Sensitivities to secret neutrino interaction at meson decay and short baseline neutrino experiments

Pouya Bakhti

JeonBuk National University (JBNU)

pouya_bakhti@jbnu.ac.kr

The second Asian-European-Institute workshop for BSM, Jeju Island

November 14, 2022

Reference

- P. Bakhti and Y. Farzan, "Constraining secret gauge interactions of neutrinos by meson decays," Phys. Rev. D **95** (2017) no.9, 095008 [arXiv:1702.04187 [hep-ph]].
- P. Bakhti, Y. Farzan and M. Rajaee, "Secret interactions of neutrinos with light gauge boson at the DUNE near detector," Phys. Rev. D **99** (2019) no.5, 055019 [arXiv:1810.04441 [hep-ph]].
- M. Bahraminasr, P. Bakhti and M. Rajaee, "Sensitivities to secret neutrino interaction at FASERν," J. Phys. G **48** (2021) no.9, 095001 [arXiv:2003.09985 [hep-ph]].
- J. L. Feng, F. Kling, M. H. Reno, *et al.* "The Forward Physics Facility at the High-Luminosity LHC," [arXiv:2203.05090 [hep-ex]].
- P. Bakhti, M. Rajaee and S. Shin, "Sensitivities to secret neutrino interaction at FASERν2, FLARE100 and SHIP ", in progress

Overview

Introduction

Physics beyond SM

- Neutrinos are massive, therefore we need to extend the standard model
- We can introduce a new gauge interaction in which neutrinos are the only charged particles in contrast to electromagnetic interaction
- So called secret neutrino interaction
- $g_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta$
- Motivated by νDM models

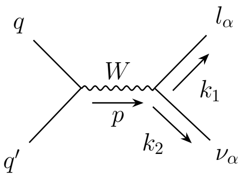
Chared mesons decay experiments

- Test of the standard model and beyond the standard model
- Leptonic meson decay is a two-body decay, and monochromatic, and is suppressed by m_l^2/m_M^2
- Leptonic meson decay is used to test lepton flavor universality
- Used to constrain new neutrino interactions
- We investigate the sensitivity of the leptonic decay of the charged meson to the new gauge interaction

Short-Baseline neutrino experiments

- Measurement of neutrino interaction cross-section
- Measurement of neutrino flux
- The standard model measurements
- Test of beyond three neutrino oscillation scheme such as sterile neutrino, Non-standard neutrino interaction, etc
- We investigate the sensitivity of short baseline neutrino experiments to the new gauge boson

Leptonic meson decay



$$\mathcal{M} = G_F f_M V_{qq'} p_\rho (u_1 \gamma^\rho P_L v_2) \quad (1)$$

P_L is chirality projection matrix, $P_L = \frac{1-\gamma^5}{2}$
f_M is meson structure constant
$V_{qq'}$ is element of the CKM matrix

Leptonic meson decay

$$|\mathcal{M}|^2 = G_F^2 f_M^2 V_{qq'}^2 p_\rho p_\sigma (u_1 \gamma^\rho P_L v_2)(v_2 P_R \gamma^\sigma u_1) \quad (2)$$

$$\sum_{spins} |\mathcal{M}|^2 = G_F^2 f_M^2 V_{qq'}^2 p_\rho p_\sigma Tr(\gamma^\rho P_L \not{k}_2 P_R \gamma^\sigma (\not{k}_1 + m_\mu)) \quad (3)$$

$$\sum_{spins} |\mathcal{M}|^2 = G_F^2 f_M^2 V_{qq'}^2 Tr(\not{p}\not{k}_2 P_R \not{p}\not{k}_1) = G_F^2 f_M^2 V_{qq'}^2 m_M^2 m_l^2 (1 - \frac{m_l^2}{m_M^2}) \quad (4)$$

$$\Gamma(M \longrightarrow l_\alpha \nu_\alpha) = \frac{G_F^2 f_M^2 V_{qq'}^2}{4\pi m_M^3} m_l^2 (m_M^2 - m_l^2)^2 \quad (5)$$

G_F is Fermi constant, f_M is Meson decay constant, and $V_{qq'}$ is element of CKM matrix

Leptonic meson decay

Leptonic branching ratio

$$R_M = \frac{\Gamma(M \longrightarrow e\nu_e)}{\Gamma(M \longrightarrow \mu\nu_\mu)} \tag{6}$$

$$R_M^{SM} = (\frac{m_e}{m_\mu})^2(\frac{m_M^2 - m_e^2}{m_M^2 - m_\mu^2})^2(1 + \delta R_{QED}), \tag{7}$$

δR_{QED} is electromagnetic correction

$m_e = 0.5109989461(13) MeV$

$m_\mu = 105.6583745(24)$

Leptonic meson decay

Leptonic branching ratio of pion decay

$$R_\pi = \frac{\Gamma(\pi \longrightarrow e\nu_e)}{\Gamma(\pi \longrightarrow \mu\nu_\mu)} = (1.2352 \pm 0.0002) \times 10^{-4} \quad (8)$$

$$m_\pi = 139.57018 \pm 0.00035 MeV$$

π^+ is made of $u\bar{d}$ and π^- is made of $\bar{u}d$

leptonic branching ratio of kaon decay

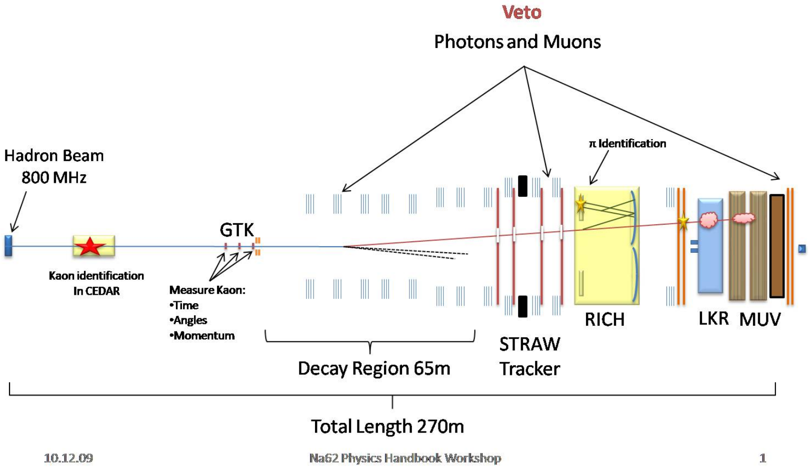
$$R_K = \frac{\Gamma(K \longrightarrow e\nu_e)}{\Gamma(K \longrightarrow \mu\nu_\mu)} = (2.477 \pm 0.0001) \times 10^{-5} \quad (9)$$

$$m_K = 493.667 \pm 0.013 MeV$$

K^+ is made of $u\bar{s}$ and K^- is made of $\bar{u}s$

Pion and Kaon rare decay experiments

NA62



https://na62.web.cern.ch/na62/Home/NA62Detector.html

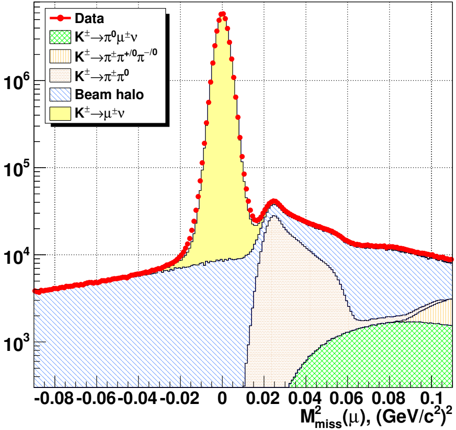
NA62

- In the North Area of the SPS accelerator at CERN
- Study rare decays of charged kaons
- In two body decay spectrum is monochromatic
  $P = p_1 + p_2$
  $p_1^2 = (P - p_2)^2 = M^2 + m_2^2 - 2E_2 M = m_1^2$
  $E_2 = \frac{M^2+m_2^2-m_1^2}{2M}$
  $E_1 = M - E_2 = \frac{M^2+m_1^2-m_2^2}{2M}$
- Kinematic identification: $M_{miss}^2(l) = (P_K - P_l)^2$

NA62

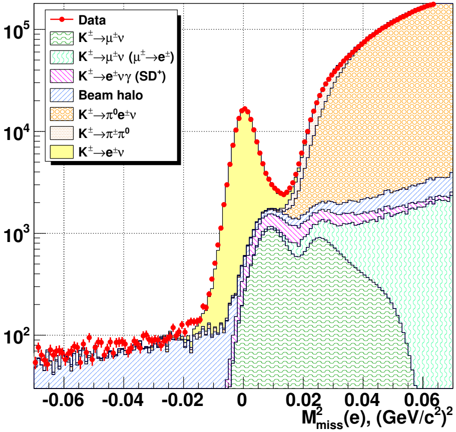
- NA62 criteria is
  $-M_1^2 < M_{miss}^2(l) < M_2^2$
  $M_1^2 \sim 0.013$ to 0.016
  $M_2^2 \sim 0.010$ to 0.013
- ~ 150000 reconstructed $K^{\pm} \longrightarrow e^{\pm}\nu_e$ events
- with 11% background
- kaons decay in flight with $74 \pm 1.4 GeV$ energy
- reconstructed lepton momentum is in the range of 13 to 65 GeV
- $R_K = (2.488 \pm 0.010) \times 10^{-5}$

NA62



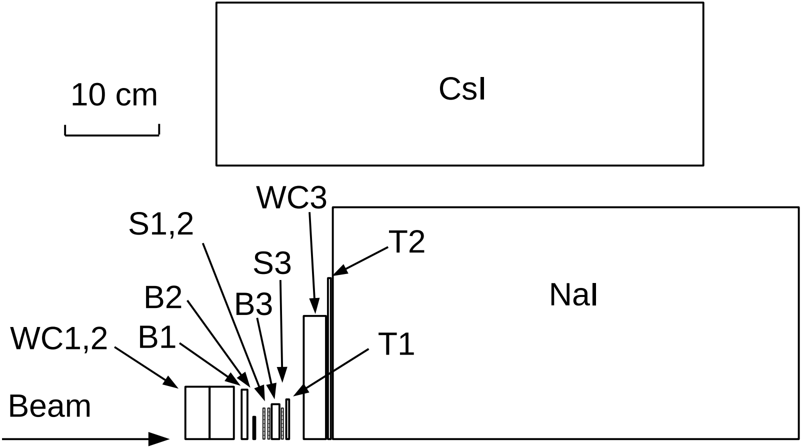
arXiv:1212.4012v2

NA62



arXiv:1212.4012v2

PIENU

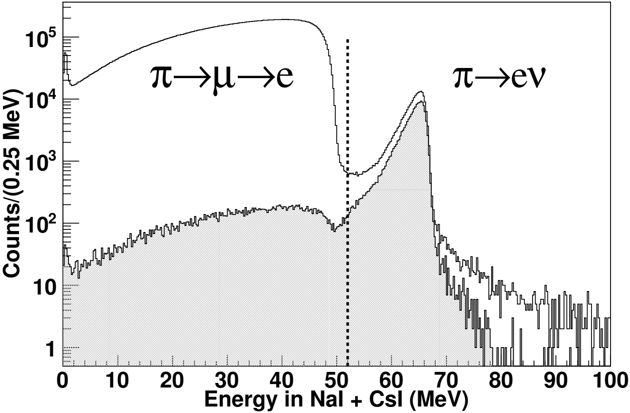


arXiv:1506.05845v2

PIENU

- $\pi^+ \to e^+\nu$, $E_{e^+} = 69.8$ MeV
- $\pi^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu$, $E_{e^+} = 0.5 - 52.8$ MeV
- pion at rest
- Energy cut equal to 53 MeV
- $R_\pi = [1.2344 \pm 0.0023(stat) \pm 0.0019(Syst)] \times 10^{-4}$
- In the near future statistical uncertainty reduces by a factor of 3

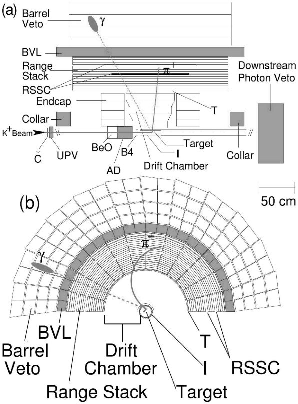
PIENU



arXiv:1506.05845v2

E949

- Brookhaven National Laboratory, USA
- 1.70×10^{12} stopped kaon
- $Br(K^+ \to \mu^+ \nu\nu\nu) < 2.4 \times 10^{-6}$ at 90 % C.L. , arXiv:1606.09054 [hep-ex]



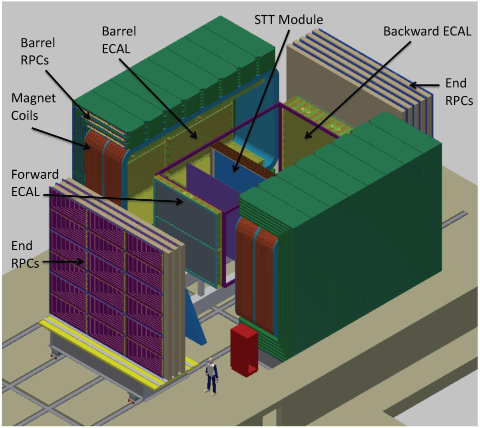
arXiv:1411.3963 [hep-ex]

Other constraints

- Old TRIUMF, (Phys. Rev. D **37** (1988) 1131),
  $R = \frac{\Gamma(\pi \to e\nu Z')}{\Gamma(\pi \to \mu\nu)} < 4 \times 10^{-6}$
- Nucl. Phys. B **149** (1979) 365,
  $Br(K^+ \to e^+\nu\nu\nu) < 6 \times 10^{-5}$ at 90 % C.L.
- KLOE, TREK, 1970s measurement of R_K

Short-baseline neutrino experiments

DUNE near detector

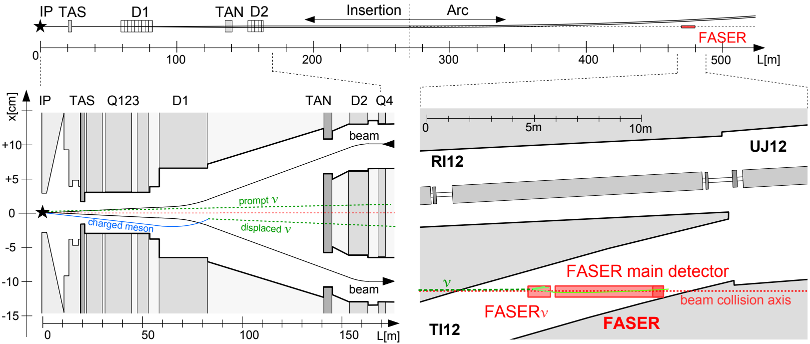


https://sciencesprings.files.wordpress.com/2019/10/fnal-dune-near-detector.png

DUNE near detector applications

- Neutrino flux measurement
- Neutrino cross-section measurements
- Determination of parton and gluon structure function
- Test of sum rules
- Nuclear structure of Ar, Pb, Fe, and C targets (Form factors, etc)
- QCD measurements
- Weak angle measurement
- Beyond SM measurements

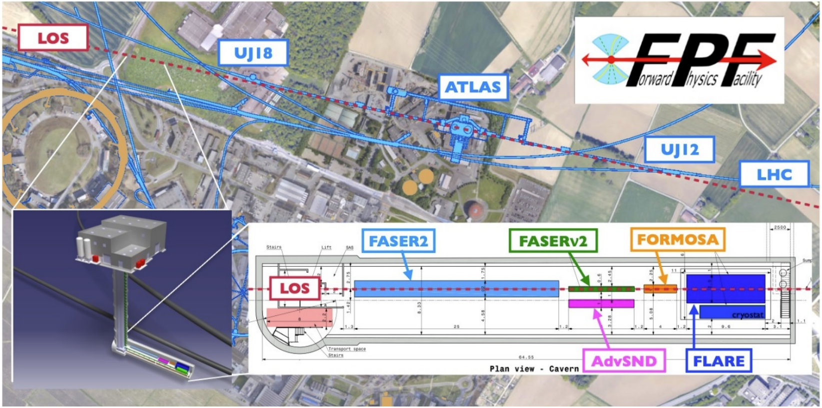
FASER and FASERν



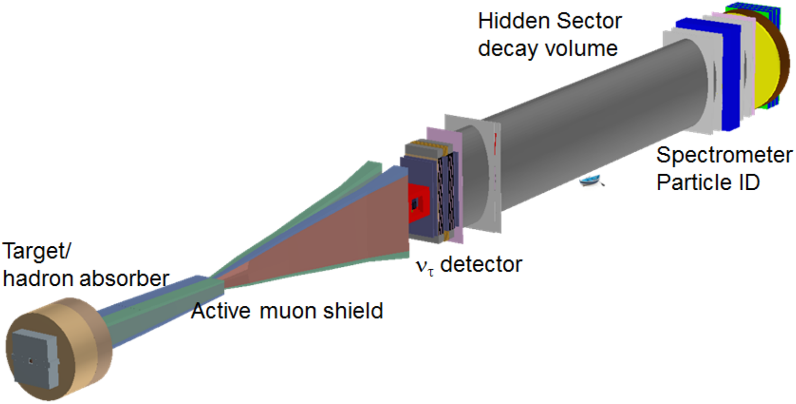
FASERν

- Detect collider neutrinos for the first time
- Detector is located 480 m from ATLAS IP
- FASERν is an emulsion detector
- Detect tau neutrinos
- Neutrino cross-section measurements and nucleon structure
- Charm meson production and decay and study Quantum Chromodynamics
- Reduction of atmospheric neutrino flux uncertainaties
- Test of physics beyond the standard model
- FASERν2 and FLARE are future detectors at high luminosity LHC

FASERν2 and FLARE

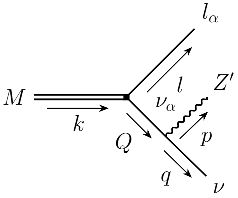


SHIP experiment (Beam Dump Facility)



A new meson decay mode

A new meson decay mode



$$\mathcal{M} = g_{\alpha i} G_F f_M V_{qq'} k_\mu \varepsilon_\alpha(p) \bar{u}(l) \gamma^\mu P_L \frac{\not{Q}}{Q^2} \gamma^\alpha P_L v(q), \tag{10}$$

$$\sum_{spins} |\mathcal{M}|^2 = g_{\alpha i}^2 G_F^2 f_M^2 V_{qq'}^2 \left(\sum_{polarization} \varepsilon_\alpha^*(p) \varepsilon_\beta(p) \right) tr \left(v(q)\bar{v}(q) P_R \gamma^\alpha \frac{Q^2 + m_l \not{Q}}{Q^2} u(l)\bar{u}(l) \frac{Q^2 + m_l \not{Q}}{Q^2} \gamma_\beta P_L \right) \tag{11}$$

A new meson decay mode

$$\sum_{spins} |\mathcal{M}|^2 = (\sum_i g_{\alpha i}^2) G_F^2 f_M^2 V_{qq'}^2 \left(g_{\alpha\beta} - \frac{p_\alpha p_\beta}{m_Z'^2} \right)$$
$$tr \left(\not{q} P_R \gamma^\alpha \frac{Q^2 + m_l \not{Q}}{Q^2} (\not{l} + m_l) \frac{Q^2 + m_l \not{Q}}{Q^2} \gamma_\beta P_L \right) \tag{12}$$

neglecting the lepton mass in the case of electron

$$\sum_{spins} |\mathcal{M}|^2 = (\sum_i g_{\alpha i}^2) G_F^2 f_M^2 V_{qq'}^2 \left(m_M^2 + m_{Z'}^2 - 2 m_M E_{Z'} \right.$$
$$\left. + \frac{(m_M^2 - m_{Z'}^2 - 2 m_M E_l)(m_M^2 - m_{Z'}^2 - 2 m_M E_\nu)}{m_{Z'}^2} \right) \tag{13}$$

A new meson decay mode

$$\Gamma(M \longrightarrow l_\alpha \nu Z') = \frac{1}{64\pi^3 m_M} \int_{E_l^{min}}^{E_l^{max}} \int_{E_\nu^{min}}^{E_\nu^{max}} dE_l dE_\nu \sum_{spins} |\mathcal{M}|^2. \qquad (14)$$

$$E_l^{min} = m_l, \qquad E_l^{max} = \frac{m_M^2 - m_{Z'}^2}{2m_M},$$

$$E_\nu^{min} = \frac{m_M^2 - m_{Z'}^2 - 2m_M E_l}{2m_M}, \qquad E_\nu^{max} = \frac{m_M^2 - m_{Z'}^2 - 2m_K E_l}{2(m_M - 2E_l)}$$

$$\Gamma(M \longrightarrow e\nu_\alpha Z') = \frac{g_{e\alpha}^2 G_F^2 \cos^2(\theta_C) f_M^2}{6144\pi^3 m_M^3 m_{Z'}^2} \left(m_M^8 + 72 m_M^4 m_{Z'}^4 - 64 m_M^2 m_{Z'}^6 + 24\left(3m_M^4 m_{Z'}^4 + 4m_M^2 m_{Z'}^6\right) \log\left(\frac{m_{Z'}}{m_M}\right) - 9m_{Z'}^8\right). \qquad (15)$$

A new meson decay mode

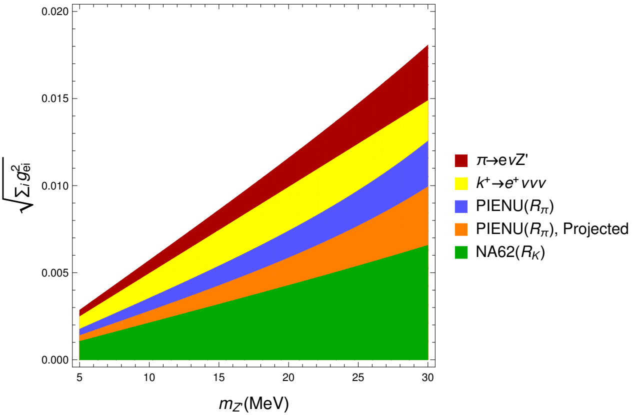
- Considering the lepton mass in the case of meson decay to the muon caused 5% correction
- In this case the decay rate is calculated numerically
- In the case of meson decay to electron, the effect of electron mass is negligible

A new meson decay mode

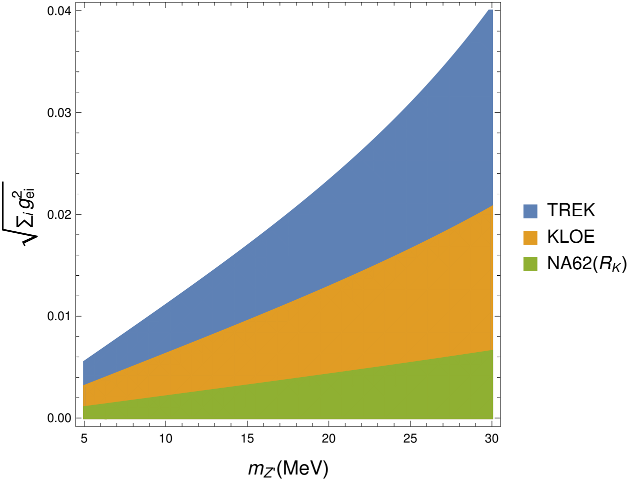
- $\Gamma_{SM}(M \longrightarrow l_\alpha \nu)$, $\Gamma(M \longrightarrow l_\alpha \nu Z')$, experimental R_M
- In the case of experimental that R_M is measured, we defined $\chi_K^2 = \frac{(R_K^{EXP} - R_K^{SM} - R_K^{NEW})^2}{\sigma^2}$
- In the case of NA62, because of kinematic criteria, $E_e > 233.68 MeV$
- We presented analitical formula for the spectrum of the Z' and produced neutrinos from meson and Z' decay, arXiv:1702.04187 [hep-ph].

Results

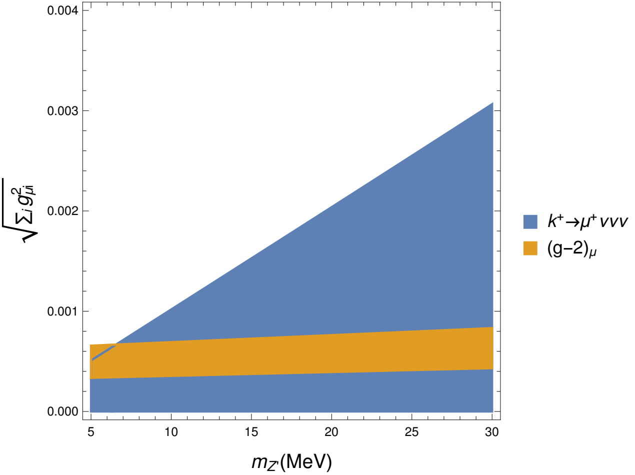
Constraining the coupling from decay to electron



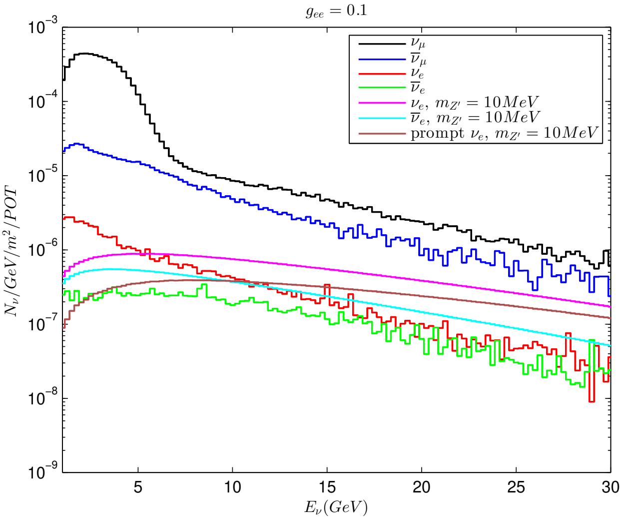
Constraining the coupling from decay to electron



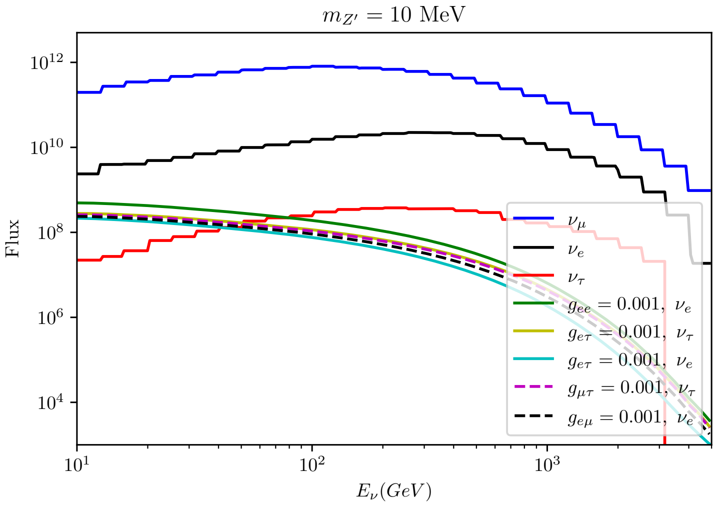
Constraining the coupling from decay to muon



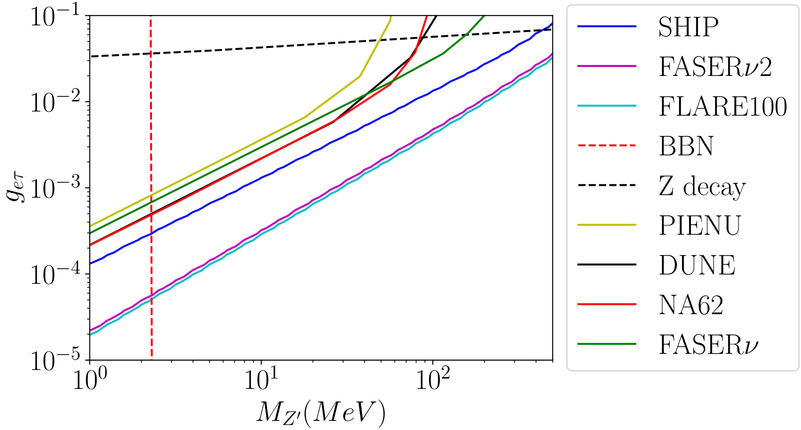
DUNE ND Spectrum



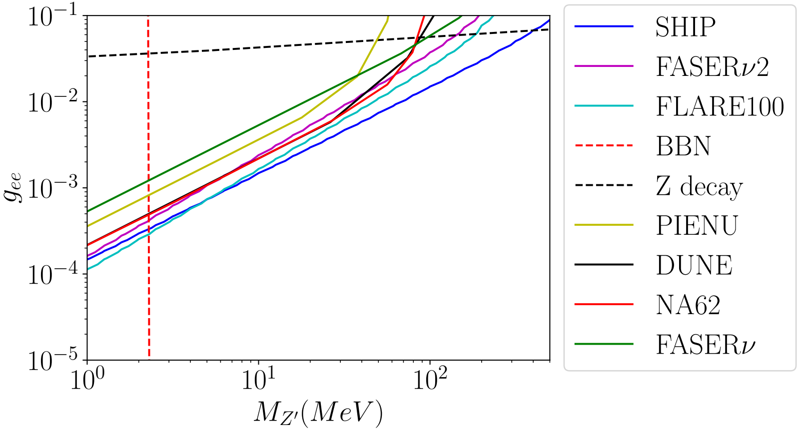
Neutrino flux at FASERν



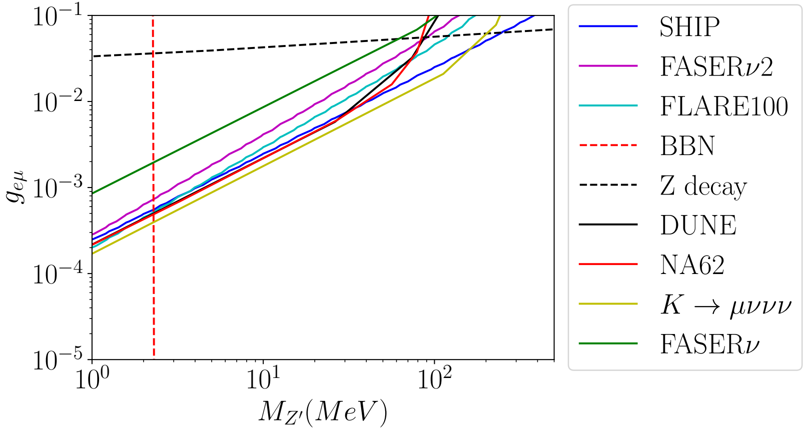
Constraining the coupling



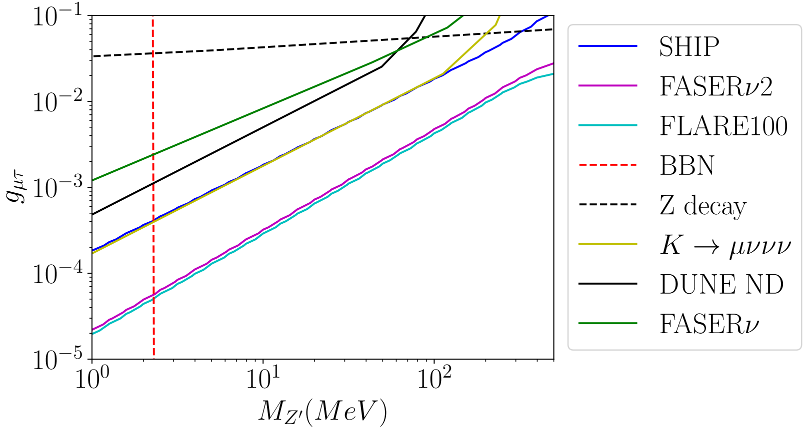
Constraining the coupling



Constraining the coupling



Constraining the coupling from FASERν



Summary

- Meson decay and short-baseline neutrino experiments constrain neutrinophilic interaction
- NA62 and E949 sets the most stringent bound on the coupling for $4\ MeV < m_{Z'} < 50\ MeV$
- DUNE ND will make comparable or more stringent constraints and has flavor sensitivity
- FASERν sets more stringent constraints for $50\ MeV < m_{Z'} < 150\ MeV$
- FASERν2, FLARE, and SHIP sets one order of magnitude more stringent constraints in $4\ MeV < m_{Z'} < 500\ MeV$

Thank you for your attention.