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Polarised and entangled hyperon-antihyperon pairs in BESIII

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Prof. Dr. Karin Schönning, Uppsala University

Outline

- Introduction
- The BESIII experiment
- Hyperon structure
- Hyperon decays
- Summary

Introduction

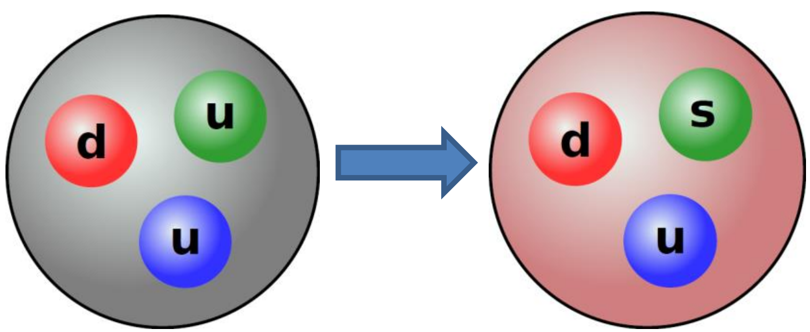
Many challenges in modern physics manifest themselves in the **nucleon.**

Challenging to describe from first principles:

- **Its abundance**
- Its mass
- Its spin
- **Its structure**
- Its radius

When you don't understand a system, you can*

- Scatter on it
- Excite it
- **Replace building blocks**

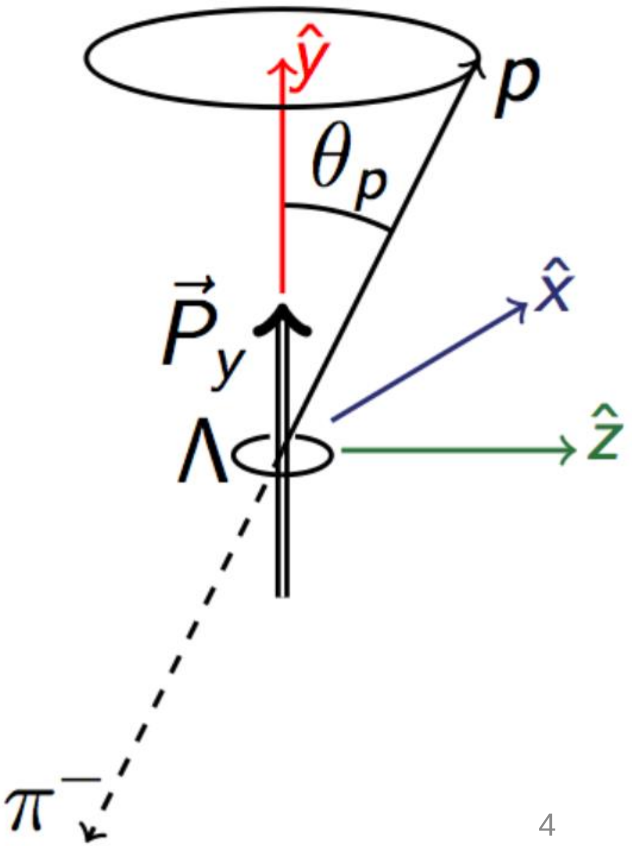


Advantage of hyperons

Polarisation experimentally accessible by the weak, parity violating decay:

Example:

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



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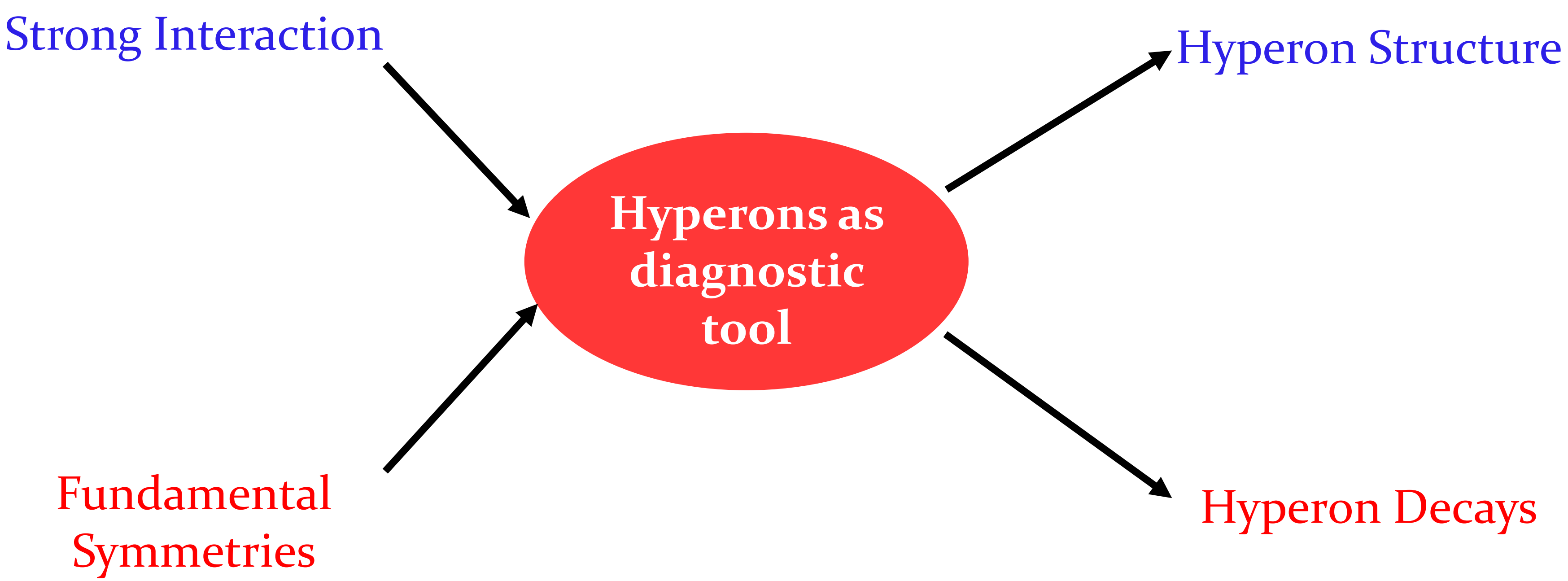
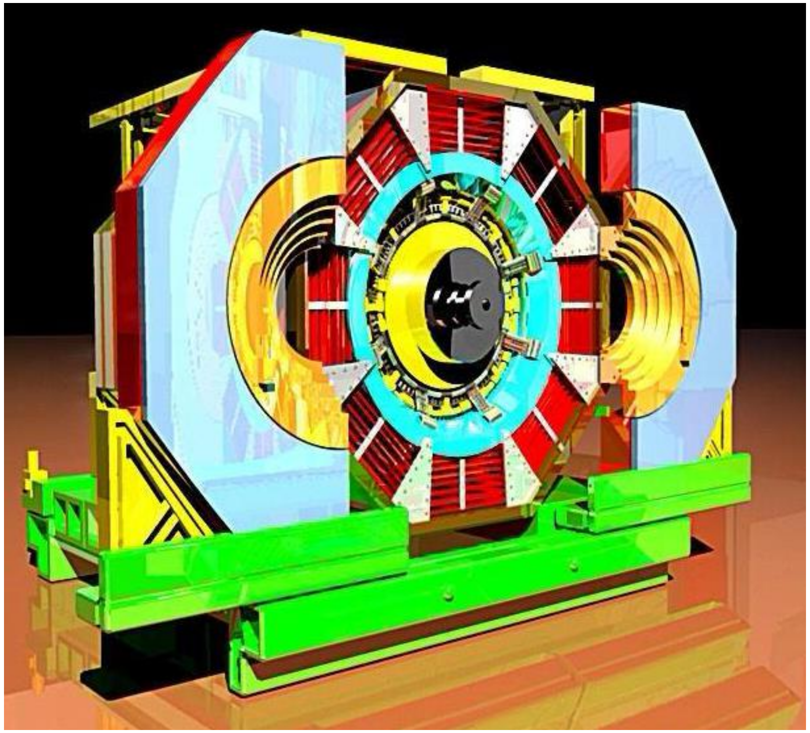
Fundamental Question

Topic



BESIII @ BEPC II

- Beijing Electron Positron Collider (BEPC II):
  - e^+e^- collider within CMS range 2.0 – 4.7 GeV.
  - Optimised in the τ-charm region.



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

Part 1

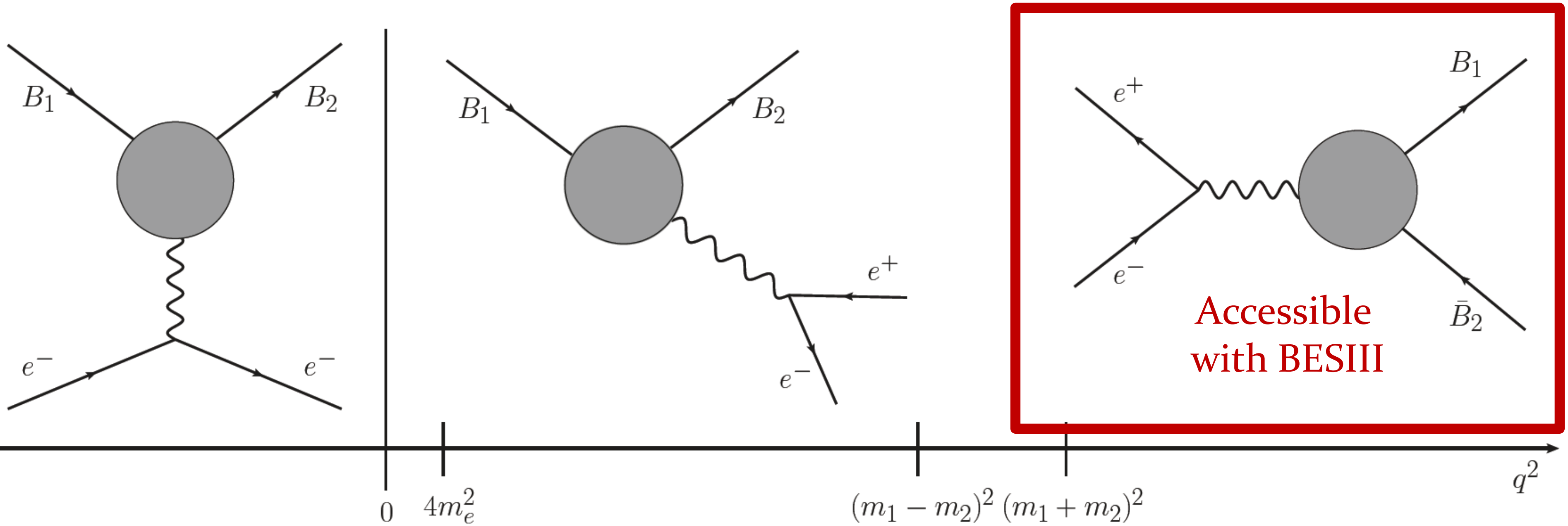
HYPERON STRUCTURE

Hyperon structure

- Quantified by Electromagnetic Form Factors (EMFFs).
- Analytic functions of q^2 of virtual photon γ^*.
- Space-like EMFFs are related to *charge* and *magnetization density*.
- Time-like EMFFs accessible also for unstable particles, *e.g.* hyperons.

Space-like

Time-like



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

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Space-like *vs.* time-like EMFFs

- Related *via* dispersion relations*.
- Time-like EMFFs can be complex with a relative phase.
  - Phase accessible *via* the measurable polarisation!
- 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!

*PRC 75 (2007) 035202

First complete measurement of Λ EMFF

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

Spin ½ baryons: Two complex amplitudes contribute → can parameterise in terms of

- Angular distribution parameter η
- Phase ΔΦ

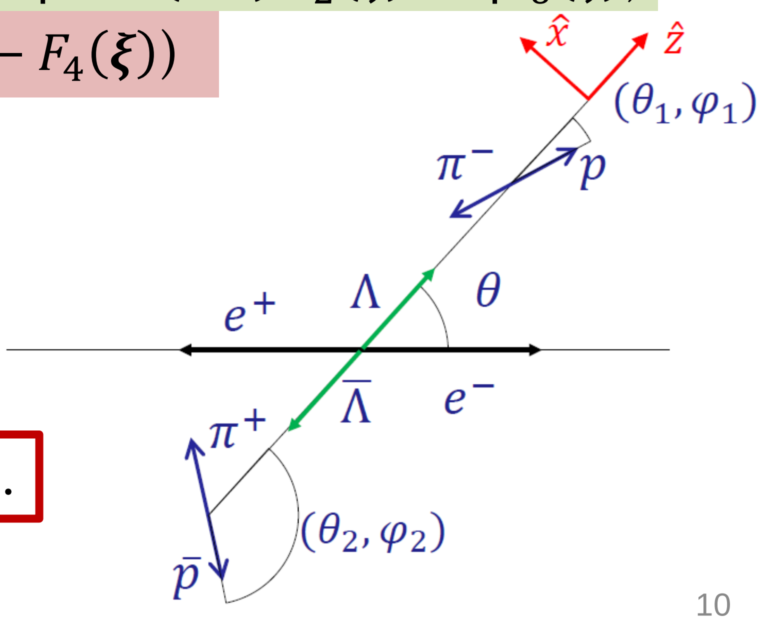
Unpolarized part **Polarized part** **Spin correlated part**

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

(assuming $\alpha = -\bar{\alpha}$)

$$\mathcal{F}_0(\xi) = 1$$
$$\mathcal{F}_1(\xi) = \sin^2\theta \sin\theta_1 \sin\theta_2 \cos\phi_1 \cos\phi_2 + \cos^2\theta \cos\theta_1 \cos\theta_2$$
$$\mathcal{F}_2(\xi) = \sin\theta\cos\theta\,(\sin\theta_1\cos\theta_2\cos\phi_1 + \cos\theta_1\sin\theta_2\cos\phi_2)$$
$$\mathcal{F}_3(\xi) = \sin\theta\cos\theta\sin\theta_1\sin\phi_1$$
$$\mathcal{F}_4(\xi) = \sin\theta\cos\theta\sin\theta_2\sin\phi_2$$
$$\mathcal{F}_5(\xi) = \cos^2\theta$$
$$\mathcal{F}_6(\xi) = \cos\theta_1\cos\theta_2 - \sin^2\theta\sin\theta_1\sin\theta_2\sin\phi_1\sin\phi_2$$

*PLB 772 (2017) 16.



First complete measurement of Λ EMFF

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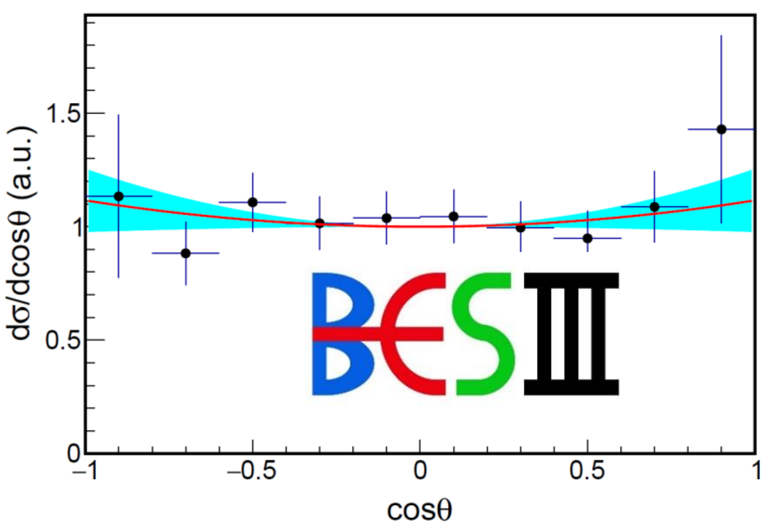
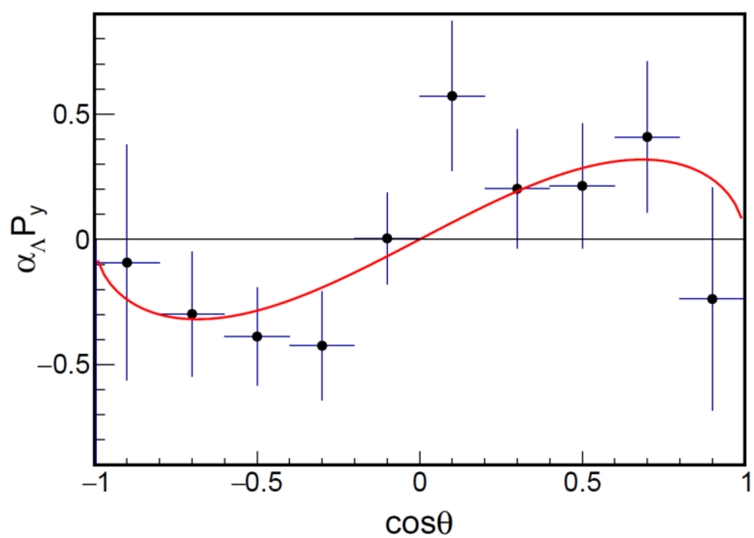
- New BESIII data at 2.396 GeV with 555 exclusive $\bar{\Lambda}\Lambda$ events in sample.
  - $R=|G_E/G_M| = \mathbf{0.96 \pm 0.14 \pm 0.02}$
  - $\Delta\Phi = \mathbf{37^o \pm 12^o \pm 6^o}$
  - $\sigma = 118.7 \pm 5.3 \pm 5.1$ pb

←PRL 123 (2019) 122003

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





Theory interpretations

- $\Lambda\bar{\Lambda}$ FSI with potentials from $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ data (PS185) ------------------------------
  - 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)

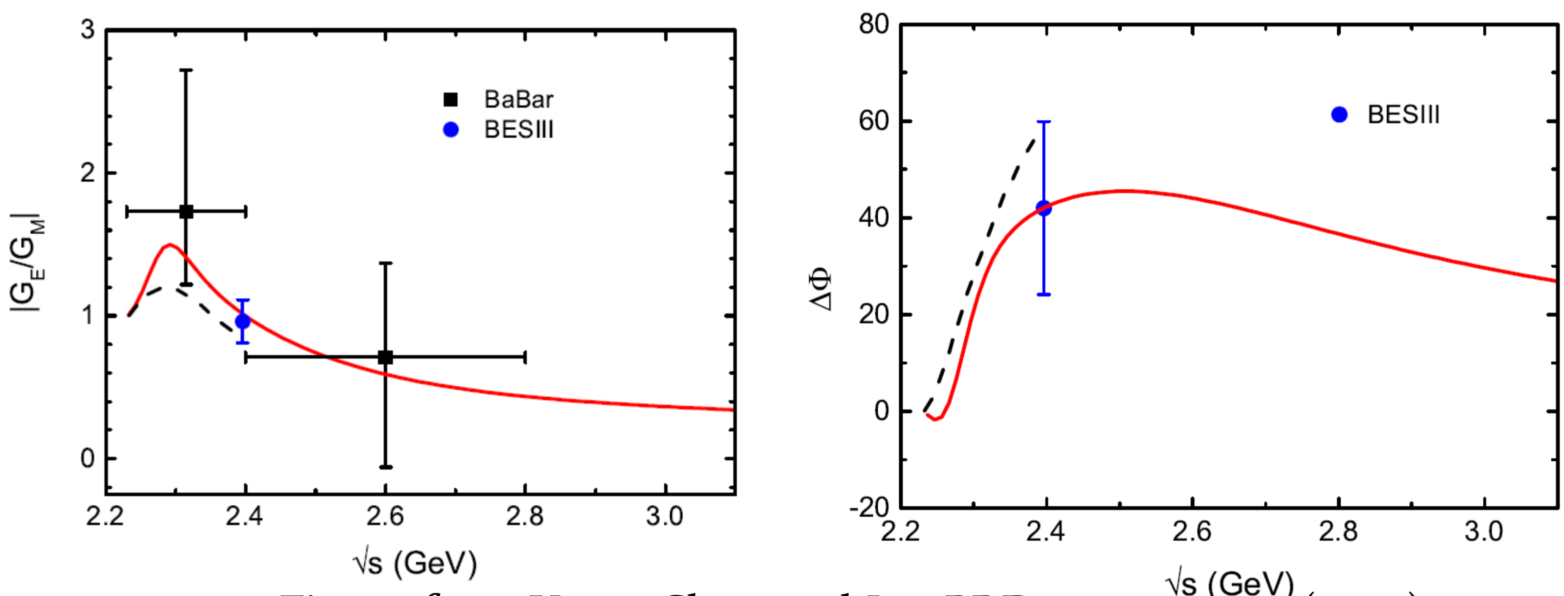


Figure from Yang, Chen and Lu, PRD 100, 073007 (2019)

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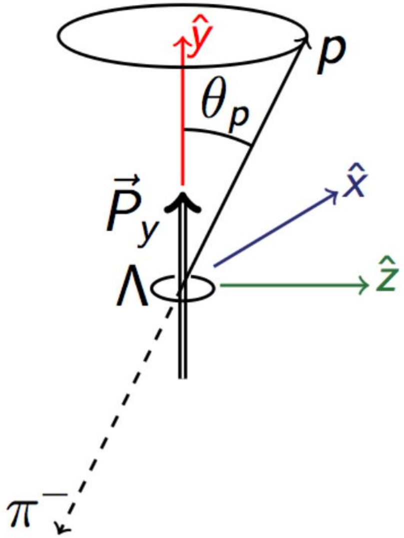
Part 2

HYPERON DECAYS

Hyperon decays

- Searchground for physics beyond the Standard Model at the precision frontier.
- Occur through an interplay between weak/BSM and strong processes.
  - Non-pQCD effects may hide CP violation.
- Two-body decays: quantified by decay parameters, *e.g.* α
  - accessible in direct decay
  - CP symmetry: $\alpha = -\bar{\alpha}$
  - CP observable defined by *e.g.*:

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}$$



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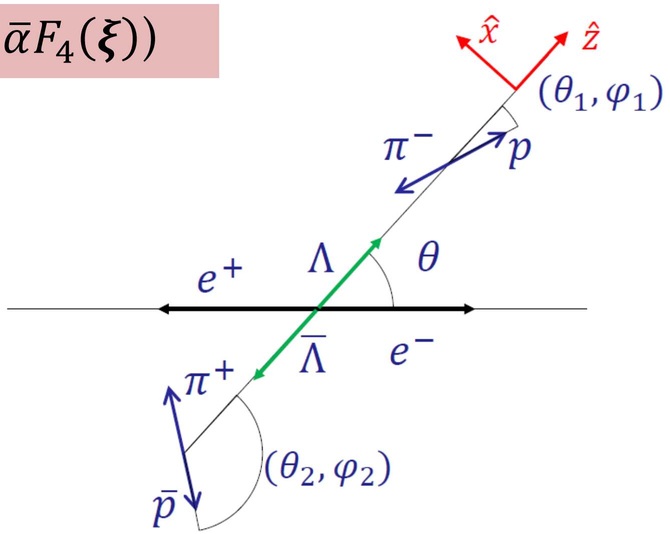
Measurement of the Λ decay parameters

Formalism for $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}, \Lambda \to p\pi^-, \bar{\Lambda} \to \bar{p}\pi^+$ *
(same as before but **without** assuming $\alpha = -\bar{\alpha}$)

Unpolarized part **Polarized part** **Spin correlated part**

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

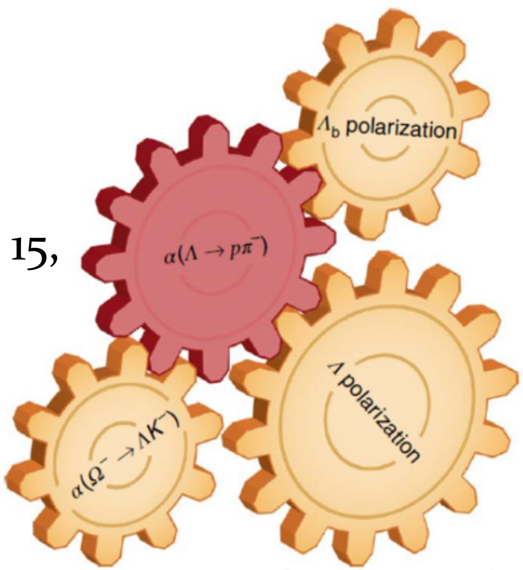


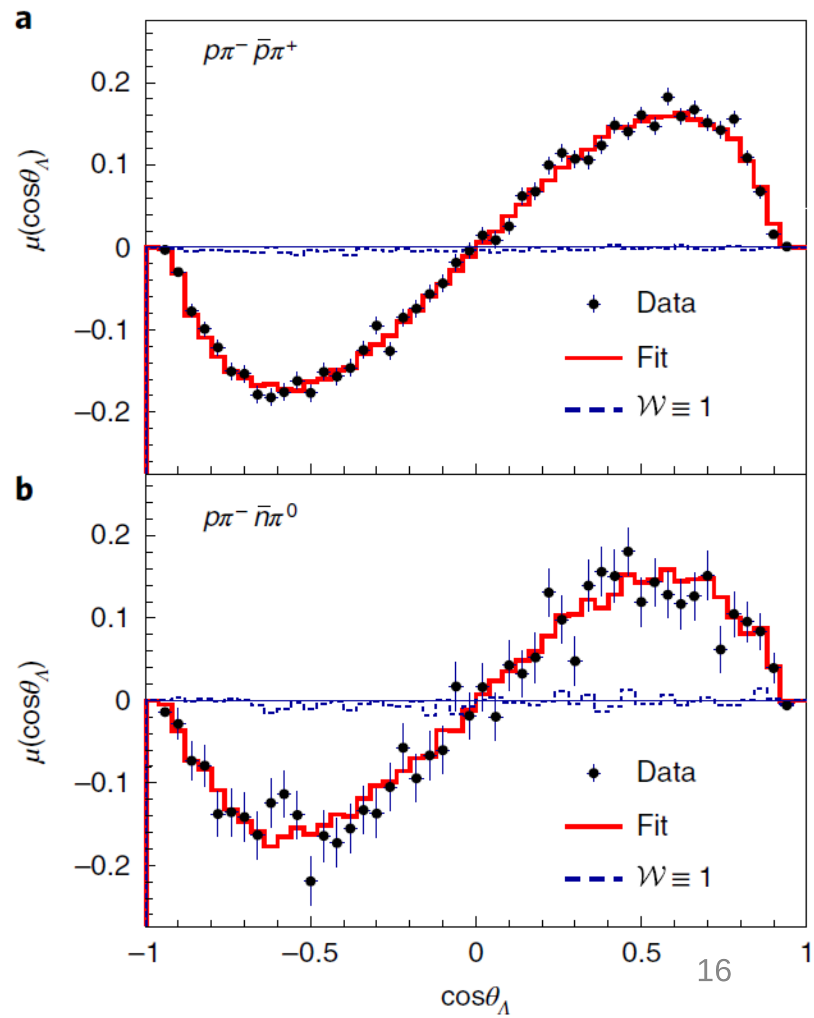
*G. Fäldt & A. Kupsc, PLB 772 (2017) 16.

Measurement of the Λ decay parameters

- New BESIII measurement of $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ using
  ~ 420 000 events of $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$
  ~ 47 000 events of $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{n}\pi^0$
- Value of α ~17% > old PDG value.

Picture cred: Nature Phys. 15, p. 625-625 (2019)





- Most precise CP test so far for Λ decay:
  $A = \frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -0.006 \pm 0.012 \pm 0.007$

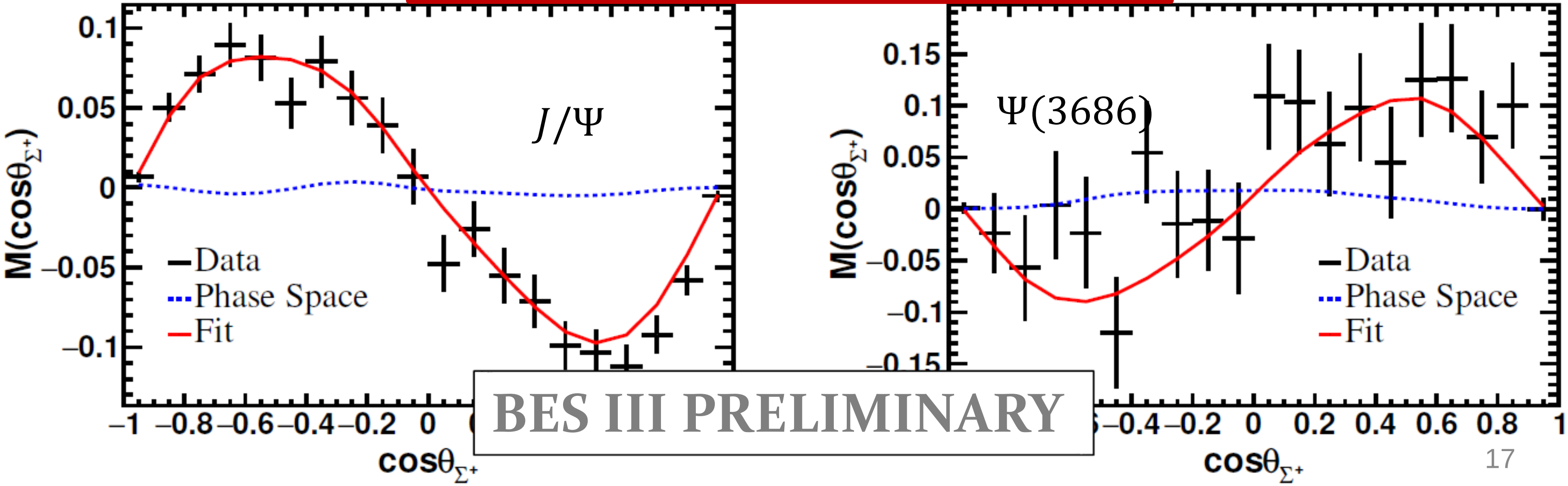
BESIII, Nature Phys. **15**, p 631-634 (2019)

Measurement of the Σ^+ decay parameter

- New BESIII measurement of $\Sigma^+ \to p\pi^0$ decay
  ~ 88 000 events of $J/\psi \to \Sigma^+\bar{\Sigma}^-$
  ~ 5300 events of $\psi(3686) \to \Sigma^+\bar{\Sigma}^-$

- Opposite sign of hadronic form factor phase at J/ψ and $\psi(3686)$ mass.
- First CP test of Σ^+ decay: $\frac{\alpha+\bar{\alpha}}{\alpha-\bar{\alpha}} = -0.004 \pm 0.037 \pm 0.010$

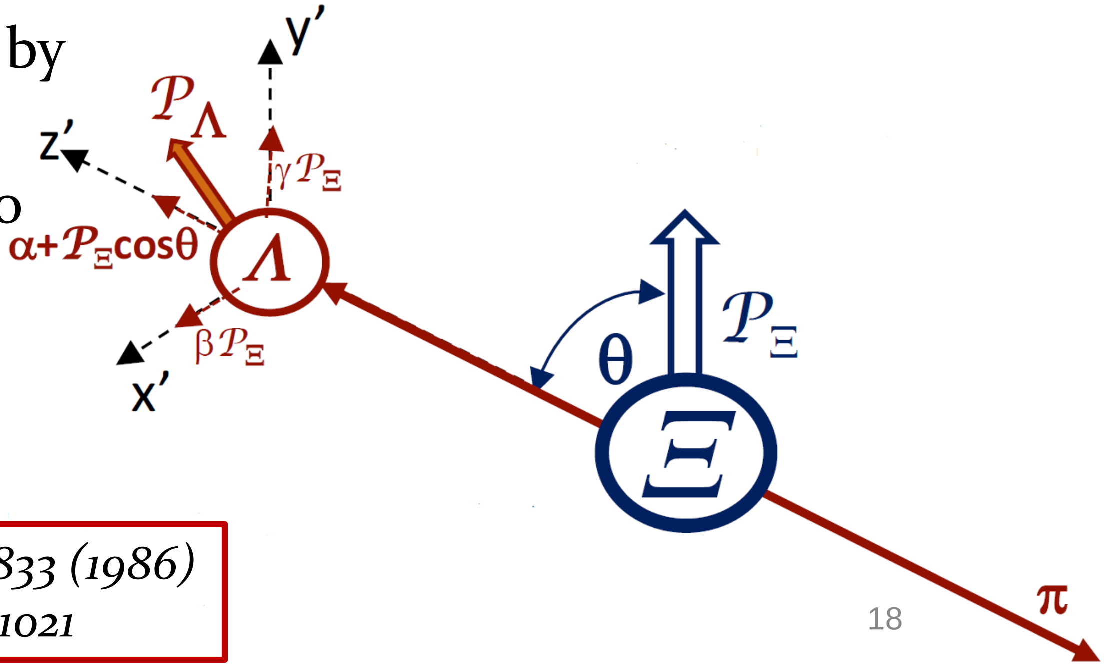
arXiv:2004.07701, acc. by Phys. Rev. Lett.



Sequential hyperon decays

- β, γ, ϕ accessible in sequential decays
- CP symmetry: $\beta = -\overline{\beta}$ etc.
  - CP observables *e.g.*: $A = \frac{\alpha+\overline{\alpha}}{\alpha-\overline{\alpha}}$ and $B = \frac{\beta+\overline{\beta}}{\beta-\overline{\beta}}$
- Can separate weak/BSM amplitudes from strong by combining A and B*

  → better sensitivity to CP violation!



Donogue, He and Pakvasa, PRD 34, 833 (1986)
Picture credit: *S. Olsen, hep-ex: 1911.01021*

Measurement of Λ_c^+ decay parameters

- 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.
  - No spin correlation could be studied.
- Indication of non-zero Λ_c^+ polarisation at $E_{CMS} = 4.6$ GeV.
- 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.
  - Method more sensitive the larger the polarisation.

M. ABLIKIM *et al.* PHYS. REV. D **100**, 072004 (2019)

TABLE I. Parameters measured in this analysis.

Parameters	$\Lambda_c^+ \to pK_S^0$	$\Lambda\pi^+$	$\Sigma^+\pi^0$	$\Sigma^0\pi^+$
α_{BP}^+	$0.18 \pm 0.43 \pm 0.14$	$-0.80 \pm 0.11 \pm 0.02$	$-0.57 \pm 0.10 \pm 0.07$	$-0.73 \pm 0.17 \pm 0.07$
α_{BP}^+ (PDG)	⋯	-0.91 ± 0.15	-0.45 ± 0.32	⋯
β_{BP}	⋯	$0.06^{+0.58+0.05}_{-0.47-0.06}$	$-0.66^{+0.46+0.22}_{-0.25-0.02}$	$0.48^{+0.35+0.07}_{-0.57-0.13}$
γ_{BP}	⋯	$-0.60^{+0.96+0.17}_{-0.05-0.03}$	$-0.48^{+0.45+0.21}_{-0.42-0.04}$	$0.49^{+0.35+0.07}_{-0.56-0.12}$
Δ_1^{BP} (rad)	⋯	$3.0 \pm 2.4 \pm 1.0$	$4.1 \pm 1.1 \pm 0.6$	$0.8 \pm 1.2 \pm 0.2$

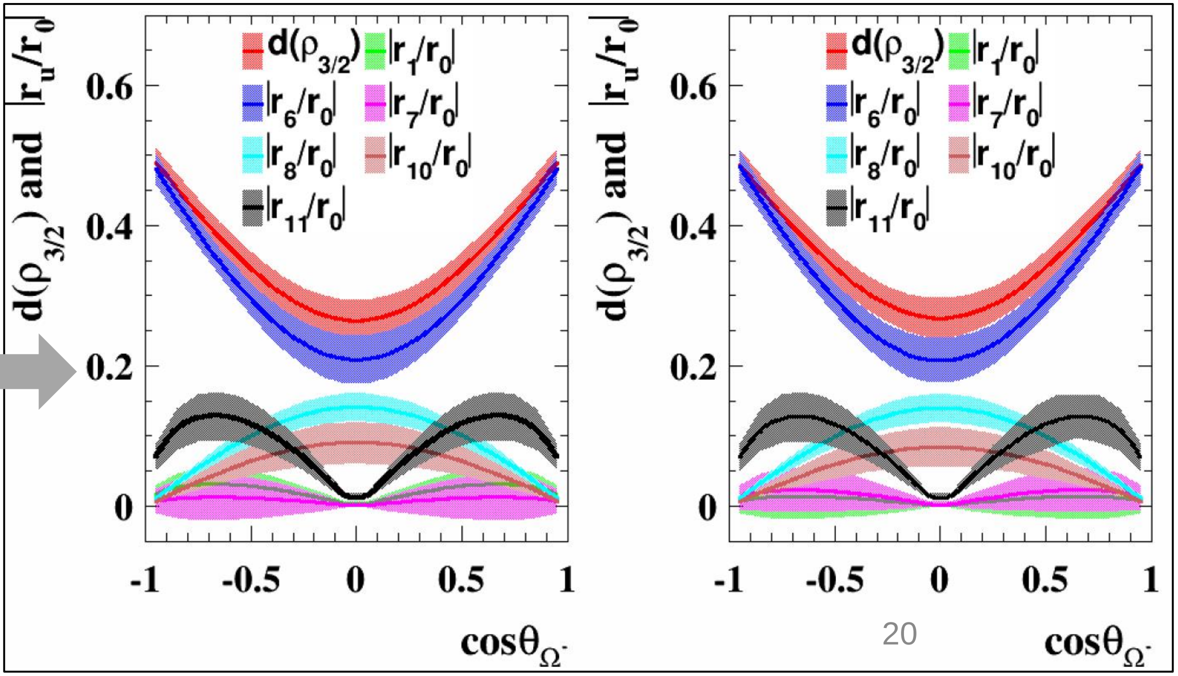
Spin properties of the Ω^-

- The process $e^+e^- \to \gamma^*/\psi(3686) \to \Omega^-\bar{\Omega}^+$ for the spin 3/2 Ω^- is described by four form factors / helicity amplitudes.*
- Single-tag study of $\psi(3686) \to \Omega^-\bar{\Omega}^+$ data to measure**:
  - Helicity amplitudes
  - Decay parameter $\phi_{\Omega^-}(\Omega^- \to \Lambda\pi^-)$ for the first time.
  - Degree of polarisation

$$d(\rho_{3/2}) = \sqrt{\sum_{\mu=1}^{15}\left(\frac{r_\mu}{r_0}\right)^2}$$

$$= 0.71 \pm 0.04$$

Solution I　　Solution II



BES III PRELIMINARY

PRD 99, 056008 (2019)
**hep-ex: 2007.03679 (2020)

Ongoing studies

- Λ EMFF phase dependence on energy
- Octet hyperon form factors
- CP tests in sequential decays of Σ^0, Ξ^- and Ξ^0.
  - Sample of 10^{10} J/ψ events available.
  - Exclusive, double-tag measurements.
  - Dedicated, model-independent formalism *,**,***.

Stay tuned!

** Phys. Rev. D 101, 033002 (2020)*
*** Phys. Lett. B 788, 535 (2019)*
****Phys. Rev. D 100, 114005 (2019)*

Summary

- Hyperons provide a powerful diagnostic tool to study
  - The strong interaction.
  - Fundamental symmetries.
- New measurements from BESIII
  - Complete measurement of Λ EM form factors.
  - Most precise test of CP symmetry in Λ decays.
  - New studies of Σ^+, Ω^- and Λ_c^+.
  - Ongoing, large-scale studies.

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Thanks for your attention!

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