Searching for $\Lambda - \bar{\Lambda}$ Bayron-Number-Violating Oscillations in the Decay $J/\psi \to pK^{-}\Lambda$+c.c.

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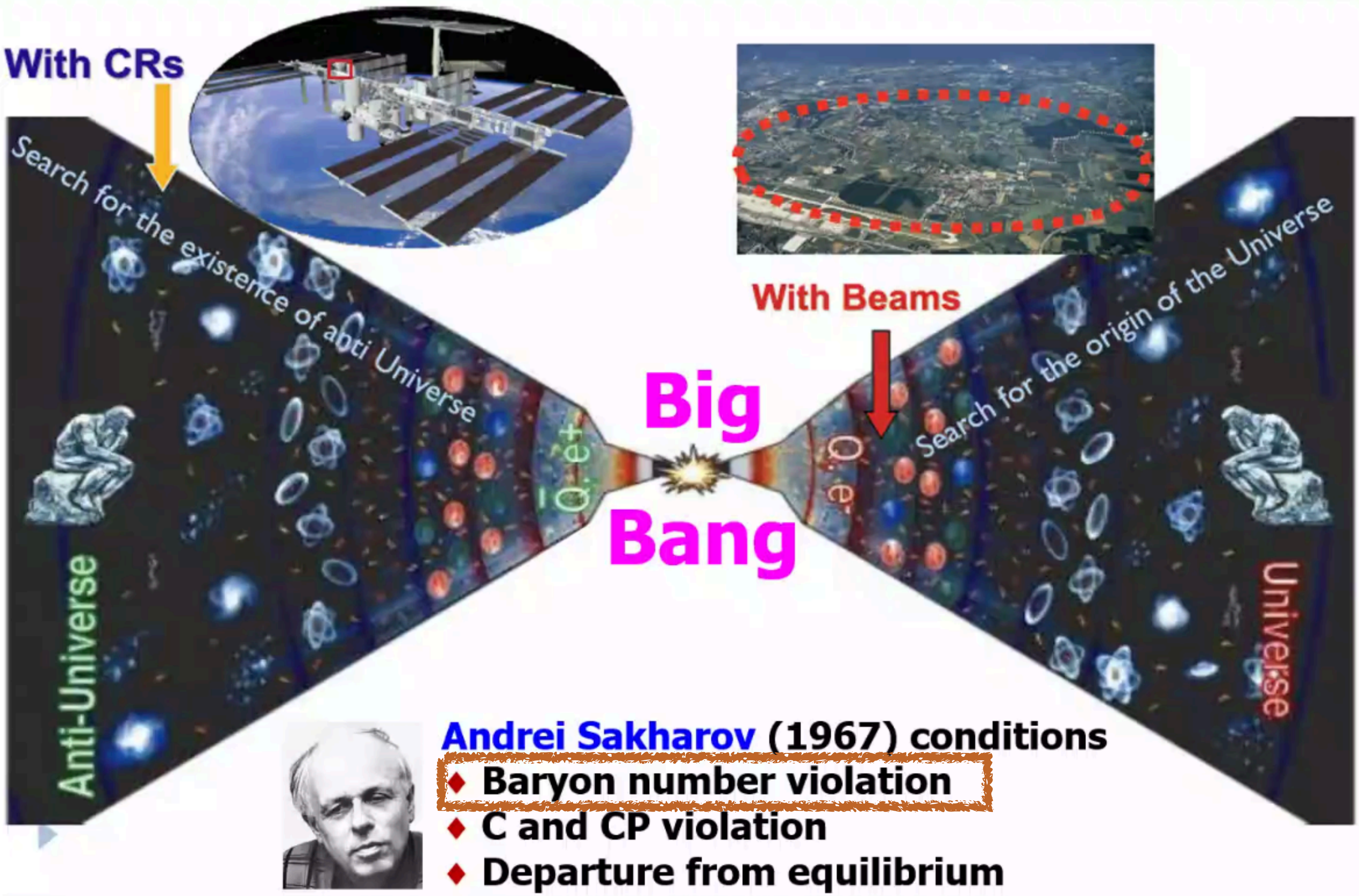
Motivation

The asymmetry of matter and antimatter in the universe is one of the major frontier issues urgently to be solved in particle physics, astrophysics and cosmology.

Motivation


With CRs
Search for the existence of anti Universe
With Beams
Search for the origin of the Universe
Big
Bang
Anti-Universe
Universe
Andrei Sakharov (1967) conditions
Baryon number violation
C and CP violation
Departure from equilibrium

Motivation

- The origin of matter-anti-matter asymmetry hints the existence of baryon number (B) processes.
- Also, non-perturbative effects of standard model lead to $\Delta B \neq 0$, while keeping $\Delta(B-L)=0$

Therefore, the baryon number (B) may not be a good symmetry of nature.

If there are the baryon-number-violating interaction, where we can find it/ them?

- some GUTs predict $\Delta(B-L)=0$: $p \to e^+\pi^0,\ J/\psi \to \Lambda_c^+ e^-$, is deeply explored.
- The discoveries of neutrino oscillations if as consequence of seesaw mechanism, indicates $\Delta B = 2$, i.e., $\Delta(B-L) \neq 0$ interactions: $N-\bar{N}$ oscillations [PRL96, 061801(2006)] , need pay more attention.

Motivation

- Since 1980[PRL44,1316], there have been many experiments searching for BNV through $n-\bar{n}$ oscillation[PDG2019] with upper limit results, while few results from other baryons.
- 2007, K.-B. Luk pointed out that $\Lambda-\bar{\Lambda}$ oscillation may also exist.
- 2010, X.-W. Kang and H.-B. Li[PRD81,051901] give a prospect of searching for $\Lambda-\bar{\Lambda}$ oscillation at the BESIII experiment.
- 2017, the LHCb experiment present a constraint on $\Xi_b^0-\bar{\Xi}_b^0$ oscillation.
- No experiment search on Λ yet till this work.

Method

- Starting with a beam of free $\bar{\Lambda}$, the probability of generating a Λ after time *t* can be described by

$$\mathcal{P}(\Lambda, t) = \sin^2(\delta m_{\Lambda\bar{\Lambda}} t) e^{-t/\tau_\Lambda}$$

where $\delta m_{\Lambda\bar{\Lambda}}$ is the oscillation parameter and *t* is the decay time, $\tau_\Lambda = (2.632 \pm 0.020) \times 10^{-10}\,(\mathrm{s})$ is the life time of Λ baryon.

- Since there is no vertex detector at the BESIII, we can only measure the time integrated result

$$\mathcal{P}(\Lambda) = \frac{\int_0^\infty \sin^2(\delta m_{\Lambda\bar{\Lambda}} t) e^{-t/\tau_\Lambda} dt}{\int_0^\infty e^{-t/\tau_\Lambda} dt}$$

where $P(\Lambda)$ is the time integrated oscillation rate of $\bar{\Lambda} \to \Lambda$.

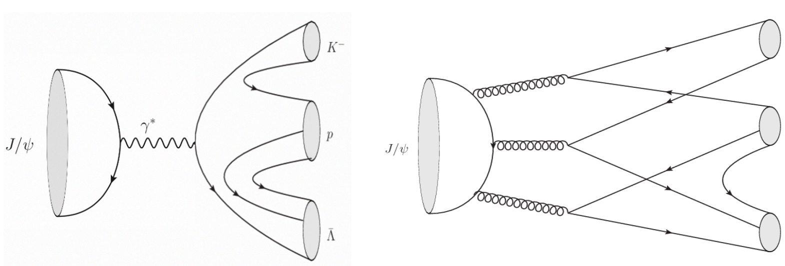
- Therefore, the oscillation parameter can be deduced as

$$(\delta m_{\Lambda\bar{\Lambda}})^2 = \frac{\mathcal{P}(\Lambda)}{2\tau_\Lambda^2}$$

Notation and Method

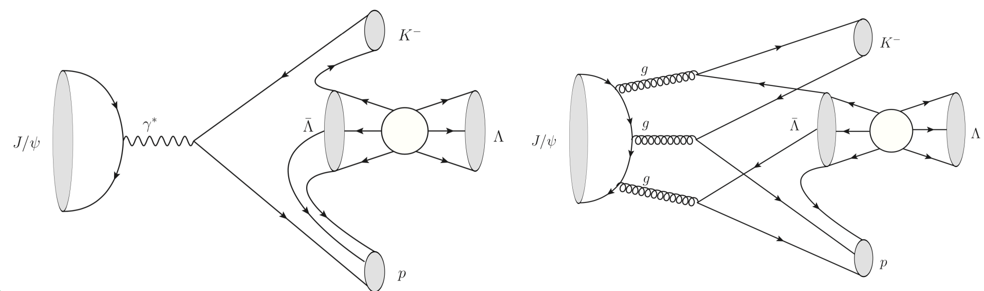
- Oscillation event (charge conjugation implied)

$$J/\psi \rightarrow pK^-\bar{\Lambda} \xrightarrow{oscillating} pK^-\Lambda$$



Right Sign Channel (Opposite Charge)

$$J/\psi \rightarrow pK^-\bar{\Lambda} \rightarrow pK^-(\bar{p}\pi^+)$$



Wrong Sign Channel (Same Charge)

$$J/\psi \rightarrow pK^-\Lambda \rightarrow pK^-(p\pi^-)$$

Notation and Method

- Oscillation event (charge conjugation implied)

$$J/\psi \to pK^-\bar{\Lambda} \xrightarrow{\quad oscillating \quad} pK^-\Lambda$$

- Time integrated oscillation rate

$$\mathcal{P}(\Lambda) = \frac{\mathcal{B}(J/\psi \to pK^-\Lambda)}{\mathcal{B}(J/\psi \to pK^-\bar{\Lambda})} = \frac{N^{obs}_{\mathrm{WS}}/\epsilon_{\mathrm{WS}}}{N^{obs}_{\mathrm{RS}}/\epsilon_{\mathrm{RS}}},$$

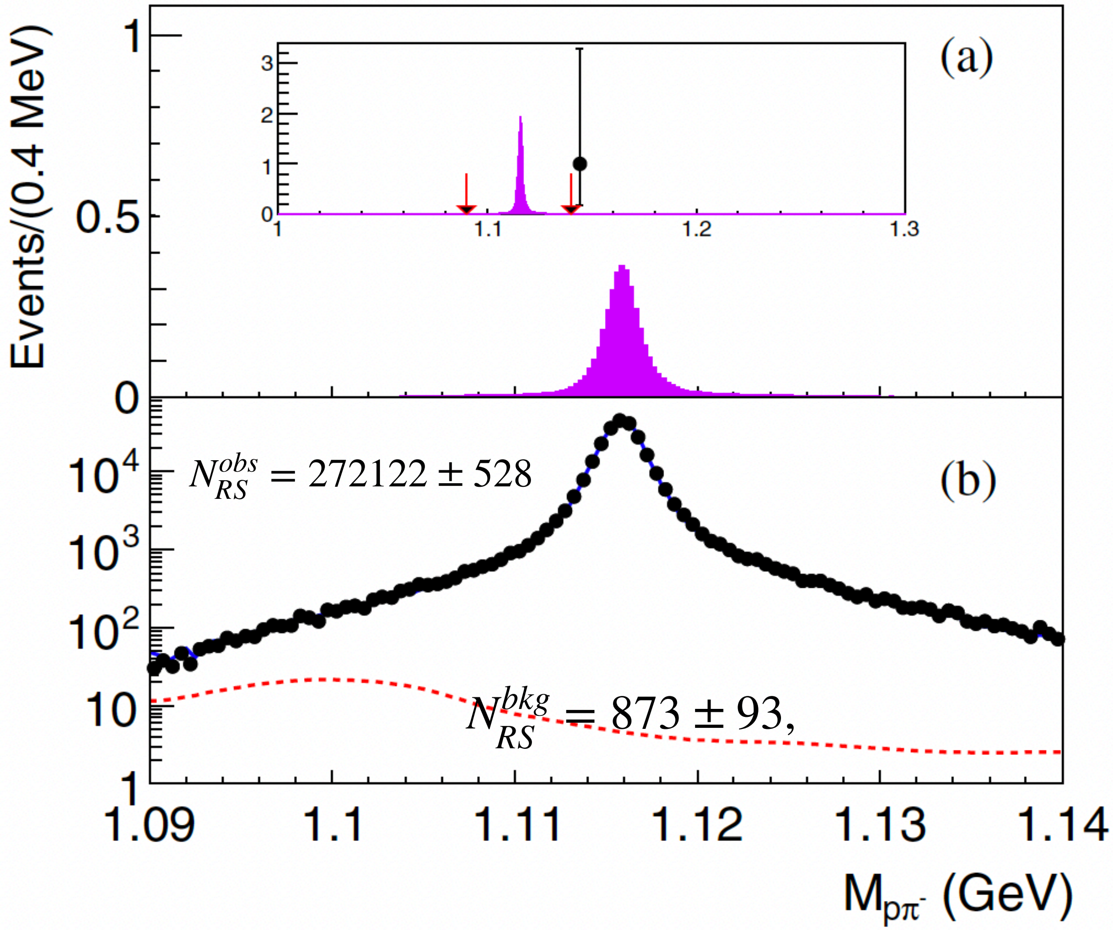
- Most of the systematic uncertainties cancelled.

Event Selection

- **Charged tracks selection:**
  1. Vertex cut: $|R_{xy}|<1.0$ cm, $|R_z|<10.0$ cm, for tracks from Λ, $|R_{xy}|<15.0$ cm, $|R_z|<30.0$ cm
  2. Polar angle: $|\cos\theta|<0.93$
  3. Charge cut: Q=±1; Sum(Q)=0;
  4. $N_{good}=4$
- **Charged PID** (combine dE/dx and TOF):
  1. Kaon ID: prob(K)>prob(π) and prob(K)>prob(p)
  2. Proton ID: prob(p)>prob(K) and prob(p)>prob(π)
  3. Num_Kaon=1 and Num_Proton=2
- **Λ reconstruction**: 2nd vertex fit ($L/\sigma_L > 2.0$)
- **4C kinematic fit:** $\chi^2_{4C} < 200$

- **To select RS Event**: the charge of two protons is opposite
- **To select WS Event**: the charge of two protons is same

Distribution for WS and RS events



The $M_{p\pi}$ distribution of:

WS events in the signal region and full span, where the dot with error bar is from data, the pink filled histogram which is normalized arbitrarily is from simulated WS signal events, the arrows in the inset figure show the edges of signal region; 1.2 expected background due to mis-PID estimated based J/psi inclusive simulated MC and continuum data away from peak of J/psi and psi(3686).

RS events from data, where the dots with error bars are from data and the blue line represents the fitting result in which the signal shape is modeled with MC simulated shape convoluted with a Gaussian function and the background shape is obtained from inclusive MC sample after excluding RS events.

Results

- Result based on 1.3 billion J/ψ events,

$$J/\psi \to pK^-\bar{\Lambda} \xrightarrow{oscillate} pK^-\Lambda$$

- Almost background free.
- Benefit from a ratio measurement, most of the Δ_{sys} are cancelled.
- Upper limit is obtained by utilizing a frequentist method[NIMA551, 493(2005)] with unbounded profile likelihood treatment of systematic uncertainties, inputing the number of signal/ background event which is assumed to have a Poisson distribution, the efficiency (ϵ_{WS}) which is assumed to follow a Gaussian distribution, and the systematic uncertainty which is considered as the standard deviation of the efficiency.

Results

- Upper limit on oscillation rate (90% CL)

$$P(\Lambda) = \frac{\mathrm{B}(J/\psi \to pK^-\Lambda)}{\mathrm{B}(J/\psi \to pK^-\bar{\Lambda})} < 4.4 \times 10^{-6}$$

- Oscillation parameter (90% CL)

$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18} \text{ GeV}$$

Conclusions

- Based on 1.31×10^9 J/ψ events collected at BESIII experiment, the $\Lambda - \bar{\Lambda}$ oscillation process is investigated for the first time, which is an alternative way to search for BNV process with $\Delta B = 2$.

- No evidence of the baryon oscillation is observed. The upper limit of the oscillation rate is set to be $P(\Lambda) < 4.4 \times 10^{-6}$ at 90% CL.

- Based on this constraint, the oscillation parameter is calculated to be $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-18}$ GeV at 90% CL corresponding to an oscillation time lower limit of $\tau_{OSC} > 1.7 \times 10^{-7}$ s. This result is comparable with the predicted one in prospect of PRD81,051901 with only about one-tenth data sample.

Conclusions

- This result expands the field of baryon anti-baryon oscillation experiments and may inspire further theoretical and experimental researches.

- Searching BNV from experiment plays key role to reveal the nature of revolution of the universe. In the future, at the next generation super τ-charm factory, the expected constraint on $\delta m_{\Lambda\bar{\Lambda}}$ can be greatly improved to 10^{-17} MeV level or even better.

- Although the upper limit of the oscillation time is much larger than the lifetime of Λ, in some special condition such as a potential well in some kind of hypernuclei[Phys. Lett. 1, 58 (1962)], the Λ might exist for much longer time to present an opportunity to obtain better constraint.


Thank you！