Baryon/Lepton number violation searches at BESIII

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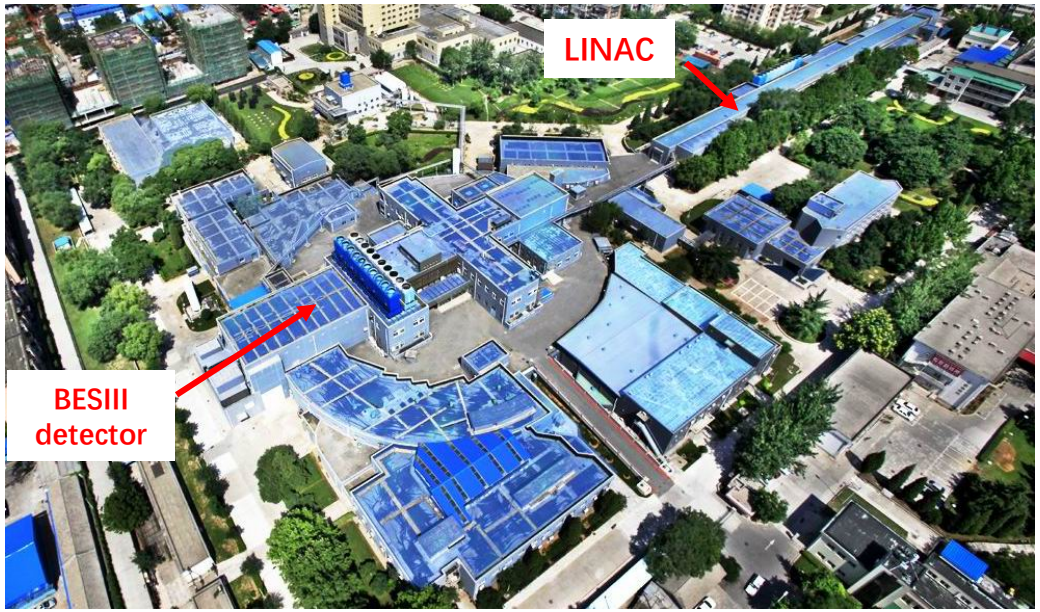
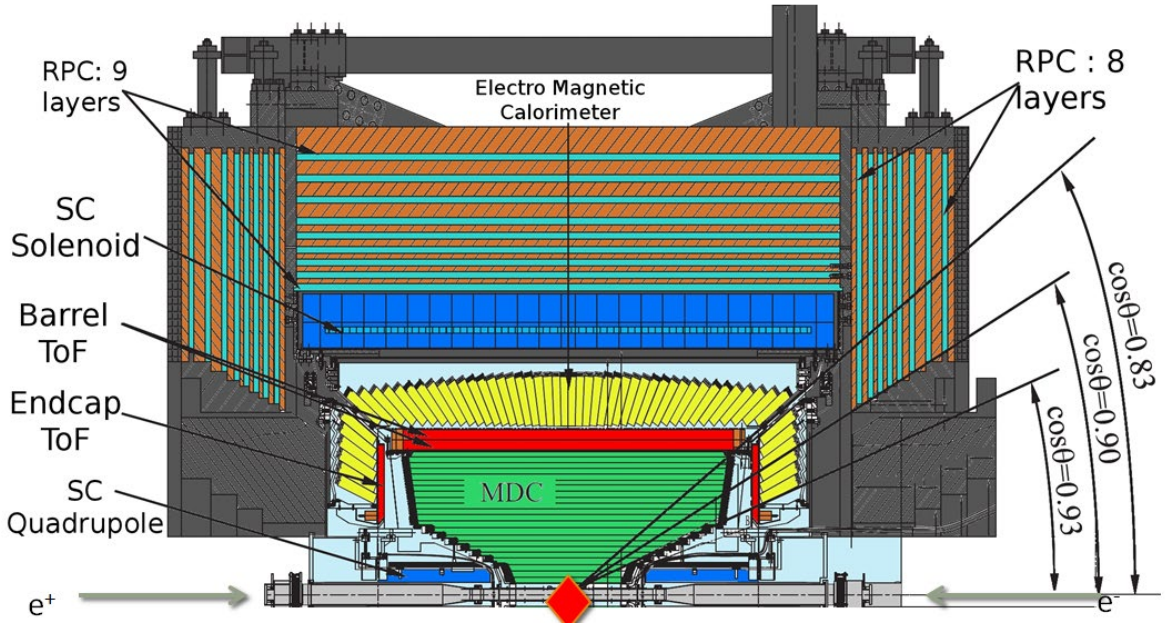
Outline

- Introduction of BEPCII and BESIII
- Charged lepton flavor violating decays
  - Search for $J/\psi \longrightarrow e^{\pm}\tau^{\mp}$
- Lepton number violating(LNV)/Baryon number violating (BNV) decays
  - $J/\psi \rightarrow \Lambda_c^+ e^-$
  - $D^+ \rightarrow \overline{\Lambda}(\overline{\Sigma}^0)e^+, D^+ \rightarrow \Lambda(\Sigma^0)e^+$
  - $\Sigma^- \rightarrow pe^-e^-, \Sigma^- \rightarrow \Sigma^+ X$
  - $\Lambda - \overline{\Lambda}$ oscillation via $J/\psi \rightarrow pK^-\overline{\Lambda}$
- Summary

BESIII experiment





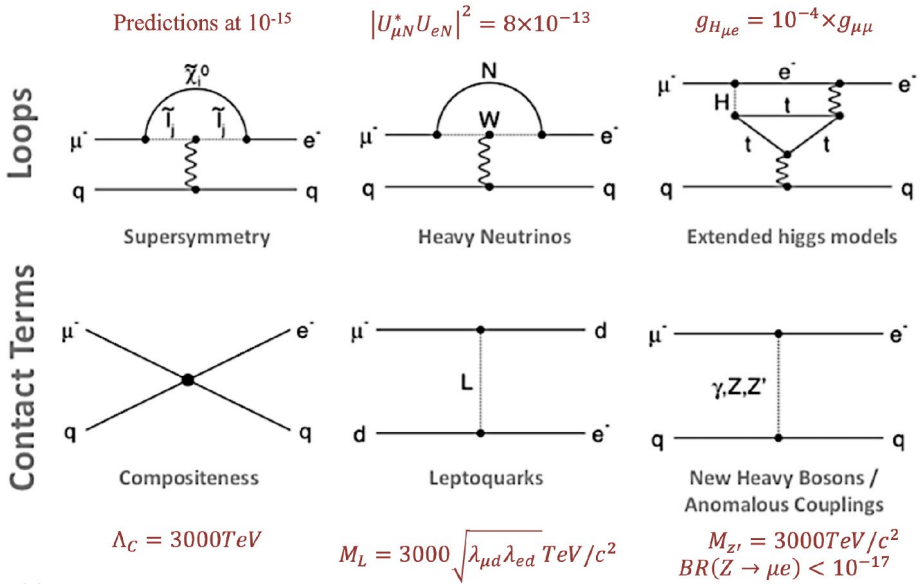
Beam energy: 1.0-2.35GeV, E_{cms} now up to ~4.95 GeV
Energy spread: 5.16×10^{-4}
Design luminosity: $1\times10^{33}/cm^2/s$ @ $\psi(3770)$
Achieved luminosity: $1.01\times10^{33}/cm^2/s$ (2016)
Crossing angle: 11mrad

MDC: $\sigma_P/P = 0.5\%$ @ 1 GeV , $\sigma_{r\phi}$ ~115μm
$\sigma_{dE/dX} = 5\%$
EMC: Energy: 2.5%@1GeV
TOF: Barrel: 68ps
Endcap: 100 → 60ps (update to MRPC)

Nucl. Instr. Meth. A614, 345(2010)

Charged Lepton Flavor Violation

- SM: $B(\mu \to e\gamma) \sim O(10^{-54})$
- Many physics models beyond the SM could allow CLFV processes to take place, such as supersymmetry, the two Higgs doublet model , and models including a fourth generation of quarks and leptons
- Activities in τ-e conversion, μ-e conversion.
  - MEG: $B(\mu \to \gamma e) < 4.2 \times 10^{-13}$
  - BaBar: $B(\tau \to \gamma e) < 3.3 \times 10^{-8}$
  - Future: Eg. COMET: single event sensitivity aim: 10^{-17}
- Many experiments searched for CLFV processes in the decays of
  - pseudoscalar mesons, vector mesons, gauge bosons, and the Higgs boson, e.g., pions, kaons, B mesons, bottomonium states, Z^0, and Higgs.
- Some predictions on CLFV in the charmonium states constrain $B(J/\psi \to e\mu)$ to the order of 10^{-13}, while $B(J/\psi \to e\tau / \mu\tau)$ to 10^{-9} :
  - model-independent methods
  - unparticle physics
  - minimal supersymmetric model with gauged baryon number and lepton number

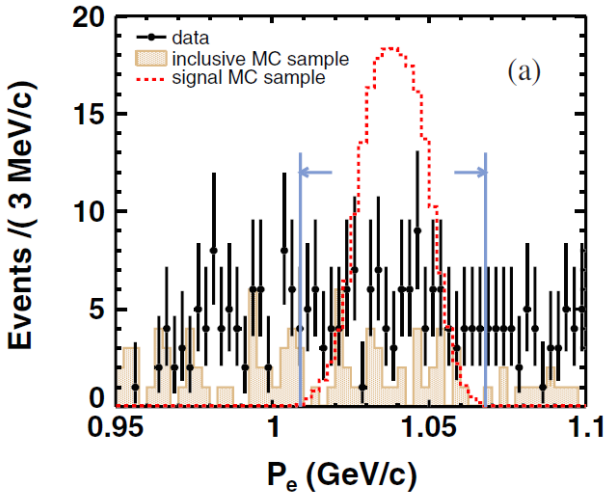


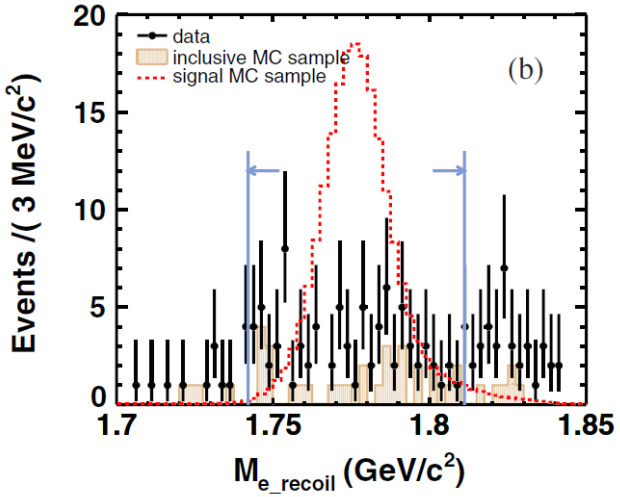
James Miller, 2006

Search for $J/\psi \to e^{\pm}\tau^{\mp}$

PRD103(2021)112007

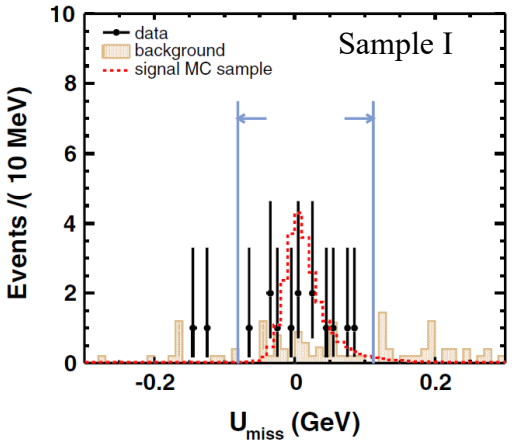
- Based on 10 billion J/ψ data set:
  1310.6M collected @2009+2012 (sample I),
  8774.01M collected @2017-2019(sample II).
- $J/\psi \to e\tau$, $\tau \to \pi\pi^0\nu$.
- Select one electron and one charged pion.
- At least two photon showers and one π^0.
- Two-body-decay:
- One undetected neutrino with
  missing energy $E_{\text{miss}} > 0.43 GeV$.
- Blind analysis to avoid possible bias.

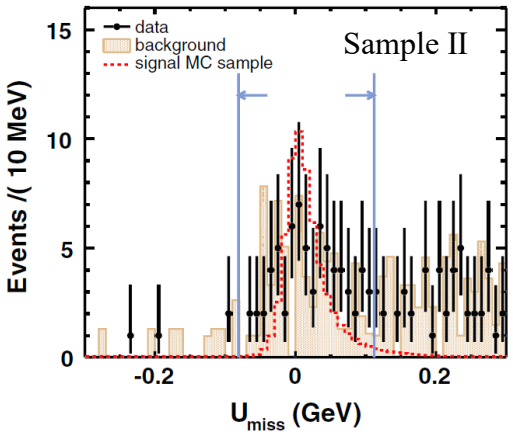




Search for $J/\psi \to e^{\pm}\tau^{\mp}$

PRD103(2021)112007



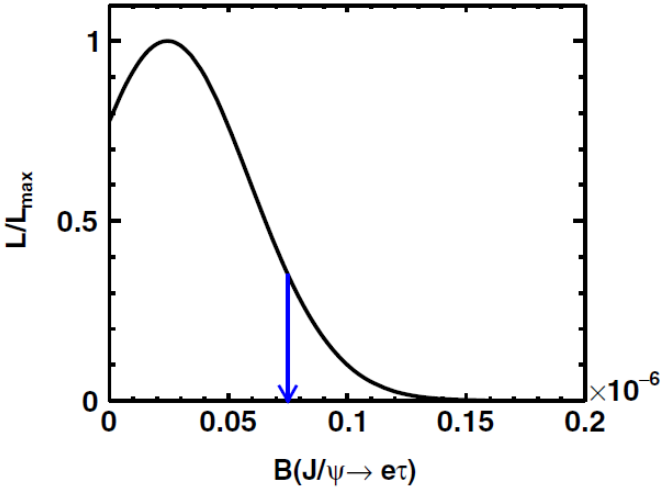


- $BR(J/\psi \to e\tau) < 7.5\times10^{-8}$ @ 90% C.L.
- This result improves the previous published limits by two orders of magnitude and comparable with the theoretical predictions.
- $BR(J/\psi \to e\mu) < 1.6\times10^{-7}$ @ 90% C.L. with 225M J/ψ events. PRD87(2013)112007

$$U_{\rm miss} = E_{\rm miss} - c|\vec{P}_{\rm miss}|$$

Results	Sample I	Sample II
$N_{\rm obs}$	13	69
$N_{\rm bkg}^{\rm exp}$	6.9	63.6
$\sigma_{\rm bkg}^{\rm exp}$	1.9	13.2
$\epsilon_{\rm eff}^{\rm mc}$	20.24%	19.37%
$\sigma_{\rm eff}^{\rm mc}$	0.79%	0.79%
BF (90% C.L.)	7.5×10^{-8}	

Sources	Sample I	Sample II
Number of J/ψ	0.5%	0.4%
Quoted BF*	0.4%	0.4%
MC model	0.6%	...
Pion PID*	1.0%	1.0%
Pion tracking*	1.0%	1.0%
Electron PID	0.4%	0.9%
Electron tracking*	0.1%	0.1%
Photon detection*	1.0%	1.0%
π^0 reconstruction*	1.0%	1.0%
P_e and M_{e_recoil} requirements	3.0%	3.3%
$E_{\rm miss}$ requirement	1.0%	0.8%
Total uncertainty	3.9%	4.1%



Baryon number violation: Why BNV?

A.D.Sakharov,Pisma Zh.Eksp.Teor.Fiz.5,32 (1967)

- Asymmetry of matter and anti-matter: big problem in the universe evolution.
- Sakharov three conditions of matter asymmetry after big bang:
  - Baryon Number violation (BNV)
  - Charge (C) and Charge-Parity (CP) violation
  - Thermal nonequilibrium.
- C and CP violation: precisely tested by theory and experiments in decades, however not enough to address the asymmetry of matter and anti-matter in the universe.
- BNV: even a small amount would have major consequences on the universe and its evolution, as many theories have suggested.
- Many theoretical models where BNV is allowed. For example, in the Grand Unified Theory, proton can decay into several modes through leptoquarks, such as $p \rightarrow e^{+}\pi^{0}$. Such mechanism simultaneously breaks BN and LN while conserving $\Delta(B-L)$.
  - Leptoquarks are hypothetical particles carrying both baryon number (B) and lepton number (L), expected to exist in various extensions of the SM and GUT.

$D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+, D^+ \to \Lambda(\Sigma^0)e^+$

PRD101(2020) 031102(R)

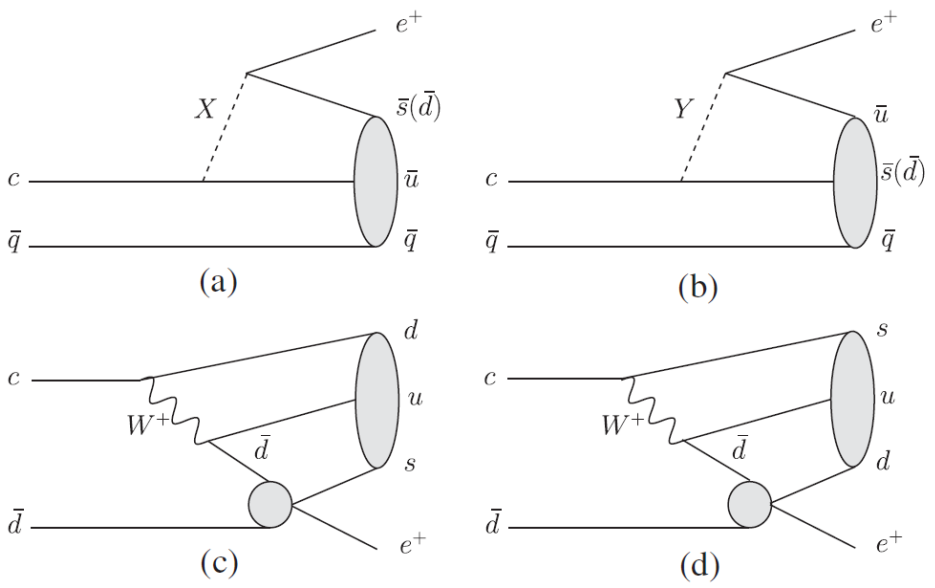


FIG. 1. Feynman diagrams for the BNV decays of D mesons with $\Delta(B-L)$ equal to 0 [(a) and (b)] and 2 [(c) and (d)].

Processes	$B_{90\%\ C.L.}$	Experiment & reference
$D^0 \to pe^-$	1×10^{-5}	CLEO-c [PRD79(2009)097101]
$D^0 \to \bar{p}e^+$	1.1×10^{-5}	
$B^0 \to \Lambda_c^+\mu^-(e^-)$	$1.8\ (5.2) \times 10^{-6}$	BABAR [PRD83(2011)091101(R)]
$B^- \to \Lambda\mu^-(e^-)$	$6.2\ (8.1) \times 10^{-8}$	
$B^- \to \bar{\Lambda}\mu^-(e^-)$	$6.1\ (3.2) \times 10^{-8}$	

- Dimension six operators: Δ(B-L)=0
- Dimension seven operators: Δ(B-L)=2

$D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+, D^+ \to \Lambda(\Sigma^0)e^+$

PRD101(2020) 031102(R)

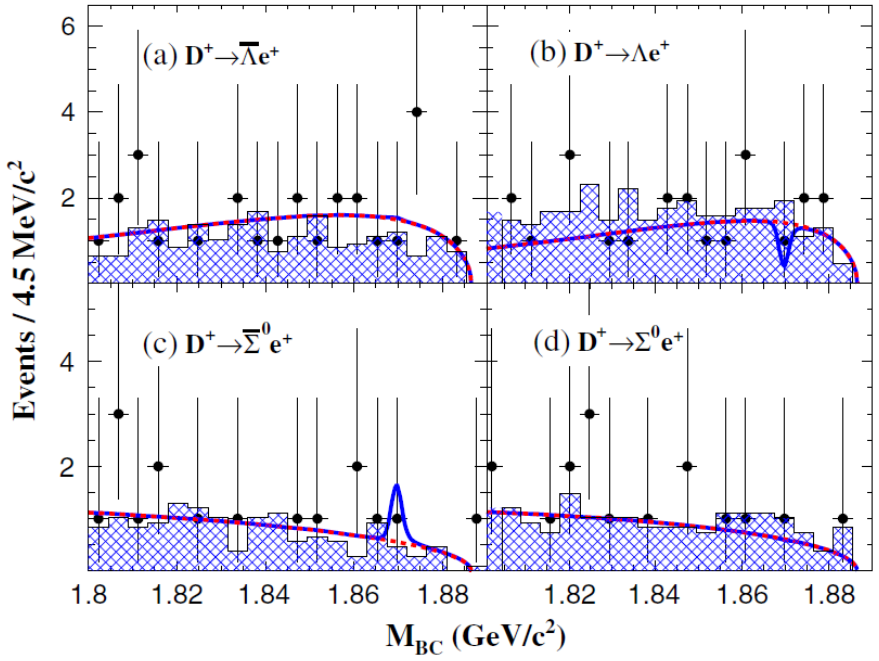
- 2.91fb^{-1} $\psi(3770)$ data
- ~8.3M D^+D^- pair
- Selection and signal extraction:

$$\Delta E = E_D - E_{\text{beam}}$$

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - p_D^2}$$

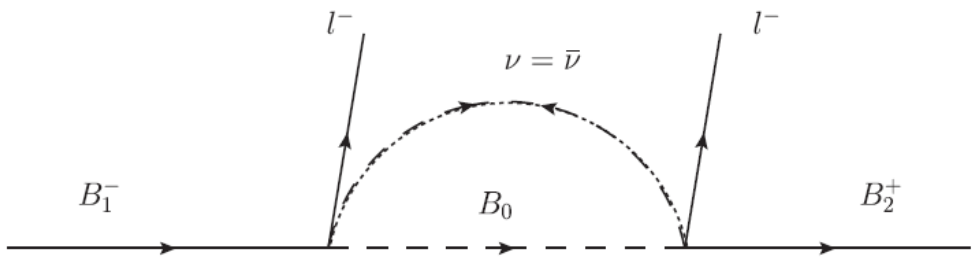
- UL estimated via scanning likelihood ratio

Source	$\bar{\Lambda}e^+$	Λe^+	$\bar{\Sigma}^0 e^+$	$\Sigma^0 e^+$
$N^{\text{tot}}_{D^+D^-}$	0.9	0.9	0.9	0.9
ΔE cut	0.6	0.6	0.9	0.9
$\Lambda(\bar{\Lambda})$ reconstruction	1.5	1.5	1.5	1.5
$\Sigma^0(\bar{\Sigma}^0)$ mass window			<0.1	<0.1
e^+ tracking	0.3	0.3	0.3	0.3
e^+ PID	1.0	1.0	1.0	1.0
γ reconstruction			1.0	1.0
MC statistics	0.3	0.4	0.4	0.4
No extra (anti-)proton	0.3	0.3	0.3	0.3
Photon conversion veto	0.5	0.5	0.5	0.5
Quoted BF(s)	0.8	0.8	0.9	0.9
Total	2.4	2.4	2.7	2.7



Mode	$N^{\text{UL}}_{\text{sig}}$	ε (%)	$\mathcal{B}^{\text{UL}}$
Λe^+	5.6	31.11 ± 0.14	1.1×10^{-6}
$\bar{\Lambda}e^+$	3.4	31.18 ± 0.10	6.5×10^{-7}
$\Sigma^0 e^+$	4.5	16.31 ± 0.07	1.7×10^{-6}
$\bar{\Sigma}^0 e^+$	3.5	16.40 ± 0.07	1.3×10^{-6}

$\Sigma^- \to pe^-e^-, \Sigma^- \to \Sigma^+ X$



$B_1^- \to B_2^+ l^- l^- (l = e, \mu)$

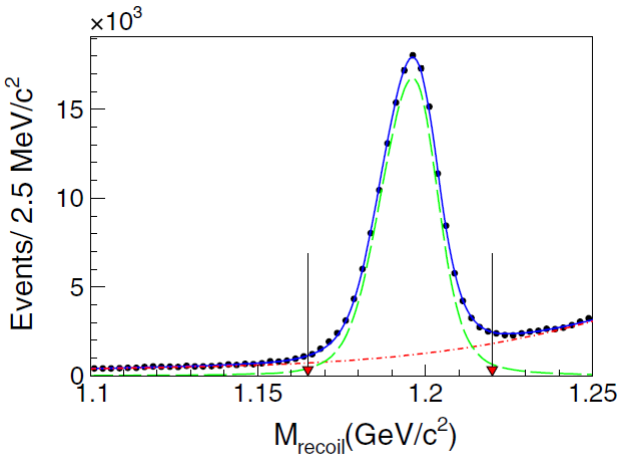
loop of virtual baryon and majorana neutrino

- 1.31 billion J/ψ events
- $J/\psi \to \bar{\Sigma}(1385)^+ \ \Sigma^-$, $\bar{\Sigma}(1385)^+ \to \bar{\Lambda}\pi^+$
- Double tag techinique:

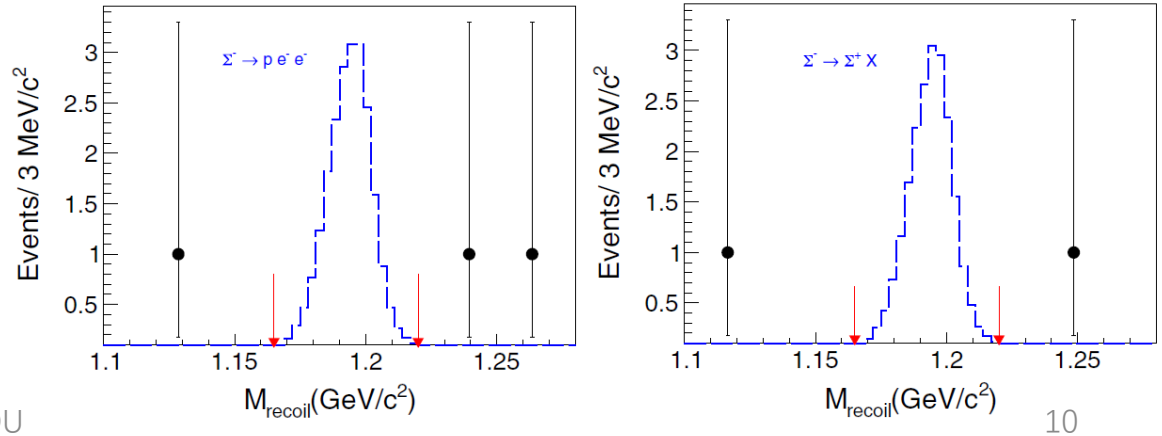
$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}^{\rm obs}}{N_{\rm ST}^{\rm obs}\epsilon_{\rm DT}/\epsilon_{\rm ST}}$$

- X particles not detected
- Use MC of $\Sigma^- \to \Sigma^+ e^- e^-$ to estimate efficiency
- $B(\Sigma^- \to pe^-e^-) < 6.7 \times 10^{-5}$
- $B(\Sigma^- \to \Sigma^+ X) < 1.2 \times 10^{-4}$

PRD103(2021)052011

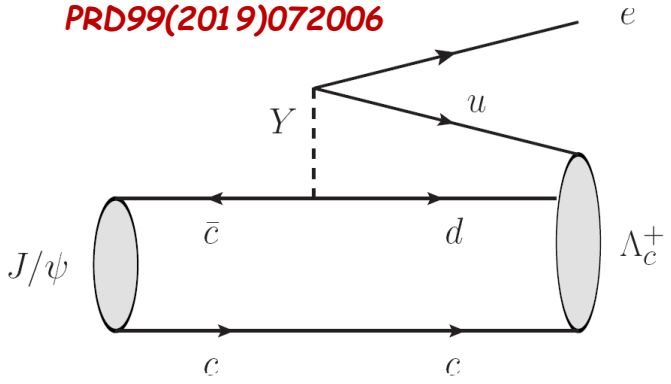


$N_{\rm ST} = 147743 \pm 563$



$J/\psi \to \Lambda_c^+ e^-$

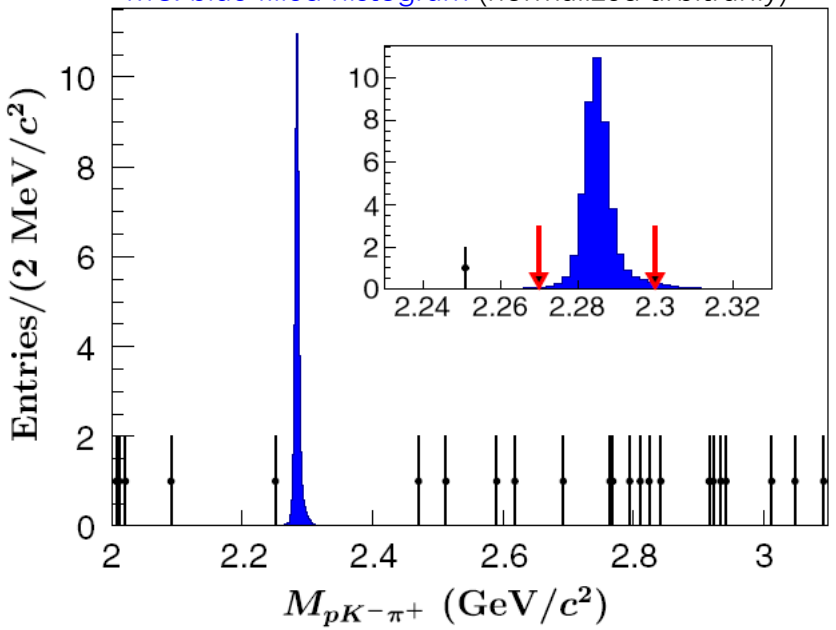
PRD99(2019)072006



- Virtual leptoquarks mediate the decay.
- First quarkonium BNV search.

- 1.3 billion J/ψ
- First search of $J/\psi \to \Lambda_c^+ e^- \to (pK^-\pi^+)e^-$
- Check $M_{pK\pi}$ distribution, no signal events in the signal region
- Total systematic uncertainty (~7%)
- Upper limit is obtained by utilizing a frequentist method with unbounded profile likelihood treatment of systematic uncertainties.
- $BR(J/\psi \to \Lambda_c^+ e^- + \text{c.c}) < 6.9\times10^{-8}$ @ 90% C.L.

Data: dot with error bar
MC: blue filled histogram (normalized arbitrarily)



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$B^0 \to \Lambda_c^+\mu^-(e^-)$	$1.8\ (5.2)\times10^{-6}$	BABAR [PRD83(2011)091101(R)]
$B^- \to \Lambda\mu^-(e^-)$	$6.2\ (8.1)\times10^{-8}$	
$B^- \to \bar{\Lambda}\mu^-(e^-)$	$6.1\ (3.2)\times10^{-8}$	
$\Lambda \to K^+e^-(\mu^-)$	$2\ (3)\times10^{-6}$	CLAS [PRD92(2015)072002]
$\Lambda \to K^-e^+(\mu^+)$	$2\ (3)\times10^{-6}$	
$\Lambda \to \pi^+e^-(\mu^-)$	$6\ (6)\times10^{-7}$	
$\Lambda \to \pi^-e^+(\mu^+)$	$4\ (6)\times10^{-7}$	
$\Lambda \to \bar{p}\pi^+$	9×10^{-7}	
$\Lambda \to K_S^0\nu$	2×10^{-5}	
$D^+ \to \Lambda(\Sigma^0)e^+$	$1.1\ (1.7)\times10^{-6}$	BESIII [PRD101(2020)031102(R)]
$D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+$	$6.5\ (13)\times10^{-7}$	
$\Sigma^- \to pe^-e^-$	6.7×10^{-5}	BESIII PRD103(2021)052011
$\Sigma^- \to \Sigma^+X$	1.2×10^{-4}	
$J/\psi \to \Lambda_c^+e^-$	6.9×10^{-8}	BESIII PRD99(2019)072006

- Sensitivity based on 10^{10} J/ψ and 3×10^9 $\psi(2S)$.

$M^\pm = \pi^\pm$ or $K^\pm$

Frontiers of Physics 12, 121301 (2017)

Decay mode	Current data $\mathcal{B}$ ($\times10^{-6}$) (90% C.L.)	Sensitivity $\mathcal{B}$ ($\times10^{-6}$)	ΔL	ΔB
$\Lambda \to M^+l^-$	< 0.4–3.0 [68]	< 0.1	$+1$	-1
$\Lambda \to M^-l^+$	< 0.4–3.0 [68]	< 0.1	-1	-1
$\Lambda \to K_S\nu$	< 20 [68]	< 0.6	$+1$	-1
$\Sigma^+ \to K_Sl^+$	CLAS [PRD92(2015)072002]	< 0.2	-1	-1
$\Sigma^- \to K_Sl^-$	–	< 1.0	$+1$	-1
$\Xi^- \to K_Sl^-$	–	< 0.2	$+1$	-1
$\Xi^0 \to M^+l^-$	–	< 0.1	$+1$	-1
$\Xi^0 \to M^-l^+$	–	< 0.1	-1	-1
$\Xi^0 \to K_S\nu$	–	< 2.0	$+1$	-1

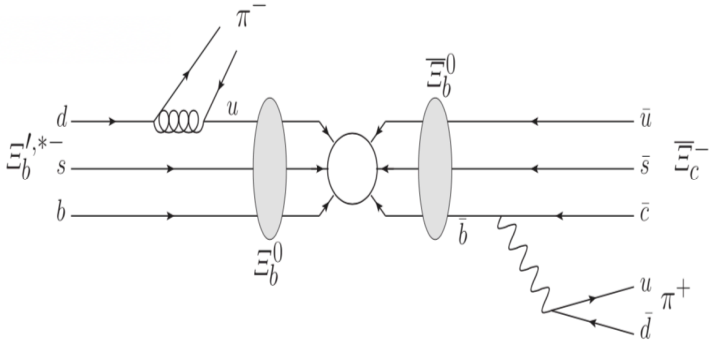
$\Lambda - \bar{\Lambda}$ oscillation

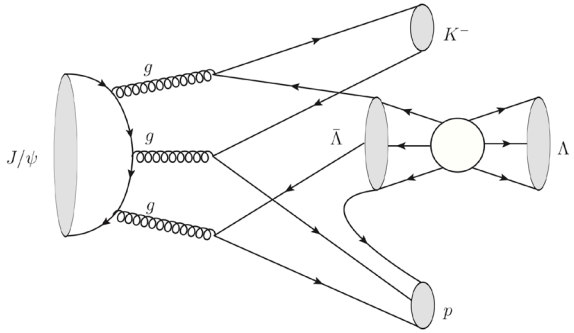
- Neutrino oscillations made $N - \bar{N}$ oscillation to be quite plausible theoretically *[PRL96, 061801(2006)]*
- Seesaw mechanism indicates the existence of $\Delta(B - L) = 2$ interactions.
- Many experiments searching $n - \bar{n}$ oscillation with upper limit results, while few results from other 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 presented a constraint on $\Xi_b^0 - \bar{\Xi}_b^0$ oscillation.

- $\Lambda - \bar{\Lambda}$ has a second generation quark, which can give further information compared 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)]*.





$\Lambda - \bar{\Lambda}$ oscillation via $J/\psi \to pK^-\bar{\Lambda}$

- Oscillation event (charge conjugation implied)

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

- Time integrated oscillation rate

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

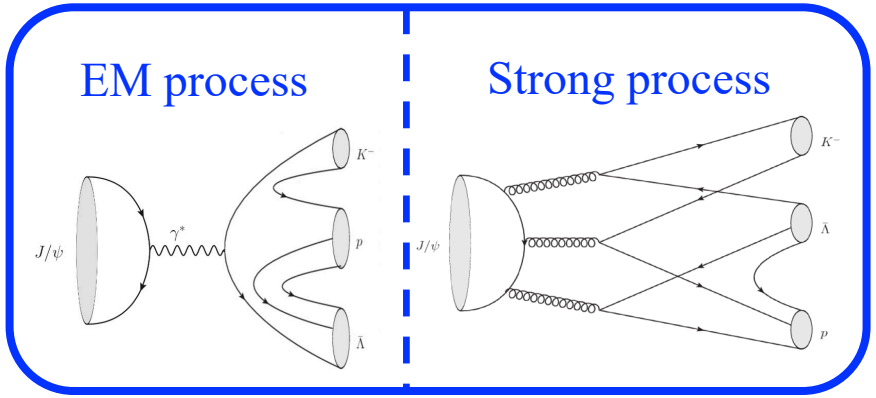
- Most of the systematic uncertainties cancelled.

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

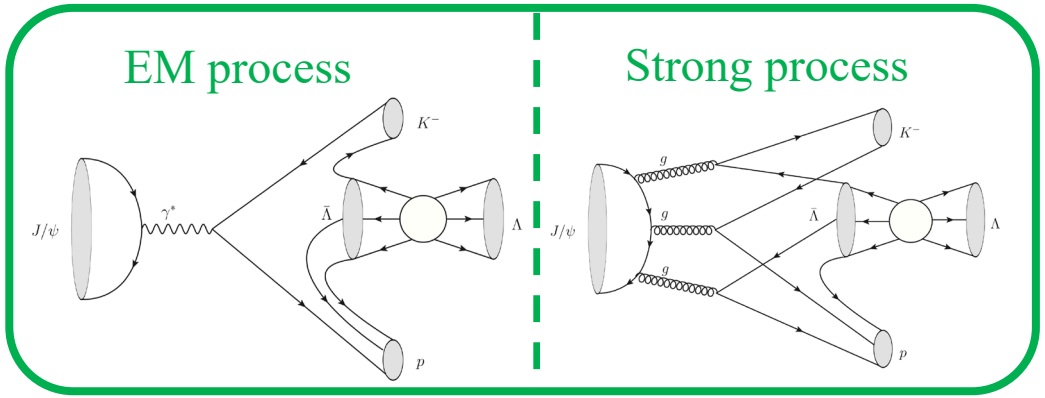
$$\mathcal{P}(\Lambda, t) = \sin^2(\delta \mathrm{m}_{\Lambda\bar{\Lambda}} \cdot \mathrm{t})$$

- oscillation parameter can be deduced as

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



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



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

$\Lambda - \bar{\Lambda}$ oscillation via $J/\psi \to pK^-\bar{\Lambda}$

- Result based on 1.3 billion J/ψ events
- $J/\psi \to pK^-\bar{\Lambda} \xrightarrow{oscillate} pK^-\Lambda$
- Almost background free.

- Upper limit based on TROLKE (90% CL)

BESIII Preliminary

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

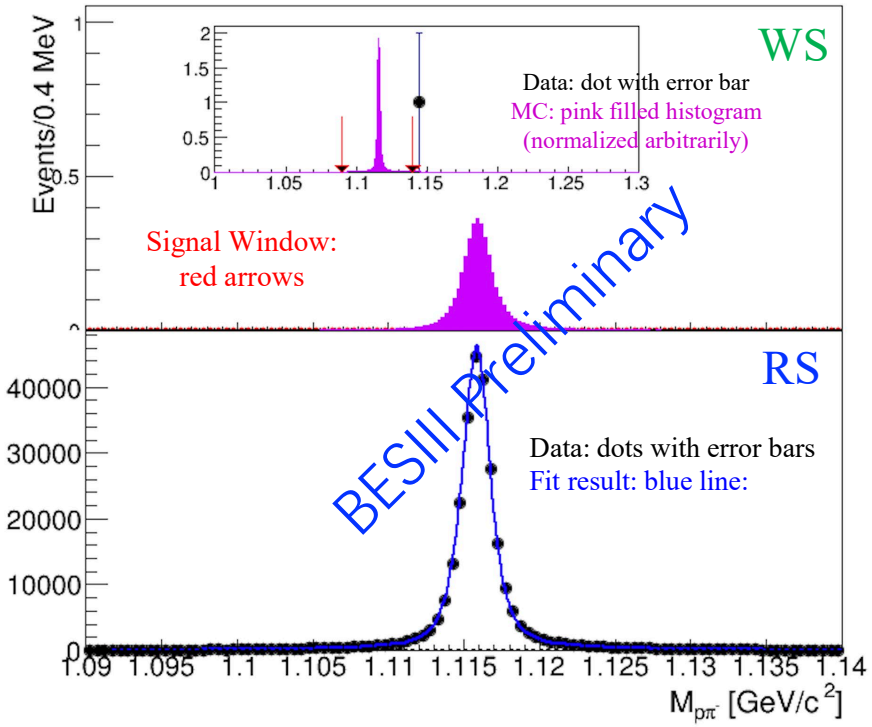
- Oscillation parameter (90% CL)

BESIII Preliminary

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

WS

MC: pink filled histogram (normalized arbitrarily)



RS

Signal shape: simulated MC shape ⊗ a Gaussian function.

Background shape: inclusive MC sample after excluding RS events.

Summary

- Many activities of searching LNV/CLFV or BNV processes in BESIII
- $BR(J/\psi \to e\tau) < 7.5\times10^{-8}$ @ 90% C.L. (10 billion)
- $BR(J/\psi \to \Lambda_c^+ e^- + \text{c.c}) < 6.9\times10^{-8}$ @ 90% C.L. (1.31 billion)
- $BR(D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+), BR(D^+ \to \Lambda(\Sigma^0)e^+) \sim O(10^{-6}, 10^{-7})$ (2.91fb^{-1})
- $BR(\Sigma^- \to pe^-e^-) < 6.7\times10^{-5}$, $BR(\Sigma^- \to \Sigma^+ X) < 1.2\times10^{-4}$ (1.31 billion)
- $\Lambda - \bar{\Lambda}$ oscillation via $J/\psi \to pK^-\bar{\Lambda}$, $\delta m_{\Lambda\bar{\Lambda}} < 3.8\times10^{-15}$ MeV @ 90% C.L. (1.31 billion) BESIII Preliminary
- More results can be achieved or improved with larger data set in the near future.

Thank you!

$\Lambda - \bar{\Lambda}$ oscillation

- 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

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