SEVENTH FRAMEWORK PROGRAMME

invisibles
neutrinos, dark matter &
dark energy physics

MARIE CURIE ACTIONS

Valentina De Romeri[1]

Indirect searches for sterile neutrinos at a high-luminosity Z-factory

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Invisibles15 Workshop

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Outline

- Introduction
  - Neutrino physics open questions
  - Inverse Seesaw (ISS)
  - Sterile neutrinos
  - Unitarity deviation
  - Experimental constraints
- Numerical analysis
  - Inverse Seesaw (ISS)
  - “3+1” Effective model
- LFV Z decays at a high luminosity Z factory
- Conclusions

Neutrino physics open questions

Among the missing ingredients there are:

- Absolute mass scale (Tritium β decays: $m_{\nu e}<2.05$eV, Cosmology: $\sum m_{\nu i}<0.66$ eV (CMB), $\sum m_{\nu i}<0.23$ eV (CMB+BAO+WMAP polarization data+high-resolution CMB experiments and flat Universe)) (Troitsk and Mainz, Planck 2013)
- Majorana versus Dirac nature ($0\nu\beta\beta$ decay) (KamLAND-Zen,EXO-200,Gerda)
- The mass ordering (normal or inverted "hierarchy") (matter effects in sun and long baseline oscillations, T2K,NOvA...)
- 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?

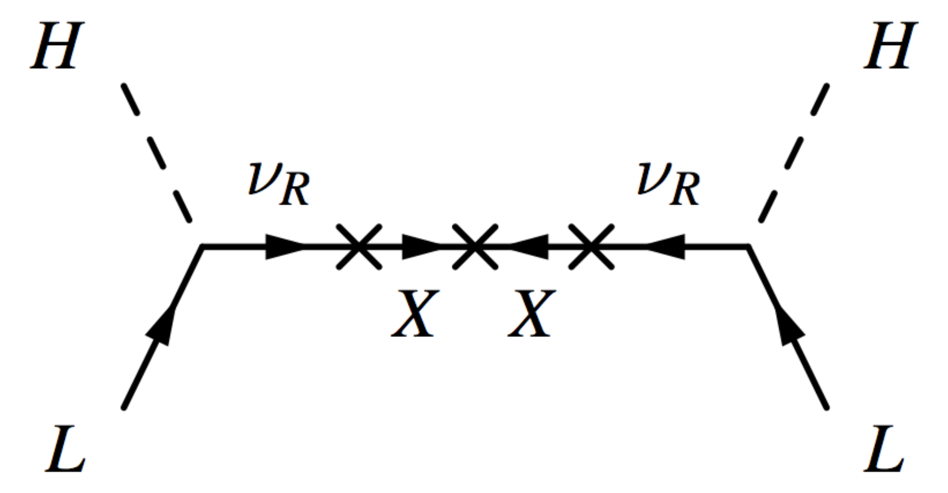
Inverse seesaw

(Mohapatra & Valle, 1986)

Add three generations of SM singlet pairs, ν_R and X (with L=+1)

Inverse seesaw basis (ν_L,ν_R,X)

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



After EWSB the effective light neutrino masses are given by

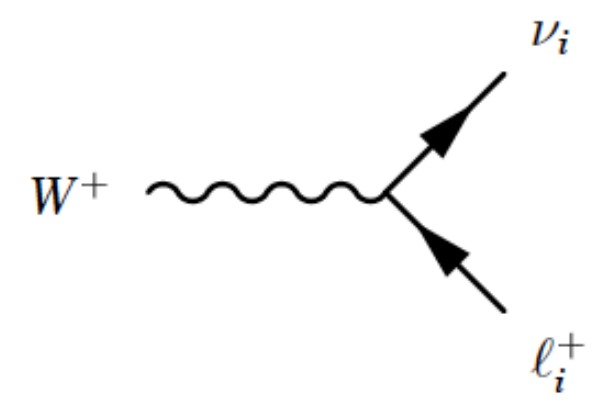
$$m_\nu = m_D (M_R^T)^{-1} \mu_X (M_R)^{-1} m_D^T$$

$Y_\nu \sim O(1)$ and $M_R \sim$ 1TeV testable at the colliders and low energy experiments.

Large mixings (active-sterile) and light sterile neutrinos are possible

Active-sterile mixing

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



Standard case (3 flavors):

$\nu_i = e,\mu,\tau$

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

ν_a = mass eigenstates, a = 1,2,3

Add sterile neutrinos:

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} U^{ji} \bar{l}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

$\nu_i = \sum_{ai} U_{ai} \; \nu_a$, a = 1,2,3,4 ..9..$n_\nu$ U = extended matrix, j=1…3, i=1…n_ν

If $n_\nu > 3$, $U \neq U_{PMNS}$ → 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)

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 ($\mu \to e \gamma$)
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)

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

(Del Aguila et al., 2008, Atre et al., 2009)

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decay modes of the Higgs boson
$h \rightarrow \nu_R\, \nu_L$ relevant for sterile neutrino masses ~100 GeV

(Bhupal Dev et al., 2012,
P. Bandyopadhyay et al,2012,
Cely et al., 2013,Arganda et al. 2014)

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

(J. Beringer et al. ,PDG, 2013)

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

e.g. $\pi^\pm \to \mu^\pm \nu_S$, the lepton spectrum would show a monochromatic line.

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7. Lepton flavor violation (μ → e γ, μ → eee ...)

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

   (Ilakovac and Pilaftsis,1995, Deppisch and Valle, 2005)

8. Neutrinoless double beta decay
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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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10. Cosmological bounds on sterile neutrinos

    Large scale structure, Lyman-α, BBN, CMB, X-ray constraints (from $\nu_i \to \nu_j \gamma$),SN1987a

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

Numerical analysis: Inverse Seesaw and Effective “3+1” model

Inverse Seesaw

couplings Yν can be written using a modified Casas-Ibarra parametrization

$$Y_\nu = \frac{\sqrt{2}}{v} D^\dagger \mathrm{diag}(\sqrt{\mathrm{M}})\mathrm{R}\,\mathrm{diag}(\sqrt{\mathrm{m}_\nu})\mathrm{U}^\dagger_{\mathrm{PMNS}}$$

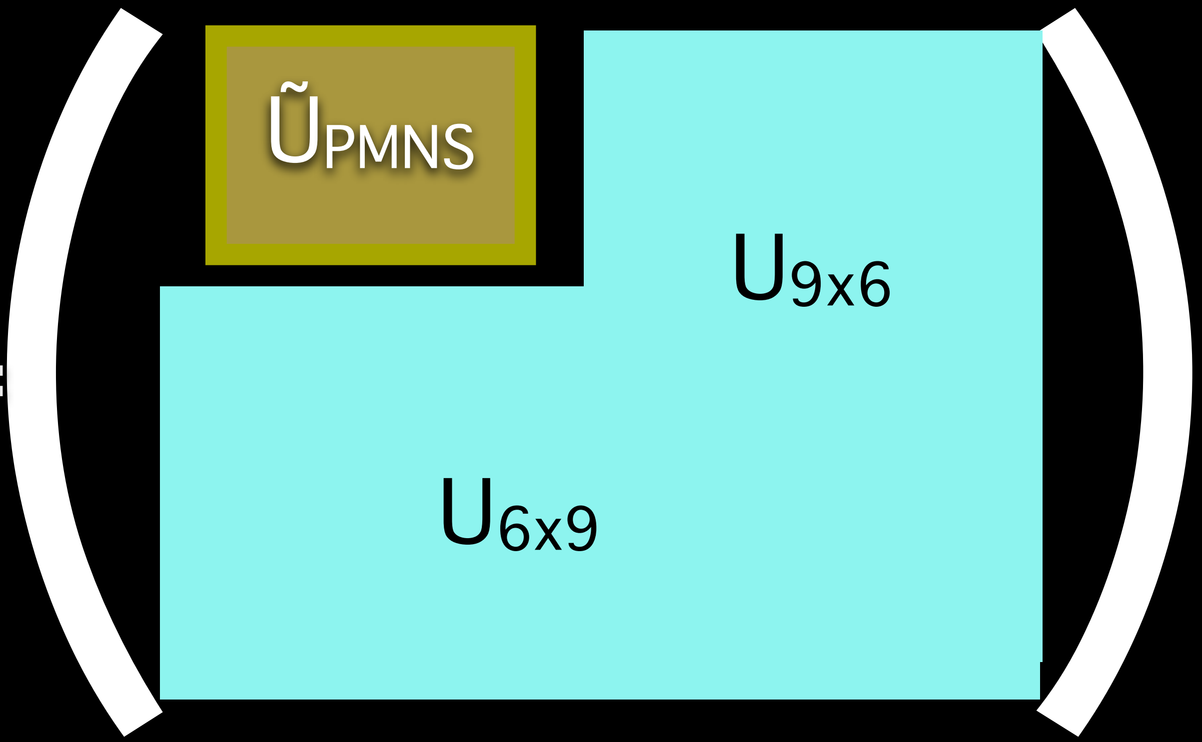
$$M = M_R \frac{1}{\mu_X} M_R^T$$

basis (ν_L,ν_R,X)

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

diagonalised by 9x9 complex matrix Uν

U_{9x9} =



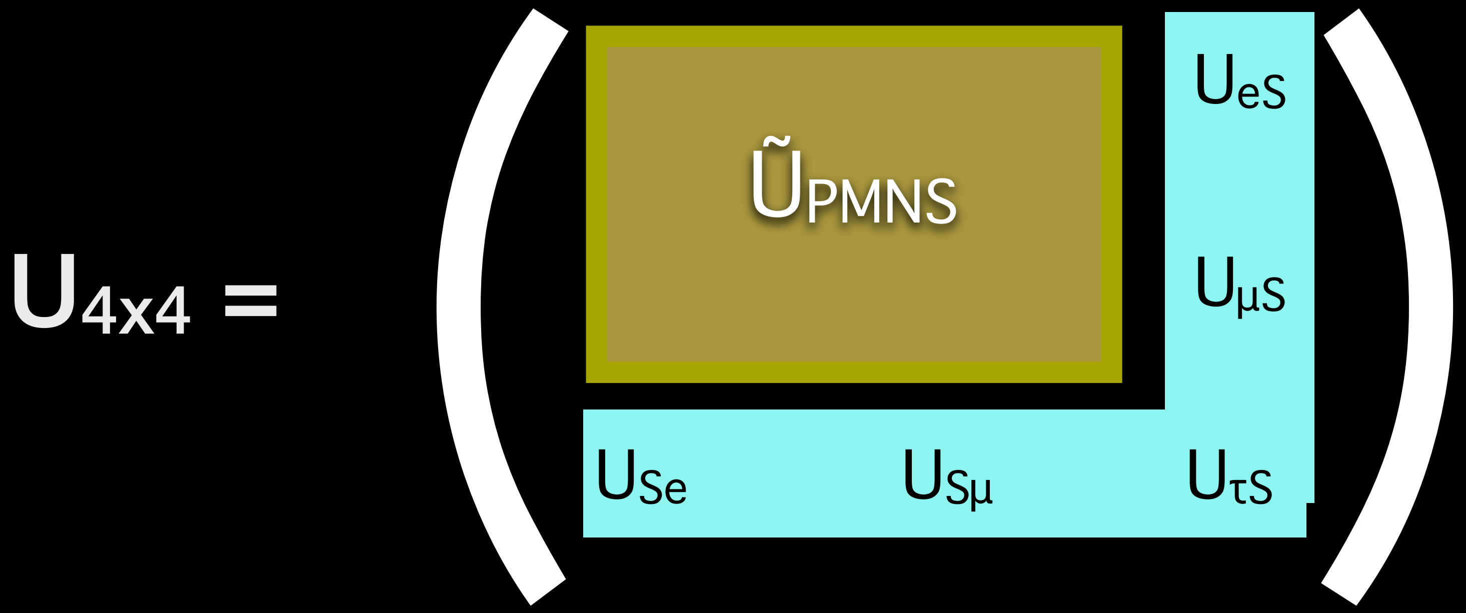
Parameters:

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

Effective model: 3+1

Add a sterile state → 3 new mixing angles actives-sterile

$$U_{4\times 4} = R_{34}.R_{24}.R_{14}.\boxed{R_{23}.R_{13}.R_{12}} \quad U_{PMNS}$$



$U_{4x4} =$

$\tilde{U}_{PMNS}$ U_{eS}

$U_{\mu S}$

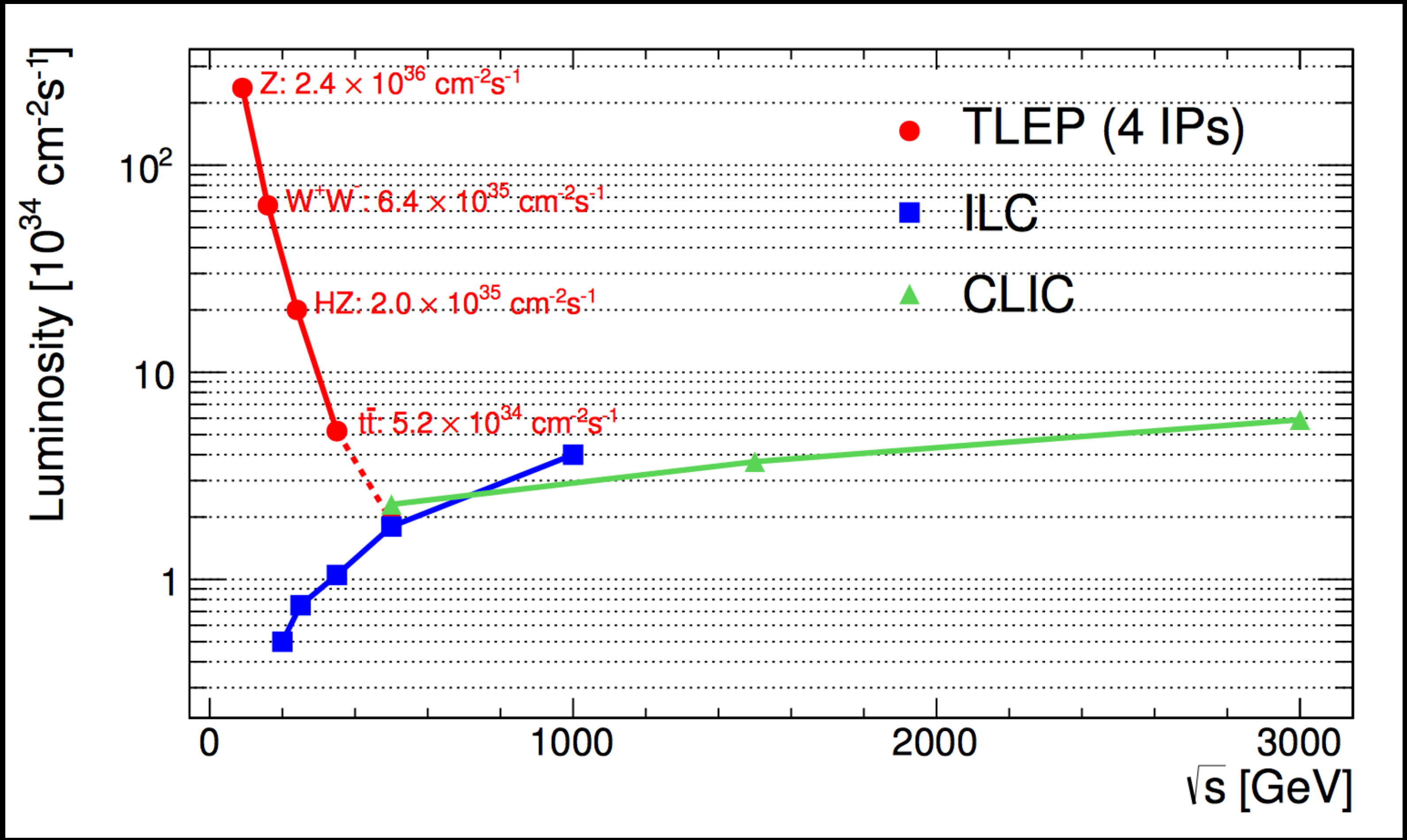
U_{Se} $U_{S\mu}$ $U_{\tau S}$

Parameters:

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

LFV Z decays at a high luminosity Z-factory

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?

New physics effects in rare Z decays

In the SM with lepton mixing (U_{PMNS}) the theoretical predictions are:

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

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

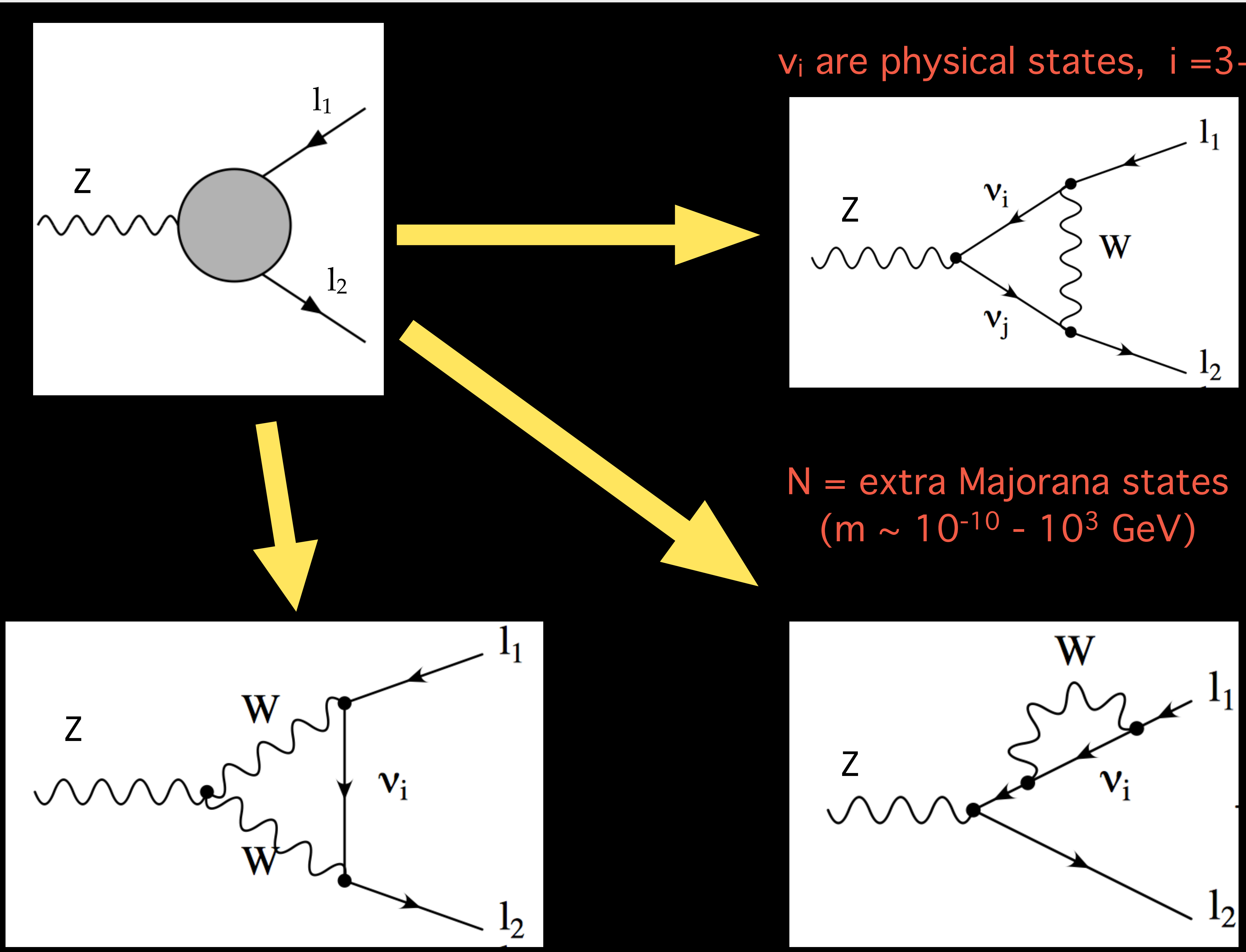
The detection of a rare decay as $Z \to l_i^{\mp} l_j^{\pm}$ (i≠j) would serve as an indisputable evidence of new physics

Current limits:

$$\begin{array}{lcl} \mathrm{BR}(Z \to e^{\mp}\mu^{\pm}) & < & 1.7 \times 10^{-6} \\ \mathrm{BR}(Z \to e^{\mp}\tau^{\pm}) & < & 9.8 \times 10^{-6} \\ \mathrm{BR}(Z \to \mu^{\mp}\tau^{\pm}) & < & 1.2 \times 10^{-5} \end{array}$$

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

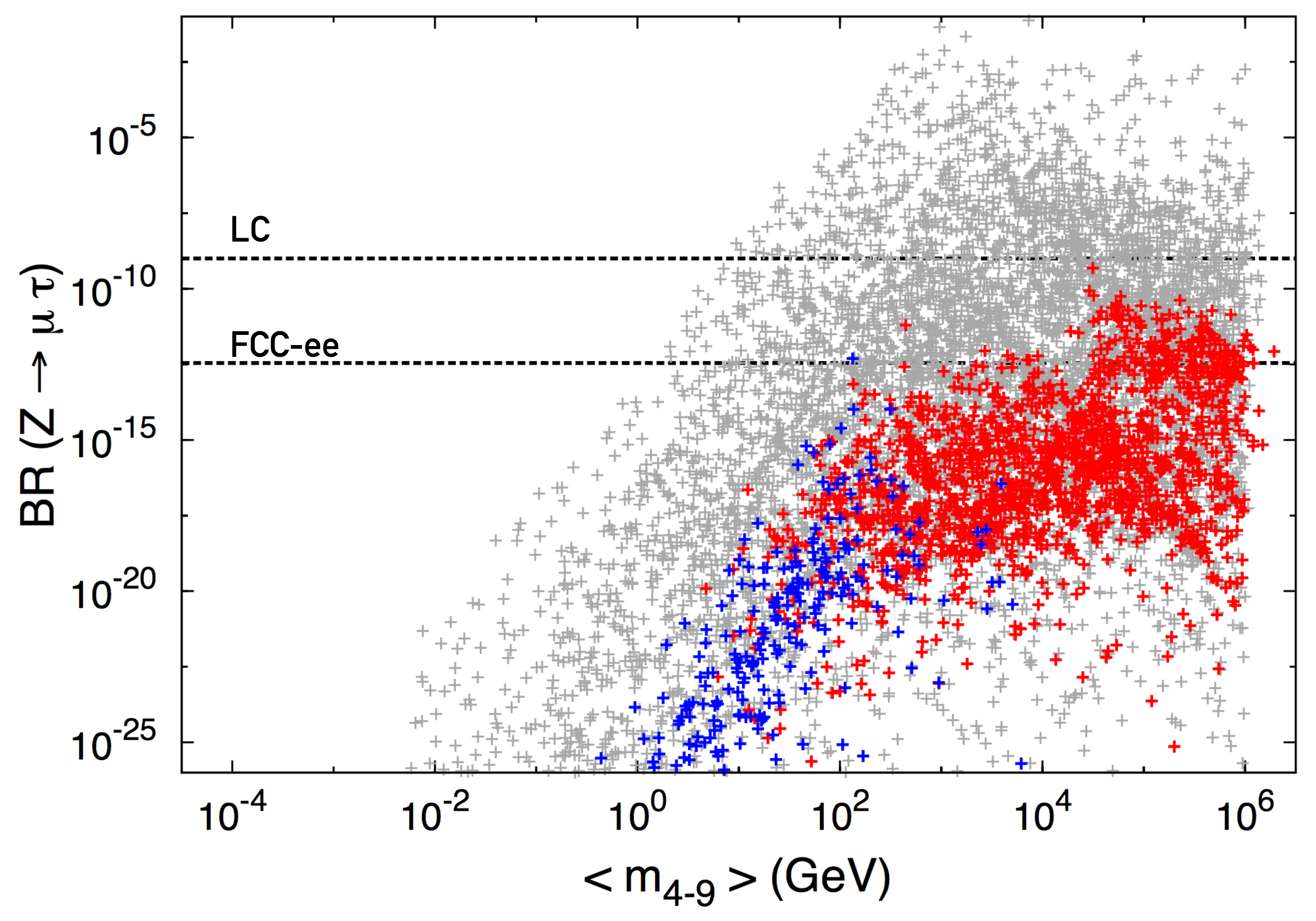
OPAL Collaboration, R. Akers et al., Z. Phys. C67 (1995) 555–564.
L3 Collaboration, O. Adriani et al., Phys. Lett. B316 (1993) 427.
DELPHI Collaboration, P. Abreu et al., Z. Phys. C73 (1997) 243.
ATLAS, CERN-PH-EP-2014-195 (2014)



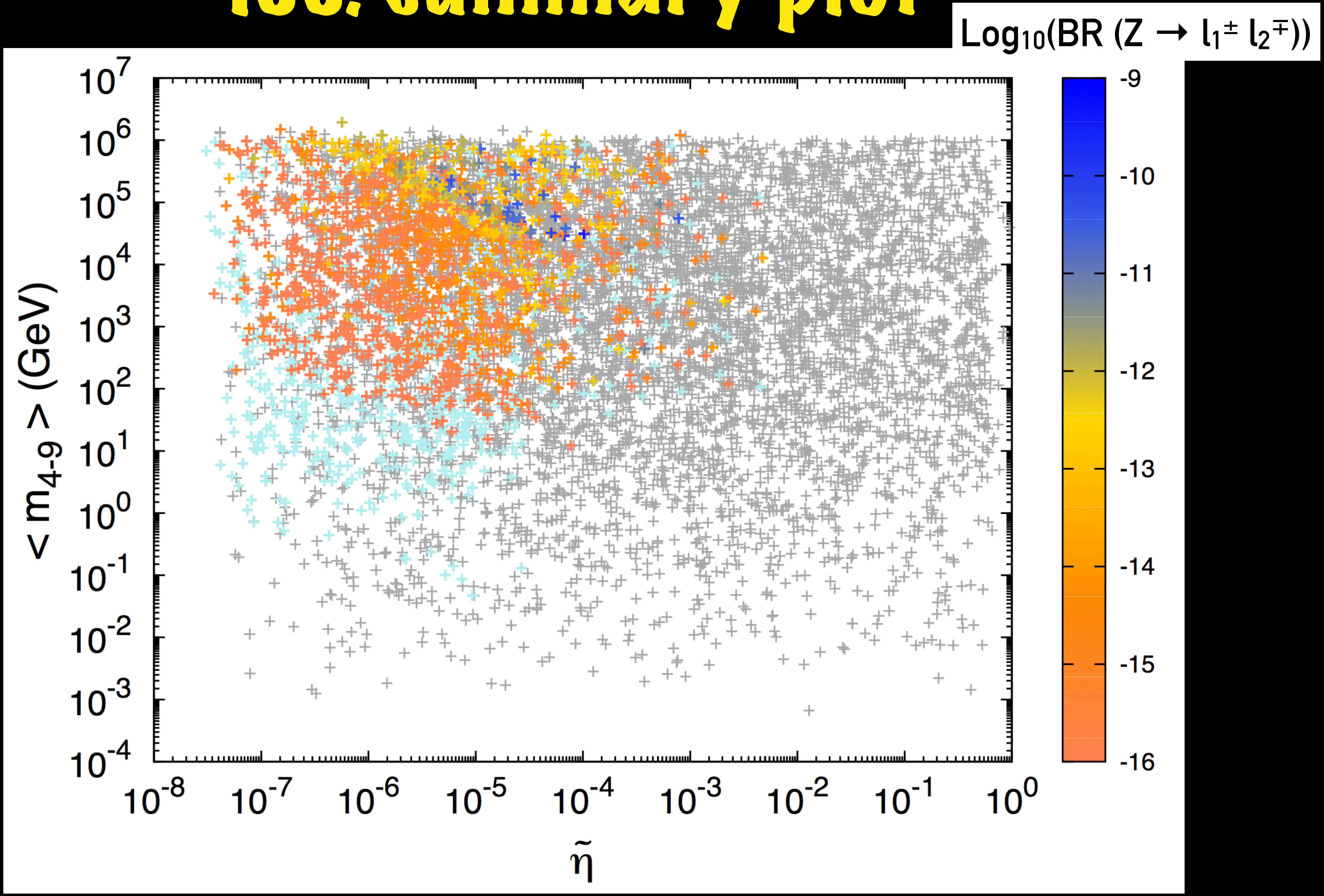
ν_i are physical states, $i = 3+N$

N = extra Majorana states
(m ~ 10^{-10} - 10^3 GeV)

ISS: $Z \to \mu^{\pm}\tau^{\mp}$



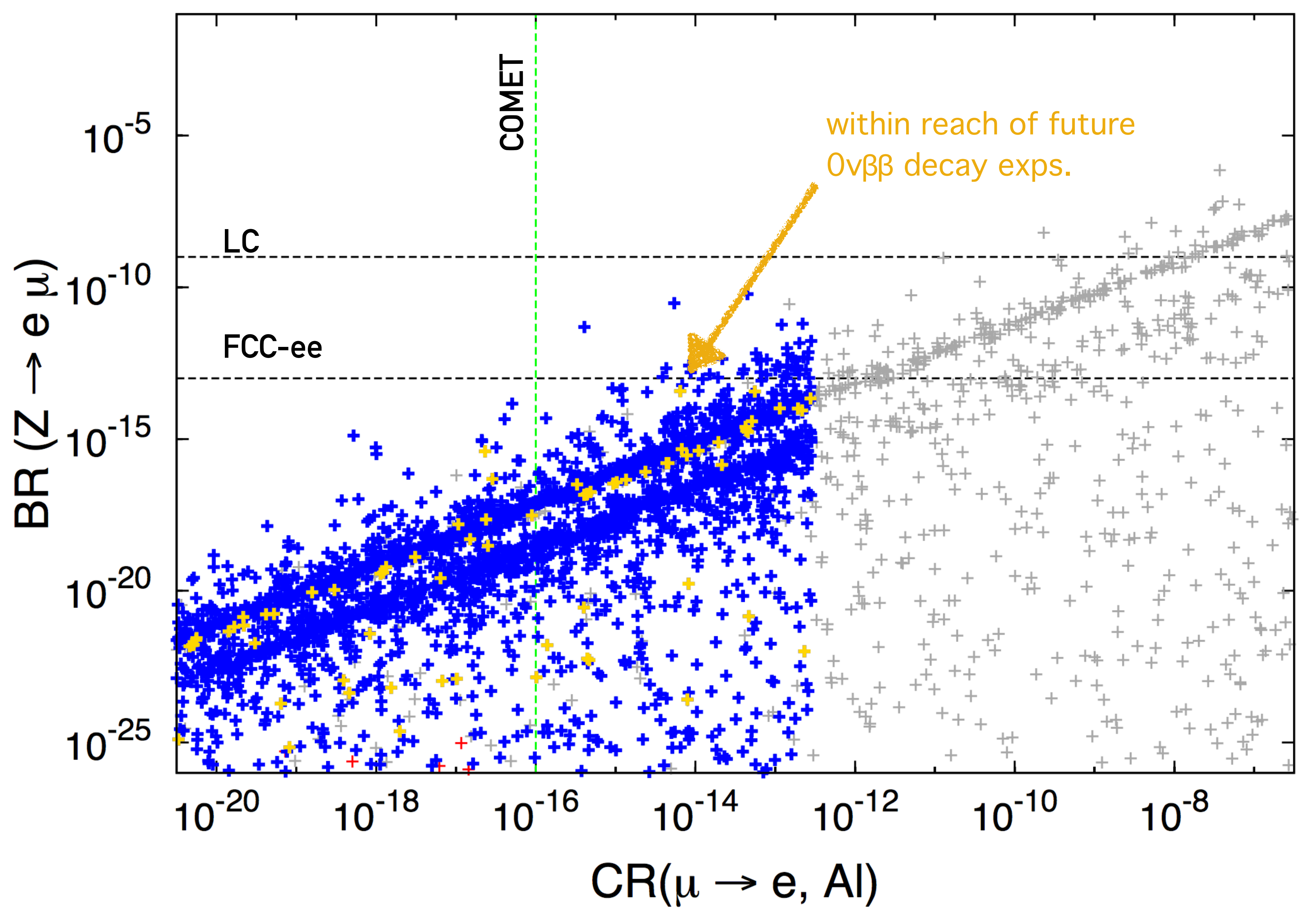
ISS: summary plot



$\tilde{\eta} = 1 - \det(\tilde{\mathrm{U}}_{\mathrm{PMNS}})$

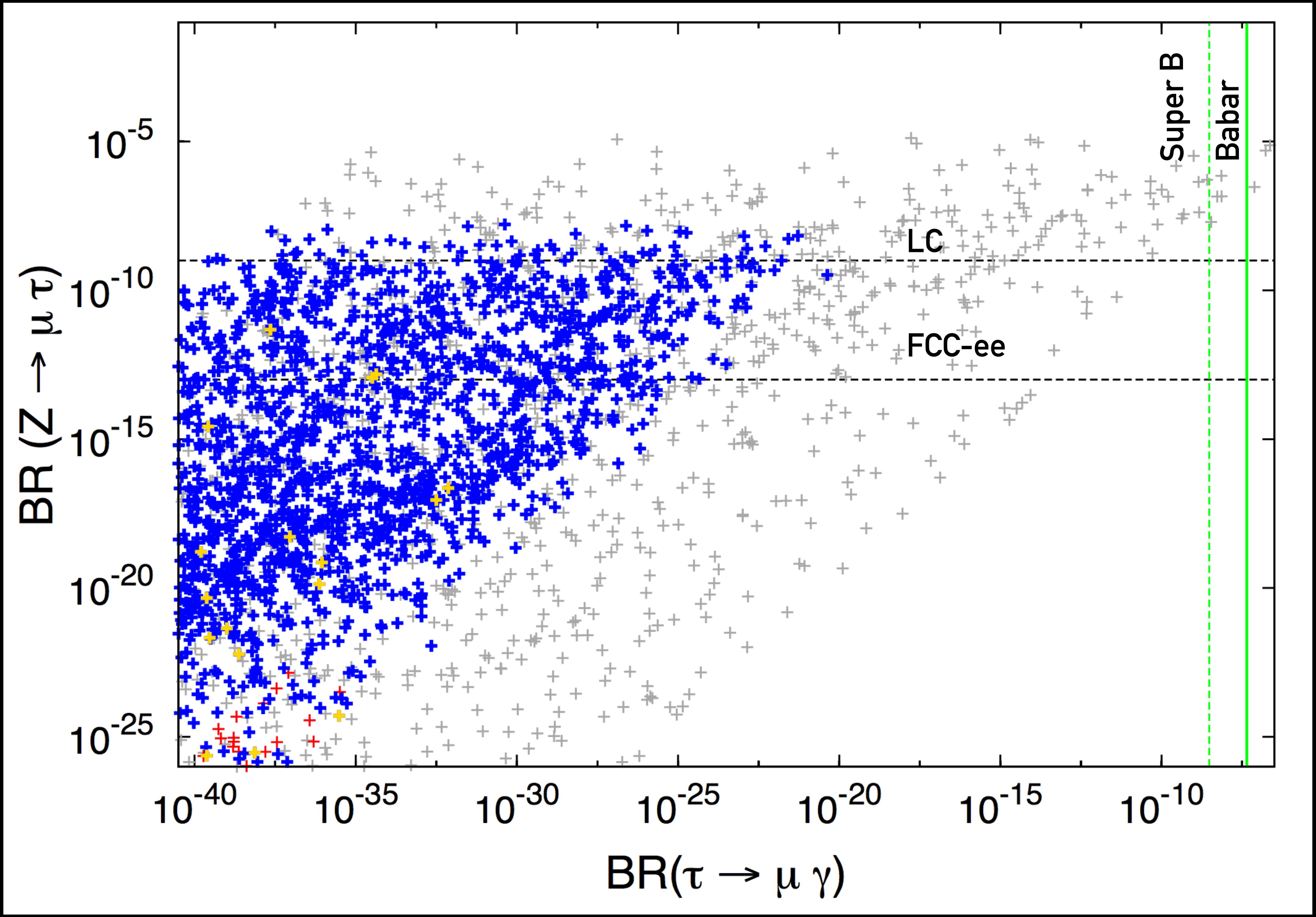
measures the deviation from unitarity.

Effective "3+1": $Z \rightarrow e^{\pm}\mu^{\mp}$ vs $\mu \rightarrow e$ conversion in Al



within reach of future $0\nu\beta\beta$ decay exps.

Effective "3+1": $Z \to \tau^{\pm}\mu^{\mp}$ vs $\tau \to \mu\gamma$



Conclusions

- We have considered two extensions of the SM (ISS and 3+1) which add to the particle content of the SM one or more sterile neutrinos.

- We have explored indirect searches for these sterile states at a future circular collider like FCC-ee running close to the Z mass threshold.

- We have considered the contribution of the sterile states to rare cLFV Z decays in these two classes of models and discussed them taking into account a number of experimental and theoretical constraints.

- Among these, low-E LFV observables receiving contributions from Z-mediated penguins like $\mu \to e$ conversion in nuclei and $\mu \to eee$ impose strong constraints on the sterile neutrinos induced $BR(Z \to l_1^{\pm} l_2^{\mp})$.

- Our analysis emphasised the underlying synergy between a high-luminosity Z factory and dedicated low-E facilities: regions of the parameter space of both models can be probed via LFV Z decays at FCC-ee, through LFV low-E decays ($\tau \to \mu\mu\mu$) and also $0\nu\beta\beta$.

- FCC-ee could probe LFV in the μ-τ sector, in complementarity to the reach of low-E exps.

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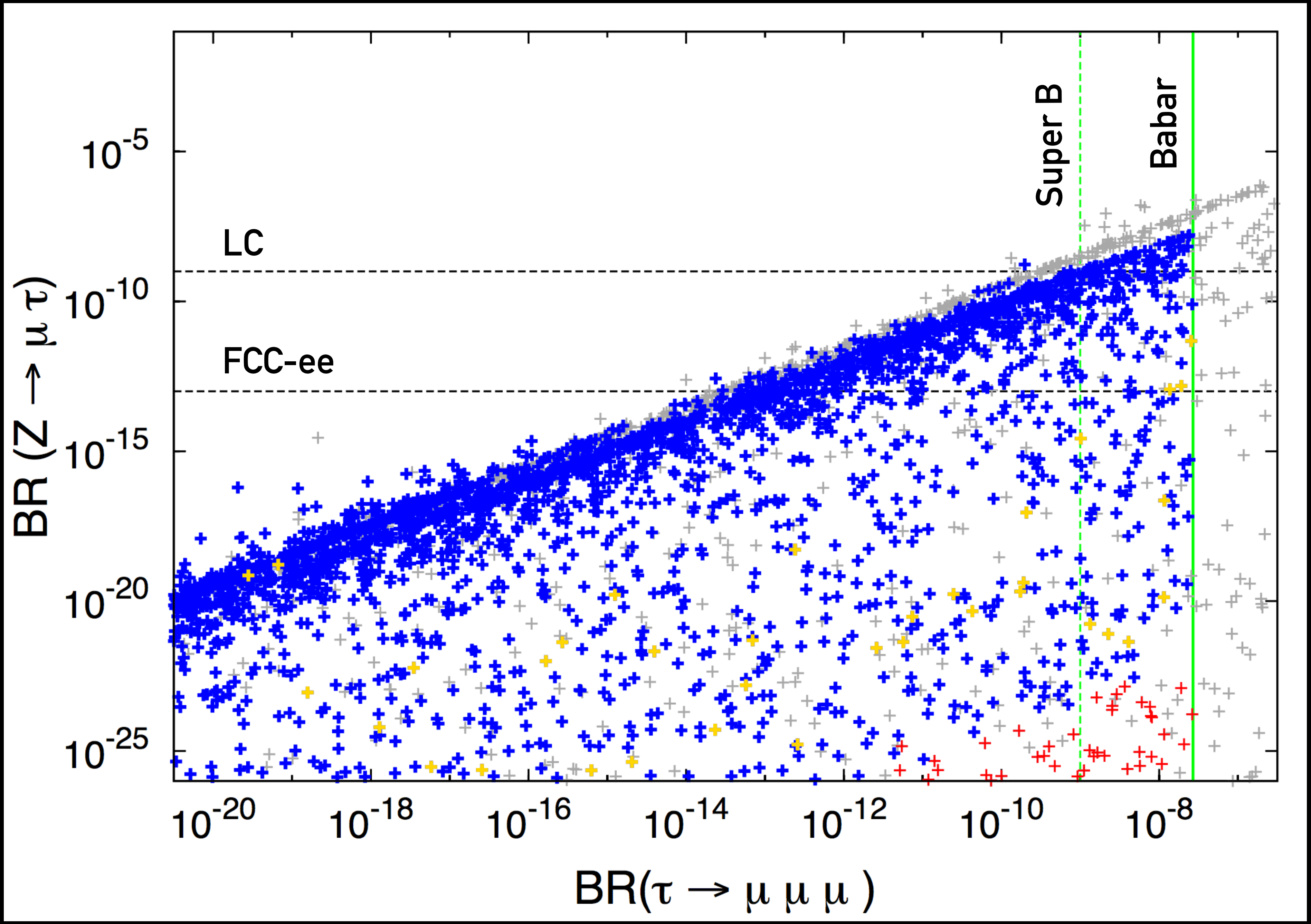
- FCC-ee could probe LFV in the μ-τ sector, in complementarity to the reach of low-E exps.

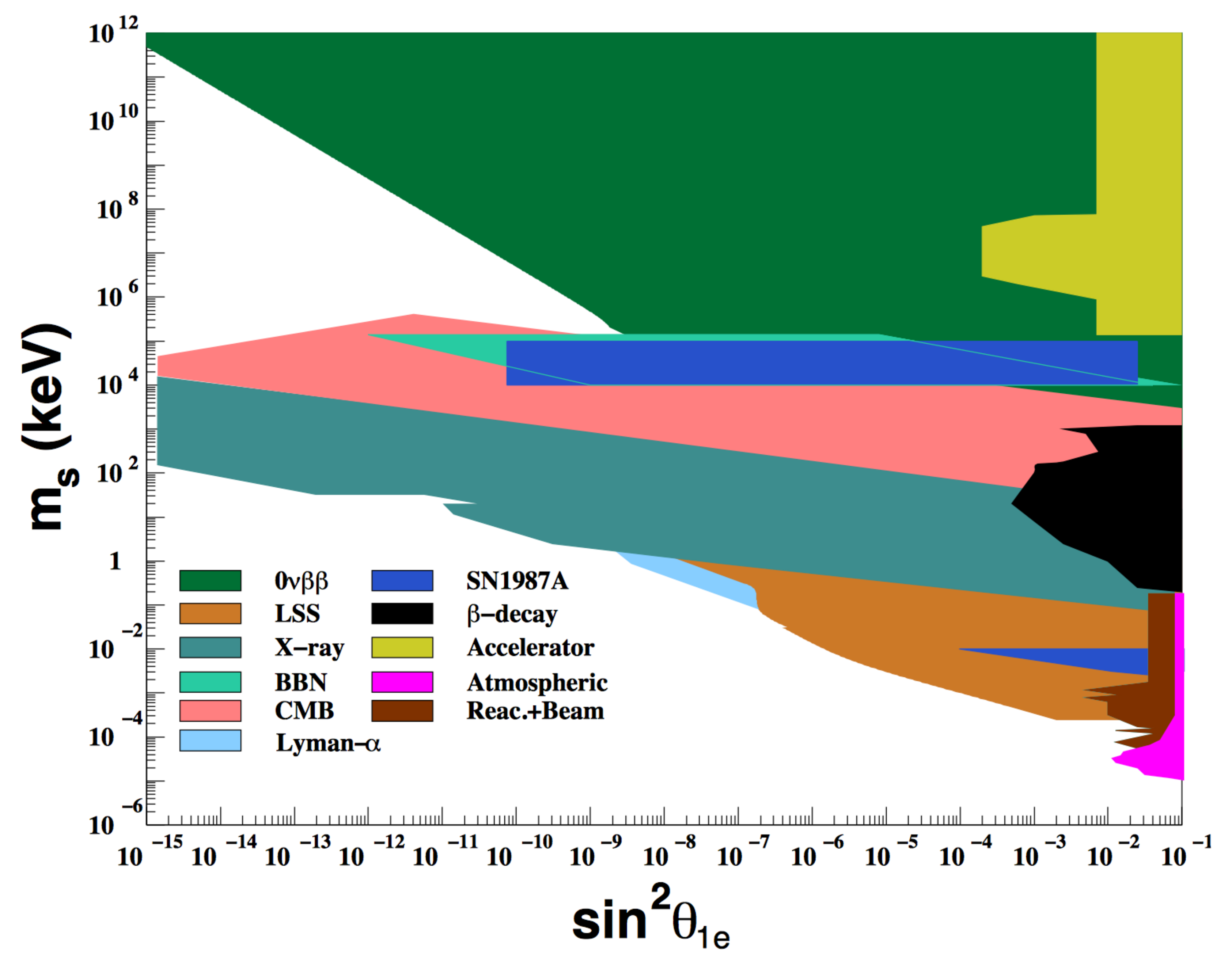
Thank you!

BACKUP

Effective “3+1”: $Z \to \tau^\pm \mu^\mp$ vs $\tau \to \mu\mu\mu$



Cosmological bounds



(Kusenko 2009)

In the SM, neutrinos are strictly massless:

- absence of RH neutrino fields ➟ no Dirac mass term (no renormalizable mass term)
- nor Higgs triplet ➟ 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)

Massive neutrinos require BSM physics

Several models of neutrino mass generation:

- Seesaw mechanism: Type-I, Type-II,Type-III, low-scale seesaws (Inverse seesaw, Linear seesaw) etc ...
- Radiative models

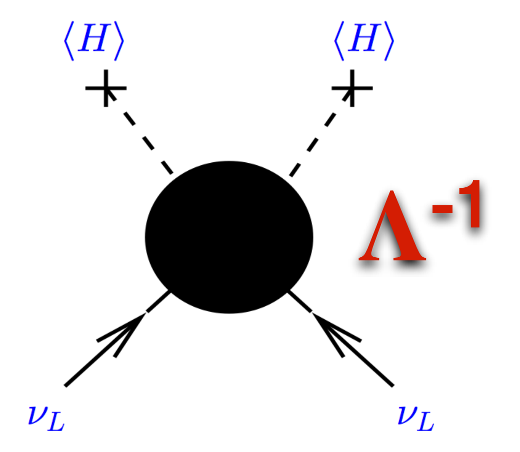
...

(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,...)

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

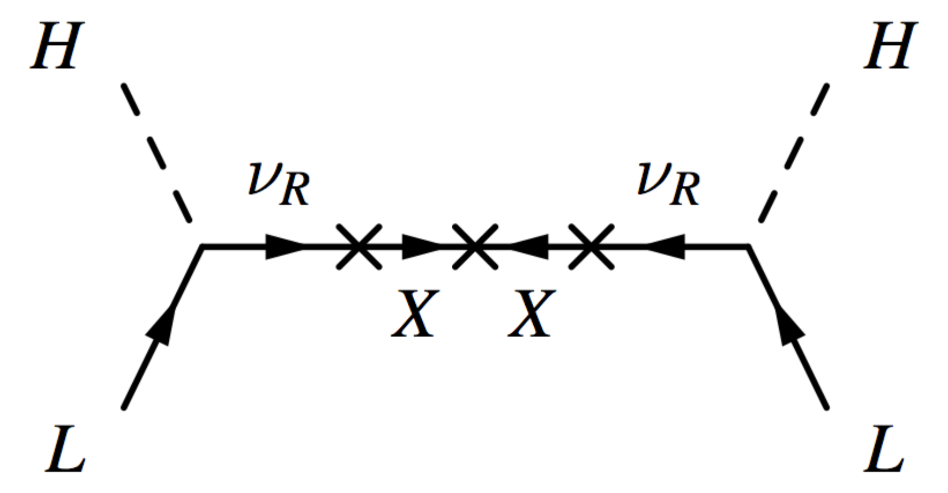
$$m_\nu \sim Y^2 \frac{v^2}{\Lambda}$$

small neutrino masses by making Λ very large and/or with Y small

The exchange of heavy messenger states provides a simple way to generate the WO.

Inverse seesaw basis (ν_L,ν_R,X)

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



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

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

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

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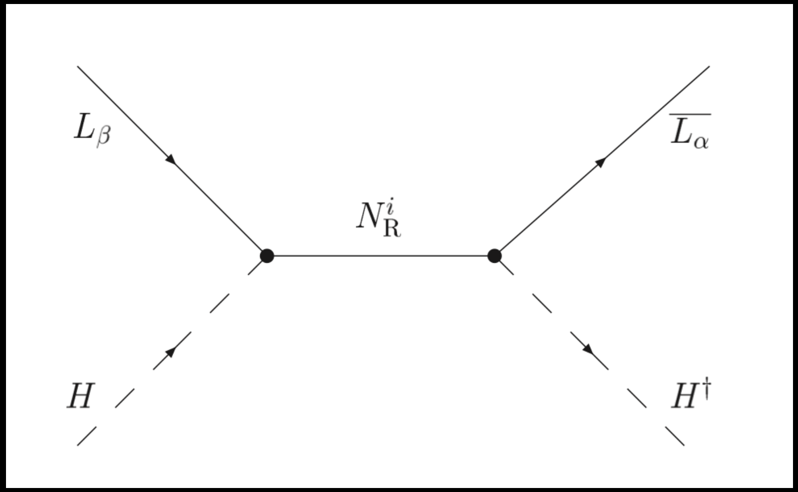
$$\mathcal{L}^{d=6}_{kin} = -c^{d=6,kin}_{\alpha\beta} (\bar{L}_\alpha \cdot H^\dagger)\, i\not{\partial}\, (H \cdot L_\beta)$$

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

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



- 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

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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;
  $\Gamma_{SM}(Z \to vv) = (501.69 \pm 0.06)$ MeV , $\Gamma_{Exp}(Z \to vv) = (499.0 \pm 1.5)$ 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 ≳ 1 TeV

Electroweak precision observables

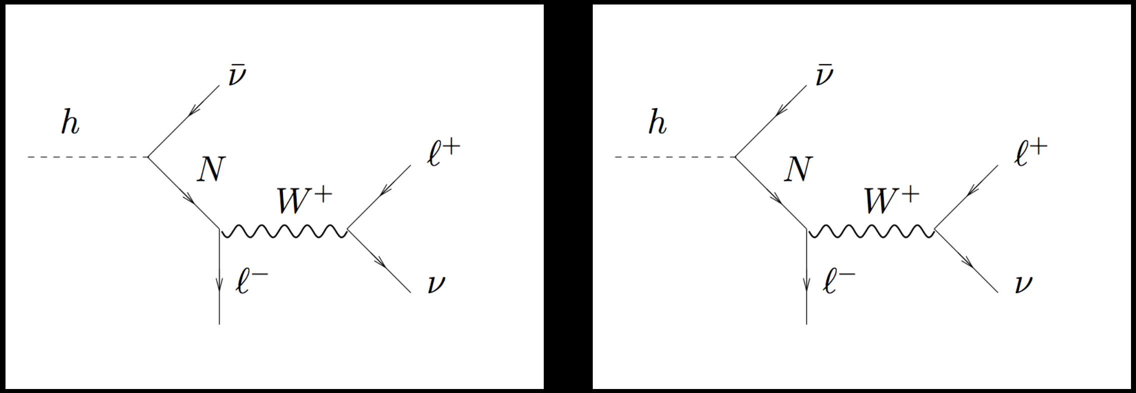
Experimental constraints

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→ν_R ν_L relevant for sterile neutrino masses ~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

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 ν_e and ν_μ are peak searches in leptonic decays of pions and kaons.

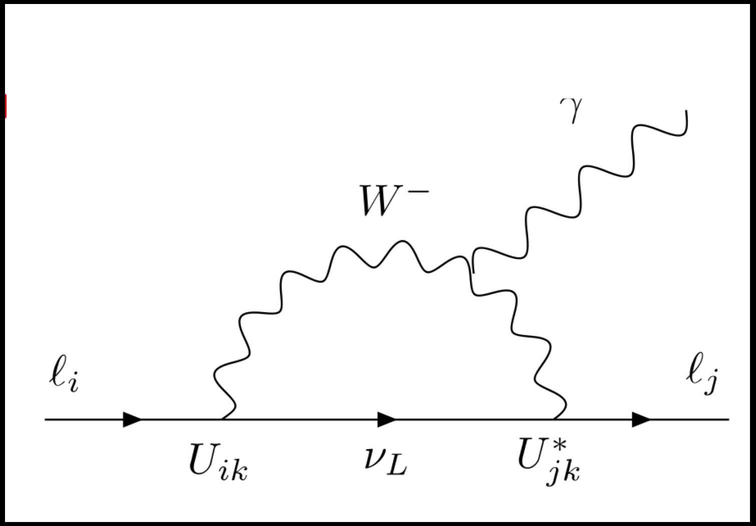
If a heavy neutrino is produced in such decays (e.g. $\pi^\pm \rightarrow \mu^\pm \nu_S$), the lepton spectrum would show a monochromatic line.

Experimental constraints

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

7. Lepton flavor violation (μ → e γ) (Ilakovac and Pilaftsis,1995, Deppisch and Valle, 2005)

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



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

(MEG, 2013)

Experimental constraints

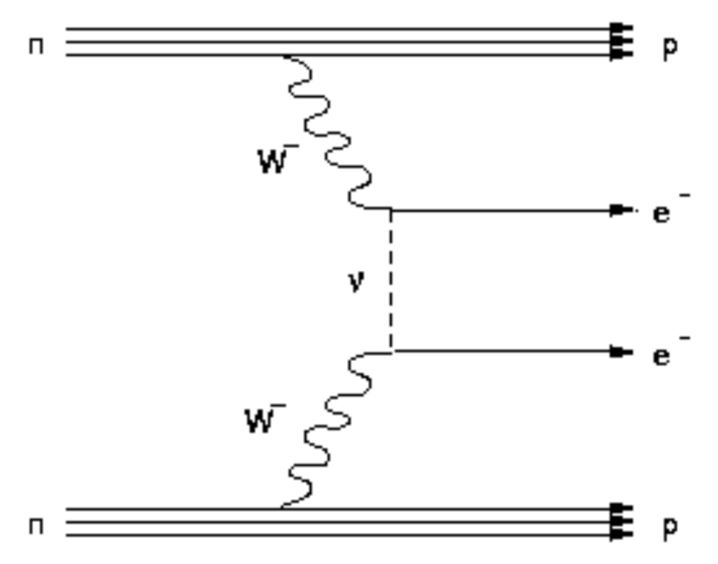
1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data
4. LHC data (invisible decays)
5. Leptonic and semileptonic meson decays (K,B and D)
6. Lepton flavor violation (μ → e γ)
7. Laboratory bounds: direct searches for sterile neutrinos

8. Neutrinoless double beta decay

Most well studied among ΔL = 2 processes

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

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



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. Lepton flavor violation ($\mu \to e \gamma$)
7. Laboratory bounds: direct searches for sterile neutrinos
8. Neutrinoless double beta decay

9. Cosmological bounds on sterile neutrinos

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

- Large scale structure
- Lyman-α
- BBN
- CMB
- X-ray constraints (from $\nu_i \to \nu_j \gamma$)
- SN1987a

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

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.
   $U_{3\times 3} = (1-\eta)U_{PMNS}$
   Strongly constrained if $m_S > \Lambda_{EW}$

3. Electroweak precision data
   (Del Aguila et al., 2008, Atre et al., 2009)
   invisible and leptonic Z-decay widths, the Weinberg angle and the values of g_L and g_R

4. LHC data (invisible decays)
   (Bhupal Dev et al., 2012, P. Bandyopadhyay et al,2012, Cely et al., 2013)
   decay modes of the Higgs boson
   $h \rightarrow \nu_R\, \nu_L$ relevant for sterile neutrino masses ~100 GeV

5. Leptonic and semileptonic meson decays (B, D and K)
   (J. Beringer et al. ,PDG, 2013)
   $\Gamma(P \rightarrow l\nu)$ with P = D,B with one or two neutrinos in the final state

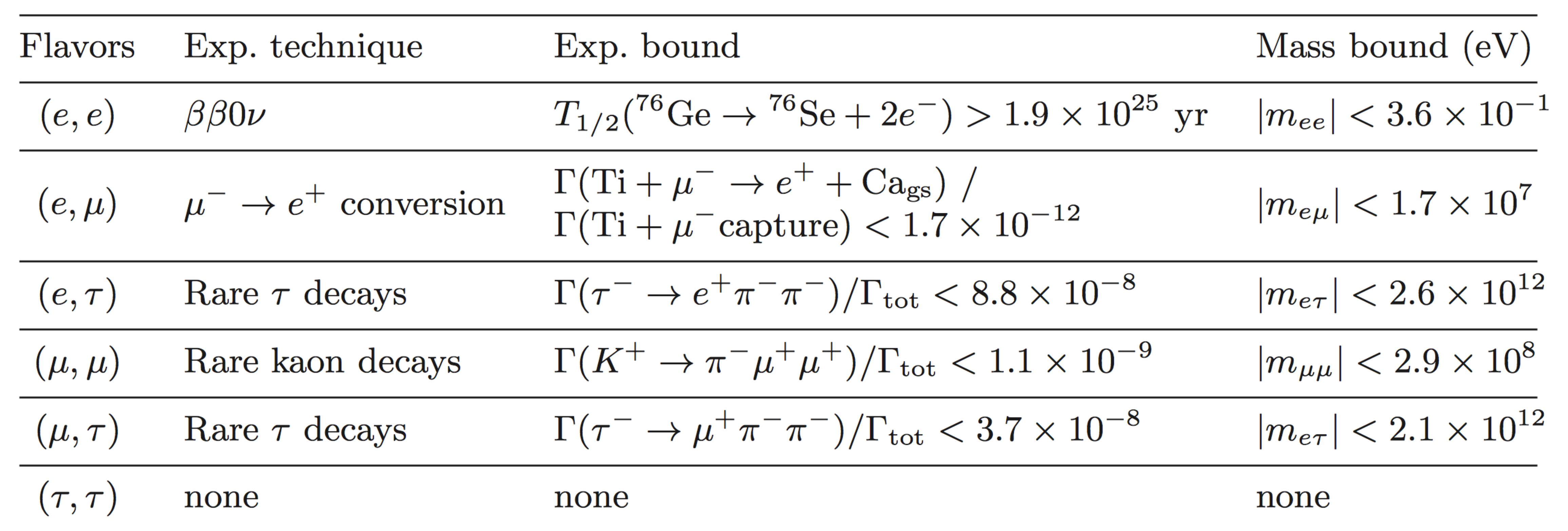
6. Laboratory bounds: direct searches for sterile neutrinos
   (Atre et al. 2009, Kusenko et al. 2009)
   e.g. $\pi^{\pm} \rightarrow \mu^{\pm}\nu_S$, the lepton spectrum would show a monochromatic line.

7. Lepton flavor violation ($\mu \rightarrow e\,\gamma$)
   (Ilakovac and Pilaftsis,1995, Deppisch and Valle, 2005)
   $Br(\mu \to e\gamma)_{MEG} = 0.57 \times 10^{-12}$

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

10. Cosmological bounds on sterile neutrinos
    (Smirnov et al. 2006, Kusenko 2009, Gelmini 2010)
    Large scale structure, Lyman-α, BBN, CMB, X-ray constraints (from $\nu_i \rightarrow \nu_j\gamma$),SN1987a

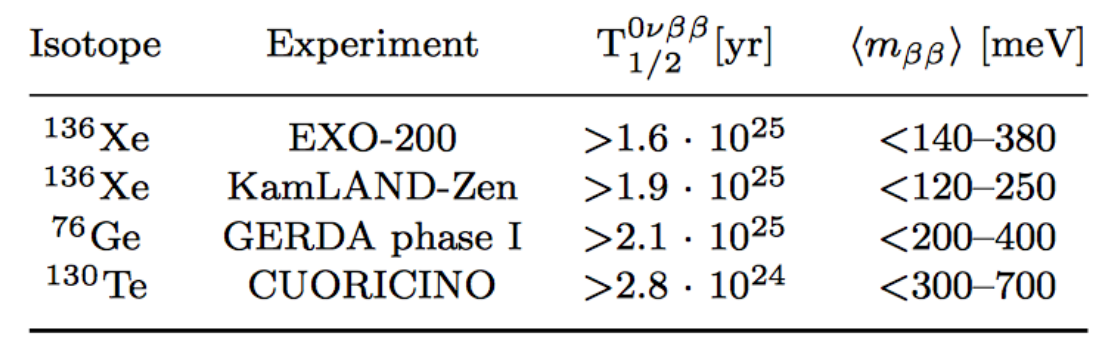
Current bounds on effective neutrino masses from total lepton number violating processes



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

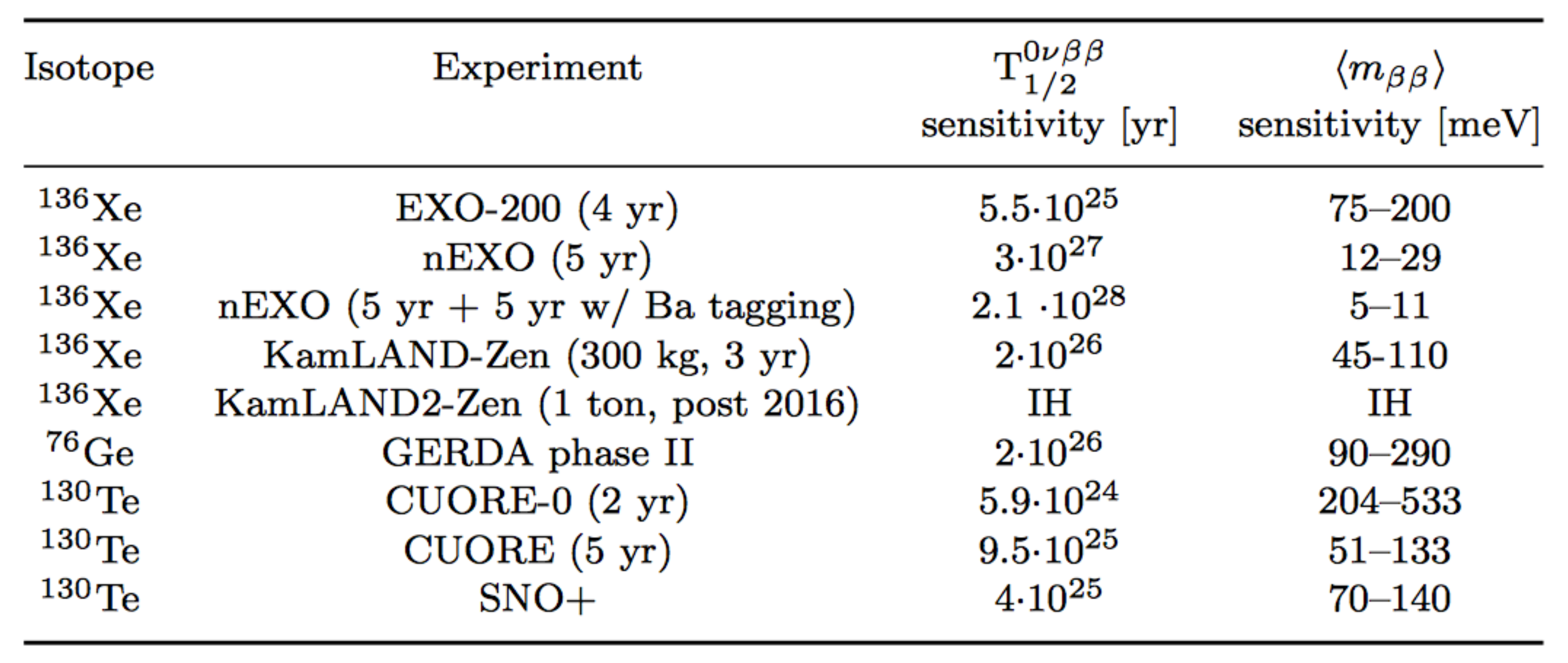
(Gómez-Cadenas et al. 2012)

Neutrinoless double beta decay



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

Future sensitivities



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

(Tosi - EXO. 2014)