Baryon/Lepton number violation searches at BESIII

Teng-Jiao Wang
On behalf of the BESIII Collaboration

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Outline

1. Motivation

2. Introduction of BEPCII and BESIII

3. Included Results

- Search for $D^0 \to pe^-$ and $D^0 \to \bar{p}e^+$
- Search for $\mathrm{J}/\psi \to \Lambda_c^+ e^- + c.c$
- Search for $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$ and $\Lambda(\Sigma^0)e^+$
- Search for $\Lambda - \bar{\Lambda}$ oscillation in $\mathrm{J}/\psi \to pK^-\bar{\Lambda}$

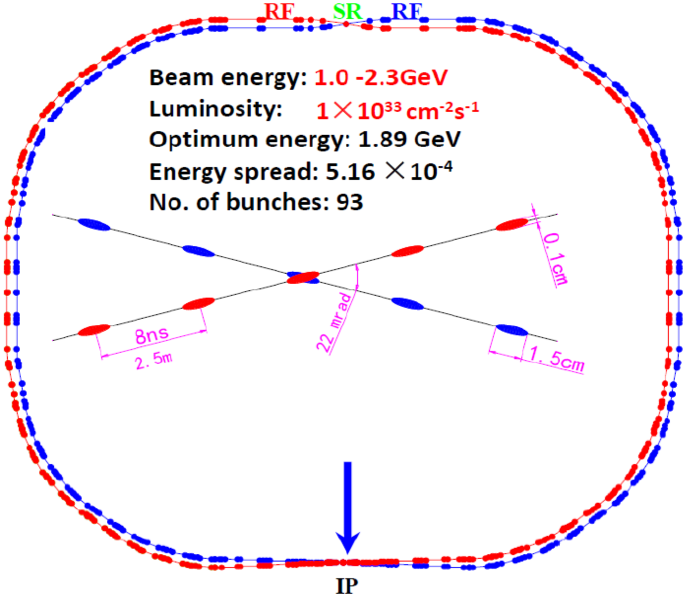
4. Summary

Motivation

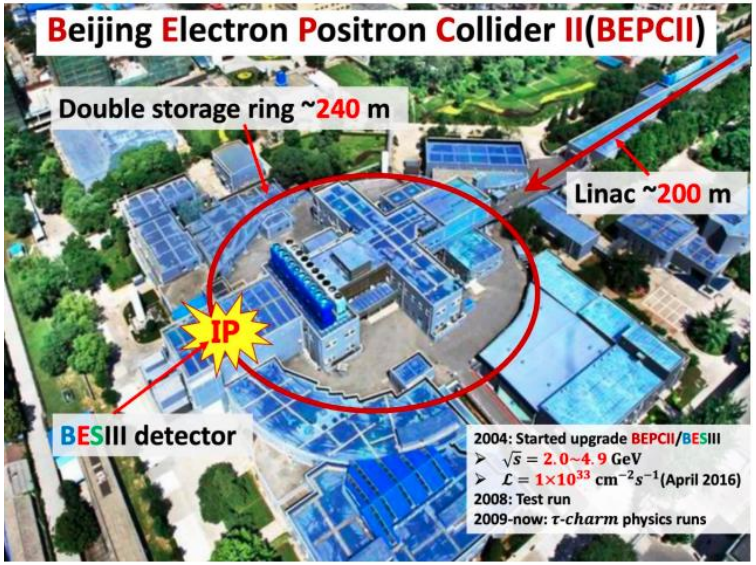
- Excess of baryons over antibaryons in the Universe $\rightarrow$
  Baryon(B) Number(N) Violating processes may exit [PRD 22 1694 (1980)]
- BN is conserved as a consequence in Stander Model (SM) $\rightarrow$
  New Physics
- BNV are allowed in GUTs and SM extensions… $\Delta(B-L)=0$
  [PRD 101, 015017 (2020)]
- Higher generation SUSY model predicts decay modes having BNV/LNV decays for τ leptons, D and B mesons [PRD 72, 095001 (2005)]
- Several models of proton decay, e.g. in GUT, superstrings, and SUSY can be augmented to provide predictions on possible decay mechanisms
  [PRD 59, 091303 (1999)]
- Furthermore, there is another BNV process possible under dimension seven operators $\Delta(B-L)=2$
- Thus, experimental searches for these BNV decays probe new physics effects and test different models beyond the SM.

Few experimental results in e^+e^- collisions!

Introduction of BEPCII and BESIII



BEPCII:



A double-ring collider with high luminosity； Center-of-mass energy: 2.0 – 5.0 GeV

Muon Chamber(MUC)

Superconducting Magnet (1 Tesla)

CsI (Tl) electromagnetic calorimeter (EMC):

$$\frac{\sigma_E}{E} = 2.5\% \text{ @1 GeV (barrel)}$$

$$\frac{\sigma_E}{E} = 5\% \text{ @1 GeV (end – caps)}$$

Time-of-Flight(TOF):

σ_t = 68 ps (barrel)

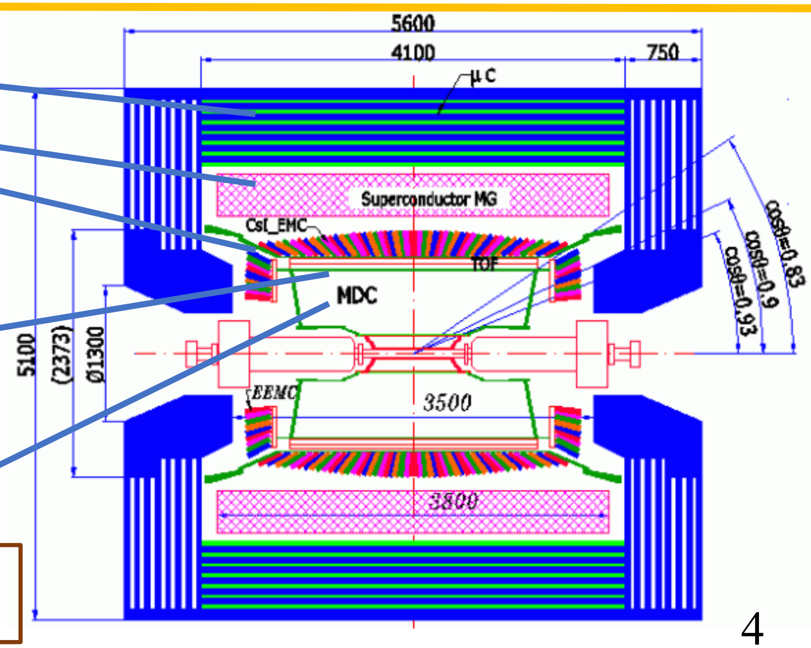
σ_t = 60 ps (endcap upgraded in 2015)

Helium-based multilayer drift chamber (MDC):

$\sigma_{\gamma\phi}$ = 130 μm (single wire)

$\sigma_{p_t}/\,p_t$ = 0.5% @ 1 GeV

BESIII:



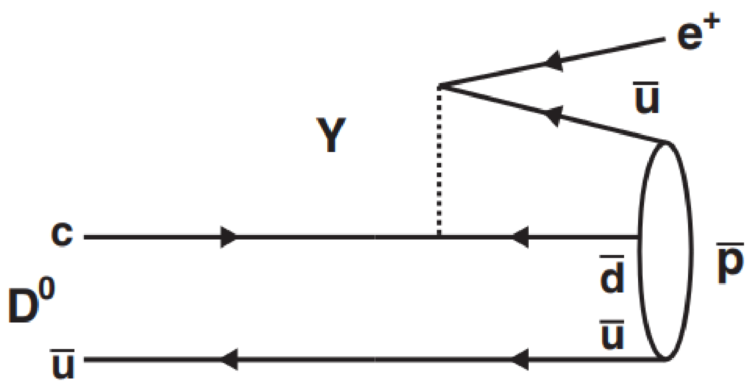
$$\Delta|B-L|=0$$

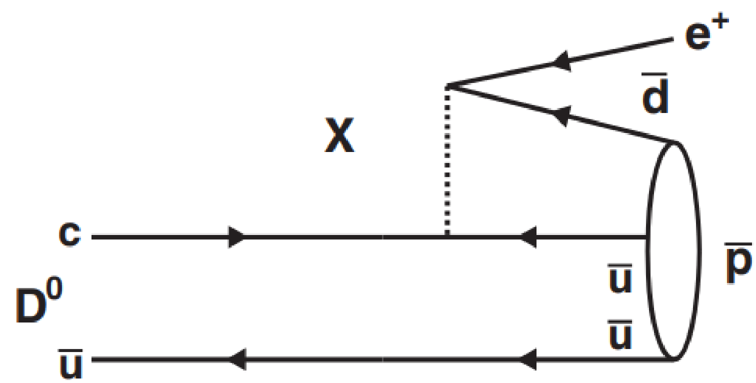
1. B/LNV processes of $D^0 \to pe^-$ and $D^0 \to \bar{p}e^+$

PHYSICAL REVIEW D 105, 032006 (2022)

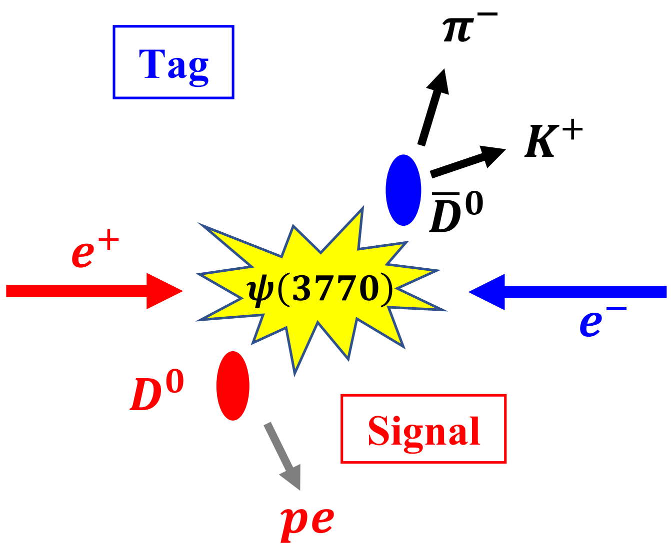
Introduction

- In theory, the semi-leptonic D^0 decay into $\bar{p}e^+$ can proceed via the following Feynman Diagram.
- The decays are mediated by heavy hypothetical gauge bosons called X and Y. The X and Y bosons have electric charge $\frac{4}{3}e$ and $\frac{1}{3}e$ and couple a quark to a lepton, hence they are sometimes called "leptoquarks". [PRD 25, 266 (1982)]
- CLEO [PRD 79, 097101] searched for the B and L violating decays $D^0 \to \bar{p}e^+$ and $D^0 \to pe^-$ and find no evidence. They obtained branching upper limits of $\mathcal{B}(D^0 \to \bar{p}e^+)[\overline{D}^0 \to \bar{p}e^+] < 1.1 \times 10^{-5}$ and $\mathcal{B}(D^0 \to pe^-)[\overline{D}^0 \to pe^-] < 1.0 \times 10^{-5}$, both at 90% C.L.





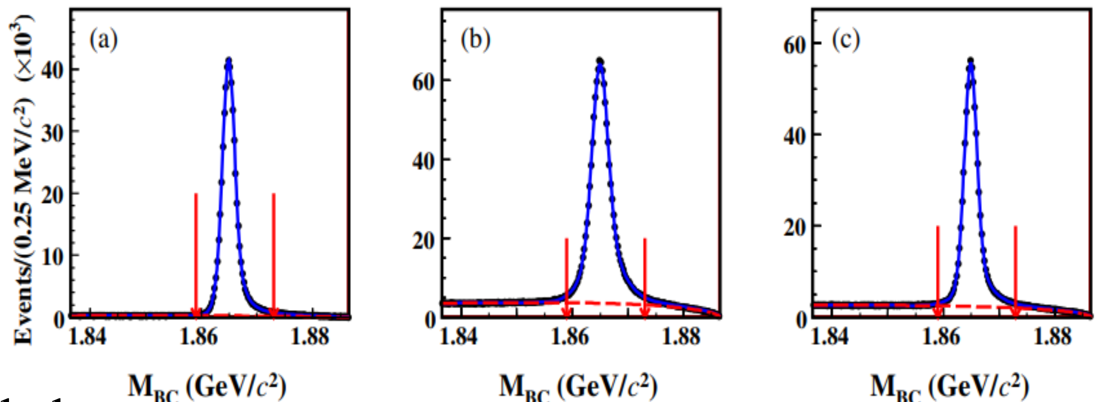
Analysis strategy (Double-tag method)



Charge conjugated processes are implied

Tag Mode	Sig Mode
$\bar{D}^0 \to K^+\pi^-$ $\bar{D}^0 \to K^+\pi^-\pi^0$ $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$	$D^0 \to pe^-$ $D^0 \to \bar{p}e^+$

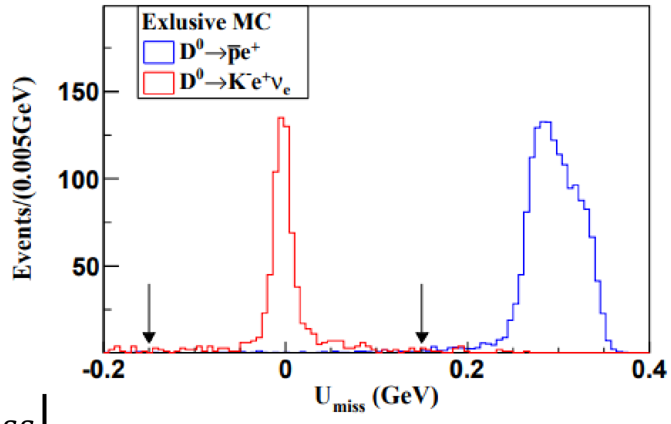
- Data: 2.93 fb^{-1} @ 3.770 GeV
- Double Tag analysis
- Absolute BFs
- Sig very clean and bkg is low
- Many sys. Uncertainties cancelled



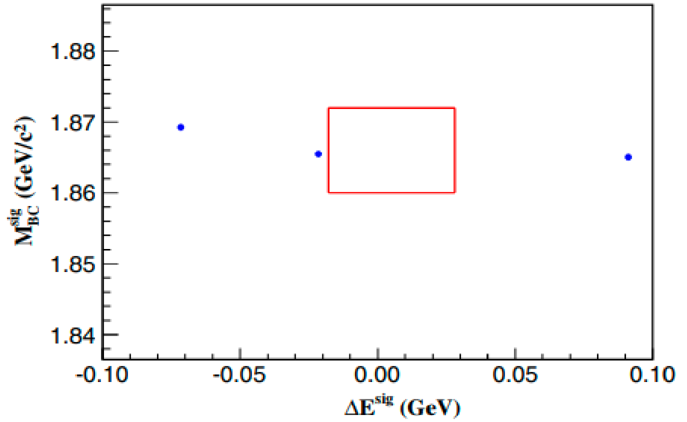
$$E_{\text{beam}} = \frac{\sqrt{s}}{2} = \frac{3.770}{2}\,\text{GeV},\ M_{\text{BC}} = \sqrt{{E_{\text{beam}}}^2 - {p_{\text{tot}}}^2}\ ,\ \Delta E = E_{\text{beam}} - E_D$$

Analysis details and branching fractions

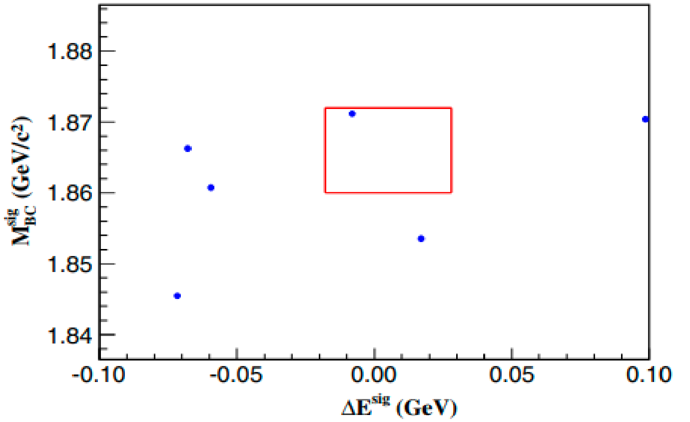
- Signal extraction: obtained by counting; assuming that the bkg are evenly distributed.
- Use U_{miss} to cut the mainly bkg: $D^0 \to K^- e^+ \nu_e$
- Use TROLKE[1,2] to get $\boldsymbol{N^{UP}}$



$$U_{miss} = E_{miss} - |\vec{p}_{miss}|$$



(a)



(b)

$\mathcal{B}(D^0 \to \bar{p}e^+)[\overline{D}^0 \to pe^-] < 1.2 \times 10^{-6}$

$\mathcal{B}(D^0 \to pe^-)[\overline{D}^0 \to \bar{p}e^+] < 2.2 \times 10^{-6}$, at 90% C.L.

UL for D^0 are improved one order.

$$\boldsymbol{B^{UP}} = \frac{\boldsymbol{N^{UP}}}{\boldsymbol{N_D^{ST}}}$$

[1] W. A. Rolke, A. M. Lopez, and J. Conrad, Nucl. Instrum. Methods Phys. Res., Sect. A 551, 493 (2005)

[2] J. Conrad and J. Lundberg, https://root.cern.ch/root/html/TRolke.html.

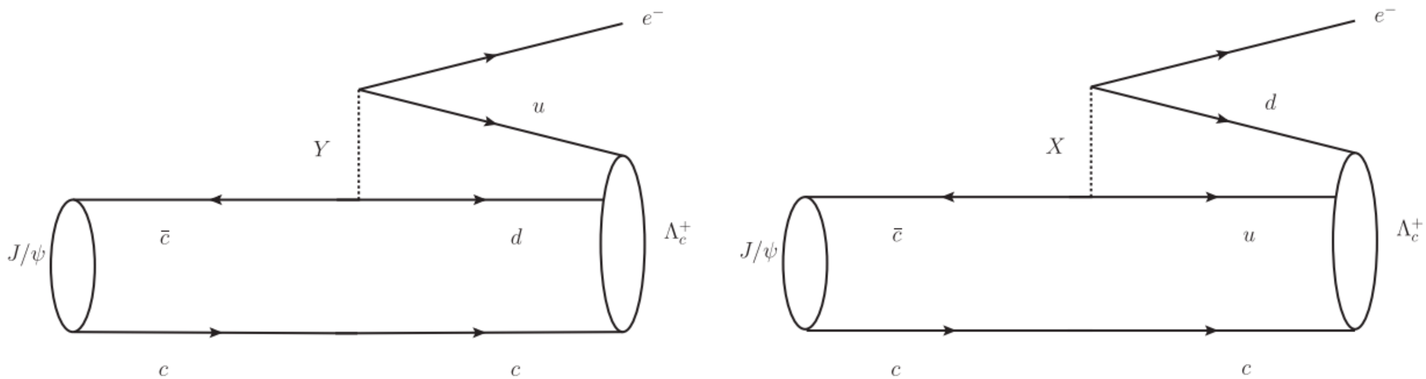
$$\Delta|B-L|=0$$

2. B/LNV process in $\mathbf{J/\psi \to \Lambda_c^+ e^- + c.}\,$c

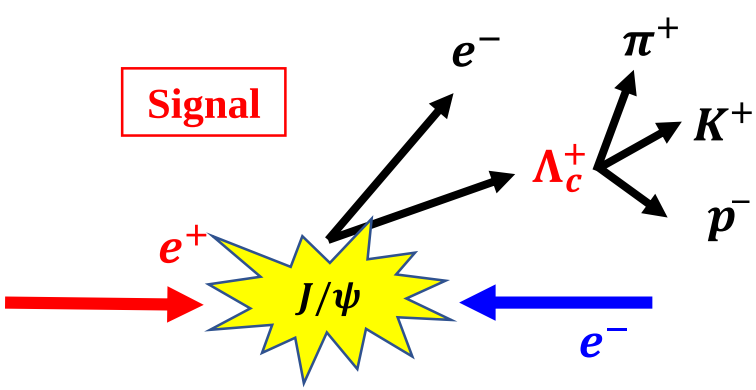
PHYSICAL REVIEW D 99, 072006 (2019)

Introduction

- Searching for the processes in quarkonium decay opens a new avenue to study the BNV.
- Expect the first constraint $[\Delta(B-L)=0]$ of BN violation from charmonium decay.



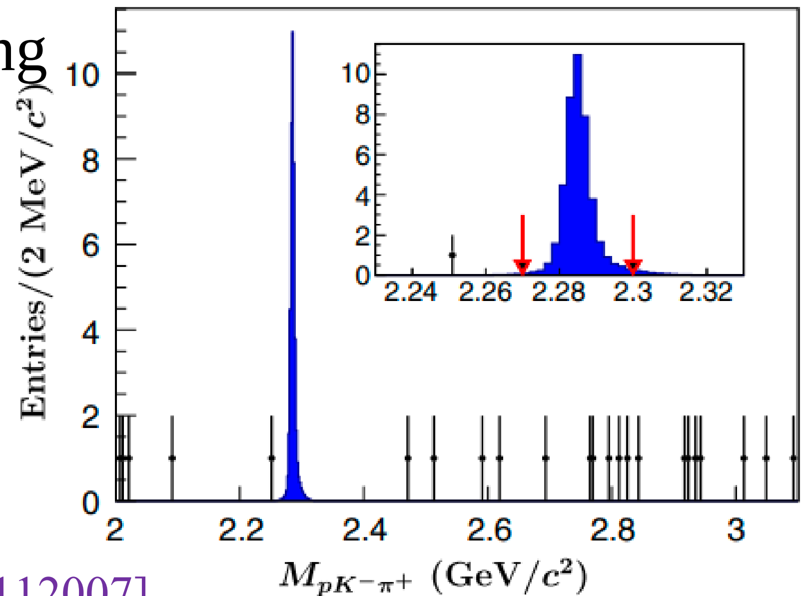
Analysis strategy(Single-tag method)



- Data: 1.3106×10^9@ 3.097 GeV
- Baryons reconstructed from $\Lambda_c^+ \to pK^-\pi^+$
- Using a kinematic fit (4C) to cut the mainly background: $J/\psi \to K^+K^-\pi^+\pi^-$

Analysis details and branching fractions

- Signal extraction: obtained by counting in the distribution of $M_{pK^-\pi^+}$;
- Using TROLKE to get $\boldsymbol{S_{90} = 5.7}$



$$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < \frac{s_{90}}{N_{J/\psi}^{\text{tot}} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$

where $N_{J/\psi} = 1.3106 \times 10^9$ [PRD.87.112007]
and $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = (6.35 \pm 0.33)\%$ [CPC 40, 100001 (2016)]

$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$, at 90% C.L.
UL for J/ψ is measured for first time.

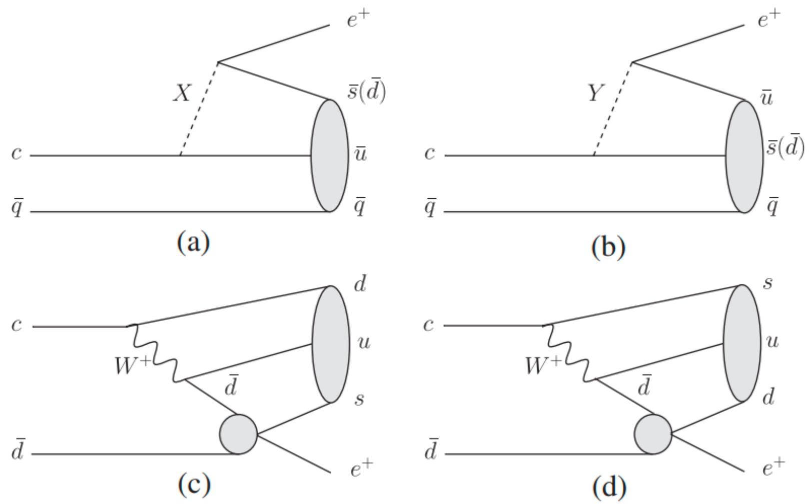
$$\Delta|B-L| = 0, 2$$

1. B/LNV processes of $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$ and $\Lambda(\Sigma^0)e^+$

PHYSICAL REVIEW D 101, 031102 (2020)

Introduction

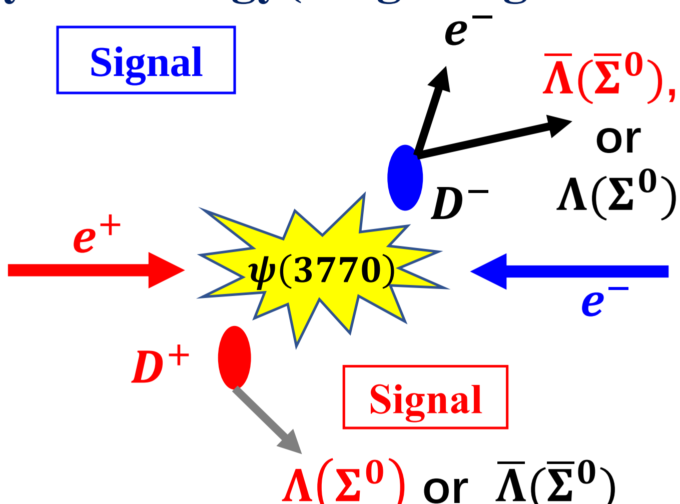
- BFs of $D \to B\ell$, $B = \Lambda, \Sigma, p$ expected to be no more than $\mathcal{O}(10^{-29})$ [PRD 72, 095001 (2005)]



Feynman diagram under operators with dimension six (a, b)/seven (c, d).

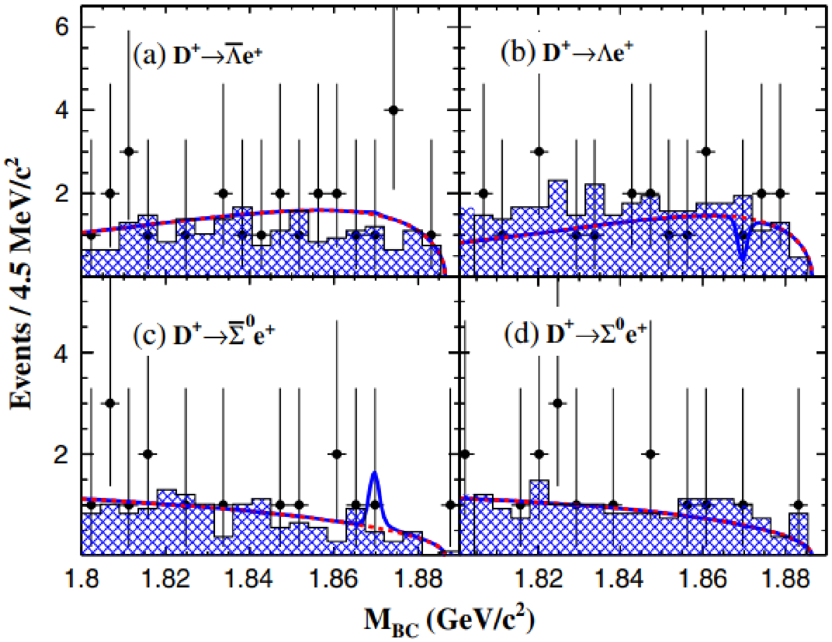
(a), (b) : $\Delta(B-L) = 0$
(c), (d) : $\Delta(B-L) = 2$

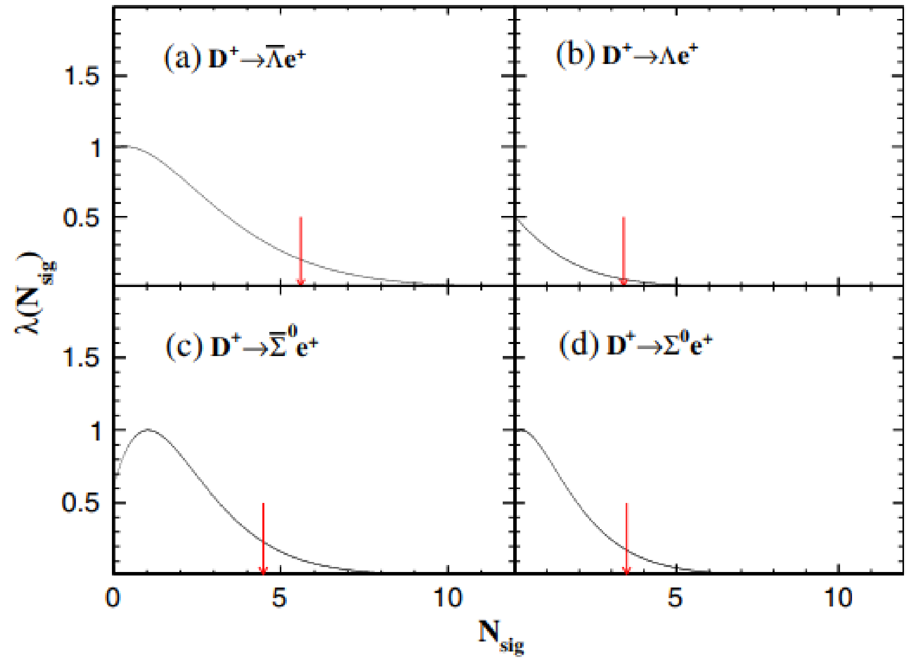
Analysis strategy(Single-tag method)



- Data: 2.93 fb^{-1} @ 3.770 GeV
- BF determined using single-tag method
- Baryons reconstructed from $\Lambda \to p\pi^-, \Sigma^0 \to \gamma\Lambda$
- Using ΔE to suppress background

Analysis details and branching fractions





- $\mathcal{B}^{\mathrm{UP}} = N_{\mathrm{sig}}^{\mathrm{UL}} / (2 \times N_{D^+D^-}^{\mathrm{tot}} \times \varepsilon \times \mathcal{B}_{\Lambda,\Sigma})$

where $N_{D^+D^-}^{\mathrm{tot}} = 8.3$ M [CPC 42, 083001 (2018)]

- Upper limit determination:

$$\int_0^{N_{\mathrm{sig}}^{\mathrm{UL}}} N_{\mathrm{sample}} dN_{\mathrm{sig}} / \int_0^{\infty} N_{\mathrm{sample}} dN_{\mathrm{sig}} = 90\%$$

Channels	Upper limits
$D^+ \to \Lambda e^+$	$< 1.1 \times 10^{-6}$
$D^+ \to \bar{\Lambda} e^+$	$< 6.5 \times 10^{-7}$
$D^+ \to \Sigma^0 e^+$	$< 1.7 \times 10^{-6}$
$D^+ \to \bar{\Sigma}^0 e^+$	$< 1.3 \times 10^{-6}$

First searches of these channels.

$$\Delta|B-L|=2$$

2. Search for $\Lambda-\overline{\Lambda}$ oscillation in $\mathrm{J}/\psi \to pK^{-}\overline{\Lambda}$

BESIII preliminary result

Introduction

- The discoveries of neutrino oscillations have made $N-\bar{N}$ oscillation to be quite plausible theoretically[PRL96, 061801(2006)] if small neutrino masses are to be understood as a consequence of the seesaw mechanism, which indicates the existence of $\Delta(B-L)=2$ interactions.
- The theoretical advantage for using $\Lambda-\bar{\Lambda}$ is it has a second generation quark, which can give further searches with the result of proton decay which only have the first generation quark.
- Since there is no vertex detector at the BESIII, we can only measure the time integrated result

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

where $P(\Lambda)$ is the time integrated oscillation rate of $\bar{\Lambda}\to\Lambda$,
$\tau_\Lambda=(2.632\pm 0.020)\times 10^{-10}$ (s) is the life time of Λ baryon.

- Therefore, the oscillation parameter can be deduced as: $(\delta m_{\Lambda\bar{\Lambda}})^2=\dfrac{\mathcal{P}(\Lambda)}{2\cdot(\tau_\Lambda/\hbar)^2}$

Analysis details and branching fractions

- Oscillation event (charge conjugation implied)

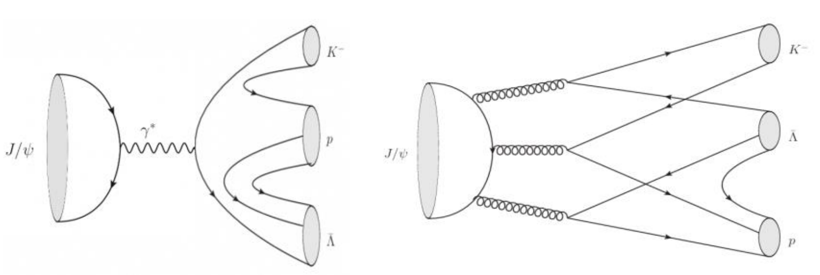
$$J/\psi \to pK^-\bar{\Lambda} \xrightarrow{\text{oscillating}} pK^-\Lambda$$

- Time integrated oscillation rate

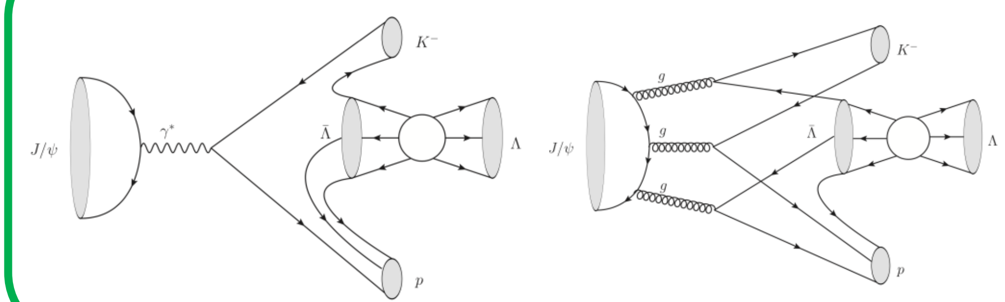
$$\mathcal{P}(\Lambda) = \frac{\mathcal{B}(J/\psi \to pK^-\Lambda)}{\mathcal{B}(J/\psi \to pK^-\bar{\Lambda})} = \frac{N^{obs}_{\mathrm{WS}}/\epsilon_{\mathrm{WS}}}{N^{obs}_{\mathrm{RS}}/\epsilon_{\mathrm{RS}}}$$

- Most of the systematic uncertainties cancelled.

Dataset:
$1.3106\times 10^9 J/\psi$ events
@ 3.097 GeV

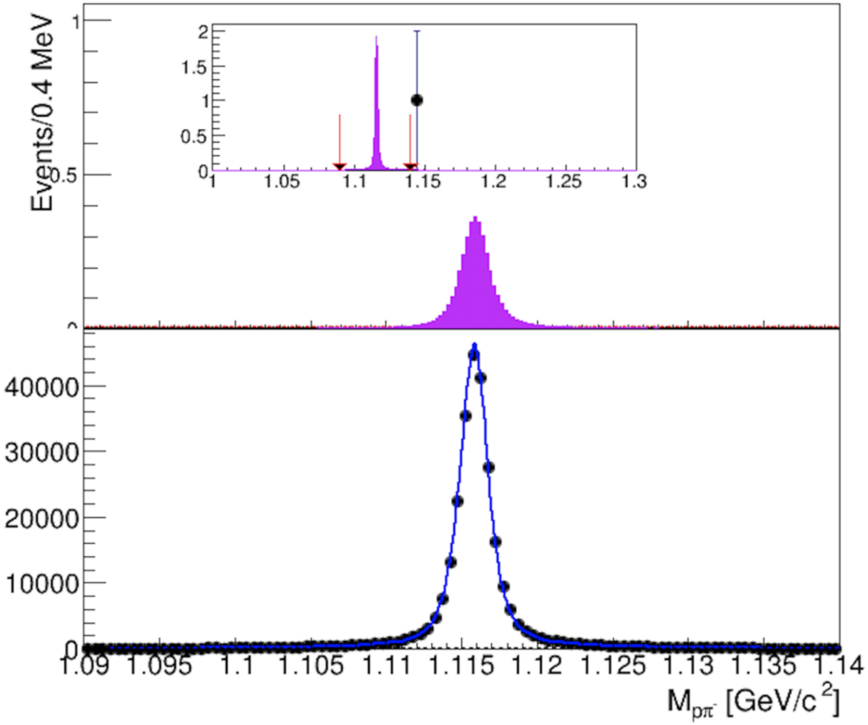


Right Sign Channel
(Opposite Charge)
$J/\psi \to pK^-\bar{\Lambda} \to pK^-(\bar{p}\pi^+)$



Wrong Sign Channel
(Same Charge)
$J/\psi \to pK^-\Lambda \to pK^-(p\pi^-)$

Analysis details and branching fractions



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
RS events from data, where the dots with error bars are from data and the blue line represents the fitting result

- Upper limit is obtained by TROLKE
- Upper limit on oscillation rate (90% C.L.)

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

- Oscillation parameter (90% CL)

$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-15}\ \mathrm{MeV}$$

BESIII Preliminary

Summary

- With 2.93 fb^{-1} @ 3.770 GeV and $1.3106\times 10^{9} J/\psi$ events @ 3.097 GeV data samples, BESIII have studied the baryon and lepton number violation D^0, D^+ and J/ψ decays , no obvious signals are found.
- **Results with a higher precision for**
  - ✓ $\mathcal{B}(D^0 \to \bar{p}e^+) < 1.2 \times 10^{-6}$
  - ✓ $\mathcal{B}(D^0 \to pe^-) < 2.2 \times 10^{-6}$
- **First measurement for**
  - ✓ $\mathcal{B}(D^+ \to \Lambda e^+) < 1.1 \times 10^{-6}$
  - ✓ $\mathcal{B}(D^+ \to \bar{\Lambda} e^+) < 6.5 \times 10^{-7}$
  - ✓ $\mathcal{B}(D^+ \to \Sigma^0 e^+) < 1.7 \times 10^{-6}$
  - ✓ $\mathcal{B}(D^+ \to \bar{\Sigma}^0 e^+) < 1.3 \times 10^{-6}$
  - ✓ $\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$
  - ✓ $P(\Lambda) = \frac{\mathrm{B}(J/\psi \to pK^-\Lambda)}{\mathrm{B}(J/\psi \to pK^-\bar{\Lambda})} < 4.4 \times 10^{-6}$

In the near future, BESIII will collect 20 fb^{-1} @ 3.770 GeV data sample.

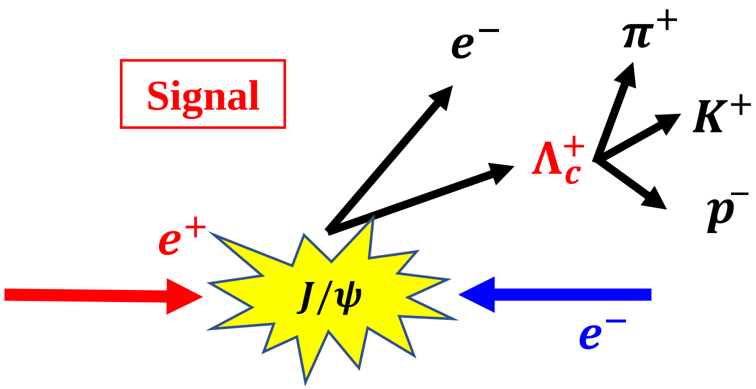
More to look forward to!

Thanks for your attention!

Email: wangtj@ihep.ac.cn

BACKUP

Analysis strategy (Single tag method)



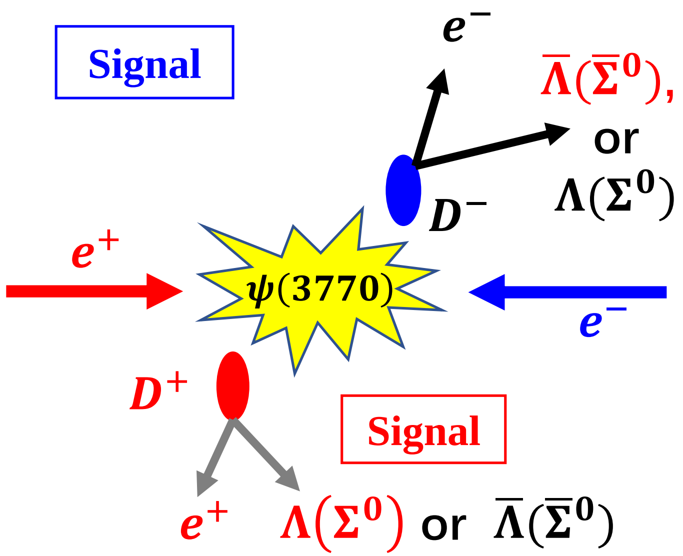
- Data: 1.3106×10^9@ 3.097 GeV
- Baryons reconstructed from $\Lambda_c^+ \to pK^-\pi^+$
- Using a kinematic fit (4C) to cut the mainly background: $J/\psi \to K^+K^-\pi^+\pi^-$

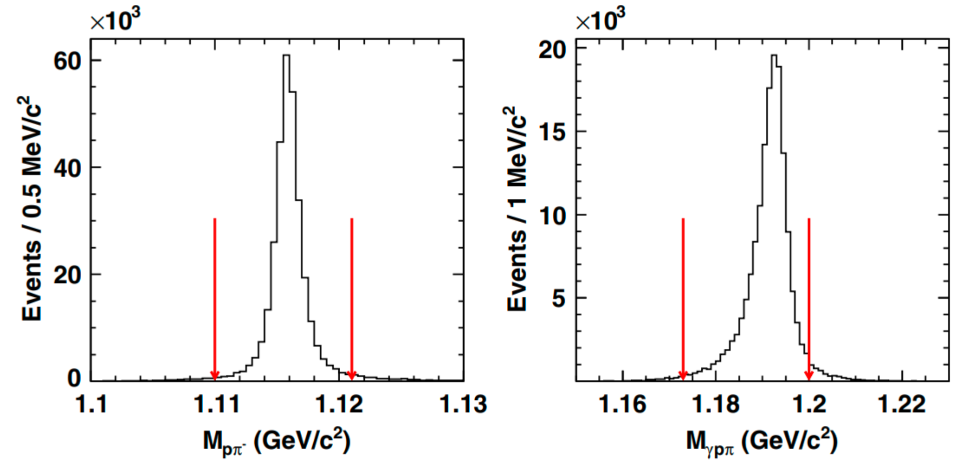
$$\chi_{4C} < 200$$

$$\chi_{4C,pK^-\pi^+e^-} < \chi_{4C,K^+K^-K^+K^-}(\pi^+\pi^+\pi^-, \pi^+\pi^-K^-K^+, \pi^+\pi^-\bar{p}p \; and \; K^+K^-\bar{p}p)$$

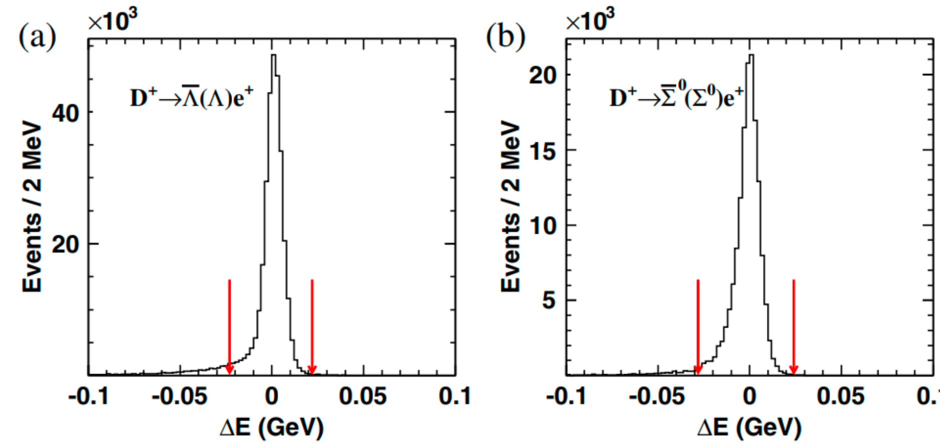
No.	decay chain	final states	iTopo	nEvt	nTot
0	$J/\psi \to K^-\pi^-\pi^0\pi^+K^+$	$J/\psi \to K^+\pi^+\pi^0\pi^-K^-$	7	4	4
1	$J/\psi \to K_S K^* f_0',\ K_S \to \pi^0\pi^0,\ K^* \to \pi^-K^+,\ f_0' \to \pi^-\pi^+$	$J/\psi \to K^+\pi^+\pi^0\pi^0\pi^-\pi^-$	1	1	5
2	$J/\psi \to \pi^0\rho^0,\ \rho^0 \to \pi^-\pi^+$	$J/\psi \to \pi^+\pi^0\pi^-$	2	1	6
3	$J/\psi \to K_2^{*-}K^{*+},\ K_2^{*-} \to K^{*-}\pi^0\pi^0,\ K^{*+} \to \pi^+K_S,$ $K_S \to \pi^0\pi^0,\ K^{*-} \to K^-\pi^0$	$J/\psi \to \pi^+\pi^0\pi^0\pi^0\pi^0\pi^0K^-$	3	1	7
4	$J/\psi \to \gamma f_1(1510),\ f_1(1510) \to K_L K^*,\ K^* \to \pi^-K^+$	$J/\psi \to \gamma K^+K_L\pi^-$	4	1	8
5	$J/\psi \to \phi f_0(1710),\ \phi \to K^-K^+,\ f_0(1710) \to K^-K^+$	$J/\psi \to K^+K^+K^-K^-$	5	1	9
6	$J/\psi \to K^{*-}\pi^0K^+,\ K^{*-} \to \pi^-K_L$	$J/\psi \to K^+K_L\pi^0\pi^-$	6	1	10
7	$J/\psi \to \bar{K}^*\gamma K^*,\ \bar{K}^* \to K^-\pi^+,\ K^* \to \pi^-K^+$	$J/\psi \to \gamma K^+\pi^+\pi^-K^-$	0	1	11

Analysis strategy (Single-tag method)





$$M_{p\pi^-} \in (1.110, 1.121)\ \mathrm{GeV}/c^2$$
$$M_{\gamma p\pi^-} \in (1.173, 1.200)\ \mathrm{GeV}/c^2$$



- Data: 2.93 fb^{-1} @ 3770 GeV
- Baryons reconstructed from $\Lambda \to p\pi^-, \Sigma^0 \to \gamma\Lambda$
- BF determined using single-tag method:
- $\mathcal{B}^{\mathrm{UP}} = N_{\mathrm{sig}}^{\mathrm{UL}} / (2 \times N_{D^+D^-}^{\mathrm{tot}} \times \varepsilon \times \mathcal{B}_{\Lambda,\Sigma})$
- Using ΔE to suppress background

$$E_{\mathrm{beam}} = \frac{\sqrt{s}}{2} = \frac{3.770}{2}\,\mathrm{GeV},\ \Delta E = E_{\mathrm{beam}} - E_D$$

Introduction

- The discoveries of neutrino oscillations have made $N-\bar{N}$ oscillation to be quite plausible theoretically[PRL96, 061801(2006)] if small neutrino masses are to be understood as a consequence of the seesaw mechanism, which indicates the existence of $\Delta(B-L)=2$ interactions.
- 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.
- The theoretical advantage for using $\Lambda-\bar{\Lambda}$ is it has a second generation quark, which can give further searches with the result of proton decay which only have the first generation quark.
- A six-fermion operator, which could arise in models with leptoquarks or R-parity violating supersymmetric extensions of the SM, could allow BNV while being consistent with the experimental limit on the proton lifetime[PLB721, 82(2013)].

Introduction

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

$$\mathcal{P}(\Lambda, t) = \sin^2(\delta \mathrm{m}_{\Lambda\bar{\Lambda}} \cdot \mathrm{t})$$

where $\delta m_{\Lambda\bar{\Lambda}}$ is the oscillation parameter and t is the decay time.

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

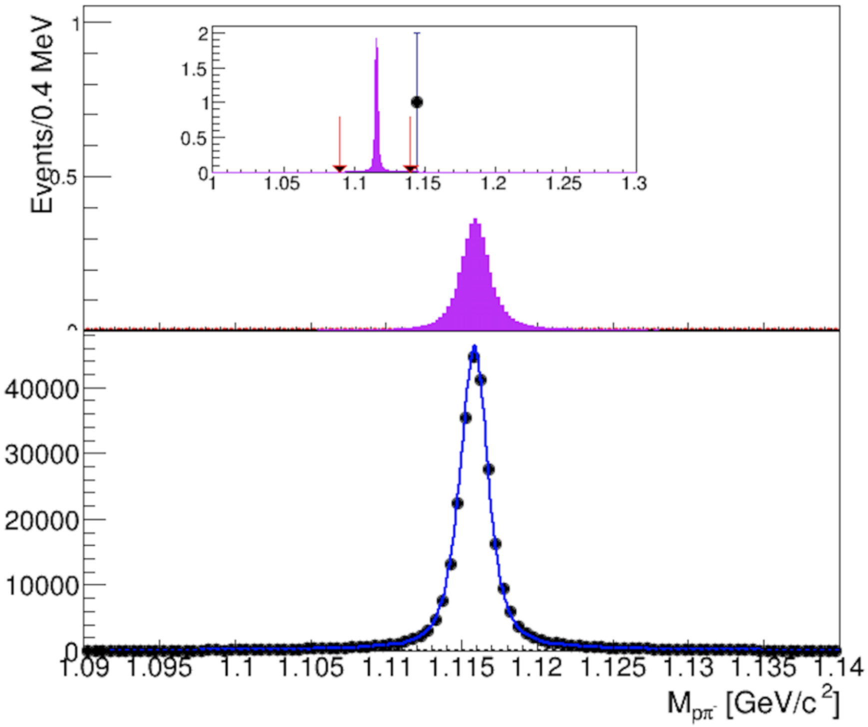
$$\mathcal{P}(\Lambda) = \frac{\int_0^\infty \sin^2(\delta \mathrm{m}_{\Lambda\bar{\Lambda}} \cdot \mathrm{t}) \cdot \mathrm{e}^{-\mathrm{t}/\tau_\Lambda} \cdot \mathrm{dt}}{\int_0^\infty e^{-t/\tau_\Lambda} \cdot dt}$$

where $P(\Lambda)$ is the time integrated oscillation rate of $\bar{\Lambda} \to \Lambda$, $\tau_\Lambda = (2.632 \pm 0.020) \times 10^{-10}$ (s) is the life time of Λ baryon.

- Therefore, the oscillation parameter can be deduced as

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

Analysis details and branching fractions



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

RS events from data, where the dots with error bars are from data and the blue line represents the fitting result

- 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.
- 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)

$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-15} \text{ MeV}$$

BESIII Preliminary

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 $\Delta B = 2$ in addition to neutron oscillation experiments.
- 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 $\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-15}$ MeV at 90% CL corresponding to an oscillation time lower limit of 1.7×10^{-7} s. Our result is comparable with the predicted one in Kang and Li's prospect with only about one-tenth data sample.
- 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.