Valentina De Romeri[1]

Impact of sterile neutrinos in lepton flavour violating processes

based on JHEP 1504 (2015) 051 and work in progress

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Outline

- Lepton flavour violation and New Physics:
  - cLFV as a signal of New Physics
  - cLFV observables and experimental status
- Extending the SM with sterile (Majorana) neutrinos:
  - Inverse Seesaw (ISS)
  - “3+1” model
  - Unitarity deviation
  - Experimental constraints
- Sterile neutrinos and LFV:
  - cLFV signals at colliders (FCC-ee and LC)
    - LFV Z decays at a high luminosity Z factory
    - Synergy between low- and high-energy cLFV observables
  - cLFV signals at high-intensity (COMET): nucleus-assisted processes
    - LFV decay of muonic atoms $\mu^- e^- \to e^- e^-$
    - $\mu^- N \to e^- N$

Flavour in the SM

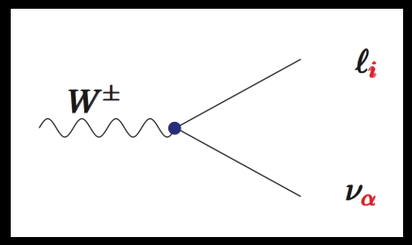
- Quark sector: flavour is violated by charged current interactions (CKM)

Observed in many oscillation/decay processes: good agreement with SM

- Lepton sector: neutral & charged lepton flavours are strictly conserved (neutrinos are massless)

BUT we know that neutral lepton flavour is violated through neutrino oscillations!

Misalignment of mass and $SU(2)_L$ states parameterised by the leptonic mixing matrix (U_{PMNS}, 3 mixing angles - solar, atmospheric, reactor)



charged currents $\propto U_{\alpha i}^{PMNS}$

Is flavour violated also in the charged sector??

In "ad-hoc extension" of the SM (m_ν $\nu_L \nu_R$ (Dirac)): Negligible charged Lepton Flavour Violation (cLFV)

$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim 10^{-54}$$

Charged lepton flavour violation

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

- Rare leptonic decays and transitions (e.g. $l_i \to l_j \gamma$, $\mu \to e\gamma$, $\mu \to eee$, mesonic τ decays, $\mu - e$ conversion (Nuclei), $\mu^- e^- \to e^- e^-$ ...) [high-intensity facilities]

- Meson decays: violation of lepton flavour universality, LFV final states lepton Number violating decays (R_K, $B \to \tau \mu$, $B \to D \mu^- \mu^-$ ...) [high-intensity; LHCb]

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

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

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cLFV and New Physics

Flavour violation in charged lepton sector: Physics beyond SM!

- Are neutral and charged LFV related?
- Does cLFV arise from ν-mass mechanism? Or entirely different nature?

cLFV in new physics models: arising in SM minimally extended via sterile neutrinos

Models of NP with Majorana fermions:

- (well-motivated) New Physics models e.g. Inverse Seesaw
- phenomenological "3+1" effective model

Compare impact of ν_S on

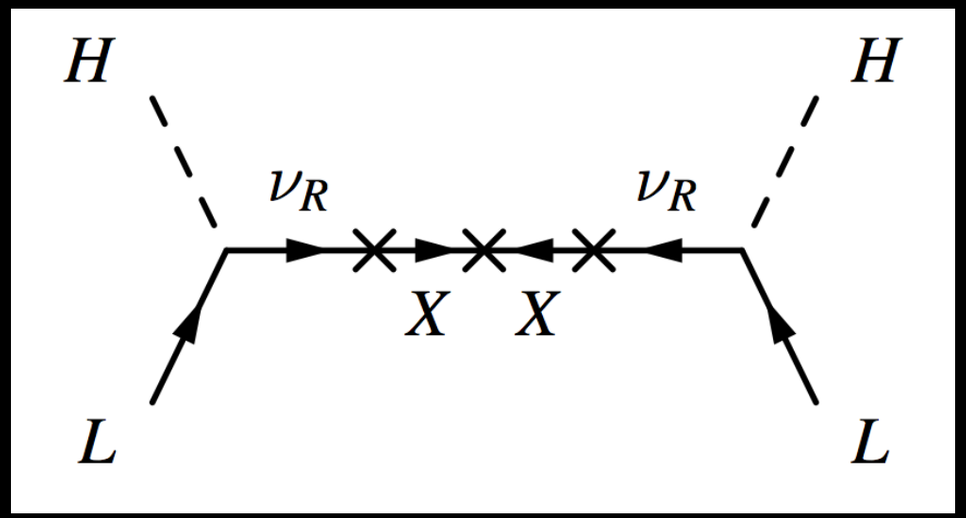
- cLFV Z decays at high luminosity Z factories (FCC-ee, LC) and
- cLFV in nucleus-assisted transitions

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

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

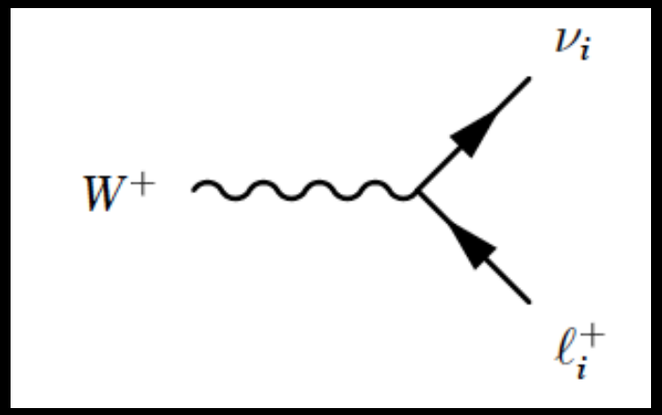
Y_ν~O(1) and M_R ~ 1TeV testable at the colliders and low energy experiments.

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):



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:

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

$\nu_i = \sum_{ai} U_{ai} \nu_a$, 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)

Inverse Seesaw

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

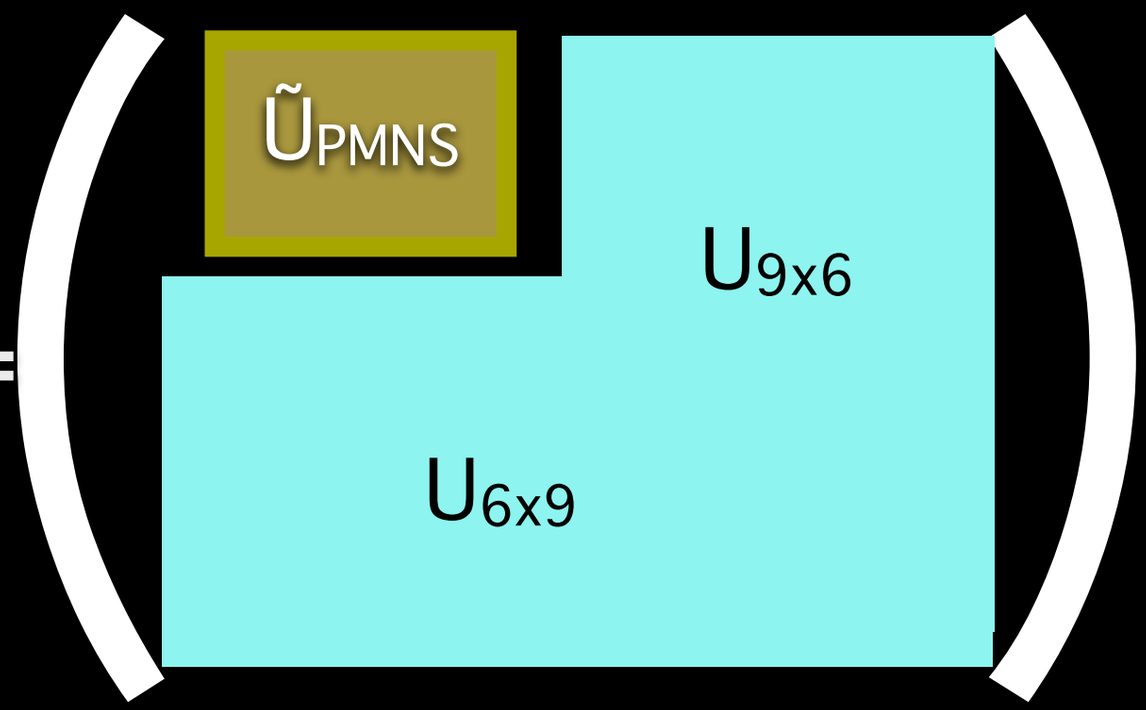
$$Y_\nu = \frac{\sqrt{2}}{v} D^\dagger \mathrm{diag}(\sqrt{\mathrm{M}})\mathrm{R}\,\mathrm{diag}(\sqrt{\mathrm{m}_\nu})\mathrm{U}^\dagger_{\mathrm{PMNS}} \qquad M = M_R \frac{1}{\mu_X} M_R^T$$

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 Uv

U_{9x9} =



Parameters:

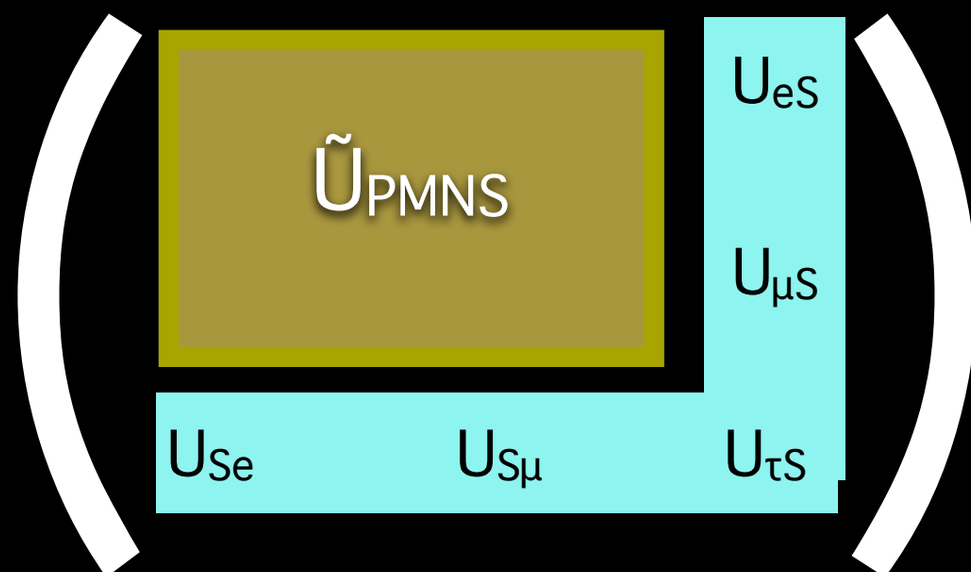
- M_R (real, diagonal) M_R = (0.1 MeV, 10^6 GeV)
- μ_X (complex,symmetric) μ_X = (0.01 eV, 1 MeV)
- R_{mat} (rotation,complex)
- 2 Majorana and 1 Dirac phases from U_{PMNS}
- Normal (NH) / Inverted (IH) hierarchy

Effective model: 3+1

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

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

U_{4x4} =



Parameters:

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

Experimental constraints

The deviations from unitarity might induce departures from 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.

$$U_{3\times3} = (1-\eta)U_{PMNS}$$

effective theory approach

(Antusch et al., 2009, 2014)

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

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4. LHC data (invisible decays) — 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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5. Leptonic and semileptonic meson decays (K,B and D) — $\Gamma(P \to l\nu)$ 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)

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

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

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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)

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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)

LFV Z decays at a high luminosity Z-factory

New physics effects in rare Z decays

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

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

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

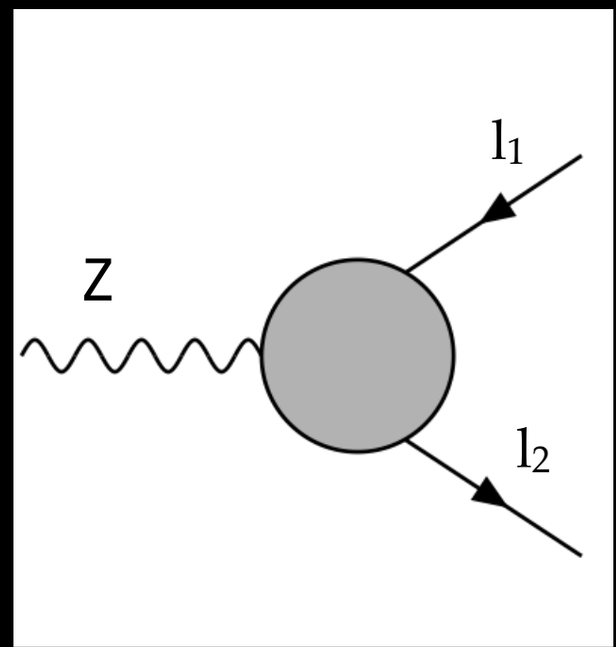
The detection of a rare decay as $Z \to l_i^{\mp} l_j^{\pm}$ (i≠j) would serve as an indisputable evidence of new physics

Current limits:

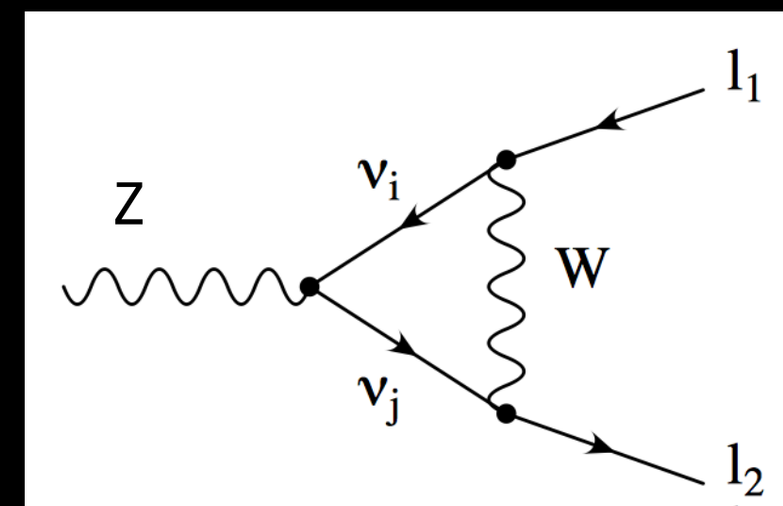
$$\begin{aligned} \mathrm{BR}(Z \to e^{\mp}\mu^{\pm}) &< 1.7 \times 10^{-6} \\ \mathrm{BR}(Z \to e^{\mp}\tau^{\pm}) &< 9.8 \times 10^{-6} \\ \mathrm{BR}(Z \to \mu^{\mp}\tau^{\pm}) &< 1.2 \times 10^{-5} \end{aligned}$$

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

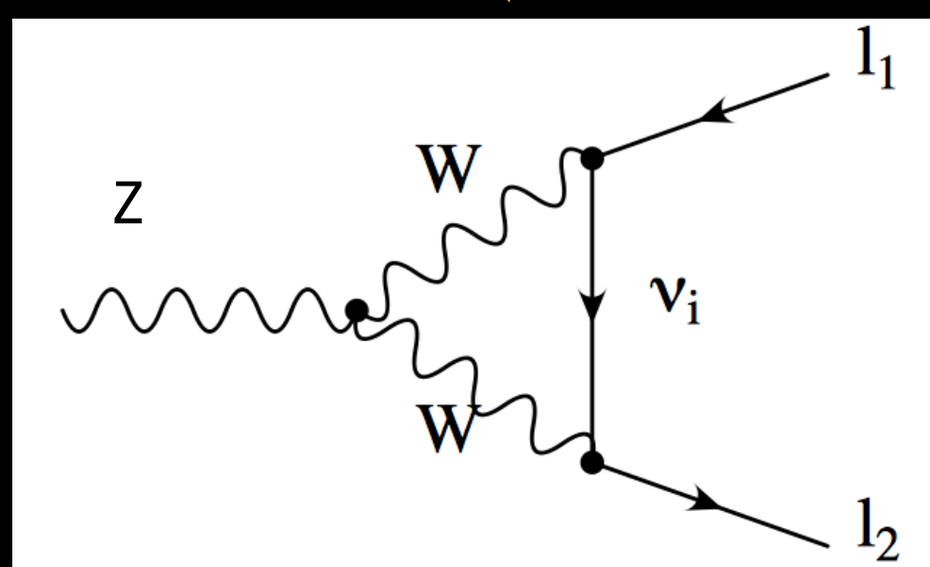
OPAL Collaboration, R. Akers et al., Z. Phys. C67 (1995) 555–564.
L3 Collaboration, O. Adriani et al., Phys. Lett. B316 (1993) 427.
DELPHI Collaboration, P. Abreu et al., Z. Phys. C73 (1997) 243.
ATLAS, CERN-PH-EP-2014-195 (2014)

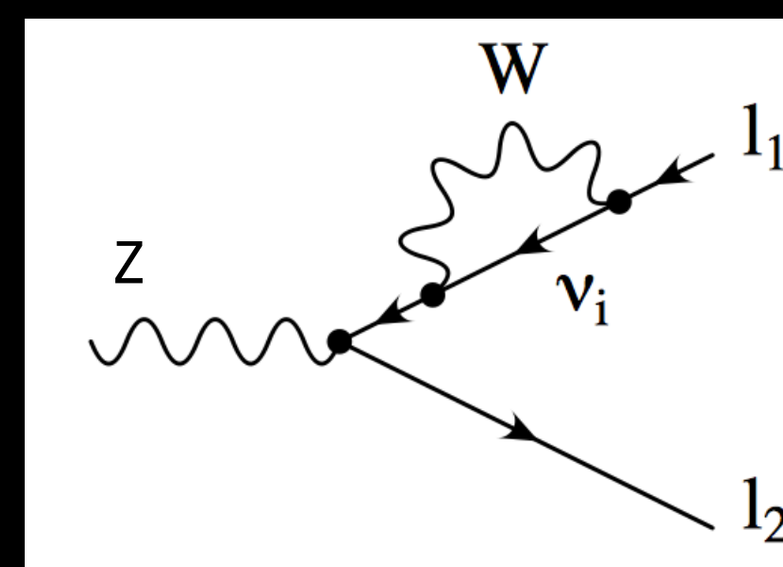


ν_i are physical states, i =3+N

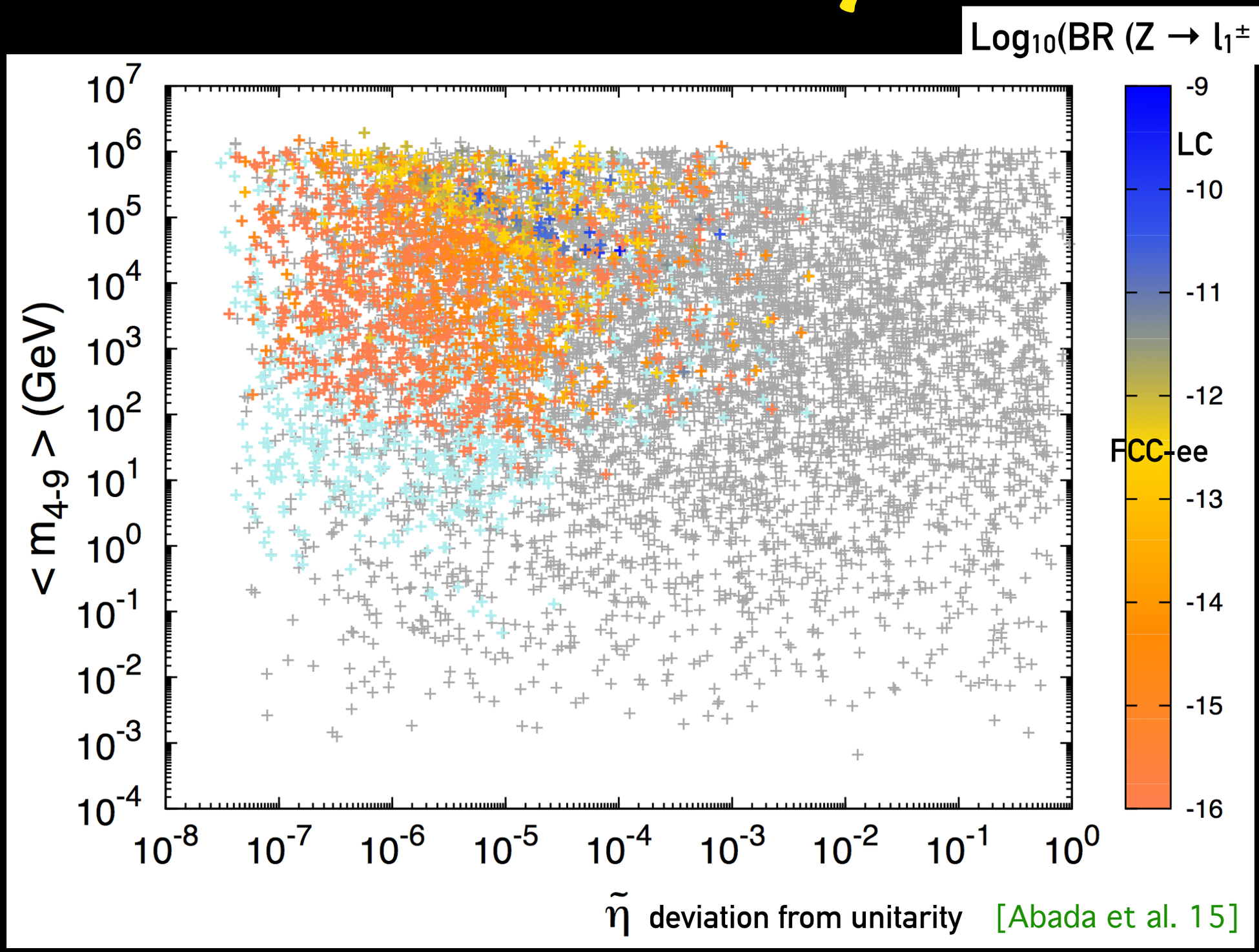


N = extra Majorana states
(m ~ 10^{-10} - 10^{3} GeV)

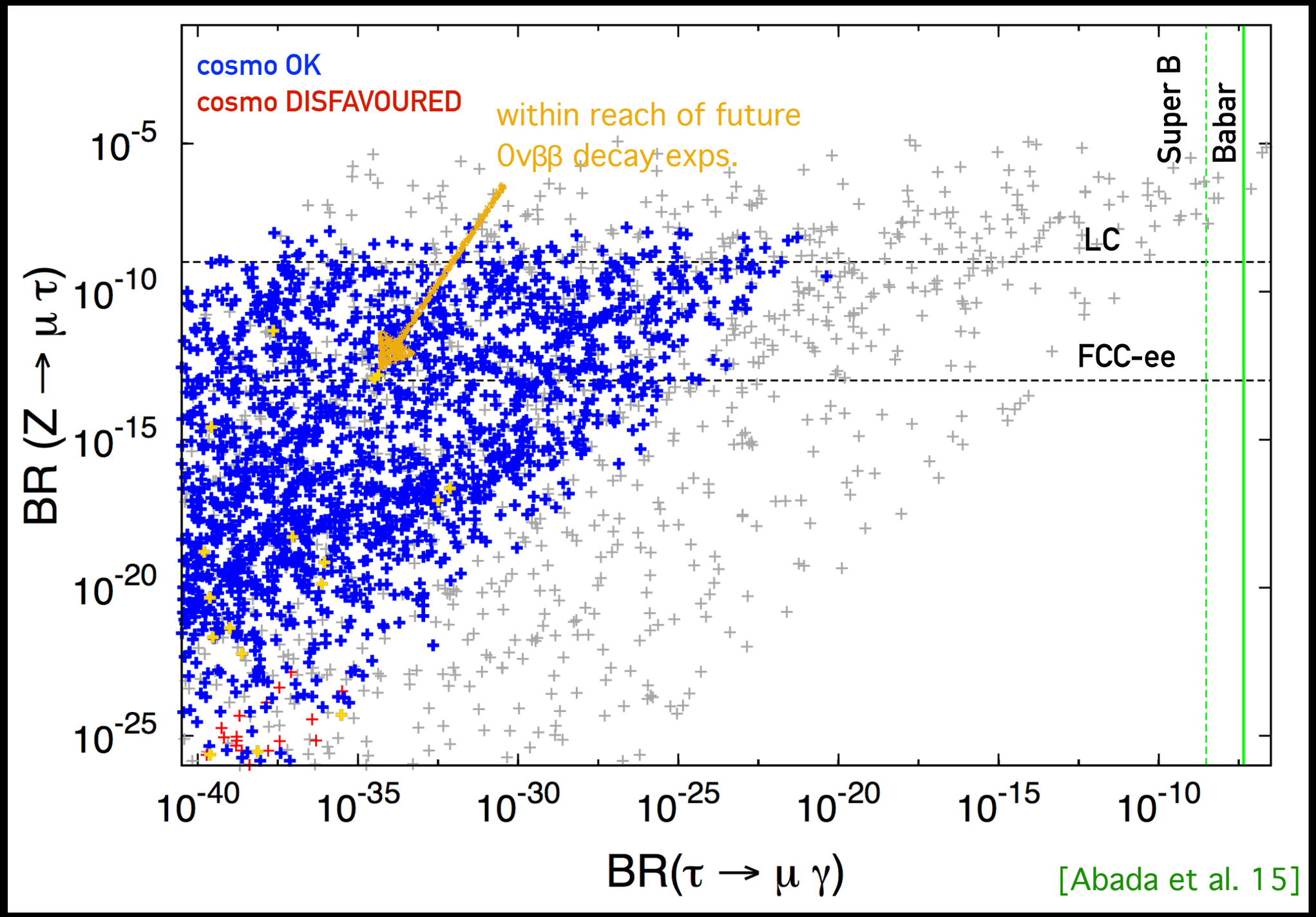




ISS: LFV Z decays



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

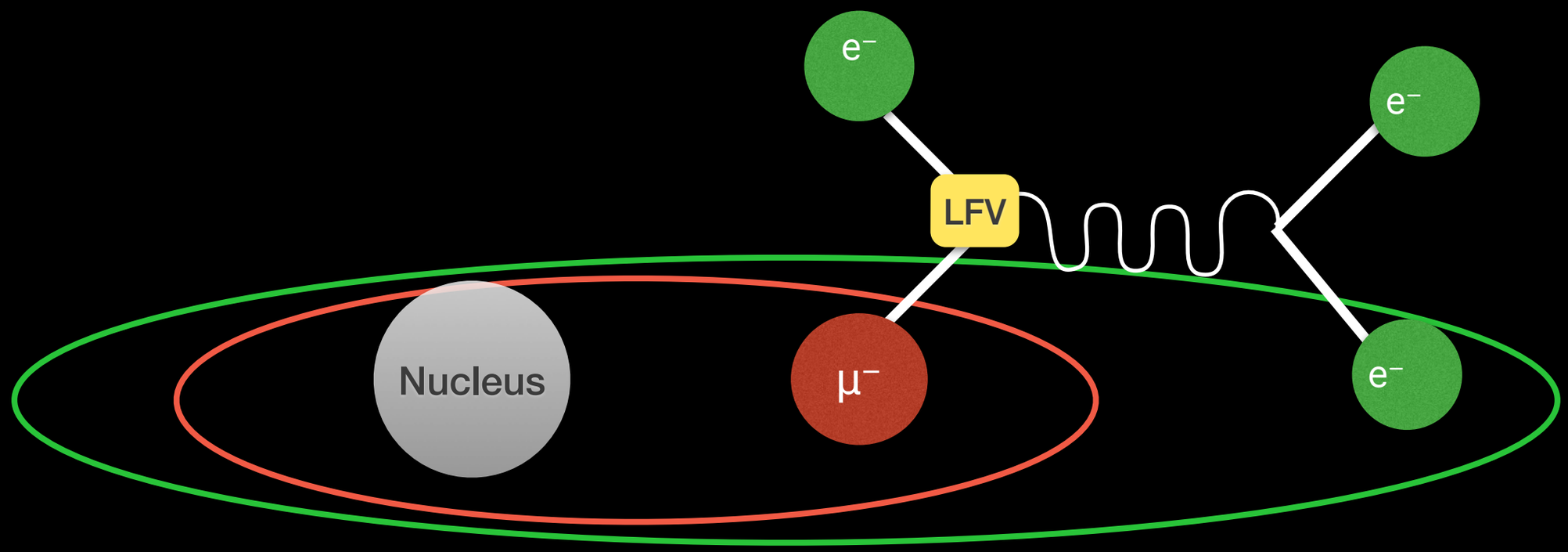


Nucleus-assisted cLFV processes:

$\mu^- e^- \rightarrow e^- e^-$ and $\mu^- N \rightarrow e^- N$

$\mu^- e^- \rightarrow e^- e^-$

New process proposed by Koike et al. of a bound μ^- in a muonic atom



$$Br(\mu^- e^- \rightarrow e^- e^-) = 24\pi(Z-1)^3 \alpha^3 (m_e/m_\mu)^3 m\, \tau_\mu / \tilde{\tau}_\mu\, G$$

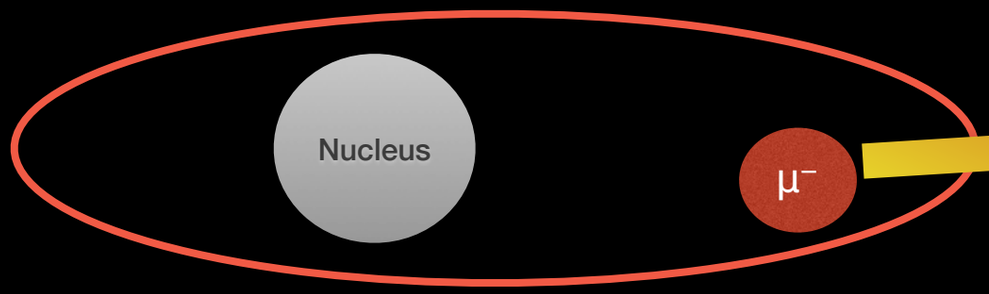
- Another channel for LFV search
- Elementary process same as $\mu^+ \rightarrow e^+ e^+ e^-$, but with opposite charge
- Effective Interactions: contact and photonic interactions
- The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate
- Heavy nuclei, large Coulomb attraction favored, enhances the transition probability by $(Z-1)^3$
- Within the reach of high-intensity muon beams

Koike et al. Phys.Rev.Lett. 105 (2010) 121601
Uesaka et al. arXiv:1508.05747

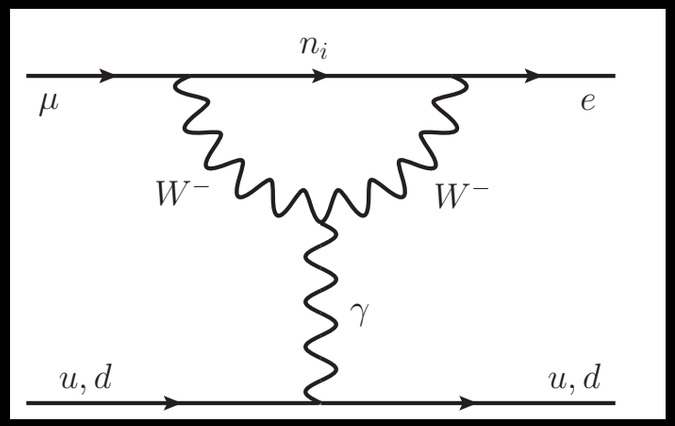
$\mu^- N \rightarrow e^- N$

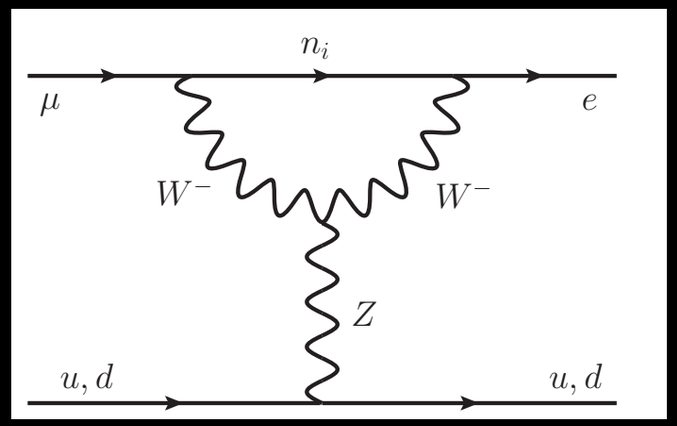
Muon to Electron Conversion in nuclei:
neutrinoless capture of a bound 1s muon in a muonic atom by the nucleus (A, Z)

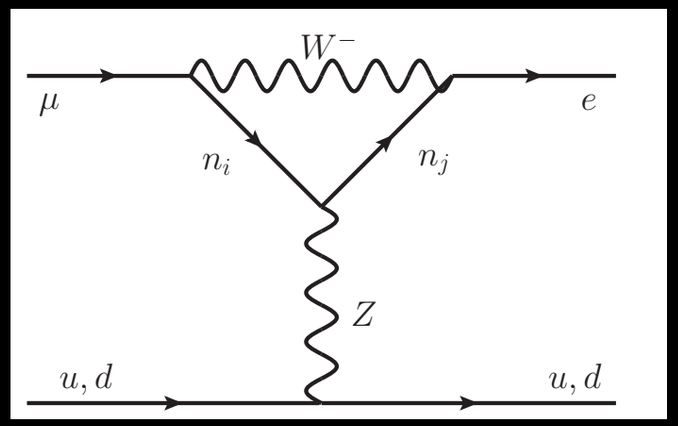
$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

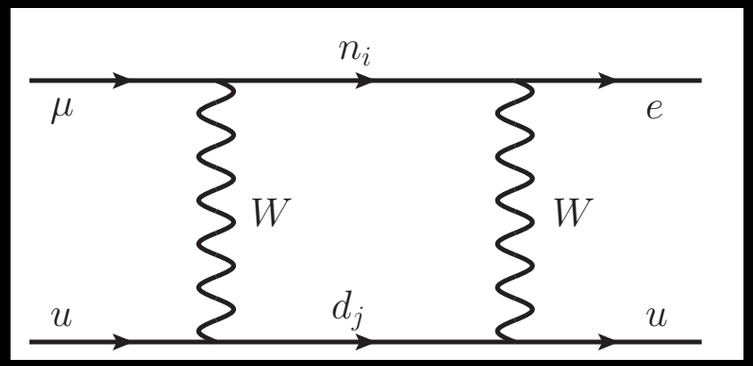


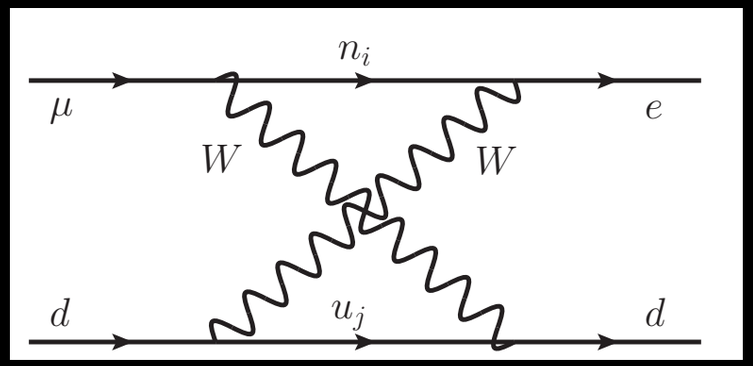
muon capture: $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$
muon decay in orbit: $\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$





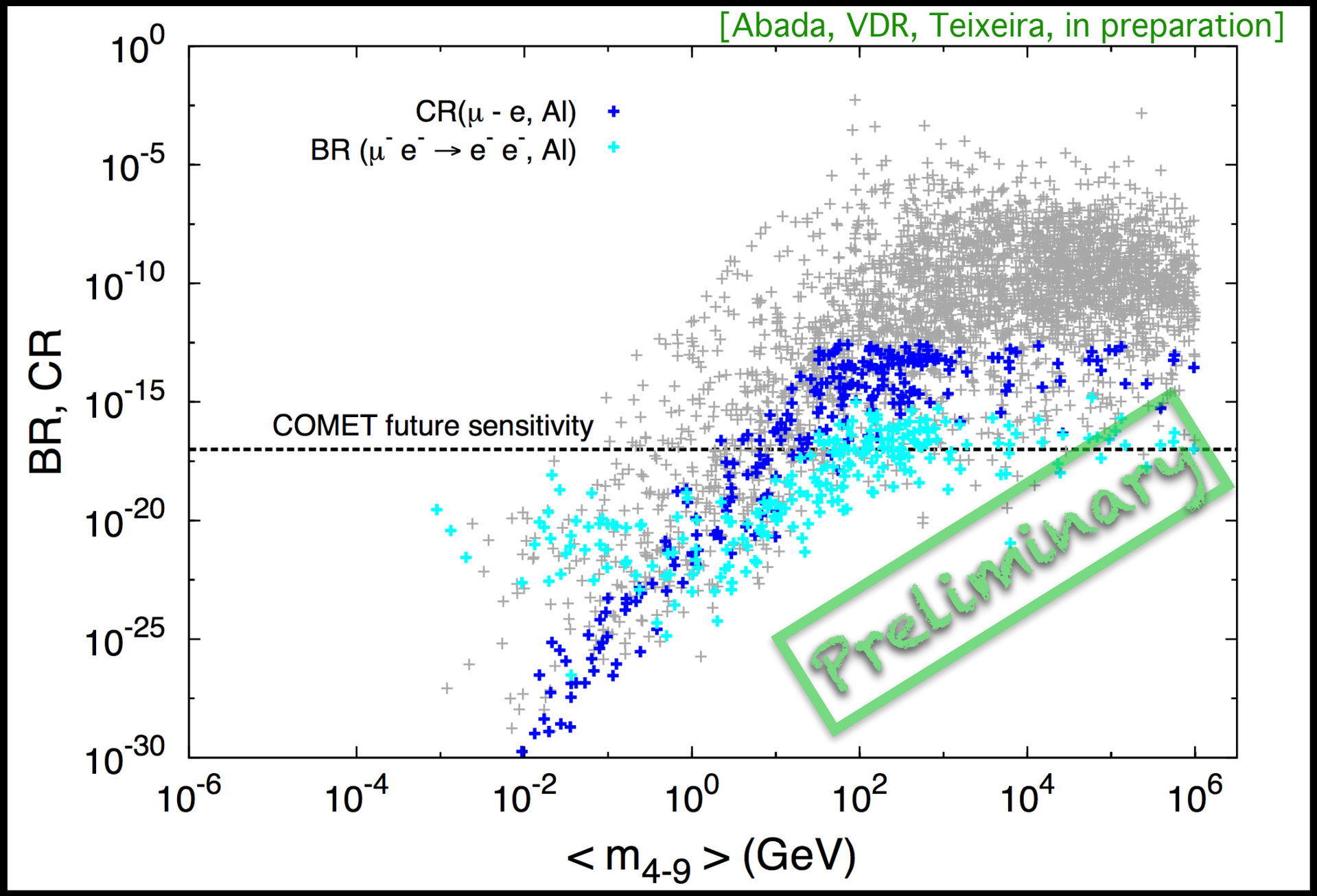






[Gronau et al, '85; Ilakovac & Pilaftsis, '95 - '14;
Deppisch et al, '05; Dinh et al, '12; Alonso et al, '12; ...]

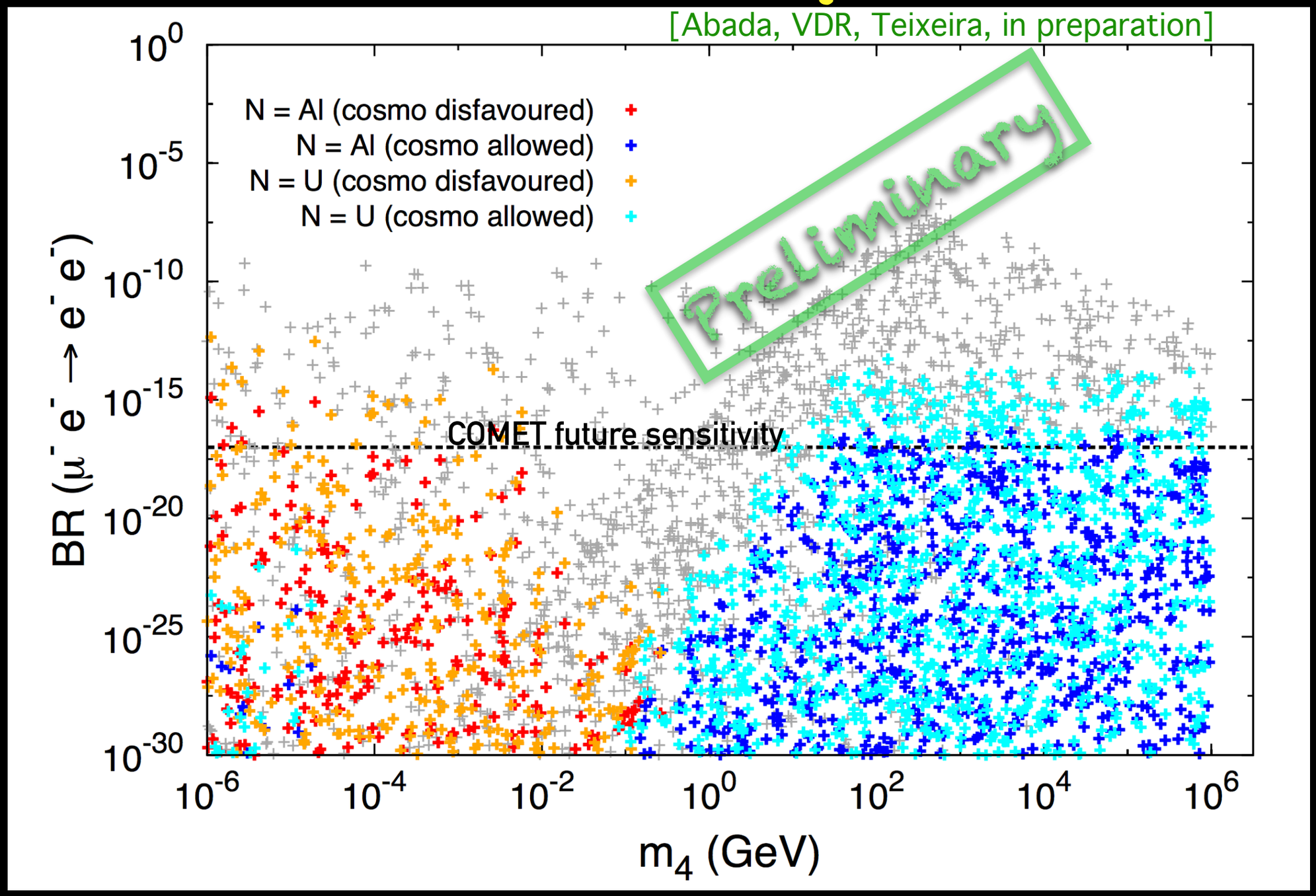
ISS: μ-e- → e-e- and mu-e conversion



COMET (COherent Muon Electron Transition) @ J-PARC

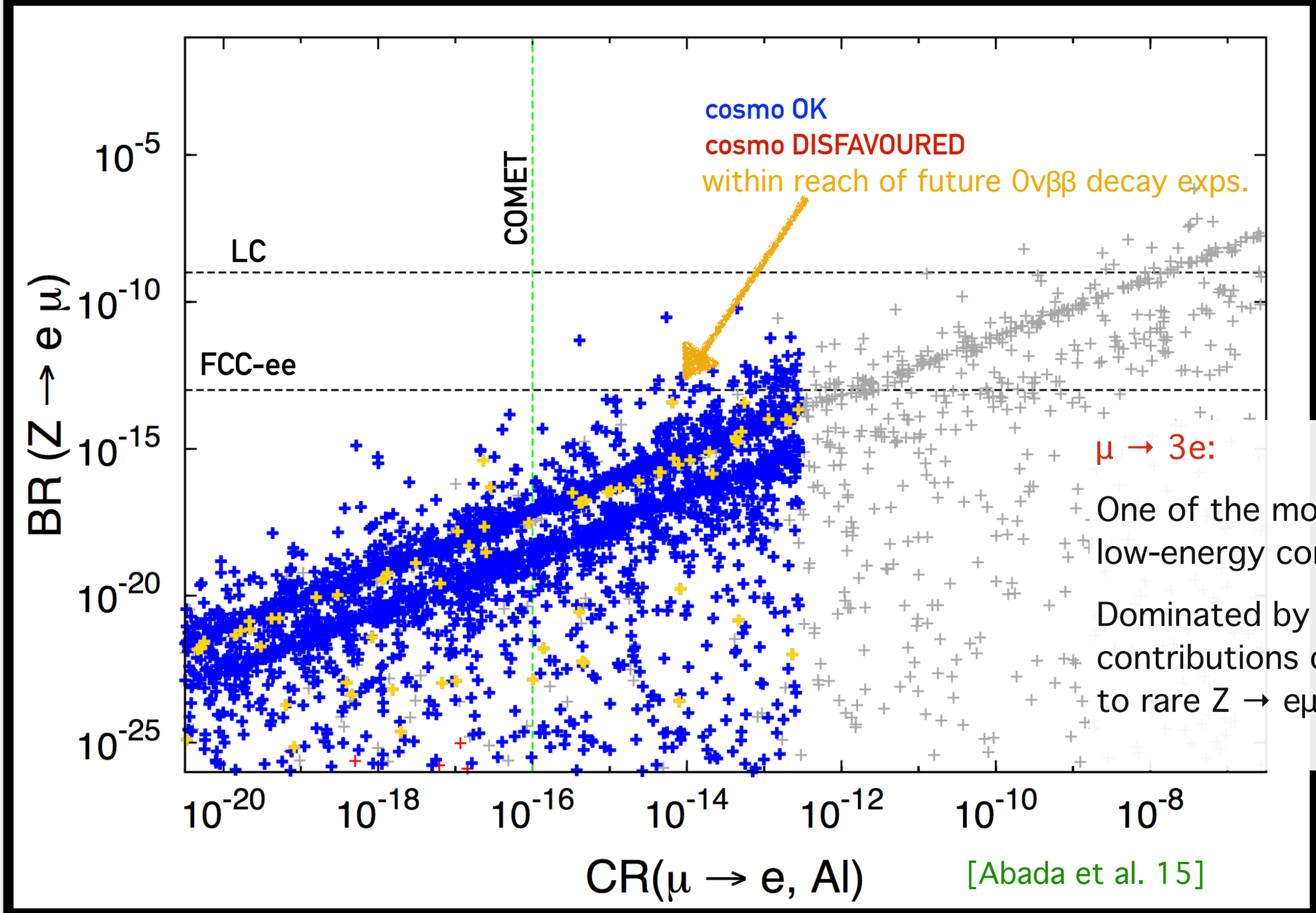
- For Aluminium [COMET], CR(μ – e) appears to have slightly stronger experimental potential .. but BR($\mu^- e^- \to e^- e^-$) interesting in the low mass regime

Effective "3+1": μ⁻e⁻ → e⁻e⁻



- Sizeable values for BR(μ⁻e⁻ → e⁻e⁻) - potentially within experimental reach! [COMET]
- Contributions for both heavy steriles and lighter states (non-unitarity)

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



[Abada et al. 15]

$\mu \to 3e$:

One of the most stringent low-energy constraints

Dominated by Z penguin contributions correlated to rare $Z \to e\mu$

Summary

- cLFV observables can provide (indirect) information on the underlying NP model
- We have considered extensions of the SM (ISS and 3+1) which add to the particle content of the SM one or more sterile neutrinos

- Sterile neutrinos provide sizeable contributions to many observables (some leading to stringent constraints)
  - Among these, 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 $BR(Z \to l_1^{\pm} l_2^{\mp})$.

- We have explored indirect searches for the sterile states at a high-luminosity Z factory (FCC-ee) and high-intensity facilities (COMET), emphasising the underlying synergy: regions of the parameter space of both models can be probed via LFV Z decays at FCC-ee, through LFV radiative decays 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.

- Important sterile contributions to $CR(\mu - e, N)$ and $BR(\mu^- e^- \to e^- e^-)$ in both mass regimes, potentially within COMET reach
  - Analysis also carried for another well motivated model: νMSM

Summary

- cLFV observables can provide (indirect) information on the underlying NP model
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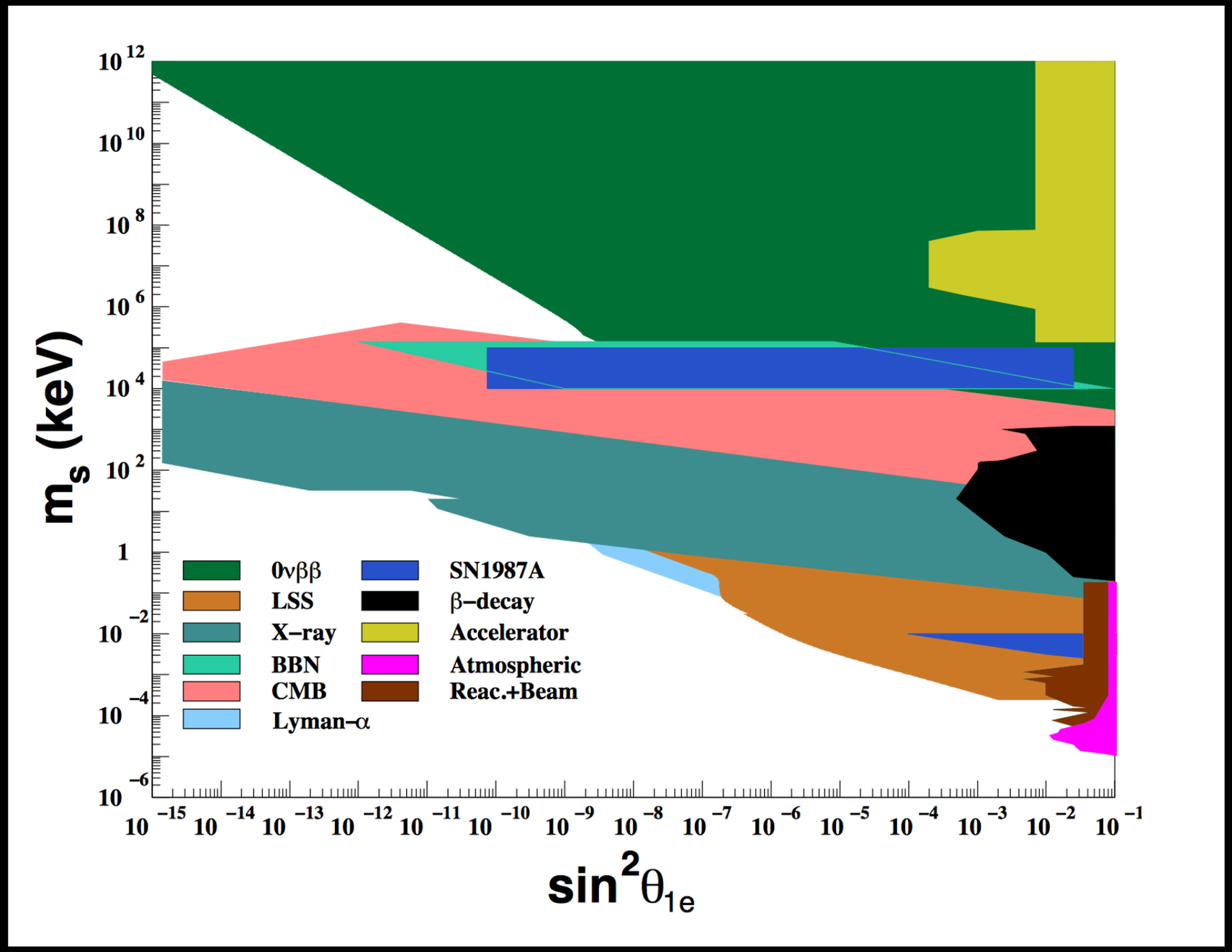
- Sterile neutrinos provide sizeable contributions to many observables (some leading to stringent constraints)
  - Among these, LFV observables receiving contributions from Z-mediated penguins like μ→e conversion in nuclei and $Z \to \ell^{\pm} l_2$ impose strong constraints on the sterile neutrinos induced BR($Z \to \ell^{\pm} l_2$)
- We have explored indirect searches for the sterile states at a high-luminosity Z factory (FCC-ee) and high-intensity facilities (COMET), emphasising the underlying synergy: regions of the parameter space of both models can be probed via LFV Z decays at FCC-ee, through LFV radiative decays and also 0νββ.
- FCC-ee could probe LFV in the μ-τ sector, in complementarity to the reach of low-E exps.
- Important sterile contributions to CR(μ – e, N) and BR($\mu^- e^- \to e^- e^-$) in both mass regimes, potentially within COMET reach
  - Analysis also carried for another well motivated model: νMSM

Thank you!

BACKUP

Cosmological bounds



(Kusenko 2009)

cLFV: nucleus assisted processes

★ **BR($\mu^- e^- \to e^- e^-$, N) vs. CR($\mu - e$, N)**

- **CR($\mu - e$)** $= \frac{2G_F^2 \alpha_w^2 m_\mu^5}{(4\pi)^2 \Gamma_{capt}(Z)} \left| 4V^{(p)} \left(2\tilde{F}_u^{\mu e} + \tilde{F}_d^{\mu e}\right) + 4V^{(n)} \left(\tilde{F}_u^{\mu e} + 2\tilde{F}_d^{\mu e}\right) + \sin^2\theta_w G_\gamma^{\mu e} D/(2\sqrt{4\pi\alpha})\right|^2$

- **BR($\mu^- e^- \to e^- e^-$)** $= 24\pi\, f[(Z-1)^3]\, \alpha_w \left(\frac{m_e}{m_\mu}\right)^3 \frac{\tilde{\tau}_\mu}{\tau_\mu} \Big(16 \Big| \frac{1}{2} \left(\frac{g_w}{4\pi}\right)^2 \left(\frac{1}{2} F_{box}^{\mu ee} + F_Z^{\mu e} - 2\sin^2\theta_w \left(F_Z^{\mu e} - F_\gamma^{\mu e}\right)\right)\Big|^2 + 4 \Big| \frac{1}{2} \left(\frac{g_w}{4\pi}\right)^2 2\sin^2\theta_w \left(F_Z^{\mu e} - F_\gamma^{\mu e}\right)\Big|^2\Big)$

- Contributions from **local γ dipole, Z and W penguins**

  (sub-dominant non-local γ and boxes)

- $V^{(i)}$: **nuclear** information (form factors, fields)

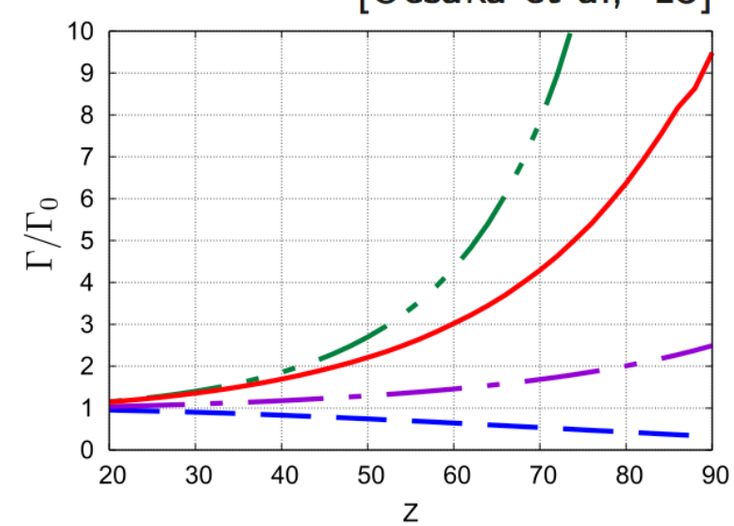
- **Element dependent $\tilde{\tau}_\mu$** and $f[(Z-1)^3]$

  Rate strongly enhanced in **large Z atoms**

  [Uesaka et al, '15]

- Consider **experimental setups for Pb, U !?**

[Uesaka et al, '15]



Courtesy of A. Teixeira

Neutrino physics: current status

- **Neutrino oscillation phenomena: favours a three active ν framework**
  - **Neutral lepton flavour violation in charged currents:**

    $\mathcal{L}^{\ell}_{\text{cc}} \sim -gU^{\text{PMNS}\dagger}_{ij} W^{+}_{\mu} \overline{\nu_{Li}} \gamma^{\mu} e_{Lj} \qquad \nu_{\ell} = U^{\text{PMNS}}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \alpha, \beta)\, \nu_i$
  - **Oscillation data** $\Rightarrow \theta_{12},\ \theta_{23},\ \theta_{13},\ \Delta^2_{21},\ |\Delta^2_{31}|$
  - **Unexplained "anomalies": reactor, LSND, MiniBooNe, ...**

- **Laboratory experiments**
  - Invisible Z decays: 3 light active states (LEP)
  - **Tritium beta decays:** $m_{\beta}^{\text{Mainz}} \leq 2.3$ **eV** $\quad m_{\beta}^{\text{Troitsk}} \leq 2.1$ **eV**
  - **Neutrinoless double deta decay:** $|m_{\beta\beta}| \lesssim 0.3$ **eV (Gerda, KamLAND-Zen)**

    Majorana nature; absolute mass scale

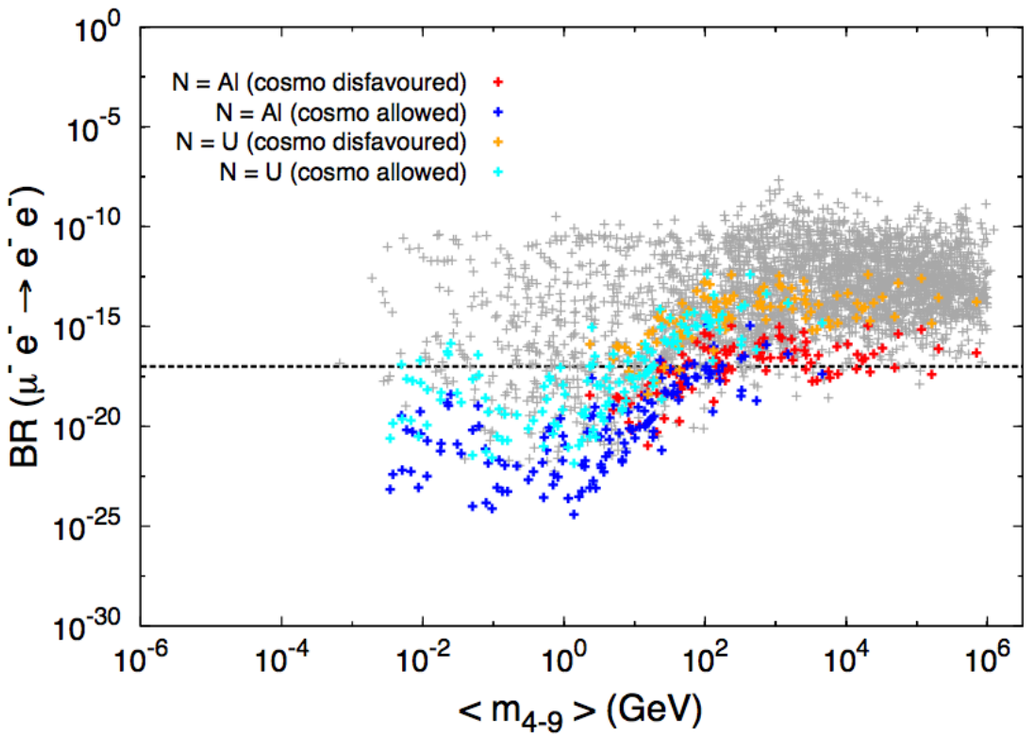
- **Cosmology and astrophysics**
  - $N_{\text{eff}} - N^{\text{SM}}_{\text{eff}} \leq 1$ **(BBN)**
  - $\sum m_{\nu} \lesssim 0.23$ **eV (CMB+BAO+WMAP+ΛCDM)**

Courtesy of A. Teixeira

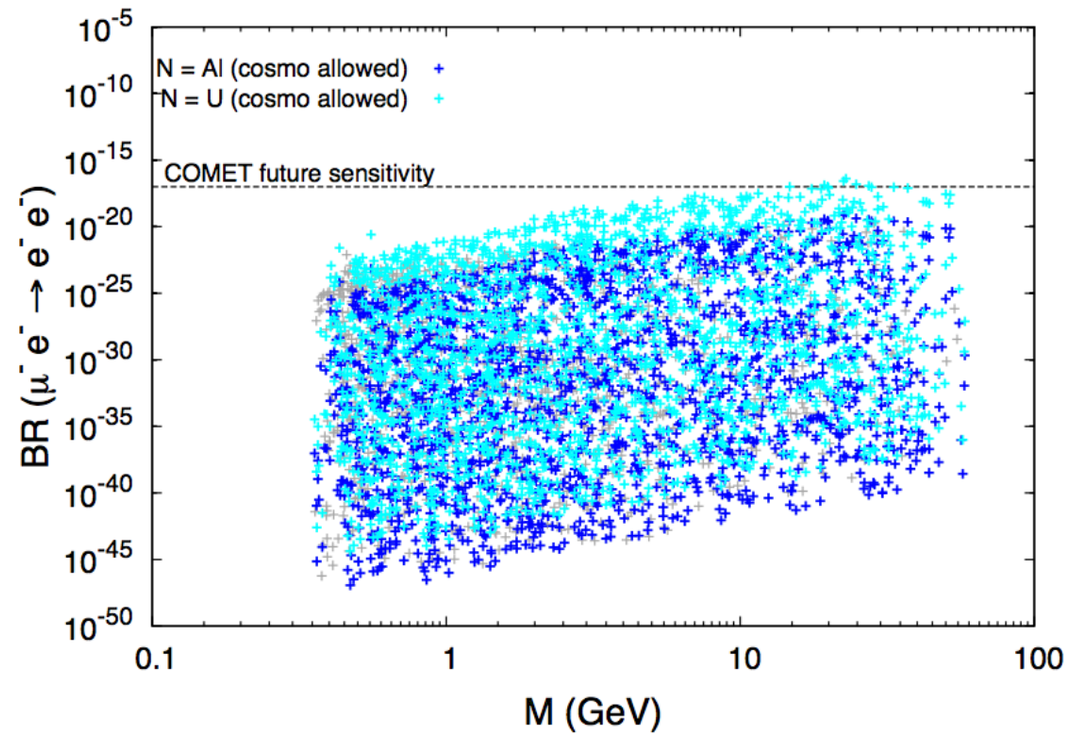
cLFV: nucleus assisted processes and sterile neutrinos

★ **BR($\mu^- e^- \to e^- e^-$, N) in low-energy seesaw models**

[PRELIMINARY (Abada, De Romeri, AMT)]



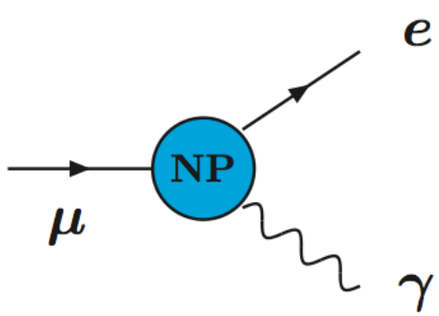
Inverse seesaw (ISS)



νMSM

Courtesy of A. Teixeira

Lepton Flavour Violation: $\mu \to e\gamma$



- **Event signature:** $E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

  Back-to-back e^+ - γ ($\theta \sim 180°$); Time coincidence

- **Backgrounds** $\Rightarrow$ prompt physics & accidental

  Prompt: radiative μ decays $\mu \to e\nu_e\nu_\mu\gamma$ (very low E_ν)

  Accidental: positron from $\mu \to e\nu_e\nu_\mu$;

  photon from $\mu \to e\nu_e\nu_\mu\gamma$; photon from in flight e^+e^- annihilation

- **MEG Experiment:** $3 \times 10^7 \mu$/s at **PSI** (Switzerland)

  2.7 ton liquid Xenon scintillation detector (good time, position and energy resolution)

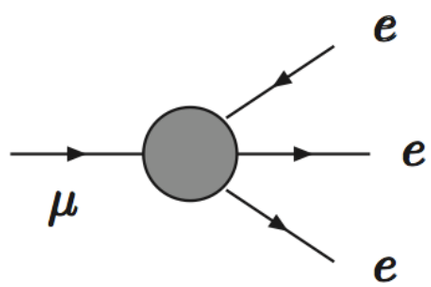
  2009 + 2010 data: 2.4×10^{-12} Upper Limit (90% CL)

  2011 + 2012 data: 10^{-13} Upper Limit (90% CL)

- **MEG II** (proposal to appear 2013): **sensitivity $\approx 10^{-14}$**

Courtesy of A. Teixeira

Lepton Flavour Violation: $\mu \to eee$



- **Event signature:** $\sum E_e = m_\mu$; $\sum \vec{P}_e = \vec{0}$

  common vertex; Time coincidence

- **Backgrounds** ⇒ physics & accidental

  Physics: $\mu \to ee\nu\nu e$ decay (very low E_ν)

  Accidental: positrons from $\mu \to e\nu\nu$;

  electrons from $\mu \to eee\nu\nu$ and/or $\mu \to e\nu\nu\gamma$; ...

- **Mu3e Experiment** at **PSI** (Switzerland)

  Stage I (2014 - 2017): $2 \times 10^8 \mu$/s at ΠE5 muon source

  Stage II (2018 -): $2 \times 10^9 \mu$/s at new muon source

  Future sensitivity: $\approx 10^{-14}$

Courtesy of A. Teixeira

Lepton Flavour Violation: $\mu - e$ conversion in atoms

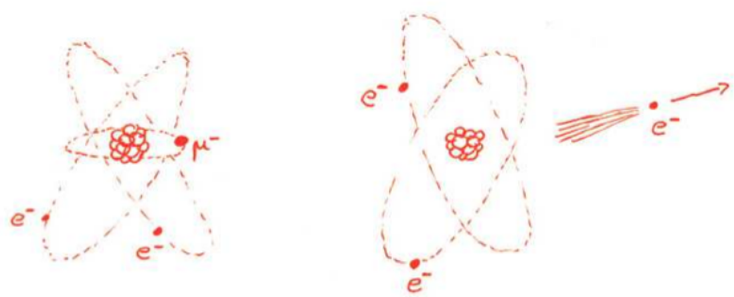
- Consider the fate of a **1s μ-state in a muonic atom:**

  SM-like muon decay in orbit $\mu^- \to e^- \nu\nu$

  SM-like nuclear muon capture $\mu^- + (A, Z) \to \nu_\mu + (A, Z-1)$

  Beyond SM - neutrinoless muon nuclear capture

$$\mu^- + (A, Z) \to e^- + (A, Z)$$



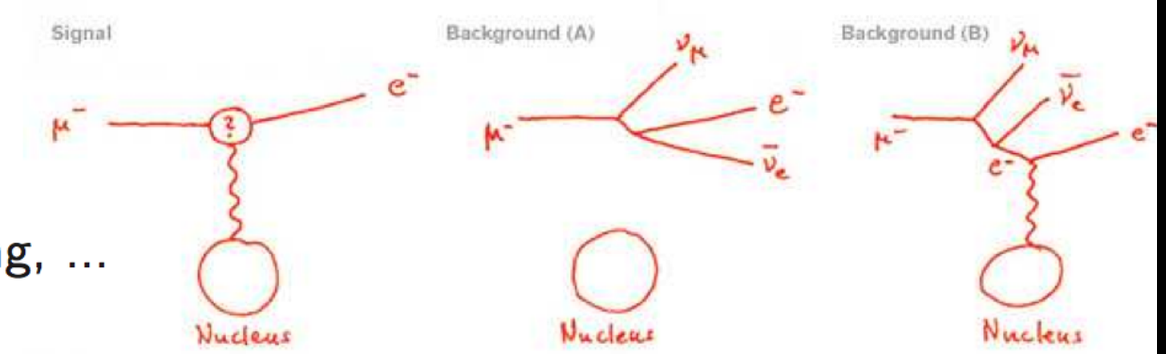
- **Event signature:** single mono-energetic electron

  $E_e \sim 100$ MeV

- **Backgrounds** $\Rightarrow$

  Physics (e.g. muon decay in orbit);

  beam-related; cosmic rays; false tracking, ...



- **SINDRUM-II** at **PSI** (max $10^8 \mu$/s beam intensity): **CR($\mu - e$, Au)** $< 7 \times 10^{-13}$

Improving the bound $\rightsquigarrow$ $\mathcal{O}(10^{-17})$: increase beam intensity $10^{11} \mu$/s (10^7 sec running)

improve background rejection...

Courtesy of A. Teixeira

Lepton Flavour Violation: $\mu - e$ conversion in atoms

- **Mu2e** at **Fermilab: CR($\mu - e$, Al)** $< 10^{-16}$ (90% CL)

  Reincarnation of MECO at BNL;

  Approved, CDO 2009, CD1 review 2012; *data taking 2019*

- **COMET (E21)** at **J-PARC: CR($\mu - e$, Al)** $< 6 \times 10^{-17}$ (90% CL)

  10^{11} muon stops/s for 56kW proton beam power

  Stage-I approved in 2009

- **DeeMe** at **J-PARC/MLF: CR($\mu - e$, Si)** $< 3.5 \times 10^{-14}$ (90% CL)

  SiC target; 15×10^9 muon stopped for 2×10^7 s running

  quick and not expensive... *not yet stage-I approved...*

Courtesy of A. Teixeira

Neutrino physics open questions

Among the missing ingredients there are:

- Absolute mass scale (Tritium β decays: $m_{\nu e}$<2.05eV, 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 (0νββ 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?

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

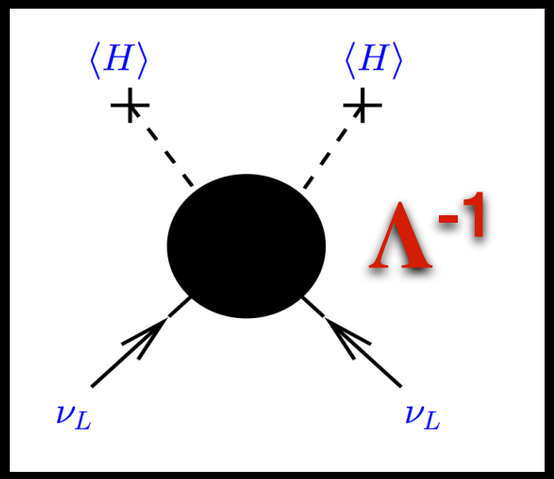
...

(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

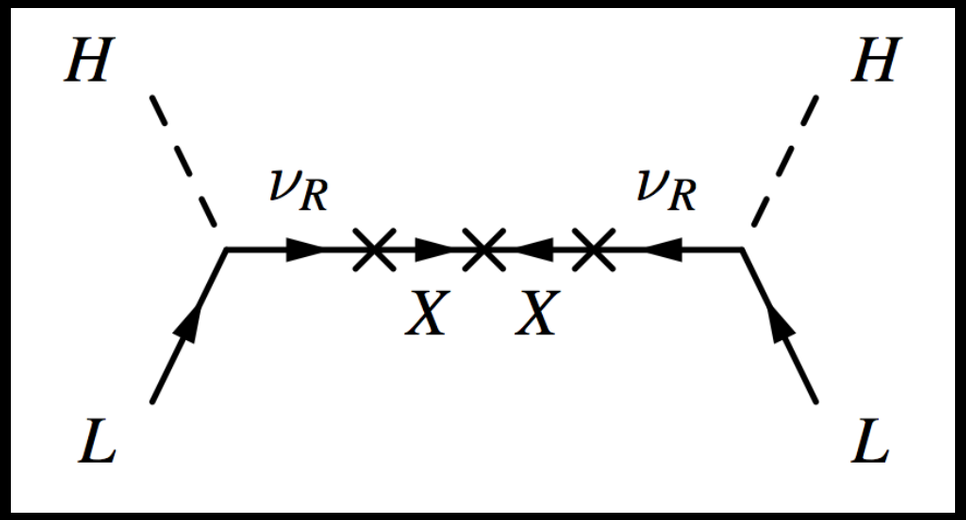
$$m_\nu \sim Y^2 \frac{v^2}{\Lambda}$$

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)

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



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

$$m_\nu \approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2}$$

$$m_{1,2} \approx \mp\sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}$$

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.

$$U_{3\times3} = (1-\eta)U_{PMNS}$$

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.

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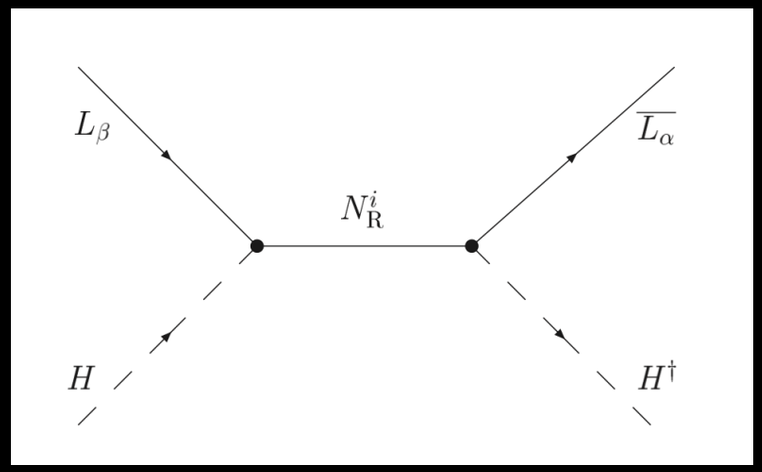
$$\mathcal{L}_{kin}^{d=6} = -c_{\alpha\beta}^{d=6,kin}(\bar{L}_\alpha \cdot H^\dagger)\, i\not{\partial}\, (H \cdot L_\beta)$$

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

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



- 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

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

Electroweak precision observables

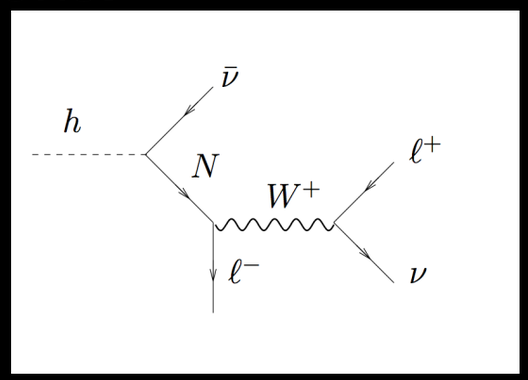
Experimental constraints

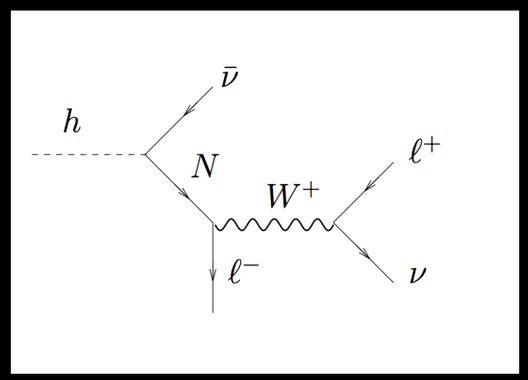
1. Neutrino oscillation parameters (seesaw approximation and PMNS)
2. Unitarity constraints
3. Electroweak precision data

4. LHC data (decay modes of the Higgs boson) (Bhupal Dev et al., 2012, P. Bandyopadhyay et al,2012, Cely et al., 2013)

$h \to \nu_R \nu_L$ 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.

$\Gamma(P \to l\nu)$ 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.

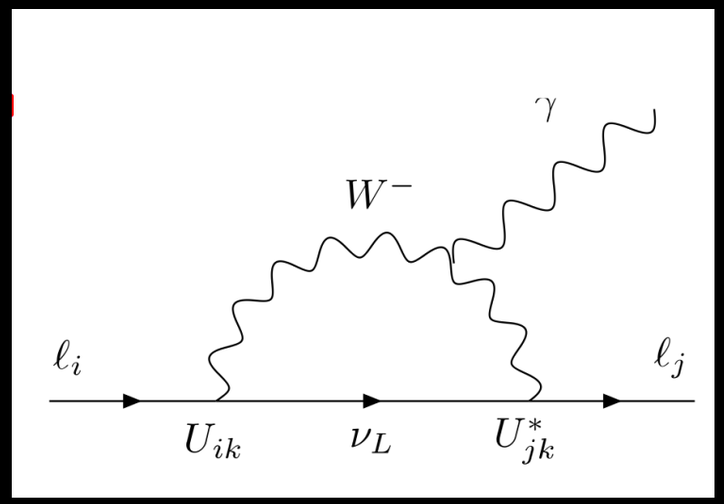
If a heavy neutrino is produced in such decays (e.g. $\pi^\pm \rightarrow \mu^\pm \nu_S$), the lepton spectrum would show a monochromatic line.

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 ($\mu \to e\,\gamma$) (Ilakovac and Pilaftsis,1995, Deppisch and Valle, 2005)

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



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

(MEG, 2013)

Experimental constraints

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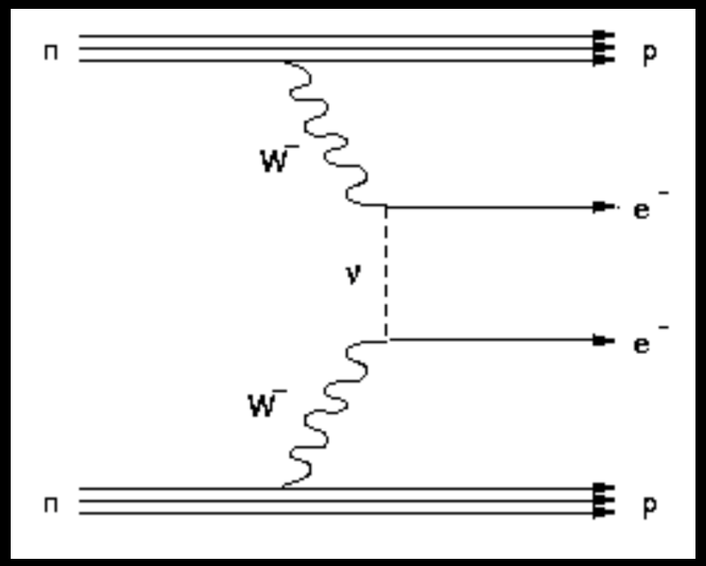
7. Laboratory bounds: direct searches for sterile neutrinos

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)



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.
$U_{3\times3} = (1-\eta)U_{PMNS}$
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
$h \to \nu_R\, \nu_L$ relevant for sterile neutrino masses ~100 GeV

5. Leptonic and semileptonic meson decays (B, D and K)
(J. Beringer et al. ,PDG, 2013)
$\Gamma(P \to l\nu)$ 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. $\pi^\pm \to \mu^\pm \nu_S$, the lepton spectrum would show a monochromatic line.

7. Lepton flavor violation ($\mu \to e\,\gamma$)
(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 $\nu_i \to \nu_j \gamma$),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

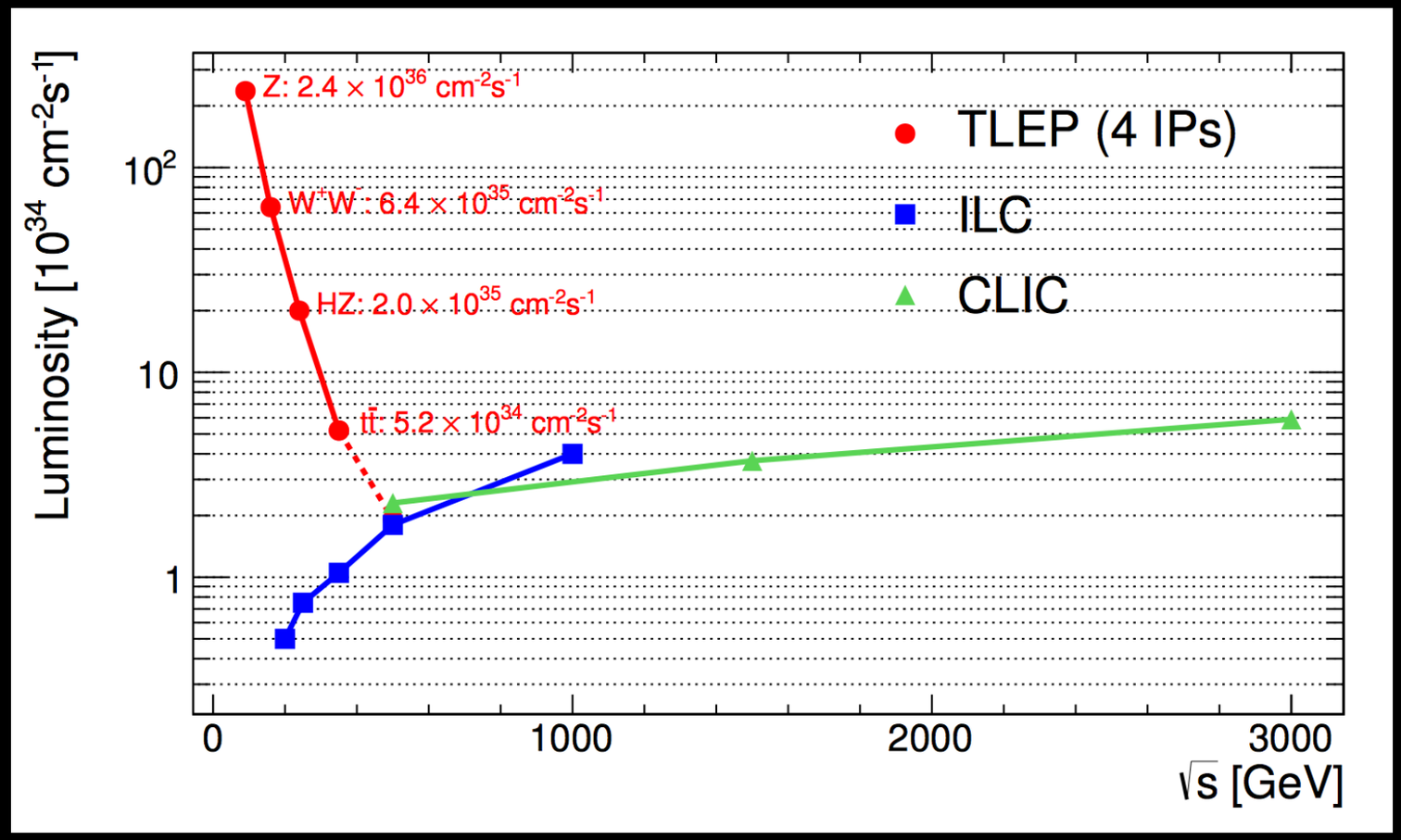
Isotope	Experiment	$T_{1/2}^{0\nu\beta\beta}$ [yr]	$\langle m_{\beta\beta} \rangle$ [meV]
^{136}Xe	EXO-200	$>1.6 \cdot 10^{25}$	<140–380
^{136}Xe	KamLAND-Zen	$>1.9 \cdot 10^{25}$	<120–250
^{76}Ge	GERDA phase I	$>2.1 \cdot 10^{25}$	<200–400
^{130}Te	CUORICINO	$>2.8 \cdot 10^{24}$	<300–700

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)

Future circular (and linear) colliders

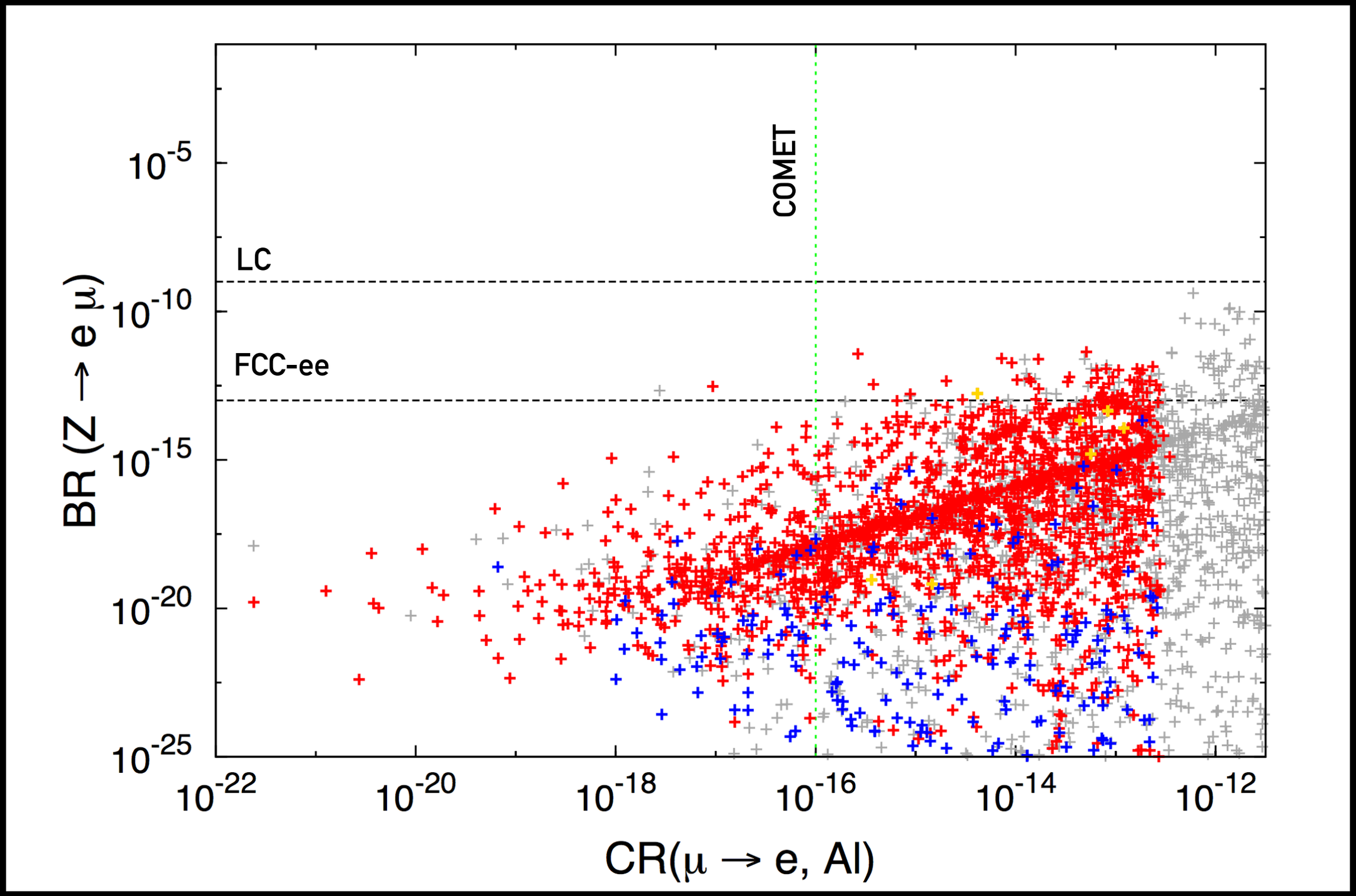


Instantaneous luminosity expected at FCC-ee, in a configuration with four interaction points operating simultaneously, as a function of the centre-of-mass energy.

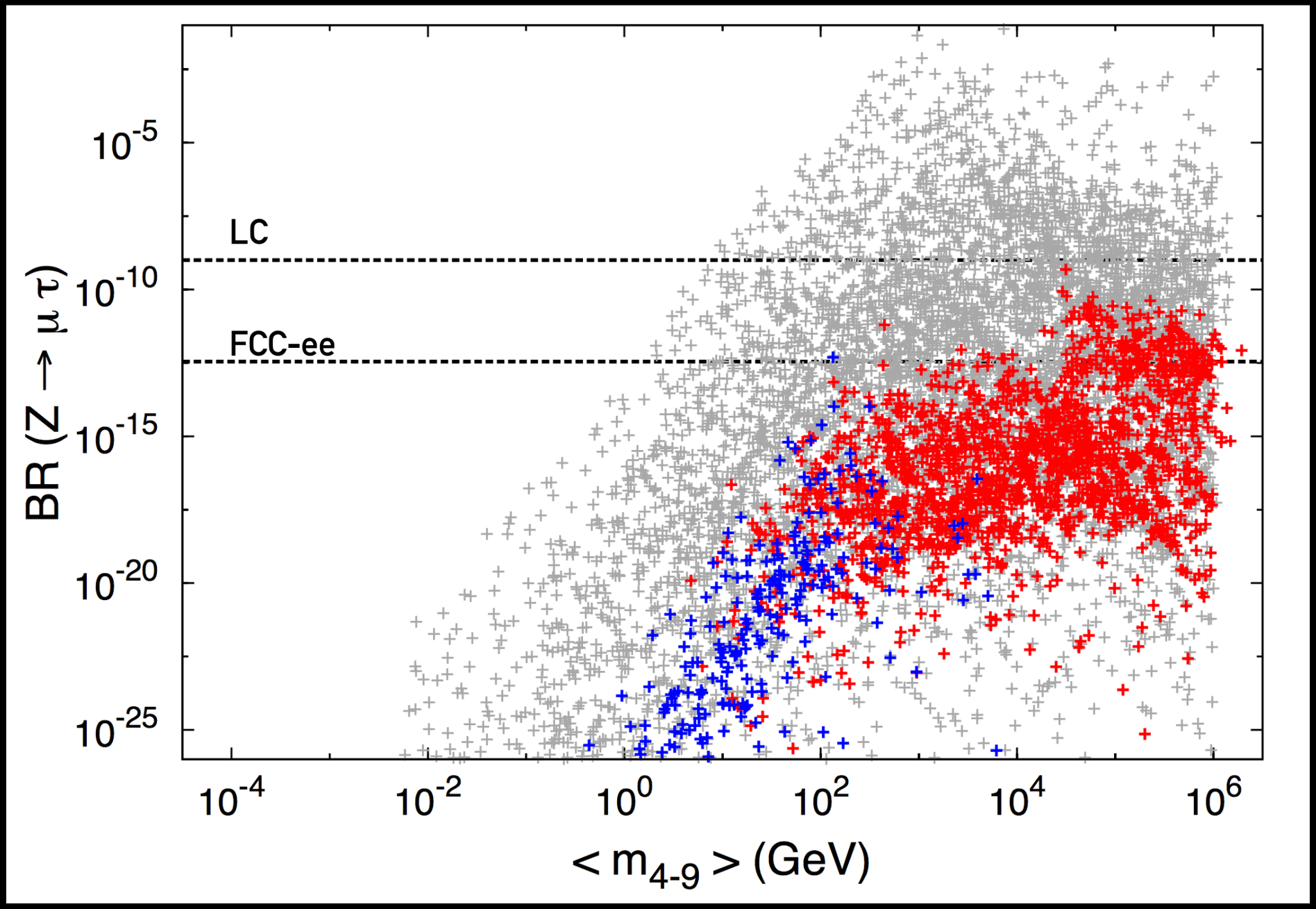
FCC-ee is designed to provide e^+e^- collisions in the beam energy range of 40 to 175 GeV.

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

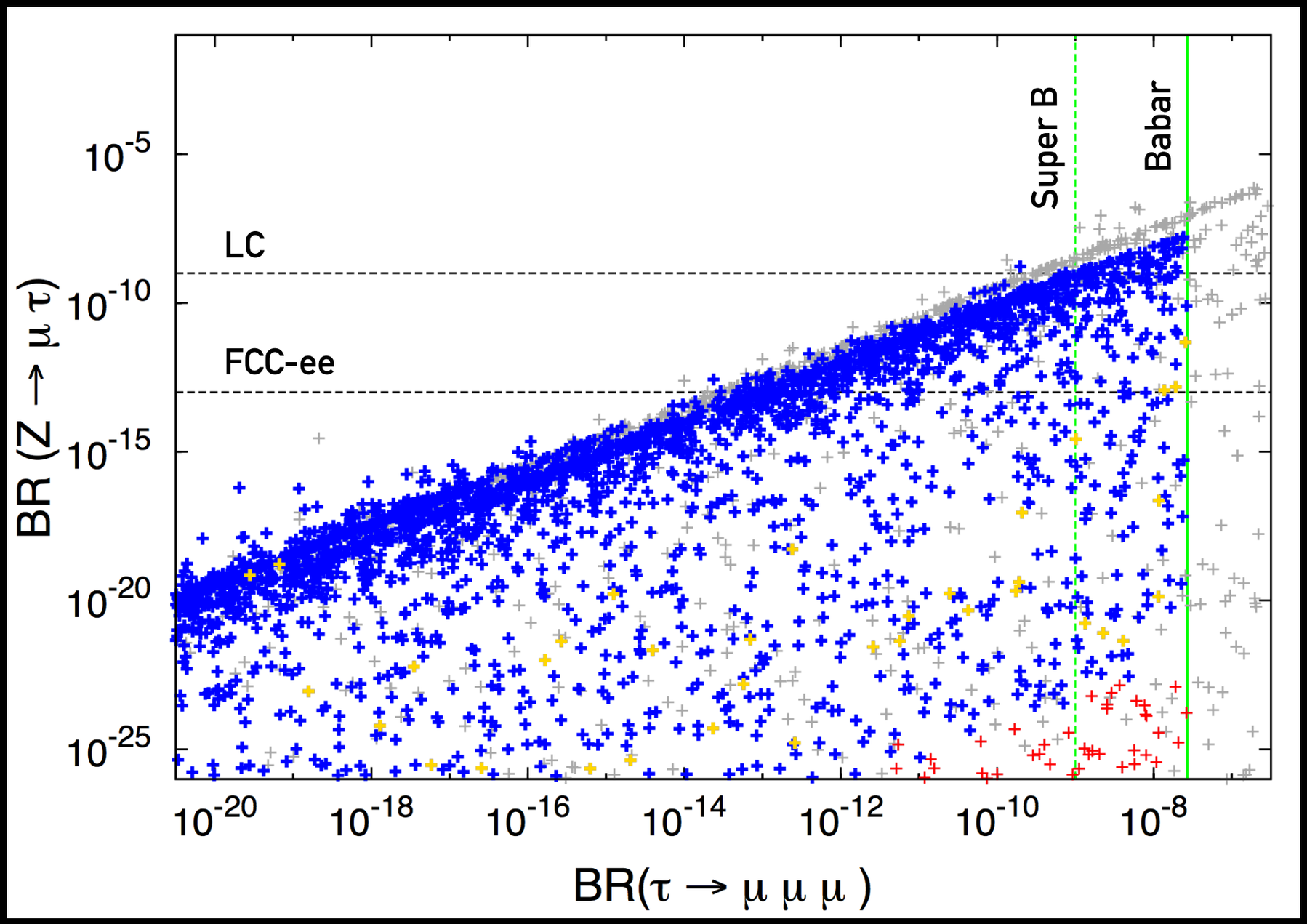
ISS: $Z \to e^{\pm}\mu^{\mp}$ vs $\mu \to e$ conversion in Al



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

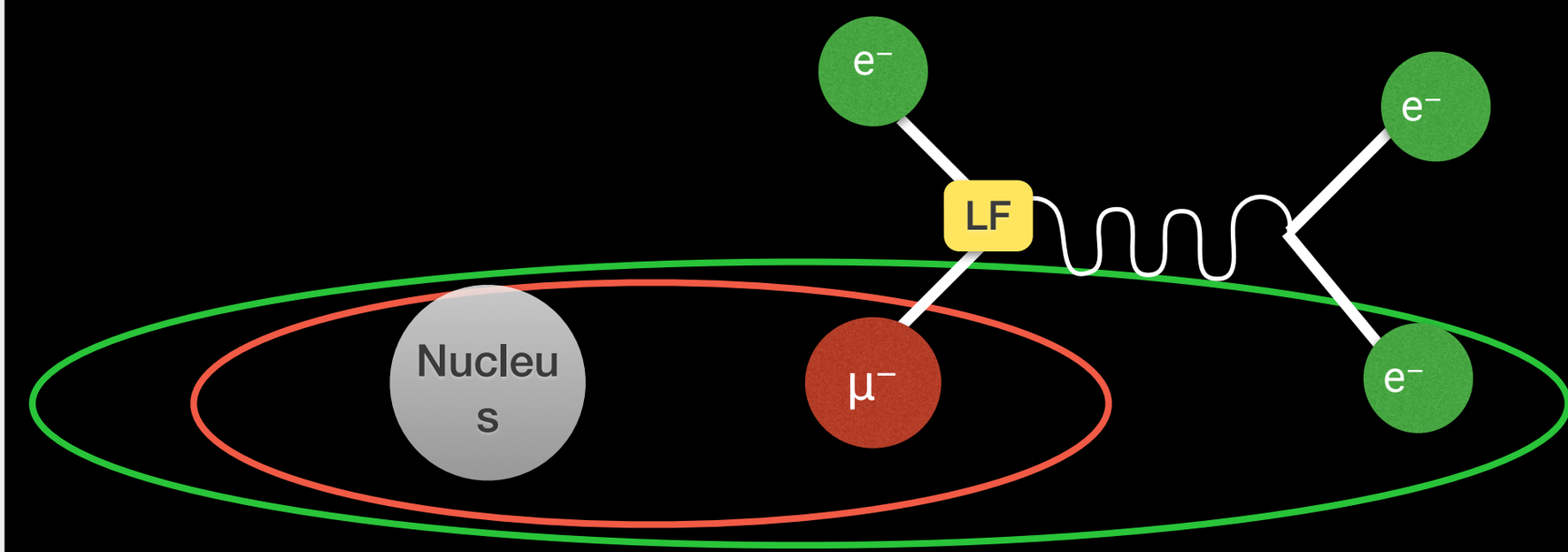


Effective "3+1": $Z \to \tau^{\pm}\mu^{\mp}$ vs $\tau \to \mu\mu\mu$



$\mu^- e^- \rightarrow e^- e^-$

New process proposed by Koike et al. of a bound μ^- in a muonic atom



$\tau_\mu = 2.197 \times 10^{-6}$ s
lifetime of free muons

$\tilde{\tau}_\mu$ is always smaller and depends on the nucleus element:

$\tilde{\tau}_\mu = 8.64 \times 10^{-7}$ s for ^{13}Al

$\tilde{\tau}_\mu = 7.5 \times 10^{-8}$ s for ^{92}U

$$Br(\mu^- e^- \rightarrow e^- e^-) = 24\pi(Z-1)^3 \alpha^3 (m_e/m_\mu)^3 m\, \tau_\mu/\tilde{\tau}_\mu\, G$$

Phys.Rev.Lett. 105 (2010) 121601
arXiv:1508.05747

Advantages:

- The Coulomb attraction from the nucleus in a heavy muonic atom leads to significant enhancement in its rate, compared to $\mu^+ e^- \rightarrow e^+ e^-$
- can probe both contact and photonic interactions similar to $\mu^+ \rightarrow e^+ e^+ e^-$ and $\mu^- N \rightarrow e^- N$
- Heavy nuclei, large Coulomb attraction favored, enhances the transition probability by $(Z-1)^3$
- improved analysis by taking into account the distortion of the out-going electrons in the nuclear Coulomb potential and the relativistic treatment of the muon and the electrons.

$\mu^- N \rightarrow e^- N$

A negative muon is stopped by some material, it is trapped by an atom, and a muonic atom is formed.
After it cascades down energy levels in the muonic atom, the muon is bound in its 1s ground state.

The fate of the muon is then to either decay in orbit ($\mu^- \rightarrow e^- \nu_\mu \nu_e$) or be captured by a nucleus of mass number A and atomic number Z, namely $\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$.
In extensions of the SM the exotic process of neutrino less muon capture is also possible: $\mu^- + (A,Z) \rightarrow e^- + (A,Z)$.

The final state of the nucleus (A,Z) could be either the ground state or one of the excited states. In general, the transition to the ground state, which is called coherent capture, is dominant.

The event signature is a mono-energetic electron.