中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Hyperon electromagnetic form factors in VMD model

谢 聚 军
Ju-Jun Xie

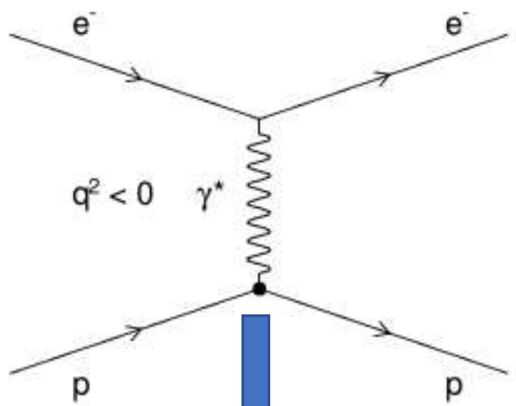
中国科学院近代物理研究所
(Institute of Modern Physics, Chinese Academy of Sciences)

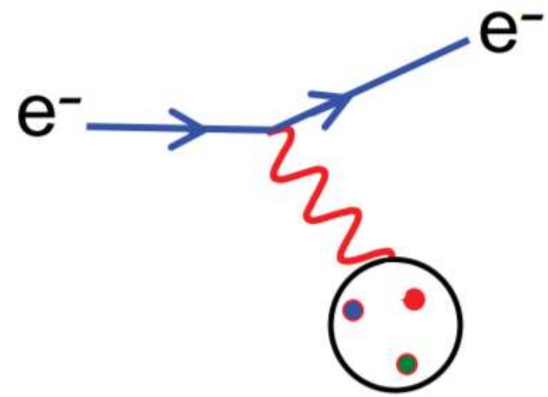
2023年7月27日@第八届XYZ粒子研讨会，长春，吉林大学

Outline

- Introduction：electromagnetic form factors
- The model: Vector Meson Dominance
- Hyperon electromagnetic form factors
- Summary

Electromagnetic form factors (space-like)





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

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

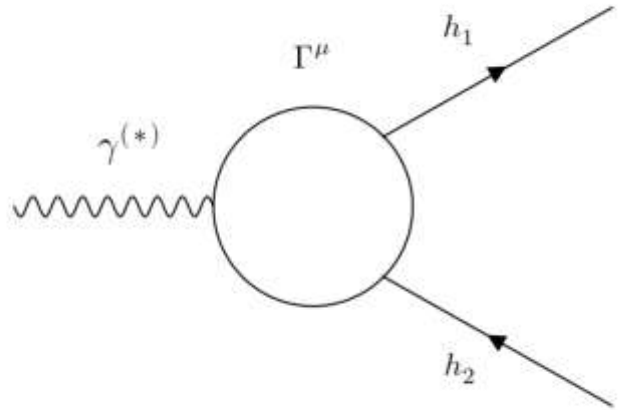
F_1^N : Dirac form factor
F_2^N: Pauli form factor

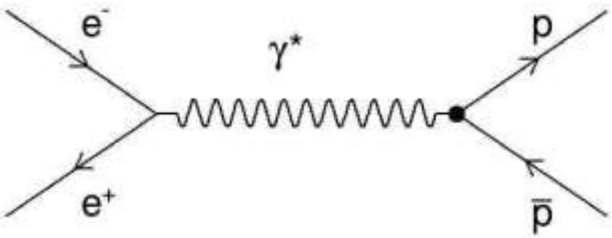
$$G_E^N(Q^2) = F_1^N(Q^2) - \tau F_2^N(Q^2) \,,\; G_M^N(Q^2) = F_1^N(Q^2) + F_2^N(Q^2) \,,\; \tau = \frac{Q^2}{4M_N^2}$$

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

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).**

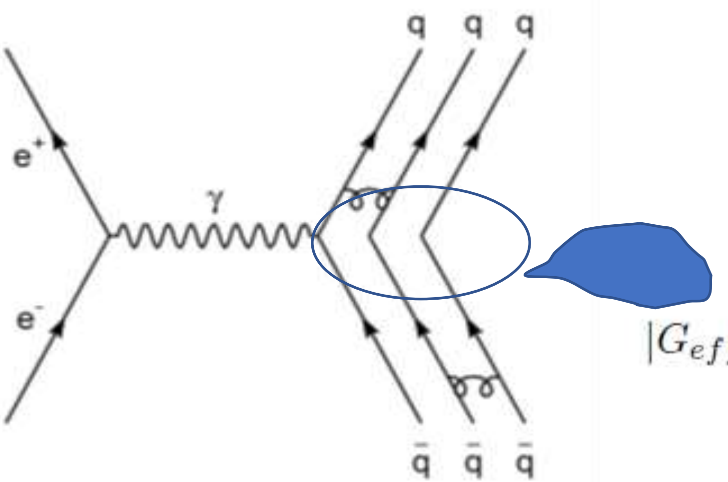
EMFFs (time-like)





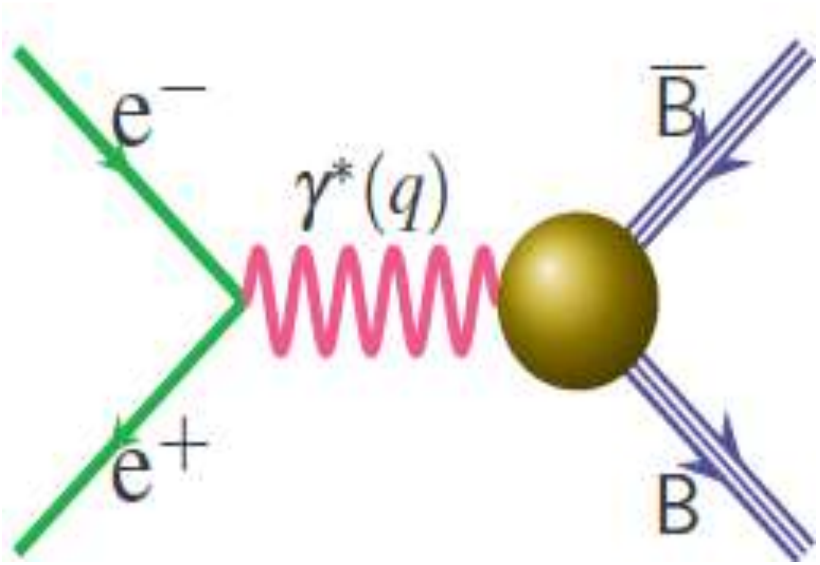
$$\left(\frac{d\sigma}{d\Omega}\right)^{th}_{e^+e^-\to N\bar{N}} = \frac{\alpha^2\beta}{4q^2} C_N(q^2)\left\{|G_M^N(q^2)|^2(1+\cos^2\theta) + |G_E^N(q^2)|^2\frac{1}{\tau}\sin^2\theta\right\}$$

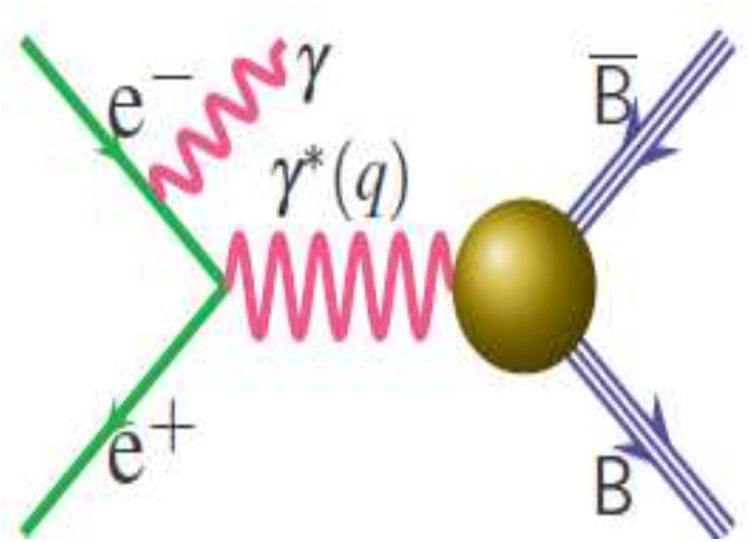
$$\sigma^{th}_{e^+e^-\to N\bar{N}} = \frac{\alpha^2\beta}{4q^2} C_N(q^2)\int d\Omega\left[|G_M^N(q^2)|^2(1+\cos^2\theta) + |G_E^N(q^2)|^2\frac{\sin^2\theta}{\tau}\right]$$
$$= \frac{4\pi\alpha^2\beta}{3q^2} C_N(q^2)\left[|G_M^N(q^2)|^2 + \frac{|G_E^N(q^2)|^2}{2\tau}\right].$$



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

Experimental measurements (time-like)



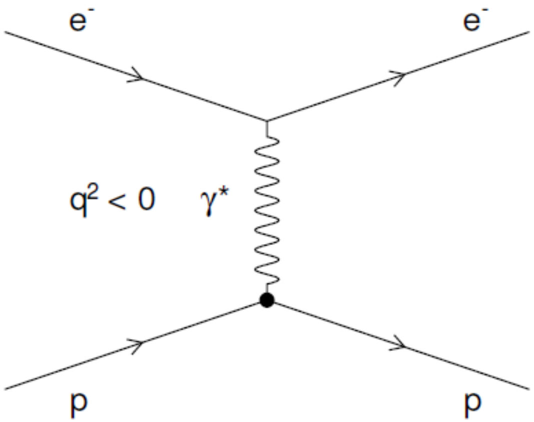


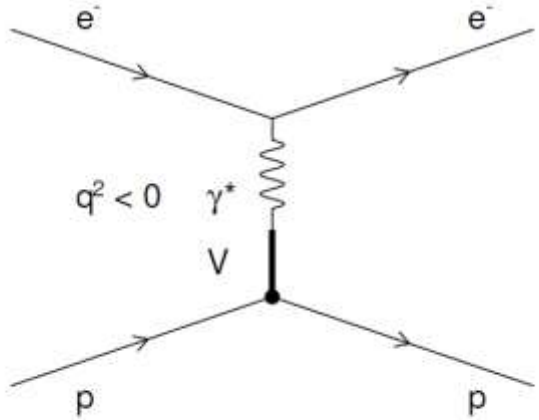
Energy Scan

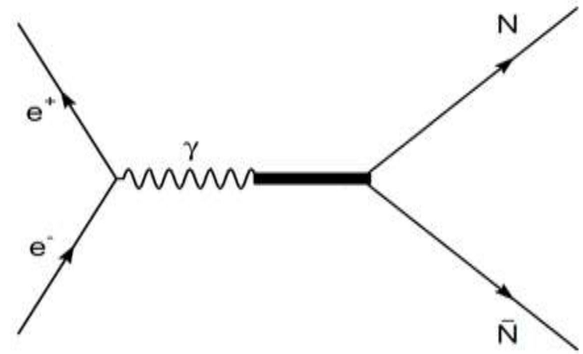
Initial State Radiation

Both techniques can be used at BESIII.

VMD: vector meson dominance model







Dirac and Pauli isoscalar and isovector form factors are

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

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

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

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

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

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

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

Volume 43B, number 3 PHYSICS LETTERS 5 February 1973

SEMI-PHENOMENOLOGICAL FITS TO NUCLEON ELECTROMAGNETIC FORM FACTORS

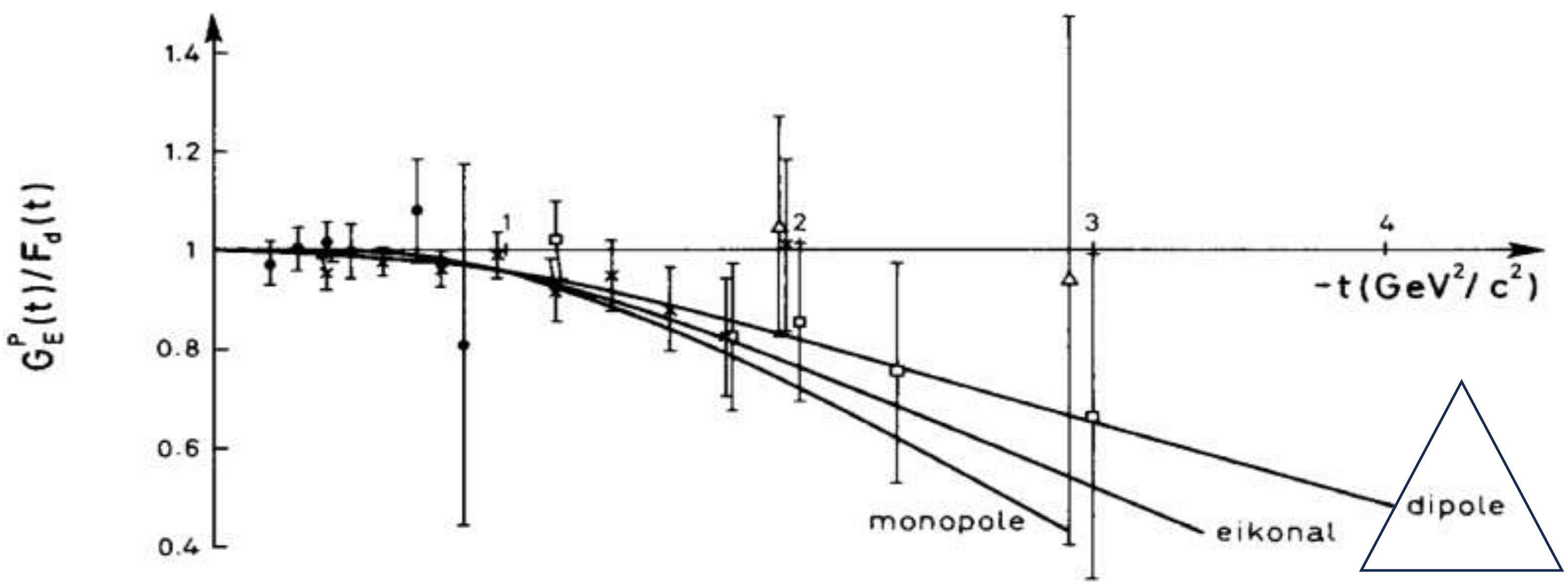
F. IACHELLO* and A.D. JACKSON**
The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark 2100

and

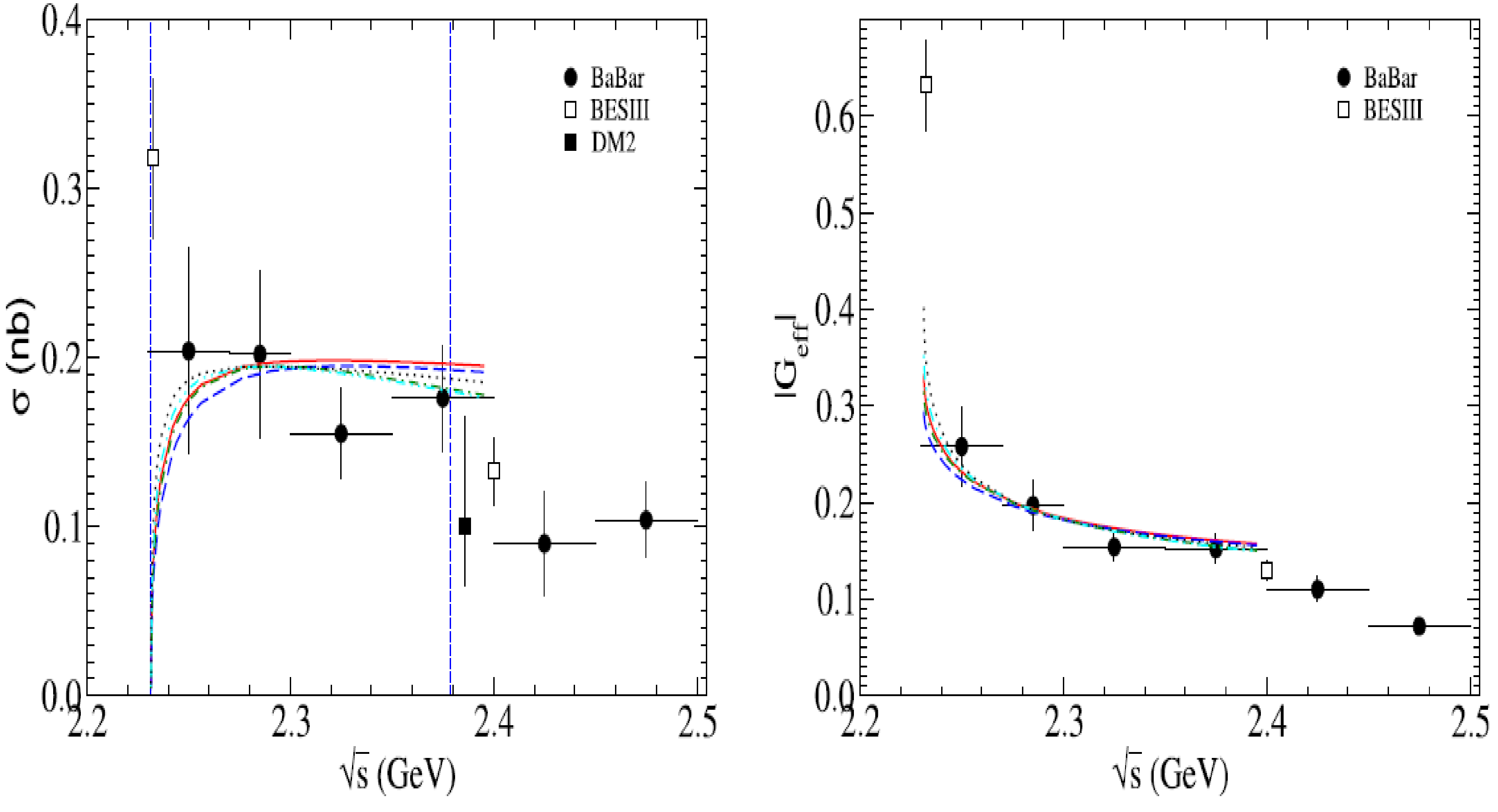
A. LANDE
Institute for Theoretical Physics, University of Groningen, Groningen, The Netherlands

Received 31 August 1972

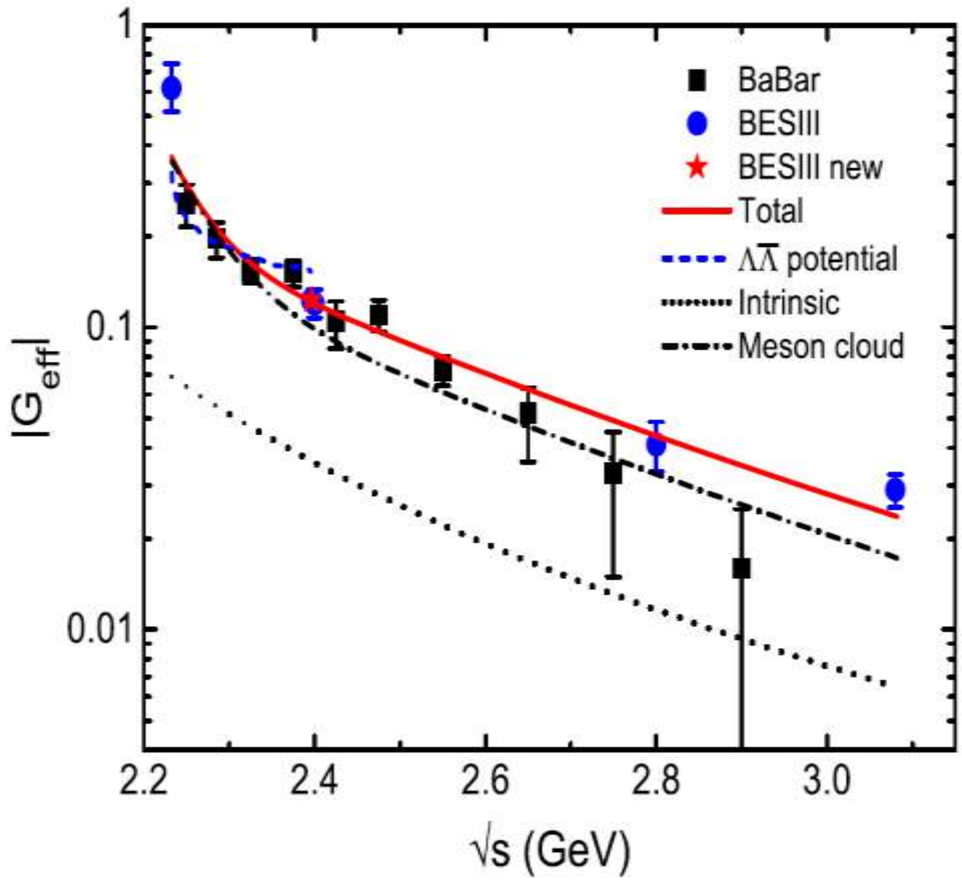
Several theoretically interesting forms of the nucleon EM form factor have been considered and found to provide quantitative descriptions of available data with as few as three adjustable parameters.



Λ



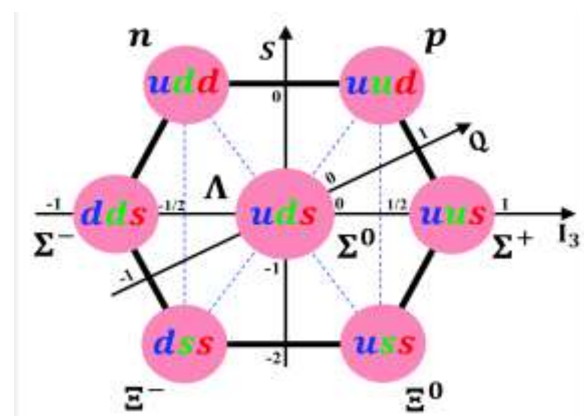
J. Haidenbauer and U. G. Meißner, Phys. Lett. B 761, 456-461(2016).



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

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

Λ EMFFs in VMD (New proposal)

$$F_1(Q^2) = g(Q^2)[-\beta_\omega - \beta_\phi + \beta_\omega \frac{m_\omega^2}{m_\omega^2 + Q^2} + \beta_\phi \frac{m_\phi^2}{m_\phi^2 + Q^2} + \beta_x \frac{m_x^2}{m_x^2 + Q^2}]$$

$$F_2(Q^2) = g(Q^2)[(\mu_\Lambda - \alpha_\phi) \frac{m_\omega^2}{m_\omega^2 + Q^2} + \alpha_\phi \frac{m_\phi^2}{m_\phi^2 + Q^2} + \alpha_x \frac{m_x^2}{m_x^2 + Q^2}]$$

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

$$Q^2 \to -q^2$$

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

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

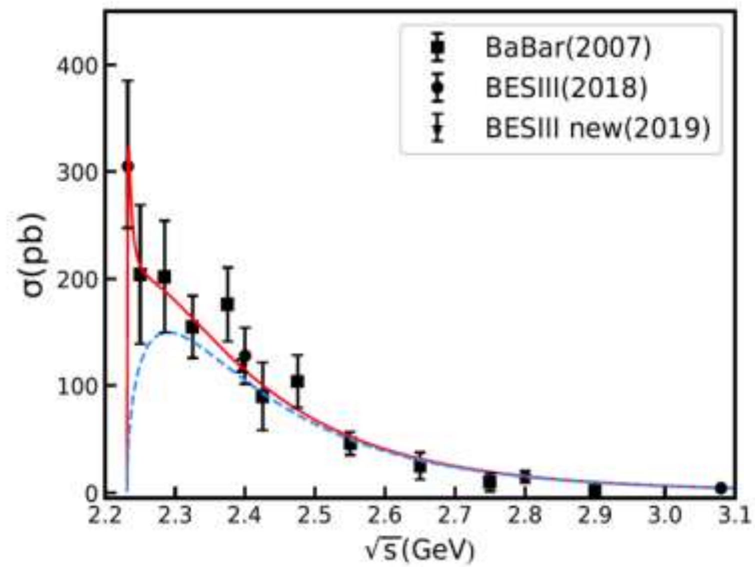
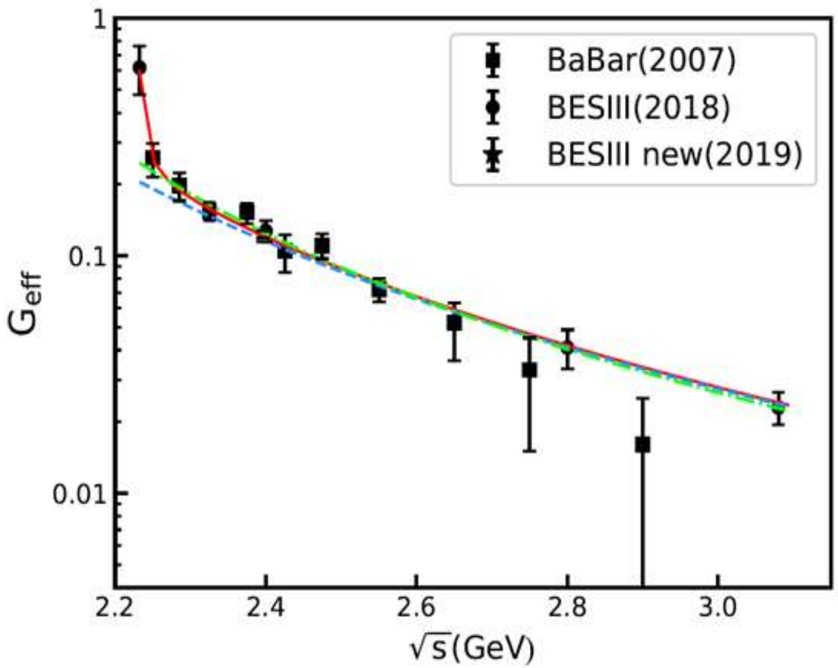


Figure: Cross section of the reaction $e^+e^- \to \bar{\Lambda}\Lambda$.



The red solid curve represents the total contributions from ω, ϕ and $X(2231)$, while the blue dashed curve stands for the results without the contribution from the new $X(2231)$ state. The green-dash-dotted curve stands for the fitted results with the effective form factor as in .

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

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 J. J. Xie, Chin. Phys. Lett. 39, 011201 (2022).

Flatte function

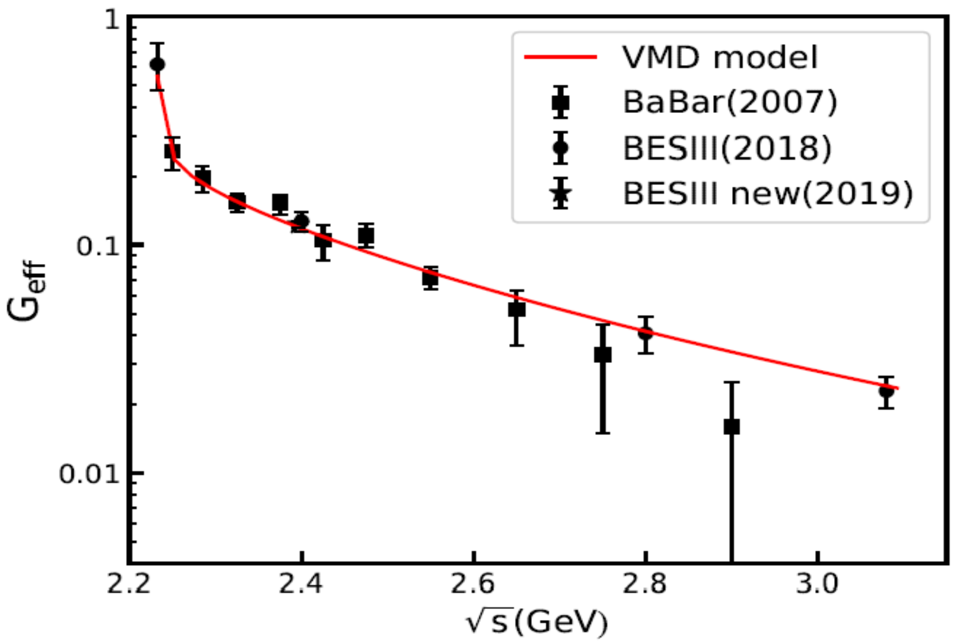


Figure: Fitting result of $|G_{eff}|$ with Flatte.

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

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

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

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

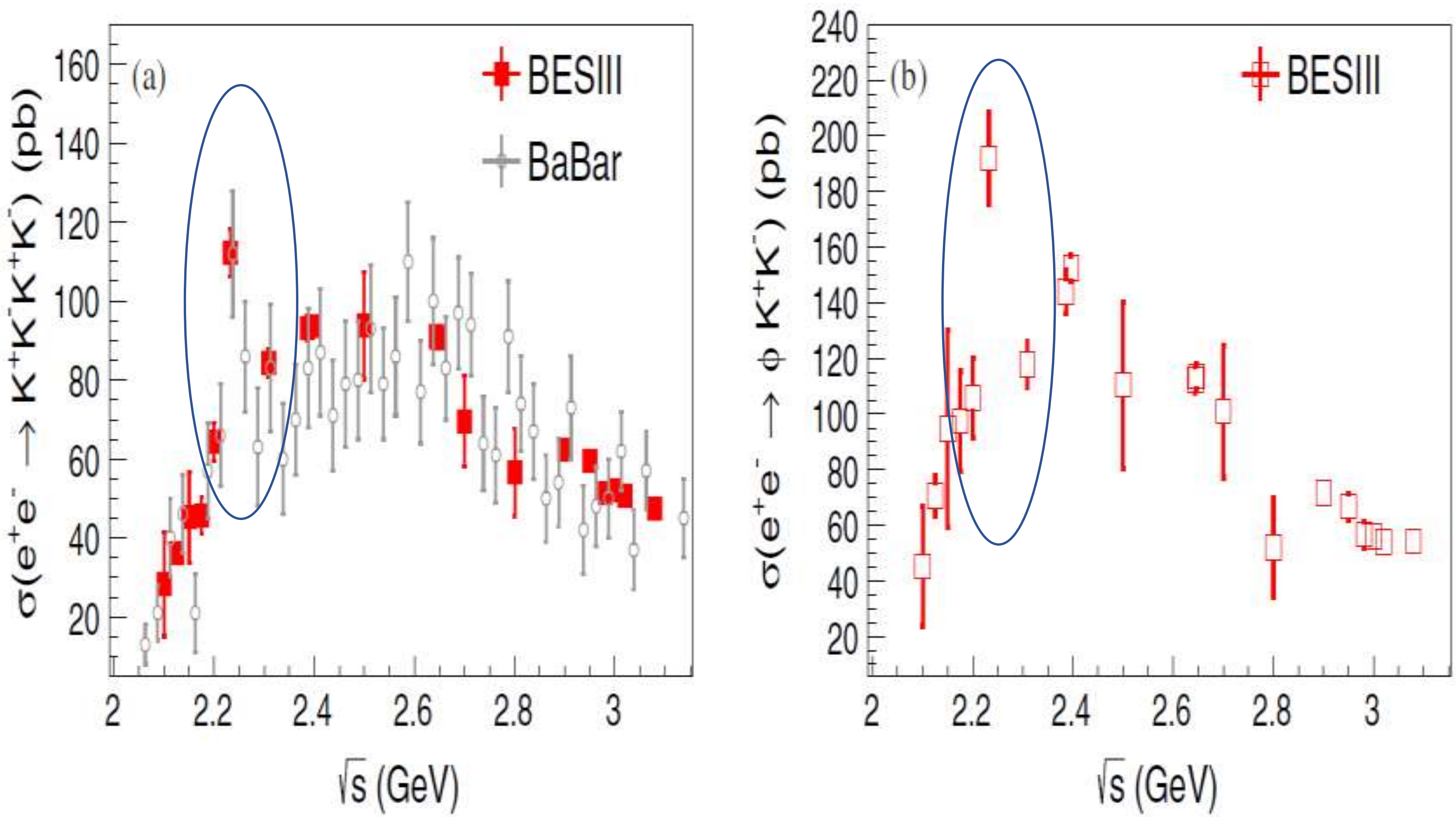
$$\Gamma_{K\bar{K}} = \begin{cases} g_K\sqrt{(1/4)m^2 - m_K^2} & \text{above threshold} \\ i g_K\sqrt{m_K^2 - (1/4)m^2} & \text{below threshold} \end{cases}$$

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

On the other hand, if one takes a Flatté form for the total decay width of $\omega(1420)$, $\omega(1650)$, $\phi(1680)$, and $\phi(2170)$, the experimental data can also be well reproduced with a strong coupling of these resonances to the $\Lambda\bar{\Lambda}$ channel.

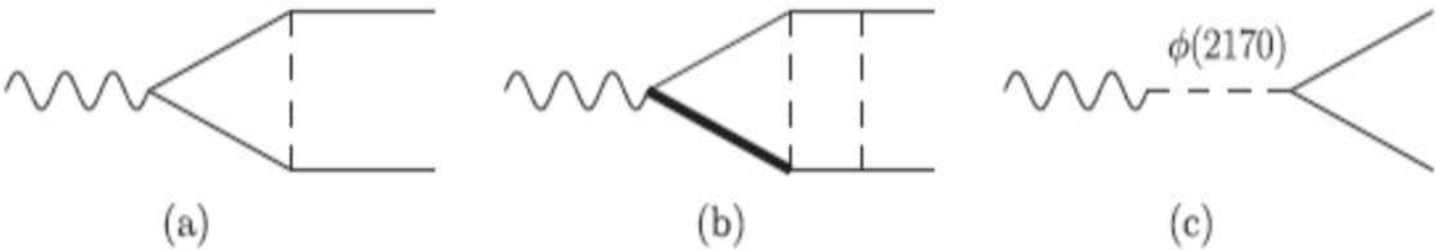
Z. Y. Li, A. X. Dai and J. J. Xie, Chin. Phys. Lett. 39, 011201 (2022).

Where is X(2231)?

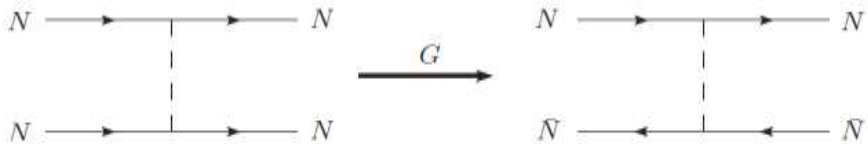


M. Ablikim, et al., Phys. Rev. D 100, 032009(2019).

Threshold enhancement：final state interaction



FSI-meson exchange *N*-excitation (Δ)* *First flavorless vector meson*



$$V_{\bar{N}N}^{\mathrm{OBE}} = (-1)^{I} V_{NN}^{\mathrm{OBE}}, \quad V_{\bar{N}N}^{\mathrm{TBE}} = (-1)^{I_1+I_2} V_{NN}^{\mathrm{TBE}}$$

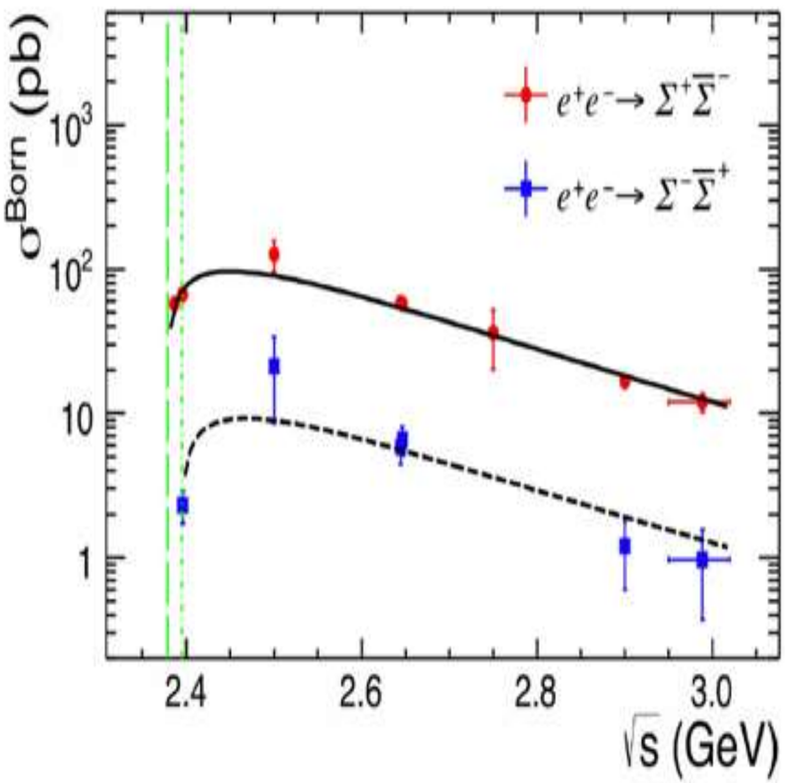
$$T_{L''L'}(p'',p';E_k) = V_{L''L'}(p'',p') + \sum_{L} \int \frac{dpp^2}{(2\pi)^3} V_{L''L}(p'',p) \frac{1}{2E_k - 2E_p + i0^+} T_{LL'}(p,p';E_k)$$

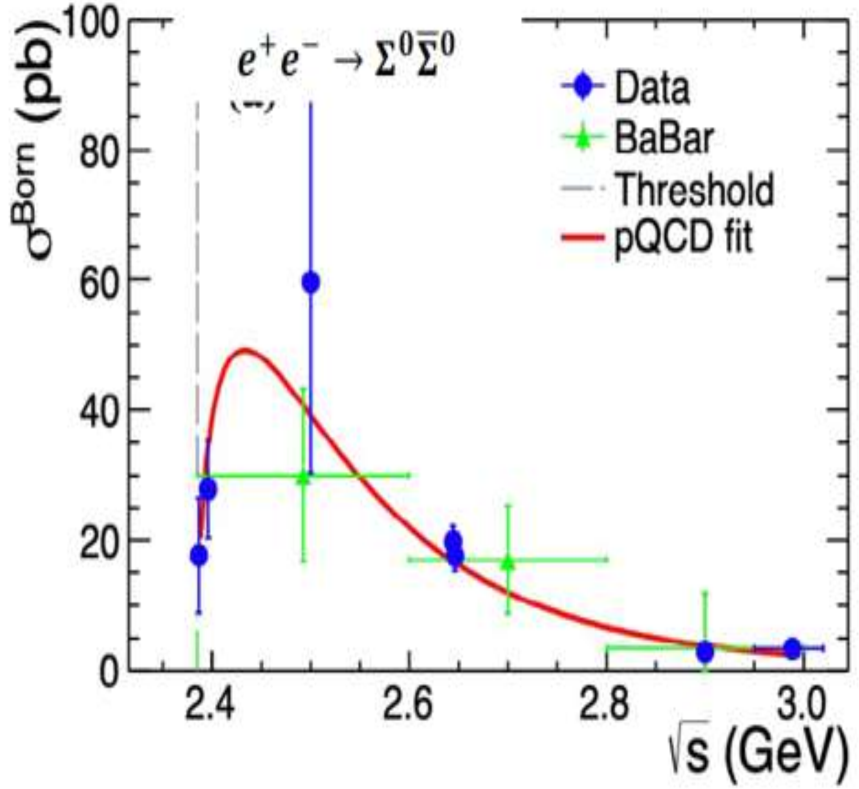
I.T. Lorenz, H.W. Hammer and U.G. Meissner, **Phys. Rev. D92, 034018 (2015).**

Q.H. Yang, L.Y. Dai, D. Guo, J. Haidenbauer, X.W. Kang and U.G. Meissner, arXiv:2206.01494.

Σ

$$\sigma(s) = \frac{4\pi\alpha^2\beta}{3s}C(s)\left[1 + \frac{2M^2}{s}\right]|G_{eff}(s)|^2 = \sigma_{point}(s)|G_{eff}(s)|^2.$$





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

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

Σ^+ and Σ^- EMFFs (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

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

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

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

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

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

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

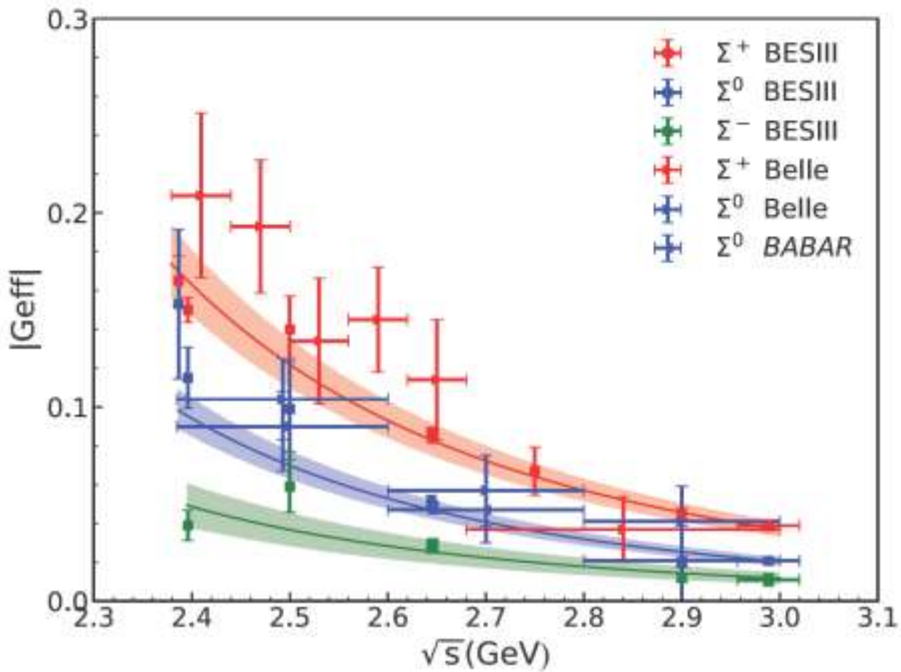
$$B_\rho = \frac{m_\rho^2}{m_\rho^2 - q^2 - im_\rho\Gamma_\rho},$$

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

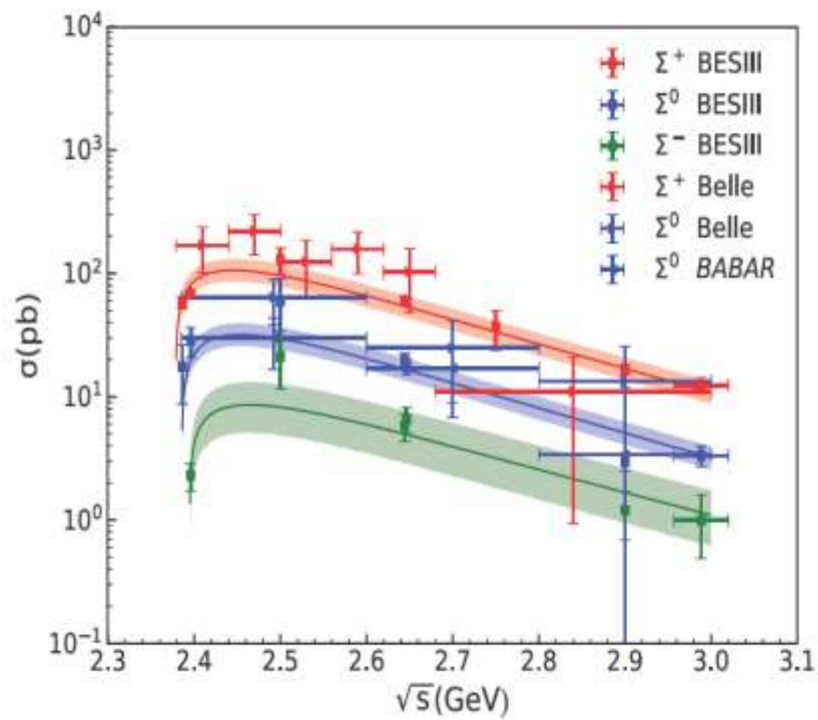
$$f_1^{\Sigma^+} = 1 - \frac{\beta_\rho}{\sqrt{2}} + \frac{\beta_{\omega\phi}}{\sqrt{3}}, \quad f_2^{\Sigma^+} = 2.112 + \frac{\alpha_{\omega\phi}}{\sqrt{3}},$$

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

Σ^+, Σ^-, and Σ^0 EMFFs (VMD)



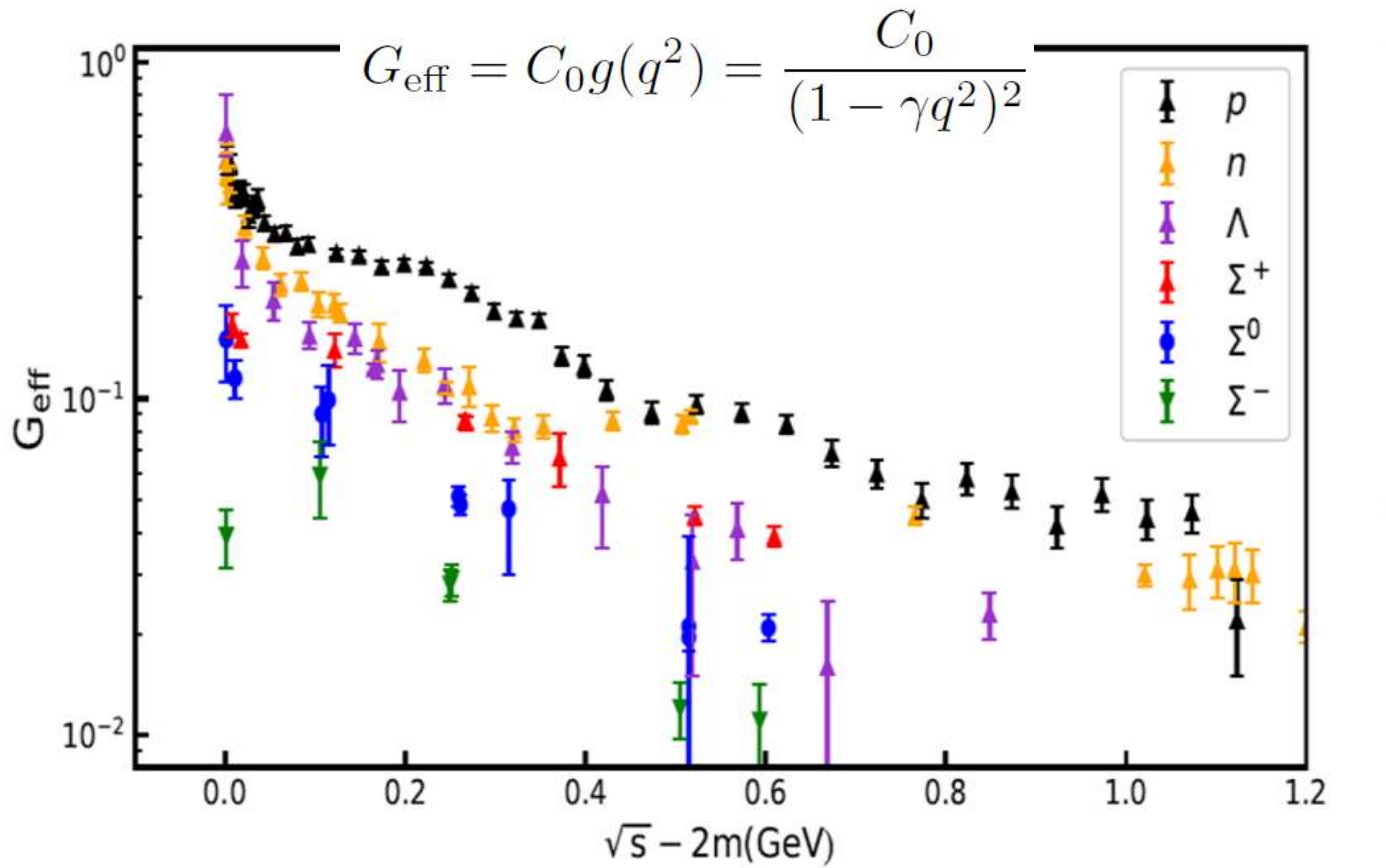
Parameter	Value	Parameter	Value
γ (GeV^{-2})	0.527 ± 0.024	$\alpha_{\omega\phi}$	-3.18 ± 0.77
$\beta_{\omega\phi}$	-0.08 ± 0.06	β_ρ	1.63 ± 0.07



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

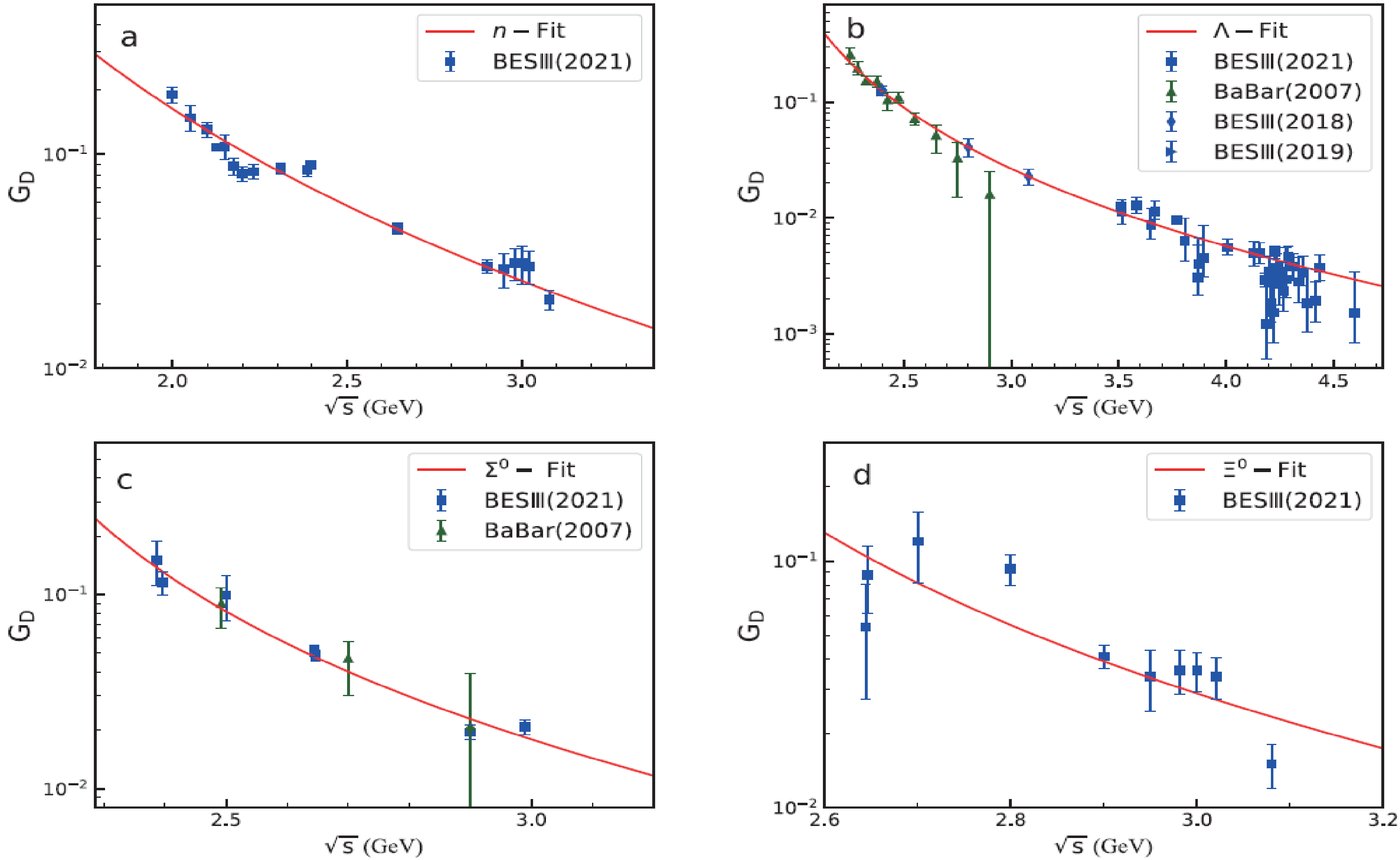
Bing Yan, Cheng Chen, and J. J. Xie, **Phys. Rev. D107, 076008 (2023).**

Dipole behavior of baryon effective form factors



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

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

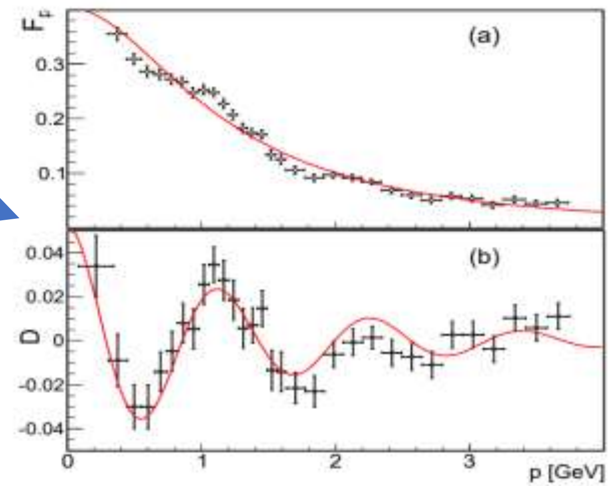


Oscillation of baryon effective form factors

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

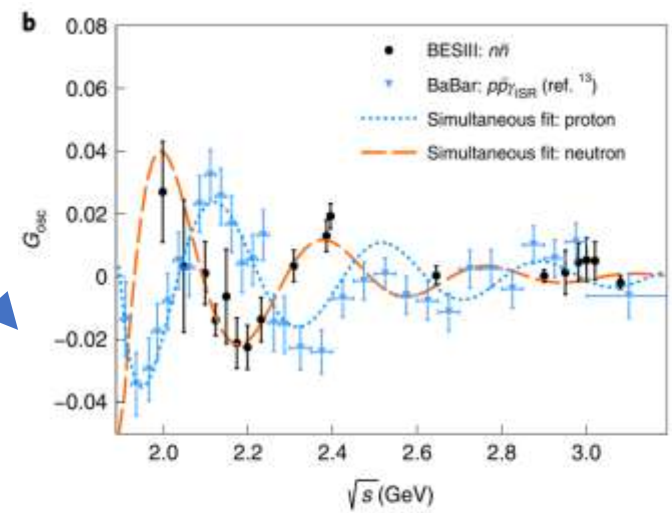
$$F_{3p}(s) = \frac{F_0}{\left(1+\frac{s}{m_a^2}\right)\left(1-\frac{s}{m_0^2}\right)^2},$$

$$F_{osc}(p(s)) = Ae^{-Bp}\cos(Cp+D).$$



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

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



New parametrization

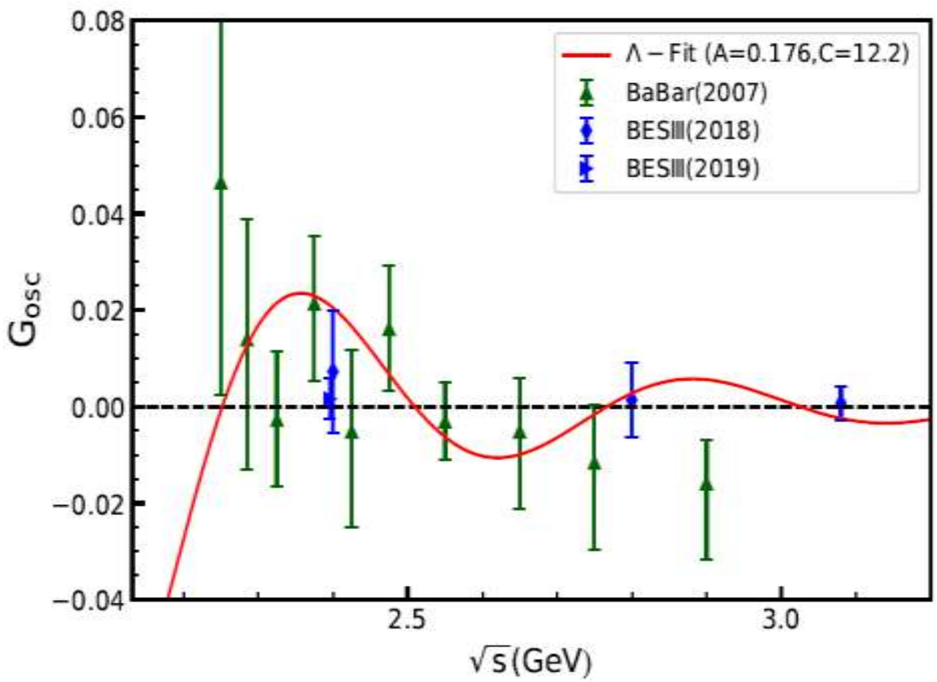
$$G_{osc} = A \cdot \frac{c_0}{(1-\gamma \cdot s)^2} \cdot \cos\left(C \cdot \sqrt{s} + D\right)$$

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

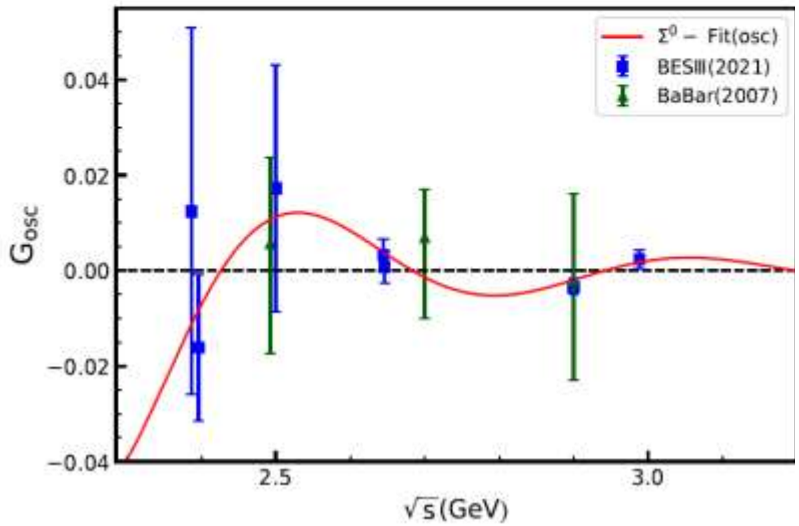
$$G_{\mathrm{eff}}(s) = G_{\mathrm{D}}(s) + G_{\mathrm{osc}}(s) = \frac{c_0}{(1-\gamma s)^2}\left(1 + A\cos(C\sqrt{s} + D)\right)$$

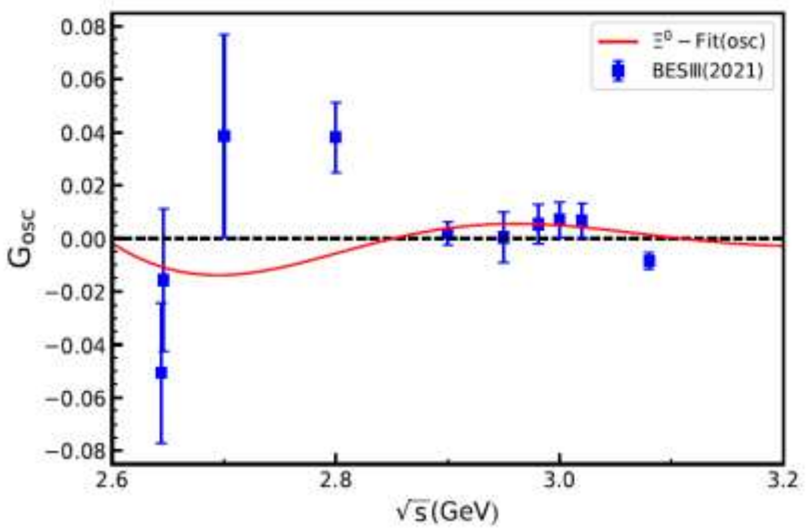
$$data = G_{eff} = G_D + G_{osc}$$

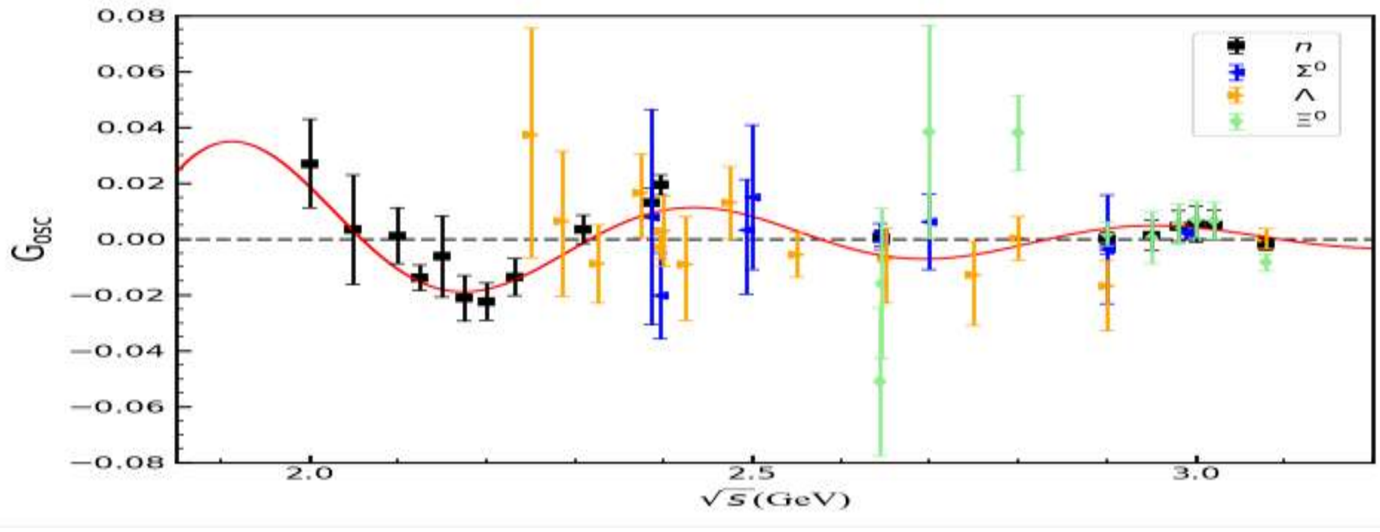
$$\rightarrow \quad G_{osc} = data - G_D$$



Numerical results







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

Oscillation

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

Letter

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

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

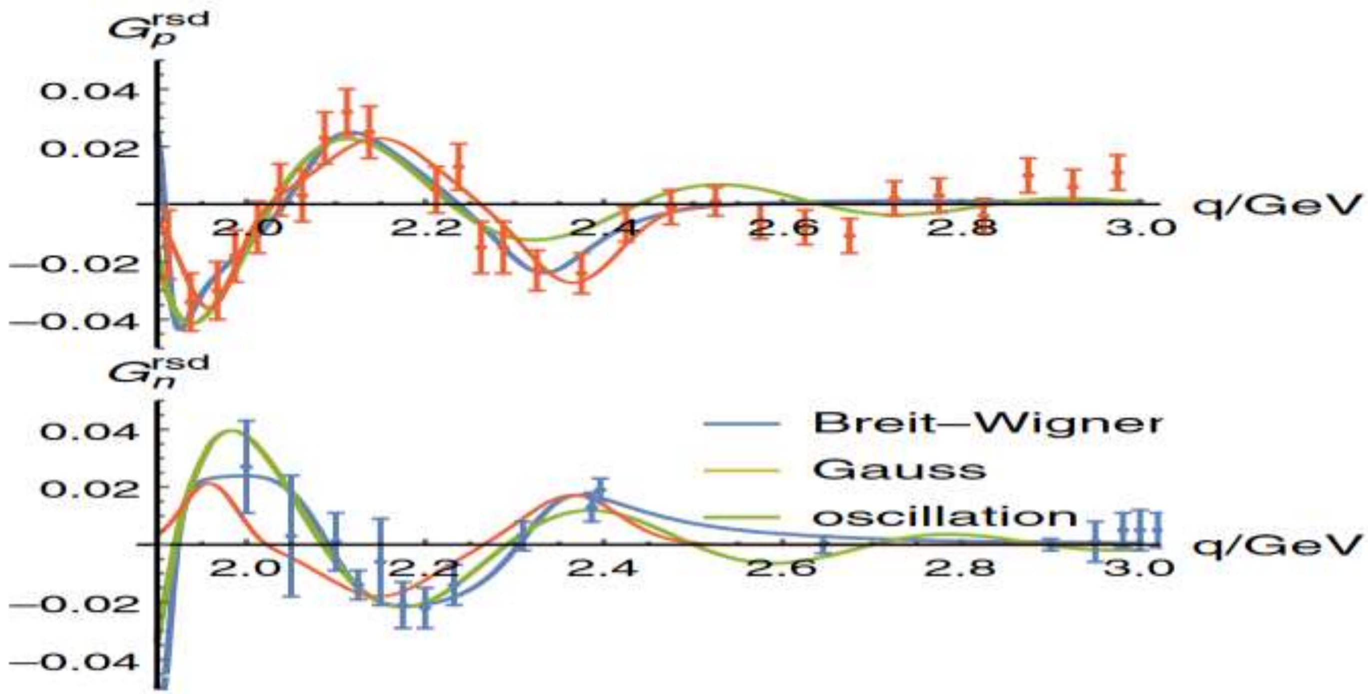


FIG. 1. The fit of the Breit-Wigner distribution and the Gauss distribution to three local structures below 2.5 GeV in comparison with BESIII data [16,18].

e-Print: 2206.01494 [nucl-th]

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 107, L091502 (2023)

Letter

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)

New Insights into the Nucleon's Electromagnetic Structure

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

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

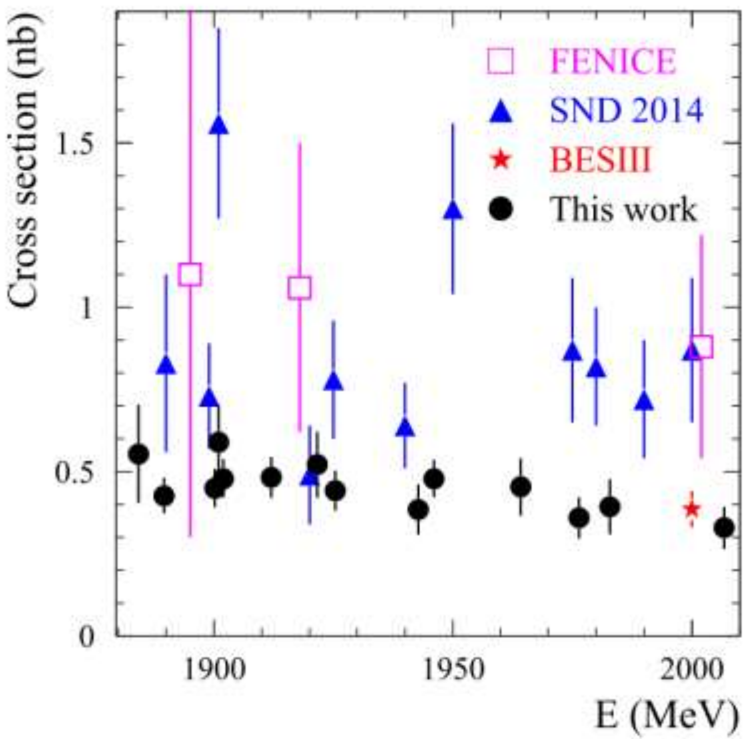
SND Collaboration

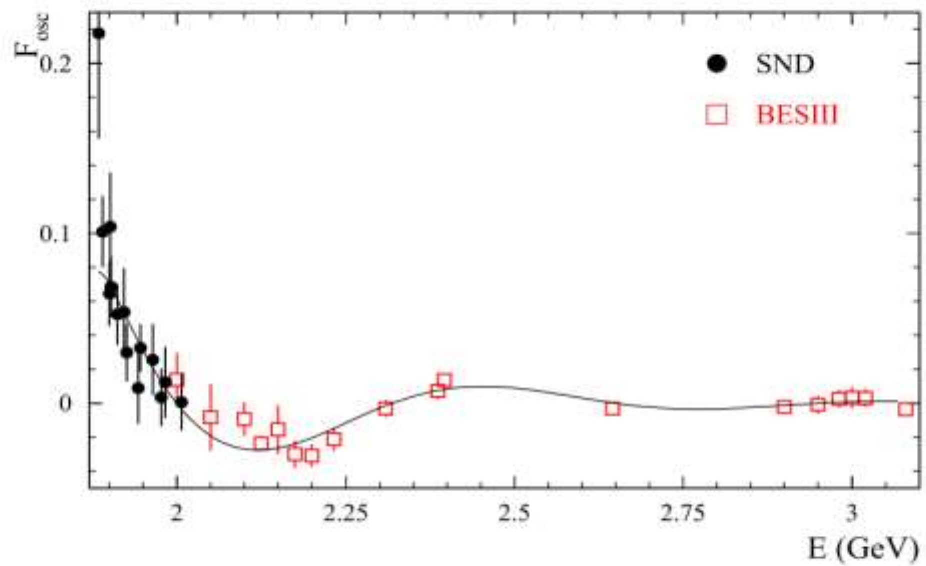
$$F(s) = F_0(s) + F_{osc}(s),$$

$$F_0(s) = \frac{\mathcal{A}_n}{\left[1 - s/0.71(\mathrm{GeV}^2)\right]^2},$$

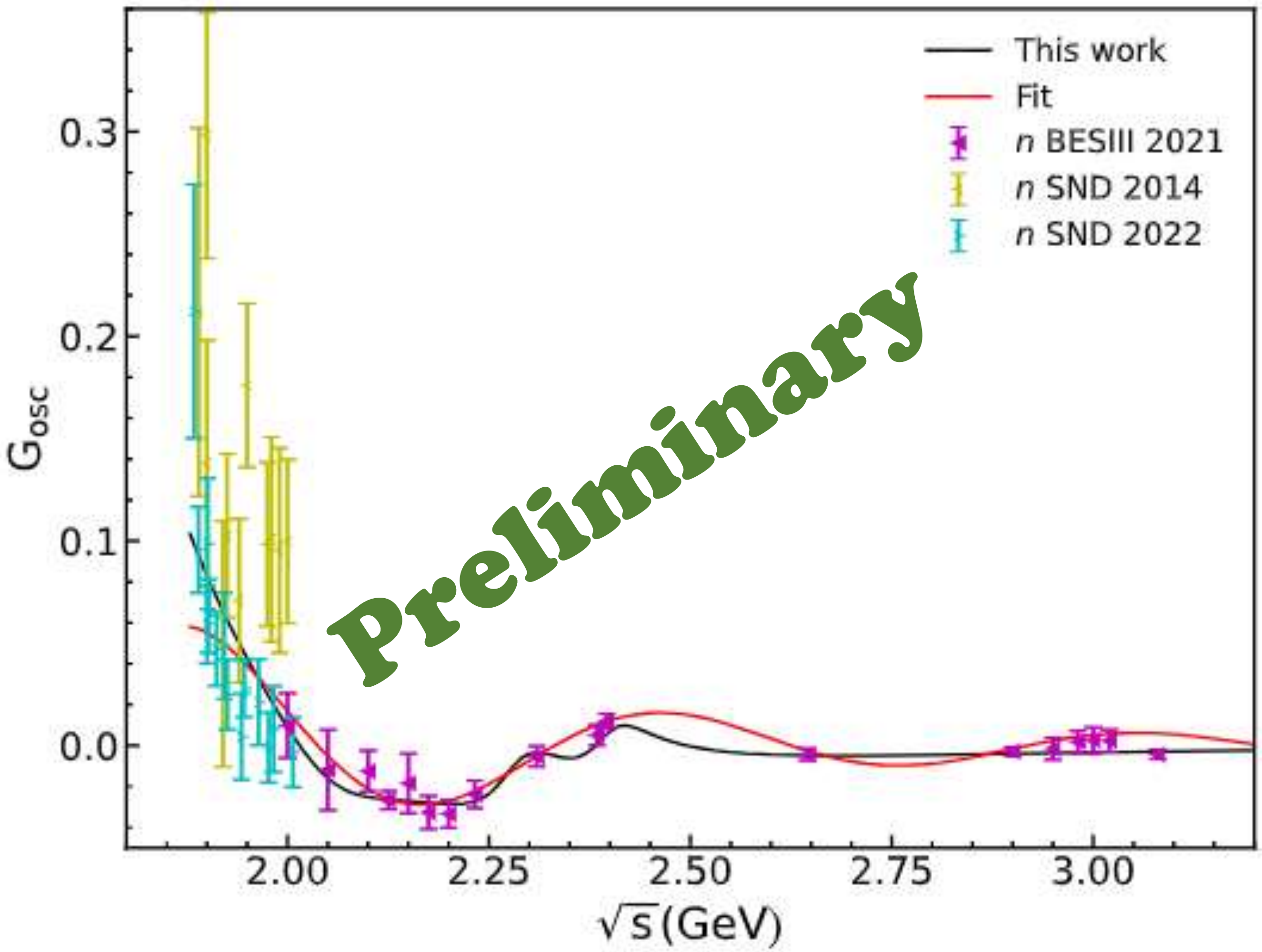
$$F_{osc}(s) = A\exp(-Bp)\cos(Cp + D),$$

$$p = \sqrt{(s/2m_n - m_n)^2 - m_n^2}.$$





Vector meson dominance



Summary

1、 Threshold enhancement

a) , Final state interaction　　　b), Flatte （strong coupling）

Vector mesons

2、 Oscillation of baryon effective form factors

a), Phenomenology　　　b), Mechanism unknown

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

Thank you very much for your attention!