Time-Like Form Factors of Baryons

Weiping Wang

Johannes Gutenberg University Mainz

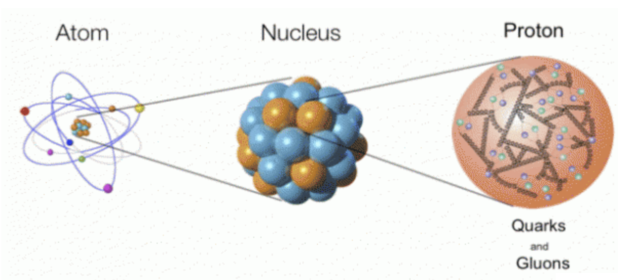
Sixth European Nuclear Physics Conference (EuNPC2025)

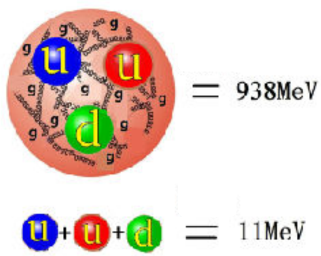
Caen, 23.09.2025

Electromagnetic form factors (EMFFs)

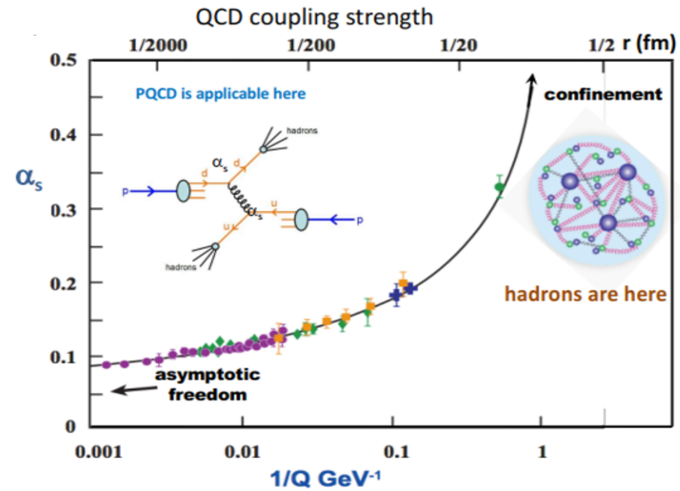
- Nucleons are composite objects with inner structure. At low Q, perturbative QCD does not work well (expansion of coupling constant $\boldsymbol{\alpha_s}$)

  ⇒ **Nucleon structure must be measured in experiments!**

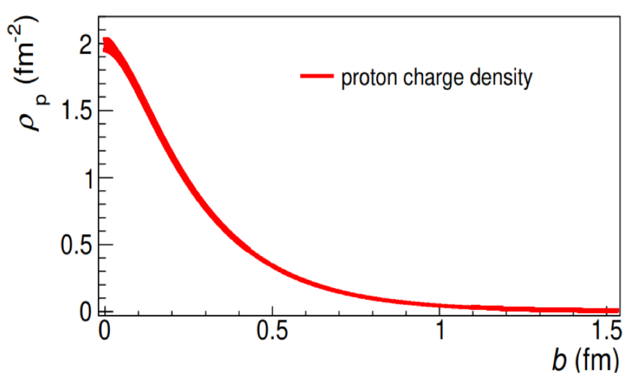


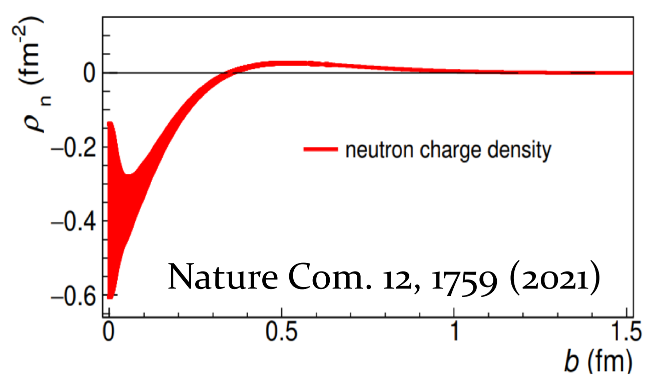


gluon contribution = 927MeV



- Using photon as a probe, the coupling to nucleon can be expressed in terms EMFFs





Electromagnetic form factors

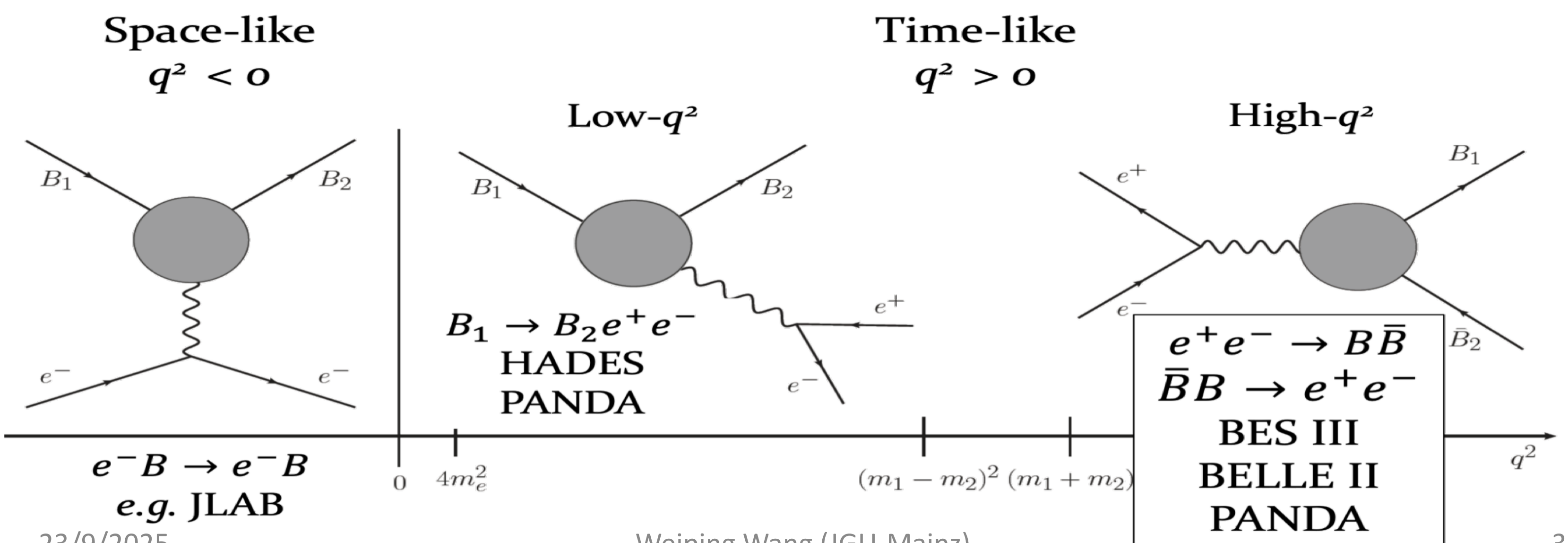
The nucleon electromagnetic vertex Γ_μ describing the hadron current:

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

Sachs FFs: $G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$, $G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$

Normalization of FF: $q^2 = 0$: $G_E = F_1(0)$, $G_M = \mu_N$ $q^2 = 4m_N^2$: $G_E = G_M$

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



Pair production of baryon

EMFFs parameterize the pair production cross section in e^+e^-

$$\frac{d\sigma_{B\bar{B}}(s)}{d\Omega} = \frac{\alpha^2\beta C}{4s}\left[|G_M(s)|^2(1+\cos^2\theta) + \frac{4m_B^2}{s}|G_E(s)|^2\sin^2\theta\right] \equiv N_0(1+\alpha_B\cos^2\theta)$$

Ratio $R_{em} = |G_E/G_M|$ reflects polar angle distribution of produced baryon!

$|G_E|$ and $|G_M|$ can be separately evaluated after determining N_0 and α_B.

After the integration over the polar angle θ

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

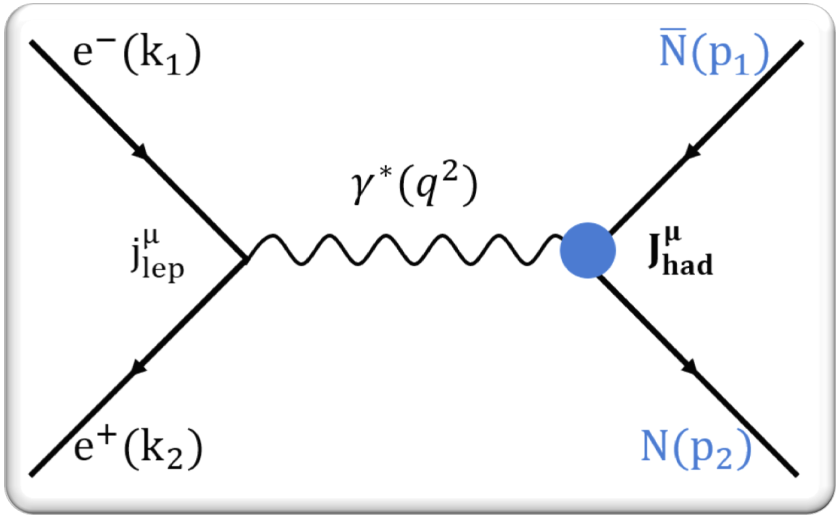
The so-called effective form factor could be defined in terms of EMFFs:

$$|G_{\text{eff}}(s)| = \sqrt{\frac{\sigma_{B\bar{B}}(s)}{\frac{4\pi\alpha^2\beta C}{3s}\left(1+\frac{2m_B^2}{s}\right)}} = \sqrt{\frac{|G_M(s)|^2 + \frac{2m_B^2}{s}|G_E(s)|^2}{1+\frac{2m_B^2}{s}}}$$

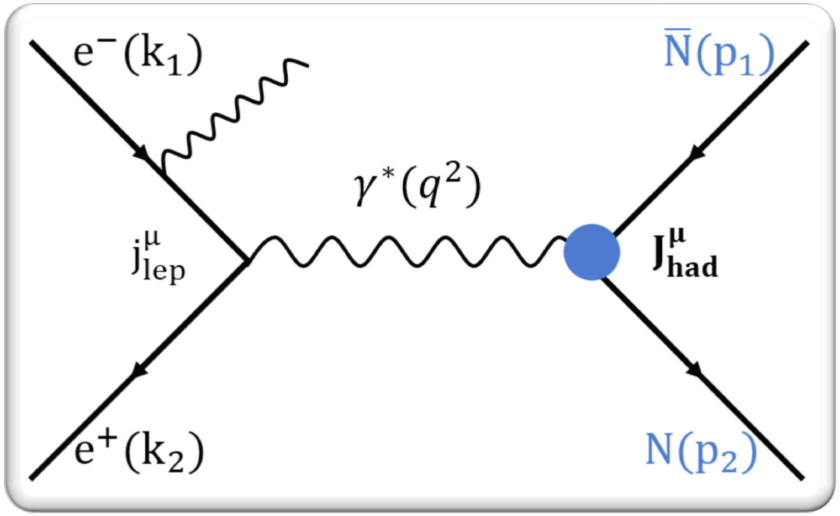
Effective FF reflects the magnitude of production cross section of baryon!

Experimental access of Time-like form factors

Energy scan

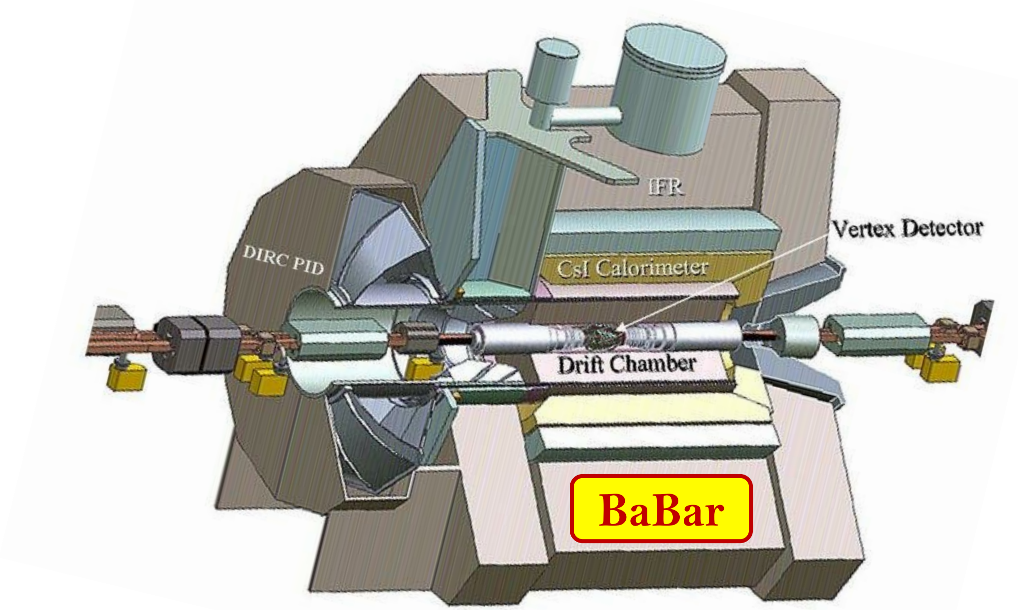


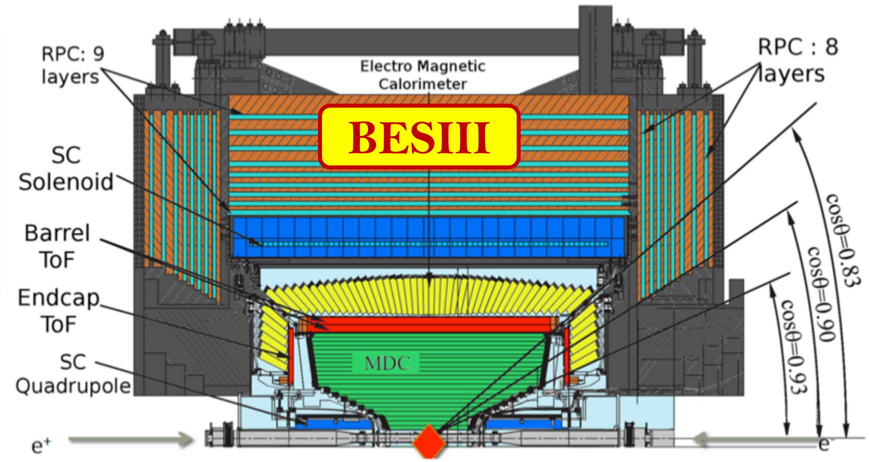
Initial-state-radiation

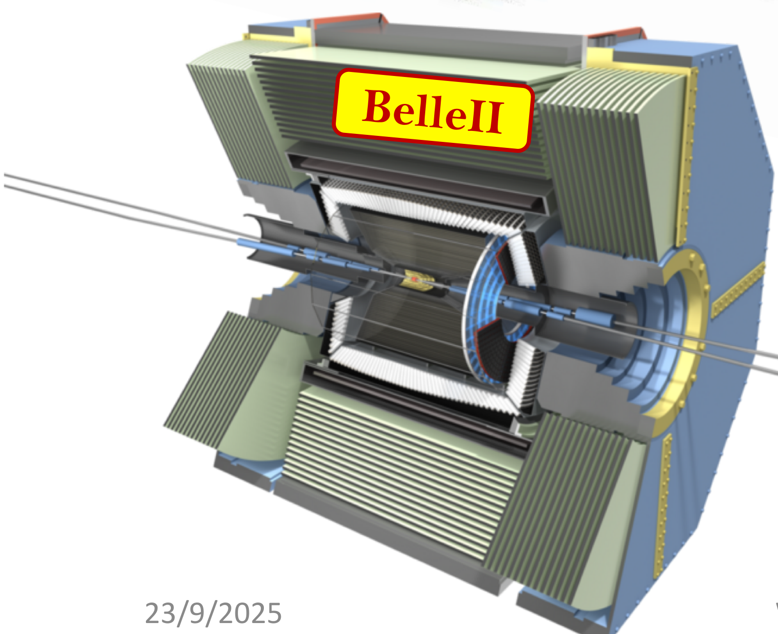


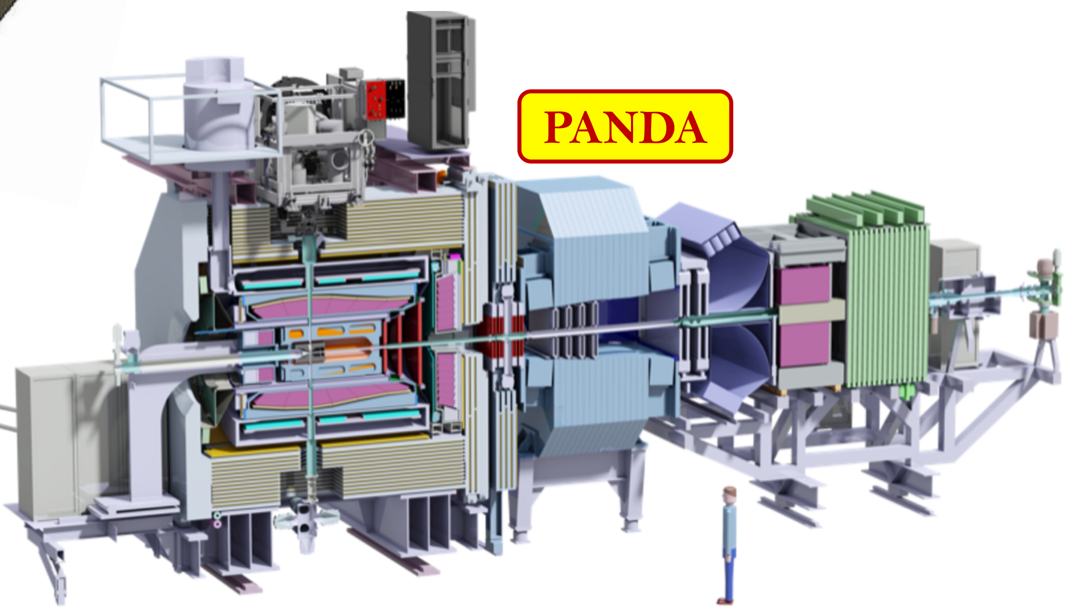
	Energy Scan	Initial State Radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	low at each beam energy	high at one beam energy
σ	$\frac{d\sigma_{p\bar{p}}}{d(\cos\theta)} = \frac{\alpha^2\beta C}{4q^2}[\lvert G_M\rvert^2(1+\cos^2\theta)$ $+\frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d^2\sigma_{p\bar{p}\gamma}}{dx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

Experimental access of Time-like form factors



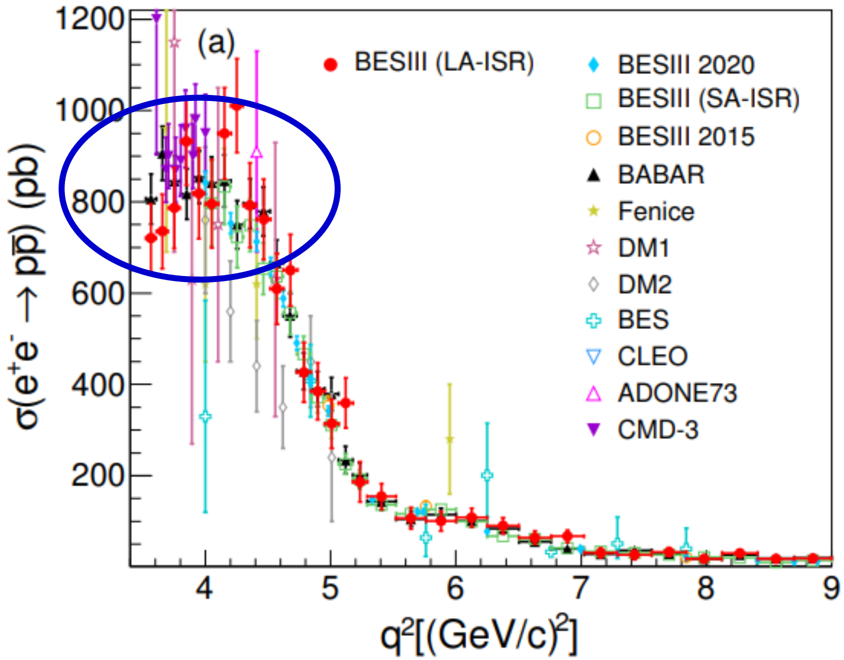


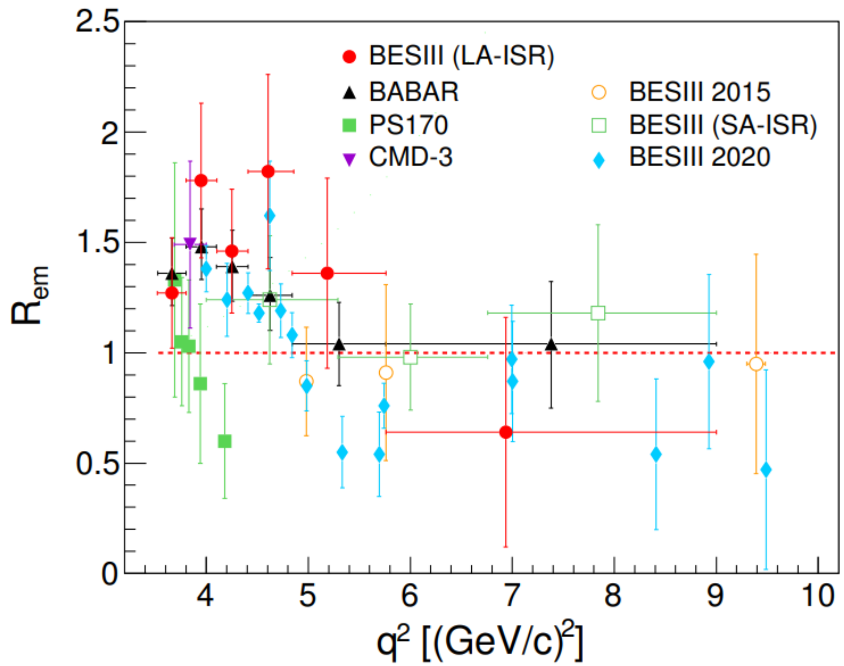




Proton form factors

ISR approach with detected and undetected ISR photon



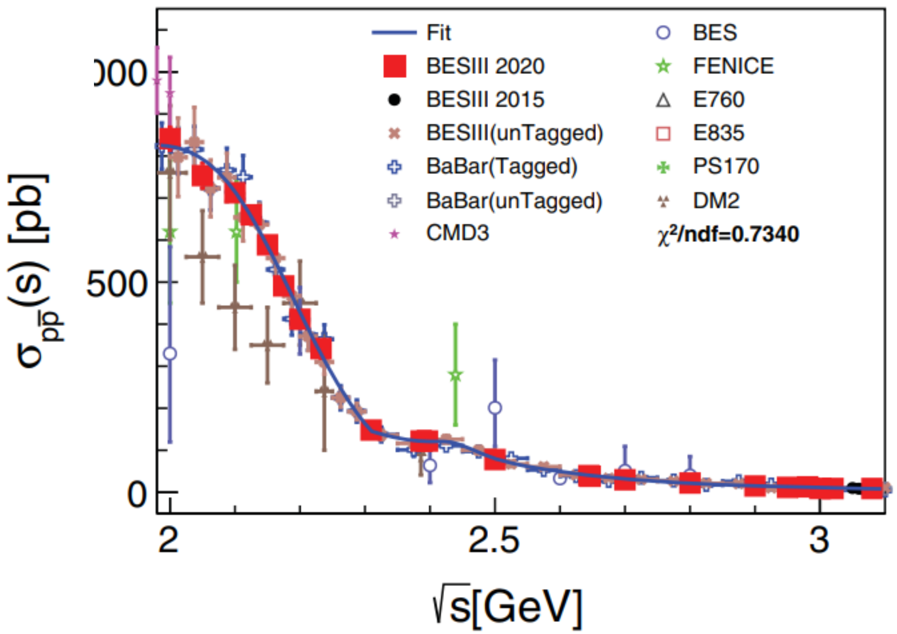


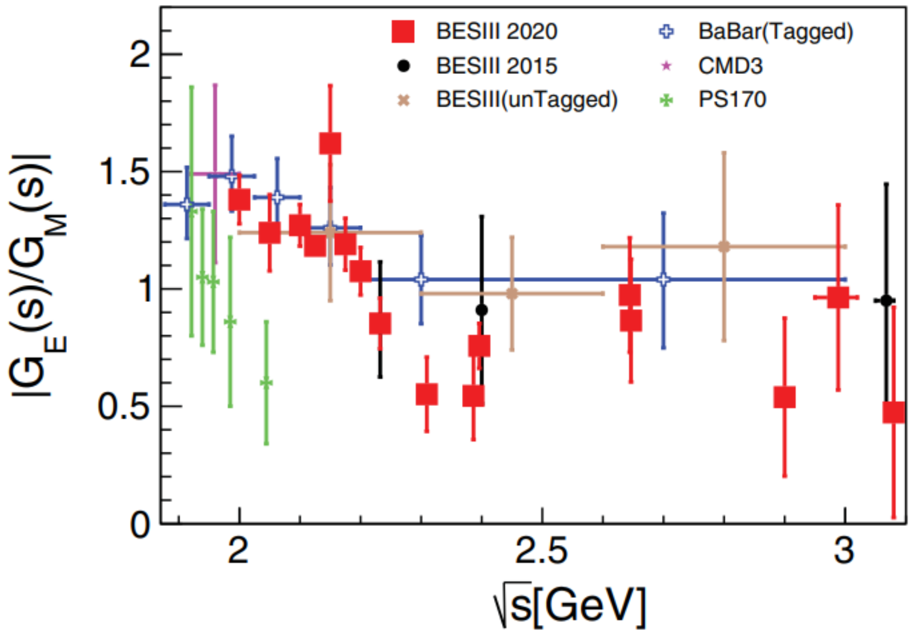
- From threshold to $q^2 = 4.0\ \mathrm{GeV}^2$, average cross section 840 pb
- Point-like cross section at threshold, $\sigma_{\text{point}} = \frac{\pi\alpha^2}{3m_B^2\tau}\left[1 + \frac{1}{2\tau}\right] = 845\ \text{pb}$

Proton form factors

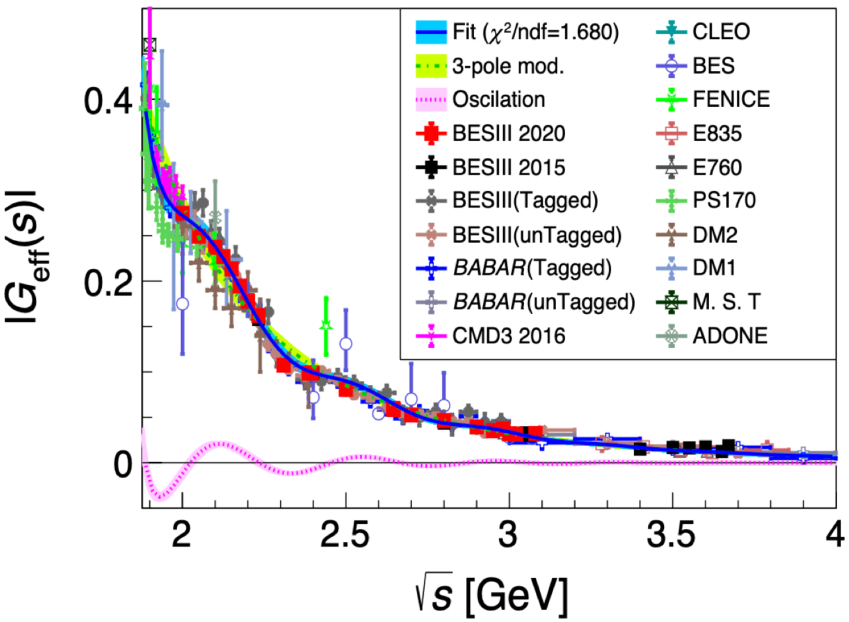
Scan technique is also used to determine EMFFs of baryons

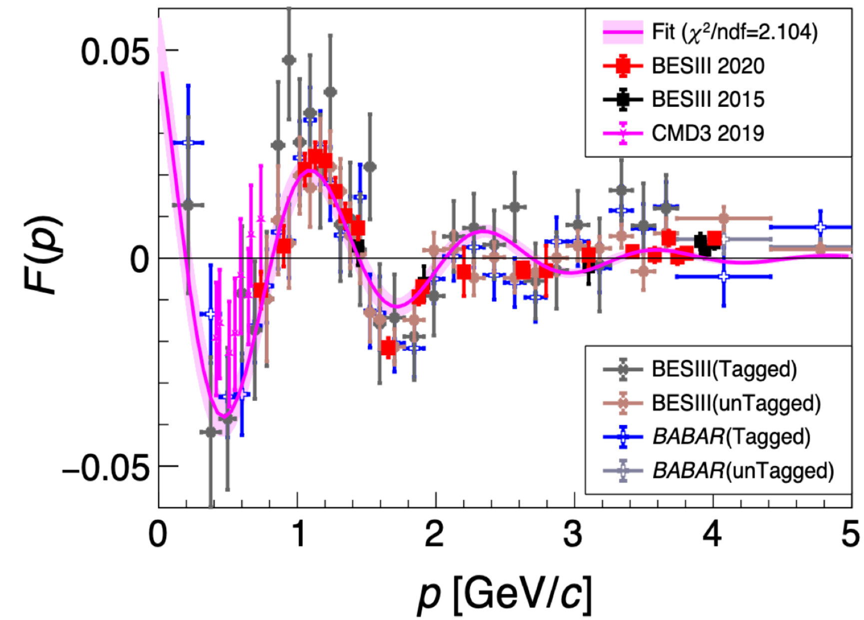
- ➢ $|G_E/G_M|$ is determined with **high accuracy**, comparable with space-like region.
- ➢ $|G_E|$ and $|G_M|$ are separated by analyzing the polar angle distribution.





Oscillation feature confirmed in $|G_{\mathrm{eff}}|$



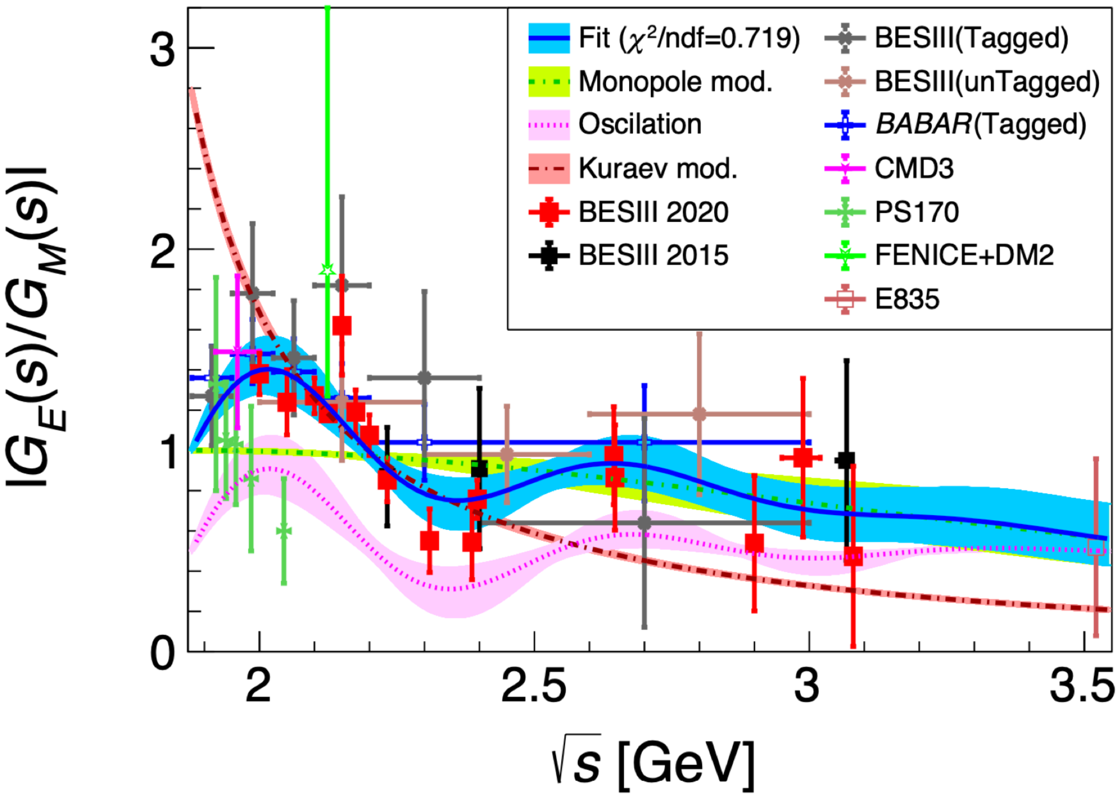


$|G_{\mathrm{eff}}|$ data are fitted with the model: the monopole decrease with a damped oscillation : *E. Tomasi-Gustafsson et al., PRL. 114, 232301 (2015), PRC 103, 035203 (2021)*

$$|G_{\mathrm{eff}}|(s) = \frac{\mathcal{A}}{\left(1+\frac{s}{a_0}\right)\left(1-\frac{s}{0.71\ \mathrm{GeV}^2}\right)^2} + b_0 e^{-b_1 p(s)} \cos[b_2 p(s) + b_3]$$

Oscillation feature in the cross section line-shape!

Oscillation feature in $|G_E/G_M|$



$|G_E/G_M|$ data can be well described by a function combining the monopole decrease with a damped oscillation

oscillation feature in the polar angle distribution of the outgoing proton!

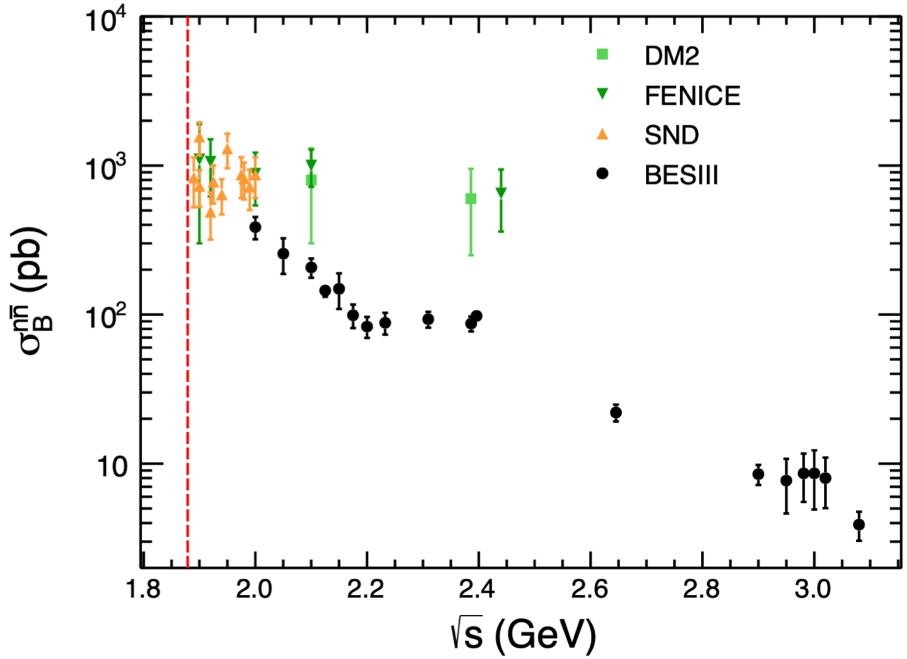
$|G_E/G_M|$ data are fitted with the model:

$$|G_E/G_M|(s) = \frac{1}{1+\omega^2(s)/r_0}\left[1 + r_1 e^{-r_2\omega(s)} \sin(r_3\omega(s))\right]$$

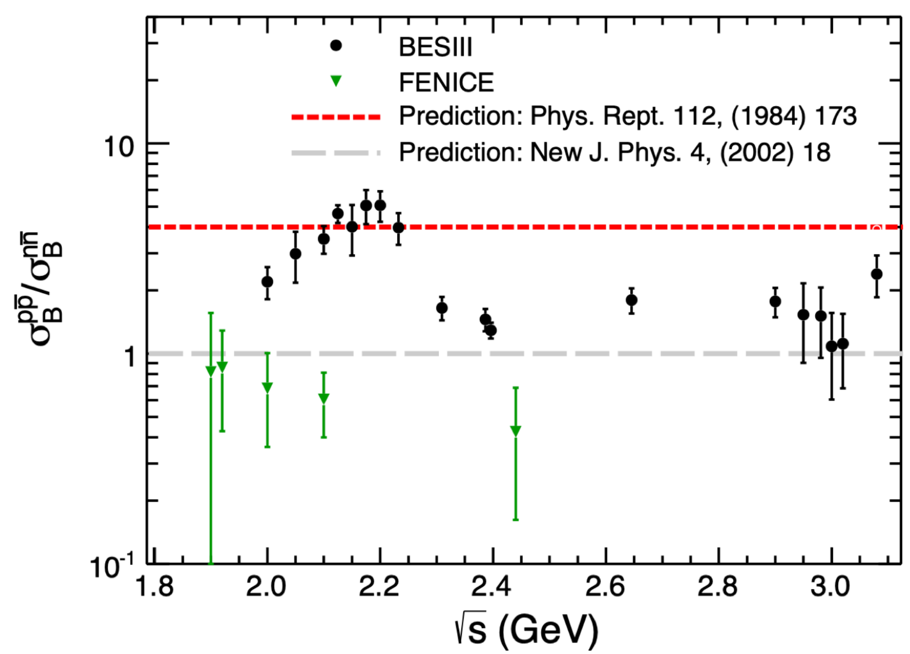
E. Tomasi-Gustafsson et al., PRL. 114, 232301 (2015), PRC 103, 035203 (2021)

Neutron form factors

- Scan technique from 2.00 to 3.08 GeV at BESIII
- Unprecedented precision achieved, smaller than 8% at 2.396 GeV
- Clearly clarify the "puzzle" that photon-neutron coupling larger than photon-proton coupling which exists over 20 years.

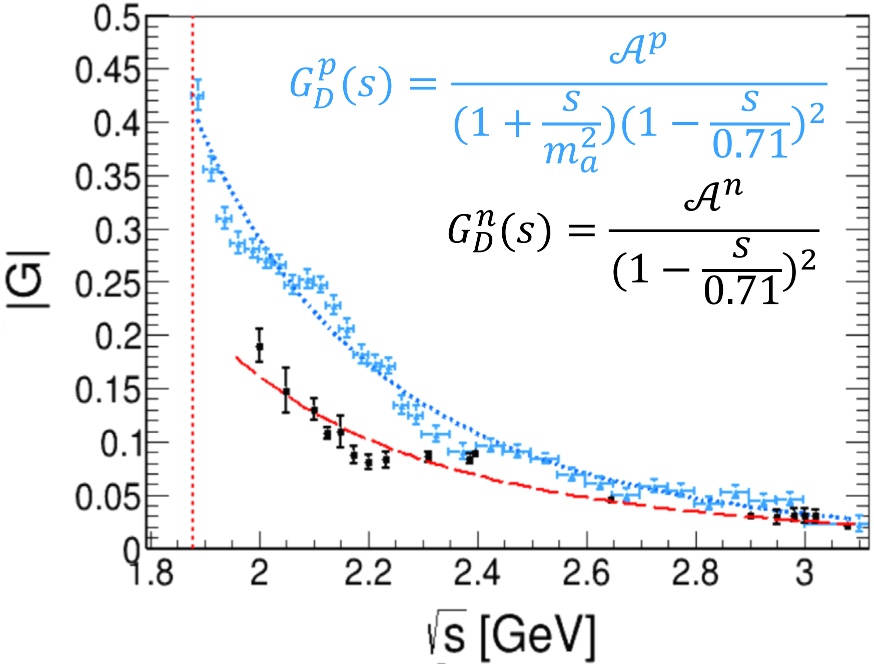


Nature Phys. 17 (2021) 11, 1200-1204

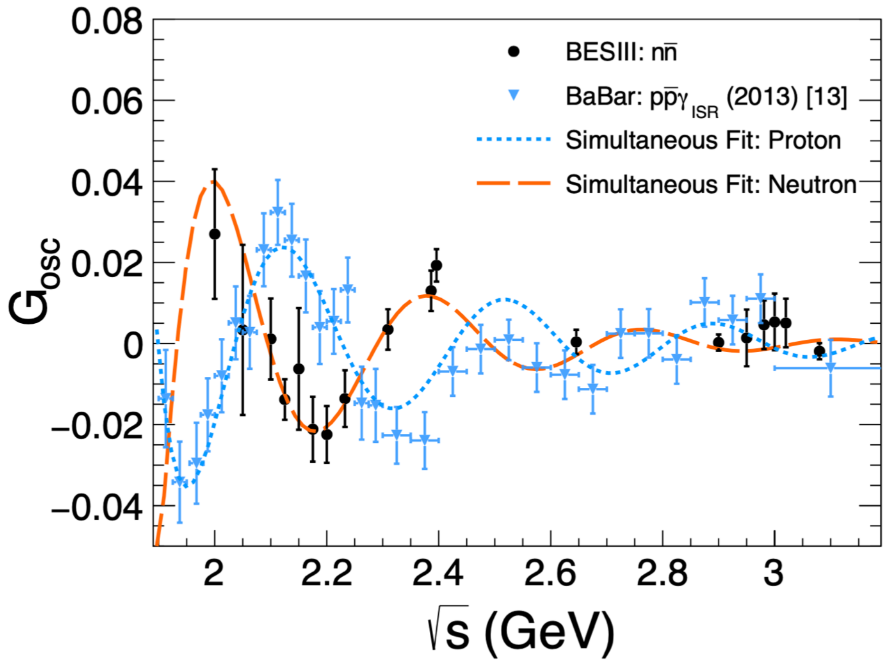


Oscillation feature in $|G_{\text{eff}}|$

- Oscillation in addition to the dipole law: $|G_{\text{eff}}^{p,n}(s)| = G_D^{p,n}(s) + G_{\text{osc}}^{p,n}(s)$
- Simultaneous fit on proton and neutron data with the same frequency but different phase: $G_{\text{osc}}^{p,n}(s) = b_0^{p,n} e^{-b_1^{p,n} p(s)} \cos[\boldsymbol{b_2} p(s) + b_3^{p,n}]$
- Fitted well but a phase shift around $(125 \pm 12)^\circ$ is observed



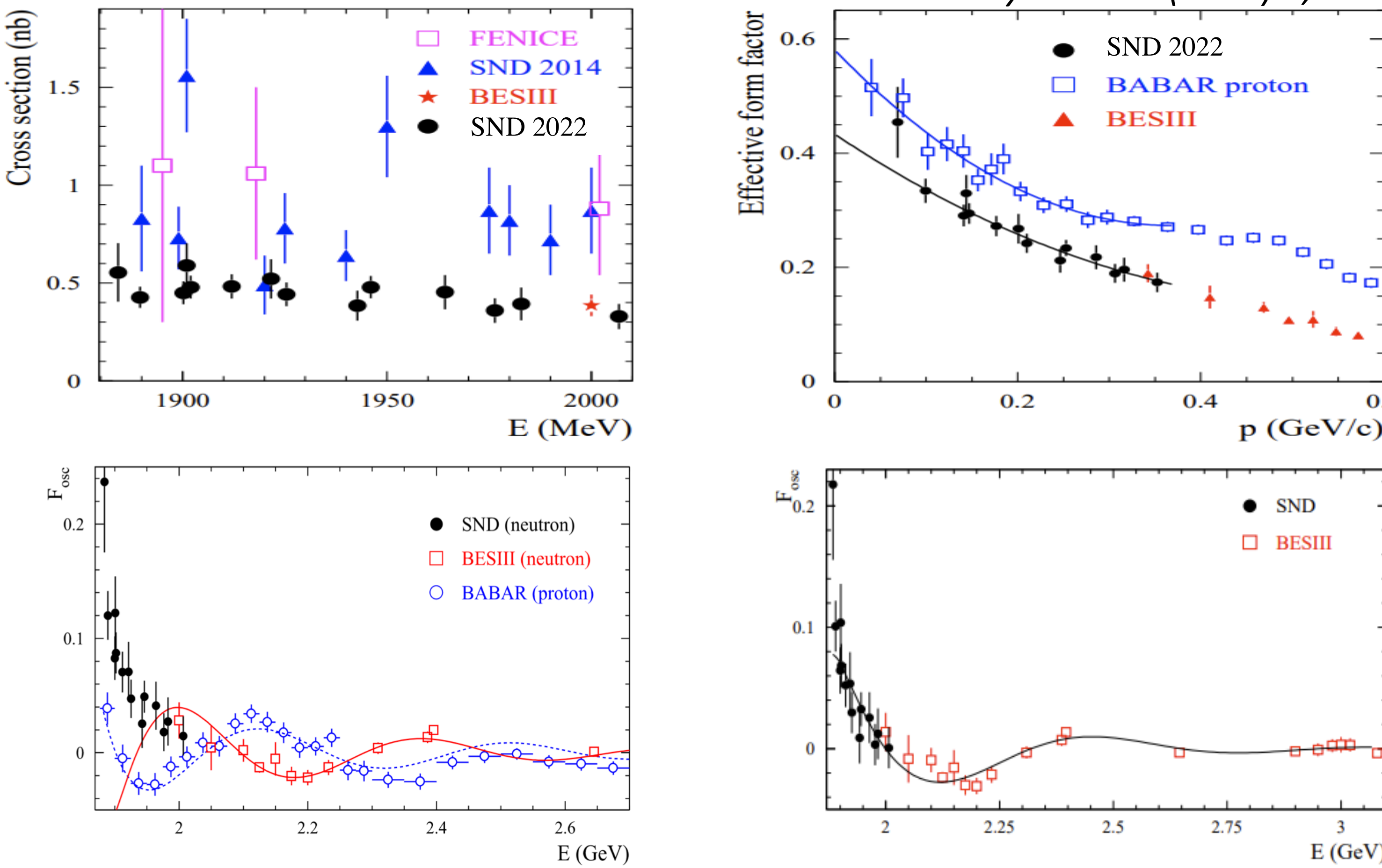
Nature Phys. 17 (2021) 11, 1200-1204



Oscillation feature in $|G_{\text{eff}}|$

Recent SND measurement suggests a different frequency:

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

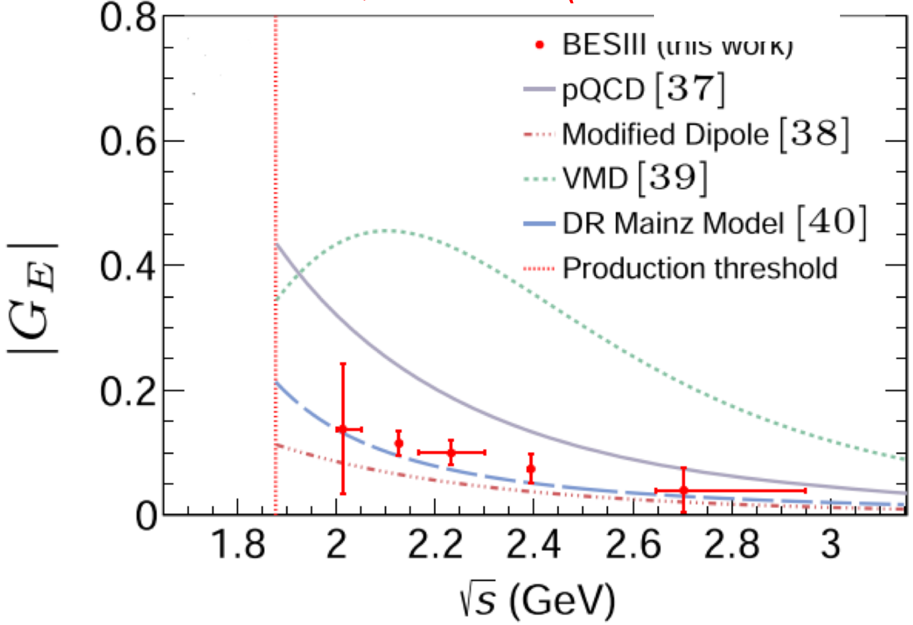


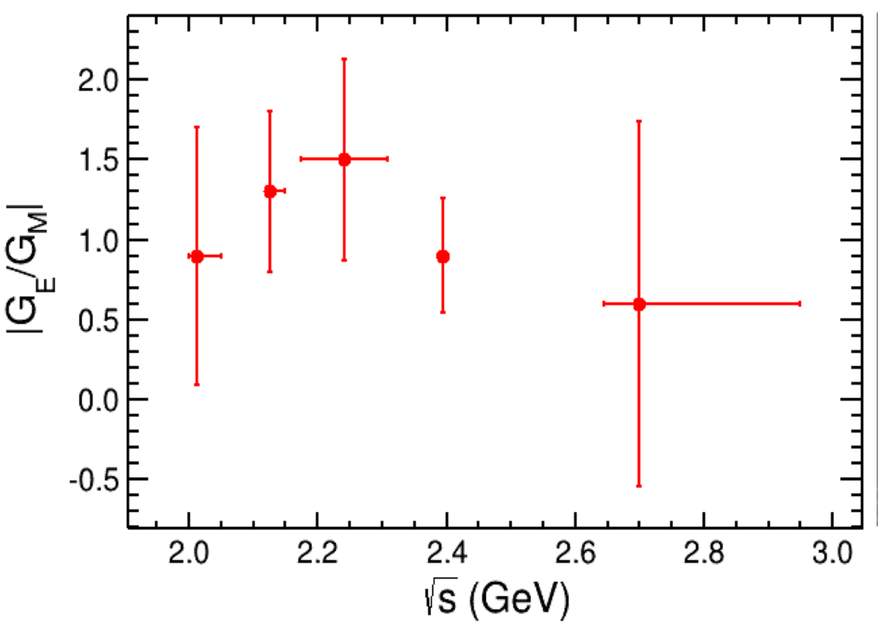
Additional experimental and theoretical inputs are desired!

$|G_E|$ and $|G_M|$ of neutron

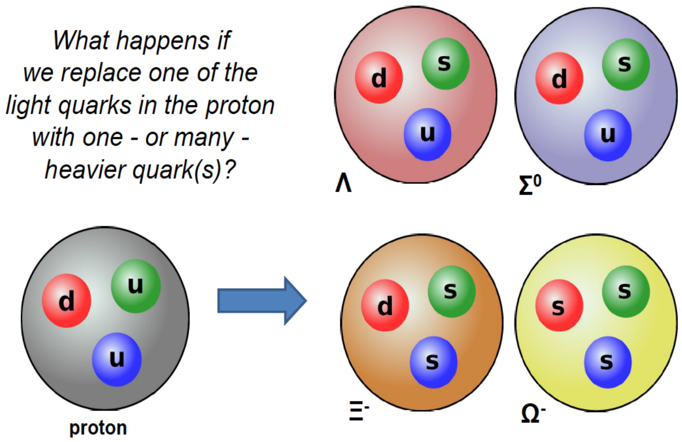
- $|G_E|$ and $|G_M|$ are obtained in 5 energy intervals due to the limited statistics, $|G_E/G_M|$ distribution is not shown in the paper
- BESIII $|G_M|$ values are smaller than that of FENICE by a factor of 2-3
- Data is compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR), where the DR model gives good consistency

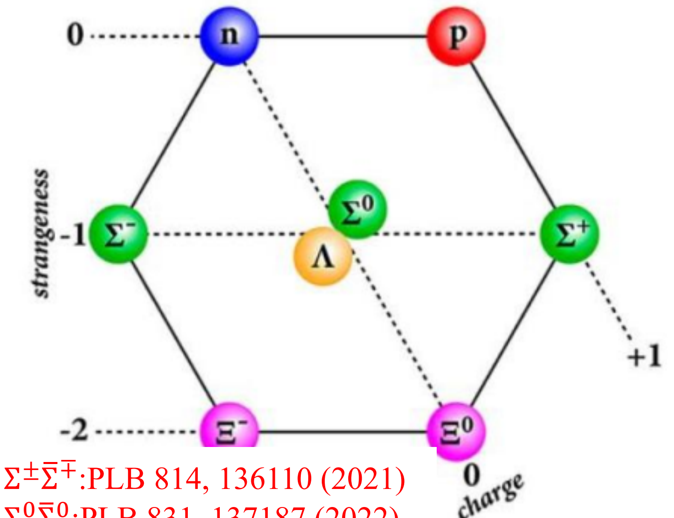
PRL 130, 151905 (2023)





Production cross section of hyperons

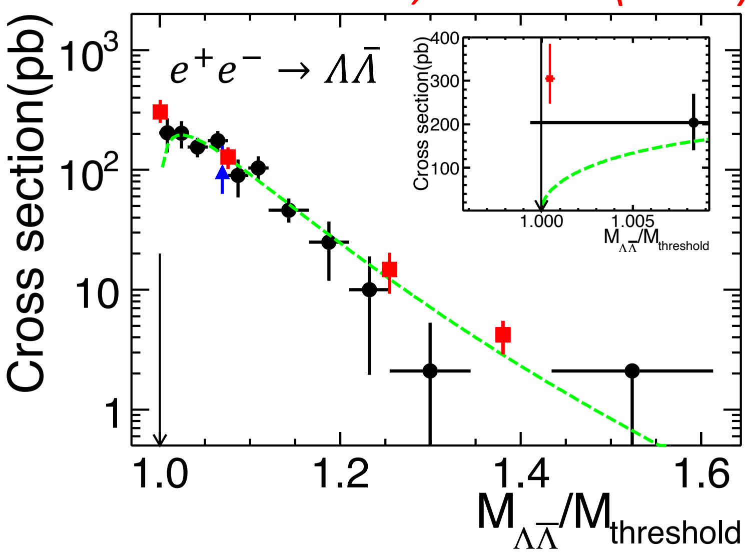


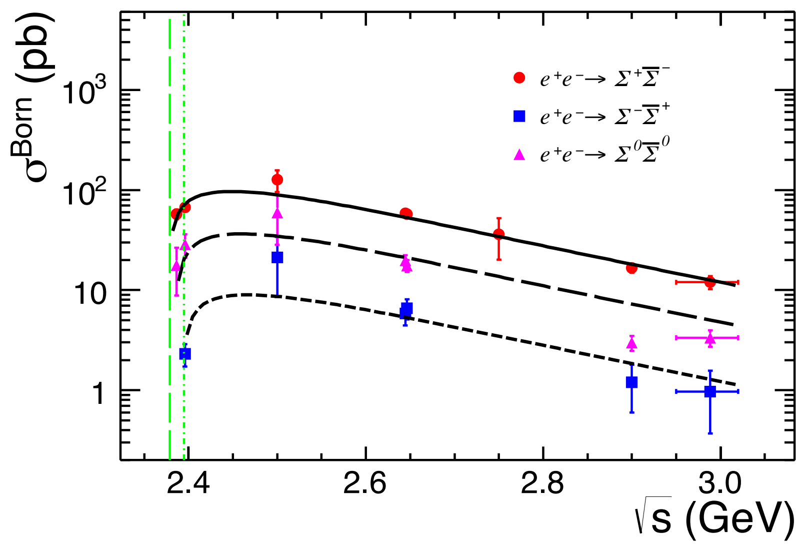


$\Sigma^{\pm}\bar{\Sigma}^{\mp}$:PLB 814, 136110 (2021)

$\Sigma^{0}\bar{\Sigma}^{0}$:PLB 831, 137187 (2022)

PRD 97, 032013 (2018)

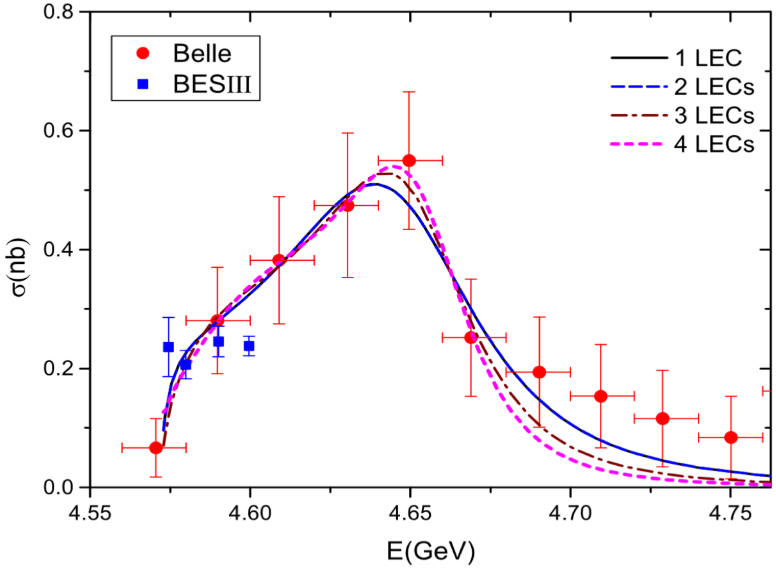




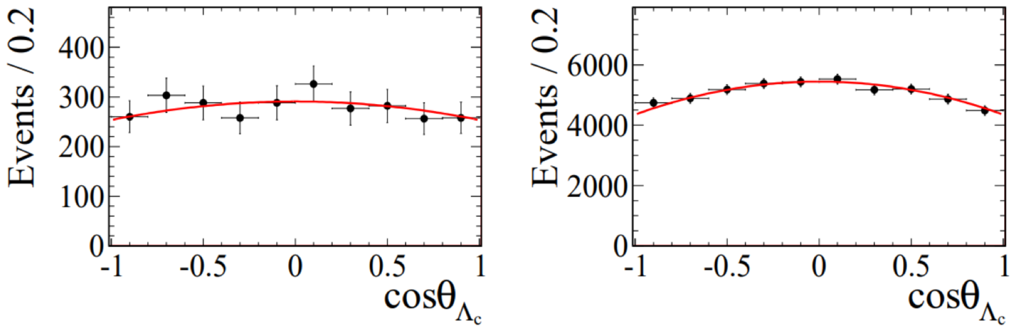
EMFF data of hyperon is limited due to the small statistics

Production of charmed hyperon

Belle and BESIII measured the production of Λ_c **near-threshold**:



PRL 120, 132001 (2018)

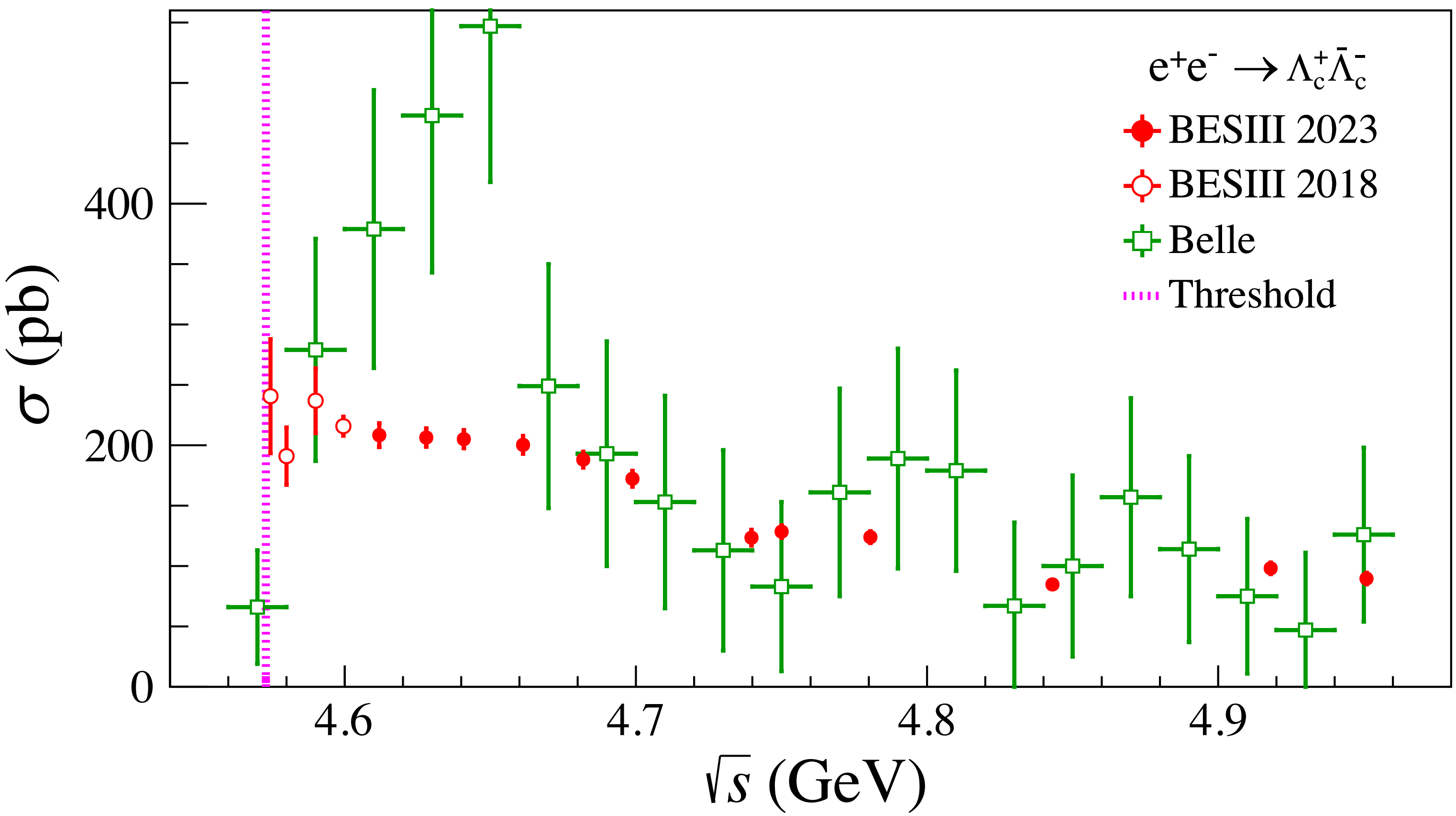


$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

- Precise non-zero cross section near the kinematic threshold, a significantly different energy-dependent trend from Belle's measurement
- $|G_E/G_M|$ is consistent with 1 near the kinematic threshold
- Results are limited in a narrow c.m. energy region near threshold

A thorough study of the cross section and EMFFs is needed!

Production cross section of Λ_c^+



Near-threshold cross-section plateau is confirmed up to 4.68 GeV, and no resonance structure is observed around 4.64 GeV -- **no charmed baryonium?**

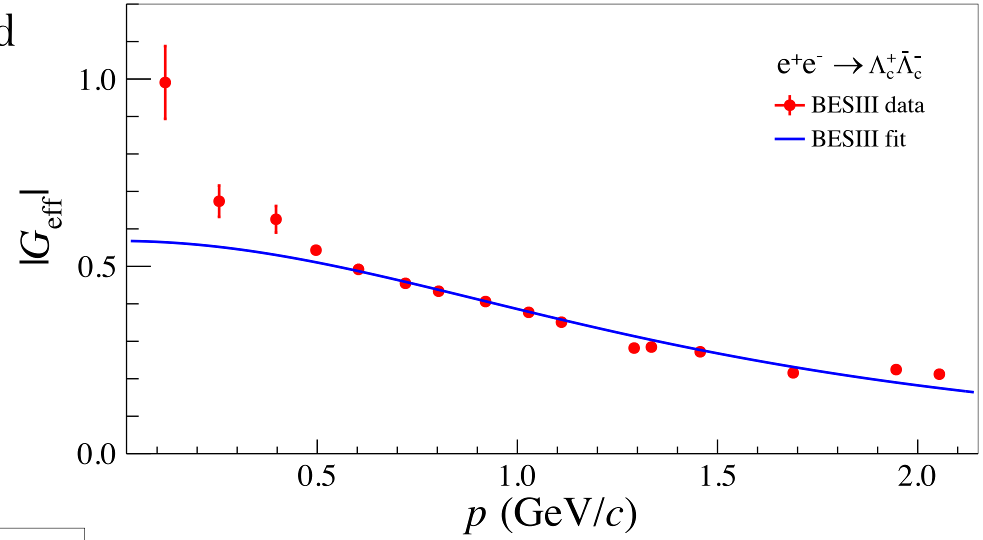
Effective form factor of Λ_c^+

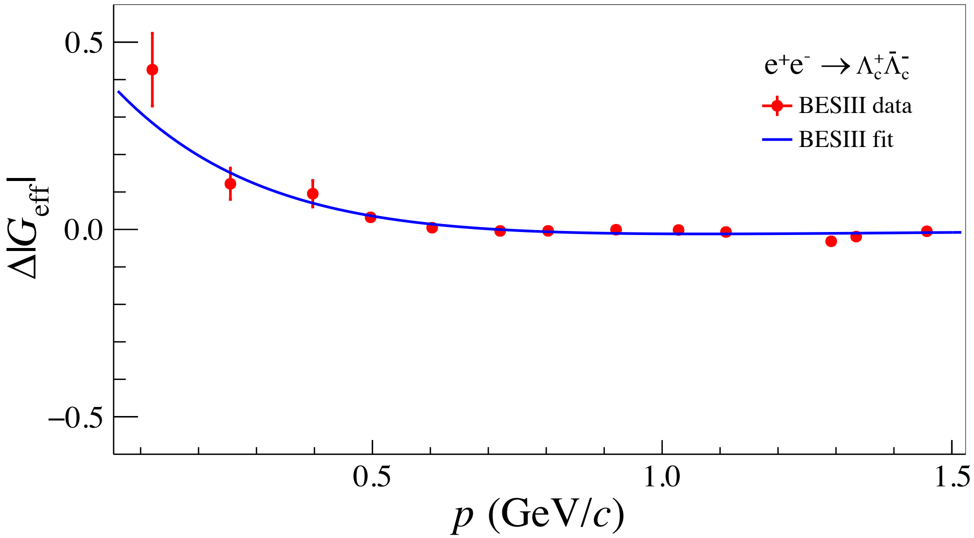
The effective form factors spectrum is fitted with a three-pole model:

$$G_{3p}(s) = \frac{g}{\left(1+\frac{s}{g_a}\right)\left(1-\frac{s}{g_b}\right)^2}$$

where

$$p = \sqrt{\left(\frac{s}{2m_{\Lambda_c^+}} - m_{\Lambda_c^+}\right)^2 - m_{\Lambda_c^+}^2}$$





The residual between effective form factors data and the three-pole model is obtained:

$$\Delta|G_{\mathrm{eff}}|(p) = |G_{\mathrm{eff}}|(p) - G_{3p}(p)$$

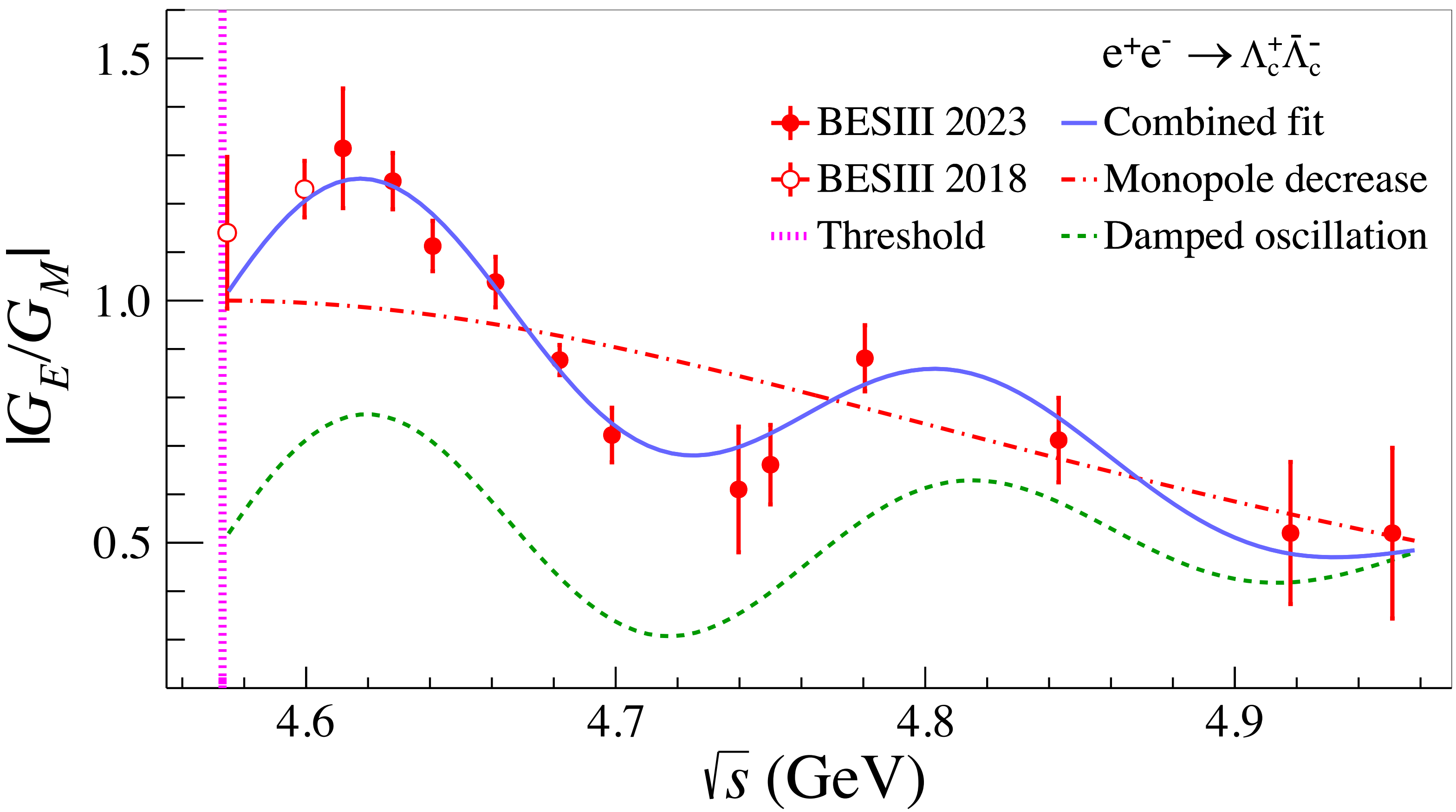
and fitted to a damped oscillation model:

$$|G_{\mathrm{osc}}|(p) = Ae^{-Bp}\cos(Cp + D)$$

$$C = (0.03 \pm 0.14)\ (\mathrm{GeV}/c)^{-1}$$

No oscillation feature is discerned in the effective form-factor spectrum of Λ_c^+

Electromagnetic form factor of Λ_c^+

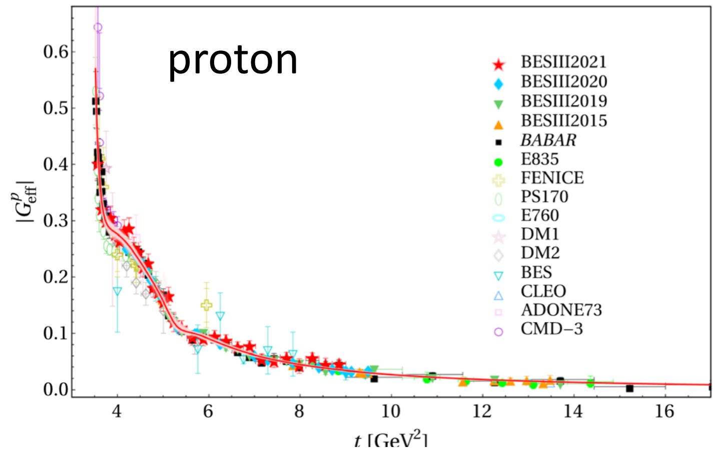


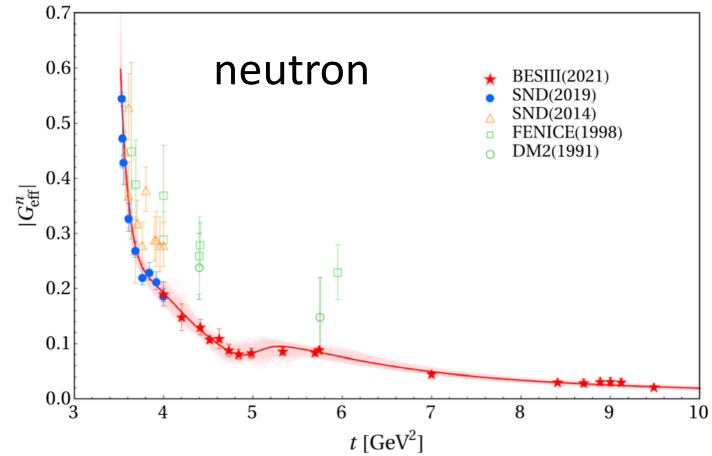
- Fitted to a function combining monopole decrease with damped oscillation
- Oscillation feature is unambiguously discerned for the charmed baryon Λ_c^+

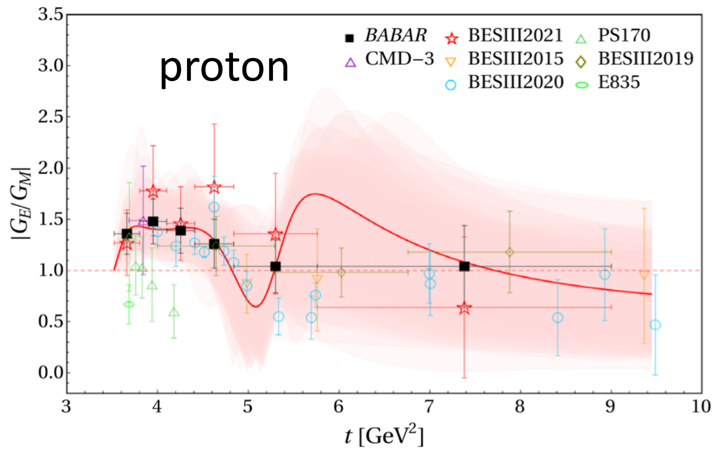
Where is the oscillation from?

Dispersion theory: broad poles above threshold in nucleon

Yong-Hui Lin, Hans-Werner Hammer, and Ulf-G. Meißner, Phys. Rev. Lett. **128**, 052002 (2022)







V_s	M_V	Γ_V	a_1^V	a_2^V
ω	0.783	0	0.701	0.338
ϕ	1.019	0	−0.526	−0.997
s_1	1.031	0	0.422	−2.827
s_2	1.120	0	0.122	3.655
s_3	1.827	0	0.955	−1.122
r_{s1}	1.903	0.973	−2.653	−1.753
r_{s2}	1.914	0.541	−3.069	2.017
r_{s3}	1.879	0.895	4.953	0.501

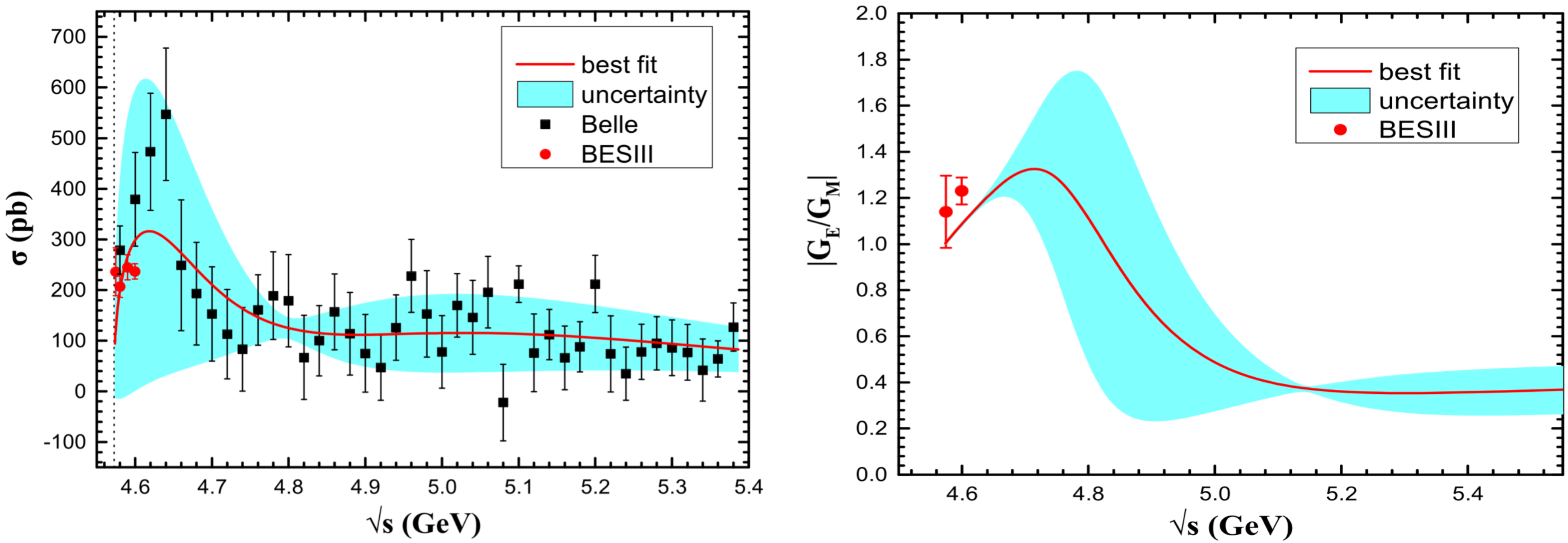
V_v	M_V	Γ_V	a_1^V	a_2^V
v_1	1.050	0	0.782	−0.132
v_2	1.323	0	−4.873	−0.645
v_3	1.368	0	3.518	−0.987
v_4	1.462	0	2.243	−3.813
v_5	1.532	0	−1.422	3.668
r_{v1}	2.256	0.239	2.552	−1.217
r_{v2}	2.253	0.245	−1.947	0.551
r_{v3}	2.220	0.362	−0.985	1.061

May not applicable for Λ_c^+ since no oscillation feature is observed $|G_{\mathrm{eff}}|$ data

Where is the oscillation from?

A prediction of $|G_E|$ and $|G_M|$ based on the **modified VMD model** :

Junyao Wan, Yongliang Yang, and Zhun Lu, Eur. Phys. J. Plus 136, 949 (2021).



- $|G_E|$ and $|G_M|$ are parameterized separately with the modified VMD model
- Contribution from the vector charmed mesons and their excitations are included
- Phenomenology parameters are determined by fitting BESIII and Belle cross section data and BESIII $|G_E/G_M|$ data

Difficult to simultaneously reproduce new BESIII cross section and $|G_E/G_M|$ data

Summary and outlook

- Time-like EMFFs of baryons are measured with the comparable precision of space-like ones
- Oscillation(-like) features are found in the effective FFs of proton and neutron, as well as $|G_E/G_M|$ of proton and charmed baryon Λ_c^+
- Correlation with the heavier excited resonance states or simply a wave-like behavior of baryon?
- Accessibility is limited for strange hyperons and heavier charmed baryons due to the low efficiency or small production cross sections
- More data of time-like EMFFs of baryon are foreseen in Belle-II and PANDA experiments

Summary and outlook

- Time-like EMFFs of baryons are measured with the comparable precision of space-like ones
- Oscillation(-like) features are found in the effective FFs of proton and neutron, as well as $|G_E/G_M|$ of proton and charmed baryon Λ_c^+
- Correlation with the heavier excited resonance states or simply a wave-like behavior of baryon?
- Accessibility is limited for strange hyperons and heavier charmed baryons due to the low efficiency or small production cross sections
- More data of time-like EMFFs of baryon are foreseen in Belle-II and PANDA experiments

Thanks for your attention!