第八届R值与QCD强子结构研讨会

Determination of the Σ^+ timelike electromagnetic form factors

Based on Phys.Rev.Lett. 132, 081904 (2024) 8

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(On behalf of BESIII Collaboration)

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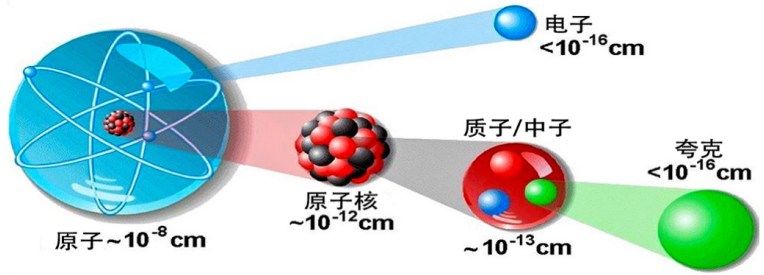
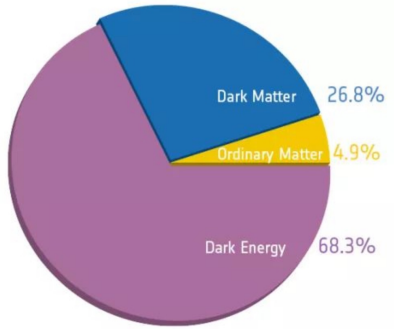
Outline

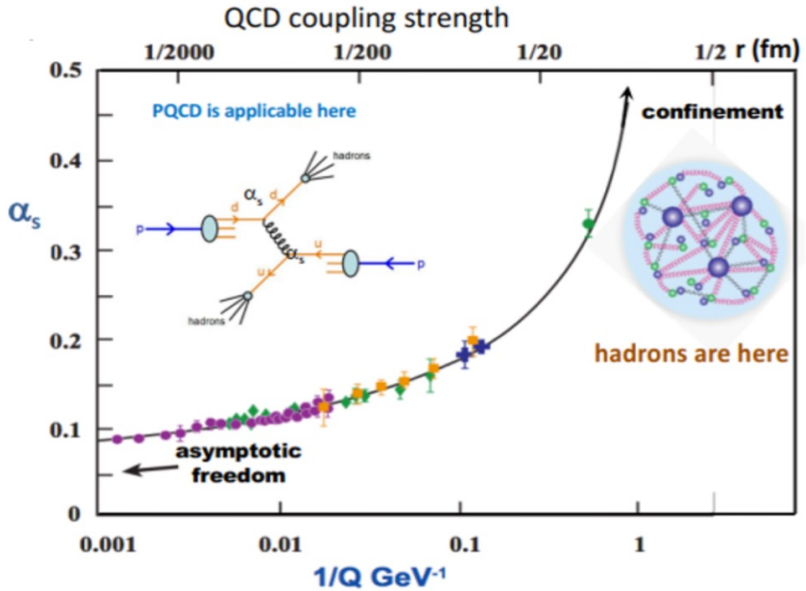
- **Introduction**
- **Study of Σ^+ TL EMFFs at BESIII**
- **Summary**

Introduction| Internal structure of nucleons

- The proton (uud) and the neutron (udd) are collectively referred to as nucleons, and they are the lightest baryons. They make up over 99% of visible matter in the universe





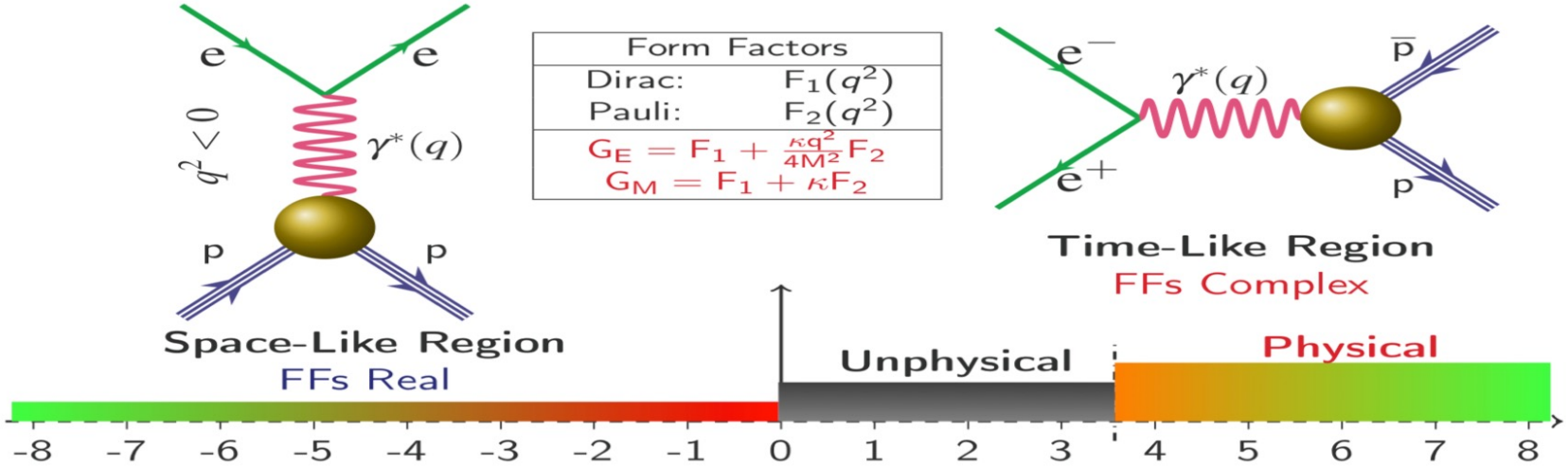


- At low Q, perturbative QCD does not work well (expansion of coupling constant α_S)

Nucleon structure must be measured in experiments!

Introduction| Electromagnetic form factors (EMFFs)

- Fundamental properties of the baryon
  - Connected to charge, magnetization distribution
  - Crucial testing ground for models of the baryon internal structure



- The baryon electromagnetic vertex Γ_μ describing the hadron current:

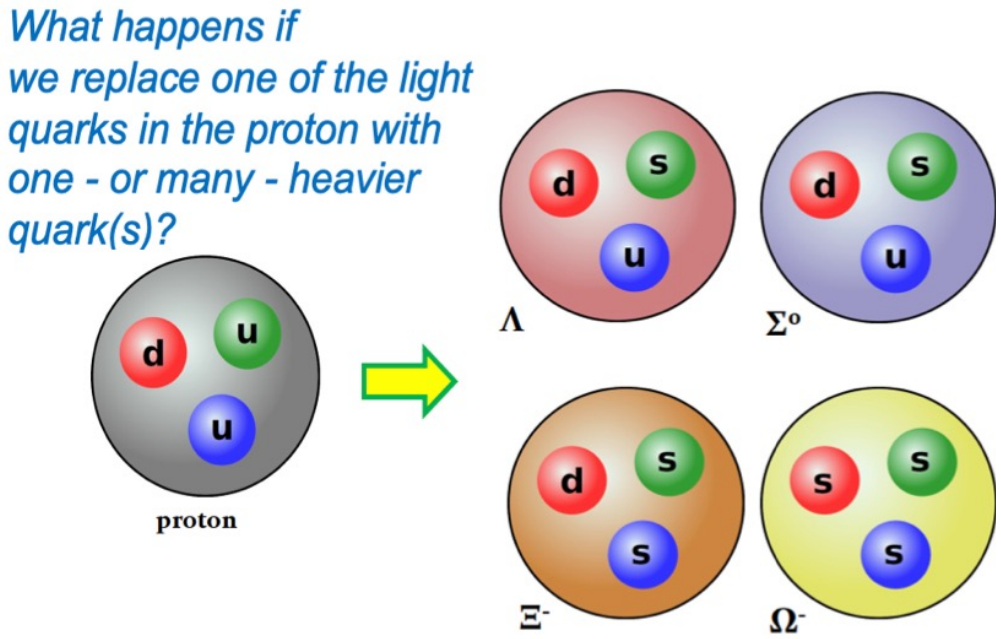
$$\Gamma_\mu(p',p) = \gamma_\mu F_1(q^2) + \frac{i\sigma_{\mu\nu}q^\nu}{2m}F_2(q^2)$$

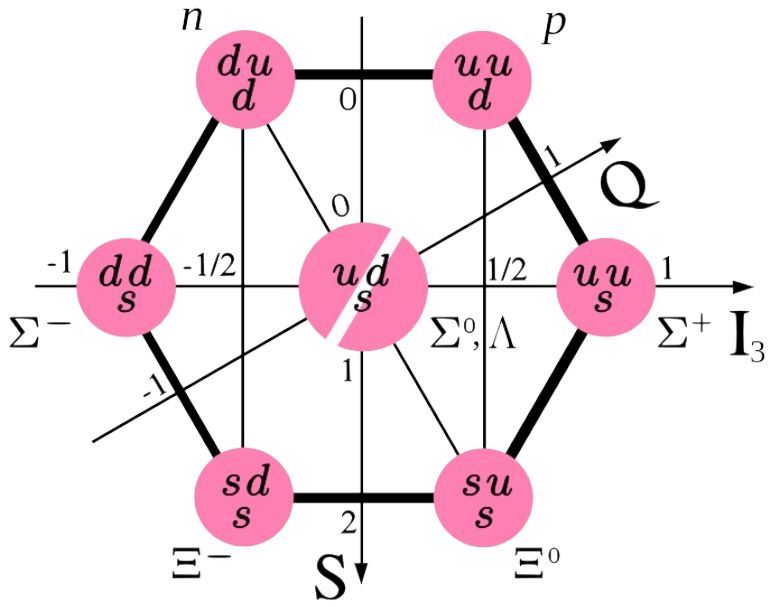
Sachs FFs: $G_E(q^2) = F_1(q^2) + \frac{q^2}{4m}F_2(q^2),\ G_M(q^2) = F_1(q^2) + F_2(q^2)$

- Dispersion relation: $F(t) = \frac{1}{\pi}\int_{t_0}^{\infty}\frac{ImF(t')}{t'-t-i\epsilon}dt',\ |G_{M,E}(-\infty)| = |G_{M,E}(\infty)|$

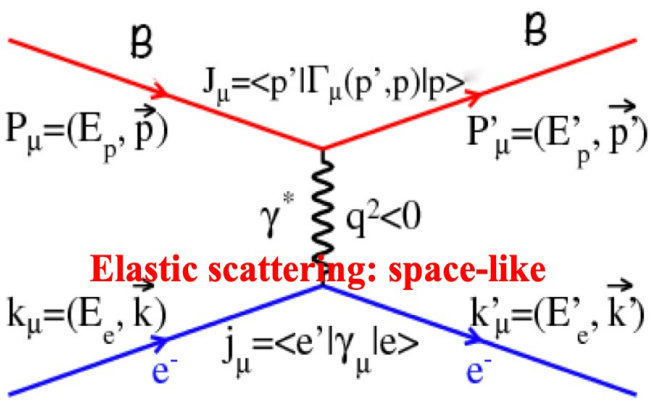
Introduction| Electromagnetic form factors (EMFFs)

- Hyperons and nucleons have very similar quark compositions
- Research on hyperons can provide more information about the baryon system



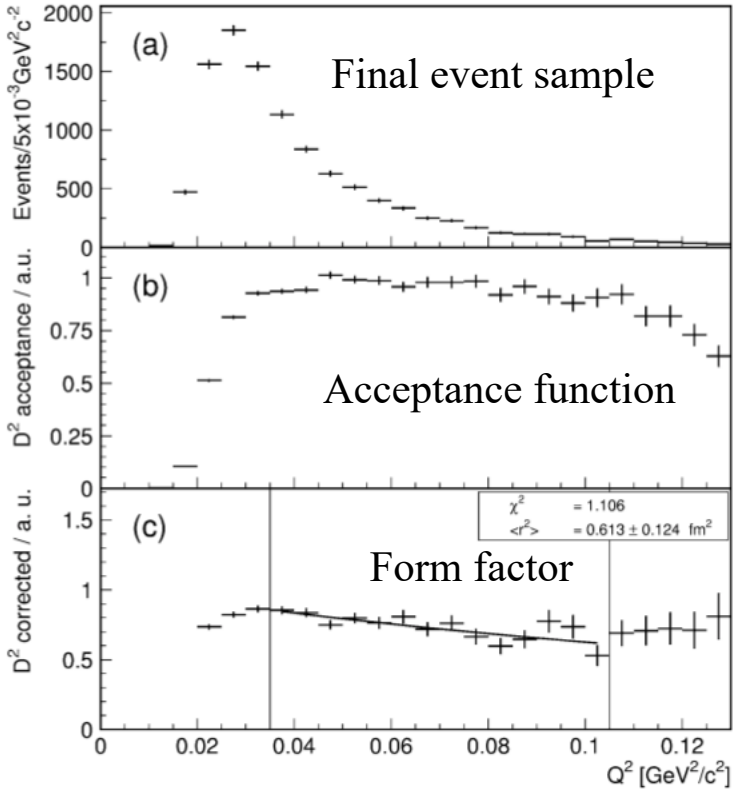


Introduction| Spacelike(SL) EMFFs of hyperon

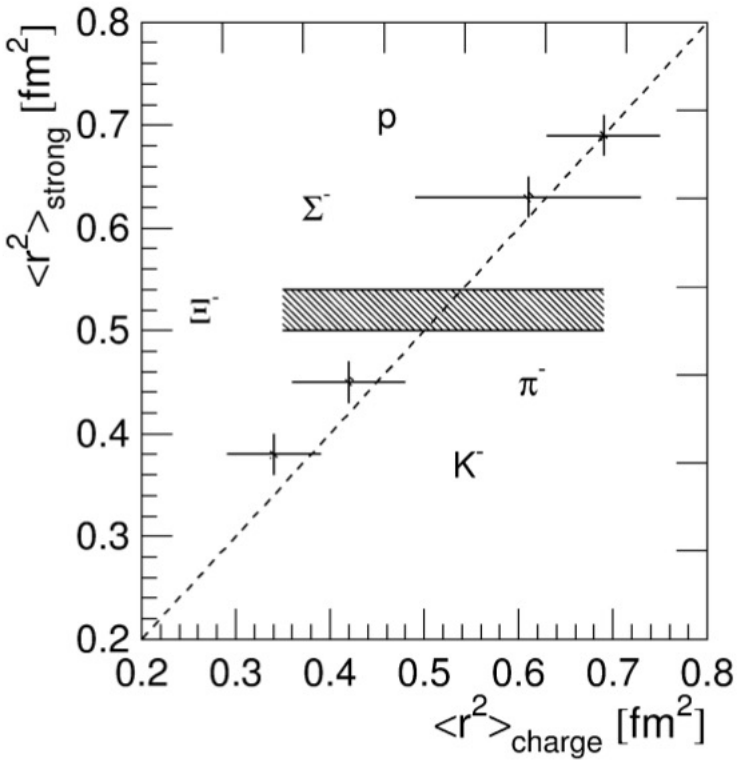


Difficult to produce stable and high-quality hyperon beams

SELEX (E781) experiment



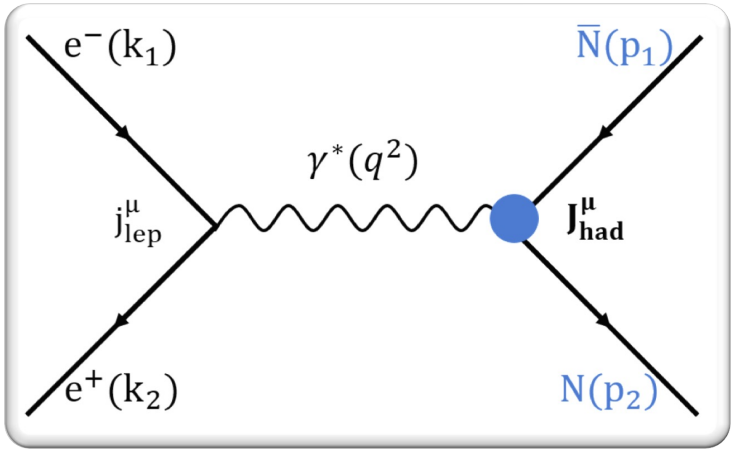
Phys. Lett. B 522, 233-239 (2001)



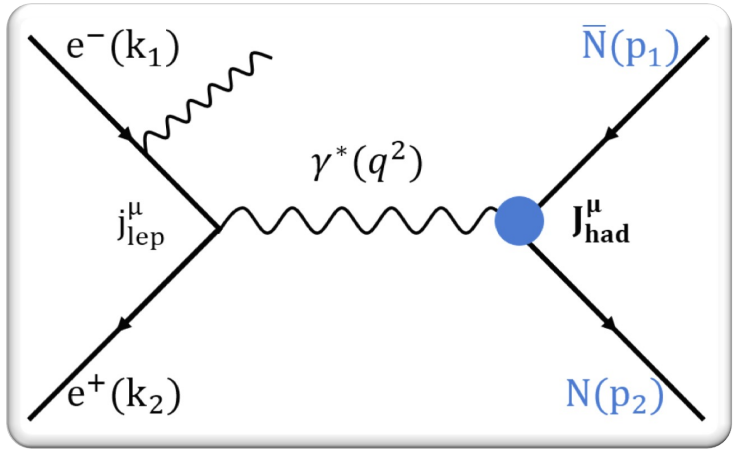
- Only one experiment by elastic scattering of a Σ^- beam off atomic electrons
- Due to kinematic constraints, the range of $|q^2|$ for exploring EMFFs is limited

Introduction| Timelike(TL) EMFFs of hyperon

Energy scan



Initial-state-radiation

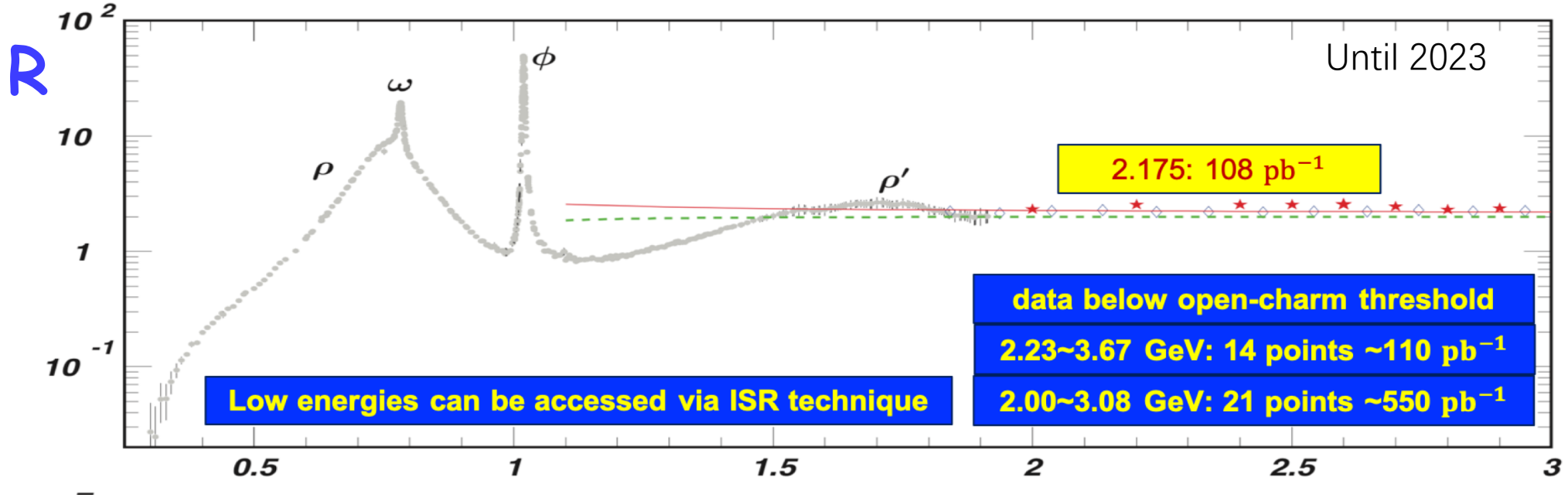


	Energy Scan	Initial State Radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\alpha^2\beta C}{4q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dx d\theta_\gamma} = W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
q^2	single at each beam energy	from threshold to s

$\sim \frac{1}{400}$

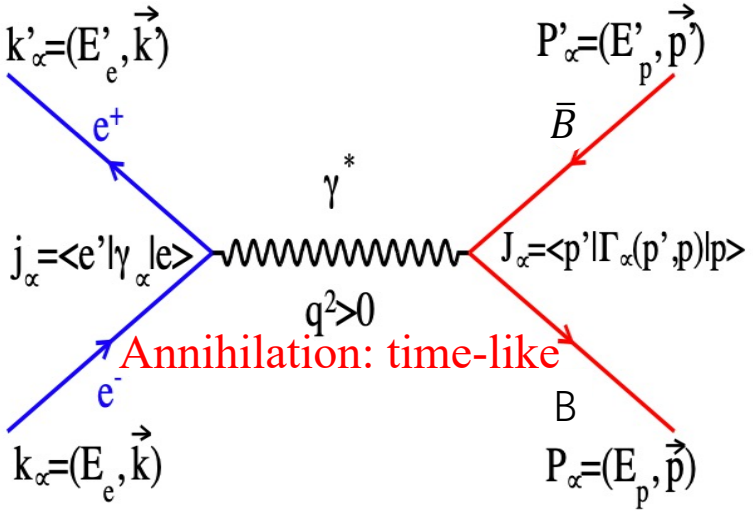
Both techniques, energy scan and initial state radiation, can be used at BESIII

Introduction| Data Samples Collected at BESIII



- R-scan (2.000-3.080 GeV, ~650 pb^{-1})
- BESIII provides an ideal platform for complete determination of the hyperon timelike EMFFs

Introduction| Complete information of TL EMFFs



The hyperons can be produced in e^+e^- annihilation above their production threshold

- Born cross section($e^+e^- \to B\bar{B}$ via one-photon exchange):

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

- Ratio $|G_E/G_M|$ reflects polar angle distribution of produced baryon!
- In the time-like region

$$G_E(q^2) = |G_E(q^2)|e^{i\Phi_E};$$

$$G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$$

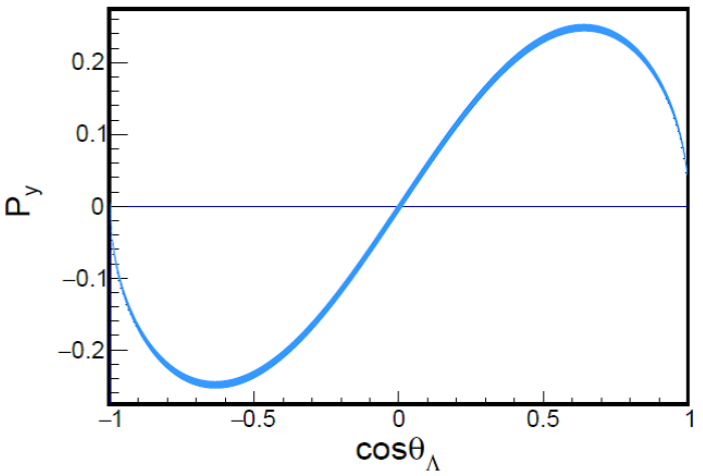
- Relative phase: $\Delta\Phi = \Phi_E - \Phi_M$

Introduction| Complete information of TL EMFFs

- A non-zero phase has polarization effect on the hyperon, $P_y \propto \sin(\Delta\Phi)$

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

Phys. Lett. B 772, 16-20 (2017)

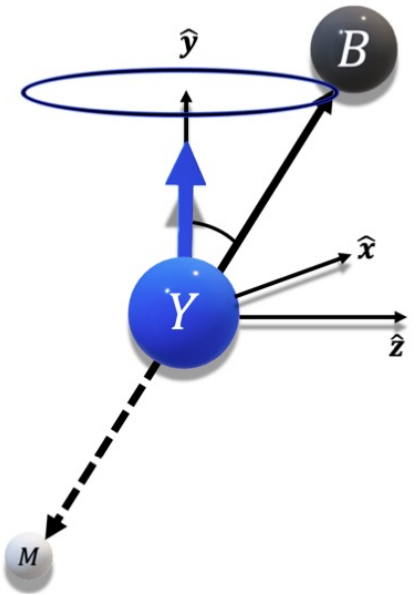


- The angular distribution of daughter baryon from Hyperon weak decay is:

$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_Y P_y \cdot \hat{q}$

  - α_Y asymmetry parameter
  - $\hat{q}$: unit vector along the daughter baryon in hyperon rest frame

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



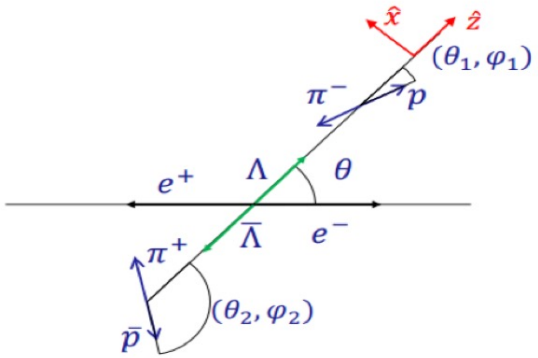
- With hyperon weak decay to Baryon+Meson, the complete information of TL EMFFs

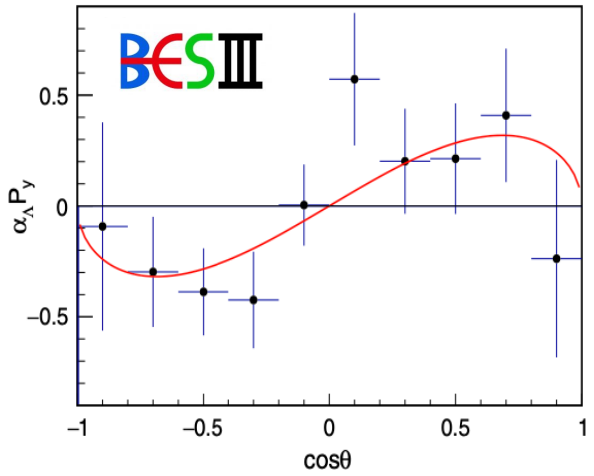
(ratio $|G_E/G_M| = \sqrt{\frac{q^2}{4m_\Sigma^2}}\sqrt{\frac{1-\alpha}{1+\alpha}}$ and relative phase $\Delta\Phi$) can be determined!

Introduction| Experimental status of hyperon TL EMFFs

- Λ EMFFs
  - The first complete measurement of the EMFFs of the hyperon at 2.3960 GeV

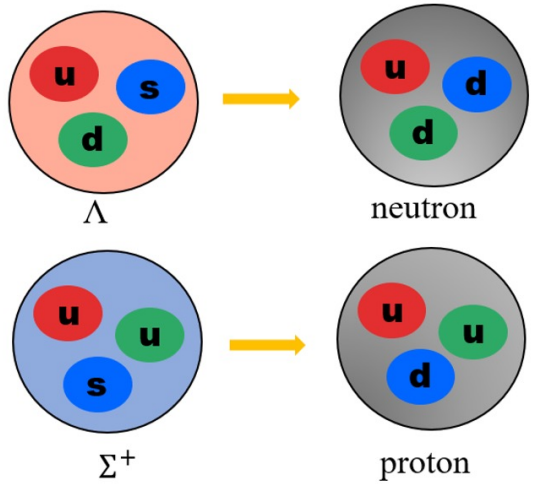
$|G_E/G_M| = 0.96 \pm 0.14(\text{stat.}) \pm 0.02(\text{syst.})$
$\Delta\Phi = 37° \pm 12°(\text{stat.}) \pm 6°(\text{syst.})$
(Confirm the complex form of EMFFs)
Phys. Rev. Lett. 123, 122003 (2019)





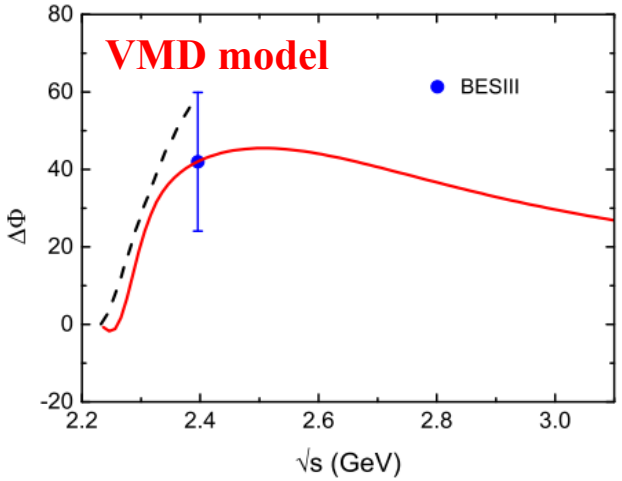
- Σ EMFFs
  - Only Σ^+ $|G_E/G_M|$ is available, the experimental complete extraction of Σ EMFFs is lack yet ($\Delta\Phi$ =?)

$|G_E/G_M| = 1.83 \pm 0.26 \pm 0.24$ at 2.3960 GeV
$|G_E/G_M| = 0.66 \pm 0.15 \pm 0.11$ at 2.6454 GeV
$|G_E/G_M| = 1.06 \pm 0.36 \pm 0.09$ at 2.9000 GeV
Phys. Lett. B 814 136110 (2021)

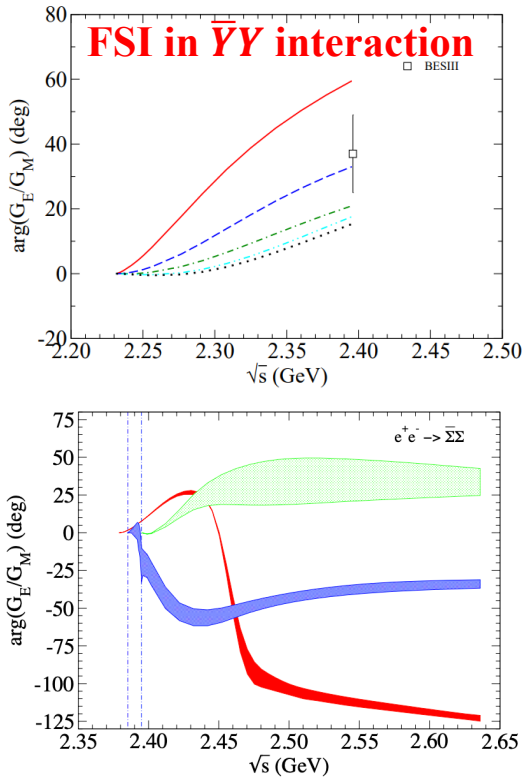


Introduction| Relative phase from various models

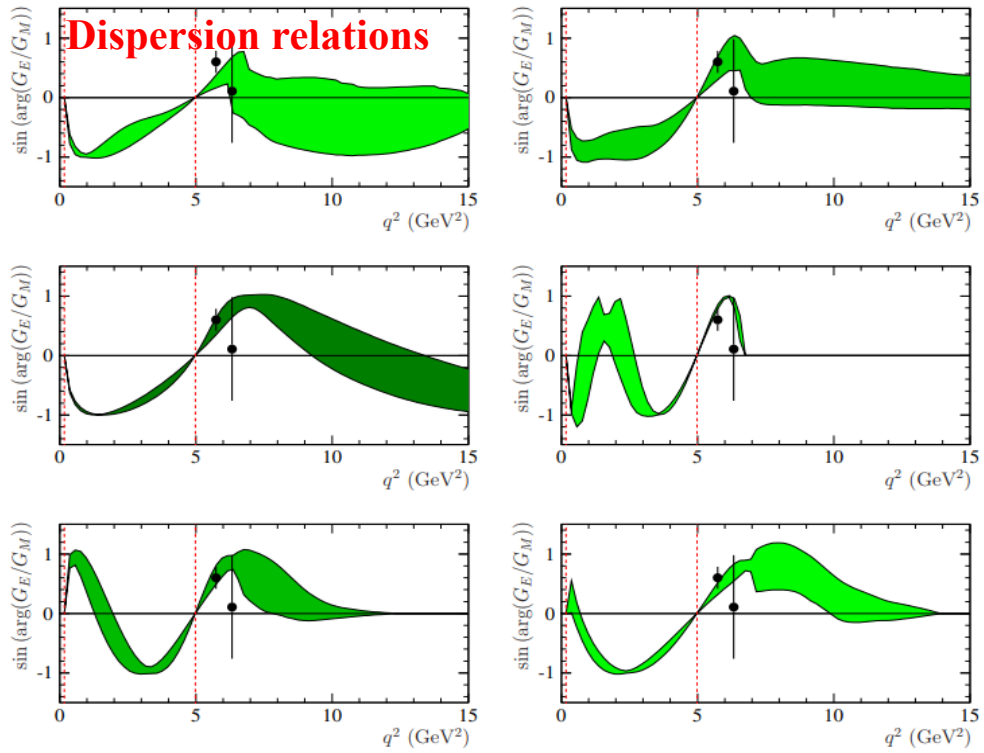
Phys. Rev. D 100, 073007(2019)



Phys. Rev. D 103, 014028 (2021)



Phys. Rev. D 104,116016 (2021)

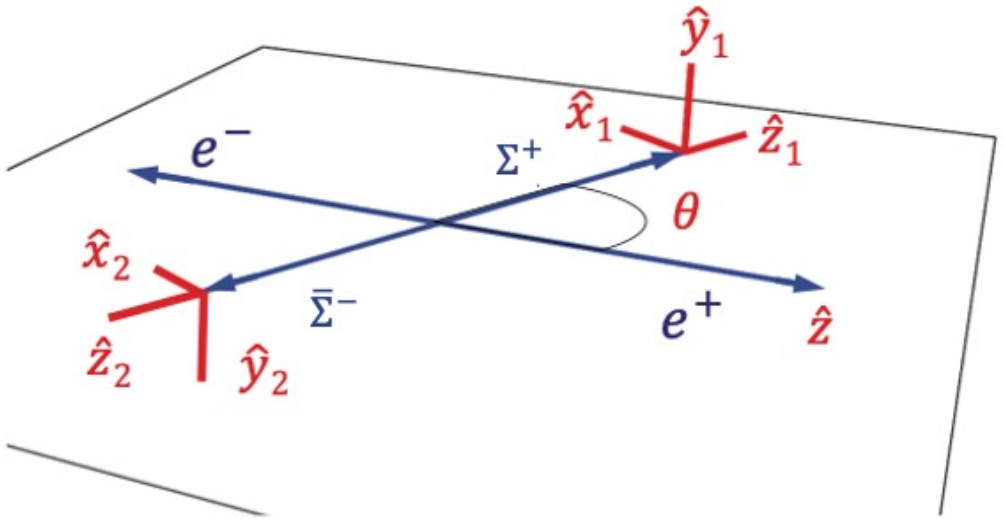


Measurement of relative phase in a wide q^2 range would be crucial for testing various theoretical models and studying the asymptotic behavior in the TL region, and it will provide essential information for studying the dynamical mechanisms

Study of Σ^+ TL EMFFs at BESIII

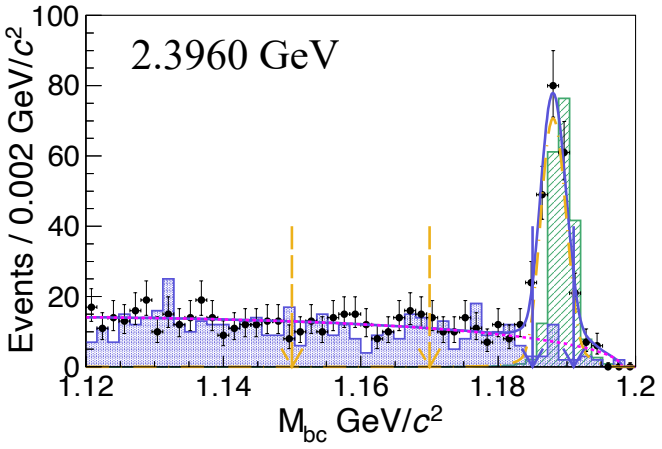
- Decay: $e^+e^- \to \Sigma^+(\to p\pi^0)\bar{\Sigma}^-(\to \bar{p}\pi^0)$
- Data:

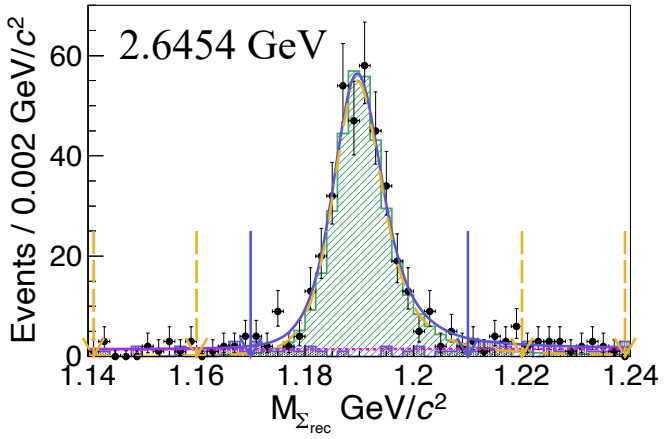
$\sqrt{s}$(GeV)	$\mathcal{L}$(pb^{-1})	
2.3960	66.87	
2.6444	33.72	Combined to 2.6454 GeV
2.6464	34.00	
2.9000	105.25	

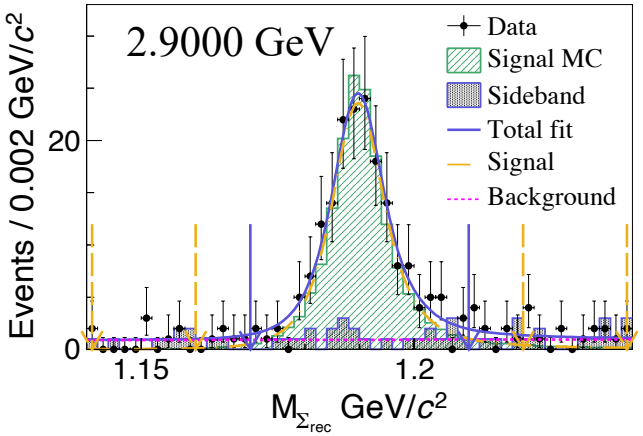


- Two different reconstruction methods are used to select $\Sigma^+\bar{\Sigma}^-$ pairs
  - Single tag(2.3960 GeV): $e^+e^- \to \Sigma^+\bar{\Sigma}^- \to anything + \bar{p}\pi^0$
  - Double tag (2.64540 and 2.9000 GeV): $e^+e^- \to \Sigma^+\bar{\Sigma}^- \to p\pi^0\bar{p}\pi^0$, but only one π^0 is reconstructed by two photons

Study of Σ^+ TL EMFFs at BESIII





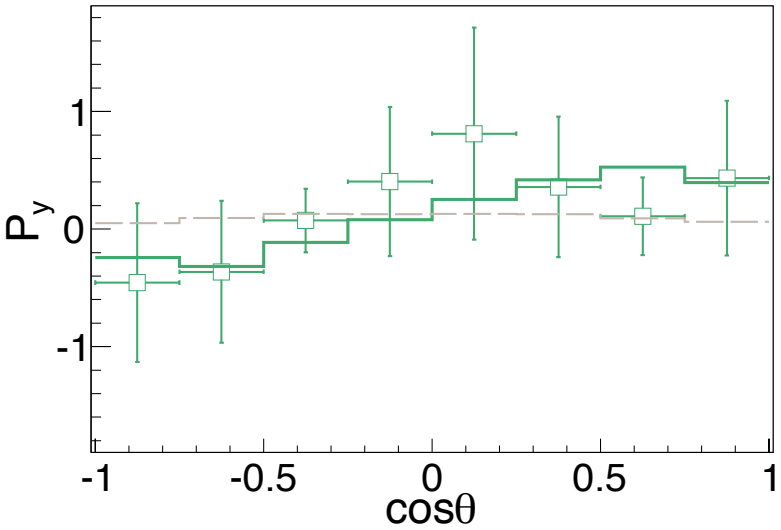


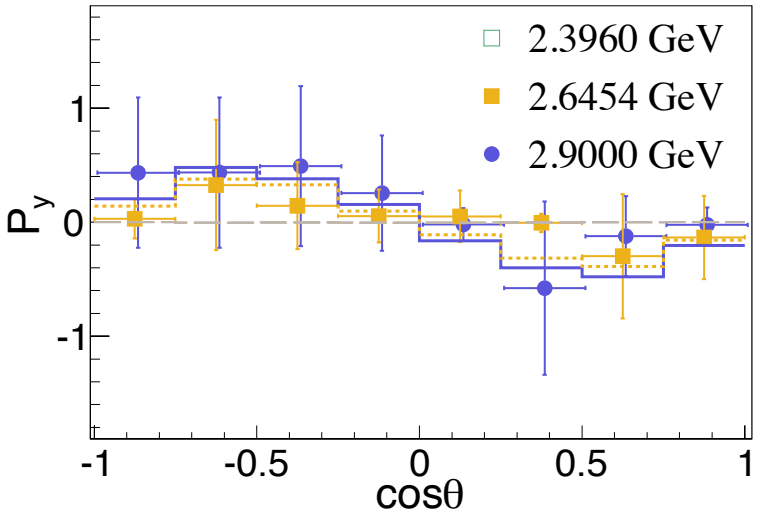
- Maximum likelihood fit
- $\mathcal{C}$: estimated by PHSP MC

$$S = -\ln \mathcal{L} = -\sum_{i=1}^{N} \ln \mathcal{C}\mathcal{W}(\xi_i; \alpha, \Delta\Phi) \qquad S = -\ln \mathcal{L}_{data} + \ln \mathcal{L}_{bkg}$$

	2.3960 GeV	2.6454 GeV and 2.9000 GeV
Signal region	$1.185 < M_{bc} < 1.191$ GeV/c^2	$1.150 < M_{bc} < 1.170$ GeV/c^2
Sideband region	$1.150 < M_{bc} < 1.170$ GeV/c^2	$1.141 < M_{\Sigma_{rec}} < 1.160$ GeV/c^2 $1.220 < M_{\Sigma_{rec}} < 1.239$ GeV/c^2
Background level	12.7%	7.7% and 10.2%

Study of Σ^+ TL EMFFs at BESIII





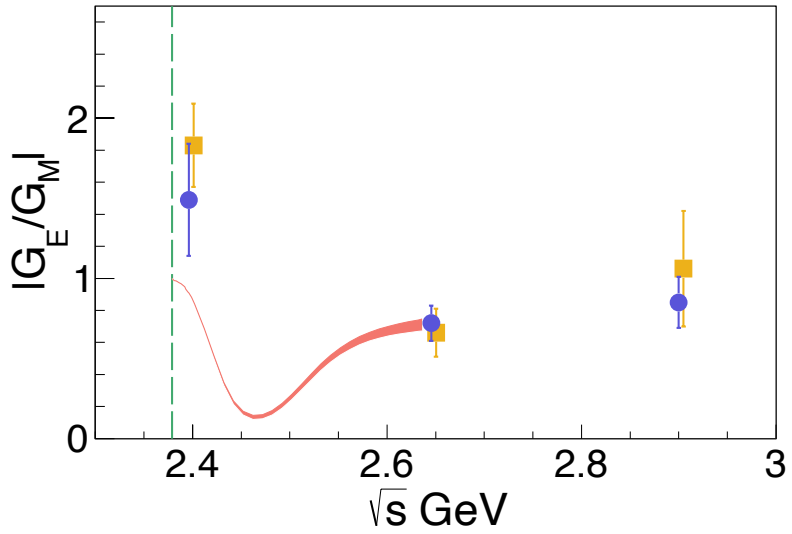
$$P_y = -\frac{\sqrt{1-\alpha^2}\sin\theta_{\Sigma^+}\cos\theta_{\Sigma^+}}{1+\alpha\cos^2\theta_{\Sigma^+}}\sin(\Delta\Phi)$$

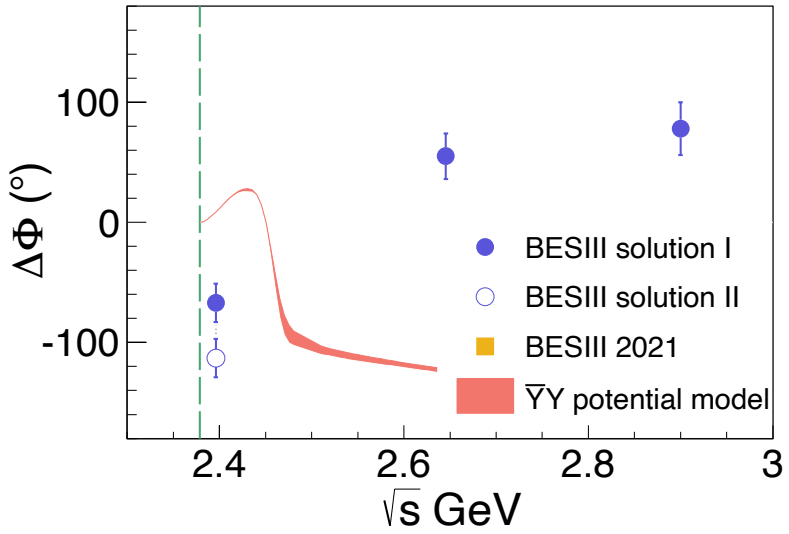
$$P_y = \frac{m}{N}\sum_{i=1}^{N_k}\frac{(3+\alpha)(n^i_{1,y}+n^i_{2,y})}{(\alpha_1-\alpha_2)(1+\alpha\cos^2\theta^i_{\Sigma^+})}$$

$\sqrt{s}$(GeV)	$\lvert G_E/G_M\rvert$	$\Delta\Phi(°)$	$\sin\Delta\Phi$
2.3960	$1.69 \pm 0.38 \pm 0.20$		$-0.67 \pm 0.29 \pm 0.18$
2.6454	$0.72 \pm 0.11 \pm 0.06$	$55 \pm 19 \pm 14$	
2.9000	$0.85 \pm 0.16 \pm 0.15$	$78 \pm 22 \pm 9$	

Summary

- ✓ The complete information of Σ^+ EMFFs in time-like is extracted
- ✓ For the first time, the phase $\Delta\Phi$ of the hyperon EMFFs is explored in a wide q^2
- ✓ $|G_E/G_M|$ 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 may be at least one $\Delta\Phi = 0°$ between 2.3960 and 2.6454 GeV
- ✓ The still increasing relative phase indicates the asymptotic threshold has not yet been reached





Thank you!