Baryon Time-like Electromagnetic Form Factors in Vector Meson Dominance model

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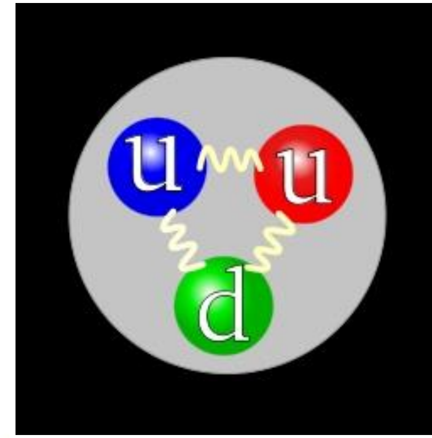
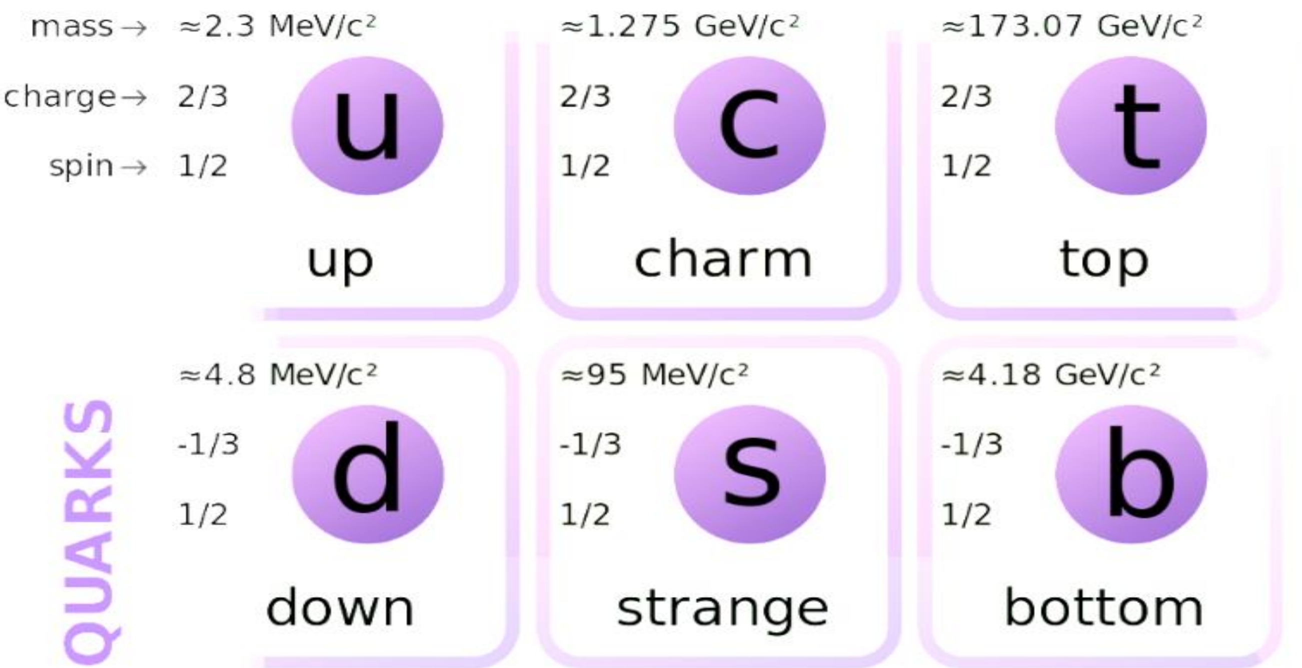
Outline

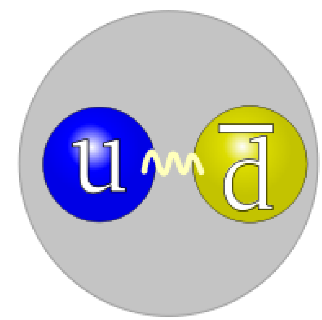
- Introduction：Electromagnetic Form Factors
- The model: Vector Meson Dominance
- Baryon electromagnetic form factors
- Summary

Hadron Physics: Strong Interaction at Low Energy

Hadrons are composite objects with inner structure.

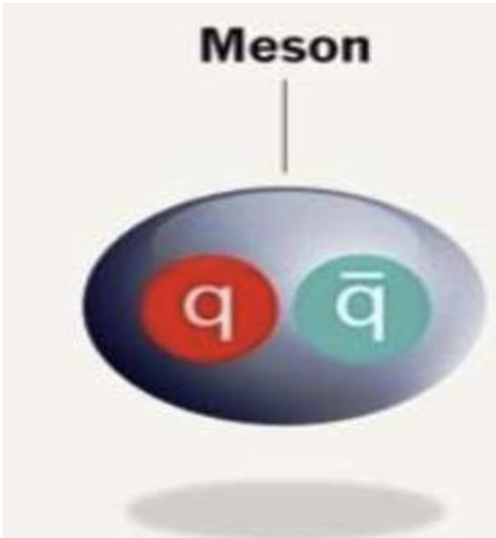


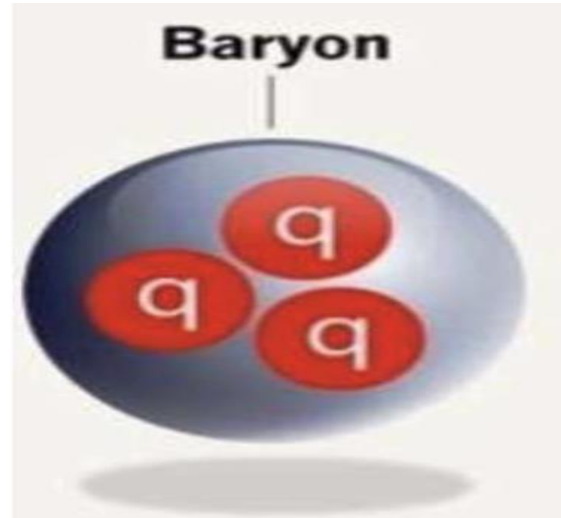




Quark Confinement

Hadrons





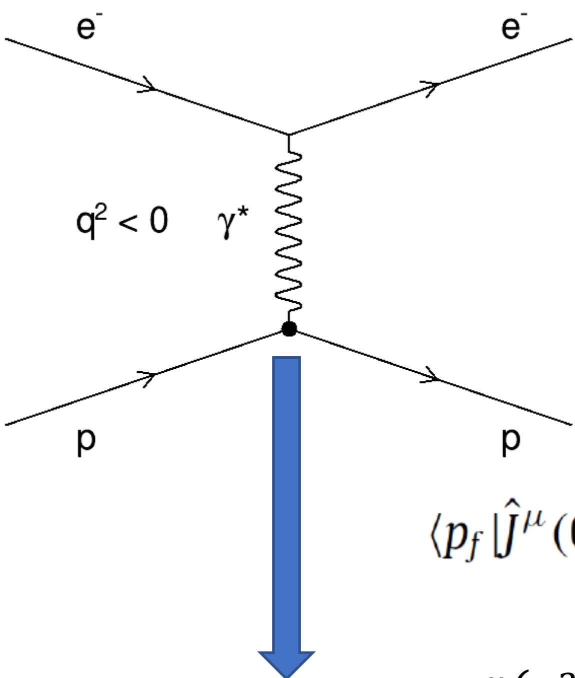
$$\psi_c^{q\bar{q}} = \frac{1}{\sqrt{3}}(r\bar{r} + g\bar{g} + b\bar{b})$$

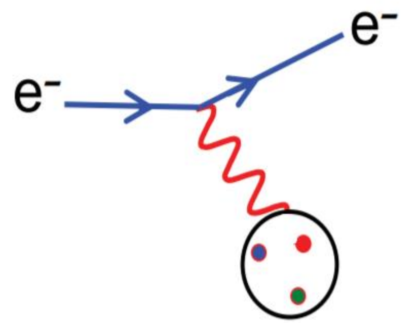
$$\psi_c^{qqq} = \frac{1}{\sqrt{6}}(rgb - rbg + gbr - grb + brg - bgr)$$

Colour confinement ➡ **bound states of qq do not exist**

$qq\bar{q}$ **bound states do not exist in nature.**

Electromagnetic form factors (space-like)





F_1^N : Dirac form factor

F_2^N: Pauli form factor

$$\langle p_f | \hat{J}^\mu(0) | p_i \rangle = \overline{u}(p_f) \left[F_1(q^2)\gamma^\mu - F_2(q^2)\frac{\sigma^{\mu\nu} q_\nu}{2M} \right] u(p_i)$$

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

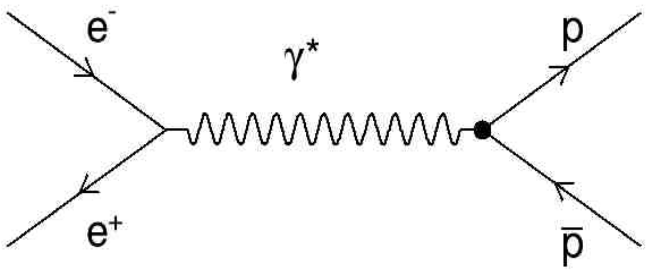
$$G_E^N(Q^2) = F_1^N(Q^2) - \tau F_2^N(Q^2)\ ,\ \ G_{\mathrm{M}}^N(Q^2) = F_1^N(Q^2) + F_2^N(Q^2)\ ,\ \ \tau = \frac{Q^2}{4M_N^2}$$

$$F_1^p(0) = 1\ ,\ F_1^n(0) = 0\ ,\ \ F_2^p(0) = \kappa_p\ ,\ F_2^n(0) = \kappa_n$$

S. Pacetti, R. Baldini Ferroli and E. Tomasi-Gustafsson, "Proton electromagnetic form factors: Basic notions, present achievements and future perspectives," **Phys. Rept. 550-551, 1-103 (2015).**

Electromagnetic form factors (time-like)

$q^2 > 0$

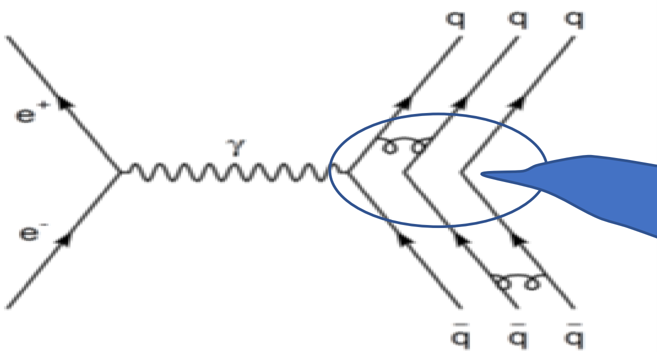


$$\left(\frac{d\sigma}{d\Omega}\right)^{th}_{e^+e^-\to N\bar{N}} = \frac{\alpha^2\beta}{4q^2} C_N(q^2)\left\{|G_M^N(q^2)|^2(1+\cos^2\theta) + |G_E^N(q^2)|^2\frac{1}{\tau}\sin^2\theta\right\}$$

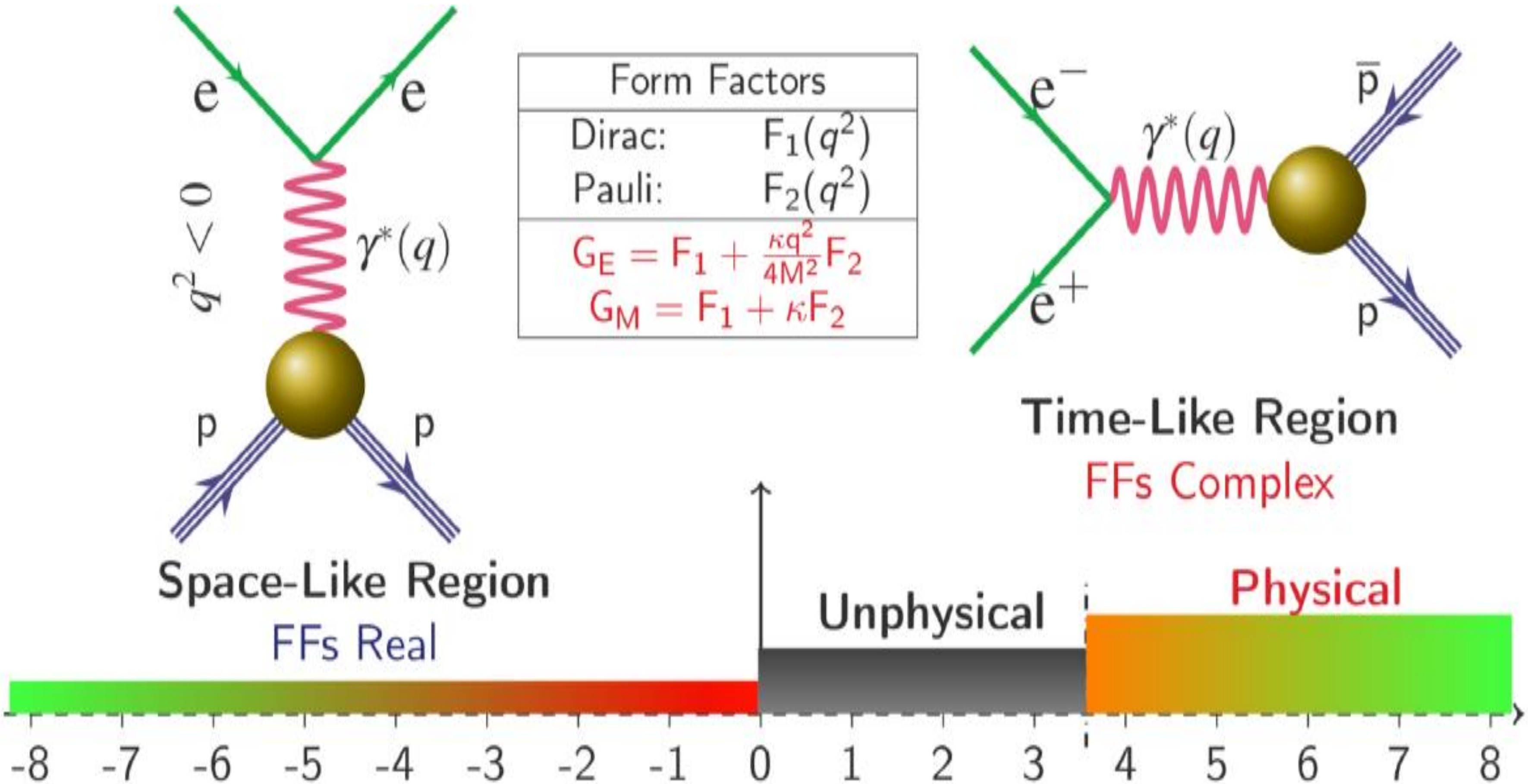
$$\sigma^{th}_{e^+e^-\to N\bar{N}} = \frac{\alpha^2\beta}{4q^2} C_N(q^2)\int d\Omega\left[|G_M^N(q^2)|^2(1+\cos^2\theta) + |G_E^N(q^2)|^2\frac{\sin^2\theta}{\tau}\right]$$

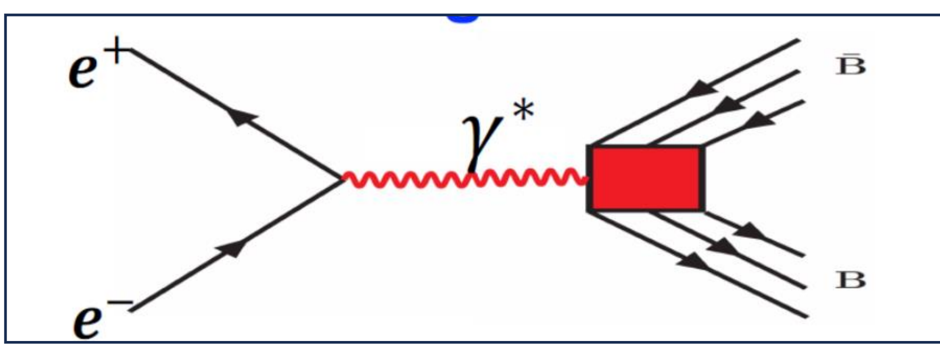
$$= \frac{4\pi\alpha^2\beta}{3q^2} C_N(q^2)\left[|G_M^N(q^2)|^2 + \frac{|G_E^N(q^2)|^2}{2\tau}\right].$$

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



$$\boxed{|G_{eff}(q^2)| = \sqrt{\frac{\sigma(q^2)}{\sigma_{point}(q^2)}} = \sqrt{\frac{|G_M(s)|^2 + \frac{2M^2}{s}|G_E(s)|^2}{1+\frac{2M^2}{s}}}}$$

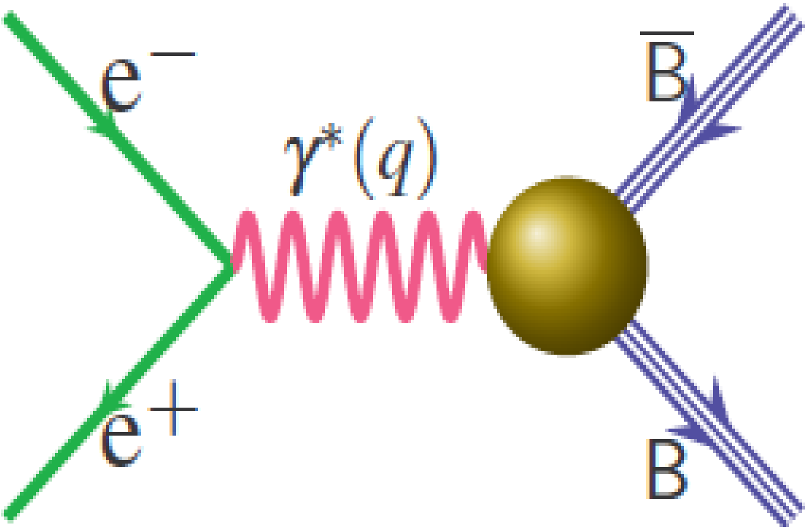


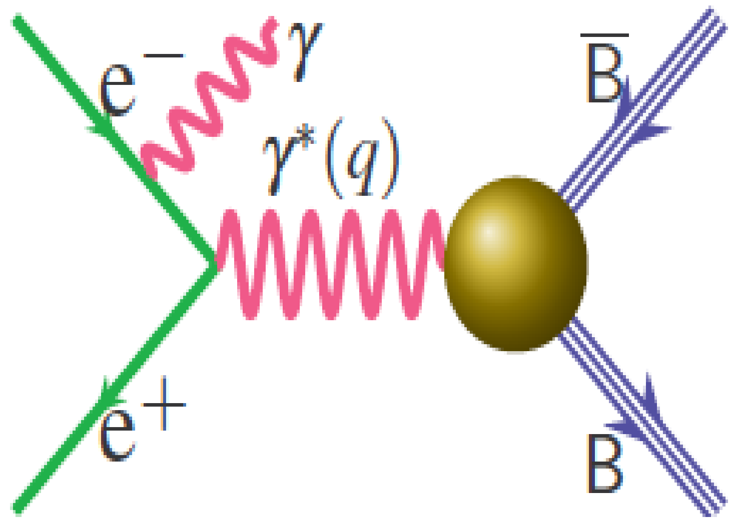


From QED to QCD

Both QED and QCD

Experimental measurements (time-like)





Energy Scan

Initial State Radiation

Both techniques can be used
on the experimental side.

VMD: vector meson dominance model

PHYSICAL REVIEW VOLUME 157, NUMBER 5 25 MAY 1967

Neutral Vector Mesons and the Hadronic Electromagnetic Current*

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(Received 6 January 1967)

FINITE-WIDTH CORRECTIONS TO THE VECTOR-MESON-DOMINANCE PREDICTION FOR $\rho \rightarrow e^+e^-$ *

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(Received 17 May 1968)

Finite-width corrections based on a generalized effective range formula for pion-pion scattering modify by a non-negligible amount the well-known relation between $\Gamma(\rho \rightarrow e^+e^-)$ and $\Gamma(\rho \rightarrow \pi\pi)$ derived on the basis of vector-meson dominance. We also present a new current-algebra prediction for the shape and magnitude of $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ and estimate the ρ-meson contribution to the Schwinger term.

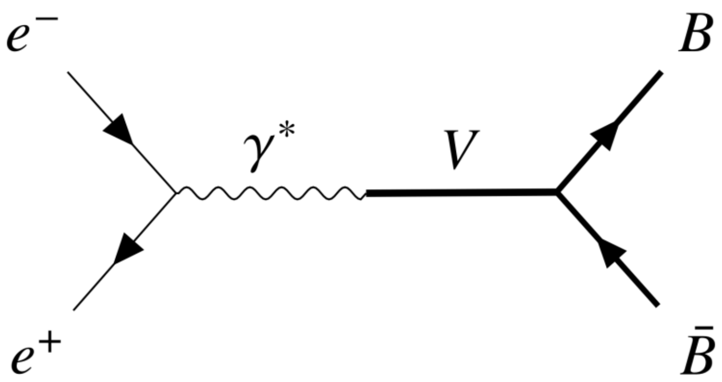
VMD: A virtual (real) photon transforms into a vector before interacting with a target.

The vector can be taken as a part of a "hadronic structure" of the photon.

VMD: vector meson dominance model

$$\mathcal{L}_{V\gamma} = e \sum_V \frac{M_V^2}{f_V} V_{\mu\nu} F^{\mu\nu}$$

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

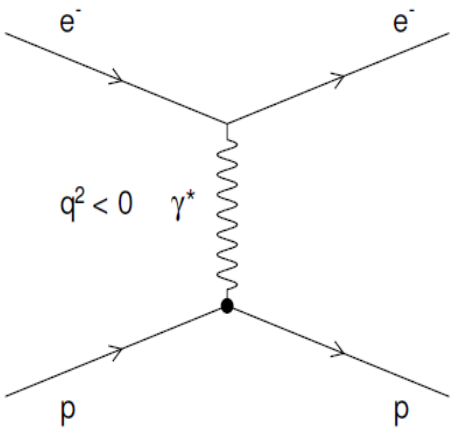


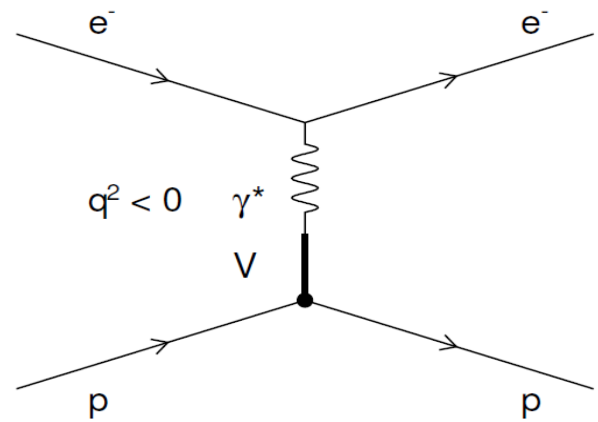
$$\Gamma_\mu^V = g_V \gamma_\mu + i \frac{\kappa_V}{2M} \sigma_{\mu\nu} q^\nu$$

$$\Gamma_\mu = \gamma_\mu F_1(q^2) + i \frac{F_2(q^2)}{2M} \sigma_{\mu\nu} q^\nu = \frac{1}{f_V} \frac{M_V^2}{M_V^2 - q^2} \Gamma_\mu^V$$

$$\Rightarrow \begin{cases} F_1(q^2) = \sum_V \beta_V \dfrac{M_V^2}{M_V^2 - q^2}, & \beta_V = \dfrac{g_V}{f_V} \\ F_2(q^2) = \sum_V \alpha_V \dfrac{M_V^2}{M_V^2 - q^2}, & \alpha_V = \dfrac{\kappa_V}{f_V} \end{cases}$$

VMD for nucleon





Dirac and Pauli isoscalar and isovector form factors are

$$F_1^s(t) = \frac{e}{2} g(t) \left[(1 - \beta_\omega - \beta_\phi) + \beta_\omega \frac{\mu_\omega^2}{\mu_\omega^2 - t} + \beta_\phi \frac{\mu_\phi^2}{\mu_\phi^2 - t} \right]$$

$$F_1^v(t) = \frac{e}{2} g(t) \left[(1 - \beta_\rho) + \beta_\rho \frac{\mu_\rho^2}{\mu_\rho^2 - t} \right]$$

$$F_2^s(t) = \frac{e}{2} g(t) \left[(-0.120 - \alpha_\phi) \frac{\mu_\omega^2}{\mu^2 \; - t} + \alpha_\phi \frac{\mu_\phi^2}{\mu_\phi^2 - t} \right]$$

$$F_2^v(t) = \frac{e}{2} g(t) \left[3.706 \frac{\mu_\rho^2}{\mu_\rho^2 - t} \right]$$

$$F_1 = F_1^S + F_1^V$$

$$F_2 = F_2^S + F_2^V$$

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

SEMI-PHENOMENOLOGICAL FITS TO NUCLEON ELECTROMAGNETIC FORM FACTORS

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and

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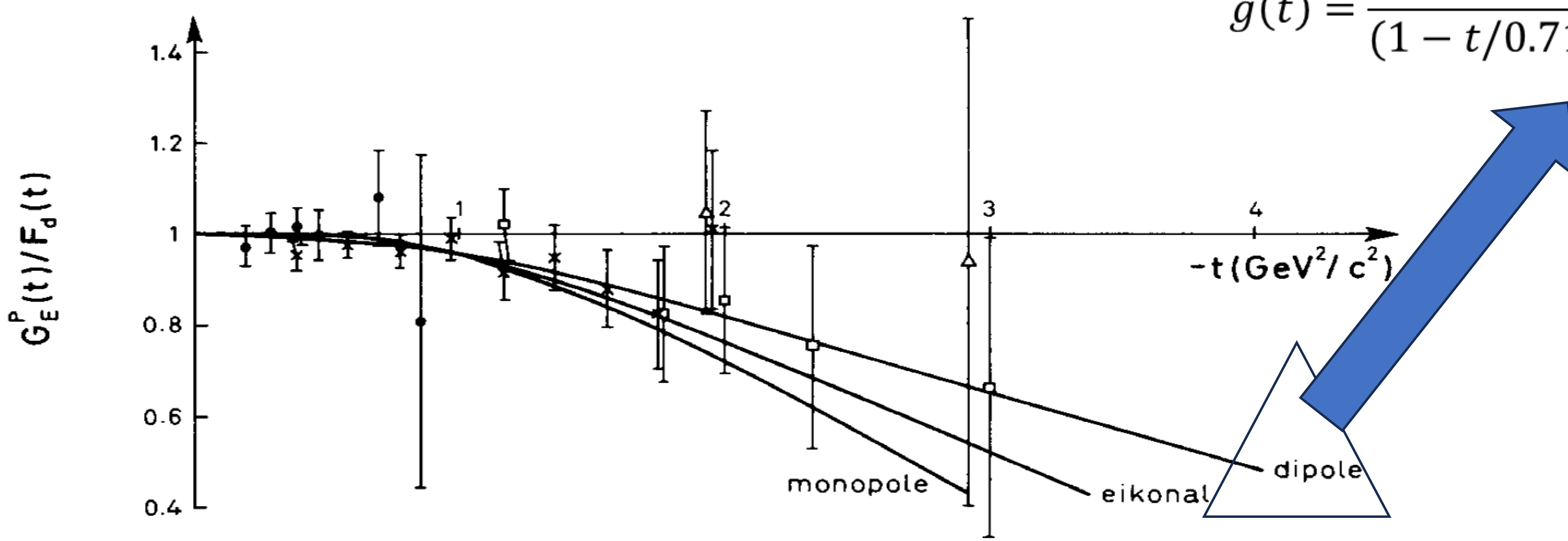
Received 31 August 1972

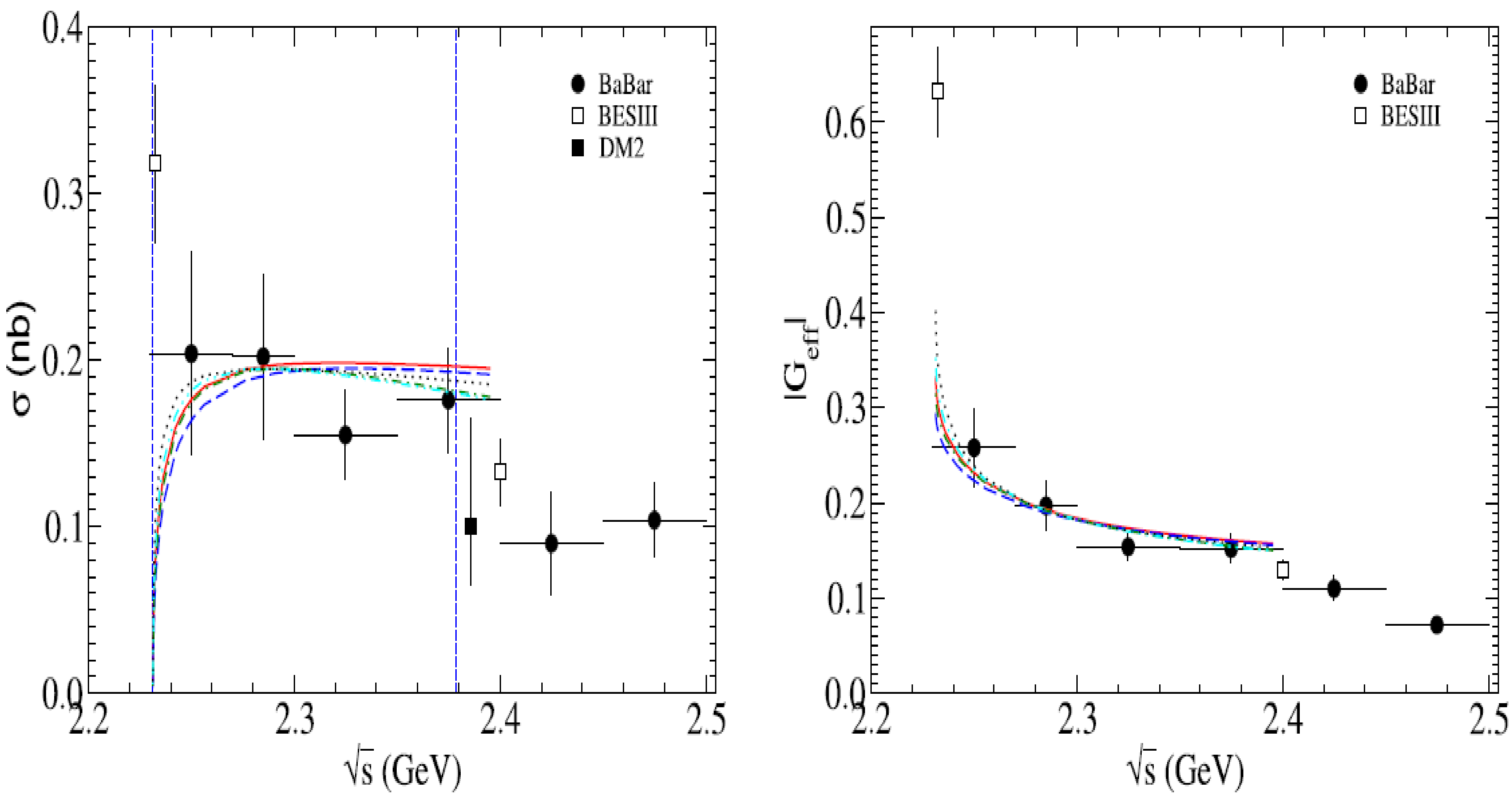
Several theoretically interesting forms of the nucleon EM form factor have been considered and found to provide quantitative descriptions of available data with as few as three adjustable parameters.

$$g(t) = \frac{1}{(1 - t/0.71)^2}$$



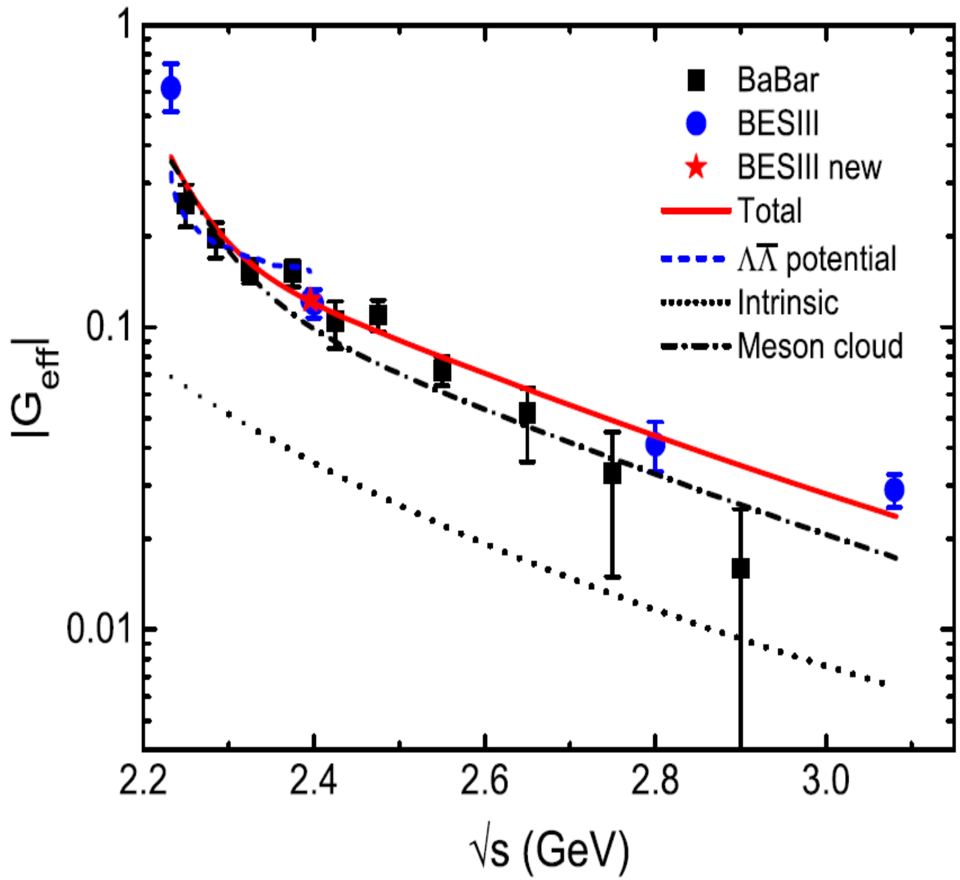
Workshop of Baryon Production at BESIII, Hefei, Sep.14-16, 2019

Λ



J. Haidenbauer and U. G. Meißner, Phys. Lett. B 761, 456-461(2016).

Y. Yang, D. Y. Chen and Z. Lu,
Phys. Rev. D 100, 073007 (2019).

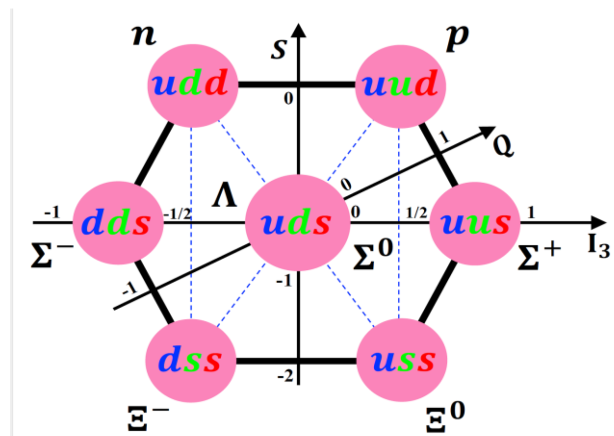


fit. In the present scenario, there are 16 experimental data and 10 free parameters. The value of intrinsic parameter γ is fitted to be 0.336 GeV^{-2} and the other parameters are summarized in Table II. It should be noticed that $g(q^2)$

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

$$\gamma_N = \frac{1}{0.71\ \mathrm{GeV}^2} = 1.408\ \mathrm{GeV}^{-2}$$

State	Mass	Width	State	Mass	Width
$\omega(782)$ [55]	782	8.1	$\phi(1020)$ [56]	1019	4.2
$\omega(1420)$ [57]	1418	104	$\phi(1680)$ [57]	1674	165
$\omega(1650)$ [57]	1679	121	$\phi(2170)$ [58]	2171	128



EMFFs of Λ in the VMD (new proposal)

$$\mathrm{F}_1(\mathrm{Q}^2) = \mathrm{g}(\mathrm{Q}^2)[-\beta_\omega - \beta_\phi + \beta_\omega \frac{\mathrm{m}_\omega^2}{\mathrm{m}_\omega^2 + \mathrm{Q}^2} + \beta_\phi \frac{\mathrm{m}_\phi^2}{\mathrm{m}_\phi^2 + \mathrm{Q}^2} + \beta_\mathrm{x} \frac{\mathrm{m}_\mathrm{x}^2}{\mathrm{m}_\mathrm{x}^2 + \mathrm{Q}^2}]$$

$$\mathrm{F}_2(\mathrm{Q}^2) = \mathrm{g}(\mathrm{Q}^2)[(\mu_\Lambda - \alpha_\phi) \frac{\mathrm{m}_\omega^2}{\mathrm{m}_\omega^2 + \mathrm{Q}^2} + \alpha_\phi \frac{\mathrm{m}_\phi^2}{\mathrm{m}_\phi^2 + \mathrm{Q}^2} + \alpha_\mathrm{x} \frac{\mathrm{m}_\mathrm{x}^2}{\mathrm{m}_\mathrm{x}^2 + \mathrm{Q}^2}]$$

$$\mathrm{g}(\mathrm{Q}^2) = 1/(1 + \gamma \mathrm{Q}^2)^2$$

$$\boxed{Q^2 \to -q^2}$$

$$G_E(q^2) = F_1(q^2) + \tau F_2(q^2)$$

$$G_M(q^2) = F_1(q^2) + F_2(q^2)$$

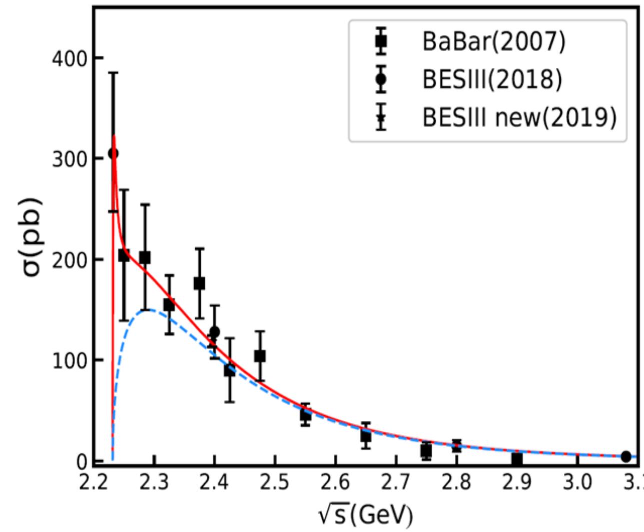
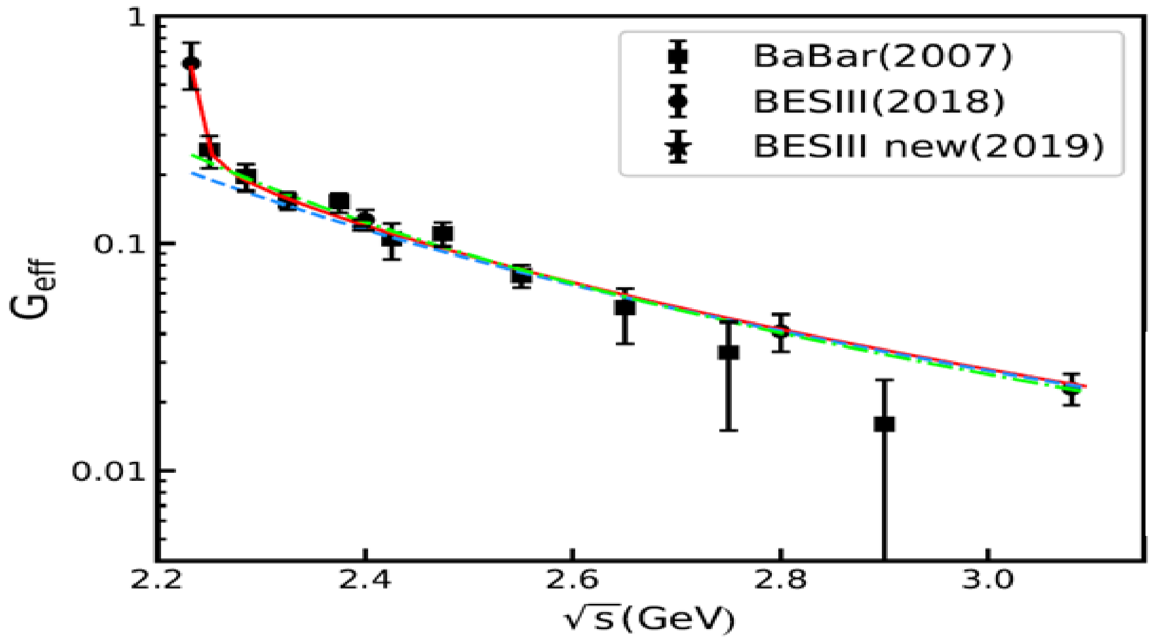


Figure: Cross section of the reaction $e^+e^- \to \bar{\Lambda}\Lambda$.



Blue: without X(2231)
Red: with X(2231)
Green: only dipole

$$G_{\rm eff} = C_0 g(q^2) = \frac{C_0}{(1-\gamma q^2)^2}$$

Table: Values of model parameters determined in this work.

Parameter	Value	Parameter	Value
γ (GeV^{-2})	0.43	β_ω	-1.13
β_ϕ	1.35	α_ϕ	-0.40
β_x	0.0015	m_x (MeV)	2230.9
Γ_x(MeV)	4.7		

New state X(2231) ?

Z. Y. Li, A. X. Dai and Ju-Jun Xie, Chin. Phys. Lett. 39, 011201 (2022).

Flatté formula for the X(2231)

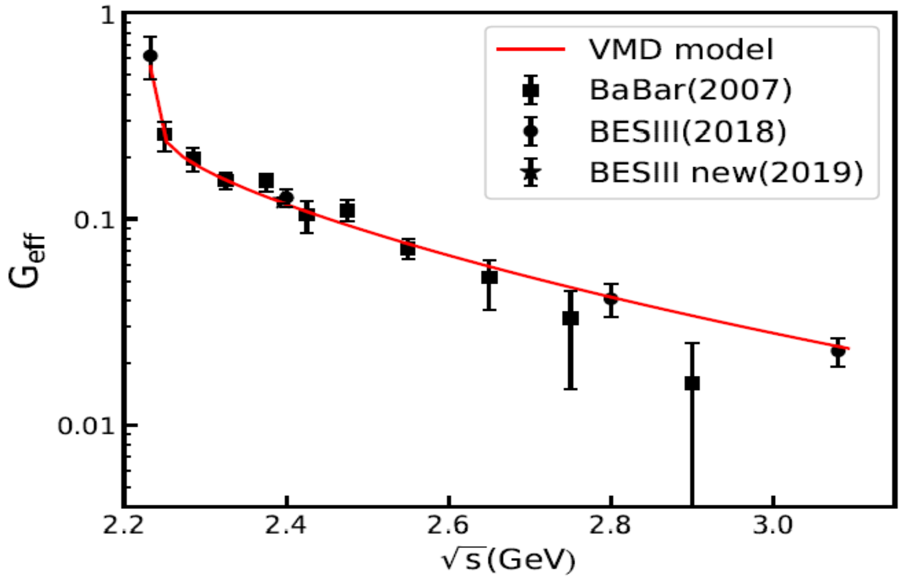


Figure: Fitting result of $|G_{eff}|$ with Flatte.

S.M. Flatte, Phys. Lett. B 63, 224-227 (1976).

$$\frac{d\sigma_i}{dm} = C \left| \frac{m_R \sqrt{\Gamma_0 \Gamma_i}}{m_R^2 - m^2 - i m_R(\Gamma_{\pi\eta} + \Gamma_{K\bar{K}})} \right|^2$$

$$\Gamma_{\pi\eta} = g_\eta q_\eta$$

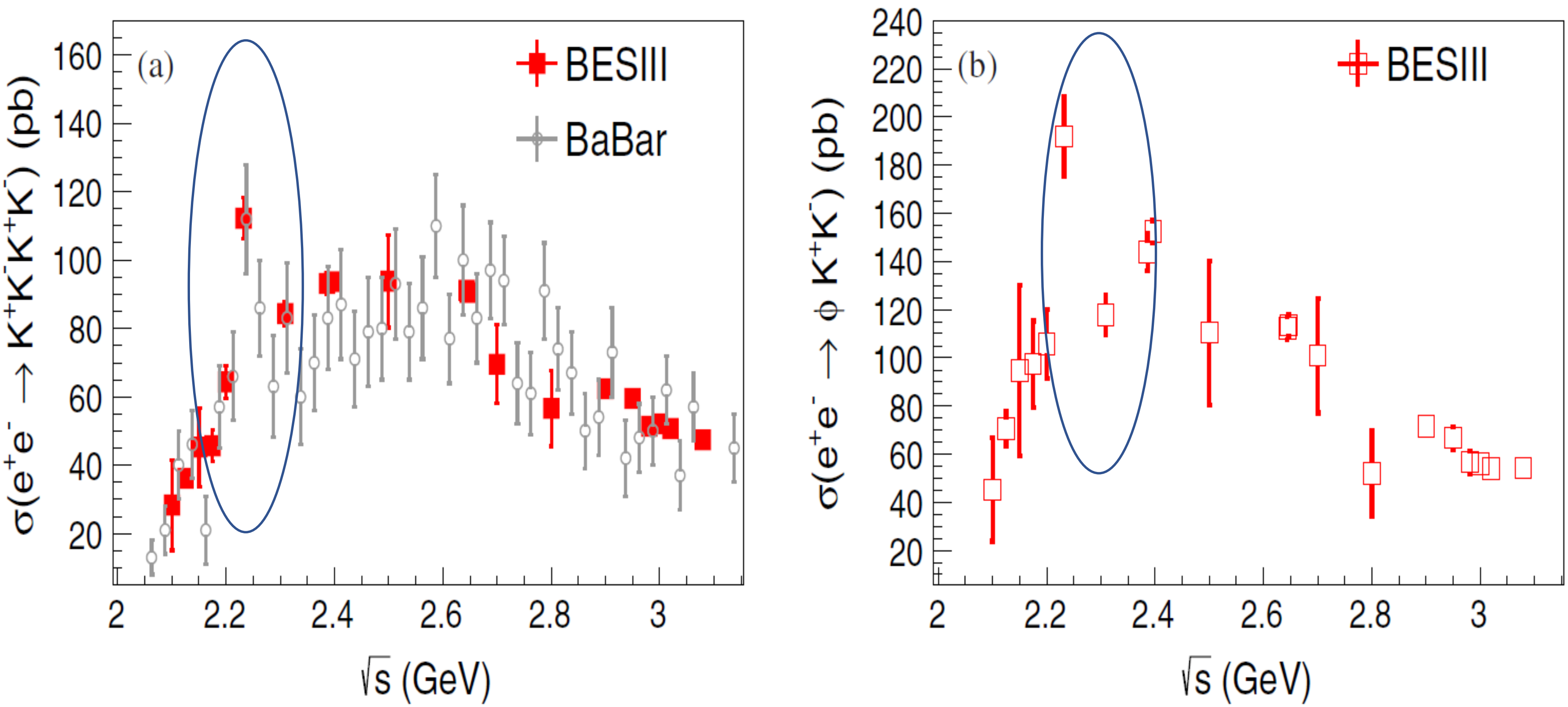
$$\Gamma_{K\bar{K}} = \begin{cases} g_K \sqrt{(1/4)m^2 - m_K^2} & \text{above threshold} \\ i g_K \sqrt{m_K^2 - (1/4)m^2} & \text{below threshold} \end{cases}$$

$$\Gamma_x = \Gamma_0 + \Gamma_{\Lambda\bar{\Lambda}}(s) \qquad \Gamma_{\Lambda\bar{\Lambda}} = \frac{g^2}{4\pi}\sqrt{\frac{s}{4} - M_\Lambda^2}$$

Parameter	Value	Parameter	Value
γ (GeV^{-2})	0.57 ± 0.21	$\beta_{\omega\phi}$	-0.3 ± 0.31
β_x	-0.03 ± 0.09	m_x(MeV)	2237.7 ± 50.2
Γ_0 (MeV)	$8.8^{+75.9}_{-8.8}$	$g_{\Lambda\bar{\Lambda}}$	3.0 ± 1.9

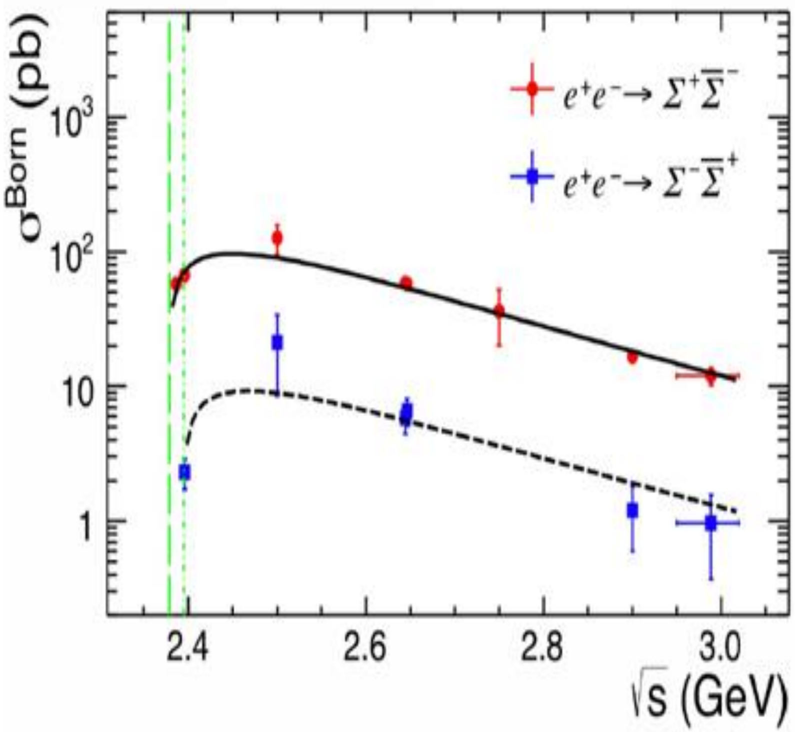
Z. Y. Li, A. X. Dai and Ju-Jun Xie, Chin. Phys. Lett. 39, 011201 (2022).

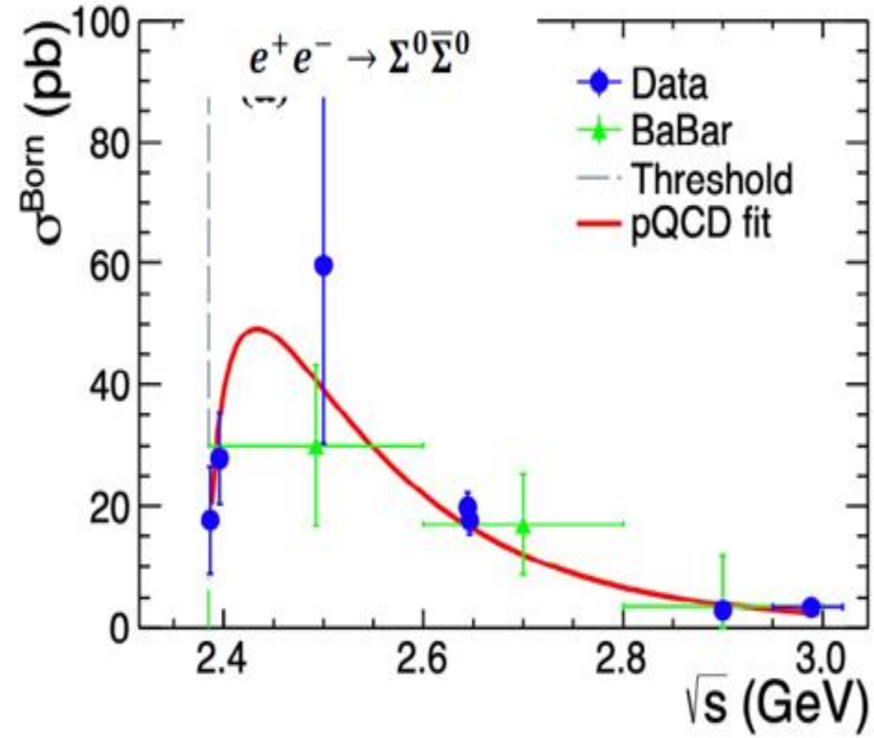
Where is the X(2231)?



M. Ablikim, et al., Phys. Rev. D 100, 032009(2019).

Σ





The ratio $\Sigma^+\bar{\Sigma}^- : \Sigma^0\bar{\Sigma}^0 : \Sigma^-\bar{\Sigma}^+$ is about $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1$.

BESIII, **Phys. Lett. B 814, 136110 (2021) ; Phys. Lett. B 831, 137187 (2022).**

EMFFs of Σ^+, Σ^-, and Σ^0 (VMD)

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

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

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

Isospin decomposition

$$F_1^{\Sigma^+} = g(q^2)(f_1^{\Sigma^+} + \frac{\beta_\rho}{\sqrt{2}}B_\rho - \frac{\beta_{\omega\phi}}{\sqrt{3}}B_{\omega\phi}),$$

$$F_2^{\Sigma^+} = g(q^2)(f_2^{\Sigma^+}B_\rho - \frac{\alpha_{\omega\phi}}{\sqrt{3}}B_{\omega\phi}),$$

$$F_1^{\Sigma^-} = g(q^2)(f_1^{\Sigma^-} - \frac{\beta_\rho}{\sqrt{2}}B_\rho - \frac{\beta_{\omega\phi}}{\sqrt{3}}B_{\omega\phi}),$$

$$F_2^{\Sigma^-} = g(q^2)(f_2^{\Sigma^-}B_\rho - \frac{\alpha_{\omega\phi}}{\sqrt{3}}B_{\omega\phi}),$$

$$F_1^{\Sigma^0} = g(q^2)(\frac{\beta_{\omega\phi}}{\sqrt{3}} - \frac{\beta_{\omega\phi}}{\sqrt{3}}B_{\omega\phi}),$$

$$F_2^{\Sigma^0} = g(q^2)\mu_{\Sigma^0}B_{\omega\phi},$$

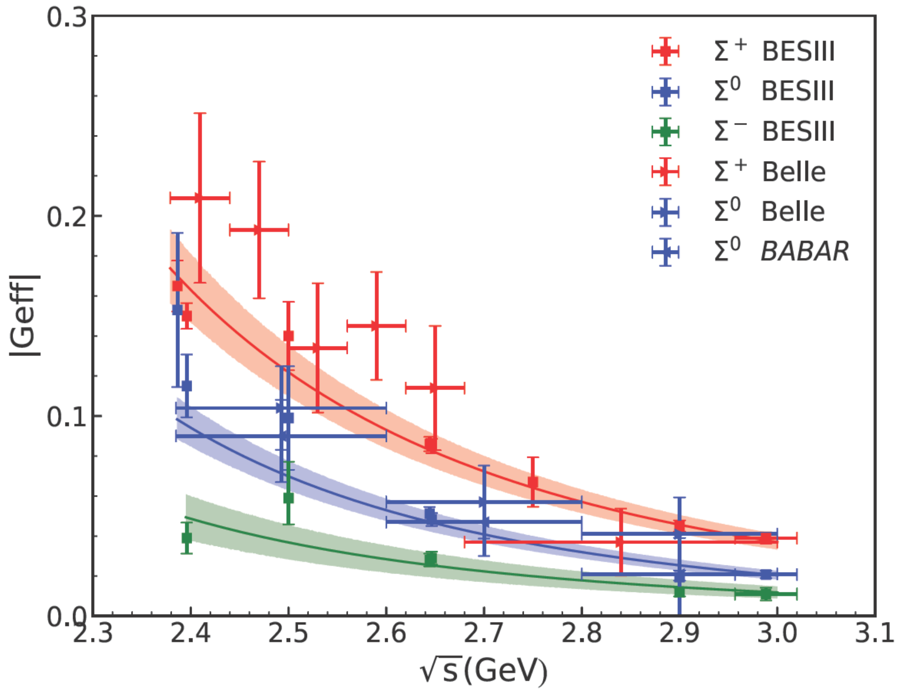
$$B_\rho = \frac{m_\rho^2}{m_\rho^2 - q^2 - im_\rho\Gamma_\rho},$$

$$B_{\omega\phi} = \frac{m_{\omega\phi}^2}{m_{\omega\phi}^2 - q^2 - im_{\omega\phi}\Gamma_{\omega\phi}},$$

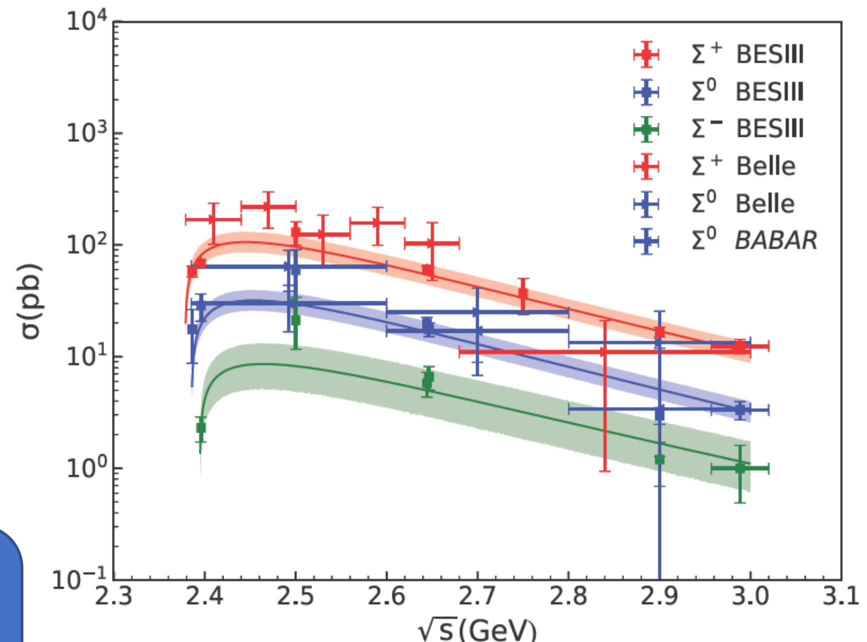
$$f_1^{\Sigma^+} = 1 - \frac{\beta_\rho}{\sqrt{2}} + \frac{\beta_{\omega\phi}}{\sqrt{3}}, \quad f_2^{\Sigma^+} = 2.112 + \frac{\alpha_{\omega\phi}}{\sqrt{3}},$$

$$f_1^{\Sigma^-} = -1 + \frac{\beta_\rho}{\sqrt{2}} + \frac{\beta_{\omega\phi}}{\sqrt{3}}, \quad f_2^{\Sigma^-} = -0.479 + \frac{\alpha_{\omega\phi}}{\sqrt{3}}$$

EMFFs of Σ^+, Σ^-, and Σ^0 : Numerical results



Parameter	Value	Parameter	Value
γ (GeV^{-2})	0.527 ± 0.024	$\alpha_{\omega\phi}$	-3.18 ± 0.77
$\beta_{\omega\phi}$	-0.08 ± 0.06	β_ρ	1.63 ± 0.07



With the same value of γ, we can describe all the current experimental data on Σ^+, Σ^-, and Σ^0 EMFFs.

Bing Yan, Cheng Chen, and Ju-Jun Xie, **Phys. Rev. D107, 076008 (2023).**

New experimental results

PHYSICAL REVIEW LETTERS **132,** 081904 (2024)

Determination of the Σ^+ Timelike Electromagnetic Form Factors

M. Ablikim *et al.*[*]
(BESIII Collaboration)

TABLE I. Fit results for α, $\Delta\Phi(°)$, $\sin(\Delta\Phi)$, and $|G_E/G_M|$ at each energy point.

$\sqrt{s}$ (GeV)	2.3960	2.6454	2.9000
α	$-0.47 \pm 0.18 \pm 0.09$	$0.41 \pm 0.12 \pm 0.06$	$0.35 \pm 0.17 \pm 0.15$
$\Delta\Phi(°)$	$-42 \pm 22 \pm 14$ $(-138 \pm 22 \pm 14)$	$55 \pm 19 \pm 14$	$78 \pm 22 \pm 9$
$\sin \Delta\Phi$	$-0.67 \pm 0.29 \pm 0.18$		
$\lvert G_E/G_M \rvert$	$1.69 \pm 0.38 \pm 0.20$	$0.72 \pm 0.11 \pm 0.06$	$0.85 \pm 0.16 \pm 0.15$

PHYSICAL REVIEW D **109,** 034029 (2024)

Measurements of Σ electromagnetic form factors in the timelike region using the untagged initial-state radiation technique

TABLE III. The cross sections ($\sigma_{\Sigma^+\bar{\Sigma}^-}$) and the effective FFs ($|G_{\text{eff}}|$) for the process $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ at all datasets. N^{sig} is the total number of signal events. $\bar{\varepsilon}$ is the average detection efficiency of all datasets weighted by the effective ISR luminosity. $\mathcal{L}_{\text{eff}}$ is the total effective ISR luminosity. For $\sigma_{\Sigma^+\bar{\Sigma}^-}$ and $|G_{\text{eff}}|$, the first and second uncertainties are statistical and systematic, respectively; for N^{sig}, the uncertainties are statistical only. The values in brackets for N^{sig}, $\sigma_{\Sigma^+\bar{\Sigma}^-}$ and $|G_{\text{eff}}|$ correspond to the upper limits at 90% confidence level.

$M_{\Sigma^+\bar{\Sigma}^-}$ (GeV/c^2)	N^{sig}	$\bar{\varepsilon}$(%)	$\mathcal{L}_{\text{eff}}$ (pb^{-1})	$\sigma_{\Sigma^+\bar{\Sigma}^-}$ (pb)	$\lvert G_{\text{eff}} \rvert (\times 10^{-2})$
2.379–2.44	$2.7^{+1.8}_{-1.9}(<6.8)$	0.91	15.13	$74^{+50}_{-52} \pm 5(<190)$	$14.1^{+4.8}_{-5.0} \pm 0.5(<22.7)$
2.44–2.50	16 ± 4	2.07	15.77	$190 \pm 50 \pm 20$	$18.2 \pm 2.4 \pm 1.0$
2.50–2.56	30 ± 6	3.69	16.82	$187 \pm 37 \pm 19$	$16.6 \pm 1.7 \pm 0.8$
2.56–2.62	28 ± 6	5.33	17.96	$112 \pm 24 \pm 11$	$12.3 \pm 1.3 \pm 0.6$
2.62–2.68	26 ± 6	6.49	19.22	$79 \pm 18 \pm 8$	$10.2 \pm 1.2 \pm 0.5$
2.68–2.74	20 ± 5	7.24	20.62	$52 \pm 14 \pm 4$	$8.1 \pm 1.1 \pm 0.3$
2.74–2.80	16 ± 5	7.85	22.16	$36 \pm 10 \pm 3$	$6.7 \pm 1.0 \pm 0.3$
2.80–2.86	13 ± 4	8.19	23.90	$26 \pm 8 \pm 2$	$5.5 \pm 0.9 \pm 0.2$
2.86–2.92	19 ± 5	8.62	25.83	$33 \pm 8 \pm 2$	$6.5 \pm 0.8 \pm 0.2$
2.92–2.98	$-0.7^{+4.5}_{-4.6}(<7.7)$	8.96	28.01	$-1.1^{+6.8}_{-7.1} \pm 0.1(<11.7)$	$-1.2^{+3.6}_{-3.8} \pm 0.1(<3.9)$
2.98–3.04	11 ± 6	9.23	30.50	$15 \pm 8 \pm 1$	$4.4 \pm 1.1 \pm 0.1$

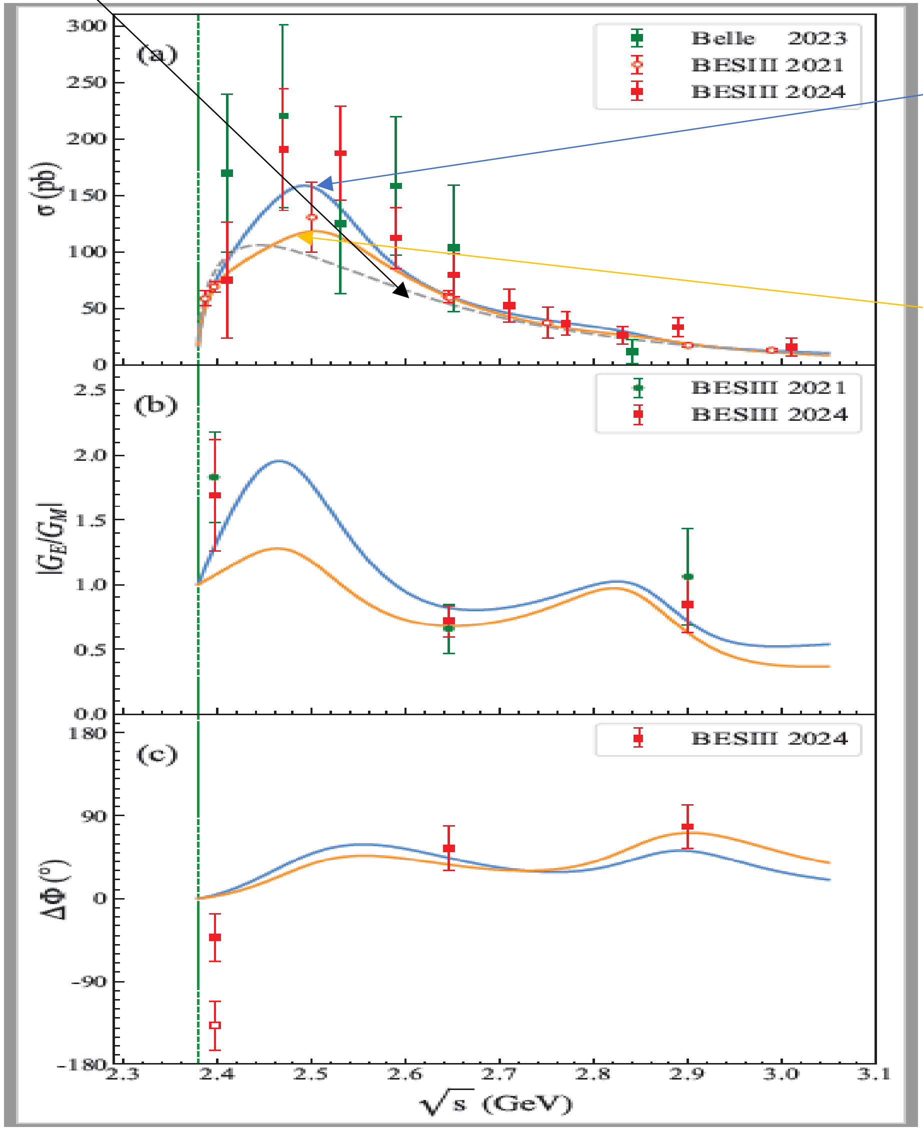
New theoretical results

Chinese Physics Letters **42**, 120201 (2025)

The Electromagnetic Form Factors of Σ and $\Sigma^0 \to \Lambda$ Transition in the Timelike Region

Cheng Chen[1,2], Bing Yan[3], Bing-Wei Long[3,4], and Ju-Jun Xie[1,2,4*]

Our previous work.



Including $\omega(3D)$ $with$ $M = 2300$ MeV and $\Gamma = 100$ MeV.

Including $\rho(3D)$ $with$ $M = 2300$ MeV and $\Gamma = 160$ MeV.

PHYSICAL REVIEW D **104,** 054045 (2021)

Deciphering the light vector meson contribution to the cross sections of e^+e^- annihilations into the open-strange channels through a combined analysis

Jun-Zhang Wang,[1,2,‡] Li-Ming Wang,[3,†] Xiang Liu,[1,2,4,*] and Takayuki Matsuki[5,§]

[1]*School of Physical Science and Technology, Lanzhou University, Lanzhou 730000, China*
[2]*Research Center for Hadron and CSR Physics, Lanzhou University and Institute of Modern Physics of CAS, Lanzhou 730000, China*
[3]*Key Laboratory for Microstructural Material Physics of Hebei Province, School of Science, Yanshan University, Qinhuangdao 066004, China*
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(Received 29 June 2021; accepted 7 September 2021; published 28 September 2021)

EMFFs of Ξ^- and Ξ^0 : Numerical results

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

$$F_1^{\Xi^0} = g(q^2)\left(f_1^{\Xi^0} + \frac{\beta_\rho}{\sqrt{2}}B_\rho + \frac{\beta_{V_1}}{\sqrt{2}}B_{V_1} + \frac{\beta_{V_2}}{\sqrt{2}}B_{V_2} + \frac{\beta_{\omega\phi}}{\sqrt{2}}B_{\omega\phi}\right)$$

$$F_2^{\Xi^0} = g(q^2)\left(f_2^{\Xi^0} B_\rho + \frac{\alpha_{V_1}}{\sqrt{2}}B_{V_1} + \frac{\alpha_{V_2}}{\sqrt{2}}B_{V_2} + \frac{\alpha_{\omega\phi}}{\sqrt{2}}B_{\omega\phi}\right)$$

$$F_1^{\Xi^-} = g(q^2)\left(f_1^{\Xi^-} - \frac{\beta_\rho}{\sqrt{2}}B_\rho - \frac{\beta_{V_1}}{\sqrt{2}}B_{V_1} - \frac{\beta_{V_2}}{\sqrt{2}}B_{V_2} + \frac{\beta_{\omega\phi}}{\sqrt{2}}B_{\omega\phi}\right)$$

$$F_2^{\Xi^-} = g(q^2)\left(f_2^{\Xi^-} B_\rho - \frac{\alpha_{V_1}}{\sqrt{2}}B_{V_1} - \frac{\alpha_{V_2}}{\sqrt{2}}B_{V_2} + \frac{\alpha_{\omega\phi}}{\sqrt{2}}B_{\omega\phi}\right)$$

$$m_{V_1} = 2.742 \pm 0.007\,\mathrm{GeV}$$

$$\Gamma_{V_1} = 71 \pm 28\,\mathrm{MeV}$$

MGI model

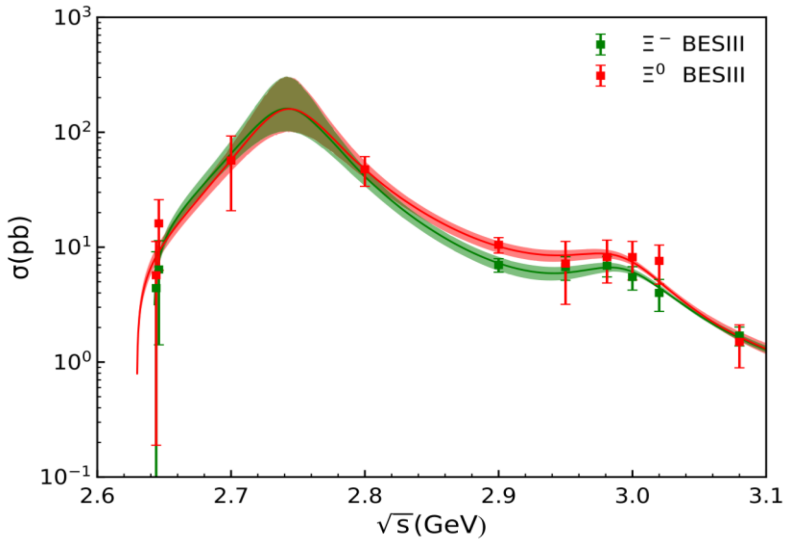
$\varphi(4D) = 2.744$ GeV

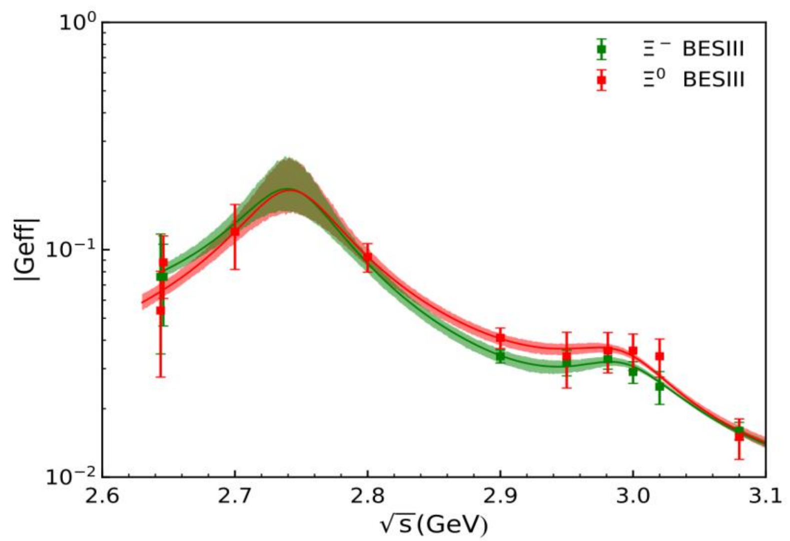
PRD.105.034011 (2022)

QCD sum rule

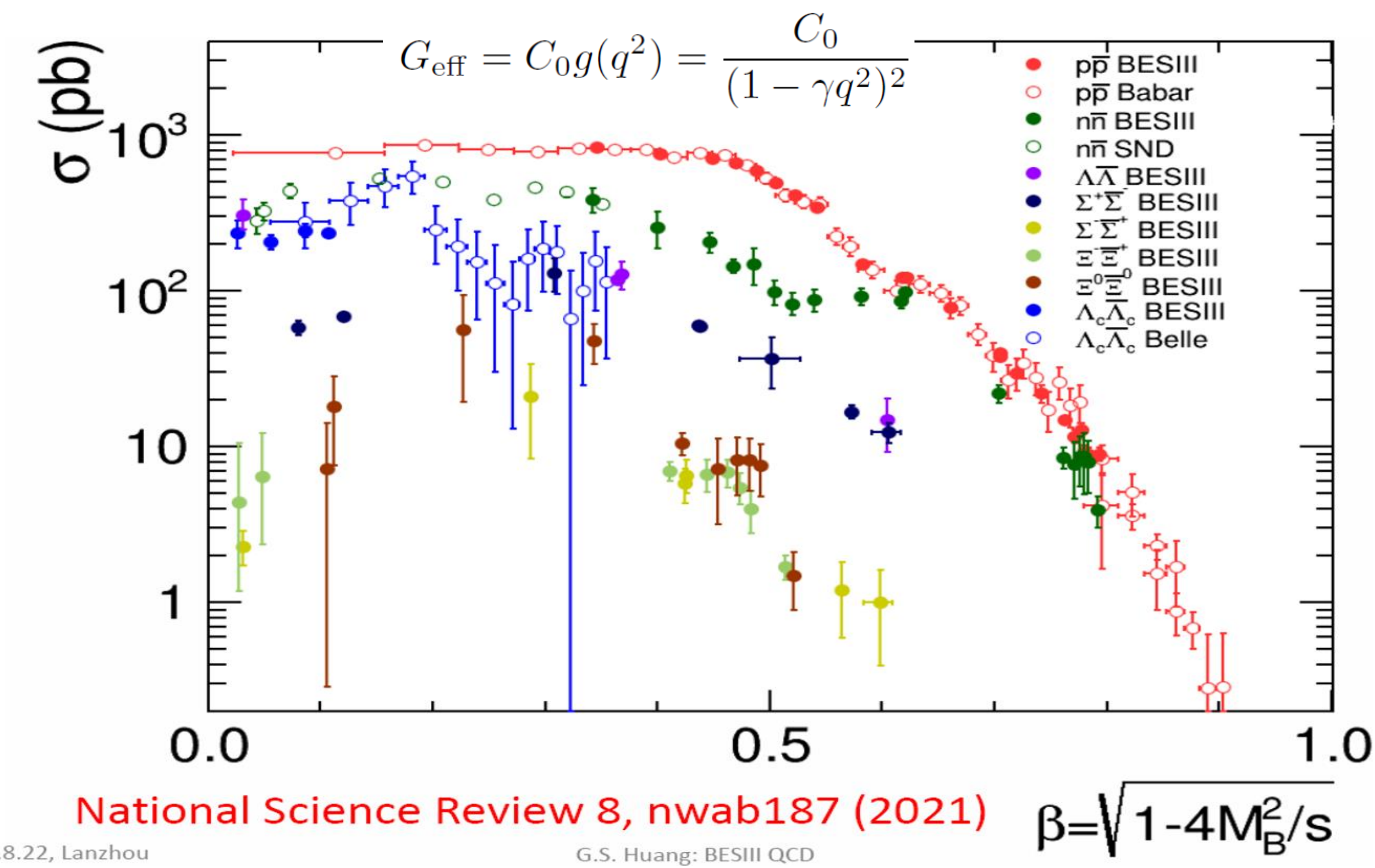
$m_{1^{--}}^{\Xi\bar{\Xi}} = 2.79 \pm 0.11$ GeV

PRD.105.014016 (2022)





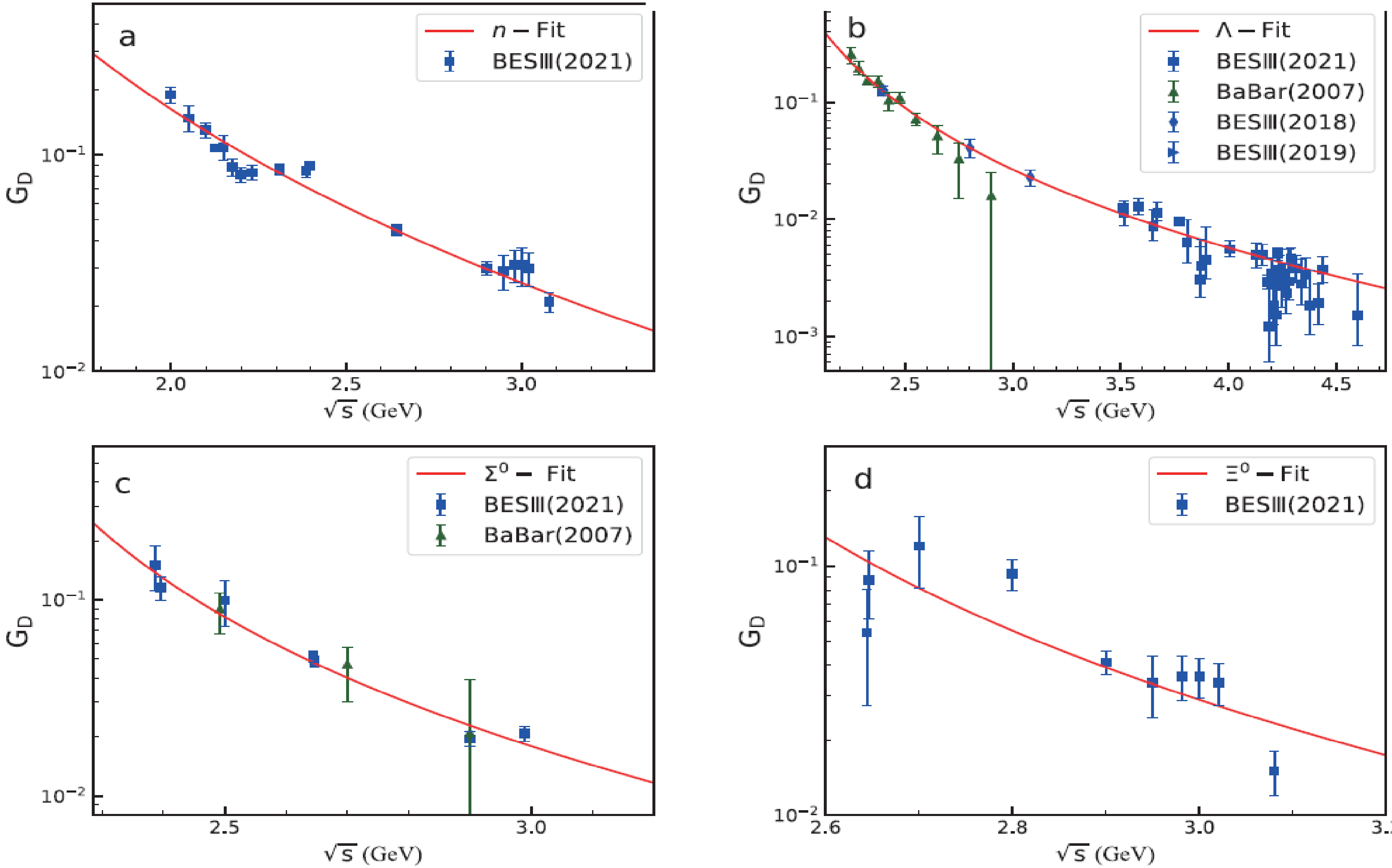
Dipole behavior of baryon effective form factors



https://doi.org/10.1093/nsr/nwab187

$$G_D(q^2) = \frac{c_0}{(1 - \gamma q^2)^2}$$

Parameter	n	Λ	Σ^0	Ξ^0
γ	1.41 (fixed)	0.34 ± 0.08	0.26 ± 0.01	0.21 ± 0.02
c_0	3.48 ± 0.06	0.11 ± 0.01	0.033 ± 0.007	0.023 ± 0.008
χ^2/dof	4.3	2.4	1.1	3.0



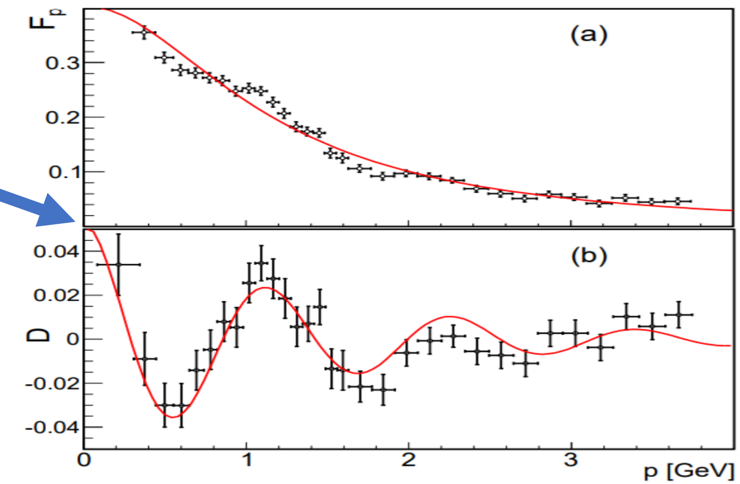
A.X. Dai, Z.Y. Li, L. Chang and Ju-Jun Xie, Chin. Phys. C 46, 073104 (2022).

“ Oscillation” of baryon effective form factors

2015, Andrea Bianconi et al., Phys. Rev. Lett., 2015, 114(23): 232301.

$$G_{eff} = F_{3p} + F_{osc} \quad \rightarrow \quad F_{osc} = data - G_D$$

$$\boxed{\begin{aligned} F_{3p}(s) &= \frac{F_0}{\left(1+\frac{s}{m_a^2}\right)\left(1-\frac{s}{m_0^2}\right)^2}, \\ F_{osc}(p(s)) &= Ae^{-Bp}\cos(Cp+D). \end{aligned}}$$

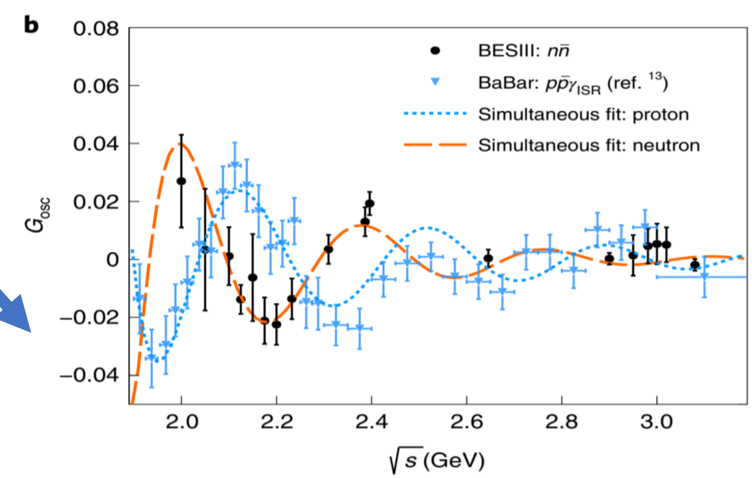


2021, BESIII Collaboration, Nature Phys., 2021, 17(11): 1200-1204.

$$data = G_{eff} = G_D + F_{osc}$$

$$\rightarrow \quad F_{osc} = data - G_D$$

$$F_{osc}^{n,p} = A^{n,p}\exp\left(-B^{n,p}p\right)\cos\left(Cp + D^{n,p}\right)$$



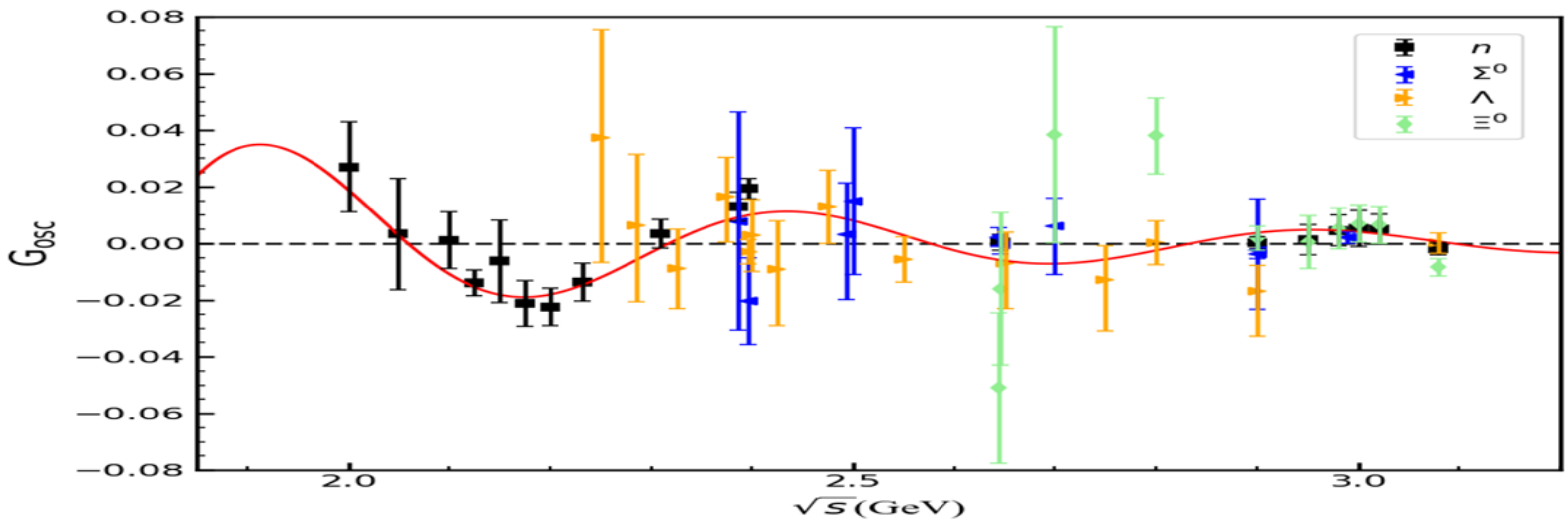
New parametrization for the “oscillation”

$$G_D(q^2) = \frac{c_0}{(1 - \gamma q^2)^2} \qquad G_{osc} = A \cdot \frac{c_0}{(1-\gamma \cdot s)^2} \cdot \cos\left(C \cdot \sqrt{s} + D\right)$$

$$G_{\rm eff}(s) = G_{\rm D}(s) + G_{\rm osc}(s)$$
$$= \frac{c_0}{(1-\gamma s)^2}\left(1 + A\cos(C\sqrt{s} + D)\right)$$

$$\boxed{data = G_{eff} = G_D + G_{osc}}$$

$$\rightarrow \boxed{G_{osc} = data - G_D}$$



A.X. Dai, Z.Y. Li, L. Chang and Ju-Jun Xie, Chin. Phys. C 46, 073104 (2022).

New experimental results

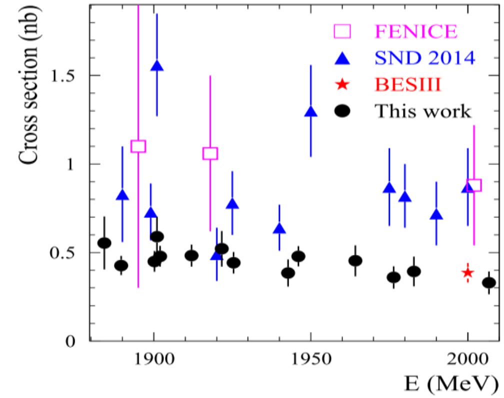
Eur. Phys. J. C (2022) 82:761
https://doi.org/10.1140/epjc/s10052-022-10696-0

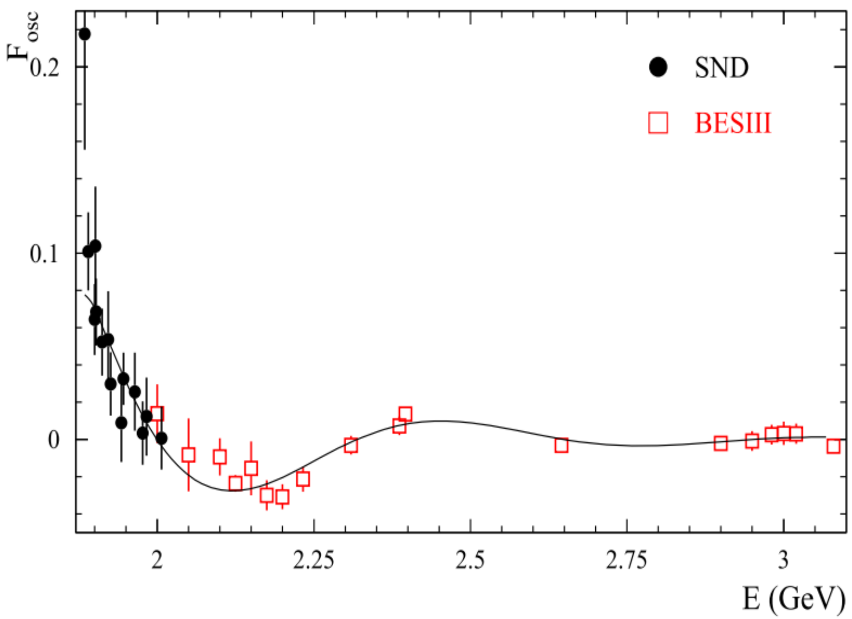
THE EUROPEAN PHYSICAL JOURNAL C

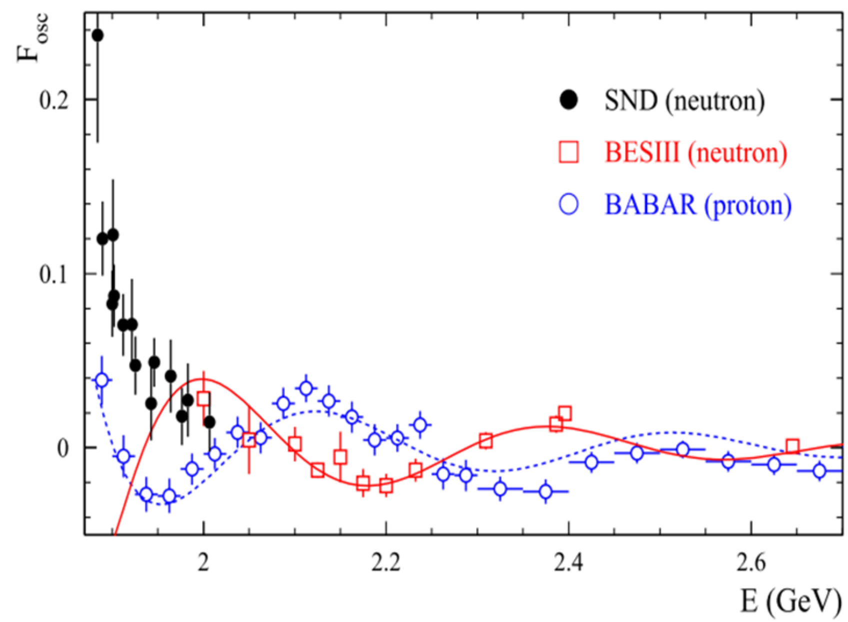
Regular Article - Experimental Physics

Experimental study of the $e^+e^- \to n\bar{n}$ process at the VEPP-2000 e^+e^- collider with the SND detector

SND Collaboration



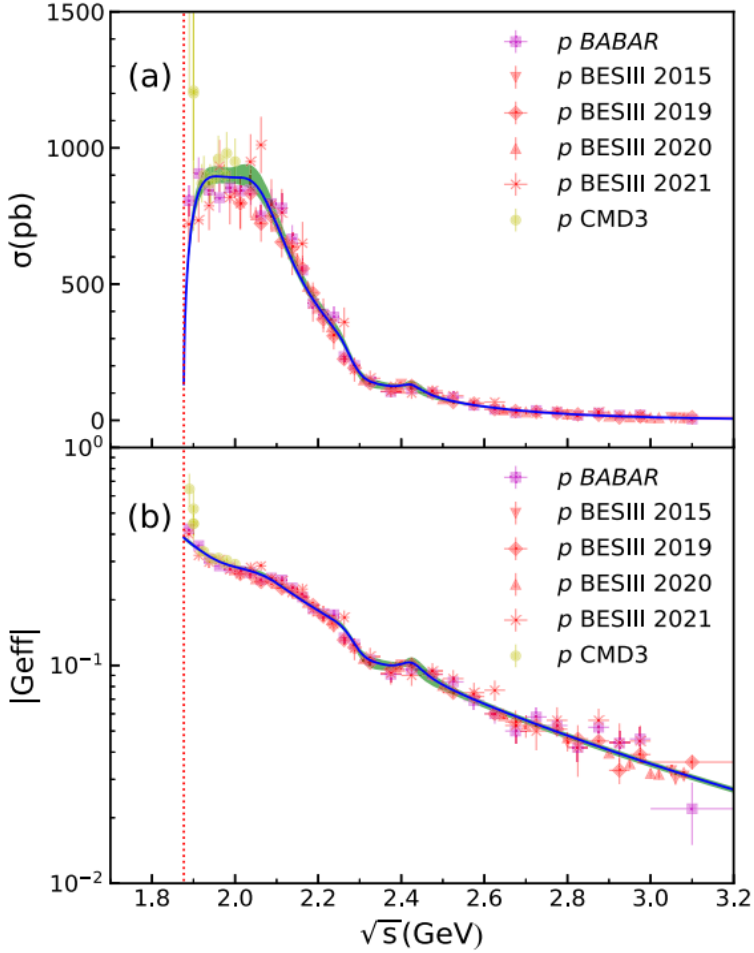




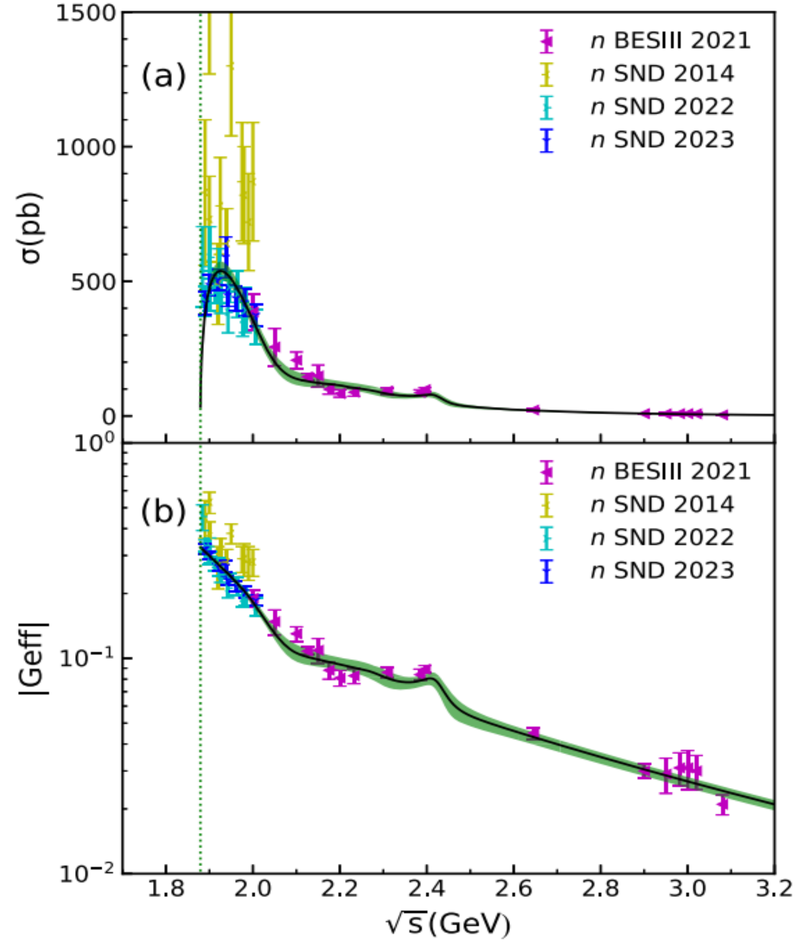
EMFFs of proton and neutron (VMD)

State	M_R (MeV)	Γ_R (MeV)
$\rho(2D)$	2040	202
$\omega(3D)$	2283	94
$\omega(5S)$	2422	64

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



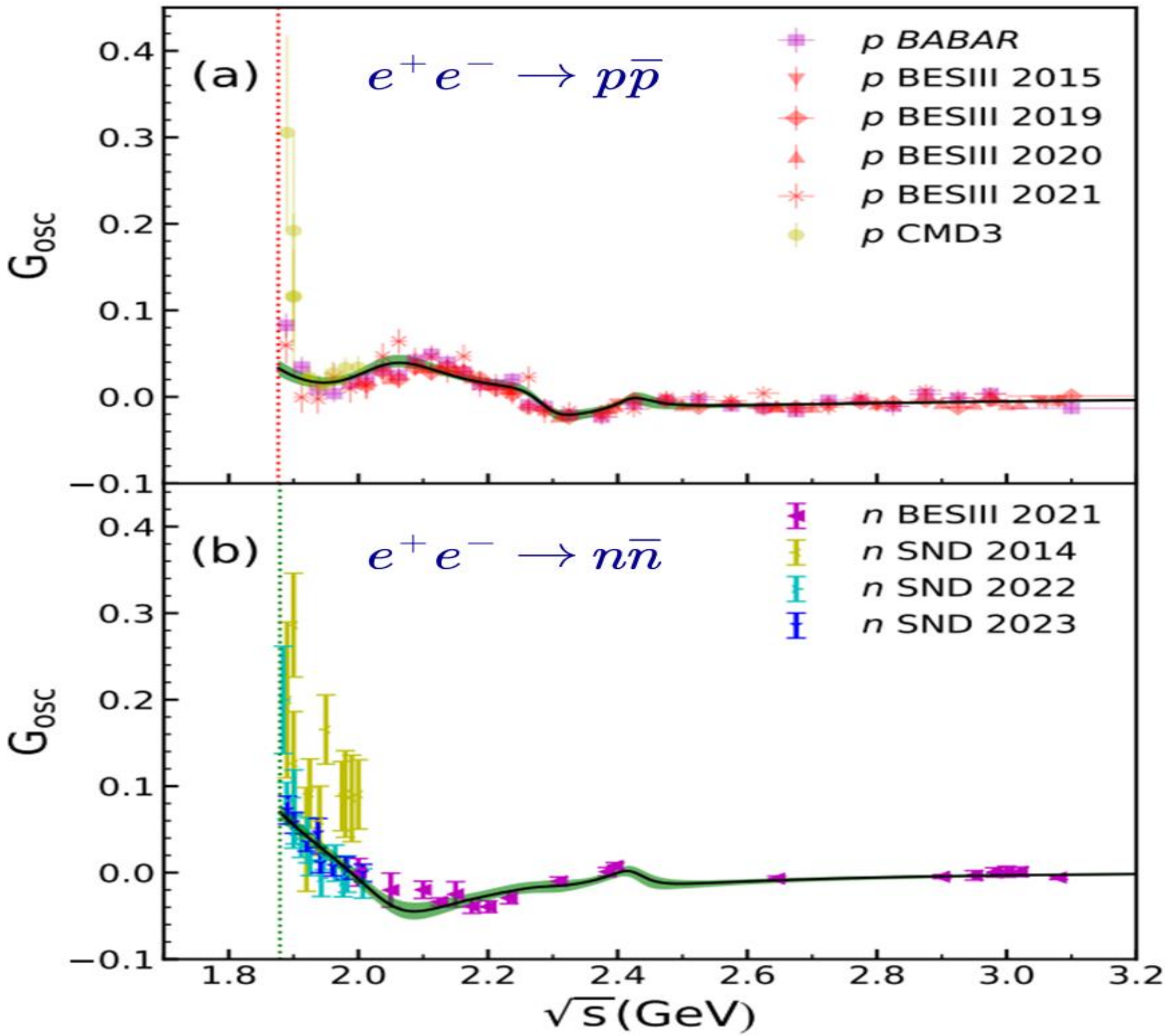
$e^+e^- \to n\bar{n}$



Bing Yan, Cheng Chen, Xia Li, Ju-Jun Xie, Phys. Rev. D109, 036003 (2024).

$$G_{\mathrm{osc}} = |G_{\mathrm{eff}}| - G_D = |G_{\mathrm{eff}}| - \frac{c_0}{(1-\gamma s)^2}$$

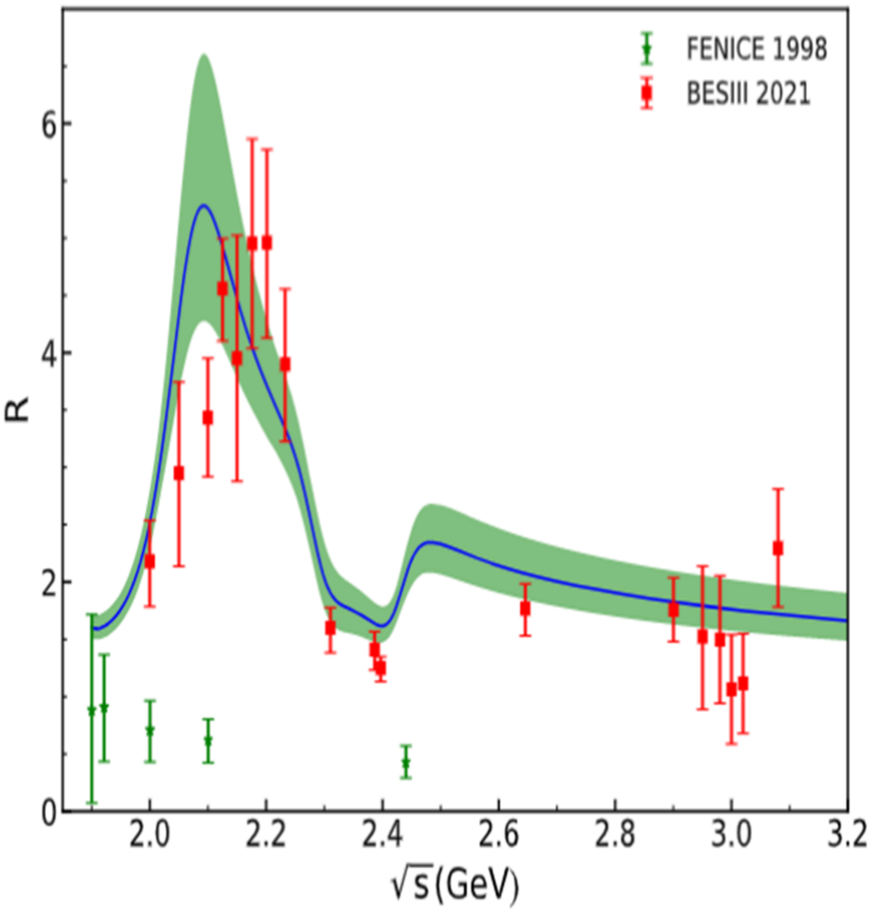
$$\gamma = \frac{1}{0.71}\ \mathrm{GeV}^{-2}$$



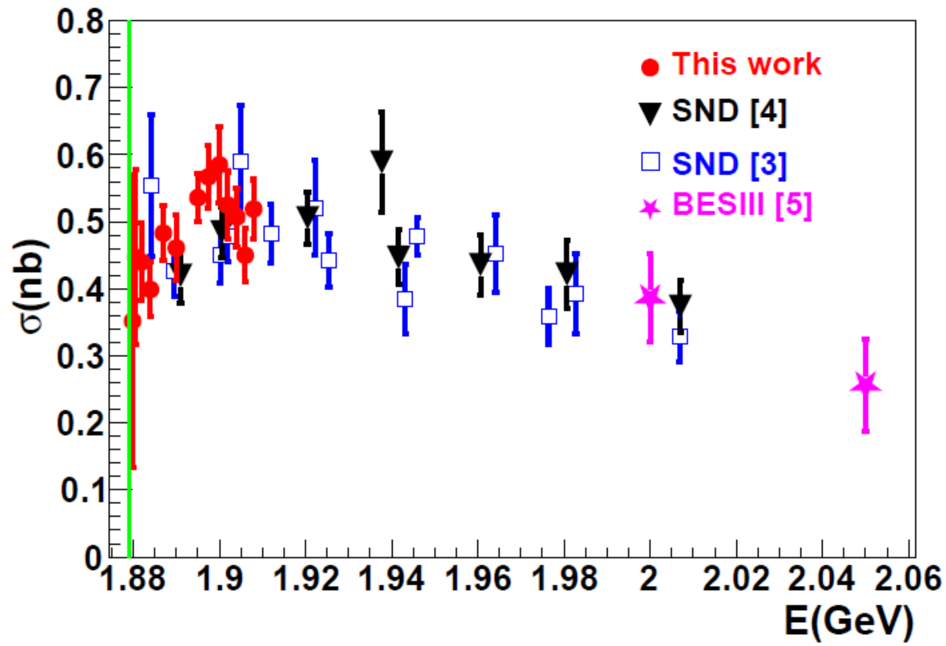
$c_0 = 5.54 \pm 0.02$
for proton

$c_0 = 4.08 \pm 0.04$
for neutron

$$R = \sigma_{e^+e^- \to p\bar{p}} / \sigma_{e^+e^- \to n\bar{n}}$$



Cross section of the process $e^+e^- \to n\bar{n}$ near the threshold



M. N. Achasov, *et al.,* Phys. Atom. Nucl. 87, 604-613 (2024). [arXiv:2407.15308 [hep-ex]].

e-Print: 2206.01494 [nucl-th]

Science Bulletin 68 (2023) 2729–2733

New insights into the oscillation of the nucleon electromagnetic form factors

Qin-He Yang[1,2], Ling-Yun Dai[1,2,*] Di Guo[1,2], Johann Haidenbauer[3], Xian-Wei Kang[4,5], and Ulf-G. Meißner[6,3,7]

PHYSICAL REVIEW D **105,** L071503 (2022)

Letter

e-Print: 2109.15132 [hep-ph]

Timelike nucleon electromagnetic form factors: All about interference of isospin amplitudes

Xu Cao,[1,2,*] Jian-Ping Dai,[3,†] and Horst Lenske[4,‡]

PHYSICAL REVIEW D **107,** L091502 (2023)

Letter

e-Print: 2211.11555 [nucl-th]

Toy model to understand the oscillatory behavior in timelike nucleon form factors

Ri-Qing Qian,[1,2,3,4,*] Zhan-Wei Liu,[1,2,3,4,†] Xu Cao,[2,3,5,6,‡] and Xiang Liu[1,2,3,4,§]

PHYSICAL REVIEW LETTERS **128,** 052002 (2022)

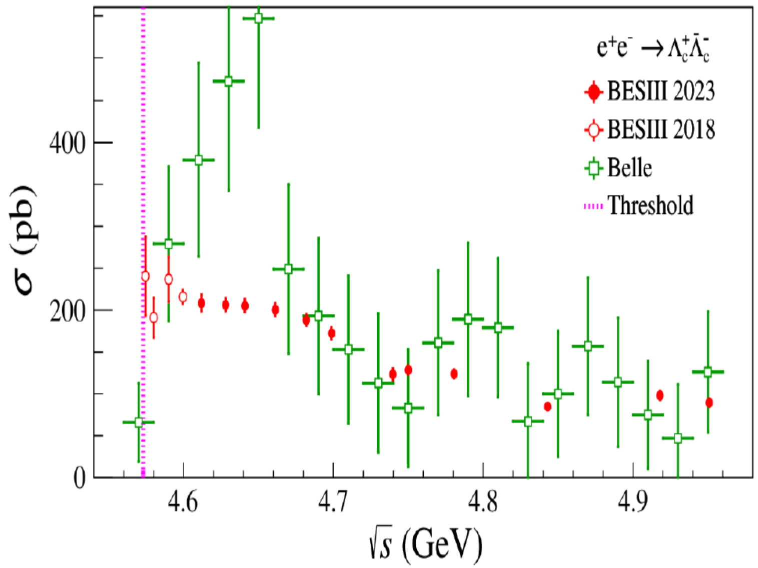
e-Print: 2109.12961 [hep-ph]

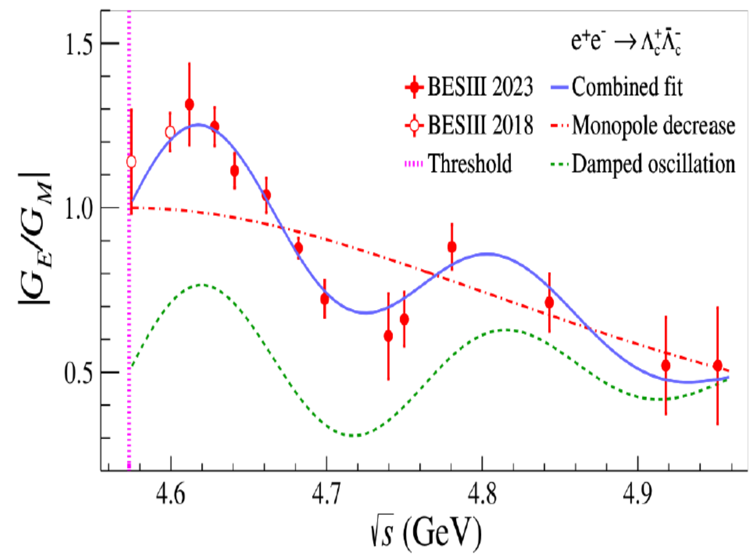
New Insights into the Nucleon's Electromagnetic Structure

Yong-Hui Lin,[1] Hans-Werner Hammer,[2,3] and Ulf-G. Meißner[1,4,5]

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

PHYSICAL REVIEW LETTERS **131**, 191901 (2023)



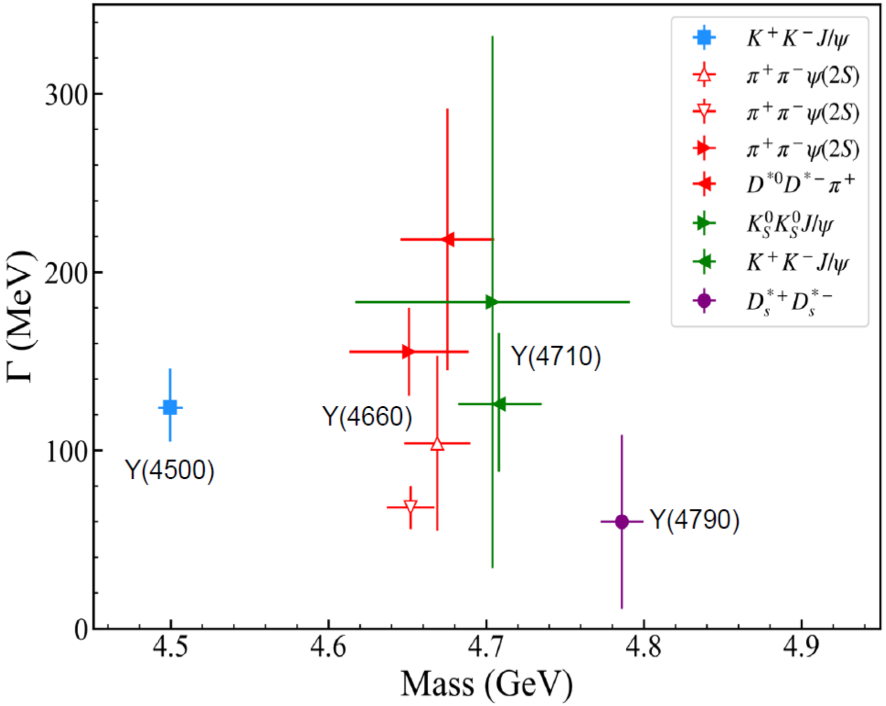


The results of BESIII revealed that there is no peak around $\sqrt{s}$ = 4.63 GeV but a long flat from the threshold to 4.68 GeV, diverging from the Belle measurements

The threshold enhancement

The long plateau figure is about 90 MeV

The oscillation behavior of the ratio



△: BABAR ▽: Belle Others: BESIII

A possible state near 4.9 GeV $\psi(4D)$

CPC.35.319 (2011); PRD.80.074001 (2009); EPL.85.61002 (2009)

Including the following charmoniumlike states:

$\psi(4500)$, $\psi(4660)$, $\psi(4790)$, $\psi(4900)$

Masses and widths of the charmoniumlike states

State	M_R (MeV)	Γ_R (MeV)
$\psi(4500)$	4500	125
$\psi(4660)$	4670	115
$\psi(4790)$	4790	100
$\psi(4900)$	4900	100

$$B_{R_i} = \frac{M_{R_i}^2}{M_{R_i}^2 - s - iM_{R_i}\Gamma_{R_i}}$$

$$F_1 = g(s)\Big(f_1 + \sum_{i=1}^{4}\beta_i B_{R_i}\Big),$$

$$\Gamma_{\psi(4500)} = \Gamma_0 + g_{\Lambda_c}\sqrt{\frac{s}{4} - M_{\Lambda_c^+}^2}$$

$$F_2 = g(s)\Big(f_2 B_{R_1} + \sum_{i=2}^{4}\alpha_i B_{R_i}\Big),$$

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

$$f_1 = 1 - \beta_1 - \beta_2 - \beta_3 - \beta_4,$$

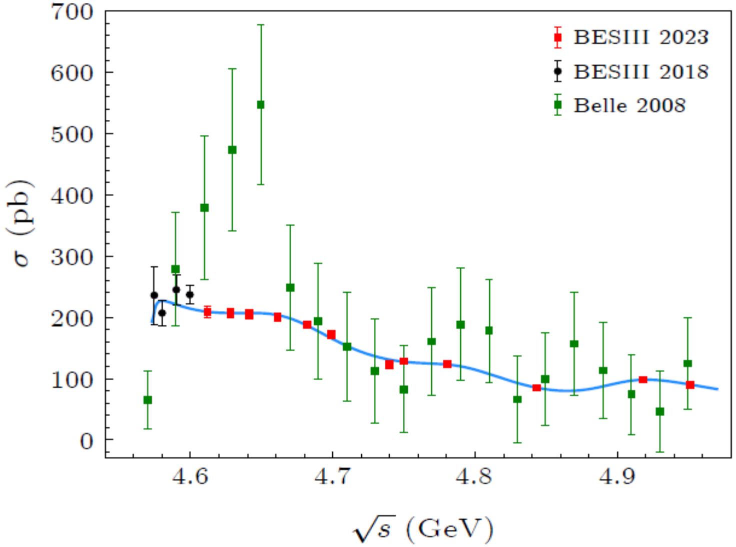
$$f_2 = \mu_{\Lambda_c^+} - 1 - \alpha_2 - \alpha_3 - \alpha_4,$$

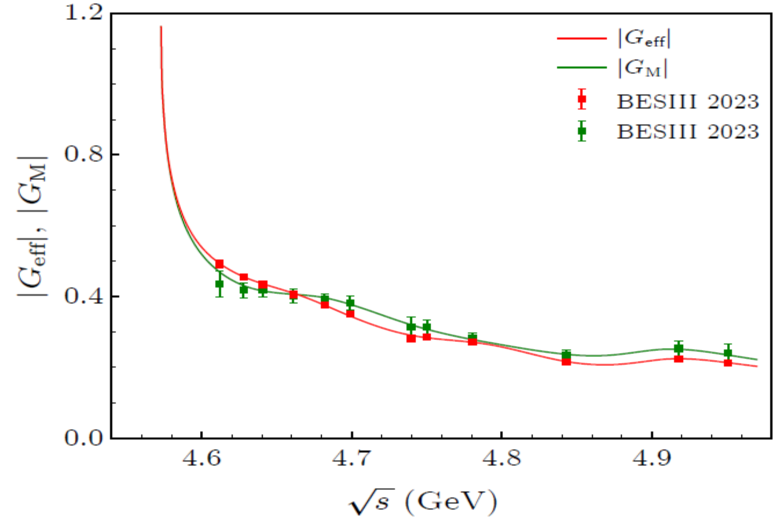
$$\gamma = 0.147 \pm 0.017\ \mathrm{GeV}^{-2}$$

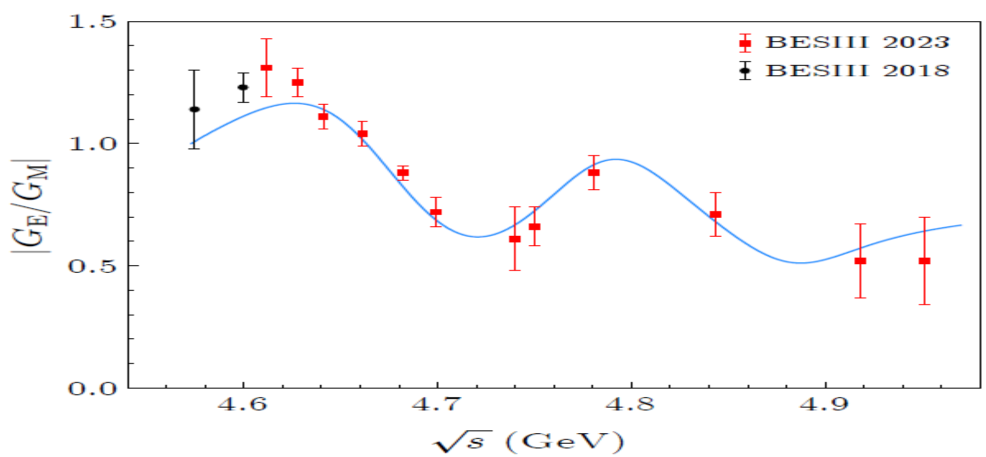
Chinese Physics Letters **41**, 021302 (2024) Express Letter

$e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ Cross Sections and the Λ_c^+ Electromagnetic Form Factors within the Extended Vector Meson Dominance Model

Cheng Chen(陈诚)[1,2*], Bing Yan(闫冰)[1,3*], and Ju-Jun Xie(谢聚军)[1,2,4*]







Summary

1、 Threshold enhancement

a) Final state interaction

b) vector states (Flatté: strong coupling)

\+ Other models

2、 "Oscillation" of baryon effective form factors

a) Phenomenology

b) **Vector excited states**

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

We conclude that
The nonmonotonic structures observed in the line shape of the $e^+e^- \to B\bar{B}$ total cross sections can be naturally explained within the vector meson dominance model.
The $e^+e^- \to B\bar{B}$ reactions can be used to study the excited vector states.

Thank you very much for your attention!