Recent results of baryon electromagnetic form factors at BESIII

Weiping Wang (On behalf of the BESIII Collaboration)

Johannes Gutenberg University Mainz (JGU)
Helmholtz-Institute Mainz (HIM)
University of Science and Technology of China (USTC)

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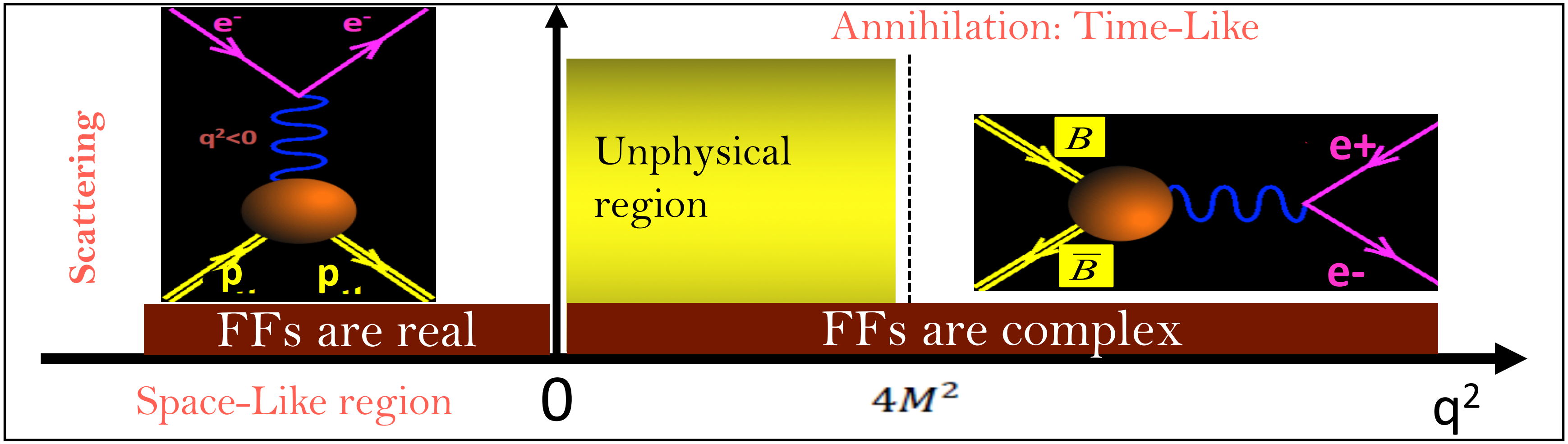
Electromagnetic form factors (EMFFs)

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



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

Pair production of baryon

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

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

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

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

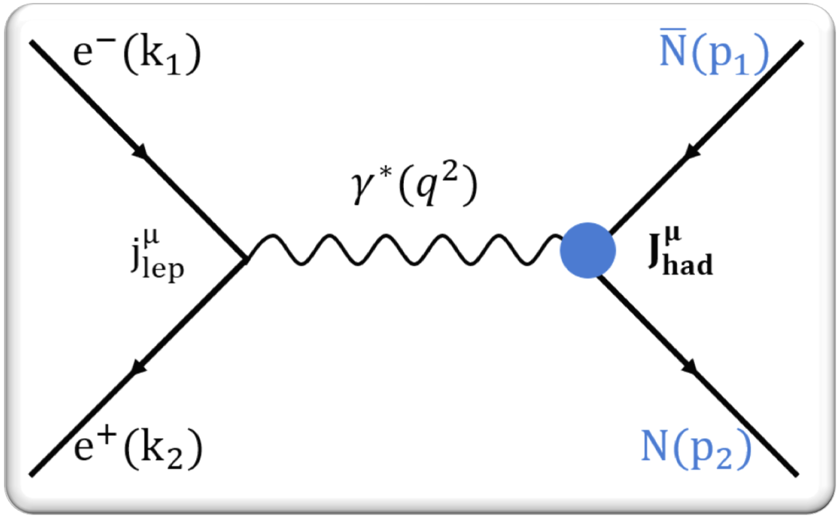
The so-called effective form factor could be defined in terms of EMFFs:

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

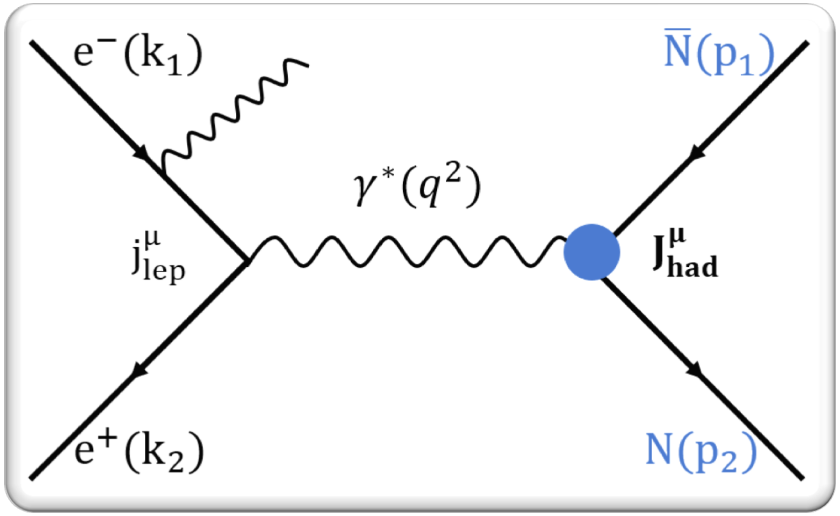
Effective FF reflects the magnitude of production cross section of baryon!

Experimental access of Time-like form factors

Energy scan

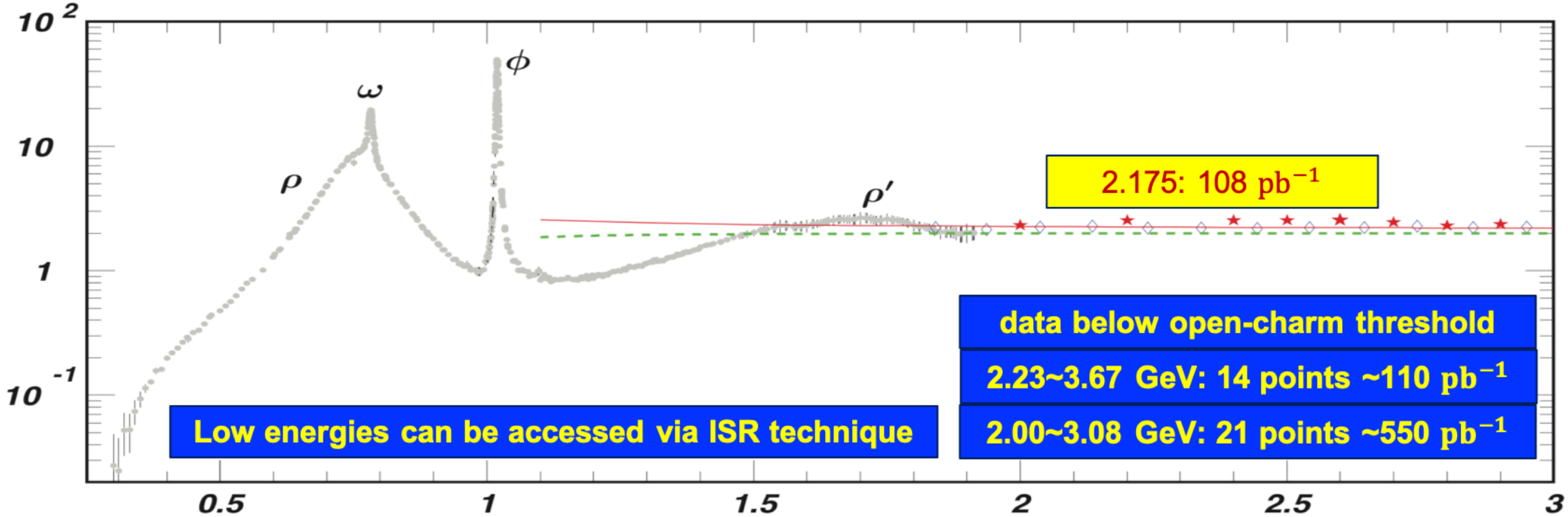


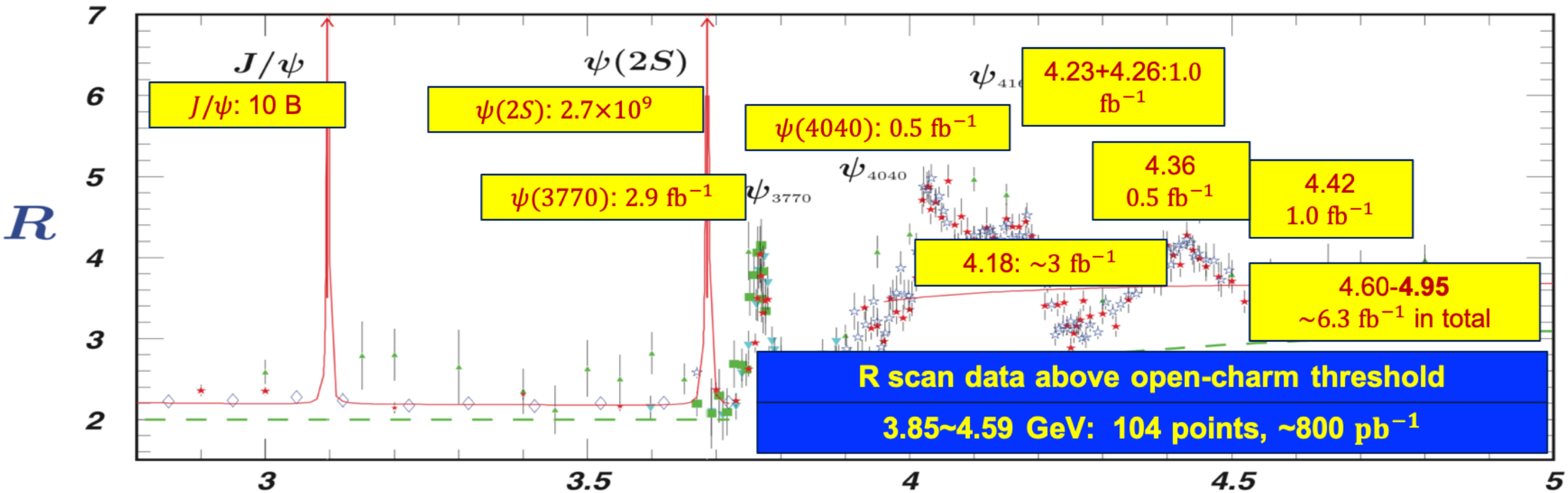
Initial-state-radiation



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

Data collected at BESIII

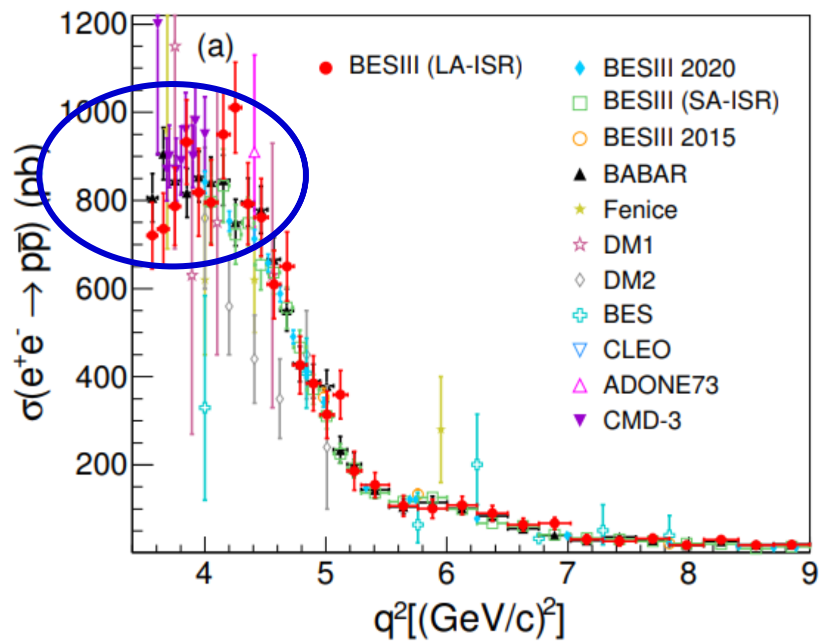


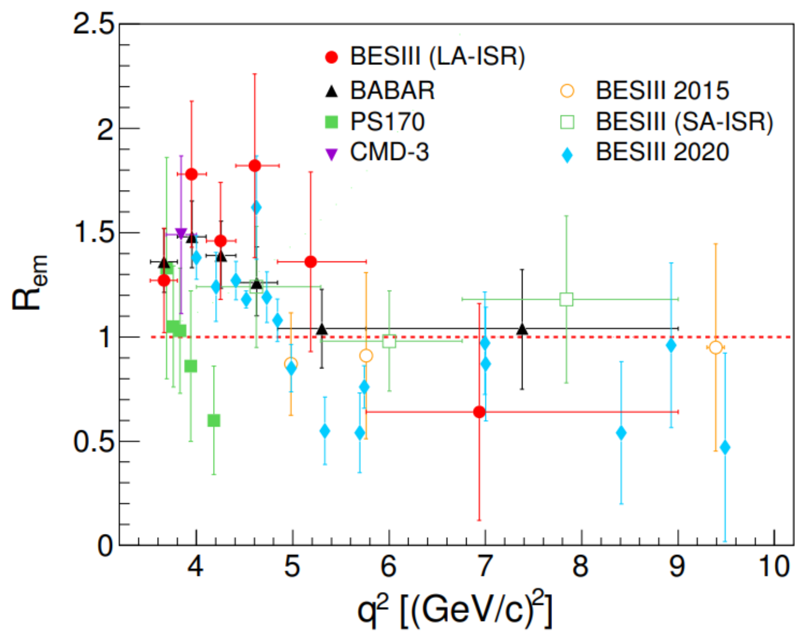


Proton form factors

ISR approach with detected and undetected ISR photon using 7.5 fb^{-1} integrated luminosity.

SA-ISR(un-tagged): PRD 99, 092002 (2019)
LA-ISR(tagged): PLB 817, 136328 (2019)



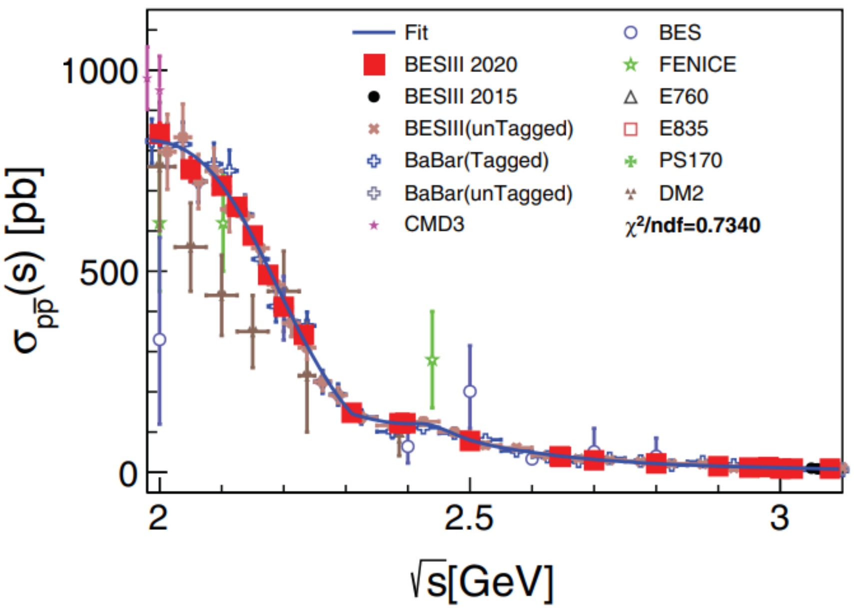


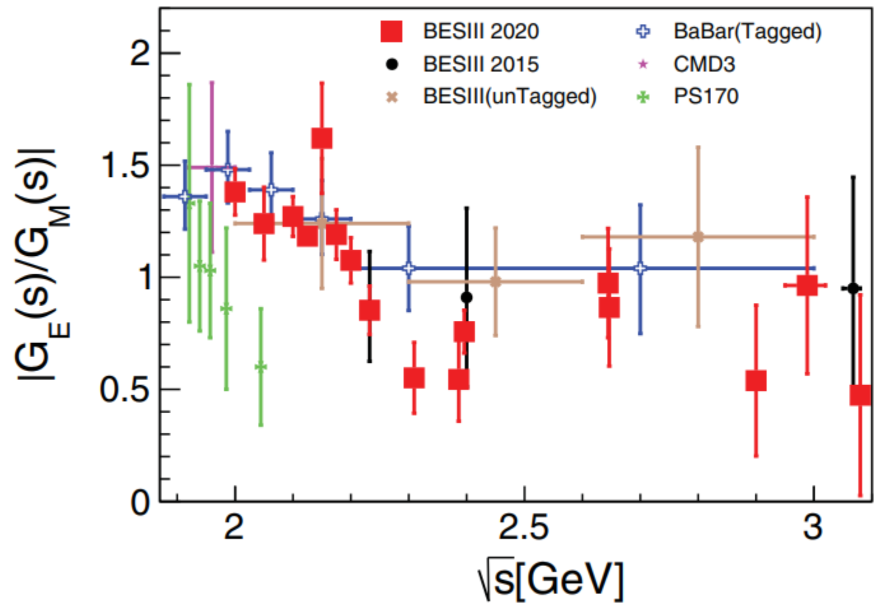
- From threshold to $q^2 = 4.0\ \text{GeV}^2$, average cross section 840 pb
- Point-like cross section at threshold, $\sigma_{\text{point}} = \frac{\pi\alpha^2}{3m_B^2\tau}\left[1 + \frac{1}{2\tau}\right] = 845\ \text{pb}$

Proton form factors

- Scan technique from 2.00 to 3.08 GeV, using data of 688.5 pb^{-1}
- $|G_E/G_M|$ is determined with **high accuracy**, comparable with space-like region.
- $|G_E|$ and $|G_M|$ are separated by analyzing the polar angle distribution.

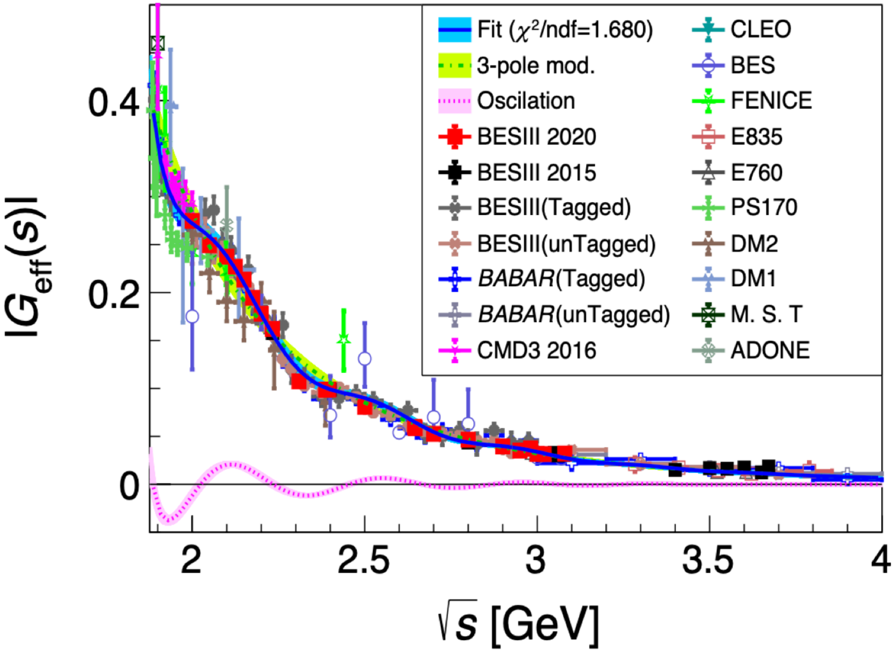
PRL 124, 042001 (2020)
PRD 91, 112004 (2015)

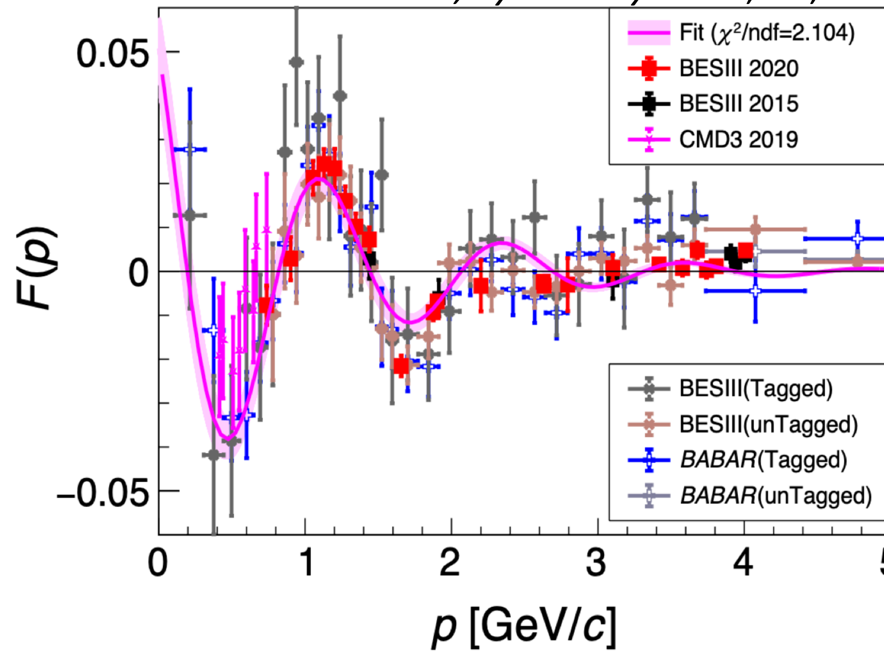




Oscillation feature confirmed in $|G_{\text{eff}}|$

Lei Xia *et al*, *Symmetry* **2022**, *14*, 231





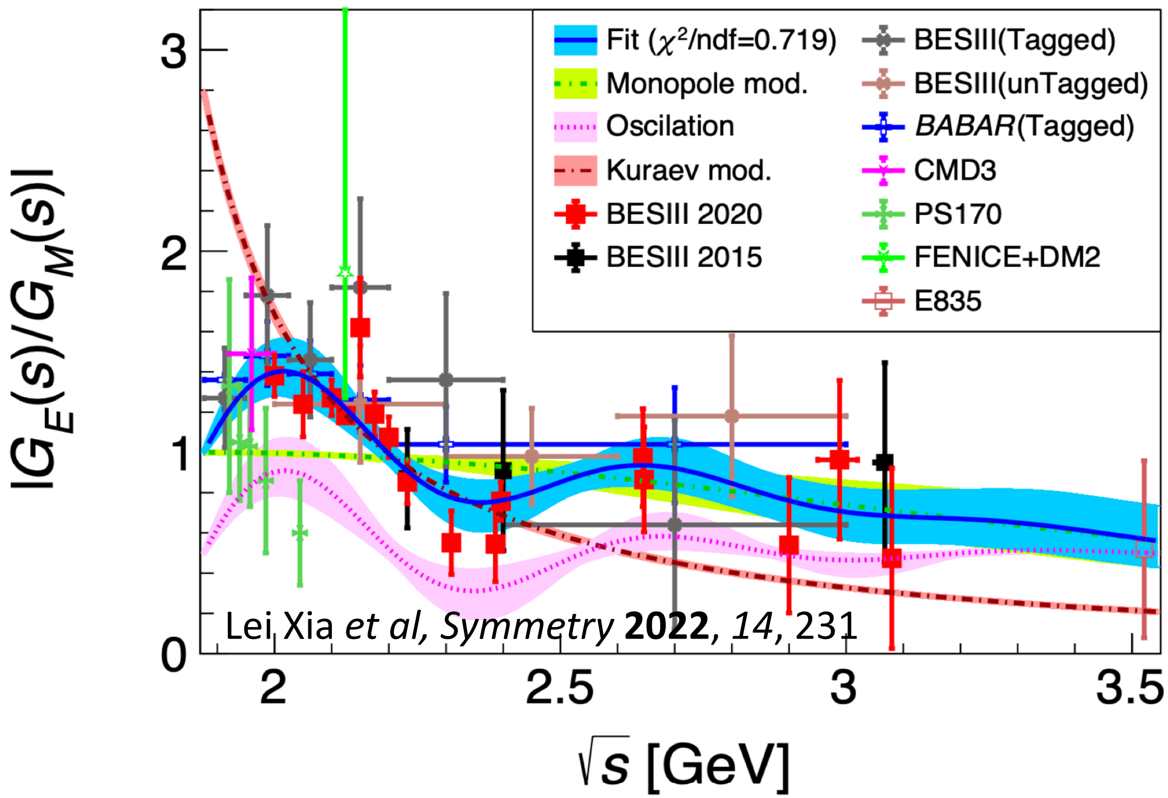
$|G_{\text{eff}}|$ data are fitted with the model: the monopole decrease with a damped oscillation : *E. Tomasi-Gustafsson et al., PRL. 114, 232301 (2015), PRC 103, 035203 (2021)*

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

Oscillation feature in the cross section line-shape!

Contribution from intermediate states?

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!

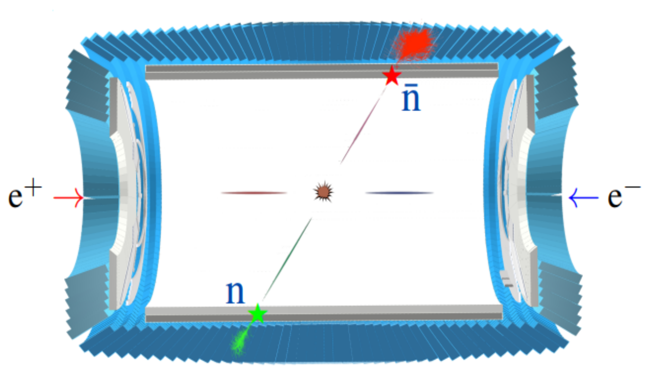
$|G_E/G_M|$ data are fitted with the model:

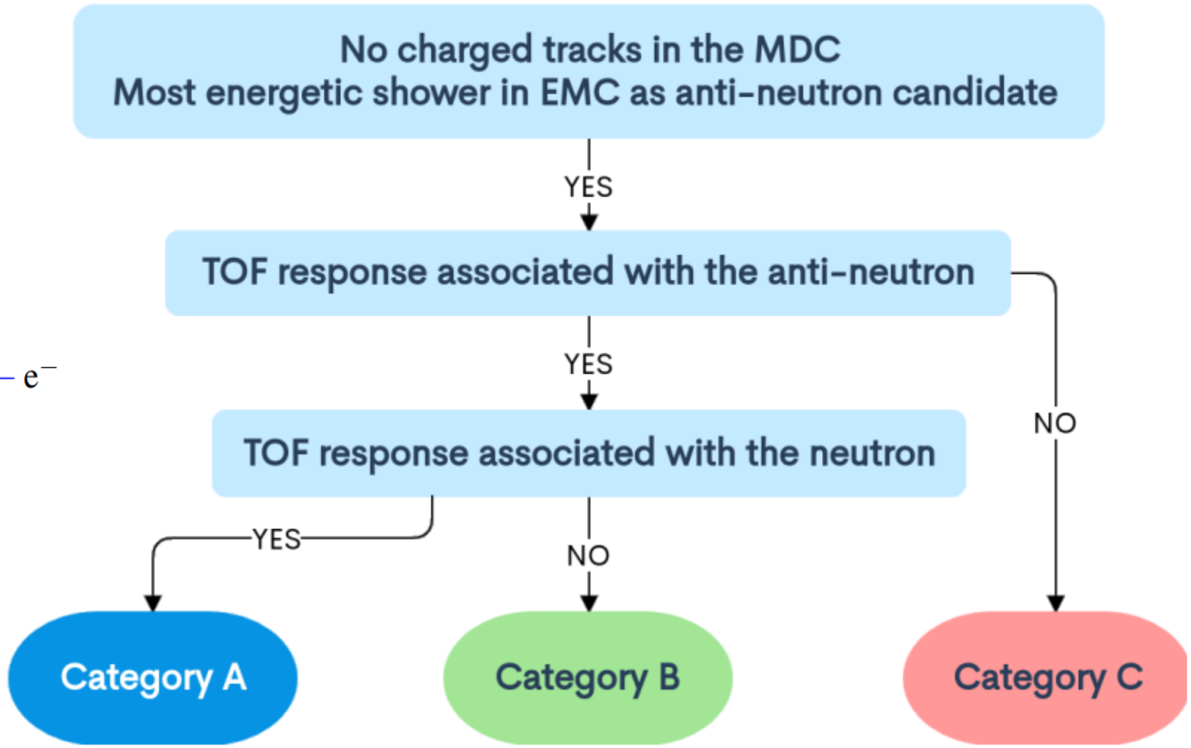
$$|G_E/G_M|(s) = \frac{1}{1+\omega^2(s)/r_0}\left[1 + r_1 e^{-r_2\omega(s)}\sin(r_3\omega(s))\right]$$

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

Neutron form factors

- High luminosity 18 scan data sets from 2.0 and 3.08 GeV, 674.9 pb^{-1}
- Pure neutral channel $e^+e^- \to n\bar{n}$, only EMC and/or TOF info.
- Sophisticated background suppression: $e^+e^- \to \gamma\gamma$, beam-associated

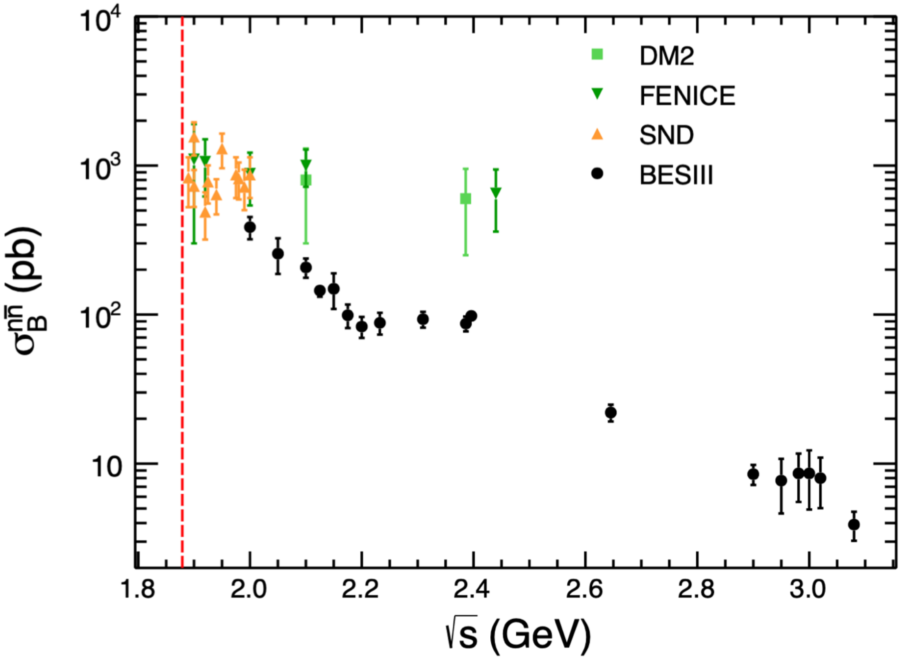


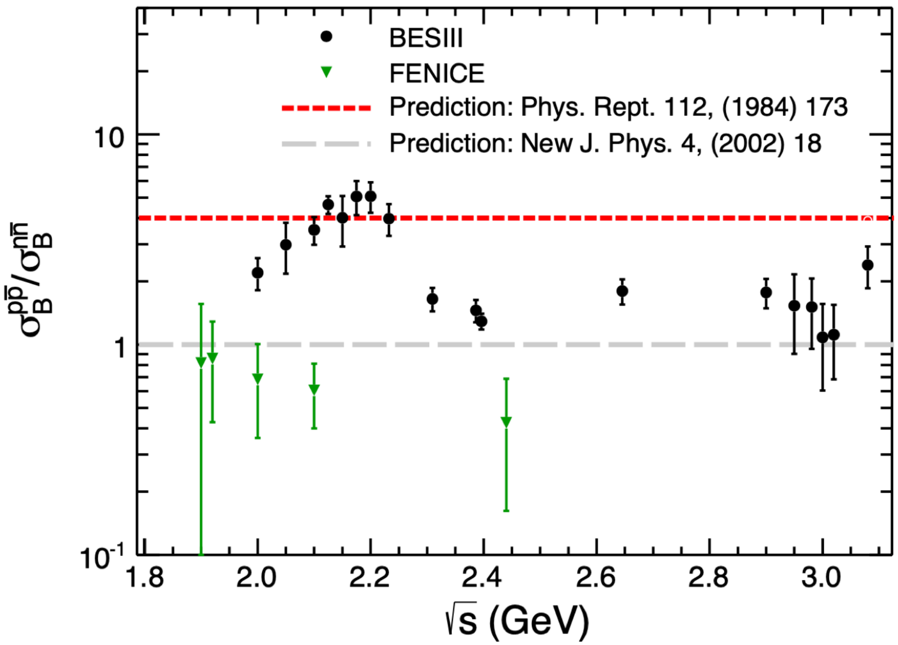


Neutron form factors

- Combine 3 categories to get the best measurement
- 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.

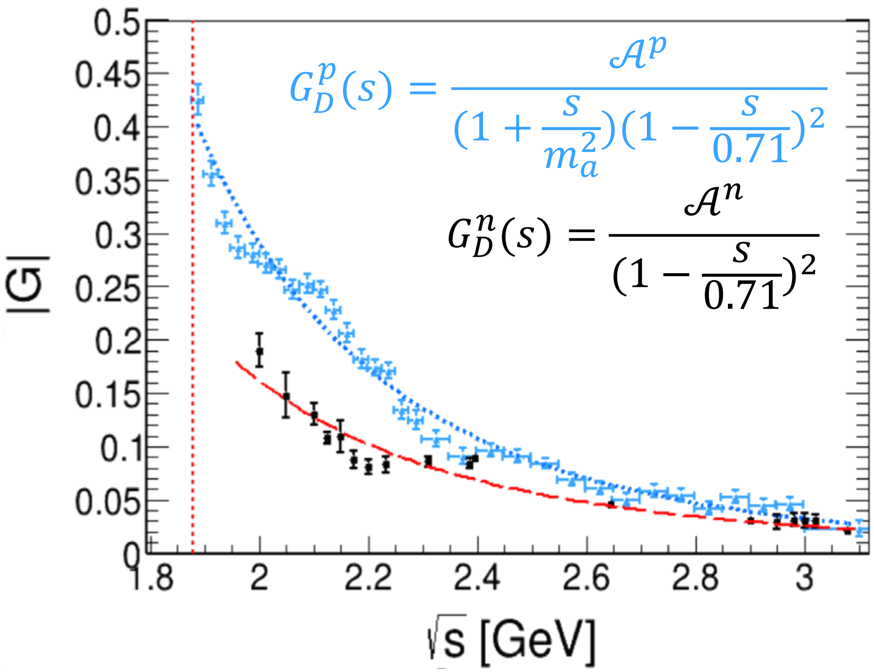
Nature Phys. 17 (2021) 11, 1200-1204



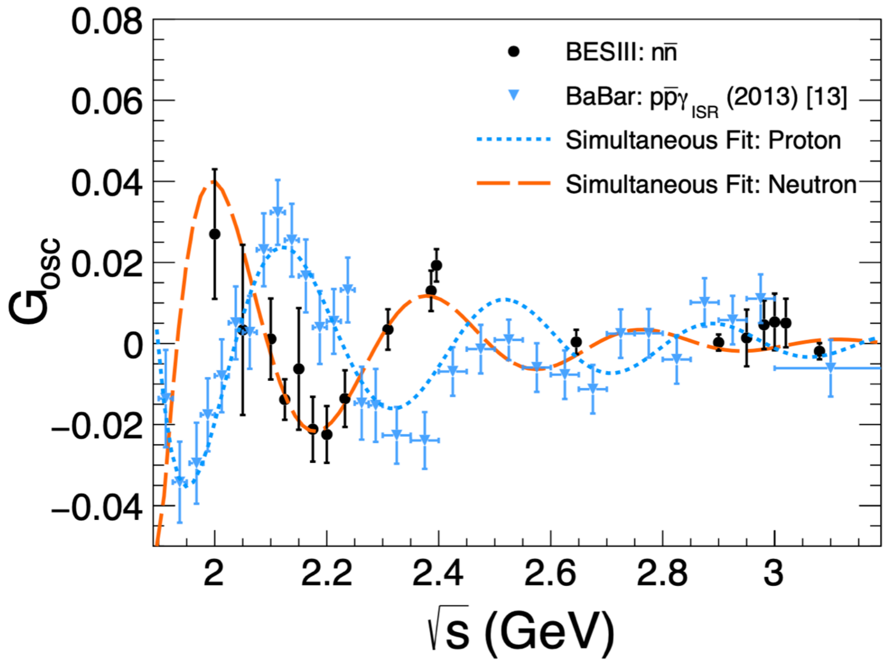


Oscillation feature in $|G_{\text{eff}}|$

- Oscillation around 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 sharing 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



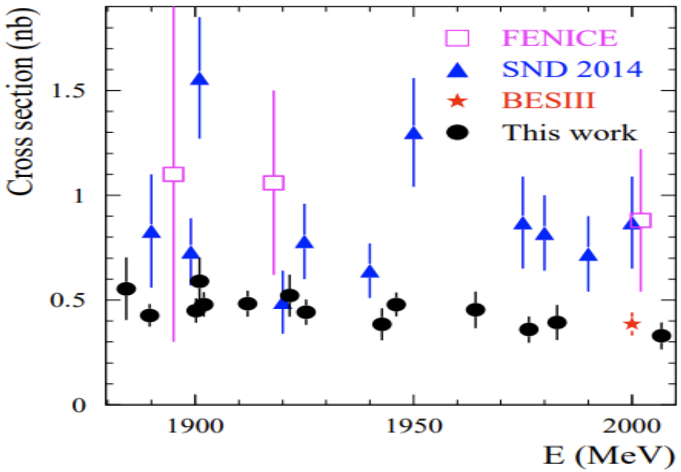
Nature Phys. 17 (2021) 11, 1200-1204

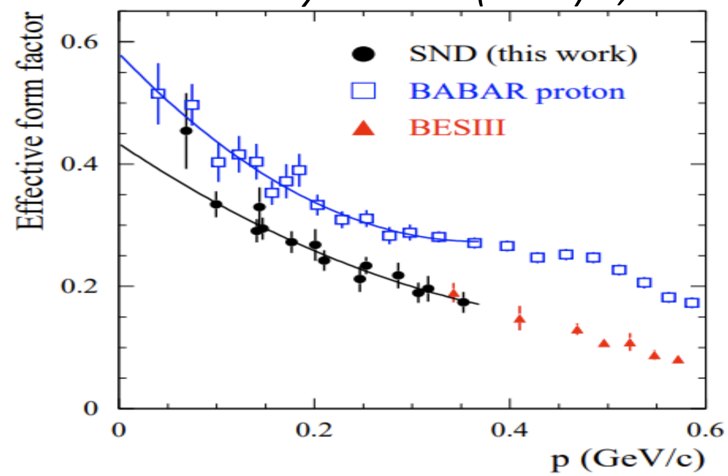


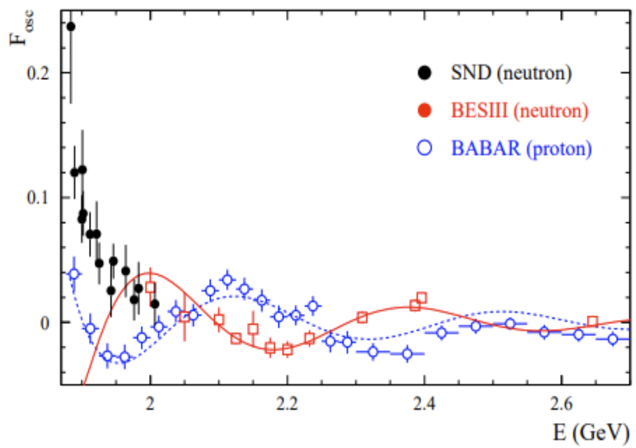
Oscillation feature in $|G_{\mathrm{eff}}|$

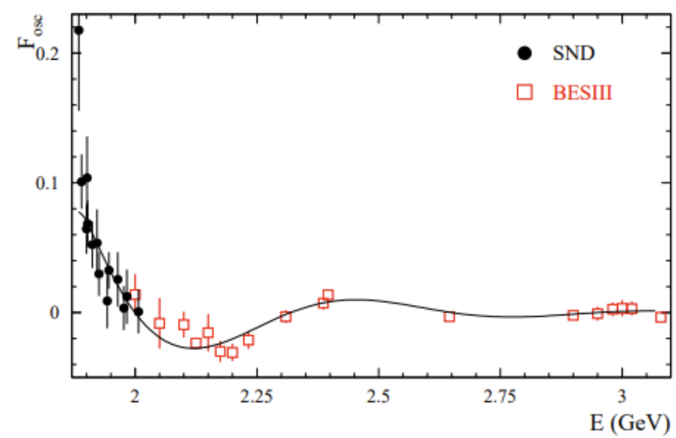
Recent SND measurement suggests a different frequency:

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





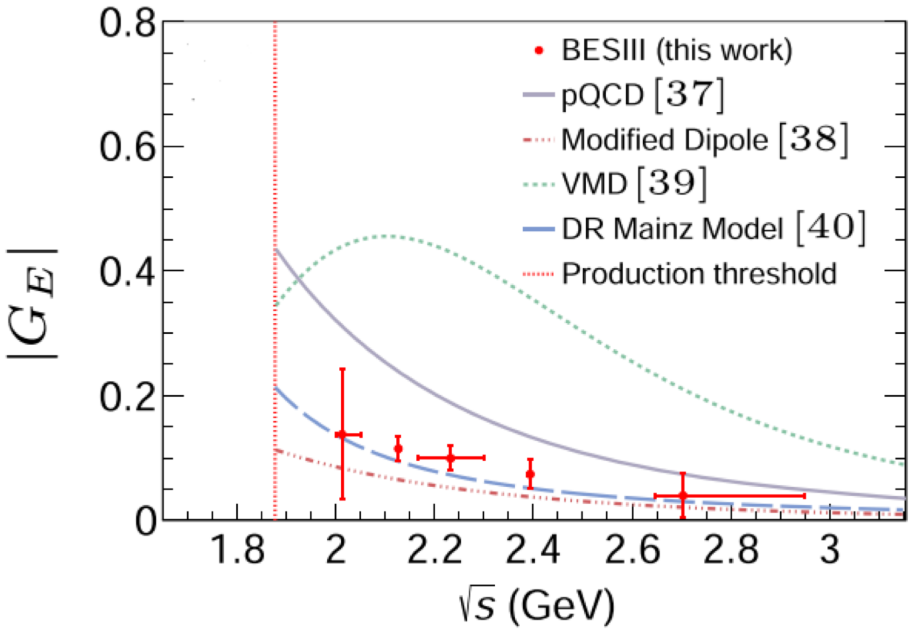




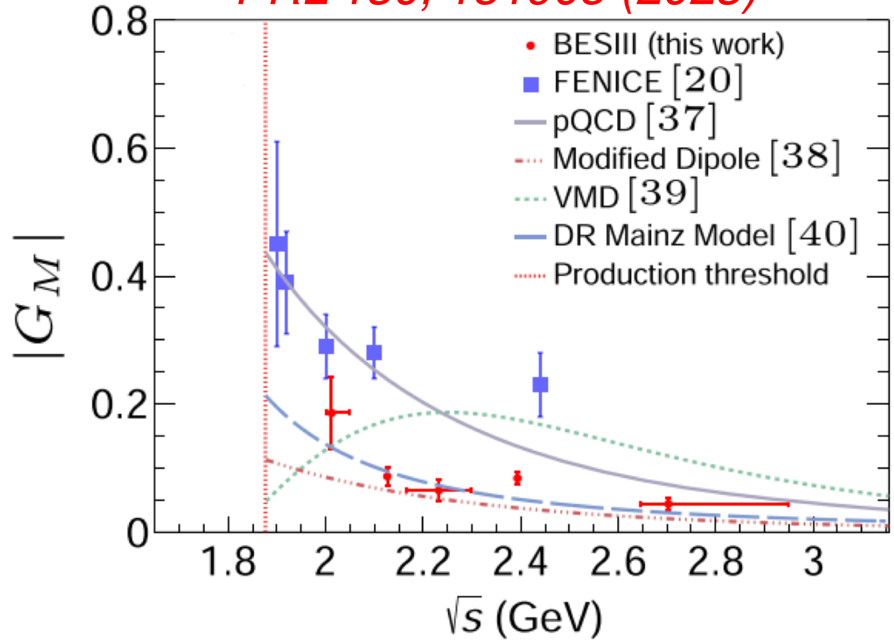
Additional experimental and theoretical inputs are desired!

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

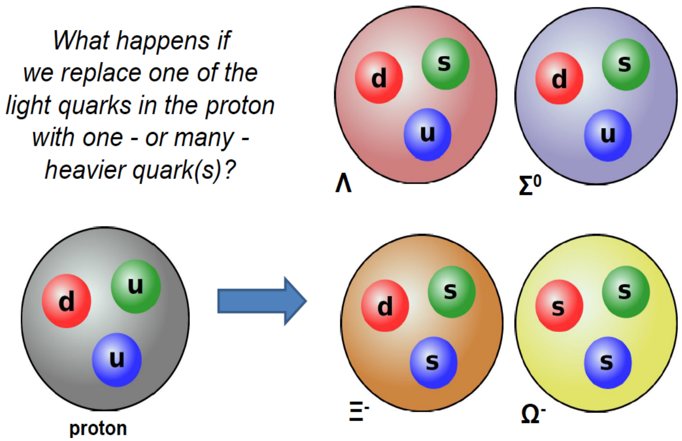
- $|G_E|$ and $|G_M|$ are obtained in 5 energy intervals due to the limited statistics, $|G_E/G_M|$ distribution is not fitted due to the large uncertainties
- BESIII $|G_M|$ values are smaller than that of FENICE by a factor of 2-3
- Data is compared with various models: pQCD, modified dipole, VMD and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

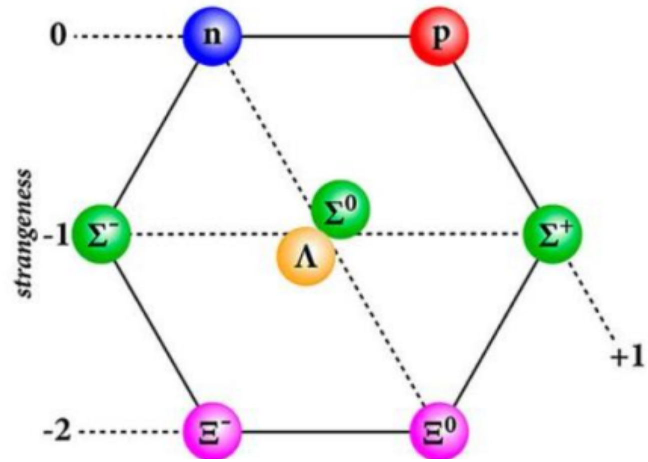


PRL 130, 151905 (2023)

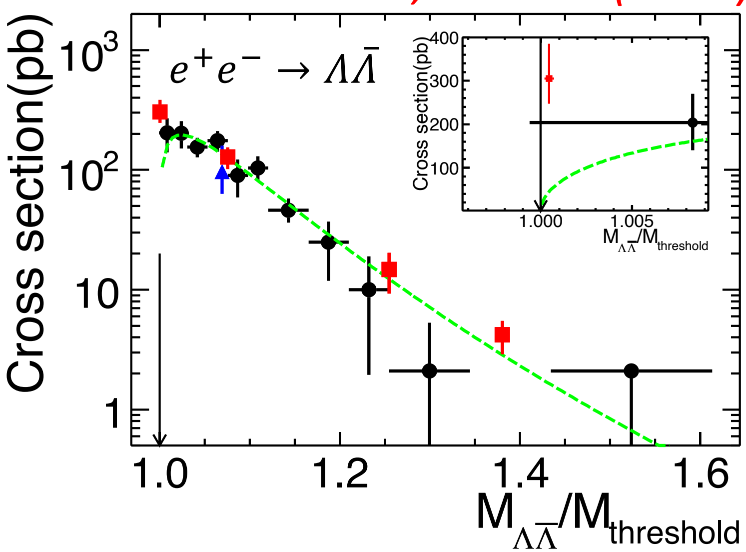


Hyperon form factors

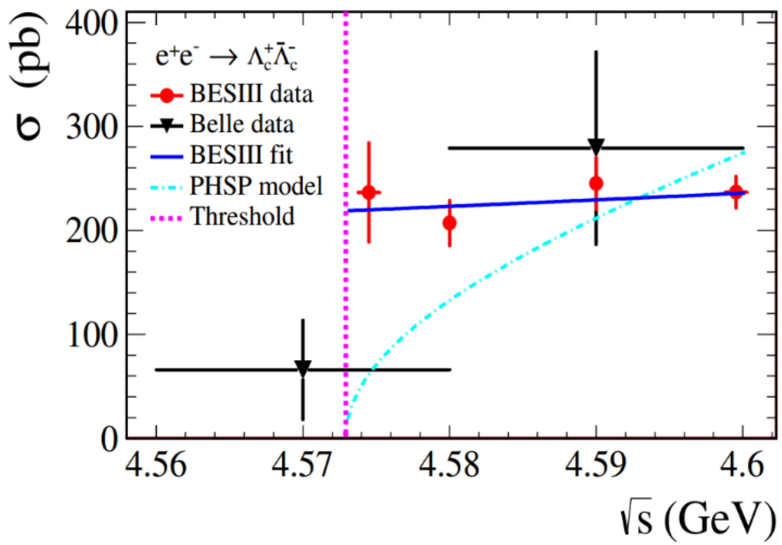




PRD 97, 032013 (2018)



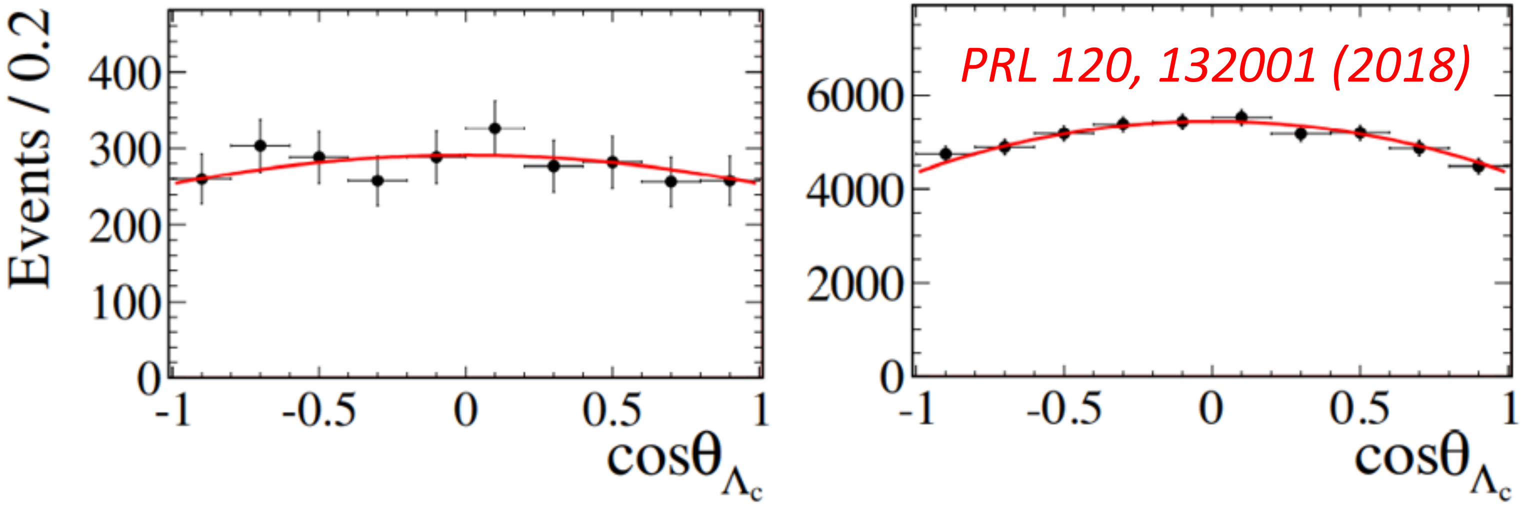
PRL 120, 132001 (2018)



BESIII could measure the production of hyperon Λ and Λ_c

Hyperon form factors

BESIII also measured the $|G_E/G_M|$ for the $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ process which is the first access of the form factors of Λ_c^+



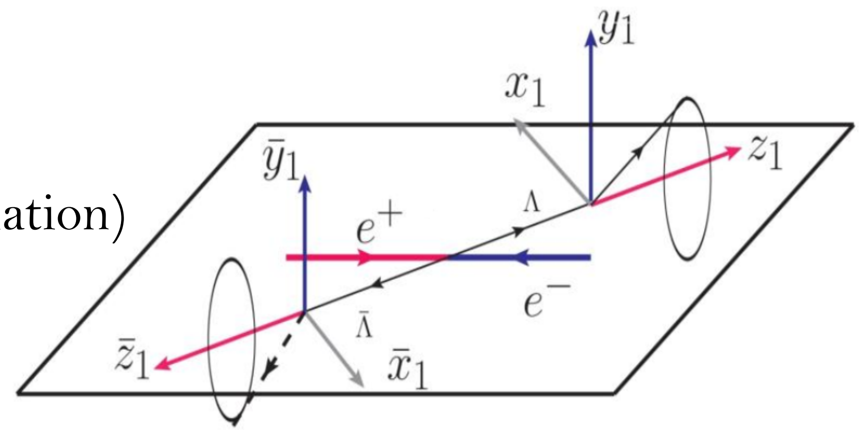
$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

$|G_E/G_M|$ is consistent with 1 near the production threshold

Results are limited in a narrow c.m. energy region near threshold

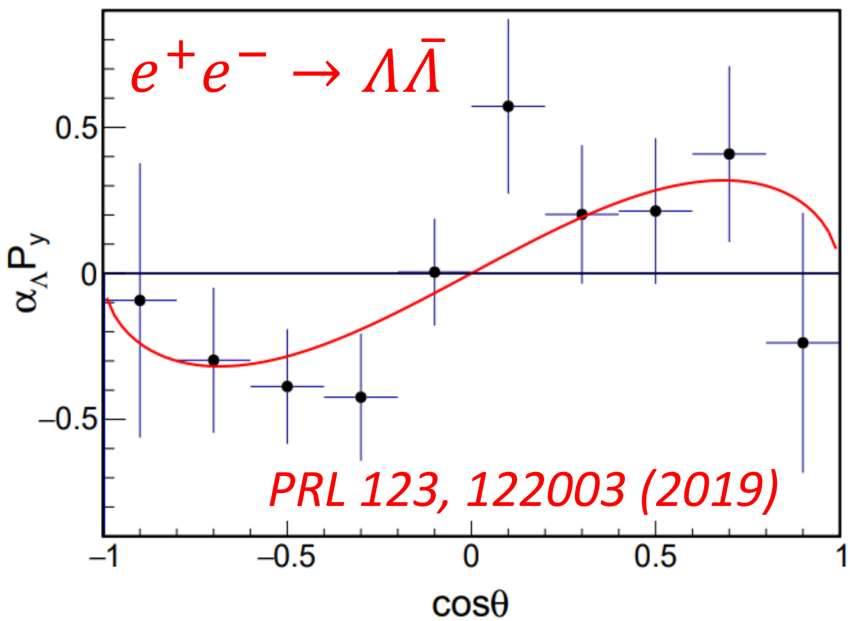
Phase between G_E and G_M of hyperon

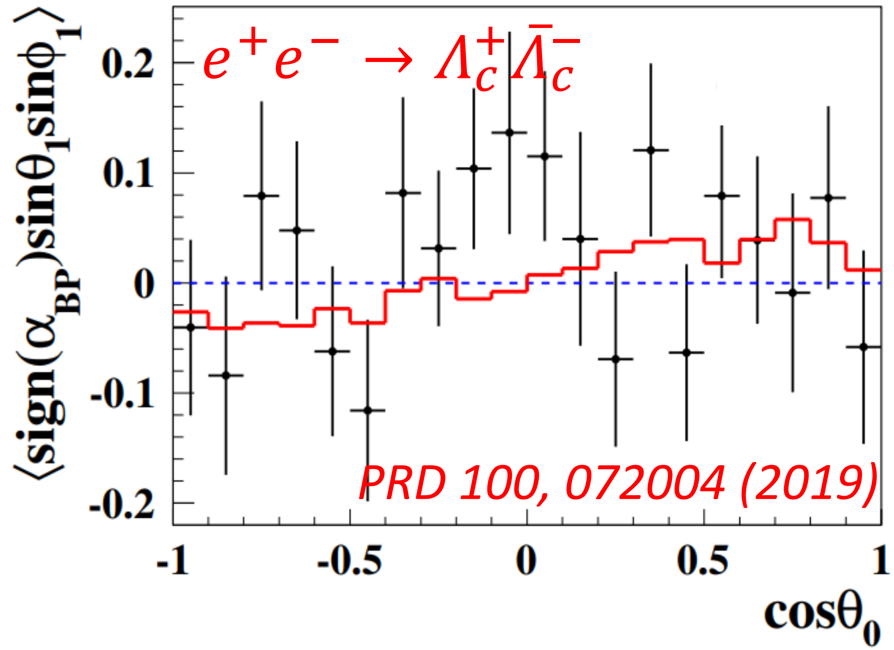
- **Complex form** of TL EMFFs:
  - $G_E = |G_E|e^{i\Phi_E}$, $G_M = |G_M|e^{i\Phi_M}$
  - Relative phase: $\Delta\Phi = \Phi_E$-Φ_M
- A non-zero relative phase results in the **polarization** effect of the hyperons: $\boldsymbol{P_y \propto \sin\Delta\Phi}$
- The **angular** distribution of daughter baryon produced in the hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}$
  - α_Λ: asymmetry parameter (P-violation)



Hyperon decays to B+P, where the polarization of hyperon can be measured, so does the relative phase between G_E and G_M !

Phase between G_E and G_M of hyperon





$|G_E/G_M| = 0.96 \pm 0.14 \pm 0.02$

Relative phase angle is measured to be $\Delta\Phi = 37^\circ \pm 12^\circ \pm 6^\circ$ at $\sqrt{s} = 2.396$ GeV

Λ_c^+ transverse polarization is $\sin\Delta\phi = -0.28 \pm 0.13 \pm 0.03$ with a statistical significance of 2.1σ at $\sqrt{s} = 4.6$ GeV

First complete determination of baryon time-like EMFFs

Summary

- Fruitful physics results of baryon EMFFs at BESIII: $p\bar{p}$, $n\bar{n}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$
- Oscillation feature confirmed in $|G_{\mathrm{eff}}|$ of p and n
- Oscillation feature discerned in $|G_E/G_M|$ distribution of proton, but not in neutron or hyperon due to limited data

The origin of these features is still unknown!

- Relative phase angle of hyperons EMFFs measured for Λ, Λ_c^+

Confirmed that time-like EMFFs of baryons are complex!

- More results from BESIII are on the way

Thank you!