Hyperon Form Factors

Viktor Thorén, Uppsala University
on behalf of the BESIII collaboration

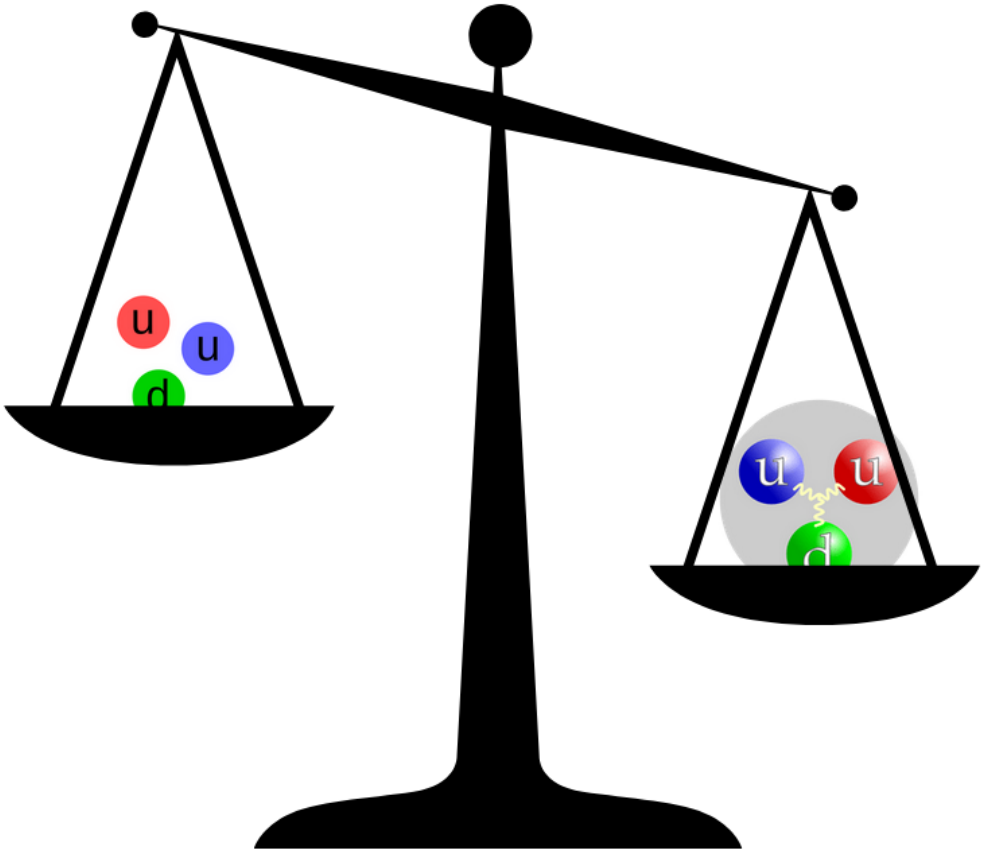
International Conference on Quarks and Nuclear Physics 2022
Online
2022-09-06

UPPSALA
UNIVERSITET

The Strong Interaction

Non-perturbative effects manifest in:

- Spin
- Mass
- **Structure** ← **Our focus**



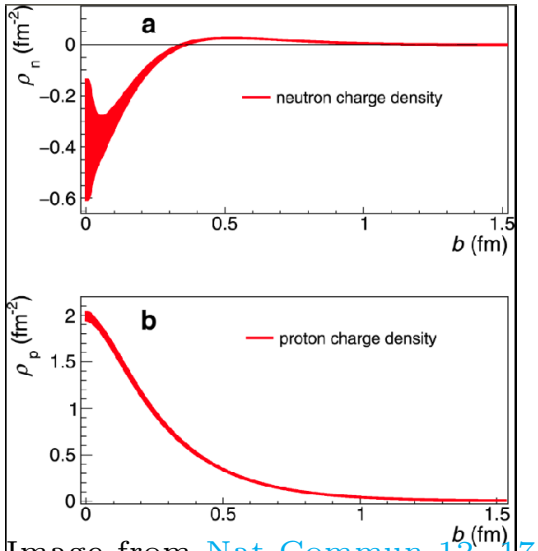


Image from Nat Commun 12, 1759 (2021).

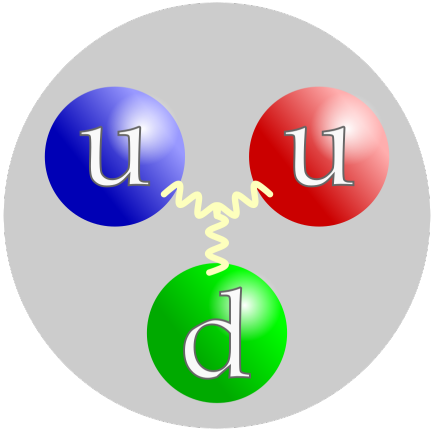
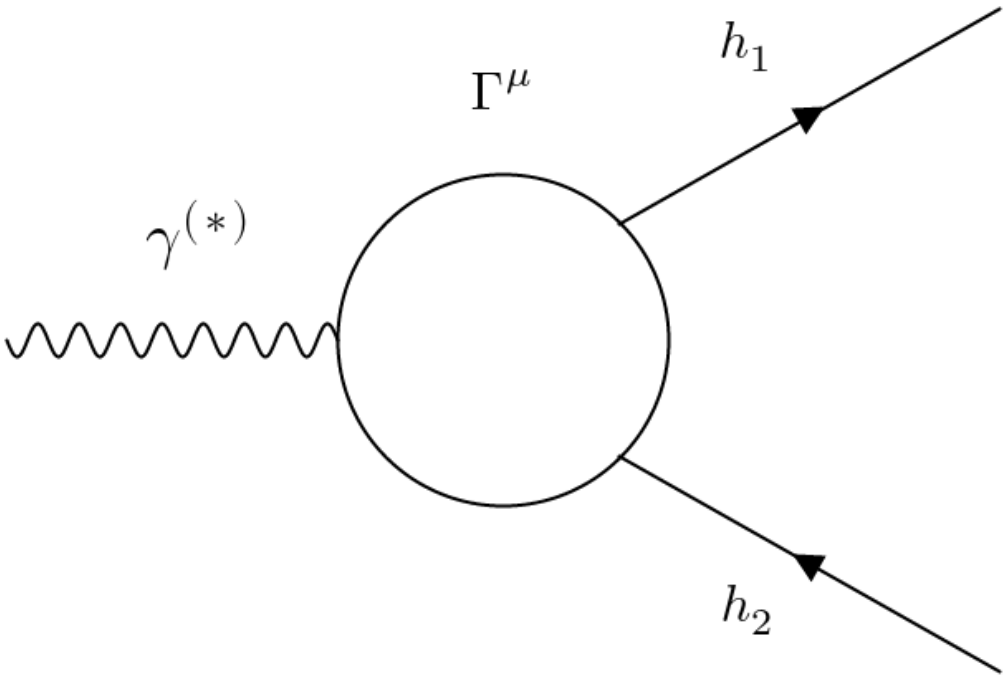


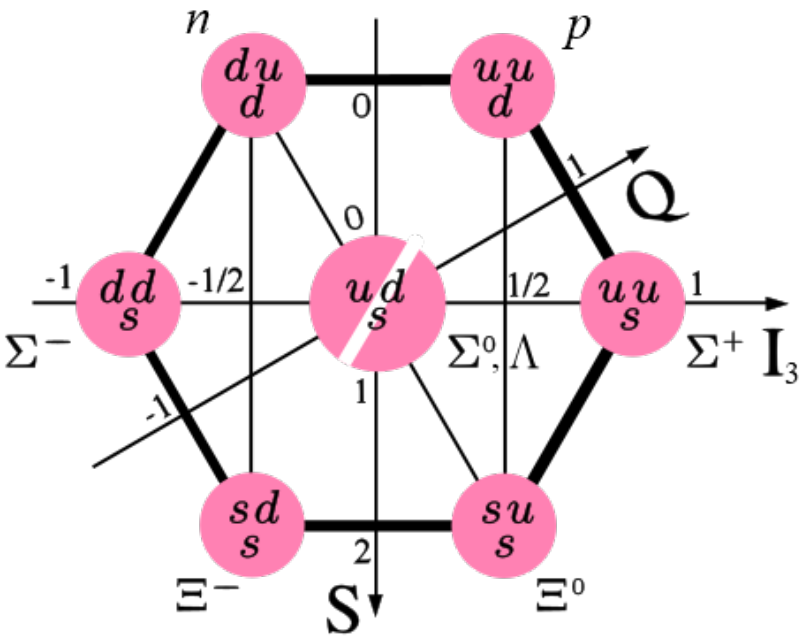
Image credit: Jacek Rybak

Electromagnetic Form Factors

- Quantify deviation from pointlike nature
- Scalar functions of momentum transfer q^2
- Elastic/transition ($h_1 = h_2 / h_1 \neq h_2$)
- Spacelike/timelike ($q^2 < 0 / q^2 > 0$)



Hyperons



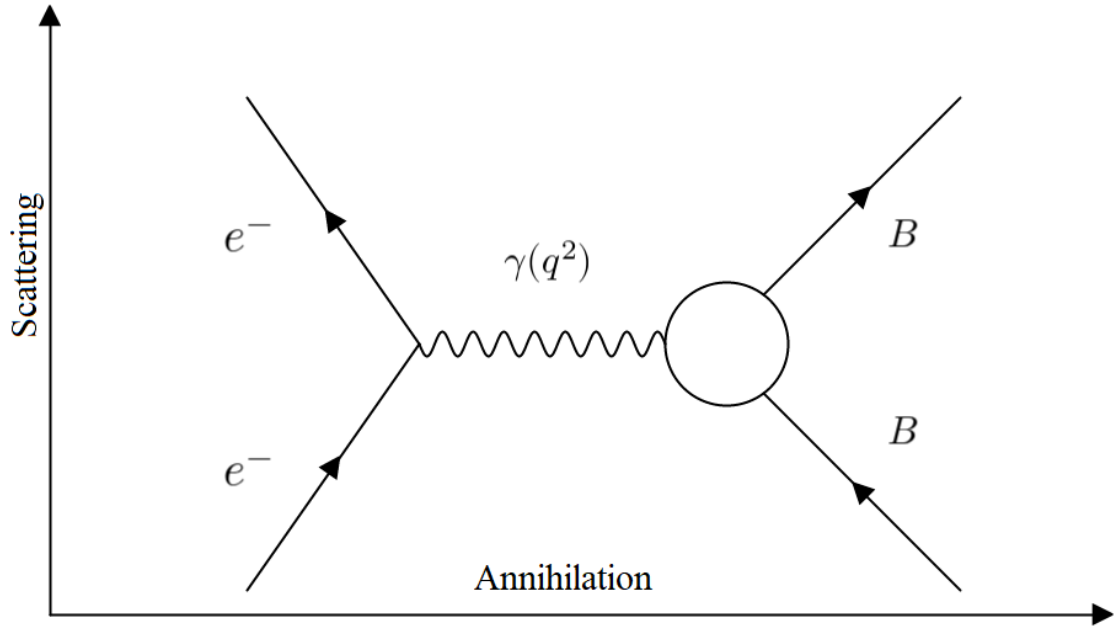
Hyperon	Mass [GeV/c^2]	Decay (BF)
Λ	1.116	$p\pi^-$ (63.9%)
		$n\pi^0$ (35.8%)
Σ^-	1.197	$n\pi^-$ (99.8%)
Σ^+	1.189	$p\pi^0$ (51.6%)
		$n\pi^+$ (48.3%)
Ξ^0	1.315	$\Lambda\pi^0$ (99.5%)
Ξ^-	1.321	$\Lambda\pi^-$ (99.8%)
Ω	1.672	ΛK^- (67.8%)
		$\Xi^0\pi^-$ (23.6%)
		$\Xi^-\pi^0$ (8.6%)

One-Photon Exchange

Spin 1/2 Baryons: Two independent form factors
Matrix element:

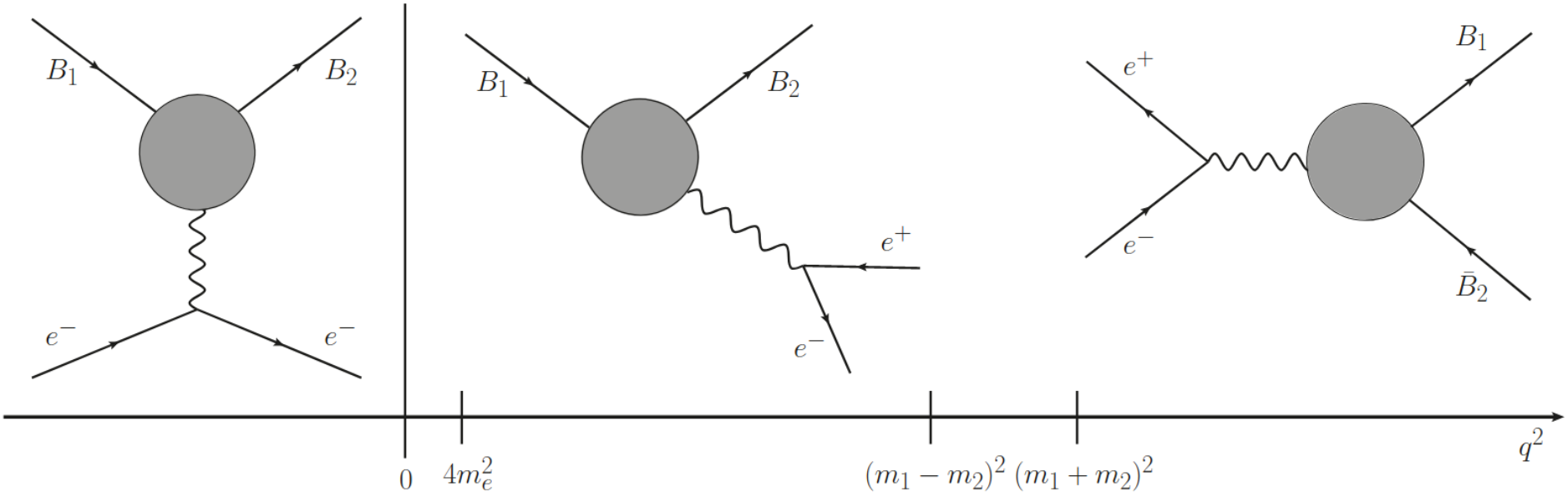
$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2)$$

- Dirac and Pauli form factors $F_1(q^2)$, $F_2(q^2)$
- Sachs form factors $G_E(q^2) = F_1 + \frac{q^2}{m_B^2} F_2$, $G_M(q^2) = F_1 + F_2$
  $G_E(0) = Q$, $G_M(0) = \mu$



Electromagnetic Form Factors

Spacelike ($\mathbf{q^2 < 0}$) **Timelike ($\mathbf{q^2 > 0}$)**

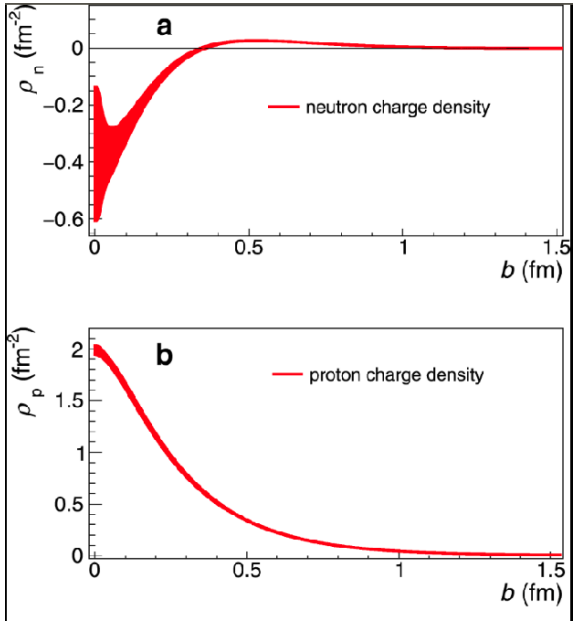


BESIII contributes here

Image credit: Perotti, E., PhD Thesis, Uppsala University (2020)

Spacelike Form Factors

- Can be studied in elastic lepton scattering
  Hyperons are unstable → Difficult!
- Real-valued functions of q^2.
- Related to charge and magnetization densities



Nat. Commun. 12, 1759 (2021).

$$< r_E >^2 = 6 \left. \frac{dG_E(q^2)}{dq^2} \right|_{q^2=0}$$

$$< r_M >^2 = \frac{6}{G_M(0)} \left. \frac{dG_M(q^2)}{dq^2} \right|_{q^2=0}$$

Timelike Form Factors

- Can be studied in lepton-antilepton annihilation
  Hyperon FFs experimentally accessible!
- Complex functions of q^2:
  $G_M(q^2) = |G_M(q^2)|e^{i\Phi_M}$, $G_E(q^2) = |G_E(q^2)|e^{i\Phi_E}$
- Observables $R = |G_E/G_M|$, $\Delta\Phi = \Phi_E - \Phi_M$

Cross section for $\mathbf{e^+e^- \to B\bar{B}}$:

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

Effective form factor:

$$\left|G_{eff}(q^2)\right|^2 = \frac{2\tau|G_M(q^2)|^2 + |G_E(q^2)|^2}{2\tau+1} = \frac{\sigma_{Born}(q^2)}{\left(1+\frac{1}{2\tau}\right)\left(\frac{4\pi\alpha^2\beta C}{3q^2}\right)}$$

Phase Measurement

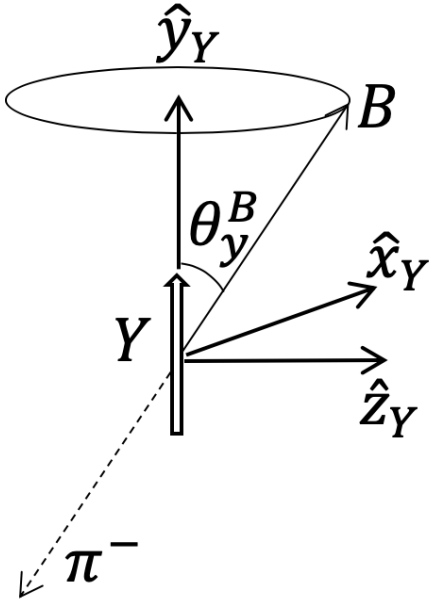
What is the significance of $\Delta\Phi$?

- SL and TL FFs related by dispersion relations.
  - As $|q^2| \to \infty$: **SL** $\to$ **TL**
    $\implies \Delta\Phi = n \cdot \pi$
  - Oscillations of $\Delta\Phi$ reveal zero-crossings

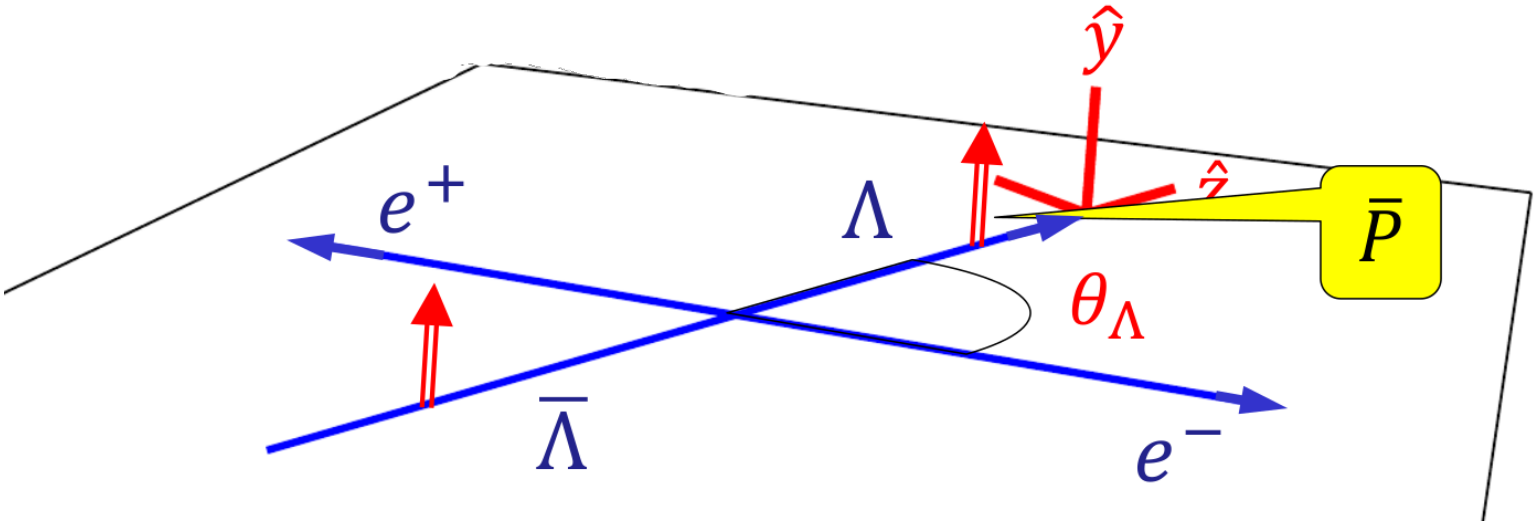
    Phys. Rev. D 104, 116016 (2021)
- Provides constraints for unmeasurable SL FFs

How to measure it?

- If $\sin\Delta\Phi \neq 0$ $B/\bar{B}$ can be polarized
- Experimental access to polarization in self-analyzing weak decays of hyperons!



$B\bar{B}$ Production in e^+e^--Annihilation



Unpolarized e^+e^- beams $\rightarrow$ Transverse polarization:

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

Angular distibution: $\frac{d\Gamma}{d\Omega} \propto 1 + \eta\cos^2\theta_\Lambda$, $-1 \leq \eta \leq 1$

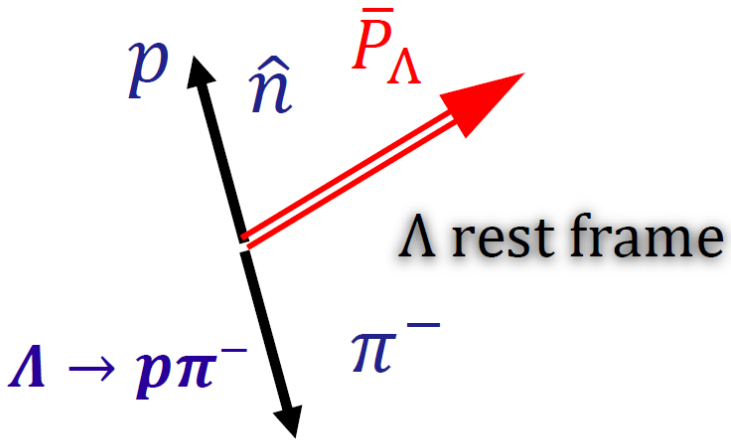
$R = \sqrt{\tau}\sqrt{\frac{1-\eta}{1+\eta}}$

Self-Analyzing Hyperon Decays

Angular distribution of daughter baryon reveals mother hyperon polarization

$$\frac{d\Gamma}{d\Omega} = \frac{1}{4\pi}(1 + \alpha_\Lambda \hat{n} \bar{P}_\Lambda)$$

Decay asymmetry parameter α_Λ
CP-conservation: $\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$



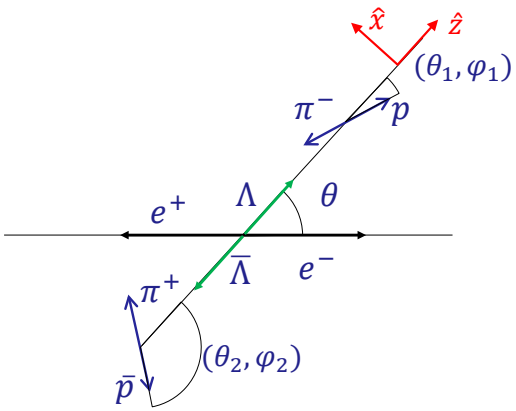
Precise measurements of α_Λ from BESIII via $J/\psi \to \Lambda\bar{\Lambda}$[1], $J/\psi \to \Xi\bar{\Xi}$[2]

BESIII, [1]Nature Phys. 15 (2019) 631, [2]Nature 606, 64–69 (2022)

Formalism for the Process $e^+e^- \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$

Full reaction described by: $\xi = (\theta,\, \theta_1,\, \phi_1,\, \theta_2,\, \phi_2) = (\theta,\, \Omega_1,\, \Omega_2)$

Fäldt, Kupsc, Phys. Lett. B 772 (2017) 16-20



$$d\Gamma \propto \mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \eta\mathcal{F}_5(\xi)$$
$$- \boxed{\alpha_\Lambda^2 \left(\mathcal{F}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \eta\mathcal{F}_6(\xi)\right)}$$
$$+ \boxed{\alpha_\Lambda \sqrt{1-\eta^2}\sin(\Delta\Phi)(\mathcal{F}_3(\xi) - \mathcal{F}_4(\xi))}$$

Spin correlations

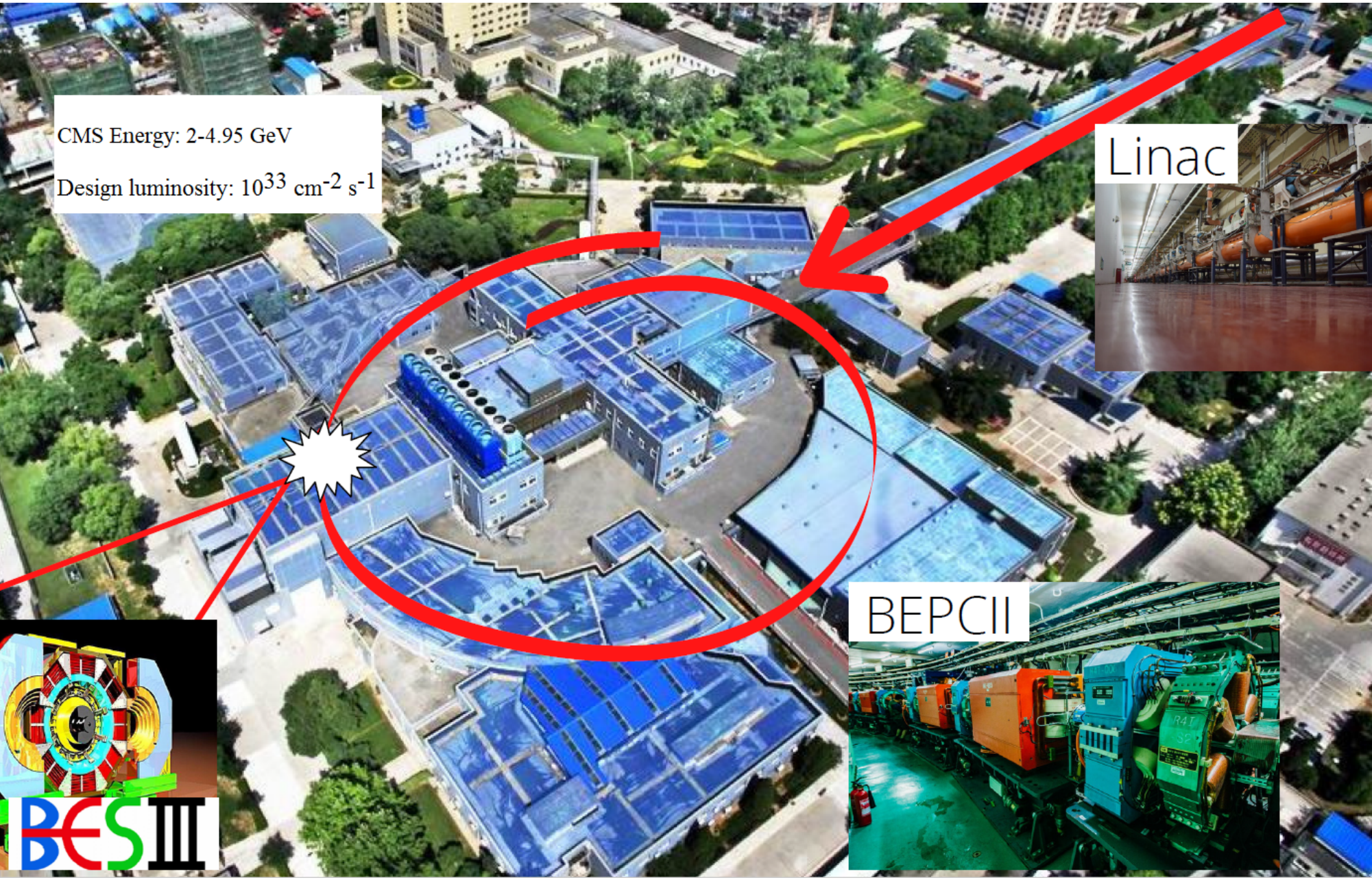
Polarization

- $\mathcal{F}_i$ are known functions of the angles
- Same method used by BESIII for precise CP-tests in $J/\psi \to \Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$, $\Xi\bar{\Xi}$ (see talk by He Li on Wednesday)

When only $\Lambda/\bar{\Lambda}$ is measured two angles $\xi = (\theta, \theta_p)$ are sufficient.

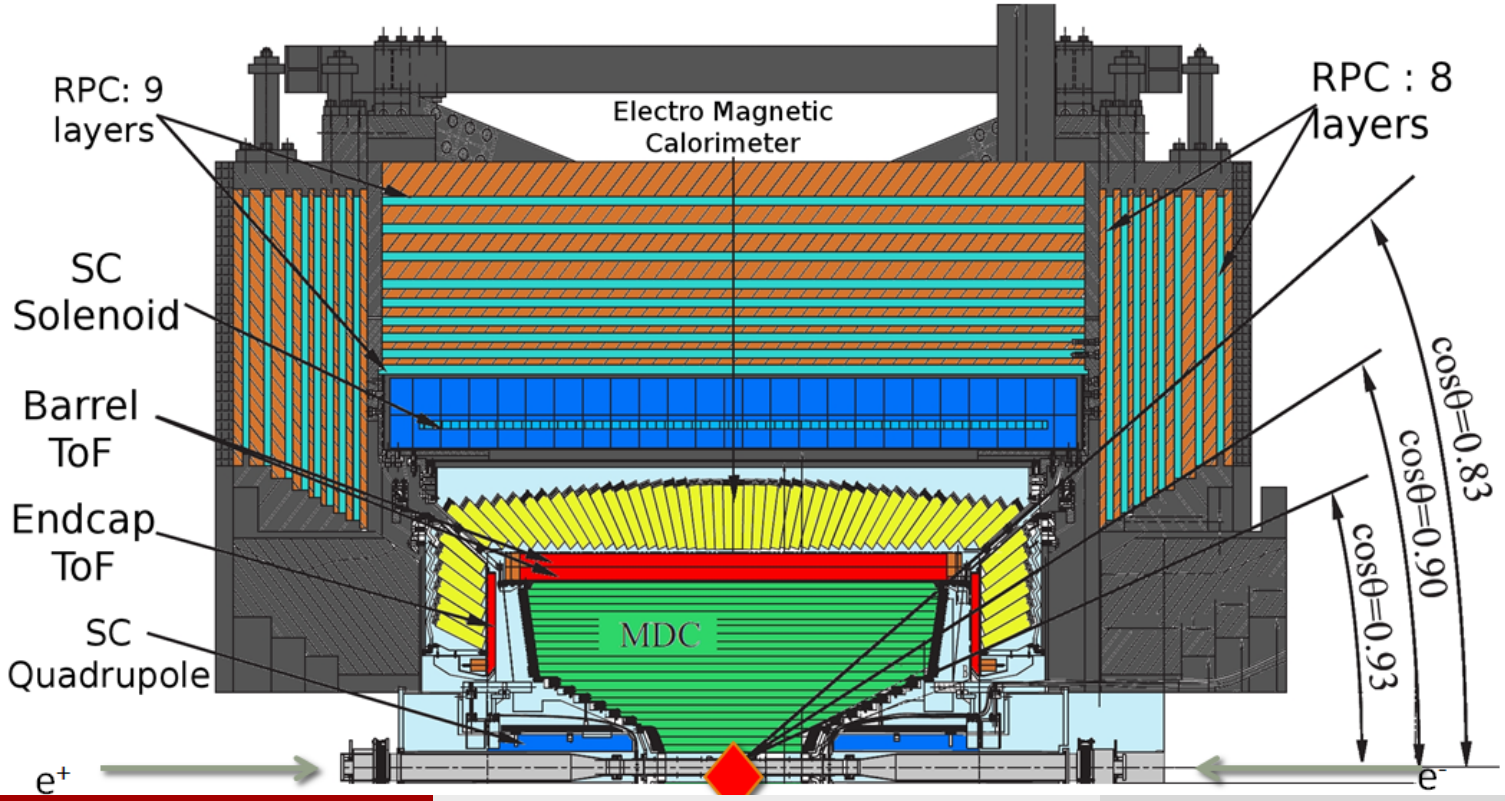
$$\mathcal{W}_{\Lambda/\bar{\Lambda}}(\xi) = 1 + \eta\cos^2\theta + \alpha_{\Lambda/\bar{\Lambda}}\sqrt{1-\eta^2}\sin(\Delta\Phi)\sin\theta\cos\theta\cos\theta_p$$

Beijing Electron-Positron Collider (BEPCII)



Beijing Spectrometer (BESIII)

- Near 4π coverage
- Helium-gas drift chamber
- CsI(Tl) crystal calorimeter
- Scan data:
  - 0.5 fb^{-1} from 2.0 to 3.08 GeV
  - 20 fb^{-1} from 3.51 to 4.6 GeV
- Plastic scintillator TOF-system (endcaps upgraded to MRPC in 2015)
- 1 T super-conducting solenoid
- RPC-based muon chamber

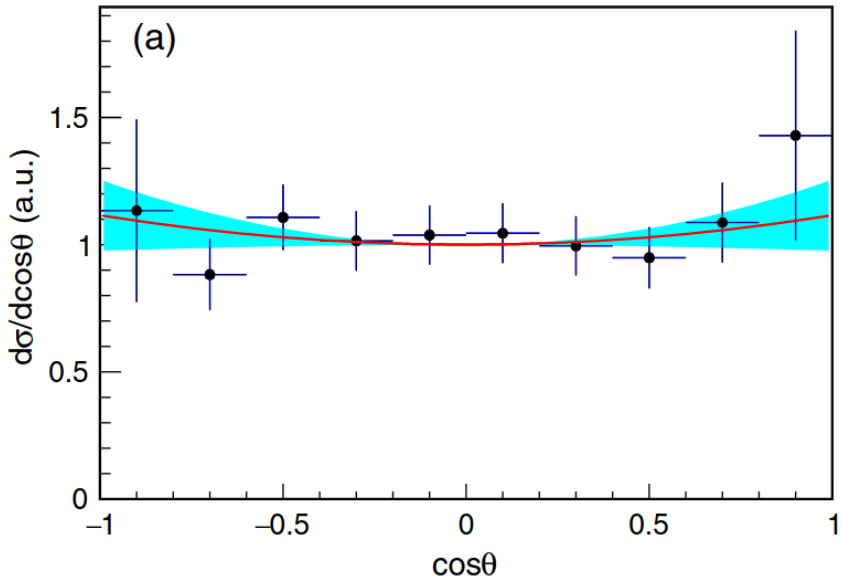


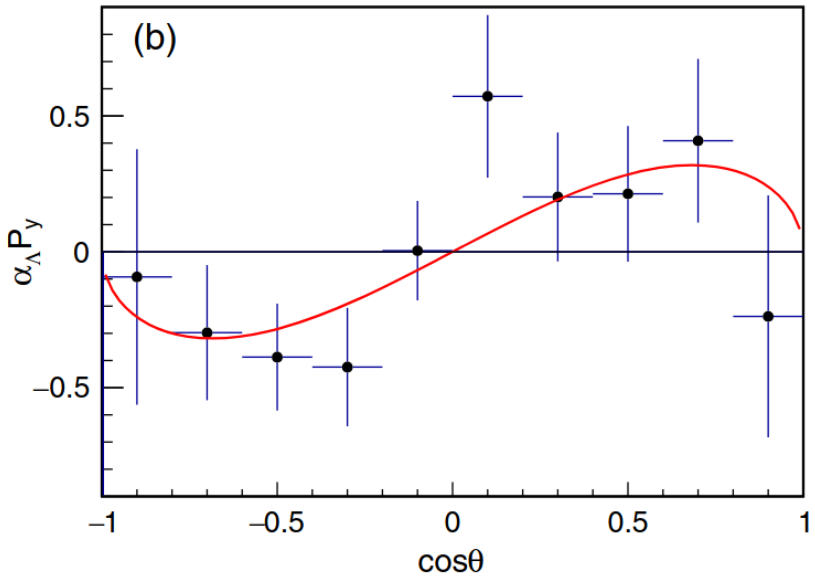
$e^+e^- \to \Lambda\bar{\Lambda}$, $\Lambda \to p\pi^- + c.c.$ at 2.396 GeV

$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.750$ fixed
555 events (2.5% bkg)

- Two-photon exchange contribution negligible
- **First measurement of relative phase for any baryon!!!**

$R = 0.96 \pm 0.14 \pm 0.02$
$\Delta\Phi = 37 \pm 12 \pm 6°$
$\sigma_{Born} = 118.7 \pm 5.3_{stat} \pm 5.1_{syst}$ pb





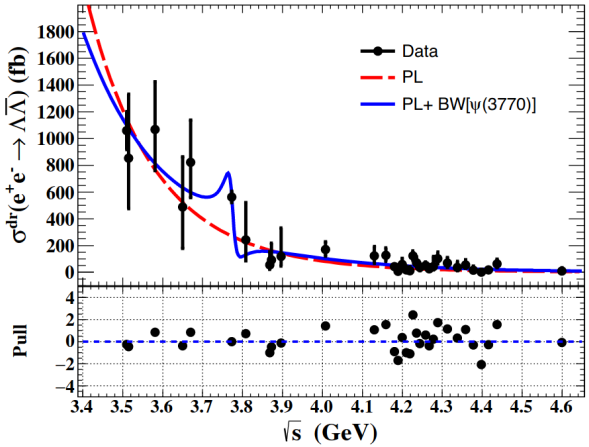
BESIII, Phys. Rev. Lett. 123 122003 (2019)

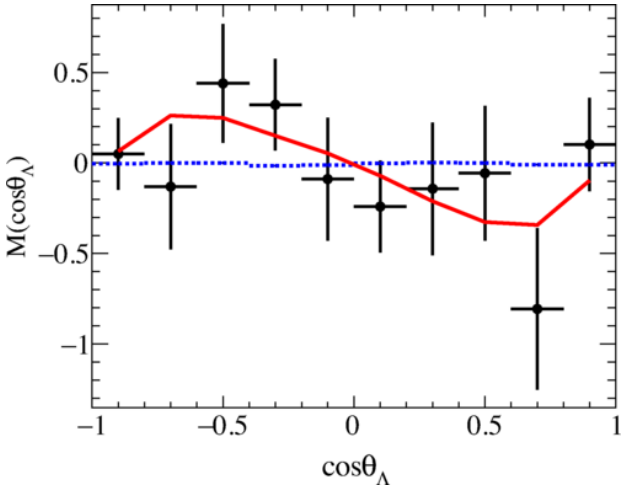
$e^+e^- \to \Lambda\bar{\Lambda}$, $\Lambda \to p\pi^- + c.c.$ at High q^2

$\mathcal{B}(\psi(3770) \to \Lambda\bar{\Lambda}) > 10$ times larger than previously assumed[1]

Spin analysis at 3.773 GeV^2:
$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} = 0.754$ fixed
262 events (0.5% bkg)

$$\eta_\psi = 0.85^{+0.12}_{-0.20} \pm 0.02$$
$$R_\psi = 0.48^{+0.21}_{-0.35} \pm 0.03$$
$$\Delta\Phi_\psi = 71^{+66}_{-46} \pm 5^\circ$$

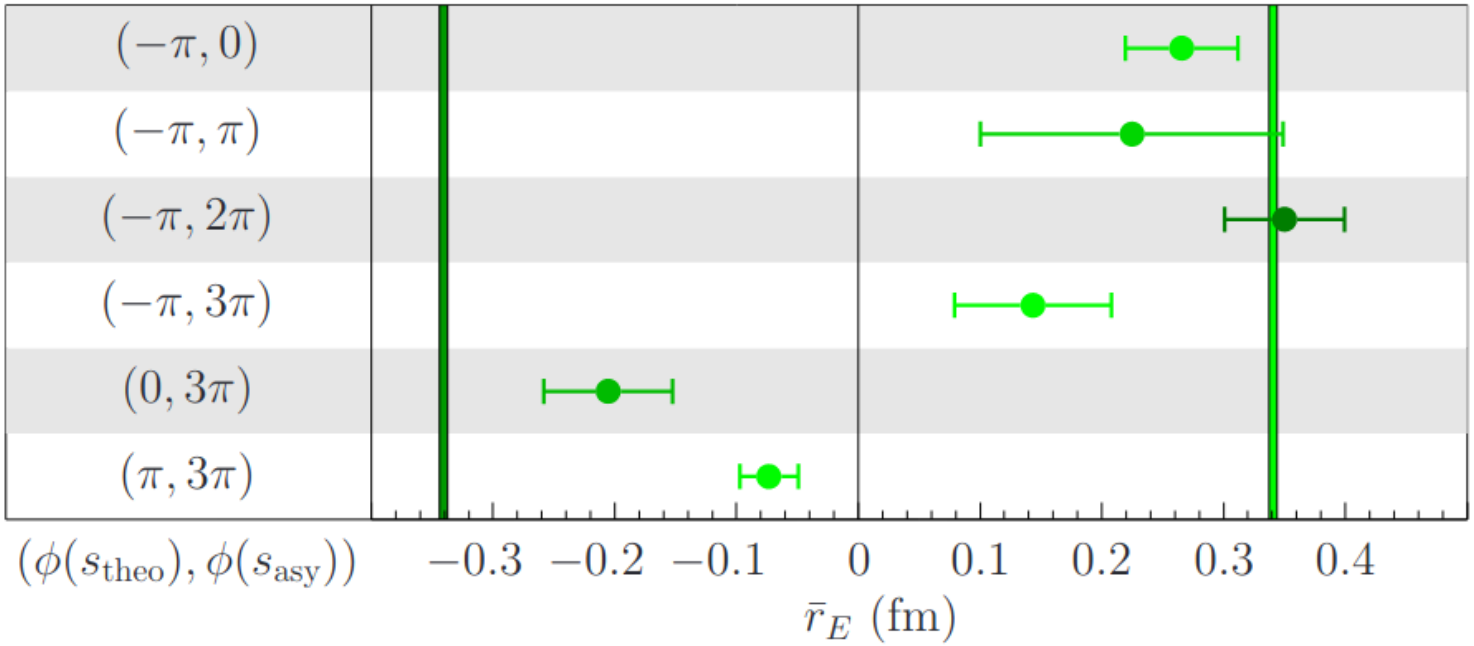




[1] BESIII, Phys. Rev. D 104 (2021) 9, L091104 [2] BESIII, Phys. Rev. D 105 L011101 (2022)

Interpretation

Phase measurement helps pin down charge Λ radius



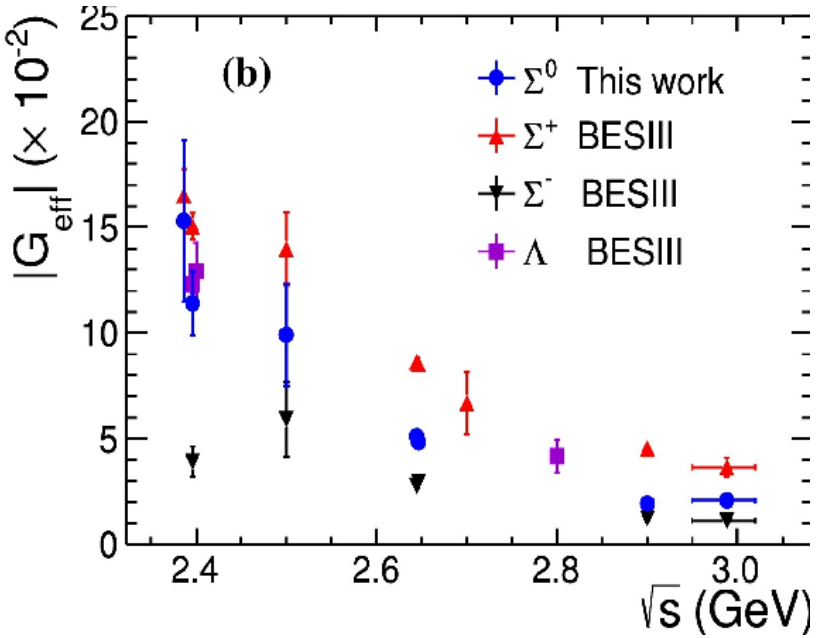
Fit[1] to data from BESIII[2] and BaBar[3] in different scenarios

Next step: What is the q^2-dependence of $\Delta\Phi$?

[1] Mangoni et al., Phys. Rev. D 104, 116016 (2021) [2] BESIII, Phys. Rev. Lett. 123 122003 (2019) [3] BaBar, Phys. Rev. D 76, 092006 (2007)

Effective FFs of Single Strange Hyperons

- Asymmetry in Σ isospin triplet FFs
- Relation between Λ/Σ FFs as expected from diquark correlations
- $\sigma_{Born}(e^+e^- \to \Sigma^+\bar{\Sigma}^-)/\sigma_{Born}(e^+e^- \to \Sigma^-\bar{\Sigma}^+) = 9.7 \pm 1.3$
  $\to$ inconsistent with predictions from *e.g*
  Phys. Rev. D 101, 014014 (2020)



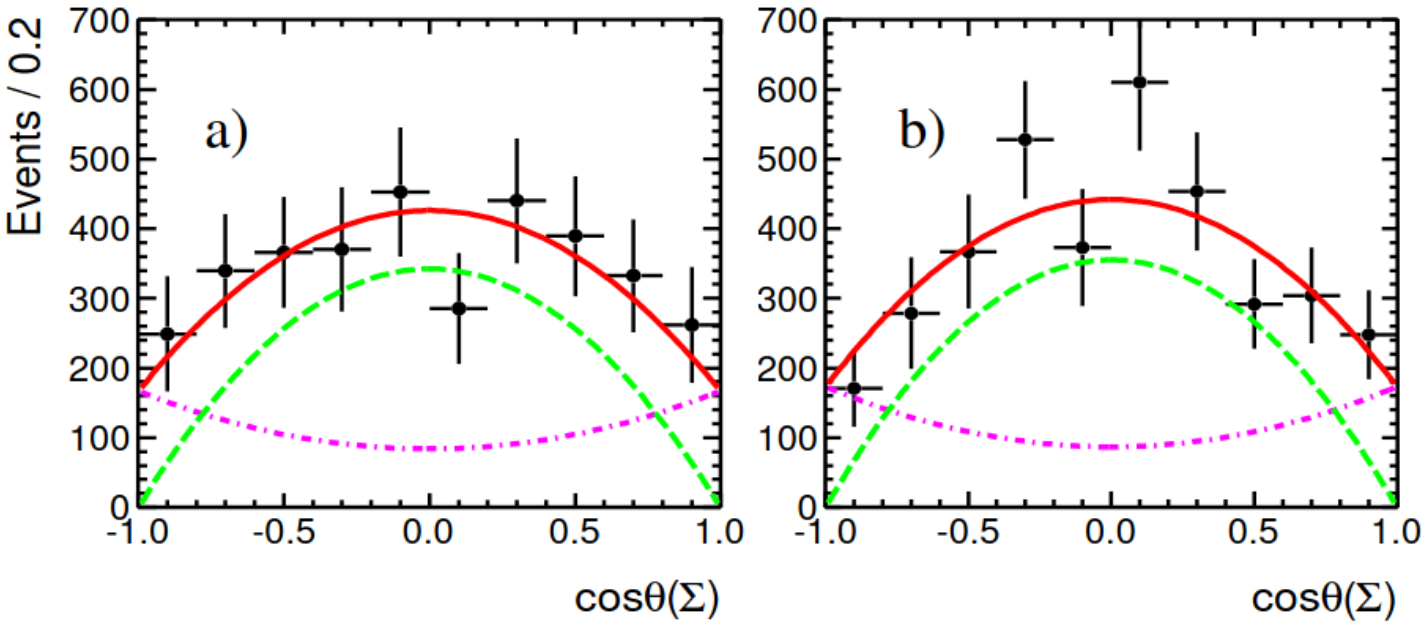
[1] BESIII, Phys. Rev. D 97, 032013 (2018) [2] BESIII, Phys. Lett. B 814, 136110 (2021)
[3] BESIII, Phys . Lett. B 831, 137187 (2022)

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

Form factor ratio $R = |G_E/G_M|$ for Σ^+

$\sqrt{s}$ [GeV]	R
2.3960	$1.83 \pm 0.26 \pm 0.24$
2.6454	$0.66 \pm 0.15 \pm 0.11$
2.9000	$1.06 \pm 0.36 \pm 0.09$

Example fit at $\sqrt{s} = 2.396$ GeV:



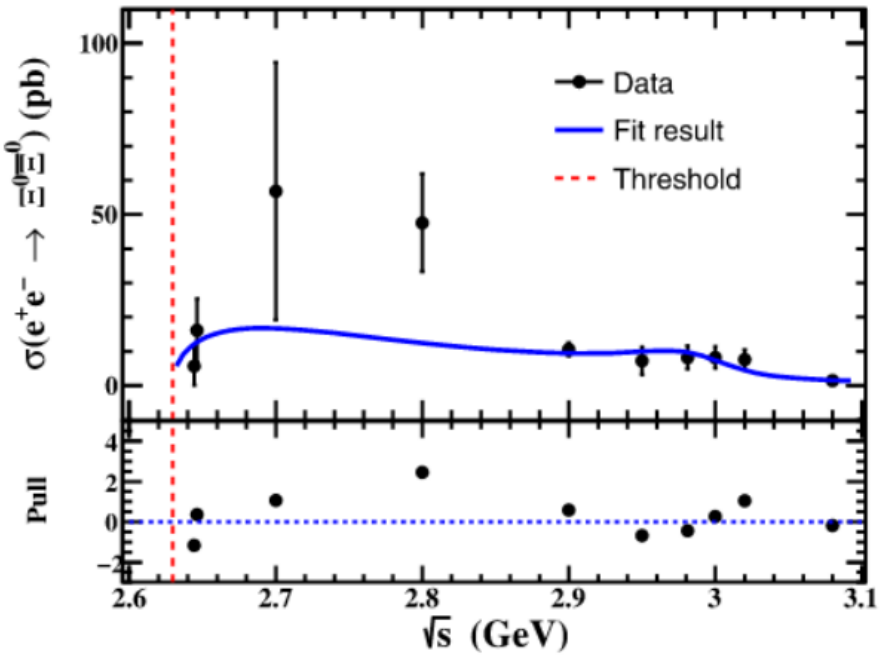
Solid line: Fit result, Dashed line: G_E, Dotted line: G_M

BESIII, Phys. Lett. B 814, 136110 (2021)

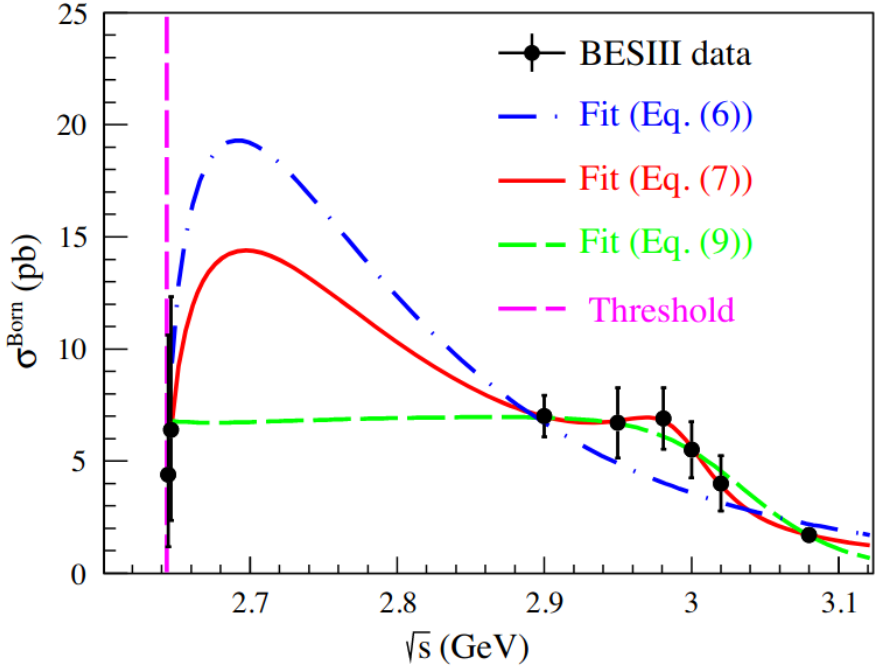
$e^+e^- \to \Xi\bar{\Xi}$

- σ_{Born} and $|G_{eff}|$ for $e^+e^- \to \Xi^0\bar{\Xi}^0$, $\Xi^-\bar{\Xi}^+$ near threshold
- $\sim 2\sigma$ resonant structure at 3.0 GeV

$e^+e^- \to \Xi^0\bar{\Xi}^0$



$e^+e^- \to \Xi^-\bar{\Xi}^+$



[1]BESIII: Phys. Rev. D 103, 012005 (2021) [2] BESIII, Phys. Lett. B 820, 136557 (2021)

Summary & Outlook

- Hyperon EMFFs are important observables for understanding the structure of baryons
- Spin-polarisation analysis enables determination of relative phase $\Delta\Phi$
- $\Delta\Phi$ helps pin down spatial structure
- Many new results from BESIII
  - **First phase measurement**: $\Delta\Phi$ for Λ^0
  - $R = |G_E/G_M|$ for Λ^0 and Σ^+
  - Effective form factors for Λ^0, $\Sigma^\pm$, Σ^0, Ξ^0, Ξ^-
  - More data to be analysed!