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Σ Electromagnetic Form Factors

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Based on: Phys. Rev. D 107, 076008; Chin. Phys. Lett. 42, 120201

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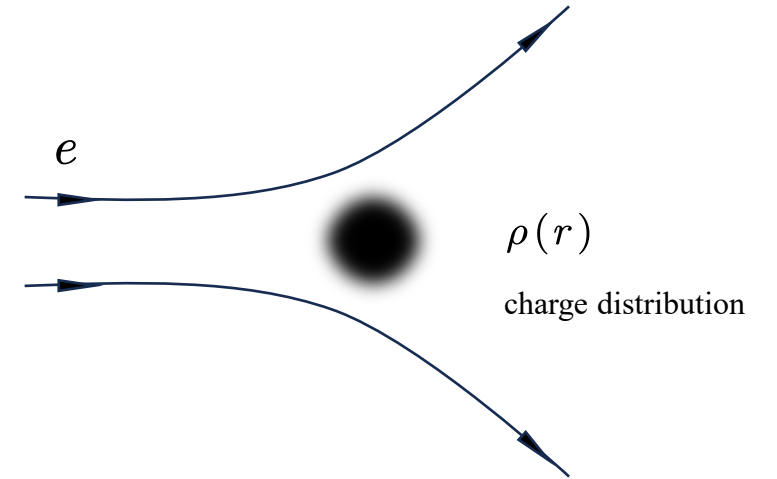
Outline

- Background
- The Vector Meson Dominance Model
- Σ Electromagnetic Form Factors
- Summary

Form Factors

Scattering of electrons in a charge distribution

Differential cross section $\frac{d\sigma}{d\Omega} = \frac{m_e^2}{4\pi} \left| -e \int U(\mathbf{r}) e^{i\vec{q} \cdot \vec{r}} d^3\vec{r} \right|^2$



Electric form factor $F^E(q^2) = \frac{1}{e} \int \rho(\mathbf{r}) e^{i\vec{q} \cdot \vec{r}} d^3\vec{r}$



Charge radius $\langle r^2 \rangle = \frac{\int r^2 \rho(\mathbf{r}) d^3\vec{r}}{\int \rho(\mathbf{r}) d^3\vec{r}} = -6 \frac{dF^E(q^2)}{d|\vec{q}|^2} \Big|_{|\vec{q}|^2=0}$

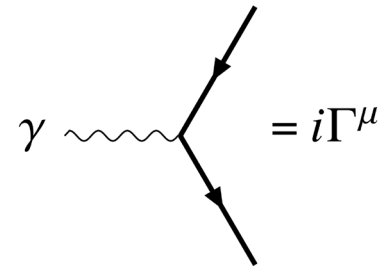
$$\nabla^2 U(\mathbf{r}) = -4\pi\rho(\mathbf{r}) \quad (\text{Poisson equation})$$

$$\int U(\mathbf{r}) e^{i\vec{q} \cdot \vec{r}} d^3\vec{r} = \frac{4\pi}{|\vec{q}|^2} \int \rho(\mathbf{r}) e^{i\vec{q} \cdot \vec{r}} d^3\vec{r}$$

Electromagnetic Form Factors

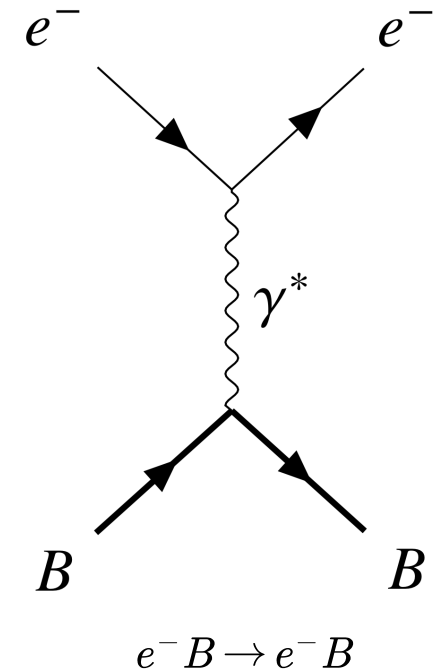
The scattering channel (spacelike region $q^2 < 0$)

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + i \frac{F_2(q^2)}{2M} \sigma^{\mu\nu} q_\nu$$



F_1 : Dirac Form Factor F_2 : Pauli Form Factor (FF)

$$G_E = F_1 + \tau F_2, \quad G_M = F_1 + F_2, \quad \tau = \frac{q^2}{4M^2}$$



G_E is electric FF, and G_M is magnetic FF. In the limit $q^2 \rightarrow 0$, the electrons are insensitive to the internal structure of baryons. Therefore, the G_E and G_M should be equal to the **charge and magnetic** at $q^2 = 0$, respectively.

$$G_E(0) = e_B, \quad G_M(0) = \mu_B$$

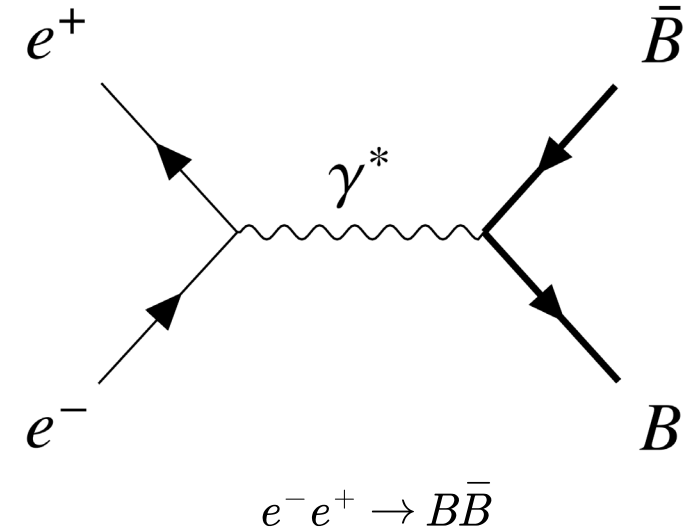
Electromagnetic Form Factors

The annihilation channel (timelike region $q^2 > 0$)

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + i \frac{F_2(q^2)}{2M} \sigma^{\mu\nu} q_\nu$$

$$G_E = F_1 + \tau F_2, \quad G_M = F_1 + F_2$$

$$\sigma_{e^+e^- \rightarrow B\bar{B}} = \frac{4\pi\alpha^2\beta C}{3s} \left(|G_M(q^2)|^2 + \frac{2M^2}{s} |G_E(q^2)|^2 \right)$$



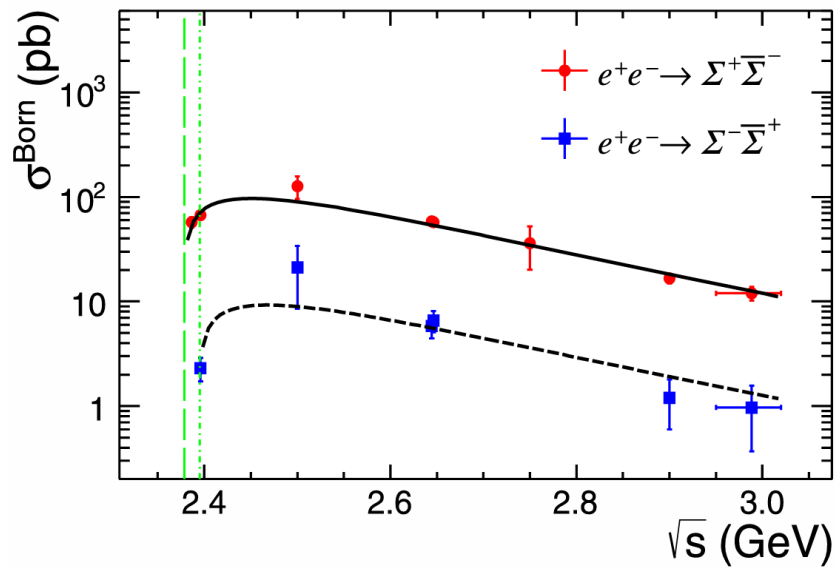
The β is the velocity of baryon B , and C is the Sommerfeld-Gamow factor

For charged baryons, the C factor leads to an unvarnished cross section at the threshold

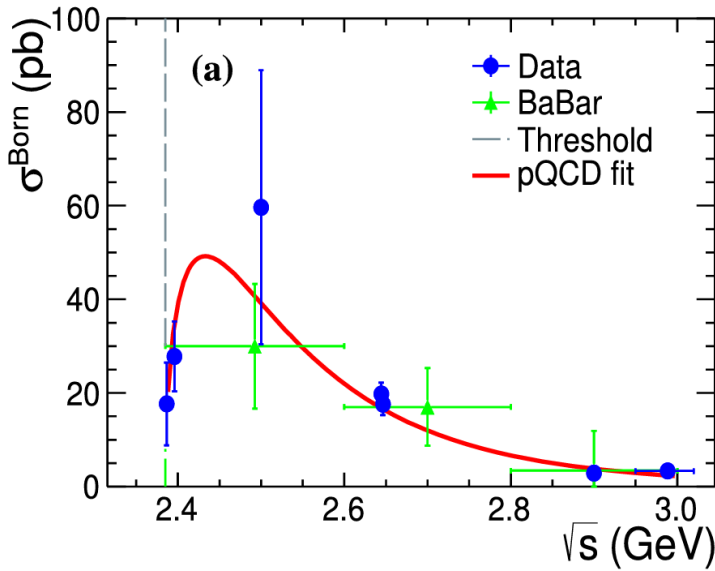
$$|G_{\text{eff}}(q^2)| = \sqrt{\frac{2\tau |G_M(q^2)|^2 + |G_E(q^2)|^2}{1 + 2\tau}} \quad \longrightarrow \quad \sigma_{e^+e^- \rightarrow B\bar{B}} = \frac{4\pi\alpha^2\beta C}{3s} \left(1 + \frac{1}{2\tau} \right) |G_{\text{eff}}(q^2)|^2$$

Effective form factor

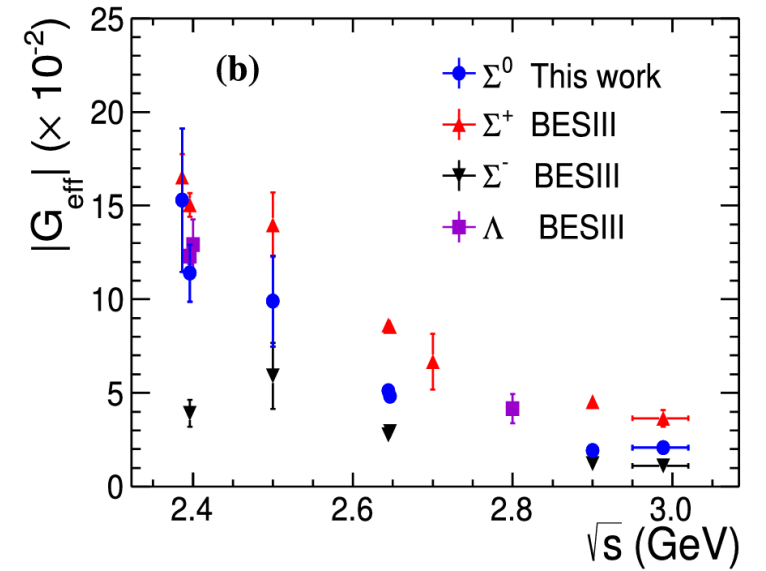
Cross Section of $e^+e^- \rightarrow \Sigma\bar{\Sigma}$



Phys. Lett. B 814, 136110 (2021).



Phys. Lett. B 831 137187 (2022)



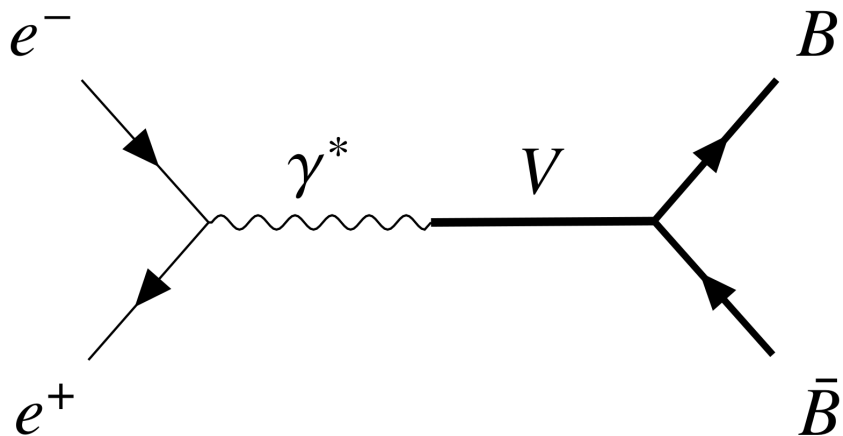
Ratio of the cross section

$$\frac{\sigma(e^+e^- \rightarrow \Sigma^+\bar{\Sigma}^-)}{\sigma(e^+e^- \rightarrow \Sigma^-\bar{\Sigma}^+)} = 9.7 \pm 1.3 \quad \frac{\sigma(e^+e^- \rightarrow \Sigma^0\bar{\Sigma}^0)}{\sigma(e^+e^- \rightarrow \Sigma^-\bar{\Sigma}^+)} = 3.3 \pm 0.7$$

$$\sigma_{\Sigma^+} : \sigma_{\Sigma^0} : \sigma_{\Sigma^-} = \left(\frac{4}{9} + \frac{4}{9} + \frac{1}{9}\right) : \left(\frac{4}{9} + \frac{4}{9} + \frac{1}{9}\right) : \left(\frac{1}{9} + \frac{1}{9} + \frac{1}{9}\right) = 3 : 2 : 1$$

Vector Meson Dominance model

In the VMD model, the coupling of photon and baryons needs to be through intermediate vector mesons



$$\mathcal{L}_{V\gamma} = \sum_V \frac{eM_V^2}{f_V} V_\mu A^\mu$$

$$\mathcal{L}_{BBV} = g_V \bar{\psi} \gamma_\mu \psi V^\mu + \frac{\kappa_V}{4M} \bar{\psi} \sigma_{\mu\nu} (\partial^\mu V^\nu - \partial^\nu V^\mu)$$

$$\Gamma_\mu^V = g_V \gamma_\mu + i \frac{\kappa_V}{2M} \sigma_{\mu\nu} q^\nu \quad (BBV \text{ vertex})$$

$$\Gamma_\mu = \gamma_\mu F_1(q^2) + i \frac{F_2(q^2)}{2M} \sigma_{\mu\nu} q^\nu = \frac{1}{f_V} \frac{M_V^2}{M_V^2 - q^2} \Gamma_\mu^V \quad \longrightarrow \quad \begin{cases} F_1(q^2) = \sum_V \beta_V \frac{M_V^2}{M_V^2 - q^2}, & \beta_V = \frac{g_V}{f_V} \\ F_2(q^2) = \sum_V \alpha_V \frac{M_V^2}{M_V^2 - q^2}, & \alpha_V = \frac{\kappa_V}{f_V} \end{cases}$$

Vector Meson Dominance model

Isospin decomposition

$$|\Sigma^+\bar{\Sigma}^-\rangle = \frac{1}{\sqrt{2}}|1,0\rangle + \frac{1}{\sqrt{3}}|0,0\rangle + \frac{1}{\sqrt{6}}|2,0\rangle$$

$$|\Sigma^0\bar{\Sigma}^0\rangle = -\frac{1}{\sqrt{3}}|0,0\rangle + \sqrt{\frac{2}{3}}|2,0\rangle$$

$$|\Sigma^-\bar{\Sigma}^+\rangle = -\frac{1}{\sqrt{2}}|1,0\rangle + \frac{1}{\sqrt{3}}|0,0\rangle + \frac{1}{\sqrt{6}}|2,0\rangle$$

No isospin tensor vector mesons

($i=1,2$)

$$F_i^{\Sigma^+} = \frac{1}{\sqrt{2}}F_i^V + \frac{1}{\sqrt{3}}F_i^S$$

$$F_i^{\Sigma^0} = -\frac{1}{\sqrt{3}}F_i^S$$

$$F_i^{\Sigma^-} = -\frac{1}{\sqrt{2}}F_i^V + \frac{1}{\sqrt{3}}F_i^S$$

Timelike

$$F_1^V = \sum_V \beta_V \frac{m_V^2}{m_V^2 - q^2 - im_V \Gamma_V}$$

$$F_1^S = \sum_S \beta_S \frac{m_S^2}{m_S^2 - q^2 - im_S \Gamma_S}$$

$$F_2^V = \sum_V \alpha_V \frac{m_V^2}{m_V^2 - q^2 - im_V \Gamma_V}$$

$$F_2^S = \sum_S \alpha_S \frac{m_S^2}{m_S^2 - q^2 - im_S \Gamma_S}$$

Spacelike

$$F_1^V = \sum_V \beta_V \frac{m_V^2}{m_V^2 + Q^2}$$

$$F_1^S = \sum_S \beta_S \frac{m_S^2}{m_S^2 + Q^2}$$

$$F_2^V = \sum_V \alpha_V \frac{m_V^2}{m_V^2 + Q^2}$$

$$F_2^S = \sum_S \alpha_S \frac{m_S^2}{m_S^2 + Q^2}$$

Vector Meson Dominance model

Behavior for the large Q^2

$$\text{pQCD} \quad F_1 \propto \frac{1}{Q^4}, \quad F_2 \propto \frac{1}{Q^6}$$

Phys. Rev. Lett. 43. 545 (1979); Phys. Rev. Lett. 91. 092003 (2003)

Intrinsic form factor (dipole) $g(q^2) = \frac{1}{(1 - \gamma q^2)^2}$

$$F_1^{\Sigma^+} = g(q^2) \left(f_1^{\Sigma^+} + \frac{1}{\sqrt{2}} F_1^V + \frac{1}{\sqrt{3}} F_1^S \right)$$

$$F_1^{\Sigma^0} = g(q^2) \left(f_1^{\Sigma^0} - \frac{1}{\sqrt{3}} F_1^S \right)$$

$$F_1^{\Sigma^-} = g(q^2) \left(f_1^{\Sigma^-} - \frac{1}{\sqrt{2}} F_1^V + \frac{1}{\sqrt{3}} F_1^S \right)$$

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SEMI-PHENOMENOLOGICAL FITS TO NUCLEON ELECTROMAGNETIC FORM FACTORS

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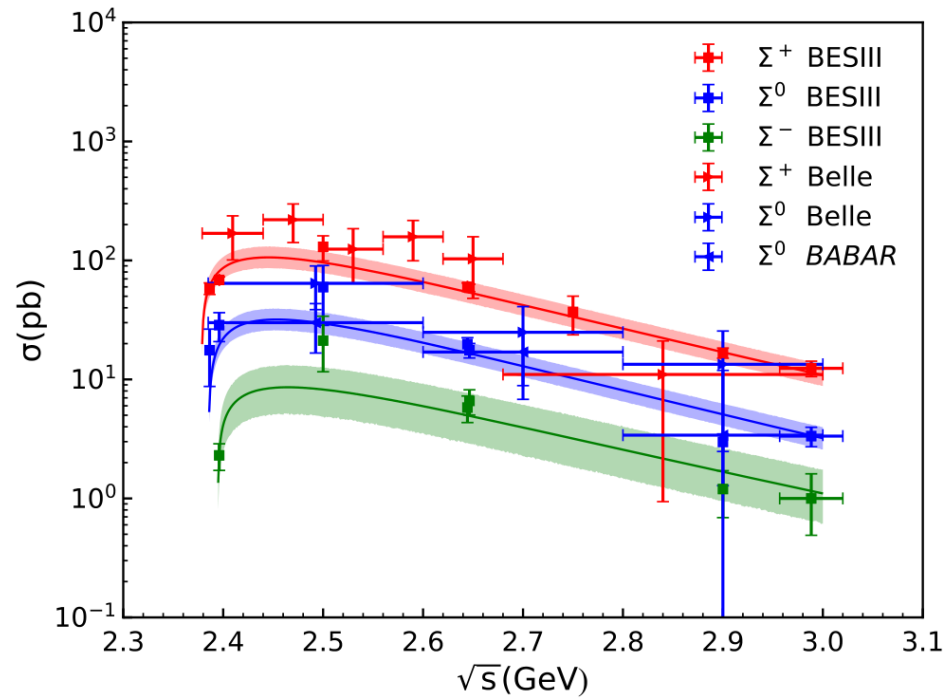
Institute for Theoretical Physics, University of Groningen, Groningen, The Netherlands

$g(t)$	P	$\chi^2(\Gamma_\rho = 0)$	$\chi^2(\Gamma_\rho = 112 \text{ MeV})$
$(1 - \gamma t)^{-1}$	3	8.79	2.63
	5	1.75	1.40
$(1 - \gamma t)^{-2}$	3	3.00	0.945
	5	1.79	0.924
Eikonal, eqs. (5-6)	3	9.36	1.80
	5	1.65	1.08

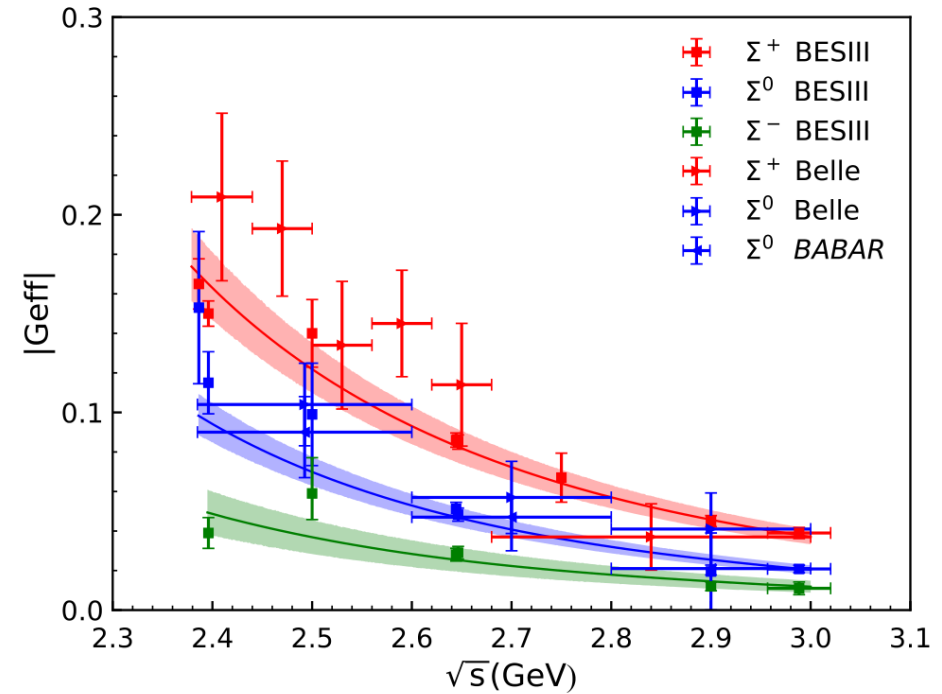
Σ Electromagnetic Form Factors

Vector mesons: ρ , ω , ϕ (ground states)

Bing Yan, Cheng Chen, Ju-Jun Xie Phys. Rev. D 107, 076008 (2023)



Total cross section



Effective form factors

Σ Electromagnetic Form Factors

Σ average square radius of charge: $\langle r_E^2 \rangle = -\frac{6}{G_E(0)} \frac{dG_E(Q^2)}{dQ^2}$

$\langle r_E^2 \rangle$ [fm ²]	This work	ChPT [1]	ChPT [2]	ChPT[3]	ChCQM [4]
Σ^+	0.80 ± 0.02	0.60 ± 0.02	0.99 ± 0.03	0.791 ± 0.116	0.825
Σ^0	0.10 ± 0.01	-0.03 ± 0.01	0.10 ± 0.02	0.010 ± 0.004	0.089
Σ^-	0.70 ± 0.02	0.67 ± 0.03	0.780	0.700 ± 0.124	0.643

$$\langle r_E^2 \rangle_{\Sigma^-} = 0.61 \pm 0.12 \pm 0.09 \text{ fm}^2$$

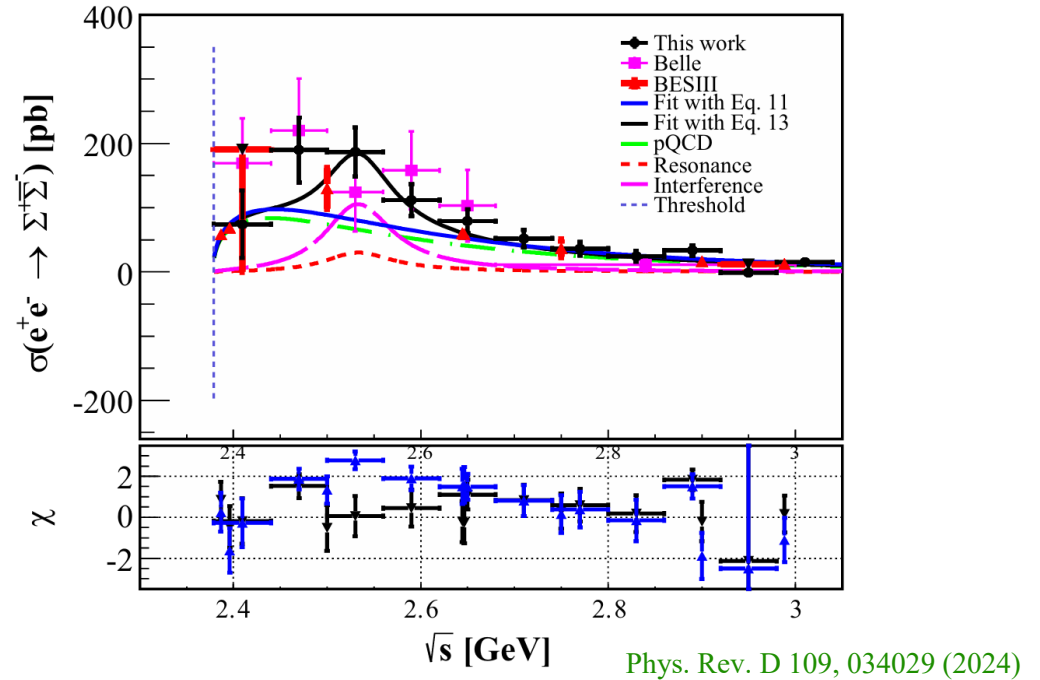
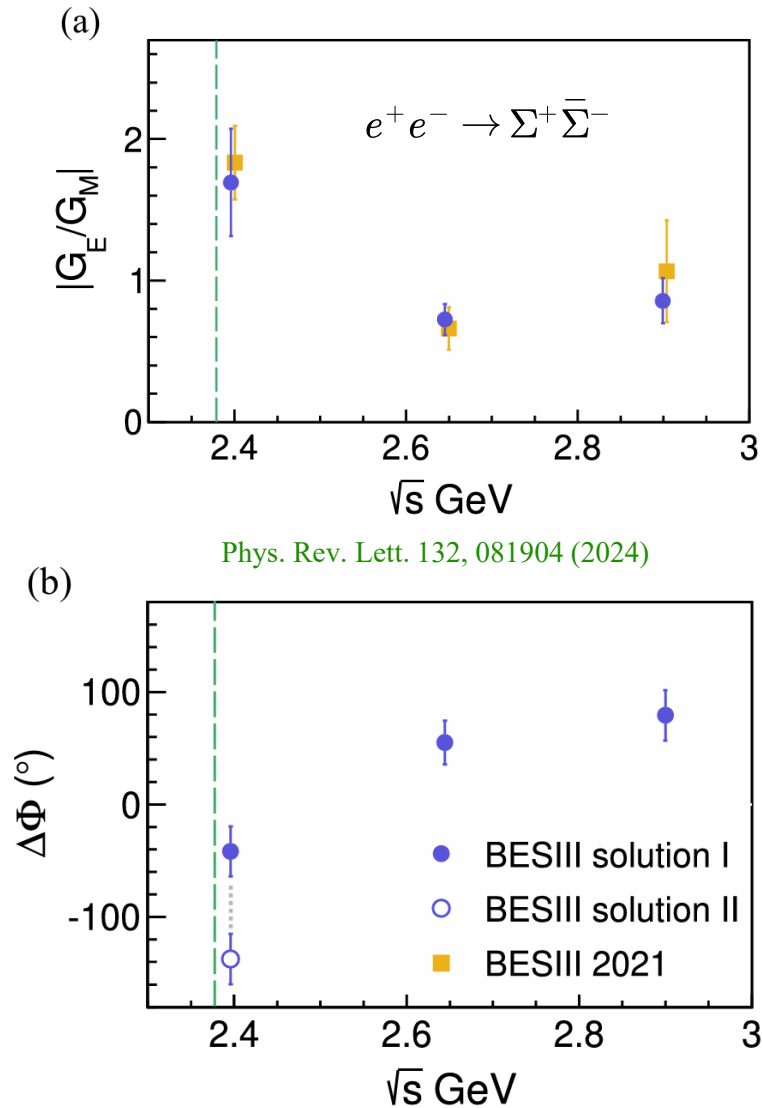
Phys. Lett. B 522, 233 (2001),(SELEX Collaboration).

$$\langle r_E^2 \rangle_{\Sigma^-} = 0.91 \pm 0.32 \pm 0.4 \text{ fm}^2$$

Eur. Phys. J. C 8, 59 (1999),(WA89 Collaboration).

- [1] B. Kubis and U. G. Meissner, Eur. Phys. J. C 18, 747 (2001).
 [2] A. N. Hiller Blin, Phys. Rev. D 96, 093008 (2017).
 [3] M. Yang and P. Wang, Phys. Rev. D 102, 056024 (2020).
 [4] G. Wagner, A. J. Buchmann, and A. Faessler, Phys. Rev. C 58, 3666 (1998).

Σ Electromagnetic Form Factors



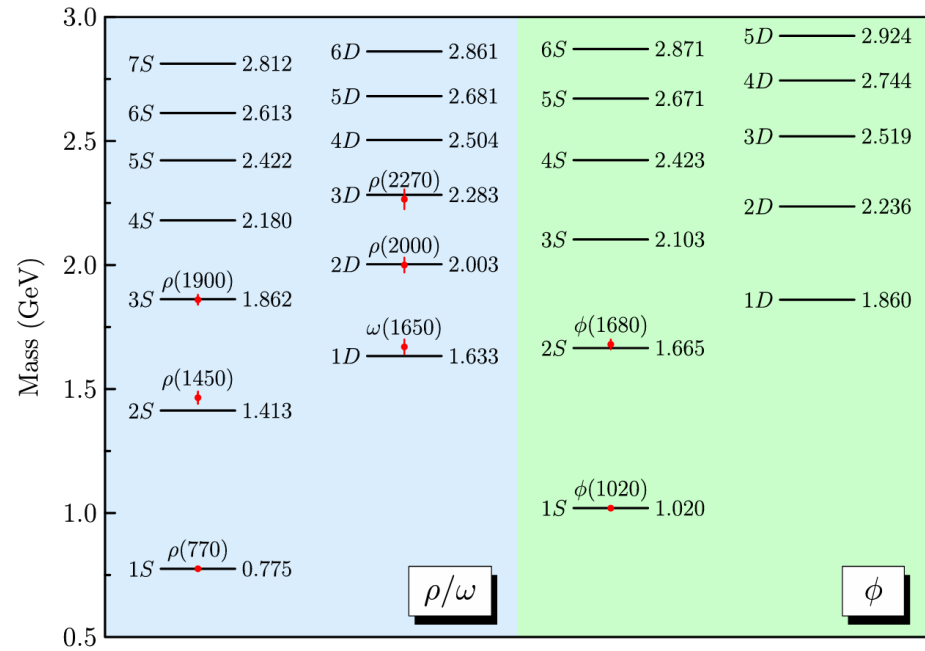
◆ Nonzero relative phase

◆ A larger cross section at $\sqrt{s} = 2.5$ GeV

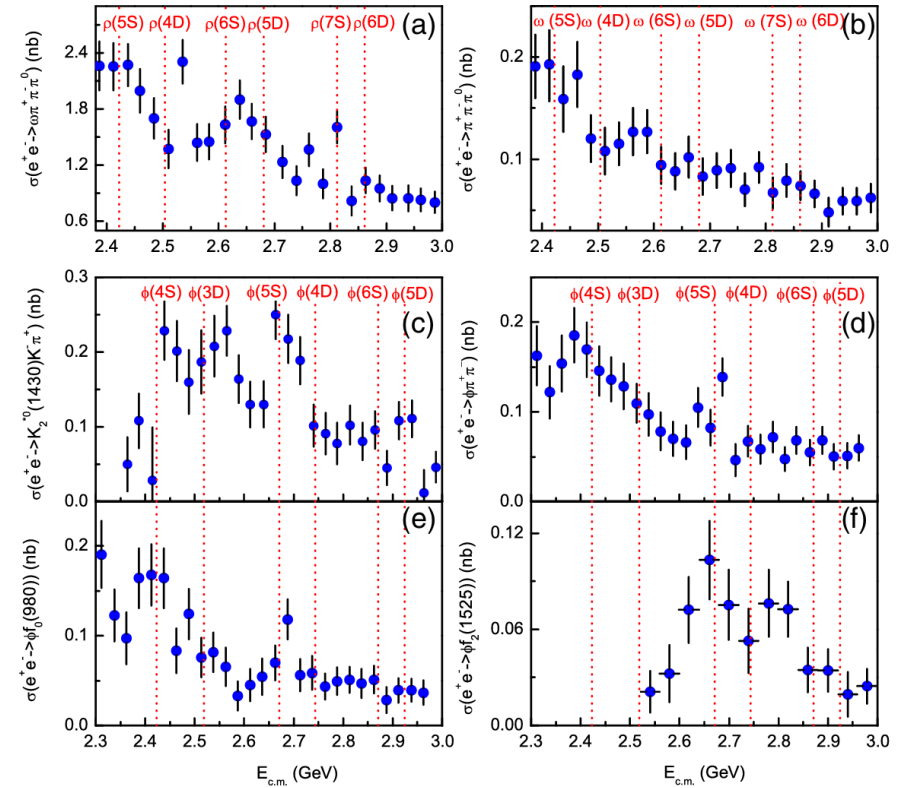
Σ Electromagnetic Form Factors

Light excited vector mesons

L.-M. Wang, S.-Q. Luo, and X. Liu, Phys. Rev. D 105, 034011 (2022)



Modified Godfrey-Isgur Model



Experimental evidence

Σ electromagnetic form factors

	State	Mass (MeV)	Width (MeV)
Scenario I	$\omega(3D)$	2300	100
Scenario II	$\rho(3D)$	2300	160
	$\phi(3D)$	2500	170
	$\rho(2850)$	2850	150

$$\text{I } \gamma = 0.42$$

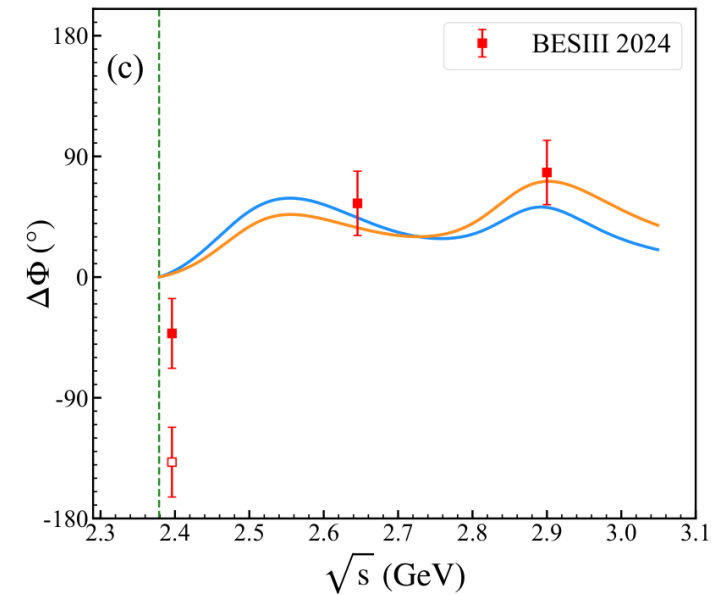
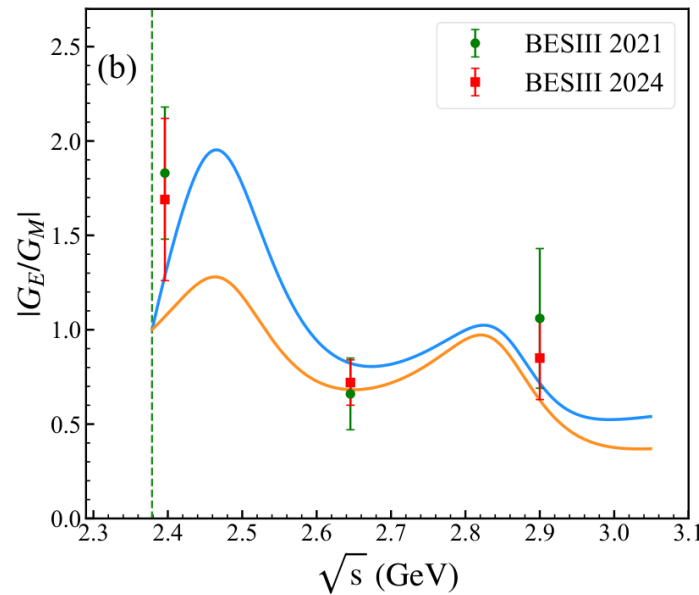
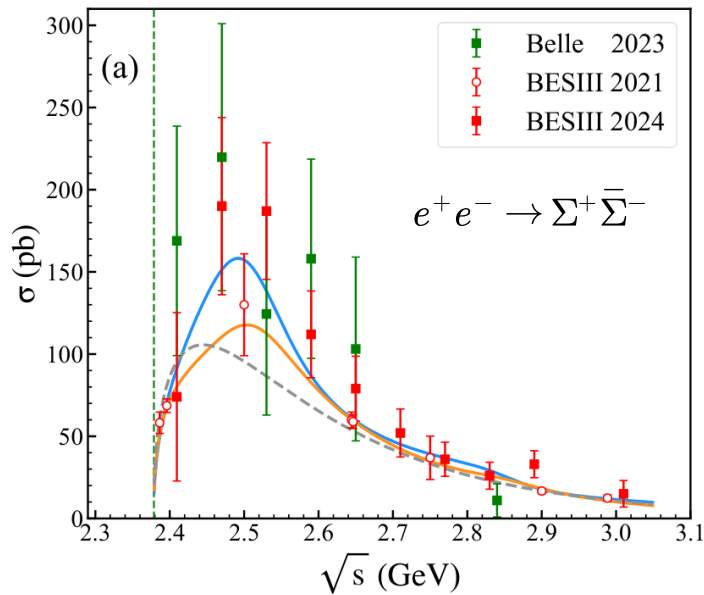
$$\text{II } \gamma = 0.46$$

$$g(q^2) = \frac{1}{(1 - \gamma q^2)^2}$$

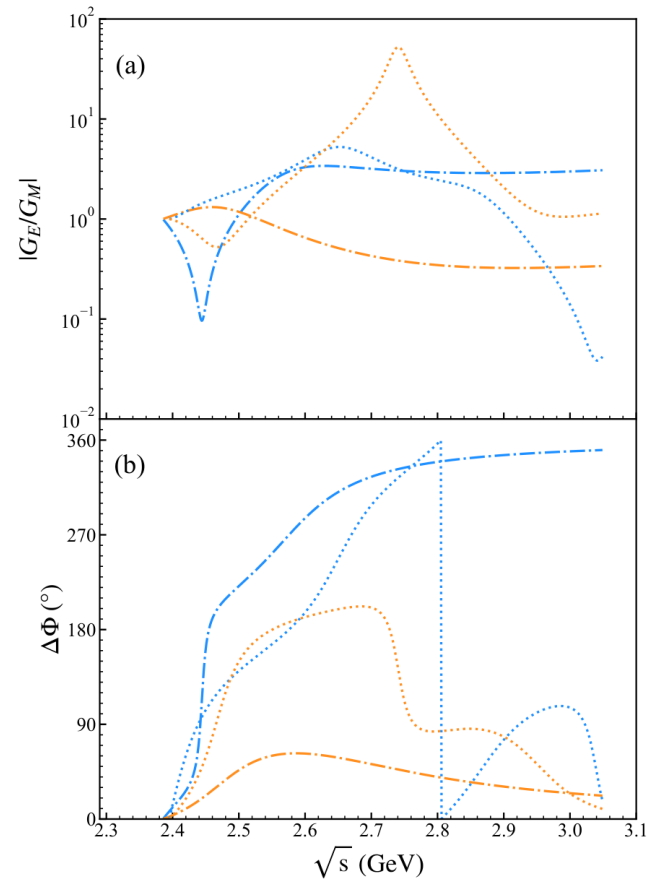
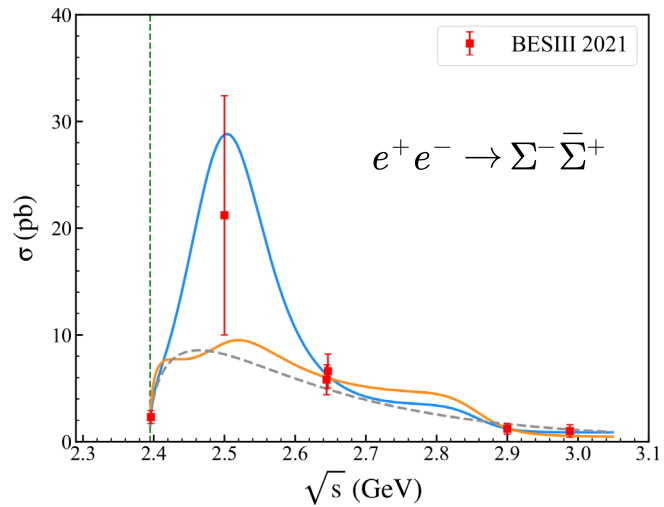
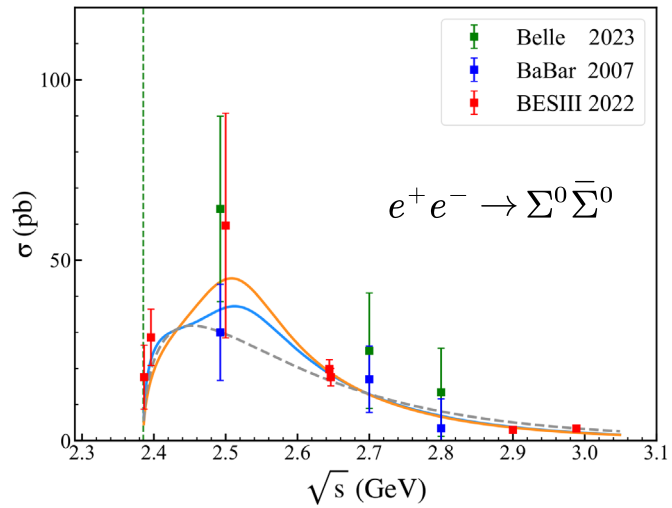
Close to the value in $e^+e^- \rightarrow \Lambda\bar{\Lambda}$

$$\gamma = 0.43 \text{ Chin. Phys. Lett. 39, 011201(2022)}$$

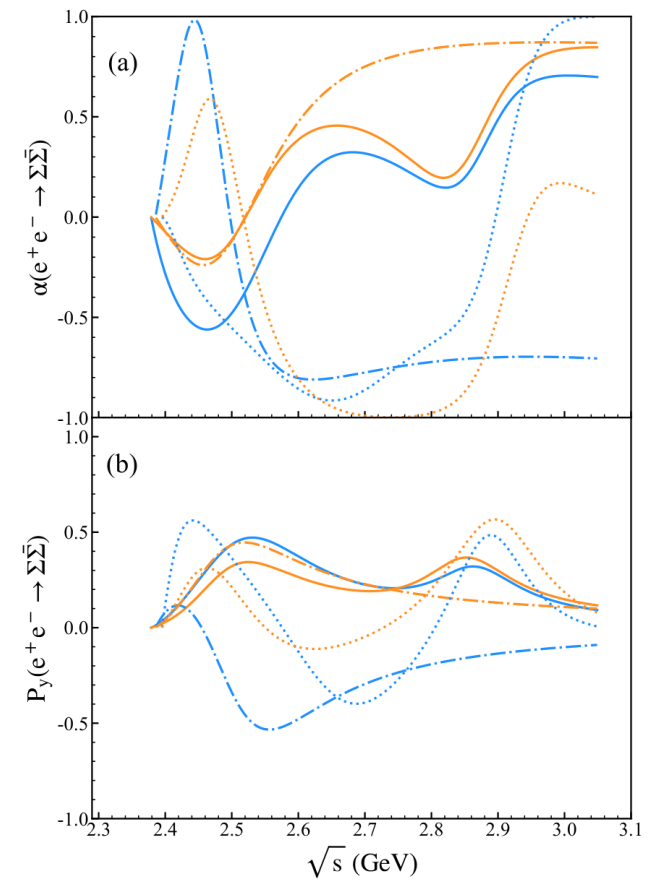
Cheng Chen, Bing Yan, Bing-Wei Long, and Ju-Jun Xie Chin. Phys. Lett. 42, 120201 (2025)



Σ Electromagnetic Form Factors



Scenario I — Σ^0 — Σ^-
 Scenario II — Σ^0 — Σ^-



Scenario I — Σ^+ — Σ^-
 Scenario II — Σ^+ — Σ^-

$\Lambda\bar{\Sigma}^0$ Electromagnetic Transition Form Factors

$e^+e^- \rightarrow \Lambda\bar{\Sigma}^0$

$$F_1 = g(q^2)(f_1^{\Lambda\bar{\Sigma}^0} + \beta_\rho^{\Lambda\bar{\Sigma}^0} B_\rho + \beta_{\rho(3D)}^{\Lambda\bar{\Sigma}^0} B_{\rho(3D)})$$

$$F_2 = g(q^2)(f_2^{\Lambda\bar{\Sigma}^0} B_\rho + \alpha_{\rho(3D)}^{\Lambda\bar{\Sigma}^0} B_{\rho(3D)})$$

$$f_1^{\Lambda\bar{\Sigma}^0} = -\beta_\rho^{\Lambda\bar{\Sigma}^0} - \beta_{\rho(3D)}^{\Lambda\bar{\Sigma}^0}$$

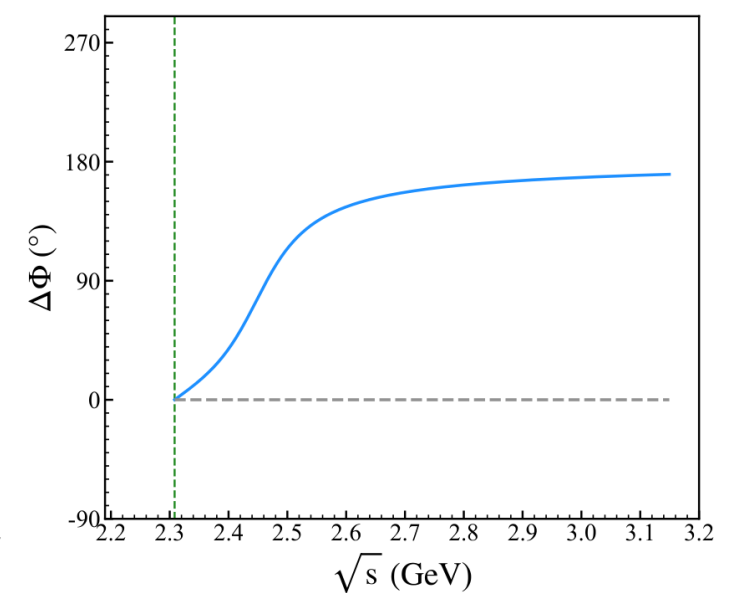
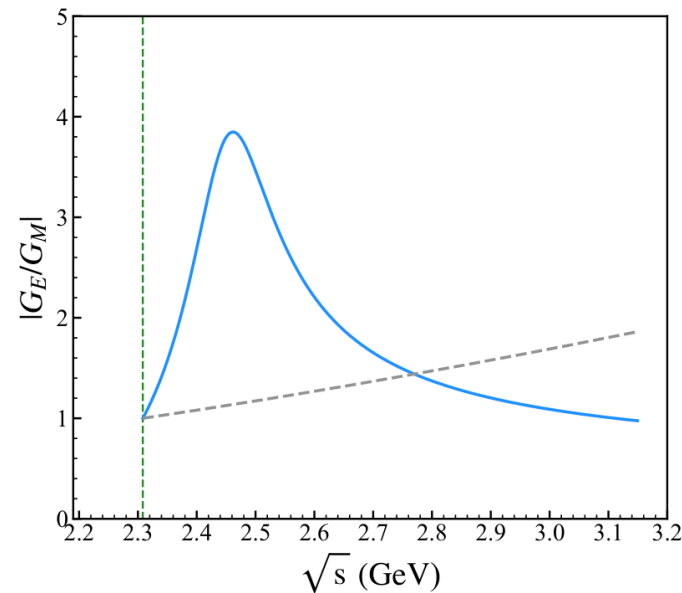
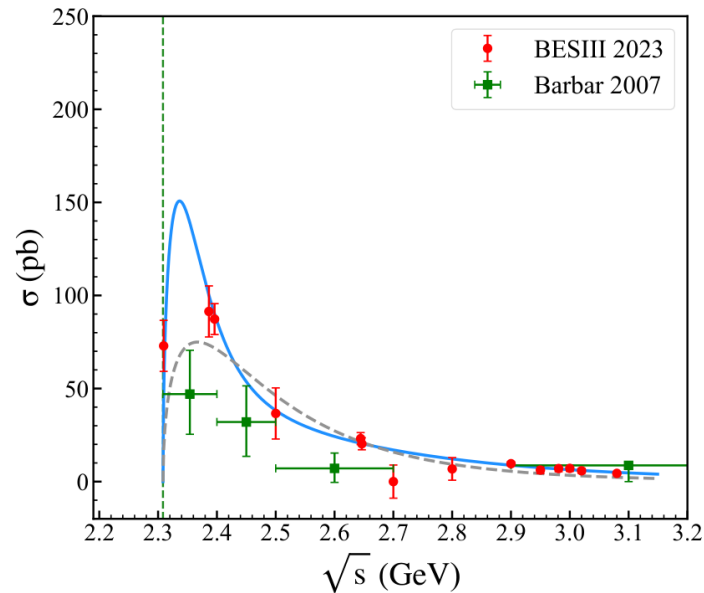
$$f_2^{\Lambda\bar{\Sigma}^0} = \kappa - \alpha_{\rho(3D)}^{\Lambda\bar{\Sigma}^0} \quad \kappa = -1.98$$

$$\gamma = 0.43 \quad \text{Chin. Phys. Lett. 39, 011201(2022)}$$

$$g_{\rho\Lambda\Sigma} = 0 \quad \begin{array}{l} \text{Phys. Rev. 155, 1562 (1967)} \\ \text{Phys. Rev. C 74, 045201 (2006)} \end{array}$$

$$\chi^2/\text{d.o.f: } 4.0 \rightarrow 1.0$$

Excited vector meson: $\rho(3D)$



Summary

- The EMFFs of Σ in the timelike region were investigated within the **VDM** model
- Reproduced the cross section of $e^+e^- \rightarrow \Sigma\bar{\Sigma}$ ratio **$9.7 \pm 1.3: 3.3 \pm 0.7 \pm 1$**
- Extended form factors to the spacelike region, the charge radii are consistent with other theoretical works, and **$\langle r_E^2 \rangle_{\Sigma^-}$** agree with the experimental data
- Light vector excited mesons were involved **$\omega(3D), \rho(3D), \phi(3D), \rho(2850)$**
- The experimental data can be described by **two isospin configurations**
- Threshold enhancement of the reaction $e^+e^- \rightarrow \Lambda\bar{\Sigma}^0$ may be coasted by **$\rho(3D)$**

Thanks!