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# Hyperon Physics with BESIII

2021 School on the Physics of Baryons  
Prof. Dr. Karin Schönning, Uppsala University  
for the BESIII collaboration



# Outline

- Introduction
- The BESIII experiment
- Polarised and entangled hyperons
- Sequentially decaying hyperons
- 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



# Introduction

## Nucleon Abundance

Universe consists of matter,  
not antimatter. Why?

- Fine-tuned in the Big Bang?
  - Dynamical generation:  
*Baryogenesis*?
- Requires CP violating processes\*

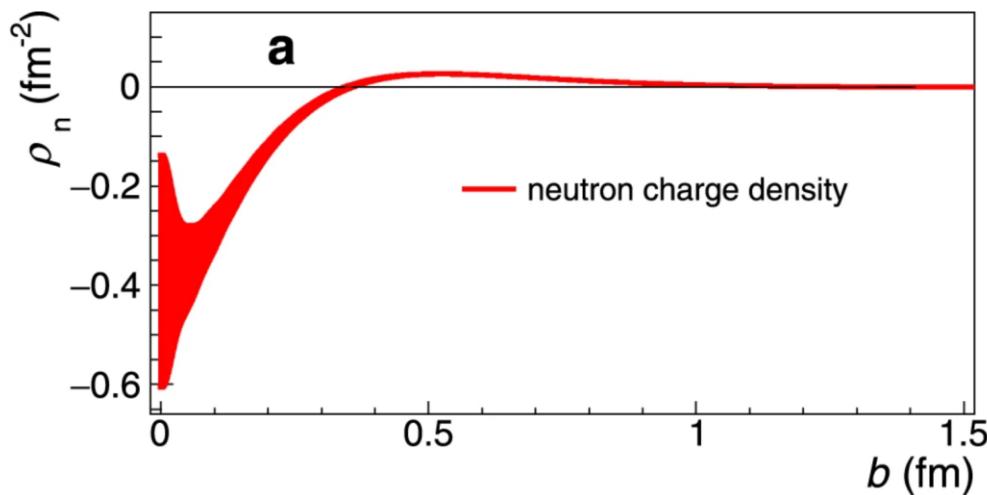


\*A. D. Sakharov, *J. Exp. Theor. Phys. Lett.* 5: 24–27.

# Introduction

## Nucleon Structure

- Fundamental observable of the strong interaction
- Interesting features in the neutron charge density
  - Asymmetric distribution of quarks → negative charge radius



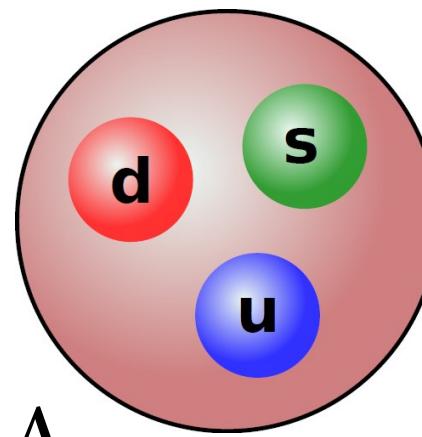
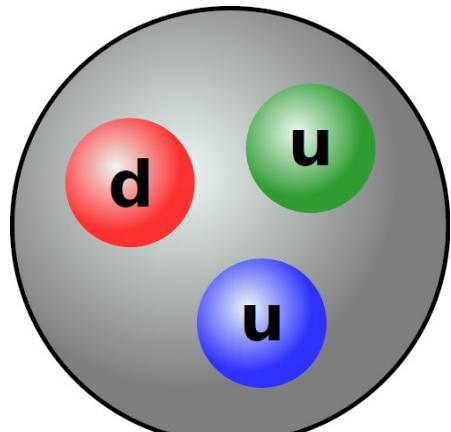
Atac *et al.*,  
Nature Com. 12, 1759 (2021)



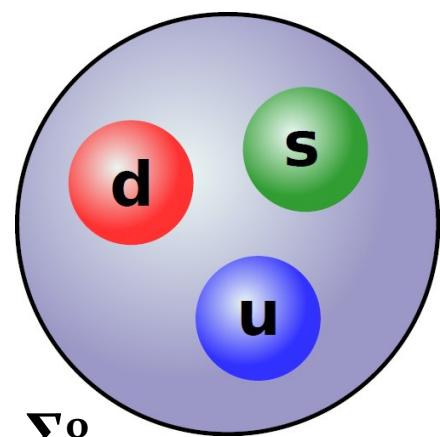
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# Hyperons

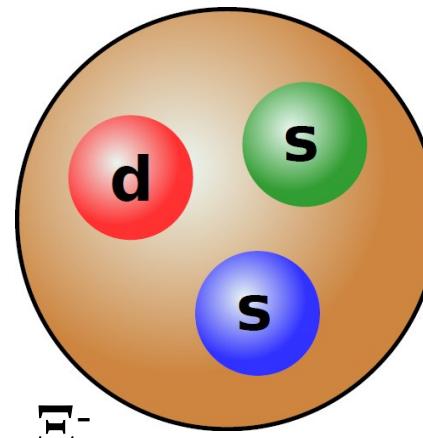
*What happens if we replace one of the light quarks in the proton with one - or many - heavier quark(s)?*



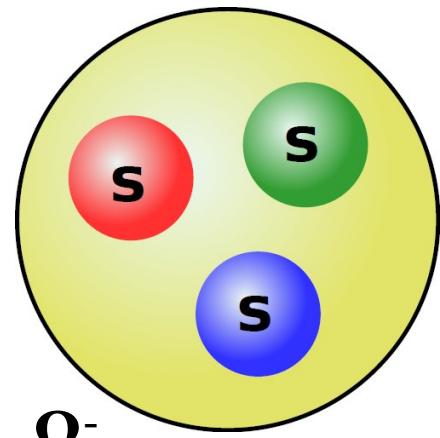
$\Lambda$



$\Sigma^0$



$\Xi^-$



$\Omega^-$

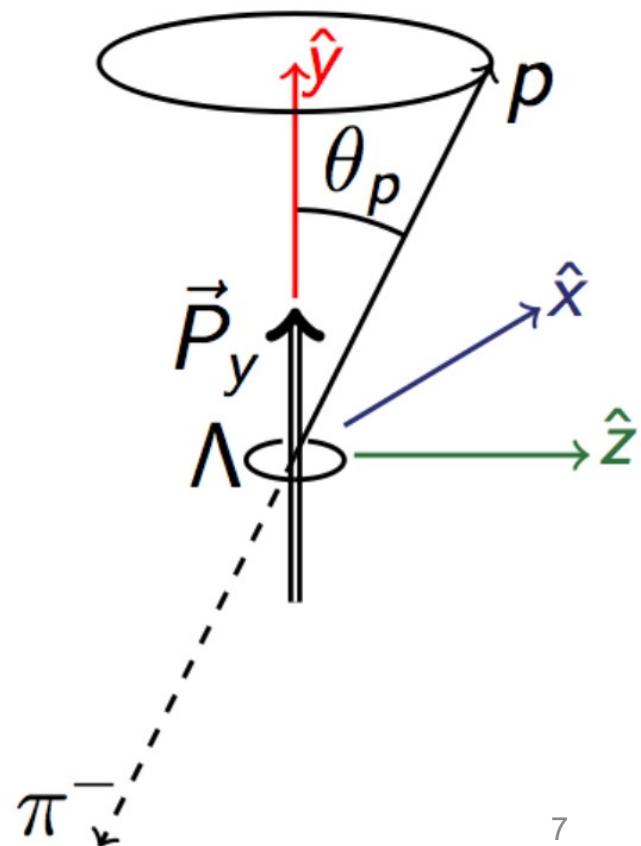
proton

# Advantage of hyperons

Polarisation experimentally accessible  
by the weak, parity violating decay:

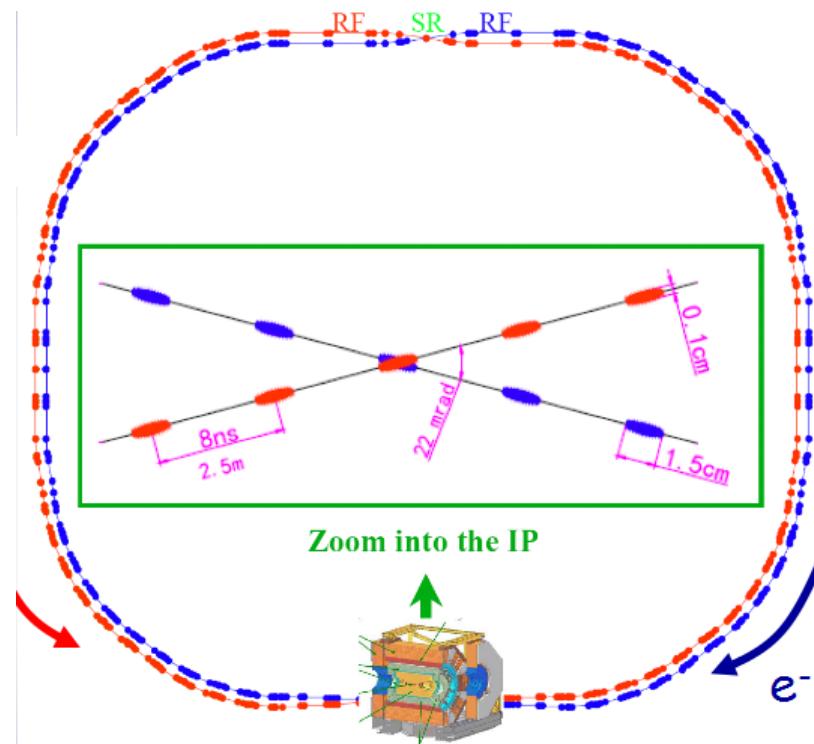
Example:

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



# BESIII @ BEPC II

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

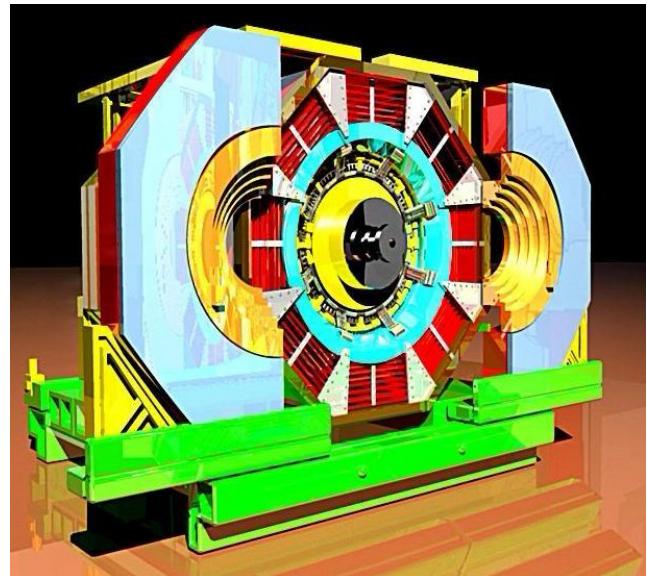


**BESIII**

# BESIII @ BEPC II

- Beijing Spectrometer (BES III):
  - Broad physics scope
    - Hadron spectroscopy
    - Electromagnetic Structure
    - Charm physics
    - Fundamental Symmetries
  - Near  $4\pi$  coverage
    - Tracking
    - PID
    - Calorimetry

**BESIII**





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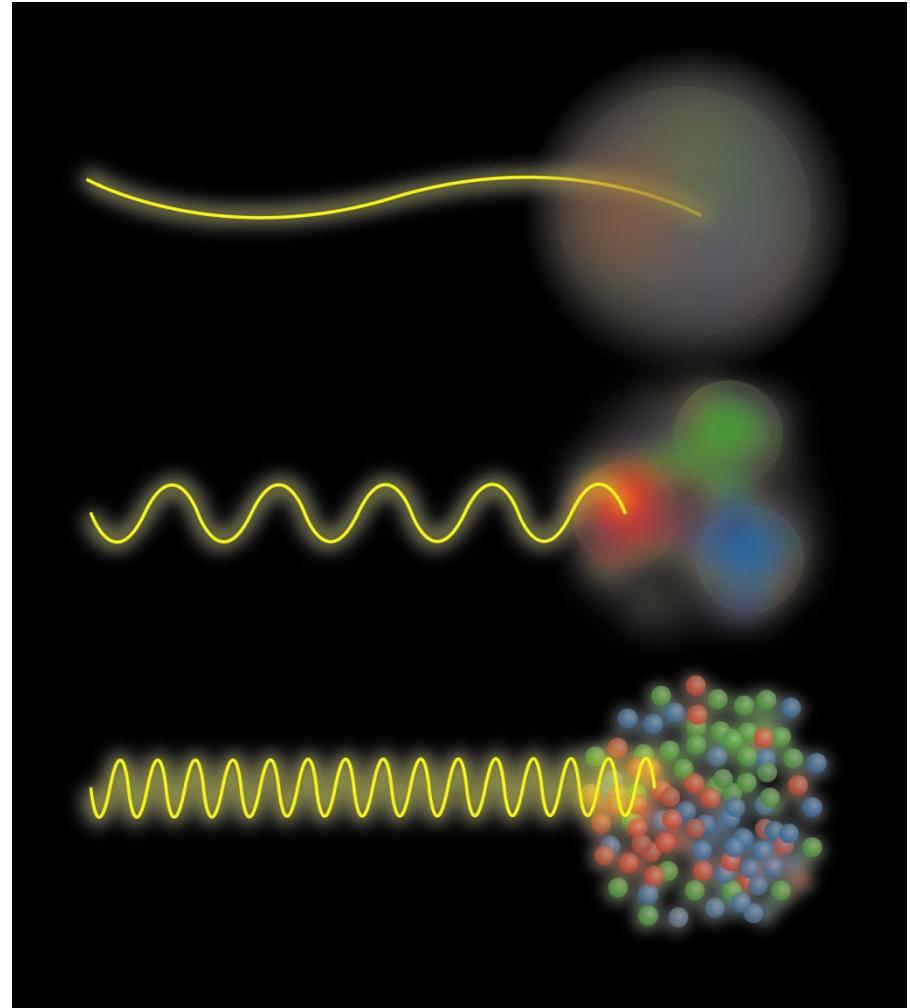


Part 1

# POLARISED AND ENTANGLED HYPERONS

# Electromagnetic Form Factors

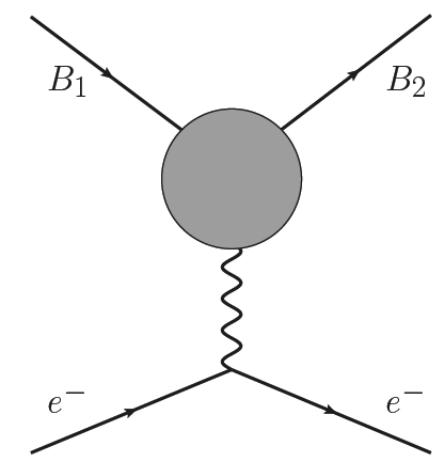
- Electromagnetic structure observable:
  - Lattice QCD, ChPT, VDM...
- Measured in interactions hadron – virtual photon  $\gamma^*$ .
- Quantify deviation from point-like case  
= depend on  $q^2$  of  $\gamma^*$ .



# Space-like vs. time-like FF's

Space-like

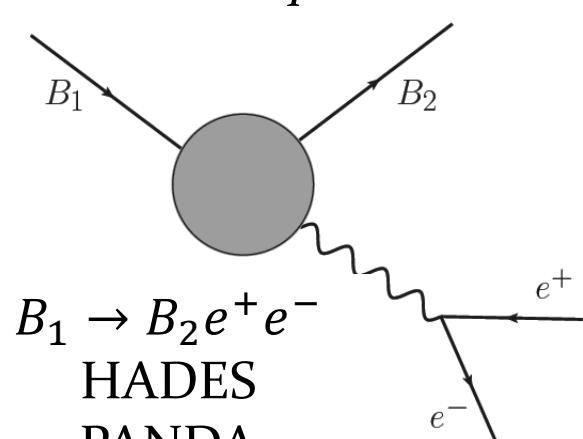
$$q^2 < 0$$



$$e^- B \rightarrow e^- B$$

e.g. JLAB

Low- $q^2$

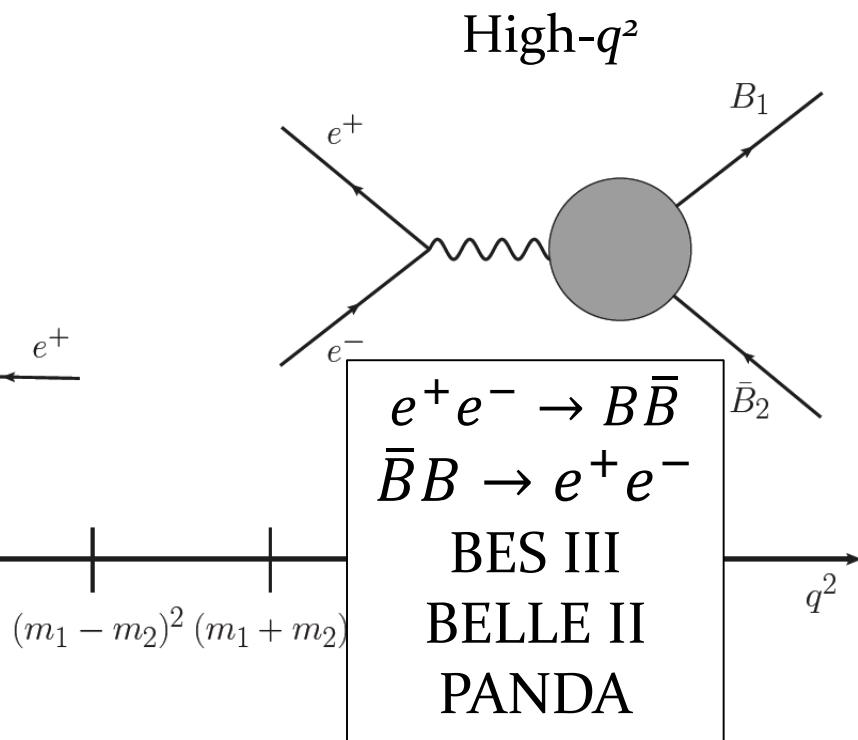


$$B_1 \rightarrow B_2 e^+ e^-$$

HADES  
PANDA

Time-like

$$q^2 > 0$$



$$\bar{B}B \rightarrow e^+ e^-$$

BES III  
BELLE II  
PANDA

# Space-like vs. time-like FF's

Space-like



Time-like



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

Production parameters of spin  $\frac{1}{2}$  baryons:

- Angular distribution parameter  $\eta$
- Phase  $\Delta\Phi$

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

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

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

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

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

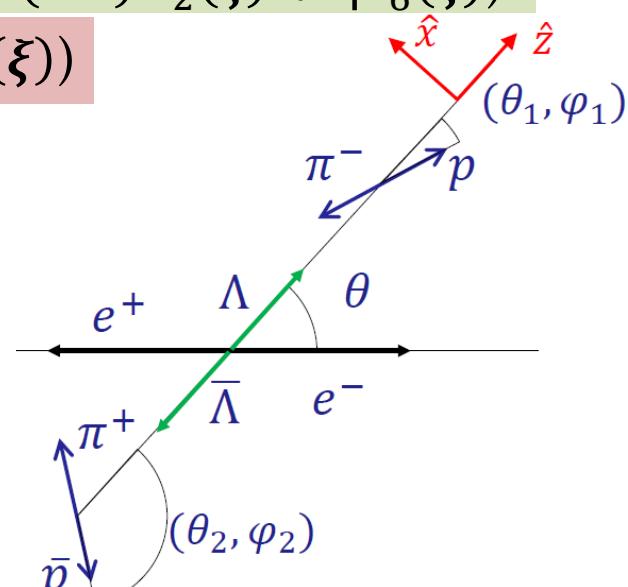
$$\mathcal{T}_2(\xi) = \sin \theta \cos \theta (\sin \theta_1 \cos \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2)$$

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

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

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

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



# Application 1: Hyperon Structure

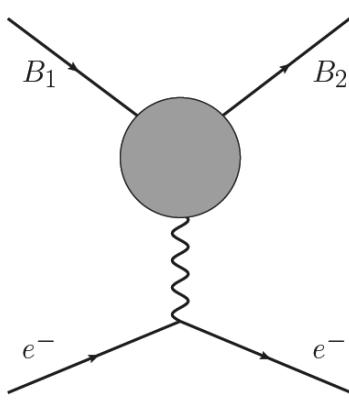
Production parameters of spin  $\frac{1}{2}$  baryons:

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

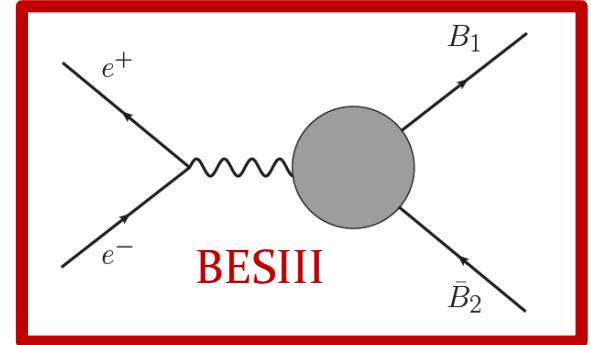
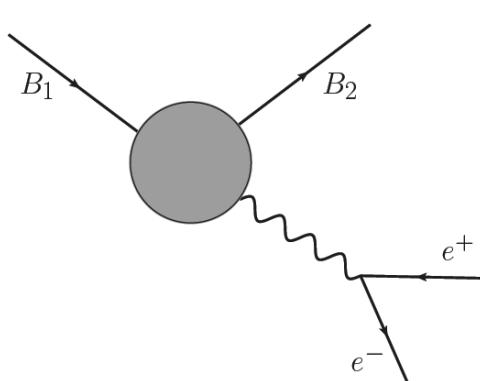
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Space-like



Time-like



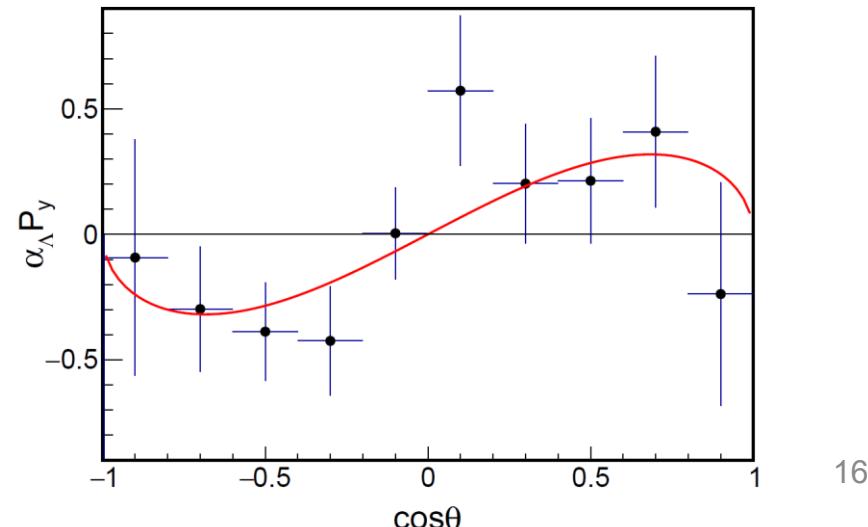
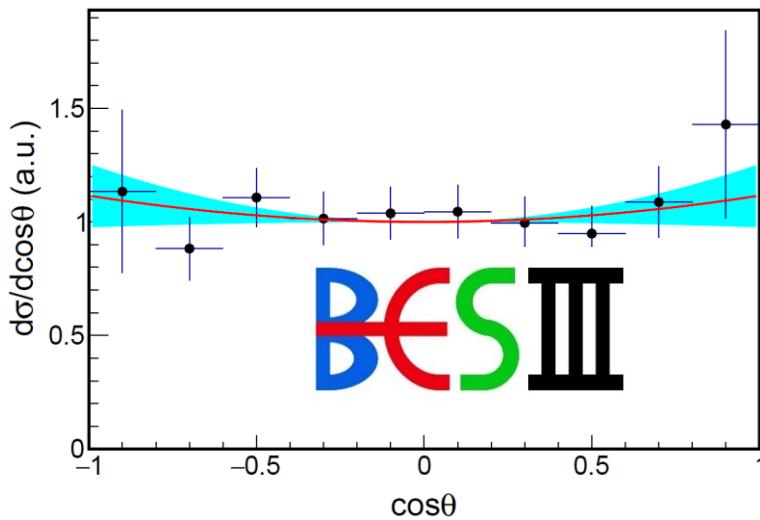
# First complete measurement of $\Lambda$ structure

- New BESIII data at 2.396 GeV with 555 exclusive  $\bar{\Lambda}\Lambda$  events in sample.

- $R = |G_E/G_M| = 0.96 \pm 0.14 \pm 0.02$
- $\Delta\Phi = 37^\circ \pm 12^\circ \pm 6^\circ$
- $\sigma = 118.7 \pm 5.3 \pm 5.1$  pb

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

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



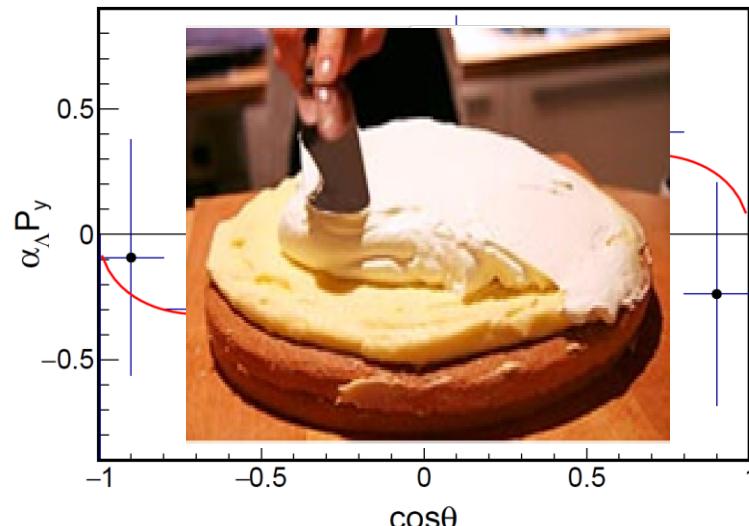
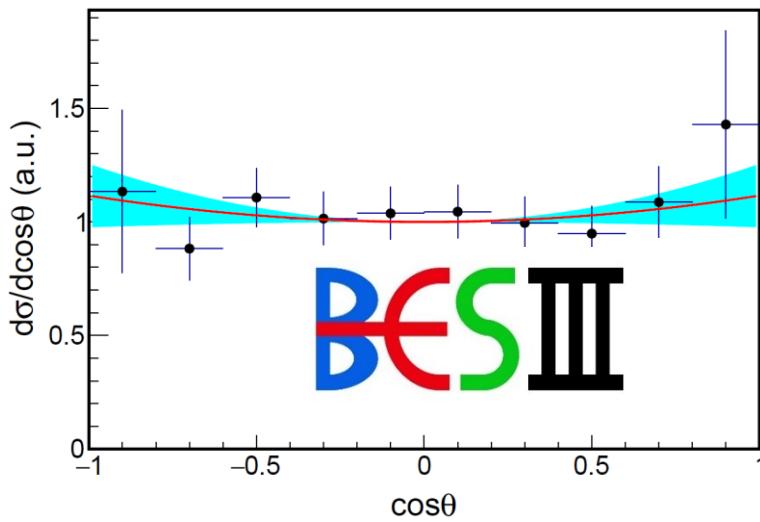
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Phys. Rev. Lett. 123, 122003 (2019)

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



# Application 2: Hyperon Decays

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

Unpolarized part	Polarised part	Correlated part
$\downarrow$	$\downarrow$	$\downarrow$
$W(\xi) = F_0(\xi) + \eta F_5(\xi)$	$- \alpha_1 \alpha_2 (F_1(\xi) + \sqrt{1 - \eta^2} \cos(\Delta\Phi) F_2(\xi) + \eta F_6(\xi))$	$+ \sqrt{1 - \eta^2} \sin(\Delta\Phi) (\alpha_1 F_3(\xi) - \alpha_2 F_4(\xi))$

- Test of CP violation
- Two-body decays: quantified by decay parameters, *e.g.*  $\alpha$ 
  - 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 $\Lambda$ and $\Sigma^+$ decay parameters

- $\Lambda$  decay parameters\* from  $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$

- Decay 1:  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$
  - Decay 2:  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{n}\pi^0$
  - Value of  $\alpha \sim 17\% >$  old PDG value.
  - Most precise CP test for  $\Lambda$  decay:

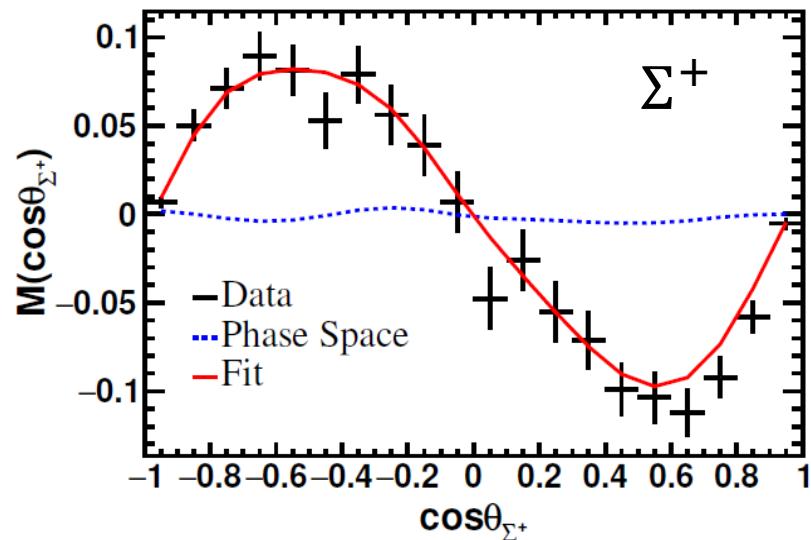
$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} = -0.006 \pm 0.012 \pm 0.007$$

- $\Sigma^+$  decay parameters from  $J/\psi \rightarrow \Sigma^+\bar{\Sigma}^-$

and  $\psi(3686) \rightarrow \Sigma^+\bar{\Sigma}^-$  \*\*

- Decay:  $\Sigma^+ \rightarrow p\pi^0$

- First CP test of  $\Sigma^+$  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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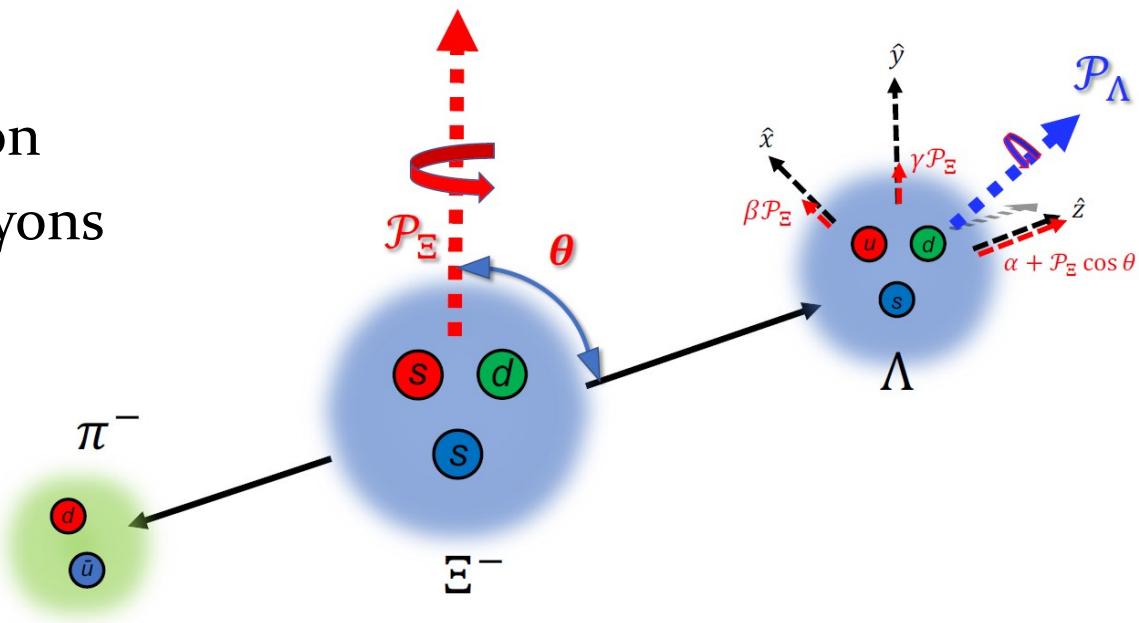


Part 2

# SEQUENTIALLY DECAYING HYPERONS

# Sequential hyperon decays

- Additional decay parameters  $\beta, \gamma, \phi$  accessible\*.
  - $\alpha^2 + \beta^2 + \gamma^2 = 1$
  - $\tan\phi = \frac{\beta}{\gamma}$
- Formalism for production and decay of spin  $1/2$  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).

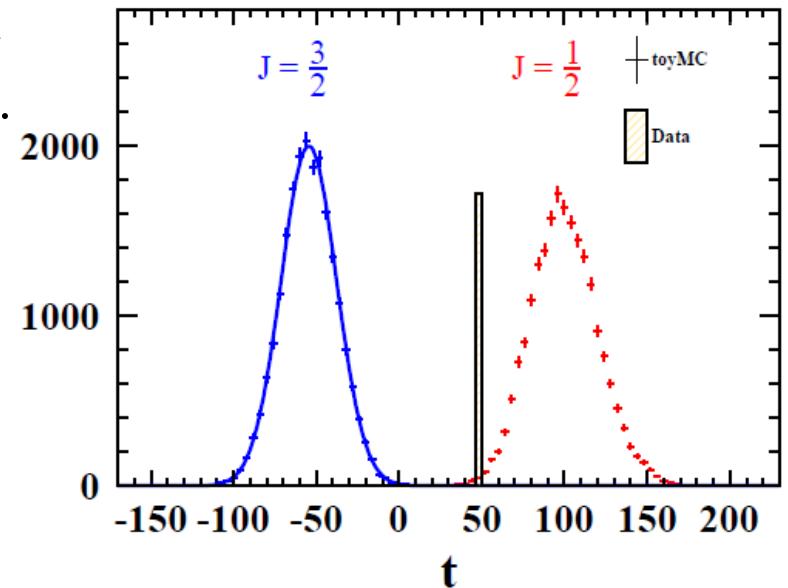
# Spin properties of the $\Lambda_c^+$

Single-tag studies of  $e^+e^- \rightarrow \Lambda_c^+\bar{\Lambda}_c^-, \Lambda_c^+ \rightarrow pK_S, \Lambda\pi^+, \Sigma^+\pi^0, \Sigma^0\pi^+ + \text{c.c.}$

- First direct determination of the  $\Lambda_c^+$  spin\*
  - Spin 1/2 favoured over spin 3/2 favoured with more than 6  $\sigma$ .
  - In line with the quark model

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

**BESIII**



\* Phys. Rev. D 103, 091101 (2021)

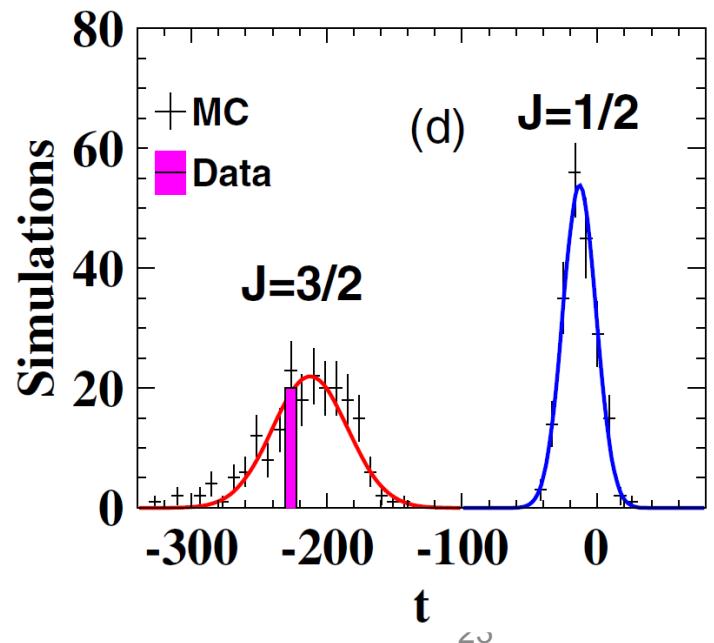
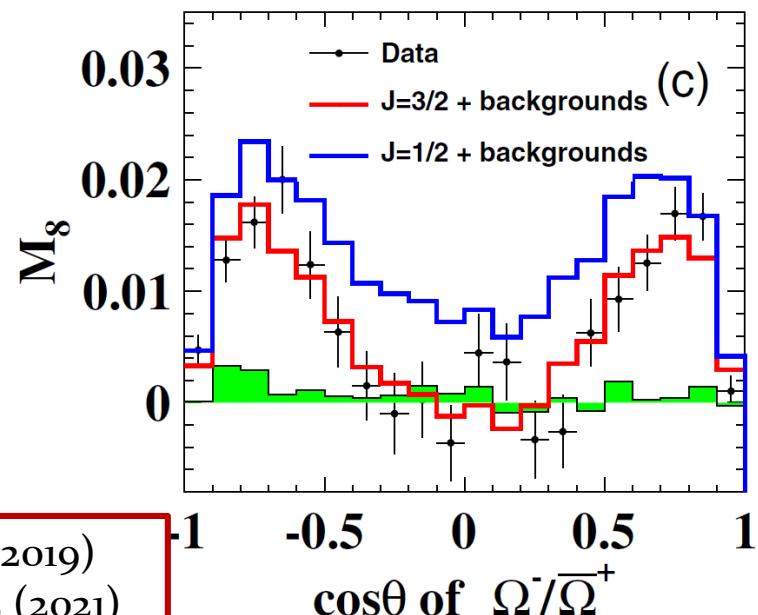
\*\* Phys. Rev. D 100, 072004 (2019)

# Spin properties of the $\Omega^-$

- 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  $\Omega^-$  spin
  - First measurement of the decay parameter  $\phi_\Omega(\Omega^- \rightarrow \Lambda\pi^-)$

**BESIII**



\*PRD 99, 056008 (2019)

\*\* PRL 126, 092002 (2021)



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Part 3

## COMBINED APPROACH

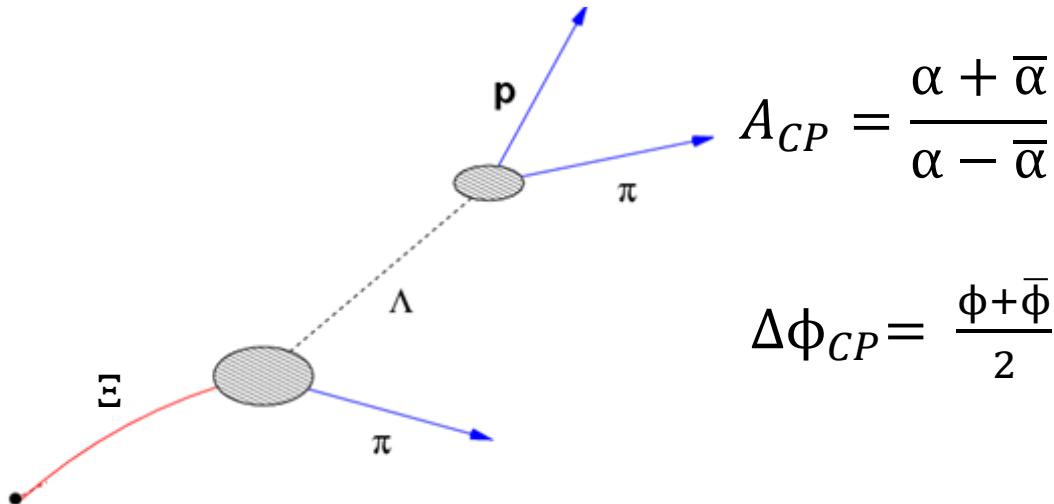
# Precision CP tests

CP symmetry:

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

Quantitatively:

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

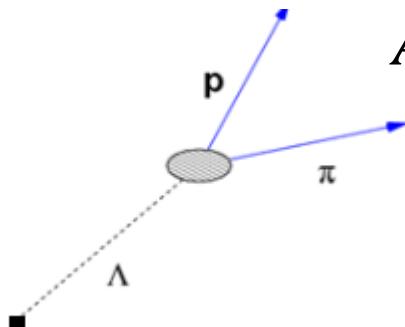


$$\Delta\phi_{CP} = \frac{\phi + \bar{\phi}}{2}$$

# 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

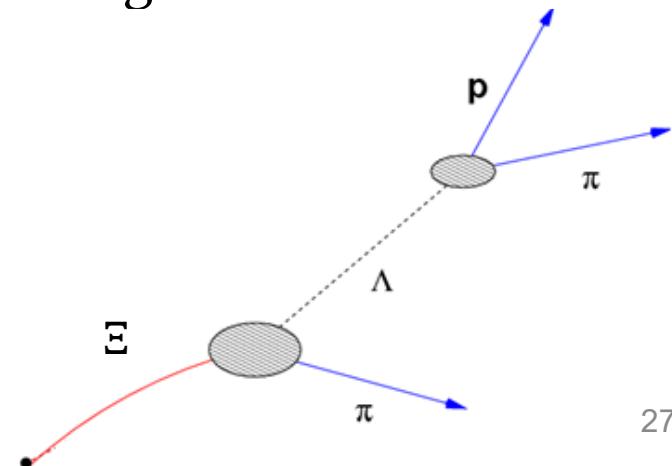
Weak phase diff.  
 Possibly  
 CP violating

# 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!



# New results from BESIII

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

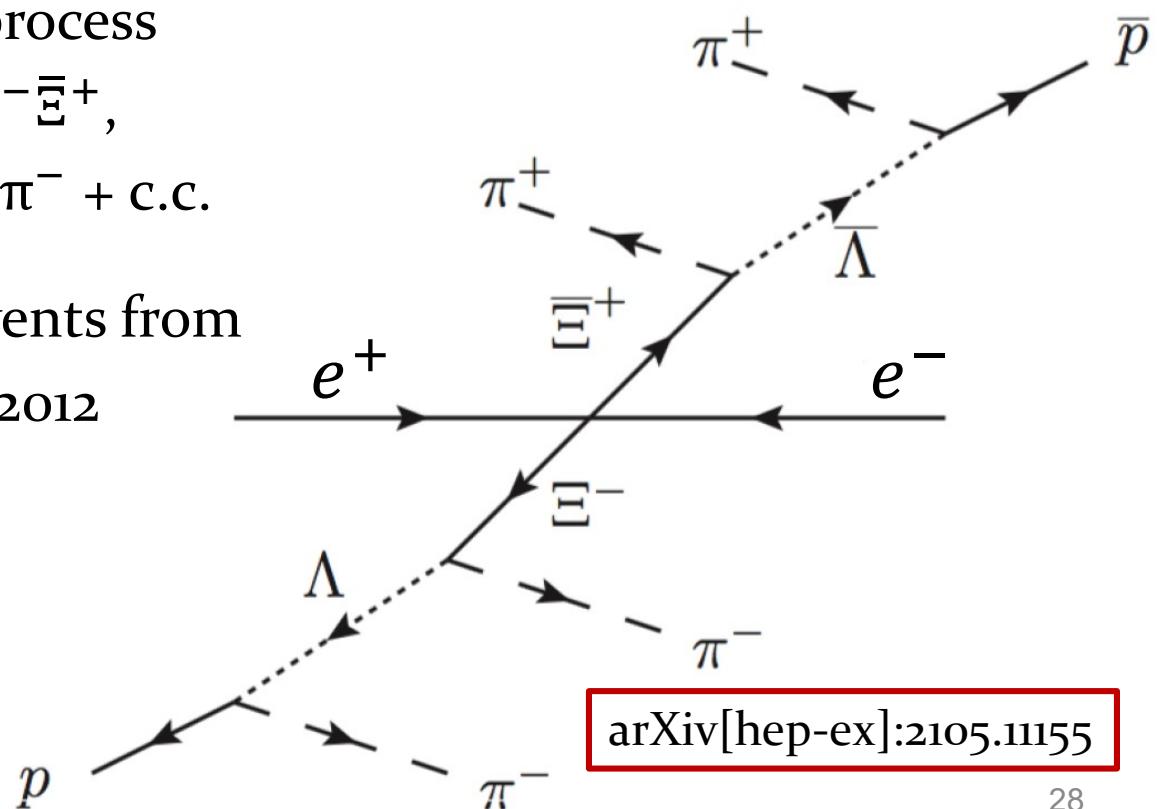
- Analyse the full process

$$e^+e^- \rightarrow J/\Psi \rightarrow \Xi^-\bar{\Xi}^+,$$

$$\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow p\pi^- + \text{c.c.}$$

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

**BESIII**



# New results from BESIII

- Formalism by Perotti *et al.*\*
- Exploits **polarisation**, **entanglement** and **sequential decays**

$$\mathcal{W}(\xi; \omega) = \sum_{\mu, v=0}^3 C_{\mu v} \sum_{\mu' v'=0}^3 a_{\mu \mu'}^{\Xi} a_{v v'}^{\Xi} a_{\mu' 0}^{\Lambda} a_{v' 0}^{\Lambda}$$

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

# 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
$\alpha_\Psi$	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$ *
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–
$\alpha_{\Xi}$	$-0.376 \pm 0.007 \pm 0.003$	$-0.401 \pm 0.010$ **
$\phi_{\Xi}$	$0.011 \pm 0.019 \pm 0.009$ rad	$-0.037 \pm 0.014$ rad **
$\bar{\alpha}_{\Xi}$	$0.371 \pm 0.007 \pm 0.002$	–
$\bar{\phi}_{\Xi}$	$-0.021 \pm 0.019 \pm 0.007$ rad	–
$\alpha_\Lambda$	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$ ***
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$ ***
$\xi_p - \xi_s$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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 ****
$A_{CP}^{\Xi}$	$(6.0 \pm 13.4 \pm 5.6) \times 10^{-3}$	–
$\Delta\phi_{CP}^{\Xi}$	$(-4.8 \pm 13.7 \pm 2.9) \times 10^{-3}$ rad	–
$A_{CP}^{\Lambda}$	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$ ***
$\langle\phi_{\Xi}\rangle$	$0.016 \pm 0.014 \pm 0.007$ 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  $\Xi$  decay parameters
- Independent measurement of  $\Lambda$  decay parameter  $\alpha_\Lambda$
- Strong phase diff. consistent with zero

\*BESIII, PRD 93, 072003 (2018)

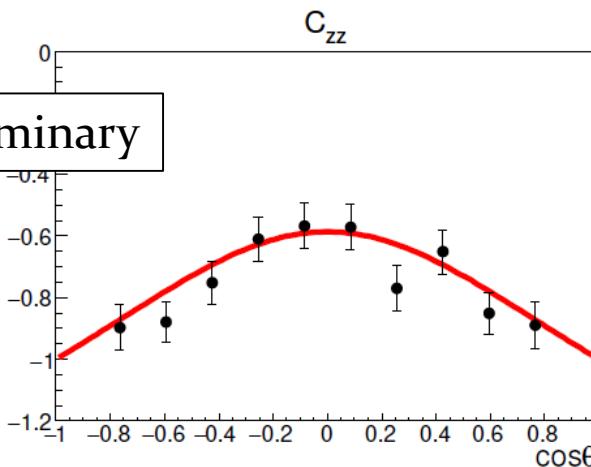
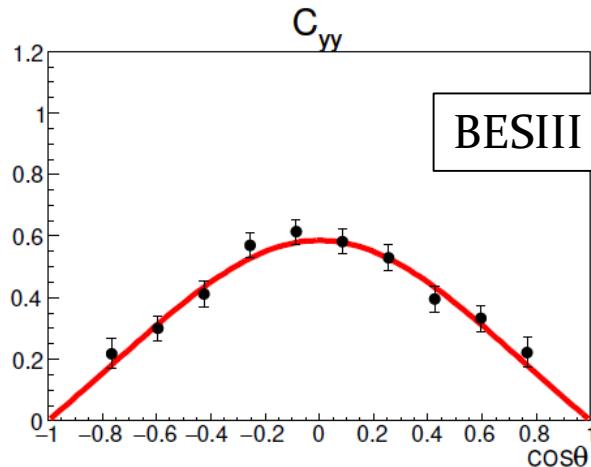
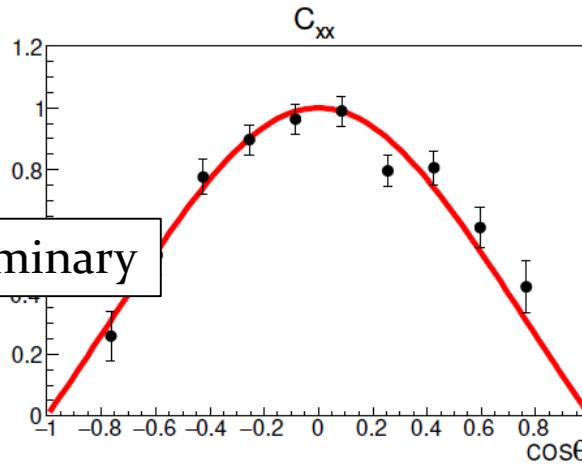
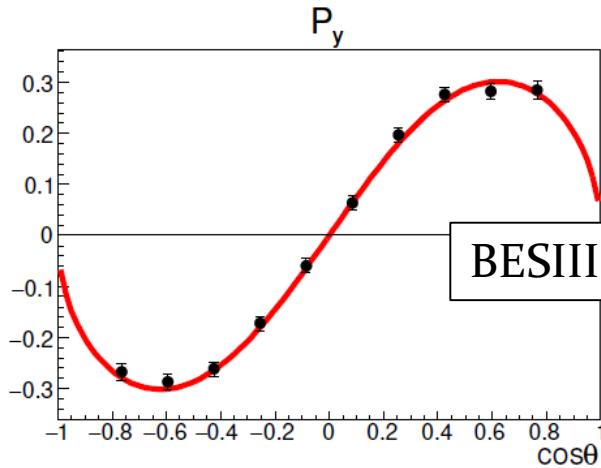
\*\* PDG 2020

\*\*\* 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!

# Summary & Outlook

- New results from BESIII
  - Proof-of-principle for new method
  - Precise CP test of  $\Xi$  decays
  - Independent CP test of  $\Lambda$  decays
- World-record data sample of  $10^{10}$   $J/\Psi$  decays under analysis

Stay tuned, and stay healthy!



# Thanks for your attention!

Special thanks to Göran Fäldt

*Knut and Alice  
Wallenberg  
Foundation*



Swedish  
Research  
Council



UPPSALA  
UNIVERSITET

# Backup

# Space-like vs. time-like EMFFs

- Asymptotic behaviour as  $|q^2| \rightarrow \infty$ : SL  $\sim$  TL
  - Nucleons: SL and TL accessible.
  - Hyperons: Only TL accessible, but also phase!  
 $SL = TL \leftrightarrow \Delta\Phi(q^2) \rightarrow 0$  as  $|q^2| \rightarrow \infty$

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

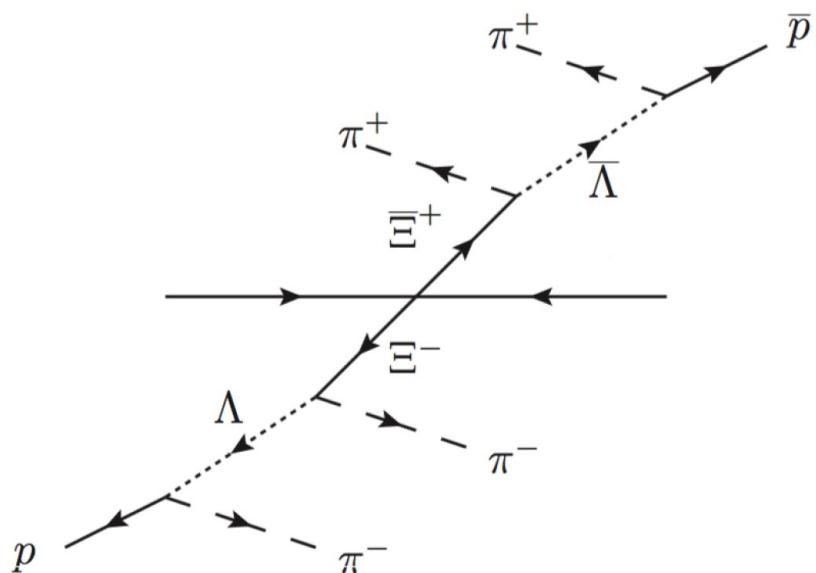
# Theory interpretations

- $Y\bar{Y}$  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)

# New results from BESIII

## Event selection

- 3 negative and 3 positive tracks in the MDC, i.e.  $\cos\theta_{lab} < 0.93$
- Protons fulfill  $p_p > 0.32 \text{ GeV}/c$ , pions  $p_\pi < 0.30 \text{ GeV}/c$
- Successful vertex fits for  $\Xi$  and  $\Lambda$  decay vertices
- Combination must minimise  $(m_{p\pi\pi} - m_\Xi)^2 + (m_{p\pi} + m_\Lambda)^2$
- $|m_{p\pi} - m_\Lambda| < 11.5 \text{ MeV}/c^2$
- $|m_{\Lambda\pi} - m_\Xi| < 11.0 \text{ MeV}/c^2$
- 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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