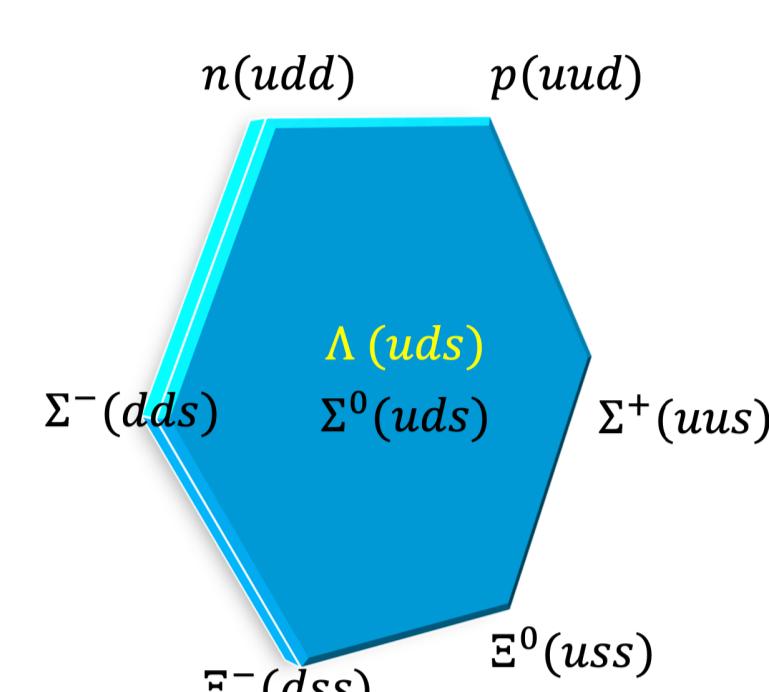
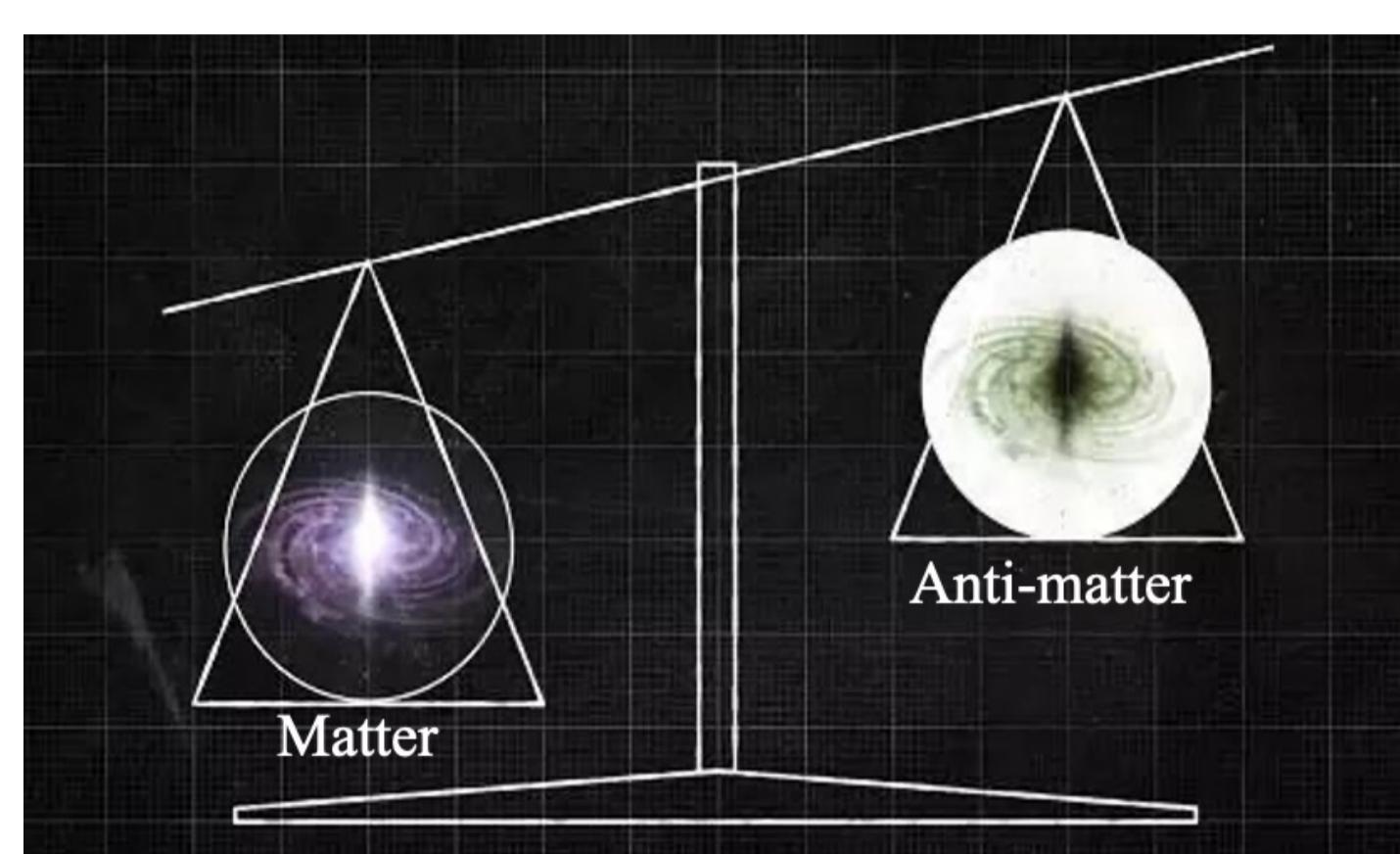


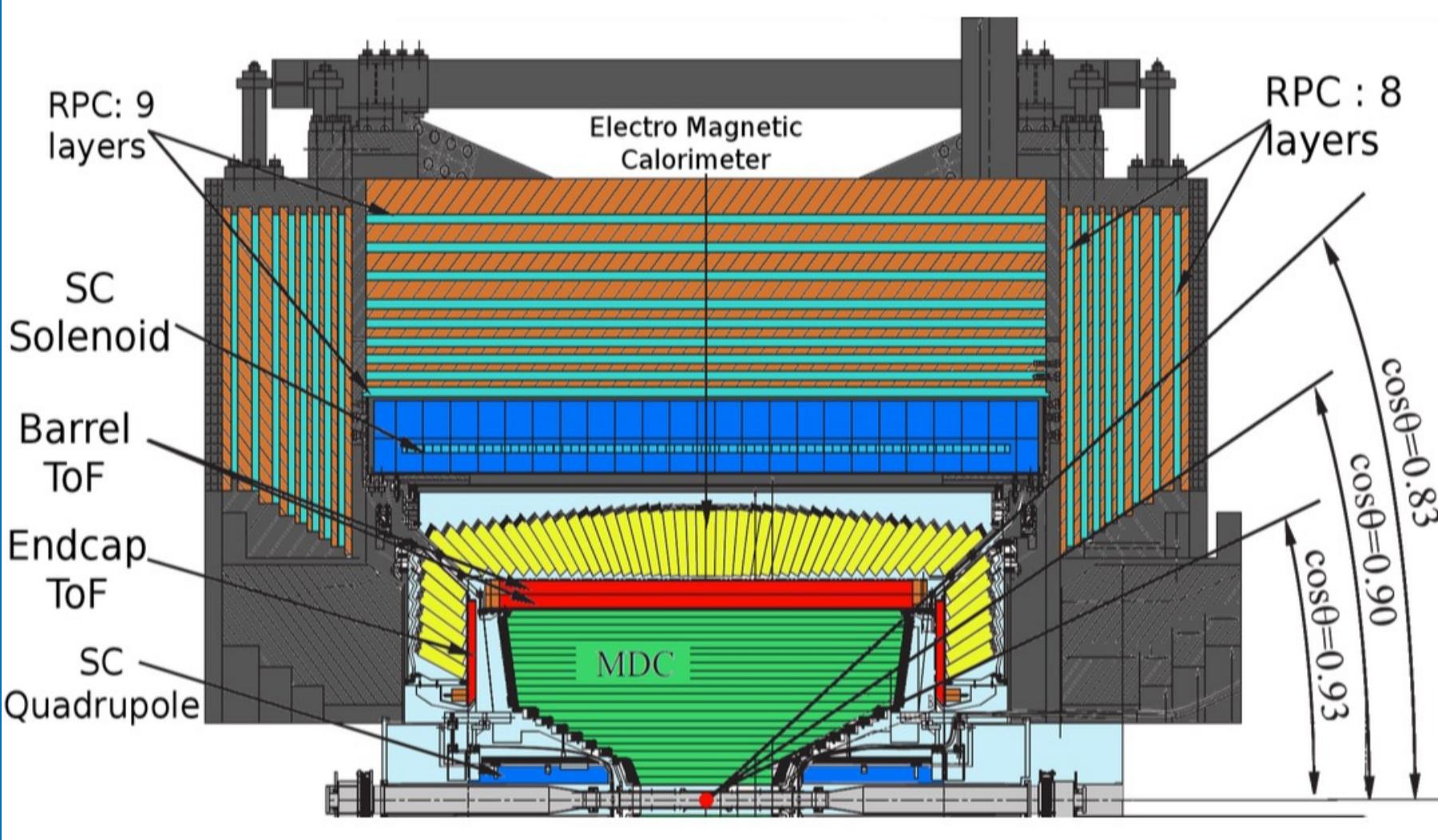
## Introduction

- ✓ The imbalance between matter-antimatter
- ✓ One of Sakharov's essential conditions: Charge-parity (CP) violation
- ✓ Quantum-entangled hyperon pairs production: a new method in CP symmetry test



Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967);  
Phys. Lett. B 772, 16 (2017);  
Phys. Rev. D 99, 056008 (2019)

## Experiment

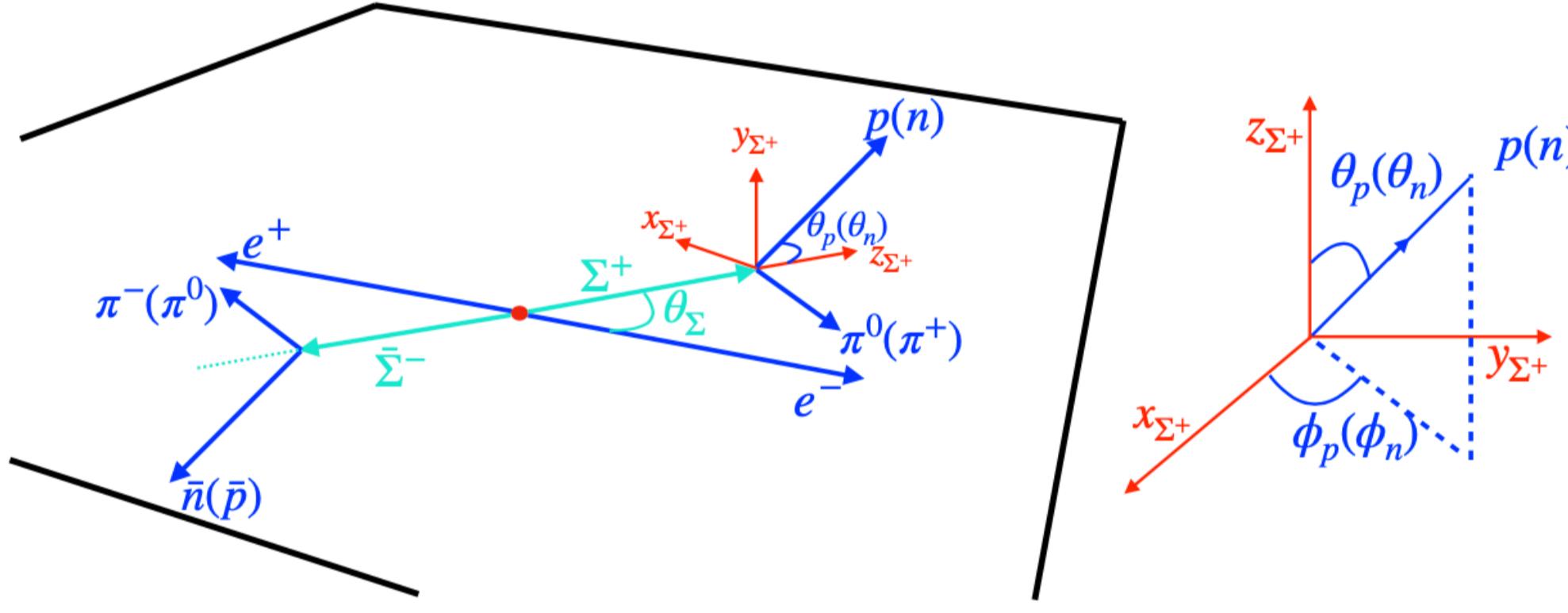


- Main Drift Chamber (MDC)
  - $\sigma(p)/p = 0.5\%$
  - $\sigma_{dE/dx} = 5.0\%$
- Time-of-flight (TOF)
  - $\sigma(t) = 68\text{ps}$  (barrel)
  - $\sigma(t) = 65\text{ps}$  (endcap)
- Electro Magnetic Calorimeter (EMC)
  - $\sigma(E)/E = 2.5\%$
  - $\sigma_{z,\phi}(E) = 0.5 - 0.7 \text{ cm}$
- RPC MUON Detector
  - $\sigma(xy) < 2 \text{ cm}$

## Method

Helicity frame definition:

Two channels:  $J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ ,  $\Sigma^+ \rightarrow p\pi^0$  ( $n\pi^+$ ),  $\bar{\Sigma}^- \rightarrow \bar{n}\pi^-$  ( $\bar{p}\pi^0$ )



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

$$P_y(\cos \theta_{\Sigma^+}) = \frac{\sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) \cos \theta_{\Sigma^+} \sin \theta_{\Sigma^+}}{1 + \alpha_{J/\psi} \cos^2 \theta_{\Sigma^+}}$$

$$d\sigma \propto \mathcal{W}(\xi) d\xi$$

$$\xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2)$$

Phys. Lett. B 772, 16 (2017)

$$\mathcal{W}(\xi) = T_0(\xi) + \alpha_{J/\psi} T_5(\xi)$$

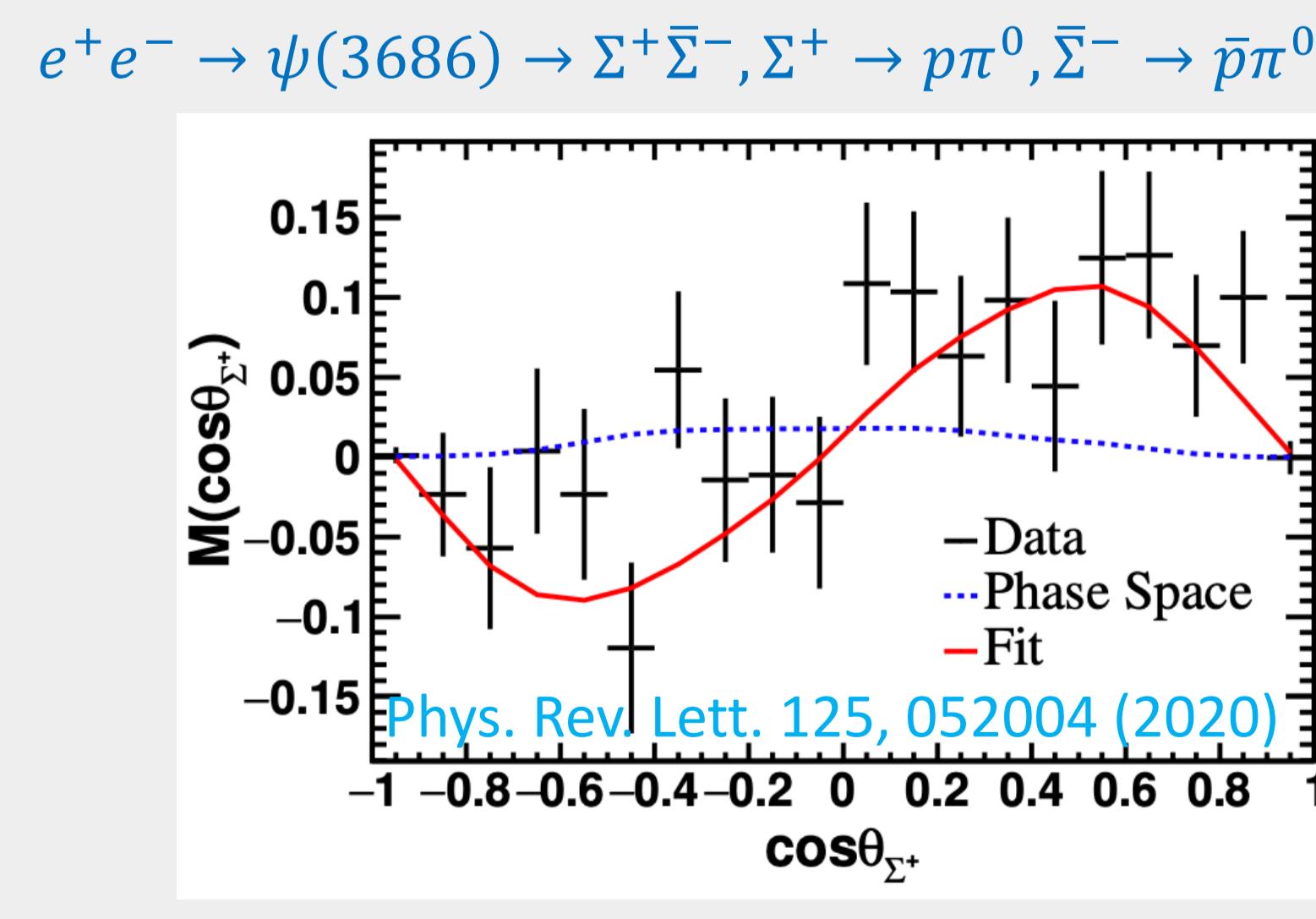
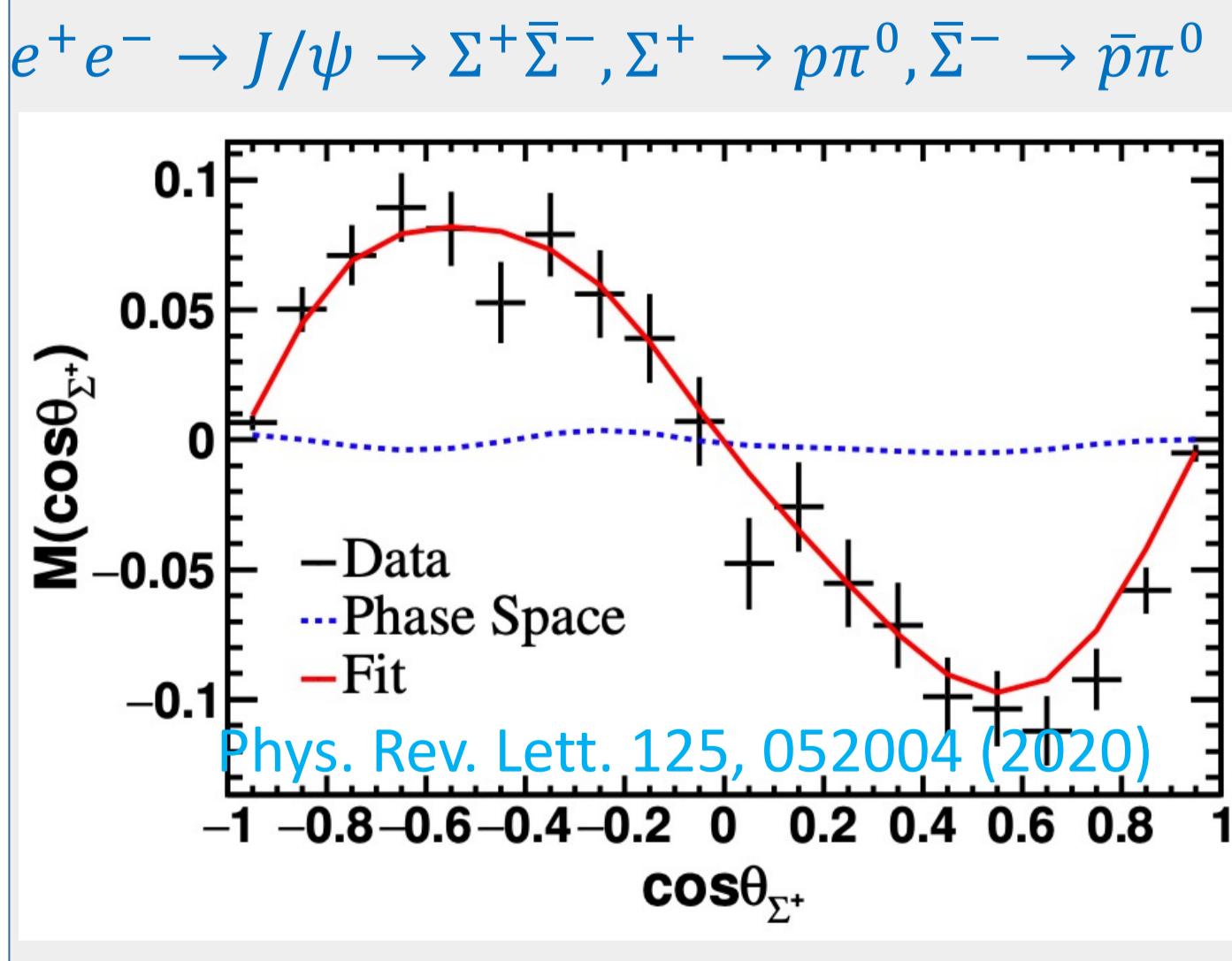
$$+ \alpha \bar{\alpha} (T_1(\xi) + \sqrt{1 - \alpha_{J/\psi}^2} \cos(\Delta\Phi) T_2(\xi) + \alpha_{J/\psi} T_6(\xi))$$

**SPIN CORRELATIONS**

$$+ \sqrt{1 - \alpha_{J/\psi}^2} \sin(\Delta\Phi) (\alpha T_3(\xi) + \bar{\alpha} T_4(\xi))$$

**POLARIZATIONS**

## Experimental Results



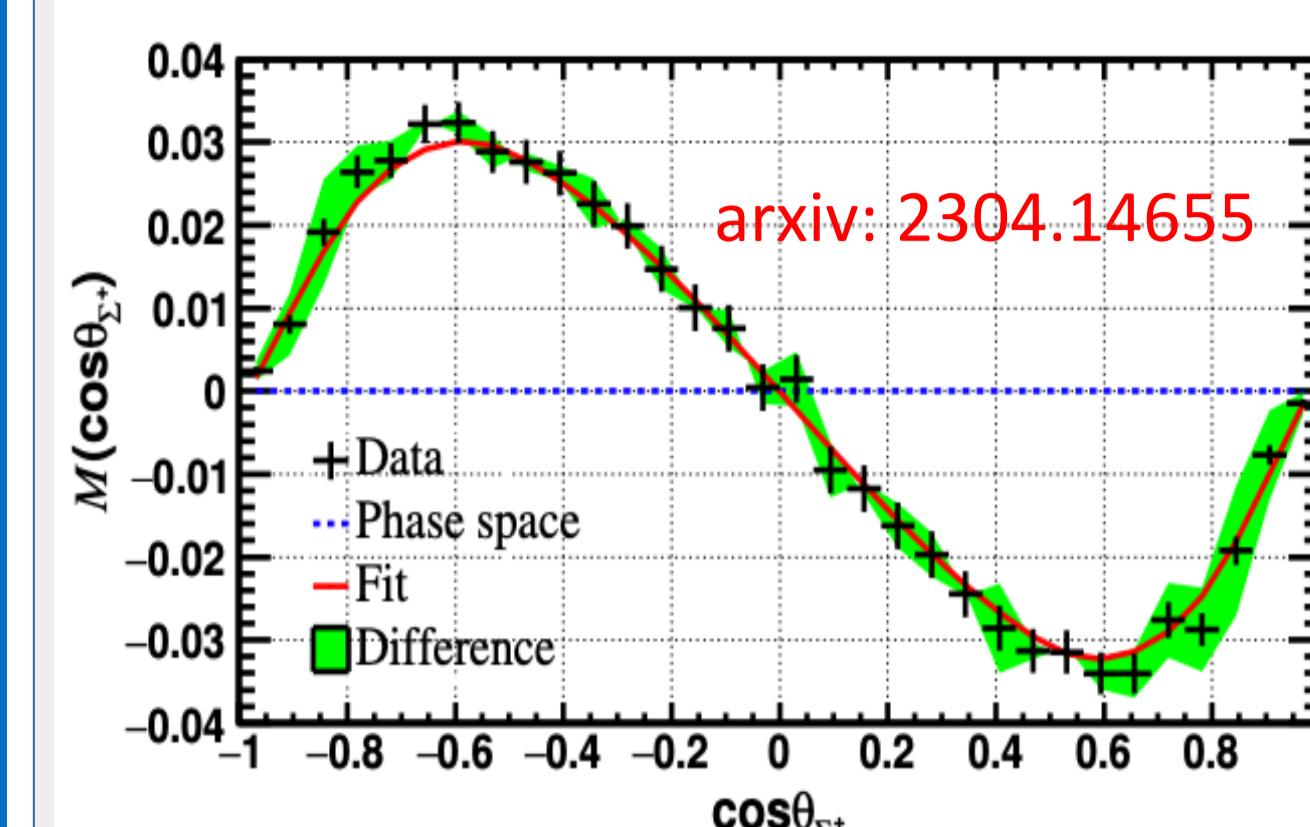
Parameter	This work
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi(3686)}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi(3686)}$	$0.379 \pm 0.07 \pm 0.014$
$\alpha_0$	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

The CP asymmetry  $A_{CP}(\Sigma^+ \rightarrow p\pi^0) = \frac{\alpha_0 + \bar{\alpha}_0}{\alpha_0 - \bar{\alpha}_0} = -0.004 \pm 0.037 \pm 0.010$  is extracted for the first time, and is found to be consistent with CP conservation.

Phys. Rev. D 99, 056008 (2019)

## Experimental Results

$e^+ e^- \rightarrow J/\psi \rightarrow \Sigma^+ \bar{\Sigma}^-$ ,  $\Sigma^+ \rightarrow p\pi^0$ ,  $\bar{\Sigma}^- \rightarrow \bar{n}\pi^-$  + c.c.



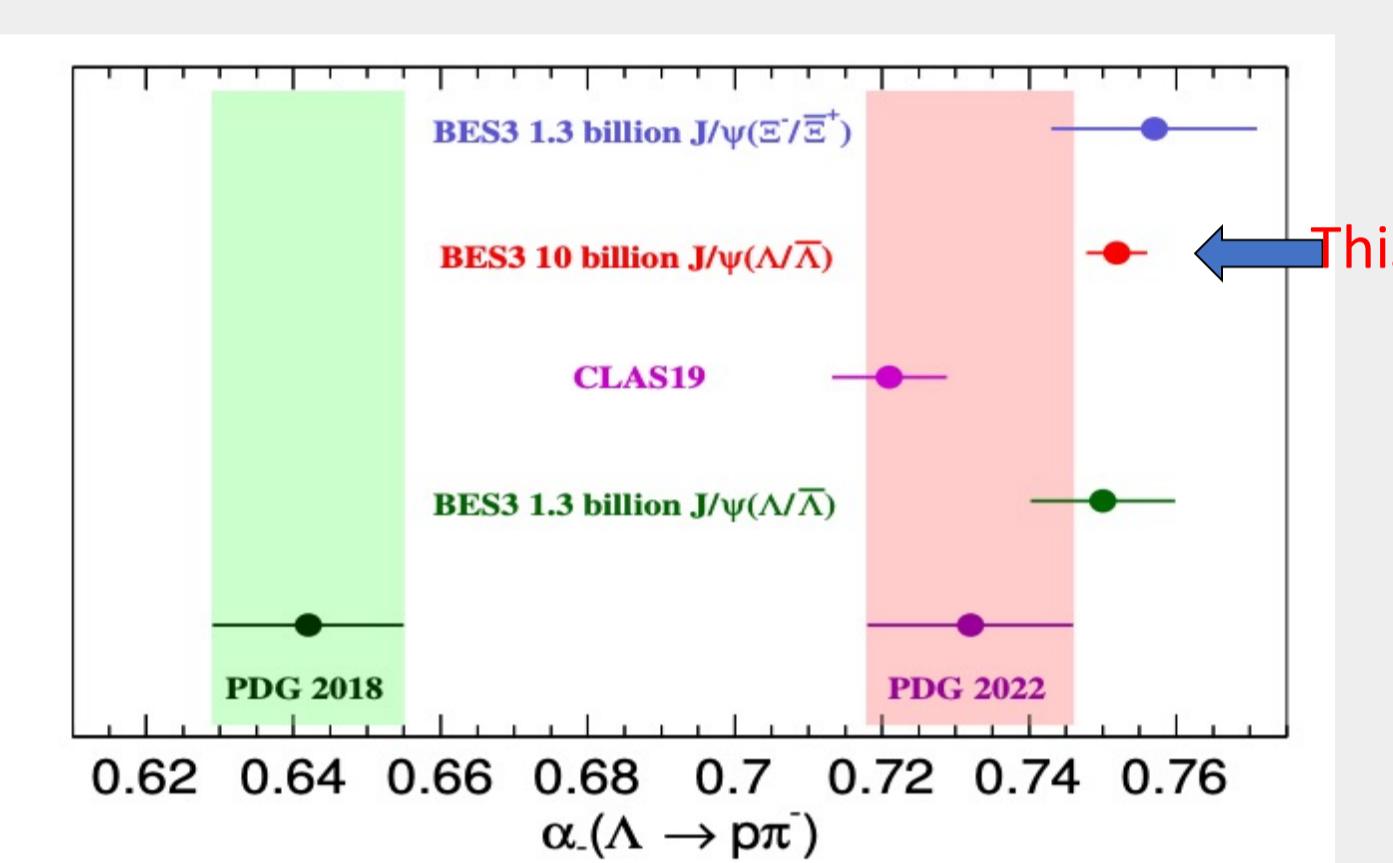
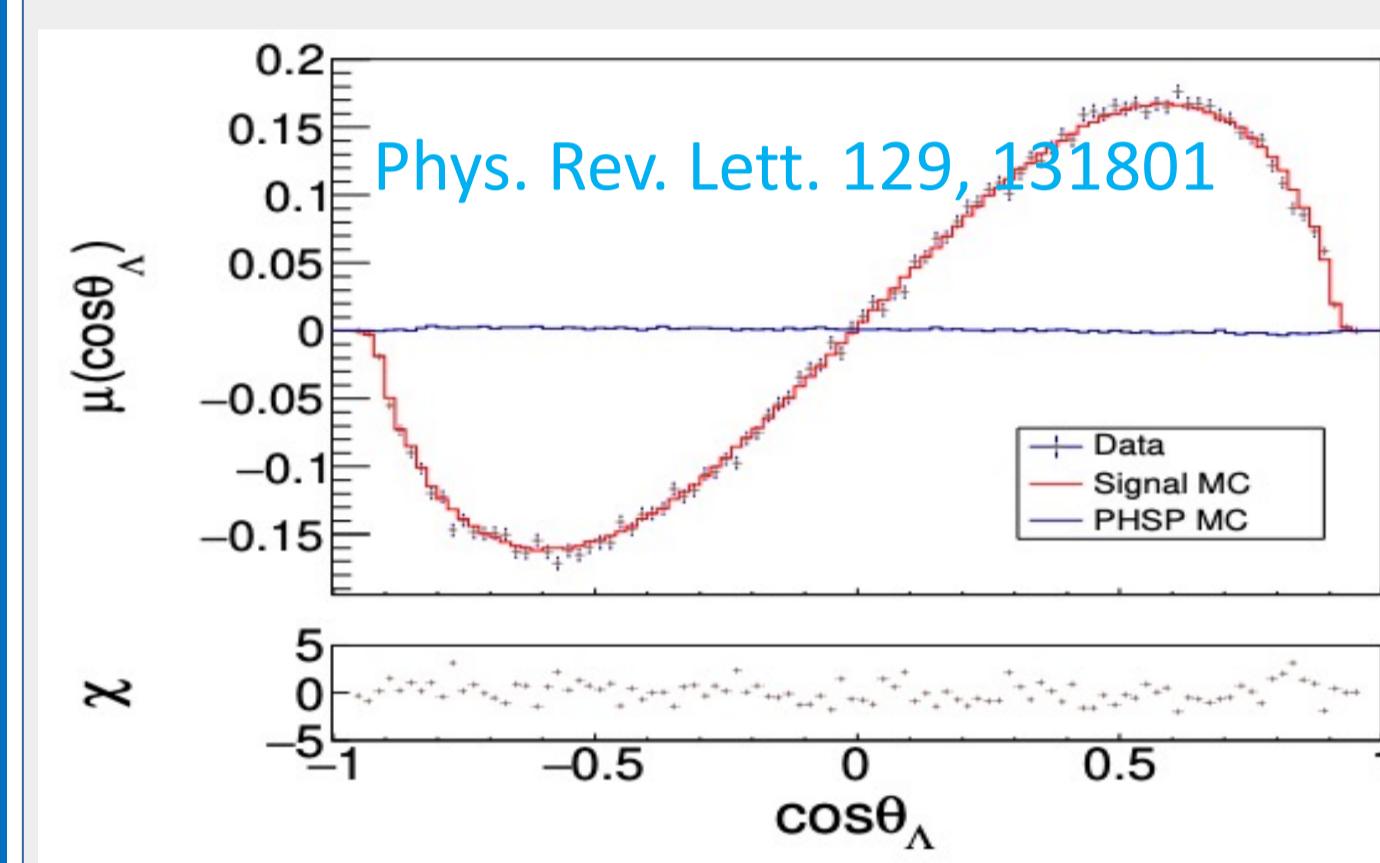
Parameter	This work	Previous work
$\alpha_{J/\psi}$	$-0.5156 \pm 0.0030 \pm 0.0061$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.2772 \pm 0.0044 \pm 0.0041$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_+$	$0.0481 \pm 0.0031 \pm 0.0019$	$0.069 \pm 0.017$
$\bar{\alpha}_-$	$-0.0565 \pm 0.0047 \pm 0.0022$	-
$\alpha_+/a_0$	$-0.0490 \pm 0.0032 \pm 0.0021$	$-0.069 \pm 0.021$
$\bar{\alpha}_-/a_0$	$-0.0571 \pm 0.0053 \pm 0.0032$	-

The precision CP symmetry  $A_{CP}(\Sigma^+ \rightarrow n\pi^+) = \frac{\alpha_+ + \bar{\alpha}_-}{\alpha_+ - \bar{\alpha}_-} = -0.080 \pm 0.052 \pm 0.028$  is measured for any hyperon decay into a neutron in the final state for the first time.

Our precise measurement of the decay asymmetry parameter in the neutron mode is of vital importance to the CP violation prediction.

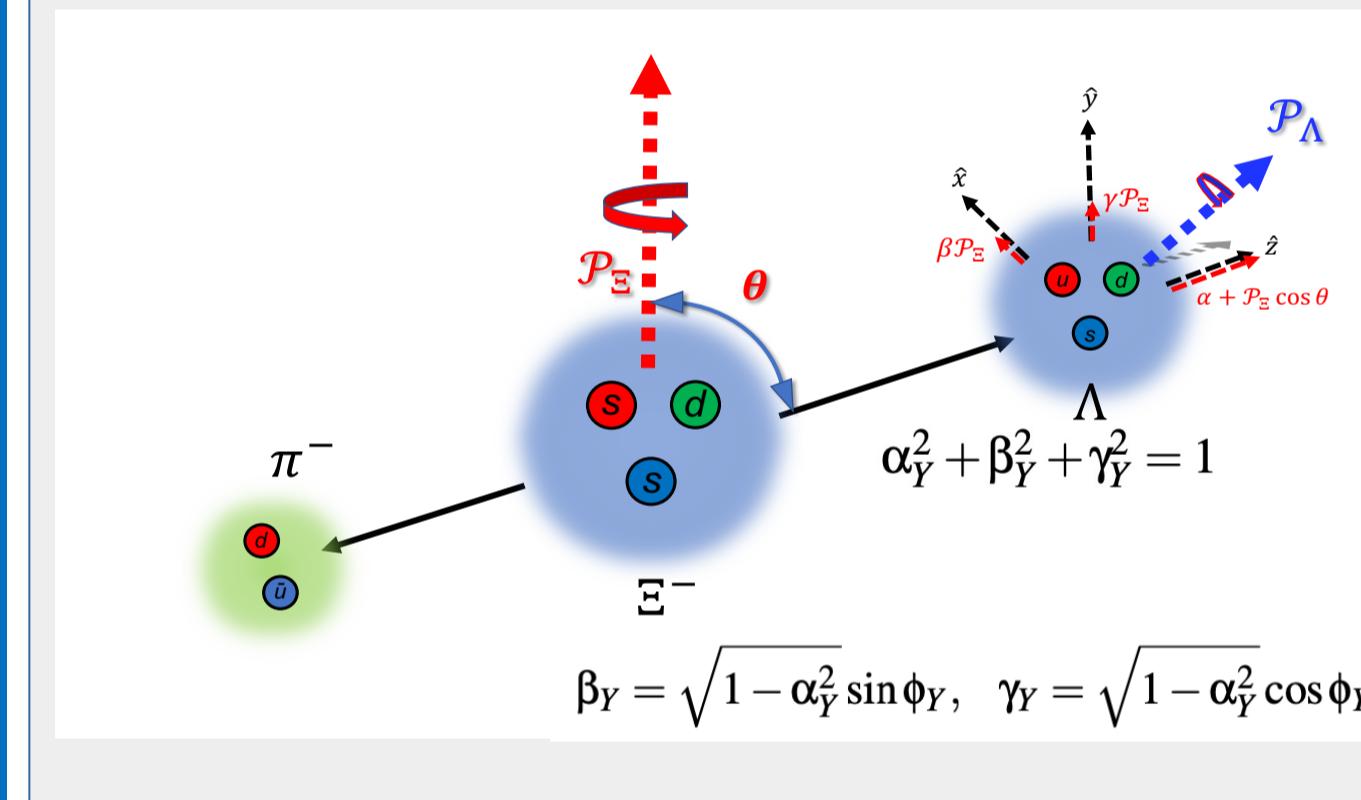
arXiv: 2304.1465; Phys. Rev. Lett. 125, 052004(2020); Phys. Rev. D 21, 2501 (1980)

$e^+ e^- \rightarrow J/\psi \rightarrow \Lambda \bar{\Lambda}$ ,  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$



Most precise CP symmetry  $A_{CP}(\Lambda \rightarrow p\pi^-) = \frac{\alpha_- + \bar{\alpha}_+}{\alpha_- - \bar{\alpha}_+} = -0.0025 \pm 0.0046 \pm 0.0011$  is measured for any hyperon sector decay. Phys. Rev. Lett. 129, 131801; Nature Phys. 15, 631-634 (2019); Phys. Rev. Lett. 123, no.18, 182301 (2019)

$e^+ e^- \rightarrow J/\psi \rightarrow \Xi^- \bar{\Xi}^+$ ,  $\Xi^- \rightarrow \Lambda \pi^-$ ,  $\bar{\Xi}^+ \rightarrow \bar{\Lambda} \pi^+$

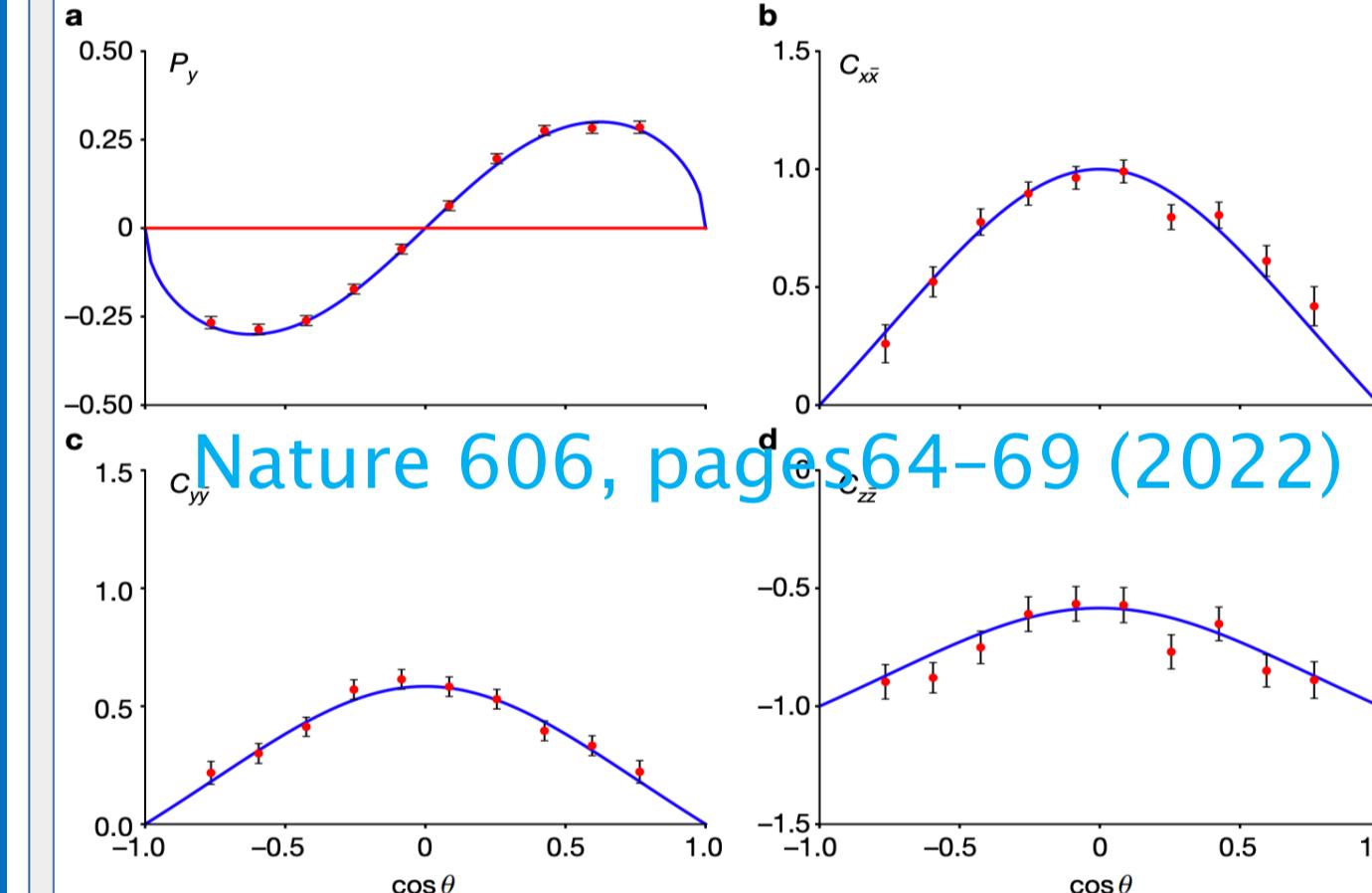


$$W = \sum_{\mu, \nu=0}^3 C_{\mu\nu} \sum_{\mu', \nu'=0}^3 a_{\mu, \mu'}^{\Xi} a_{\bar{\nu}, \bar{\nu}'}^{\Xi} a_{\mu, 0}^{\Lambda} a_{\bar{\nu}', 0}^{\bar{\Lambda}}$$

Phys. Rev. D 99, 056008 (2019)

8 parameters:

$$\omega = (\alpha_\Psi, \Delta\Phi, \alpha_\Xi, \phi_\Xi, \alpha_\Lambda, \bar{\alpha}_\Xi, \bar{\phi}_\Xi, \bar{\alpha}_\Lambda)$$



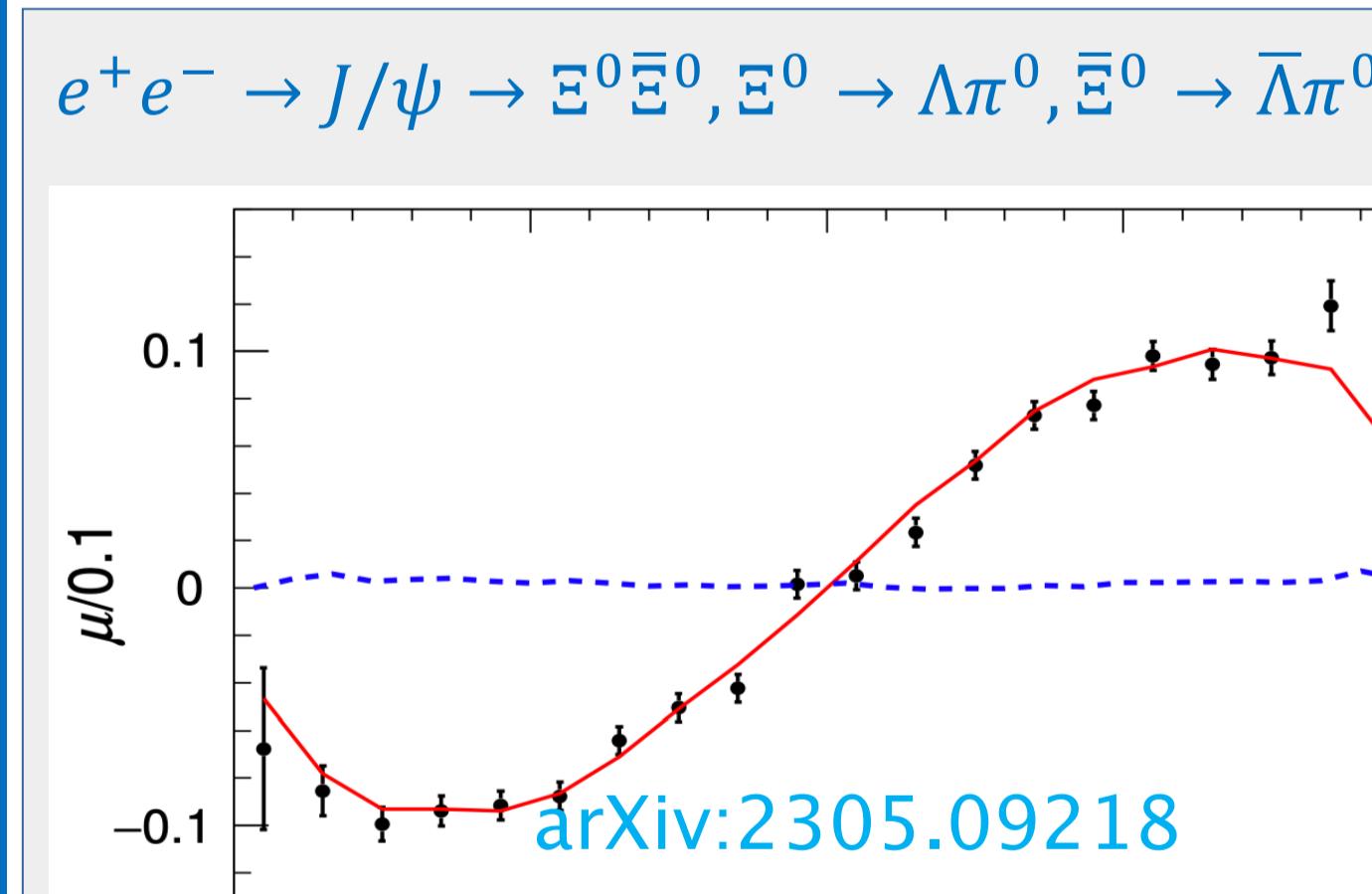
Parameter	This work	Previous result
$\alpha_\Psi$	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$	-
$\alpha_\Xi$	$-0.376 \pm 0.007 \pm 0.003$	$-0.401 \pm 0.010$
$\phi_\Xi$	$0.01 \pm 0.019 \pm 0.009 \text{ rad}$	$-0.037 \pm 0.014 \text{ rad}$
$\bar{\alpha}_-$	$0.371 \pm 0.007 \pm 0.002$	-
$\bar{\alpha}_+$	$-0.021 \pm 0.019 \pm 0.007 \text{ rad}$	-
$\alpha_\Lambda$	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$
$\xi_P - \xi_S$	$(1.23 \pm 0.8) \times 10^{-2} \text{ rad}$	-
$\delta_P - \delta_S$	$(-4.0 \pm 3.3 \pm 1.7) \times 10^{-2} \text{ rad}$	$(10.2 \pm 3.9) \times 10^{-2} \text{ rad}$
$A_{CP}^\Xi$	$(6 \pm 13 \pm 6) \times 10^{-3}$	-
$\Delta\Phi_{CP}^\Xi$	$(-5.14 \pm 3) \times 10^{-3} \text{ rad}$	-
$A_{CP}^\Lambda$	$(-4 \pm 12 \pm 9) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$
$\langle \phi_\Lambda \rangle$	$0.016 \pm 0.014 \pm 0.007 \text{ rad}$	-

Independent measurement of  $\alpha_\Lambda$

First measurement of weak phase difference!

Strong phase difference

3 CP test



Parameter	This work	Previous result
$\alpha_{J/\psi}$	$0.514 \pm 0.006 \pm 0.015$	$0.66 \pm 0.06$
$\Delta\Phi(\text{rad})$	$1.168 \pm 0.019 \pm 0.018$	-
$\alpha_\Xi$	$-0.3750 \pm 0.0034 \pm 0.0016$	$-0.358 \pm 0.044$
$\phi_\Xi(\text{rad})$	$0.3790 \pm 0.0034 \pm 0.0021$	$0.363 \pm 0.043$
$\bar{\alpha}_-$	$0.0051 \pm 0.0096 \pm 0.0018$	$0.03 \pm 0.12$
$\bar{\phi}_\Xi(\text{rad})$	$-0.0053 \pm 0.0097 \pm 0.0019$	$-0.19 \pm 0.13$
$\alpha_\Lambda$	$0.7551 \pm 0.0052 \pm 0.0023$	$0.7519 \pm 0.0043$
$\bar{\alpha}_\Lambda$	$-0.7448 \pm 0.0052 \pm 0.0017$	$-0.7559 \pm 0.0047$
$\xi_P - \xi_S(\text{rad})$	$(0.0 \pm 1.7 \pm 0.2) \times 10^{-2}$	-
$\delta_P - \delta_S(\text{rad})$	$(-1.3 \pm 1.7 \pm 0.4) \times 10^{-2}$	-
$A_{CP}^\Xi$	$(-5.4 \pm 6.5 \pm 3.1) \times 10^{-3}$	$(-0.7 \pm 8.5) \times 10^{-2}</$