河南師範大學 HENAN NORMAL UNIVERSITY

BESIII

Baryon/Lepton number violation searches at BESIII

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(On behalf of BESIII Collaboration)

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The 19 th International Conference on Hadron Spectroscopy and Structure (HADRON 2021)

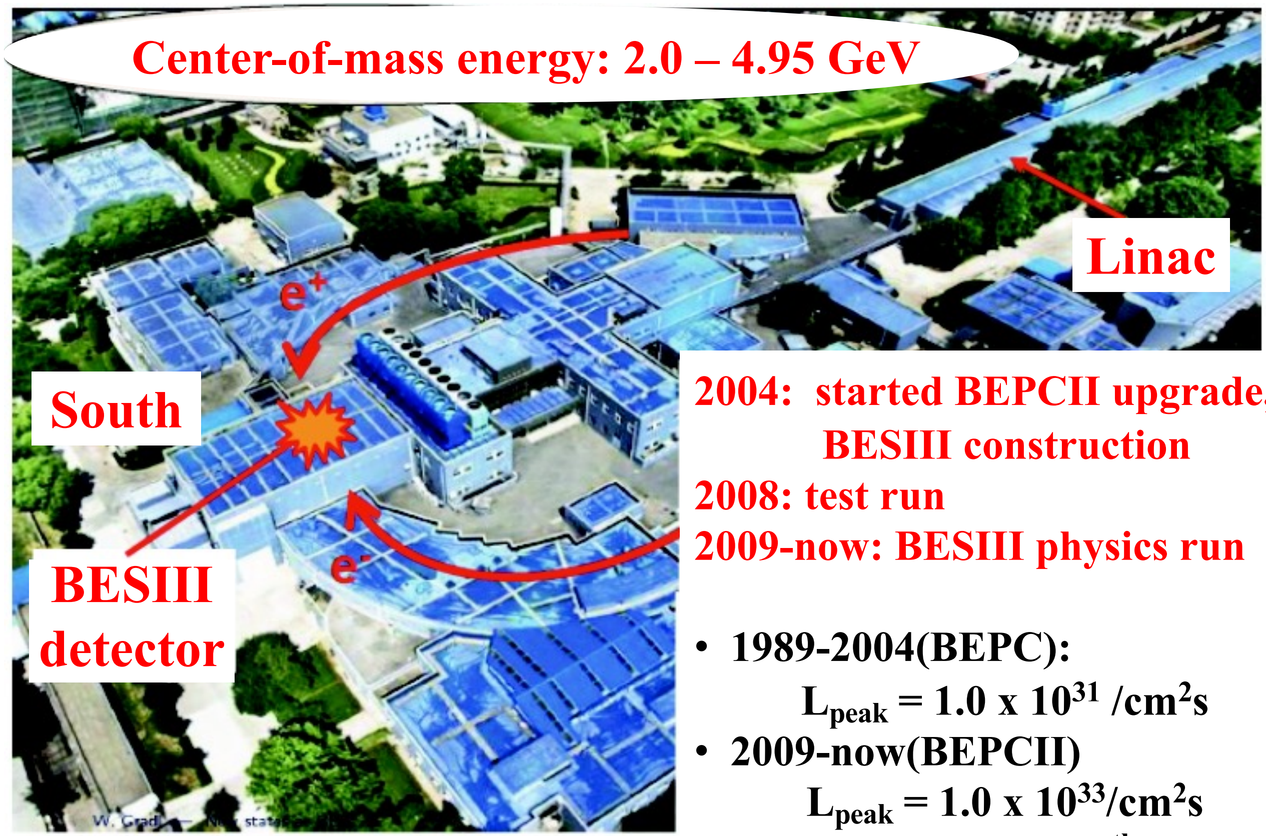
Jul. 26th –31st, 2021, Mexico.

Outline

- Introduction
- D mesons
  - $D^+ \to \bar{\Lambda}(\bar{\Sigma}^0)e^+; \Lambda(\Sigma^0)e^+$ PRD 101 (2020) 031102(R)
  - $D \to K\pi e^+e^+$ PRD 99 (2019) 112002
- J/ψ meson
  - $J/\psi \to \Lambda_c^+ e^-$ PRD 99 (2019) 072006
  - $J/\psi \to pK^-\bar{\Lambda} \to pK^-\Lambda$ BESIII Preliminary
- Σ^- baryon
  - $\Sigma^- \to pe^-e^-, \Sigma^- \to \Sigma^+X$ PRD 103 (2021) 052011
- Summary

Beijing Electron Positron Collider (BEPCII) in China

A double-ring collider with high luminosity



2004: started BEPCII upgrade, BESIII construction
2008: test run
2009-now: BESIII physics run

- 1989-2004(BEPC): $L_{peak} = 1.0 \times 10^{31}$ /cm^{2}s
- 2009-now(BEPCII) $L_{peak} = 1.0 \times 10^{33}$/cm^{2}s (Achieved on Apr. 5th, 2016)

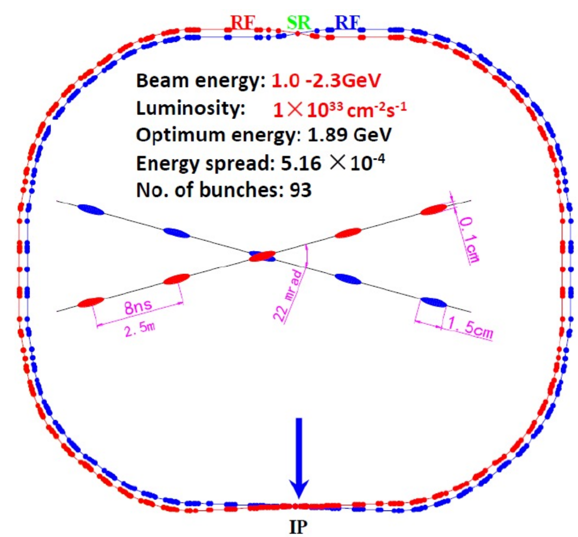
Tuesday, 27 July 2021

07:00 - 08:45 ★ Plenary **Please see Nils's talk**

07:00 **Recent results from BESIII** *35'*

The BESIII experiment has accumulated la $\psi(3770)$ as well as at various other ce things, these datasets allow us to study lig mesons, and both well known and newly d perspectives will be discussed.

Speaker: Nils Huesken (Indiana Uni



BESIII Detector

Please see Nils's talk

From inner to outside[1]:

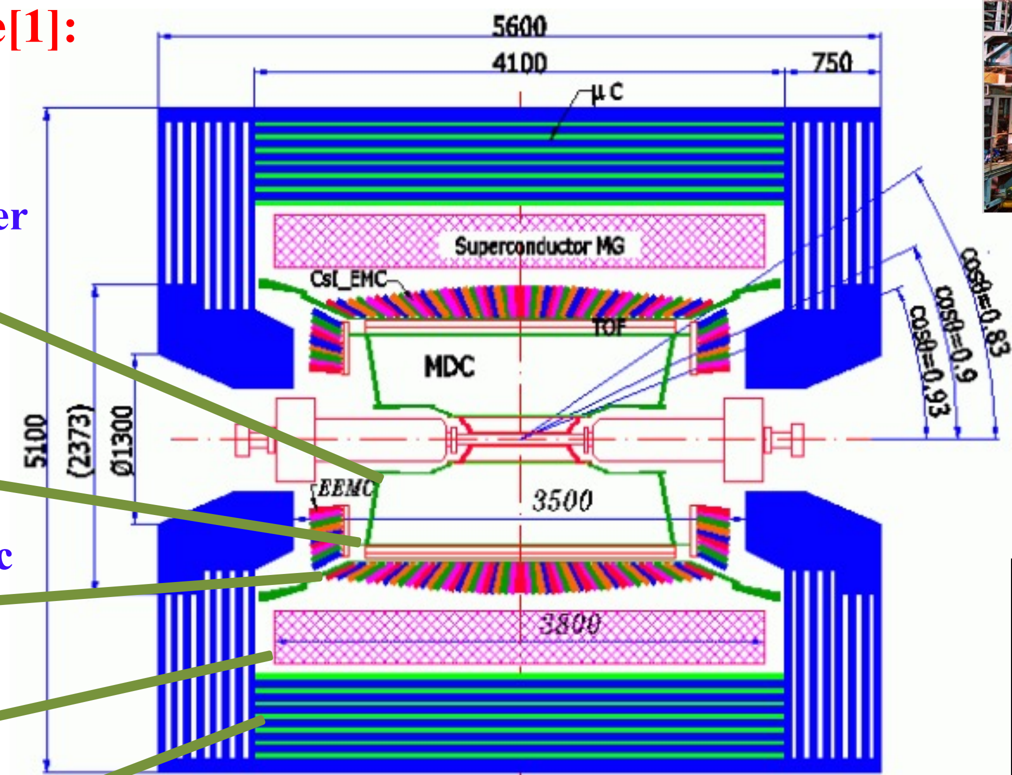
Helium-based multilayer drift chamber (MDC):

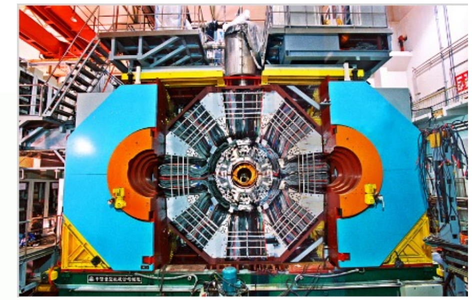
Plastic scintillator time-of-flight (TOF):

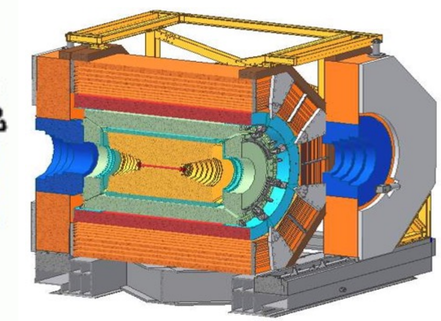
CsI (Tl) electromagnetic calorimeter (EMC):

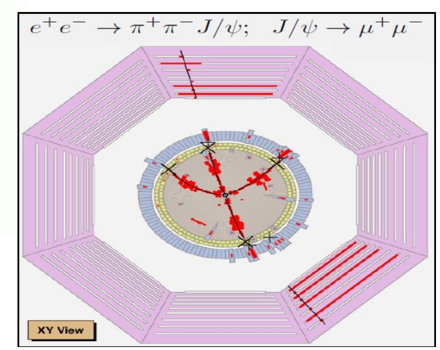
Superconducting solenoidal magnet:

Muon Chamber (MUC):









[1] M. Ablikim *et al*. (BESIII Collaboration), Nucl. Instr. Meth. A 614, 345 (2010).

Data sets

$\sqrt{s}$(GeV)	The number of total events	Decay chain of interest
3.097	10^9 J/ψ	$e^+e^- \to J/\psi$
3.773	Integrated luminosity $2.93\ \text{fb}^{-1}$	$e^+e^- \to \psi(3770) \to D^0\bar{D}^0$ $e^+e^- \to \psi(3770) \to D^+D^-$

Baryon Number Violation

- **Fact: matter anti-matter asymmetry in the Universe.**

- **Sakharov three conditions [1]:**

  - **Baryon number violation (BNV)**
  - **C&CP violation**
  - **Departure from thermal equilibrium**

- **In the standard model (SM), baryon number is conserved as a consequence of the $SU(2)\times SU(1)$ and $SU(3)$ gauge symmetries.**

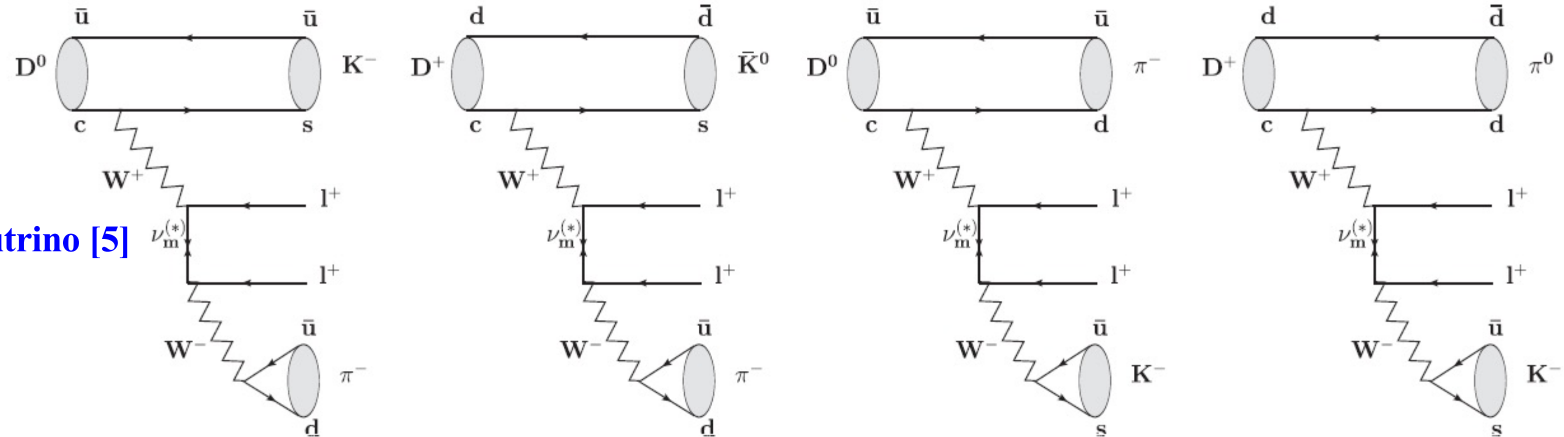
- **So the search for BNV processes can probe new physics beyond SM, and can also shed light on the evolution of the Universe.**

[1] A. D. Sakharov, JETP Lett. 5, 24 (1967).

Lepton Number Violation

- **Fact**: neutrino oscillation [1-3] → neutrinos have a tiny mass.
- **Nature**: Dirac or Majorana neutrino?
  - Lepton number violation (LNV) by two units ($\Delta L = -2$)
  - $0\nu\beta\beta$ decay, $(A, Z) \rightarrow (A, Z+2) + 2e^-$, most promising;
  - Three body or four body decays of K, B, D, τ [4].

Majorana neutrino [5]



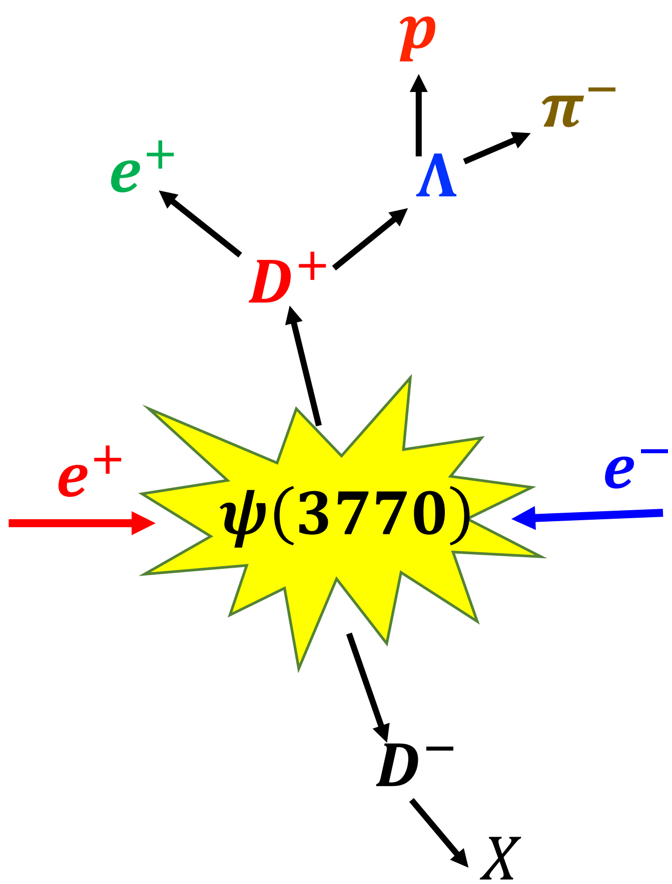
(a) $D^0 \to K^-\pi^-l^+l^+$ (CF) (b) $D^+ \to \bar{K}^0\pi^-l^+l^+$ (CF) (c) $D^0 \to K^-\pi^-l^+l^+$ (DCS) (d) $D^+ \to K^-\pi^0l^+l^+$ (DCS)

[1] Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 81, 1562 (1998).
[2] Q. R. Ahmad et al. (SNO Collaboration), Phys. Rev. Lett. 89, 011301 (2002).
[3] K. Eguchi et al. (KsmLAND Collaboration), Phys. Rev. Lett. 90, 021802 (2003).
[4] A. Atre, T. Han, S. Pascoli, and B. Zhang, J. High Energy Phys. 05 (2009) 030.
[5] H. R. Dong, F. Feng and H. B. Li, Chin, Phys. C 39 013101 (2015);
M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. D 99, 112002 (2019).

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

PRD 101 (2020) 031102(R)

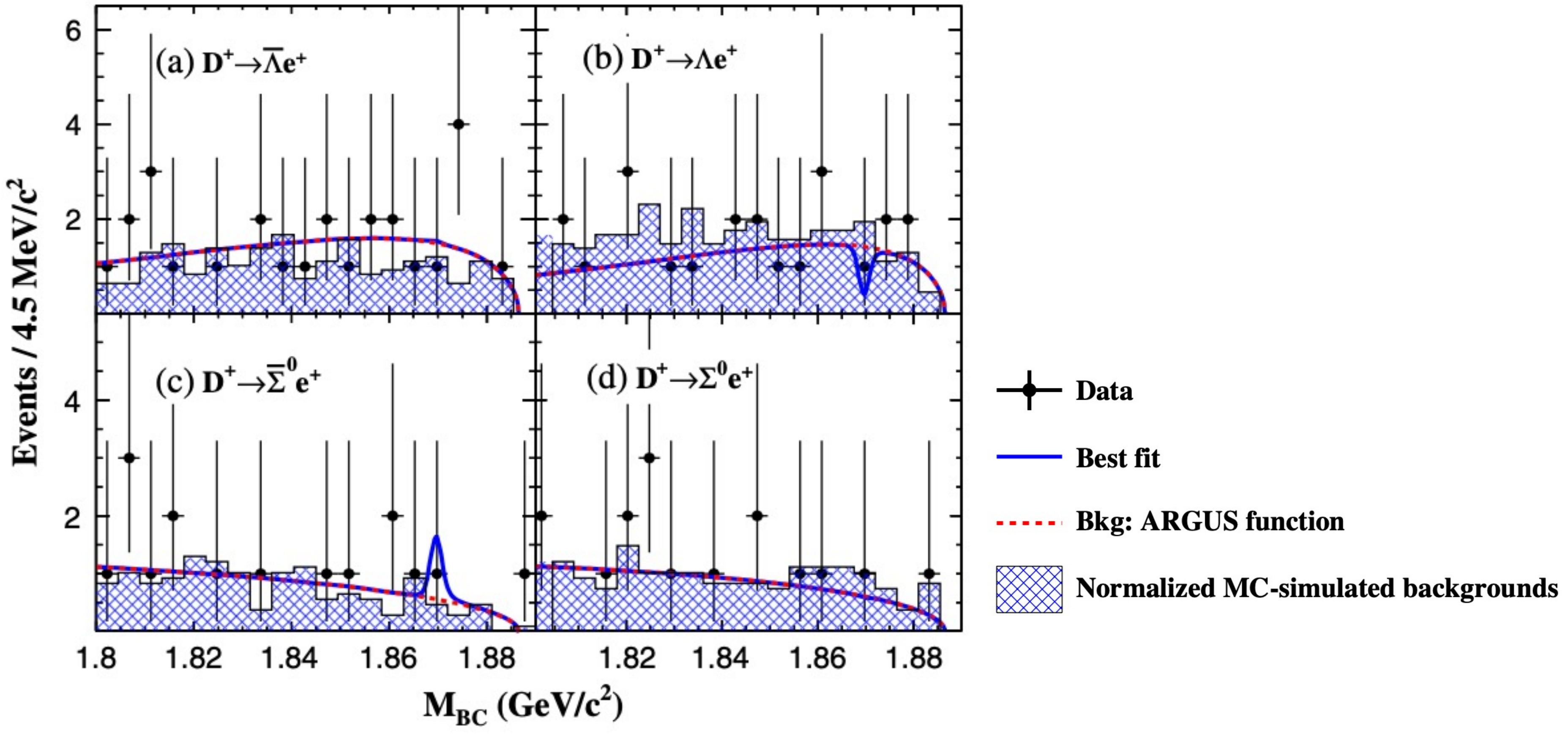
- The predicted branching fraction (BF) of $D^+ \to \bar{\Lambda}\, l^+\ (l = e, \mu)$ * is no more than 10^{-29} with a higher generation supersymmetry (SUSY) model [1].
- $N^{\rm tot}_{D^+D^-} = (8,296 \pm 31 \pm 64\,)\times 10^3$[2]
- A blind analysis technique
- $\Lambda \to p\,\pi^-, \Sigma^0 \to \gamma\Lambda$
- Single tag (ST)
  - ✓ $\Delta E = E_{D^+} - E_{\rm beam}$: select the best D^+ candidate with the smallest $|\Delta E|$ for a specific signal mode.
  - ✓ $M_{\rm BC} = \sqrt{E^2_{\rm beam} - p^2_{D^+}}$



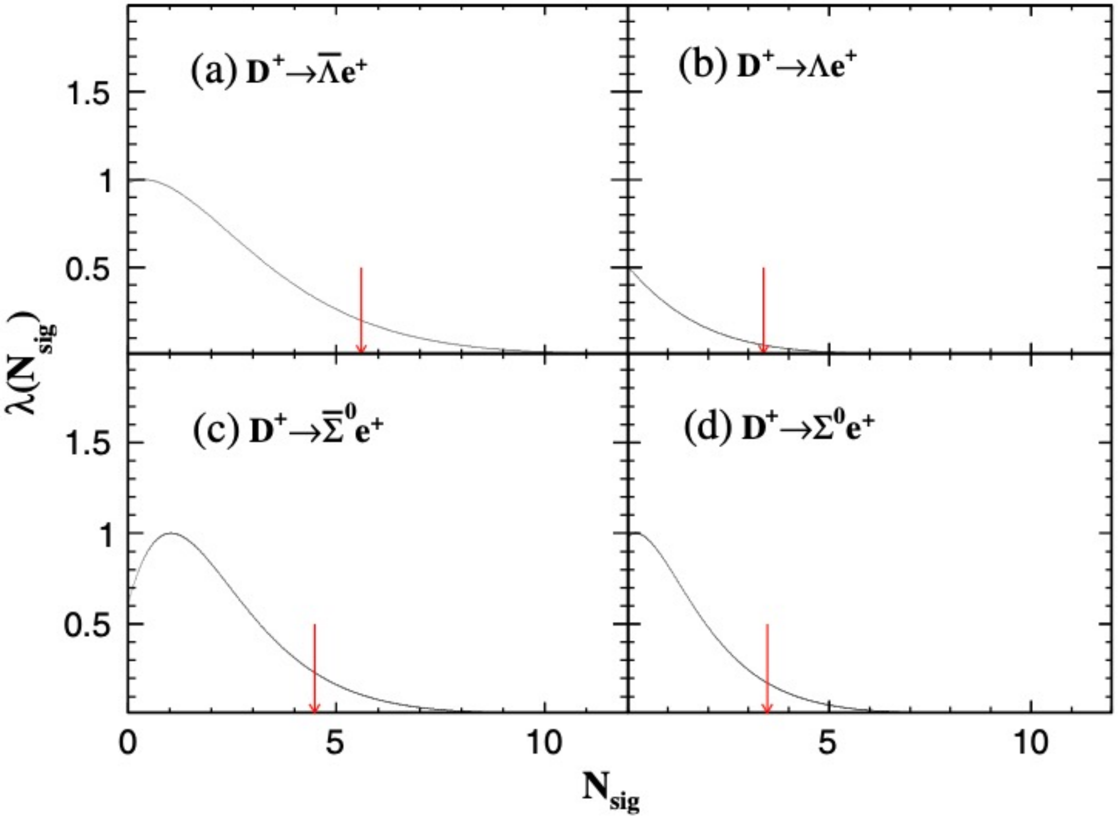
* Throughout this report, charge-conjugated channels are also implied unless explicitly stated.

[1] W. S. Hou, M. Nagashima, and A. Soddu, Phys. Rev. D 72, 095001 (2005).
[2] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C 42, 083001 (2018).

- **A maximum likelihood fit**
- **No significant signals are observed with the current statistics**



- **Set the upper limits (ULs) on signal events ($N_{\rm sig}^{\rm UL}$) at 90% confidence level (CL)**
- **Scan the normalized likelihood value $[\lambda(N_{\rm sig})]$ with the given number of signal events ($N_{\rm sig}$) in the $M_{\rm BC}$ fit.**
- **$\lambda(N_{\rm sig})$ is convoluted with a Gaussian function with corresponding width to incorporate the systematic uncertainties.**



$$\frac{\int_0^{N_{\rm sig}^{\rm UL}} N_{\rm sample}\, dN_{\rm sig}}{\int_0^{\infty} N_{\rm sample}\, dN_{\rm sig}} = 90\%$$

$N_{\rm sample}\, dN_{\rm sig}$: the number of samples with the signal events between $N_{\rm sig}$ and $N_{\rm sig} + dN_{\rm sig}$.

- **The ULs on the branching fraction (BF) are set at the level of 10^{-6} @ 90% CL, which are far above the prediction of the higher generation model [1].**

$$B^{\text{UL}} = \frac{N_{\text{sig}}^{\text{UL}}}{2 \cdot N_{D^+D^-}^{tot} \cdot \varepsilon \cdot B_{\Lambda,\Sigma^0}}$$

Mode	$N_{\text{sig}}^{\text{UL}}$	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}

[1] W. S. Hou, M. Nagashima, and A. Soddu, Phys. Rev. D 72, 095001 (2005).

- **Single tag**

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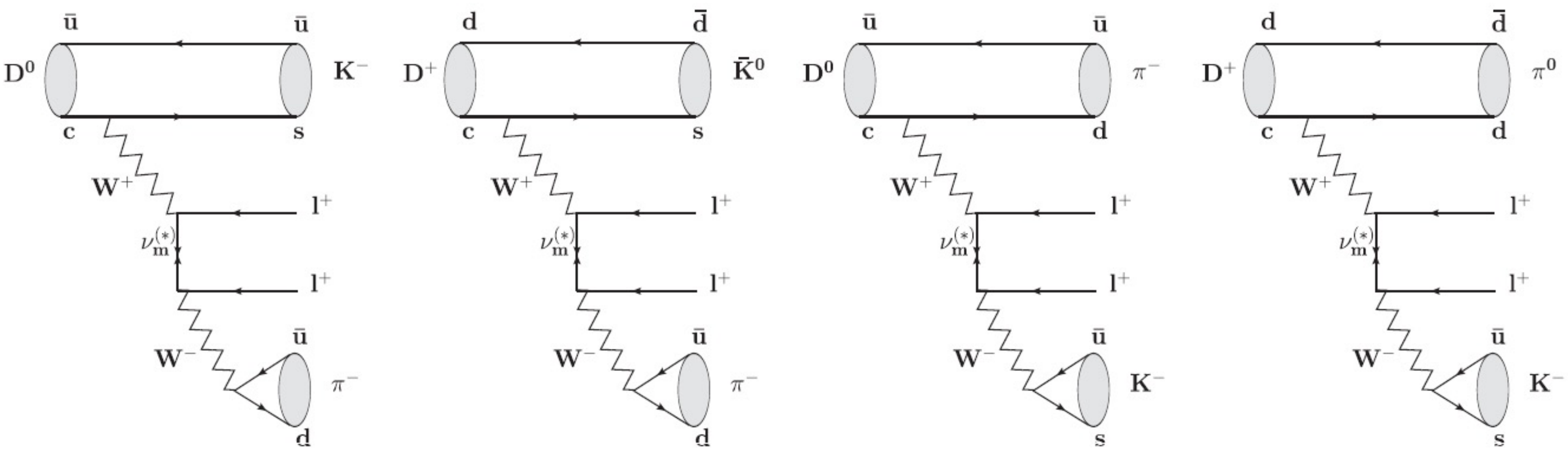
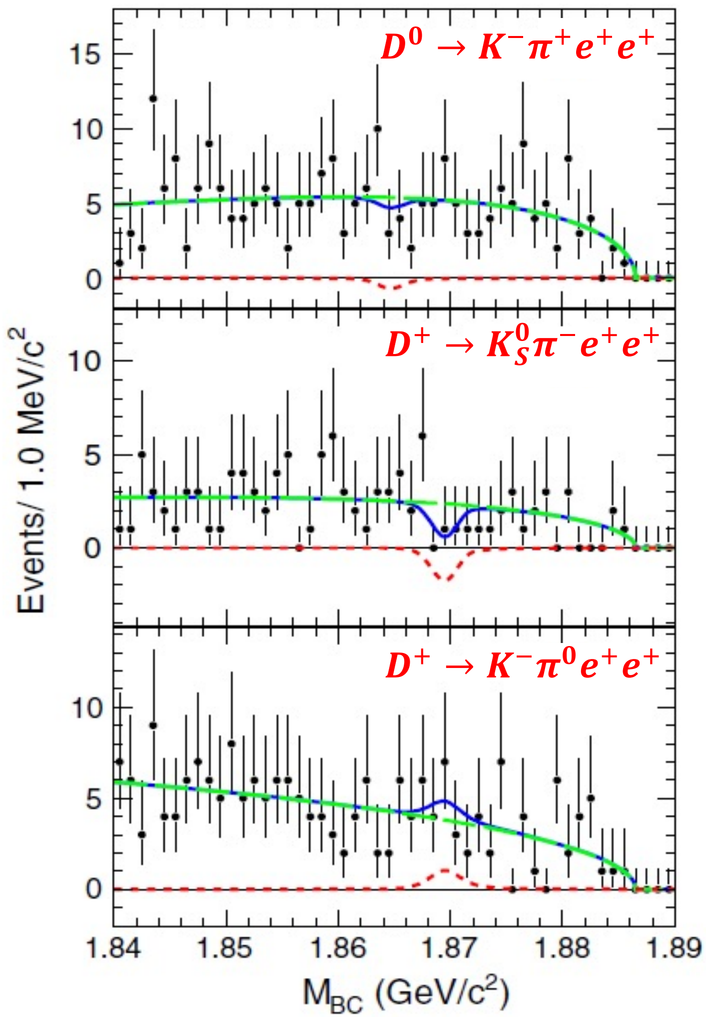
- $N^{tot}_{D^0\bar{D}^0} = (10,597 \pm 28 \pm 98\ )\times 10^3$[1]
- **Decay diagrams**

$D^0 \to K^-\pi^+ e^+ e^+$ $D^+ \to K^0_S \pi^- e^+ e^+$ $D^0 \to K^-\pi^+ e^+ e^+$ $D^+ \to K^-\pi^0 e^+ e^+$



[1] M. Ablikim *et al*. (BESIII Collaboration), Chin. Phys. C 42, 083001 (2018).

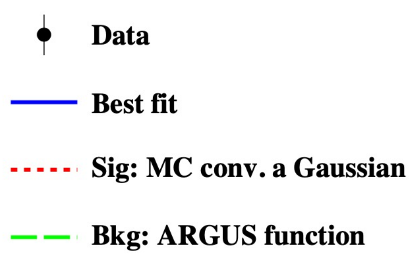
- Unbinned maximum likelihood
- No signals observed



- **Upper limit**: scan the likelihood value*

Channel	$\epsilon(\%)$	$N_{\rm sig}^{\rm UL}$	$\mathcal{B}_{\rm sig}^{\rm UL}(\times 10^{-6})$
$D^0 \to K^-\pi^-e^+e^+$	16.8	10.0	<2.8
$D^+ \to K_S^0\pi^-e^+e^+$	11.5	4.4	<3.3
$D^+ \to K^-\pi^0e^+e^+$	10.6	14.8	<8.5

*The systematic uncertainty has been considered



Search for heavy Majorana neutrino (ν_m):

- ✓ On-shell, $\nu_m \to \pi^- e^+$
- ✓ m_{ν_m}: $[m_e + m_\pi,\ m_D - m_e - m_K]$, only with $[0.25, 1.0]$ GeV$/c^2$
- ✓ Model independent [1]
- ✓ $D^0 \to K^- e^+ \nu_m(\pi^- e^+)$
- ✓ $D^+ \to K_S^0 e^+ \nu_m(\pi^- e^+)$

- ULs on signal yields @ 90% CL: the profile likelihood method [2] incorporating the systematic uncertainty.

[1] H.R. Dong, F. Feng and H.B. Li, Chin, Phys. C 39 013101 (2015).
[2] W. A. Rolke, A. M. Lopez, and J. Conrad, Nucl, Instrum, Methods Phys. Res., Sect. A 551, 493 (2005).

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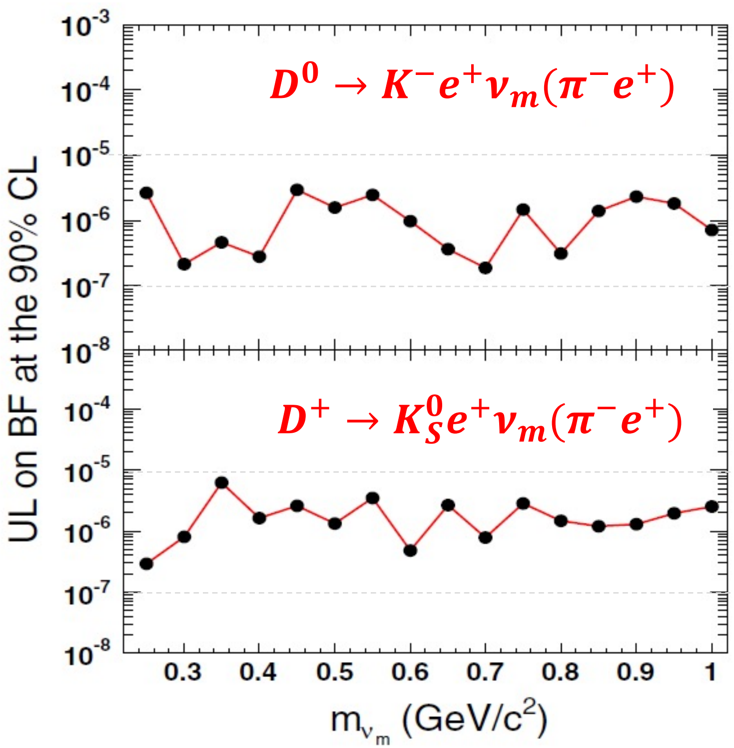
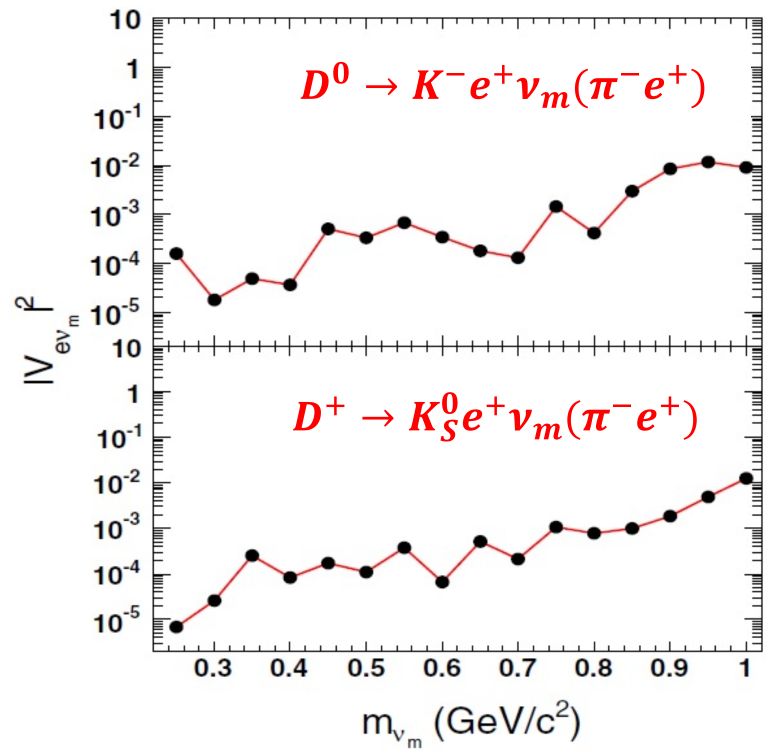
- **The ULs on BF @ 90% CL : $10^{-7} \sim 10^{-6}$**



- **The mixing matrix element $|V_{e\nu_m}|^2$**



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

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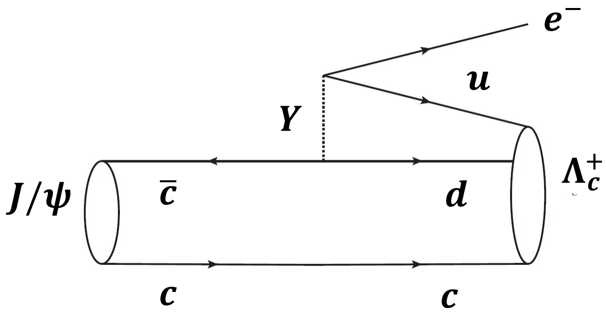
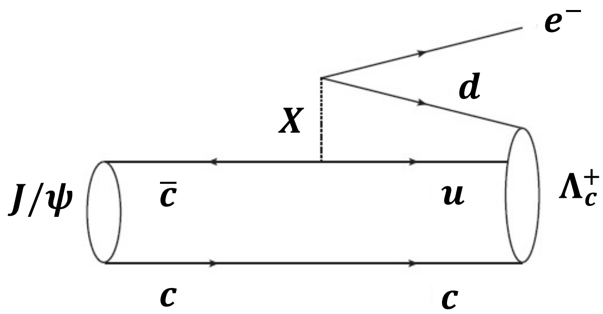
- First constraint of BNV from charmonium decay
- Right plots shows the decay diagrams
- $N_{J/\psi}^{tot} = (1310.6 \pm 7.0)\times 10^6$ [1]
- Simulate $\Lambda_c^+ \to p\, K^- \pi^+$: based on a partial wave analysis result [2] by considering
  - ✓ nonresonant 3-body decay;
  - ✓ intermediate states: $\Delta^{++}, \Delta(1600)^{++}$, excited Λ states, excited Σ states;
  - ✓ interferences.





X, *Y* are leptoquarks, carrying color charge, fractional electric charge, and both lepton and baryon quantum numbers[3].

[1] M. Ablikim *et al.* (BESIII Collaboration), Chin. Phys. C 41, 013001 (2017).
[2] M. Ablikim *et al.* (BESIII Collaboration), Phys. Rev. Lett. 116, 052001 (2016).
[3] J. C. Pati, and A. Salam, Phys. Rev. D 10, 275 (1974); 11, 703 (1975).

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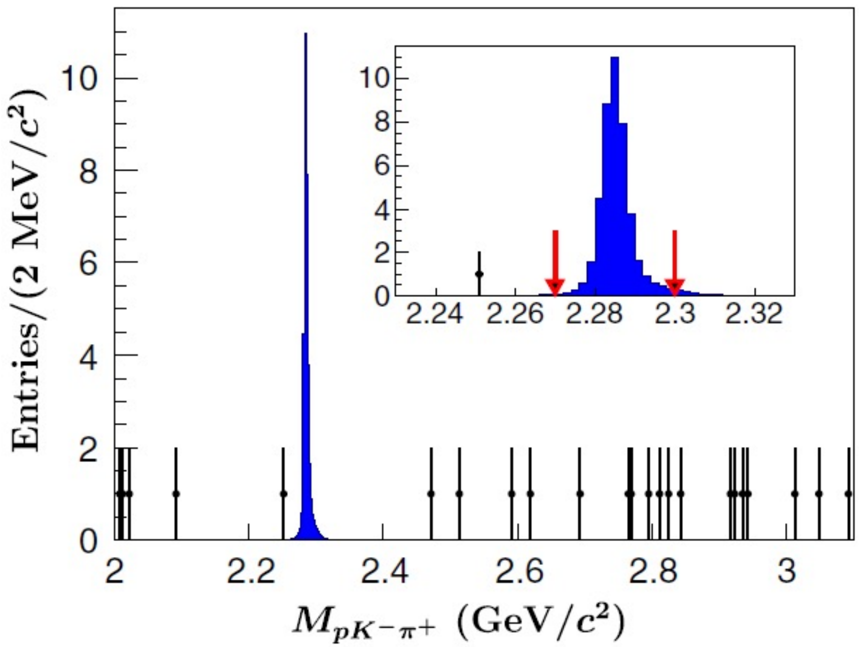
- **No signal observed in signal regions between two red arrows.**
- **Upper limit on the signal yield @ 90% CL: Frequentist method [1] with unbounded profile likelihood treatment of systematic uncertainties.**



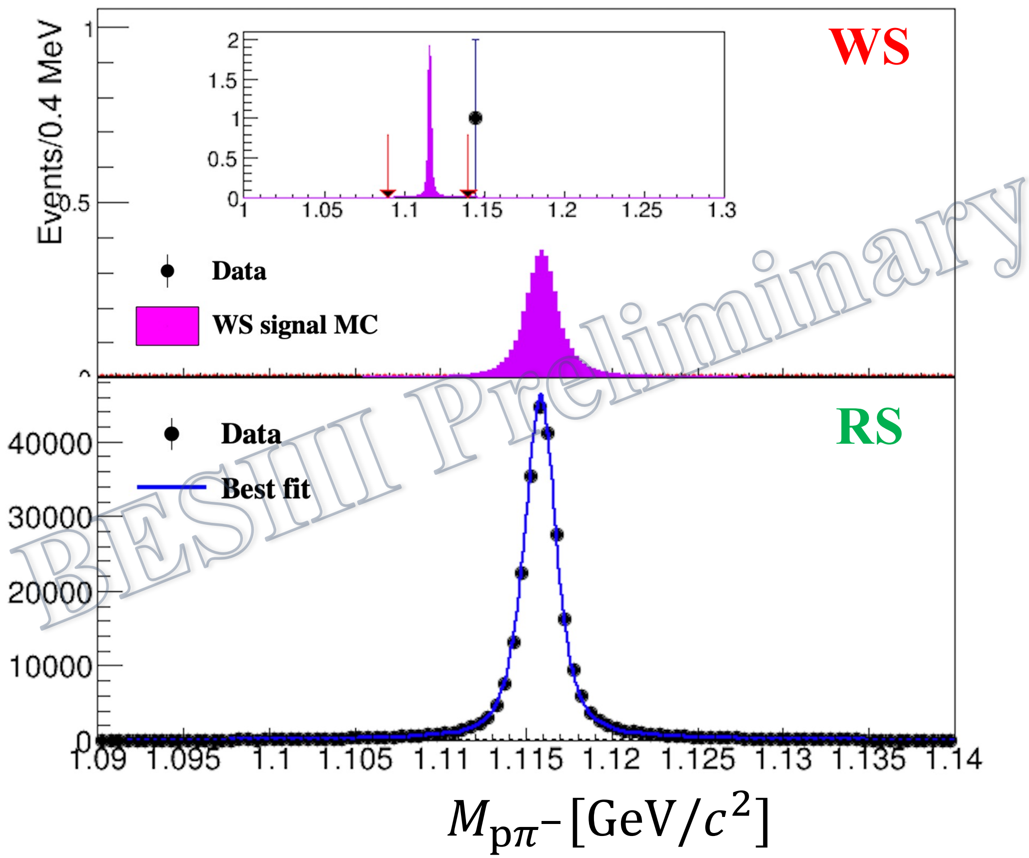
$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < 6.9\times10^{-8}$ @90% C.L

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

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

☐ Search for Λ- $\bar{\Lambda}$ oscillation

- **Right sign (RS):** $J/\psi \to pK^-\bar{\Lambda}(\to \bar{p}\pi^+) + c.c.$
- **Wrong sign (WS):** $J/\psi \to pK^-\Lambda\ (\to p\pi^-) + c.c.$



- **UL on oscillation rate @ 90% CL: Frequentist method [1] with unbounded profile likelihood treatment of systematic uncertainties.**

$$P(\Lambda) = \frac{B(J/\psi \to pK^- \Lambda)}{B(J/\psi \to pK^- \bar{\Lambda})} = \frac{N_{\mathrm{WS}}^{\mathrm{obs}}/\epsilon_{\mathrm{WS}}}{N_{\mathrm{RS}}^{\mathrm{obs}}/\epsilon_{\mathrm{RS}}} < 4.4\times10^{-6}$$

- **UL on oscillation parameter @ 90% CL:**

$$\delta m_{\Lambda\bar{\Lambda}} = \sqrt{\frac{P(\Lambda)}{2\cdot(\tau_\Lambda/\hbar)^2}} < 3.8\times10^{-15}\ \mathrm{MeV}$$

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

$\Sigma^- \to p e^- e^-$ and $\Sigma^- \to \Sigma^+ X$

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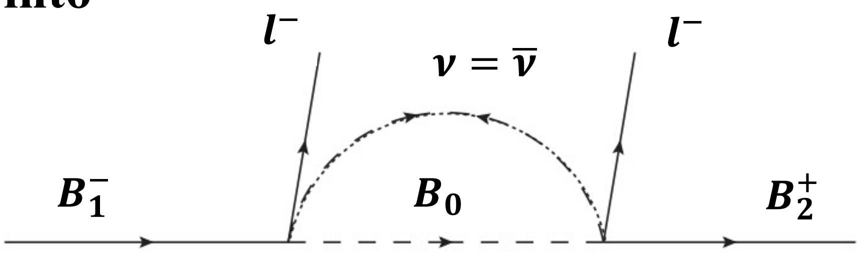
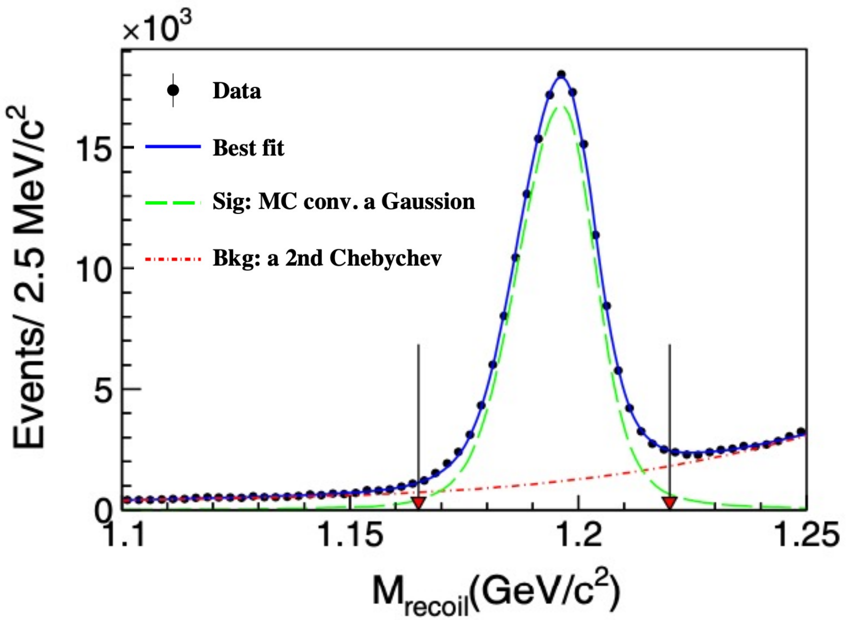
- **Two down-type (d or s) quarks convert into two up-quarks[1-2], similar to $0\nu\beta\beta$**
- **A blind analysis technique**
- **Double tag (DT)**
  - ✓ **ST events: $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^- + c.c.$, $\bar{\Sigma}(1385)^+ \to \pi^+\bar{\Lambda}(\to \bar{p}\pi^+)$, save all $\bar{\Sigma}(1385)^+$ candidates; fit the recoil mass of $\bar{\Sigma}(1385)^+$.**





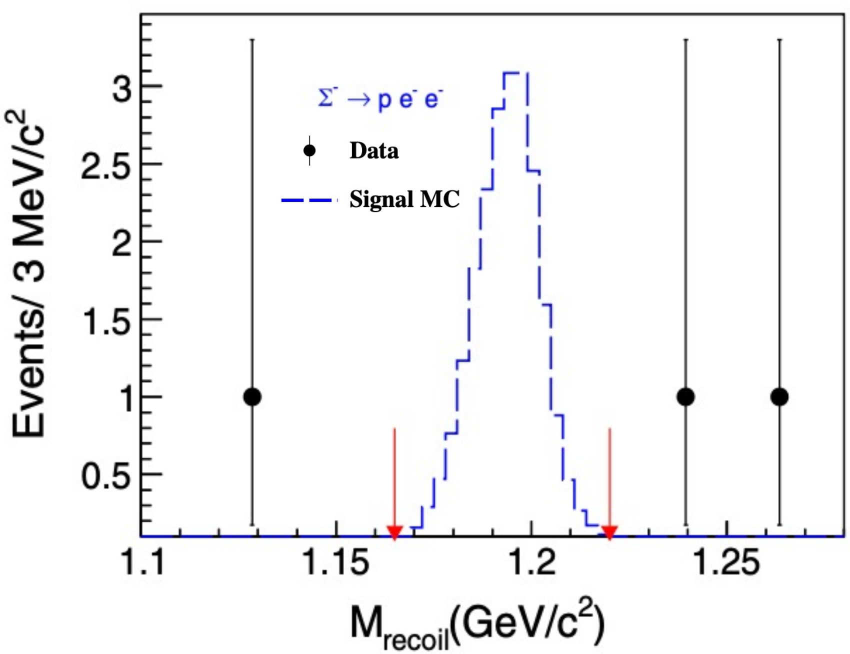
$$N_{ST} = 147743 \pm 563_{stat.}$$

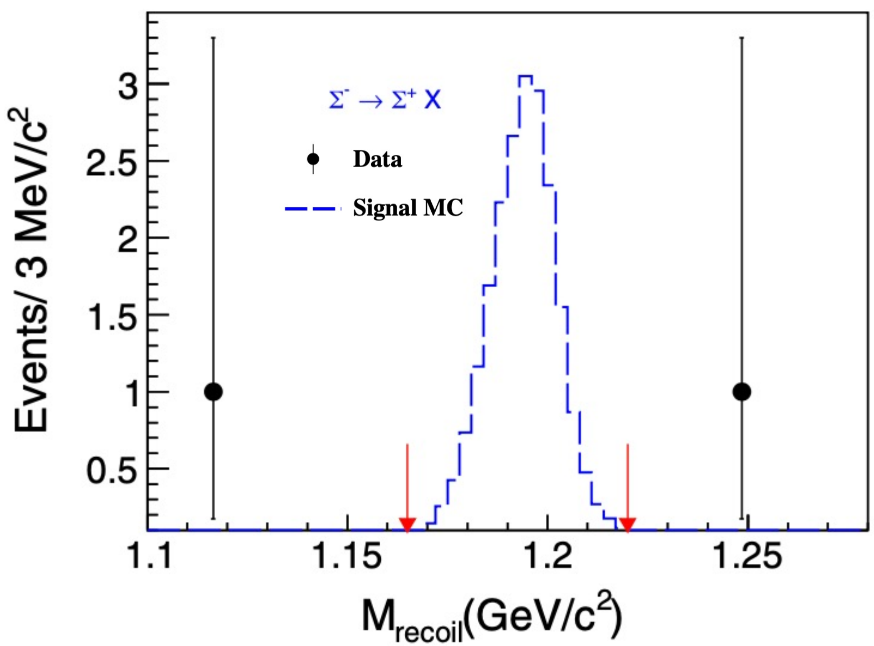
$$B(J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-) = (3.21 \pm 0.07_{stat.})\times 10^{-4}$$

[1] C. Barbero, G. Lopez Castro, and A. Mariano, Phys. Lett. B 556, 98 (2003).
[2] C. Barbero, L. F. Li, G. Lopez Castro, and A. Mariano, Phys. Rev. D 76, 116008 (2007); Phys. Rev. D 87, 036010 (2013).

✓ DT events:

- in the recoil side of the selected ST events
- $\Sigma^- \to p e^- e^-$; $\Sigma^- \to \Sigma^+(\to p\,\pi^0)X$
- ULs @90 CL： Frequentist method [1] with unbounded profile likelihood treatment of systematic uncertainties.





$B(\Sigma^- \to p e^- e^-) < 6.7 \times 10^{-5}$

$B(\Sigma^- \to \Sigma^+ X) < 1.2 \times 10^{-4}$

Summary

- At BESIII, the BNV/LNV processes have been searched in the decays of D, J/ψ, and Σ^-, the ULs on BFs are at the level of $10^{-8}\sim10^{-4}$, as summarized below.

Data sample	Source	Mode	$\lvert\Delta(B-L)\rvert$	UL on BF @ 90% CL
$\sqrt{s} = 3.773$ GeV $2.93\ \mathrm{fb}^{-1}$ $N^{tot}_{D^+D^-} = (8,296 \pm 31 \pm 64)\times10^3$ $N^{tot}_{D^0\bar{D}^0} = (10,597 \pm 28 \pm 98)\times10^3$	D mesons	$D^+ \to \bar{\Lambda} e^+$	0	6.5×10^{-7}
		$D^+ \to \bar{\Sigma}^0 e^+$	0	1.3×10^{-6}
		$D^+ \to \Lambda e^+$	2	1.1×10^{-6}
		$D^+ \to \Sigma^0 e^+$	2	1.7×10^{-6}
		$D^0 \to K^-\pi^+e^+e^+$	2	2.8×10^{-6}
		$D^+ \to K^0_S\pi^-e^+e^+$	2	3.3×10^{-6}
		$D^+ \to K^-\pi^0e^+e^+$	2	8.5×10^{-6}
$\sqrt{s} = 3.097$ GeV $N^{tot}_{J/\psi} = (1,310.6 \pm 7.0)\times10^6$	J/ψ meson	$J/\psi \to \Lambda_c^+ e^-$	0	6.9×10^{-8}
		$J/\psi \to pK^-\bar{\Lambda} \to pK^-\Lambda$	2 [BF ratio $P(\Lambda) < 4.4\times10^{-6}$]	
	Σ^- baryon	$\Sigma^- \to pe^-e^-$	2	6.7×10^{-5}
		$\Sigma^- \to \Sigma^+ X$	2	1.2×10^{-4}

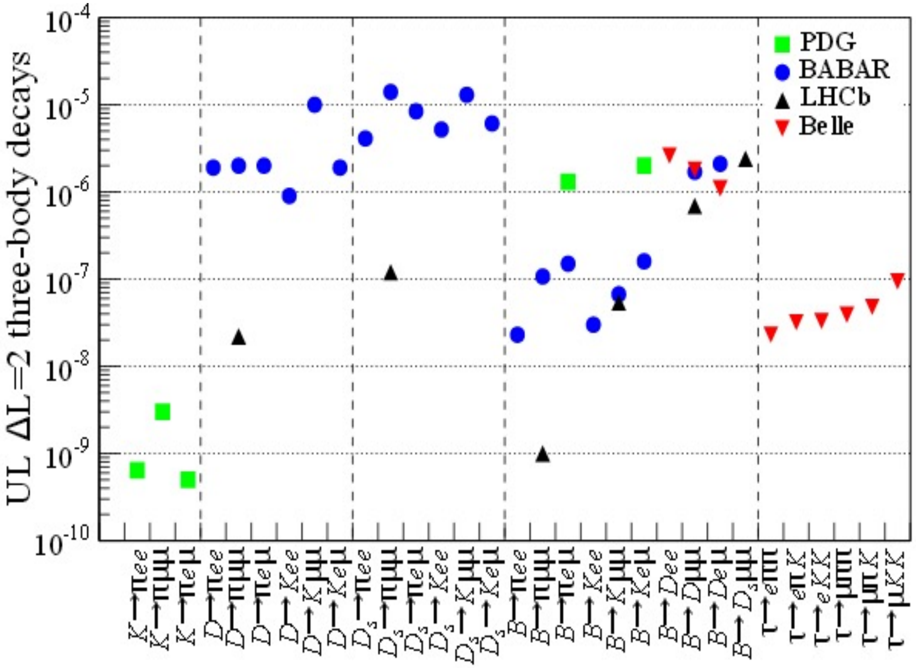
- **BESIII has collected about 10^{10} J/ψ events, which is the largest data sample directly from e^+e^- annihilation in the current world, better/more results will be coming soon.**
- **BESIII will collect 20 fb^{-1} @ 3.773 GeV data sample in the future, better/more constraints on BNV/LNV processes can be expected.**

Thanks for your attention!

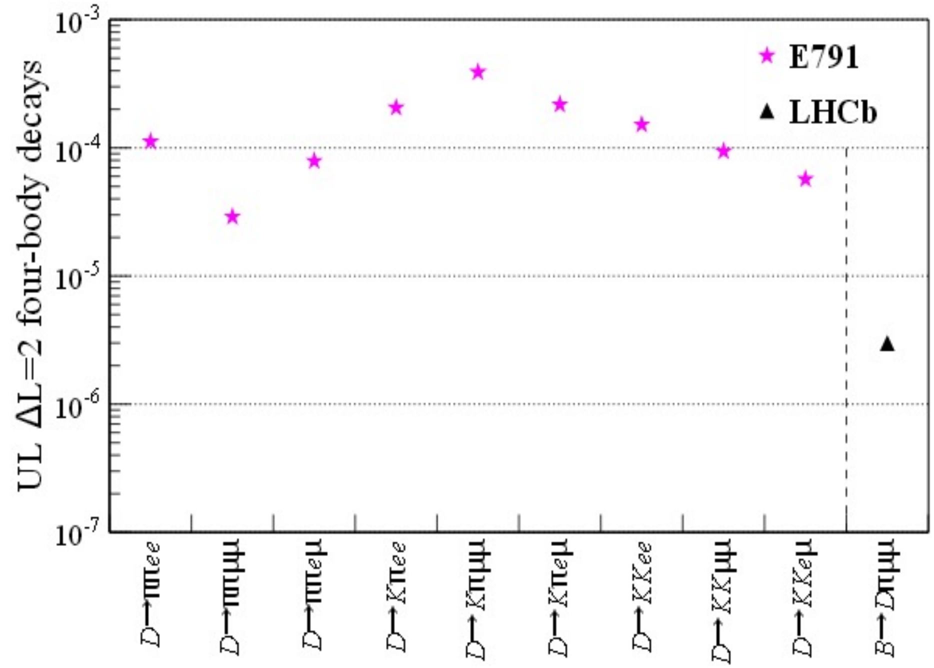
Backup

Upper limits on the branching fractions for LNV decays of K, B, D, τ

Three body decays [1]



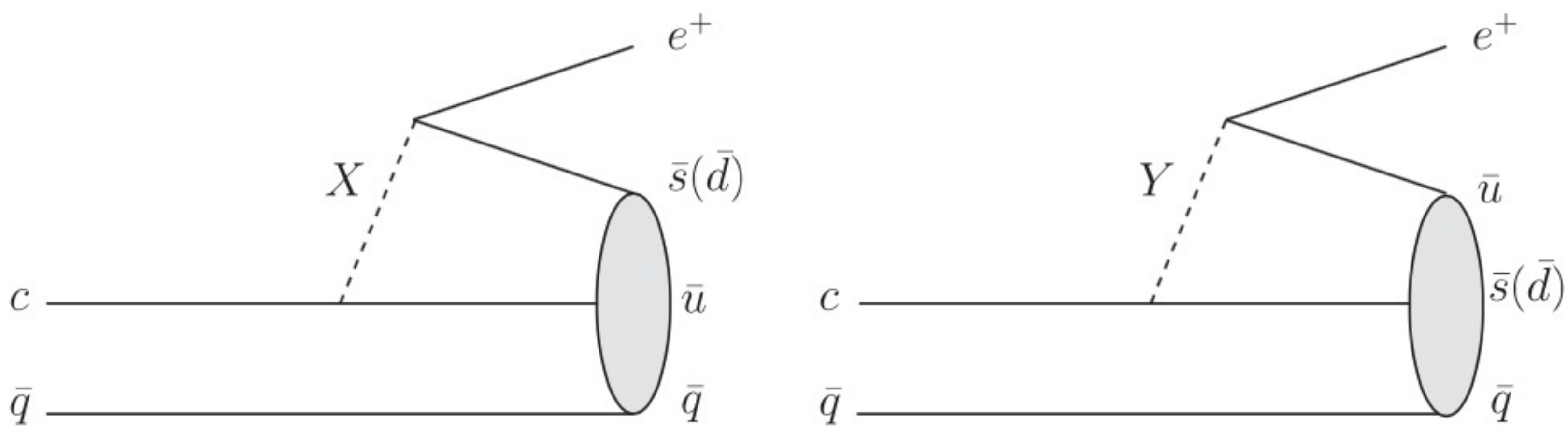
Four body decays [1]



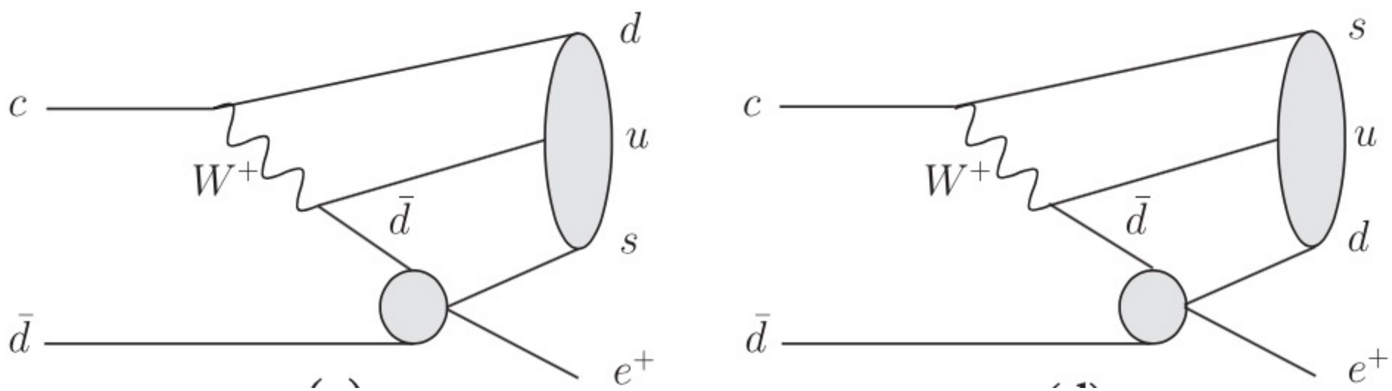
[1] D. Milanés, N. Quintero, and C. E. Vera, Phys. Rev. D 93 094026 (2016).

- **Various SM extensions with BNV processes have been proposed.**

- **Under dimension six operators, BNV processes can happen with $\Delta(\mathrm{B}-\mathrm{L})=0$, where $\Delta(\mathrm{B}-\mathrm{L})$ is the change in the difference between baryon and lepton numbers.**
    - **In models including heavy gauge bosons *X* with charge $\frac{4}{3}$ and gauge bosons *Y* with charge $\frac{1}{3}$, one obtains the Feynman diagrams for BNV decays of *D* mesons:**



- **Another class of BNV operators is the class of dimension seven operators where $\Delta(\mathrm{B}-\mathrm{L})=2$:**



- **Reference [1] argues that the decay amplitudes of these two kinds of BNV processes $\Delta(\mathrm{B}-\mathrm{L})=0$ and $\Delta(\mathrm{B}-\mathrm{L})=2$ may be comparable.**

Motivation

- 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

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

03 Search for $\Lambda - \overline{\Lambda}$ Oscillation

- Oscillation event (charge conjugation implied)

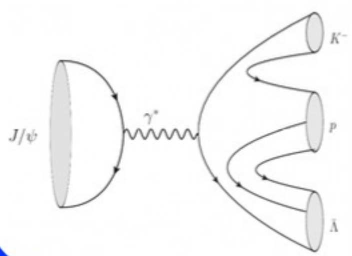
$$J/\psi \rightarrow pK^-\overline{\Lambda} \xrightarrow{oscillating} pK^-\Lambda$$

- Time integrated oscillation rate

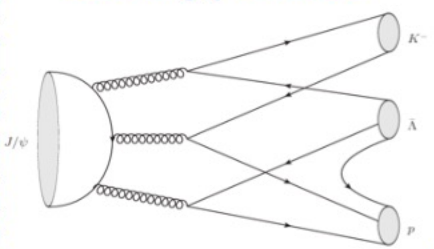
$$\mathcal{P}(\Lambda) = \frac{\mathcal{B}(J/\psi \rightarrow pK^-\Lambda \rightarrow pK^-p\pi^-)}{\mathcal{B}(J/\psi \rightarrow pK^-\bar{\Lambda} \rightarrow pK^-\bar{p}\pi^+)} = \frac{N_{\rm WS}^{obs}/\epsilon_{\rm WS}}{N_{\rm RS}^{obs}/\epsilon_{\rm RS}},$$

- Most of the systematic uncertainties cancelled.

EM process



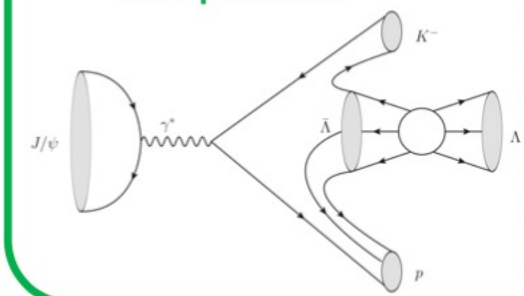
Strong process



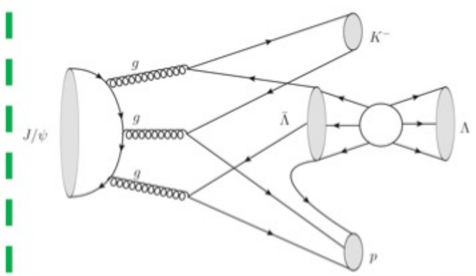
Right Sign Channel (Opposite Charge)

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

EM process



Strong process



Wrong Sign Channel (Same Charge)

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