Recent results of baryon EM form factors at BESIII

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(on behalf of BESIII collaboration)

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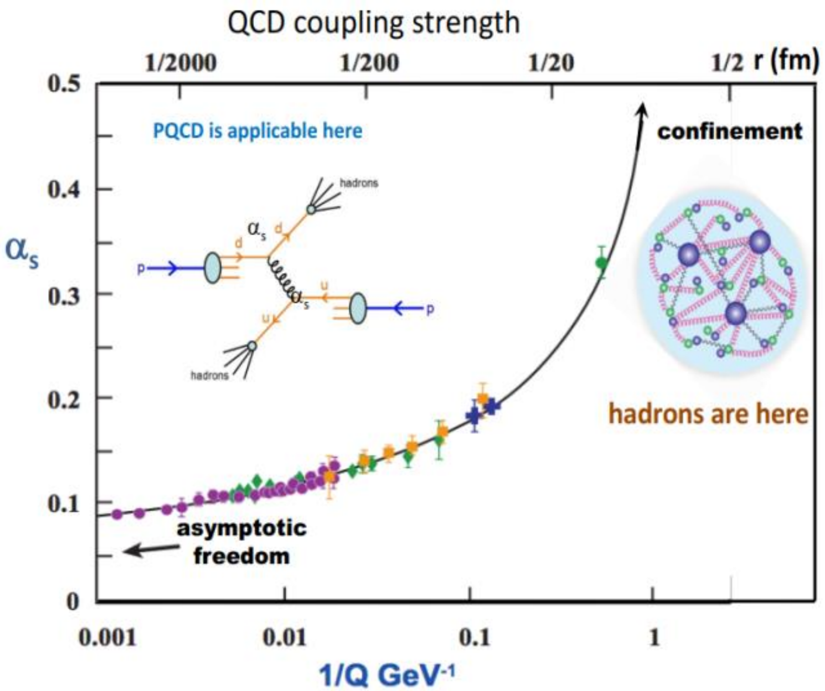
November 10 to 14, 2025

Baryon structure

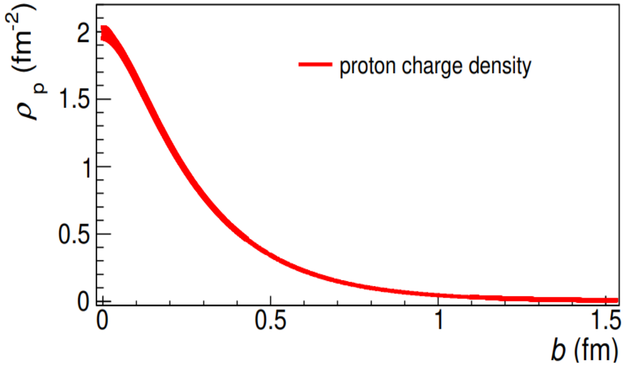
- At low Q, perturbative QCD not possible (expansion of coupling constant $\boldsymbol{\alpha_s}$)

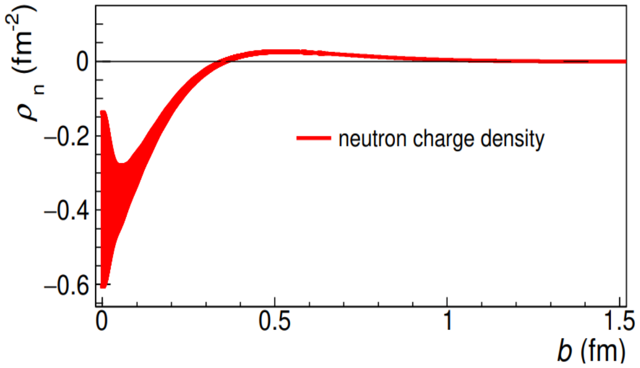
  ⇒ Baryon structure must be measured in experiments!

- Electromagnetic Form Factors are fundamental properties of the baryon, describing the internal structure/shape of the non-point-like particle
  - ➢ Connected to charge, magnetization distribution
  - ➢ Crucial testing ground for models of the baryon internal structure



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

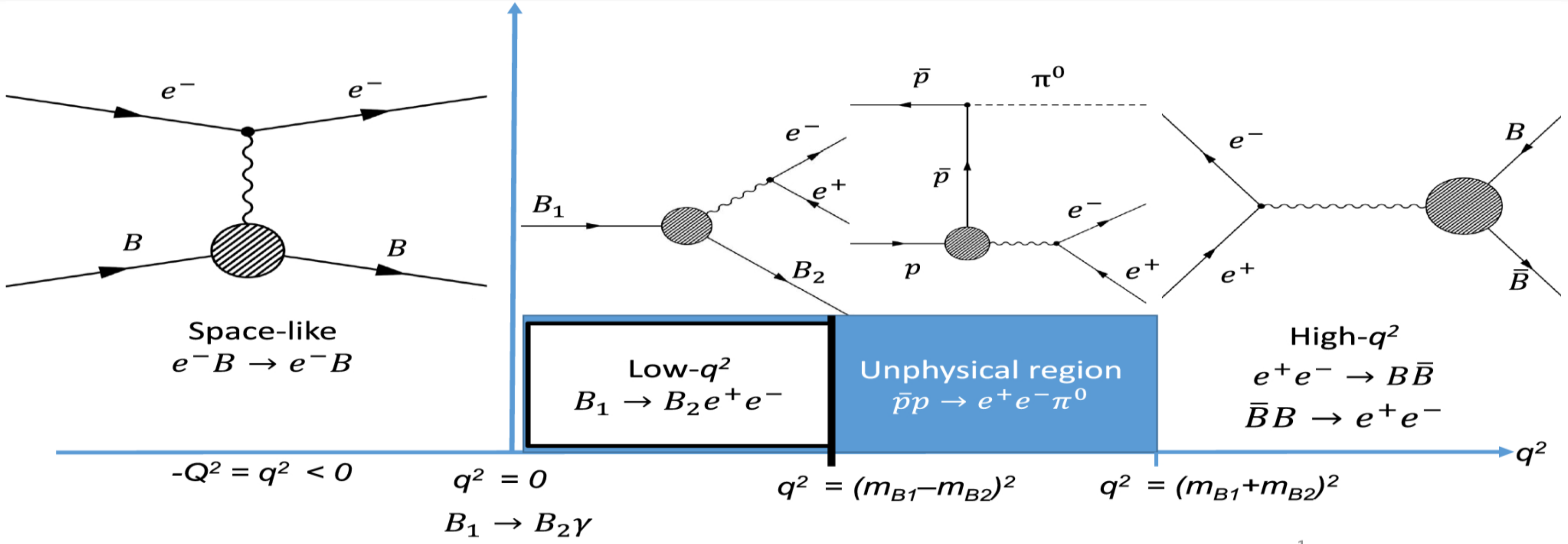




$$\langle r_n^2 \rangle = -6 \left. \frac{\left(dG_E^n(Q^2)\right)}{dQ^2} \right|_{Q^2 \to 0}$$

Nature Com. 12, 1759 (2021)

Electromagnetic Form Factors (EMFFs)



- $eB \to eB$ scattering
- Stable baryon beam
- Momentum transfer $\boldsymbol{q^2 = -Q^2 < 0}$
- $\boldsymbol{Q^2 \to 0}$ (0.00021 GeV^2)

- $e^+e^- \to B\bar{B}$ or $B\bar{B} \to e^+e^-$
- Baryons produced paired
- Momentum transfer $\boldsymbol{q^2 > 0}$
- $\boldsymbol{q^2 \geq M^2_{B\bar{B}}}$ for current running experiment

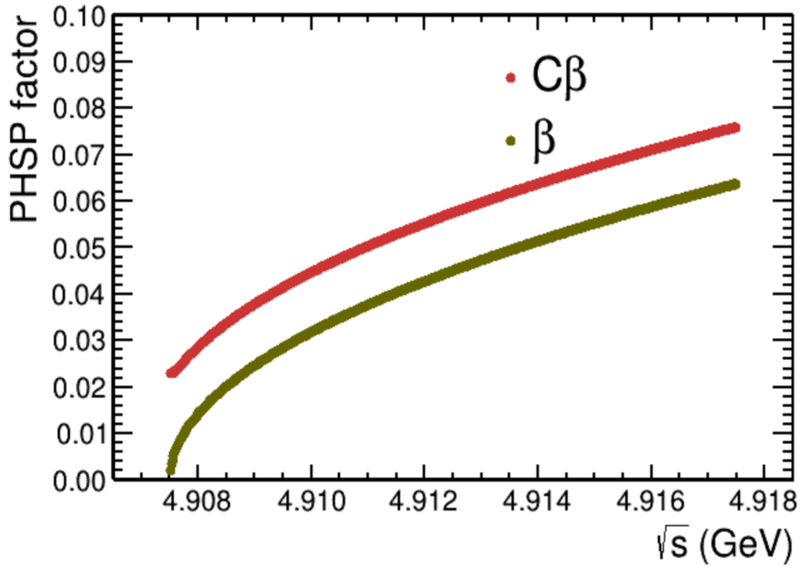
- Dispersion theoretical analysis provides a coherent framework for the joint interpretation of SL and TL EMFFs over the entire physical range of q^2.

Time-like EMFFs: theoretic review

- Spin-$\frac{1}{2}$ baryons: two Form Factors (G_E and G_M)
- Assuming one γ exchange, $e^+e^- \to B\bar{B}$:

$$\frac{d\sigma_{B\bar{B}}}{d\cos\theta} = \frac{\pi\alpha^2 \boldsymbol{C}\beta}{2q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta\right]$$

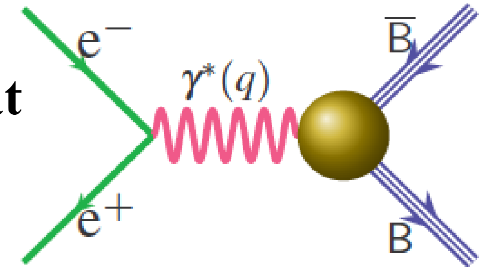
  - For charged baryon: $C = \frac{\pi\alpha}{\beta}\frac{1}{1-\exp(-\frac{\pi\alpha}{\beta})}$
  - For neutral baryon: C=1



- Or write in partial waves: $\sigma = 2\pi\alpha^2\beta\frac{4M^2}{(q^2)^2}[C|G_S(4M^2)|^2 + 2|G_D(q^2)^2|]$
- $G_S = \frac{2G_M\sqrt{\frac{q^2}{4M^2}}+G_E}{3}$ $\quad G_D = \frac{G_M\sqrt{\frac{q^2}{4M^2}}-G_E}{3}$
- **At threshold, S-wave only** $\Rightarrow$ $G_D(4M^2)=0$ $\Rightarrow$ $G_E(4M^2)=G_M(4M^2)$ $\Rightarrow$ $\frac{|G_E|}{|G_M|} = 1$

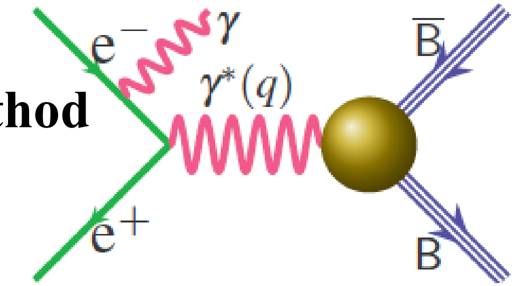
Time-like EMFFs: experiment review

- **Energy scan method at discrete c.m. energies**



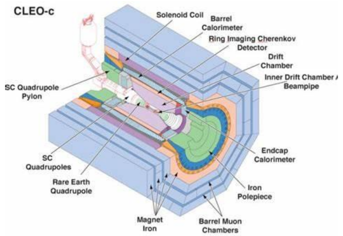
  - Well-defined c.m.energy, low background
  - Very good energy resolution
  - Discrete values, leaving gaps without information

- **Initial state radiation method at a fixed c.m. energy**

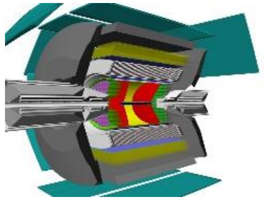


  - At a fixed c.m.energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
  - Systematic uncertainty in a coherent way
  - Large luminosity needed
  - Higher background

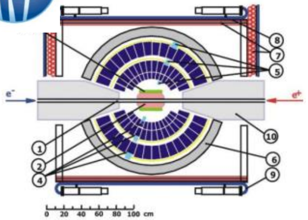
CLEO-c



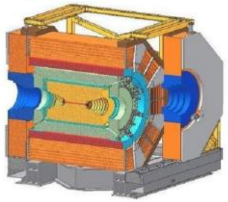
CMD-3



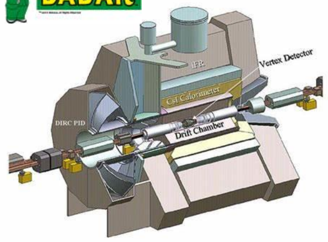
SND



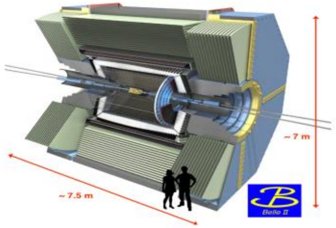
BESIII



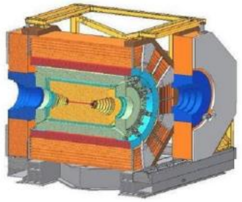
BABAR



BELLE

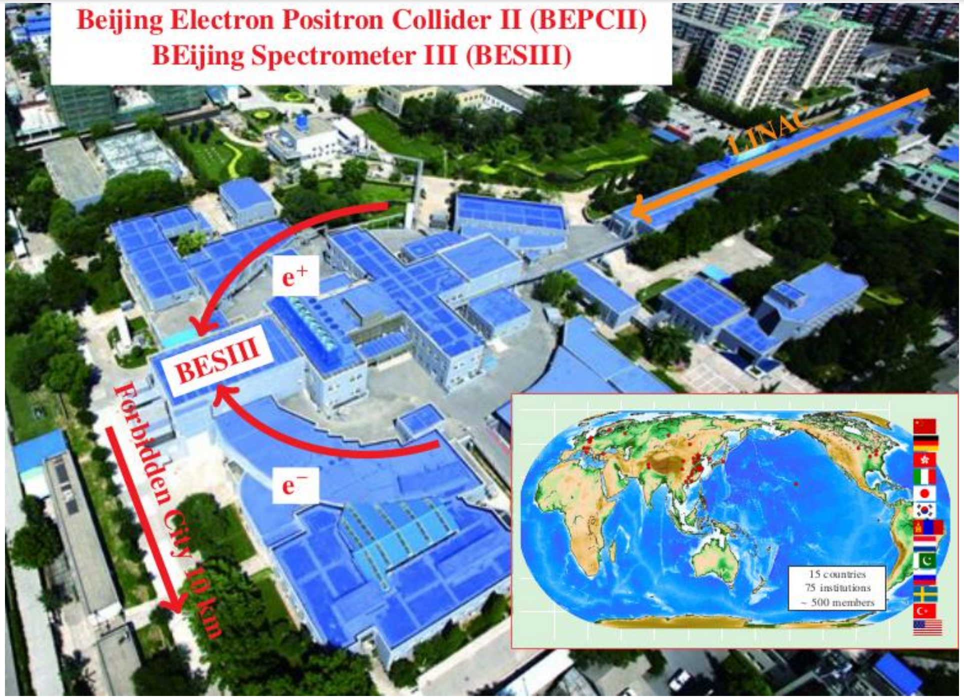


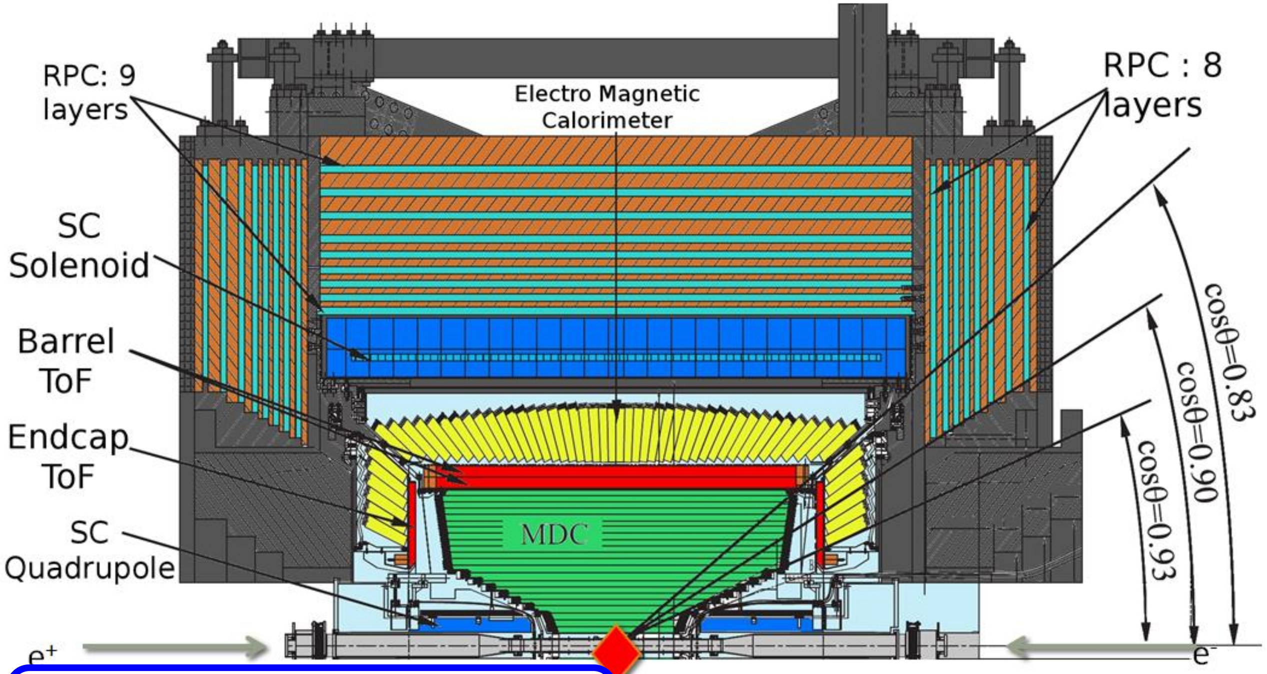
BESIII



Both techniques can be used at BESIII.

BEPCII and BESIII





- Located at the BEPCII collider (Beijing/China)
- Symmetric beams (2-5 GeV C.M. Energy)
- Maximum Luminosity: 1 nb^{-1}/s
- 93% coverage of the solid angle
- Installed inner track detector CGEM, will run at 5.6 GeV in a few years

Superconducting solenoid:
- **1T magnetic field**

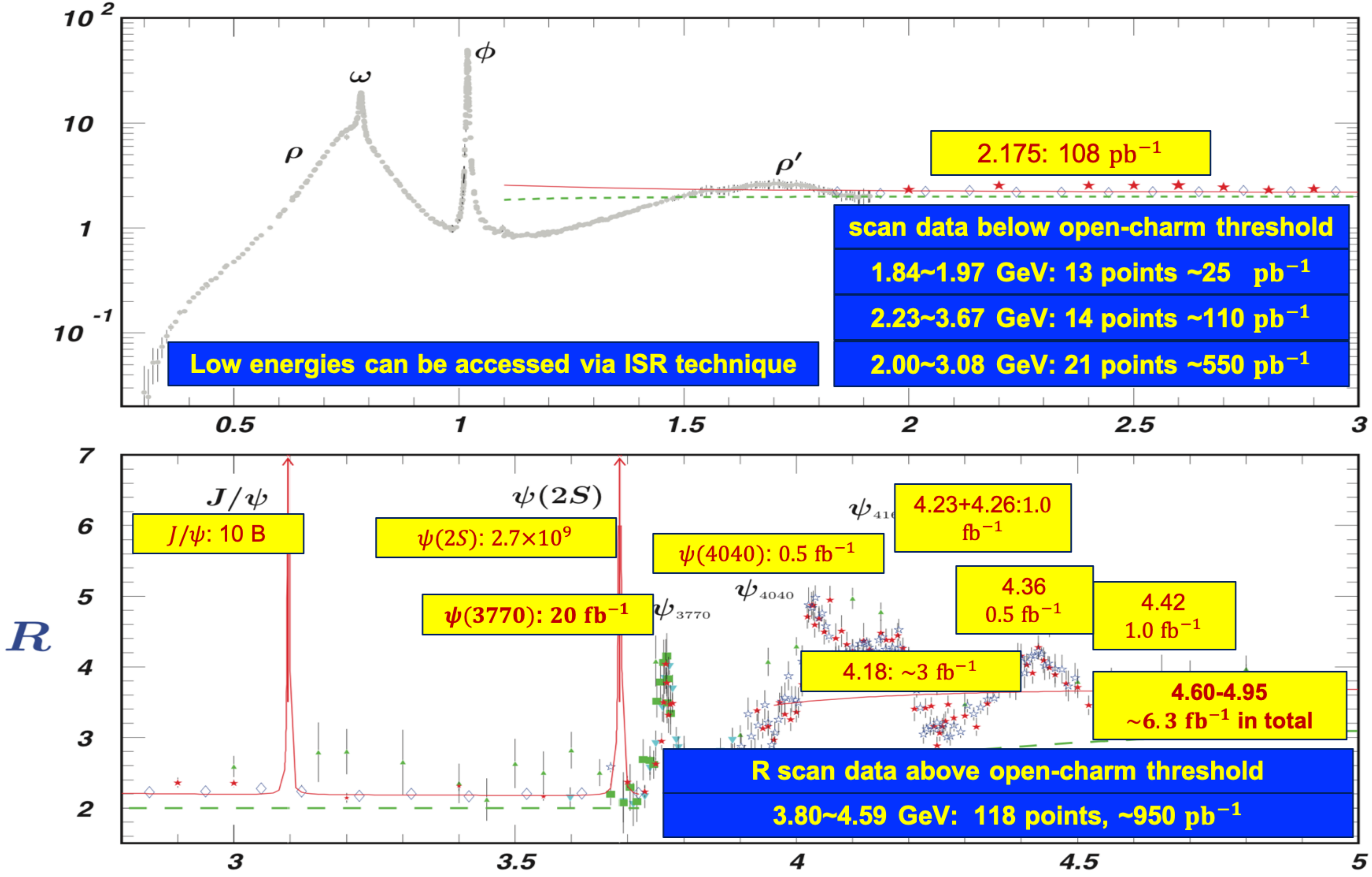
Time-of-Flight System:
- **90-110 ps resolution**

Drift chamber:
- **0.5% momentum resolution**
- **6% dE/dx resolution**

Muon Chambers:
- **8-9 layers of RPCs**
- **1.4-1.7 cm resolution**

Electromagnetic Calorimeter:
- **6240 CsI(Tl) crystals**
- **2.5% energy resolution**
- **0.5-0.7 cm spatial resolution**

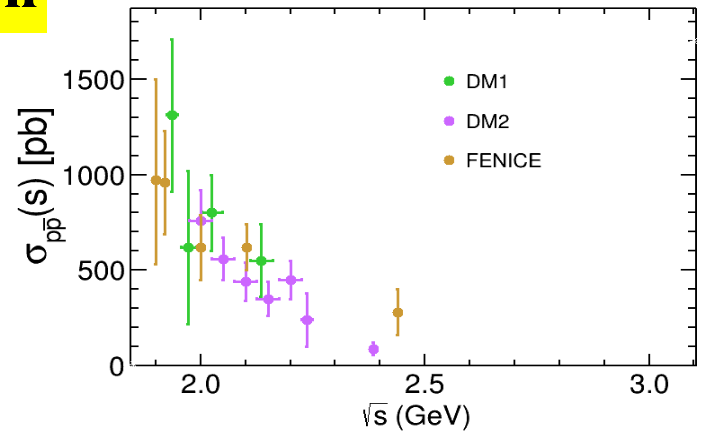
Data collected at BESIII



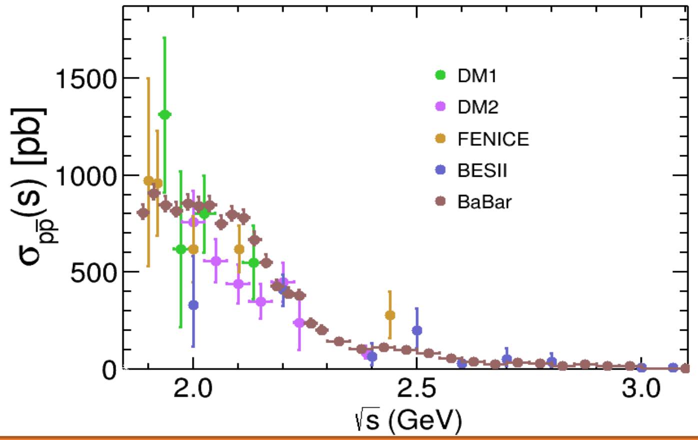
Timeline of Proton EMFFs

Cross section

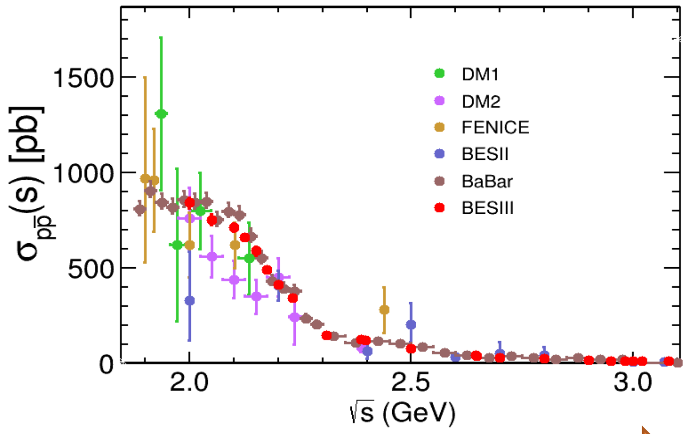
200 signal events in total, limited narrow energy region



BaBar observed threshold effect via ISR

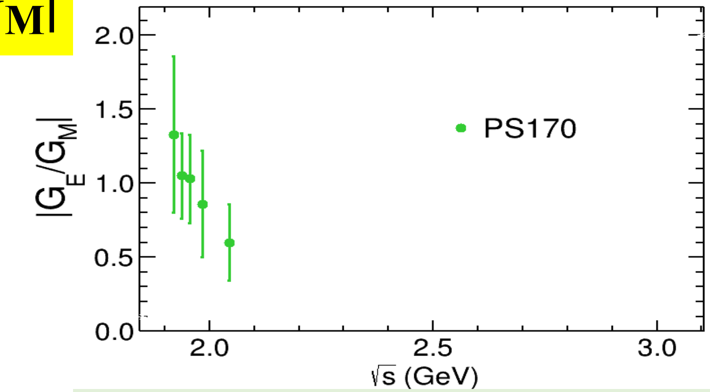


BESIII obtained best precision via energy scan

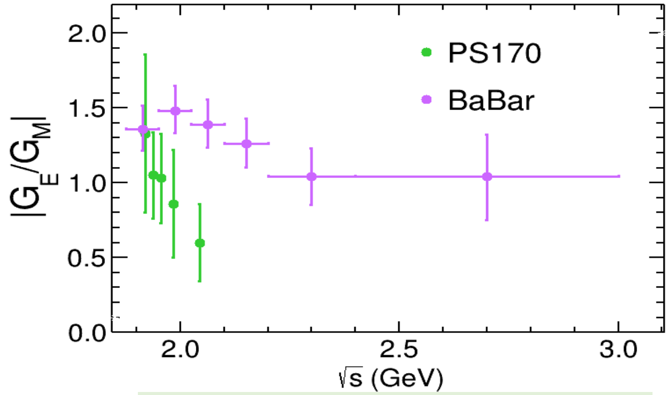


Before 2000 | **2005 to 2015** | **2020** | **Year**

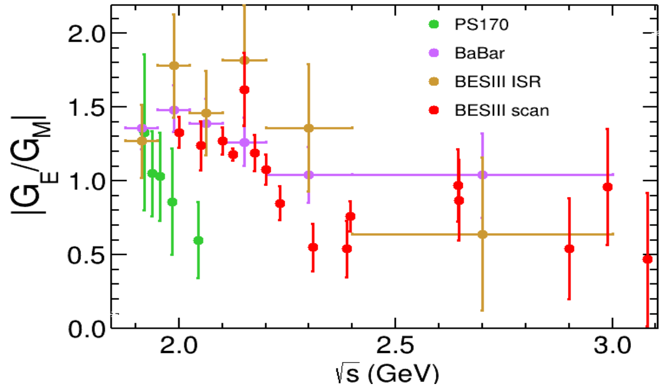
$|G_E/G_M|$



PS170 observed $|G_E/G_M|$ ratio for the first time at LEAR



Result from BaBar is inconsistent with PS170

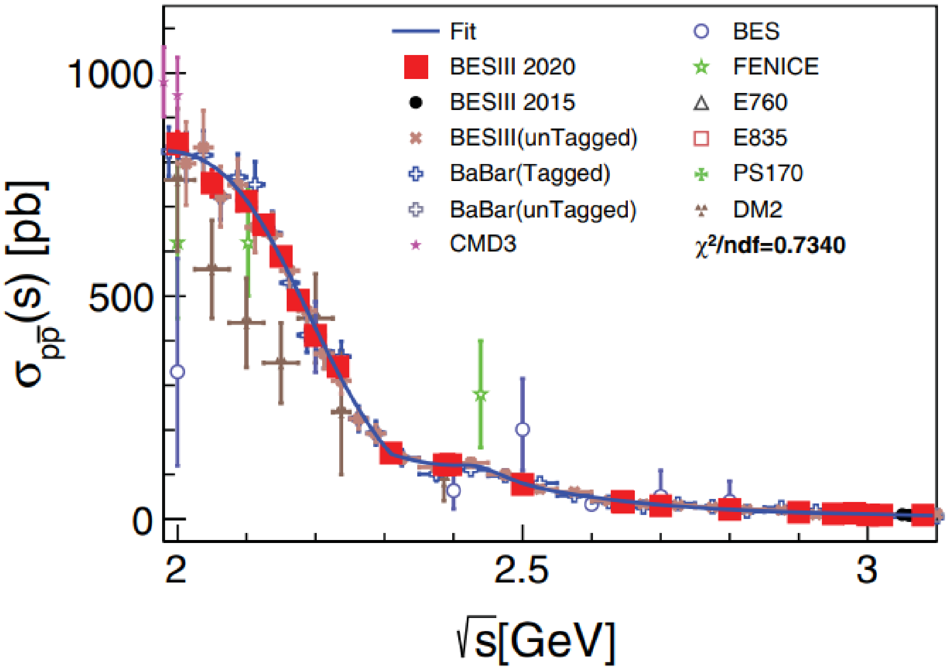


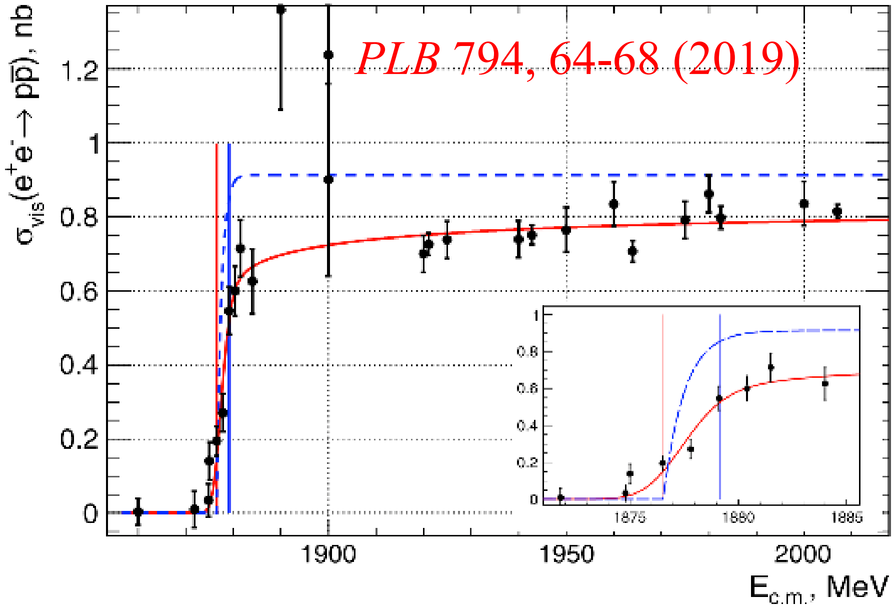
BESIII observed oscillation in the $|G_E/G_M|$ lineshape

Recent results of proton EMFFs

- Data and method:
  - Scan technique from 2.0 to 3.08 GeV, using 688.5 pb^{-1} integrated luminosity.
  - ISR method at 3.773 GeV with detected photon and undetected using 7.5 fb^{-1} integrated luminosity
- Cross section of $e^+e^- \to p\bar{p}$ near threshold shows very sharp step-like behavior
- The plateau indicates anomaly **threshold effect** in the production cross section

BESIII





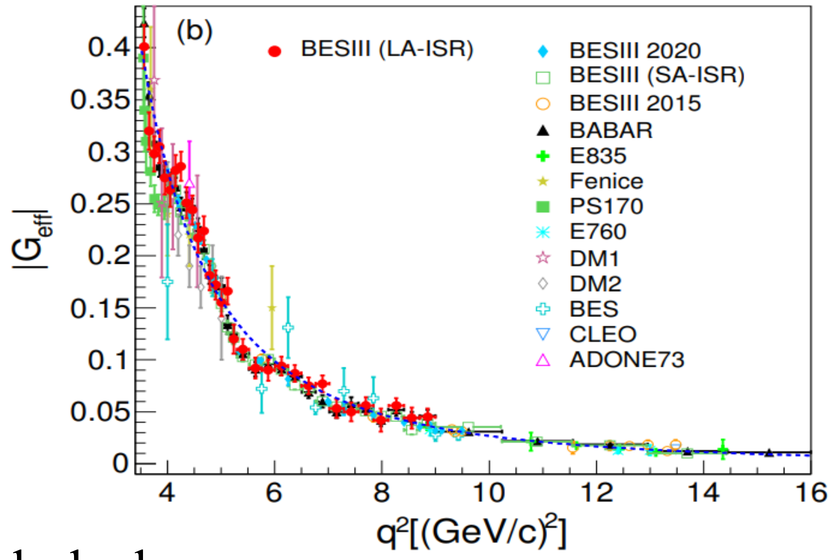
CMD-3

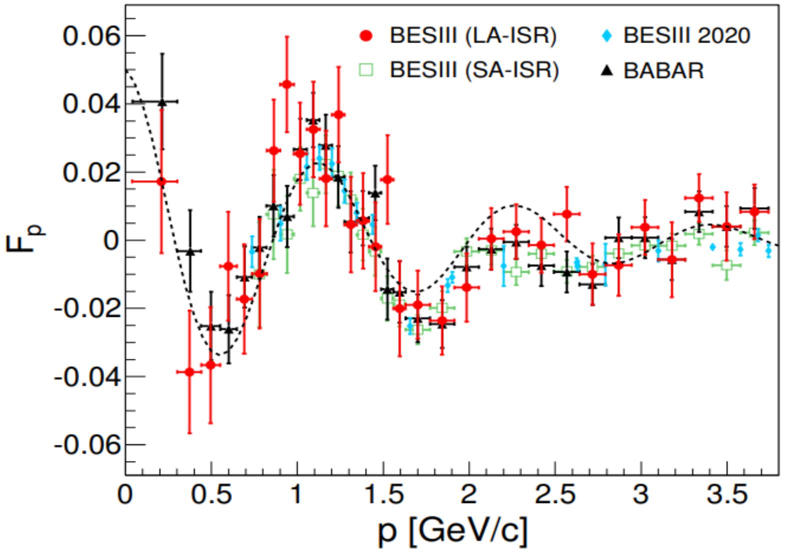
$$\sigma_{\text{Born}}(E_{\text{c.m.}}) = A + B\left[1 - \exp\left(-\frac{(E_{\text{c.m.}} - E_{\text{thr}})}{\sigma_{\text{thr}}}\right)\right]$$

Recent results of proton EMFFs

- ➢$|G_E/G_M|$, $|G_M|$ are determined with **high accuracy**, comparable to data in SL.
- ➢**Damped oscillation** distribution after subtracting the modified dipole.

PLB 817, 136328 (2021)





Blue dashed:

$$|G_{\mathrm{eff}}| = \frac{\mathcal{A}}{(1+q^2/m_a^2)[1-q^2/q_0^2]^2},\ q_0^2 = 0.71\ (\mathrm{GeV}/c)^2$$

Black dashed:

$$F_p = A^{\mathrm{osc}} \exp(-B^{\mathrm{osc}} p) \cos(C^{\mathrm{osc}} p + D^{\mathrm{osc}})$$

Time-like EMFFs: theoretic review

- Various theoretical models describe TLFF in non-perturbative region: ChEFT, VMD, Relativistic CQM, parton model, pQCD etc.

Parametrization of EMFF

pQCD predicts the scaling behavior at $q^2 \to \infty$, based on simple constituent counting rules and helicity conservation: $F_1 \propto q^{-4}, F_2 \propto q^{-6}$

→

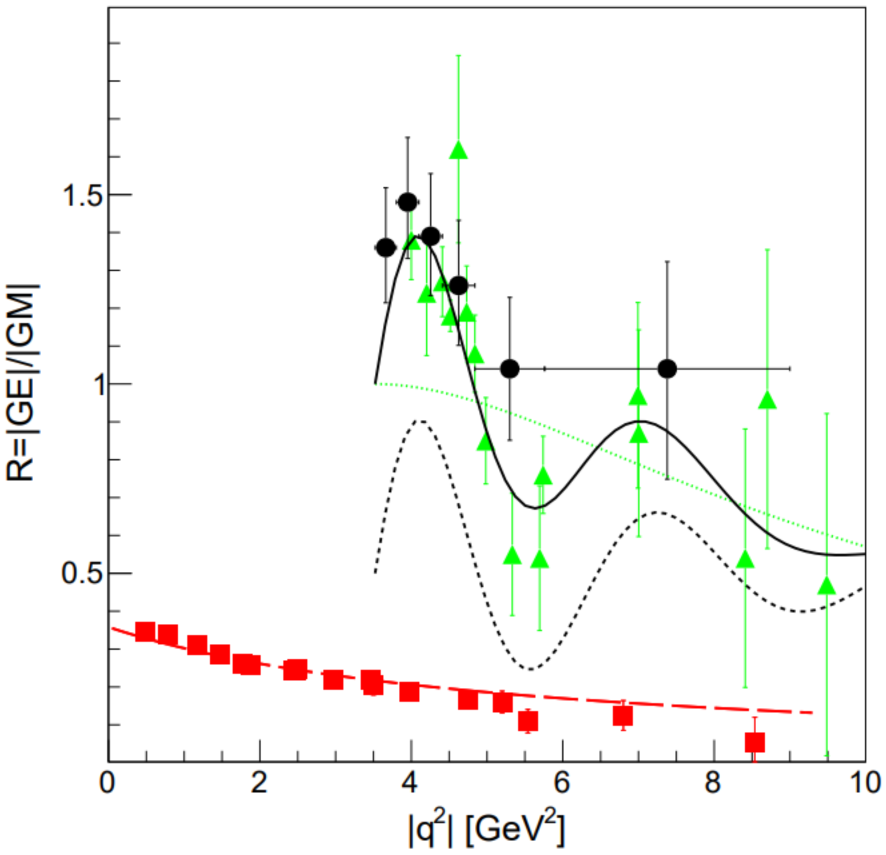
Modified scaling expression in nonperturbative region: $\frac{q^2 F_2}{F_1} \propto \ln(\frac{q^2}{\Lambda^2})$, with $\Lambda \approx$ 0.3 GeV

→

VMD model described the effect of meson cloud
$|G_{\text{eff}}| = \frac{\mathcal{A}}{q^4[\ln^2(\frac{q^2}{\Lambda^2})+\pi^2]}$ or
$|G_{\text{eff}}| = \frac{\mathcal{A}}{\left(1+\frac{q^2}{m_a^2}\right)[1-q^2/q_0^2]^2}$

- Dispersion theoretical analysis, provide a coherent framework for the joint interpretation of SL and TL EMFFs over the entire physical range of q^2.

Analyticity of proton EMFFs



E. Tomasi-Gustafsson et al., PRC 103, 035203 (2021)

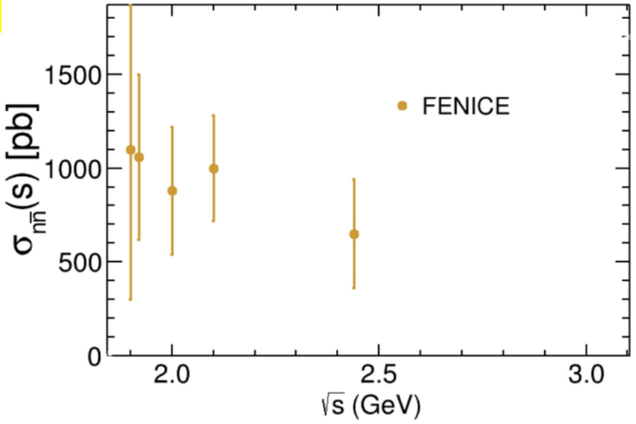
- SL data shows a monotone decrease from $q^2 = 0$
- TL data decreases from 1 at threshold $q^2 = 4m_p^2$
- $\mathrm{G_E}(q^2)$ decreases faster than $G_M(q^2)$, both for SL and TL, is expected as a consequence of the presence of an inner volume inside the nucleon that is electrically neutral.
- Another damped oscillation feature observed in $|\mathrm{G_E}/\mathrm{G_M}|$

$$F_R(\omega(s)) = \frac{1}{1+\omega^2/r_0}\left[1 + r_1 e^{-r_2\omega}\sin(r_3\omega)\right], \ \omega = \sqrt{s} - 2m_p$$

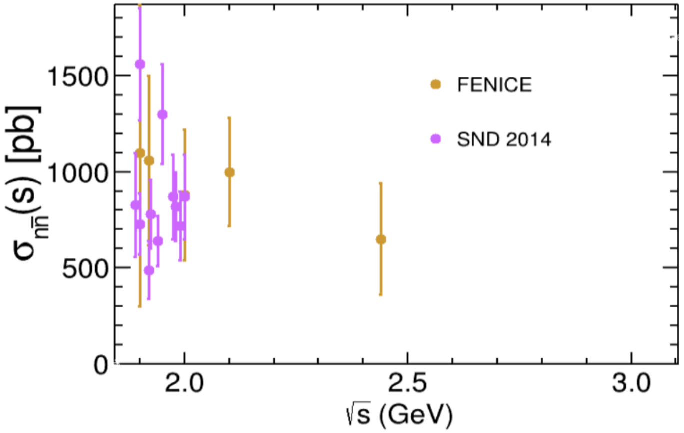
Timeline of Neutron EMFFs

Cross section

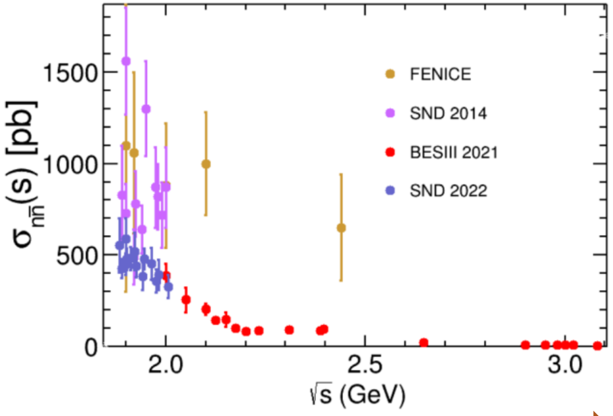
First result from FENICE, large cross section



SND scan near threshold, plateau observed



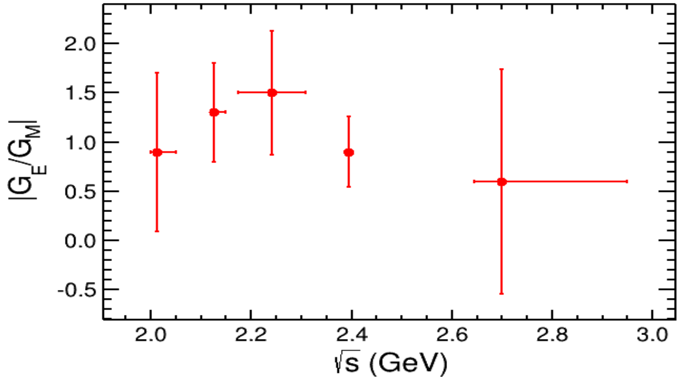
BESIII and SND obtained more precision



Before 2000 **2005 to 2015** **2020** **Year**

$|G_E/G_M|$

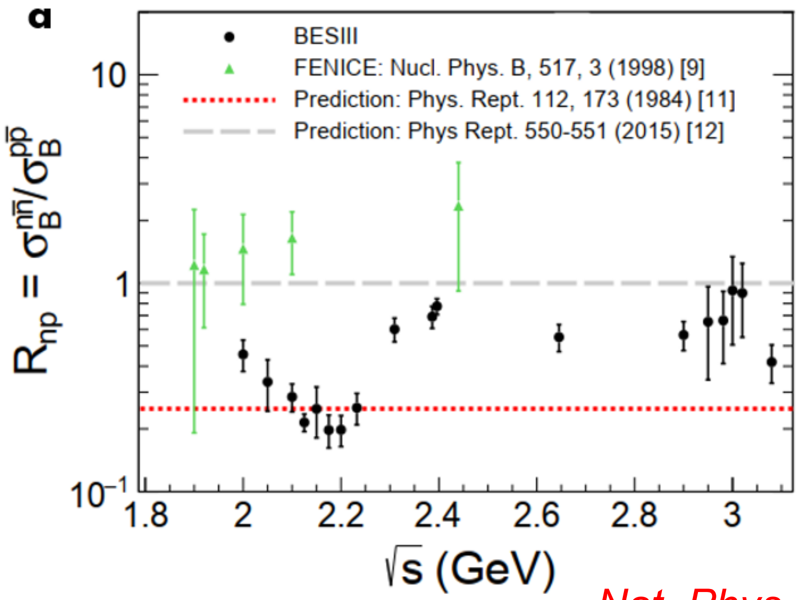
No experimental result

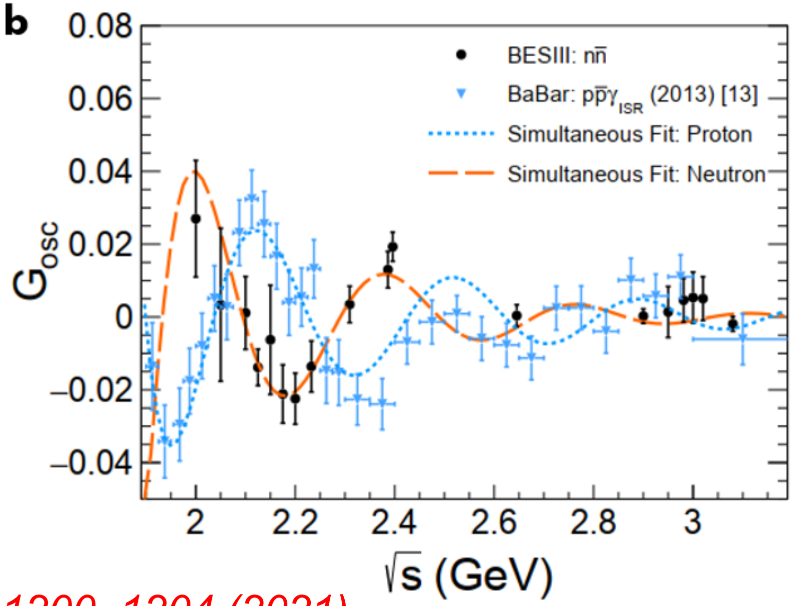


BESIII measured $|G_E/G_M|$ for the first time

Recent results of neutron EMFFs

- $e^+e^- \to n\bar{n}$ from 2.0-3.08 GeV, 647.9 pb^{-1}.
- $\gamma - p$ coupling larger than $\gamma - n$ coupling => consistent with theoretical predictions: VMD, Skyrme etc.
- Oscillation of reduced-|G| observed in neutron with a phase orthogonal to that of proton.

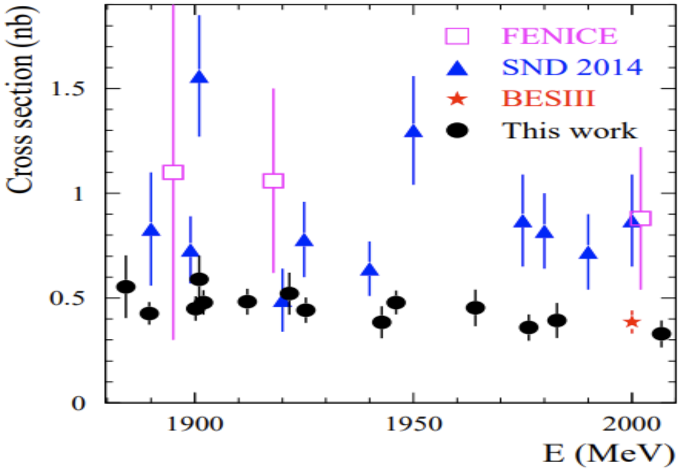


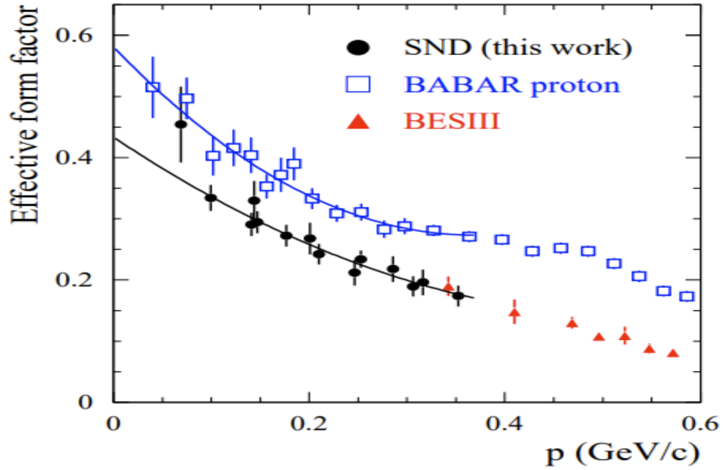


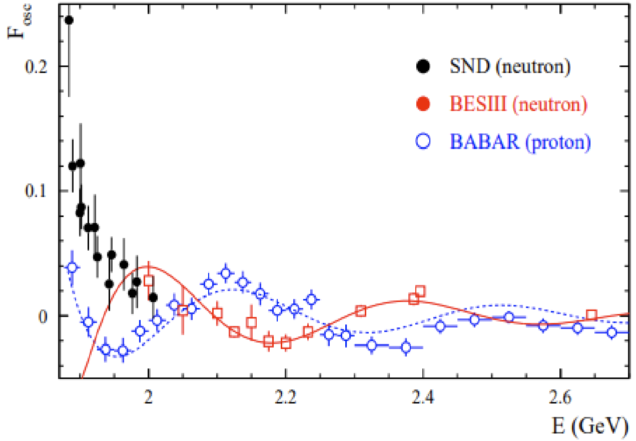
Nat. Phys. 17, 1200–1204 (2021)

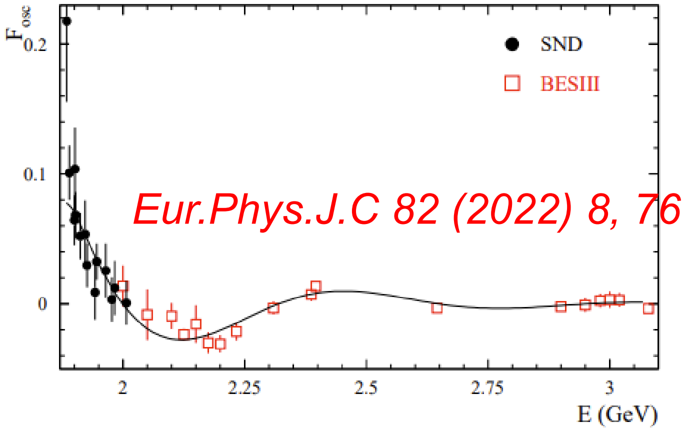
Recent results of neutron EMFFs

- $e^+e^- \to n\bar{n}$ from 1.884 to 2.007 GeV, ~30 pb^{-1}
- $\sigma \approx 0.4$ nb below 2 GeV. Possible threshold effect
- Reduced-|G| contracts the common proton /neutron oscillation frequency





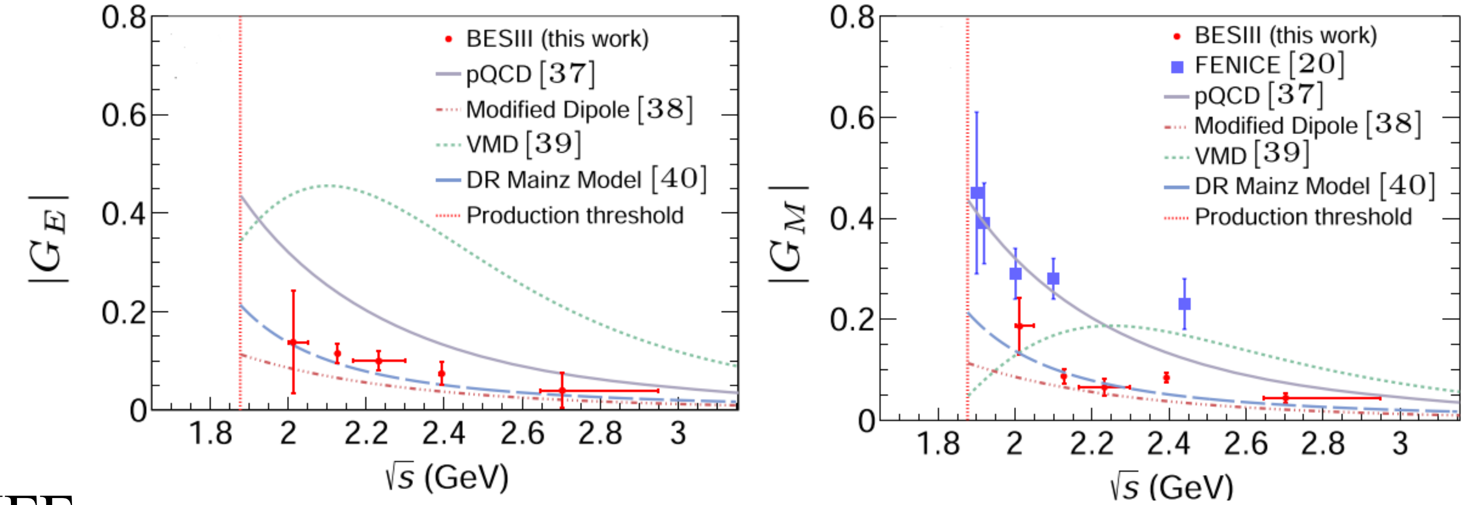




Eur.Phys.J.C 82 (2022) 8, 761

Recent results of neutron EMFFs

- Compared with the FENICE results, the values for $|G_M|$ from this work are smaller by a factor of 2-3.
- Compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR).
- DR model gives good consistency.

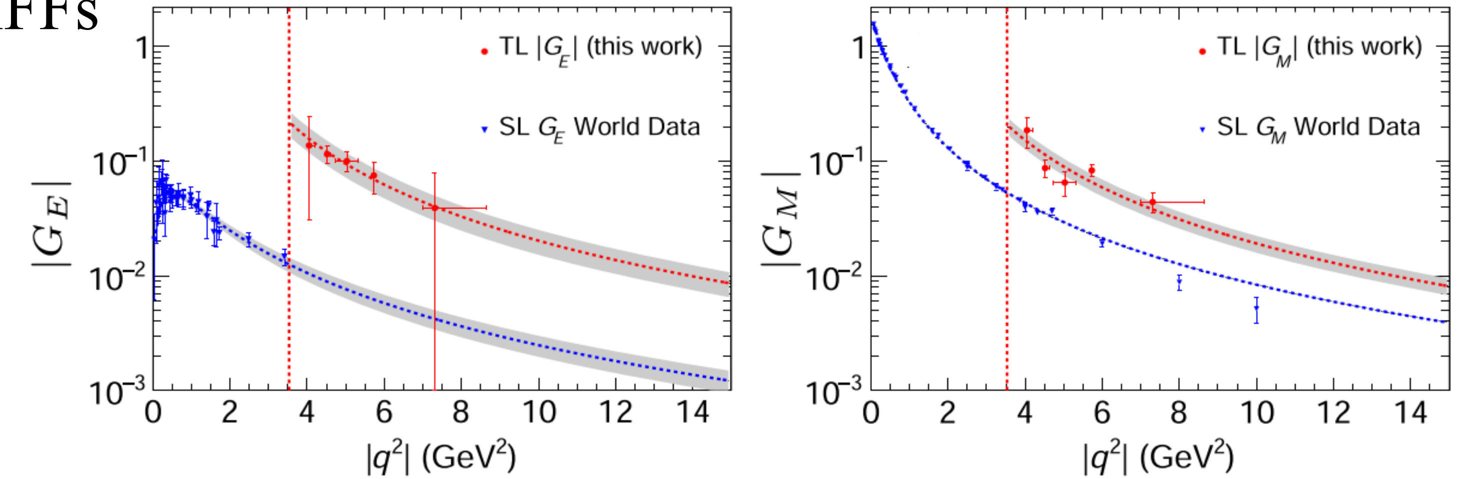


- The analyticity of neutron EMFFs between SL and TL:

$$\mathcal{R}^{E,M} \equiv |G^{TL}_{E,M}(q^2)/G^{SL}_{E,M}(-q^2)| \overset{|q^2|\to\infty}{\longrightarrow} 1$$

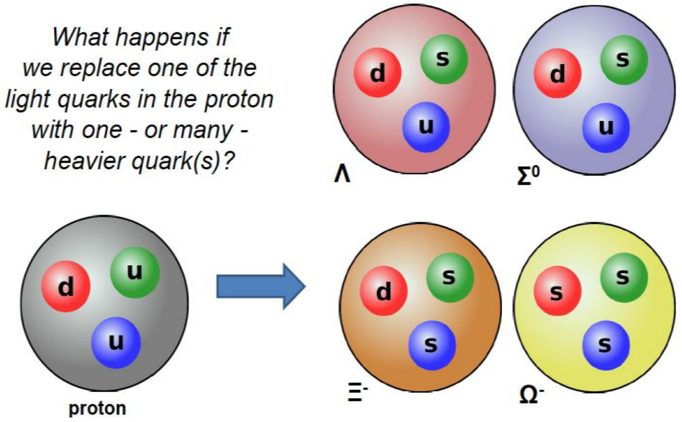
$$\mathcal{R}^{E} = 5.18 \pm 1.18$$

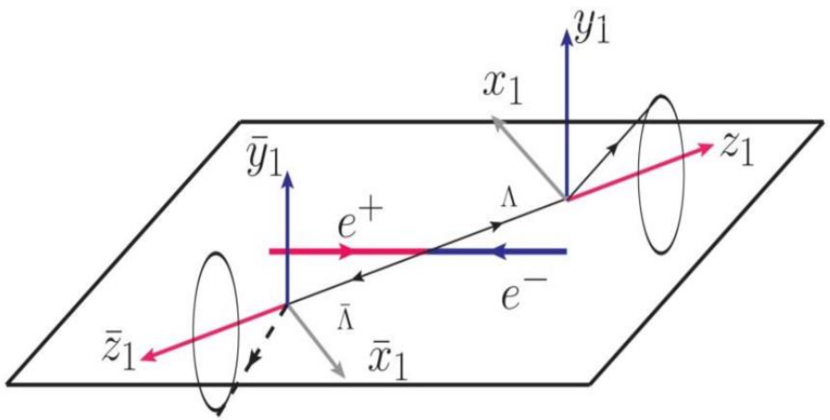
$$\mathcal{R}^{M} = 1.72 \pm 0.14$$



PRL 130, 151905 (2023)

Hyperon form factors





- **Complex form** of TL EMFFs:

  $$G_E = |G_E|e^{i\Phi_E},\ G_M = |G_M|e^{i\Phi_M}$$

  Relative phase: $\Delta\Phi = \Phi_E\text{-}\Phi_M$
- Analyticity requires $\lim_{s\to\infty}\Delta\Phi = 0$, since SL and TL EMFFs should converge to the same value
- $\Delta\Phi \neq 0$ when $s > 0$ results in the **polarization** effect of the hyperons: $\boldsymbol{P_y \propto \sin\Delta\Phi}$
- **Angular** distribution of daughter baryon from Hyperon weak decay is
  - $\boldsymbol{\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda P_y \cdot \hat{q}}$
  - α_Λ: asymmetry parameter (P-violation)

ΔΦ and the polarization of hyperon can be measured!

Timeline of hyperon EMFFs

Cross section

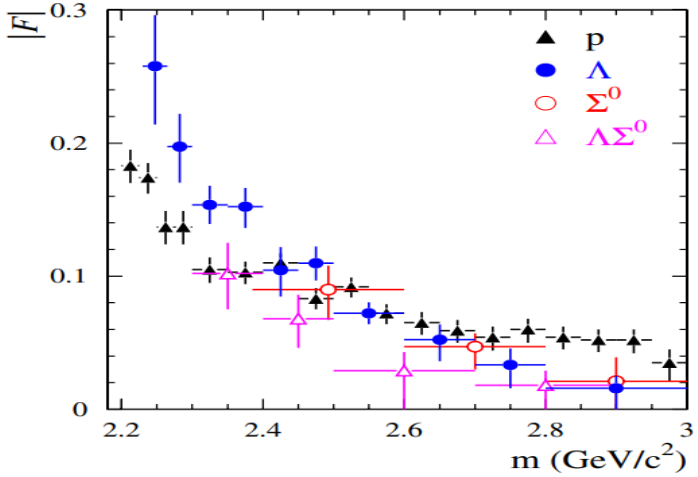
First hyperon result at 2.4 GeV from **DM2**

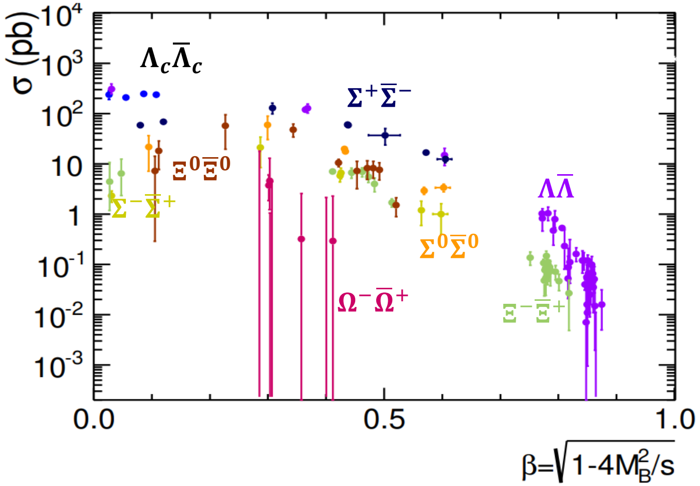
$\sigma(e^+e^- \to \Lambda\bar{\Lambda}) = 100^{+65}_{-35}$ pb

$\sigma(e^+e^- \to \Lambda\bar{\Sigma}^0 + c.c) < 75$ pb

$\sigma(e^+e^- \to \Sigma^0\bar{\Sigma}^0 + c.c) < 120$ pb

BaBar measured hyperon EMFFs via ISR





Before 2000 **2005 to 2015** **2020**

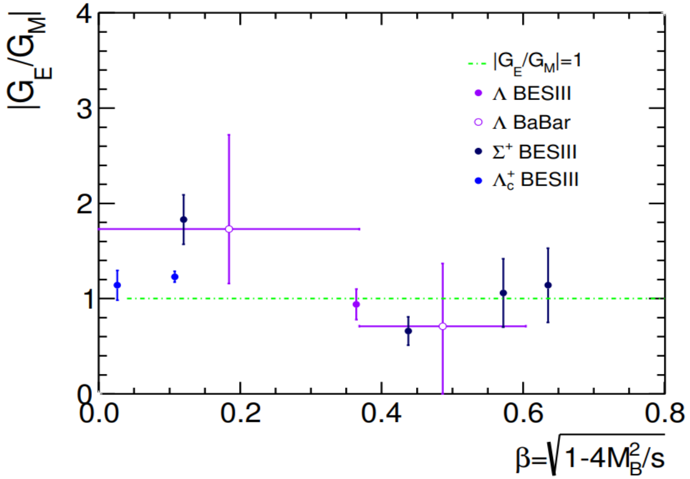
$|G_E/G_M|$

First $|G_E/G_M|$ and phase from **BaBar**

$\left|\frac{G_E}{G_M}\right| = 1.73^{+0.99}_{-0.57}$ for 2.23-2.40 GeV/c^2

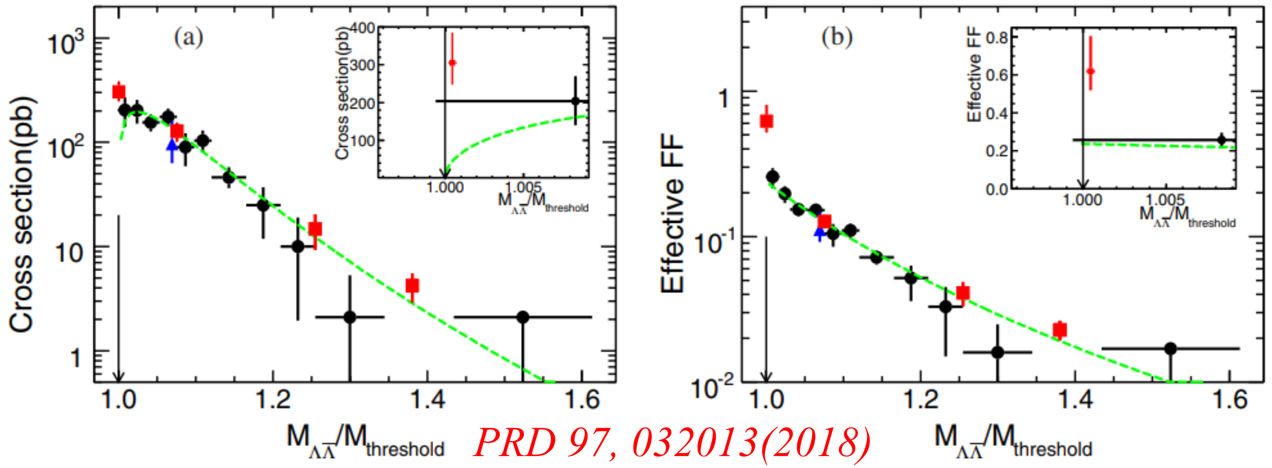
$\left|\frac{G_E}{G_M}\right| = 0.70^{+0.66}_{-0.71}$ for 2.40-2.80 GeV/c^2

$-0.76 < \sin\phi < 0.98$

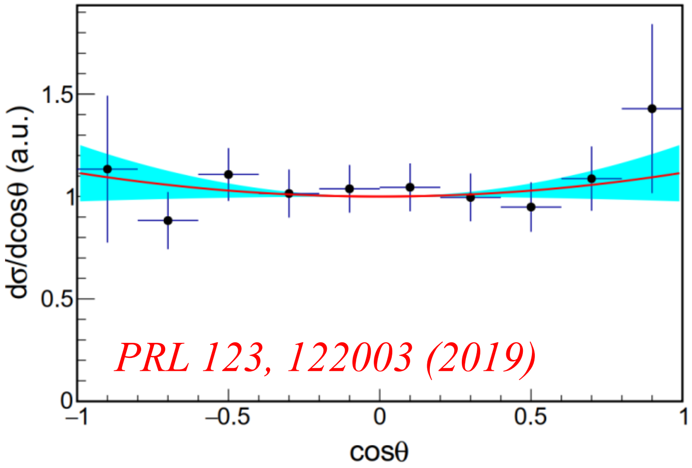


Complete measurement of $e^+e^- \to \Lambda\bar{\Lambda}$

scan method

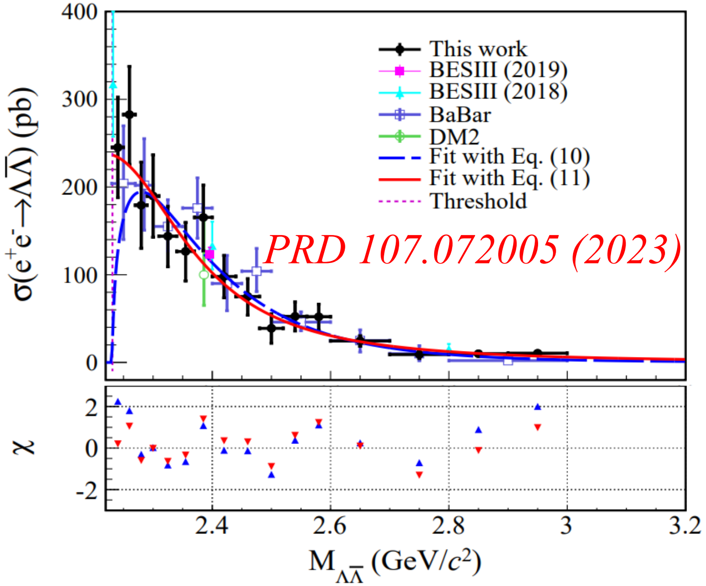


PRD 97, 032013(2018)



PRL 123, 122003 (2019)

ISR method

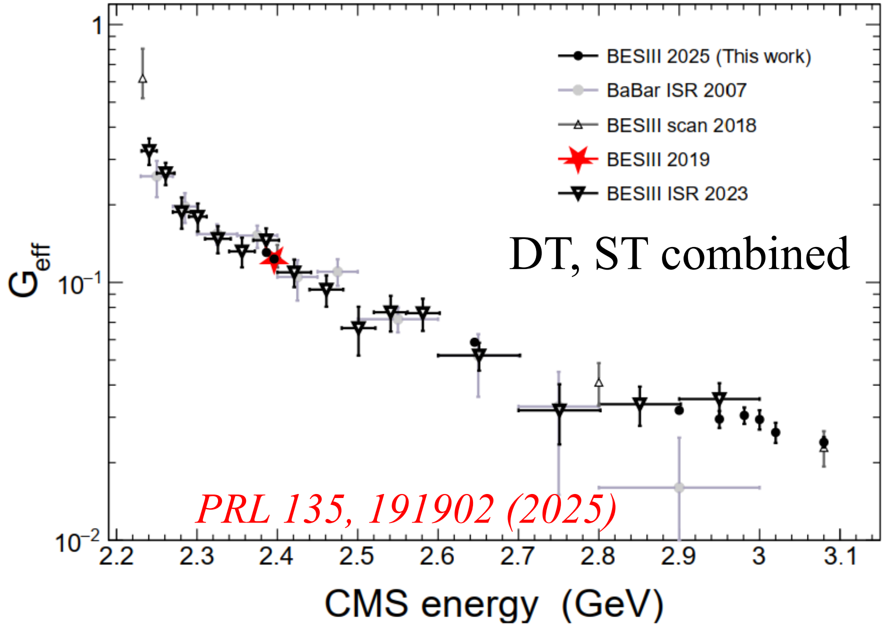


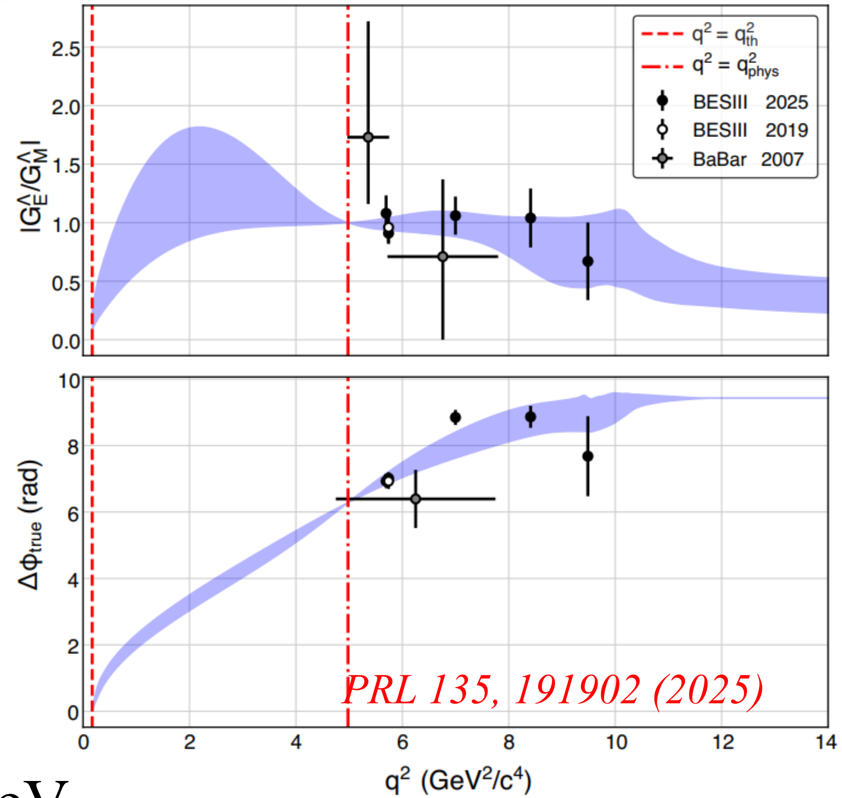
PRD 107.072005 (2023)

- ✓ The non-zero $\sigma^{Born} = (305 \pm 45^{+66}_{-36})$ pb at $\sqrt{s} =$ 2.2324 GeV (1 MeV above threshold) is observed.
- ✓ $\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14 \pm 0.02$ @ 2.396 GeV
- ✓ $\Delta\Phi = 37^\circ \pm 12^\circ \pm 6^\circ$ @ 2.396 GeV, measured for the first time, confirm the complex form of EMFFs.

Complete measurement of $e^+e^- \to \Lambda\bar{\Lambda}$

scan method





- $R = |G_E(q^2)/G_M(q^2)|$ remains constant, while $\Delta\Phi$ changes by more than 90° between 2.396 and 2.6544 GeV.

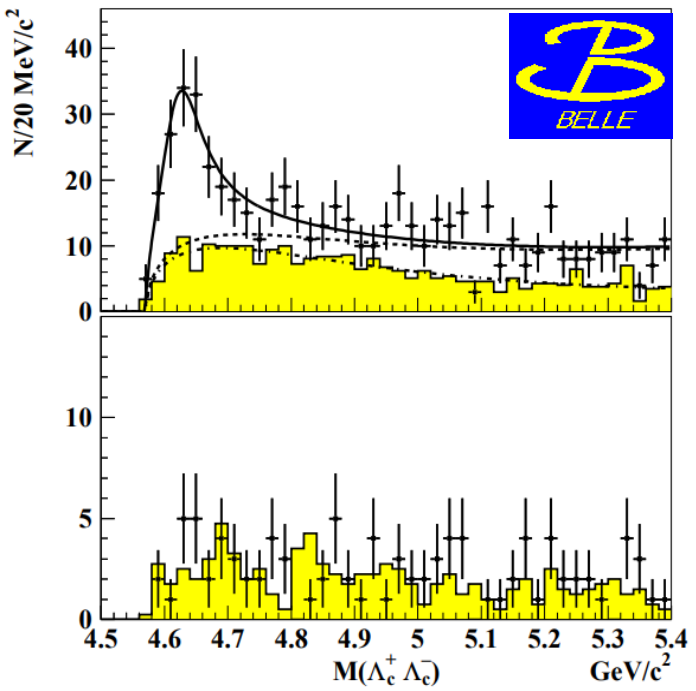
$$\boxed{\langle r_E \rangle^2 = 6\mu \left.\frac{dR(q^2)}{dq^2}\right|_{q^2=0} = -0.076 \pm 0.043 \text{ fm}}$$

$\Rightarrow$ an asymmetric charge distribution where the *ds* quark pair lies close to the center of the Λ hyperon.

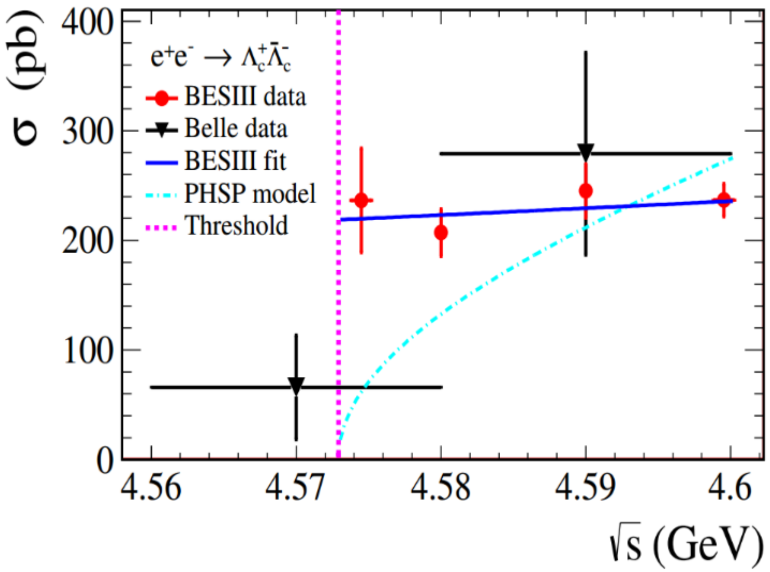
Complete measurement of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- The pronounced signal observed in $\Lambda_c^+\bar{\Lambda}_c^-$ at Belle ---- Y(4660) as charmed baryonium ?
- A plateau in $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$ ---- similar to $e^+e^- \to p\bar{p}$
- Similar oscillation in Λ_c^+ $|G_E/G_M|$ distribution as proton observed.

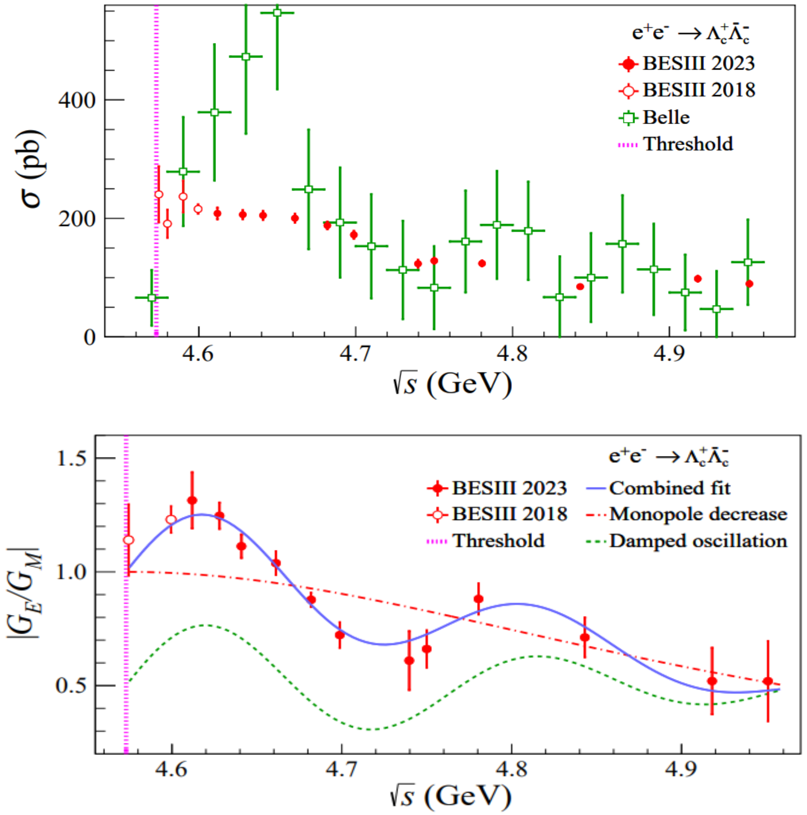
PRL 101, 172001 (2008)



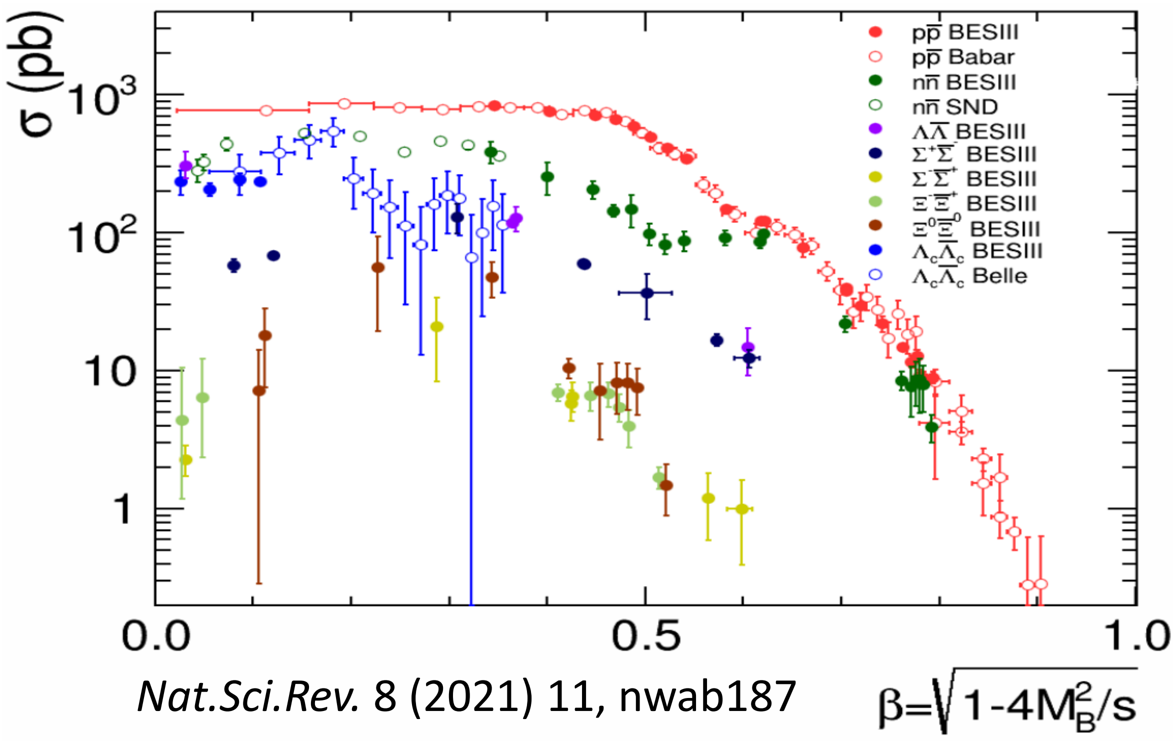
PRL 120, 132001 (2018)



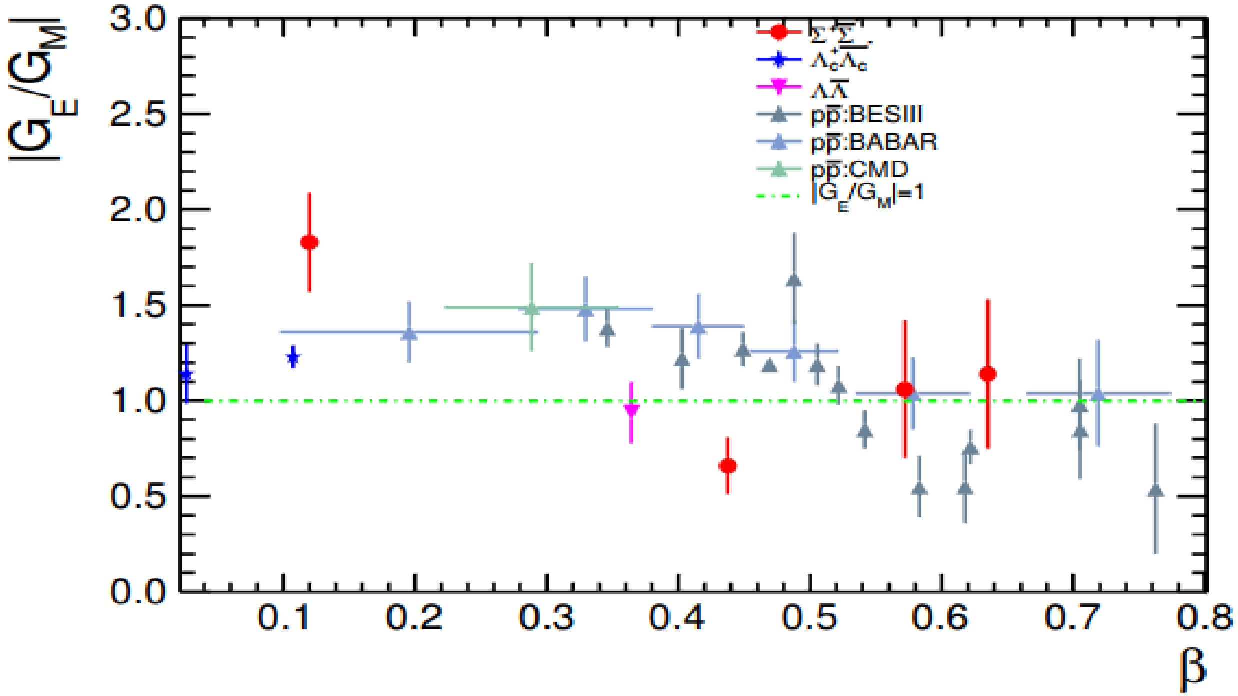
PRL 131,191901 (2023)



Results of EMFFs at BESIII



Nat.Sci.Rev. 8 (2021) 11, nwab187

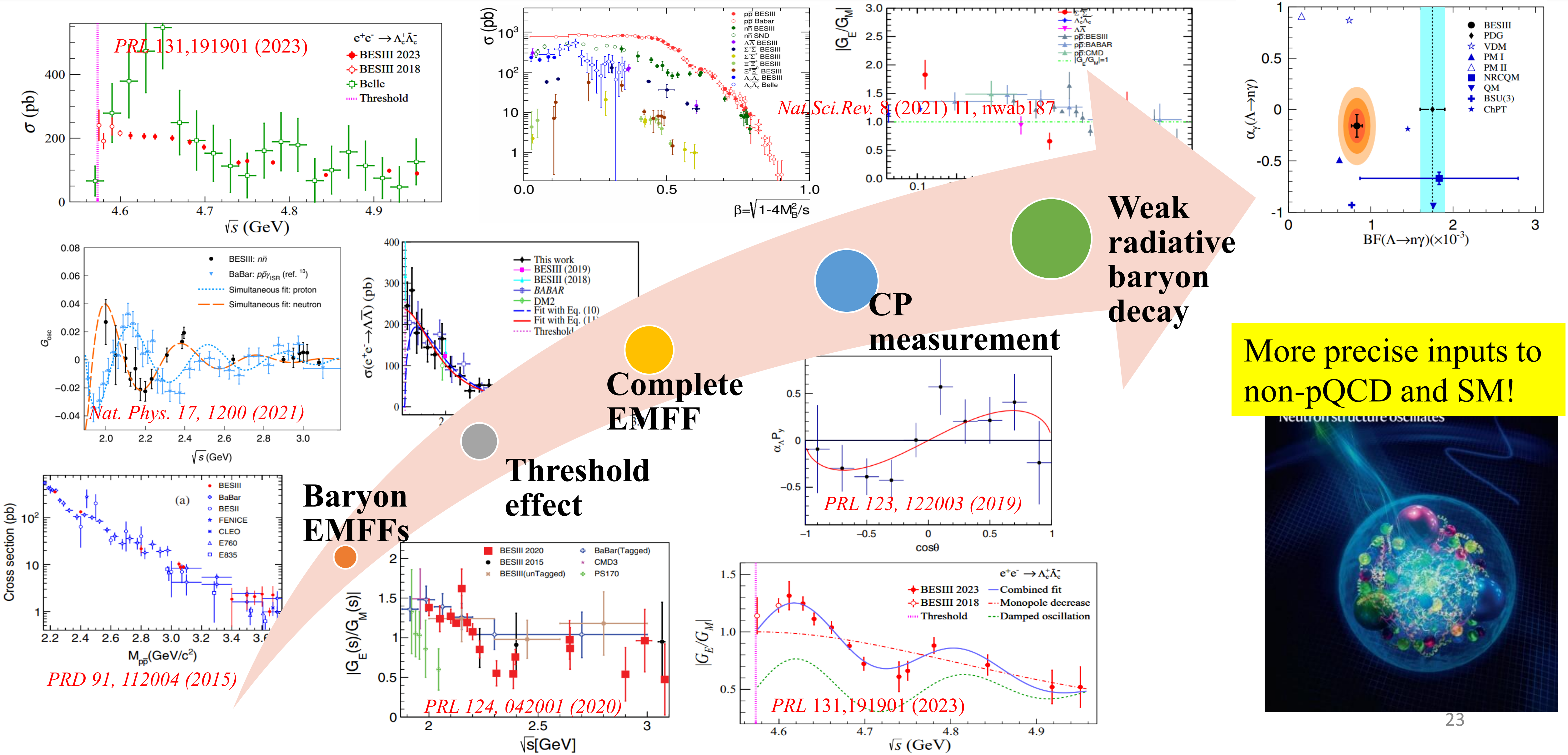


- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- Oscillation structures observed
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave near threshold
- Relative phase angle of form factor $\Delta\phi(\sin\Delta\phi)$ measured for Λ, Λ_c^+, etc

See more details in Souvik Maity's talk

Summary

More talks in the next days



More precise inputs to non-pQCD and SM!

Thanks for your attention!