Valentina De Romeri
(IFT - Universidad Autonoma de Madrid)

Flavour Changing in Z decays at FCC-ee

10th FCC-ee physics workshop - CERN
4-5 February 2016

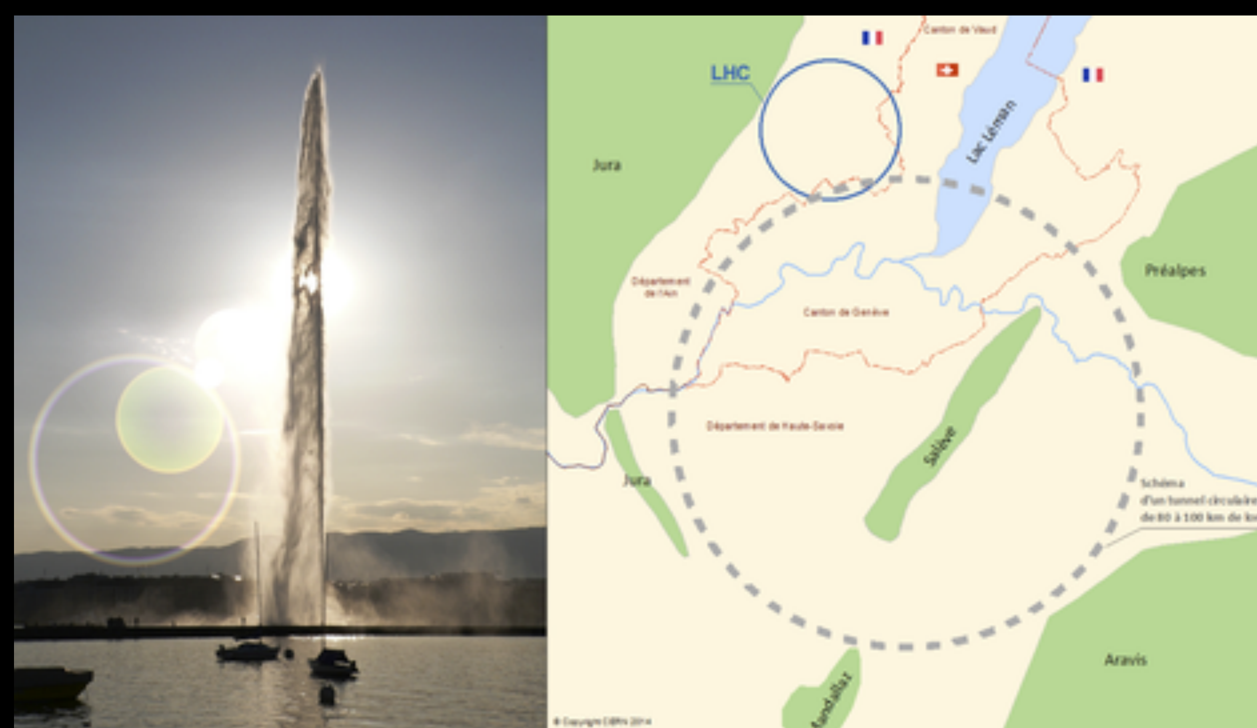
Based on a work done in collaboration with A. Abada, A. Teixeira, S.Monteil, J.Orloff,
JHEP 1504 (2015) 051

Outline

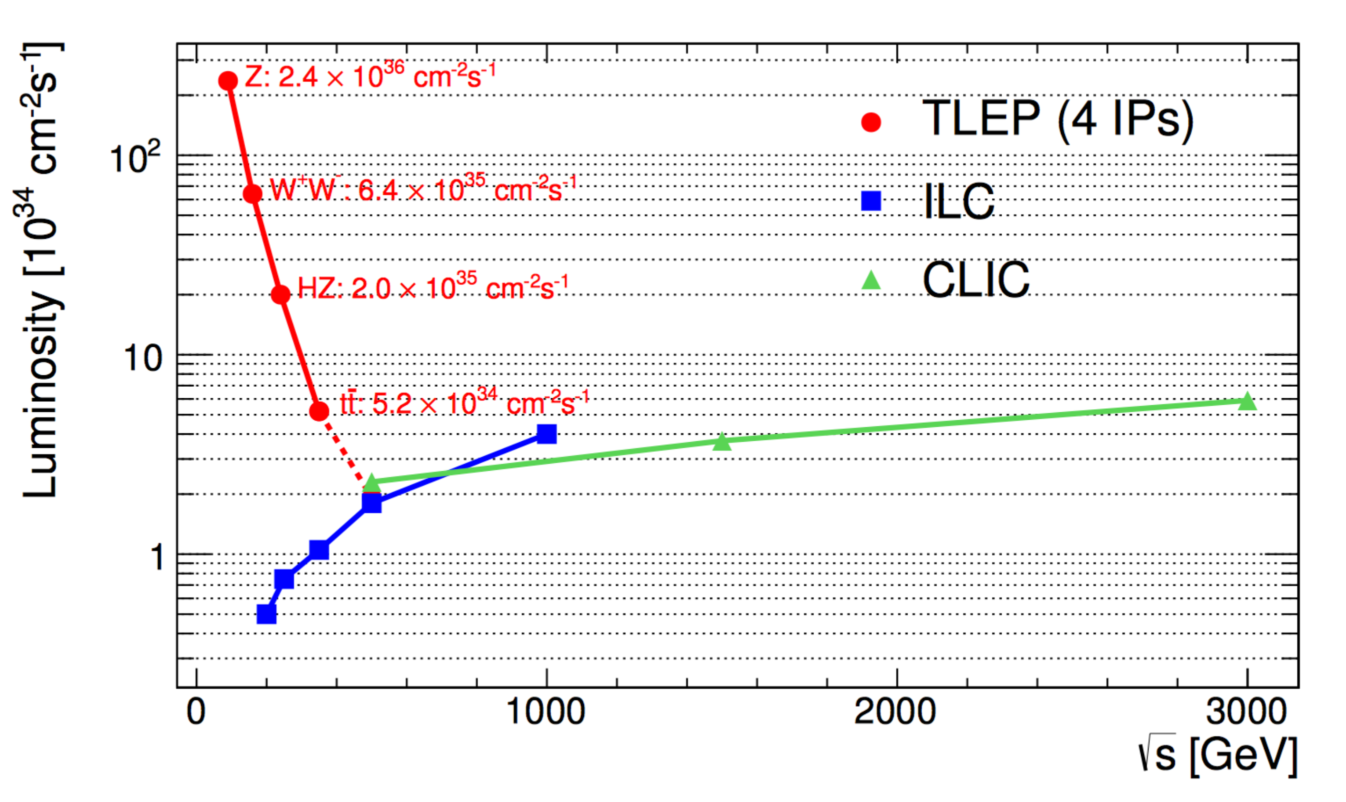
- FCC-ee: a high luminosity Z-factory
  - rare cLFV Z decays
- Extending the SM with sterile fermions
  - Motivation and theoretical framework
  - Phenomenological impact and observational constraints
- cLFV Z decays at a high luminosity Z factory
- Conclusions

- Status of the flavour WG

1) A high luminosity Z-factory



A future high-luminosity Z factory as a tool to study sterile neutrinos



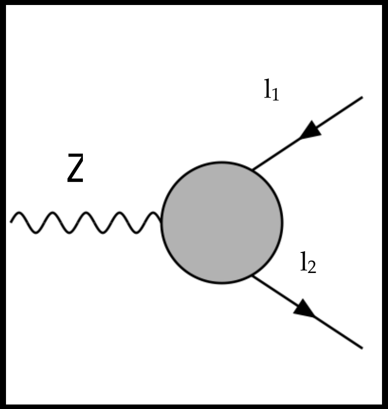
- FCC-ee is designed to provide e^+e^- collisions in the beam energy range of 40 to 175 GeV.
- Instantaneous luminosity expected at FCC-ee, in a configuration with four interaction points operating simultaneously, as a function of the centre-of-mass energy.
- Highest foreseen luminosity scheme: 10^{13} Z

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

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:

$$BR(Z \to e^{\pm}\mu^{\mp}) \sim BR(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54}$$
$$BR(Z \to \mu^{\pm}\tau^{\mp}) \sim 4 \times 10^{-60}$$



- 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

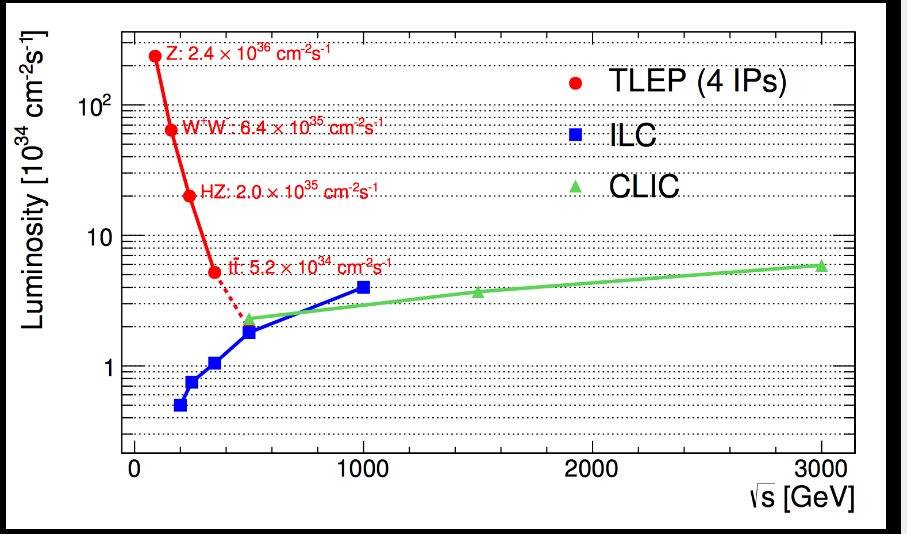
- Current limits:

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

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

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)

- Future experimental prospects: Linear Collider / FCC-ee



2) Extending the SM with sterile fermions

cLFV: observables of New Physics

- Flavour violation in charged lepton sector: a window on physics beyond the SM!
  - Are neutral and charged LFV related?
  - Does cLFV arise from ν-mass mechanism? Or entirely different nature?

- Two phenomenological approaches to account for these observables:
  - effective [e.g. Broncano et al. 2003, Davidson, De Gouvea ...]
  - model dependent (specific NP scenario)

- LFV in models of new physics:
  - 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_ν (and nature - Majorana!?) → new mechanism of mass generation

<u>cLFV arising in SM minimally extended via sterile fermions !</u>

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

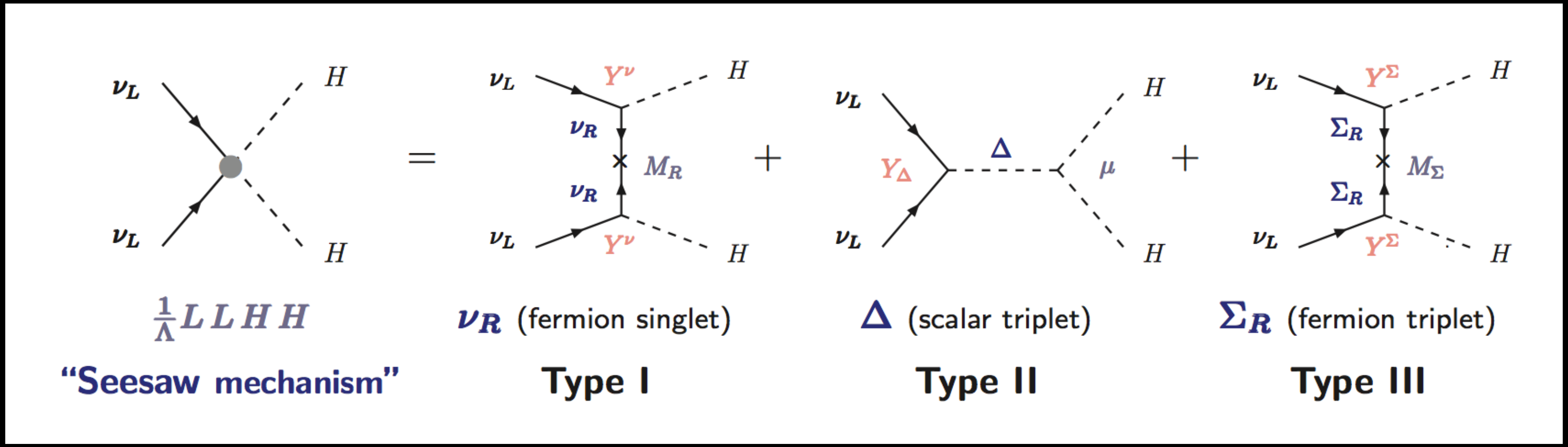
  Reactor ν anomaly: $\Delta m^2 \gtrsim 0.5$ eV^2
  Galium ν anomaly: $\Delta m^2 \gtrsim 1$ eV^2
  LSND ν anomaly: $\Delta m^2 \gtrsim 0.1$ eV^2
  …

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

- keV scale: motivations for sterile neutrinos from cosmology, e.g. warm dark matter or to explain pulsar velocities

Sterile fermions: theoretical appeal

- Present in numerous SM extensions aiming at accounting for ν masses and mixings: e.g right-handed neutrinos (Seesaw type-I, νMSM..), other sterile fermions (Inverse Seesaw)



Explain small ν 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 Yν 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

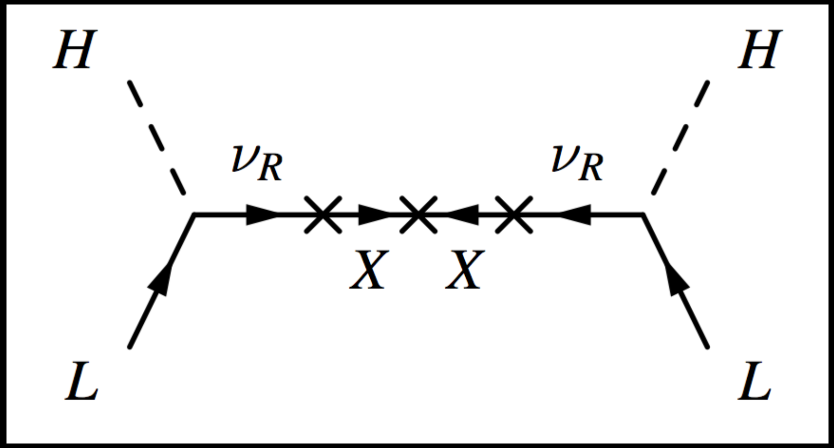
Low scale: Inverse seesaw (ISS) (Mohapatra & Valle, 1986)

- Add three generations of SM singlet pairs, ν_R and X (with L=+1)
- Inverse seesaw basis (ν_L,ν_R,X):

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

$$\Rightarrow \begin{cases} \textbf{3 light } \boldsymbol{\nu} : m_\nu \approx \frac{(Y_\nu v)^2}{(Y_\nu v)^2 + M_R^2} \boldsymbol{\mu_X} \\ \textbf{3 pseudo-Dirac pairs} : \boldsymbol{m_{N^\pm}} \approx \boldsymbol{M_R} \pm \boldsymbol{\mu_X} \end{cases}$$

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



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

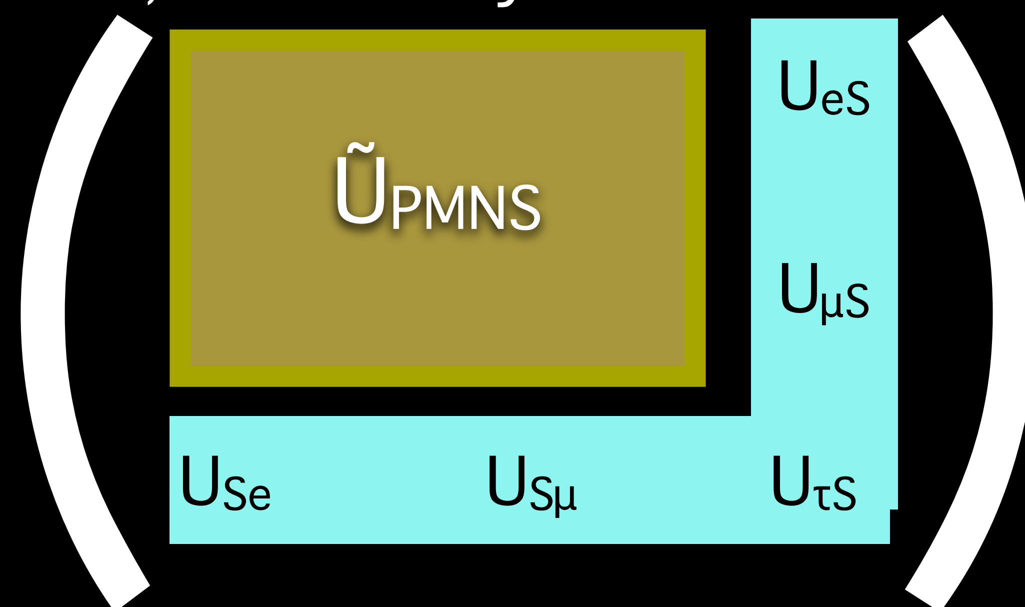
"Toy model" for pheno analyses: SM + ν_s

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

$$U_{4\times4} = R_{34}.R_{24}.R_{14}.\underbrace{R_{23}.R_{13}.R_{12}}_{U_{PMNS}}$$

- From the interaction to the physical mass basis: $n_L = U_{4\times4}\nu_i$
- Spectrum: 3 light active neutrinos + 1 heavier (mostly) sterile state
- Active-sterile mixing $U_{\alpha i}$: rectangular matrix
- Left-handed leptons mixing: 3x3 sub-block, non unitary!

U_{4x4} =



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

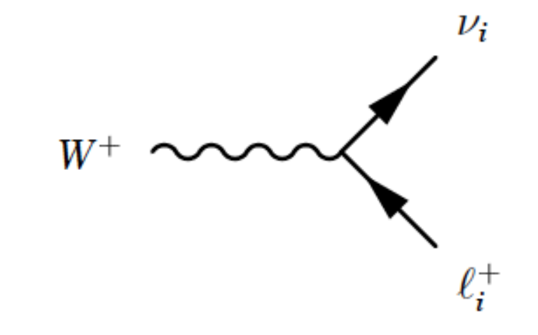
  If sufficiently light, sterile states may be produced as final products

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

  Standard case (3 flavors): ν_i = e,μ,τ

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

  ν_a = mass eigenstates, a = 1,2,3



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

$\nu_i = \sum_{ai} U_{ai}\ \nu_a$, a = 1,2,3,4 ..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)

- Modified neutral currents:

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

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 ($\mu \to e \gamma$)
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., 2009,2014)

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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

   $h \to \nu_R\, \nu_L$ 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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   (CLEO, Belle, BaBar, NA62, LHCb, BES III, J. Beringer et al. ,PDG, 2013,Shrock, '81; Atre et al, '09; Abada et al, '13-'15 …)

   $\Gamma(P \to l\nu)$ with P = K,D,B with one or two neutrinos in the final state
6. Laboratory bounds: direct searches for sterile neutrinos
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   (Shrock 1980, Atre et al. 2009, Kusenko et al. 2009, Lello 2013)

   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 ($\mu \to e\,\gamma$, 3body decays)

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

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

Experimental constraints

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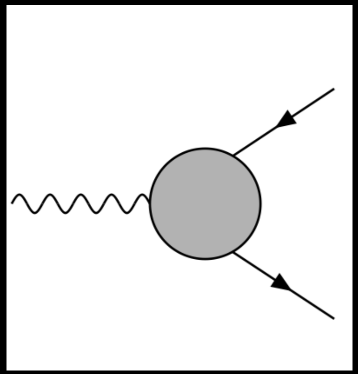
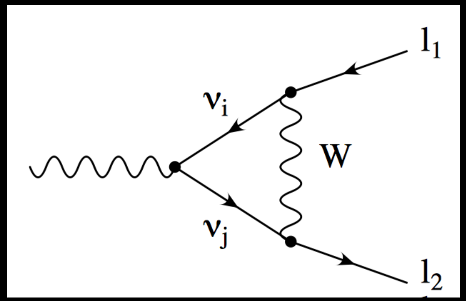
9. Neutrinoless double beta decay $m_\nu^{\beta\beta} = \sum_i U_{ei}^2 m_i \leq (140-700)meV$
10. Cosmological bounds on sterile neutrinos — Large scale structure, Lyman-α, BBN, CMB, X-ray constraints (from $\nu_i \rightarrow \nu_j\gamma$),SN1987a

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

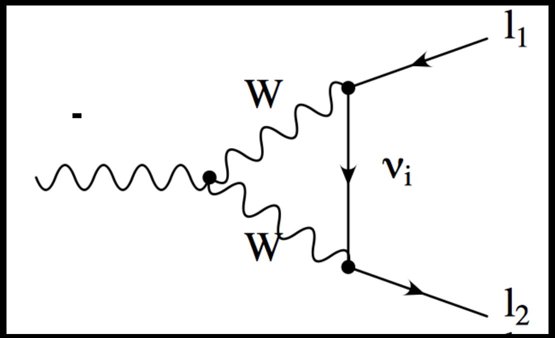
3) Impact of ν_s on cLFV Z decays

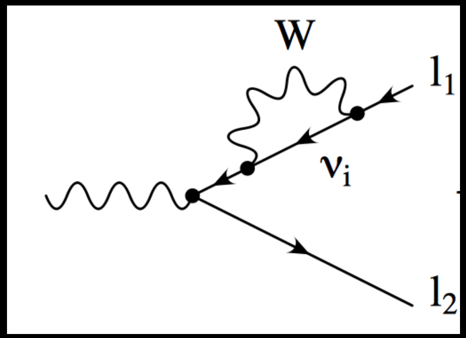




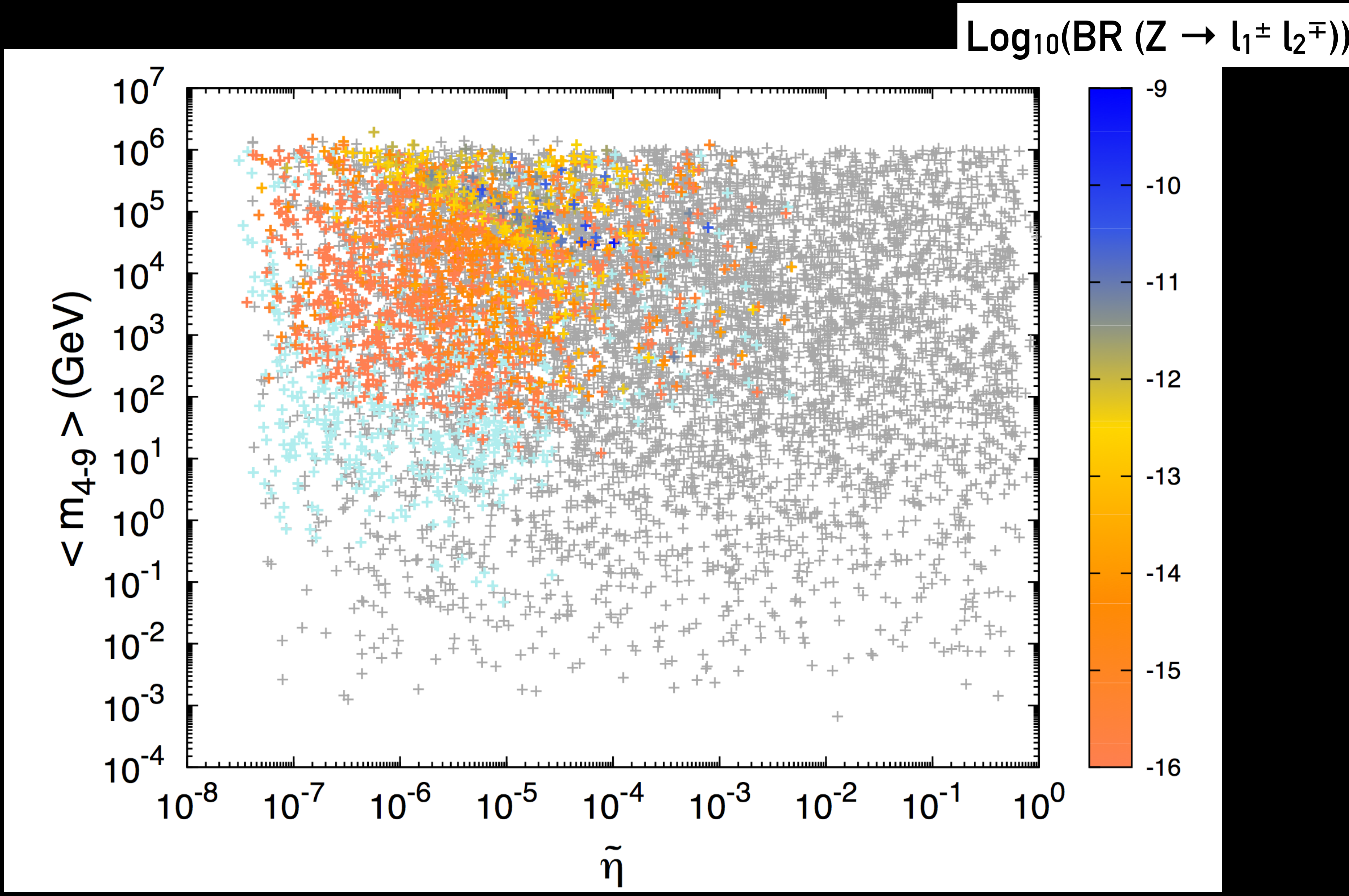
ν_i are physical states, i =3+N

N = extra Majorana states





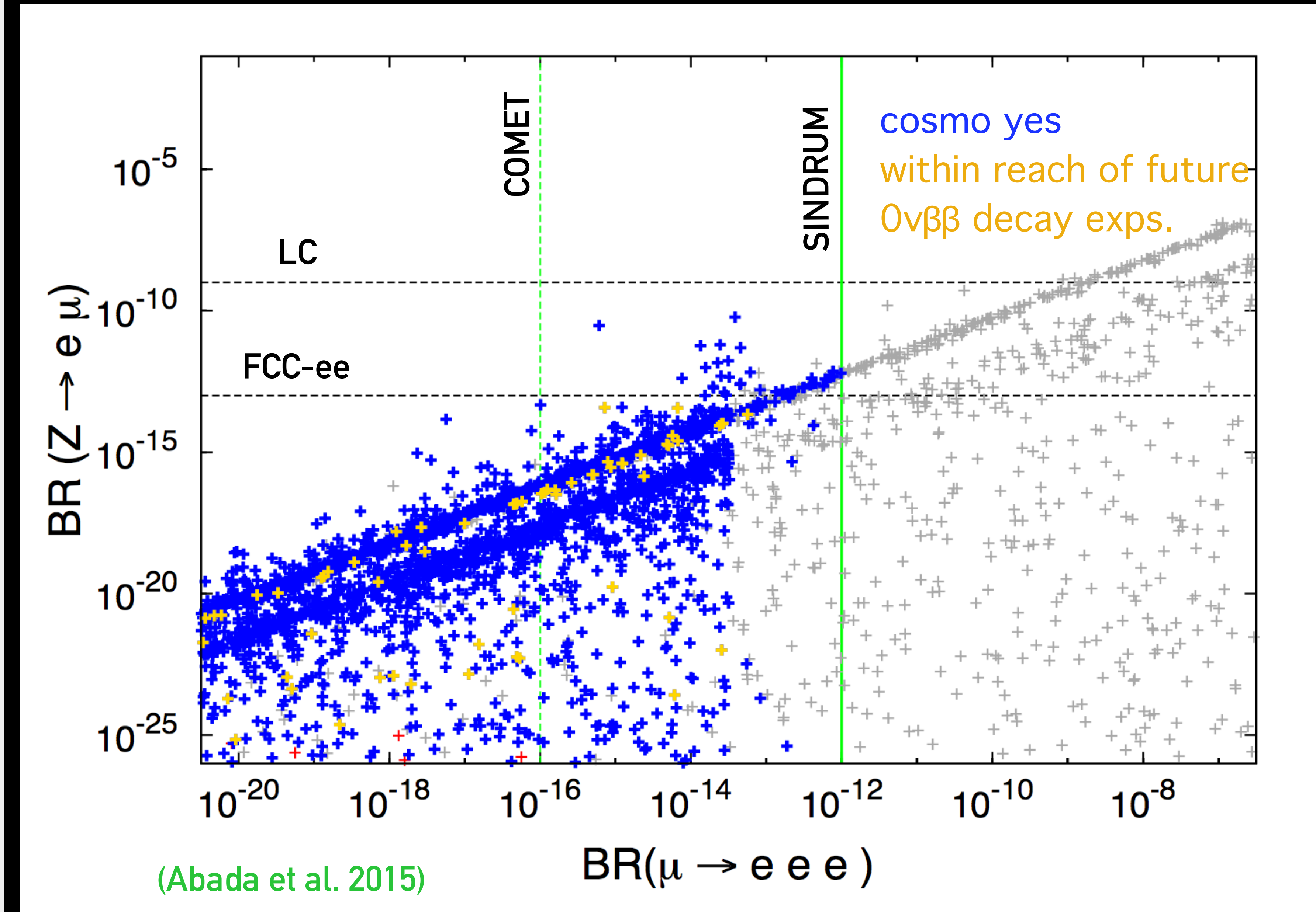
ν_s and cLFV in the ISS: $Z \to l_1^{\pm} l_2^{\mp}$



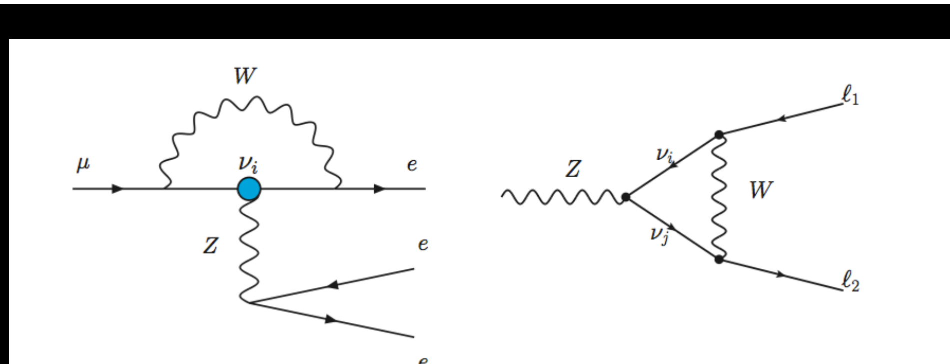
$$\tilde{\eta} = 1 - \det(\tilde{U}_{PMNS})$$

measures the deviation from unitarity.

νs and cLFV: cLFV Z decays & three-body decays



(Abada et al. 2015)

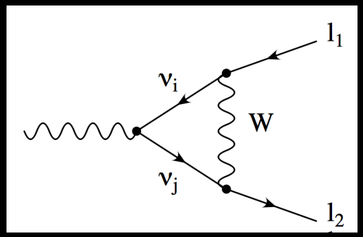


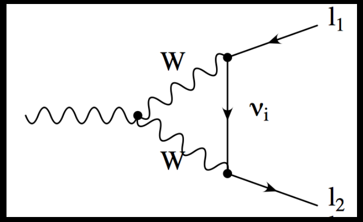
- dominated by Z penguins (same contribution to three body $\mu \to e\, e\, e$)

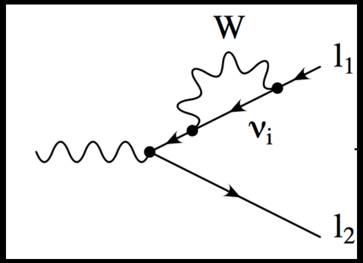
ν_s and cLFV: rare Z decays

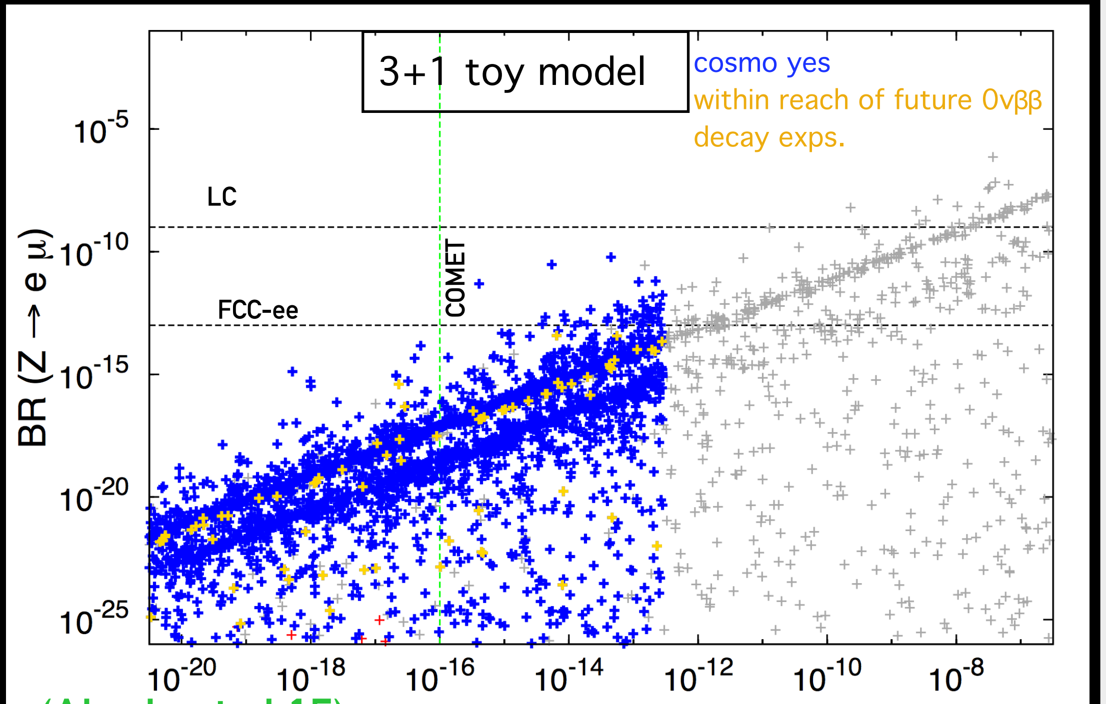
- rare cLFV Z decays at a high luminosity Z factory:

$$Z \to l_i^{\mp} l_j^{\pm}$$

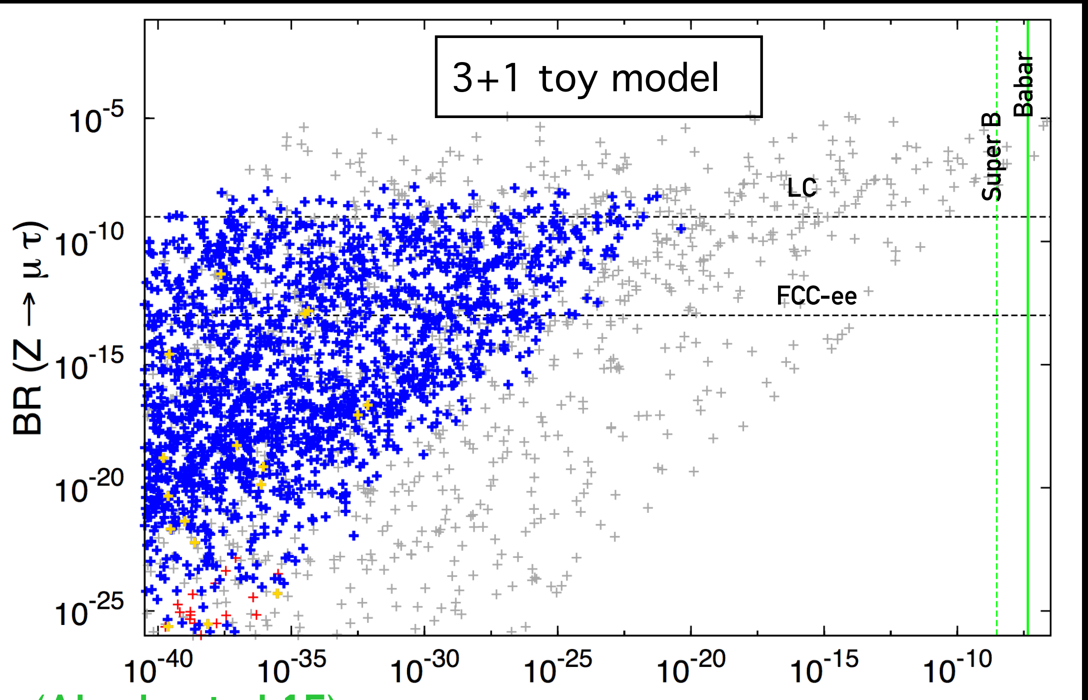








(Abada et al.15)



(Abada et al.15)

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

- Other searches for sterile neutrinos at colliders:
  - direct searches for heavy N at colliders
  - cLFV Higgs decays (Arganda et al.14,15)

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.

Status and plans in the Flavours WG

- A preliminary Physics Case for Flavour Physics has been built relative to the anticipated results of the soon to be running LHCb upgrade and Belle II experiments.
  http://indico.cern.ch/event/313708/contribution/25/material/slides/0.pdf

- This served as a basis for a kick-off discussion meeting (mainly with an audience of theoreticians) to criticize and eventually amend / refine / enhance the Physics scope of the WG. Held 1.5 years ago, September 2014.
  https://indico.cern.ch/event/336998/

- A provisional strategy/hierarchy has been defined and contacts have been taken to initiate the phenomenological and experimental studies. Four other meetings followed where actual work started to be reported.
  https://indico.cern.ch/event/359433/
  https://indico.cern.ch/event/380986/
  https://indico.cern.ch/event/403492/
  https://indico.cern.ch/event/462662/

Actual work:

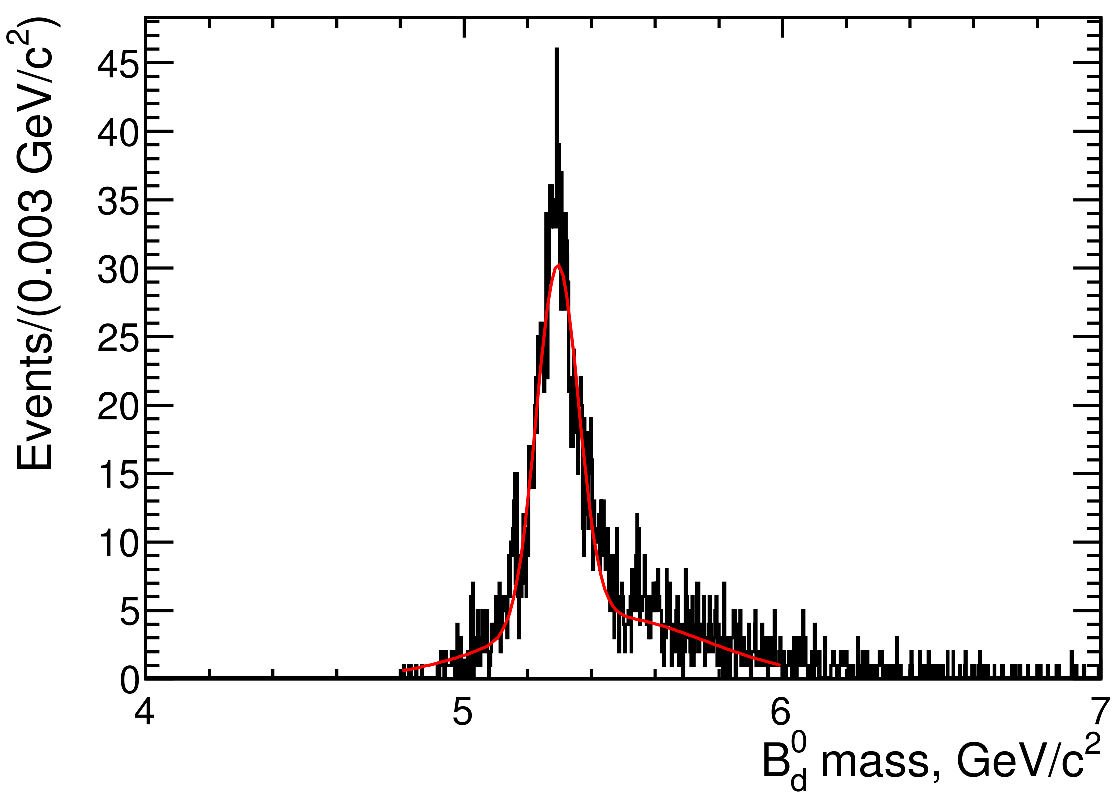
- Lepton Flavour Violation studies in $Z \rightarrow e\mu, e\tau, \tau\mu$
  - Institutes: LPC Clermont, LPT Orsay.
  - Goals:
    a) revisit and complete the phenomenological study relating the observed branching fractions (BF) to the mass of the hypothetical sterile neutrinos.
    b) estimate the experimental limit achievable on BF. Ongoing.

- Angular analysis of the decay mode $B_s \rightarrow \tau\tau$
  - Institutes: Marseille, CPT and CPPM.
  - Goals:
    a) phenomenological build up the angular analysis.
    b) exploration of partial reconstruction techniques.
    c) estimate the expected precision on BF and angular parameters.
  - Recent results: https://indico.cern.ch/event/462662/contribution/1/attachments/1194584/1735242/talk_FCCee.pdf

Actual work:

- Angular analysis of the decay mode $B^0 \rightarrow K^*(892)\tau\tau$
  - Proponents: W. Altmanshoffer, J. Kamenik, D. Straub, S. Monteil, A. Semkiv
  - Goals:

  a) phenomenological build up the angular analysis.
  b) exploration of partial reconstruction techniques.
  c) estimate the expected precision on BF and angular parameters.



Obtained with FCC software
Follow-up with A. Semkiv's Master thesis (Kyiv).

Some perspectives:

- Discussions have started on new or connected subjects, where there have been an expression of interest for experimentalists to commit to. Among them, one can find:

- Angular analysis of the decay mode $B^0 \rightarrow K^*(892)ee$: *this is interesting to complete the picture of the rare radiative leptonic decays (and test lepton universality incidentally).*

- *CP*-violating phases γ and ϕ_s from $B_s \rightarrow D_s K$: *this is interesting per se but mostly useful to determine which type of Particle Identification detector would be needed to complete this physics program.*

- *Rare, exclusive hadronic Z decays: theoretically extremely clean; powerful tests of QCD factorization, can be used to probe directly both flavor conserving and FCNC couplings of the Z to quarks.*

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