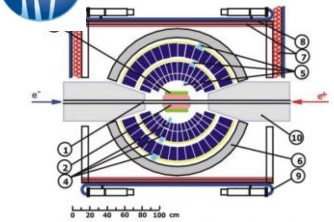
CLEO-c



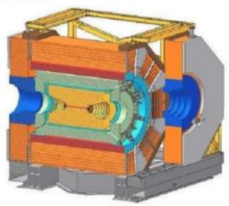
CMD-3



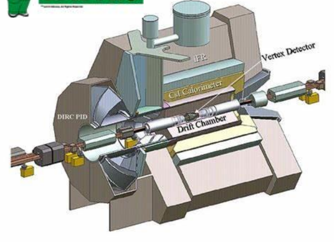
SND



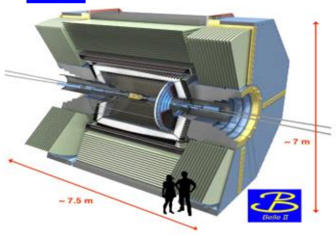
BESIII



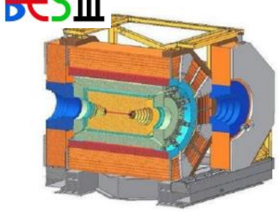
BABAR



BELLE



BESIII



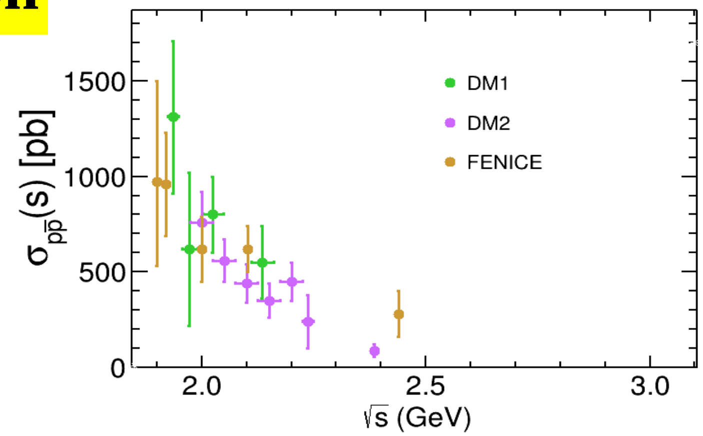
Timeline of Proton EMFFs

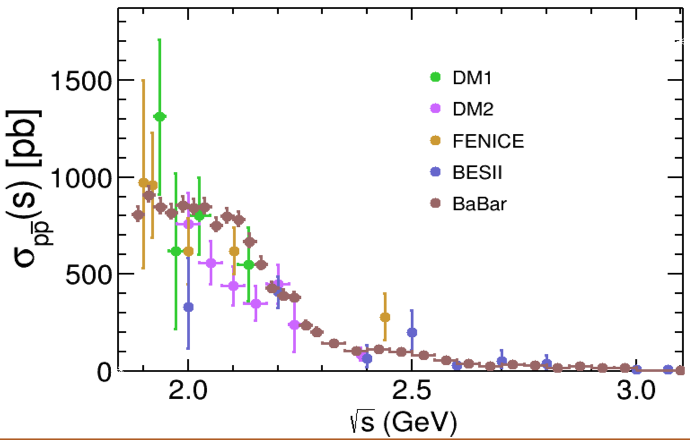
Cross section

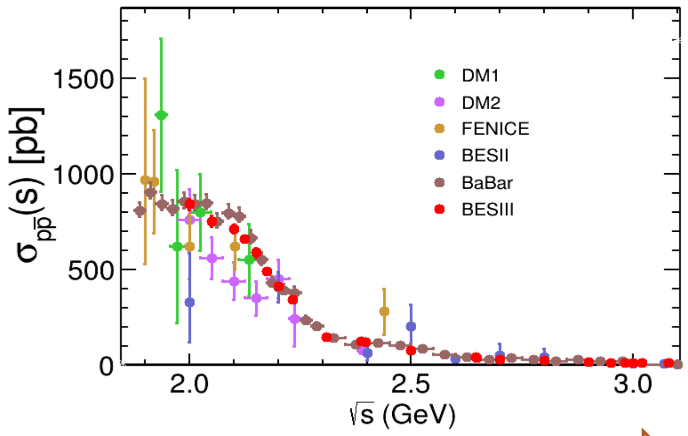
200 signal events in total, limited narrow energy region

BaBar observed threshold effect via ISR

BESIII obtained best precision via energy scan

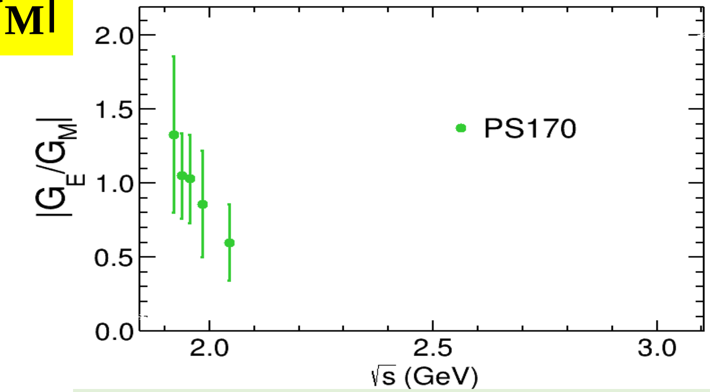


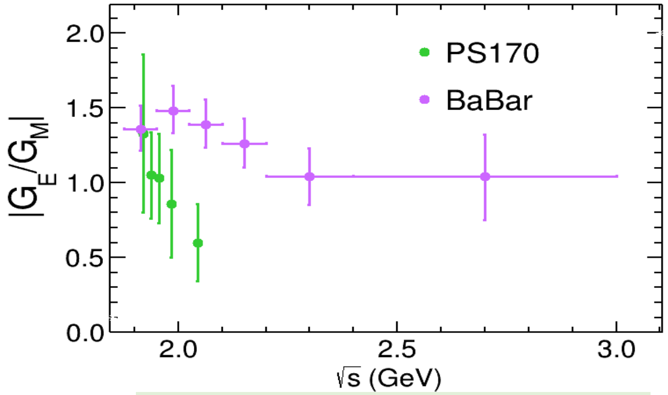


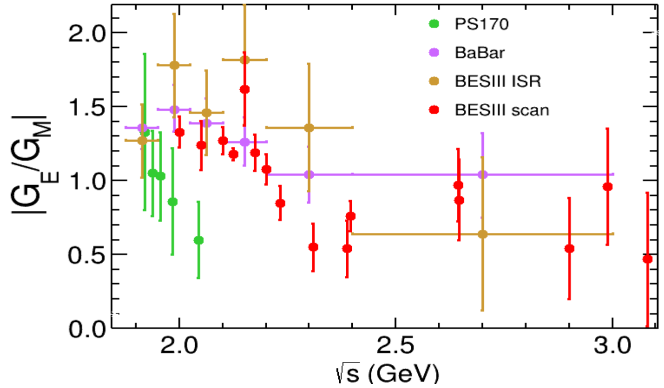


Before 2000 | **2000 to 2020** | **2020** | **Year**

$|G_E/G_M|$







PS170 observed $|G_E/G_M|$ ratio for the first time at LEAR

Result from BaBar is inconsistent with PS170

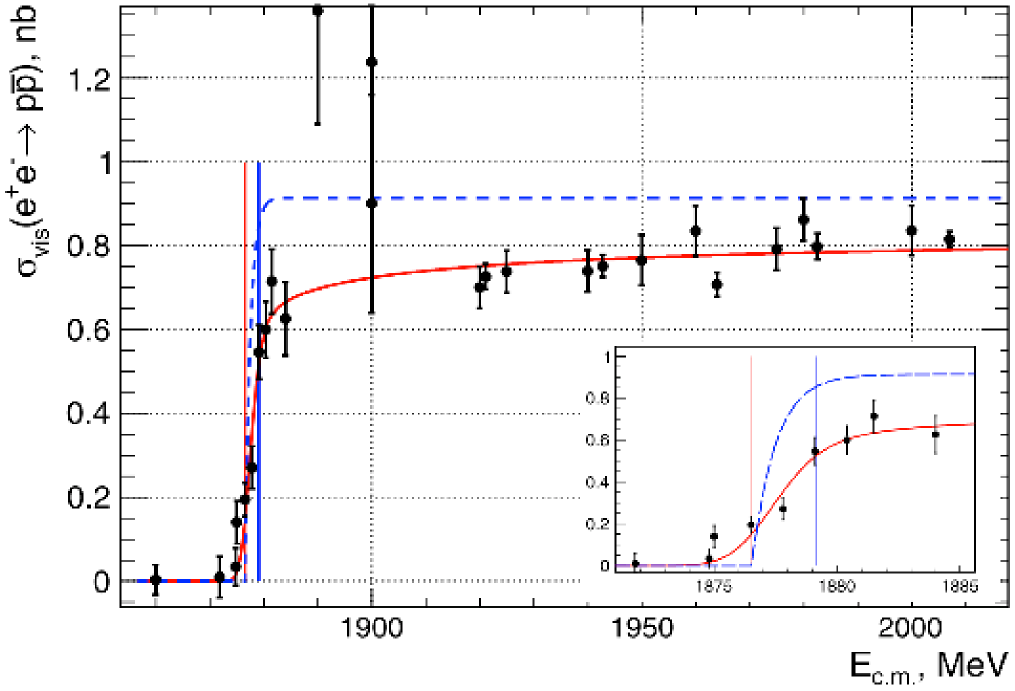
BESIII observed oscillation in the $|G_E/G_M|$ lineshape

Recent results of proton EMFFs

CMD-3

- Cross section of $e^+e^- \to p\bar{p}$ near threshold shows very sharp step-like behavior.
- The plateau indicates anomaly **threshold effect** in the production cross section.

PLB 794, 64-68 (2019)



- The Born cross section is described with

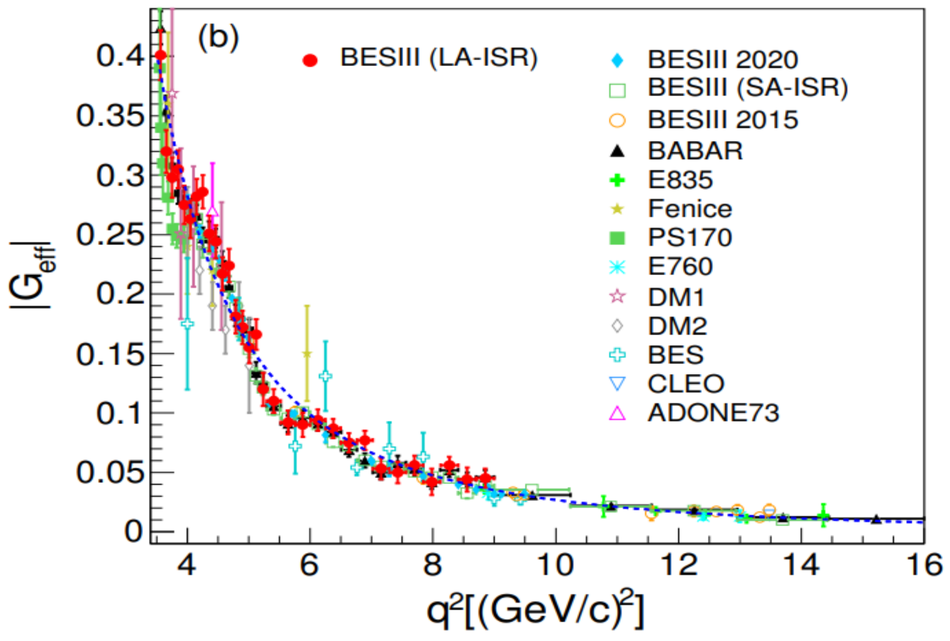
$$\sigma_{Born}(E_{c.m.}) = A + B\left[1 - \exp\left(-\frac{(E_{c.m.} - E_{thr})}{\sigma_{thr}}\right)\right]$$

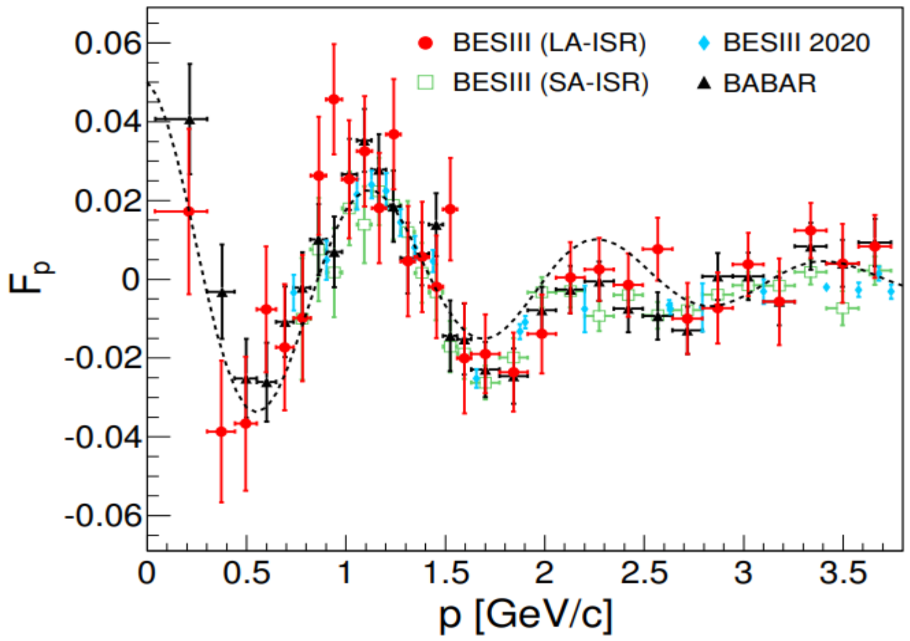
Reac.	A, nb	B, nb	E_{thr}, MeV	σ_{thr}, MeV	χ^2/ndf
$p\bar{p}$	0 – fxd	0.91±0.02	1877.1±0.2	0.18±0.27	29/26
$p\bar{p}$	0 – fxd	0.91±0.02	1876.54-fxd	0.76±0.28	31/27

Recent results of proton EMFFs

- ISR method with detected photon and undetected at BESIII.
- **Damped oscillation** distribution after subtracting the modified dipole.

PLB 817, 136328 (2021)





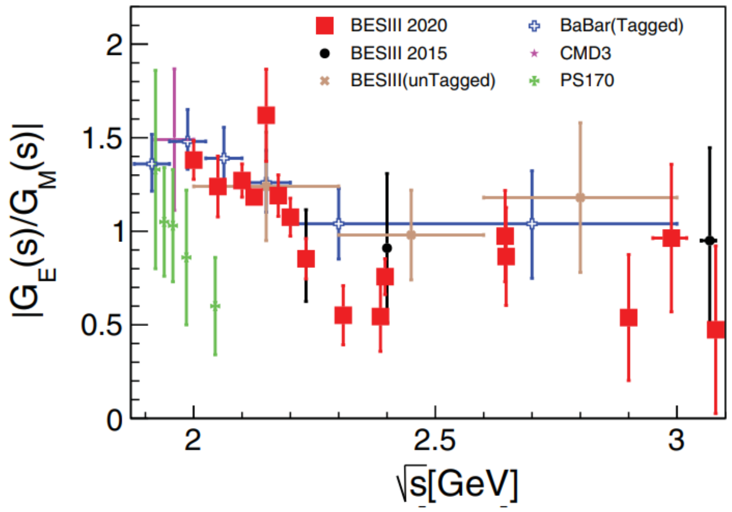
Blue dashed: $|G_{\text{eff}}| = \dfrac{\mathcal{A}}{(1+q^2/m_a^2)[1-q^2/q_0^2]^2}$, $q_0^2 = 0.71\ (\text{GeV}/c)^2$,

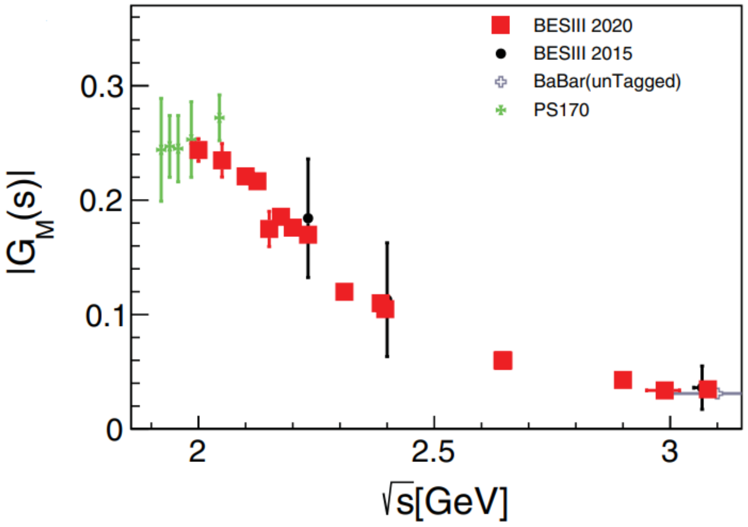
Black dashed: $F_p = A^{\text{osc}} \exp(-B^{\text{osc}} p) \cos(C^{\text{osc}} p + D^{\text{osc}})$,

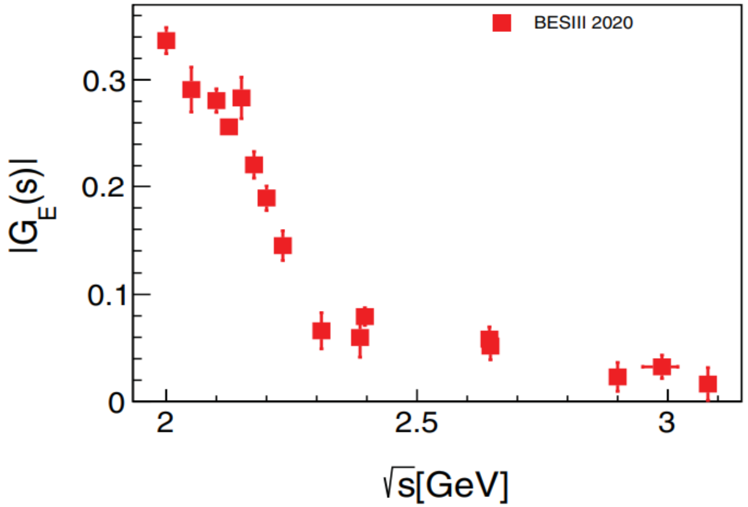
Recent results of proton EMFFs

- Scan technique from $\sqrt{s} = 2.0$ to 3.08 GeV, using 688.5 pb^{-1} integrated luminosity.
- $|G_E/G_M|$, $|G_M|$ are determined with **high accuracy**, $|G_E|$ is measured for the first time.

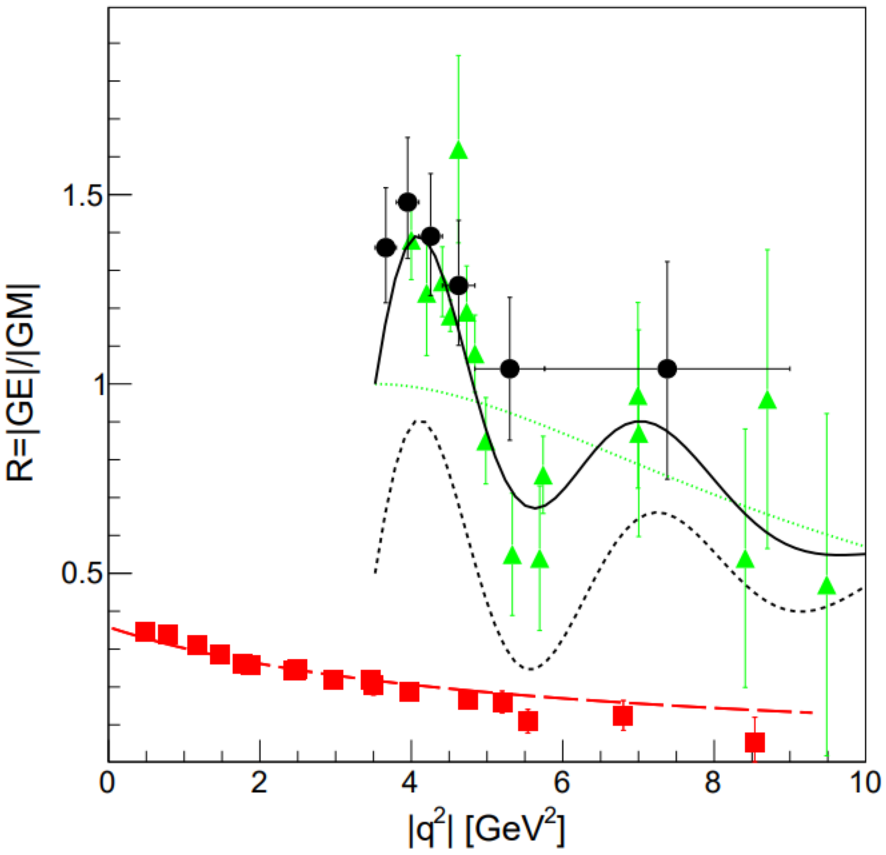
PRL 124, 042001 (2020)







Analyticity of proton EMFFs



- SL data shows a monotone decrease from $1/\mu_p$ at $q^2 = 0$.
- TL data decreases from 1 at threshold $q^2 = 4m_p^2$.
- Damped oscillation feature of $|G_E/G_M|$ in Time-like

$$F_R(\omega(s)) = \frac{1}{1+\omega^2/r_0}\left[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)\right], \quad \omega = \sqrt{s} - 2m_p$$

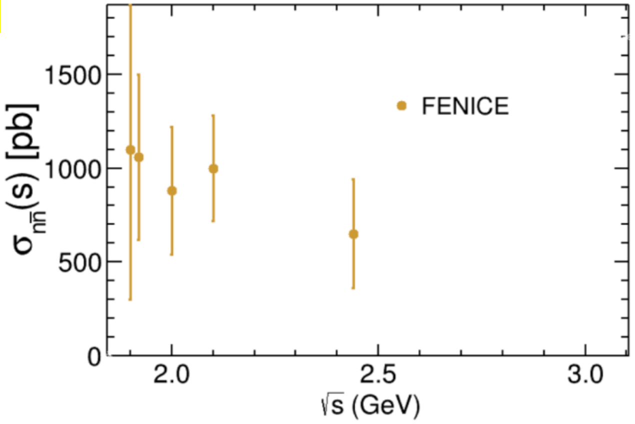
- Perturbative domain has not been reached.

E. Tomasi-Gustafsson et al., PRC 103, 035203 (2021)

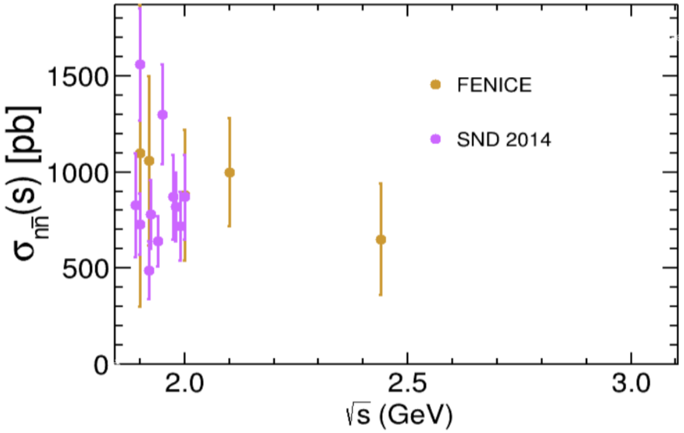
Timeline of Neutron EMFFs

Cross section

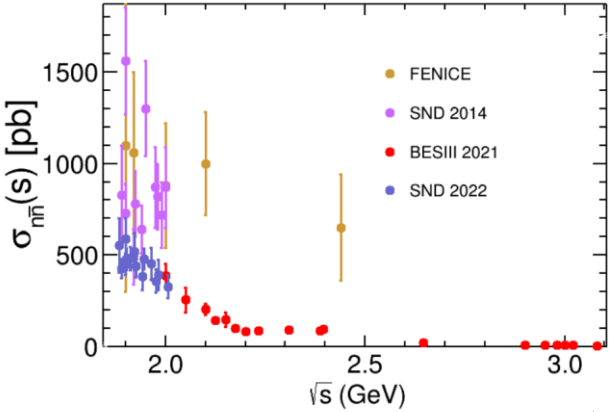
First result from FENICE, large cross section



SND scan near threshold, plateau behavior observed



BESIII and SND obtain precision results



Before 2000

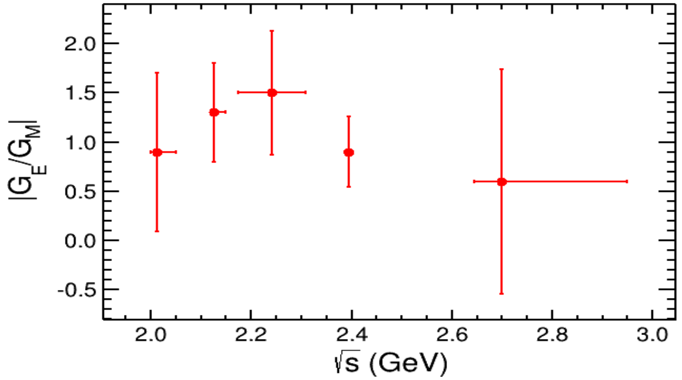
2000 to 2020

2020

Year

$|G_E/G_M|$

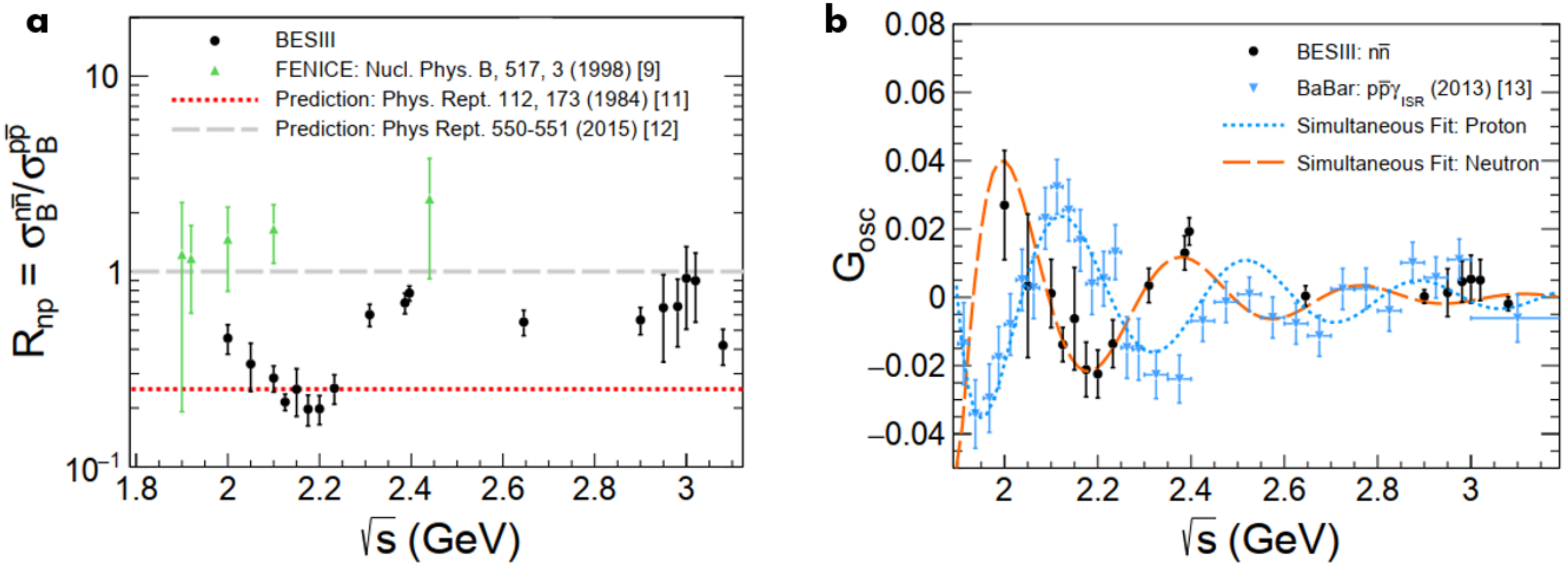
No experimental result



BESIII measured $|G_E/G_M|$ for the first time

Recent results of neutron EMFFs

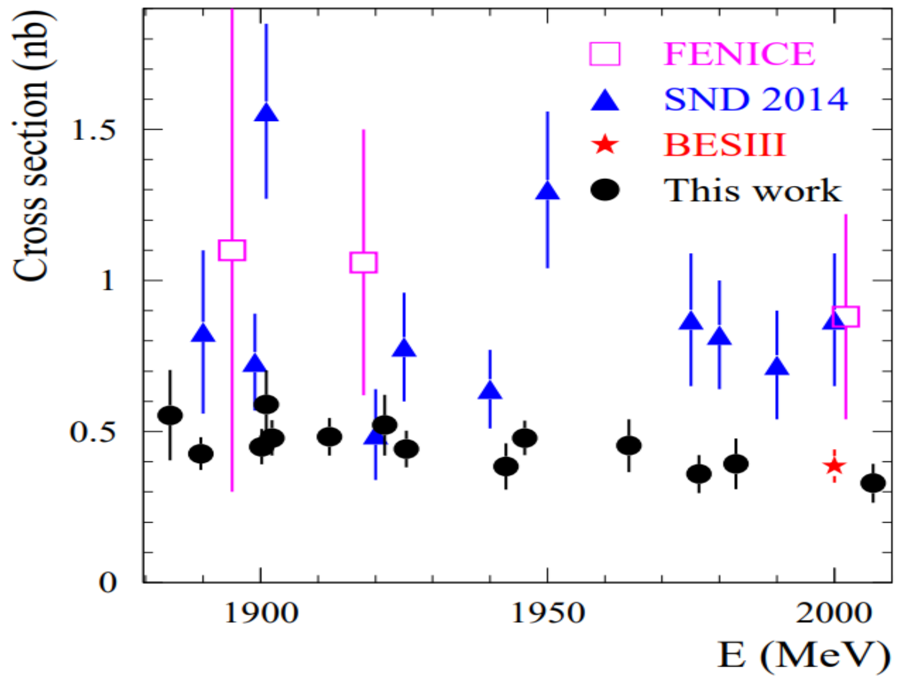
- $e^+e^- \to n\bar{n}$ from $\sqrt{s} = $ 2.0-3.08 GeV, 647.9 pb^{-1}.
- $\gamma - p$ coupling larger than $\gamma - n$ coupling => consistent with theoretical limits from VMD, Skyrme etc.
- Oscillation of reduced-|G| observed in neutron with a phase orthogonal to that of proton.

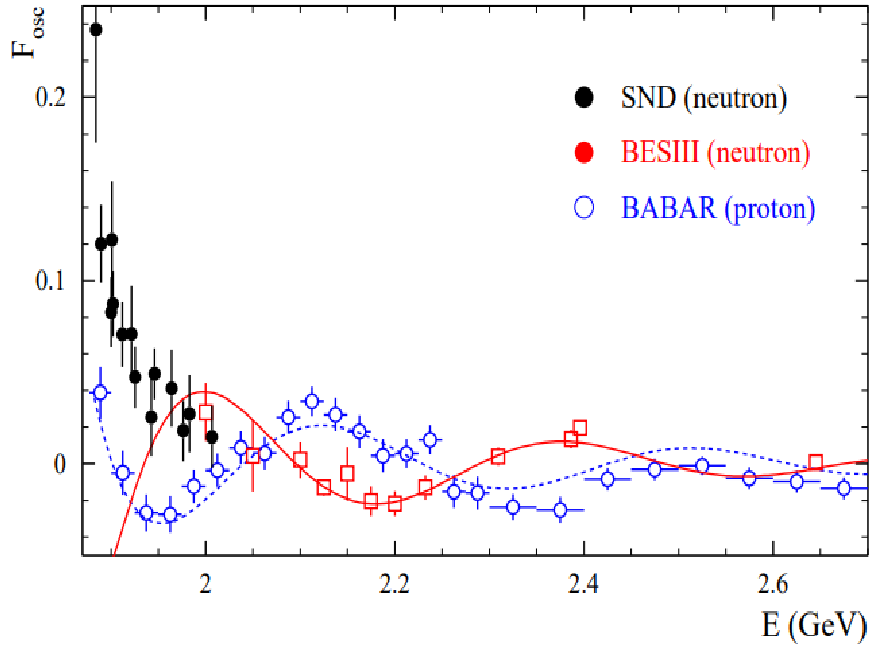


Nat. Phys. 17, 1200–1204 (2021)

Recent results of neutron EMFFs

- $e^+e^- \to n\bar{n}$ from $\sqrt{s} = 1.884$ to 2.007 GeV, ~30 pb^{-1}
- $\sigma \approx 0.4$ nb below 2 GeV. Similar plateau as in $e^+e^- \to p\bar{p}$.
- Reduced-|G| contracts the common proton /neutron oscillation frequency.



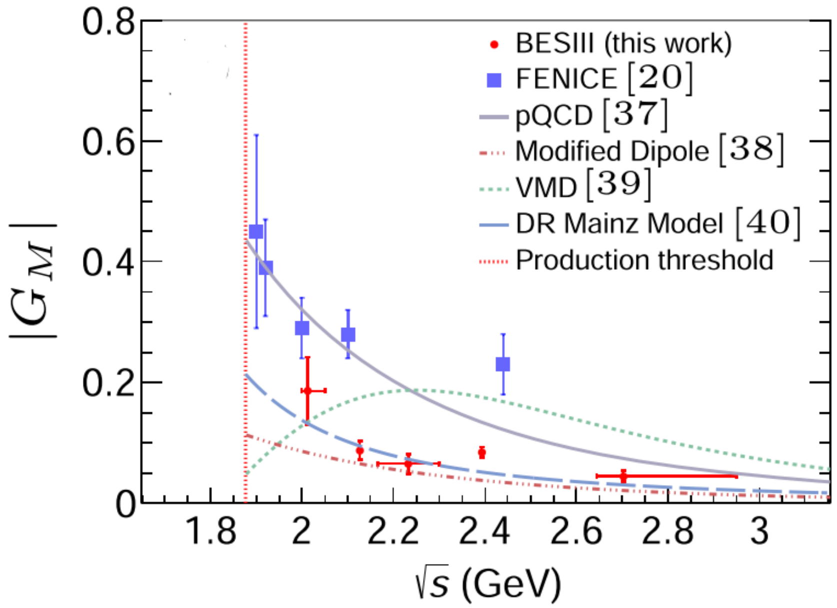


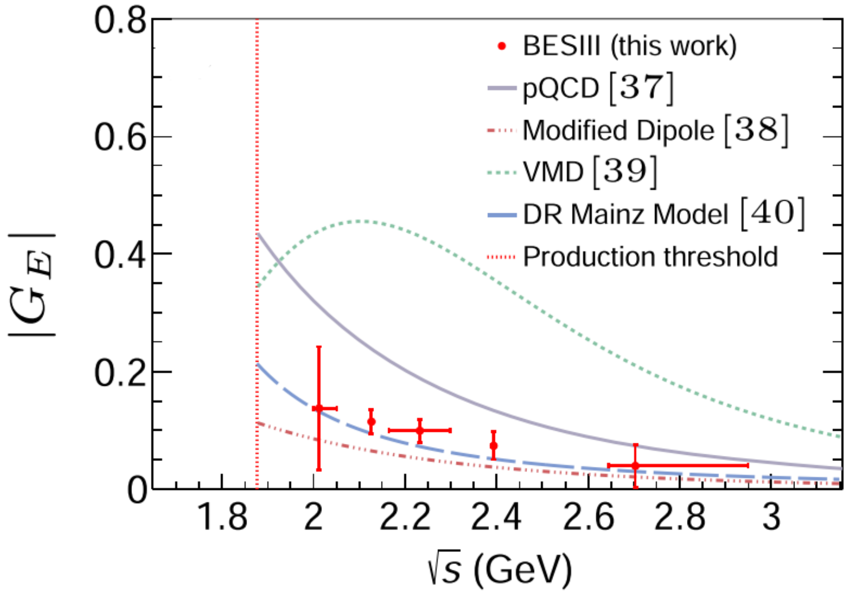
Eur.Phys.J.C 82 (2022) 8, 761

Recent results of neutron EMFFs

- 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)





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:

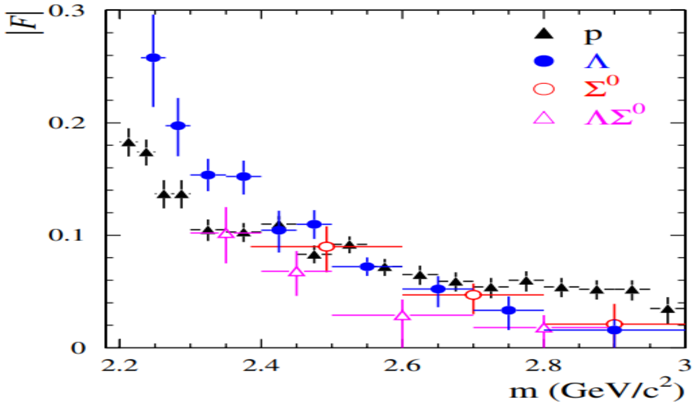
- Cross section can be obtained very close to threshold with finite PHSP of final state.
- With hyperon weak decay to B+P, the polarization of hyperon can be measured, so does the relative phase between G_E and G_M!

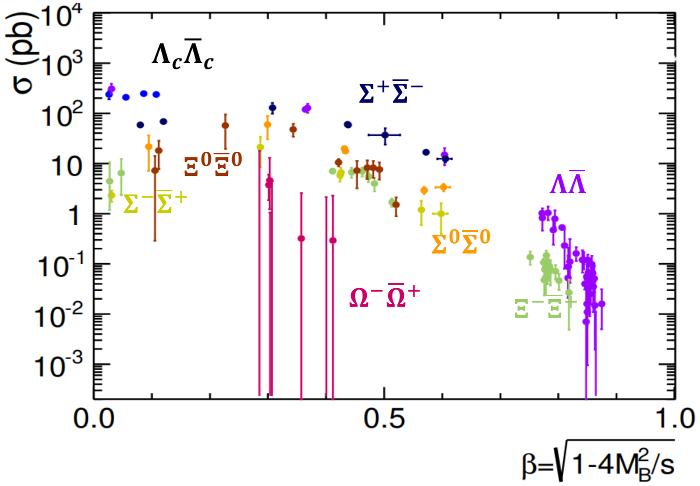
Timeline of hyperon EMFFs

Cross section

First hyperon result at 2.4 GeV from **DM2**
$\sigma(e^+e^- \to \Lambda\bar{\Lambda}) = 100^{+65}_{-35}$ pb
$\sigma(e^+e^- \to \Lambda\bar{\Sigma}^0 + c.c) < 75$ pb
$\sigma(e^+e^- \to \Sigma^0\bar{\Sigma}^0 + c.c) < 120$ pb

BaBar measured hyperon EMFFs via ISR

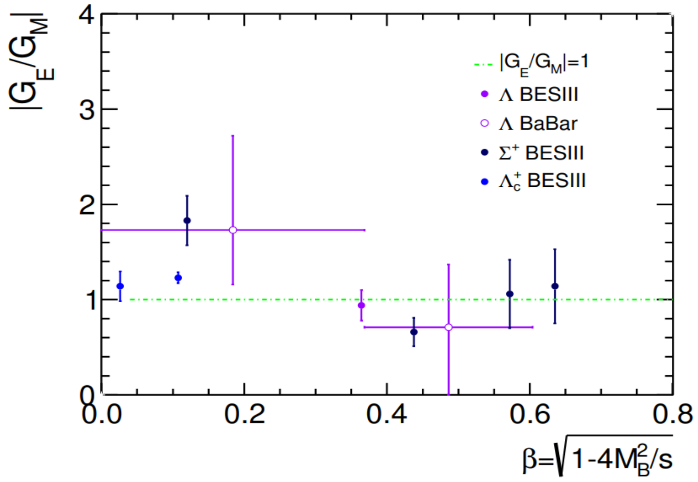




Before 2000 | **2000 to 2020** | **2020** | **Year**

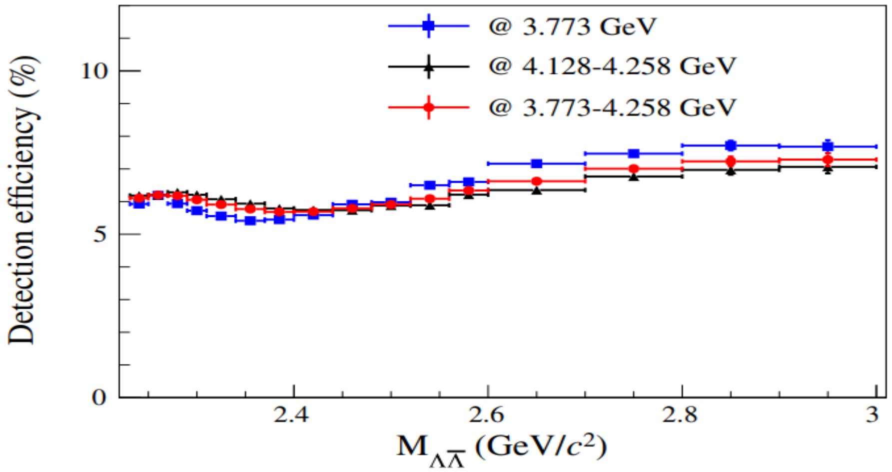
$|G_E/G_M|$

First $|G_E/G_M|$ and phase from **BaBar**
$$\left|\frac{G_E}{G_M}\right| = 1.73^{+0.99}_{-0.57} \text{ for } 2.23\text{-}2.40 \text{ GeV/c}^2$$
$$\left|\frac{G_E}{G_M}\right| = 0.70^{+0.66}_{-0.71} \text{ for } 2.40\text{-}2.80 \text{ GeV/c}^2$$
$$-0.76 < \sin\phi < 0.98$$



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.

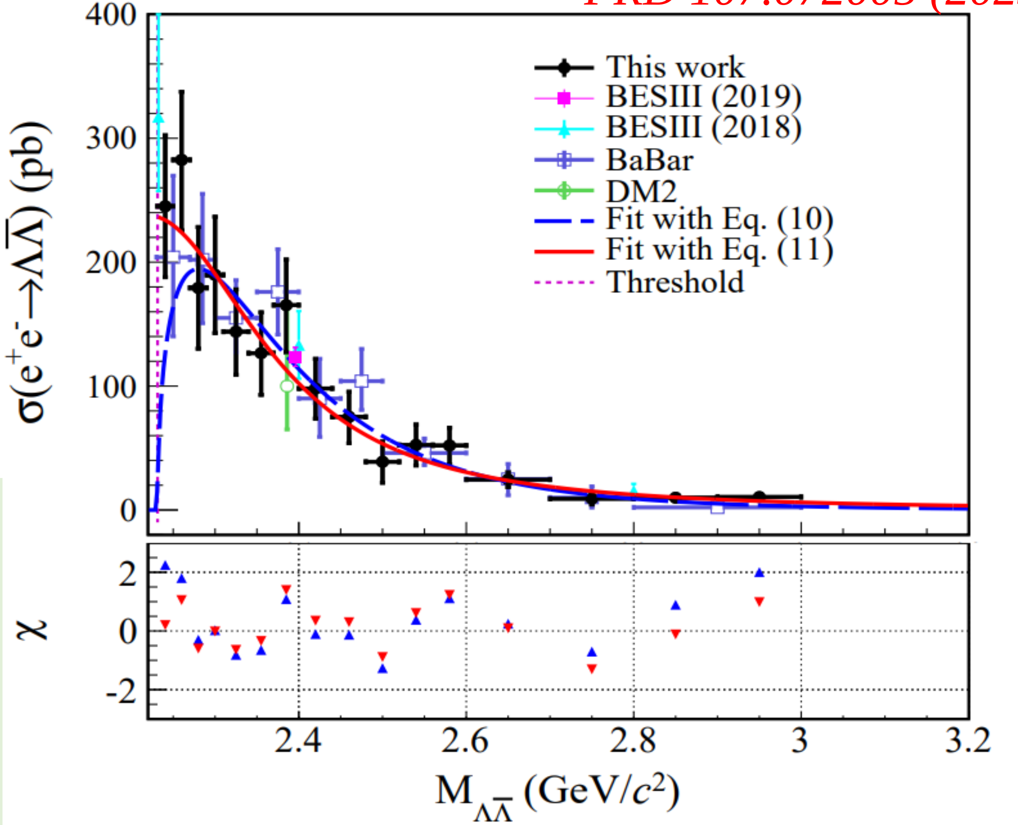


BESIII scan: $312 \pm 45^{+66}_{-36}$ pb at 2.2324 GeV (1 MeV above threshold)

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

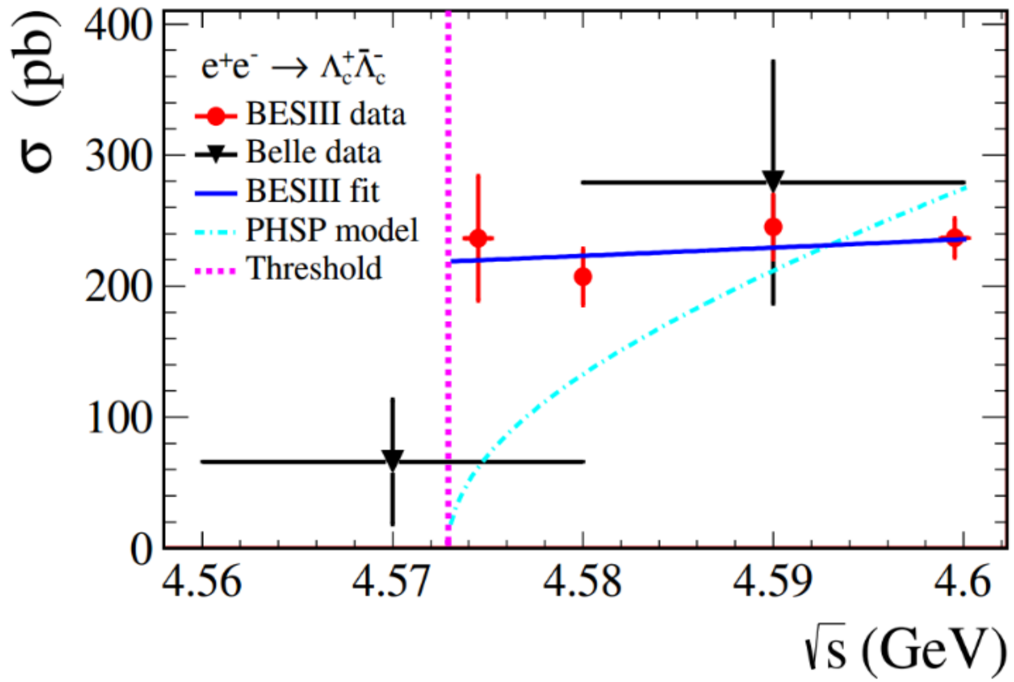
PRD 107.072005 (2023)

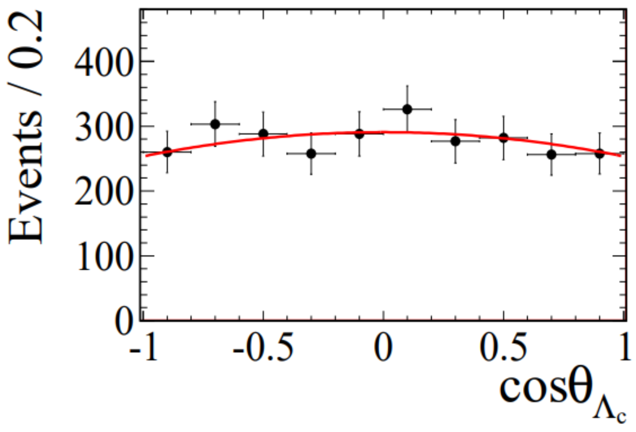


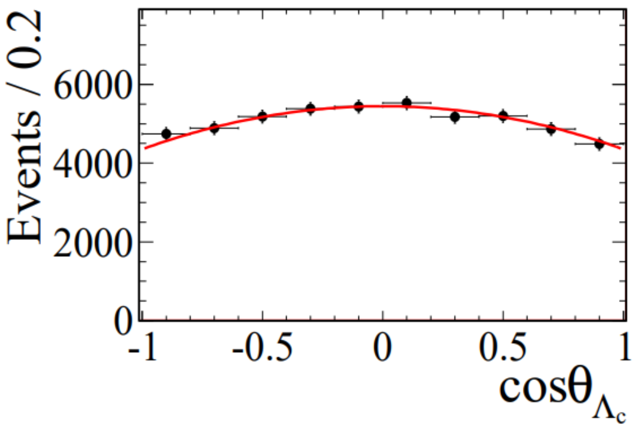
Cross section of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- The BESIII measurements indicate that there is indeed a step in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$, 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	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

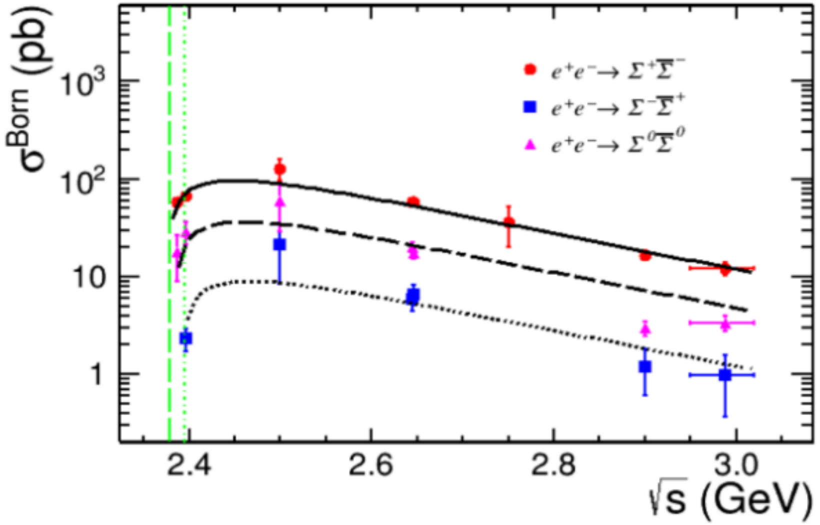
Cross section of $e^+e^- \to \Sigma\bar{\Sigma}$

- Born cross sections of $e^+e^- \to \Sigma^+\bar{\Sigma}^-, \Sigma^-\bar{\Sigma}^+, \Sigma^0\bar{\Sigma}^0$ are measured from threshold to $\sqrt{s} = 3.02$ GeV
  - The cross sections can be well described by pQCD-motivated functions

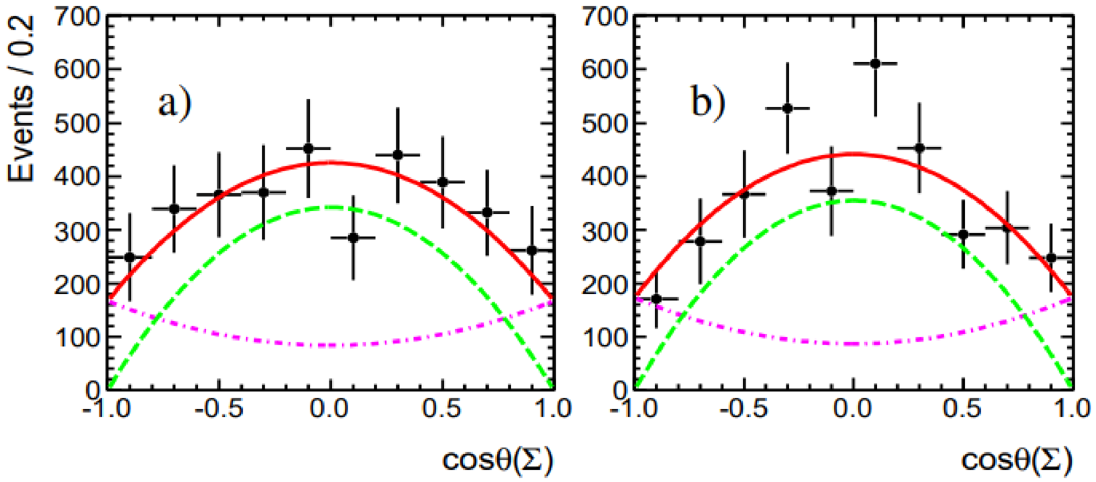
$$\sigma^{\mathrm{B}}(s) = \frac{\beta C}{s}\left(1+\frac{2m_B^2}{s}\right)\frac{c_0}{(s-c_1)^4(\pi^2+\ln^2(s/\Lambda_{\mathrm{QCD}}^2))^2}$$

  - An asymmetry in cross sections for Σ isospin triplets: 9.7 ± 1.3 : 3.3 ± 0.7 : 1 =>related with valence quark?

$\Sigma^{\pm}\bar{\Sigma}^{\mp}$:PLB 814, 136110 (2021)
$\Sigma^0\bar{\Sigma}^0$:PLB 831, 137187 (2022)



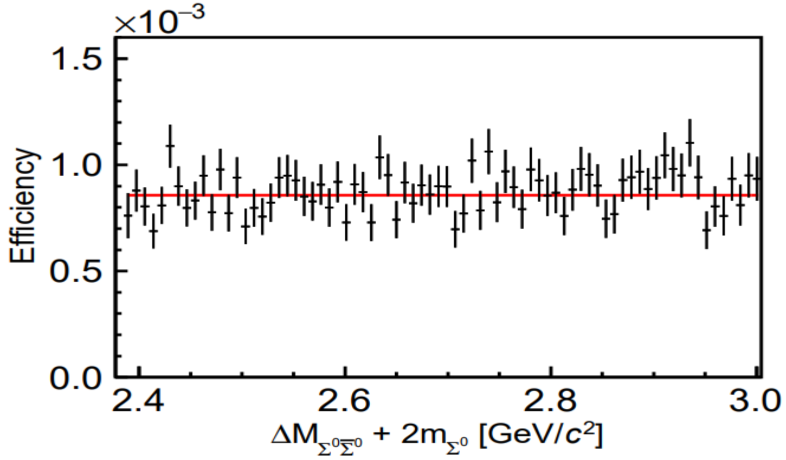
$\left|\frac{G_E}{G_M}\right| = 1.83 \pm 0.26$, Σ^+ @ 2.396 GeV

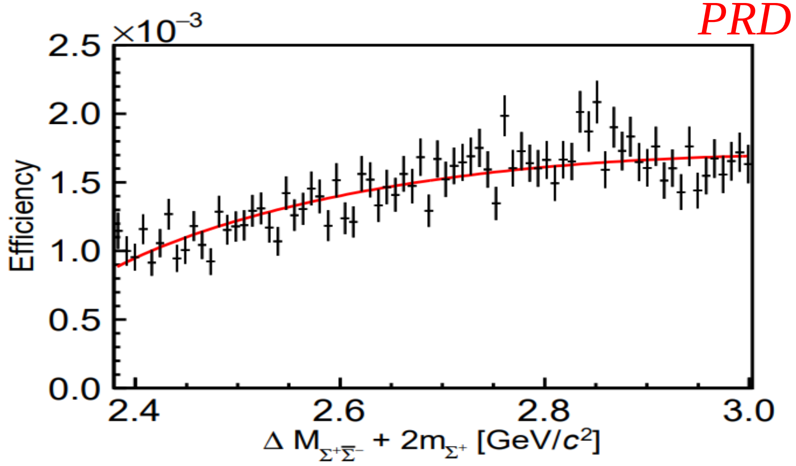


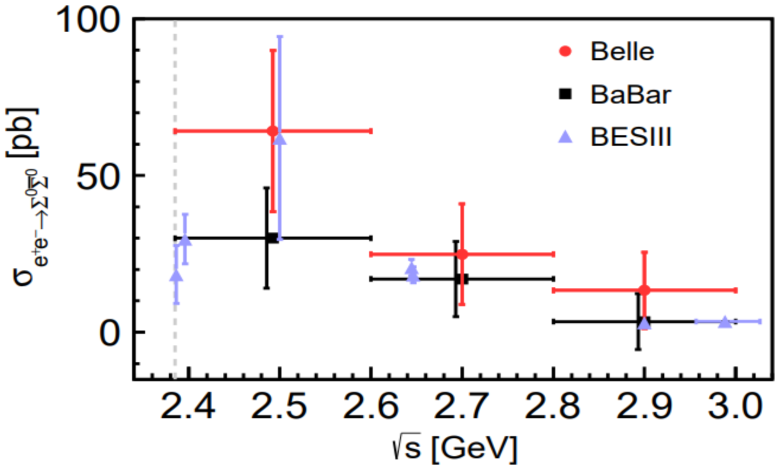
Cross section of $e^+e^- \to \Sigma\bar{\Sigma}$

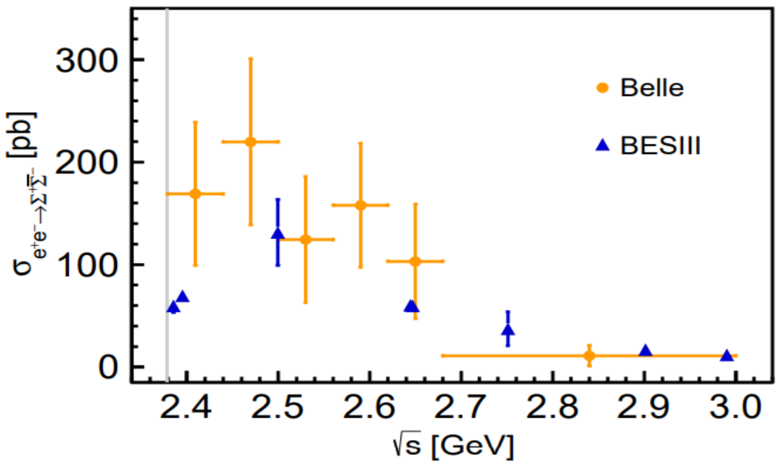
- Measured cross sections are consistent with previous measurements, with 980 fb^{-1} data collected at $\sqrt{s}$ from $\Upsilon(1S)$ to $\Upsilon(5S)$.
- Filling the gap of cross section in 2.4~2.5 GeV/c^2 and 2.5~2.6 GeV/c^2.

PRD 107 072008(2023)





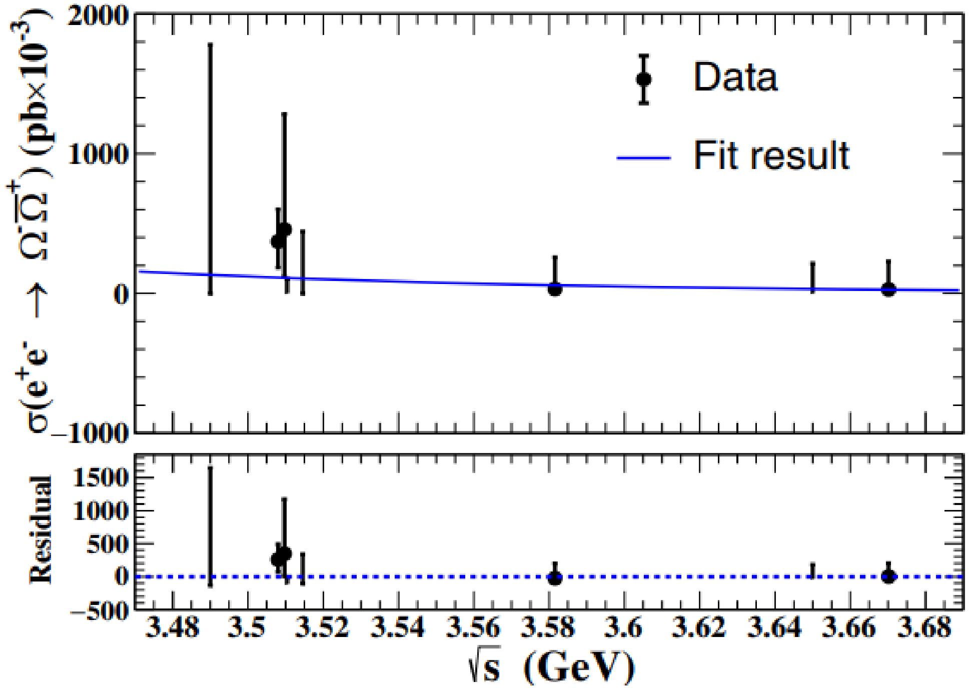




Cross section of $e^+e^- \to \Omega\bar{\Omega}/\Delta\bar{\Delta}$

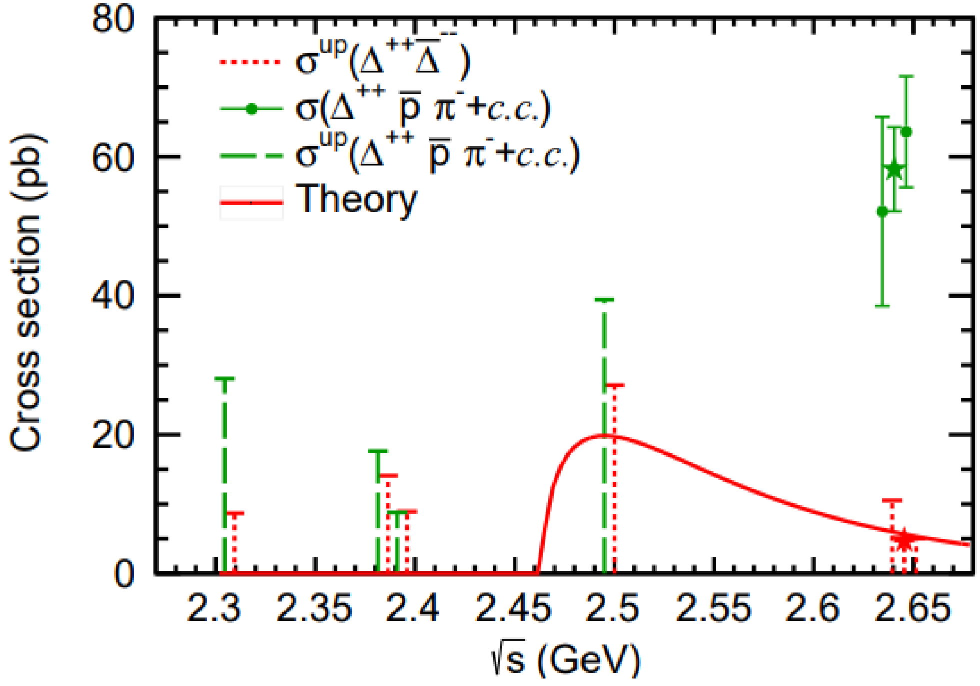
- Born cross sections of $e^+e^- \to$ $\Omega^-\bar{\Omega}^+$ at 8 energy points between $\sqrt{s} = 3.49$ and 3.67 GeV.
  - No significant signal observed.
  - Upper limit of effective FF is consistent with pQCD driven prediction.

PRD 107, 052003, 2023



- $e^+e^- \to \Delta^{++}\bar{\Delta}^{--}$ 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



Complete measurement of Λ EMFFs

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

$$\omega(\xi,\Delta\Phi,\alpha_\psi,\alpha_-,\alpha_\gamma) = 1+\alpha_\psi cos^2\theta_\Lambda$$

Unpolarized part

$$+\alpha_-\alpha_\gamma[sin^2\theta_\Lambda(n_{1,x},n_{2,x}-\alpha_\psi n_{1,y},n_{2,y})+(cos^2\theta_\Lambda+\alpha_\psi)n_{1,z},n_{2,z}]$$
$$+\alpha_-\alpha_\gamma\sqrt{1-\alpha_\psi{}^2}\,cos(\Delta\Phi)\,sin\theta_\Lambda cos\theta_\Lambda(n_{1,x},n_{2,z}+n_{1,z},n_{2,x})$$

Correlated part

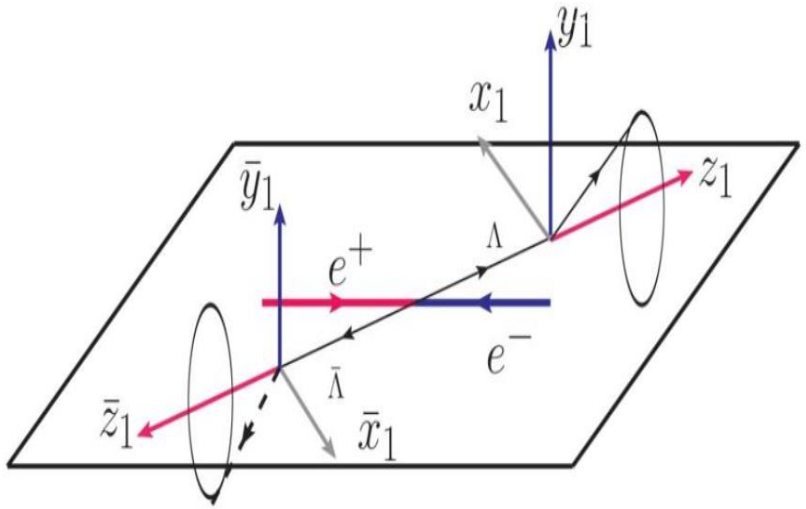
$$+\sqrt{1-\alpha_\psi{}^2}\,sin(\Delta\Phi)\,sin\theta_\Lambda cos\theta_\Lambda(\alpha_- n_{1,y}+\alpha_\gamma n_{2,y})$$

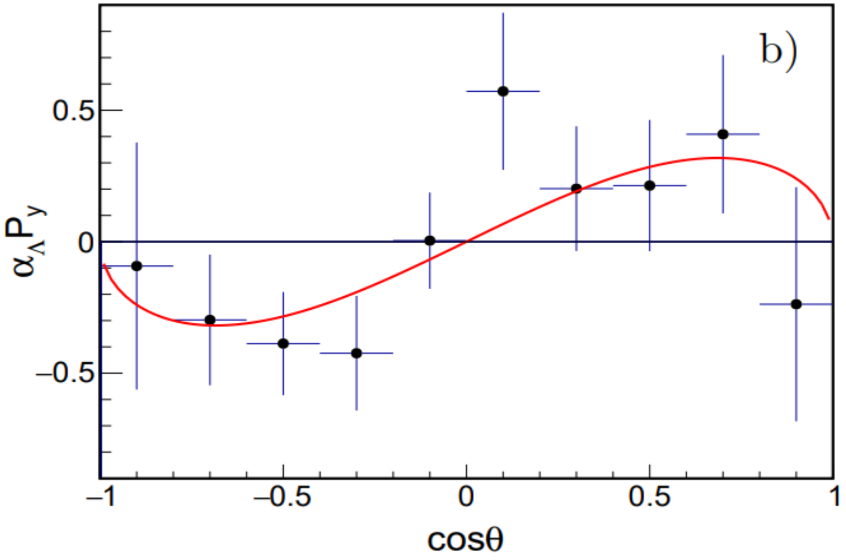
Polarized part

$$\left|\frac{G_E}{G_M}\right| = 0.96\pm0.14(\text{stat.})\pm0.02(\text{sys.})$$

$$\Delta\Phi = 37^\circ\pm12^\circ(\text{stat.})\pm6^\circ(\text{sys.})$$

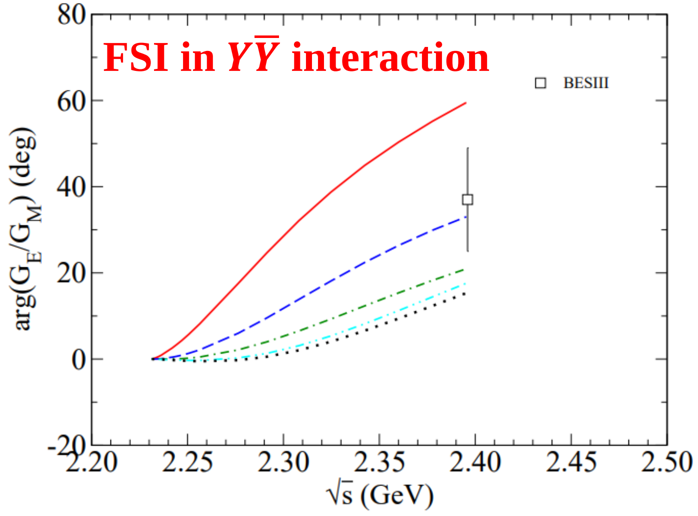
(Confirm the complex form of EMFFs)



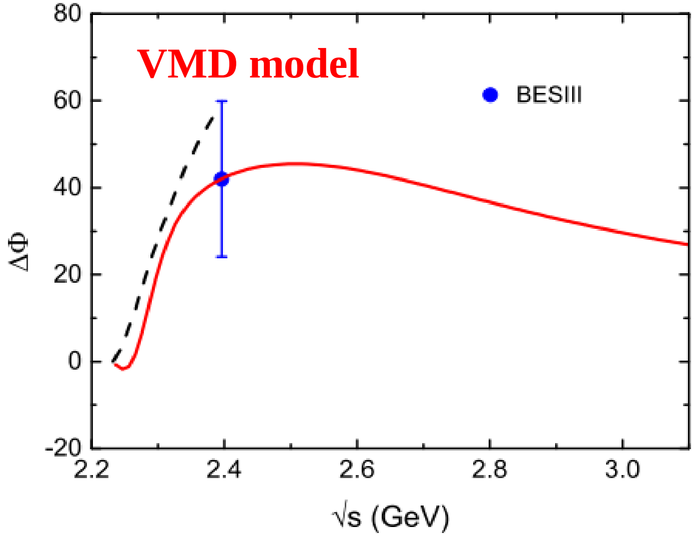


$|G_E/G_M|$ phase from various models

PRD 103, 014028 (2021)

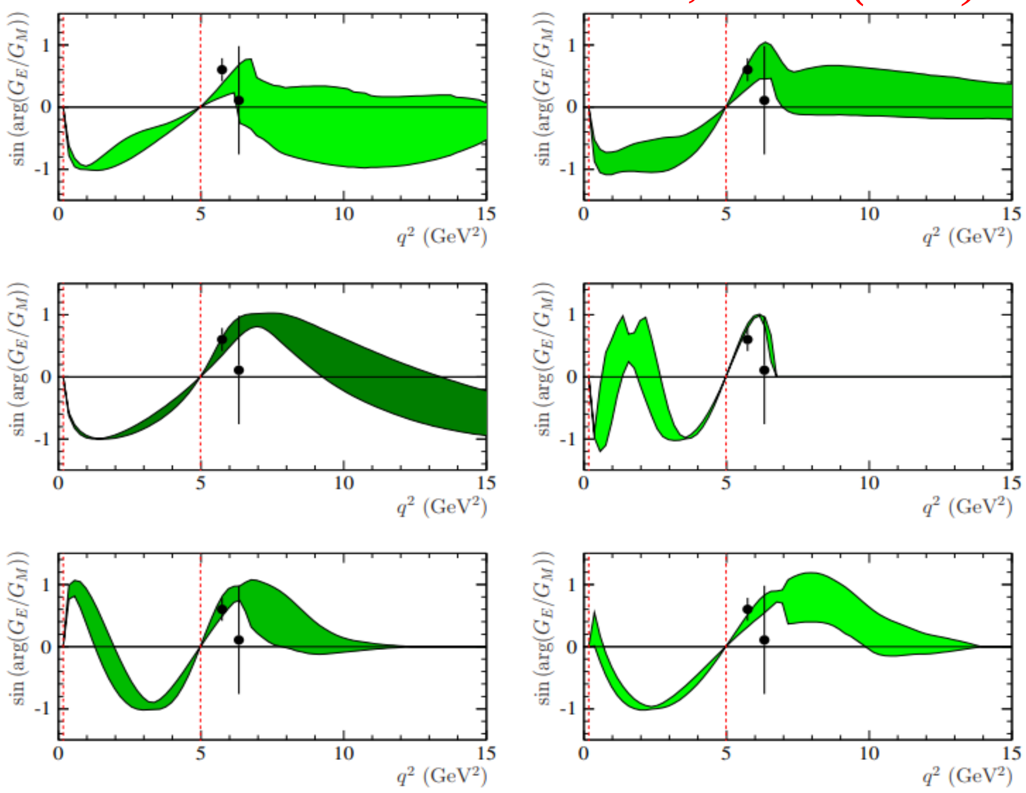


PRD 100, 073007(2019)



Dispersion relations

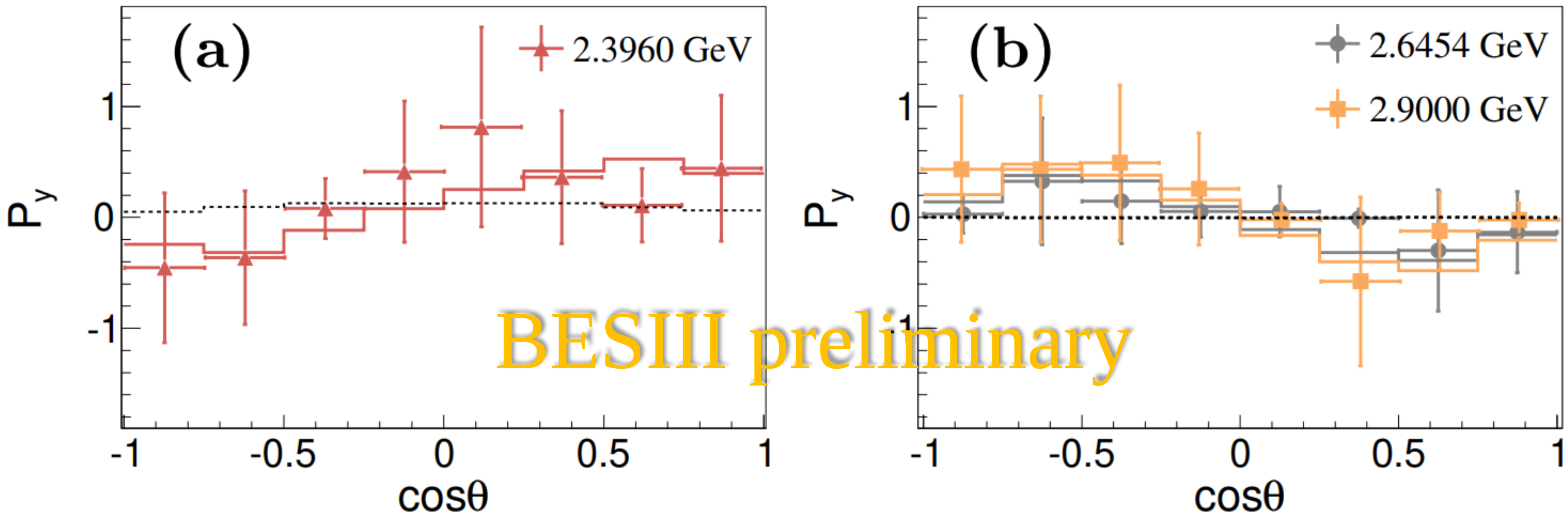
PRD 104,116016 (2021)



- Measurement of relative phase in a wide q^2 range would be crucial to enhance the predictive power of various model and test its asymptotic behavior in TL.

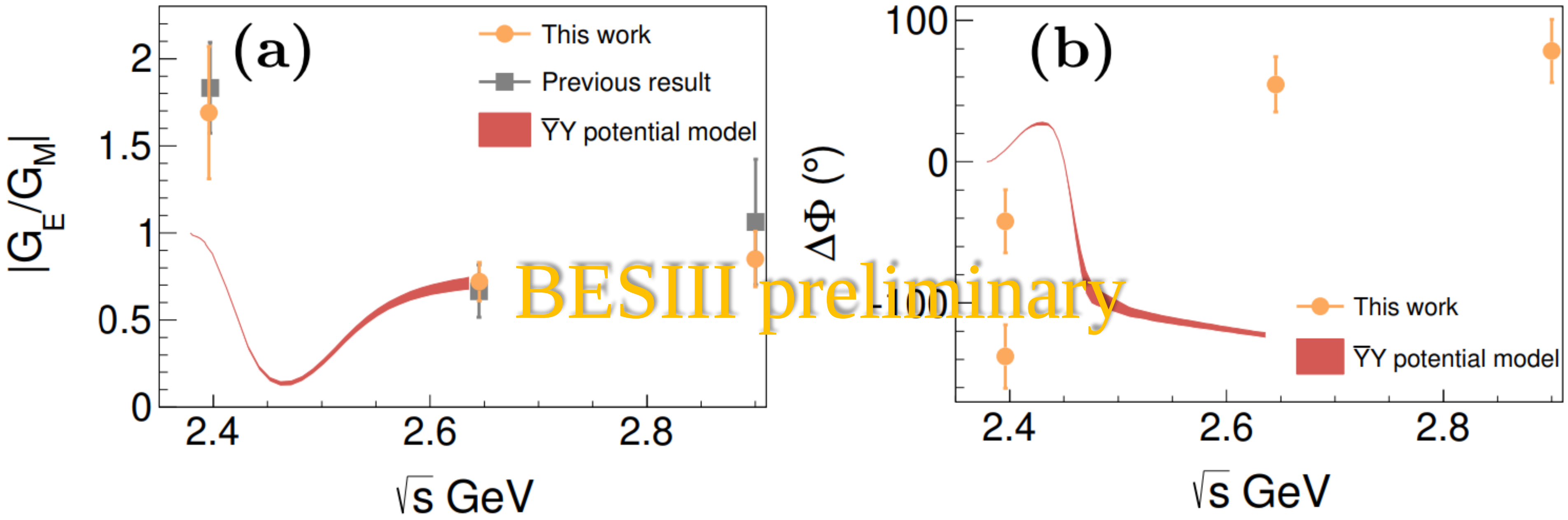
Complete measurement of Σ^+ EMFFs

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



Complete measurement of Σ^+ EMFFs

- $|G_E/G_M|$ and $\Delta\Phi$ line-shape is compared with $\bar{Y}Y$ model (J. Haidenbauer, U. G. Meißner, and L. Y. Dai, PRD 103, 014028 (2021)), different tendency in $\Delta\Phi$.
- $\Delta\Phi$ distribution indicates there are integer multiples of π radians, from threshold to cross point.
- The still increasing relative phase indicates the asymptotic threshold has not yet been reached.



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.
- The asymptotic behavior of baryon EMFFs have been tested, and the asymptotic threshold is not yet reached.

Thank you!