The Structure of Something Strange

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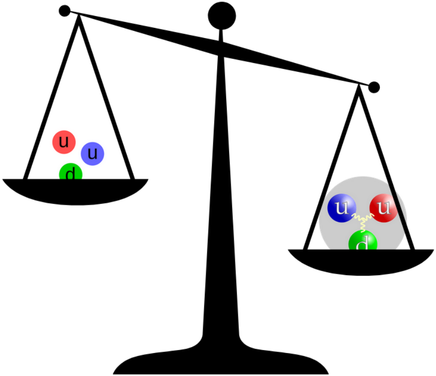
Why Hadrons?

Difficult to describe

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



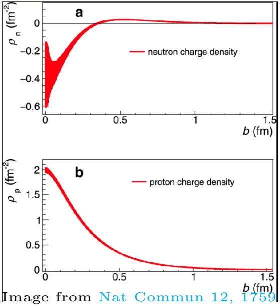


Image from Nat Commun 12, 1759 (2021).

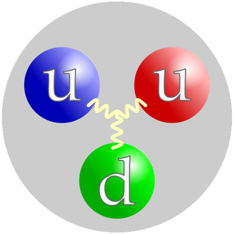
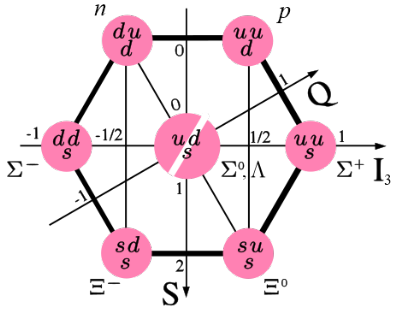


Image credit: Jacek Rybak

Hyperons: What are they and why study them?

- Baryons with strangeness ≥ 1
- Complementary to nucleons, relatively unexplored



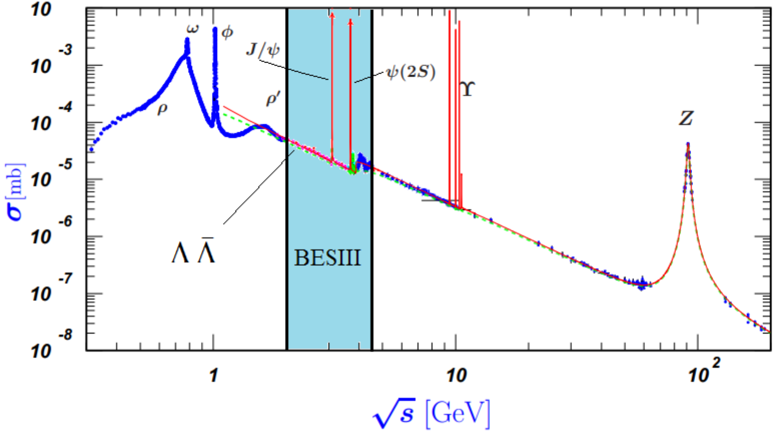
Hyperon	Mass [GeV/c^2]	Decay (BF)
Λ	1.116	$p\pi^-$ (63.9%)
		$n\pi^0$ (35.8%)
Σ^-	1.197	$n\pi^-$ (99.8%)
Σ^+	1.189	$p\pi^0$ (51.6%)
		$n\pi^+$ (48.3%)
Ξ^0	1.315	$\Lambda\pi^0$ (99.5%)
Ξ^-	1.321	$\Lambda\pi^-$ (99.8%)
Ω	1.672	ΛK^- (67.8%)
		$\Xi^0\pi^-$ (23.6%)
		$\Xi^-\pi^0$ (8.6%)

$+\,\Omega^-(sss)$ Spin 3/2

Λ Hyperon:

- Two dominating decay modes: $\Lambda \to p\pi$ (63.9%) and $\to n\pi^0$ (35.8%)
- Decays weakly $\to$ long-lived. Travels measurable distance before decaying.

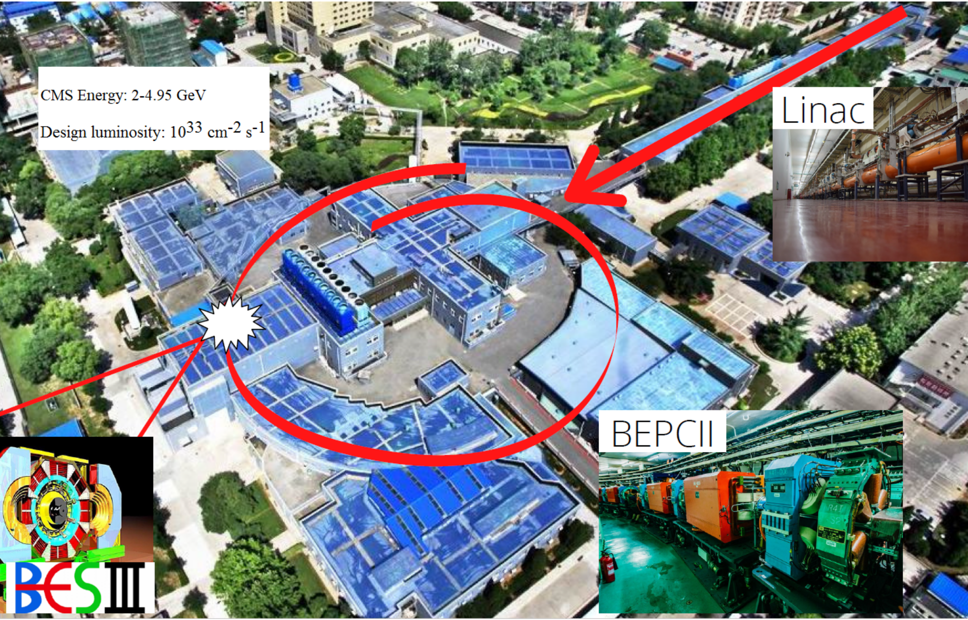
$e^+e^- \to$ Hyperons



Two possible approaches for studying energy-dependent phenomena:

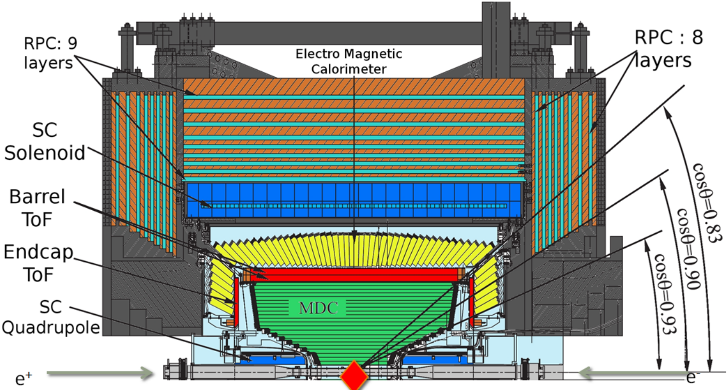
- Initial state radiation (ISR)
- Energy scan ← **Chosen here**

Beijing Electron-Positron Collider (BEPCII)



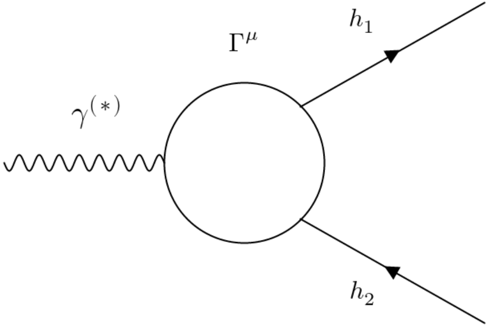
Beijing Spectrometer (BESIII)

- Near 4π coverage
- Helium-gas drift chamber
- CsI(Tl) crystal calorimeter
- Plastic scintillator TOF-system
- 1 T super-conducting solenoid
- RPC-based muon chamber



Electromagnetic Form Factors

- Depends on complex internal structure
- 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 ($q^2 < 0 / q^2 > 0$)



Electromagnetic Form Factors of Hyperons

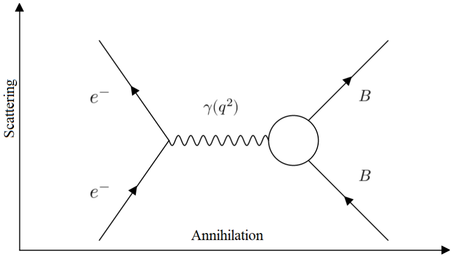
Spin 1/2: Two independent form factors G_E, G_M

SL FFs ($q^2 < 0$)

- Can be studied in elastic lepton scattering **Hyperons are unstable → Difficult!**
- Real-valued functions of q^2.

TL FFs ($q^2 > 0$)

- 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 $R = |G_E/G_M|$, $\Delta\Phi = \Phi_E - \Phi_M$



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

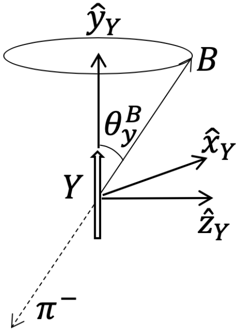
- SL and TL FFs related by dispersion relations.
  - As $|q^2| \to \infty$: **SL** $\to$ **TL** $\implies \Delta\Phi = n \cdot \pi$
  - Oscillations of $\Delta\Phi$ reveal zero-crossings

    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!
- Utilized by BESIII to measure the Λ FFs

  Phys. Rev. Lett. **123** (2019) 12, 122003

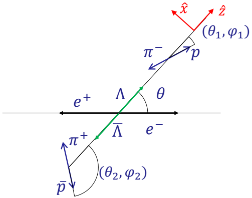


Next step: What is the q^2 dependence of $\Delta\Phi$?
We look at $e^+e^- \to \Lambda\bar{\Lambda}, \Lambda/\bar{\Lambda} \to p\pi$

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



$$d\Gamma \propto \mathcal{W}(\xi) = \mathcal{F}_0(\xi) + \eta\mathcal{F}_5(\xi)$$

Spin correlations

$$- \alpha_\Lambda^2 \left(\mathcal{F}_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\mathcal{F}_2(\xi) + \eta\mathcal{F}_6(\xi)\right)$$

$$+ \alpha_\Lambda\sqrt{1-\eta^2}\sin(\Delta\Phi)(\mathcal{F}_3(\xi) - \mathcal{F}_4(\xi))$$

Polarization

- $\mathcal{F}_i$ are known functions of the angles
- R can be extracted as $R = \sqrt{\tau}\sqrt{\frac{1-\eta}{1+\eta}}$, $\tau = \frac{q^2}{4m_\Lambda^2}$
- α_Λ: Λ decay asymmetry parameter $\leftarrow$ **CP-tests** e.g. BESIII, Nature 606, 64–69 (2022)

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

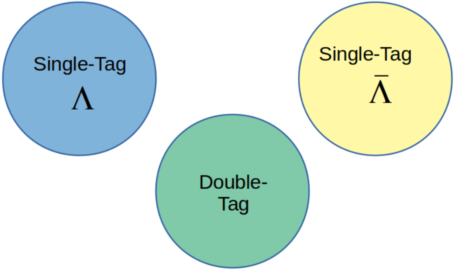
$$\mathcal{W}_{\Lambda/\bar{\Lambda}}(\xi) = 1 + \eta\cos^2\theta + \alpha_{\Lambda/\bar{\Lambda}}\sqrt{1-\eta^2}\sin(\Delta\Phi)\sin\theta\cos\theta\cos\theta_p$$

Polarization

Analysis Strategy

Two possible ways of selecting $e^+e^- \rightarrow \Lambda\bar{\Lambda}$ events:

- Double-Tag: Reconstruct **both** Λ and $\bar{\Lambda}$
- Single-Tag: Reconstruct **either** Λ **or** $\bar{\Lambda}$



E_{cm} [GeV]	$\mathcal{L}$ [pb^{-1}]
2.3864	$22.59 \pm 0.01 \pm 0.17$
2.3960	$66.89 \pm 0.02 \pm 0.46$
2.6444	$33.65 \pm 0.01 \pm 0.21$
2.6464	$34.06 \pm 0.01 \pm 0.28$
2.9000	$105.53 \pm 0.03 \pm 0.90$
3.0800	$126.21 \pm 0.03 \pm 0.90$

Three statistically independent samples at each energy.
Combine to determine:

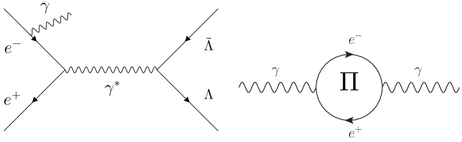
- σ_{Born} as inverse-variance weighted mean
- R, $\Delta\Phi$ through simultaneous fit

Data at 2.396 GeV used to illustrate event selection procedure

Determination of the Born Cross Section

To determine σ_{Born}, correct for

- Initial state radiation (ISR)
- Vacuum polarization (VP)



$$\sigma_{obs.} = \frac{N}{\mathcal{L}\mathcal{B}(\Lambda \to p\pi^-)\left[\epsilon_1 \mathcal{B}(\Lambda \to p\pi^-) + \epsilon_2 \mathcal{B}(\Lambda \to n\pi^0)\right]}$$

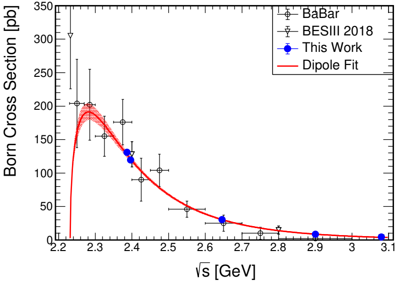
$$\sigma_{Born} = \frac{\sigma_{obs.}}{(1+\delta)_{ISR+VP}}$$

Need energy dependence of Born cross section to estimate correction factor.

Dipole approximation:

$$\sigma_{Born}(q^2) = \frac{1}{q^2}\frac{c_0 \cdot \beta}{(q^2 - c_1^2)^4},$$

$c_1 = 1.77 \pm 0.01$ GeV indicates mix of $\phi(1680)$ and $\phi(2170)$ in line with Chin. Phys. Lett. 39 011201

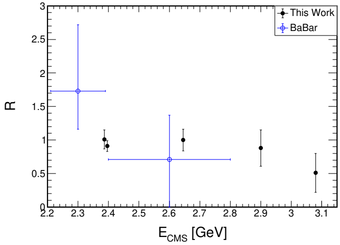


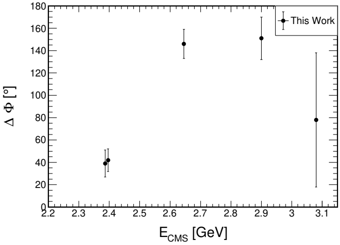
Parameters R, $\Delta\Phi$ determined by unbinned MLL fit.
Λ decay asymmetry parameter fixed $\alpha_\Lambda = 0.754$ (BESIII, Nature Phys. 15 (2019) 631)

$$-\ln\mathcal{L} = -\sum_{i=1}^{N} \ln \frac{\mathcal{W}(\xi_i;\eta,\Delta\Phi)}{\mathcal{N}(\eta,\Delta\Phi)} - \sum_{i=1}^{N} \ln \epsilon(\xi_i), \qquad \mathcal{N}(\eta,\Delta\Phi) = \int \mathcal{W}(\xi;\eta,\Delta\Phi)\epsilon(\xi)d\xi$$

$$-\ln\mathcal{L}_{tot.} = -\ln\mathcal{L}_{\Lambda\bar{\Lambda}} - \ln\mathcal{L}_{\bar{\Lambda}} - \ln\mathcal{L}_{\Lambda}$$

Results:





Note that $\Delta\Phi$ moves from first to second quadrant between 2.396 and 2.64 GeV!

Summary & Outlook

What has been done:

- Combination of full and partial reconstruction
- R, $\Delta\Phi$, σ_{Born} measured at five energies from 2.3864 GeV to 3.08 GeV
  - First measurement of energy dependence of $\Delta\Phi$

To be done:

- Study unexpected behavior of $\Delta\Phi$
  - Related to method/size of data samples?
  - If true, due to resonance, rescattering?
- Interpretation of result in terms of Λ charge radius

  Phys. Rev. D 104, 116016
- Cross section measurement at additional data points.