Recent results of baryon EM form factors at BESIII

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(on behalf of BESIII collaboration)

第七届全国重味物理和量子色动力学研讨会

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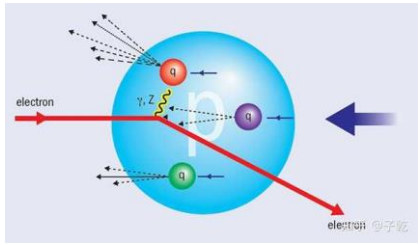
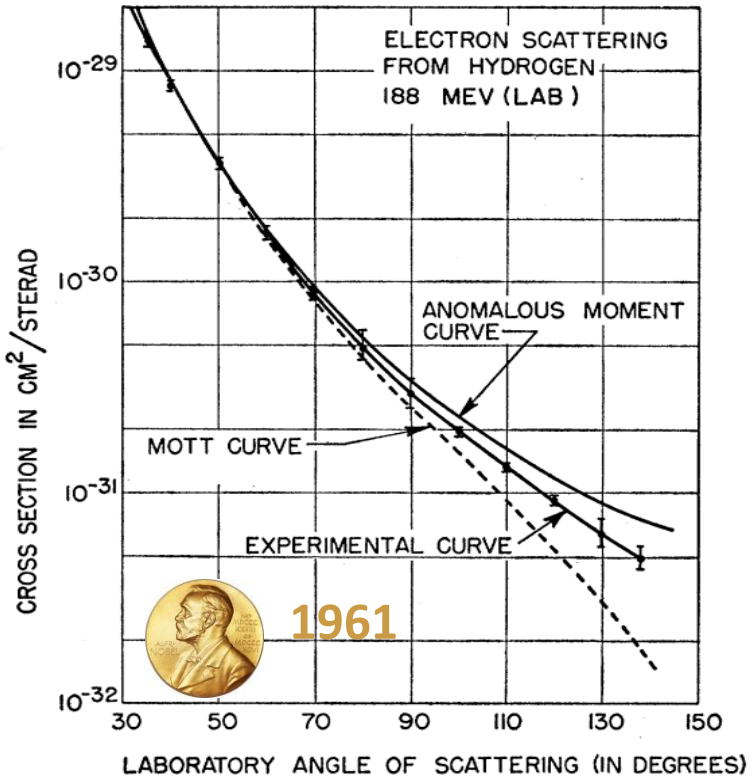
Nucleon structure

R. Hofstadter





- 非点状散射截面 = 点状散射截面*形状因子

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} F(Q^2)$$

→ 代表与点状粒子的偏离程度

- 形状因子与电荷密度构成傅里叶变换

$$F(q^2) = \int d^3r' e^{i\vec{q}\cdot\vec{r}'} \rho(\vec{r}')$$

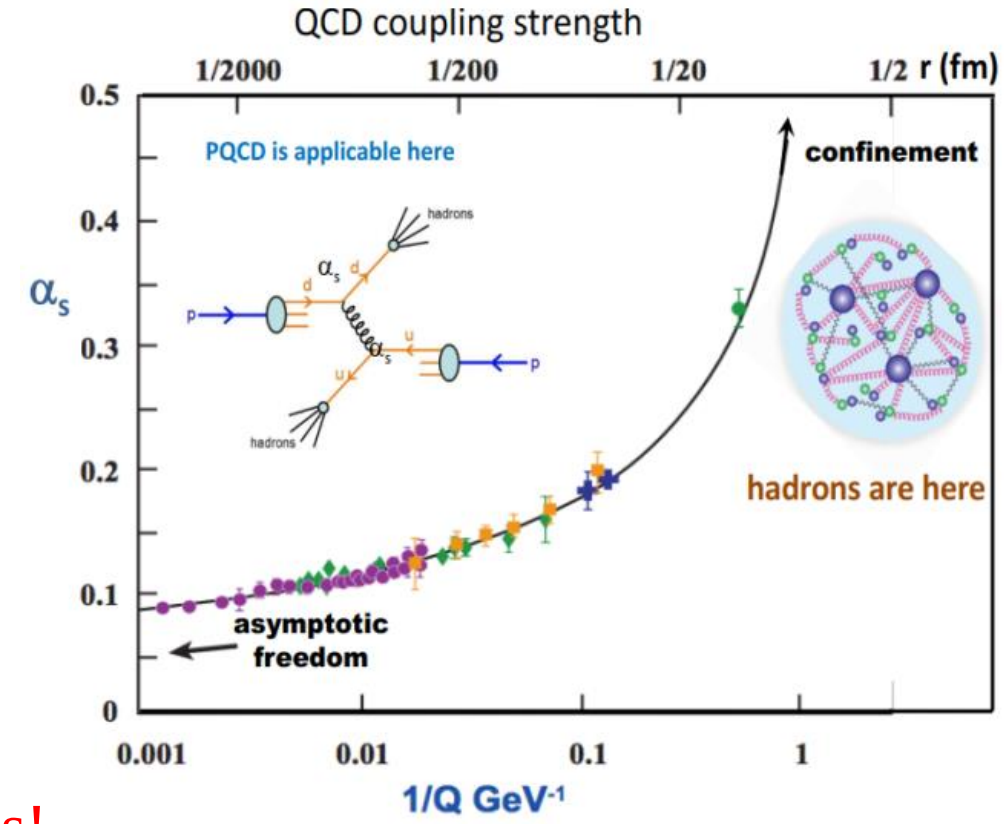
$$\rho(\vec{r}) = \int \frac{d^3q}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} F(q^2)$$

- 历史上首次测量质子半径

$$\sqrt{\langle r^2 \rangle} = (7.4 \pm 2.4) \times 10^{-14} \text{ cm}$$

Nucleon structure

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

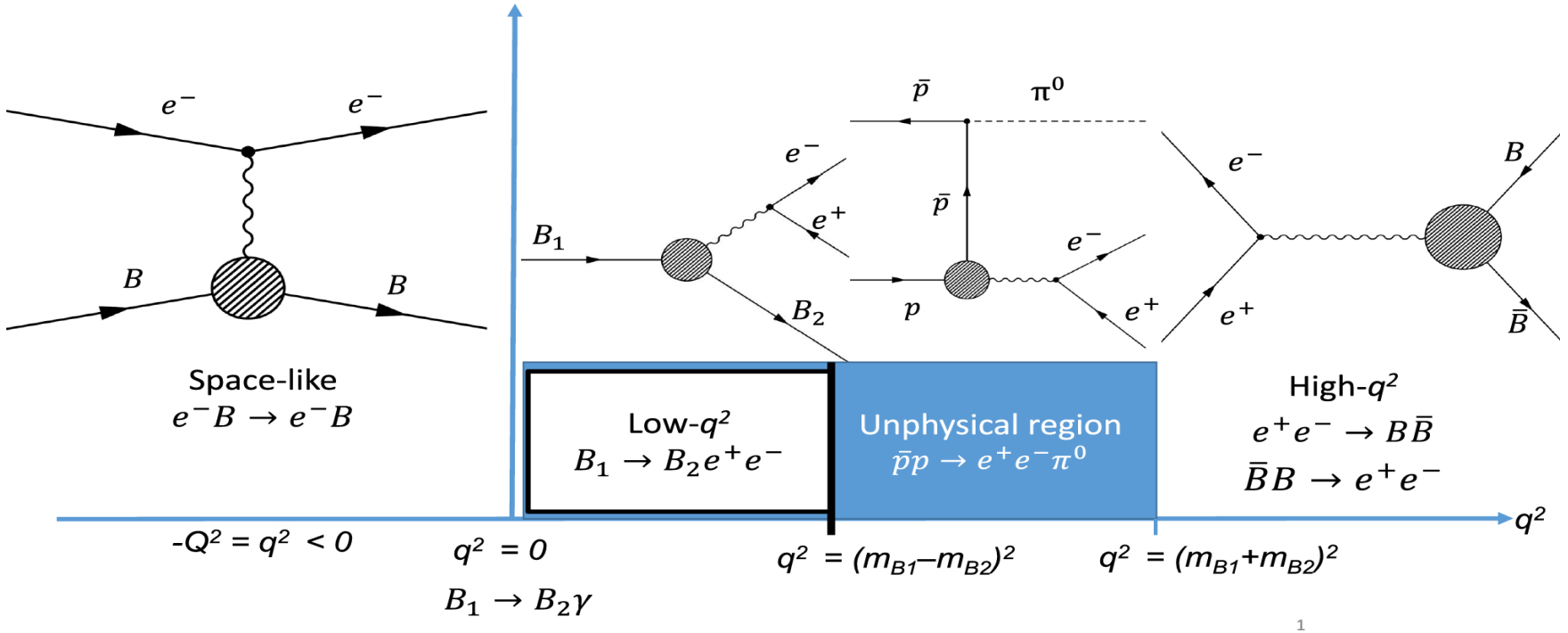


- Nucleons are composite objects with inner structure.
- At low Q, perturbative QCD not possible (expansion of coupling constant $\boldsymbol{\alpha_s}$)

⇒ Nucleon structure must be measured in experiments!

- The experimental FF is a powerful tool to test various theories in perturbative QCD.

Electromagnetic Form Factors (EMFFs)



- 电子-重子散射
- 需要稳定的重子束流
- 四动量转移$q^2 = -Q^2$为负
- Q^2能够无限接近0（0.00021 GeV^2)

- 正负电子湮没到重子对或逆过程
- 重子成对产生
- 四动量转移q^2为正
- q^2从阈值（$M_{B\bar{B}}$）开始

Time-like EMFFs: theoretic review

- Dispersion theoretical analysis, provide a coherent framework for the joint interpretation of SL and TL EMFFs over the entire physical range of q^2.
- Spin-$\frac{1}{2}$ baryons: two Form Factors (Electro and Magnetic, EMFFs)
- Assuming one photon exchange, the baryon 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 Form Factors: $G_E(q^2) = F_1(q^2) + \frac{\kappa q^2}{4m_p^2} F_2(q^2)$

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

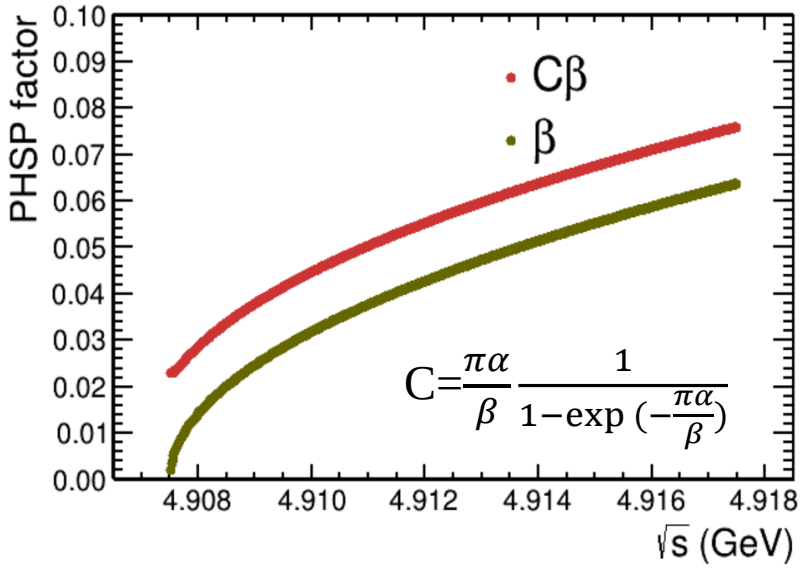
κ is the anomalous magnetic moment

Time-like EMFFs: theoretic review

- Interaction of final states, lead to a non-zero cross section for charged baryon at threshold (Andrei D Sakharov *Sov. Phys. Usp.* **34** 375(1991))

$$\frac{d\sigma_{B\bar{B}}}{d\cos\theta} = \frac{\pi\alpha^2 C\beta}{2q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}|G_E|^2\sin^2\theta\right], \tau = \frac{q^2}{4m_B^2}$$

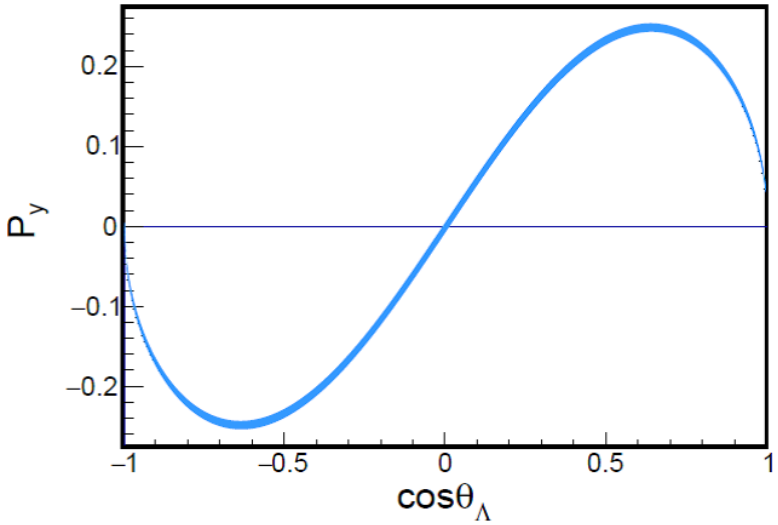
Integrated version: $\sigma_{B\bar{B}} = \frac{4\pi\alpha^2 C\beta}{3q^2}[|G_M|^2 + \frac{1}{2\tau}|G_E|^2]$



- Complex form of TLFFs leads to transversely polarized baryon even the beams are unpolarized.

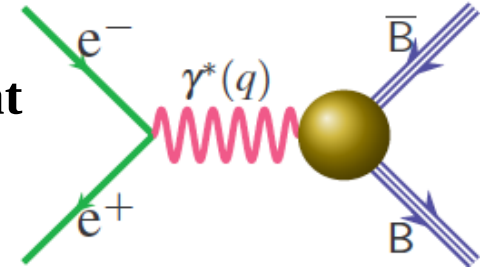
Nuov Cim A **109**, 241–256 (1996)

$$P_y = -\frac{\sin 2\theta\ \mathrm{Im}[G_E G_M^*]/\sqrt{\tau}}{\frac{|G_E|^2\sin^2\theta}{\tau} + |G_M|^2(1+\cos^2\theta)}$$



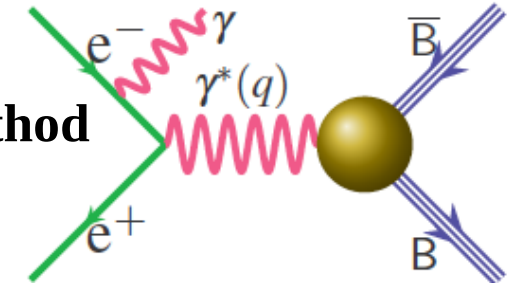
Time-like EMFFs: experiment review

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



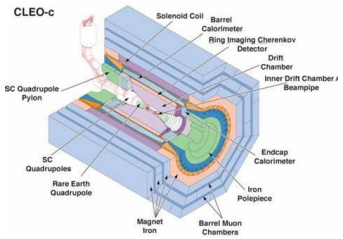
  - Well-defined c.m.energy, low background
  - Very good energy resolution
  - Discrete values, leaving gaps without information

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

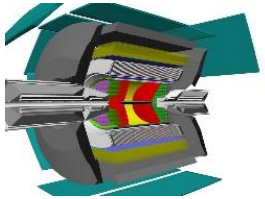


  - At a fixed c.m.energy $\sqrt{s}$, collecting events from threshold to $\sqrt{s}$
  - Systematic uncertainty in a coherent way
  - Large luminosity needed
  - Higher background

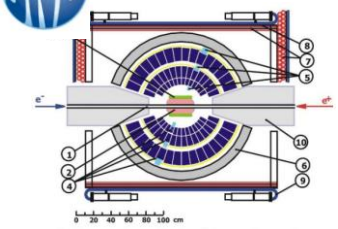
CLEO-c



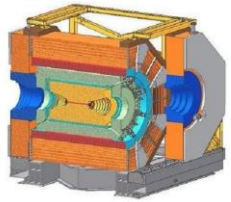
CMD-3



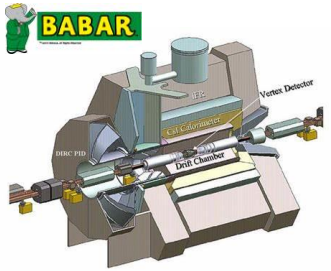
SND



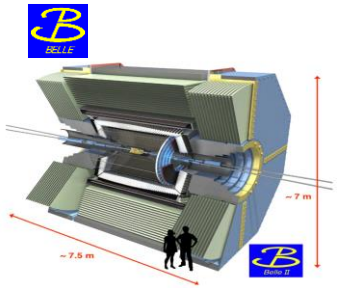
BESIII



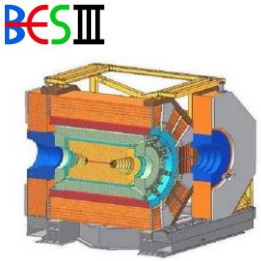
BABAR



BELLE



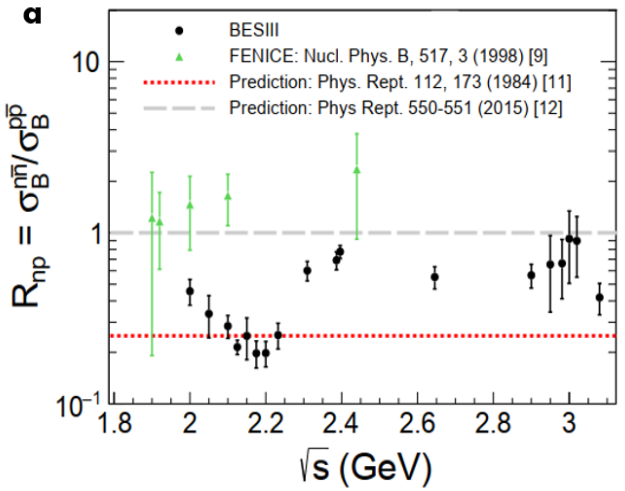
BESIII



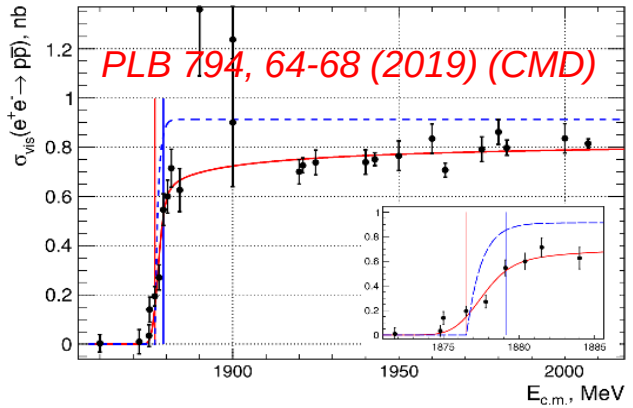
Both techniques can be used at BESIII

Results of nucleon EMFFs

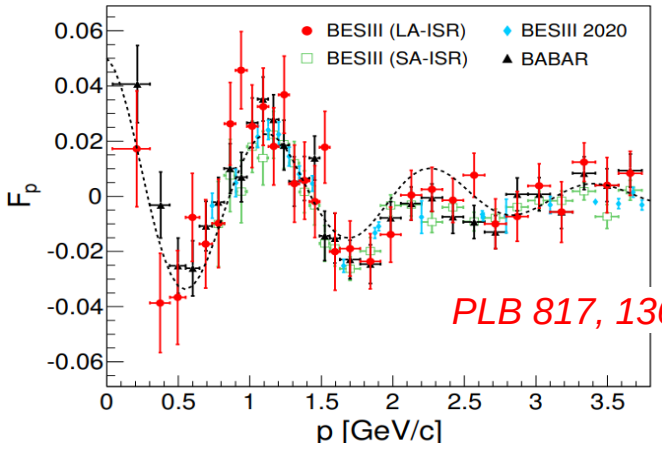
- $\gamma - p$ coupling larger than $\gamma - n$ coupling => consistent with theoretical predictions: VMD, Skyrme etc.
- Very sharp step-like behavior of production cross section, anomaly threshold effect
- Damped oscillation distribution after subtracting the modified dipole $|G_{\text{eff}}| = A/\left(1+\frac{q^2}{m_a^2}\right)[1-q^2/q_0^2]^2$



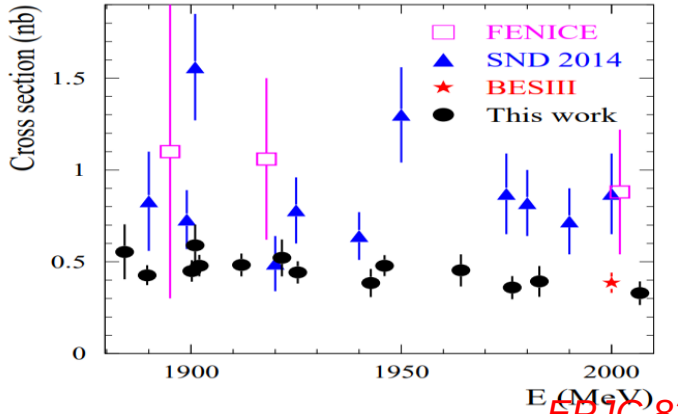
Nat. Phys. 17, 1200–1204 (2021)

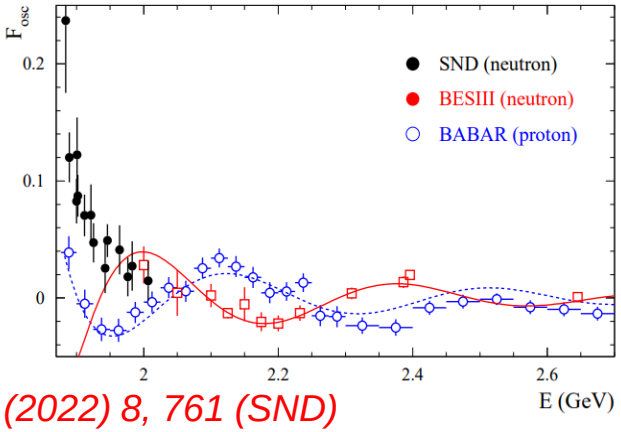


PLB 794, 64-68 (2019) (CMD)



PLB 817, 136328 (2021)

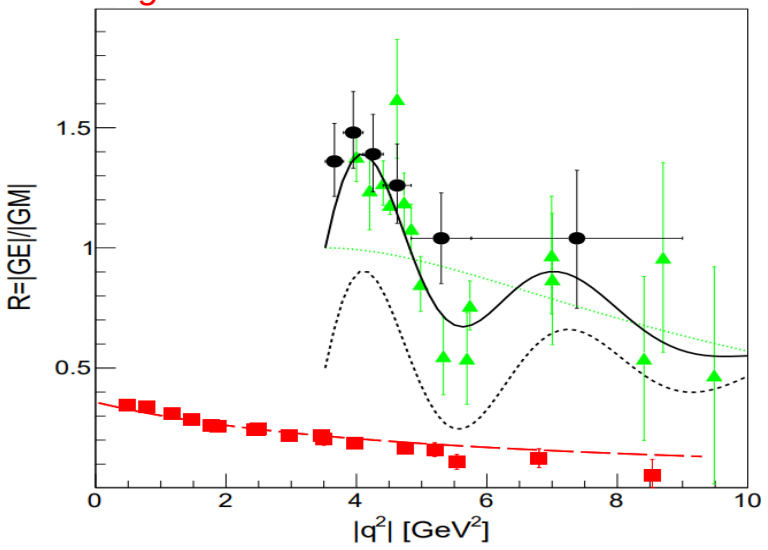




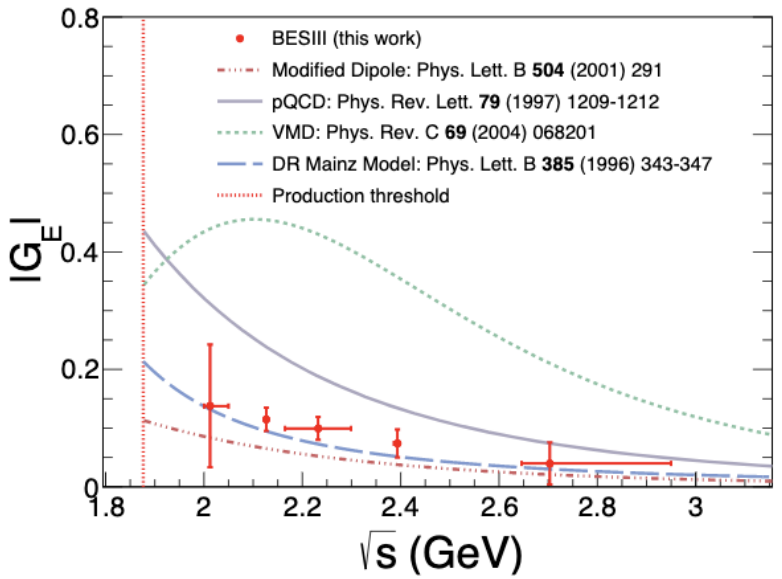
EPJC 82 (2022) 8, 761 (SND)

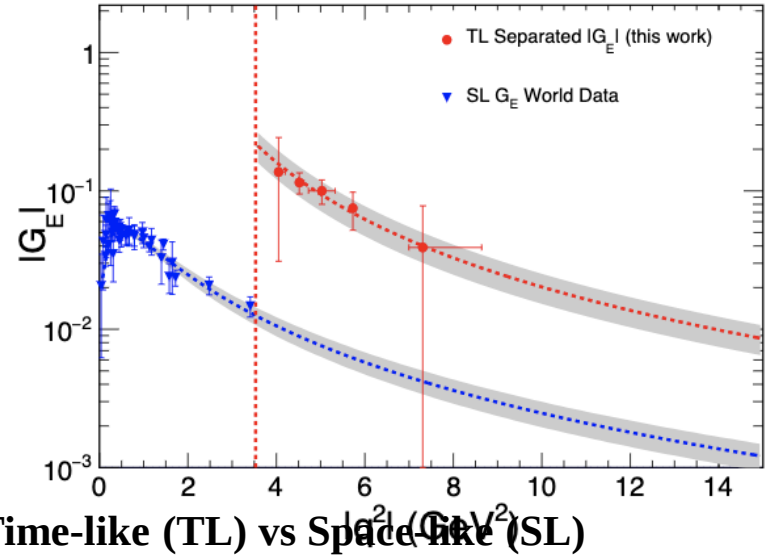
Results of nucleon EMFFs

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



PRL 130, 151905 (2023)





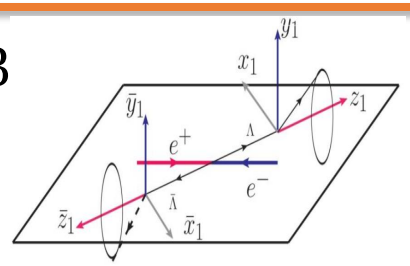
Time-like (TL) vs Space-like (SL)

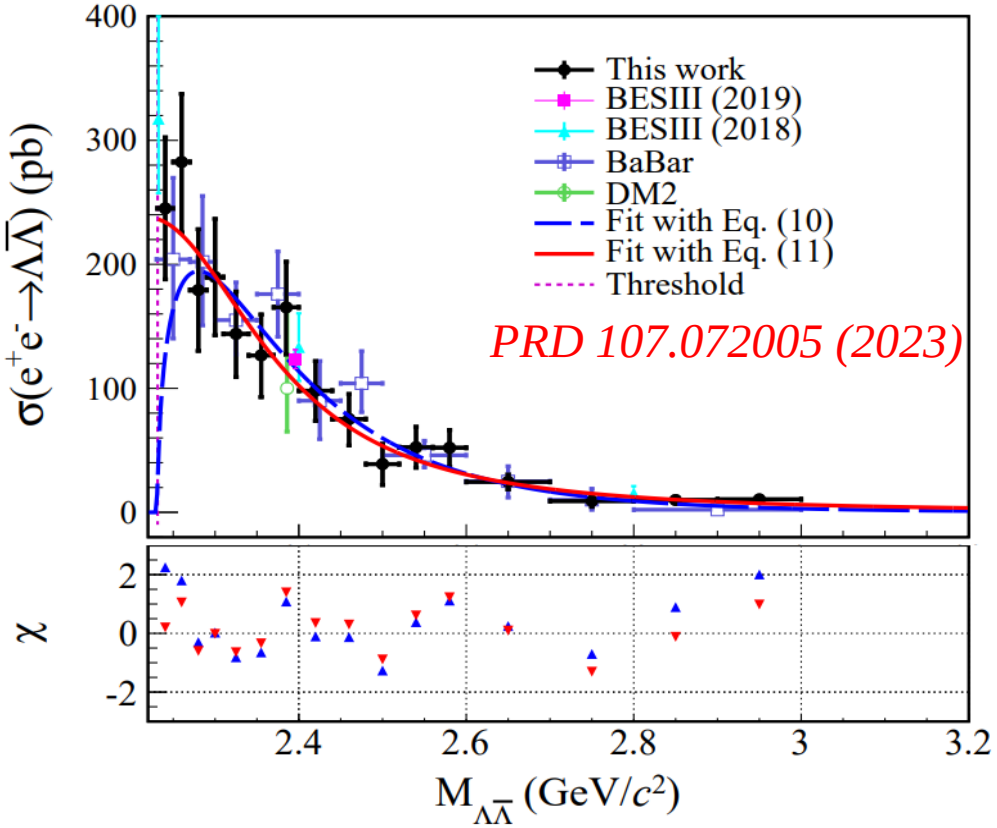
- ✓ Damped oscillation of proton $|G_E/G_M|$ in TL, unlike SL data
- ✓ Data is compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR), where the DR model gives good consistency
- ✓ A local test whether electric and magnetic form factors are continuous along the whole q^2 domain?

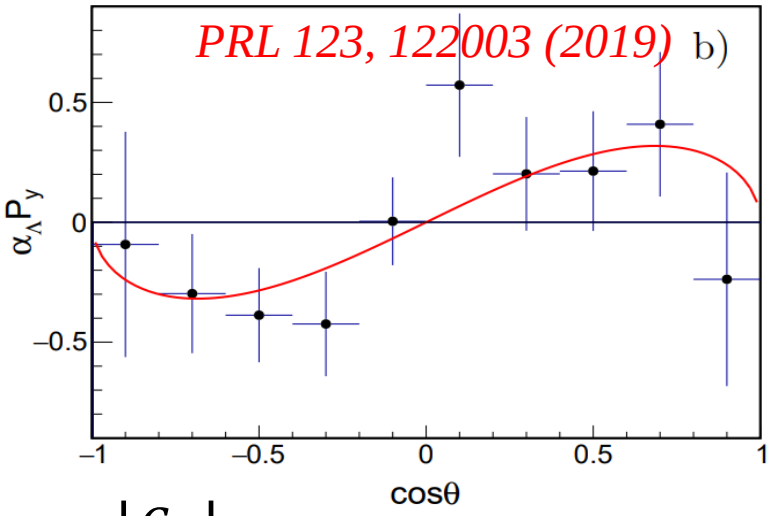
$$\mathcal{R}^{E,M} \equiv \left|\frac{G^{TL}_{E,M}(q^2)}{G^{SL}_{E,M}(-q^2)}\right| \xrightarrow{|q^2|\to\infty} 1$$

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

- Cross section of $e^+e^- \to \Lambda\bar{\Lambda}$ is measured with 11.9 fb^{-1} data collected from 3.773 to 4.258 GeV by ISR method
- The non-zero cross section is consistent with previous measurement
- The relative phase between G_E and G_M is measured for the first time.



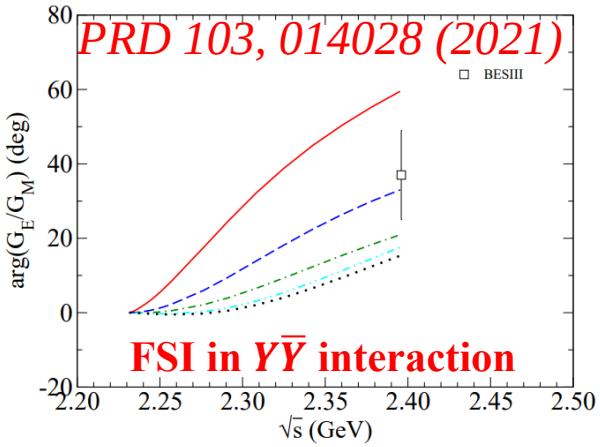


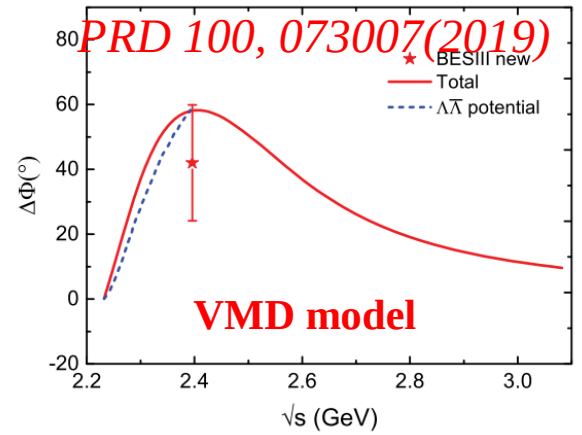


$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14 \pm 0.02$$

$$\Delta\Phi = 37^\circ \pm 12^\circ \pm 6^\circ$$

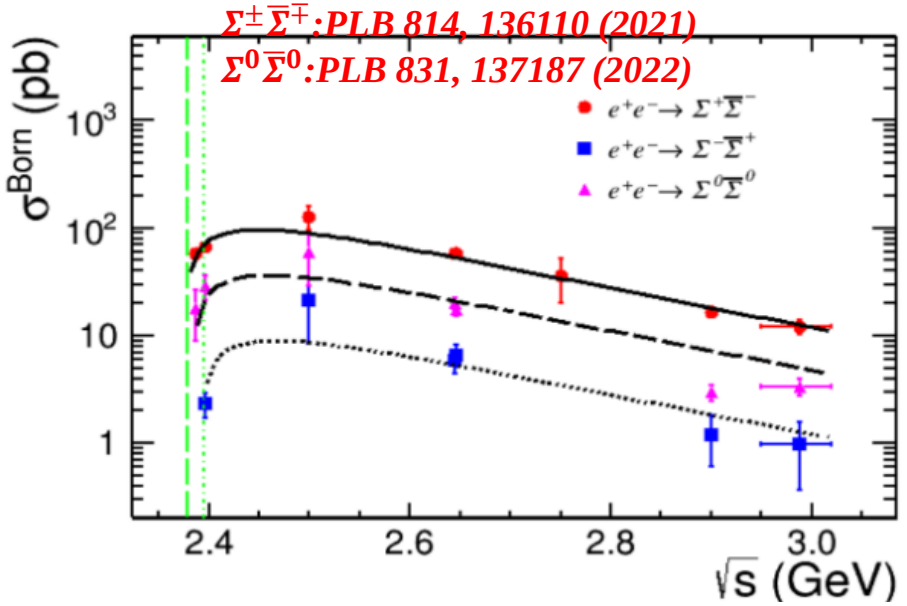
(Confirm the complex form of EMFFs)





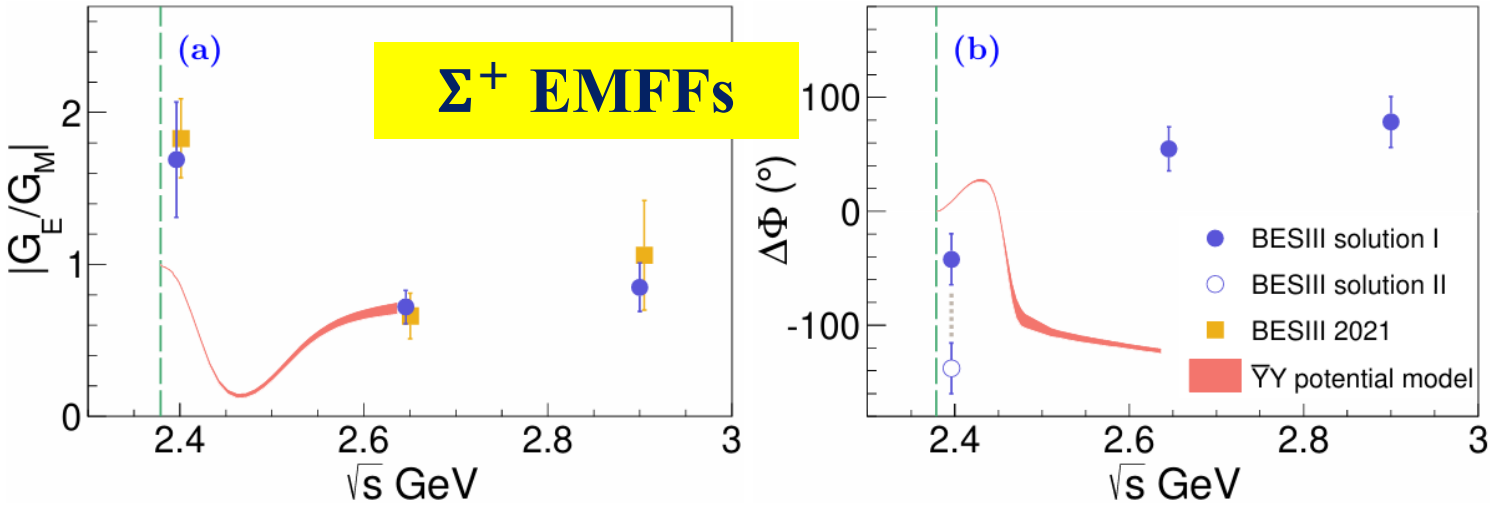
Measurement of $e^+e^- \to \Sigma\bar{\Sigma}$

- The cross sections can be well described by pQCD-motivated functions
- An asymmetry in cross sections $9.7 \pm 1.3 : 3.3 \pm 0.7 : 1$ => related with valence quark?
- EMFF compared with $\bar{Y}Y$ model → different tendency in $\Delta\Phi$.
- $\Delta\Phi$ distribution indicates there are integer multiples of π radians, from threshold to cross point.
- The still increasing relative phase indicates the asymptotic threshold has not yet been reached.



$$\sigma^{\mathrm{B}}(s) = \frac{\beta C}{s}\left(1+\frac{2m_B^2}{s}\right)\frac{c_0}{(s-c_1)^4(\pi^2+\ln^2(s/\Lambda_{\mathrm{QCD}}^2))^2}$$

PRL132,081904 (2024)

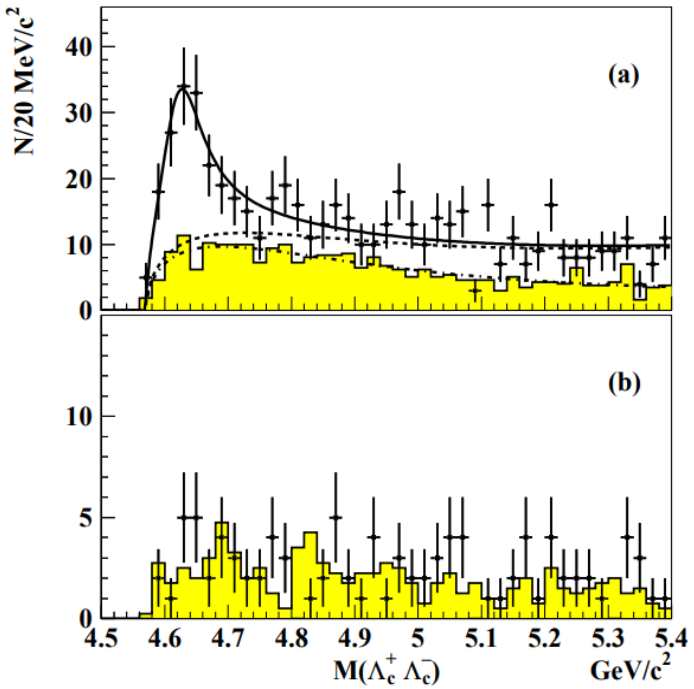


Model from J. Haidenbauer, U. G. Meißner, and L. Y. Dai, PRD 103, 014028 (2021)

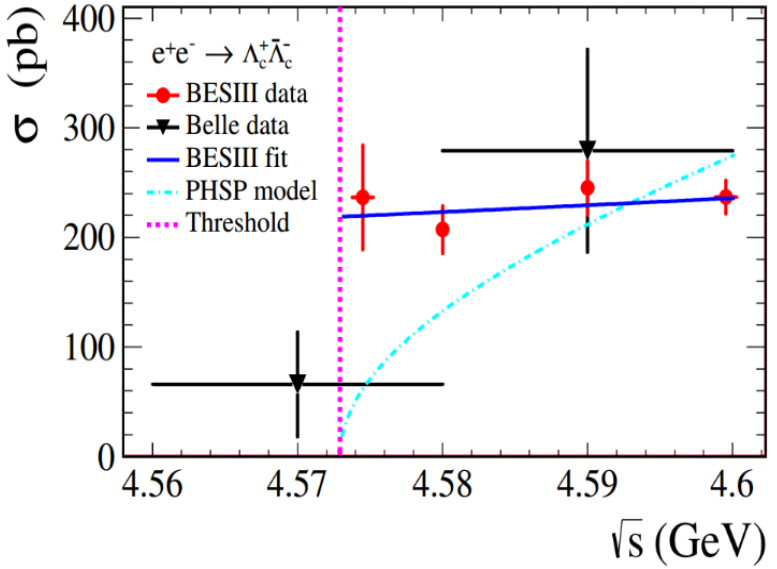
Complete measurement of $e^+e^- \to \Lambda_c^+\bar{\Lambda}_c^-$

- 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.

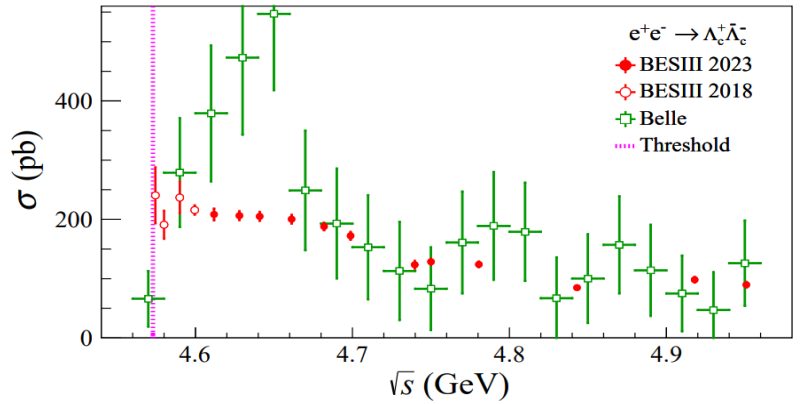
PRL 101, 172001 (2008)

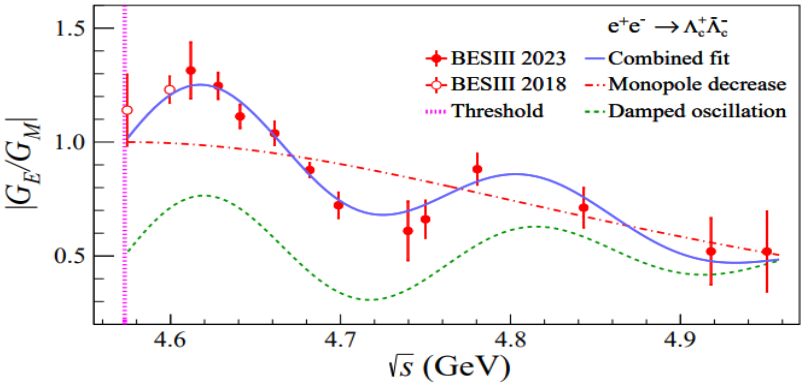


PRL 120, 132001 (2018)

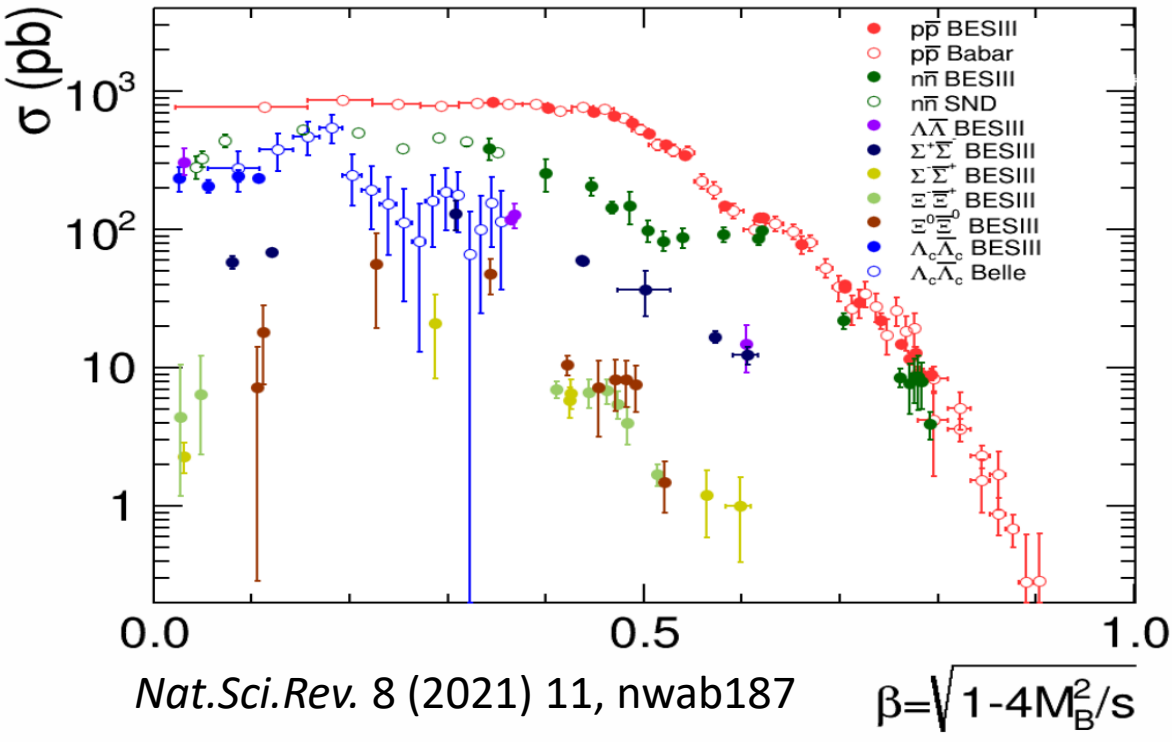


PRL 131,191901 (2023)

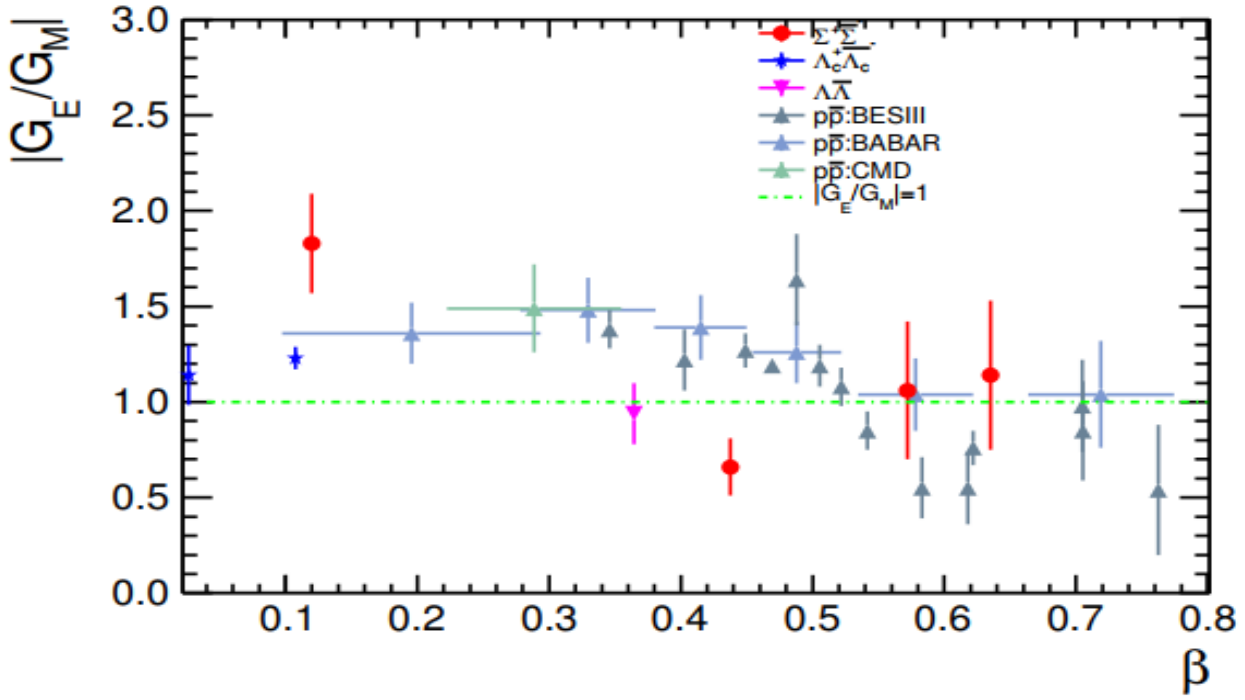




Results of EMFFs at BESIII

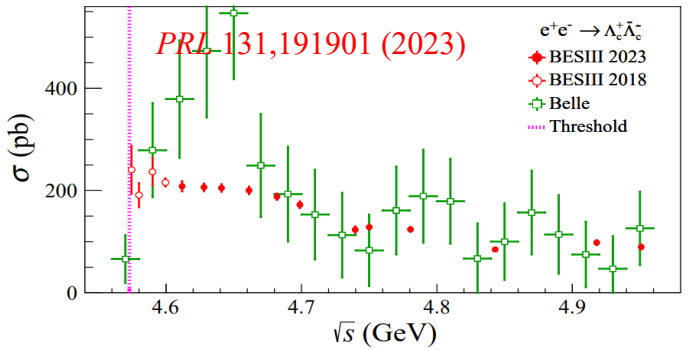


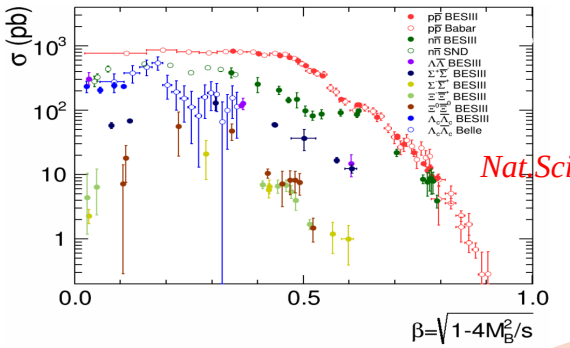
Nat.Sci.Rev. 8 (2021) 11, nwab187

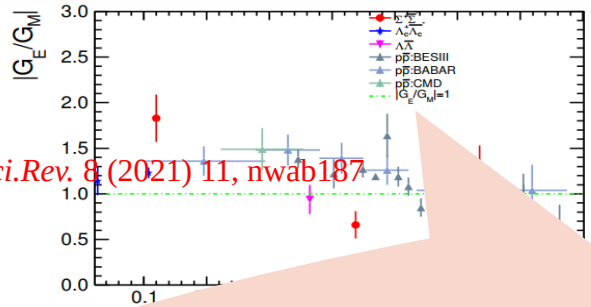


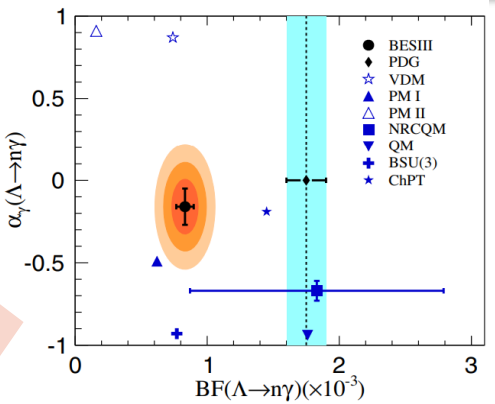
- Abnormal threshold effects observed in various baryon pair production: $p\bar{p}$, $\Lambda\bar{\Lambda}$, $\Lambda_c^+\bar{\Lambda}_c^-$ …
- Oscillation structures observed in $p\bar{p}$, $n\bar{n}$
- $|G_E/G_M|$ ratio significantly larger than 1 at low beta for p, Λ_c^+, Σ^+, indicating large D-wave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

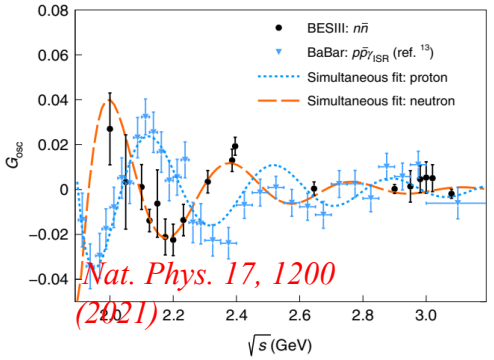
Summary



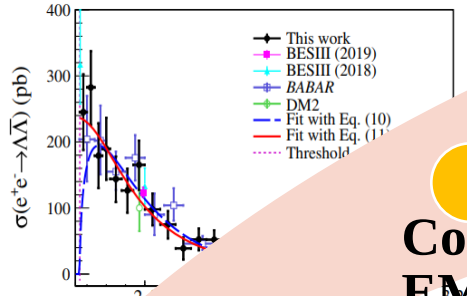








Nat. Phys. 17, 1200 (2021)



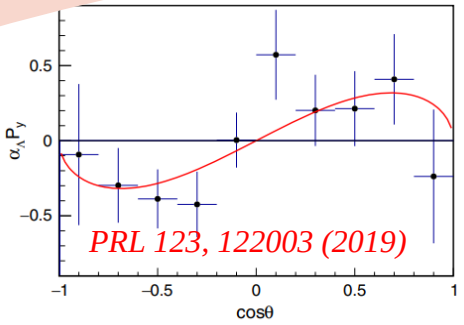
Weak radiative baryon decay

CP measurement

Complete EMFF

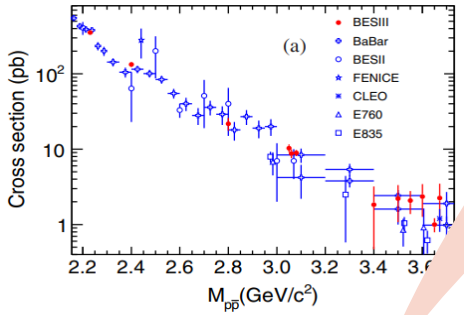
Threshold effect

Baryon EMFFs

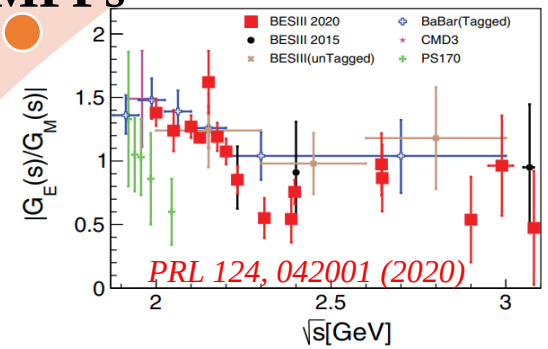


PRL 123, 122003 (2019)

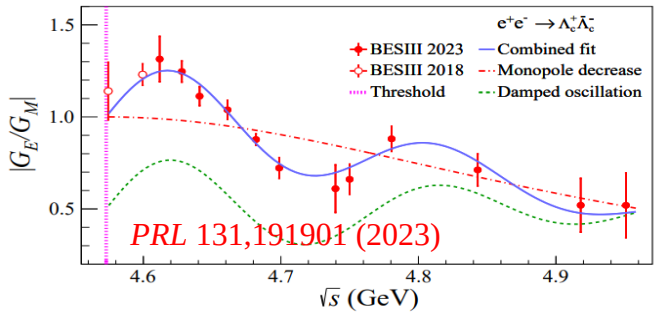
More precise results input to non-pQCD and SM!



PRD 91, 112004 (2015)



PRL 124, 042001 (2020)

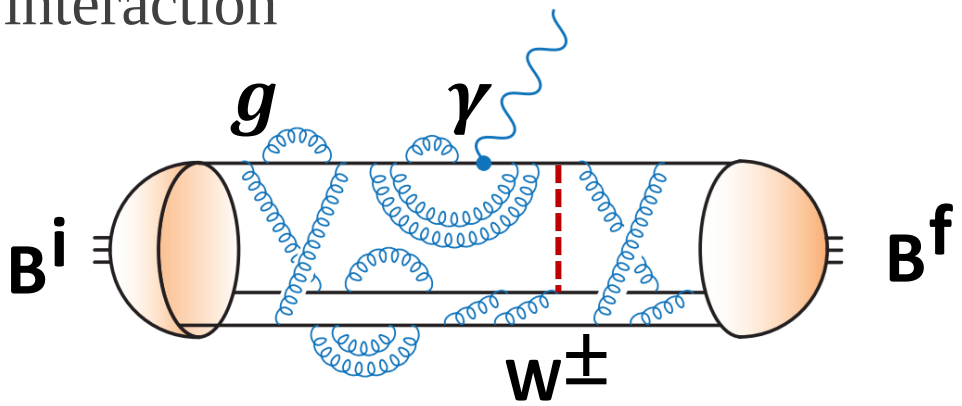


PRL 131,191901 (2023)

Thanks for your attention!

Weak Radiative Hyperon Decays

- Weak radiative decays
  - flavor changing neutral current (FCNC) process ($s \to d\gamma$ transition)
  - Significant non-perturbative QCD effects
  - A symphony of strong, weak and EM interaction



j.ppnp.2016.07.001

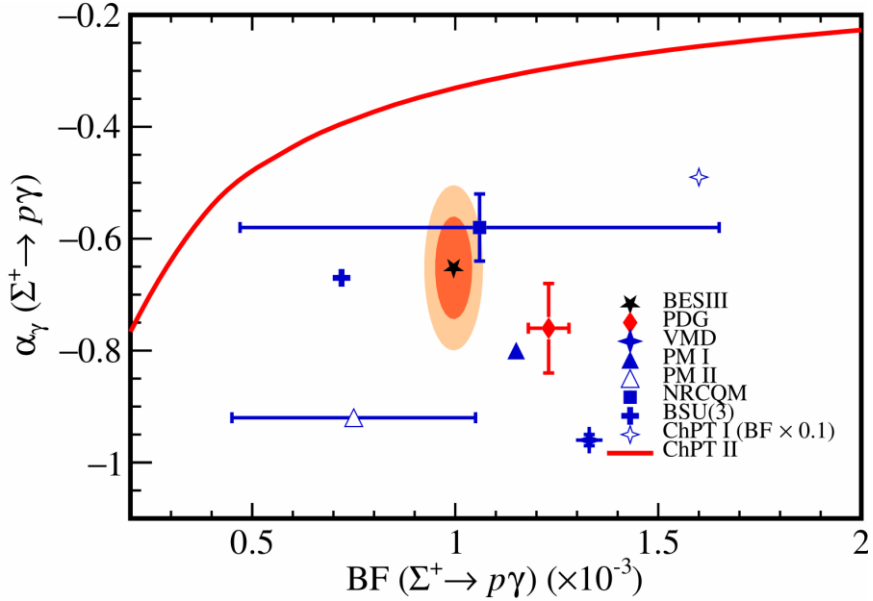
$$\frac{dN}{d\Omega} = \frac{N}{4\pi}(1 + \alpha_\gamma P_i \cdot \hat{p})$$

- P_i -- polarization of the decaying hyperon,
- $\hat{p}$ -- the unit vector of the daughter baryon's momenta in the hyperon rest frame
- α_γ -- the decay asymmetry parameter characterizing the mixing of S and P waves.

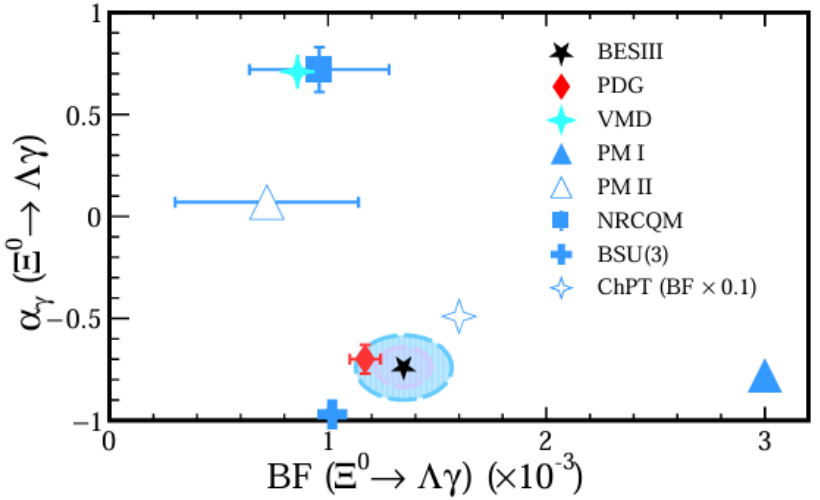
✓ α_γ predicted to be 0 in the limit of unitary symmetry

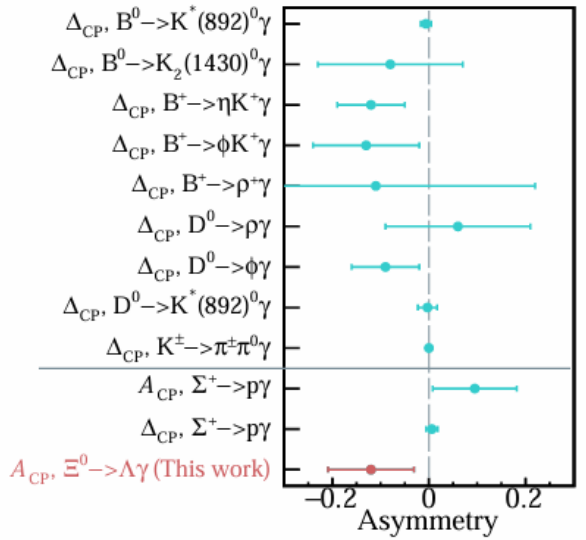
$B \to B'\gamma$ Analysis

PRL130, 211901 (2023)



Science Bulletin 70 (2025) 454



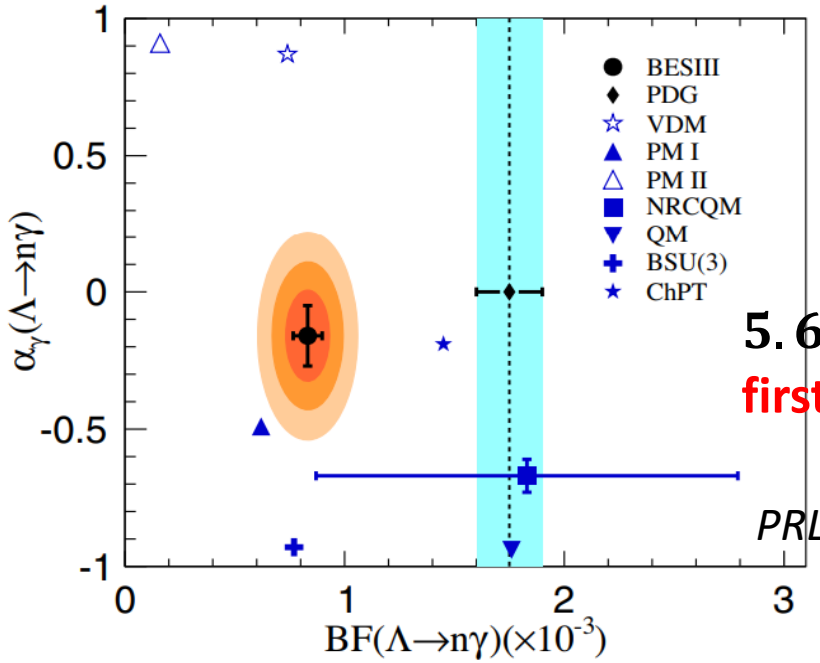


Significantly improved accuracy

BF: 78% ; α_γ: 34%

$$\Delta_{CP} = \frac{\mathcal{B}_+ - \mathcal{B}_-}{\mathcal{B}_+ + \mathcal{B}_-} = 0.006 \pm 0.011_{\text{stat.}} \pm 0.004_{\text{syst.}},$$

$$A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = 0.095 \pm 0.087_{\text{stat.}} \pm 0.018_{\text{syst.}}.$$



5.6σ deviation in BF

first measurement α_γ

PRL 129, 212002 (2022)

Complete measurement of Λ EMFFs

- An event of the reaction $e^+e^- \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ is formalized by joint angular distribution:

$$\omega(\xi, \Delta\Phi, \alpha_\psi, \alpha_-, \alpha_\gamma) = 1 + \alpha_\psi cos^2\theta_\Lambda$$ *Unpolarized part*

$$+\alpha_-\alpha_\gamma[sin^2\theta_\Lambda(n_{1,x}, n_{2,x} - \alpha_\psi n_{1,y}, n_{2,y}) + (cos^2\theta_\Lambda + \alpha_\psi)n_{1,z}, n_{2,z}]$$

$$+ \alpha_-\alpha_\gamma\sqrt{1-\alpha_\psi{}^2}\, cos(\Delta\Phi)\, sin\theta_\Lambda cos\theta_\Lambda(n_{1,x}, n_{2,z} + n_{1,z}, n_{2,x})$$ *Correlated part*

$$+\sqrt{1-\alpha_\psi{}^2}\, sin(\Delta\Phi)\, sin\theta_\Lambda cos\theta_\Lambda(\alpha_- n_{1,y} + \alpha_\gamma n_{2,y})$$ *Polarized part*

$$\left|\frac{G_E}{G_M}\right| = 0.96 \pm 0.14(\text{stat.}) \pm 0.02(\text{sys.})$$

$$\Delta\Phi = 37^\circ \pm 12^\circ(\text{stat.}) \pm 6^\circ(\text{sys.})$$

(Confirm the complex form of EMFFs)

PRL 123, 122003 (2019)