Symmetry Test in Hyperon Weak Decays at BESIII

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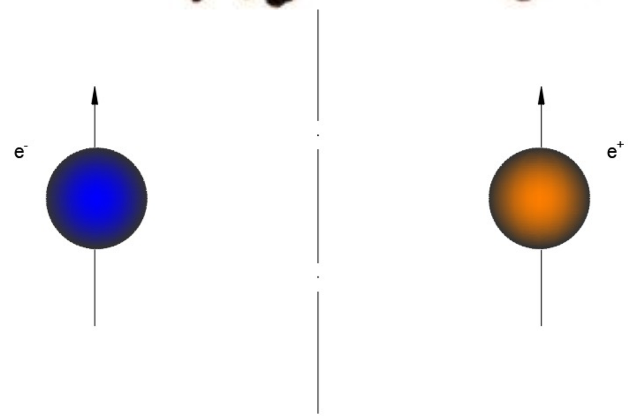
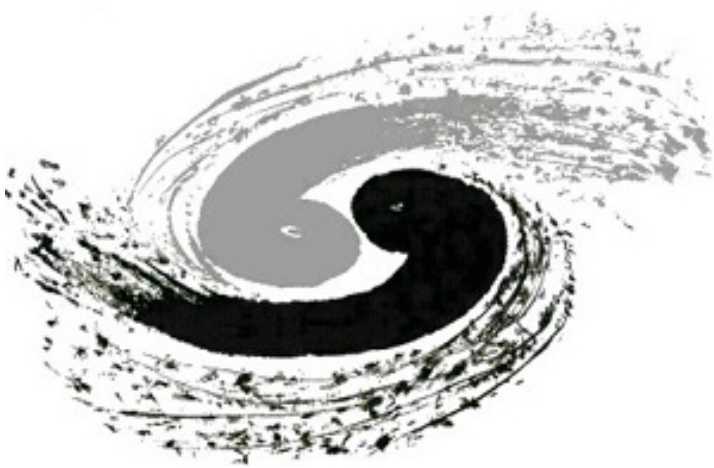
Outline

- **Introduction**
  - **The transform of *C* & *P***
  - **The *CP* violation in meson sector**
  - **The *CP* violation in neutrino sector**
- **The *CP* violation in baryon sector**
- **Summery**

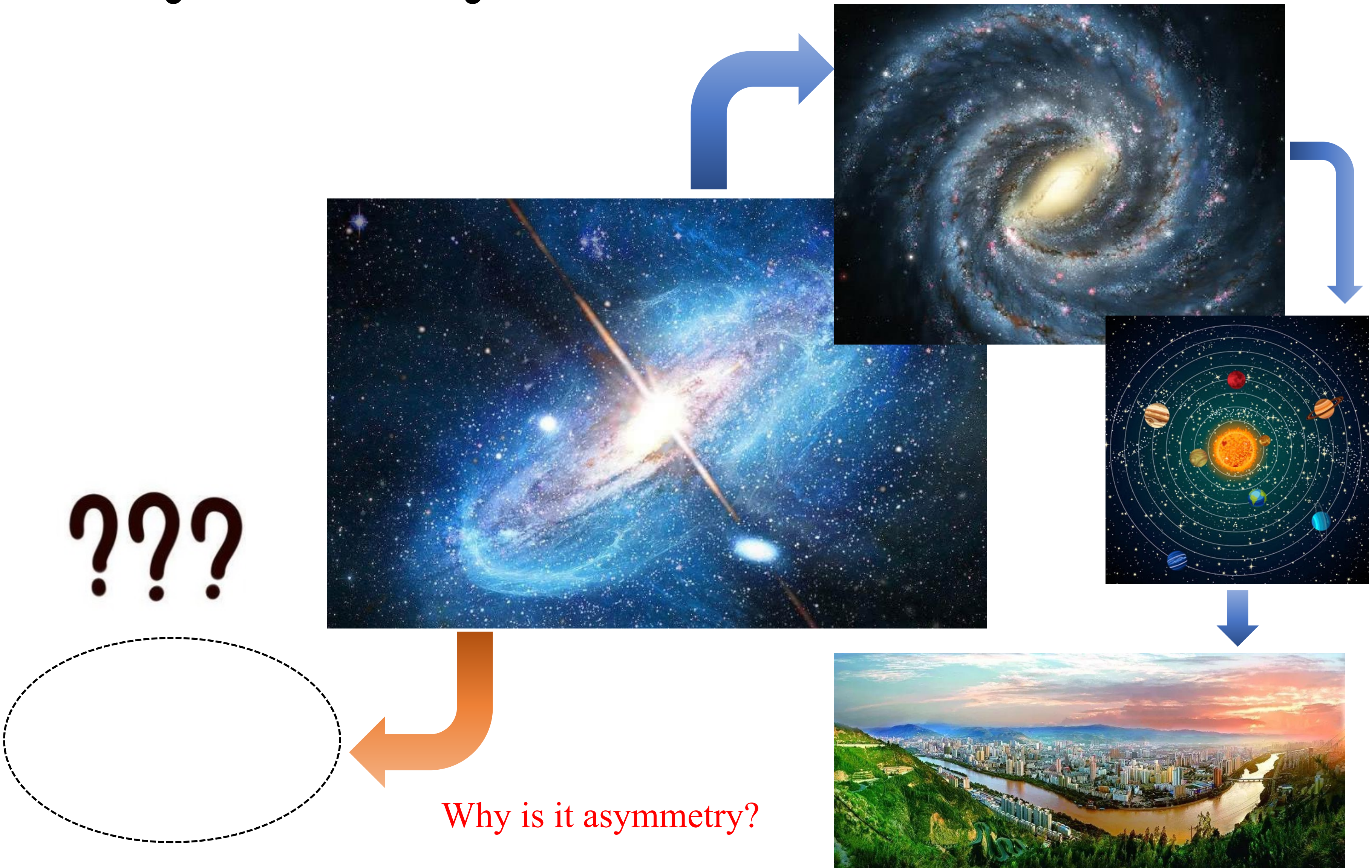
Symmetry in our life





It seems that both human and the nature prefer symmetry?

Asymmetry in our universe



Standard model

The transform of C

Charge conjugation:

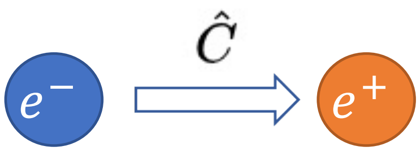
Definition that:

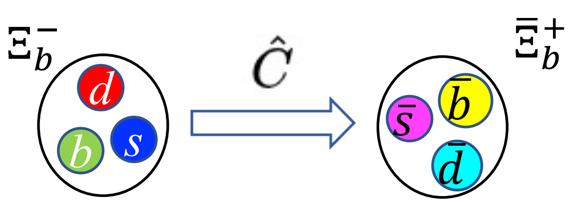
$$C : Q \rightarrow -Q$$

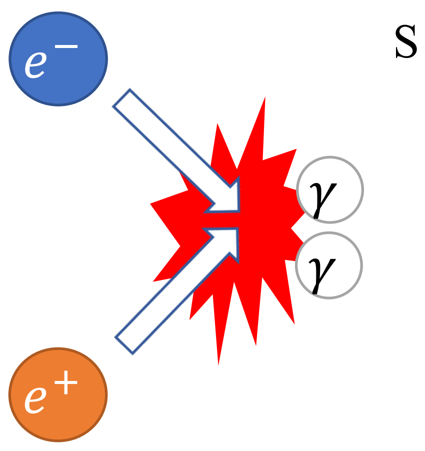
Consider as an operator, it should be:

$$\hat{C}\psi(Q, L, S, B) = \eta_C \psi(-Q, -L, -S, -B)$$

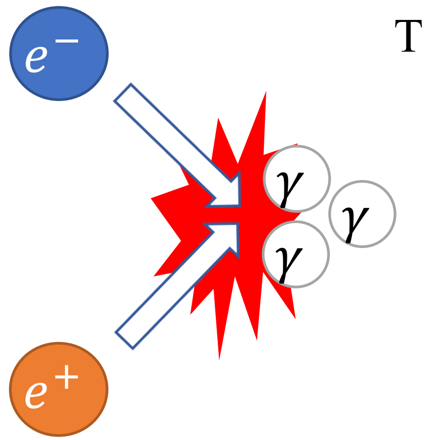
The eigenfunction should only be neutral system!





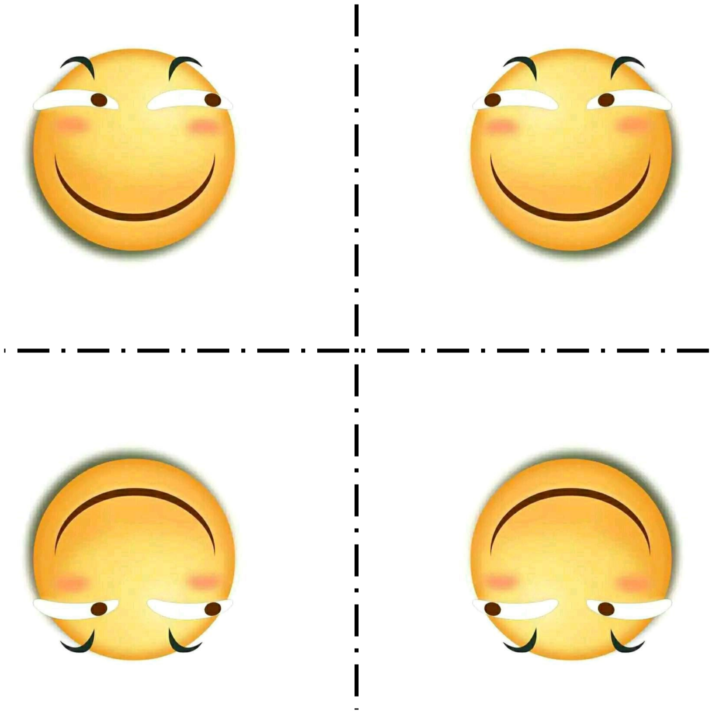


C conservation



C violation

The transform of *P*



Parity conjugation:

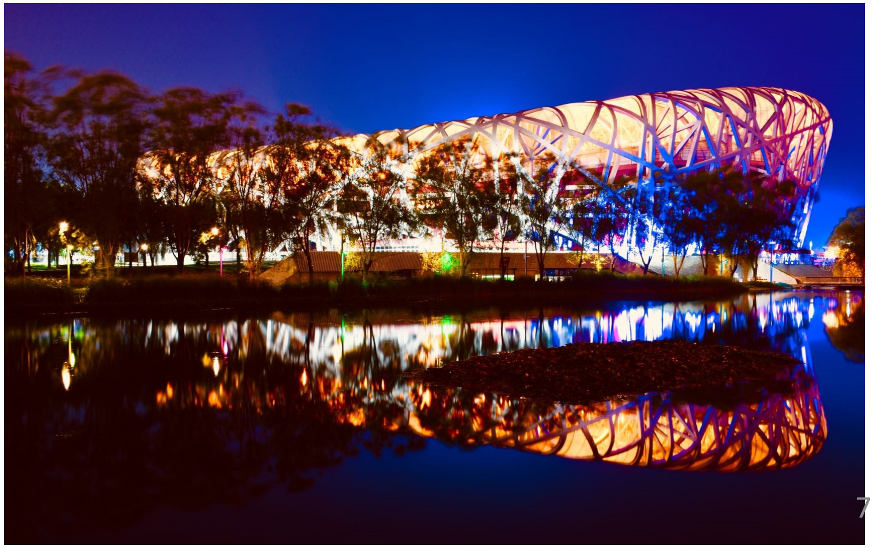
Definition that:

$$P : \boldsymbol{r} \to -\boldsymbol{r}$$

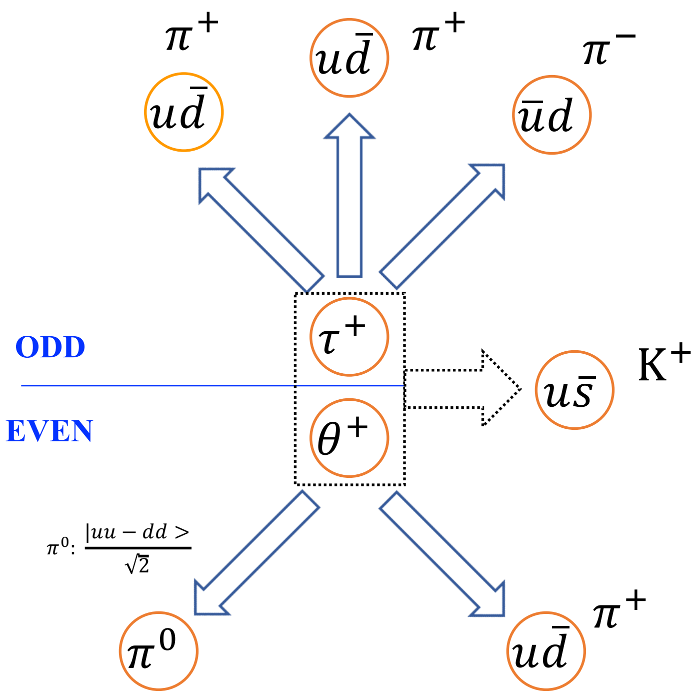
Parity conjugation is very easy to be observed, it seems that P conservation is the most general symmetry, and it is working well in strong and electromagnetic interaction.

But P conversation doesn't agree with weak interaction. Such as τ-θ puzzle.

Does is really perfect?



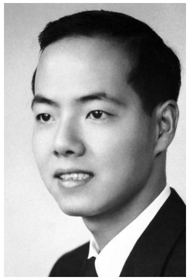
The τ-θ puzzle



They have similar spin, charge, life and mass, except parity, maybe they are the same particle?

There is no evidence shows that parity will be conservative in weak interaction, why don't we assume that parity is not conserved?

Chin-Ning Yang (1922-now)



Tsung-Dao Lee (1926-now)

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

RECENT experimental data indicate closely identical masses[1] and lifetimes[2] of the $\theta^+(\equiv K_{\pi 2}^+)$ and the $\tau^+(\equiv K_{\pi 3}^+)$ mesons. On the other hand, analyses[3] of the decay products of τ^+ strongly suggest on the grounds of angular momentum and parity conservation that the τ^+ and θ^+ are not the same particle. This poses a rather puzzling situation that has been extensively discussed.[4]

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime. We wish to analyze this possibility in the present paper against the background of the existing experimental evidence of parity conservation. It will become clear that existing experiments do indicate parity conserva-

PRESENT EXPERIMENTAL LIMIT ON PARITY NONCONSERVATION

If parity is not strictly conserved, all atomic and nuclear states become mixtures consisting mainly of the state they are usually assigned, together with small percentages of states possessing the opposite parity. The fractional weight of the latter will be called $\mathfrak{F}^2$. It is a quantity that characterizes the degree of violation of parity conservation.

The existence of parity selection rules which work well in atomic and nuclear physics is a clear indication that the degree of mixing, $\mathfrak{F}^2$, cannot be large. From such considerations one can impose the limit $\mathfrak{F}^2 \lesssim (r/\lambda)^2$, which for atomic spectroscopy is, in most cases, $\sim 10^{-6}$. In general a less accurate limit obtains for nuclear spectroscopy.

T.D. Lee, C.N. Yang Phys. Rev. **104** (1956) 254-258

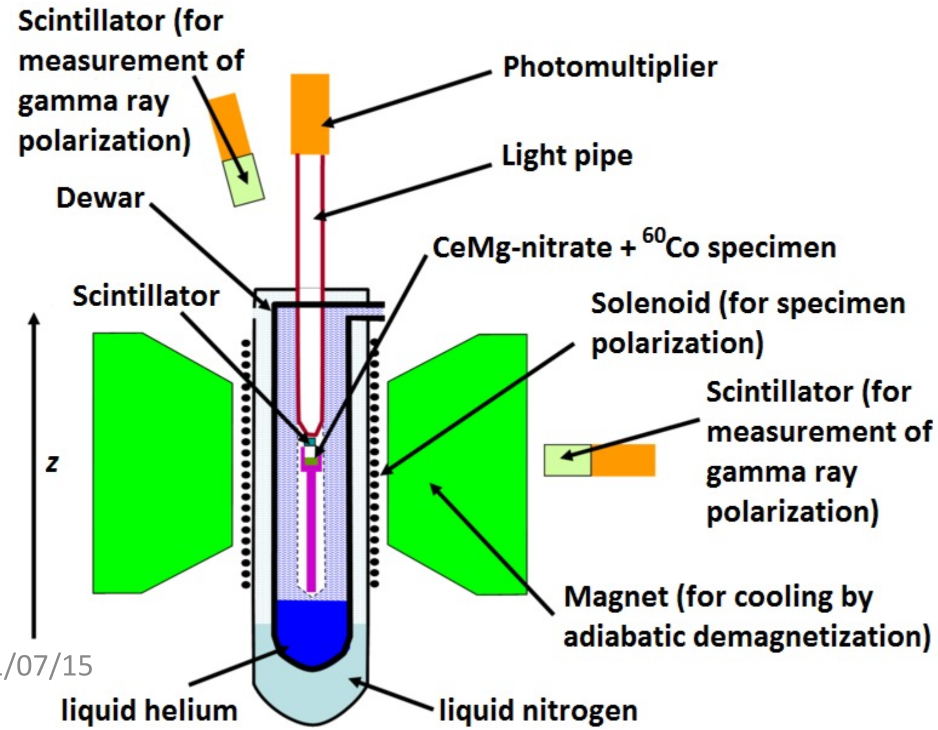
Wu Experiment

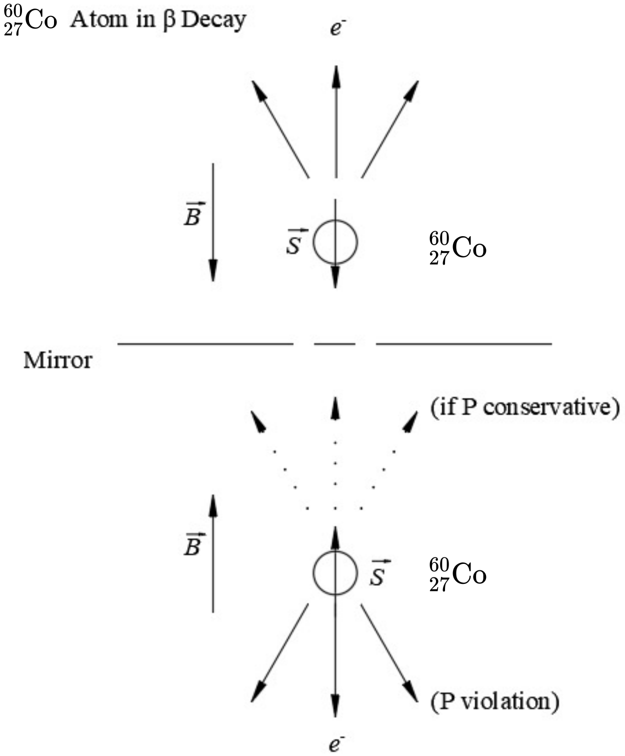
Wu C S *et al* Phys. Rev. **105** (1956) 1413-1414

P violation could be examined in β decay in ${}^{60}_{27}\mathrm{Co}$ atom:

$$ {}^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^{-} + \bar{\nu}_e $$

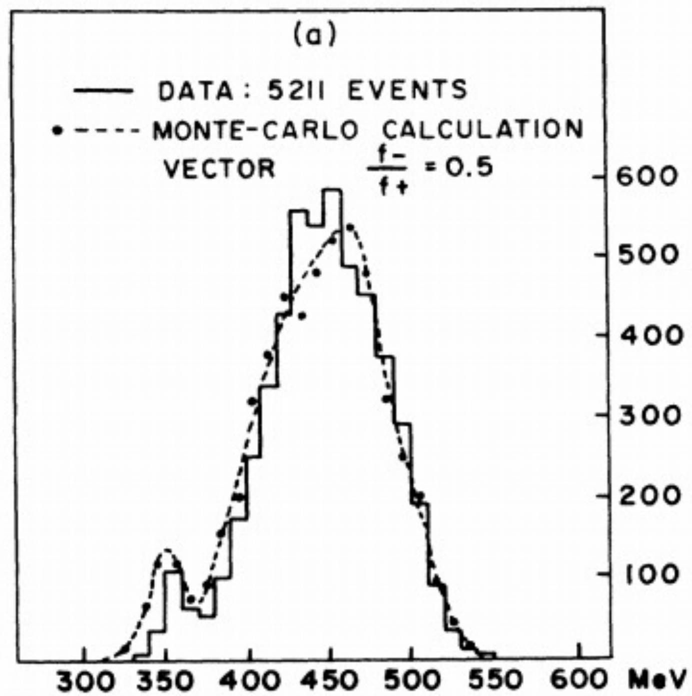
Chien-Shiung Wu(1912-1997)





CP violation in K^0

Phys. Rev. Lett. **13**(1964), 138



In neutral kaon K^0, we have found two "different" meson:

$$K_L^0 \quad \eta_{CP} = -1$$
$$K_S^0 \quad \eta_{CP} = 1$$

Considering $\eta_{CP}^{\pi^{0,\pm}} = -1$, theoretically the positive should only decay to 3 pions, and the other one 2 pions permitted, but both channel exist.

Thanks to the improvement of accuracy nowadays, we could see their difference:

$$K_L^0 \to \begin{cases} 3\pi & BR \approx (32.06 \pm 0.13)\% \\ 2\pi & BR \approx (28.31 \pm 0.12) \times 10^{-4} \end{cases} \quad K_S^0 \to \begin{cases} 3\pi & BR \approx 3.5^{+1.1}_{-0.9} \times 10^{-7} \\ 2\pi & BR \approx 99.99\% \end{cases}$$

CP violation in K^0

We may define this parameter to describe CP violation:

$$|\eta_{+-}| = \sqrt{\frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)}}$$

$$|\eta_{00}| = \sqrt{\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_S \to \pi^0\pi^0)}}$$

Or:

$$A_{CP}(K_L \to \pi^-\mu^+\nu_\mu) = \frac{\Gamma(K_L \to \pi^-\mu^+\nu_\mu) - \Gamma(K_L \to \pi^+\mu^-\bar{\nu}_\mu)}{\Gamma(K_L \to \pi^-\mu^+\nu_\mu) + \Gamma(K_L \to \pi^+\mu^-\bar{\nu}_\mu)}$$

For equation above:

$$A_{CP} \approx (0.64 \pm 0.08)\%$$

Which means CP violation exists.

CP violation in B_s^0 and D^0

B_s^0

$$A_{CP}(B_s^0 \to K^-\pi^+) = 0.213 \pm 0.015 \pm 0.007$$

$$\sigma = 12.9!!$$

LHCb Collaboration, Phys. Rev. D 98 (2018), 032004

D^0

$$\Delta A_{CP} \equiv A_{CP}(D^0 \to K^-K^+) - A_{CP}(D^0 \to \pi^-\pi^+)$$
$$= (15.4 \pm 2.9) \times 10^{-4}$$

$$\sigma = 5.3!!$$

LHCb Collaboration, Phys. Rev. Lett. 122 (2019) 21, 211803

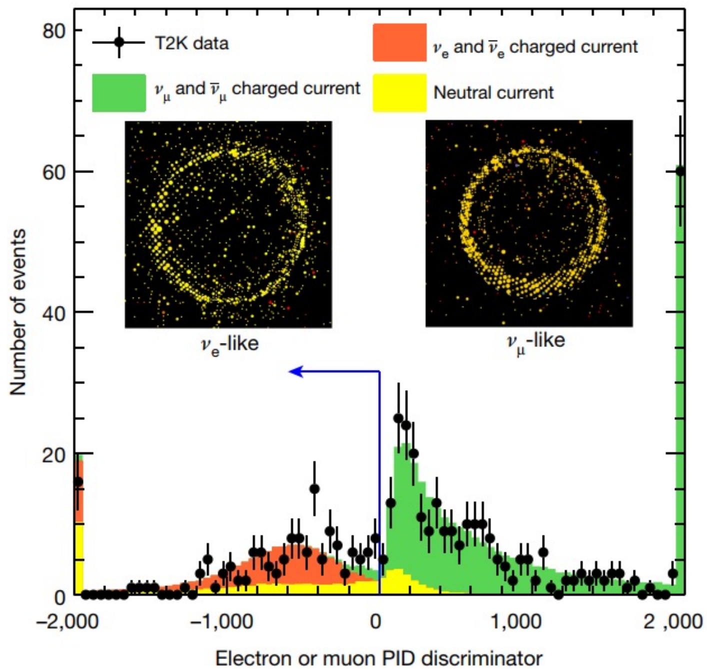
CP violation in neutrino

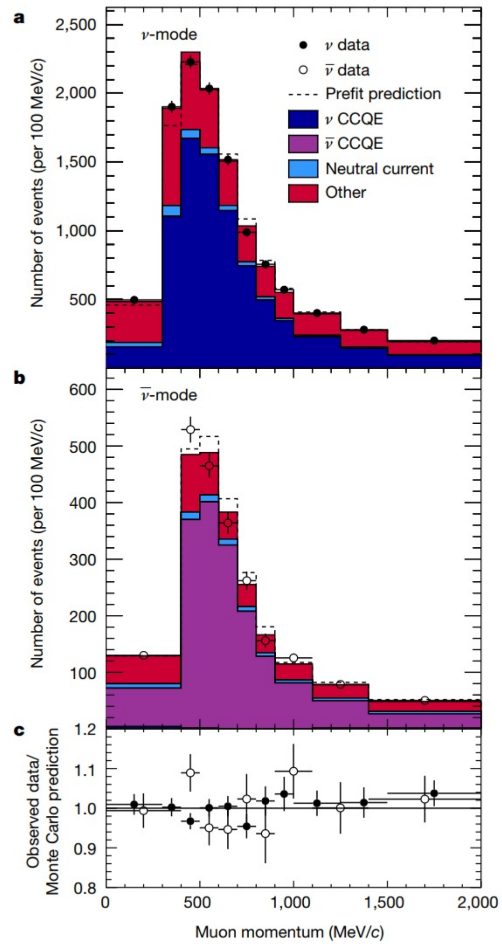
Nature 580(2020), 339-344

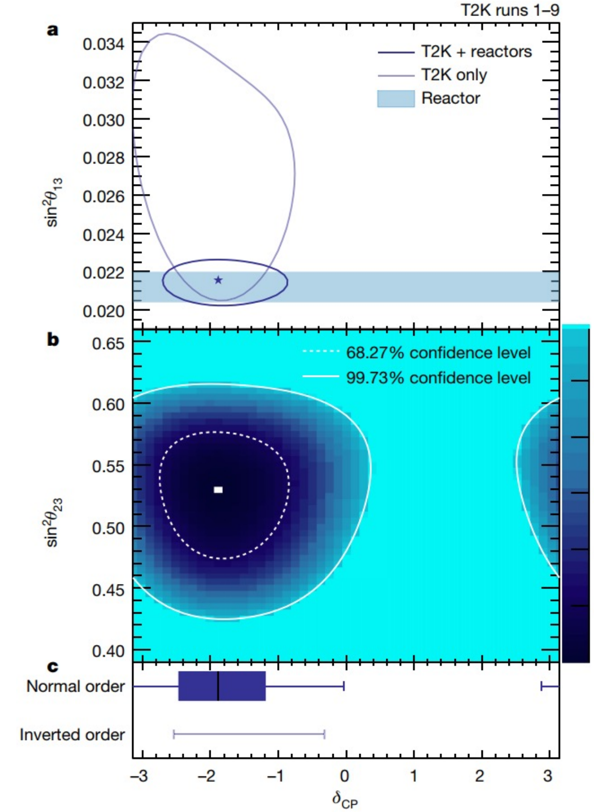
Recently The T2K Collaboration reports CP asymmetry in lepton by searching for using neutrinos. Results give that CP conservation at a 95% confidence level.

If CP conservative,

$$P(\nu_\mu \to \nu_e) = P(\bar{\nu}_\mu \to \bar{\nu}_e)$$







	1e0de ν-mode	1e0de $\bar{\nu}$-mode	1e1de ν-mode
$\nu_\mu \to \nu_e$	59.0	3.0	5.4
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	7.5	0.0
Background	13.8	6.4	1.5
Total predicted	73.2	16.9	6.9
Systematic uncertainty	8.8%	7.1%	18.4%
Data	75	15	15

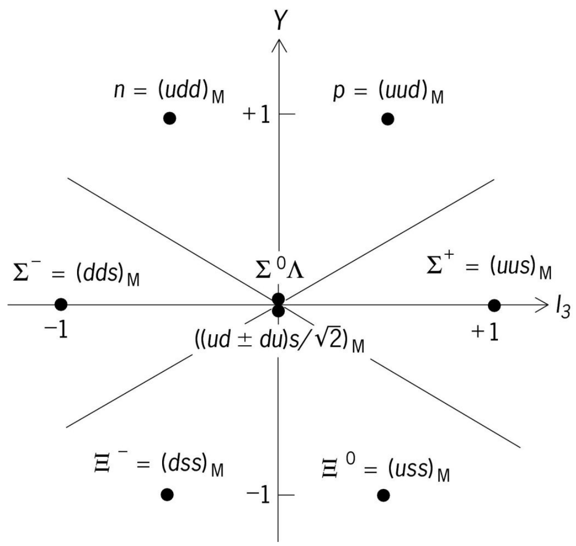
- 1e0de: sample with only a single e-like ring.
- 1e1de: sample containing an e-like ring, with an additional delayed e from the decay of $\pi^{\pm}$ and subsequent μ.

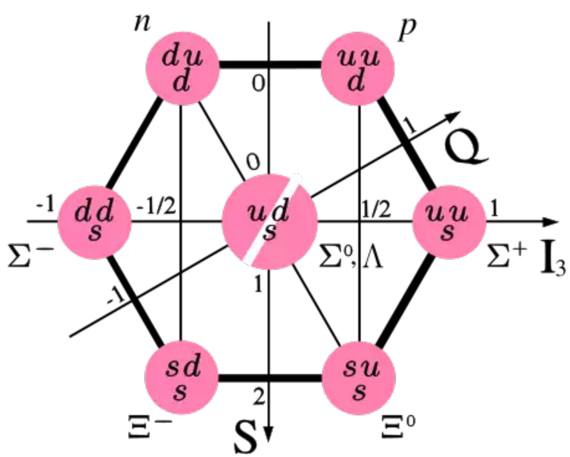
Brief Summary

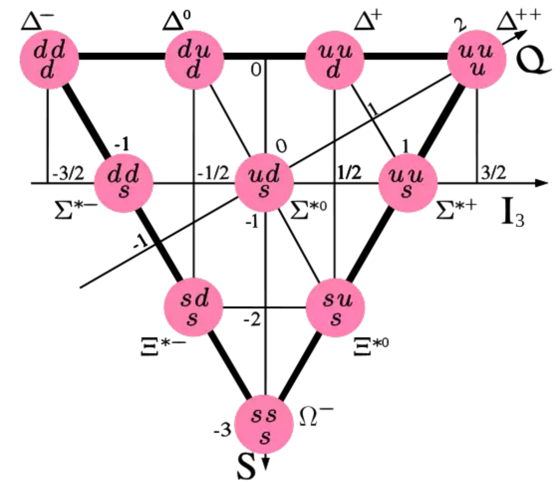
- CP violation causes asymmetry in our universe, it is a necessary condition for the Big Bang Theory, if we could find out what cause CP violation, we may understand why we are living in so-called "positive" world.
- Even now we have found *CP* violation in K^0, B^0, D^0 meson and neutrino oscillating, but what about baryon and other particle?

So it is worthy to continue this study！

Baryon States







Baryon Octet (spin 1/2) **Baryon Decupled (spin 3/2)**

- Baryons are the important component of the matter in the cosmic. The searches of asymmetry evidence in baryon sector is very important.
- First observation of CP violation in $\boldsymbol{\Lambda_b(udb) \rightarrow p\pi^-\pi^+\pi^-}$ at LHCb with a 3.3σ significance level. [Nature Physics 13, 391 (2017)]

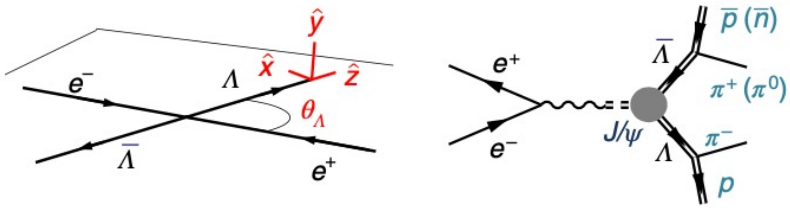
Outline

- $J/\psi \to \Lambda\bar{\Lambda}$
- $J/\psi,\ \psi(3686) \to \Sigma^{+}\bar{\Sigma}^{-}$
- $\psi(3686) \to \Omega^{-}\bar{\Omega}^{+}$
- $J/\psi \to \Xi^{-}\bar{\Xi}^{+}$

Observation of Λ baryon spin polarization in decay $J/\psi \to \Lambda\bar{\Lambda}$

Nature Physics 15,631 (2019)

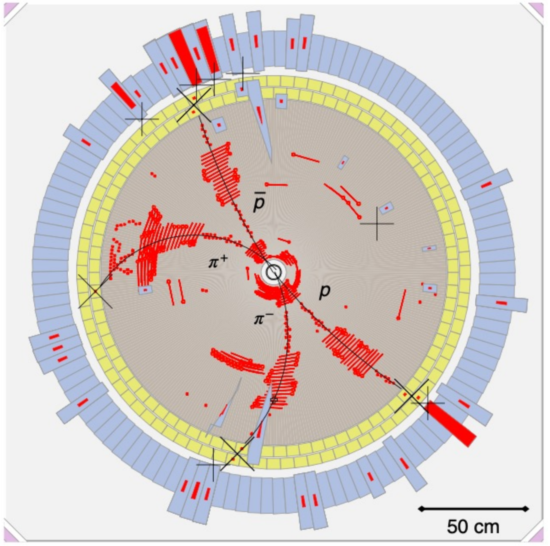
- Joint Angular Distribution



$$\mathcal{W}(\xi;\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+)$$
$$=1+\alpha_\psi\cos^2\theta_\Lambda+\ \alpha_-\alpha_+[\sin^2\theta_\Lambda(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y})$$
$$+(\cos^2\theta_\Lambda+\alpha_\psi)n_{1,z}n_{2,z}]$$
$$+\ \alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\ \cos(\Delta\Phi)\sin\theta_\Lambda\cos\theta_\Lambda(n_{1,x}n_{2,z}+n_{1,z}n_{2,x})$$
$$+\sqrt{1-\alpha_\psi^2}\ \sin(\Delta\Phi)\ \sin\theta_\Lambda\cos\theta_\Lambda(\alpha_-n_{1,y}+\alpha_+n_{2,y})$$

- A non-zero $\Delta\Phi$ has polarization

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



Event display in cross section of the detector.

Observation of Λ baryon spin polarization in decay $J/\psi \to \Lambda\bar{\Lambda}$

Nature Physics 15,631 (2019)

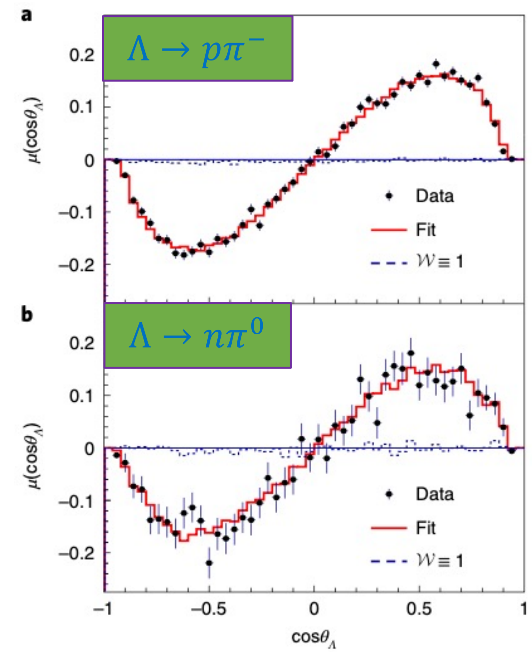
Data sample: $1.3B\ J/\psi$

$$\mu(\cos\theta_\Lambda) = \frac{m}{N}\sum_i^{N_\theta}(\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$$

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 (ref. [14])
$\Delta\Phi$	$42.4 \pm 0.6 \pm 0.5°$	-
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 (ref. [6])
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 (ref. [6])
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	-
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 (ref. [6])
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	-

First measurement of transverse polarization

test of CP violation: $A_{CP} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+}$, $A_{CP,\Lambda}^{SM} \approx 10^{-4}$



The clear polarization signals

Improve: $10B\ J/\psi$

- **The angular distribution** α_- is for $\Lambda \to p\pi^-$ and α_+ is for $\bar{\Lambda} \to \bar{p}\pi^+$. These parameters values are obtained independently.
- The larger data samples are expected in various extensions of the Standard Model aiming to explain the observed baryon–antibaryon asymmetry in the universe.

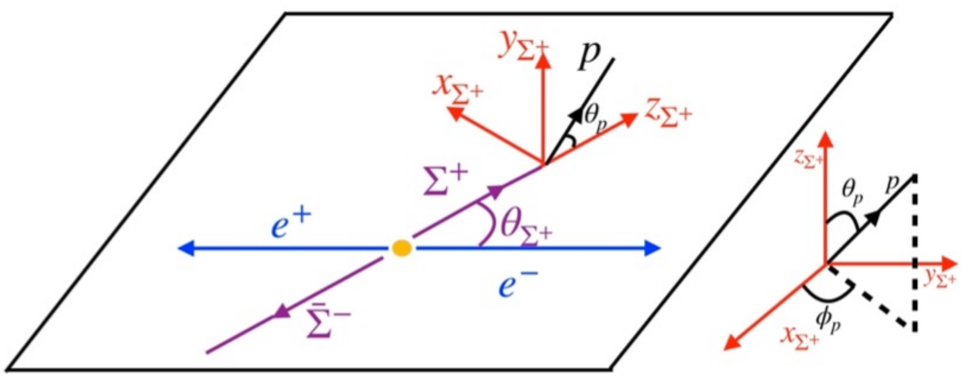
Observation of Σ baryon spin polarization in decay $J/\psi, \psi(3686) \to \Sigma^+\bar{\Sigma}^-$

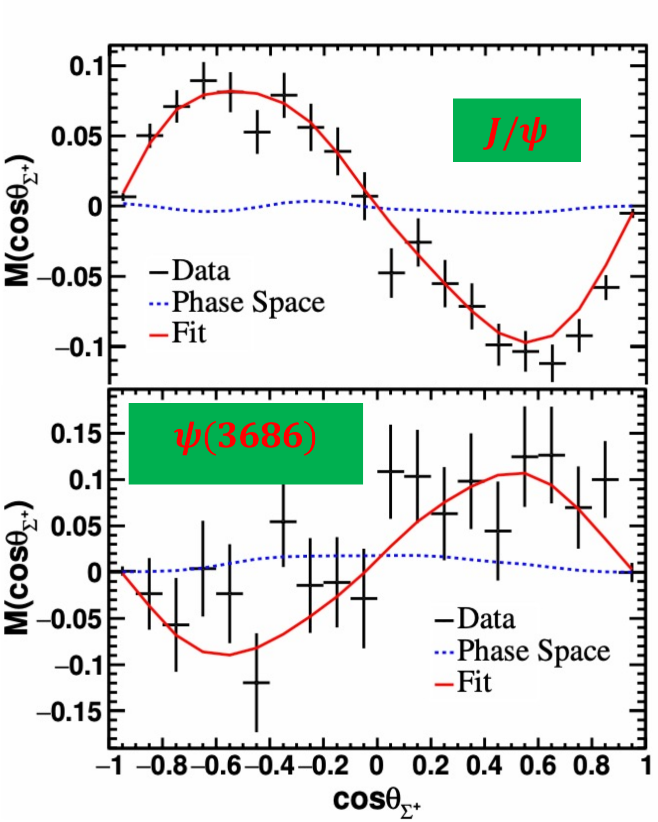
Phys.Rev.Lett. 125, 052004 (2020)

- Joint angular distribution

$$\mu(\cos\theta_\Sigma) = \frac{m}{N}\sum_i^{N_\theta}(\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$$

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi}) =& \mathcal{T}_0(\boldsymbol{\xi}) + \alpha_\psi \mathcal{T}_5(\boldsymbol{\xi}) \\ &+\alpha_0\bar{\alpha}_0\left(\mathcal{T}_1(\boldsymbol{\xi}) + \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)\mathcal{T}_2(\boldsymbol{\xi}) + \alpha_\psi\mathcal{T}_6(\boldsymbol{\xi})\right) \\ &+\sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)\left(\alpha_0\mathcal{T}_3(\boldsymbol{\xi}) + \bar{\alpha}_0\mathcal{T}_4(\boldsymbol{\xi})\right).\end{aligned}$$





The clear polarization signals

Observation of Σ baryon spin polarization in decay $J/\psi, \psi(3686) \rightarrow \Sigma^+\bar{\Sigma}^-$

Phys.Rev.Lett. 125, 052004 (2020)

1.3B J/ψ sample & 448M $\psi(3686)$ sample

Parameter	Measured value
$\alpha_{J/\psi}$	$-0.508 \pm 0.006 \pm 0.004$
$\Delta\Phi_{J/\psi}$	$-0.270 \pm 0.012 \pm 0.009$
$\alpha_{\psi'}$	$0.682 \pm 0.03 \pm 0.011$
$\Delta\Phi_{\psi'}$	$0.379 \pm 0.07 \pm 0.014$
α_0	$-0.998 \pm 0.037 \pm 0.009$
$\bar{\alpha}_0$	$0.990 \pm 0.037 \pm 0.011$

Statistical significance level:
- more than **20σ** for J/ψ data;
- near **5.5σ** for $\psi(3686)$ data.

$A_{CP,\Sigma}^{SM} \approx 3.6\times10^{-6}$

$$A_{CP} = \frac{\alpha_0+\bar{\alpha}_0}{\alpha_0-\bar{\alpha}_0} = -0.004 \pm 0.037 \pm 0.010 \approx 0$$

Helicity amplitude analysis of $\psi(3686) \to \Omega^-\overline{\Omega}^+$ decay

arXiv:2007.03679v1

448M $\psi(3686)$ sample

Assuming that there is no CP-violation

- Joint angular distribution

$$\rho_{3/2} = \Sigma_{\mu=0}^{15}\Sigma_{\nu=0}^{3} r_\mu b_{\mu\nu} a_{\nu 0},$$

two solutions

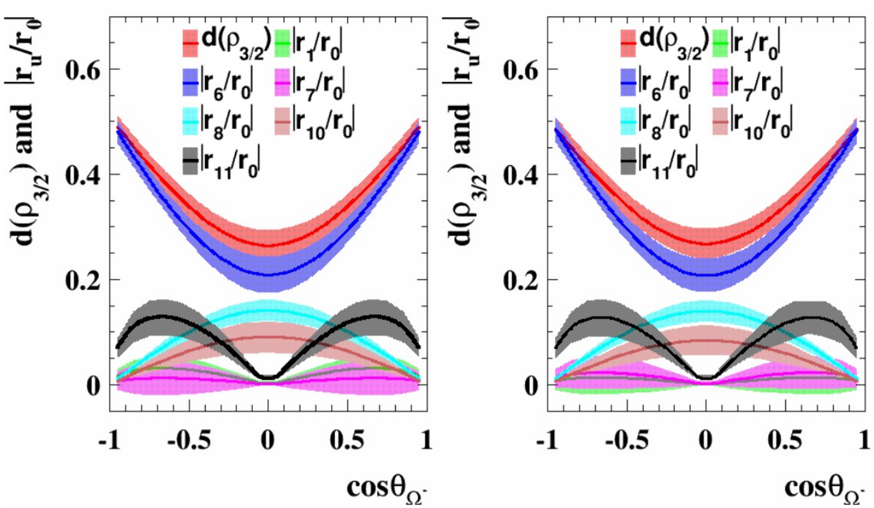
parameter	solution I	solution II
h_1	0.30±0.11±0.04	0.31±0.10±0.04
ϕ_1	0.69±0.41±0.13	2.38±0.37±0.13
h_3	0.26±0.05±0.02	0.27±0.05±0.01
ϕ_3	2.60±0.16±0.08	2.57±0.16±0.04
h_4	0.51±0.03±0.01	0.51±0.03±0.01
ϕ_4	0.34±0.80±0.31	1.37±0.68±0.16
ϕ_Ω	4.29±0.45±0.23	4.15±0.44±0.16

Branching fraction: $(5.85 \pm 0.12 \pm 0.25) \times 10^{-5}$

The statistics are limited!

Degree of polarization

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



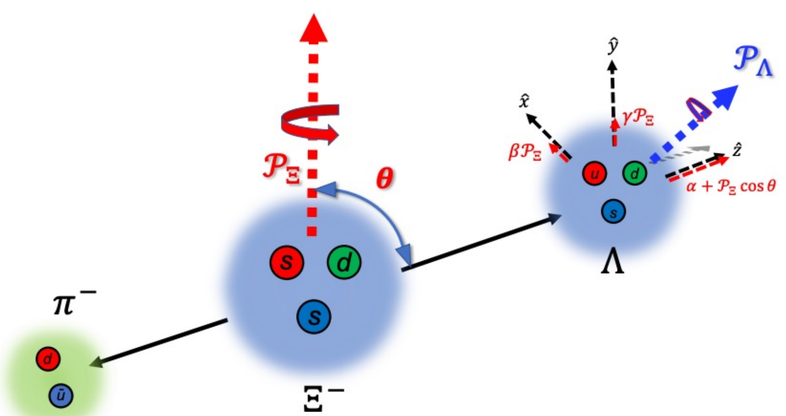
Observation of Ξ^- baryon spin polarization in decay $J/\psi \to \Xi^- \bar{\Xi}^+$

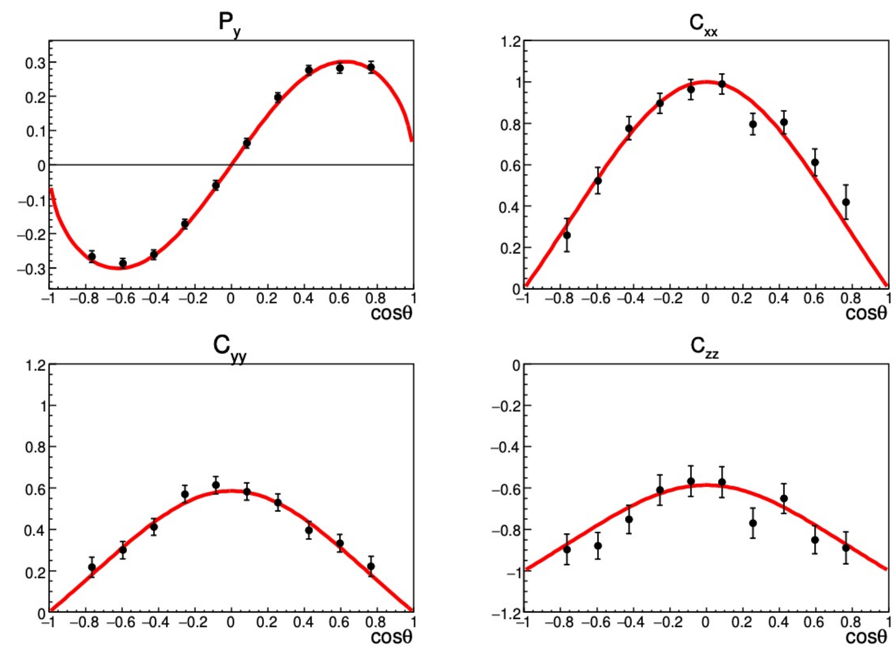
arXiv: 2105.11155

- Joint angular distribution

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

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





Polarization and spin correlations.

Observation of Ξ^- baryon spin polarization in decay $J/\psi \to \Xi^-\bar{\Xi}^+$

arXiv: 2105.11155

Parameter	This work	Previous result	
α_ψ	$0.586 \pm 0.012 \pm 0.010$	$0.58 \pm 0.04 \pm 0.08$	[39]
$\Delta\Phi$	$1.213 \pm 0.046 \pm 0.016$ rad	–	
α_Ξ	$-0.376 \pm 0.007 \pm 0.003$	-0.401 ± 0.010	[21]
ϕ_Ξ	$0.011 \pm 0.019 \pm 0.009$ rad	-0.037 ± 0.014 rad	[21]
$\bar{\alpha}_\Xi$	$0.371 \pm 0.007 \pm 0.002$	–	
$\bar{\phi}_\Xi$	$-0.021 \pm 0.019 \pm 0.007$ rad	–	
α_Λ	$0.757 \pm 0.011 \pm 0.008$	$0.750 \pm 0.009 \pm 0.004$	[14]
$\bar{\alpha}_\Lambda$	$-0.763 \pm 0.011 \pm 0.007$	$-0.758 \pm 0.010 \pm 0.007$	[14]
$\xi_P - \xi_S$	$(1.2 \pm 3.4 \pm 0.8) \times 10^{-2}$ 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	[17]
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}	$(-3.7 \pm 11.7 \pm 9.0) \times 10^{-3}$	$(-6 \pm 12 \pm 7) \times 10^{-3}$	[14]
$\langle\phi_\Xi\rangle$	$0.016 \pm 0.014 \pm 0.007$ rad		

Data sample: 1.3B J/ψ

Weak phase

Strong phase

$A_{CP,\Xi}^{SM} \approx -0.6\times10^{-5}$

- Researches in other decay channels
  - $J/\psi, \psi(3686) \rightarrow \Xi\bar{\Xi}$,
  - $J/\psi, \psi(3686) \rightarrow \Sigma(1385)\bar{\Sigma}(1385)$,
  - $\mathrm{J}/\psi, \psi(3686) \rightarrow \Lambda\bar{\Lambda}, \Sigma^0\bar{\Sigma}^0$,
  - $\psi(3686) \rightarrow \Xi(1530)^-\bar{\Xi}(1530)^+, \Xi(1530)^-\bar{\Xi}^+$,
  - ……

The researches are ongoing!

Summary

- The CP violation of mesons, neutrino and baryons are introduced.
- Through the two-body hyperons weak decay system, the clear polarization signals can be seen, but the CP violation in strange baryons has not observed due to the limited statistics.
- Hope higher sensitive test of CP symmetry in strange baryons using larger data sets at BESIII and future Super Tau-Charm facility!

Thanks for your attention!