Study of hyperon form factor at BESIII

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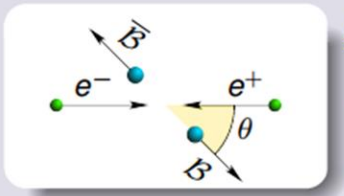
Outline

- Introduction
- Production and internal structures of hyperons:
  - $\boldsymbol{e^+e^- \to \Lambda\bar{\Lambda}}$
  - $\boldsymbol{e^+e^- \to \Lambda_c\bar{\Lambda}_c}$
- Summary

Baryon production from e^+e^- annihilation



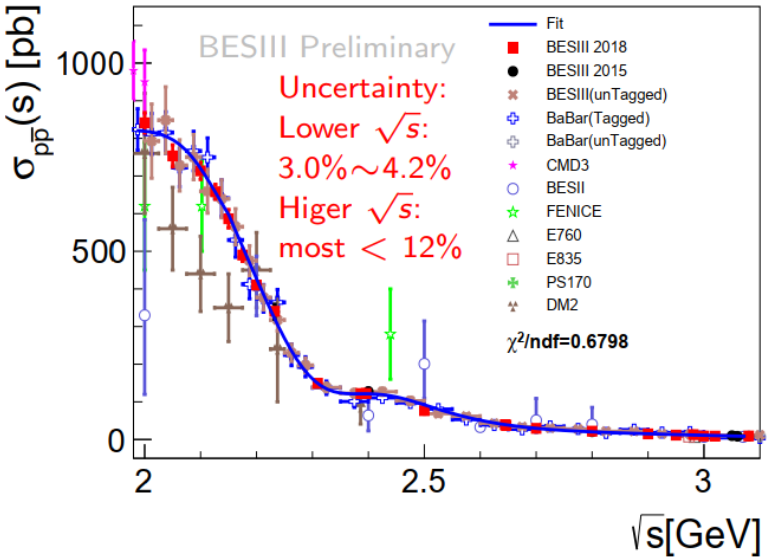
Annihilation **Coulomb correction**

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta C}{4q^2}\left[(1+\cos^2\theta)|G_M|^2 + \frac{1}{\tau}\sin^2\theta|G_E|^2\right]$$

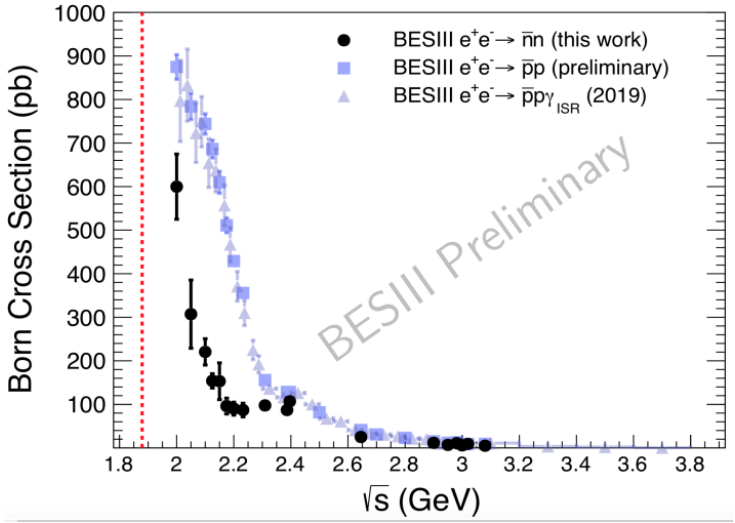
S-wave: $C = \dfrac{\frac{\pi\alpha}{\beta}}{1-\exp\left(-\frac{\pi\alpha}{\beta}\right)} \xrightarrow{\beta\to 0} \dfrac{\pi\alpha}{\beta}$

D-wave: $C = 1$

$e^+e^- \to p\bar{p}$ (arxiv:1905.09001)



$e^+e^- \to n\bar{n}$ (preliminary)

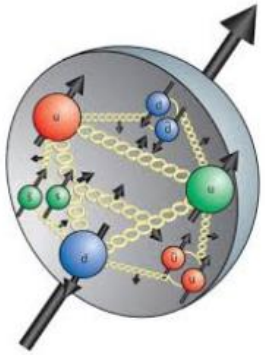


Analyticity → $G_S(4M_B^2) \neq 0$, $G_D(4M_B^2) = 0$
Hence:

- charged baryons σ should show a step @ threshold:
  1/β factor cancels the phase space β
- neutral baryons $\sigma \sim \beta \to 0$ @ threshold

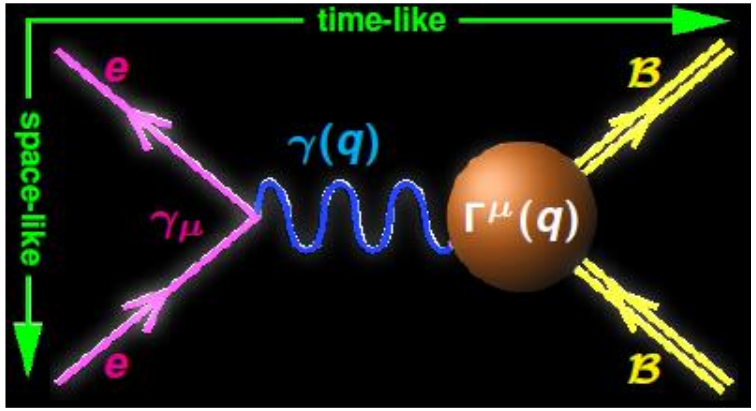
- For $e^+e^- \to p\bar{p}$ close threshold, σ~850 pb → $|G_E^p(4M_p^2)| = |G_E^p(4M_p^2)|$~1, $p\bar{p}$ pairs at threshold behave as pointlike fermions?
- For $e^+e^- \to n\bar{n}$ close threshold, $\sigma \neq 0$?
- Resonances, FSI or other effects on the mass spectrum of $B\bar{B}$?

Electromagnetic Form Factors (FF)



Hadrons are not point-like particles

- internal structure
- internal dynamics: $M_{hadron} \neq \Sigma m_{q\text{-valence}}$
- the vertex Γ_μ contains the unknown structure
- FFs parametrize structure and internal dynamics
- 2 FFs needed for S=½ baryons



- Time-like FF's are complex, $G_E = |G_E|e^{i\Phi_M}$, $G_M = |G_M|e^{i\Phi_M}$
  Relative phase: $\Delta\Phi(q^2) = \Phi_E - \Phi_M$
- A non-zero phase has polarization effect on the Baryons, even for unpolarized initial state*: $P_y \propto \sin\Delta\Phi$
- Phase is **production related** and depends on q^2.

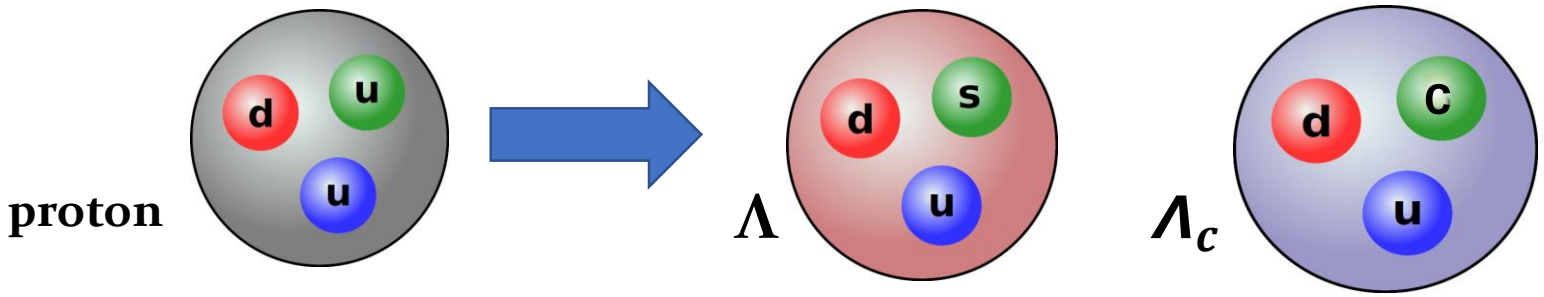
  Constraint 1: Phase result of interfering amplitudes (*e.g. s-* and *d* waves)
  → $\Delta\Phi(q^2) = 0$ at threshold

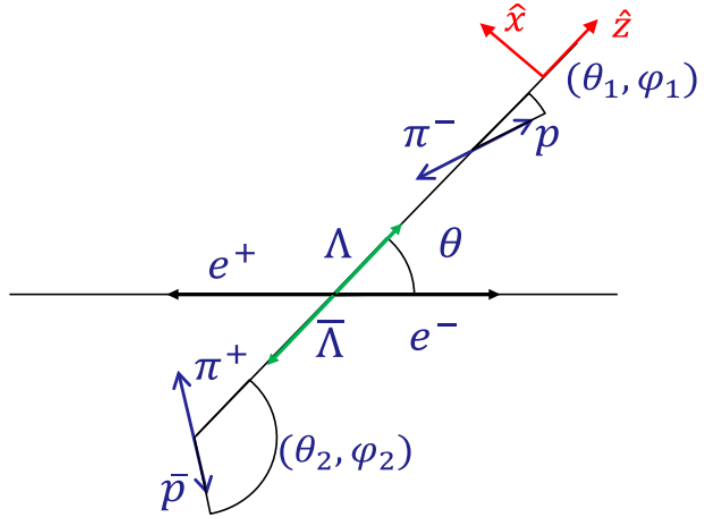
  Constraint 2: Analyticity requires TL FF ~ SL FF as $|q^2| \to \infty$ **,***
  → $\Delta\Phi(q^2) \to 0$ as $|q^2| \to \infty$

✓$\Delta\Phi(q^2)$ cannot be measured for nucleon produced at BESIII (no detection of polarization).

*Nuovo Cim. A **109** (1996) 241.
** Theor. Mat. Fiz. **15** (1973) 332.
*** Phys. Rev. Lett. 31 (1973) 1153.

Hyperons – key to the strong interaction





- **Polarization experimentally accessible by the weak, parity violating.** The angular distribution of daughter baryon from Hyperon weak decay is: $\frac{d\sigma}{d\Omega} \propto 1 + \alpha_\Lambda \boldsymbol{P_y} \cdot \hat{\boldsymbol{q}}$
  - α_Λ: asymmetry parameter
  - $\hat{q}$: unit vector along the daughter baryon in hyperon rest frame
- Systems with strangeness
  - Scale: $m_s \approx 100$ MeV ~ $\Lambda_{QCD} \approx 200$ MeV: Relevant degrees of freedom?
  - **Probes QCD in the confinement domain.**
- Systems with charm
  - Scale: $m_c \approx 1300$ MeV: Quarks and gluons more relevant.
  - **Probes QCD just below pQCD.**

Example: Angular distribution of $\Lambda \rightarrow p\pi^-$

$I(\cos\theta_p) = N(1+\alpha_\Lambda P_\Lambda \cos\theta_p)$

$P_\Lambda = P_\Lambda(\cos\theta_\Lambda)$: polarisation (production)

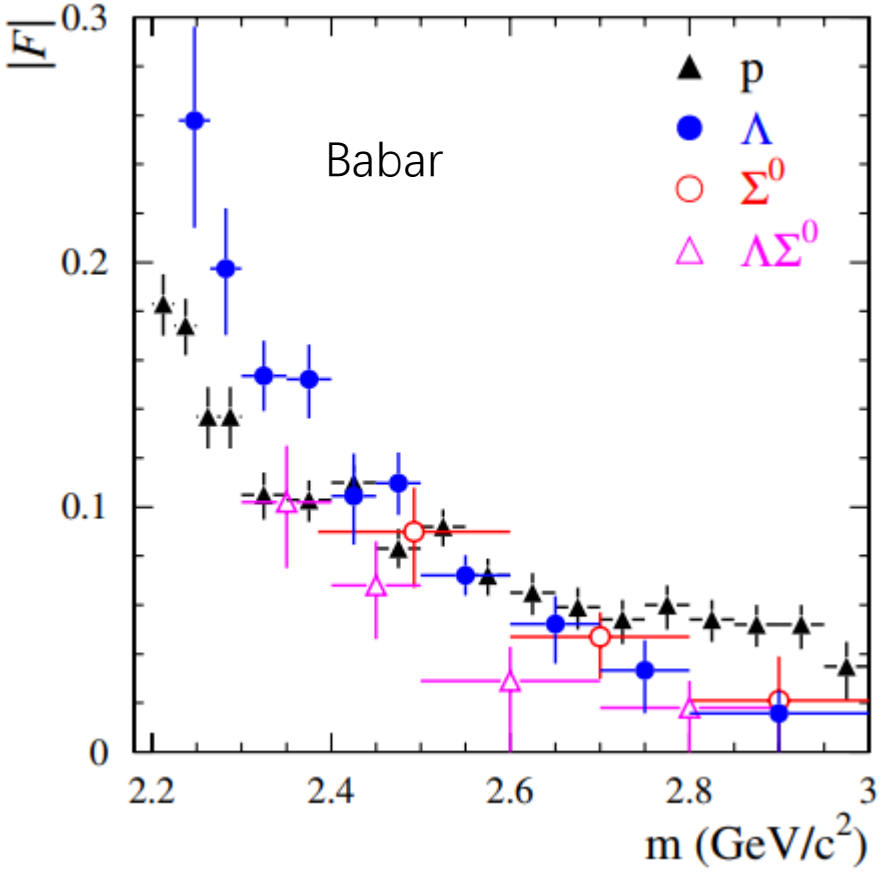
α_Λ : asymmetry parameter (decay)

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 !

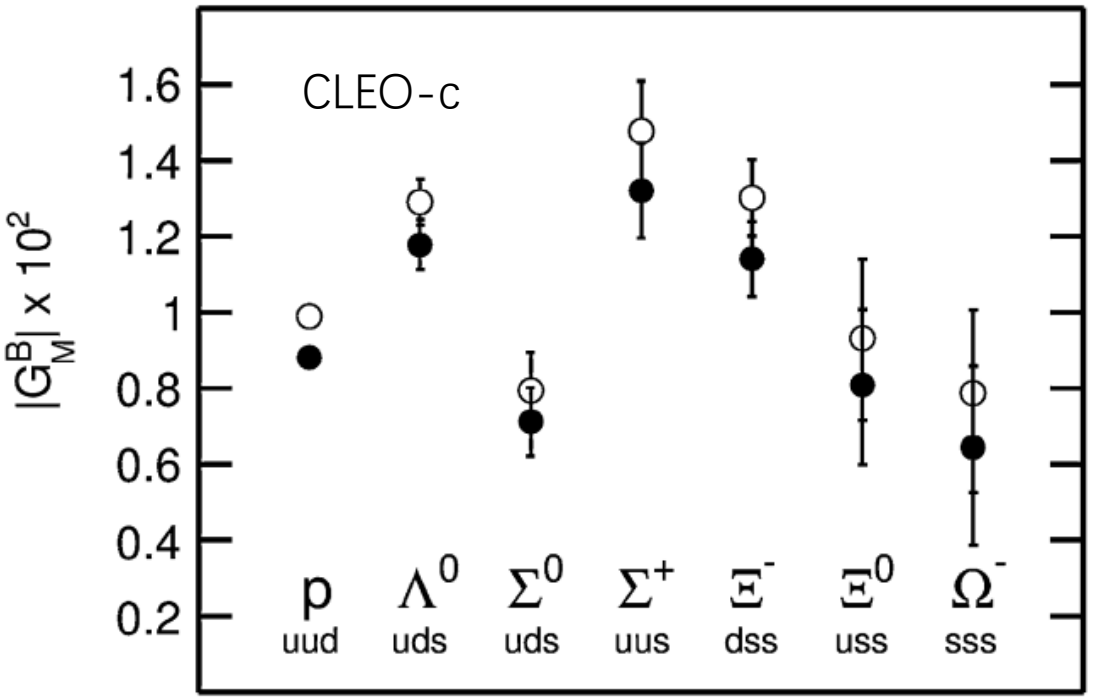
Status on hyperon FFs

Rare experimental results on Hyperon FF

Phys. Rev. D **76,** 092006 (2007)



Phys. Lett. B 739 (2014) 90–94



q^2=14.2 GeV^2

- diquark correlation evidence
- favor spin–isospin singlet

Complete measurement of Λ EMFFs @ q=2.396 GeV

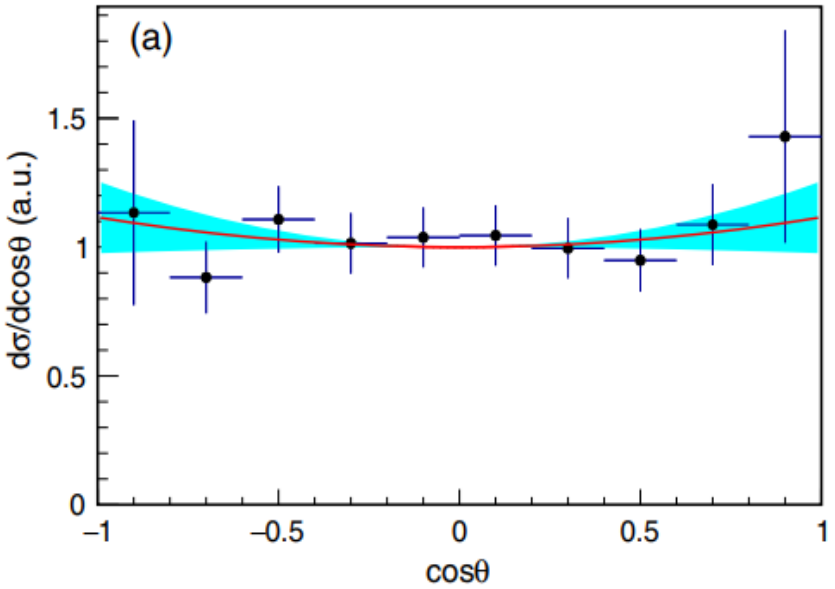
An event of the reaction $e^+e^- \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ is specified by the five dimensional vector $\xi = (\theta, \Omega_1, \Omega_2)$, the differential cross section is:

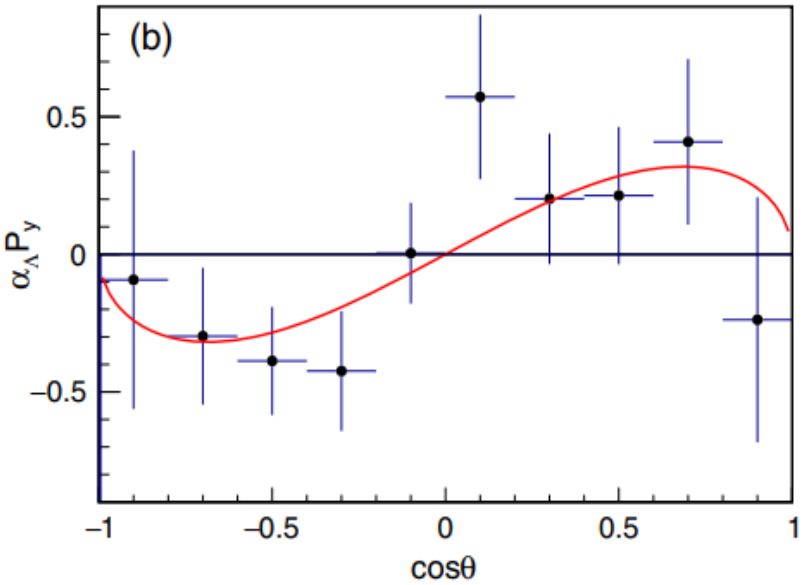
Phys. Lett. B 772, 16 (2017)
Phys. Rev. Lett. 123, 122003 (2019)

$$\mathcal{W}(\xi) = \mathcal{T}_0(\xi) + \eta\,\mathcal{T}_5(\xi) \longrightarrow \text{scattering angle distribution of } \Lambda$$

$$-\alpha_\Lambda^2\left(\mathcal{T}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,\mathcal{T}_2(\xi) + \eta\,\mathcal{T}_6(\xi)\right) \longrightarrow \text{the spin correlations between the two hyperons.}$$

$$+\alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)\,(\mathcal{T}_3(\xi) - \mathcal{T}_4(\xi)). \longrightarrow \text{transverse polarization } P_y \text{ of the } \Lambda \text{ and } \bar{\Lambda}$$





$$P_y = \frac{\sqrt{1-\eta^2}\sin\theta\cos\theta}{1+\eta\cos^2\theta}\sin(\Delta\Phi)$$

- σ= 118.7±5.3(stat)±5.1(syst) pb
- |G|= 0.123±0.003(stat) ±0.003(syst)
- R=|G_E/G_M|=0.96±0.14(stat) ±0.02(syst)
- $\Delta\Phi = 37^o \pm 12^o(\text{stat}) \pm 6^o(\text{syst})$

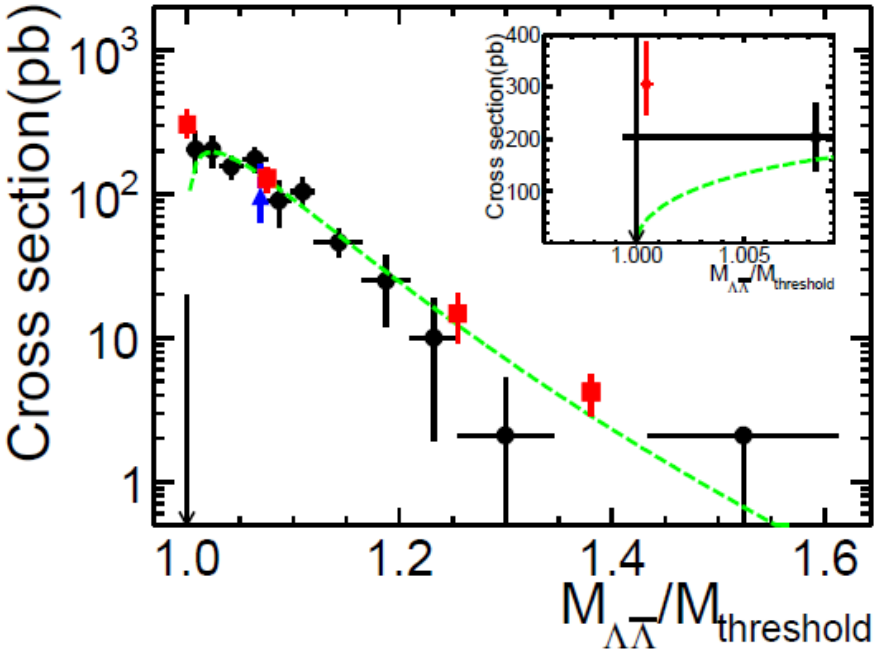
Non-zero phase means: not only the s-wave but also the d-wave amplitude contribute to the production
interference between s-d waves results in a polarized final state.

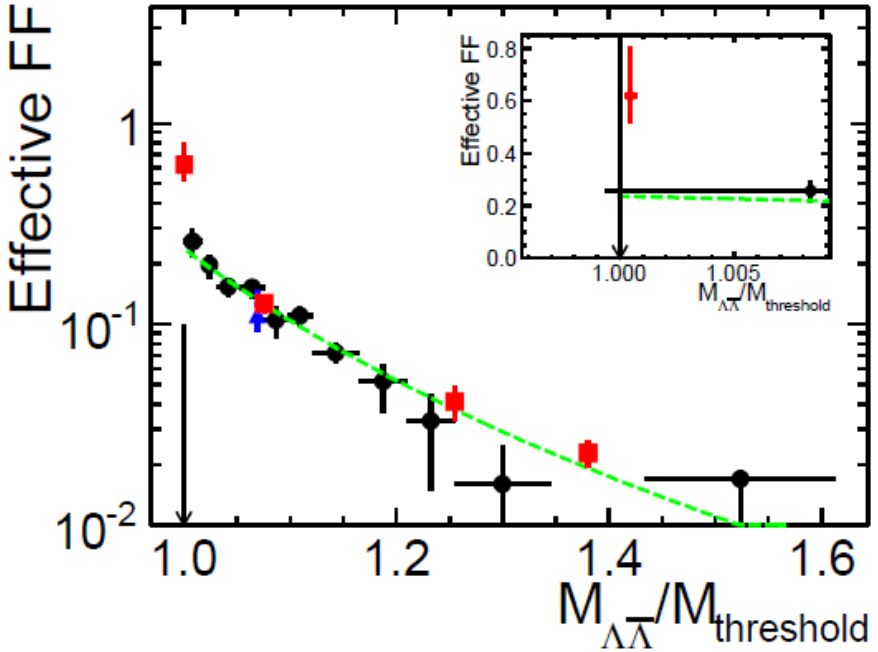
The first complete hyperon EMFF measurement, and a milestone in the study of hyperon structure.

Measurement of $e^+e^- \to \Lambda\bar{\Lambda}$ @ q=2.2324 ~ 3.08 GeV

Phys. Rev. D 97, 032013 (2018)

- $\mathcal{L}$ = 40.5 pb^{-1} @ 4 CM energies: 2.2324, 2.4, 2.8 and 3.08 GeV:
  - 2.2324 GeV is just 1 MeV above the $M_{\Lambda\bar{\Lambda}}$ threshold!
- **σ and $|G_{eff}|$ near threshold and small PHSP**
  - $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$: indirect search for the antiproton
  - $\Lambda \to X$, $\bar{\Lambda} \to \bar{n}\pi^0$: Λ inclusive decays, search for mono-energetic π^0
- For other energies, full reconstruction

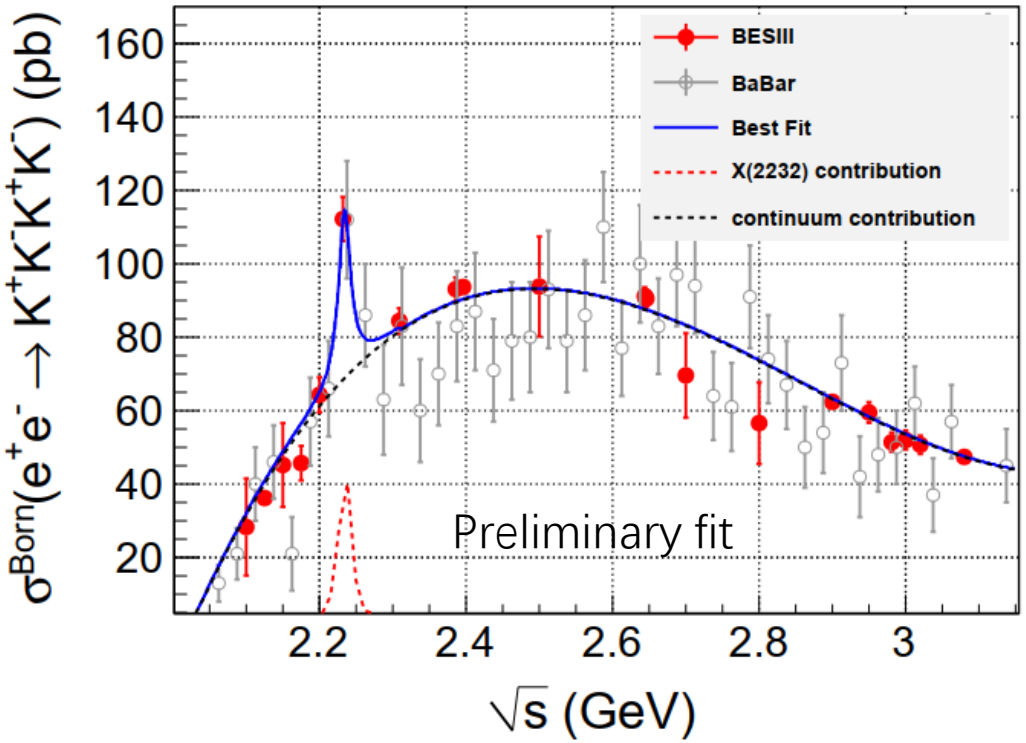


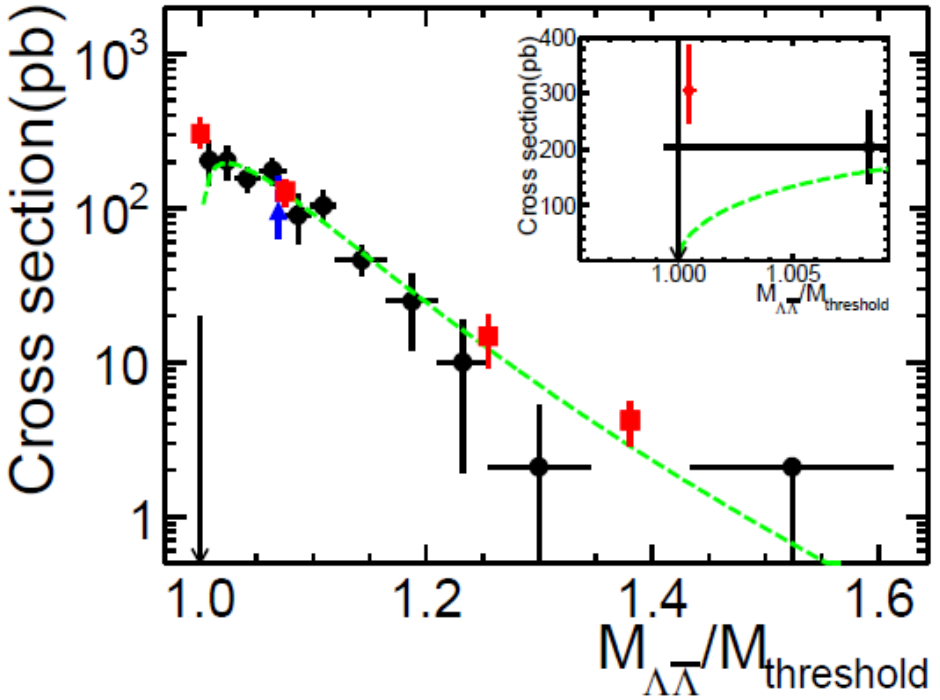


No Coulomb effect for neutral baryons BUT **unexpected rise at the threshold !!!**

A possible resonance around $\Lambda\bar{\Lambda}$ resonance?

Phys. Rev. D 100, 032009 (2019)



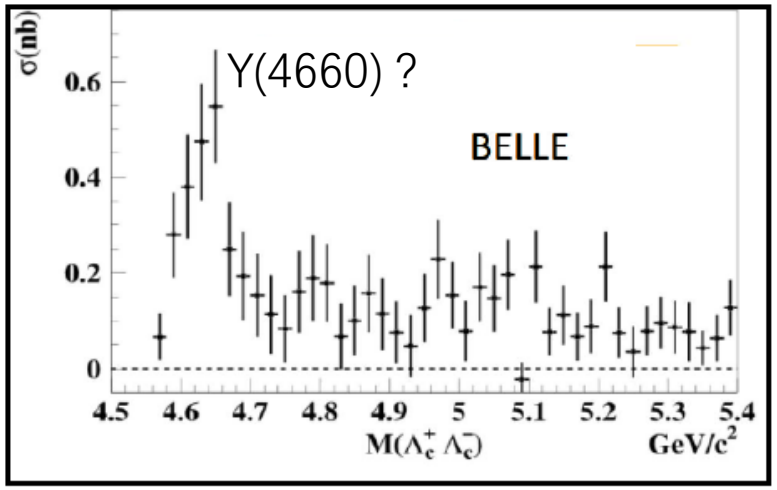


A hint for resonance around $\Lambda\bar{\Lambda}$ threshold in $e^+e^- \to KKKK$ cross section

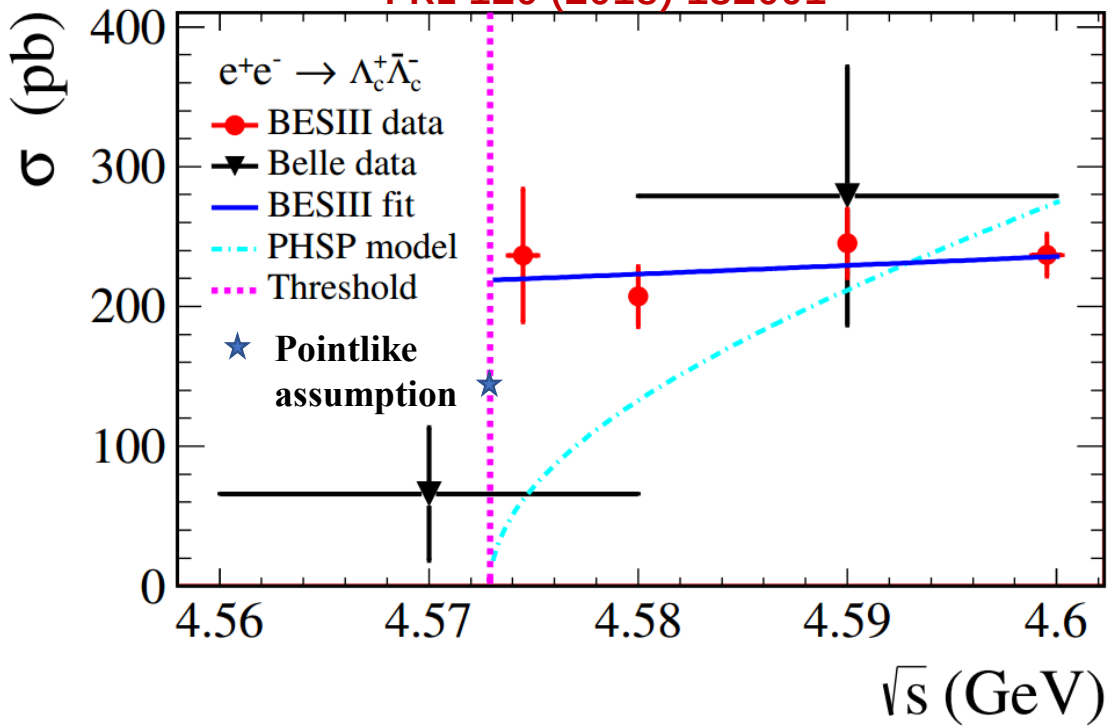
- Mass=2232±3.5 MeV， width=20 MeV

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

PRL 101 (2010) 172001



PRL 120 (2018) 132001



- the Λ_c weak decay allows for the experimental detection of $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ with good efficiency even right at threshold
- single tag method: only one of the baryons is reconstructed
- 10 Cabibbo-favored + c.c. hadronic decay modes considered
- total cross section: weighted average over all the 20 decay modes
- very high precision achieved (1.3% @ 4.6 GeV)

$\sqrt{s}$ (MeV)	$\mathcal{L}_{\rm int}$ (pb^{-1})	$f_{\rm ISR}$	σ (pb)
4574.5	47.67	0.45	$236 \pm 11 \pm 46$
4580.0	8.54	0.66	$207 \pm 17 \pm 13$
4590.0	8.16	0.71	$245 \pm 19 \pm 16$
4599.5	566.93	0.74	$237 \pm 3 \pm 15$

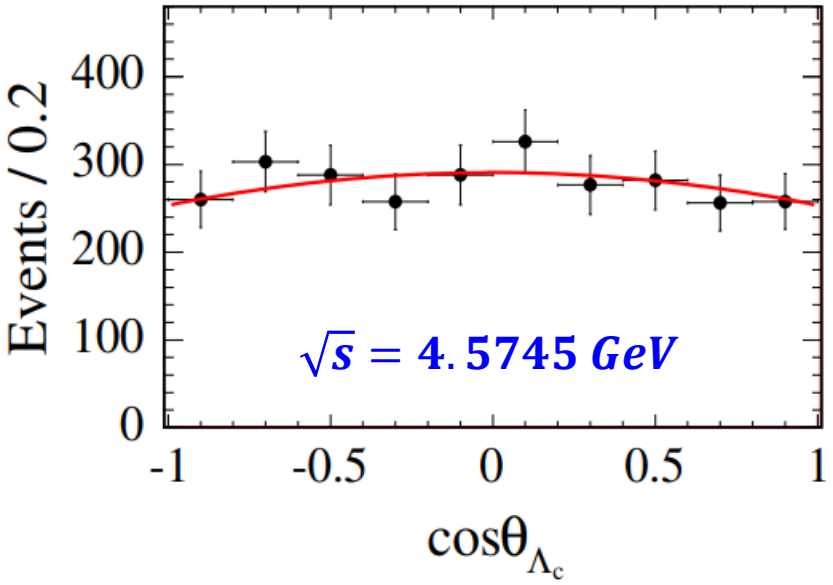
- $e^+e^- \to \Lambda_c\bar{\Lambda}_c$ behavior is similar to $e^+e^- \to p\bar{p}$: different with that from BELLE
- strong enhancement at threnshold followed by a plateau

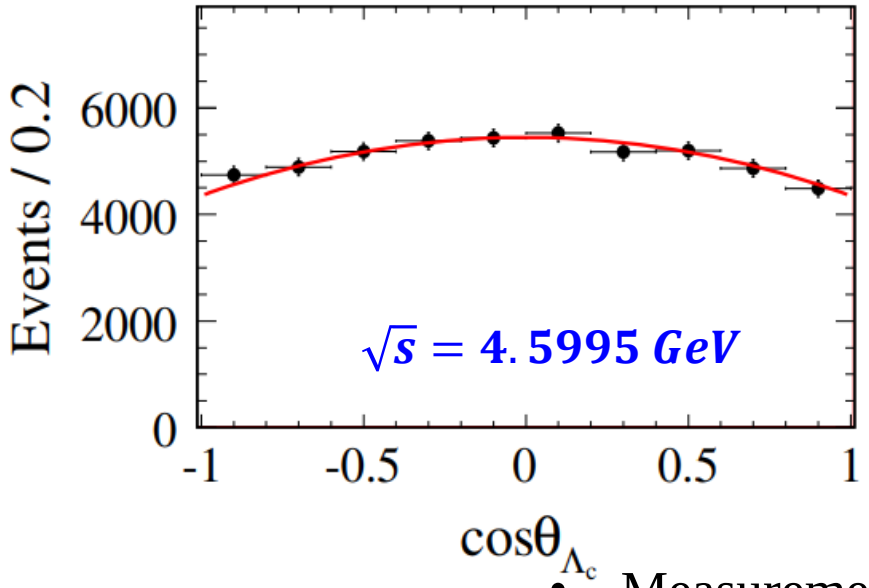
- $\sigma(e^+e^- \to \Lambda_c\bar{\Lambda}_c) \sim \frac{\pi^2\alpha^3}{2M_B} \sim$ 145 pb from pointlike assumption

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

PRL 120 (2018) 132001

- differential cross section, evaluated in the $\Lambda_c\bar{\Lambda}_c$CM, fitted by $1 + \alpha_{\Lambda_c} cos^2\theta$
- $|G_E| / |G_M|$ extracted from the equation $|\frac{G_E}{G_M}|^2(1-\beta^2) = (1-\alpha_{\Lambda_c})/(1+\alpha_{\Lambda_c})$





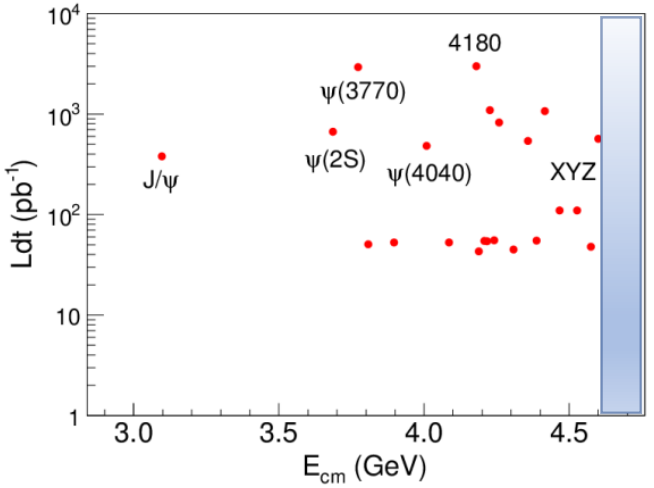
$\sqrt{s}$ (MeV)	α_{Λ_c}	$\lvert G_E/G_M \rvert$
4574.5	$-0.13 \pm 0.12 \pm 0.08$	$1.14 \pm 0.14 \pm 0.07$
4599.5	$-0.20 \pm 0.04 \pm 0.02$	$1.23 \pm 0.05 \pm 0.03$

- Measurement of the Born cross section at 4 energy points below 4.6 GeV with **unprecedented statistical accuracy** (~1.3% at 4.6 GeV)
- **$|G_E| / |G_M|$ measured for the first time!**
- **more data needed @ 4.6 GeV by BESIII**

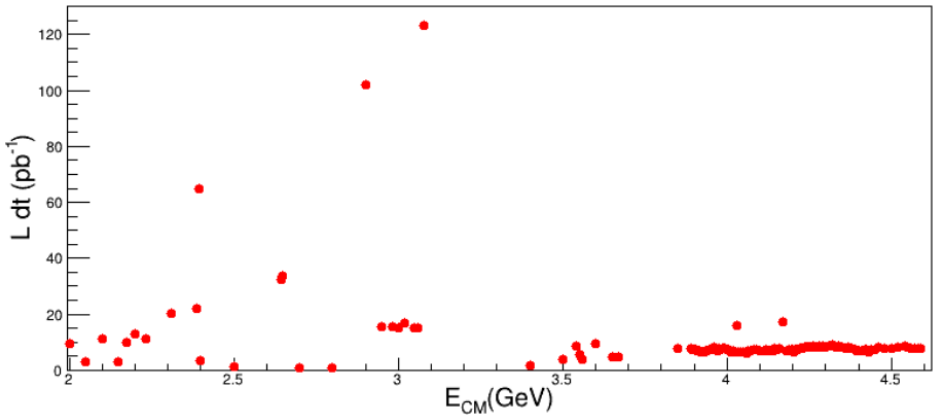
Summary

- With the large data set, precise results on Hyperon FFs and the first full measurement of $e^+e^- \to \Lambda\bar{\Lambda}$ have been done.
  - $e^+e^- \to \Lambda\bar{\Lambda}$
  - $e^+e^- \to \Lambda_c\bar{\Lambda}_c$

- With more data sets in the future, more precise results are expected at BESIII.
  - More precise cross section line-shape
  - Test on threshold effect
  - Complete determination of G_E and G_M
- Long time goal: to describe charge and magnetization densities for hyperons in the same way as for nucleons



500 pb^{-1} data at 4 energy points E_{cm}>4.6 GeV coming



Thanks for your attention!