Searching for *Baryon/Lepton Number Violation* Processes at BESIII

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Outline

- Introduction
- Results on BESIII Experiments
  - (B-L) conserved processes
  - (B-L) violated processes
- Summary

Introduction

- SM achieved great success, including the discovery of Higgs particle. However, It is regard as an low energy effective theory which can not explain:
  - experimentally:
    - small mass raising in neutrino oscillation
    - dark matter
    - dark energy
    - CKM based CPV is not enough to produce matter/anti-matter asymmetry in universe
  - theoretically:
    - mass hierarchy
    - why only three generation of fermion
    - …
- Pursue theory of everything
  - …

Why LNV?

- Lepton number (LN) is conserved in the Standard Model.
- Neutrino oscillation →$m \neq 0$→New Physics scenario.
- Nature of neutrino: Majorana or Dirac?

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\uparrow \\ \bar{\nu}_\downarrow \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

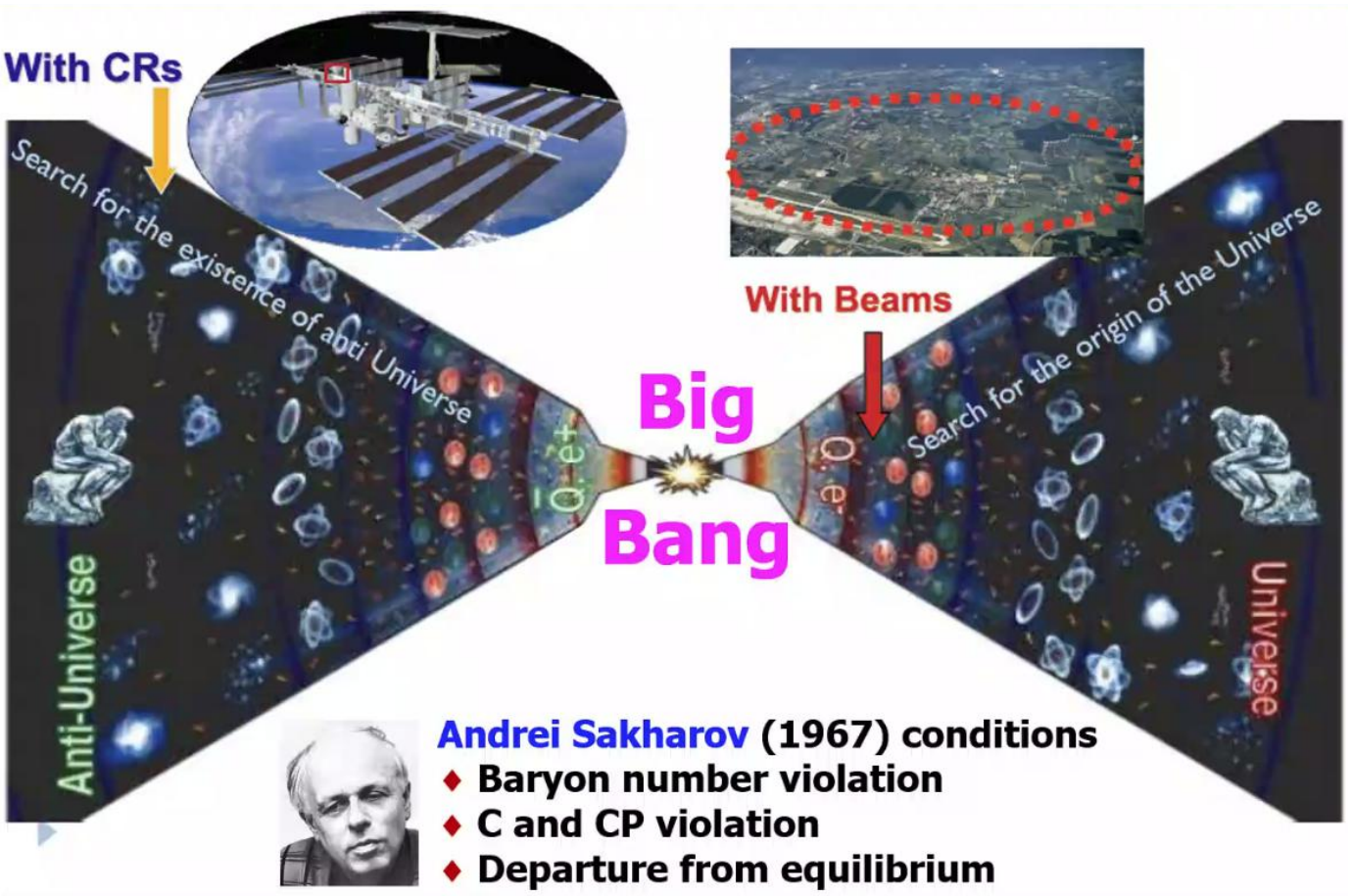
Dirac Majorana

- Majorana neutrino can violate LN by two unit

- Also LNV is introduced in many New Physics models

✓ 4th quark generation	PRD 93 094026 (2016)
✓ SO(10) SUSY GUT	JHEP 08 068 (2011)
✓ Exotic Higgs	PRD 51 6524 (1995)
✓	PLB 93 389 (1980)
	.....

Why BNV?



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.

Types of B/L NV

- Types
  - (*B*-*L*) conserved: $p \to e^+\pi^0, \quad J/\psi \to \Lambda_c^+ e^- \ldots$
    - GUT models(after proton decay, SO(10), E(6), flipped SU(5)): heavy mass gauge bossons X(4e/3),Y(e/3) ...
    - sphalerons none perturbation ...
    - others in SUSY
    - ...
  - (*B*-*L*) violated: $B - \bar{B}$ oscillation, 0νββ decay...
    - neutrino no zero mass
    - majorana neutrino model require ΔL=2
    - $B - \bar{B}$ oscillation require ΔB=2

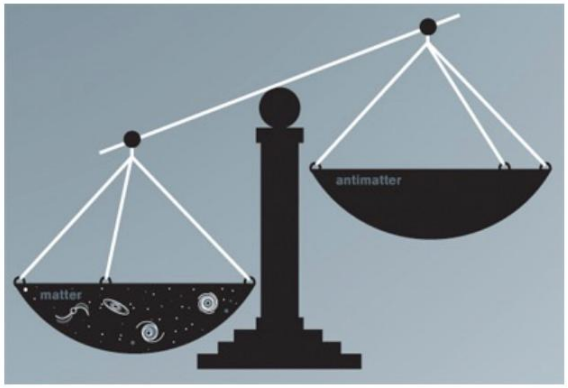
Status of BNV&LNV at BESIII

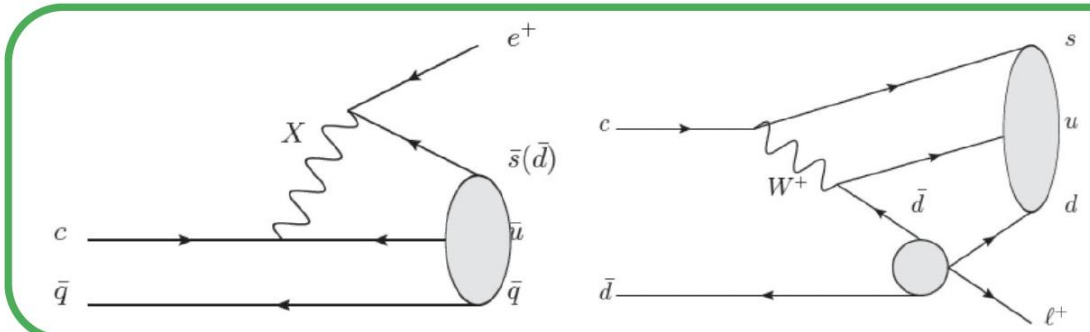
- Lepton Number Violation
  - ✓ $D^0 \to K^-\pi^-e^+e^+$, $D^+ \to K^0_S\pi^-e^+e^+$, $D^0 \to K^-\pi^0e^+e^+$ (PRD99, 112002)
  - ✓ $\Sigma^- \to \Sigma^+X$(including e^+e^+), $\Sigma^- \to pe^+e^+$ (PRD103, 052011)
- • Baryon Number Violation
  - ✓ $\Lambda - \bar{\Lambda}$ oscillation in $J/\psi \to pK^-\bar{\Lambda}$ (preliminary)

- Baryon Number Violation&&Lepton Number Violation
  - ✓ $J/\psi \to \Lambda_c e^+$ (PRD99, 072006)
  - ✓ $D^+ \to \Lambda(\bar{\Lambda})e^+$, $D^+ \to \Sigma^0(\bar{\Sigma}^0)e^+$ (PRΔ101, 031102)

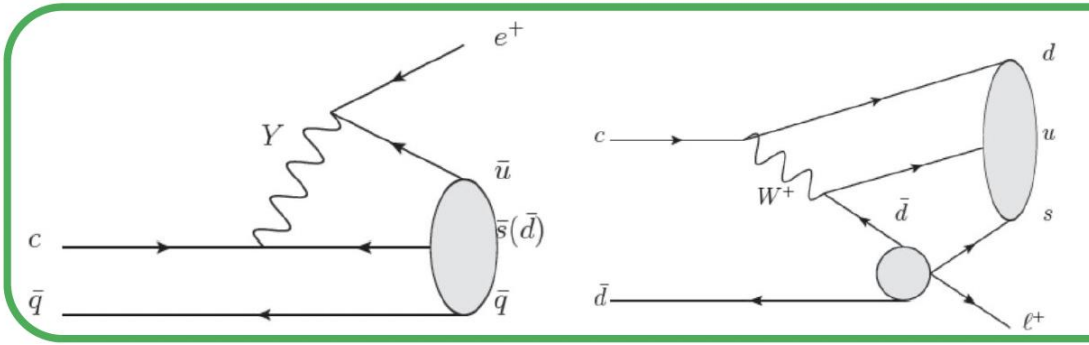
(*B*-*L*) Conserved Processes

- Asymmetry of matter and anti-matter: big problem in the universe evolution.
- BNV: even a small amount would have major consequences on the universe and its evolution.
- BNV is allowed in GUTs and SM extensions
- Prediction of $B(D^+ \to \overline{\Lambda}\, l^+)$ is no more than 10^{-29} (PRD72, 095001)





SM extension: under six operators $\Delta(B-L) = 0$



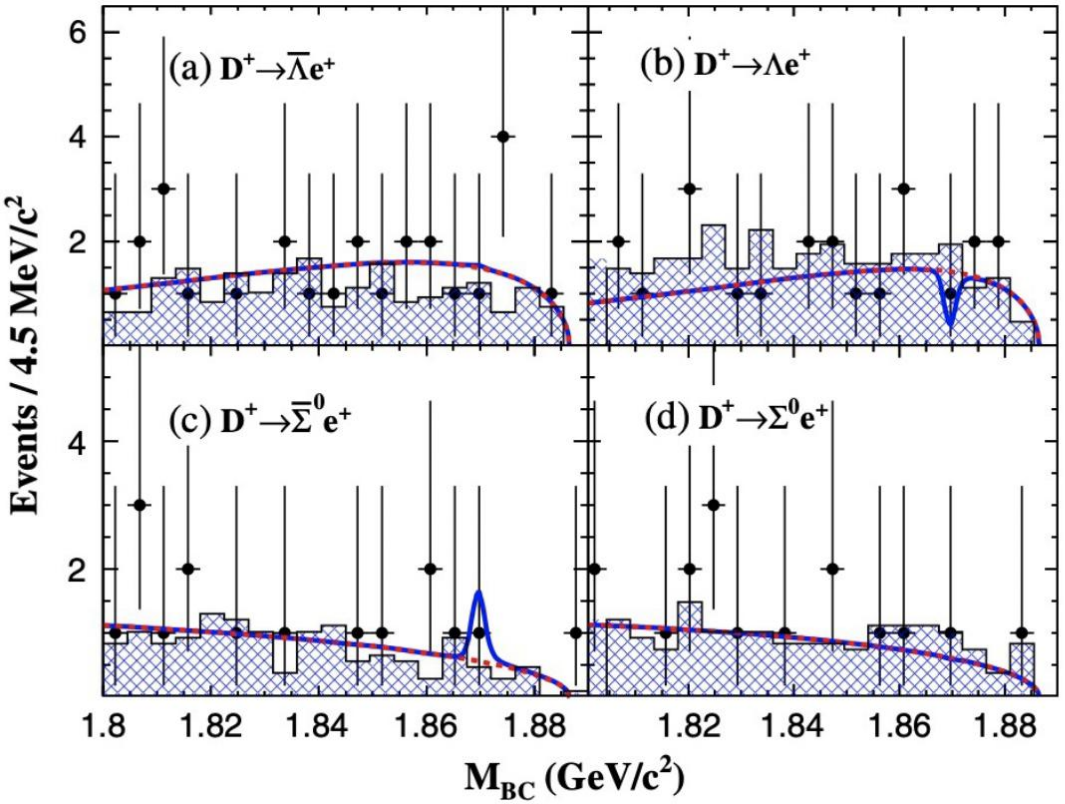
SM extension: under seven operators $\Delta(B-L) = 2$

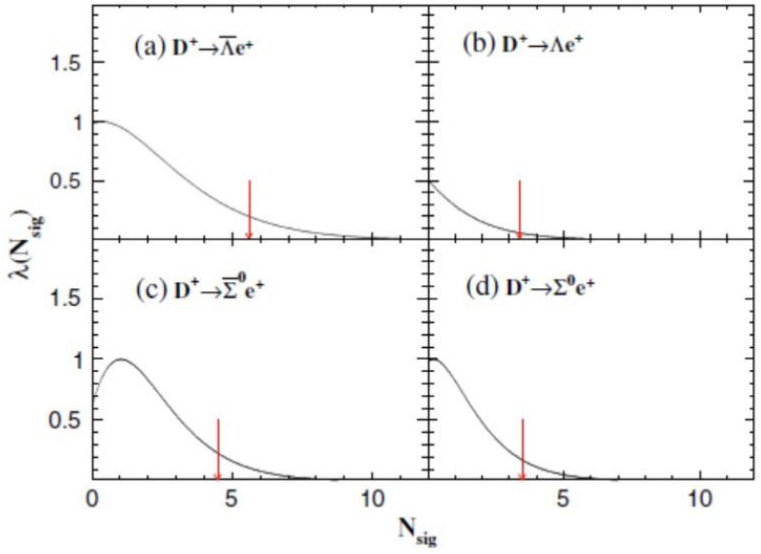
(*B-L*) Conserved Processes

- Data: 2.9 fb^{-1} @3.773 GeV
- Double Tag analysis

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

$$M_{\text{BC}} = \sqrt{E_{\text{beam}}^2 - |\vec{p}_D|^2}$$



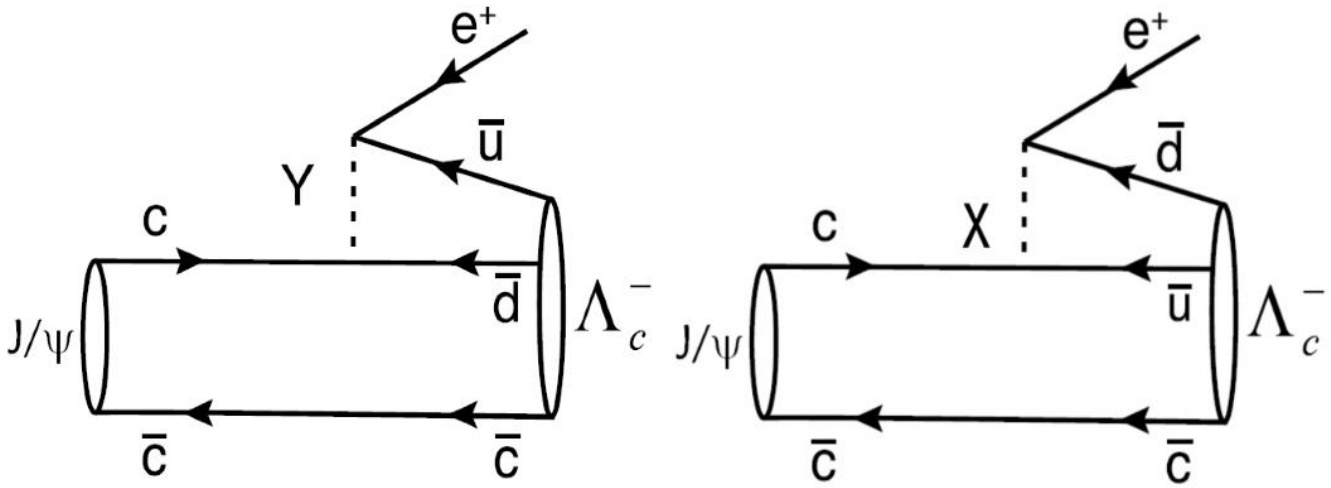


Channels	Upper Limit
$D^+ \to \Lambda\, e^+$	1.1×10^{-6}
$D^+ \to \bar{\Lambda}\, e^+$	6.5×10^{-7}
$D^+ \to \Sigma^0\, e^+$	1.7×10^{-6}
$D^+ \to \bar{\Sigma}^0\, e^+$	1.3×10^{-6}

PRD 101 (2020) 031102

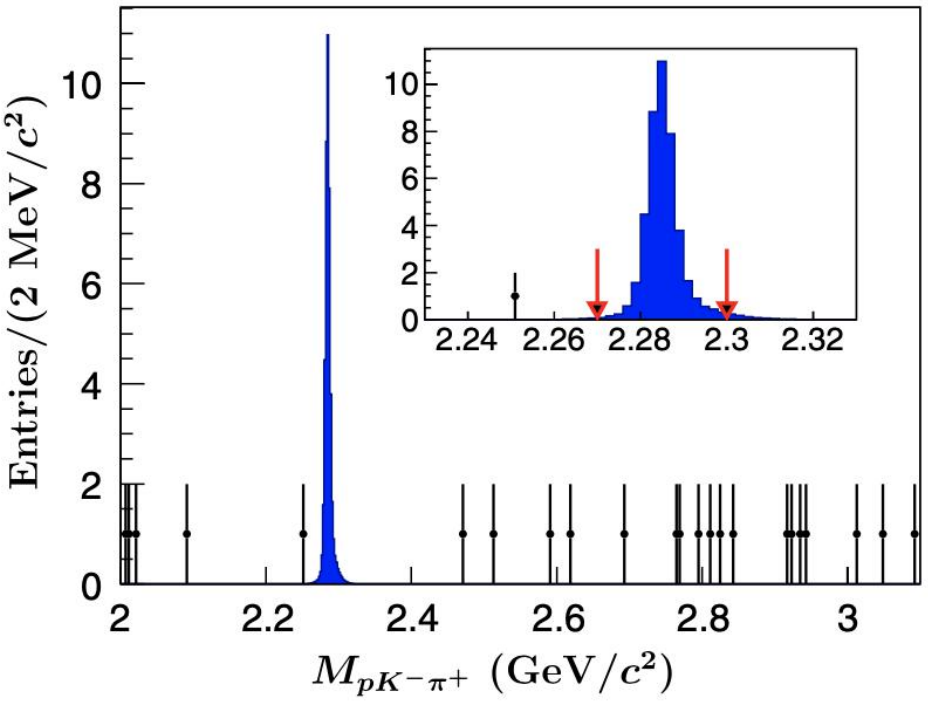
(*B*-*L*) Conserved Processes

- Precise measurements on various proton decays.
- Enormous searching for BNV in lepton/meson decays.
- First searching for $\Delta(B-L)=0$ process in J/ψ decay.



(*B-L*) Conserved Processes

- Data: 1.31 billion @J/ψ energy point
- $$\mathcal{B}(J/\psi \to \Lambda_c^+ e^-) < \frac{s_{90}}{N_{J/\psi}^{\rm tot} \times \mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)}$$



- Look for signal in mass of *pKπ* combination.
- $B(J/\psi \to \Lambda_c^+ e^-) < 6.9 \times 10^{-8}$@90% C.L.

- two orders of magnitude more strict than analogous process in CLEO.
- the best conclusion from meson decay now

PRD 99(2019) 072006

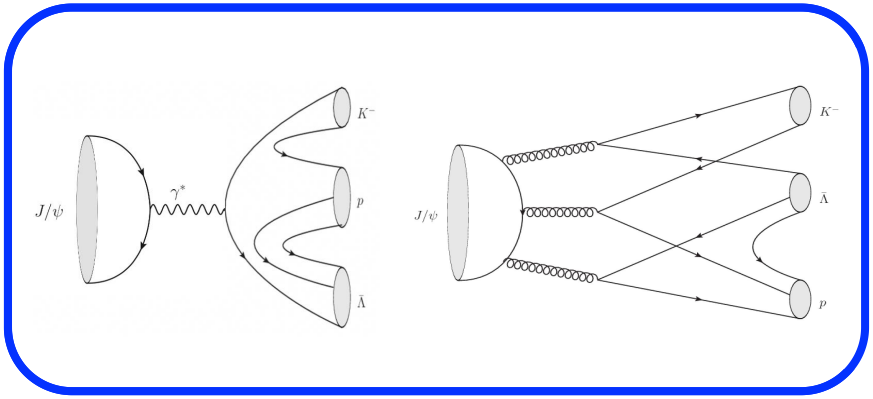
(*B-L*) violated Processes

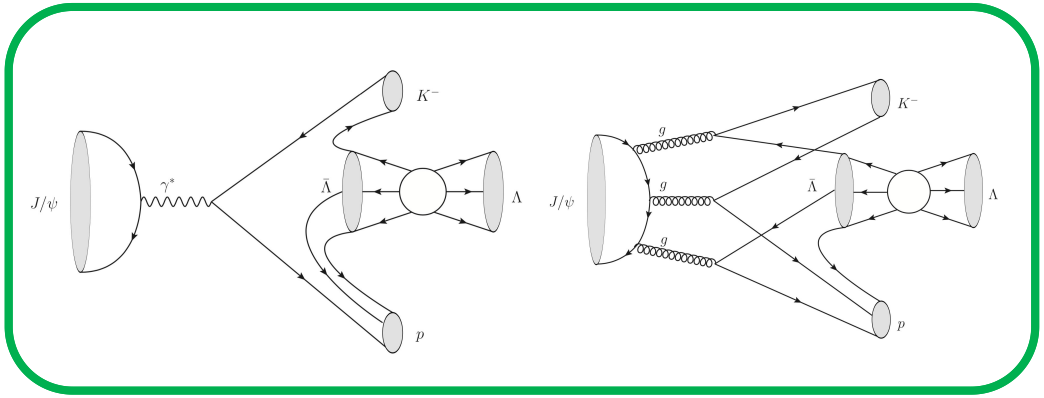
- Since 1980[PRL44,1316], there have been many experiments searching for BNV through $n-\bar{n}$ oscillation[PDG2019] with upper limit results, while few results from other baryons.
- 2007, K.-B. Luk pointed out that $\Lambda-\bar{\Lambda}$ oscillation may also exist.
- 2010, X.-W. Kang and H.-B. Li[PRD81,051901] 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.
- 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)].
- 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.

Δ(*B*-*L*) violated Processes

- Oscillation event (charge conjugation implied)

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





Right Sign Channel (Opposite Charge)

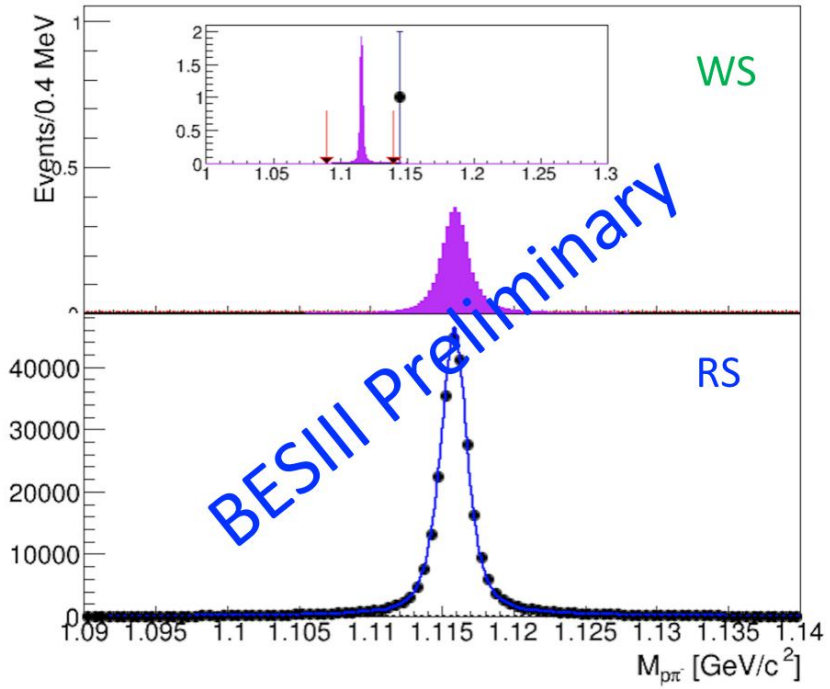
$J/\psi \to pK^-\bar{\Lambda} \to pK^-(\bar{p}\pi^+)$

Wrong Sign Channel (Same Charge)

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

(B-L) violated Processes

- Data: 1.31 billion @J/ψ energy point



- Upper limit on oscillation rate (90% CL)

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

BESIII Preliminary

- Oscillation parameter (90% CL)

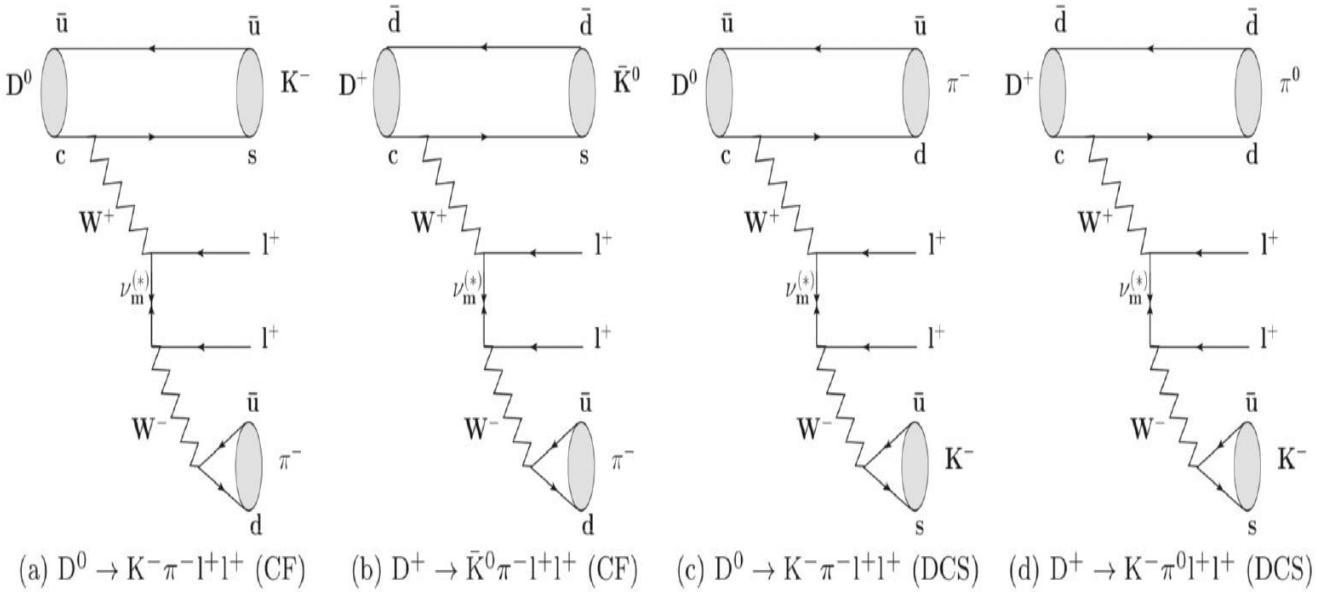
$$\delta m_{\Lambda\bar{\Lambda}} < 3.8 \times 10^{-15}\ \text{MeV}$$

BESIII Preliminary

- 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.

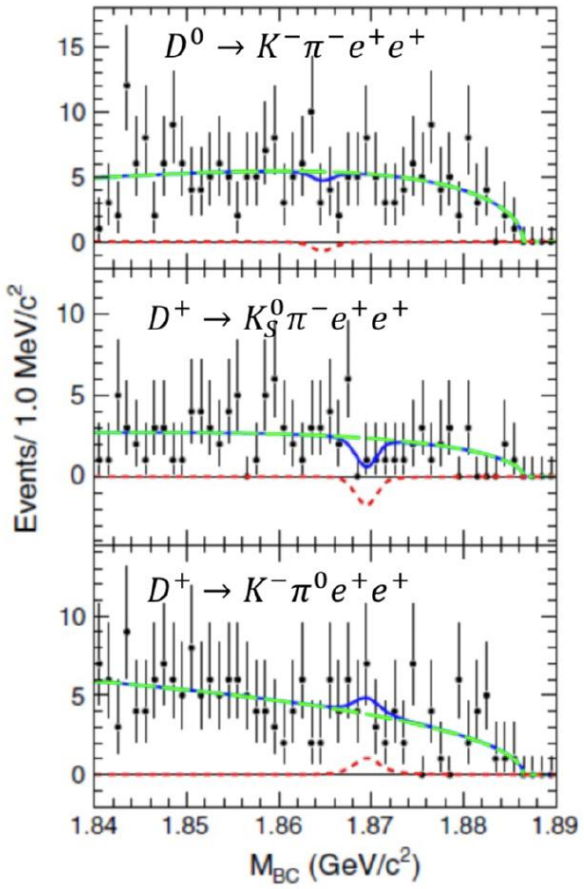
(*B-L*) violated Processes

- Nature: Dirac or Majorana neutrino?
- Three body or four body decays of $\boldsymbol{K}$, $\boldsymbol{B}$, $\boldsymbol{D}$, $\boldsymbol{\tau}$
- Decay diagram proposed at BESIII [Chin.Phys. C39,013101(2015)]



(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) $D^+ \to K^-\pi^0 l^+ l^+$ (DCS)

(*B-L*) violated Processes



- Data: 2.9 fb^{-1} @3.773 GeV
- A single tag analysis

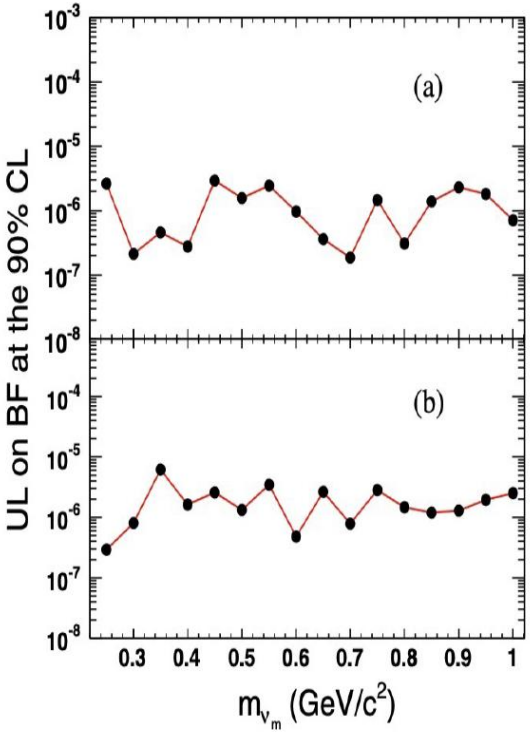
PRD 99(2019) 112002

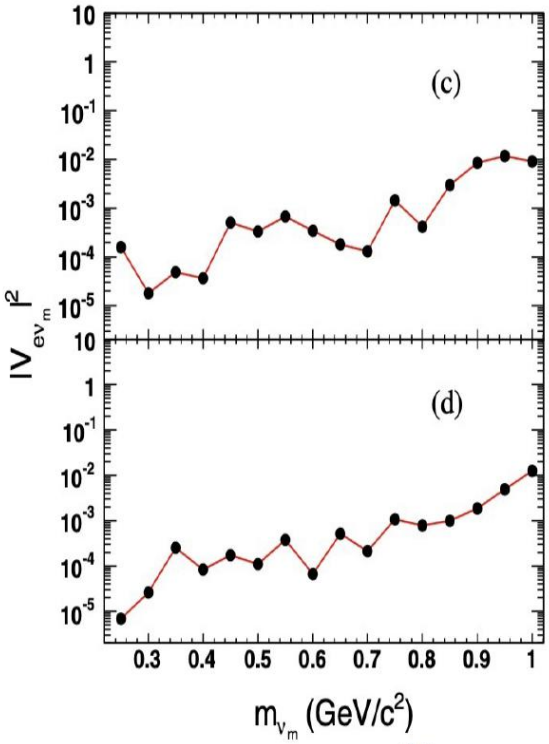
$$\Delta E = E_D - E_{\text{beam}}$$

$$M_{\text{BC}} = \sqrt{E^2_{\text{beam}} - |\vec{p}_D|^2}$$

$$\frac{\Gamma(m_{\nu_m}, V_{e\nu_m}(m_{\nu_m}))}{\Gamma(m_{\nu_m}, V'_{e\nu_m}(m_{\nu_m}))} = \frac{|V_{e\nu_m}(m_{\nu_m})|^4}{|V'_{e\nu_m}(m_{\nu_m})|^4}$$

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



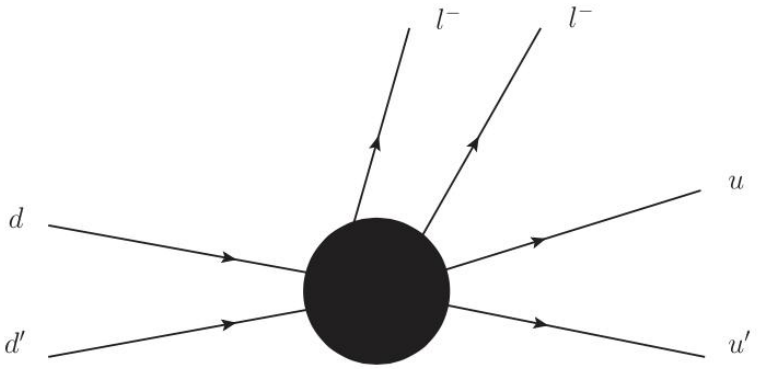


Channels	Upper Limit
$D^0 \to K^-\pi^-e^+e^+$	2.8×10^{-6}
$D^+ \to K^0_S\pi^-e^+e^+$	3.3×10^{-6}
$D^+ \to K^-\pi^0e^+e^+$	8.5×10^{-6}

best limits on these channels up to now

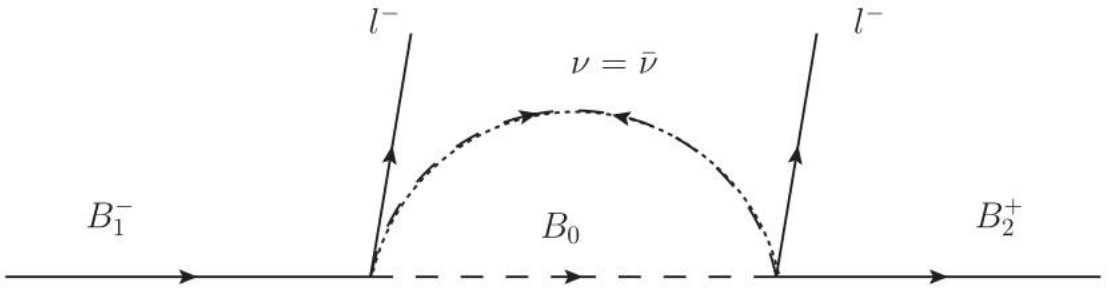
(*B-L*) violated Processes

- tiny neutrino mass
- nature of neutrino: Dirac or Majorana
- similar to $\boldsymbol{0\nu\beta\beta}$, two down-type ($\boldsymbol{d}$ **or** $\boldsymbol{s}$) quarks convert into two up-quarks, two same sign lepton, determined by local four quark operators[PLB566,98;PRD76,116008;PRD87,036010]



- $\Sigma^- \rightarrow p e^- e^-$,
- $\Sigma^- \rightarrow \Sigma^+ X$ $(\Sigma^- \rightarrow \Sigma^+ e^- e^-)$

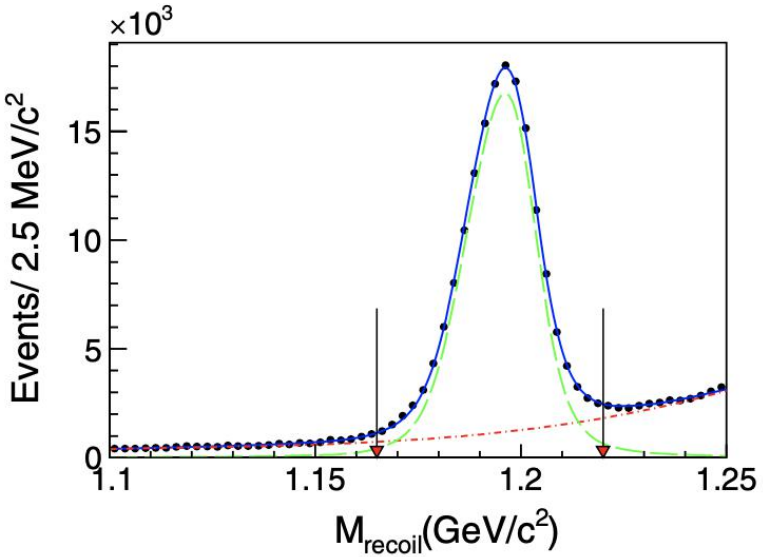
- Based on loop feynman diagram, predict 10^{-35}~10^{-31}
- Based on MIT bag Model, can reach to 10^{-23}



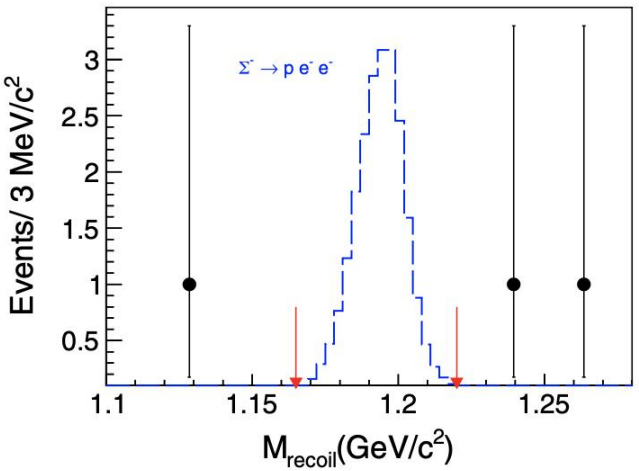
(*B-L*) violated Processes

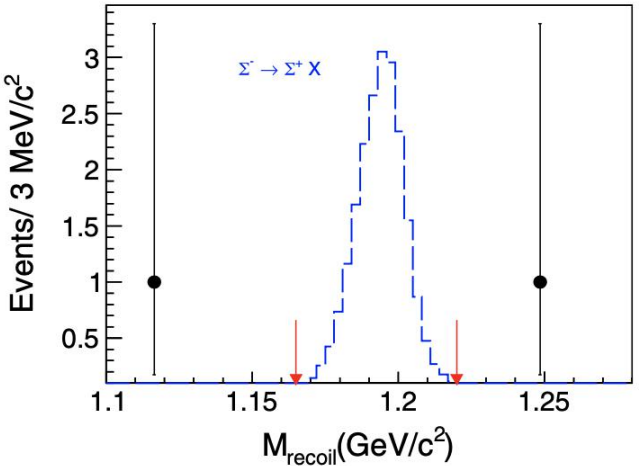
- 1 billion J/ψ events @3.09GeV
- $J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-, \bar{\Sigma}(1385)^+ \to \Lambda\pi^+$
- double tag Method
- look signal in recoil mass of $\bar{\Sigma}(1385)^+$

$$M_{\text{recoil}} = \sqrt{(E_{J/\psi} - E_{\bar{\Lambda}} - E_{\pi^+})^2 - (\vec{\mathbf{p}}_{J/\psi} - \vec{\mathbf{p}}_{\bar{\Lambda}} - \vec{\mathbf{p}}_{\pi^+})^2}$$



$N_{ST} = 147743 \pm 563$





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

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

@ 90% C.L.

PRD 103(2021) 052011

Summary

- Searching BNV&LNV from experiment plays key role to reveal the nature of neutrino and revolution of the universe.

- Present limits are still above SM predictions, no BNV or LNV have been found yet.

- In the future, more data on BESIII will collected, new result and more strict constraint can be expected.

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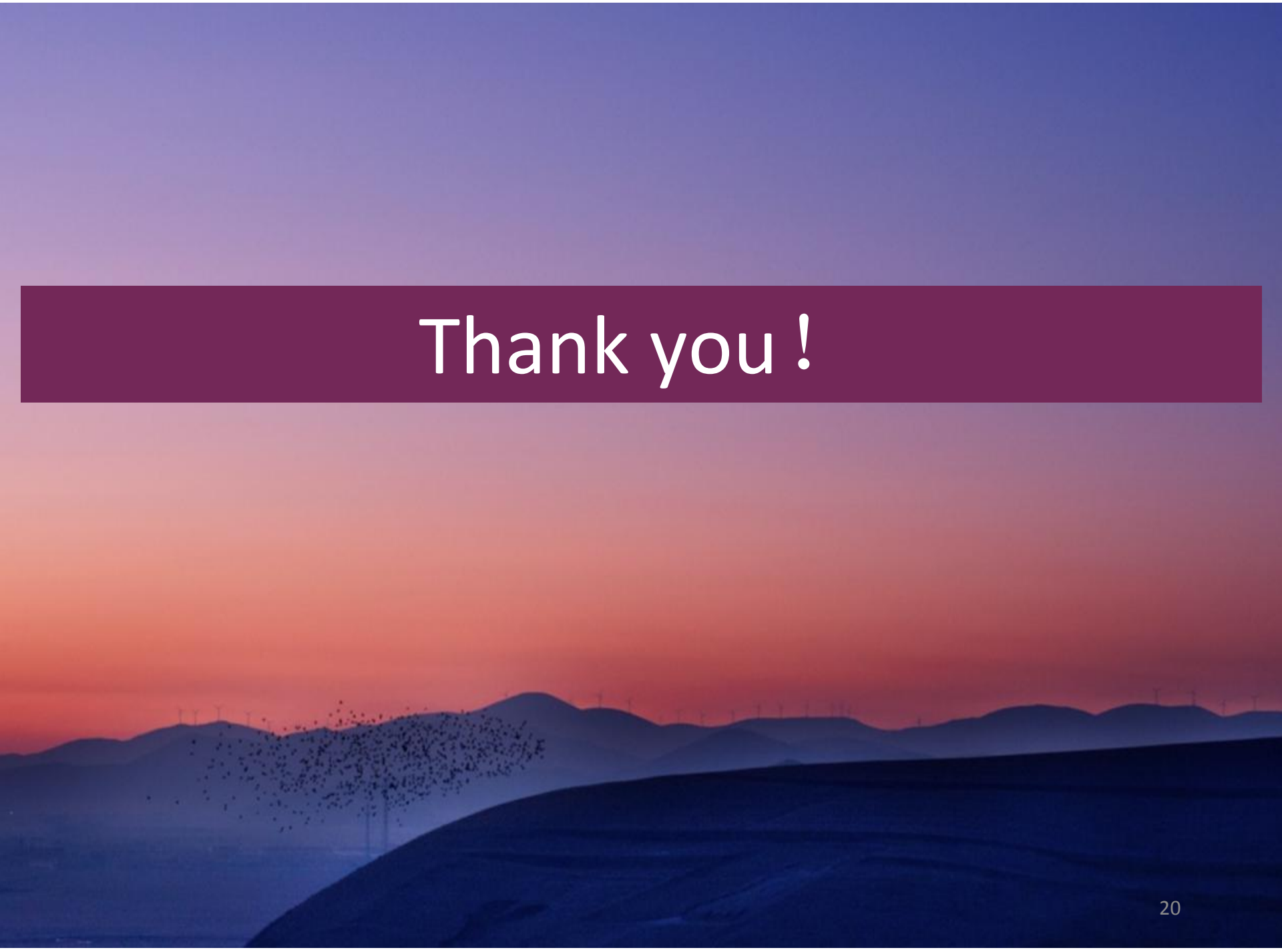
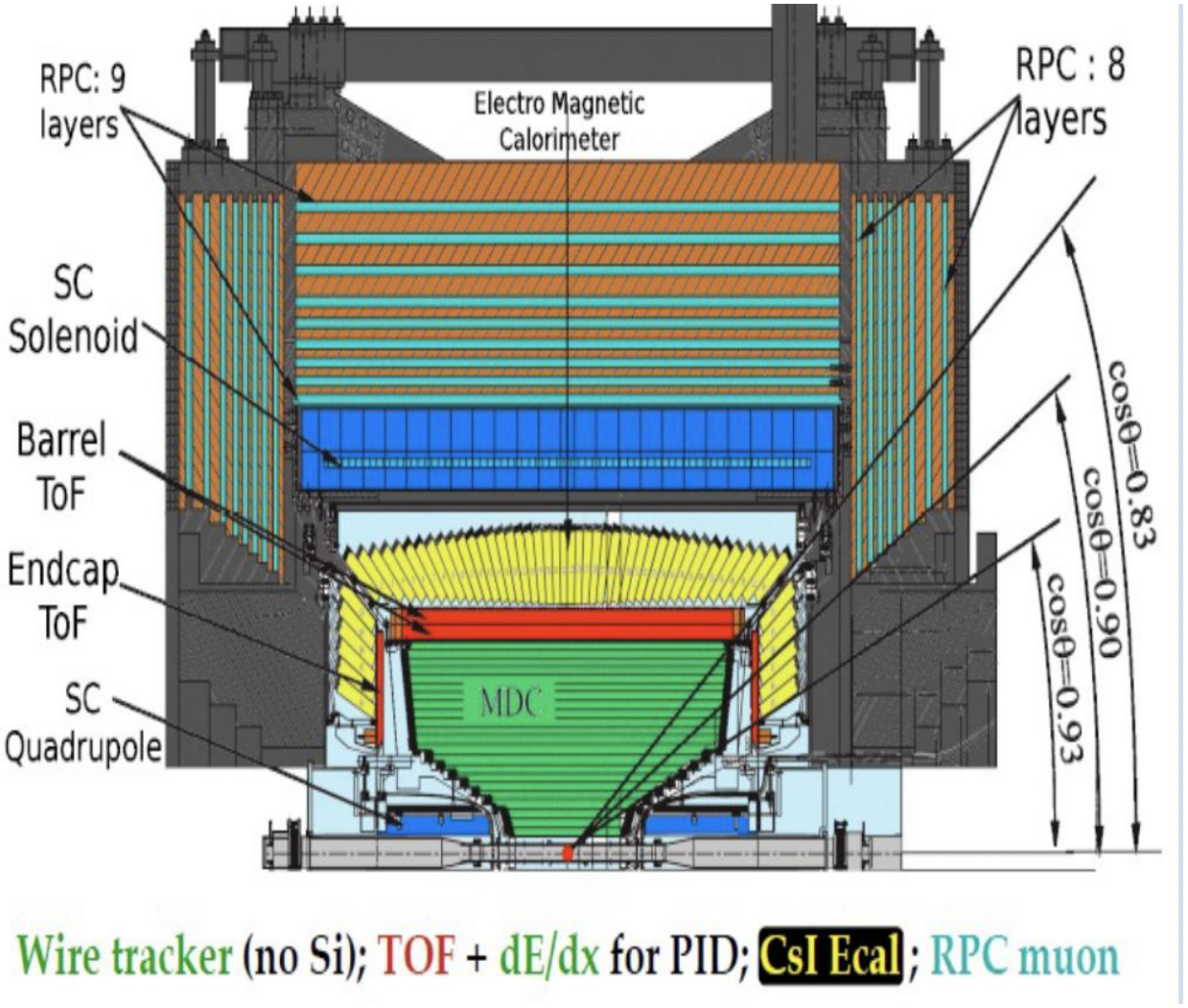

Thank you !

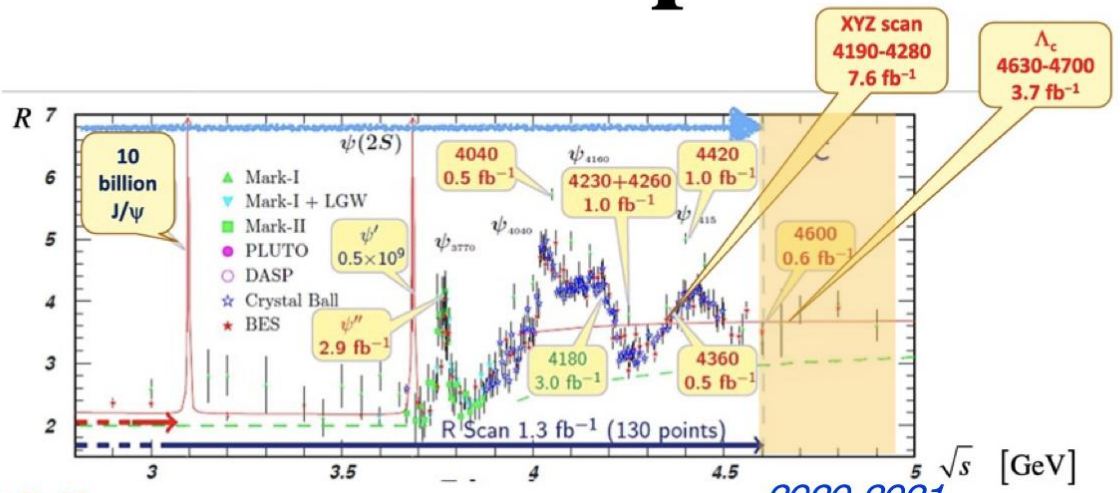
Backup Slides

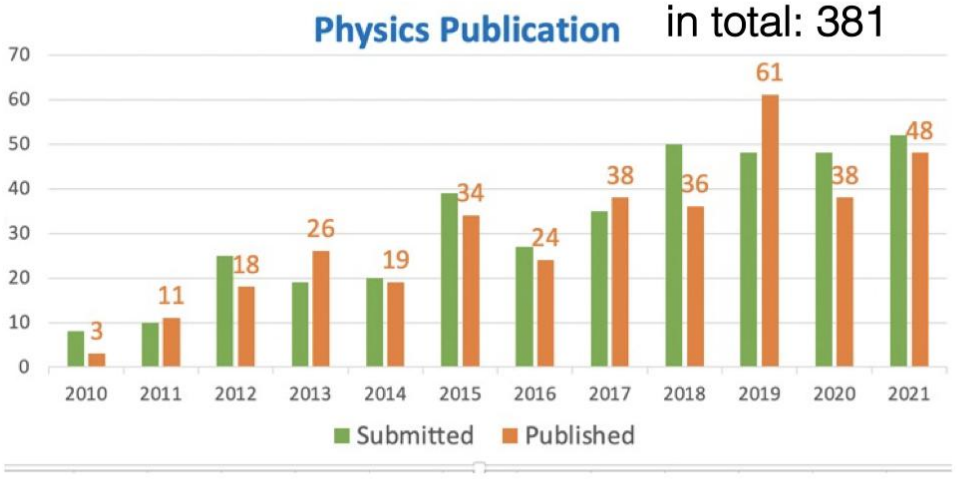
BESIII Detector

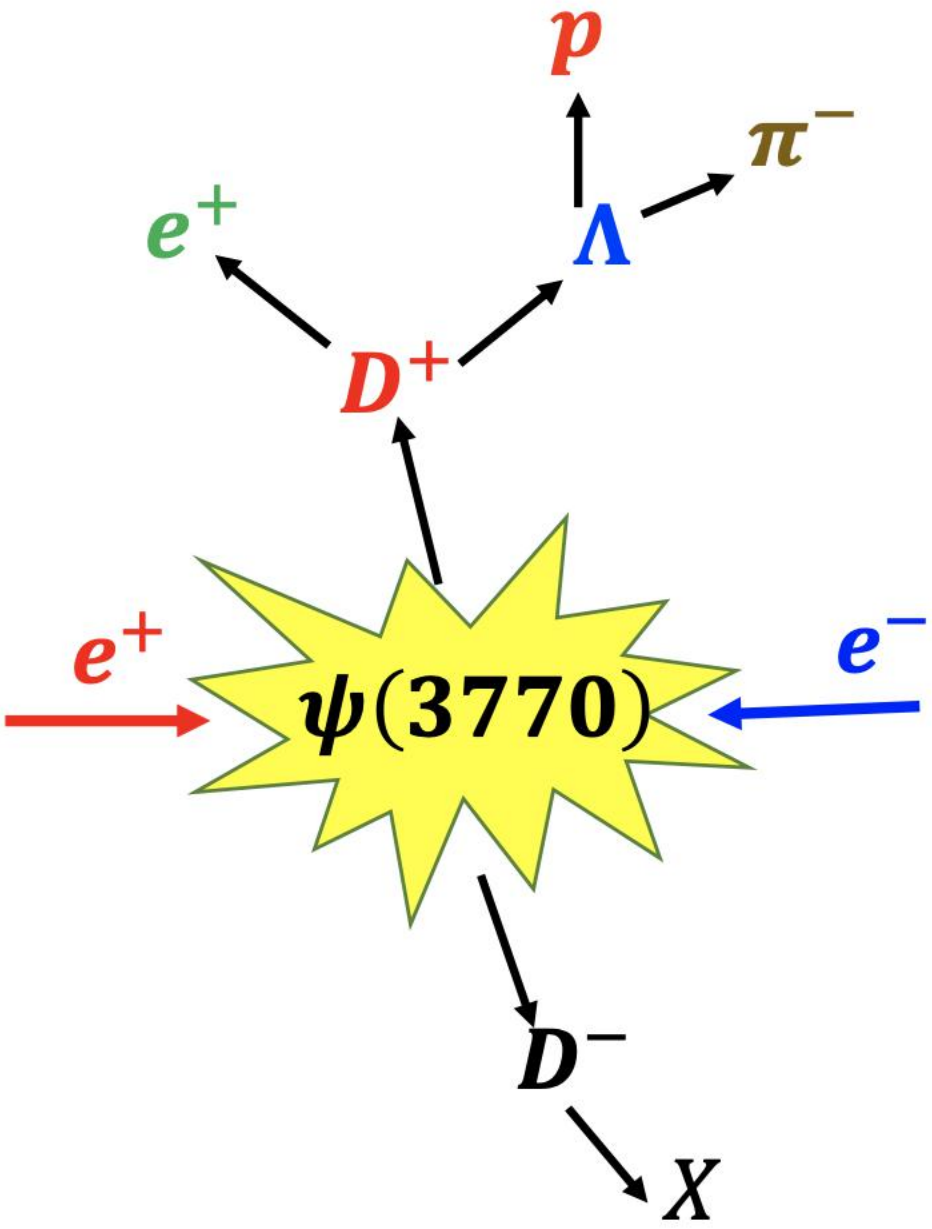


BESIII data sample

2009: 106M $\psi(2S)$
225M J/ψ
2010: 975 pb^{-1} at $\psi(3770)$
2011: 2.9 fb^{-1} *(total)* at $\psi(3770)$
482 pb^{-1} at 4.01 GeV
2012: 0.45B *(total)* $\psi(2S)$
1.3B *(total)* J/ψ
2013: 1092 pb^{-1} at 4.23 GeV
826 pb^{-1} at 4.26 GeV
540 pb^{-1} at 4.36 GeV
10 × 50 pb^{-1} scan 3.81 — 4.42 GeV
2014: 1029 pb^{-1} at 4.42 GeV
110 pb^{-1} at 4.47 GeV
110 pb^{-1} at 4.53 GeV
48 pb^{-1} at 4.575 GeV
567 pb^{-1} at 4.6 GeV
0.8 fb^{-1} R-scan 3.85 — 4.59 GeV
2015: R-scan 2 — 3 GeV + 2.175 GeV
2016: ~3fb^{-1} at 4.18 GeV (for D_s)
2017: 7 × 500 pb^{-1} scan 4.19 — 4.27 GeV
2018: more J/ψ *(and tuning new RF cavity)*
2019: 10B *(total)* J/ψ
8 × 500 pb^{-1} scan 4.13, 4.16, 4.29 — 4.44 GeV
2020 : 3.8 fb^{-1} scan **4.61-4.7 GeV**
2021 : 2 fb^{-1} scan **4.74-4.95 GeV**;
2.55B ψ(2S)






p
π^-
e^+
Λ
D^+
e^+
e^-
$\psi(3770)$
D^-
X

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

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