Hyperon Physics with BESIII

16th International Workshop on Meson Physics

Prof. Dr. Karin Schönning, Uppsala University
for the BESIII collaboration

Outline

- Introduction
- The BESIII experiment
- Polarised and entangled hyperons
- Sequentially decaying hyperons
- BRAND NEW: Combined Approach!
- Summary

Introduction

Many challenges in modern physics manifest themselves in the **nucleon.**

Challenging to describe from first principles:

- **Its abundance**
- Its spin
- **Its structure**

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Introduction

Nucleon Abundance

Universe consists of matter,
not antimatter. Why?

- Fine-tuned in the Big Bang?
- Dynamical generation: *Baryogenesis*?

→ Requires CP violating processes*

A. D. Sakharov,. J. Exp. Theor. Phys. Lett.* **5*: 24–27.*

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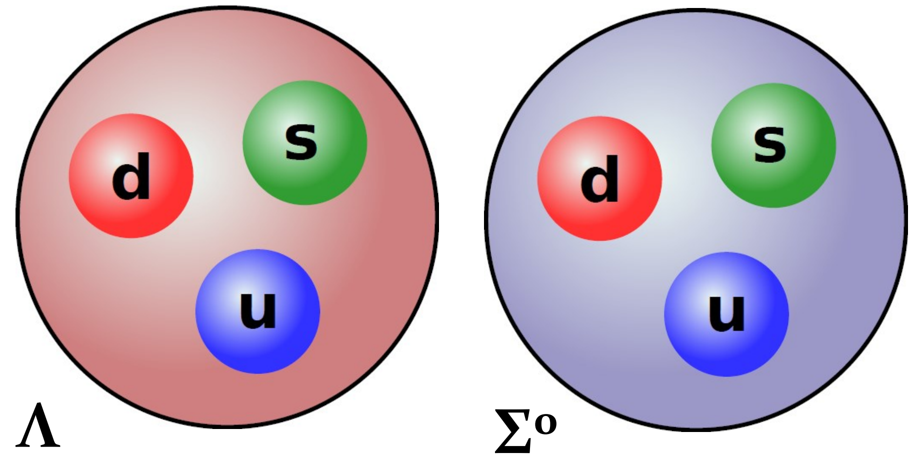
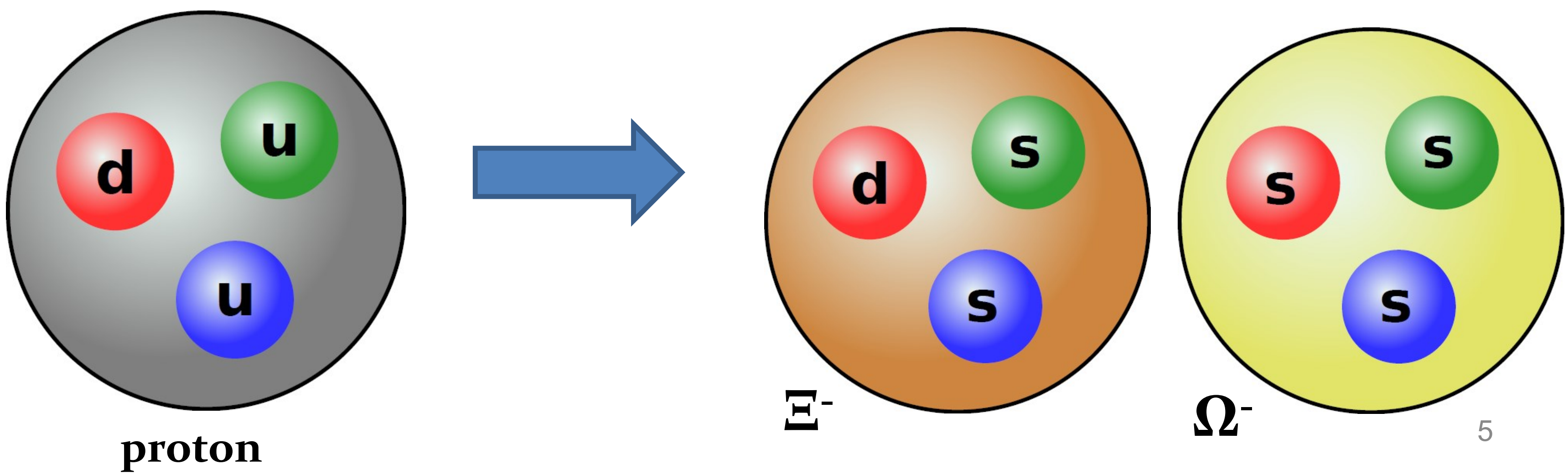
Hyperons

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



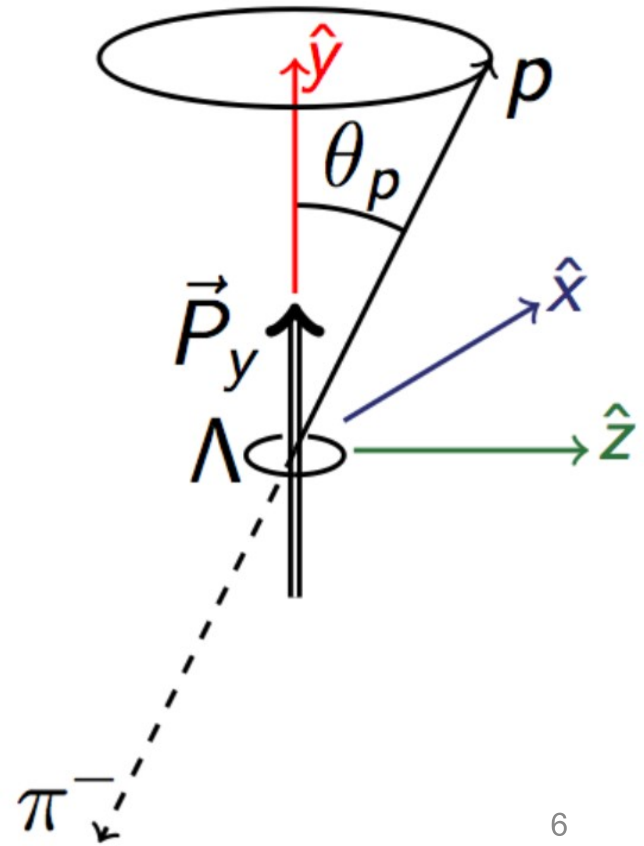


Advantage of hyperons

Polarisation experimentally accessible by the weak, parity violating decay:

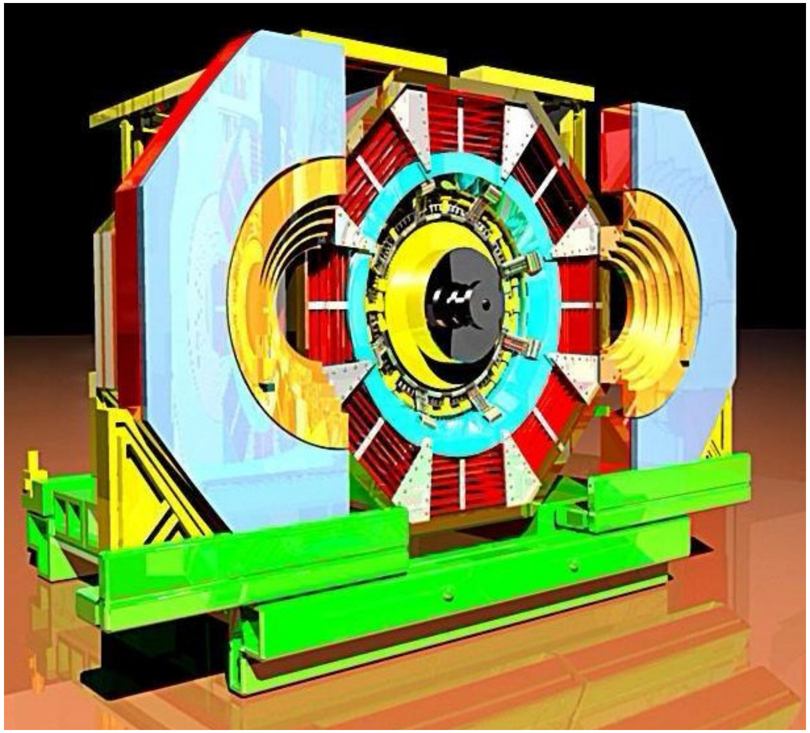
Example:

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



BESIII @ BEPC II

- Beijing Electron Positron Collider (BEPC II):
  - e^+e^- collider within CMS range 2.0 – 4.95 GeV.
  - Optimised in the τ-charm region.



- Beijing Spectrometer (BES III):
  - Near 4π coverage
  - Tracking, PID, calorimetry
  - Broad physics scope

See also talks by M. Pelizaeus and F. Nerling

Part 1

POLARISED AND ENTANGLED HYPERONS

Formalism for $e^+e^- \to \bar{Y}Y, Y \to BM + c.c.$

Production parameters of spin ½ baryons:

- Angular distribution parameter η
- Phase ΔΦ

Decay parameters for 2-body decays: α_1 and α_2.

Unpolarized part **Polarised part** **Correlated part**

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) - \alpha_1\alpha_2\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\,F_2(\xi) + \eta F_6(\xi)\right) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\alpha_1 F_3(\xi) - \alpha_2 F_4(\xi)\right)$$

$$\mathcal{F}_0(\xi) = 1$$

$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$

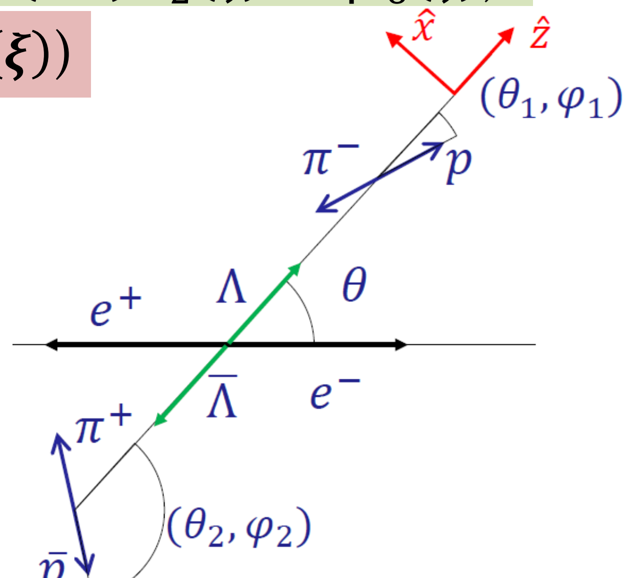
$$\mathcal{F}_2(\xi) = \sin\theta \cos\theta\,(\sin\theta_1 \cos\theta_2 \cos\phi_1 + \cos\theta_1 \sin\theta_2 \cos\phi_2)$$

$$\mathcal{F}_3(\xi) = \sin\theta \cos\theta \sin\theta_1 \sin\phi_1$$

$$\mathcal{F}_4(\xi) = \sin\theta \cos\theta \sin\theta_2 \sin\phi_2$$

$$\mathcal{F}_5(\xi) = \cos^2\theta$$

$$\mathcal{F}_6(\xi) = \cos\theta_1 \cos\theta_2 - \sin^2\theta \sin\theta_1 \sin\theta_2 \sin\phi_1 \sin\phi_2$$



*Fäldt & Kupsc, PLB 772 (2017) 16.

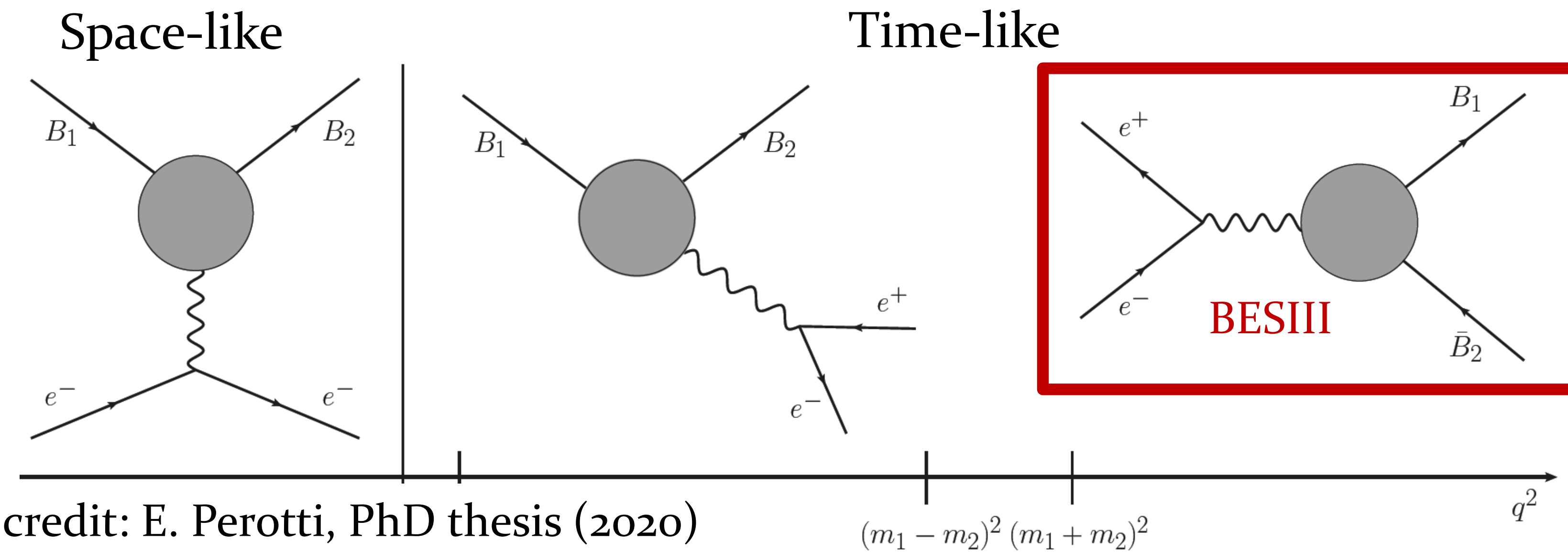
Application 1: Hyperon Structure

Production parameters of spin ½ baryons:

- Angular distribution parameter **η** ← Related to form factor ratio $\frac{|G_E|}{|G_M|}$
- Phase **ΔΦ** ← between form factors $\Delta\Phi = \Phi_E - \Phi_M$

Unpolarized part Polarised part Correlated part

$$W(\boldsymbol{\xi}) = F_0(\xi) + \boldsymbol{\eta}F_5(\xi) - \alpha_1\alpha_2(F_1(\xi) + \sqrt{1-\boldsymbol{\eta}^2}\,cos(\boldsymbol{\Delta\Phi})\,F_2(\xi) + \boldsymbol{\eta}F_6(\xi)) + \sqrt{1-\boldsymbol{\eta}^2}sin(\boldsymbol{\Delta\Phi})(\alpha_1F_3(\xi) - \alpha_2F_4(\xi))$$



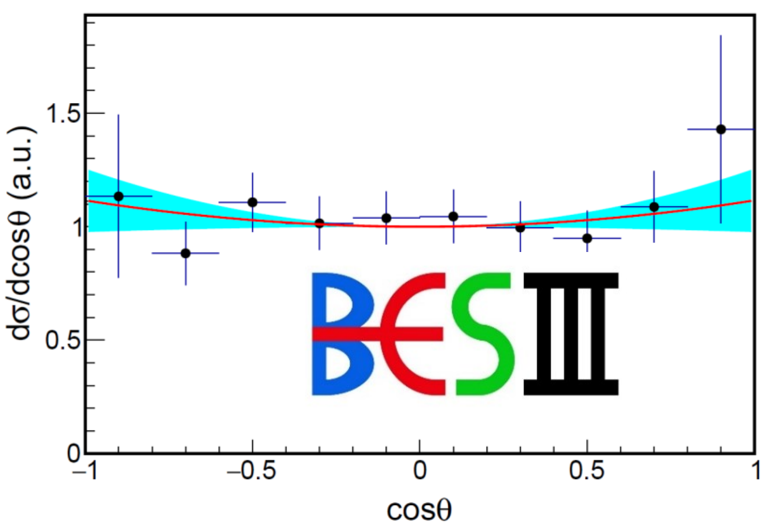
Picture credit: E. Perotti, PhD thesis (2020)

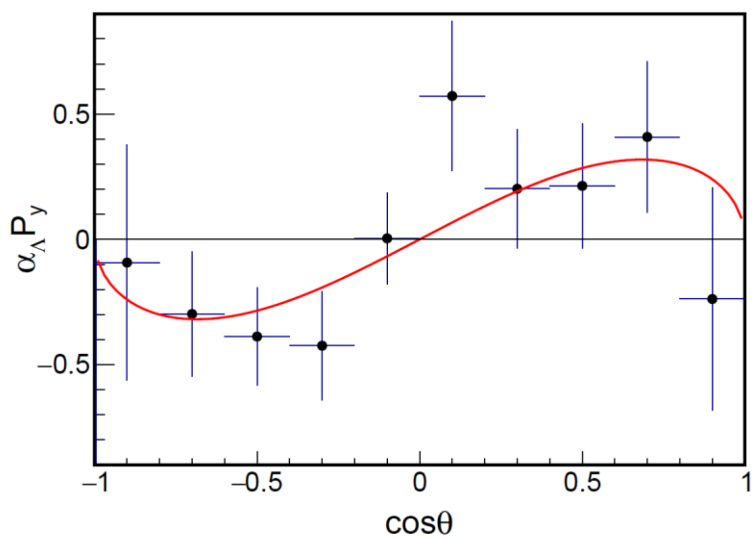
First complete measurement of Λ structure

- New BESIII data at 2.396 GeV with 555 exclusive $\bar{\Lambda}\Lambda$ events in sample.
  - R=$|G_E/G_M|$ = $\mathbf{0.96 \pm 0.14 \pm 0.02}$
  - $\Delta\Phi$ = $\mathbf{37^o \pm 12^o \pm 6^o}$
  - σ = $118.7 \pm 5.3 \pm 5.1$ pb

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

- Most **precise** result on R and σ
- **First** conclusive result on $\Delta\Phi$





Application 2: Hyperon Decays

Decay parameters for 2-body decays: $\boldsymbol{\alpha_1}$ and $\boldsymbol{\alpha_2}$.

Unpolarized part — Polarised part — Correlated part

$$W(\xi) = F_0(\xi) + \eta F_5(\xi) - \boldsymbol{\alpha_1\alpha_2}\left(F_1(\xi) + \sqrt{1-\eta^2}\cos(\Delta\Phi)\, F_2(\xi) + \eta F_6(\xi)\right) + \sqrt{1-\eta^2}\sin(\Delta\Phi)\left(\boldsymbol{\alpha_1} F_3(\xi) - \boldsymbol{\alpha_2} F_4(\xi)\right)$$

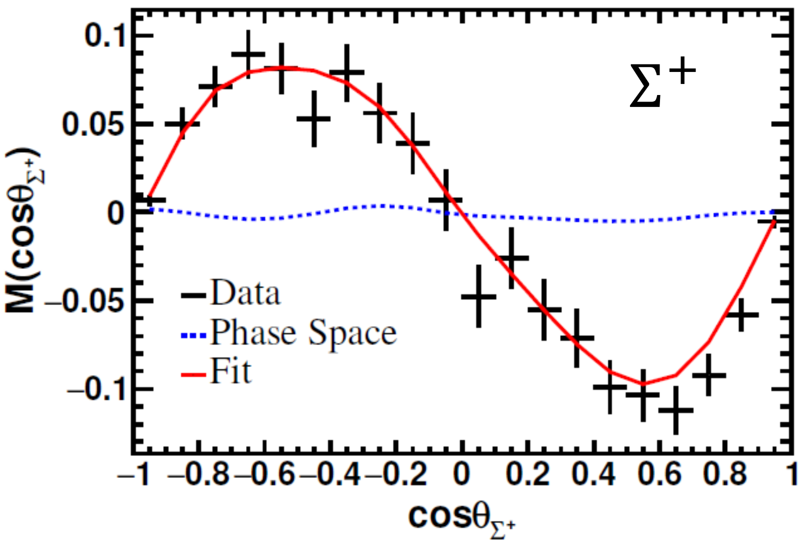
- Test of CP violation
- Two-body decays: quantified by decay parameters, *e.g.* α
  - Accessible in direct decay
  - CP symmetry: $\alpha = -\bar{\alpha}$ $(\alpha_1 = -\alpha_2)$
  - CP observable defined by $A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}}$

The Λ and Σ^+ decay parameters

- Λ decay parameters* from $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$
  - Decay 1: $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$
  - Decay 2: $\Lambda \to p\pi^-, \bar{\Lambda} \to \bar{n}\pi^0$
  - Value of α ~17% > old PDG value.
  - Most precise CP test for Λ decay:

$$A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -0.006 \pm 0.012 \pm 0.007$$

- Σ^+ decay parameters from $J/\psi \to \Sigma^+\bar{\Sigma}^-$ and $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$ **
  - Decay: $\Sigma^+ \to p\pi^0$
  - First CP test of Σ^+ decay: $\frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -0.004 \pm 0.037 \pm 0.010$



*BESIII, Nature Phys. **15**, p 631-634 (2019)
** Phys. Rev. Lett. 125, 052004 (2020)

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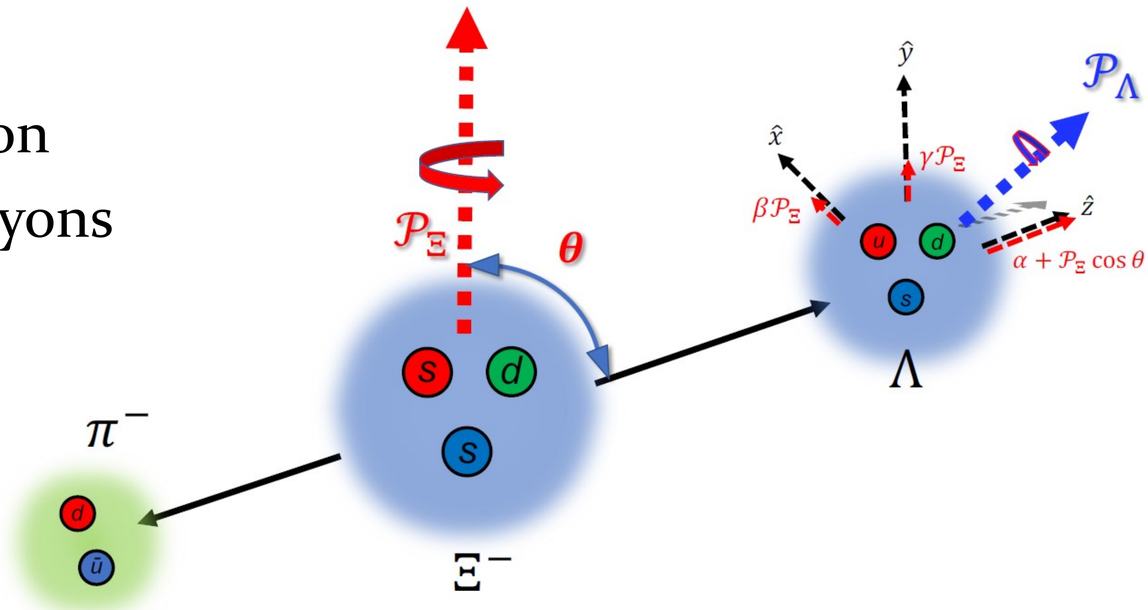
Part 2

SEQUENTIALLY DECAYING HYPERONS

Sequential hyperon decays

- Additional decay parameters β, γ, ϕ accessible*.
  - $\alpha^2 + \beta^2 + \gamma^2 = 1$
  - $\tan\phi = \frac{\beta}{\gamma}$
- Formalism for production and decay of spin ½ baryons by Fäldt**
- Spin 1/2 and 3/2 by Perotti *et al.****



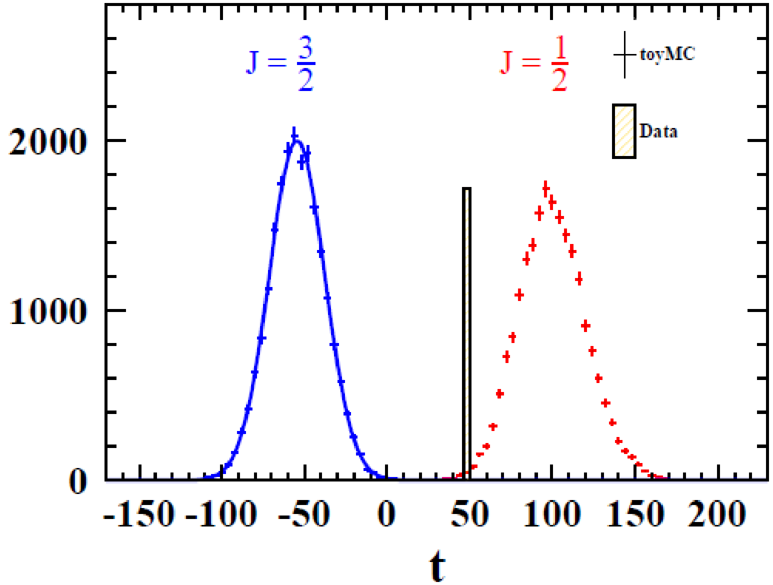
*Phys. Rev. 108, 1645 (1957)
** Phys. Rev. D 97, 053002 (2018)
*** Phys. Rev. D 99, 056008 (2019).

Spin properties of the Λ_c^+

Single-tag studies of $e^+e^- \to \Lambda_c^+\overline{\Lambda}_c^-$, $\Lambda_c^+ \to pK_s, \Lambda\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+$ + c.c.

- First direct determination of the Λ_c^+ spin*
  - Spin 1/2 favoured over spin 3/2 favoured with more than 6 σ.
    - → In line with the quark model

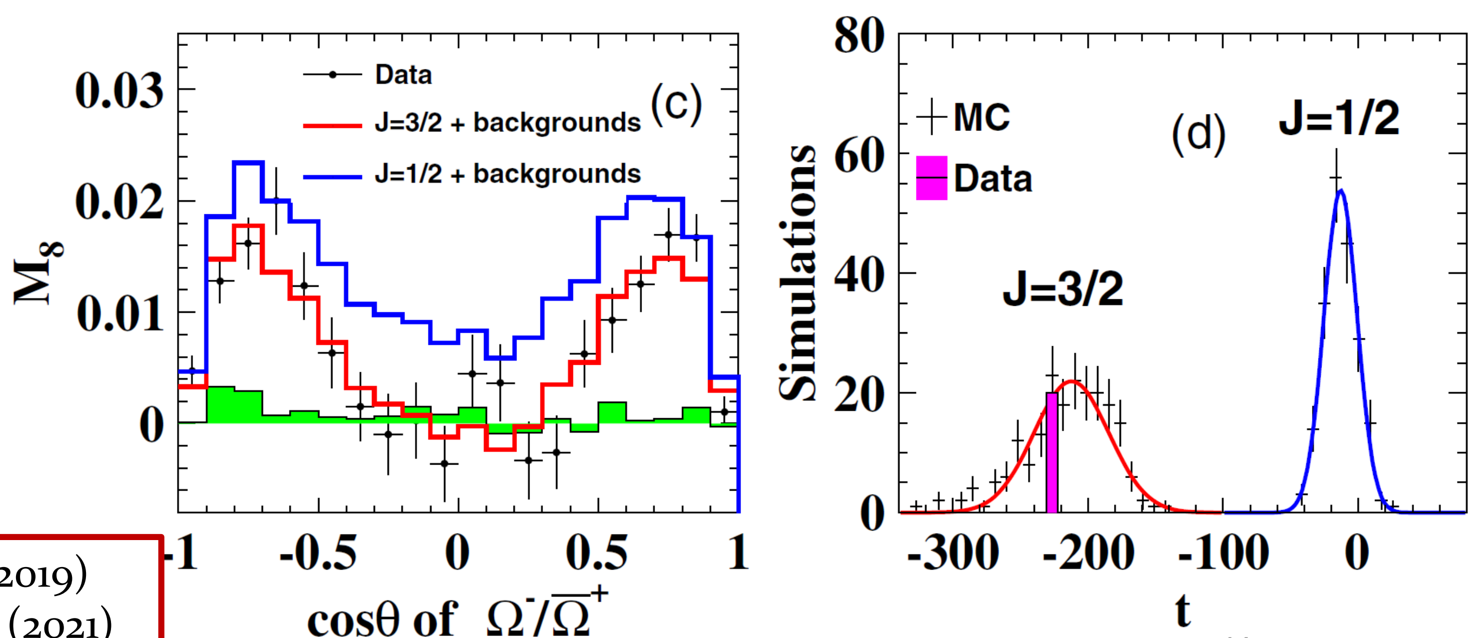
- Decay parameters of the Λ_c^+**
  - First measurements of α_{pK} and $\alpha_{\Sigma^0\pi^+}$.
  - Improved precision for $\alpha_{\Lambda\pi}$ and $\alpha_{\Sigma^+\pi^0}$.
  - "Proof-of-principle" of measurements of β and γ



*Acc. by Phys. Rev. D, arXiv: 2011.00396
** Phys. Rev. D 100, 072004 (2019)

Spin properties of the Ω^-

- Analysed $e^+e^- \rightarrow \psi(3686) \rightarrow \Omega^-\bar{\Omega}^+$ with spin 1/2 and 3/2 formalism.*
- Single-tag study of $\psi(3686) \rightarrow \Omega^-\bar{\Omega}^+$ data for**:
  - Model-independent determination of Ω^- spin
  - First measurement of the decay parameter $\phi_\Omega(\Omega^- \rightarrow \Lambda\pi^-)$



*PRD 99, 056008 (2019)
** PRL 126, 092002 (2021)

Part 3

COMBINED APPROACH

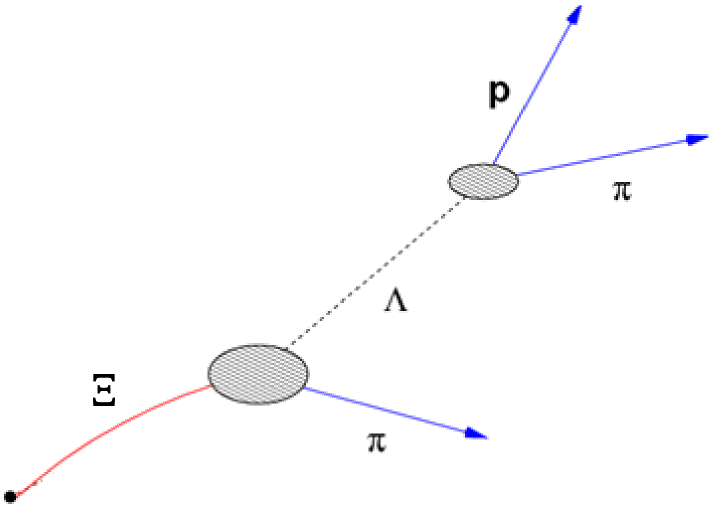
Precision CP tests

CP symmetry:

Qualitatively: Hyperons and antihyperons have the same decay patterns with inverted spatial coordinates.

Quantitatively:

$$\alpha, \beta, \gamma, \phi = -\bar{\alpha}, -\bar{\beta}, -\bar{\gamma}, -\bar{\phi}$$



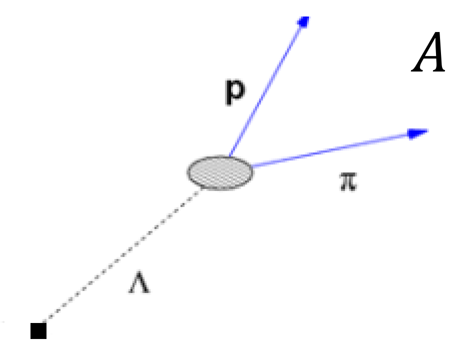
$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$

$$\Delta\phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

Precision CP tests

Challenge: Hyperon decays interplay of strong and weak processes!

→ CP observable from direct decay
= function of strong and weak phases.



$$A_{CP} = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \approx -\tan(\delta_p - \delta_s)\tan(\xi_p - \xi_s)\ ^{*}$$

Strong phase diff.
CP conserving

Weak phase diff.
Possibly
CP violating

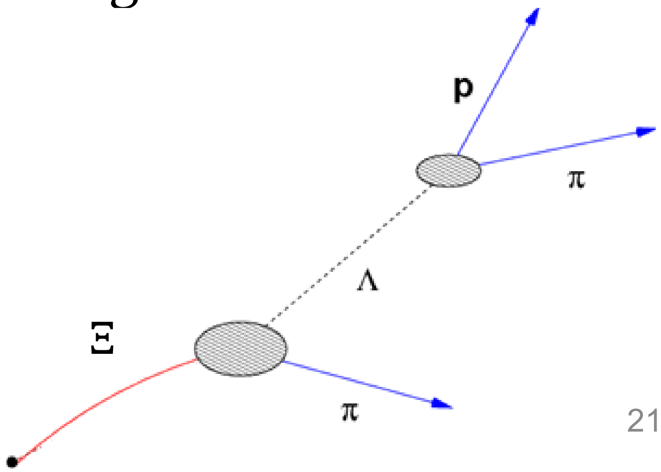
*Donogue, He and Pakvasa, PRD 34, 833 (1986)

Precision CP tests

CP observable from sequential decay function of weak phase difference only!

$$\Delta\phi_{CP} = \frac{\phi+\bar{\phi}}{2} \approx \frac{\alpha}{\sqrt{1-\alpha^2}}(\xi_p - \xi_s)_{LO}$$

→ More sensitive to CP violating effects!



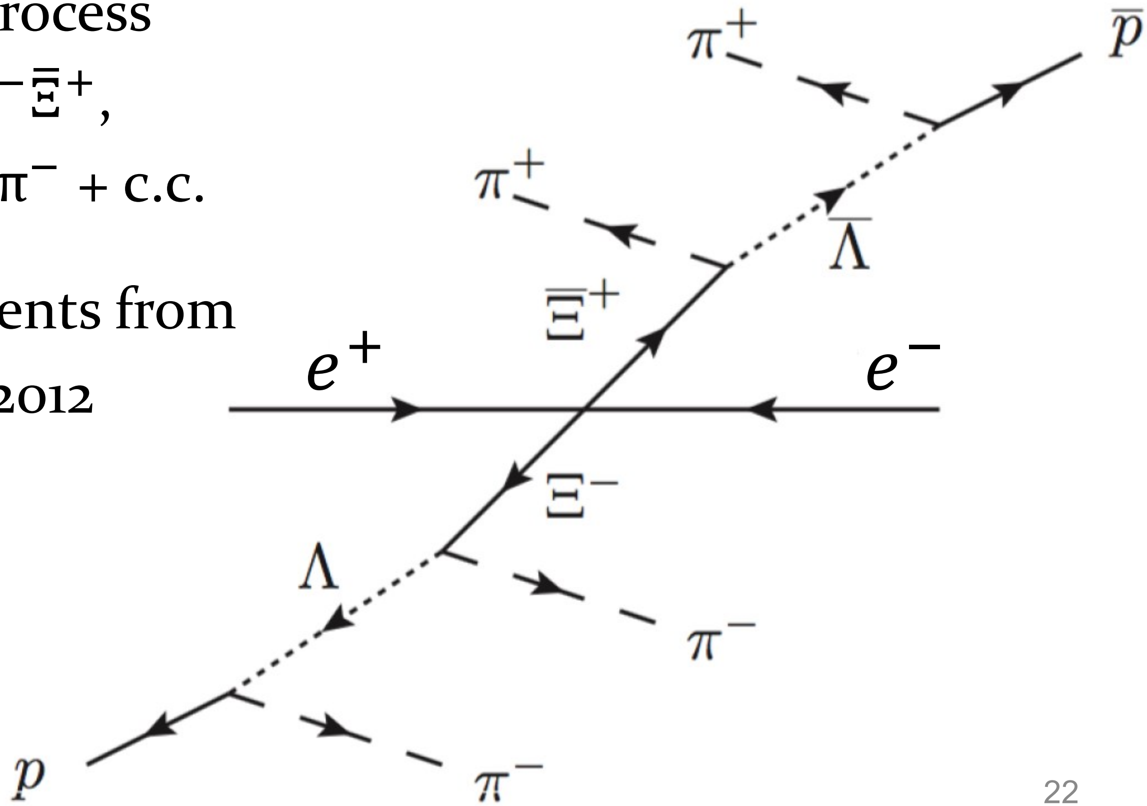
*Donogue, He and Pakvasa, PRD 34, 833 (1986)

New results from BESIII

Polarised and entangled $\Xi^-\bar{\Xi}^+$ pairs decaying by sequential two-body decays.

- Analyse the full process
  $e^+e^- \to J/\Psi \to \Xi^-\bar{\Xi}^+$,
  $\Xi^- \to \Lambda\pi^-, \Lambda \to p\pi^- +$ c.c.

- $1.31 \cdot 10^9$ J/Ψ events from BESIII 2009 and 2012



New results from BESIII

- Formalism by Perotti *et al.* * and Adlarson & Kupsc**
- Exploits polarisation, entanglement and sequential decays

$$\mathcal{W}(\boldsymbol{\xi};\boldsymbol{\omega}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu'\nu'=0}^{3} a^{\Xi}_{\mu\mu'} a^{\bar{\Xi}}_{\nu\nu'} a^{\Lambda}_{\mu'0} a^{\bar{\Lambda}}_{\nu'0}$$

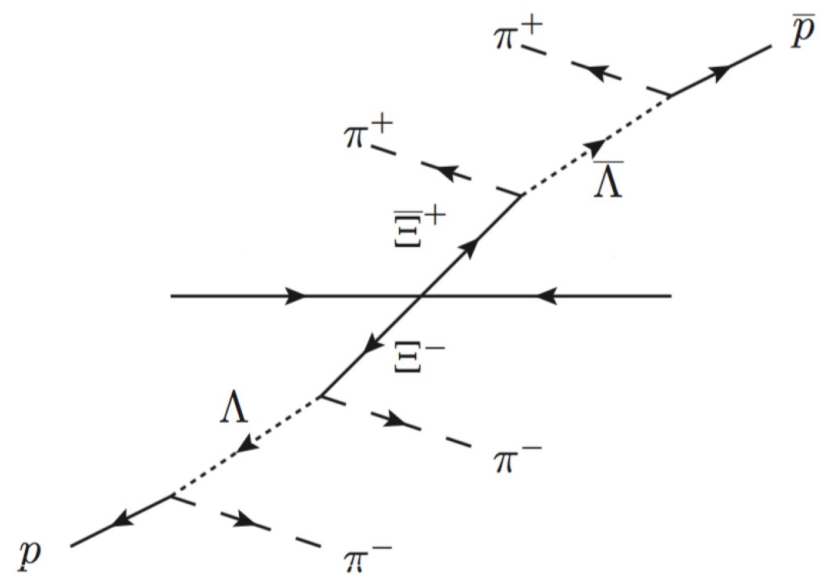
$$C_{\mu\nu} = (1+\alpha_\psi \cos^2\theta) \begin{pmatrix} 1 & 0 & P_y & 0 \\ 0 & C_{xx} & 0 & C_{xz} \\ -P_y & 0 & C_{yy} & 0 \\ 0 & -C_{xz} & 0 & C_{zz} \end{pmatrix}$$

* Phys. Rev. D 99, 056008 (2019)
** Phys. Rev. D 100, 114005 (2019)

New results from BESIII

Event selection

- 3 negative and 3 positive tracks in the MDC, *i.e.* $cos\theta_{lab} < 0.93$
- Protons fulfill $p_p > 0.32$ GeV/c, pions $p_\pi < 0.30$ GeV/c
- Successful vertex fits for Ξ and Λ decay vertices
- Combination must minimise $(m_{p\pi\pi} - m_\Xi)^2 + (m_{p\pi} + m_\Lambda)^2$
- $|m_{p\pi} - m_\Lambda| < 11.5$ MeV/c²
- $|m_{\Lambda\pi} - m_\Xi| < 11.0$ MeV/c²
- Positive decay length $\frac{\Delta L}{L} > 0$
- 4C fit of $e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+$
- $|cos\theta_\Xi| < 0.84$



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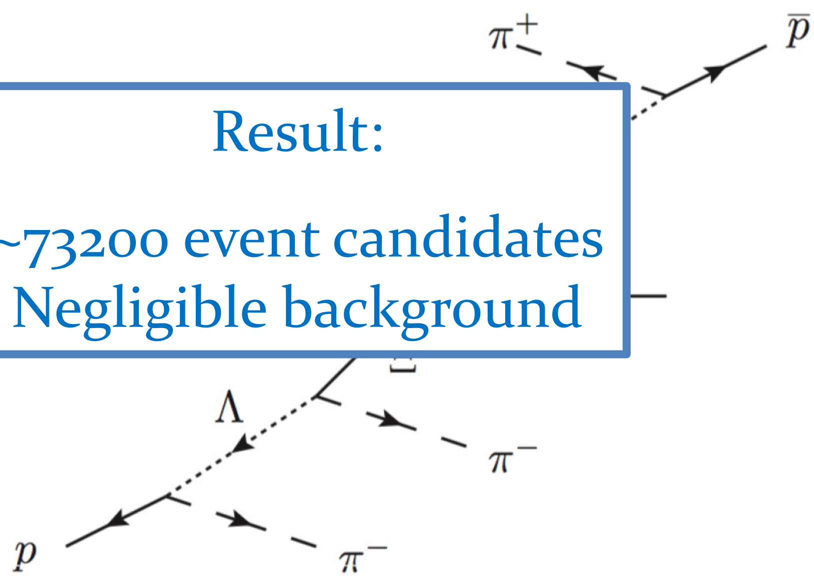
- Positive decay length $\frac{\Delta L}{L} > 0$
- 4C fit of $e^+e^- \to J/\Psi \to \Xi^-\bar{\Xi}^+$
- $|cos\theta_\Xi| < 0.84$

Result:

~73200 event candidates
Negligible background



New results from BESIII

Analysis:

- Parameter estimation: Maximum log-likelihood fit
  - Measured: 9 decay angles
  - Estimated: 8 parameters $\alpha_\psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda$
- Consistency check
  - Independent estimation of polarisation and spin correlations
- Systematic uncertainties
  - Small, mainly from selection criteria

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New results from BESIII

BESIII PRELIMINARY

Parameter	This work	Previous result
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$ *
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010 **
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad **
$\overline{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–
$\overline{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$ ***
$\overline{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$ ***
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad	–
$\delta_p - \delta_s$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2}$ rad	$(10.2 \pm 3.9) \times 10^{-2}$ rad ****
A_{CP}^{Ξ}	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–
A_{CP}^{Λ}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ ***
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad	

- More precise for a given sample size
- First measurement of weak phase difference:
  $(\xi_p - \xi_s) = (1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ rad
- All results consistent with CP symmetry

*BESIII, PRD 93, 072003 (2018)
** PDG 2020
*** BESIII, Nat.P. 15, 631 (2019)
**** HyperCP, PRL 93, 011802 (2004)

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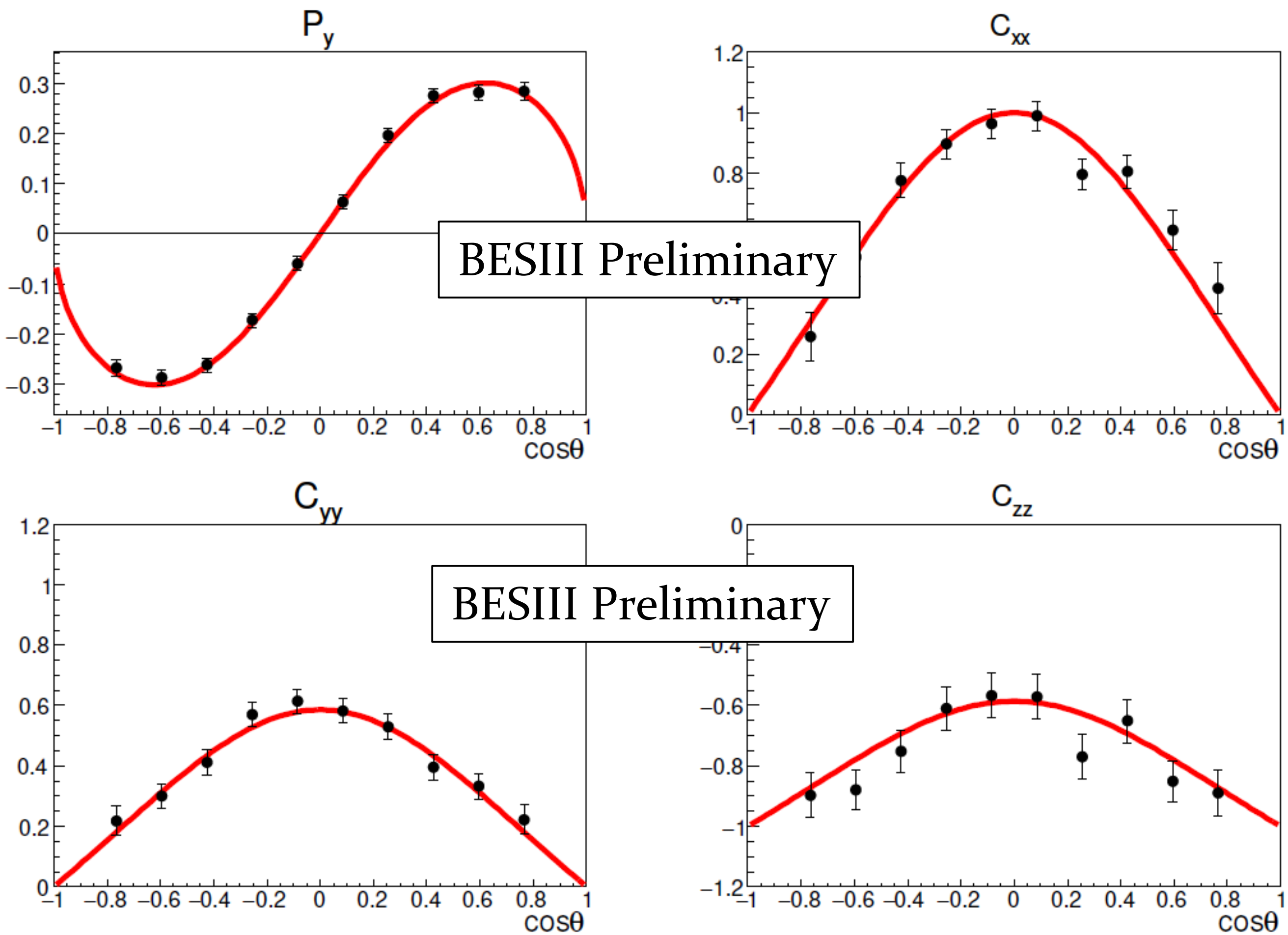
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

- First direct measurement of Ξ decay parameters
- Independent measurement of Λ decay parameter α_Λ
- Strong phase diff. consistent with zero

*BESIII, PRD 93, 072003 (2018)
** PDG 2020
*** BESIII, Nat.P. 15, 631 (2019)
**** HyperCP, PRL 93, 011802 (2004)

New results from BESIII

Consistency check



- Fit values
- Independent estimate

Summary

- The **accessible spin properties** of hyperons make them excellent diagnostic tools for various phenomena.
- **Polarised** and **entangled** hyperon-antihyperon pairs enable
  - Complete determination of hyperon time-like structure
  - CP tests in hyperon decays
- **Sequentially decaying** multi-strange and charm hyperons enable
  - Model independent determination of spin
  - Production- and decay parameters
- A **combination** of the two approaches enables
  - Separation of strong and weak decay phases

→ More sensitive CP tests!

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Summary & Outlook

- New results from BESIII
  - Proof-of-principle for new method
  - Precise CP test of Ξ decays
  - Independent CP test of Λ decays

- World-record data sample of 10^{10} J/Ψ decays under analysis

Stay tuned, and stay healthy!

BESIII

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Thanks for your attention!

Special thanks to Göran Fäldt

Knut and Alice Wallenberg Foundation

Swedish Research Council

Backup

Space-like *vs.* time-like EMFFs

- Asymptotic behaviour as $|q^2| \to \infty$: SL ~TL
  - Nucleons: SL and TL accessible.
  - Hyperons: Only TL accessible, but also phase!

    SL = TL $\leftrightarrow \Delta\Phi(q^2) \to 0$ as $|q^2| \to \infty$

Hyperon polarisation offers an alternative way to study asymptotic behaviour of form factors!

Theory interpretations

- $Y\bar{Y}$ FSI with potentials from $\bar{p}p \rightarrow \bar{Y}Y$ data (PS185)
  - Haidenbauer, Meissner and Dai, Phys. Rev. D 103,014028 (2021)
  - Haidenbauer and Meissner, Phys. Lett. B 761, 456 (2016)
- Vector meson dominance
  - Yang, Chen and Lu, Phys. Rev. D 100, 073007 (2019)
- Dispersion theory
  - Pacetti, talk at the *Workshop on Baryon Production at BESIII,* USTC Hefei, China (2019)