Search for Lepton Number Violation Processes at BESIII

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Outline

- Introduction

- LNV Results at BESIII
  - $D^0 \to K^-\pi^-e^+e^+$, $D^+ \to K_S^0\pi^-e^+e^+$, $D^+ \to K^-\pi^0e^+e^+$ (PRD99, 112002)
  - $\Sigma^- \to pe^-e^-$, $\Sigma^- \to \Sigma^+X$ (including e^-e^-) (PRD103, 052011)
  - $\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$ (arXiv: 2308.05490)

- Prospects

- Summary

Introduction

- Lepton number is conserved in the Standard Model.

- SM can’t explain the finite mass of neutrinos.

- The nature of neutrinos (Dirac or Majorana), is still an open question.
    - If neutrinos are Majorana particles, they can be manifested through $\Delta L = 2$ processes.
    - $\Delta L = 2$ processes are widely viewed as the cleanest test of the Majorana neutrino.

Introduction

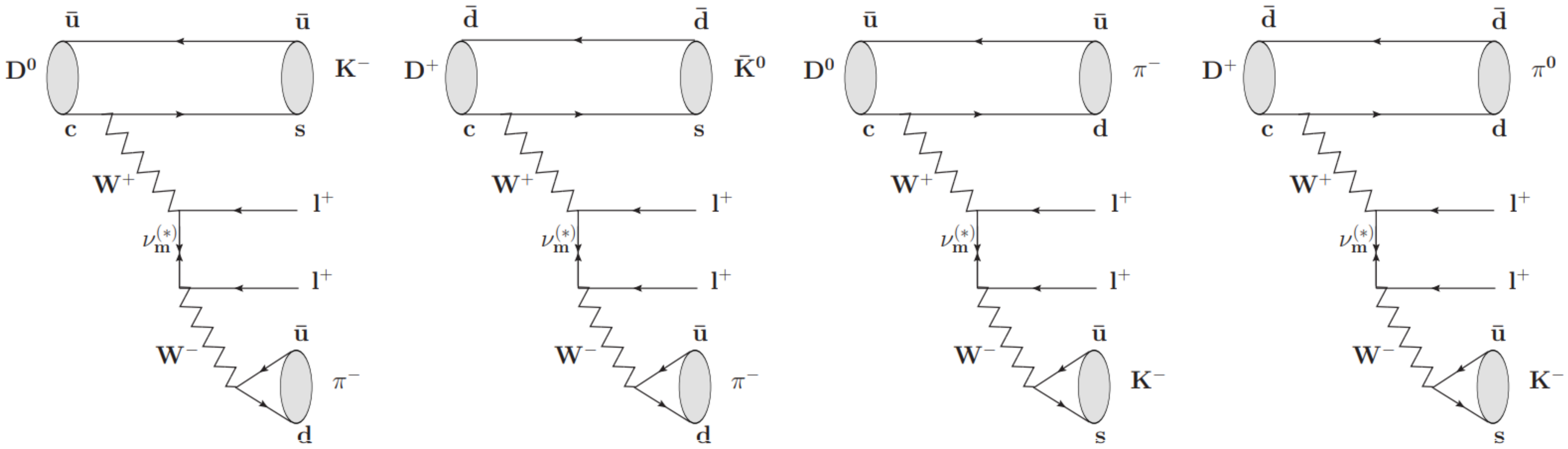
- The asymmetry of matter and antimatter in the universe → possible BNV

  - Many theories believe that if there is BNV, there will also be LNV.

- LNV is also introduced in many New Physics models.
  - ➢ 4^{th} quark generation
  - ➢ SO(10) SUSY GUT
  - ➢ Exotic Higgs
  - ➢ ……

$D^{0(+)} \to hh'e^+e^+$

- $\Delta L = 2$ processes
- Decay diagrams 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) $D^+ \to K^-\pi^0l^+l^+$ (DCS)

$D^{0(+)} \to hh'e^+e^+$

PRD99, 112002

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

- Single tag analysis

- Two variables are used to identify the signal candidates：

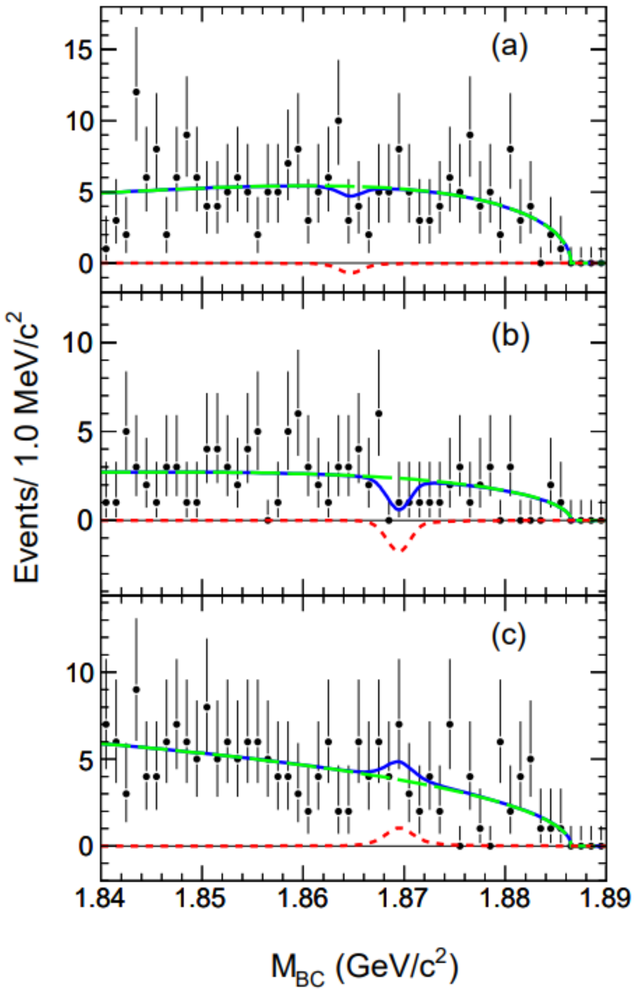
$$M_{\mathrm{BC}} = \sqrt{E_{\mathrm{beam}}^2 - |\vec{p}_D|^2},$$
$$\Delta E = E_D - E_{\mathrm{beam}},$$

- Fit the ΔE distribution in signal MC samples.

Channel	ΔE (MeV)
$D^0 \to K^-\pi^-e^+e^+$	$[-33.0, 19.7]$
$D^+ \to K_S^0\pi^-e^+e^+$	$[-30.6, 19.3]$
$D^+ \to K^-\pi^0e^+e^+$	$[-54.8, 24.4]$

$D^{0(+)} \to hh'e^+e^+$

PRD99, 112002



MC simulated shape convolved with a Gaussian function + ARGUS function

- Scanning likelihood value for different number of signal events.
- Likelihood curve convolved with a Gaussian function.

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

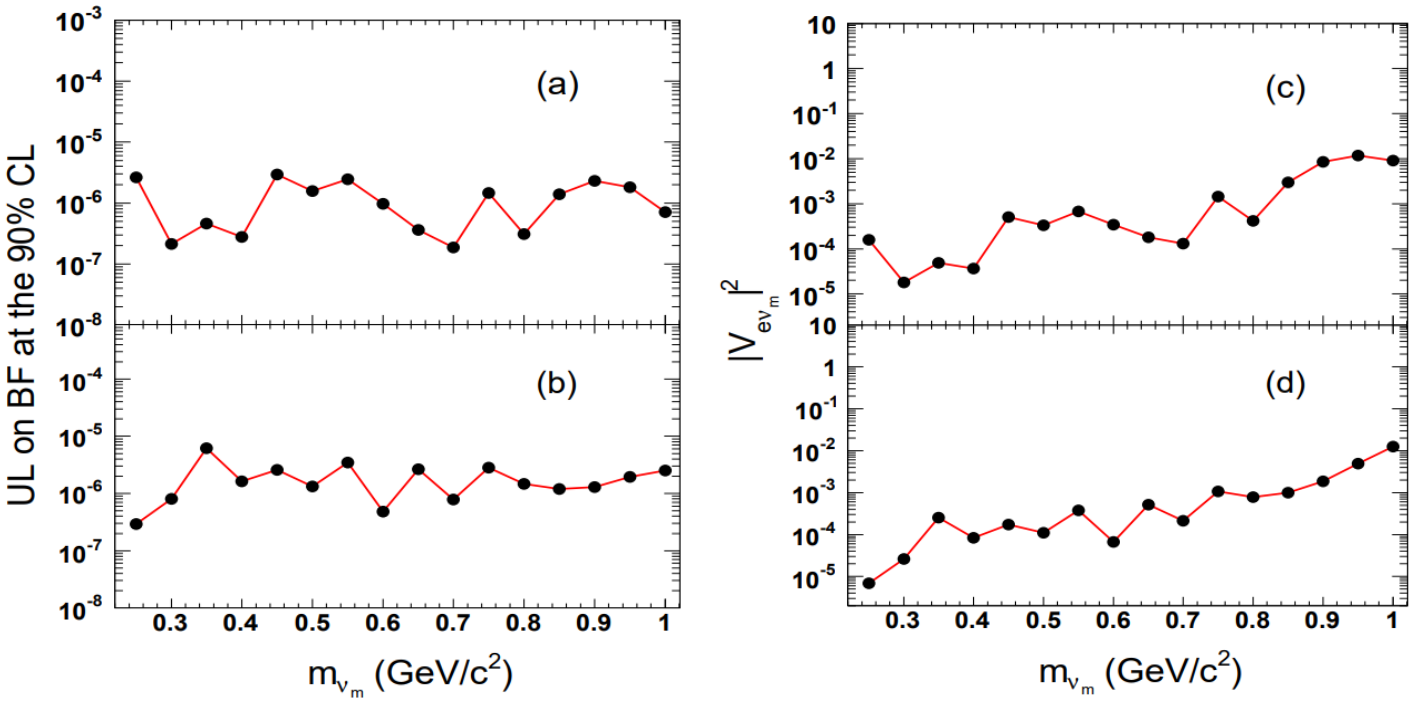
improved by 2 orders of magnitude

first search

$D^{0(+)} \to hh'e^+e^+$

PRD99, 112002

- Neutiono mass related UL for $D^0 \to K^- e^+ \nu_m (\pi^- e^+)$ and $D^+ \to K_s^0 e^+ \nu_m (\pi^- e^+)$

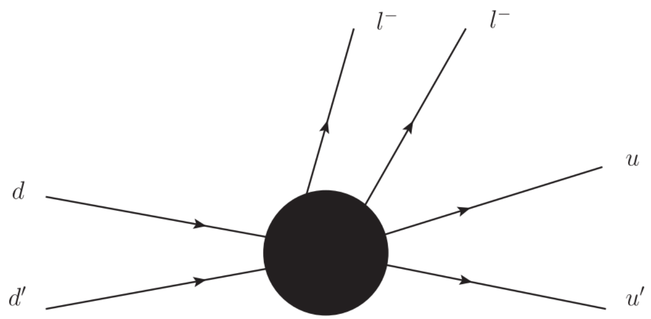


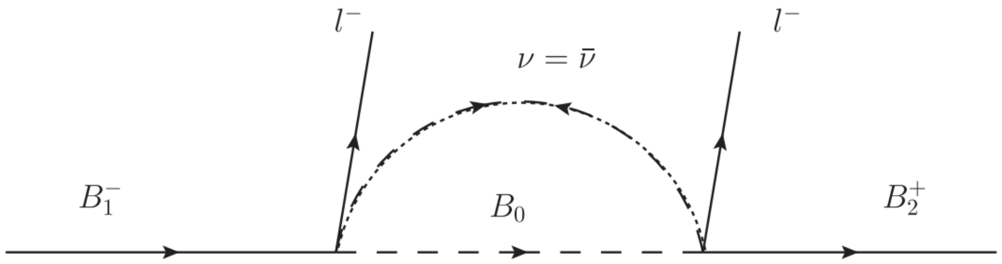
$$\frac{\Gamma(m_{\nu_m}, V_{e\nu_m}(m_{\nu_m}))}{\Gamma(m_{\nu_m}, V'_{e\nu_m}(m_{\nu_m}))} = \frac{|V_{e\nu_m}(m_{\nu_m})|^4}{|V'_{e\nu_m}(m_{\nu_m})|^4}$$

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

- Two down-type (d or s) quarks convert into two up-quarks
- Determined by local four-quark operators
- Underlying mechanism similar to that of $0\nu\beta\beta$ nuclear decay

[PLB566,98; PRD76,116008; PRD87,036010]





- Based on MIT bag Model, predicted BF of $\Sigma^- \to pe^-e^-$ can reach 10^{-23}

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

PRD103, 052011

- Data: about 1 billion J/ψ events @3.097 GeV

- Double tag analysis

$$\mathcal{B}^{\text{sig}} = \frac{N^{\text{sig}}/\varepsilon^{\text{tag,sig}}}{N^{\text{tag}}/\varepsilon^{\text{tag}}}$$

$J/\psi \to \bar{\Sigma}(1385)^+\Sigma^-$

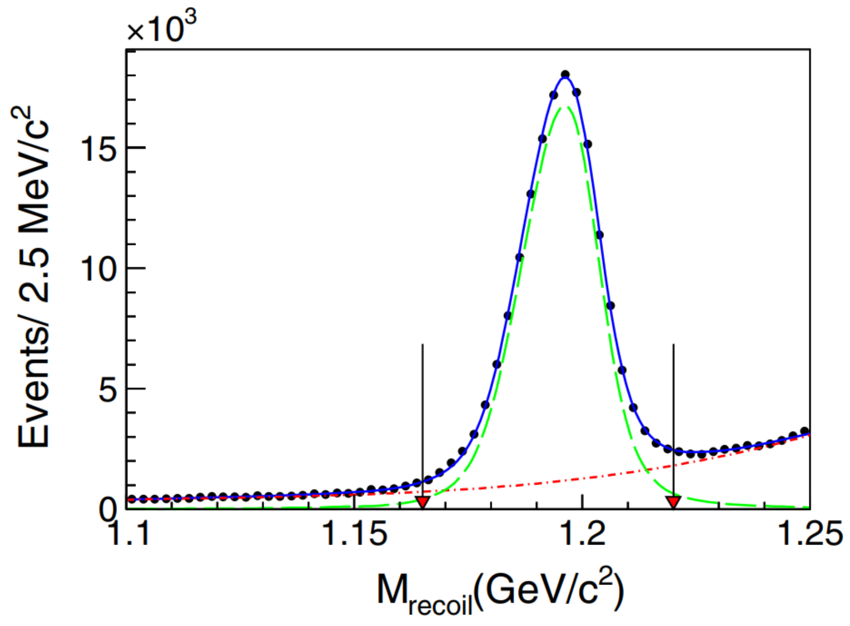
tag side: $\bar{\Sigma}(1385)^+ \to \bar{\Lambda}\pi^+$

Search for signal by looking at the recoiling mass of $\bar{\Sigma}(1385)^+$

Only reconstruct Σ^+ for $\Sigma^- \to \Sigma^+ X$

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

- Blind analysis



MC simulated shape convolved with a Gaussian function + 2nd order Chebyshev polynomial

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

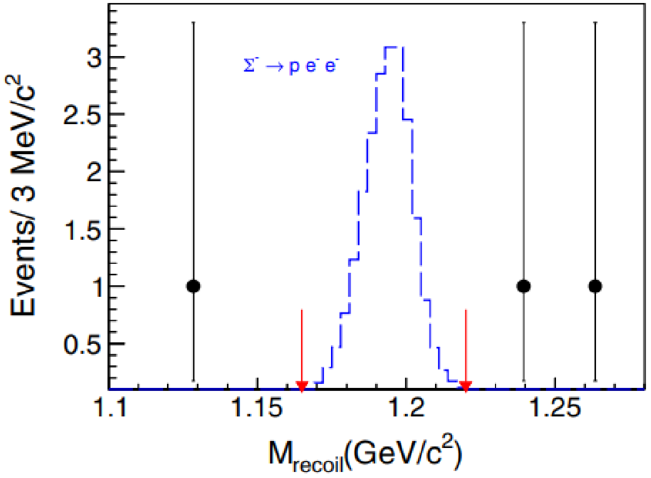
PRD103, 052011

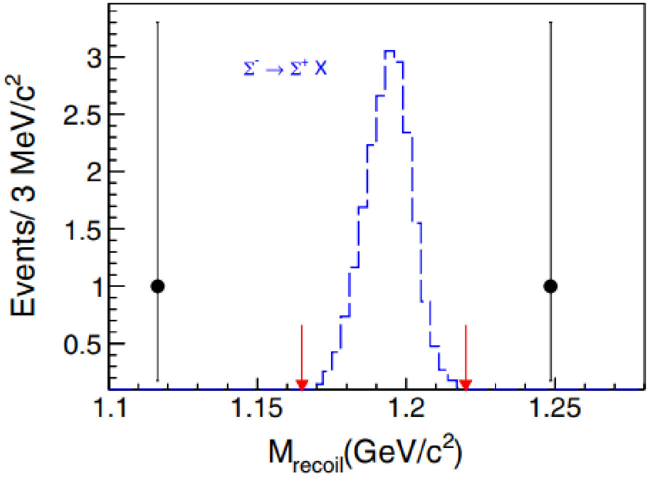
- Implemented by the package TROLKE

- UL @ 90% C.L.

$$\mathcal{B}(\Sigma^- \to pe^-e^-) < 6.7 \times 10^{-5},$$
$$\mathcal{B}(\Sigma^- \to \Sigma^+ X) < 1.2 \times 10^{-4}.$$

first search



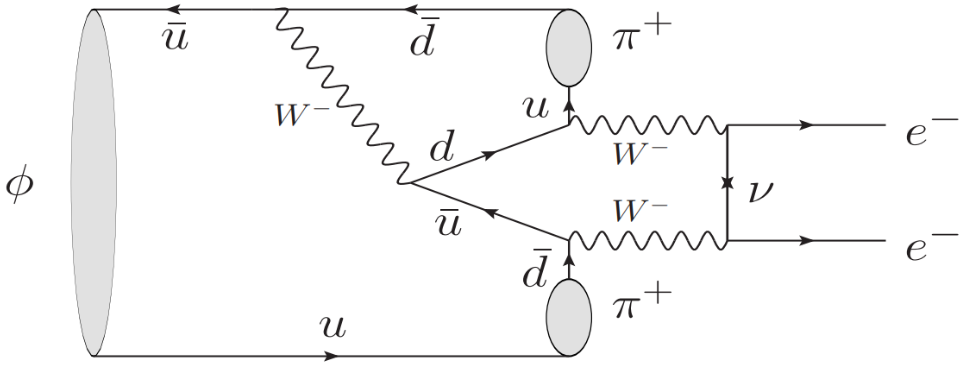


$\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$

arXiv: 2308.05490

- Extremely suppressed by several loops

- If any hint can be seen, definitely signal for new physics



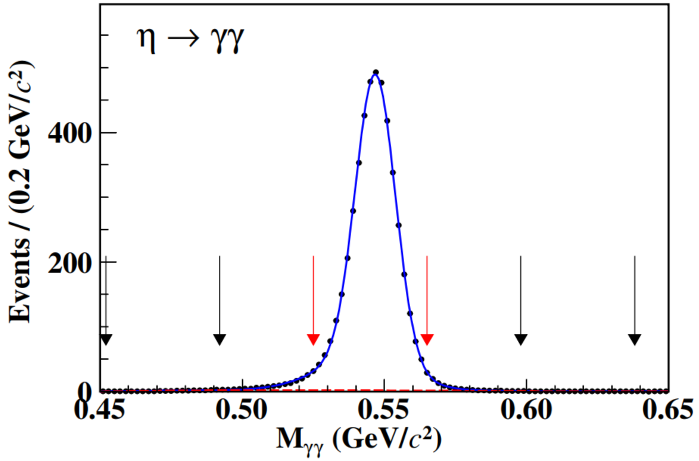
$\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$

arXiv: 2308.05490

- Data: about 10 billion J/ψ events @3.097 GeV

- Relative measurement to $\phi \to K^+K^-$, lots of uncertainties cancelled

$$\mathcal{B}(\phi \to \pi\pi ee) = \mathcal{B}(\phi \to KK) \times \frac{\frac{N^{\text{net}}_{\pi\pi ee}}{\varepsilon_{\pi\pi ee}}}{\frac{N^{\text{net}}_{KK}}{\varepsilon_{KK}}} = \mathcal{B}(\phi \to KK) \times \frac{N^{\text{net}}_{\pi\pi ee}/\varepsilon_{\pi\pi ee}}{N^{\text{net}}_{KK}/\varepsilon_{KK}}$$

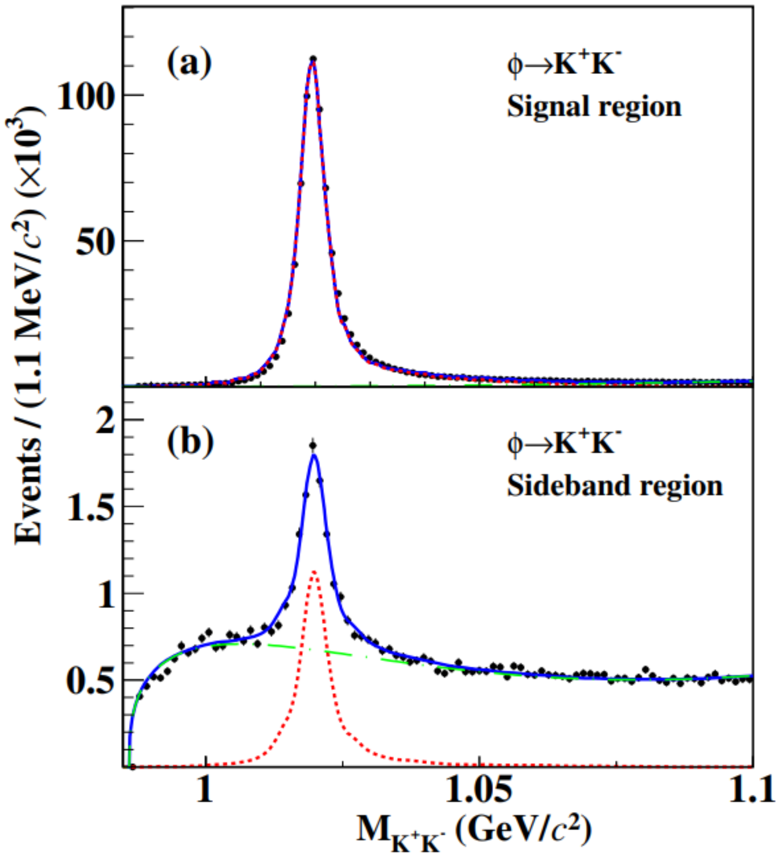


- Signal identified with two variables: $M_{\pi^+\pi^+e^-e^-}$ & $M_{\gamma\gamma}$

- Blind analysis

$\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$

arXiv: 2308.05490



$$N_{\rm obs}^{\rm MC} = N_{\phi\to K^+K^-}^{\rm signal} - \frac{1}{2} \times N_{\phi\to K^+K^-}^{\rm sideband}$$

$$\varepsilon_{KK} = \frac{N_{\rm obs}^{\rm MC}}{N_{\rm total}^{\rm MC}} = \frac{471297}{1000000} = 47.1\%$$

$$N_{K^+K^-}^{\rm net} = N_{\rm signal} - \frac{1}{2} \times N_{\rm sideband} = 822665 \pm 1149$$

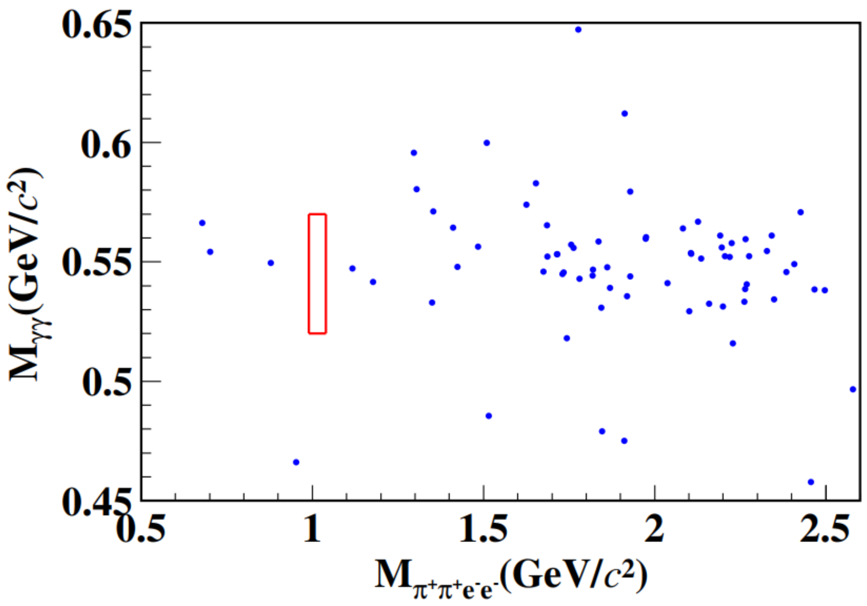
MC simulated shape convolved with a double Gaussian function

+

inverted ARGUS function multiplied by a 4th order polynomial

$\phi \to \pi^+\pi^+e^-e^-$ via $J/\psi \to \phi\eta$

arXiv: 2308.05490



- No signal was observed. UL @ 90% C.L. calculated with TROLKE

first search

$$\mathcal{B}(\phi \to \pi^+\pi^+e^-e^-) < 3.7 \times 10^{-6}$$

Prospects

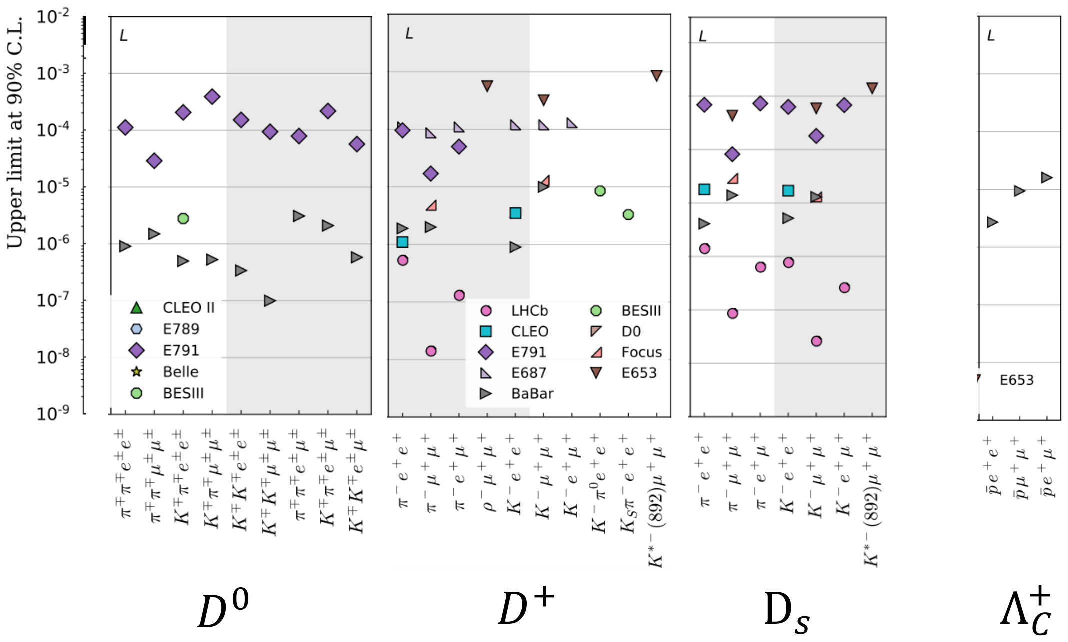
BESIII Collaboration, Future physics programme of BESIII,
Chin. Phys. C 44 (2020), 040001

- BESIII has a potential to search for LNV transitions such as $D^+ \to l^+ l^+ X^-$ and $D_s^+ \to l^+ l^+ X^-$, due to the clean environment and low charge confusion rates.

- With the coming 20 fb^{-1} of $\psi(3770)$ data, can perform more sensitive searches for LNV processes of D mesons.
  - could improve the best upper limit to 4.6×10^{-7} and 2.3×10^{-7} for $D^+ \to \pi^- e^+ e^+$ and $D^+ \to K^- e^+ e^+$.

Prospects

Averages of b-hadron, c-hadron, and τ-lepton properties as of 2021. (HFLAV Collaboration). PhysRevD.107.052008



- Many modes haven't been searched for.
- Four-body LNV decays of D_s; LNV processes of charmed baryons.

Prospects

- LNV processes of charmonium particles such as J/ψ

- of mesons such as ω, η/η', K_S^0

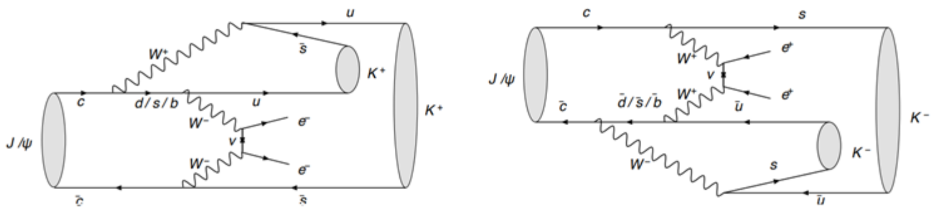


Figure 1: One possible Feynman diagram of $J/\psi \to K^+K^+e^-e^- + c.c.$.

BESIII Document 1091

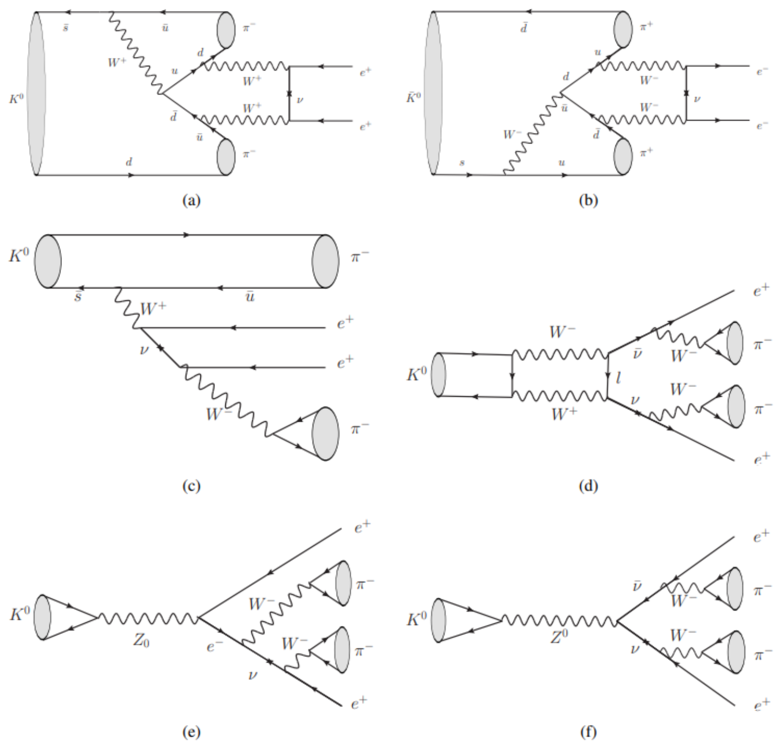


Fig. 1: Possible Feynman diagrams of $\bar{K}^0 \to \pi^+\pi^+e^-e^- + c.c.$

BESIII BAM-00651

Summary

- In recent years, BESIII have searched for LNV processes.

  Upper limits of many processes have been determined, providing stringent restrictions on the parameters of the future theoretical development.

- With the coming 20 fb^{-1} data samples, more and better results for LNV process searching are expected.

Back Up

Chin.Phys. C39,013101

$$\begin{aligned}\mathcal{M} &= 2G_{\mathrm{F}}^2 V_{\mathrm{cs}} V_{\mathrm{ud}} \langle K|\bar{s}\gamma^\mu(1-\gamma_5)c|D\rangle\langle\pi|\bar{u}\gamma^\nu(1-\gamma_5)d|0\rangle \\ &\times\Bigg[V_{1\mathrm{N}}^2 m_{\mathrm{N}}\bar{u}(p_2)\Bigg(\frac{\gamma^\mu\gamma^\nu}{q_{\mathrm{N}}^2-m_{\mathrm{N}}^2+\mathrm{i}\Gamma_{\mathrm{N}}m_{\mathrm{N}}} \\ &+\frac{\gamma^\nu\gamma^\mu}{q_{\mathrm{N}}'^2-m_{\mathrm{N}}^2+\mathrm{i}\Gamma_{\mathrm{N}}m_{\mathrm{N}}}\Bigg)P_{\mathrm{R}}v(p_3)\Bigg], \qquad (4)\end{aligned}$$

$$f_i=\frac{|\mathcal{M}_i|^2}{\sum_i|\mathcal{M}_i|^2}|\sum_i\mathcal{M}_i|^2,$$

$$|\mathcal{M}|^2=|\sum_i\mathcal{M}_i|^2=\sum_i f_i.$$

$$\begin{aligned}\mathcal{C}_1 =\ & f_\pi^2|PN_2|^2G_{\mathrm{F}}^4|V_{\mathrm{cs}}|^2|V_{\mathrm{ud}}|^2\Big\{8D_0^2(f_0-f_1)^2m_{\mathrm{K}}^4(-2m_\pi^2((p_{23}+p_{24}-p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4-2p_{23}p_{34}) \\ &+4p_{34}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23})+m_{\mathrm{K}}^2(16f_1(-D_0(f_0-f_1)(-2m_\pi^2((p_{12}+p_{13}+p_{23}+p_{24}-p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-p_{14}p_{23}+p_{13}p_{24}-p_{12}p_{34}-2p_{23}p_{34})+4p_{34}((p_{14}+p_{34})m_{\mathrm{l}}^2+p_{14}p_{23}-p_{13}p_{24}+p_{12}p_{34} \\ &+p_{23}p_{34})+m_\pi^4p_{23})+2f_1m_\pi^2p_{23}-4f_1p_{24}p_{34})-16D_0^2(f_0-f_1)^2m_{\mathrm{D}}^2(-2m_\pi^2((p_{23}+p_{24}-p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-2p_{23}p_{34})+4p_{34}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23}))+8D_0^2(f_0-f_1)^2m_{\mathrm{D}}^4(-2m_\pi^2((p_{23}+p_{24}-p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-2p_{23}p_{34})+4p_{34}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23})+16D_0(f_0-f_1)f_1m_{\mathrm{D}}^2(-2m_\pi^2((p_{12}+p_{13}+p_{23} \\ &+p_{24}-p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4-p_{14}p_{23}+p_{13}p_{24}-p_{12}p_{34}-2p_{23}p_{34})+4p_{34}((p_{14}+p_{34})m_{\mathrm{l}}^2+p_{14}p_{23} \\ &-p_{13}p_{24}+p_{12}p_{34}+p_{23}p_{34})+m_\pi^4p_{23})+8f_1^2(-2m_\pi^2((2p_{12}+2p_{13}+p_{23}+p_{24}-p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4 \\ &+4p_{12}p_{13}-2p_{14}p_{23}+2p_{13}p_{24}-2p_{12}p_{34}-2p_{23}p_{34})+4p_{34}((2p_{14}+p_{34})m_{\mathrm{l}}^2+4p_{12}p_{14}+2p_{14}p_{23} \\ &-2p_{13}p_{24}+2p_{12}p_{34}+p_{23}p_{34})+m_\pi^4p_{23})\Big\}\end{aligned}$$

$$\begin{aligned}\mathcal{C}_2 =\ & f_\pi^2|PN_3|^2G_{\mathrm{F}}^4|V_{\mathrm{cs}}|^2|V_{\mathrm{ud}}|^2\Big\{8D_0^2(f_0-f_1)^2m_{\mathrm{K}}^4(-2m_\pi^2((p_{23}-p_{24}+p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4-2p_{23}p_{24}) \\ &+4p_{24}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23})+m_{\mathrm{K}}^2(16f_1(-D_0(f_0-f_1)(-2m_\pi^2((p_{12}+p_{13}+p_{23}-p_{24}+p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-p_{14}p_{23}-p_{13}p_{24}-2p_{23}p_{24}+p_{12}p_{34})+4p_{24}((p_{14}+p_{24})m_{\mathrm{l}}^2+p_{14}p_{23}+p_{13}p_{24}+p_{23}p_{24} \\ &-p_{12}p_{34})+m_\pi^4p_{23})+2f_1m_\pi^2p_{23}-4f_1p_{24}p_{34})-16D_0^2(f_0-f_1)^2m_{\mathrm{D}}^2(-2m_\pi^2((p_{23}-p_{24}+p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-2p_{23}p_{24})+4p_{24}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23}))+8D_0^2(f_0-f_1)^2m_{\mathrm{D}}^4(-2m_\pi^2((p_{23}-p_{24}+p_{34})m_{\mathrm{l}}^2 \\ &+m_{\mathrm{l}}^4-2p_{23}p_{24})+4p_{24}^2(m_{\mathrm{l}}^2+p_{23})+m_\pi^4p_{23})+16D_0(f_0-f_1)f_1m_{\mathrm{D}}^2(-2m_\pi^2((p_{12}+p_{13}+p_{23} \\ &-p_{24}+p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4-p_{14}p_{23}-p_{13}p_{24}-2p_{23}p_{24}+p_{12}p_{34})+4p_{24}((p_{14}+p_{24})m_{\mathrm{l}}^2+p_{14}p_{23} \\ &+p_{13}p_{24}+p_{23}p_{24}-p_{12}p_{34})+m_\pi^4p_{23})+8f_1^2(-2m_\pi^2((2p_{12}+2p_{13}+p_{23}-p_{24}+p_{34})m_{\mathrm{l}}^2+m_{\mathrm{l}}^4 \\ &-2(p_{14}p_{23}+(p_{13}+p_{23})p_{24})+2p_{12}(2p_{13}+p_{34}))+4p_{24}((2p_{14}+p_{24})m_{\mathrm{l}}^2+2p_{14}p_{23}+p_{23}p_{24} \\ &+2p_{13}(2p_{14}+p_{24})-2p_{12}p_{34})+m_\pi^4p_{23})\Big\}\end{aligned}$$

$$\begin{aligned}\mathcal{C}_3 =\ & f_\pi^2PN_2^*PN_3G_{\mathrm{F}}^4|V_{\mathrm{cs}}|^2|V_{\mathrm{ud}}|^2\Big\{8D_0^2(f_0-f_1)^2(p_{23}m_\pi^4+2(m_{\mathrm{l}}^4+p_{23}m_{\mathrm{l}}^2+p_{23}(p_{24}+p_{34}))m_\pi^2 \\ &-2(m_{\mathrm{l}}^2(p_{24}^2+p_{34}^2)-2p_{23}p_{24}p_{34}))m_{\mathrm{D}}^4+16D_0(f_0-f_1)f_1(p_{23}m_\pi^4+2(m_{\mathrm{l}}^4+(p_{12}+p_{13}+p_{23})m_{\mathrm{l}}^2 \\ &+p_{23}(p_{14}+p_{24}+p_{34}))m_\pi^2-2((p_{24}^2+p_{34}^2+p_{14}(p_{24}+p_{34}))m_{\mathrm{l}}^2+p_{13}p_{24}^2+p_{12}p_{34}^2-p_{12}p_{24}p_{34} \\ &-p_{13}p_{24}p_{34}-2p_{23}p_{24}p_{34}-p_{14}p_{23}(p_{24}+p_{34})))m_{\mathrm{D}}^2+\zeta(-32\mathrm{i}(m_\pi^2+2p_{14}+p_{24}+p_{34})f_1^2 \\ &-32iD_0(f_0-f_1)m_{\mathrm{D}}^2(m_\pi^2+p_{24}+p_{34})f_1+32iD_0(f_0-f_1)m_{\mathrm{K}}^2(m_\pi^2+p_{24}+p_{34})f_1) \\ &+8D_0^2(f_0-f_1)^2m_{\mathrm{K}}^4(p_{23}m_\pi^4+2(m_{\mathrm{l}}^4+p_{23}m_{\mathrm{l}}^2+p_{23}(p_{24}+p_{34}))m_\pi^2-2(m_{\mathrm{l}}^2(p_{24}^2+p_{34}^2)-2p_{23}p_{24}p_{34})) \\ &+8f_1^2(p_{23}m_\pi^4+2(m_{\mathrm{l}}^4+(2p_{12}+2p_{13}+p_{23})m_{\mathrm{l}}^2+4p_{12}p_{13}+p_{23}(2p_{14}+p_{24}+p_{34}))m_\pi^2 \\ &-2((p_{24}^2+p_{34}^2)m_{\mathrm{l}}^2-4p_{14}^2p_{23}+2p_{14}((p_{24}+p_{34})m_{\mathrm{l}}^2+2p_{13}p_{24}-p_{23}p_{24}+2p_{12}p_{34}-p_{23}p_{34}) \\ &-2(p_{13}(p_{34}-p_{24})p_{24}+p_{34}(p_{12}p_{24}+p_{23}p_{24}-p_{12}p_{34}))))+m_{\mathrm{K}}^2(-16D_0^2(f_0-f_1)^2(p_{23}m_\pi^4 \\ &+2(m_{\mathrm{l}}^4+p_{23}m_{\mathrm{l}}^2+p_{23}(p_{24}+p_{34}))m_\pi^2-2(m_{\mathrm{l}}^2(p_{24}^2+p_{34}^2)-2p_{23}p_{24}p_{34}))m_{\mathrm{D}}^2 \\ &-16D_0f_1(f_0(p_{23}m_\pi^4+2(m_{\mathrm{l}}^4+(p_{12}+p_{13}+p_{23})m_{\mathrm{l}}^2+p_{23}(p_{14}+p_{24}+p_{34}))m_\pi^2 \\ &-2((p_{24}^2+p_{34}^2+p_{14}(p_{24}+p_{34}))m_{\mathrm{l}}^2+p_{13}p_{24}^2+p_{12}p_{34}^2-p_{12}p_{24}p_{34}-p_{13}p_{24}p_{34}-2p_{23}p_{24}p_{34} \\ &-p_{14}p_{23}(p_{24}+p_{34})))+f_1(p_{23}m_\pi^4-2(m_{\mathrm{l}}^4+(p_{12}+p_{13}-p_{23})m_{\mathrm{l}}^2-2p_{23}^2+p_{14}p_{23}-p_{23}p_{24} \\ &-p_{23}p_{34}+2p_{24}p_{34})m_\pi^2+2((p_{24}^2-4p_{34}p_{24}+p_{34}^2+p_{14}(p_{24}+p_{34}))m_{\mathrm{l}}^2+p_{13}p_{24}^2+p_{12}p_{34}^2-4p_{24}p_{34}^2 \\ &-4p_{24}^2p_{34}-p_{12}p_{24}p_{34}-p_{13}p_{24}p_{34}-6p_{23}p_{24}p_{34}-p_{14}p_{23}(p_{24}+p_{34})))))\Big\}+\mathrm{h.c.}\end{aligned}$$

$$|\mathcal{M}|^2=\mathcal{C}_1+\mathcal{C}_2+\mathcal{C}_3$$

PRD87,036010

The most general form of the low-energy effective Lagrangian that is relevant for LNV semileptonic hyperon decays

$$
\begin{aligned}
-\mathcal{L}_{\beta\beta} = \frac{G_F^2}{\Lambda_{\beta\beta}}\{c_1(\bar{u}\Gamma_i d)(\bar{u}\Gamma_j d) + c_2[(\bar{u}\Gamma_i d)(\bar{u}\Gamma_j s) \\
+ (\bar{u}\Gamma_i s)(\bar{u}\Gamma_j d)] + c_3(\bar{u}\Gamma_i s)(\bar{u}\Gamma_j s)\}\{d_1(\bar{e}\Gamma_k e^c) \\
+ d_2(\bar{\mu}\Gamma_k \mu^c) + d_3(\bar{e}\Gamma_k \mu^c + \bar{\mu}\Gamma_k e^c)\}. \qquad (1)
\end{aligned}
$$