

**Valentina De Romeri**  
(IFT - Universidad Autonoma de Madrid)

# Impact of sterile neutrinos on cLFV processes

Workshop on Short Baseline Neutrino Oscillation Physics  
University of Pittsburgh - 26th January 2015



Based on works done in collaboration with A. Abada, A. Teixeira, S. Monteil, J. Orloff,  
JHEP 09 (2014) 074, JHEP 1504 (2015) 051, arXiv:1510.06657

# Outline

## 1) Lepton flavour violation and New Physics

- cLFV as a signal of New Physics
- cLFV observables and experimental status

## 2) Extending the SM with sterile fermions

- Motivation and theoretical framework
- Phenomenological impact and observational constraints

## 3) Sterile neutrinos and cLFV

- Radiative and 3 body decays
- Rare cLFV Z decays
- Nucleus assisted processes
- LNV: Neutrinoless double beta decay



# 1) Lepton flavour violation and new physics

# New physics beyond the SM?

- The Standard Model can explain most of the experimental results.  
However, there are some **theoretical and observational issues** to address:

- neutrino oscillations



- dark matter



- baryon asymmetry of the Universe

- Neutrino oscillations provide 1st laboratory evidence of New Physics

- The Standard Model **must be extended** (or embedded in larger framework)  
Many candidate models...

- New Physics actively searched for in many fronts:

- **High energy colliders** - direct searches of new states

LHC and future FCC, LC ...

- **High intensity facilities** - indirect searches (rare processes, deviations from SM)

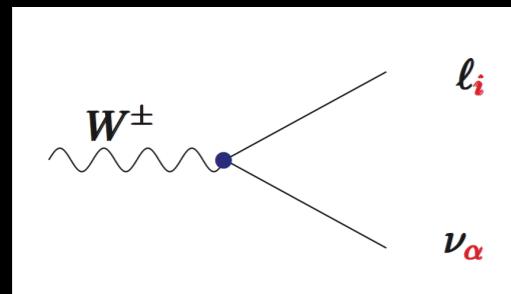
Belle, BaBar, MEG, ..., COMET

# Flavour in the SM

- Quark sector: the SM EW interactions preserve u,d, ... flavours
  - After EWSB there is misalignment of physical and interaction eigenstates
  - Quark flavour is violated by charged current interactions (CKM):  $V_{ij}^{\text{CKM}} W^\pm \bar{q}_i q_j$
  - Observed in many oscillation/decay processes: (mostly) very good agreement with SM  
 $K^0 - \bar{K}^0, b \rightarrow s\gamma, D^+ \rightarrow \pi^+ \mu^+ \mu^- (c\bar{d} \rightarrow u\bar{d})\dots$
- Lepton sector: original formulation only includes  $\nu_L$ 
  - Fermion generations are put by hand in separate doublets
  - In the SM, neutrinos are strictly massless (accidental  $U(1)_{B-L}$  symmetry):
    - absence of RH neutrino fields  $\rightarrow$  no Dirac mass term (no renormalizable mass term)
    - no Higgs triplet  $\rightarrow$  no Majorana mass term (would break the electroweak gauge symmetry, because it is not invariant under the weak isospin symmetry; does not conserve the lepton number L)
  - Strict conservation of total lepton number ( $L$ ) and lepton flavours ( $L_i$ )
- BUT ... neutral lepton flavour is violated through neutrino oscillations!  
(solar, atmospheric, reactor neutrino data)

# The SM lepton sector: lepton mixing

- Extend the SM to accommodate neutrino oscillations:
  - A new lepton sector: flavour violated in charged current interactions
  - Misalignment of physical (mass) eigenstates and  $SU(2)_L$  interaction eigenstates parameterised by the leptonic mixing matrix ( $U_{PMNS}$ )
- Pontecorvo-Maki-Nakagawa-Sakata matrix:  $U_{PMNS}$



$$\mathcal{L}_{\text{charged}}^{\text{lepton}} = U_{PMNS} \bar{\ell}_L W^\pm \nu_L + \text{h.c.} \quad (\nu_e, \nu_\mu, \nu_\tau) \xleftrightarrow{U_{PMNS}} (\nu_1, \nu_2, \nu_3)$$
$$|\nu_\alpha\rangle = U_{\alpha i}^* |\nu_i\rangle$$

- New degrees of freedom must be added to the SM:

$U_{PMNS}$ : 3 angles	Solar	$\theta_{12}, \theta_\odot$	CPV phases	Dirac	$\delta$
	Atmospheric	$\theta_{23}, \theta_\oplus$		[Majorana	$\phi_{1,2}$ ]
	Reactor	$\theta_{13}, \theta_{\text{Chooz}}$			

+ Neutrino masses ( $\Delta m^2$ )

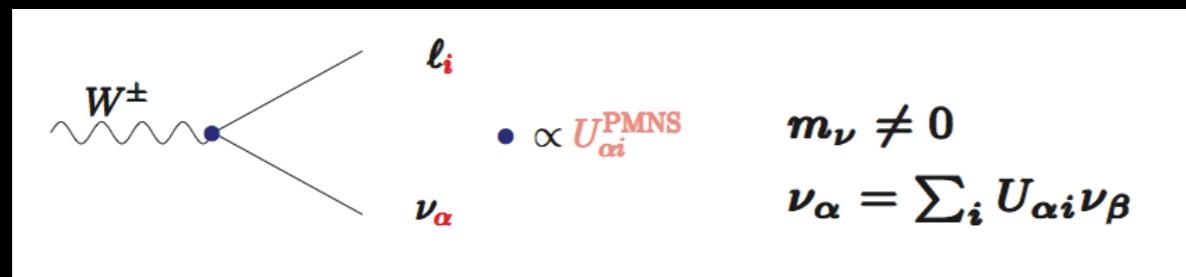
# Flavour violation in the SM

## ► Quark sector:

Quark flavour is violated by charged current interactions (CKM):  $V_{ij}^{CKM} W^\pm \bar{q}_i q_j$   
Observed in many oscillation/decay processes

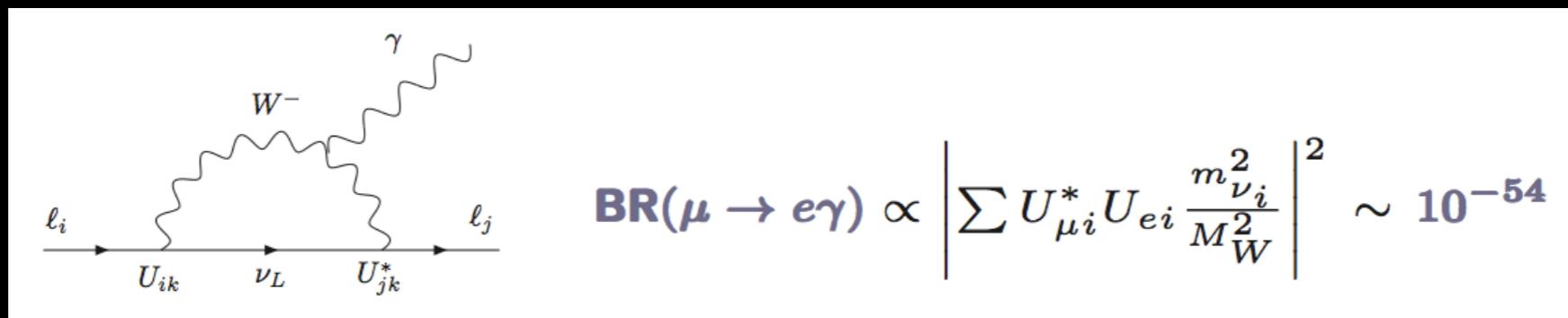
## ► Lepton sector:

Assume most minimal “ad-hoc extension” of the SM ( $m_\nu$   $\nu_L \nu_R$  (Dirac)):  $SM_{m_\nu}$   
Lepton flavour is also violated by charged current interactions ( $U_{PMNS}$ ) in  $SM_{m_\nu}$ !



[Cheng and Li '77; Petcov '77;  
Marciano and Sanda '77; Shrock  
and Lee...]

BUT... Negligible charged Lepton Flavour Violation (cLFV)



## ► Flavour violation in the lepton sector: new physics beyond $SM_{m_\nu}$ !

# Signals of lepton flavour violation

- Neutrino oscillations (neutral lepton flavour violation) [Dedicated experiments]

So far we have only upper bounds ... on possible cLFV observables

- Rare leptonic decays and transitions [High intensity facilities]  
(e.g.  $\mu - e$  conversion (Nuclei),  $\mu \rightarrow e\gamma$ ,  $\mu \rightarrow eee$ , mesonic  $\tau$  decays,  $\mu^- e^- \rightarrow e^- e^- \dots$ )

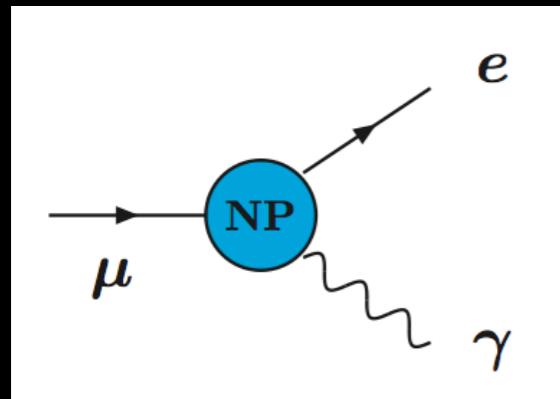
- Meson decays [LHCb, High intensity facilities]  
Violation of lepton flavour universality e.g.  $R_K$   
LFV final states  $B \rightarrow \tau \mu \dots$   
LNV decays  $B^- \rightarrow D^+ \mu^- \mu^- \dots$

- Rare (new) heavy particle decays (typically model-dependent): [colliders]  
 $Z \rightarrow l_1^\mp l_2^\pm$  , SUSY  $\tilde{l}_i \rightarrow l_j \chi^0$  , FV KK-excitation decays ...  
impact of LFV for new physics searches at colliders ...

e.g.  $H \rightarrow \tau \mu$  possible signal at  $2.4 \sigma$  (CMS) ??

- And many others ... all without SM theoretical background

# cLFV in muon channels: radiative decays



- ▶ cLFV decay:  $\mu^+ \rightarrow e^+ \gamma$
- ▶ Event signature:  $E_e = E_\gamma = m_\mu/2$  ( $\sim 52.8$  MeV)  
Back to back  $e^+ \gamma$  ( $\theta \sim 180^\circ$ ); time coincidence

- ▶ Backgrounds: prompt physics and accidental

Correlated: radiative  $\mu$  decays  $\mu^+ \rightarrow e^+ \gamma v_e \bar{v}_\mu$  (very low  $E_\gamma$ )

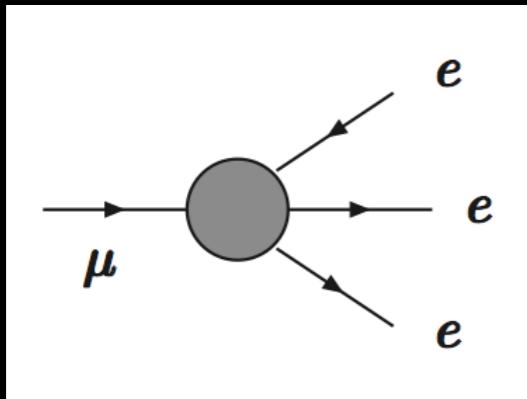
Accidental: coincidence of  $\gamma$  with positron from Michel decays  $\mu^+ \rightarrow e^+ v_e \bar{v}_\mu$ ;  
 $\gamma$  from  $\mu^+ \rightarrow e^+ \gamma v_e v_\mu$ ;  $\gamma$  from in flight  $e^+ e^-$  annihilation

- ▶ Current experimental status:

Collaboration	year	$BR(\mu \rightarrow e\gamma)$ 90% C.L.
LAMPF/MEGA	1999	$1.2 \times 10^{-11}$
PSI/MEG	2011	$2.8 \times 10^{-11}$
PSI/MEG	2013	$5.7 \times 10^{-13}$

- ▶ Future proposals: MEG II PSI (proposal 2013) sensitivity  $6 \times 10^{-14}$   
... intense proton beams: CERN (NuFact), FNAL (project X), JPARC, ...

# cLFV in muon channels: $\mu^+ \rightarrow e^+ e^- e^+$



► cLFV decay:  $\mu^+ \rightarrow e^+ e^- e^+$

► Event signature:  
common vertex, time coincidence

$$\sum E_e = m_\mu; \sum \vec{P}_e = \vec{0}$$

► Backgrounds:  $\Rightarrow$  correlated & accidental:

Prompt physics:  $\mu^+ \rightarrow e^+ e^- e^+ \nu_e \bar{\nu}_\mu$  decay (internal conversion of radiative  $\mu$  decay)

Accidental: Bhabha scattering of Michel  $e^+$  from  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$  with atomic  $e^-$ ;  
coincidence of Michel positrons with  $e^+ e^-$  from  $\gamma$ -ray conversion...

► Current experimental status:

Collaboration	year	$\text{BR}(\mu \rightarrow eee)$ 90% C.L.
LAMPF/Crystal Box	1988	$3.5 \times 10^{-11}$
<b>PSI/SINDRUM</b>	<b>1988</b>	<b><math>1.0 \times 10^{-12}</math></b>
JINR	1991	$3.6 \times 10^{-11}$

► Future prospects:

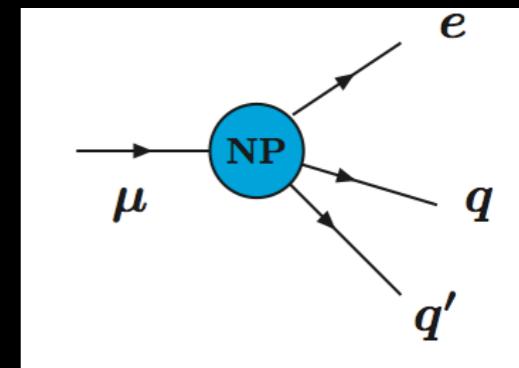
Mu3e Experiment at PSI Phase I ( $\sim 2017$ ):  $10^{-15} \Rightarrow$  Phase II ( $> 2018$ ):  $10^{-16}$

# cLFV in “muonic” atoms: $\mu^- - e^-$ conversion

- Muonic atoms: 1s bound state formed when  $\mu^-$  stopped in target
- Coherent conversion in a muonic atom [ $\mu + \text{Nucleus}$ ]:  $\mu^- + (\text{A}, \text{Z}) \rightarrow e^- + (\text{A}, \text{Z})$

SM-like processes: muon capture:  $\mu^- + (\text{A}, \text{Z}) \rightarrow \nu_\mu + (\text{A}, \text{Z}-1)$

muon decay in orbit:  $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$



- Event signature: single mono-energetic electron

$$E_{\mu e}^N = m_\mu - E_B(A, Z) - E_R(A, Z), \quad E_{\mu e}^{\text{Al, Pb, Ti}} \approx \mathcal{O}(100 \text{ MeV})$$

coherent conversion, increases with  $Z$  (maximal for  $30 \leq Z \leq 60$ )

- Backgrounds: SM processes; beam purity, cosmic rays..
- Experimental status (current and future)

CR( $\mu - e$ , N) bound	material	year
$4.3 \times 10^{-12}$	Ti	1993
$4.6 \times 10^{-11}$	Pb	1996
$7 \times 10^{-13}$	Au	2006

SINDRUM II

Experiment (material)	future sensitivity	year
Mu2e (Al)	$3 \times 10^{-17}$	$\sim 2021$
COMET (Al) - Phase I (II)	$10^{-15} (10^{-17})$	$\sim 2018(21)$
PRISM/PRIME (Ti)	$10^{-18}$	
DeeMe (SiC)	$10^{-14}$	

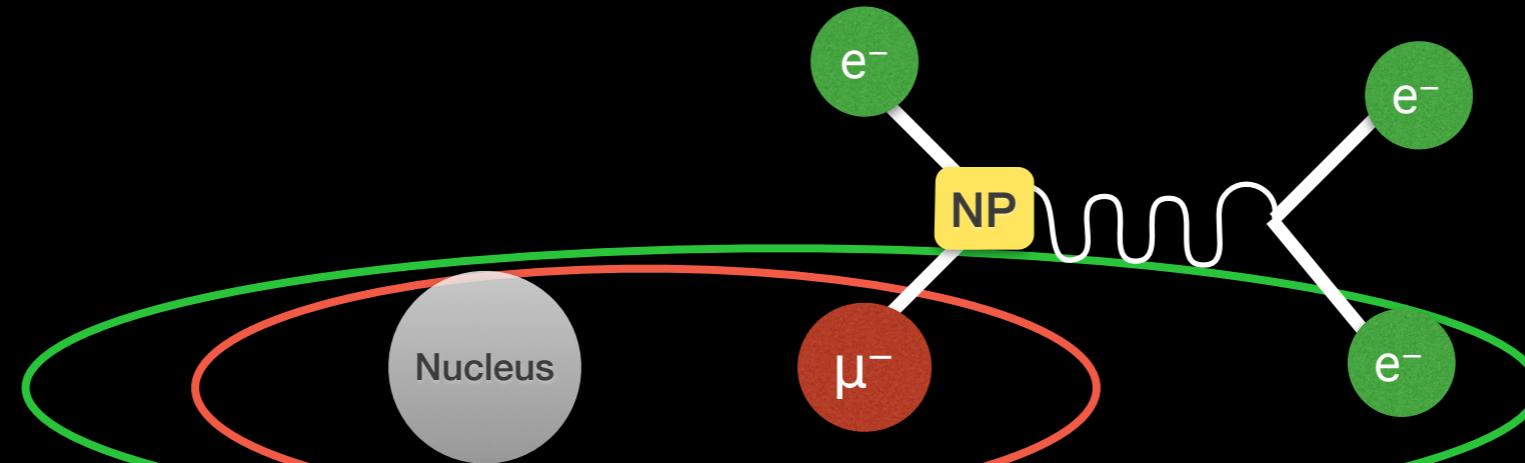
- $\mu^- - e^+$  conversion: (cLFV &  $\Delta L=2$ )  $\mu^- + (\text{A}, \text{Z}) \rightarrow e^+ + (\text{A}, \text{Z}-2)^*$

# cLFV in “muonic” atoms: rare decay $\mu^-e^- \rightarrow e^-e^-$

► Muonic atom decay:  $\mu^-e^- \rightarrow e^-e^-$

New process proposed by Koike et al.: decay of a bound  $\mu^-$  in a muonic atom

► Initial  $\mu^-$  and  $e^-$ : 1s states bound in Coulomb field of the muonic atom's nucleus



$$\Gamma(\mu^-e^- \rightarrow e^-e^-, N) \propto \sigma_{\mu e \rightarrow ee} v_{\text{rel}} [(Z-1)\alpha m_e]^3 / \pi$$

► Elementary process same as  $\mu^+ \rightarrow e^+e^+e^-$ , but with opposite charge

Clearer experimental signature (back to back electrons) and larger phase space

► Effective Interactions: contact and photonic interactions

► The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate (increasing overlap between  $\Psi_{\mu^-}$  and  $\Psi_{e^-}$ ) by  $(Z-1)^3$

► Within the reach of high-intensity muon beams (COMET's Phase II)

► Distortion effect of  $e^-e^-$  and relativistic treatment of the wave function of the bound leptons

Koike et al. Phys.Rev.Lett. 105 (2010) 121601

Uesaka et al. arXiv:1508.05747

# cLFV in “muonic” atoms: Muonium

- ▶ Muonium: hydrogen-like Coulomb bound state ( $e^-\mu^+$ ); free of hadronic interactions!

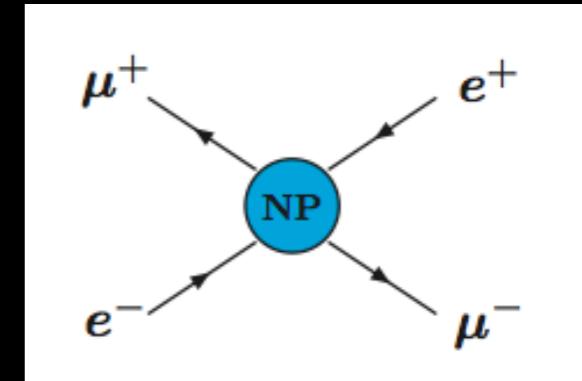
- ▶ Mu- $\overline{\text{Mu}}$  conversion:

Spontaneous conversion of a ( $e^-\mu^+$ ) into ( $e^+\mu^-$ )

Reflects a double lepton number violation:  $\Delta L_e = \Delta L_\mu = 2$

- ▶ Experimental status:  $P(\text{Mu}-\overline{\text{Mu}}) < 8.3 \times 10^{-11}$

(PSI, Willmann et al, 1999)



- ▶ cLFV Mu decay:  $\text{Mu} \rightarrow e^+e^-$

Clear signal compared to SM decay  $\text{Mu} \rightarrow e^+ e^- \nu_\mu \bar{\nu}_e$  (no missing energy)

- ▶ Experimental status: no clear roadmap (nor bounds)...

Hopefully included in COMET's Phase II programme

# Rare lepton processes: cLFV tau decays

► Tau production and decay:  $\tau^+ \tau^-$  production in  $e^+ e^-$  storage rings; candidate events are separated in 2 hemispheres in the centre of mass:

- signal hemisphere (search for cLFV)
- tagging hemisphere e.g.  $\tau \rightarrow e^+ e^- \nu_\tau \bar{\nu}_e$

► Radiative decays:  $\tau^\pm \rightarrow l^\pm \gamma$

- Event signature:  $E_{\text{final}} - \sqrt{s}/2 = \Delta E \sim 0$ ;  
 $M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$

Process	BR (BaBar, 2010)
$\tau \rightarrow e\gamma$	$3.3 \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$4.4 \times 10^{-8}$

- Backgrounds: coincidence of isolated leptons with  $\gamma$  (ISR, FSR); mistagging

► 3-body decays:  $\tau^\pm \rightarrow l_i^\pm l_j^\pm l_k^\pm$

- Event signature:  $E_{3\ell} - \sqrt{s}/2 \sim 0$ ;  $M_{3\ell} \sim m_\tau$

$3\ell$ final state	BR (BaBar)	BR (Belle)
$e^- e^+ e^-$	$2.9 \times 10^{-8}$	$2.7 \times 10^{-8}$
$\mu^- e^+ e^-$	$2.2 \times 10^{-8}$	$1.8 \times 10^{-8}$
$\mu^- e^- e^-$	$1.8 \times 10^{-8}$	$1.5 \times 10^{-8}$
$e^+ \mu^- \mu^-$	$2.6 \times 10^{-8}$	$1.7 \times 10^{-8}$
$e^- \mu^+ \mu^-$	$3.2 \times 10^{-8}$	$2.7 \times 10^{-8}$
$\mu^- \mu^+ \mu^-$	$3.3 \times 10^{-8}$	$2.1 \times 10^{-8}$

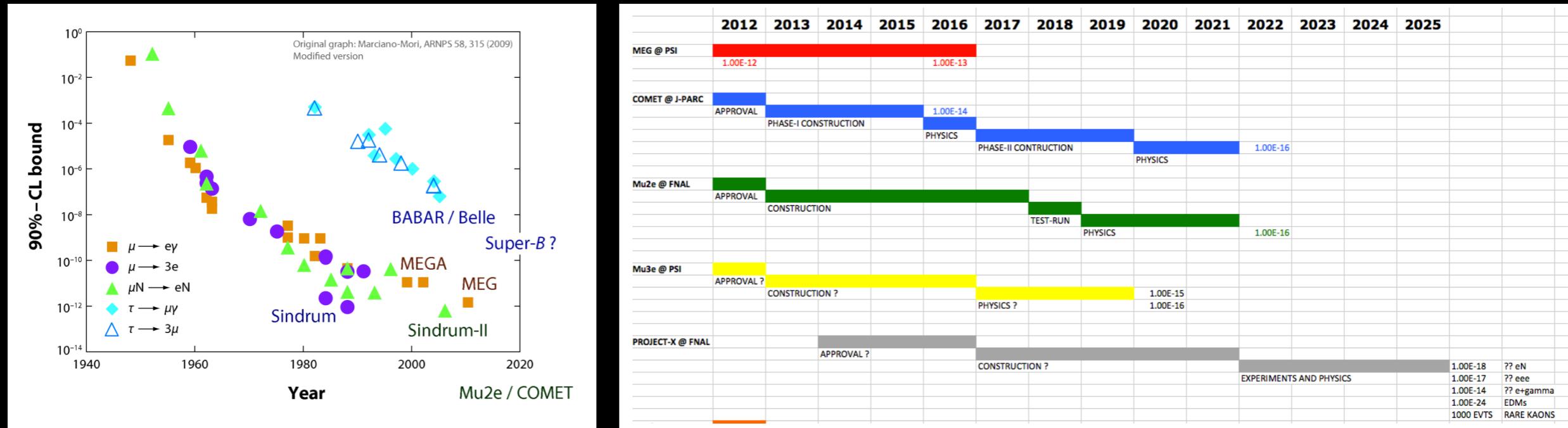
- Backgrounds: No irreducible bkg! small bkg from  $q\bar{q}$  and Bhabha pairs ...

► Experimental prospects: SuperB (SuperBelle) and/or Tau-charm factories

$$\text{BR}(\tau \rightarrow \ell\gamma) \leq 1 - 3 \times 10^{-9} \quad \text{BR}(\tau \rightarrow 3\ell) \leq 1 - 2 \times 10^{-10}$$

# CLFV: observables and experimental status

Remarkable experimental commitment world-wide!



	90% C.L. upper-limit	Future Sensitivity
$BR(\mu \rightarrow e\gamma)$	$5.7 \times 10^{-13}$ (MEG, '13)	$6 \times 10^{-14}$ (MEG)
$BR(\tau \rightarrow \mu\gamma)$	$4.4 \times 10^{-8}$ (BaBar, '10)	$10^{-(9-10)}$ (Super-KEKB)
$BR(\tau \rightarrow e\gamma)$	$3.3 \times 10^{-8}$ (BaBar, '10)	$10^{-(9-10)}$ (Super-KEKB)
$CR(\mu - e, Ti)$	$4.3 \times 10^{-12}$ (SINDRUM II, '93)	$10^{-18}$ (PRISM/PRIME)
$CR(\mu-e, Au)$	$7.0 \times 10^{-13}$ (SINDRUM II, '06)	–
$CR(\mu-e, Al)$	–	$10^{-16}$ (Mu2e/COMET)
$BR(\mu \rightarrow 3e)$	$1.0 \times 10^{-12}$ (SINDRUM, '88)	$10^{-14}$ (Mu3e)

► Impressive sensitivity to rare processes:  $10^{-18} \rightarrow$  about  $10^{19}$  muons  
(and  $\sim 10^{19}$  grains of sand on Earth...)



# cLFV collider signatures

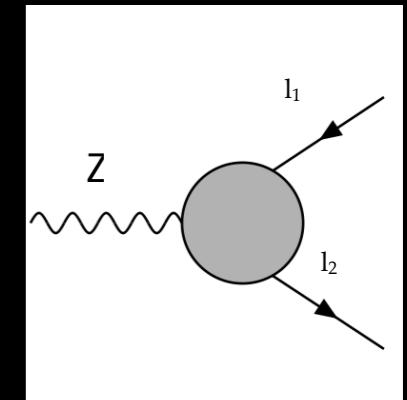
- ▶ Higgs boson decays:  $H \rightarrow l_1^\mp l_2^\pm$  (CMS, e.g. Arganda et al 14,15)  
A Higgs factory at LHC: ability to study rare processes..  
Current bounds:  $\text{BR}(H \rightarrow \mu^\mp \tau^\pm) < 0.0157$  Possible signal at  $2.4\sigma$  ??
- ▶ Exotic top quark decays:  $t \rightarrow q l_1^\mp l_2^\pm$  (Davidson et al. 14)  
If present, possibly within reach - LHC “top” factory
- ▶ At high energies, production of “on shell” new physics states:  
New interactions open the way to cLFV decays
- ▶ Future experimental prospects: Exciting ones at LHC run 2 !!  
Linear colliders / FCC-ee running at ZZ, HH, tt thresholds
- ▶ Multiplicity, composition, .. properties of final state strongly model-dependent  
e.g. SUSY cLFV extension of the SM

# cLFV collider signatures: rare Z decays

- Z bosons abundantly produced at LEP and at the LHC
- In the SM with lepton mixing ( $U_{PMNS}$ ) the theoretical predictions are:

$$BR(Z \rightarrow e^\pm \mu^\mp) \sim BR(Z \rightarrow e^\pm \tau^\mp) \sim 10^{-54}$$

$$BR(Z \rightarrow \mu^\pm \tau^\mp) \sim 4 \times 10^{-60}$$



- The detection of a rare decay as  $Z \rightarrow l_i^\mp l_j^\pm$  ( $i \neq j$ ) would serve as an indisputable evidence of new physics
- Current limits:

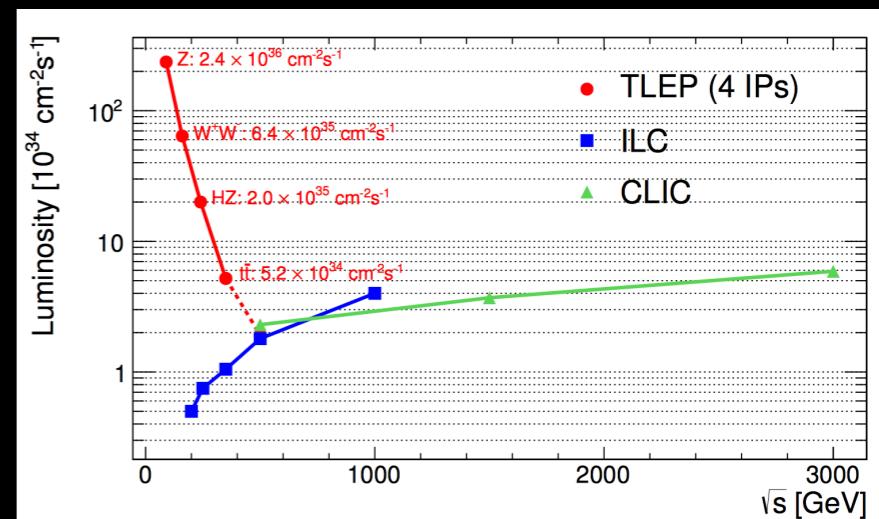
$BR(Z \rightarrow e^\mp \mu^\pm) < 1.7 \times 10^{-6}$	■ ■ ■ ■ →
$BR(Z \rightarrow e^\mp \tau^\pm) < 9.8 \times 10^{-6}$	
$BR(Z \rightarrow \mu^\mp \tau^\pm) < 1.2 \times 10^{-5}$	

$$Br (Z \rightarrow e\mu) < 7.5 \cdot 10^{-7}$$



OPAL Collaboration, R. Akers et al., Z. Phys. C67 (1995) 555-564.  
L3 Collaboration, O. Adriani et al., Phys. Lett. B316 (1993) 427.  
DELPHI Collaboration, P. Abreu et al., Z. Phys. C73 (1997) 243.  
ATLAS, CERN-PH-EP-2014-195 (2014)

- Future experimental prospects: Linear Collider / FCC-ee



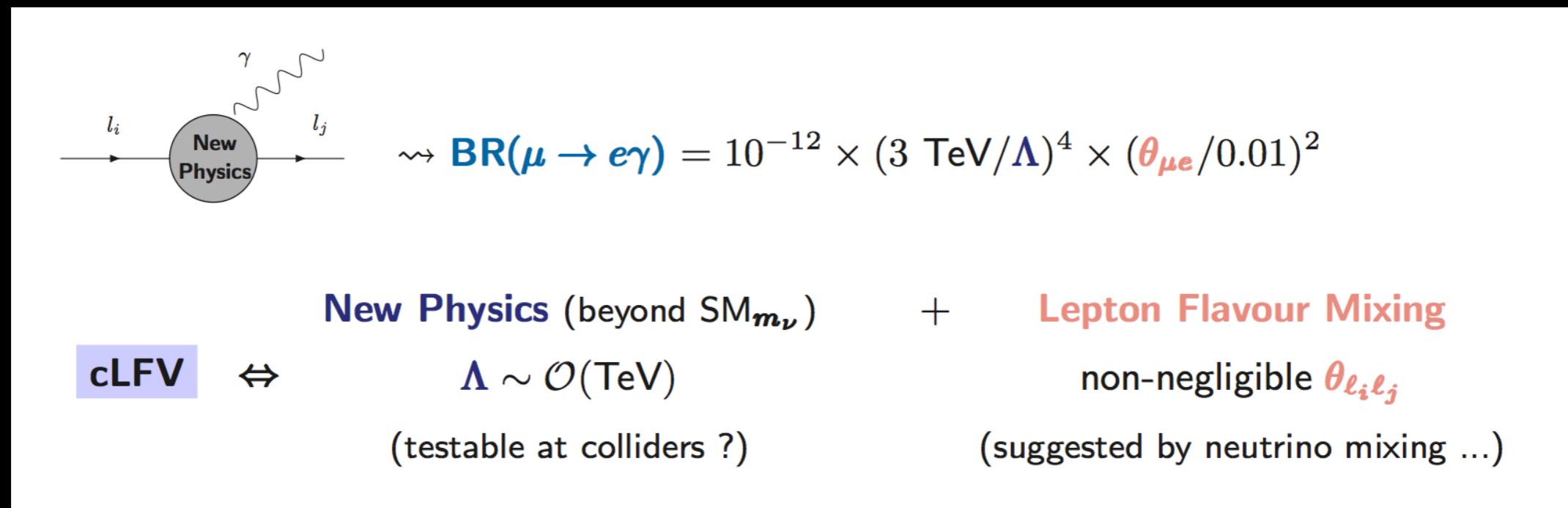
# **After the experiments: understanding (negative) searches**



# cLFV: observables of New Physics

- In the absence of cLFV [and other] signals:
  - ⇒ constraints on parameter space (scale and couplings)
  - ⇒ constraints on the neutrino mass generation mechanism
- If cLFV observed: compare with peculiar features of given model
  - ⇒ predictions for cLFV observables
  - ⇒ identify correlations among different nonstandard effects that can reveal the flavour-breaking pattern of the new physics

What is required of a SM extension to have “observable” cLFV?



# Which New Physics?

► Two phenomenological approaches to account for these observables:

- effective [e.g. Broncano et al. 2003, Davidson, De Gouvea ...]
- model dependent (specific NP scenario)

► Many Models:

cLFV from generic BSM models: well-motivated SM extensions to ease (some) of its th & exp problems generic cLFV extensions (SUSY, little Higgs, ...); extended frameworks (gauge / flavour symmetries, extra dims, ...) models of massive neutrinos (SM seesaws, or extended frameworks)



Smallness of  $m_\nu$  (and nature - Majorana!?) → new mechanism of mass generation

► Are neutral and charged LFV related?

Does cLFV arise from  $\nu$ -mass mechanism? Or entirely different nature?

cLFV arising in SM minimally extended via sterile fermions !

## 2) Extending the SM with sterile fermions



# Neutrino physics open questions



Among the missing ingredients there are:

- ▶ **Absolute mass scale** (Tritium  $\beta$  decays:  $m_{\nu_e} < 2.05 \text{ eV}$ , Cosmology:  $\sum m_{\nu_i} < 0.66 \text{ eV}$  (CMB),  
 $\sum m_{\nu_i} < 0.23 \text{ eV}$  (CMB+BAO+WMAP polarization data+high-resolution CMB experiments and flat Universe))
- ▶ **Majorana versus Dirac nature** ( $0\nu\beta\beta$  decay) [\(Troitsk and Mainz, Planck\)](#)

See talk by Massi Lattanzi!
- ▶ **The mass ordering (normal or inverted "hierarchy")** (matter effects in sun and long baseline oscillations, T2K, NOvA...) [\(KamLAND-Zen, EXO-200, Gerda\)](#)
- ▶ **Is there CP violation in the lepton sector?**
- ▶ **Are there extra sterile states?**
- ▶ **What is the underlying mechanism responsible for the generation of their masses?**

# Sterile neutrinos

- ▶ From the invisible decay width of the Z boson [LEP]:  
⇒ extra neutrinos must be sterile (=EW singlets) or cannot be a Z decay product
- Any singlet fermion that mixes with the SM neutrinos
  - Right-handed neutrinos • Other singlet fermions
- ▶ Sterile neutrinos are SM gauge singlets - colourless, no weak interactions, electrically neutral  
Interactions with SM fields: through mixings with active neutrinos (via Higgs)
- ▶ No bound on the number of sterile states, no limit on their mass scale(s)
- ▶ Phenomenological interest (dependent on the mass scale):
  - eV scale: Several oscillation results or anomalies (reactor antineutrino anomaly, LSND, MiniBooNe...) cannot be explained within 3-flavour oscillations  
⇒ need at least an extra neutrino
  - Reactor  $\nu$  anomaly:  $\Delta m^2 \gtrsim 0.5 \text{ eV}^2$
  - Galium  $\nu$  anomaly:  $\Delta m^2 \gtrsim 1 \text{ eV}^2$
  - LSND  $\nu$  anomaly:  $\Delta m^2 \gtrsim 0.1 \text{ eV}^2$
  - ...
- keV scale: motivations for sterile neutrinos from cosmology, e.g.  
warm dark matter or to explain pulsar velocities

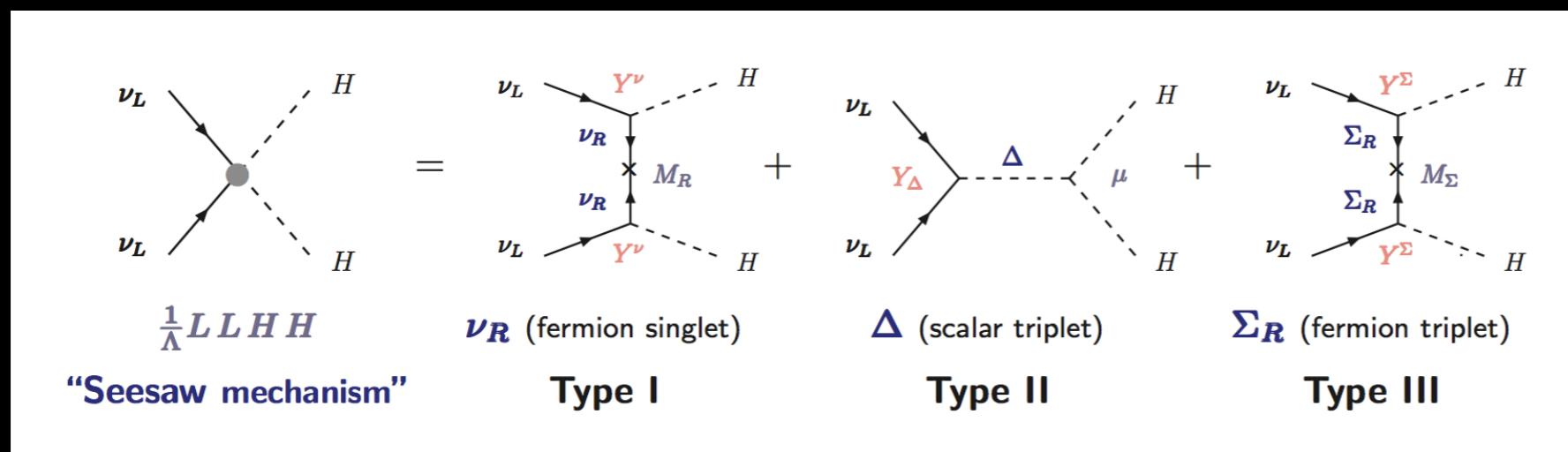
(Partial riconciliation of anomalies:  
Gariazzo et al. 15)

See talk by  
Carlo Giunti!

See talk by Massi  
Lattanzi!

# Sterile fermions: theoretical appeal

- Present in numerous SM extensions aiming at accounting for  $\nu$  masses and mixings: e.g right-handed neutrinos (Seesaw type-I, vMSM..), other sterile fermions ([Inverse Seesaw](#))



Explain small  $\nu$  masses with “natural” couplings via new dynamics at heavy scale

(Minkowski 77, Gell-Mann Ramond Slansky 80, Glashow, Yanagida 79, Mohapatra Senjanovic 80, Lazarides Shafi Wetterich 81, Schechter-Valle, 80 & 82, Mohapatra Senjanovic 80, Lazarides 80, Foot 88, Ma, Hambye et al., Bajc, Senjanovic, Lin, Abada et al., Notari et al...)

LFV observables: depend on powers of  $Y\nu$  and on the mass of the (virtual) NP propagators

- Simplified [toy models](#) for phenomenological analysis: “ad-hoc” construction (no specific assumption on mechanism of mass generation) encodes the effects of N additional sterile states in a single one



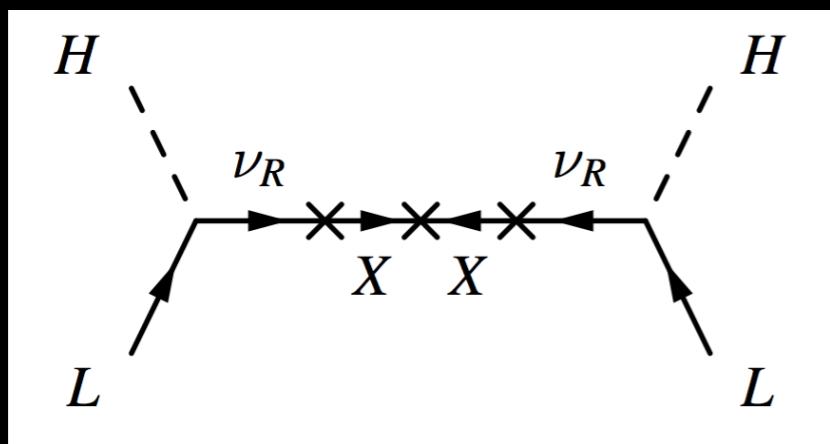
# Low scale: Inverse seesaw (ISS)

(Mohapatra & Valle, 1986)

- Add three generations of SM singlet pairs,  $\nu_R$  and  $X$  (with  $L=+1$ )
- Inverse seesaw basis ( $\nu_L, \nu_R, X$ ):

$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix} \Rightarrow \begin{cases} \text{3 light } \nu : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \mu_X \\ \text{3 pseudo-Dirac pairs} : m_{N^\pm} \approx M_R \pm \mu_X \end{cases}$$

- New (virtual) states & modified couplings: cLFV, non-universality, signals at colliders!
- $Y_\nu \sim O(1)$  and  $M_R \sim 1 \text{ TeV}$  testable at the colliders and low energy experiments.
- Large mixings (active-sterile) and light sterile neutrinos are possible



Parameters:

- $M_R$  (real, diagonal)  $M_R = (0.1 \text{ MeV}, 10^6 \text{ GeV})$
- $\mu_X$  (complex,symmetric)  $\mu_X = (0.01 \text{ eV}, 1 \text{ MeV})$
- $R_{\text{mat}}$  (rotation,complex)
- 2 Majorana and 1 Dirac phases from  $U_{\text{PMNS}}$
- Normal (NH) / Inverted (IH) hierarchy

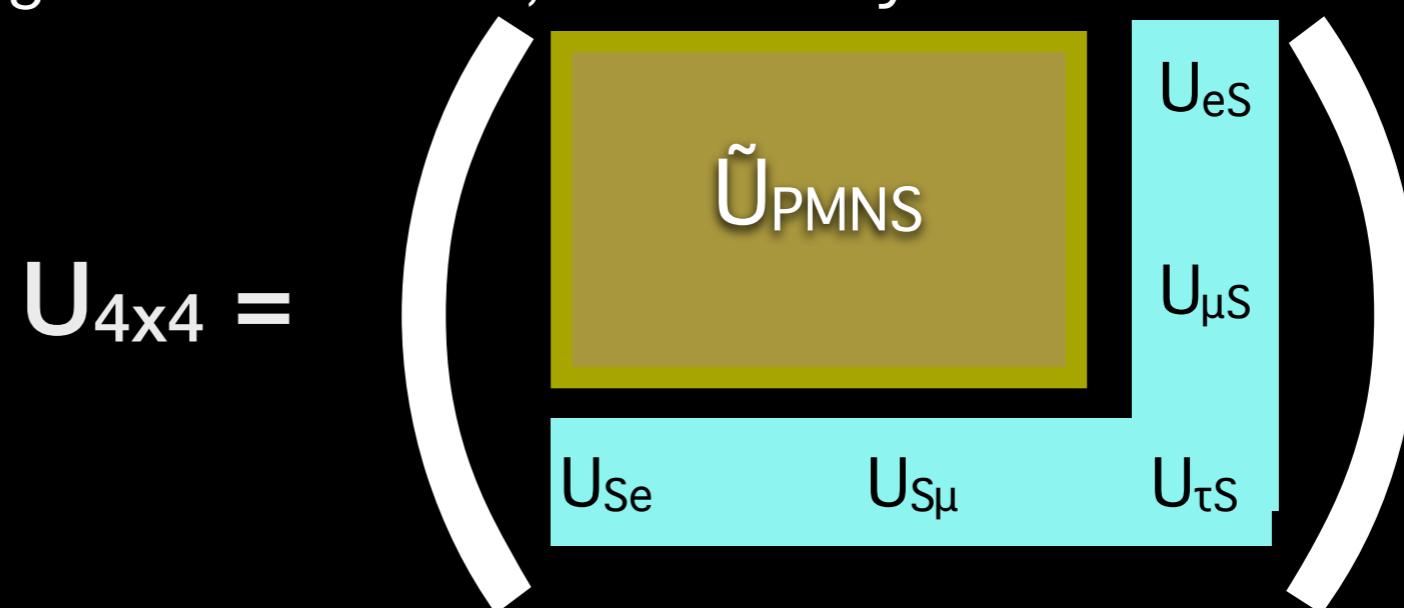
# “Toy model” for pheno analyses: SM + Vs

- Add one sterile neutrino     $n_L = (\nu_{Le}, \nu_{L\mu}, \nu_{L\tau}, \nu_s^c)^T$  → 3 new mixing angles  
active-sterile

$$U_{4 \times 4} = R_{34}.R_{24}.R_{14}.$$

$U_{PMNS}$

- From the interaction to the physical mass basis:  $n_L = U_{4 \times 4} \nu_i$
- Spectrum: 3 light active neutrinos + 1 heavier (mostly) sterile state
- Active-sterile mixing  $U_{ai}$ : rectangular matrix
- Left-handed leptons mixing: 3x3 sub-block, non unitary!



Parameters:

- $\theta_{14}, \theta_{24}, \theta_{34}$
- 3 Majorana and 3 Dirac phases
- Normal (NH) / Inverted (IH) hierarchy

# Phenomenological impact

- Modified  $W^\pm$  charged currents and  $Z^0$ ,  $H$  neutral currents  
If sufficiently light, sterile states may be produced as final products

- Leptonic charged currents can be modified due to the mixing with the steriles:

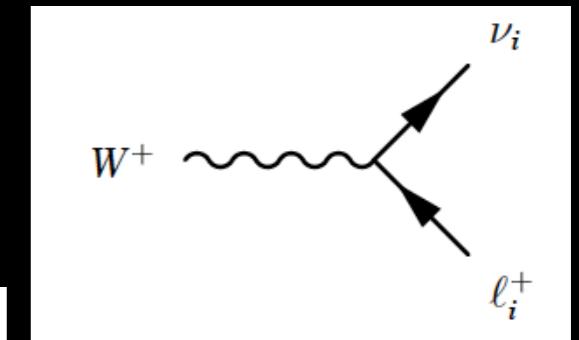
Standard case (3 flavors):  $\nu_i = e, \mu, \tau$

$$\nu_i = \text{flavor eigenstate} = \sum_{ai} U_{ai}^{\text{PMNS}} \nu_a$$

$\nu_a$  = mass eigenstates,  $a = 1, 2, 3$

Add sterile neutrinos:

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W_\mu^\pm \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+n_s} \mathbf{U}_{\alpha i} \bar{\ell}_\alpha \gamma^\mu P_L \nu_i$$



$$\nu_i = \sum_{ai} U_{ai} \nu_a, a = 1, 2, 3, 4 \dots n_\nu$$

$U$  = extended matrix,  $j=1 \dots 3$ ,  $i=1 \dots n_\nu$

If  $n_\nu > 3, U \neq U_{\text{PMNS}}$  → the 3x3 sub matrix is not unitary

$$U_{\text{PMNS}} \rightarrow \tilde{U}_{\text{PMNS}} = (\mathbb{1} - \eta) U_{\text{PMNS}}$$

(see also: Fernandez-Martinez et al. 2007, Gavela et al. 2009, Abada et al. 2014, Arganda et al. 2014)

- Modified neutral currents:

$$\mathcal{L}_{Z^0} = -\frac{g_w}{2 \cos \theta_w} Z_\mu \sum_{i,j=1}^{3+n_s} \bar{\nu}_i \gamma^\mu \left[ P_L (\mathbf{U}^\dagger \mathbf{U})_{ij} - P_R (\mathbf{U}^\dagger \mathbf{U})_{ij}^* \right] \nu_j$$

# Experimental constraints

The deviations from unitarity and the possibility of having steriles as final decay products, might induce departures from the SM expectations.

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data
4. LHC data (invisible decays)
5. Leptonic and semileptonic meson decays (B and D)
6. Laboratory bounds: direct searches for sterile neutrinos
7. Lepton flavor violation ( $\mu \rightarrow e \gamma$ )
8. Neutrinoless double beta decay
9. Cosmological bounds on sterile neutrinos

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints Non-standard neutrino interactions with matter can be generated by NP. 
$$U_{3 \times 3} = (1 - \eta) U_{PMNS}$$
 effective theory approach  
(Antusch et al., 2009,2014)
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P. Bandyopadhyay et al., 2012,  
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 $\Gamma(P \rightarrow l\nu)$  with  $P = K, D, B$   
(CLEO, Belle, BaBar, NA62, LHCb, BES III, J. Beringer et al., PDG, 2013, Shrock, '81; Atre et al., '09; Abada et al., '13-'15 ...)  
with one or two neutrinos in the final state
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(Shrock 1980, Atre et al. 2009, Kusenko et al. 2009, Lello 2013)
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7. Lepton flavor violation ( $\mu \rightarrow e \gamma$ , 3body decays)

$$Br(\mu \rightarrow e\gamma)_{MEG} = 0.57 \times 10^{-12}$$

(Gronau et al. '85; Ilakovac & Pilaftsis, '95 - '14,  
Deppisch et al. '05; Dinh et al. '12; Alonso et al. '12; ... )

8. Neutrinoless double beta decay

9. Cosmological bounds on sterile neutrinos

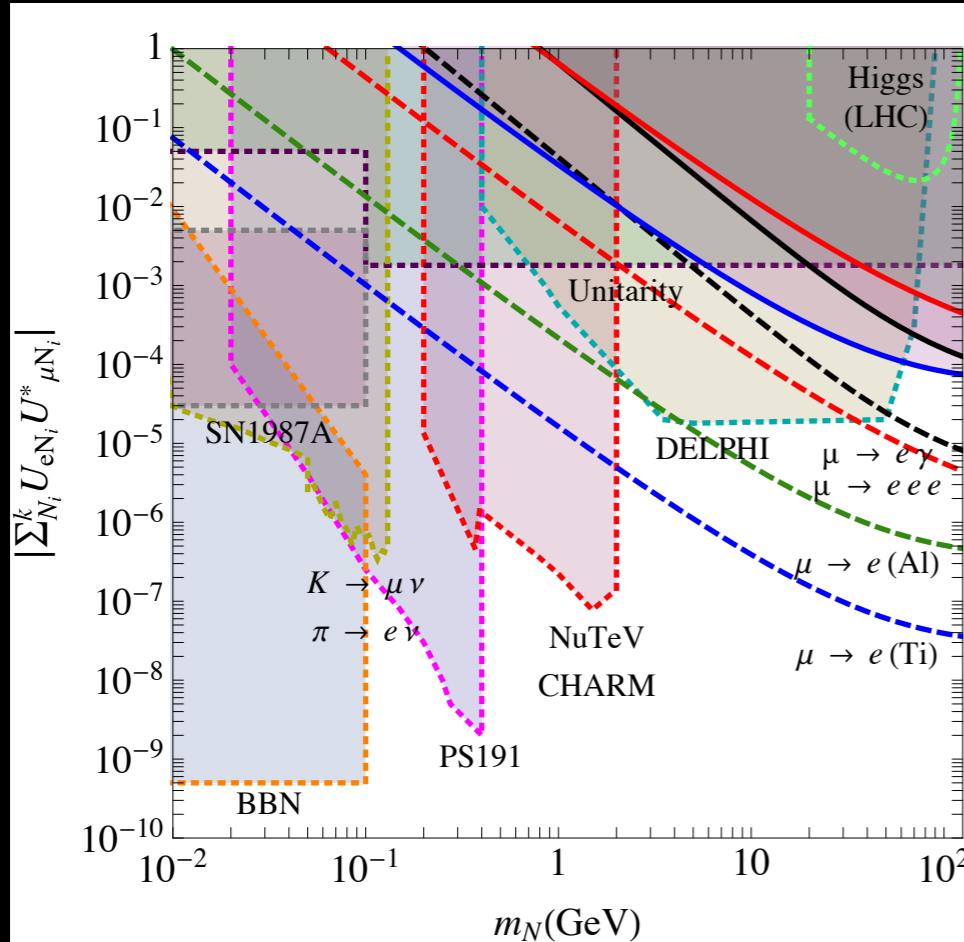
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9. Neutrinoless double beta decay  $m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (140 - 700) meV$  (EXO-200,KamLAND-Zen,GERDA,CUORICINO)  
(see also: Blennow et al. 2010, Lopez-Pavon et al. 2013, Abada et al. 2014)
10. Cosmological bounds on sterile neutrinos

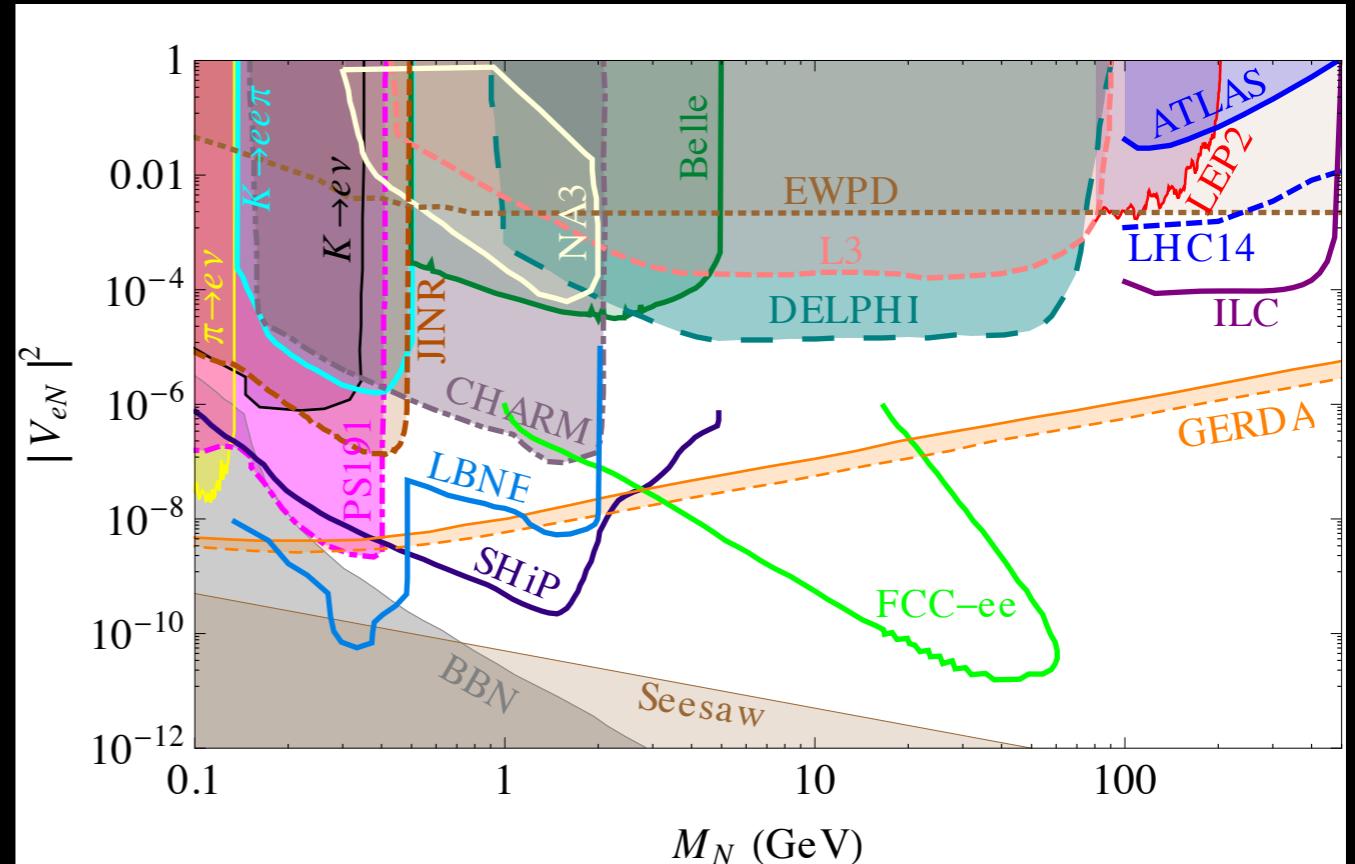
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(Smirnov et al. 2006, Kusenko 2009, Gelmini 2010)  
Large scale structure, Lyman- $\alpha$ , BBN, CMB, X-ray constraints  
(from  $\nu_i \rightarrow \nu_j \gamma$ ), SN1987a

# Experimental constraints: examples



(Alonso et al. 2009)



(Deppisch et al. 2015)

- Analysis carried for two kind of models: ISS and “3+1” toy model

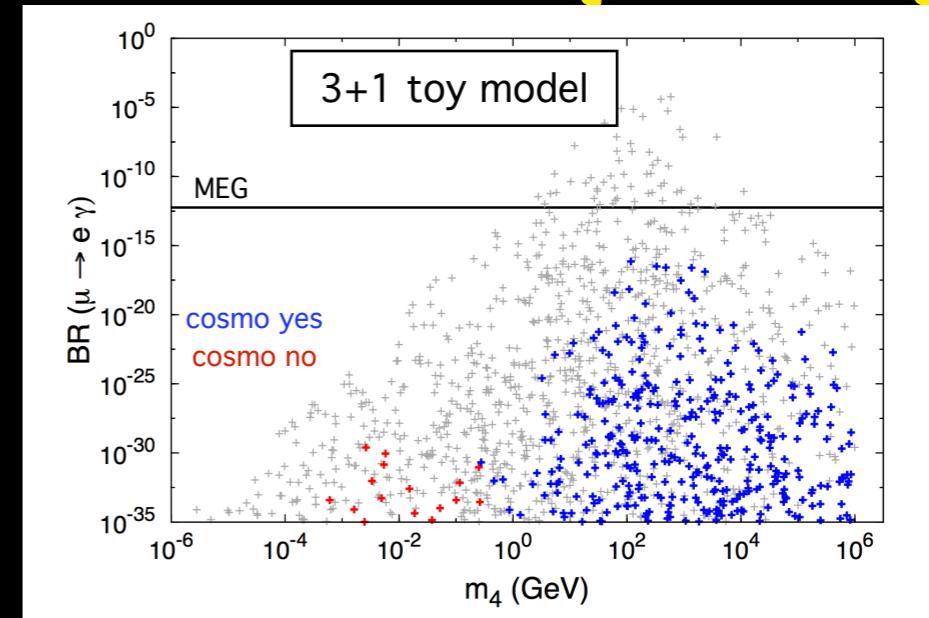
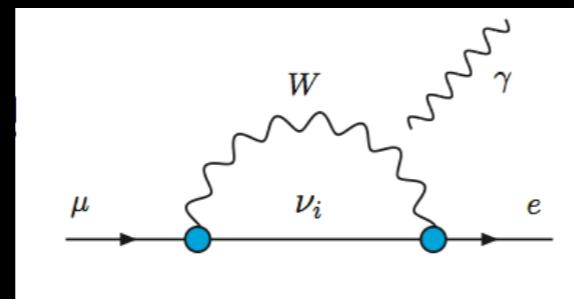
### 3) Sterile neutrinos and cLFV



# vs and cLFV: radiative and three-body decays

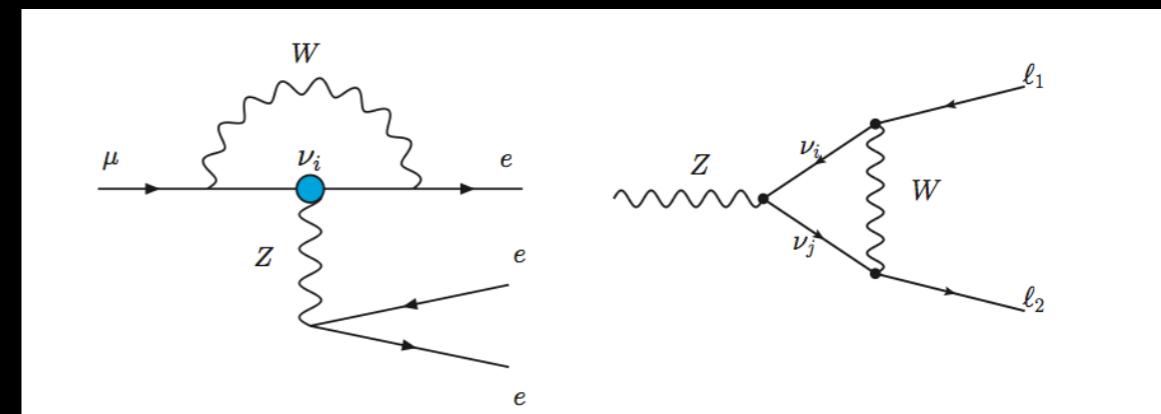
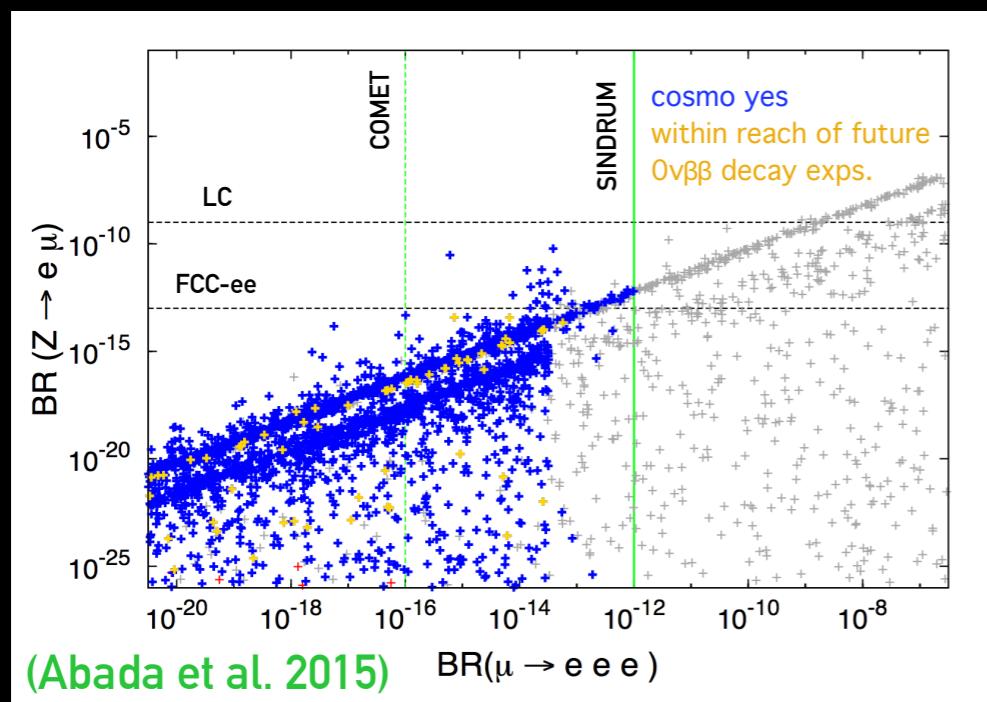
► Radiative decays:  $\ell_i \rightarrow \ell_j \gamma$

► Consider  $\mu \rightarrow e \gamma$ :



For  $m_4 \geq 10$  GeV sizeable  $v_s$  contributions .. but precluded by other cLFV observables

► 3-body decays:  $\mu \rightarrow eee$

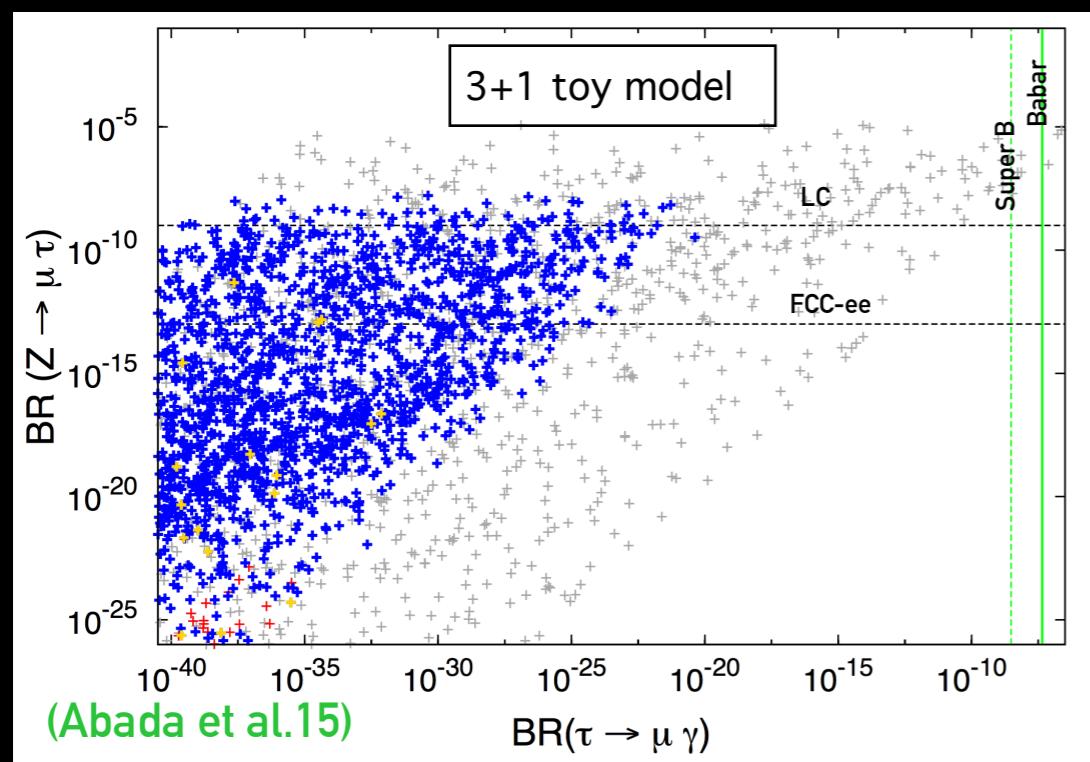
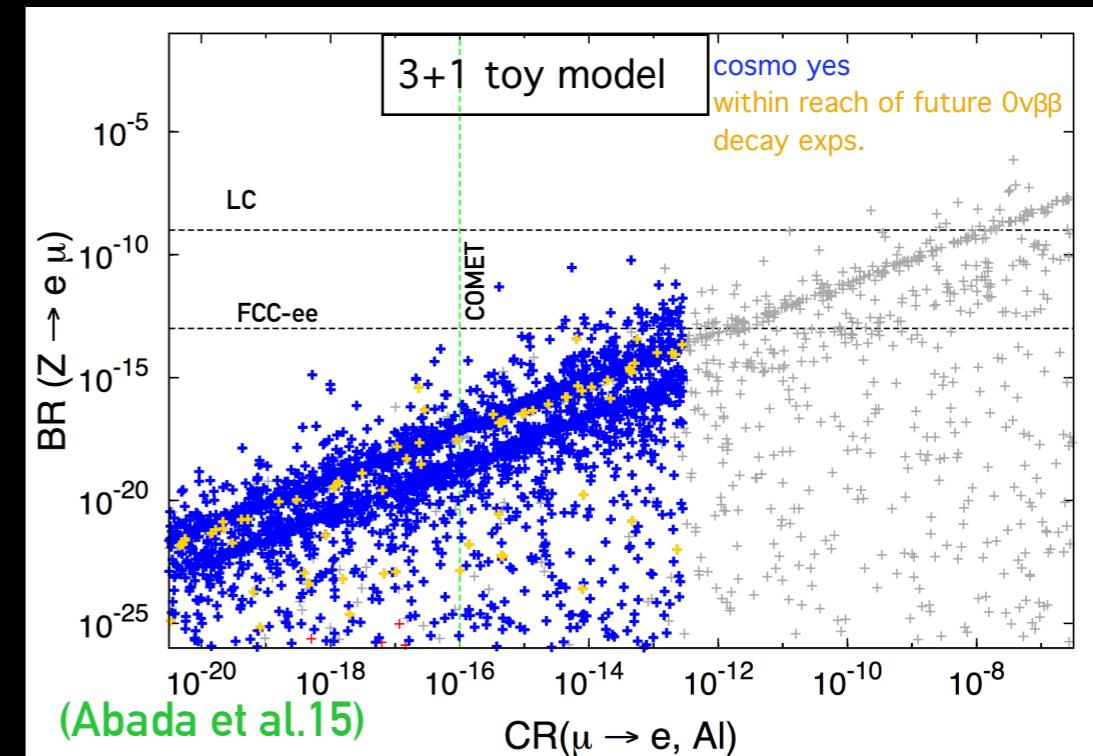
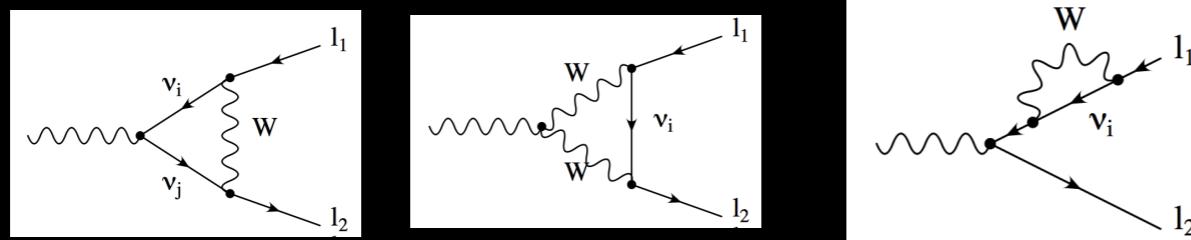


► dominated by  $Z$  penguins  
(same contribution to rare  $Z \rightarrow e \mu$ )

# V<sub>s</sub> and cLFV: rare Z decays

- rare cLFV Z decays at a high luminosity Z factory:

$$Z \rightarrow l_i^\mp l_j^\pm$$



- allows to probe cLFV in mu-tau sector beyond superB reach

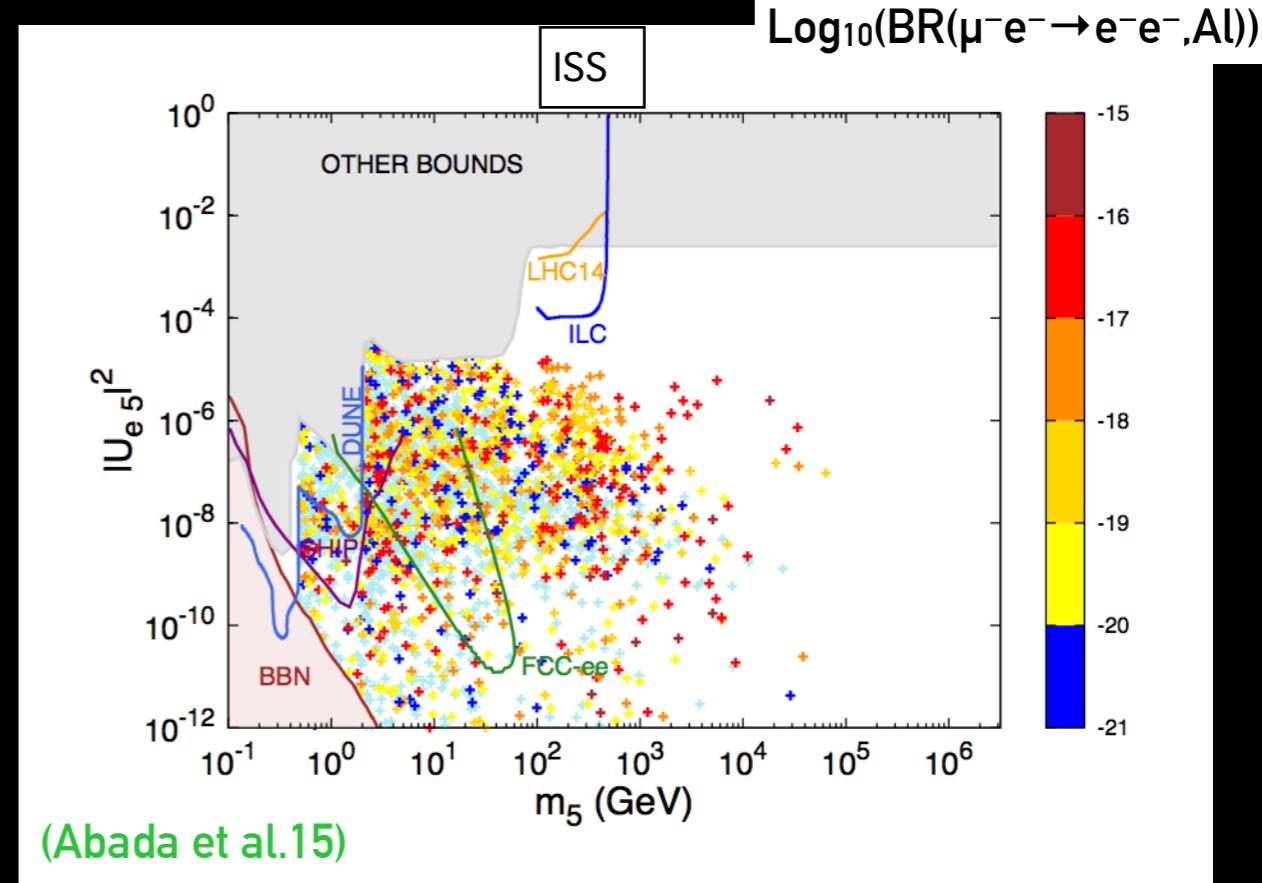
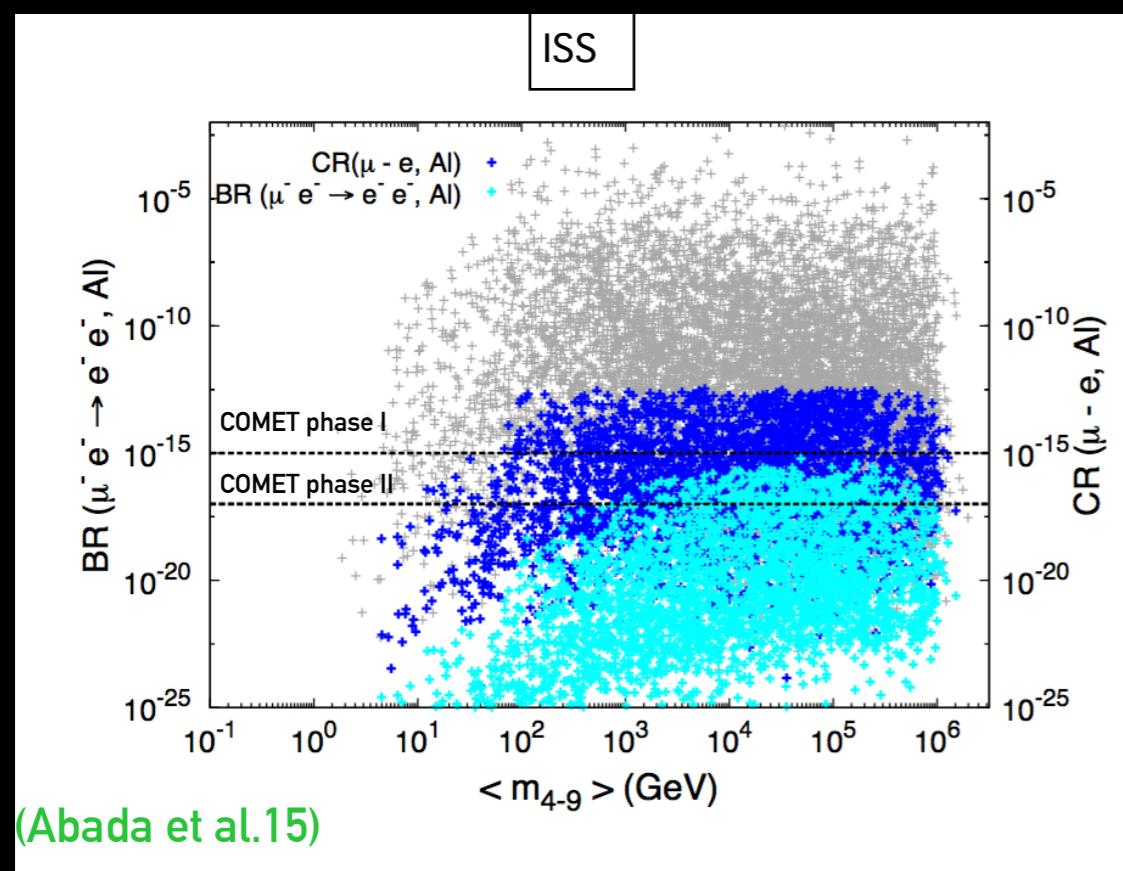
- Other searches for sterile neutrinos at colliders:

- searches for heavy N at LHC  $qq' \rightarrow \tau\mu + 2 \text{ jets}$
- cLFV Higgs decays **(Arganda et al.14,15)**

# VS and cLFV: nucleus-assisted processes

►  $\text{BR}(\mu^- e^- \rightarrow e^- e^-, \text{Al})$  vs  $\text{CR}(\mu^- e, \text{Al})$

► Sizeable values for  $\text{BR}(\mu^- e^- \rightarrow e^- e^-)$  - potentially within experimental reach! [COMET]



- For Aluminium [COMET],  $\text{CR}(\mu^- e^- \rightarrow e^- e^-, \text{Al})$  appears to have slightly stronger experimental potential
- Rate strongly enhanced in large Z atoms

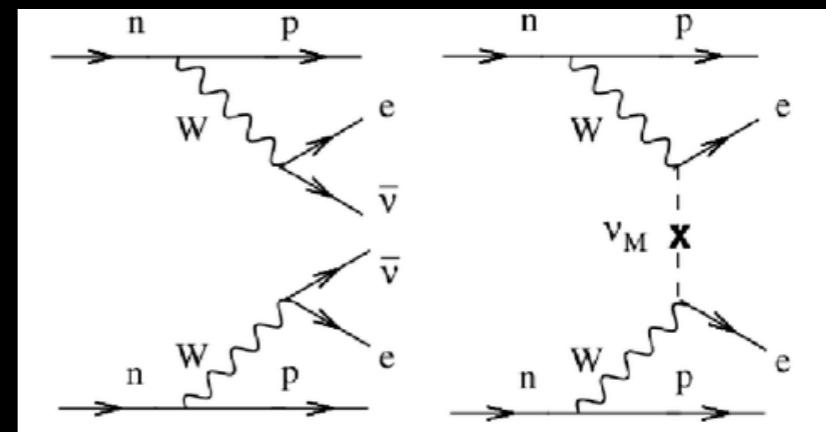
# LNV: neutrinoless double beta decay

► 2νββ vs 0νββ decay:

$$N(A,Z) \rightarrow N(A,Z+2) + e^+ + e^- + \nu_e + \bar{\nu}_e$$

second order weak interaction process in the SM

$$N(A,Z) \rightarrow N(A,Z+2) + e^+ + e^-$$



► Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \langle m_{ee} \rangle^2$$

phase space      nuclear matrix element

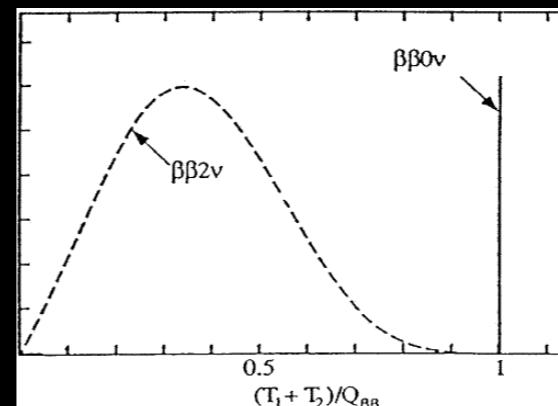
$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

lepton mixing  
matrix, complex

► Experimental signal:

⇒ peak at  $Q_{\beta\beta} = m(A,Z) - m(A,Z+2)$

⇒ two electrons from vertex



2 electron spectra

Ge-76:  
 $Q_{\beta\beta} = 2039$  keV

► Discovery would imply:

⇒ lepton number violation  $\Delta L = 2$

⇒ neutrinos have Majorana character

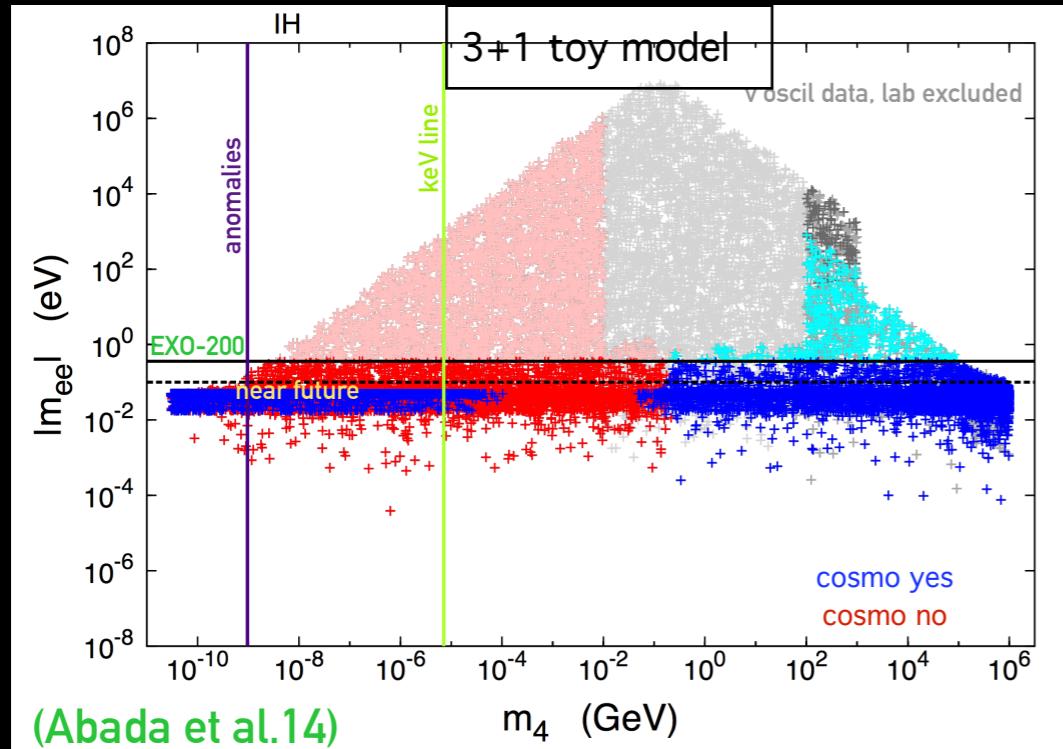
⇒ mass scale & hierarchy

⇒ physics beyond the SM

(Tosi - EXO. 2014)

Isotope	Experiment	$T_{1/2}^{0\nu\beta\beta}$ sensitivity [yr]	$\langle m_{\beta\beta} \rangle$ sensitivity [meV]
$^{136}\text{Xe}$	EXO-200 (4 yr)	$5.5 \cdot 10^{25}$	75–200
$^{136}\text{Xe}$	nEXO (5 yr)	$3 \cdot 10^{27}$	12–29
$^{136}\text{Xe}$	nEXO (5 yr + 5 yr w/ Ba tagging)	$2.1 \cdot 10^{28}$	5–11
$^{136}\text{Xe}$	KamLAND-Zen (300 kg, 3 yr)	$2 \cdot 10^{26}$	45–110
$^{136}\text{Xe}$	KamLAND2-Zen (1 ton, post 2016)	IH	IH
$^{76}\text{Ge}$	GERDA phase II	$2 \cdot 10^{26}$	90–290
$^{130}\text{Te}$	CUORE-0 (2 yr)	$5.9 \cdot 10^{24}$	204–533
$^{130}\text{Te}$	CUORE (5 yr)	$9.5 \cdot 10^{25}$	51–133
$^{130}\text{Te}$	SNO+	$4 \cdot 10^{25}$	70–140

# V<sub>s</sub> and LNV: 0νββ decay



$$m_{ee} \simeq \sum_{i=1}^4 U_{ei}^2 p^2 \frac{m_i}{p^2 - m_i^2}$$

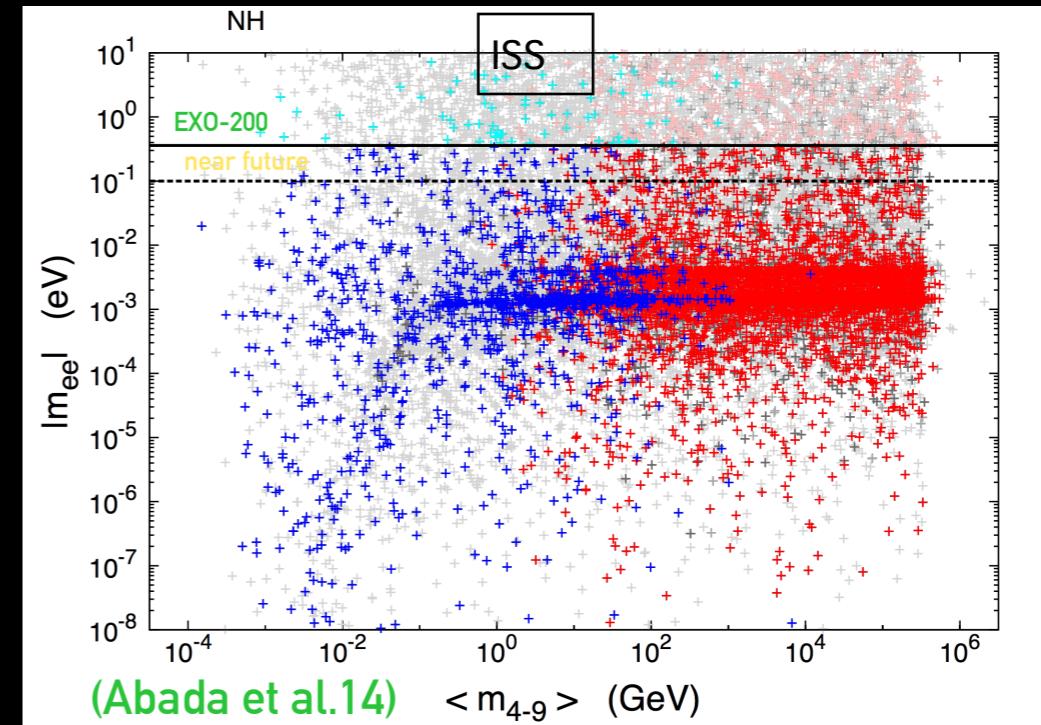
p: momentum exchanged in the process (mean nucleon momentum)  
 $(p^2 \sim - (100 \text{ MeV})^2$  virtual momentum of the ν)

- 0νββ decay excludes some solutions
- points within the reach of actual and near-future experiments

$m_s \ll l_p l$ : in this regime the effective mass goes to zero

$m_s \approx l_p l$ : the contribution of the pseudo-Dirac states becomes more important, and can induce sizeable effects to  $m_{ee}$

$m_s \gg l_p l$ : in this regime the heavy states decouple, and the contributions to  $m_{ee}$  only arise from the 3 light neutrino states.



# Summary

- ▶ Flavour violation observed in quarks & neutral leptons...
  - why should Nature “conserve” charged lepton flavour?
- ▶ Lepton flavour violation and New Physics
  - New Physics can be manifest via cLFV even before any direct discovery!
  - cLFV observables can provide (indirect) information on the underlying NP model
  - Data from cLFV might even exclude regimes/scenarios of SM extensions
- ▶ Numerous observables currently being searched for:
  - Closely follow with theoretical studies and phenomenological analyses, exploring diverse cLFV observables, of different origin, infer pattern/correlation  
⇒ Unveil the underlying mechanism of flavour violation in the lepton sector!
- ▶ Extending the SM with sterile states
  - Theoretically and phenomenologically motivated; impact on many observables!
  - Sterile states: actively searched for at high energy, high intensity and in cosmology
- ▶ Sterile neutrinos and cLFV
  - Sizeable contributions to many observables (some leading to stringent constraints e.g.  $0\nu\beta\beta$ )
  - “Toy model”: important  $\nu_s$  contributions to  $CR(\mu - e, N)$  and  $BR(\mu^- e^- \rightarrow e^- e^-)$ , potentially within COMET reach
  - Sizeable rare  $BR(Z \rightarrow \mu \tau)$  within FCC-ee reach
  - Analysis also carried for well motivated models: Inverse Seesaw (and also vMSM)

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# BACKUP

## cLFV in “muonic” atoms: Muonium

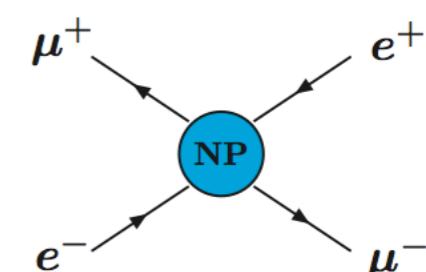
- **Muonium:** hydrogen-like Coulomb bound state ( $e^- \mu^+$ ); free of hadronic interactions!

- **Mu –  $\overline{\text{Mu}}$  conversion**

Spontaneous conversion of a ( $e^- \mu^+$ ) into ( $e^+ \mu^-$ )

Reflects a **double lepton number violation**:  $\Delta L_e = \Delta L_\mu = 2$

Rate suppressed by external electromagnetic fields



- **Experimental status:**  $P(\text{Mu} - \overline{\text{Mu}}) < 8.3 \times 10^{-11}$  [Willmann et al, 1999]

- **cLFV Mu decay:**  $\text{Mu} \rightarrow e^+ e^-$

clear signal compared to SM decay  $\text{Mu} \rightarrow e^+ e^- \bar{\nu}_\mu \nu_e$  (no missing energy)

- **Experimental status:** no clear roadmap (nor bounds)...

Hopefully included in **COMET's Phase II** programme

## Rare lepton processes: cLFV tau decays

- **Tau production and decay:**  $e^+e^- \rightarrow \tau^+\tau^-$   $\rightsquigarrow$  signal hemisphere  
 $\rightsquigarrow$  tagging hemisphere: e.g.  $\tau \rightarrow \bar{\nu}_\tau \nu_e e^+$
- **Radiative decay:**  $\tau^\pm \rightarrow \ell^\pm \gamma$
- **Event signature:**  $E_{\text{final}} - \sqrt{s}/2 = \Delta E \sim 0$ ;  
 $M_{\text{final}} = M_{\ell\gamma} \sim m_\tau$
- **Backgrounds**  $\Rightarrow$  coincidence of isolated leptons with  $\gamma$  (ISR, FSR); mistagging

Process	BR (BaBar, 2010)
$\tau \rightarrow e\gamma$	$3.3 \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$4.4 \times 10^{-8}$

- **3-body decays:**  $\tau^\pm \rightarrow \ell_i^\pm \ell_j^\mp \ell_k^\pm$
- **Event signature:**  $E_{3\ell} - \sqrt{s}/2 \sim 0$ ;  $M_{3\ell} \sim m_\tau$
- **Backgrounds**  $\Rightarrow$  No irreducible backgd!  
small backgd from  $q\bar{q}$  and Bhabha pairs...

$3\ell$ final state	BR (BaBar)	BR (Belle)
$e^-e^+e^-$	$2.9 \times 10^{-8}$	$2.7 \times 10^{-8}$
$\mu^-e^+e^-$	$2.2 \times 10^{-8}$	$1.8 \times 10^{-8}$
$\mu^-e^-e^-$	$1.8 \times 10^{-8}$	$1.5 \times 10^{-8}$
$e^+\mu^-\mu^-$	$2.6 \times 10^{-8}$	$1.7 \times 10^{-8}$
$e^-\mu^+\mu^-$	$3.2 \times 10^{-8}$	$2.7 \times 10^{-8}$
$\mu^-\mu^+\mu^-$	$3.3 \times 10^{-8}$	$2.1 \times 10^{-8}$

- **Future experimental prospects:** SuperB (SuperBelle) and/or Tau-Charm factories

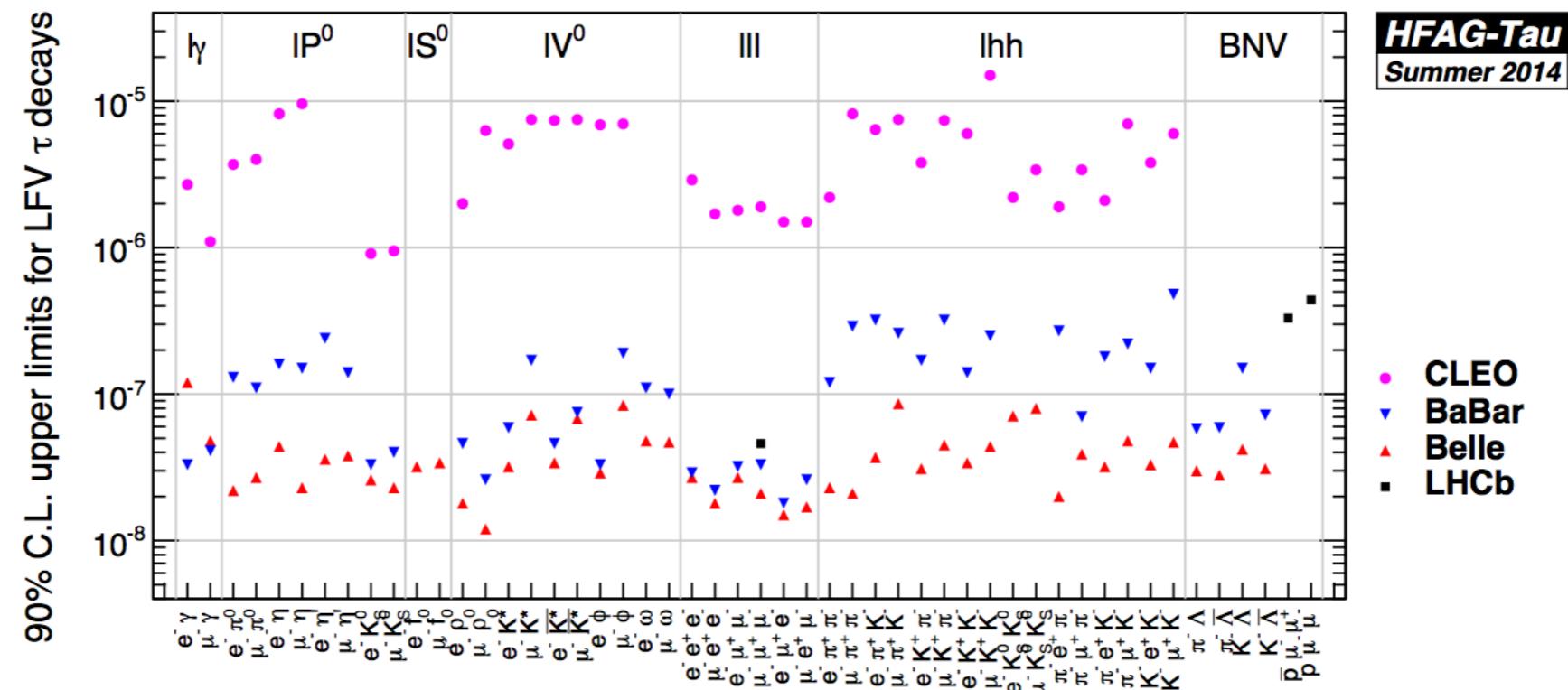
$$\text{BR}(\tau \rightarrow \ell\gamma) \leq 1 - 3 \times 10^{-9} \quad \text{BR}(\tau \rightarrow 3\ell) \leq 1 - 2 \times 10^{-10}$$

## Rare lepton processes: cLFV tau decays

- **cLFV tau decays into mesons:** “large”  $\tau$  mass  $\Rightarrow$  possible to have semi-leptonic decays
- **Meson & charged lepton:**  $\tau \rightarrow \ell h^0$  pseudoscalar, scalar or vector neutral meson
- **3 body meson & charged lepton:**  $\tau \rightarrow \ell h_i h_j$   $h \leftrightarrow \pi^\pm, K^\pm, K_s^0$
- **cLFV exotic modes:** violating total lepton number and baryon number

$\tau^- \rightarrow \ell^+ h_i^\pm h_j^\pm$  where  $h^\pm = \pi^\pm, K^\pm$  (LNV)

$\tau^- \rightarrow \Lambda h^-$  where  $h^\pm = \pi^\pm, K^\pm$  and  $\tau \rightarrow p \mu \mu$  (BNV)



## cLFV meson decays

- Meson decays: excellent testing grounds for lepton flavour dynamics! Examples...

- Lepton Universality Violation in  $K$  and  $\pi$  decays

$$R_P = \frac{\Gamma(P \rightarrow e\nu)}{\Gamma(P \rightarrow \mu\nu)} \quad \text{comparison with SM th predictions} \quad \Delta r_P = \frac{R_P^{\text{exp}}}{R_P^{\text{SM}}} - 1$$

► Limits from **NA62** at CERN:  $\Delta r_K = (4 \pm 4) \times 10^{-3}$ ;  $\Delta r_\pi = (-4 \pm 3) \times 10^{-3}$

Future sensitivity:  $\delta R_K / R_K \sim 0.1\% \Rightarrow$  measure  $\Delta r_K \sim \mathcal{O}(10^{-3})$

- Lepton Universality Violation in  $B$  decays

$$R_K^B = \frac{\text{BR}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{BR}(B^+ \rightarrow K^+ e^+ e^-)}$$

► **LHCb**:  $R_K^B = 0.745 + 0.090 - 0.074(\text{stat}) \pm 0.036(\text{syst})$

Also in  $\bar{B}^0 \rightarrow D^* \ell \nu$  decays...

- cLFV & LNV in  $D$  and  $B$  meson decays (Used as indirect test of Majorana mediators)

► Abundant data from **LHCb, BNL, KTeV, BaBar, Cleo, Belle, ...**

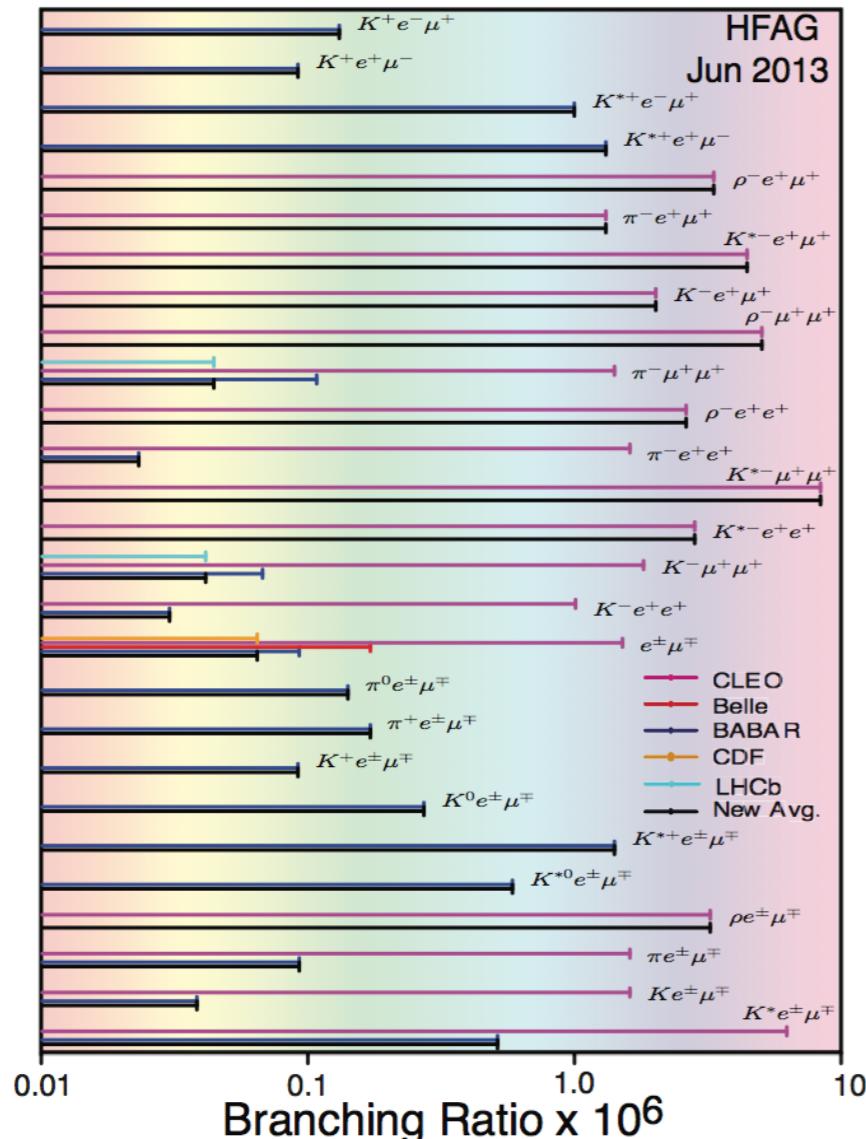
$$\text{BR}(D^0 \rightarrow \mu e) < 1.5 \times 10^{-8}; \text{BR}(B \rightarrow \mu e) < 2.8 \times 10^{-9};$$

$$\text{BR}(B^- \rightarrow D^+ \mu^- \mu^-) < 7 \times 10^{-7}; \text{BR}(B^- \rightarrow D^0 \pi^+ \mu^- \mu^-) < 2 \times 10^{-6}, \dots$$

## cLFV meson decays

► Many processes being searched for! From B-factories to high-energy colliders...

Lepton Number Violating Charmless B Decays



Decay mode	BF UL 90% CL ( $10^{-6}$ )
$D^+ \rightarrow \pi^+ e^+ \mu^-$	2.9
$D^+ \rightarrow \pi^+ e^- \mu^+$	3.6
$D^+ \rightarrow K^+ e^+ \mu^-$	1.2
$D^+ \rightarrow K^+ e^- \mu^+$	2.8
$D_s^+ \rightarrow \pi^+ e^+ \mu^-$	12
$D_s^+ \rightarrow \pi^+ e^- \mu^+$	20
$D_s^+ \rightarrow K^+ e^+ \mu^-$	14
$D_s^+ \rightarrow K^+ e^- \mu^+$	9.7
$\Lambda_c^+ \rightarrow p e^+ \mu^-$	9.9
$\Lambda_c^+ \rightarrow p e^- \mu^+$	19

[BaBar, '12]

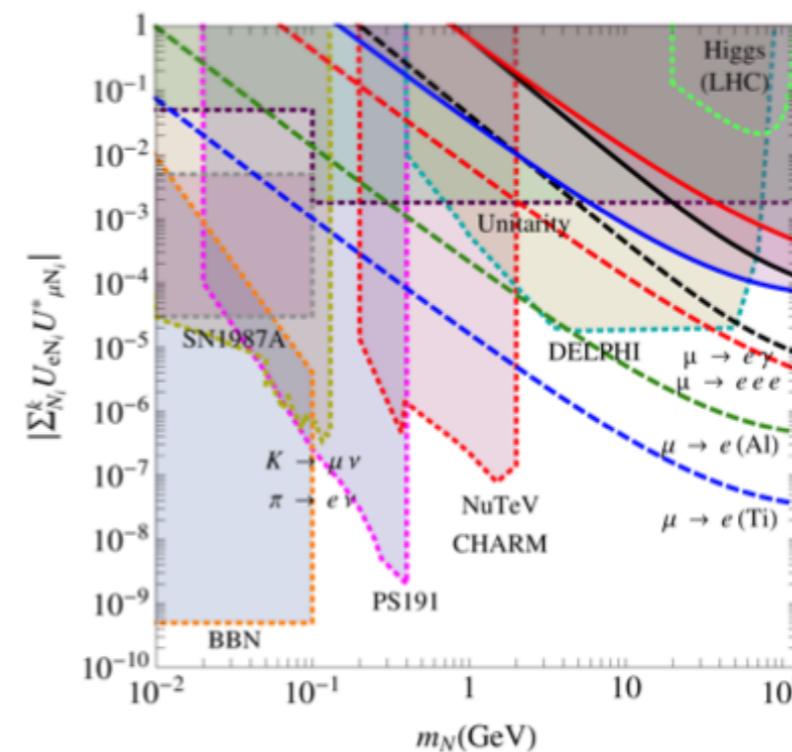
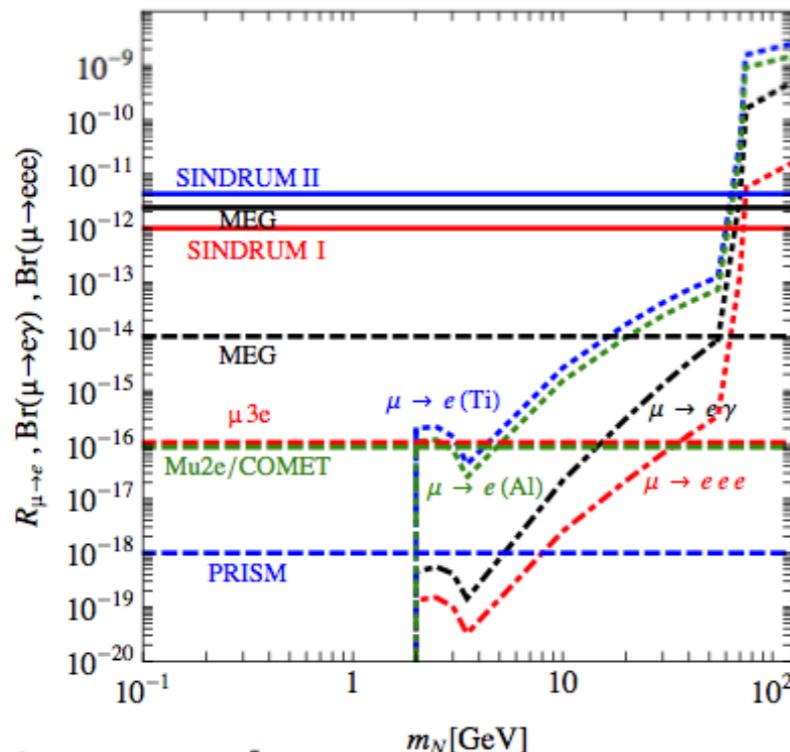
Decay mode	BF UL 90% CL ( $10^{-6}$ )
$D^+ \rightarrow \pi^- e^+ e^+$	1.9
$D^+ \rightarrow \pi^- \mu^+ \mu^+$	2.0
$D^+ \rightarrow \pi^- e^+ \mu^+$	2.0
$D^+ \rightarrow K^- e^+ e^+$	0.9
$D^+ \rightarrow K^- \mu^+ \mu^+$	10
$D^+ \rightarrow K^- e^+ \mu^+$	1.9
$D_s^+ \rightarrow \pi^- e^+ e^+$	4.1
$D_s^+ \rightarrow \pi^- \mu^+ \mu^+$	14
$D_s^+ \rightarrow \pi^- e^+ \mu^+$	8.4
$D_s^+ \rightarrow K^- e^+ e^+$	5.2
$D_s^+ \rightarrow K^- \mu^+ \mu^+$	13
$D_s^+ \rightarrow K^- e^+ \mu^+$	6.1
$\Lambda_c^+ \rightarrow \bar{p} e^+ e^+$	2.7
$\Lambda_c^+ \rightarrow \bar{p} \mu^+ \mu^+$	9.4
$\Lambda_c^+ \rightarrow \bar{p} e^+ \mu^+$	16

► Also in Kaon decays! e.g.  $\text{BR}(K_L \rightarrow \mu e) < 4.7 \times 10^{-12}$ ;  $\text{BR}(K^+ \rightarrow \pi^+ \mu^+ e^-) < 2.1 \times 10^{-11}$ ; ...

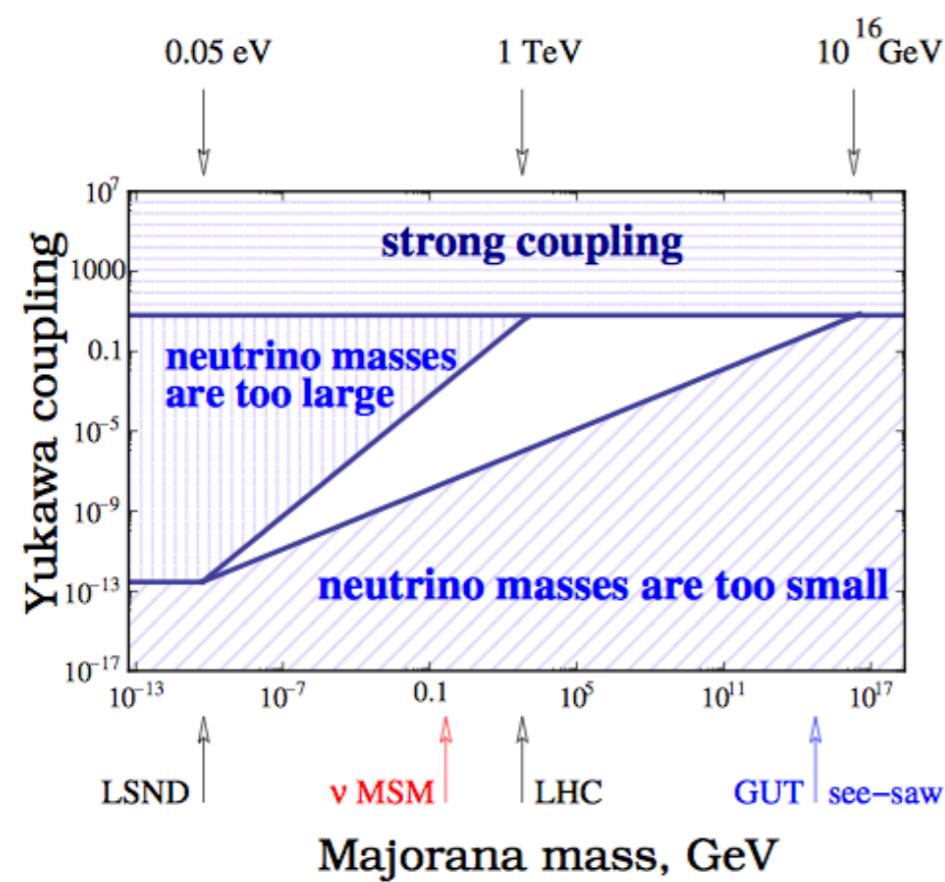
## Low scale type I seesaw

- ▶ Addition of 3 “heavy” Majorana RH neutrinos to SM;  $\text{MeV} \lesssim m_{N_i} \lesssim 10^{\text{few}} \text{TeV}$
- ▶ Spectrum and mixings:  $m_\nu \approx -v^2 Y_\nu^T M_N^{-1} Y_\nu$   $\mathbf{U}^T \mathcal{M}_\nu^{6 \times 6} \mathbf{U} = \text{diag}(m_i)$   

$$\mathbf{U} = \begin{pmatrix} \mathbf{U}_{\nu\nu} & U_{\nu N} \\ U_{N\nu} & U_{NN} \end{pmatrix} \quad \mathbf{U}_{\nu\nu} \approx (1 - \varepsilon) \mathbf{U}_{\text{PMNS}}$$
 Non-unitary leptonic mixing  $\tilde{\mathbf{U}}_{\text{PMNS}}!$
- ▶ Heavy states do not decouple  $\Rightarrow$  modified neutral and charged leptonic currents
- ▶ Rich phenomenology at high-intensity/low-energy



(see also Dinh et al, '12-'14)



	N mass	$\nu$ masses	eV $\nu$ anomalies	BAU	DM	$M_H$ stability	direct search	experiment
GUT see-saw	$10^{10-16} \text{ GeV}$	YES	NO	YES	NO	NO	NO	-
EWSB	$10^{2-3} \text{ GeV}$	YES	NO	YES	NO	YES	YES	LHC
$\nu$ MSM	keV - GeV	YES	NO	YES	YES	YES	YES	a'la CHARM
$\nu$ scale	eV	YES	YES	NO	NO	YES	YES	a'la LSND

Figure 4. Left: possible values of the Yukawa couplings and Majorana masses of the sterile neutrinos in seesaw models. Right: the table shows whether the corresponding choice of the mass for Majorana fermions may explain neutrino masses and oscillations, accommodate eV neutrino anomalies, lead to baryogenesis, provide the dark matter candidate, ensure the stability of the Higgs mass against radiative corrections, and be directly searched at some experiments.

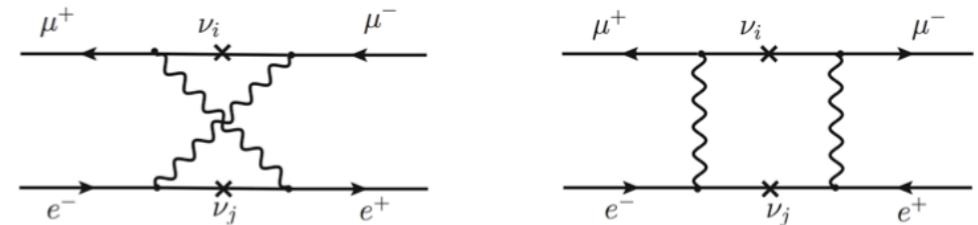
## Other interesting processes (I)

### ★ Muonium conversion: $Mu - \bar{Mu}$

[PRELIMINARY (Abada, De Romeri, AMT)]

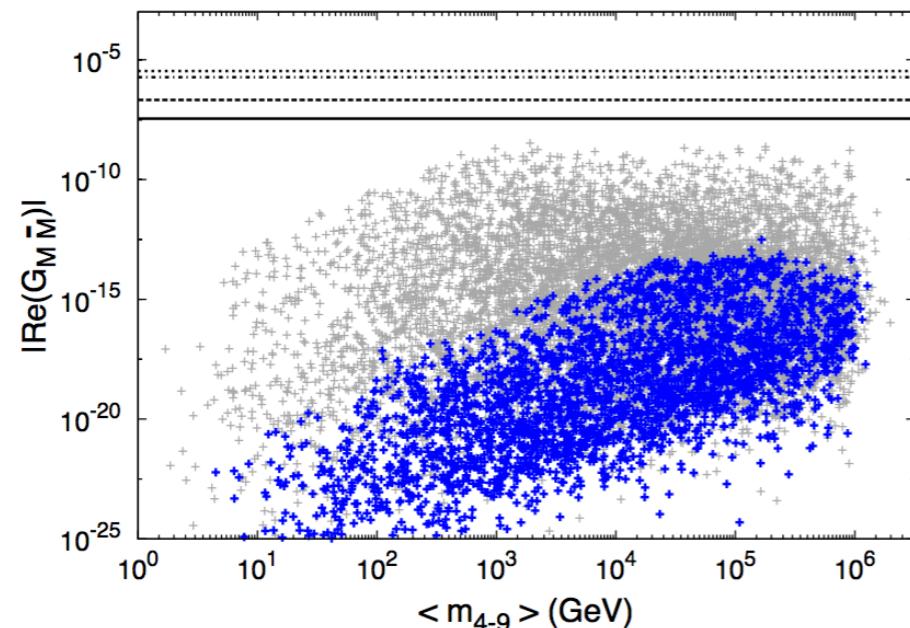
- ▶ Describing the transition via an **effective 4-fermion interaction**

$$\mathcal{L}_{\text{eff}} \sim G_{M\bar{M}} [\bar{\mu} \gamma^\alpha (1 - \gamma_5) e] [\bar{\mu} \gamma_\alpha (1 - \gamma_5) e]$$



- ▶ Sterile neutrino contribution given by

$$G_{M\bar{M}} = G_F \frac{\alpha_W}{32\pi} \sum_{i,j=1}^{3+n_S} [2U_{ie}U_{je}U_{i\mu}^*U_{j\mu}^* F_{\text{Box}}(x_i, x_j) - (U_{ie})^2(U_{j\mu}^*)^2 G_{\text{Box}}(x_i, x_j)]$$

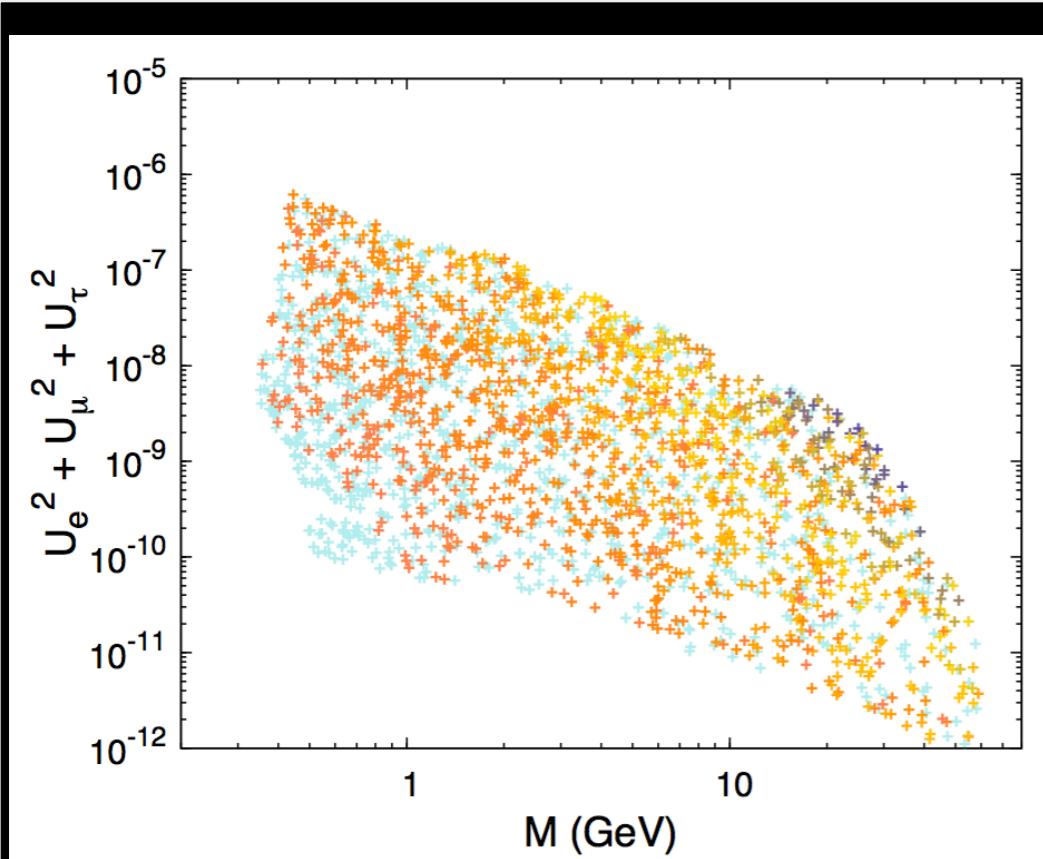


- ▶ Present **experimental limit** (PSI)

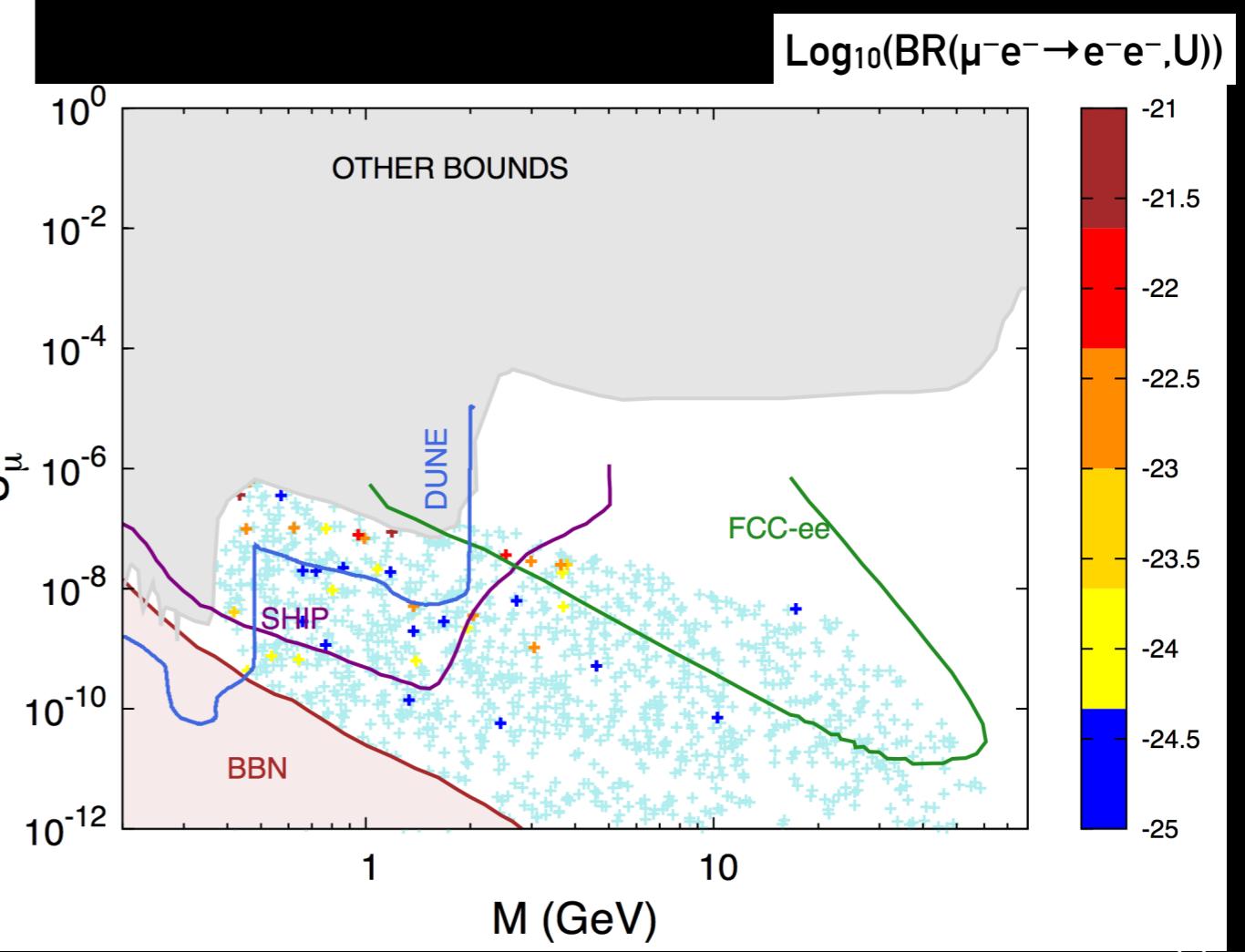
$$G_{M\bar{M}}/G_F < 3 \times 10^{-3} \quad [\text{Willimann et al, '98}]$$

- ▶ Small sterile contribution...

$$G_{M\bar{M}}|_{\nu_s} < 3 \times 10^{-8}$$



# vMSM

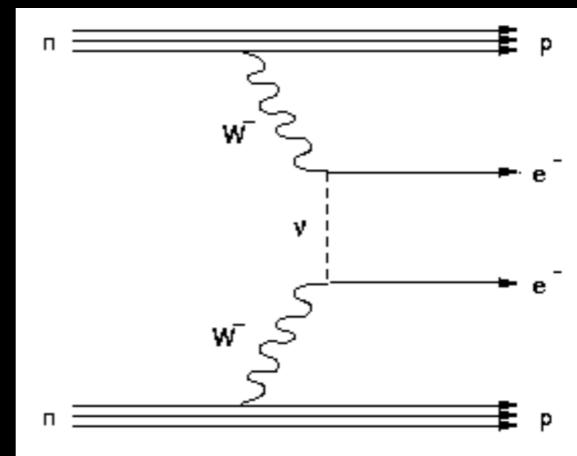


# Sterile fermions contribute to several observables:

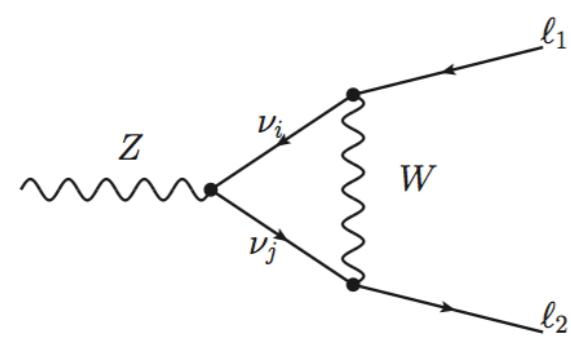
► Examples of some observables:

**Lepton properties:** {

- Anomalous magnetic moments
- Neutrinoless double beta decay
- Violation of flavour universality (e.g.  $\Delta r_K$ )



Low and high energies



**Rare decays:** {

- Violation of lepton flavour (e.g.  $\mu \rightarrow 3e$ )
- LFV  $Z$  decays
- Invisible  $H$  decays

# Lepton magnetic moments

The Dirac theory predicts a magnetic dipole moment in the presence of an external magnetic field, for any lepton ( $l=e,\mu,\tau$ )

with gyromagnetic ratio  $g_\ell = 2$

$$\vec{M} = g_\ell \frac{q}{2m_\ell} \vec{S}$$

Quantum loop effects lead to a small calculable deviation, which is parametrized by the anomalous magnetic moment ( $g-2$ )

$$g_\ell = 2(1 + a_\ell)$$

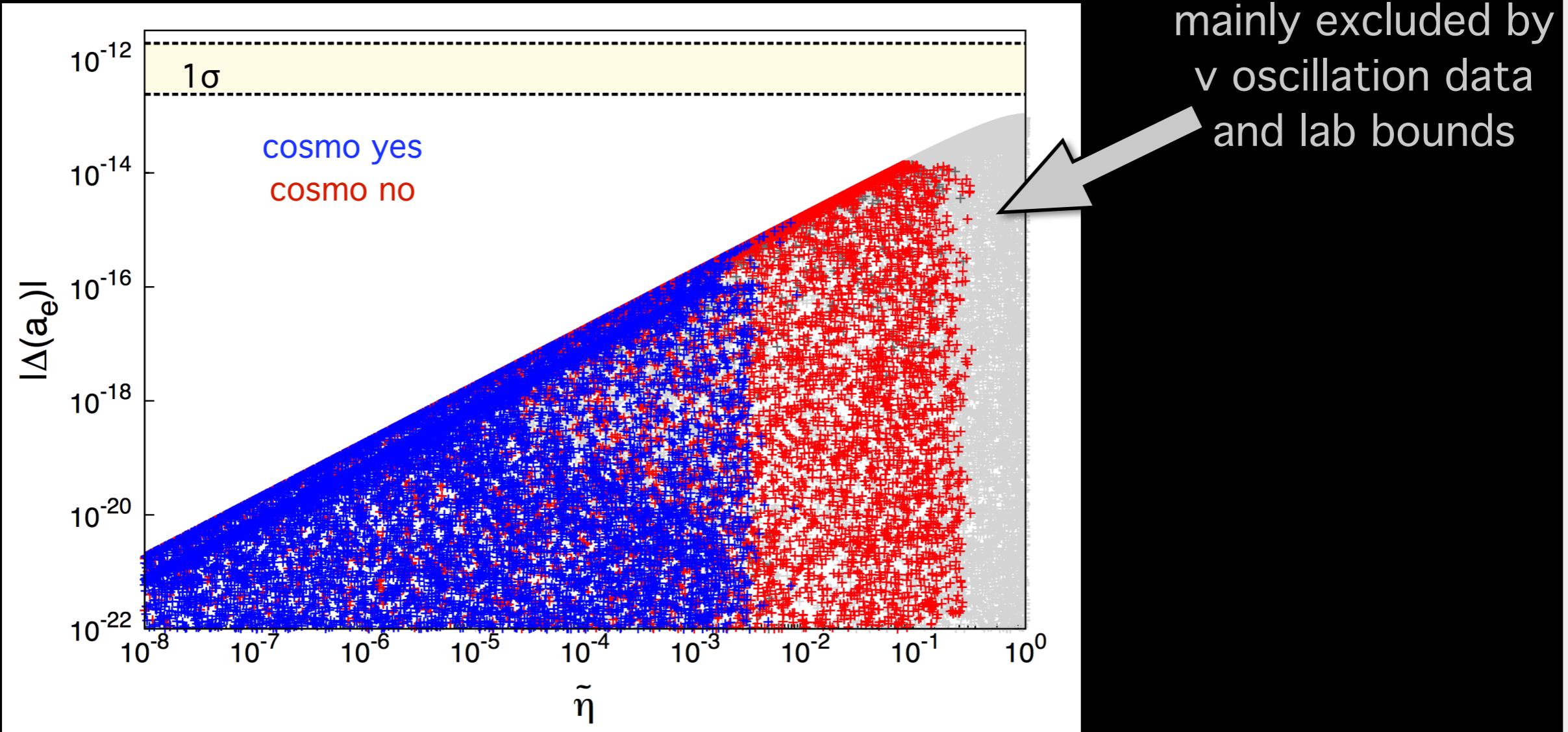
$$a_l = a_l^{QED} + a_l^{EW} + a_l^{had} + a_l^{NP}$$

$$\Delta a_e = a_e^{exp} - a_e^{SM} = -10.5(8.1) \times 10^{-13}$$

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 288(63)(49) \times 10^{-11}$$

(J. Beringer et al. PDG, 2013)

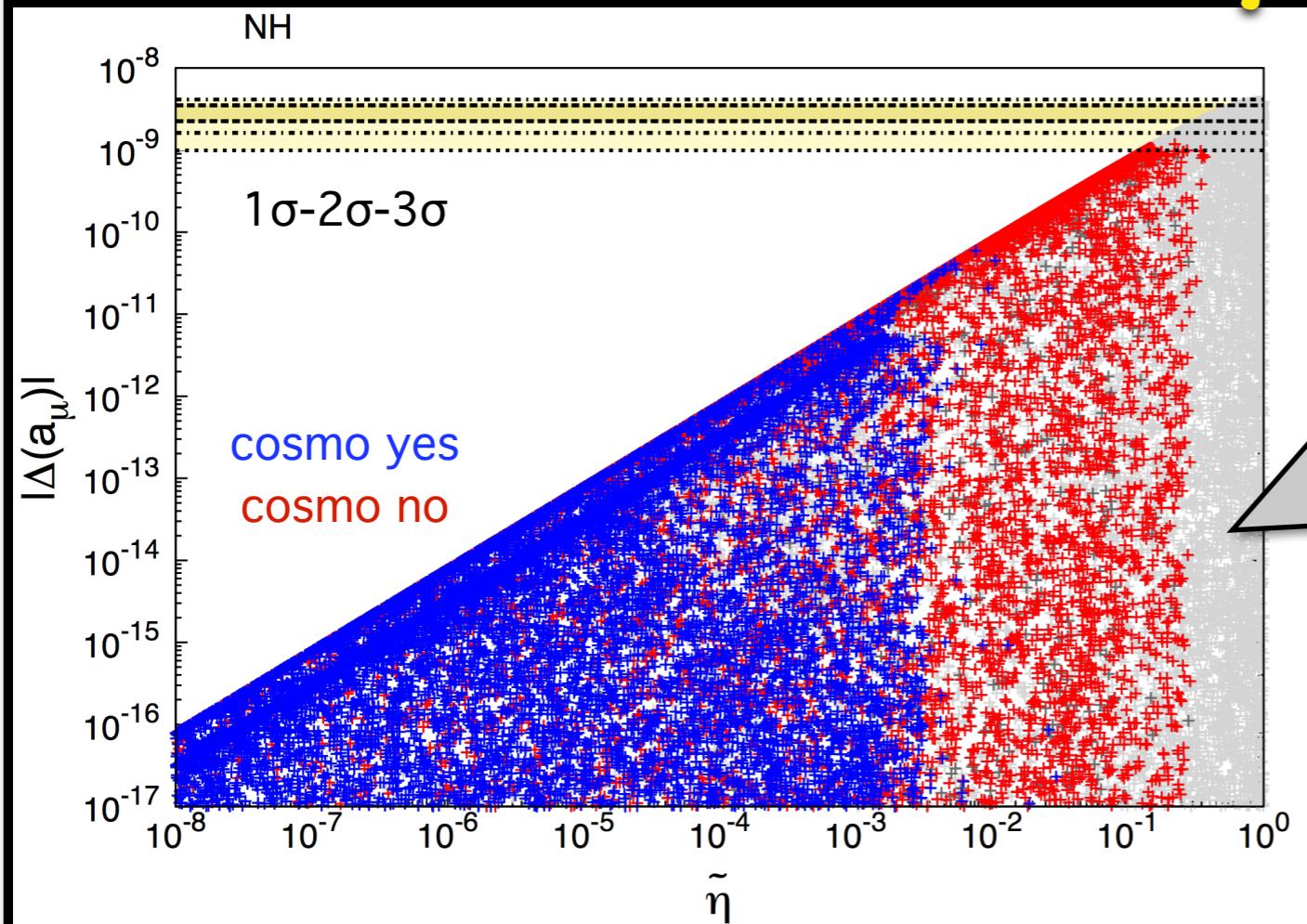
# Effective “3+1”: $a_e$



$\tilde{\eta} = 1 - \det(\tilde{U}_{\text{PMNS}})$   
measures the deviation from  
unitarity.

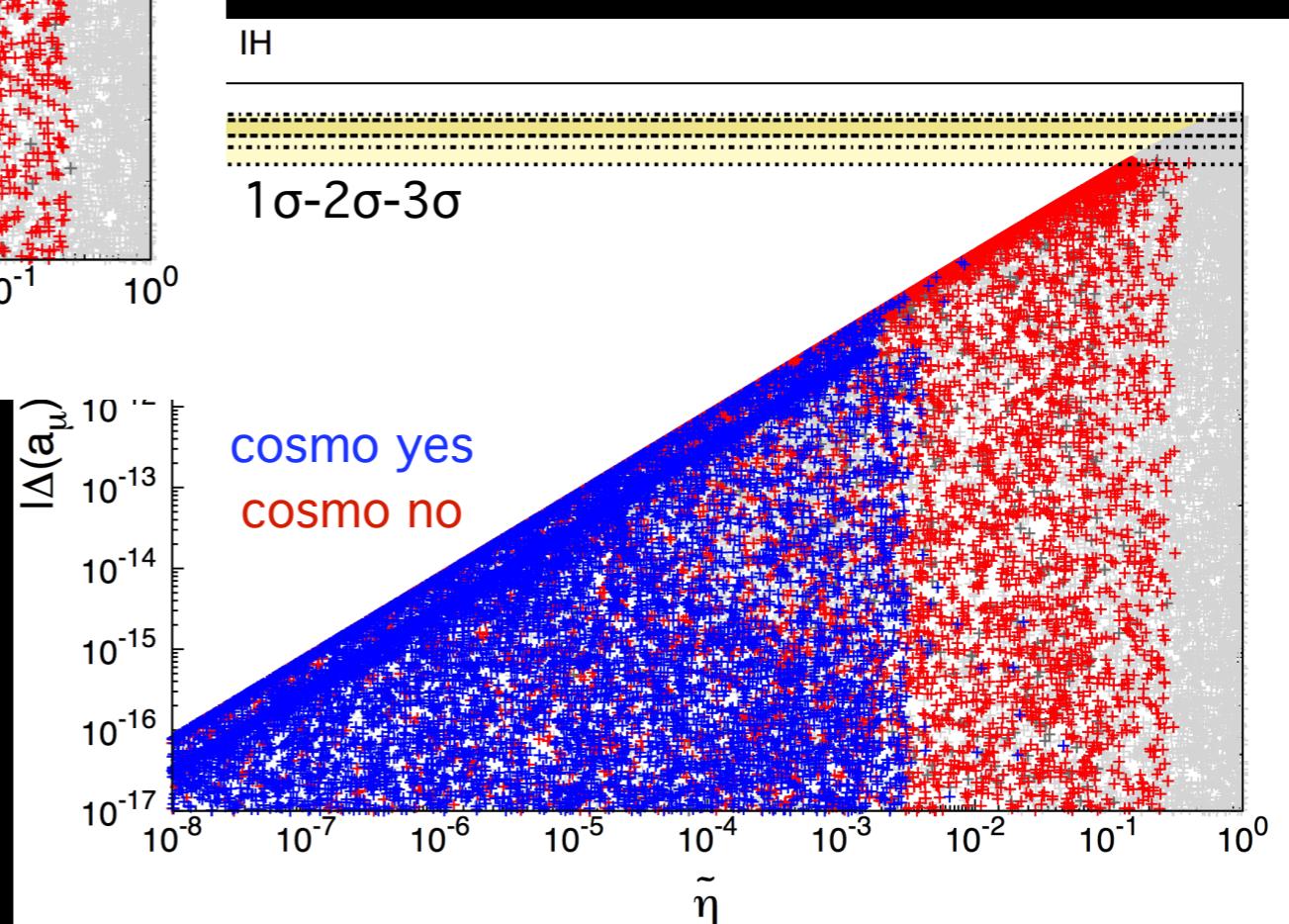
No relevant contribution  
 $\Delta(a_e)$ : no new constraint on the  
model

# Effective “3+1”: $a_\mu$



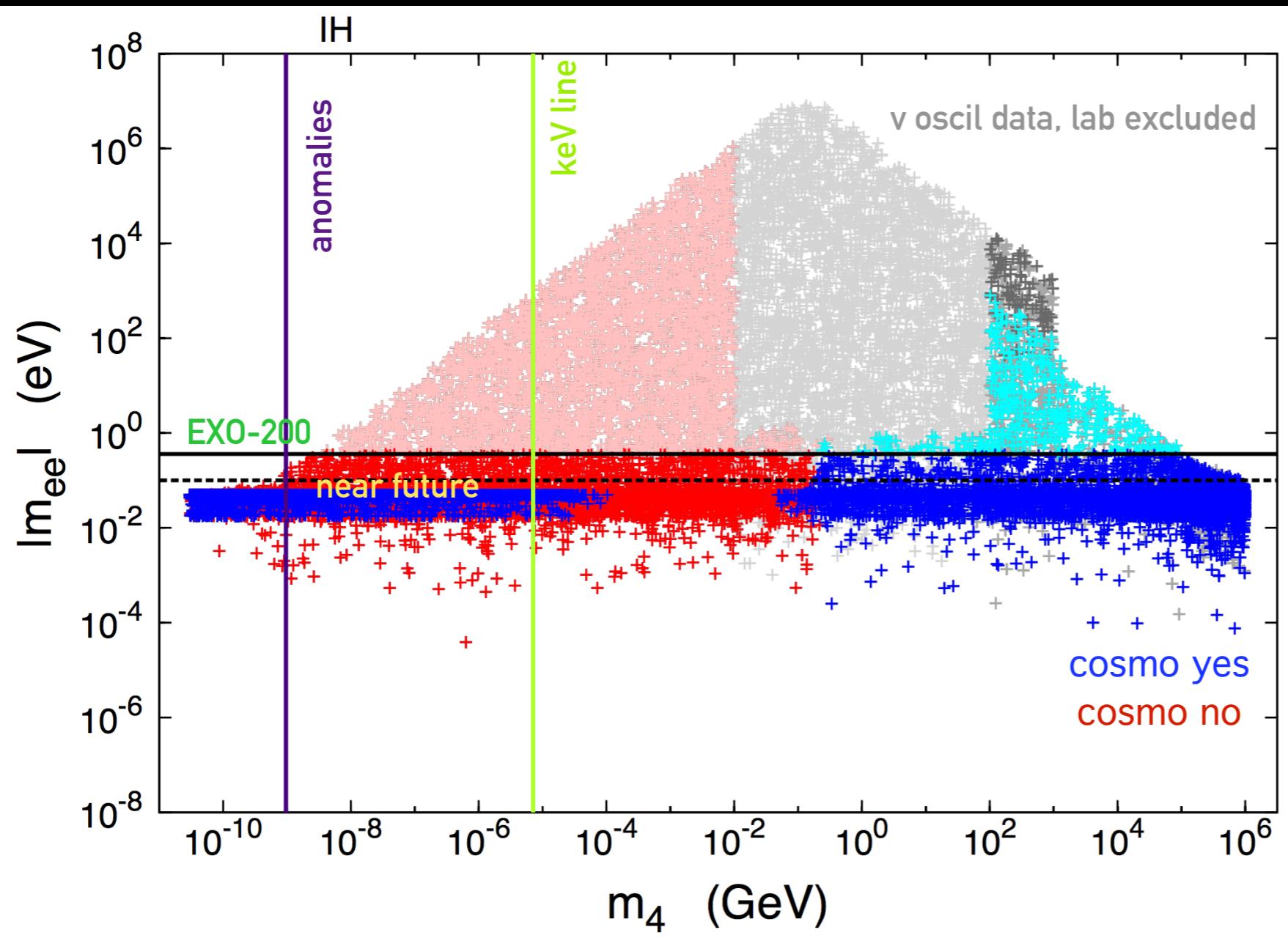
$\tilde{\eta} = 1 - \det(\tilde{U}_{\text{PMNS}})$   
measures the deviation from unitarity.

mainly excluded by  
 $\nu$  oscillation data  
and lab bounds



- Constraint from active neutrino oscillations (entries of  $U_{\text{PMNS}}$ ) rules out most solutions with large  $\tilde{\eta}$

# Effective “3+1”: $0\nu\beta\beta$ decay

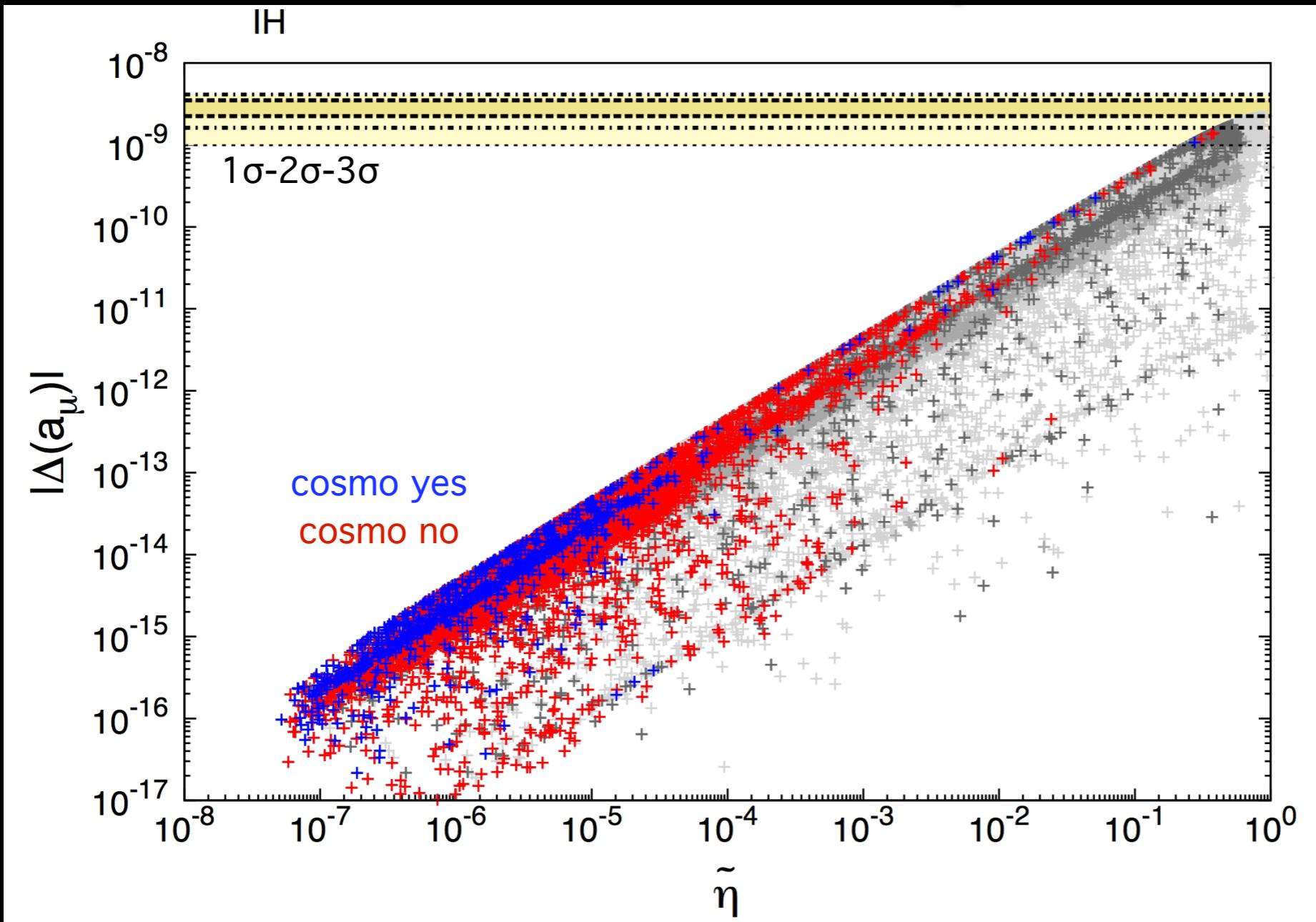


$$m_{ee} \simeq \sum_{i=1}^4 U_{ei}^2 p^2 \frac{m_i}{p^2 - m_i^2}$$

p: momentum exchanged in the process  
 $(p^2 \sim - (100 \text{ MeV})^2$   
 virtual momentum of the neutrino)

We also studied effective masses  $|Im_{\mu\mu}|$  and  $|Im_{e\mu}|$ , no significant contribution.

# ISS: $a_\mu$

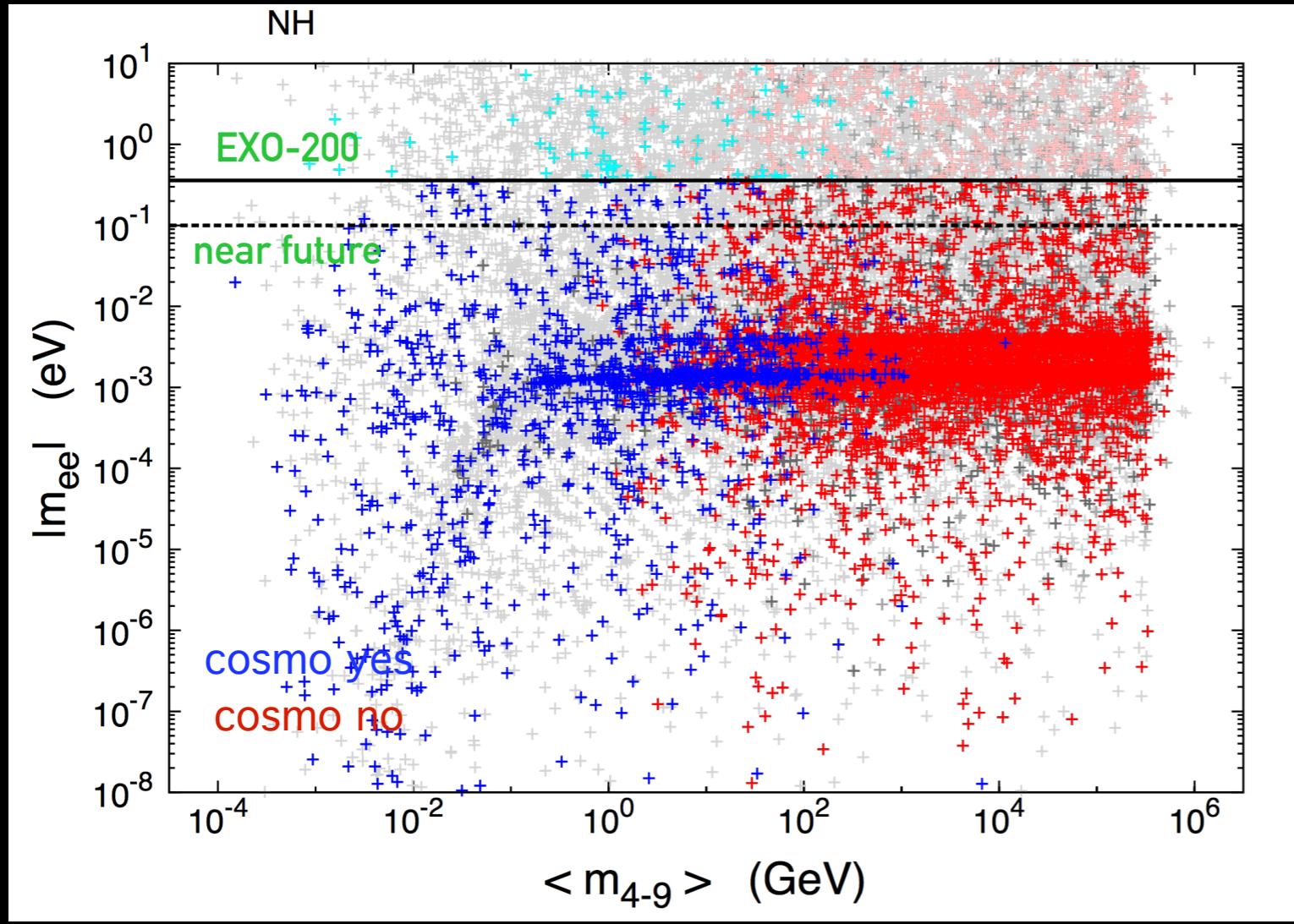


$\tilde{\eta} = 1 - \det(\tilde{U}_{\text{PMNS}})$   
measures the deviation from  
unitarity.

For large  $\tilde{\eta}$  we can get points with  
 $a_\mu$  within  $3\sigma$  of the expected value

# ISS: $0\nu\beta\beta$ decay

$p$ : momentum exchanged in the process



$m_s \ll |p|$ : in this regime the effective mass goes to zero

$$m_{\text{eff}}^{\nu_e} = p^2 \sum_{i=1}^7 U_{e,i}^2 \frac{m_i}{p^2 - m_i^2} \simeq \sum_{i=1}^7 U_{e,i}^2 m_i$$

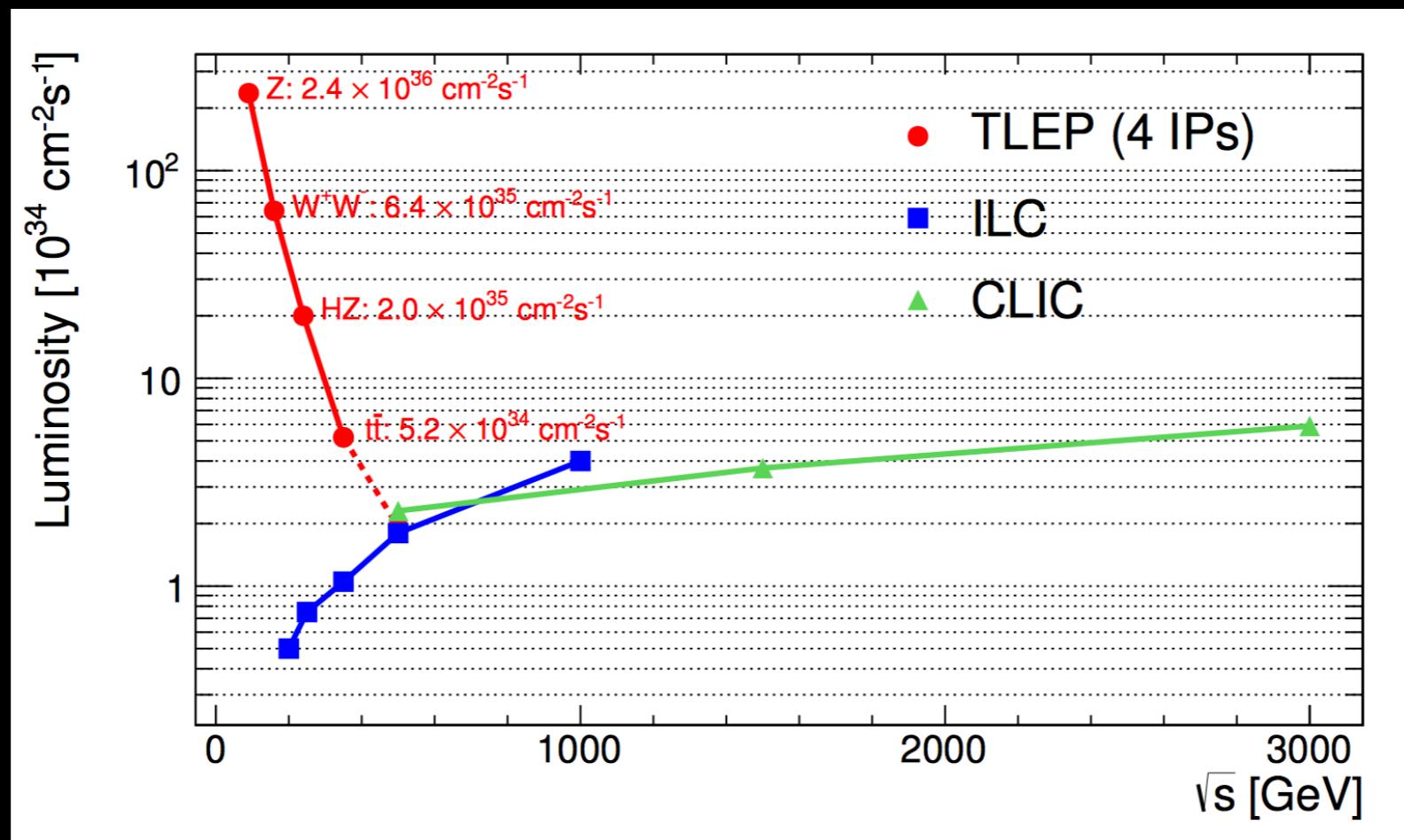
$m_s \approx |p|$ : the contribution of the pseudo-Dirac states becomes more important, and can induce sizeable effects to  $m_{ee}$

$m_s \gg |p|$ : in this regime the heavy states decouple, and the contributions to  $m_{ee}$  only arise from the 3 light neutrino states.

$$m_\nu^{\beta\beta} = \sum_i U_{ei}^2 p^2 \frac{m_i}{p^2 - m_i^2}$$

- $0\nu\beta\beta$  decay excludes some solutions
- points within the reach of actual and near-future experiments

# Future circular (and linear) colliders



Instantaneous luminosity expected at FCC-ee, in a configuration with four interaction points operating simultaneously, as a function of the centre-of-mass energy.

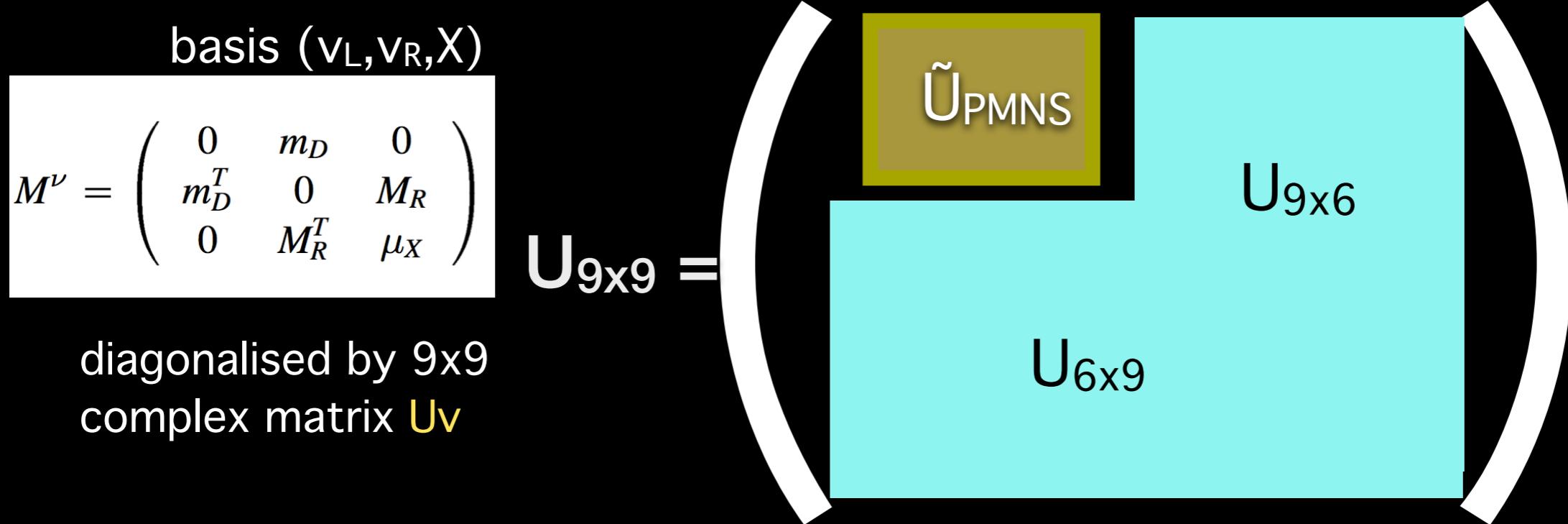
FCC-ee is designed to provide  $e^+e^-$  collisions in the beam energy range of 40 to 175 GeV.

What would we like see with  $10^{12} Z$ ?

# Low scale: Inverse seesaw (ISS)

couplings  $Y_\nu$  can be written using a modified Casas-Ibarra parametrization

$$Y_\nu = \frac{\sqrt{2}}{v} D^\dagger \text{diag}(\sqrt{M}) R \text{diag}(\sqrt{m_\nu}) U_{\text{PMNS}}^\dagger \quad M = M_R \frac{1}{\mu_X} M_R^T$$



Parameters:

- $M_R$  (real, diagonal)  $M_R = (0.1 \text{ MeV}, 10^6 \text{ GeV})$
- $\mu_X$  (complex, symmetric)  $\mu_X = (0.01 \text{ eV}, 1 \text{ MeV})$
- $R_{\text{mat}}$  (rotation, complex)
- 2 Majorana and 1 Dirac phases from  $U_{\text{PMNS}}$
- Normal (NH) / Inverted (IH) hierarchy

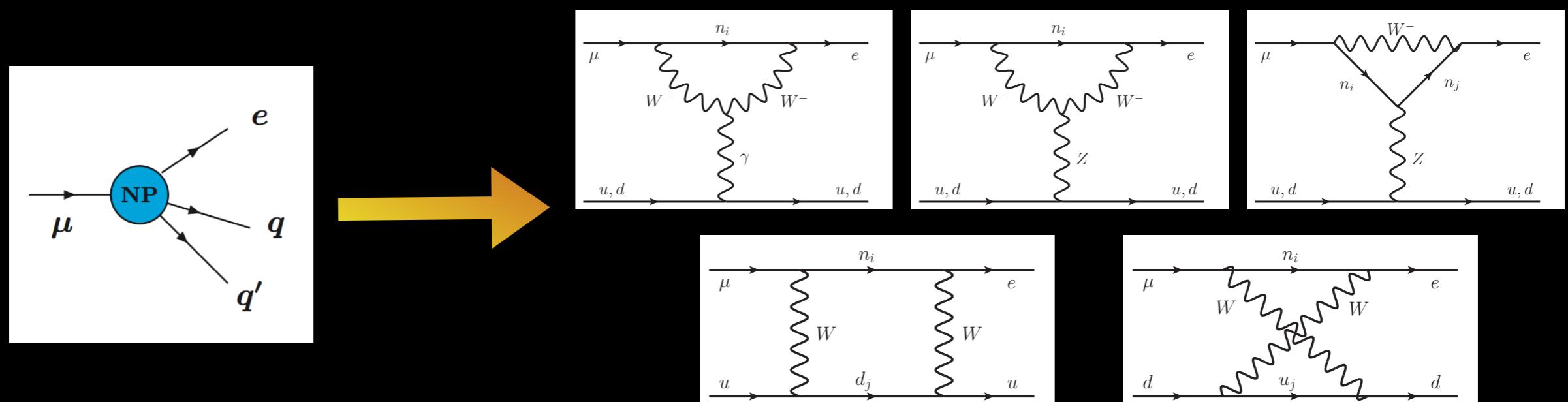
# cLFV in “muonic” atoms: $\mu^- - e^-$ conversion

► Coherent conversion in a muonic atom [ $\mu^-$ +Nucleus]:  $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$

Neutrinoless capture of a bound 1s muon in a muonic atom by the nucleus ( $A, Z$ )



Several NP sources of LFV; sensitive to contact and photon interactions...

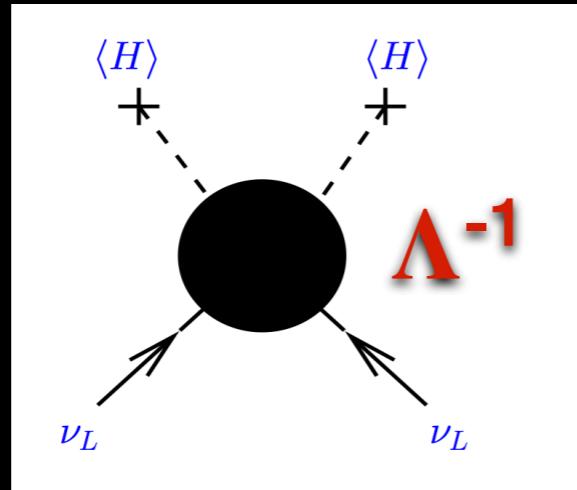


[Gronau et al, '85; Ilakovac & Pilaftsis, '95 - '14;  
Deppisch et al, '05; Dinh et al, '12; Alonso et al, '12; ...]

# Majorana neutrinos

If Lepton Number is Violated:

The lowest order operator, which generates Majorana neutrino masses is the Weinberg's d=5 operator (WO)



$$\mathcal{L} \ni \frac{LLHH}{\Lambda}$$

S. Weinberg, Phys. Rev. Lett. 43, 1566 (1979)

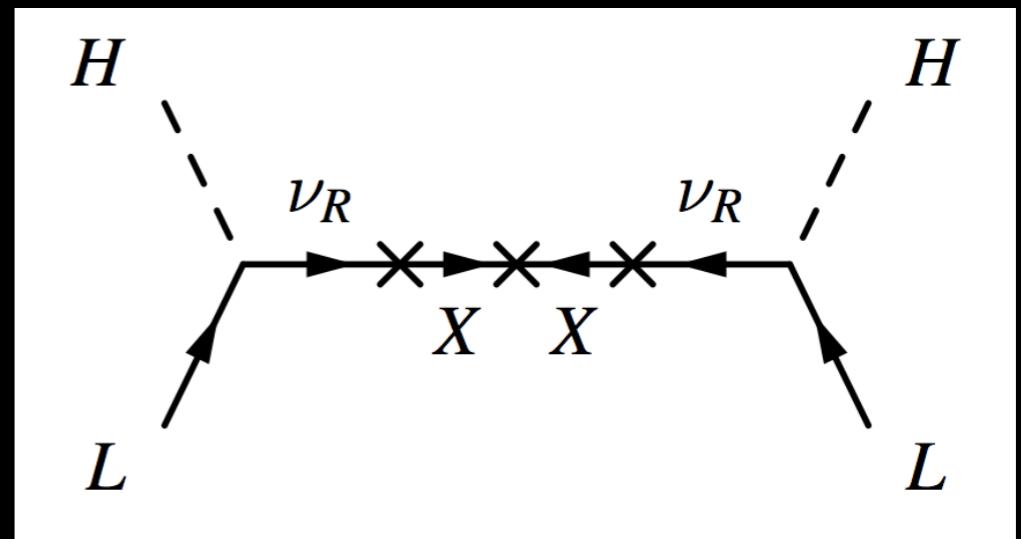
After EWSB takes place, through the nonzero vev  $v$ , Majorana neutrino masses are induced

$$m_\nu \sim Y^2 \frac{v^2}{\Lambda}$$

small neutrino masses by making  $\Lambda$  very large and/or with  $Y$  small  
The exchange of heavy messenger states provides a simple way to generate the WO.

## Inverse seesaw basis ( $\nu_L, \nu_R, X$ )

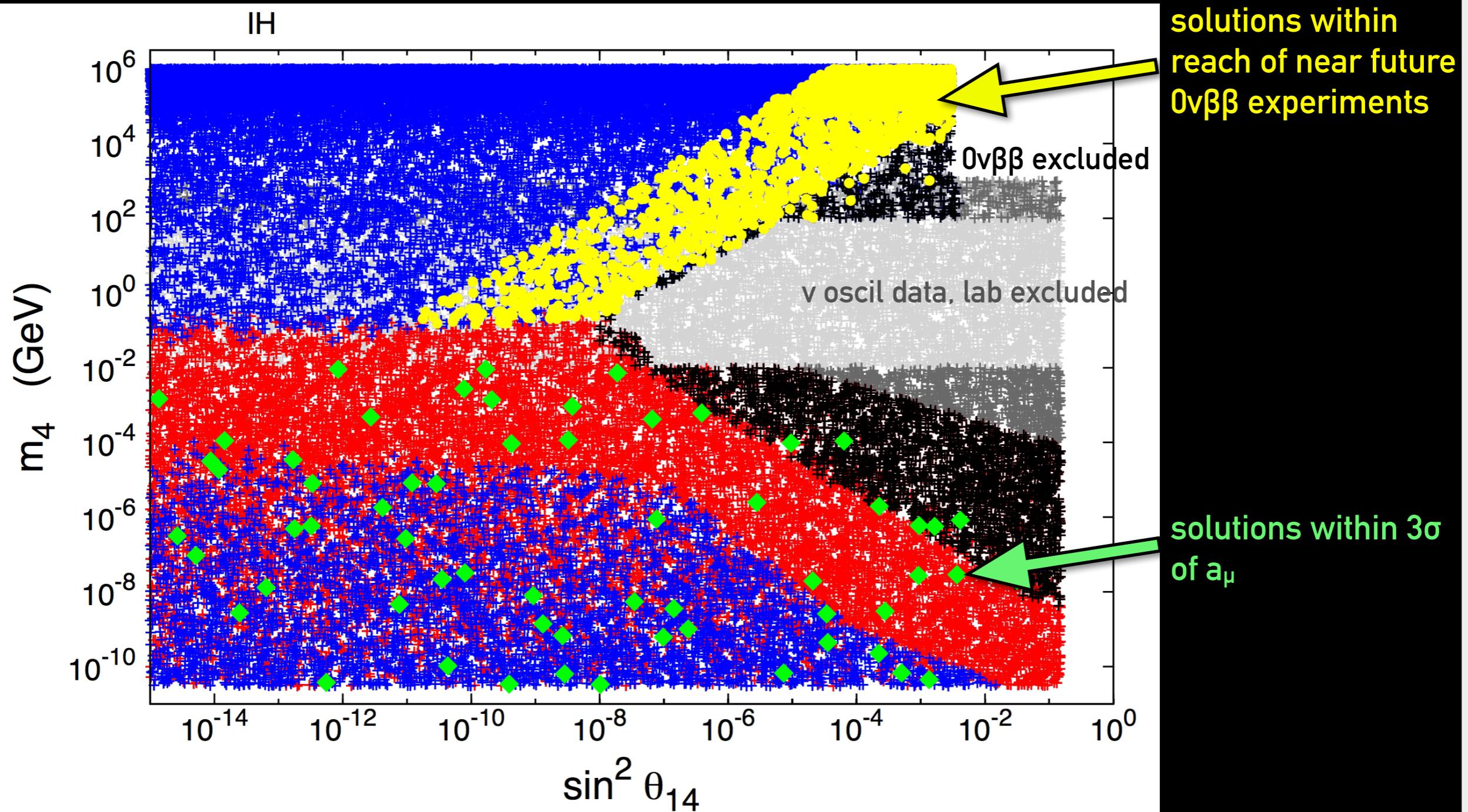
$$M^\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$



$$m_\nu = m_D (M_R^T)^{-1} \mu_X (M_R)^{-1} m_D^T$$

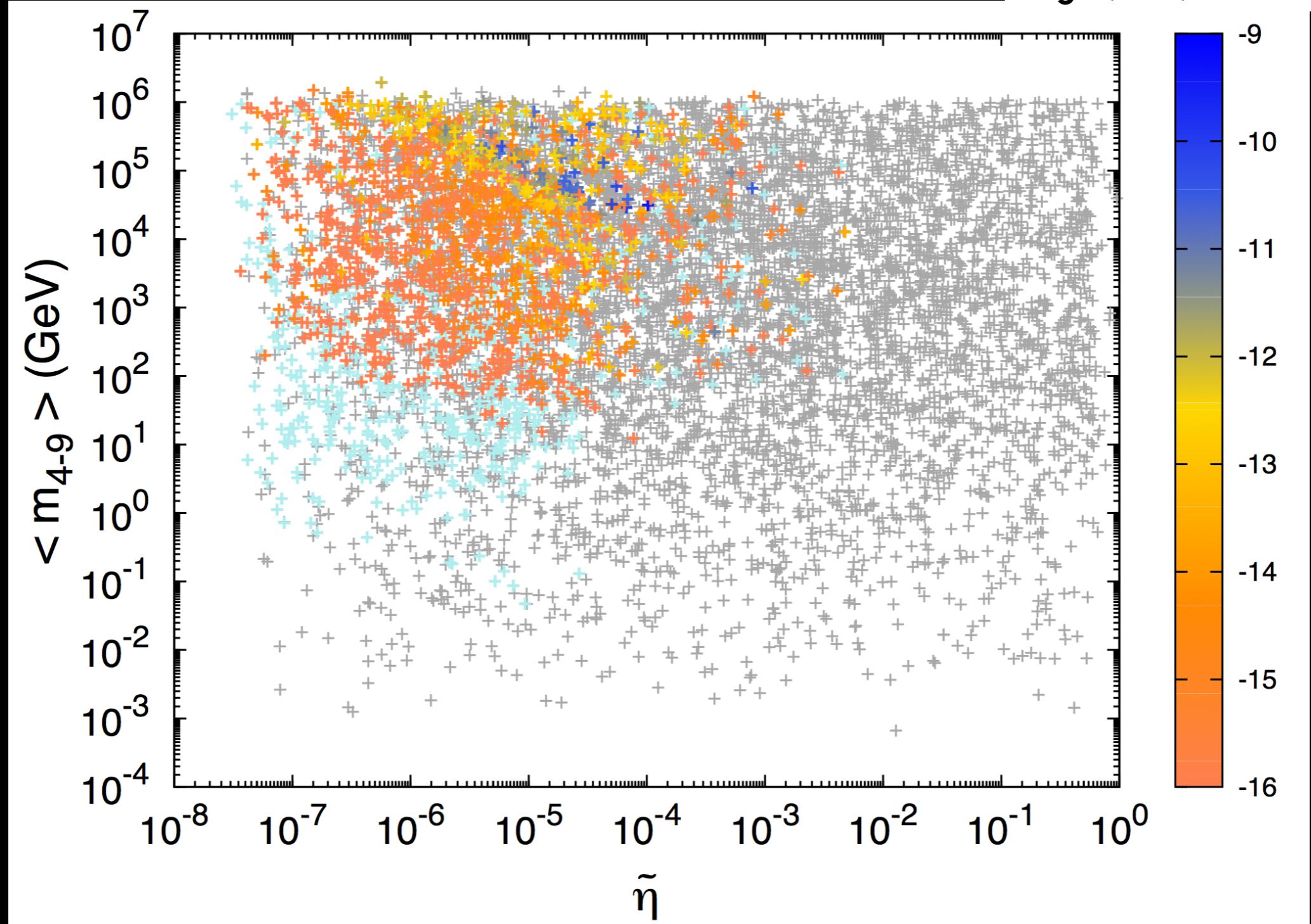
$$\begin{aligned} m_\nu &\approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2} \\ m_{1,2} &\approx \mp \sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)} \end{aligned}$$

# Effective case



# ISS: summary plot

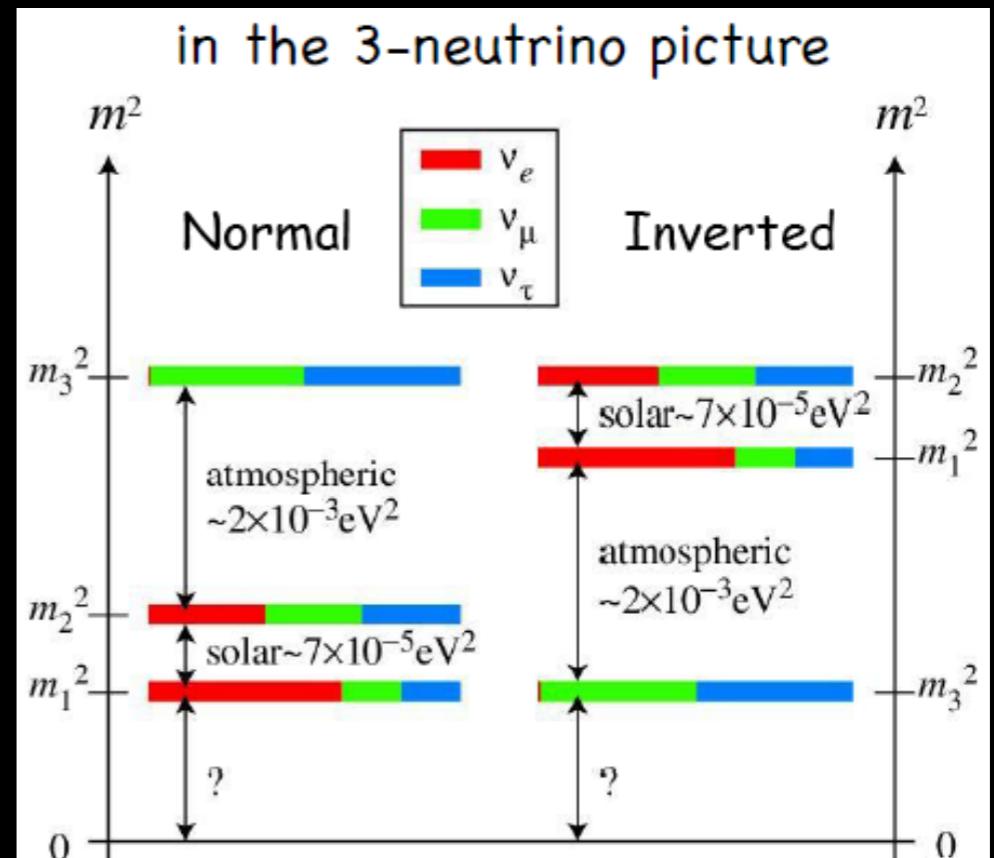
$\text{Log}_{10}(\text{BR } (Z \rightarrow l_1^\pm l_2^\mp))$



# Experimental constraints

## 1. Neutrino oscillation parameters (seesaw approximation and PMNS)

parameter	best fit $\pm 1\sigma$	$2\sigma$	$3\sigma$
$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$	$7.62 \pm 0.19$	7.27–8.01	7.12–8.20
$\Delta m_{31}^2 [10^{-3}\text{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	2.34 – 2.69 $-(2.25 - 2.59)$	2.26 – 2.77 $-(2.15 - 2.68)$
$\sin^2 \theta_{12}$	$0.320^{+0.015}_{-0.017}$	0.29–0.35	0.27–0.37
$\sin^2 \theta_{23}$	$0.49^{+0.08}_{-0.05}$ $0.53^{+0.05}_{-0.07}$	0.41–0.62 0.42–0.62	0.39–0.64
$\sin^2 \theta_{13}$	$0.026^{+0.003}_{-0.004}$ $0.027^{+0.003}_{-0.004}$	0.019–0.033 0.020–0.034	0.015–0.036 0.016–0.037
$\delta$	$(0.83^{+0.54}_{-0.64}) \pi$ $0.07\pi^a$	$0 - 2\pi$	$0 - 2\pi$



(Forero, Tortola, Valle 2012)

We fix active neutrino masses and mixings in order to reproduce neutrino oscillation data, with normal and inverted hierarchy

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints (Antusch et al., 2009)

Non-standard neutrino interactions with matter can be generated by NP BSM.

$$U_{3 \times 3} = (1 - \eta) U_{PMNS}$$

Strongly constrained if  $m_N > \Lambda_{EW}$

When singlet fermions (RH neutrinos) with Y couplings and a (Majorana) mass matrix are introduced, this can in general lead to two effective operators at tree-level: the WO (LN violating) and the dim-6 operator which contributes to the kinetic energy of the neutrinos and induces non-unitarity of the leptonic mixing matrix.

After diagonalising and normalising the neutrino kinetic terms, a non-unitary lepton mixing matrix is produced from this operator.

# Experimental Bounds

1. Neutrino oscillation parameters (seesaw approximation and PMNS)

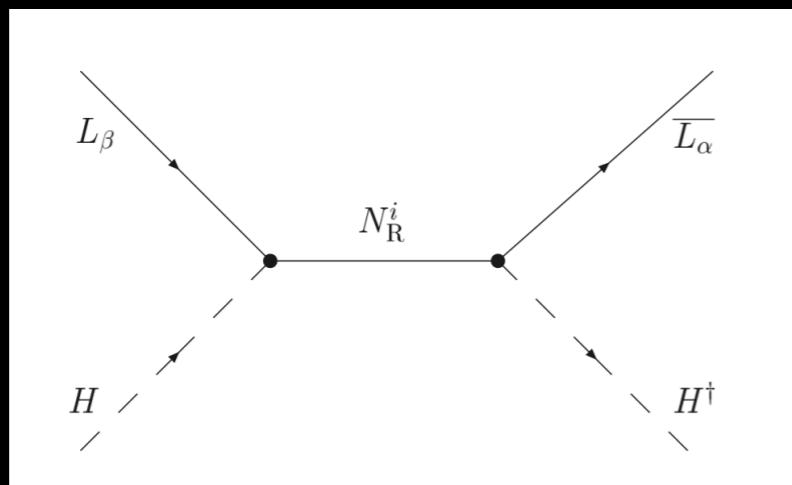
2. Unitarity constraints (Antusch et al., 2009)

When singlet fermions (RH neutrinos) with Y couplings and a (Majorana) mass matrix are introduced, this can in general lead to two effective operators at tree-level: the WO (LN violating) and the dim-6 operator which contributes to the kinetic energy of the neutrinos and induces non-unitarity of the leptonic mixing matrix.

$$\mathcal{L}_{kin}^{d=6} = -c_{\alpha\beta}^{d=6,kin} (\bar{L}_\alpha \cdot H^\dagger) i\not{\partial} (H \cdot L_\beta)$$

After diagonalising and normalising the neutrino kinetic terms, a **non-unitary lepton mixing matrix** is produced from this operator.

$$\mathcal{L}_{int}^Y = -Y_{\alpha i}^* (\bar{L}_\alpha \cdot H^\dagger) N_R^i + \text{H.c.}$$



- No new interactions of four charged fermions
- No cancellations between diagrams with different messenger particles
- Tree-level generation of the NSIs through dimension 6 and 8 operators
- Electroweak symmetry breaking is realised via the Higgs mechanism

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data (Del Aguila et al., 2008, Atre et al., 2009)

The presence of singlet neutrinos can affect the electroweak precision observables via tree-level as well as loop contributions, as a consequence of non-unitarity of the active neutrino mixing matrix. The couplings of the light neutrinos to the Z and W bosons are suppressed with respect to their SM values, reducing the tensions:

  - LEP measurement of the invisible Z-decay width is two sigma below the value expected in the SM;  
 $\Gamma_{\text{SM}}(Z \rightarrow vv) = (501.69 \pm 0.06) \text{ MeV}$ ,  $\Gamma_{\text{Exp}}(Z \rightarrow vv) = (499.0 \pm 1.5) \text{ MeV}$
  - The neutral-to-charged-current ratio in neutrino scattering experiments is three sigma below the value expected in the SM - NuTeV anomaly;
  - The input parameters of the ew fit and the experimentally observed value of the W boson mass (derived from other SM parameters)

invisible and leptonic Z-decay widths, the Weinberg angle and the values of  $g_L$  and  $g_R$

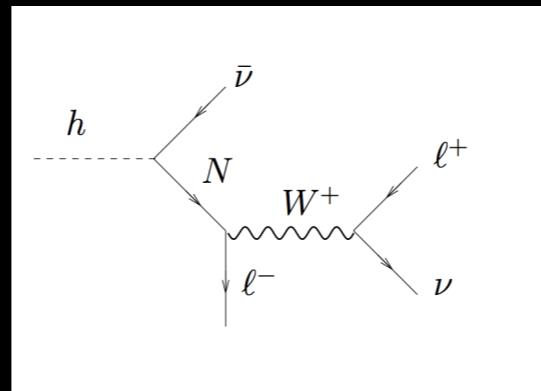
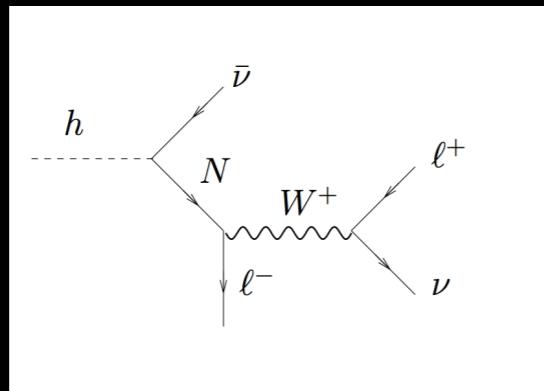
Apply to sterile neutrino masses  $\gtrsim 1 \text{ TeV}$

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data
4. LHC data (decay modes of the Higgs boson)  
(Bhupal Dev et al., 2012,  
P. Bandyopadhyay et al., 2012,  
Cely et al., 2013)

$h \rightarrow v_R v_L$  relevant for sterile neutrino masses  $\sim 100$  GeV

Bounds on the Dirac Yukawa couplings of the neutrinos in seesaw models using the LHC data on Higgs decays for the case where the SM singlet heavy leptons needed for the seesaw mechanism have masses in the 100 GeV range. Such scenario with large Yukawa couplings is natural in ISS models since the small neutrino mass owes its origin to a small Majorana mass of a new set of singlet fermions.



Higgs decay modes into  $llvv$  mediated by the ISS couplings

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data
4. LHC data (invisible decays)
5. Leptonic meson decays (B and D) (J. Beringer et al. ,PDG, 2013)

Decays of pseudoscalar mesons into leptons, whose dominant contributions arise from tree-level W mediated exchanges.

$\Gamma(P \rightarrow l\nu)$  with  $P = D, B$  with one or two neutrinos in the final state

⚠ The theoretical prediction of some decays can be plagued by hadronic matrix element uncertainties

# K decays

Why do not apply  $K \rightarrow l\nu$  as a laboratory constraint?

In order to use this channel as a lab channel we need also to have  $K \rightarrow \pi l\nu$  since in  $K \rightarrow l\nu$  one needs  $V_{us}$  and  $f_K$  (decay constant). In order to have  $V_{us}$  you need  $f_K$  and viceversa.

People then use  $K \rightarrow \pi l\nu$  which depends on  $V_{us}$  and  $F(0)$  (a form factor at zero recoil).

$K \rightarrow l\nu$  cannot be a "lab constraint" since it depends on another measurement or a global fit of CKM (which calls for many channels)

The other point is that even if we assume to know  $V_{us}$  perfectly, then this decay is not free from soft photon contributions (a photon issued for instance by the charged lepton). This call for radiative contributions (loop).

Study of the tree-level enhancement to the violation of lepton flavor universality in light meson decays arising from modified  $W l\nu$  couplings. ([Abada et al. 2014](#))

# Experimental constraints

1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data
4. LHC data (invisible decays)
5. Leptonic and semileptonic meson decays (K,B and D)
  
6. Laboratory bounds: direct searches for sterile neutrinos

(Atre et al. 2009, Kusenko et al. 2009)

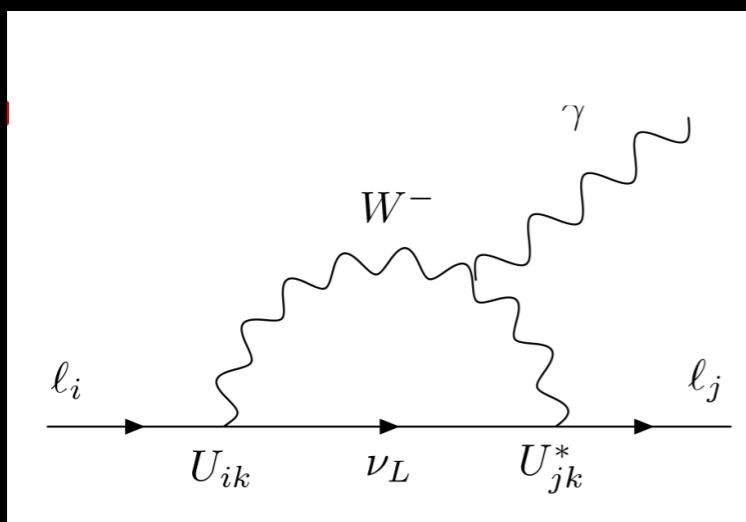
A very powerful probe of the mixing of heavy neutrinos with both  $\nu_e$  and  $\nu_\mu$  are peak searches in leptonic decays of pions and kaons.

If a heavy neutrino is produced in such decays (e.g.  $\pi^\pm \rightarrow \mu^\pm \nu_s$ ), the lepton spectrum would show a monochromatic line.

# Experimental constraints

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7. Lepton flavor violation ( $\mu \rightarrow e \gamma$ ) (Ilakovac and Pilaftsis, 1995, Deppisch and Valle, 2005)

$$Br(\mu \rightarrow e\gamma) = \frac{a_W^3 s_W^2 m_\mu^5}{256\pi^2 m_W^4 \Gamma_\mu} \left| \sum_k U_{ek} U_{\mu k}^* G_\gamma\left(\frac{m_{\nu k}^2}{m_W^2}\right) \right|^2$$



$$Br(\mu \rightarrow e\gamma)_{MEG} = 0.57 \times 10^{-12}$$

(MEG, 2013)

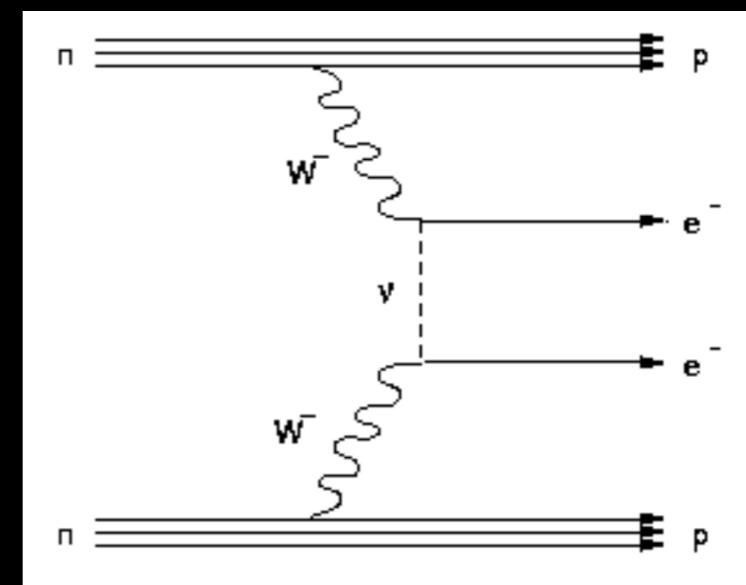
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8. Neutrinoless double beta decay

Most well studied among  $\Delta L = 2$  processes

$$m_{\nu}^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (140 - 700) meV$$

(EXO-200,KamLAND-Zen,GERDA,CUORICINO)



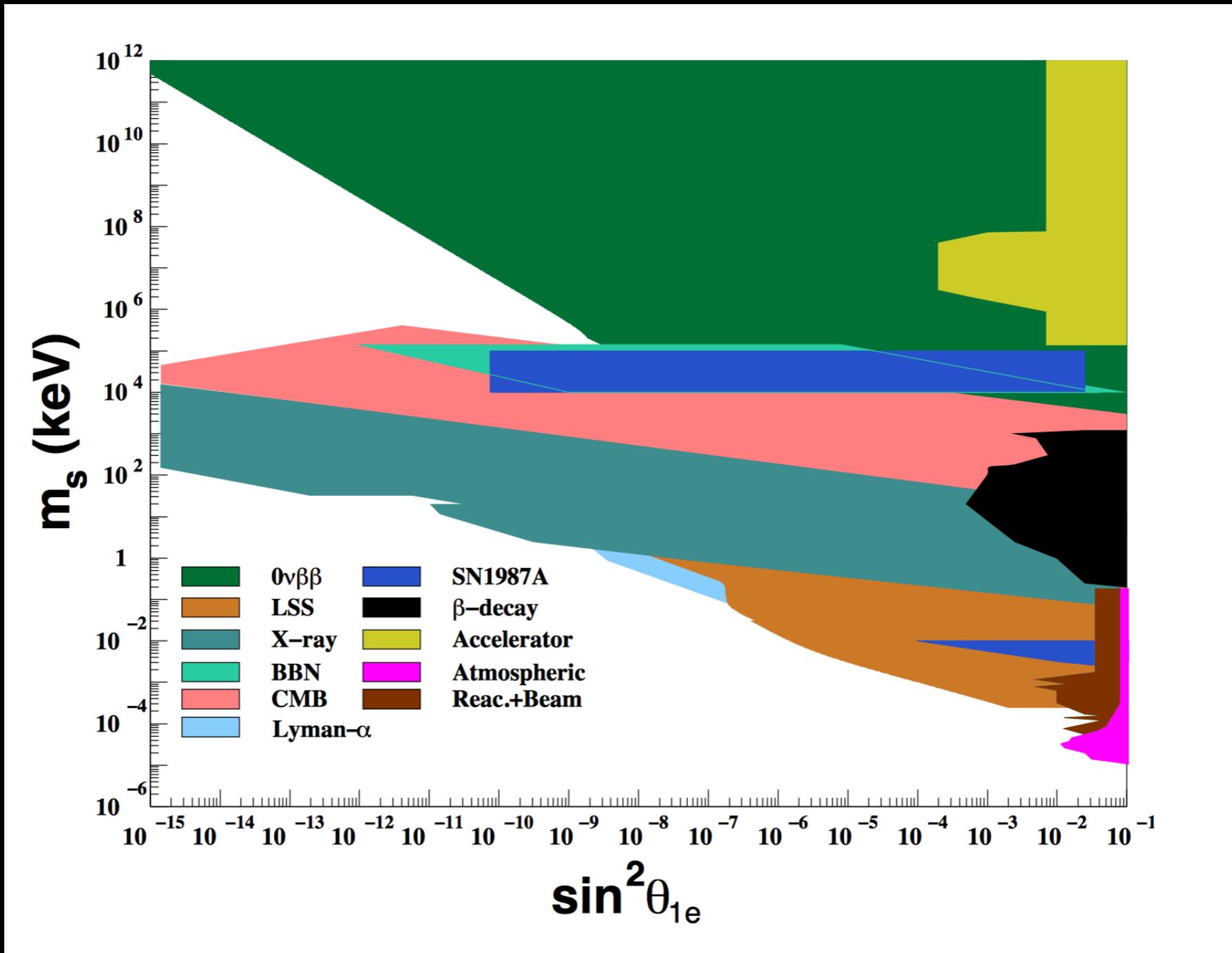
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- 
9. Cosmological bounds on sterile neutrinos
    - Large scale structure
    - Lyman-a
    - BBN
    - CMB
    - X-ray constraints (from  $\nu_i \rightarrow \nu_j \gamma$ )
    - SN1987a

(Smirnov et al. 2006  
Kusenko 2009, Gelmini 2010)

some cosmological bounds can be evaded with a non-standard cosmology  
(e.g. low reheating temperature < 1 GeV)

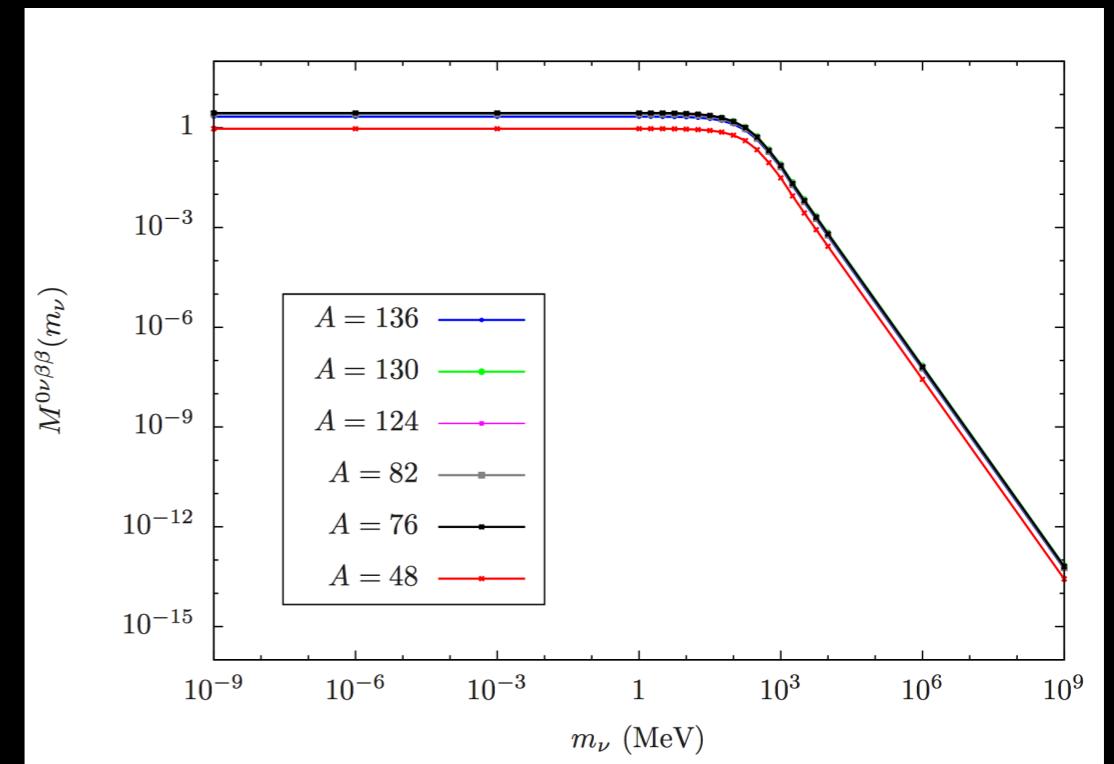
# Cosmological bounds



(Kusenko 2009)

# Nuclear matrix element dependence on the neutrino mass

There are two distinct regions where the behaviour of the NME as a function of the neutrino mass changes from almost constant up to  $m_i \approx 100$  MeV to decreasing quadratically as the neutrino mass increases beyond 100 MeV. The neutrino can be characterized as light if  $m_i^2 \ll |p^2|$  or heavy if  $m_i^2 \gg |p^2|$ , which would mean that the neutrino propagator in the NME would be dominated by  $|p^2|$  or  $m_i^2$ , respectively, where  $p$  is the momentum exchanged in the process.



$$m_{\text{eff}}^{\nu_e} \simeq \sum_{i=1}^7 U_{e,i}^2 p^2 \frac{m_i}{p^2 - m_i^2} \simeq \left( \sum_{i=1}^3 U_{e,i}^2 m_{\nu_i} \right) + p^2 \left( -U_{e,4}^2 \frac{|m_4|}{p^2 - m_4^2} + U_{e,5}^2 \frac{|m_5|}{p^2 - m_5^2} - U_{e,6}^2 \frac{|m_6|}{p^2 - m_6^2} + U_{e,7}^2 \frac{|m_7|}{p^2 - m_7^2} \right)$$

(Fernandez-Martinez et al,  
2010, Abada and Luente, 2014)

# Current bounds on effective neutrino masses from total lepton number violating processes

Flavors	Exp. technique	Exp. bound	Mass bound (eV)
( $e, e$ )	$\beta\beta0\nu$	$T_{1/2}({}^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-) > 1.9 \times 10^{25} \text{ yr}$	$ m_{ee}  < 3.6 \times 10^{-1}$
( $e, \mu$ )	$\mu^- \rightarrow e^+$ conversion	$\frac{\Gamma(\text{Ti} + \mu^- \rightarrow e^+ + \text{Ca}_{\text{gs}})}{\Gamma(\text{Ti} + \mu^- \text{ capture})} < 1.7 \times 10^{-12}$	$ m_{e\mu}  < 1.7 \times 10^7$
( $e, \tau$ )	Rare $\tau$ decays	$\Gamma(\tau^- \rightarrow e^+ \pi^- \pi^-)/\Gamma_{\text{tot}} < 8.8 \times 10^{-8}$	$ m_{e\tau}  < 2.6 \times 10^{12}$
( $\mu, \mu$ )	Rare kaon decays	$\Gamma(K^+ \rightarrow \pi^- \mu^+ \mu^+)/\Gamma_{\text{tot}} < 1.1 \times 10^{-9}$	$ m_{\mu\mu}  < 2.9 \times 10^8$
( $\mu, \tau$ )	Rare $\tau$ decays	$\Gamma(\tau^- \rightarrow \mu^+ \pi^- \pi^-)/\Gamma_{\text{tot}} < 3.7 \times 10^{-8}$	$ m_{\mu\tau}  < 2.1 \times 10^{12}$
( $\tau, \tau$ )	none	none	none

(Gómez-Cadenas et al. 2012)

# Neutrinoless double beta decay

Isotope	Experiment	$T_{1/2}^{0\nu\beta\beta}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]
$^{136}\text{Xe}$	EXO-200	$>1.6 \cdot 10^{25}$	$<140\text{--}380$
$^{136}\text{Xe}$	KamLAND-Zen	$>1.9 \cdot 10^{25}$	$<120\text{--}250$
$^{76}\text{Ge}$	GERDA phase I	$>2.1 \cdot 10^{25}$	$<200\text{--}400$
$^{130}\text{Te}$	CUORICINO	$>2.8 \cdot 10^{24}$	$<300\text{--}700$

## Future sensitivities

Isotope	Experiment	$T_{1/2}^{0\nu\beta\beta}$ sensitivity [yr]	$\langle m_{\beta\beta} \rangle$ sensitivity [meV]
$^{136}\text{Xe}$	EXO-200 (4 yr)	$5.5 \cdot 10^{25}$	75–200
$^{136}\text{Xe}$	nEXO (5 yr)	$3 \cdot 10^{27}$	12–29
$^{136}\text{Xe}$	nEXO (5 yr + 5 yr w/ Ba tagging)	$2.1 \cdot 10^{28}$	5–11
$^{136}\text{Xe}$	KamLAND-Zen (300 kg, 3 yr)	$2 \cdot 10^{26}$	45–110
$^{136}\text{Xe}$	KamLAND2-Zen (1 ton, post 2016)	IH	IH
$^{76}\text{Ge}$	GERDA phase II	$2 \cdot 10^{26}$	90–290
$^{130}\text{Te}$	CUORE-0 (2 yr)	$5.9 \cdot 10^{24}$	204–533
$^{130}\text{Te}$	CUORE (5 yr)	$9.5 \cdot 10^{25}$	51–133
$^{130}\text{Te}$	SNO+	$4 \cdot 10^{25}$	70–140

(Tosi - EXO. 2014)

# Moreover...

No dependence of the leptons anomalous magnetic moments on the phases (nor Majorana nor Dirac).

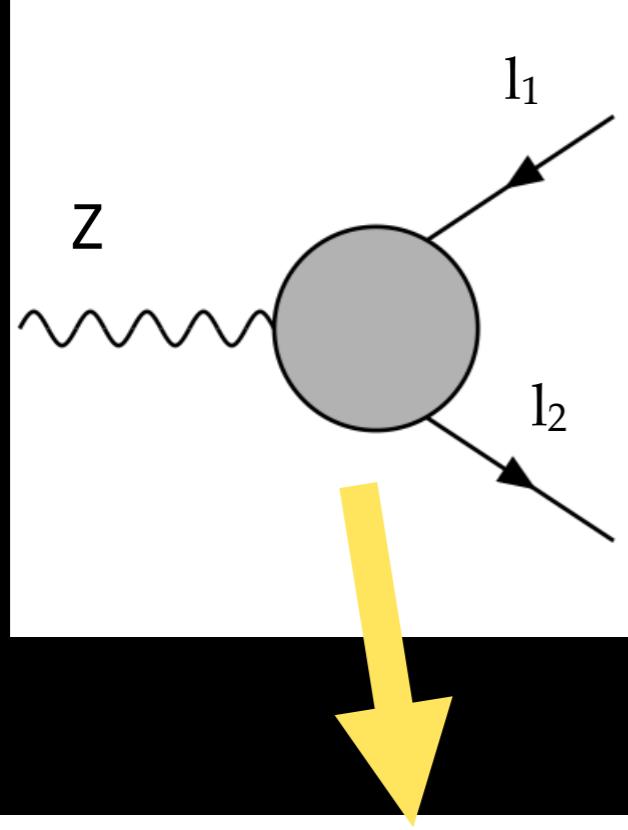
We calculated also  $a_\tau$ , which is of the order of  $10^{-14} - 10^{-6}$ , while the experimental precision is too low to be compared.

Modified  $W\ell\nu$  vertex : Effect of the tree-level enhancement to the violation of lepton flavor universality in light meson decays arising from modified  $W\ell\nu$  couplings.

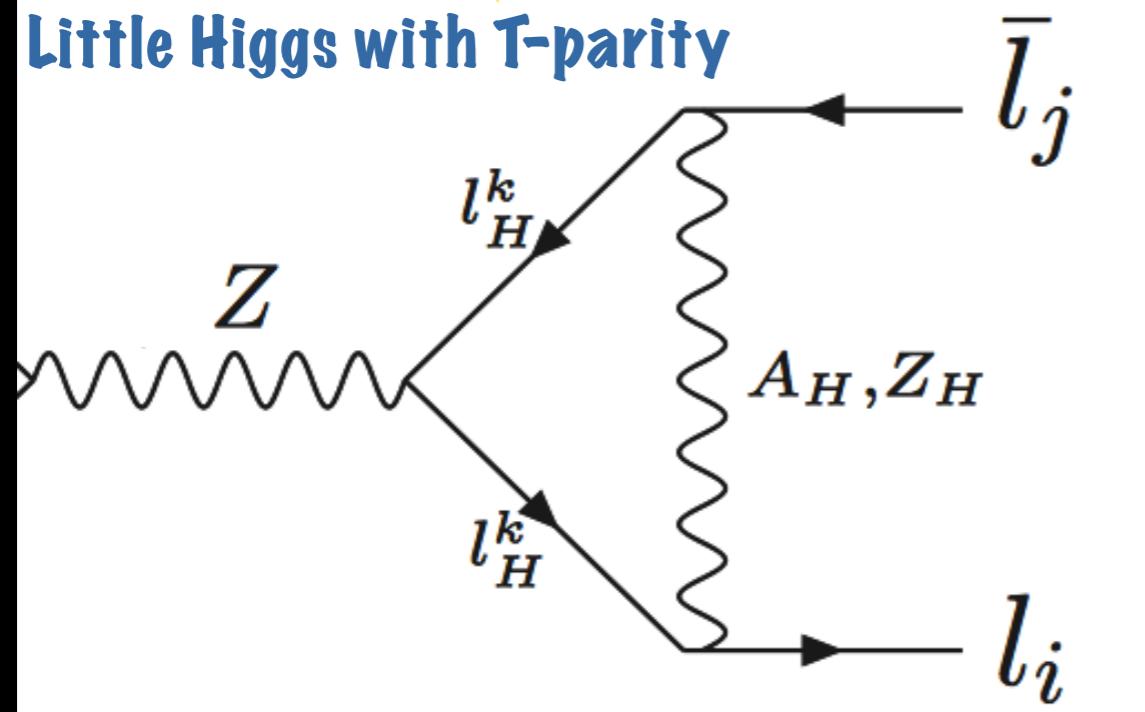
Study of the possibility of new Higgs leptonic decays, beyond the Standard Model, with the singular feature of being LFV.

realizations of minimal flavor violation (MFV) for the lepton sector: it can be realized within those seesaw models where a separation of the lepton number and lepton flavor violating scales can be achieved, such as scalar mediated (type II) and inverse seesaw models. We present in particular a simple implementation of the MFV hypothesis which differs in nature from those previously discussed.

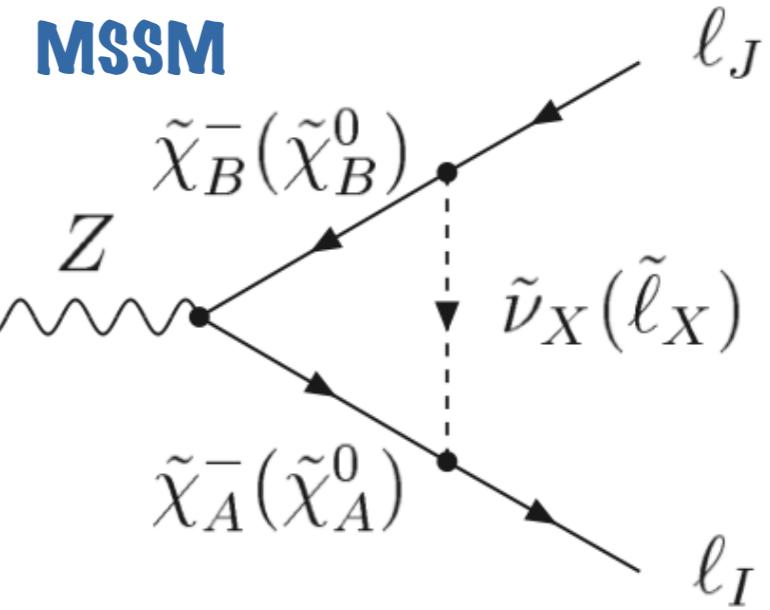
$$\Gamma_\rho = \gamma_\rho(f_V - f_A\gamma_5) + \frac{q^\nu}{M_W}(if_M + f_E\gamma_5)\sigma_{\rho\nu}.$$



**Little Higgs with T-parity**



Valentina De Romeri - IFT/UAM Madrid



some examples...

**R-parity violation**

