Recent results of Baryon electromagnetic form factors at BESIII

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(on behalf of the BESIII Collaboration)

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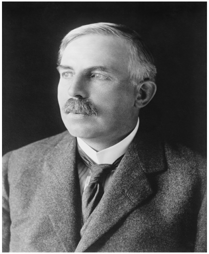
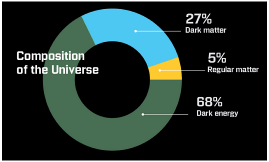
Outline



Preamble

- Baryon mass is the main component of the mass of the universe. It comes from the strong force, not from the Higgs mechanism. (K.Huang, Story of Gauge Fields, 2007, F. Wilczeck, A beautiful question, 2016).



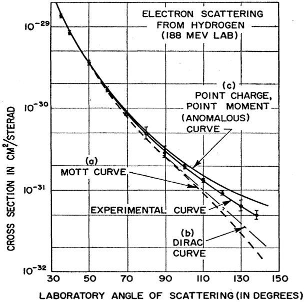
- Baryons, what they really are, is far from being understood.
- Many meson features come from QED to QCD, once $\alpha \to \alpha_s$. Baryon: no analogue in QED and unique QCD feature.
- For instance:
  - A fermion with mass, magnetic moment and other parameters close to proton and neutron ones can be obtained as a soliton of a π point-like boson field, by means of a non linear Lagrangian with one free parameter only (**Skyrme model**, T. H. R. Skyrme, Proc. Roy. Soc. **A 260**, (1961), 127)!
  - The baryon spin is not due to the spins of the valence quarks (**Proton Spin Crisis**, J. Ashman *et al.* (European Muon Collaboration), PLB **206**, 364, (1988))!
- Therefore it is meaningful to point out open questions, concerning baryon structure.

Baryon Form Factors

- Elastic scattering of electron and proton (Phys. Rev. **98**, 217 R. Hofstadter, Nobel Prize 1961).
  - Theoretically, differential cross section is:

$$(\frac{d\sigma}{d\Omega})_{ep} = (\frac{d\sigma}{d\Omega})_{\text{Mott}}(1 + 2\tau tan^2\frac{\theta}{2})F(q^2)$$

  - The deviation represents the effect of a form factor (FF) for the proton.



- The nucleon electromagnetic vertex Γ_μ describing the hadron current:

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

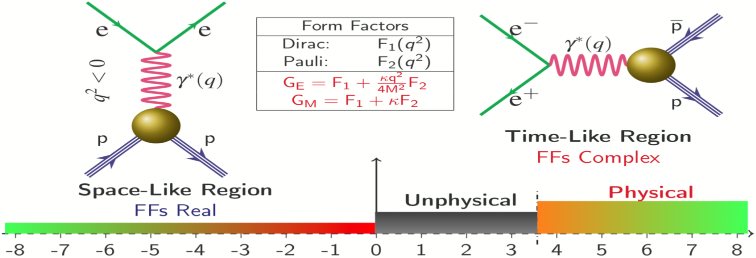
- Sachs FFs:

$$\text{Electron FF:} G_E(q^2) = F_1(q^2) + \tau\kappa_p F_2(q^2)$$

$$\text{Magnet FF:} G_M(q^2) = F_1(q^2) + \kappa_p F_2(q^2)$$

Baryon Form Factors

- Fundamental properties of the nucleon:
  - Connected to charge, magnetization distribution,
  - Crucial testing ground for models of the nucleon internal structure.
- Measurement of baryon FF: Space-like (SL) and Time-like (TL).



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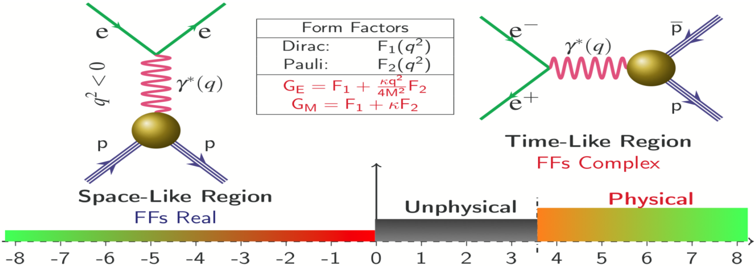
Baryon Form Factors

- Measurement of baryon FF: Space-like (SL) and Time-like (TL).



- TL process includes energy scan and initial state radiation (ISR), both techniques can be used at BESIII.

	Energy scan	Initial state radiation
E_{beam}	discrete	fixed
$\mathcal{L}$	Low at each beam energy	High at one beam energy
σ	$\frac{d\sigma^{\text{Born}}_{p\bar{p}}}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[\lvert G_M\rvert^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}\lvert G_E\rvert^2\sin^2\theta]$	$\frac{d\sigma_{p\bar{p}\gamma}}{dq^2 d\theta_\gamma} = \frac{1}{s}W(s,x,\theta_\gamma)\sigma_{p\bar{p}}(q^2)$ $\sim\frac{1}{400}$ $W(s,x,\theta_\gamma) = \frac{\alpha}{\pi x}(\frac{2-2x+x^2}{\sin^2\theta_\gamma} - \frac{x^2}{2})$
q^2	Single at each beam energy	From threshold to s

Sommerfeld enhancement and resummation factors

- The nucleon EMFF in TL region:

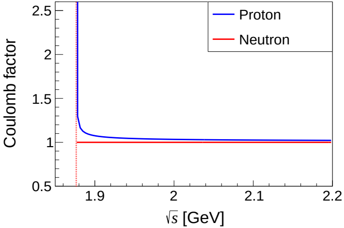
$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta}{2q^2}[|G_M(q^2)|^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}|G_E(q^2)|^2\sin^2\theta].$$

- Sommerfeld enhancement and resummation factors:
  - Coulomb factor C, for S-wave only:

$$C \equiv |\psi_{L=0}(0)|^2 = \frac{\alpha\pi}{\beta}\frac{1}{1-e^{-\frac{\pi\alpha}{\beta}}}.$$

  - Step at threshold:

$$C = \frac{\alpha\pi}{\beta},$$



$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[|G_M(q^2)|^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}|G_E(q^2)|^2\sin^2\theta].$$

- One of the objectives of measuring TLFF is to test the QCD theories such as Coulomb factor.

Threshold effects

- Born cross section $\sigma^{\rm Born}_{p\bar{p}}$ in TL:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta} = \frac{\pi\alpha^2\beta C}{2q^2}[|G_M(q^2)|^2(1+\cos^2\theta) + \frac{4m_p^2}{q^2}|G_E(q^2)|^2\sin^2\theta],$$

$$\sigma^{\rm Born}_{p\bar{p}}(q^2) = \frac{4\pi\alpha^2\beta C}{3q^2}[|G_M(q^2)|^2 + \frac{2m_p^2}{q^2}|G_E(q^2)|^2]$$

$$= \frac{4\pi\alpha^2\beta C}{3q^2}(1+\frac{2m_p^2}{q^2})|G_{\rm eff}(q^2)|^2.$$

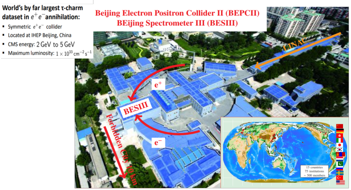
which $|G_{\rm eff}(q^2)|$ is effective FF:

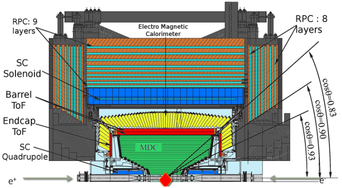
$$|G_{\rm eff}(q^2)| = \sqrt{\frac{|G_M(q^2)|^2 + \frac{2m_p^2}{q^2}|G_E(q^2)|^2}{1+\frac{2m_p^2}{q^2}}}.$$

- Near the threshold, C leads the $\sigma^{\rm Born}_{p\bar{p}}$ none-zero:

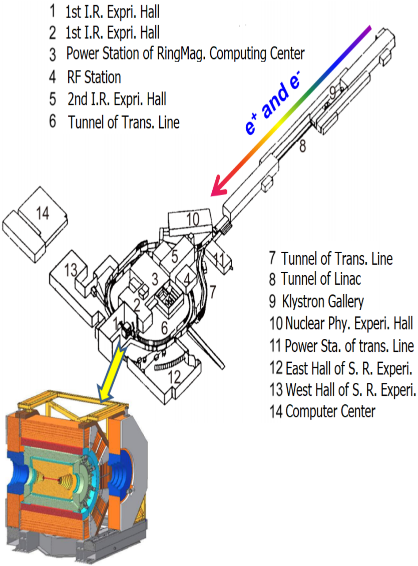
$$|G_E(q^2)| = |G_M(q^2)| = |G_{\rm eff}(q^2)|, \sigma^{\rm Born}_{p\bar{p}}(4m_p^2c^4) \approx \frac{\pi^2\alpha^3}{4m_p^2c^4}|G_{\rm eff}(4m_p^2c^4)|^2.$$

Accelerator and Detector

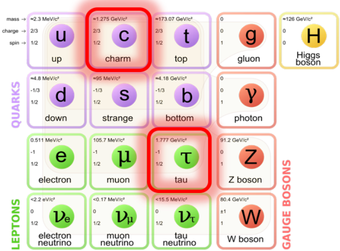




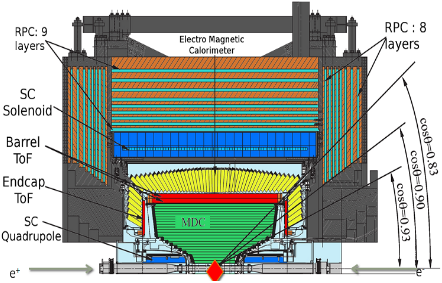
Beijing Electron Positron Collider II



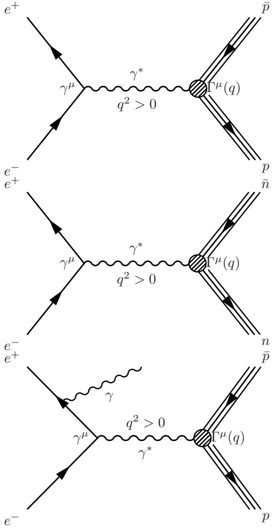
- $E_{\rm cm}$: 2.00-4.96 GeV;
- Double storage ring: e^+ and e^-;
- No. of bunches: 93;
- Luminosity: 1.0×10^{33} cm^{-2}s^{-1} @3770MeV



BEijing Spectrometer III

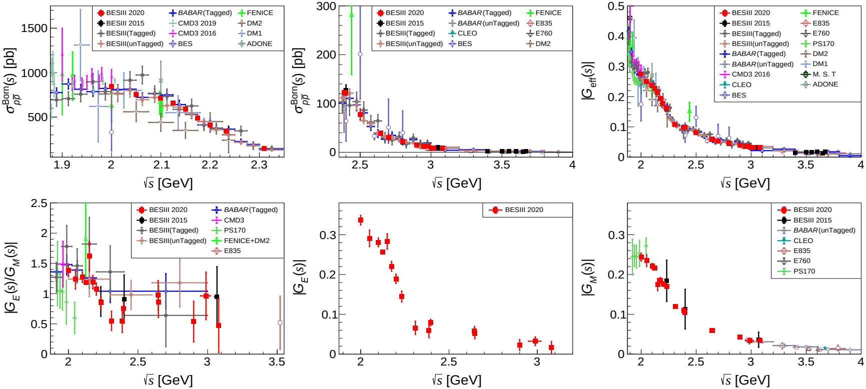


- Main Drift Chamber (MDC): (He/C_3H_8=60/40)
  - $\sigma_{xy}\approx$130 μm, $dE/dx \sim$6%;
  - $\sigma_p/p\approx$0.5% at 1 GeV.
- Time Of Flight (TOF): (Barrel: plastic scintillator, endcap: MRPC)
  - σ_{time}(barrel)$\approx$80 ps,
  - σ_{time}(endcap)$\approx$65 ps.
- ElectroMagnetic Calorimeter (EMC): (CsI(Tl))
  - σ_E/E(barrel)$\approx$2.5% at 1 GeV,
  - σ_E/E(endcap)$\approx$5% at 1 GeV.
- Superconducting Magnet: B =1 T.
- Muon Counter: Resistive Plate Chambers (RPC):
  - barrel: 9 layers;
  - endcap: 8 layers.
  - $\sigma_{spatial}$=2 cm.


e^+
$\bar{p}$
γ^*
γ^μ
$\Gamma^\mu(q)$
$q^2 > 0$
e^-
p
e^+
$\bar{n}$
γ^*
γ^μ
$\Gamma^\mu(q)$
$q^2 > 0$
e^-
n
e^+
$\bar{p}$
γ
$q^2 > 0$
γ^μ
$\Gamma^\mu(q)$
γ^*
e^-
p

Proton Form Factors at BESIII

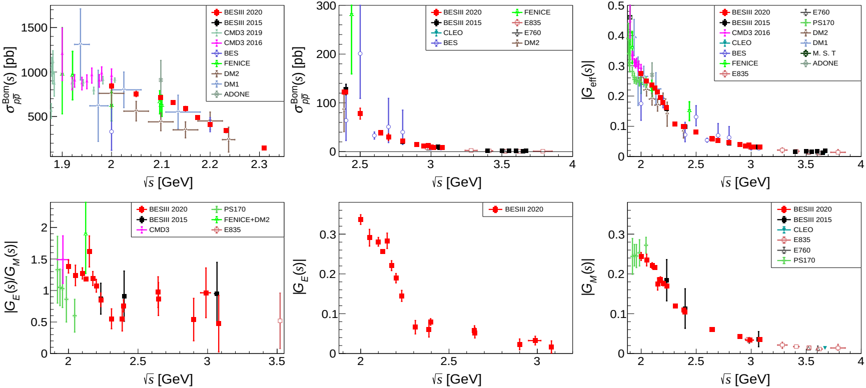
- **Energy scan**:
  - M. Ablikim *et al.* (BESIII Collaboration), PRL **124**, 042001 (2020),
  - Review: Lei Xia *et al.*, Symmetry **14**, 231 (2022),
  - M. Ablikim *et al.* (BESIII Collaboration), PRD **91**, 112004 (2015).



- **Initial state radiation**:
  - M. Ablikim *et al.* (BESIII collaboration), PRD **99**, 092002 (2019)
  - M. Ablikim *et al.* (BESIII collaboration), PLB **817**, 136328 (2021).

Energy scan technique

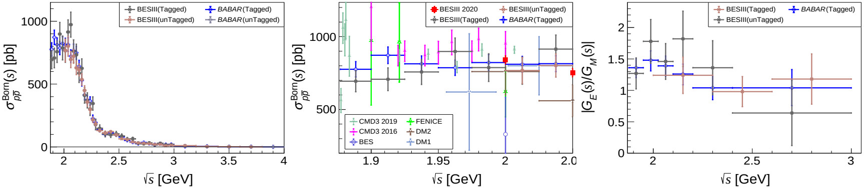
- **Energy scan**:
  - M. Ablikim *et al.* (BESIII Collaboration), PRL **124**, 042001 (2020),
  - Review: Lei Xia *et al.*, Symmetry **14**, 231 (2022),
  - M. Ablikim *et al.* (BESIII Collaboration), PRD **91**, 112004 (2015).



- Most precise measurement, i.e. at $\sqrt{s} = 2.125$ GeV, $\frac{\delta^{\rm stat}\sigma^{\rm Born}_{p\bar{p}}}{\sigma^{\rm Born}_{p\bar{p}}} \sim 0.45\%$.

Proton Form Factors at BESIII:
Initial state radiation technique

- Initial state radiation:
  - Tagged: M. Ablikim *et al.* (BESIII collaboration), PRD **99**, 092002 (2019)
  - Untagged: M. Ablikim *et al.* (BESIII collaboration), PLB **817**, 136328 (2021),
  - Review: Dexu Lin *et al.*, Symmetry **14**, 91 (2022).



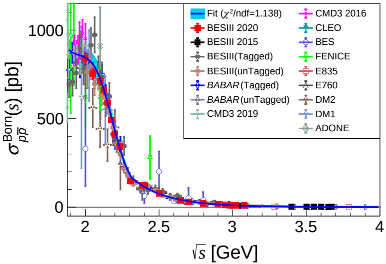
$M^{inv}_{p\bar{p}}$ [GeV/c^2]	N_{obs}	$\frac{\Delta N_{obs}}{N_{obs}}$	$\frac{\Delta\lvert G_E/G_M\rvert}{\lvert G_E/G_M\rvert}$	Compare	Collaboration
$2.025 \sim 2.100$	1328	2.74%	10.79%	3.9	*BABAR* LA-ISR
$2.025 \sim 2.100$	560	4.23%	18.49%	4.4	BESIII LA-ISR
$2.0 \sim 2.3$	4283	1.53%	$\sim$ 23.39%	...	BESIII SA-ISR
2.125	50312	0.45%	3.39%	7.6	BESIII Scan
$1.92 \sim 2.00$	2577	1.97%	15.44%	7.8	CMD-3 (combined)

- From the threshold to $\sqrt{s} = 2.0$ GeV, the average Born cross section, $\sigma^{Born}_{p\bar{p}}(s)$, is approximately 840 pb, while under the assumption of point-like particles, $\sigma^{Born}_{p\bar{p}(point)}(s) = \frac{4\pi\alpha^2}{3s}\left[1 + \frac{2m_p^2}{s}\right] = 845$ pb.

Threshold effects

- Improved precision in time-like (TL) region ;
- Low-energy-eff-QCD (O. P. Solovtsova *et al.*, Phys. Atom. Nucl. **73**, 1612 (2010)) and pQCD (A. Bianconi *et al.*, PRL **114**, 232301 (2015)) are authenticated.

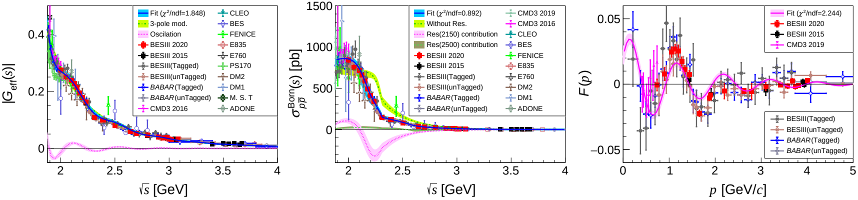
$$\sigma^{\text{Born}}_{p\bar{p}}(s) = \begin{cases} \dfrac{e^{a_c}\pi^2\alpha^3}{s\left[1-e^{-\frac{\pi\alpha_S(s)}{\beta(s)}}\right]\left[1+\left(\frac{\sqrt{s}-2m_pc^2}{a_0}\right)^{a_1}\right]}, & \sqrt{s}\le 2.3094\text{ GeV},\\[2ex] \dfrac{2\pi\alpha^2\beta(s)C\left[2+\left(\frac{2m_pc^2}{\sqrt{s}}\right)^2\right]e^{2a_2}}{3s^5\left[4\ln^2\left(\frac{\sqrt{s}}{a_0}\right)+\pi^2\right]^2}, & \sqrt{s}> 2.3094\text{ GeV},\end{cases}$$



- Consider strong interaction effects near the threshold.
  - ✓ a_0: Overall QCD parameter Λ_{QCD};
  - ✓ a_1: power-law dependence, related to the number of valence quarks;
  - ✓ a_2: normalization constant.

Periodic Interference Structures

- The oscillation in $|G_{\rm eff}|$ is observed by *BABAR* (A. Bianconi *et al.*, PRL **114**, 232301 (2015)), and confirmed by BESIII.



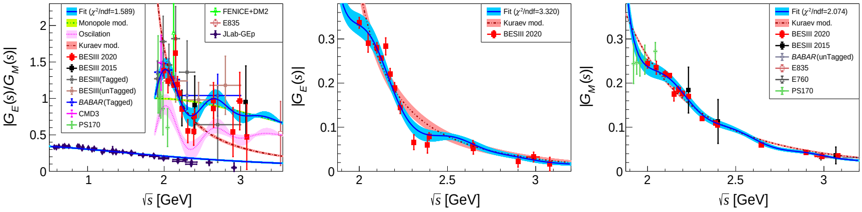
$$F_{\rm 3p}(s) = \frac{\mathcal{A}}{(1+\frac{s}{m_a^2c^4})[1-\frac{s}{0.71\ \rm GeV^2}]^2},$$

$$F_{\rm osc}[p(s)] = b_0^{\rm osc} e^{-b_1^{\rm osc}p(s)} \cos(b_2^{\rm osc}p(s) + b_3^{\rm osc}),$$

$$|G_{\rm eff}(s)| = F_{\rm 3p}(s) + F_{\rm osc}[p(s)].$$

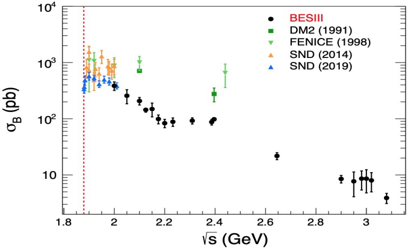
- Periodic structures:
  - Possibility of resonant structures around 2.15 GeV and 2.50 GeV;
  - An oscillating function superimposed on the smooth dipole parametrization.

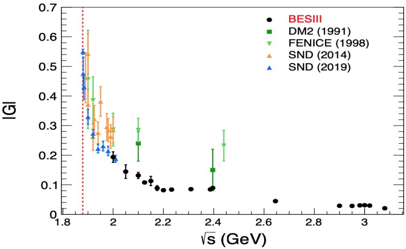
- Electromagnetic Form Factor ratio ($|G_E/G_M|$), Electric and magnetic Form Factors ($|G_E|$ and $|G_M|$):
  - Improved precision, (comparable to space-like (SL) region):
    - ✓ $|G_M|$ is the most accurate result, $|G_E|$ is measured for the first time.
  - Periodic structures:
    - ✓ Can be related to subhadronic-scale processes;
    - ✓ Extend to $|G_E|$ and $|G_M|$ from $|G_{\text{eff}}|$ and $|G_E/G_M|$.
  - TL-SL joint fit improves our comprehension of the radius of the proton.

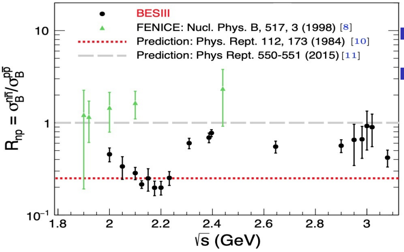


Neutron Form Factors at BESIII

- M. Ablikim *et al.* (BESIII collaboration), Nat. Phys. **17**, 1200 (2021),
- M. Ablikim *et al.* (BESIII collaboration), PRL **130**, 151905 (2023),
- Review: P. Larin *et al.*, Symmetry **14**, 298 (2022).

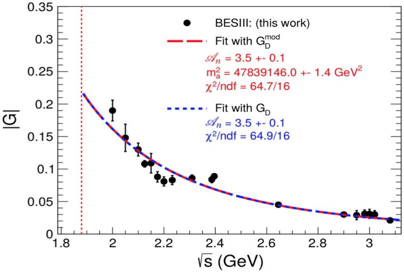


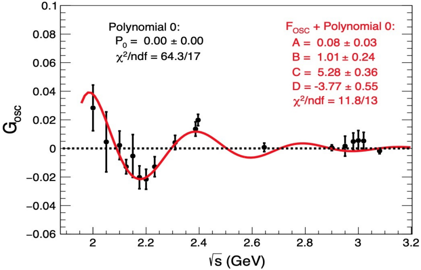




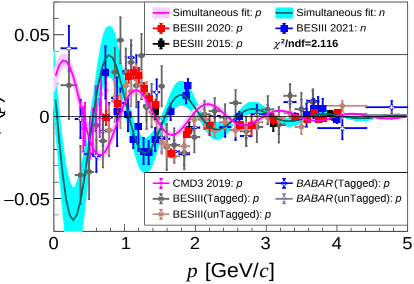
- From 2.00 to 3.08 GeV, 647.9 pb^{-1}.
- $\gamma - p$ coupling larger than $\gamma - n$, consistent with theoretical limits from VMD, (V. L Chernyak *et al.*, Phys. Rept. **112**, 173 (1984)): $\sigma^{\text{Born}}_{B\bar{B}} \propto |\sum_{q\in B} Q_q a^B_q(s)|$ $\frac{\sigma^{\text{Born}}_{p\bar{p}}}{\sigma^{\text{Born}}_{n\bar{n}}} \to \frac{Q_u^2}{Q_d^2} = 4.$

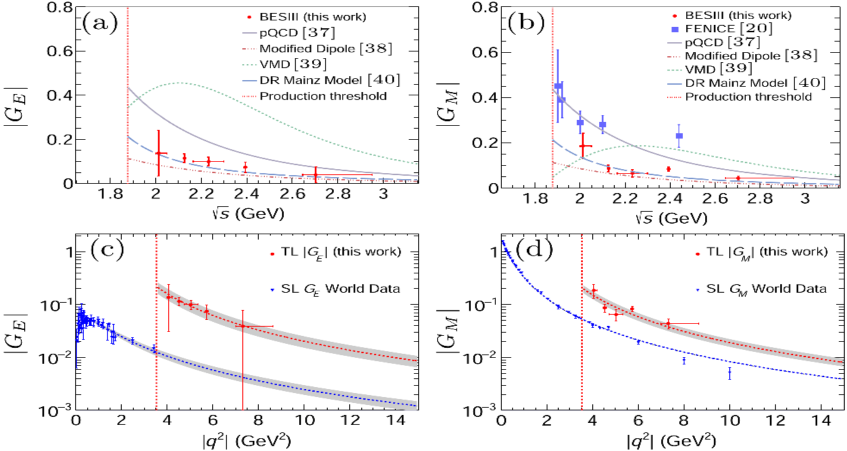
Periodic Interference Structures





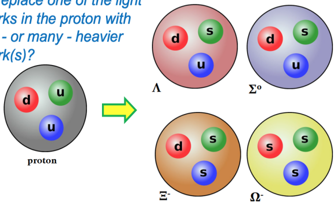
- A similar oscillation effect is also discovered in the $|G_{\rm eff}|$ of the neutron.
- Simultaneously fitting the reduced-$|G_{\rm eff}|$ for protons and neutrons (Lei Xia *et al.*, Symmetry **14**, 231 (2022)):
  - Conjoint frequency of p and n: $b_2^{\rm osc} = (5.05^{+0.10}_{-0.09})\ ({\rm GeV}/c)^{-1}$,
  - A phase difference from the proton: $\Delta b_3^{\rm osc} = (129^{+11}_{-10})^\circ$.





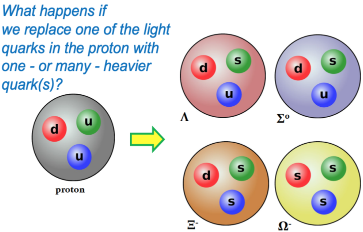
- Compared with the FENICE results, the values for $|G_M|$ from this work are smaller by a factor of $2-3$.
- Results is compared with various models: pQCD, modified dipole, VMD and dispersion relations (DR), and DR model gives good consistency.

What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?



From nucleon to hyperon

- It is difficult to study EMFFs of hyperons in SL due to the difficulty in stable and high-quality hyperon beams.
- The hyperons can be produced in e^+e^- annihilation above their production threshold.



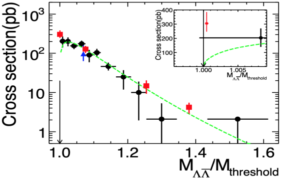
- The angular distribution of daughter baryon from Hyperon weak decay is:
  - $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \mathbf{P_y} \cdot \hat{\mathbf{q}}$,
  - α_Λ: asymmetry parameter (P-violation)

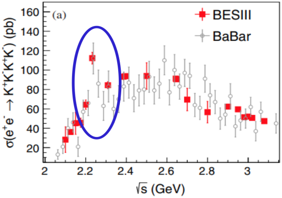
Advantages:

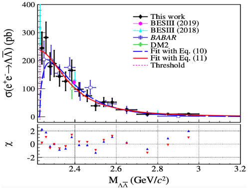
- $\sigma^{\text{Born}}_{B\bar{B}}$ can be obtained very close to threshold with finite PHSP of final state.
- With hyperon weak decay to $B + P$, the polarization of hyperon can be measured, so does the relative phase between G_E and G_M!

Λ Form Factors at BESIII

- **Energy scan:**
  - M. Ablikim *et al.* (BESIII collaboration), PRD **97**, 032013 (2018),
  - M. Ablikim *et al.* (BESIII collaboration), PRD **100**, 032009 (2019),
  - Review: Xiaorong Zhou *et al.*, Symmetry **14**, 144 (2022).
- **Initial state radiation:**
  - M. Ablikim *et al.* (BESIII collaboration), PRD **107**, 072005 (2023).

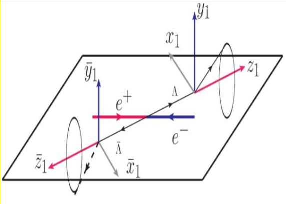


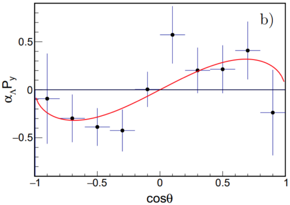


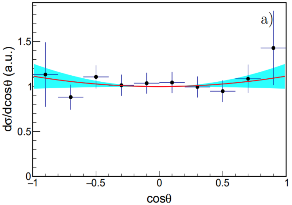


- The non-zero $\sigma^{\rm Born}_{\Lambda\bar{\Lambda}}$ is consistent with previous measurement.
  - Energy scan: $312 \pm 45^{+66}_{-36}$ pb at 2.2324 GeV (1 MeV above threshold),
  - Initial state radiation: $245 \pm 56 \pm 14$ pb in [2.231,2.250] GeV, $283^{+53}_{-55} \pm 15$ pb in [2.25,2.27] GeV.
- Possible structure near the threshold in $\sigma^{\rm Born}_{\Lambda\bar{\Lambda}}$ for $e^+e^- \to K^+K^-K^+K^-$.
  - $m_R = 2232 \pm 3.5$ MeV, $\Gamma_R < 20$ MeV.

Complete measurement of Λ Form Factors at BESIII





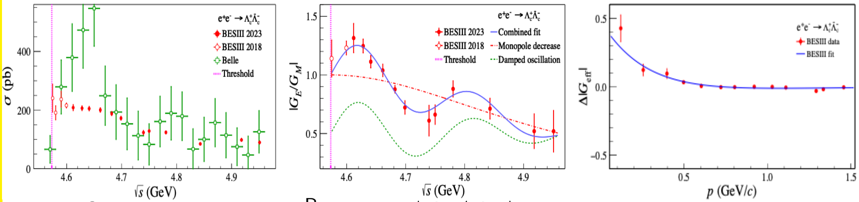


- M. Ablikim *et al.* (BESIII collaboration), PRL **123**, 122003 (2019).
- An event of the reaction $e^+e^- \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ is formalized by joint angular distribution:

$$\omega(\xi, \Delta\Phi, \alpha_-, \alpha_\gamma) = 1 + \alpha_\psi \cos^2\theta_\Lambda \text{ Unpolarized part}$$
$$+\alpha_-\alpha_\gamma[\sin^2\theta_\Lambda(n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y}) + (\cos^2\theta_\Lambda + \alpha_\psi)n_{1,z}n_{2,z}]$$
$$+\alpha_-\alpha_\gamma\sqrt{1-\alpha_\psi^2}\cos(\Delta\Psi)\sin\theta_\Lambda\cos\theta_\Lambda(n_{1,x}n_{2,z} + n_{1,z}n_{2,x}) \text{ Correlated part}$$
$$+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Psi)\sin\theta_\Lambda\cos\theta_\Lambda(\alpha_- n_{1,y} + \alpha_\gamma n_{2,y}). \text{ Polarized part}$$

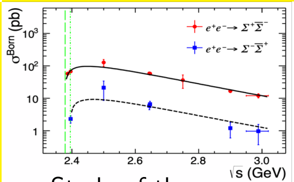
- Confirm the complex form of EMFFs:
  - $|G_E/G_M| = 0.94 \pm 0.14 \pm 0.02$,
  - $\Delta\phi = 37^\circ \pm 12^\circ \pm 6^\circ$.

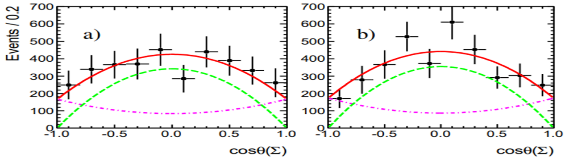
Λ_c Form Factors at BESIII



- BESIII measured the $\sigma^{\mathrm{Born}}_{\Lambda_c^+\bar{\Lambda}_c^-}$ and $|G_E/G_M|$ with unprecedented precision.
  - M. Ablikim *et al.* (BESIII collaboration), arXiv:2307.07316,
  - M. Ablikim *et al.* (BESIII collaboration), PRL **120**, 132001 (2018),
  - Review: Weiping Wang *et al.*, Symmetry **14**, 5 (2022)).
- The $\sigma^{\mathrm{Born}}_{\Lambda_c^+\bar{\Lambda}_c^-}$ plateau is confirmed up to 4.66 GeV and the decay process $Y(4630) \to \Lambda_c^+\bar{\Lambda}_c^-$ is not observed.
- Contradict to the case in proton and neutron, the oscillation feature is not observed in the $|G_{\mathrm{eff}}|$ spectrum of Λ_c^+.
- Oscillation is discerned in $|G_E/G_M|$ distribution of Λ_c^+, but with a significantly different frequency from that of proton.
- Similar to the proton, $|G_E/G_M|$ for Λ_c^+ approach 1 near the threshold.

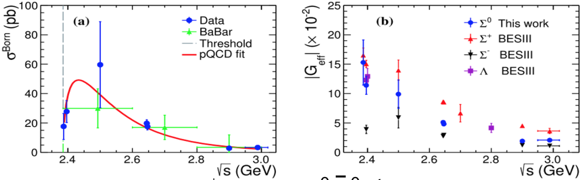
$\Sigma^{\pm}$ Form Factors at BESIII





- Study of the processes $e^+e^- \to \Sigma^+\bar{\Sigma}^-$ and $e^+e^- \to \Sigma^-\bar{\Sigma}^+$ M. Ablikim *et al.* (BESIII collaboration), PLB **814**, 136110 (2021), M. Irshad *et al.*, Symmetry **14**, 69 (2022)).
  - $\sqrt{s}$ from 2.3864 - 3.0200 GeV, (330 pb^{-1}).
  - Nonzero $\sigma^{Born}_{\Sigma^{\pm}\bar{\Sigma}^{\mp}}$ is observed near threshold, no significant enhancement.
  - $\sigma^{Born}_{\Sigma^{\pm}\bar{\Sigma}^{\mp}}$ near threshold disagree with the point-like expectations (e.g. p).
- $|G_E/G_M|$ of Σ^+ is determined for the first time, with study of angular distribution at three high-statistic points:
  - $|G_E/G_M| = 1.83 \pm 0.26$ @2.396 GeV, > 1 near threshold, similar to p, Λ.
- $\frac{\sigma^{Born}_{e^+e^- \to \Sigma^+\bar{\Sigma}^-}}{\sigma^{Born}_{e^+e^- \to \Sigma^-\bar{\Sigma}^+}} = 9.7 \pm 1.3$:
  - Consist: G. Ramalho *et al.*, PRD **101**, 014014 (2020).
  - Inconsistent: V .L. Chernyak *et al.*, Phys. Rept **112**, 173 (1984), V. L. Chernyak *et al.*, Z. Phys. C **42**, 569 (1989), M. Anselmino *et al.*, RMP **65**, 1199 (1993), R. Jaffe *et al.*, PRL **91**, 232003 (2003), R. L. Jaffe, Phys. Rept **409**, 1 (2005).

Σ^0 Form Factors at BESIII

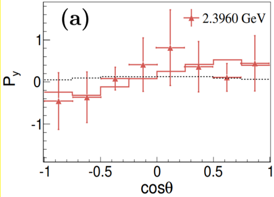


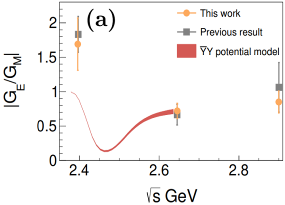
- Study of the processes $e^+e^- \to \Sigma^0\bar{\Sigma}^0$ (M. Ablikim *et al.* (BESIII collaboration), PLB **831**, 137187 (2022)):
  - $\sqrt{s}$ from 2.3864 - 3.0200 GeV, (329 pb^{-1}).
  - Near threshold: Novel method is applied at 2.3864 and 2.3960 GeV.
  - No significant threshold effect is observed similar to $\sigma^{\text{Born}}_{\Sigma^\pm\bar{\Sigma}^\mp}$.
  - Single-tag baryon technique is applied at $\sqrt{s}$ from 2.3960 - 3.0200 GeV.
  - Good agreement with *BABAR*, precision is improved significantly.
  - $\sigma^{\text{Born}}_{\Sigma\bar{\Sigma}}$ can be well described by pQCD-motivated function:

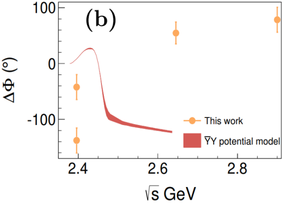
$$\sigma^{\text{Born}}_{\Sigma\bar{\Sigma}} = \frac{\beta(s)C}{s}\left(1+\frac{2m_{\Sigma}^2c^4}{s}\right)\frac{c_0}{(s-c_1)^4\left[4\ln^2\left(\frac{\sqrt{s}}{a_0}\right)+\pi^2\right]^2}$$

- An asymmetry in $\sigma^{\text{Born}}_{\Sigma\bar{\Sigma}}$ Σ triplet:
  - $(9.7\pm1.3) : (3.3\pm0.7) : 1$, related with valence quark?
- $|G_{\text{eff}}|$ result provide experimental inputs, $Y\bar{Y}$ potential model, and understanding of di-quark correlation (J. Haidenbauer *et al.*, PRD **103**, 014028 (2021)).

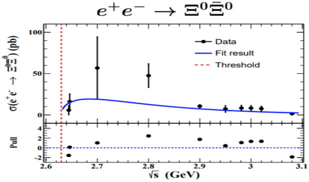
Complete measurement of Σ^+ Form Factors at BESIII

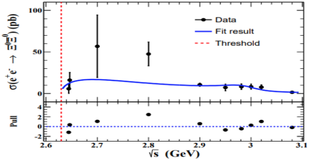


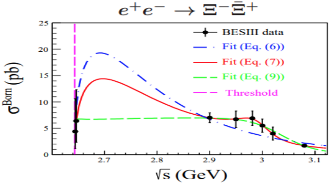


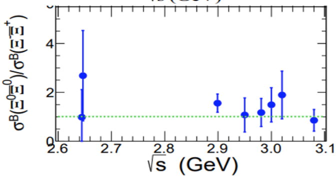


- M. Ablikim *et al.* (BESIII collaboration), arXiv:2307.15894.
- An event of the reaction $e^+e^- \to \Sigma^+(\to p\pi^0)\bar{\Sigma}^-(\to \bar{p}\pi^0)$ is formalized by joint angular distribution.
- Polarization is observed at 2.396, 2.644 and 2.90 GeV with a significance of 2.2σ, 3.6σ and 4.1σ.
- Relative phase is determined for the first time in a wide q^2 range.
- $|G_E/G_M|$ and $\Delta\Phi$ line-shape is compared with $Y\bar{Y}$ model (J. Haidenbauer *et al.*, PRD **103**, 014028 (2021)), 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.

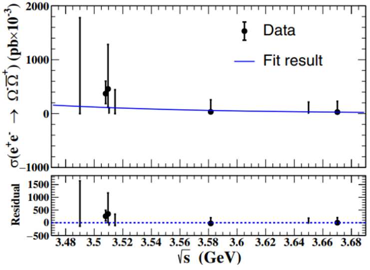


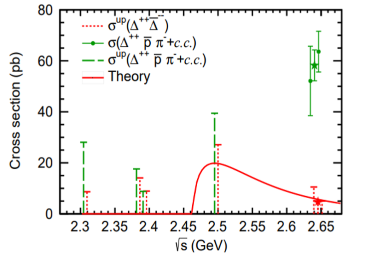






- First study for $e^+e^- \to \Xi\bar{\Xi}$ production near threshold:
  - $e^+e^- \to \Xi^-\bar{\Xi}^+$: M. Ablikim *et al.* (BESIII collaboration), PRD **103**, 012005 (2021),
  - $e^+e^- \to \Xi^0\bar{\Xi}^0$: M. Ablikim *et al.* (BESIII collaboration), PLB **820**, 136557 (2021),
  - Review: Xiongfei Wang *et al.*, Symmetry **14**, 65 (2022)).
  - $\sqrt{s}$ from 2.6444 - 3.0800 GeV, (360 pb^{-1}).
- No obvious $\Xi^-\bar{\Xi}^+$ and $\Xi^0\bar{\Xi}^0$ threshold enhancement is observed.
- $\frac{\sigma^{Born}_{\Xi^0\bar{\Xi}^0}}{\sigma^{Born}_{\Xi^-\bar{\Xi}^+}}$ agrees with the expectation of isospin symmetry.





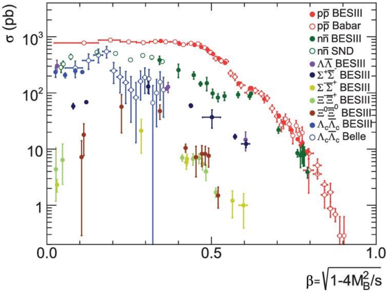
- Study for $e^+e^- \to \Omega^-\bar{\Omega}^+$ production near threshold:
  - M. Ablikim *et al.* (BESIII collaboration), PRD **107**, 052003 (2023)
  - 8 energy points $\sqrt{s}$ from 3.49 - 3.67 GeV.
  - No significant signal observed.
  - Upper limit of G_{eff} is consistent with pQCD driven prediction.
- Study for $e^+e^- \to \Delta^{++}\bar{\Delta}^{--}$ production near threshold:
  - M. Ablikim *et al.* (BESIII collaboration), arXiv:2305.12166.
  - 5 energy points $\sqrt{s}$ from 2.3094 - 2.6464 GeV.
  - No significant signal observed, but signal for $e^+e^- \to \Delta^{++}p\pi^-$ observed.

Summary

Summary

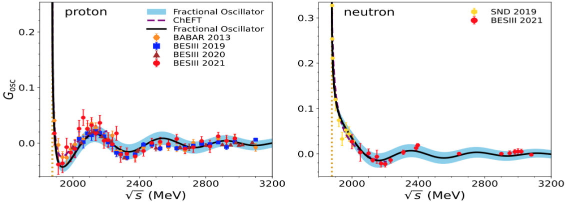
- Fruitful physics results of EMFFs from e^+e^- colliders, via energy scan and ISR methods.
- Conventional parameterization of EMFFs is facing challenge from experimental observations (threshold effect, oscillation in reduced FFs and $|G_E/G_M|$ ratio).
- Relative phase and pQCD are authenticated.
- Periodic structure of EMFFs gives rise to polarization of final baryons, and will play an important role in distinguishing various theoretical models.

- The asymptotic behavior of baryon EMFFs have been tested, and the asymptotic threshold is not yet reached.

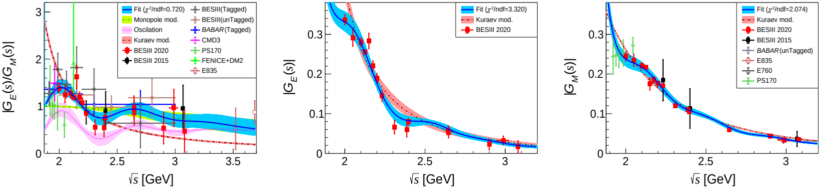


Danke für Ihre Aufmerksamkeit!

Phenomenological explanations for oscillation behavior



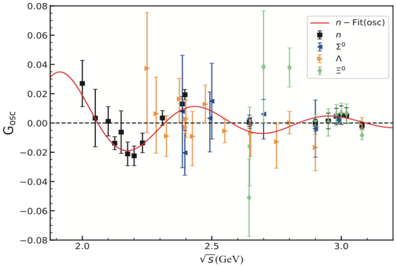
- Distorted wave Born approximation: EMFFs of p and n are described by two fractional oscillators. (Q. H. Yang *et al.*, arXiv: 2206.01494)
  - 'overdamped' dominates near the threshold;
  - 'underdamped' plays an important role in the high-energy region.



- Periodic behavior of $|G_E/G_M|$, $|G_E|$ and $|G_M|$ is also observed (E. Tomasi-Gustafsson *et al.*, PRD **103**, 035203 (2021), Lei Xia *et al.*, Symmetry **14**, 231 (2022)).

New explanations of oscillation of $|G_{\rm eff}|$

$$G_D(q^2) = \frac{c_0}{(1-\gamma q^2)^2},\ G^{\rm osc}(q^2) = A\frac{c_0}{(1-\gamma s)^2}\cos(C\sqrt{s}+D).$$



A. X. Dai *et al.*, CPC **46**, 073104 (2022).

- Oscillation makes the χ^2 of fitting smaller.
- As the mass of baryon larger:
  - A become larger,
  - C become smaller.

Parameter	p	n	Λ	Σ^0	Ξ^0
γ	0.82 ± 0.04	1.41 (fixed)	0.34 ± 0.08	0.26 ± 0.01	0.21 ± 0.02
c_0	1.44 ± 0.18	3.48 ± 0.06	0.11 ± 0.01	0.033 ± 0.007	0.023 ± 0.008
χ^2/dof	3.9	4.3	2.4	1.1	2.0
A	10.2 ± 1.2	17.6 ± 2.7	17.6 (fixed)	19.9 ± 10.2	23.2 ± 9.6
C	17.2 ± 0.5	12.2 ± 0.6	12.2 (fixed)	11.9 ± 1.1	10.6 ± 2.2
D	1.09 ± 1.06	1.66 ± 1.41	2.37 ± 1.88	0.99 ± 3.13	1.34 ± 6.39
χ^2/dof	1.8	1.4	0.6	0.4	1.9

New explanations of oscillation of $|G_{\rm eff}|$

X. Cao *et al.*, Phys. Rev. D **105**, L071503 (2022)
Y. H. Lin *et al.*, Phys. Rev. Lett **128**, 052002 (2022)

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,‡]

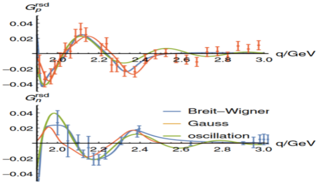


FIG. 1. The fit of the Breit-Wigner distribution and the Gauss distribution to three local structures below 2.5 GeV in comparison with BESIII data [16,18].

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]

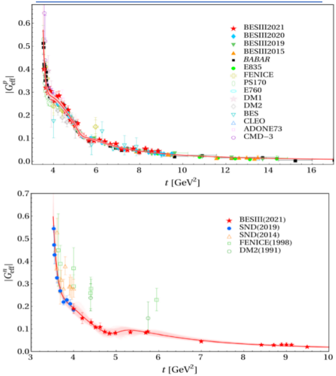
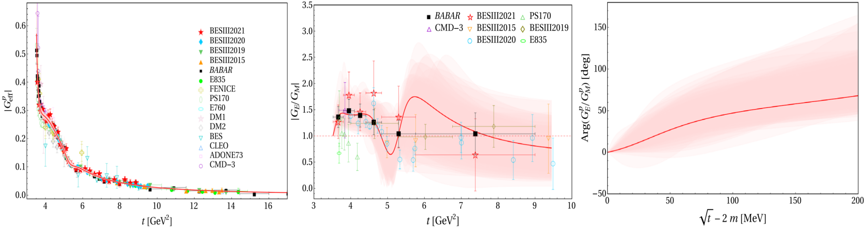


FIG. 1. Complete fit to space- and timelike data with bootstrap error (shaded band) compared to data for $|G_{\rm eff}|$ of the proton (upper) and neutron (lower). Fitted data are depicted by closed symbols; data given by open symbols are shown for comparison only (see Supplemental Material [15] for explicit references).

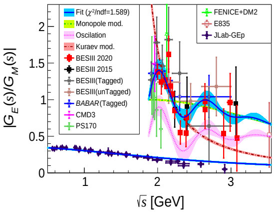
Impact on the charge radius of proton

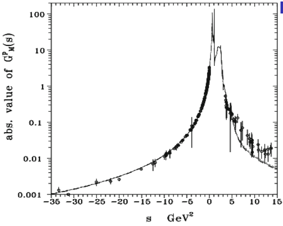
Recent results of Baryon electromagnetic form factors at BESIII

Lei Xia



- Test for dispersion theory, perform a high-precision extraction of the nucleon radii (Y. H. Lin *et al.*, PRL **128**, 052002 (2022)).
- TL-SL joint fit provide new sight on nucleon radii(M. Yu. Barabanov *et al.*, Prog. Part. Nucl. Phys. **116**, 103835 (2021), L. Xia *et al.*, Symmetry **14**, 231 (2022)).

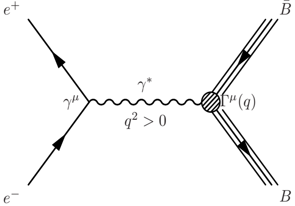




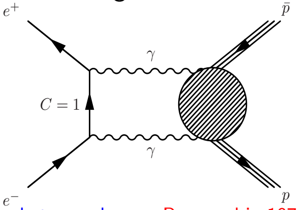
- Verifying different theoretical models: chiral pQCD and lattice QCD (A. Z. Dubničková *et al.*, EPJA **57**, 307 (2021), A. Zuzana *et al.*, arXiv: 2010.15872, S. Dubnička *et al.*, arXiv: 2103.08385).

Two-Photon Exchange

- Two-photon exchange VS One-photon exchange:



One-photon exchange.



Two-photon exchange. Proposed in 1970s. (V. BoiPhytsov *et al.*, Sov. J. Nucl. Phys. **16**, 287 (1972)). (V. Franco, PRD **8**, 826 (1973)). (F. Lev, Sov. J. Nucl. Phys. **21**, 145 (1975)).

- One-photon Exchange:

$$J_\mu = \frac{e^2}{q^2}\bar{u}(k_2)\gamma_\mu u(k_1)\bar{u}(p_2)[\gamma_\mu F_1(q^2) - \frac{\sigma_{\mu\nu}}{2m_p}F_2]u(p_1).$$

- Two-photon Exchange:

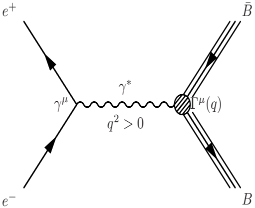
$$J_\mu = \frac{e^2}{q^2}\bar{u}(k_2)\gamma_\mu u(k_1)\bar{u}(p_2)[\gamma_\mu \mathcal{A}_1(s,q^2) - \frac{\sigma_{\mu\nu}}{2m_p}\mathcal{A}_2(s,q^2) + \hat{K}P_\mu \mathcal{A}_3(s,q^2)]u(p_1).$$

- Connection: 4 real amplitudes $\rightarrow$ 6 complex amplitudes.

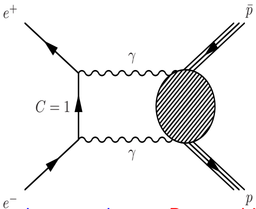
$$\mathcal{A}_1(s,q^2) \rightarrow F_1(q^2), \mathcal{A}_2(s,q^2) \rightarrow F_2(q^2), \mathcal{A}_3(s,q^2) \rightarrow 0.$$

Two-Photon Exchange

- Two-photon exchange VS One-photon Exchange:



One-photon exchange.



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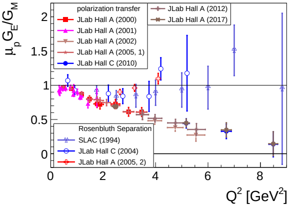
(V. BoiPhytsov *et al.*, Sov. J. Nucl. Phys. **16**, 287 (1972)).
(V. Franco, PRD **8**, 826 (1973)).
(F. Lev, Sov. J. Nucl. Phys. **21**, 145 (1975)).



Two-photon exchange in SL.

One-photon exchange	Two-photon exchange
Complex $F_i(q^2)$	Complex $\mathcal{A}_i(s, q^2)$
$J^{PC} = 1^{--}$	$J^{PC} \neq 1^{--}$, with only $C = +1$ known
$\frac{\sigma(e^+p)}{\sigma(e^-p)} = 1$	$\frac{\sigma(e^+p)}{\sigma(e^-p)} \neq 1$
$\frac{\mu_p G_E}{G_M} \sim 1$	$\frac{\mu_p G_E}{G_M}(q^2)$
$\frac{d\sigma_{p\bar{p}}}{d\Omega} = a(q^2) + b(q^2)\cos^2\theta$	$\frac{d\sigma^{int}_{p\bar{p}}}{d\Omega} = \cos\theta[c_0(q^2) + c_1(q^2)\cos^2\theta + c_2(q^2)\cos^4\theta + ...]$

- Angular distribution access to interference.