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Effect of sterile states on lepton magnetic moments

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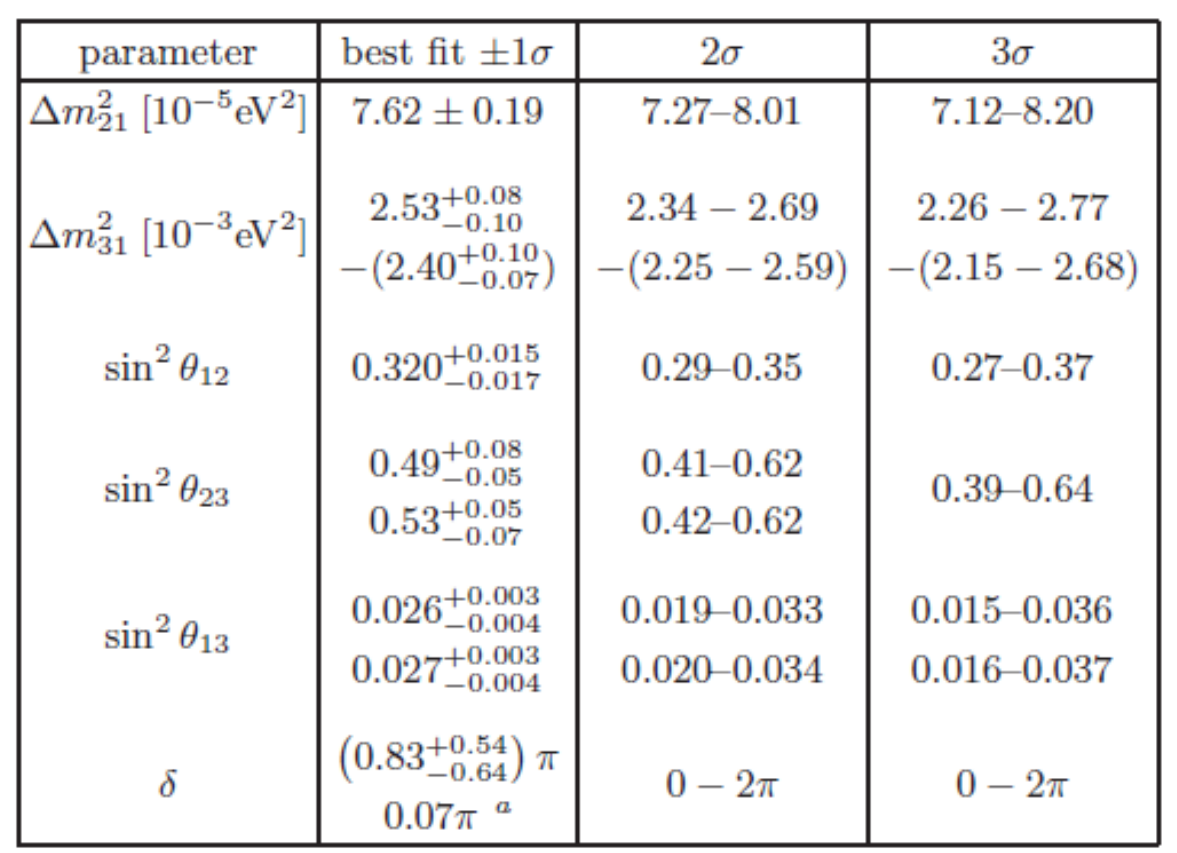
Outline

We consider the effect of the presence of sterile neutrinos to the anomalous magnetic moments of leptons, in two extensions of the SM.

- Introduction
  - Neutrino Masses and Mixings
  - Inverse Seesaw (ISS)
  - Sterile neutrinos
  - Unitarity deviation
- Lepton magnetic moments
- Numerical analysis
  - Experimental constraints
  - ISS
  - 3+1
- Conclusions

Neutrino masses and mixings



parameter	best fit $\pm 1\sigma$	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.62 ± 0.19	7.27–8.01	7.12–8.20
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$2.53^{+0.08}_{-0.10}$ $-(2.40^{+0.10}_{-0.07})$	$2.34 - 2.69$ $-(2.25 - 2.59)$	$2.26 - 2.77$ $-(2.15 - 2.68)$
$\sin^2\theta_{12}$	$0.320^{+0.015}_{-0.017}$	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
δ	$(0.83^{+0.54}_{-0.64})\,\pi$ 0.07π [a]	$0 - 2\pi$	$0 - 2\pi$

(Forero, Tortola, Valle 2012)

Super-K → θ_{Atm}

MINOS → m^2_{Atm}

Solar data → $\theta_{\odot}$

KamLAND → $m^2_{\odot}$

D-Chooz,Daya-Bay,Reno,T2K → θ_{13}

(Troitsk and Mainz, Planck 2013)

- 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))
- Majorana versus Dirac nature (0νββ decay) (KamLAND-Zen,EXO-200,Gerda)
- Which hierarchy: Normal or inverted? (matter effects in sun and long baseline oscillations, T2K,NOνA...)
- Is there CP violation in the lepton sector?
- Are there extra sterile states?

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

…

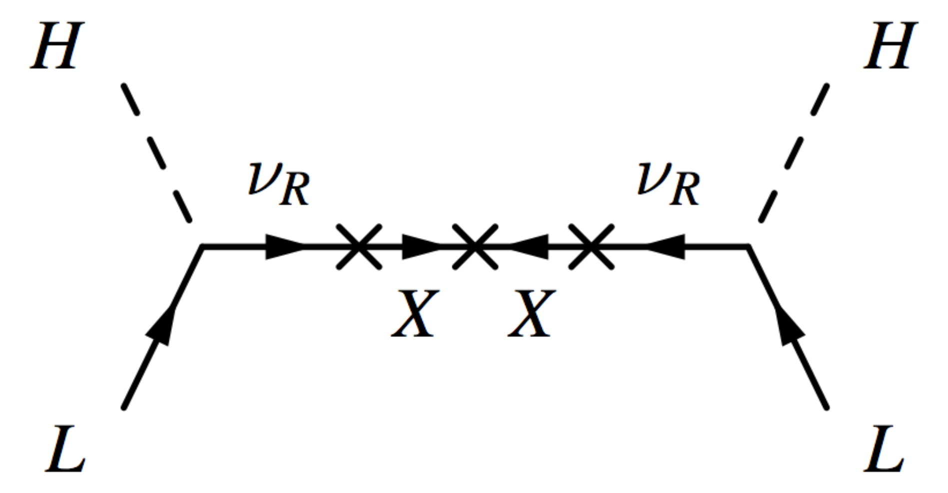
(Minkowski 77, Gell-Mann Ramond Slansky 80, Glashow, Yanagida 79,Mohapatra Senjanovic 80,Lazarides Shafi Wetterich 81, Schechter-Valle, 80 & 82, Mohapatra Senjanovic 80,Lazarides 80,Foot 88,…)

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

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

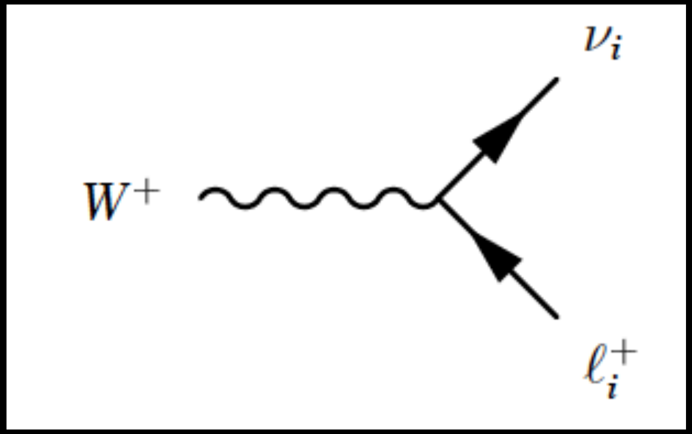
Sterile neutrinos are SM gauge singlets - only interact via their mixing with the active ones

Several oscillation results or anomalies (reactor antineutrino anomaly, LSND, MiniBooNe...) cannot be explained within 3-flavor oscillations
⇒ need at least an extra neutrino

Other motivations for sterile neutrinos from cosmology, e.g. keV sterile neutrino as warm dark matter or to explain pulsar velocities

Active-sterile mixing

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



Active-sterile mixing

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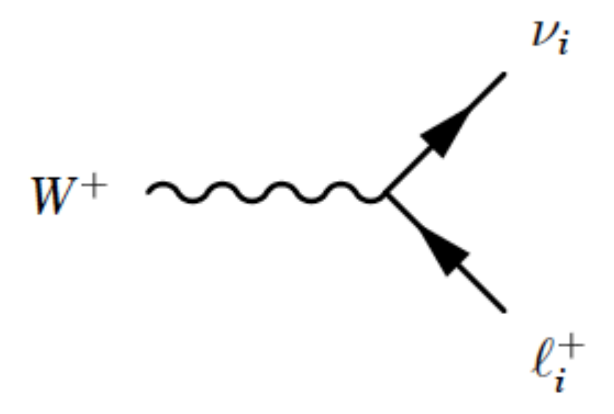
Standard case (3 flavors):



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

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..

U = 4x4 (9x9) unitary matrix

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

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

(see also: Gavela et al. 2009,Abada et al. 2014,Arganda et al. 2014)

We address the impact of the modified charged current vertex on the magnetic moments of leptons and other observables (e.g. $0\nu\beta\beta$ decay), assuming that all NP effects are encoded in the modified leptonic weak current vertices and do not affect the hadronic sector.

Lepton magnetic moments

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

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

with gyromagnetic ratio $g_\ell = 2$

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

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

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

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

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

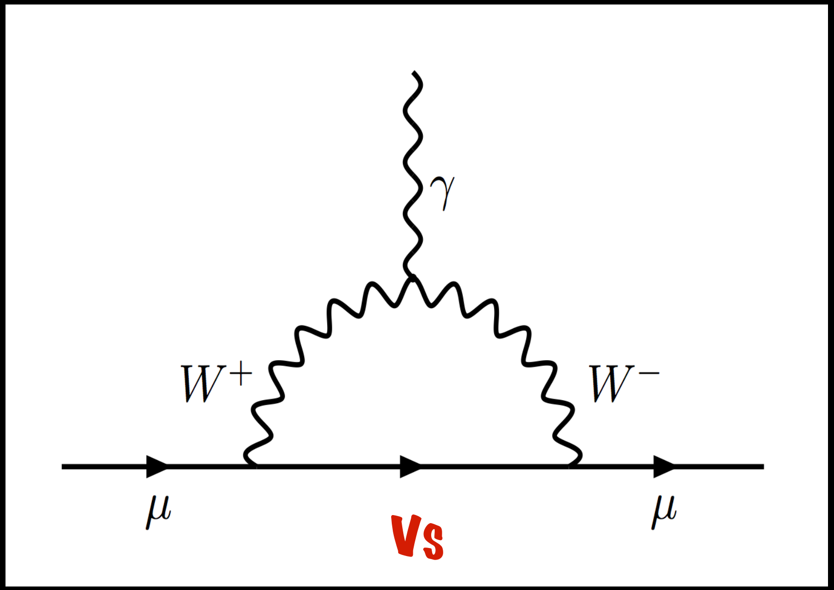
(J. Beringer et al. PDG, 2013)

Sterile states contribution to a_l

One-loop diagram involving weak gauge bosons contributes to the e.m. form factors with the sterile states

$$\mathcal{L}_{CC} = \frac{g}{2}(U^*_{li}\bar{\nu}_i\gamma^\alpha W^+_\alpha P_L l + U_{li}\bar{\mu}\gamma^\alpha W^-_\alpha P_L \nu_i)$$

$$a^\nu_\mu = \frac{G_F}{\sqrt{2}}\frac{m_\mu^2}{8\pi^2}\sum_{i=1}^{9} U^{\nu *}_{\mu i}U^\nu_{\mu i} f((m_{\nu_i}/M_W)^2)$$



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 (K,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.

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

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

(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)

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

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

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

   (Atre et al. 2009, Kusenko et al. 2009)
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7. Lepton flavor violation ($\mu \rightarrow e\, \gamma$)

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

(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)

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)

We consider the effect of the presence of sterile neutrinos to the magnetic moments of leptons in two extensions of the SM, the ISS and an effective case with 3+1 neutrinos

Inverse Seesaw

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

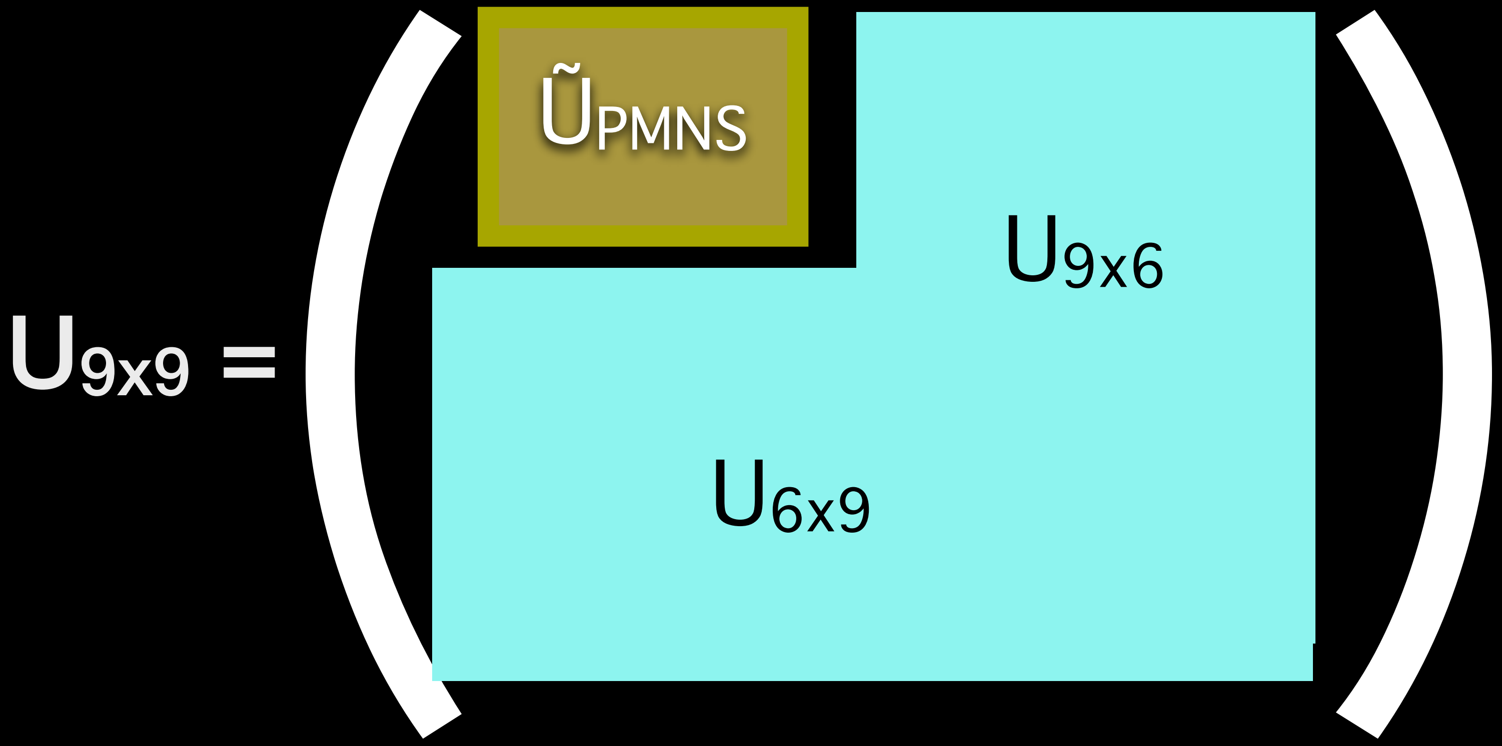
$$Y_\nu = \frac{\sqrt{2}}{v} D^\dagger \mathrm{diag}(\sqrt{\mathrm{M}}) \mathrm{R} \mathrm{diag}(\sqrt{\mathrm{m}_\nu}) \mathrm{U}^\dagger_{\mathrm{PMNS}}$$

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

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 U_ν



Parameters:

- M_R (real, diagonal)
- μ_X (complex,symmetric)
- R_{mat} (rotation,complex)
- 2 Majorana and 1 Dirac phases from U_{PMNS}
- Normal (NH) / Inverted (IH) hierarchy

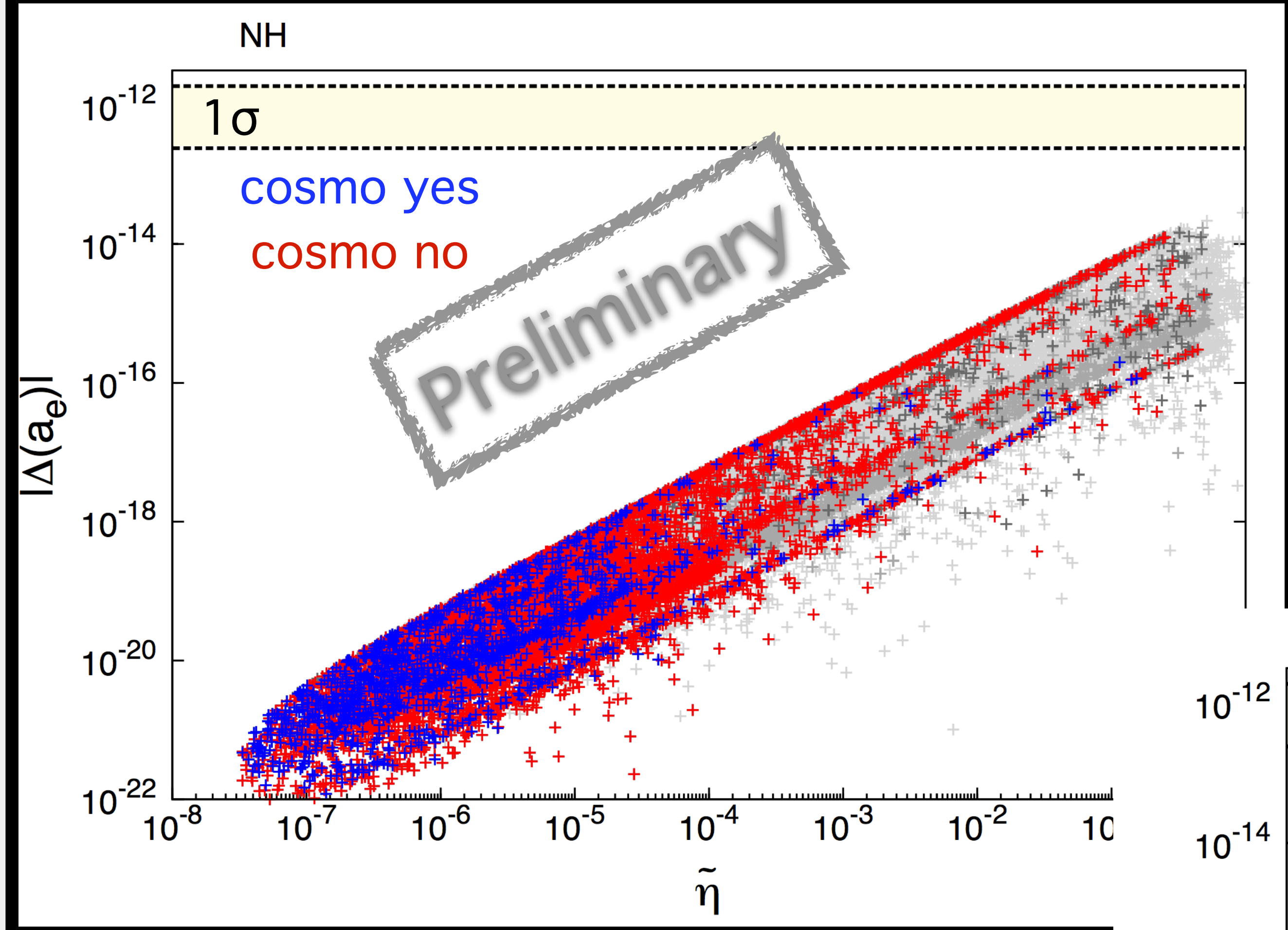
M_R = (0.1 MeV, 10^6 GeV)

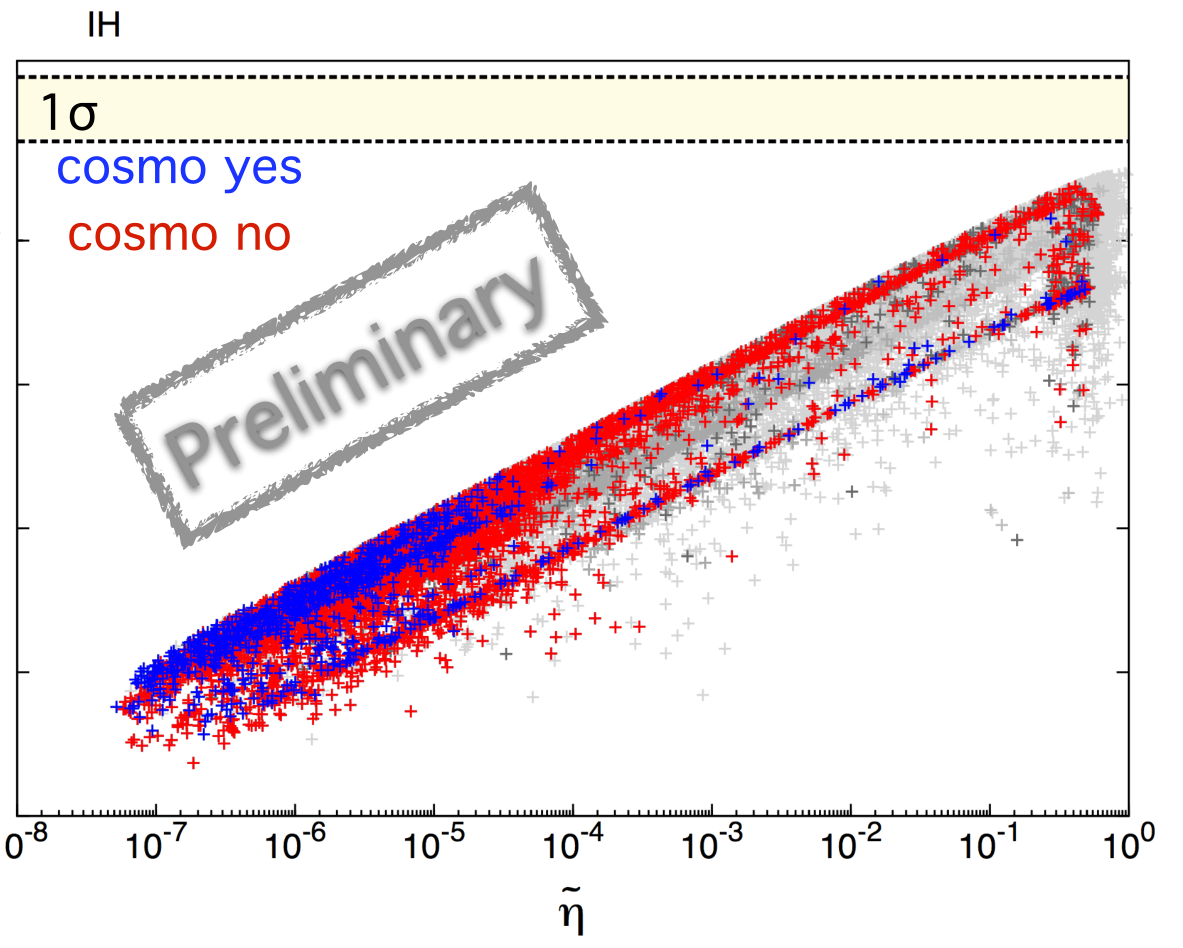
μ_X = (0.01 eV, 1 MeV)

ISS: a_e

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

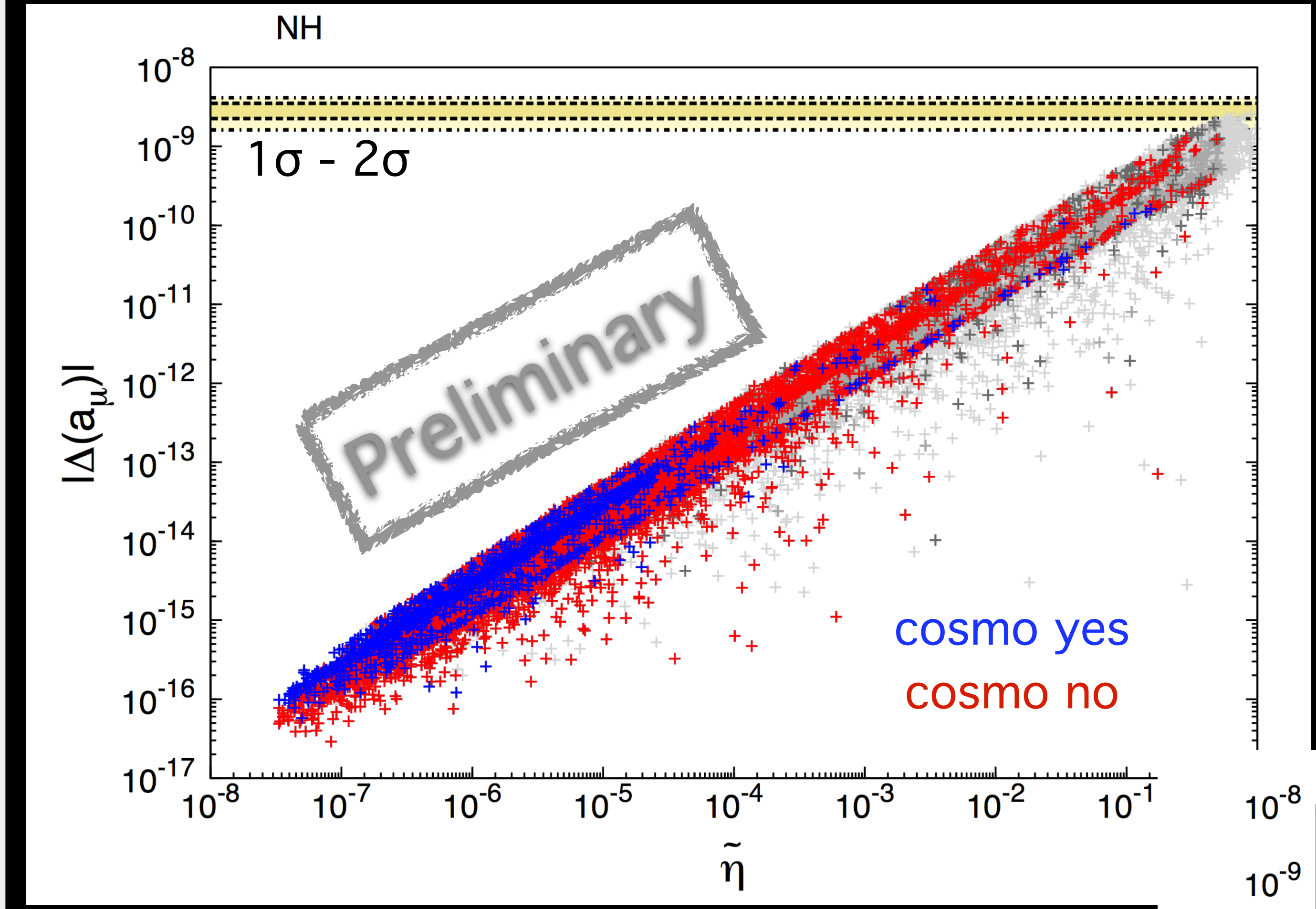
measures the deviation from unitarity.





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

ISS a_μ



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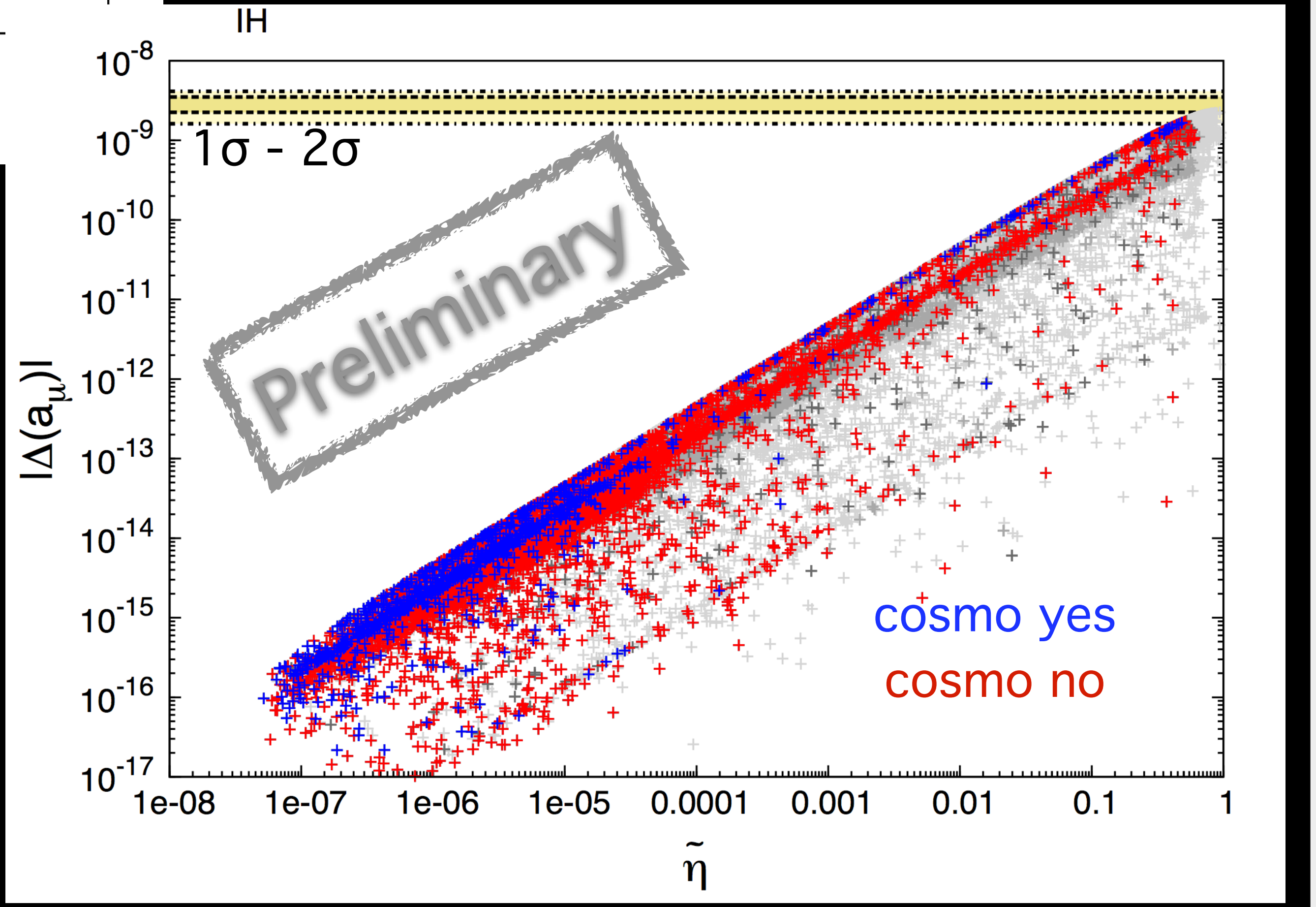
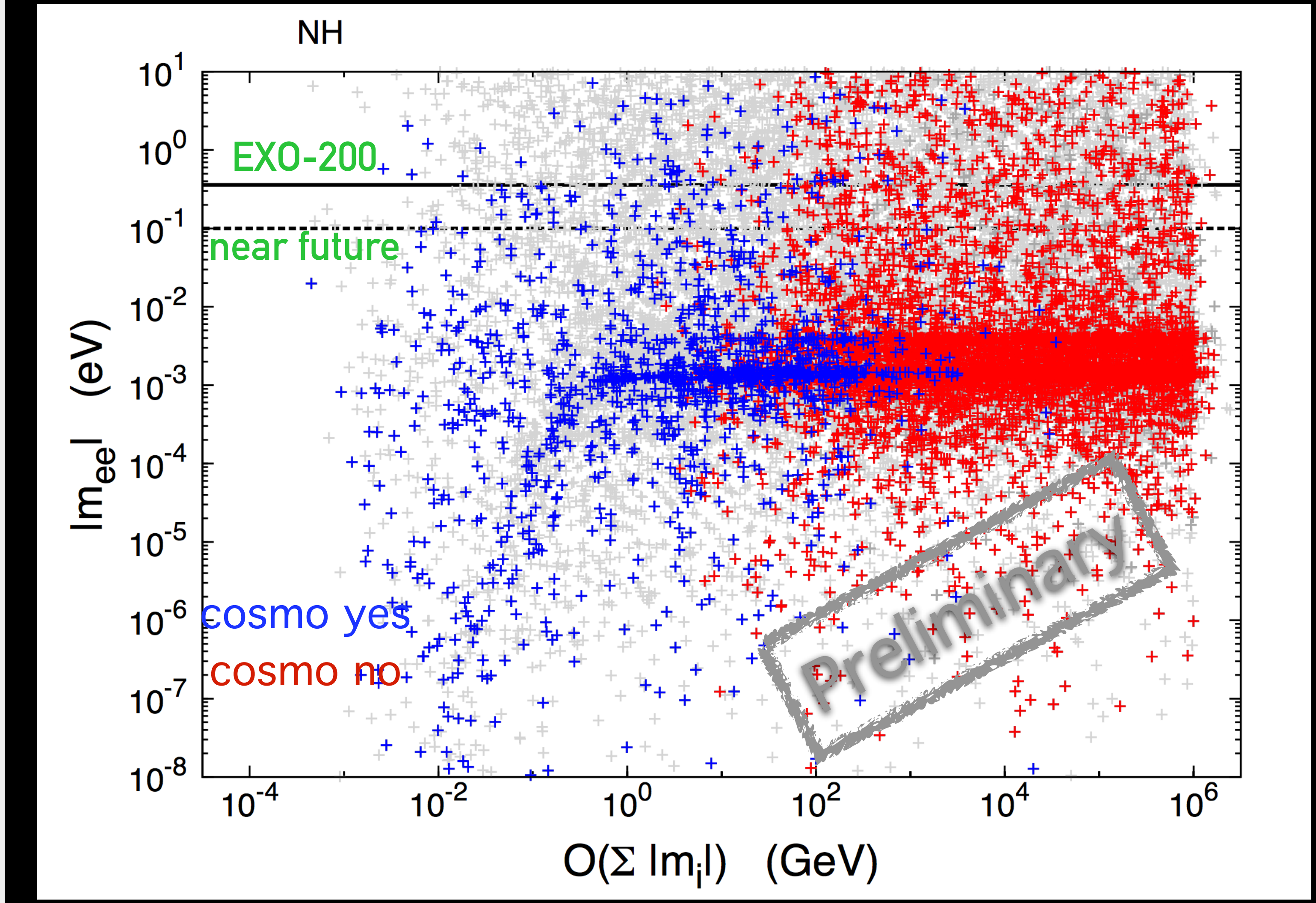


For large $\hat{\eta}$ we can get points with a_μ within 2σ of the expected value

ISS: 0νββ decay



p: momentum exchanged in the process

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

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

$m_s \approx |p|$: 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.

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

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

Effective model: 3+1

Add a sterile state → 3 new mixing angles active-steriles

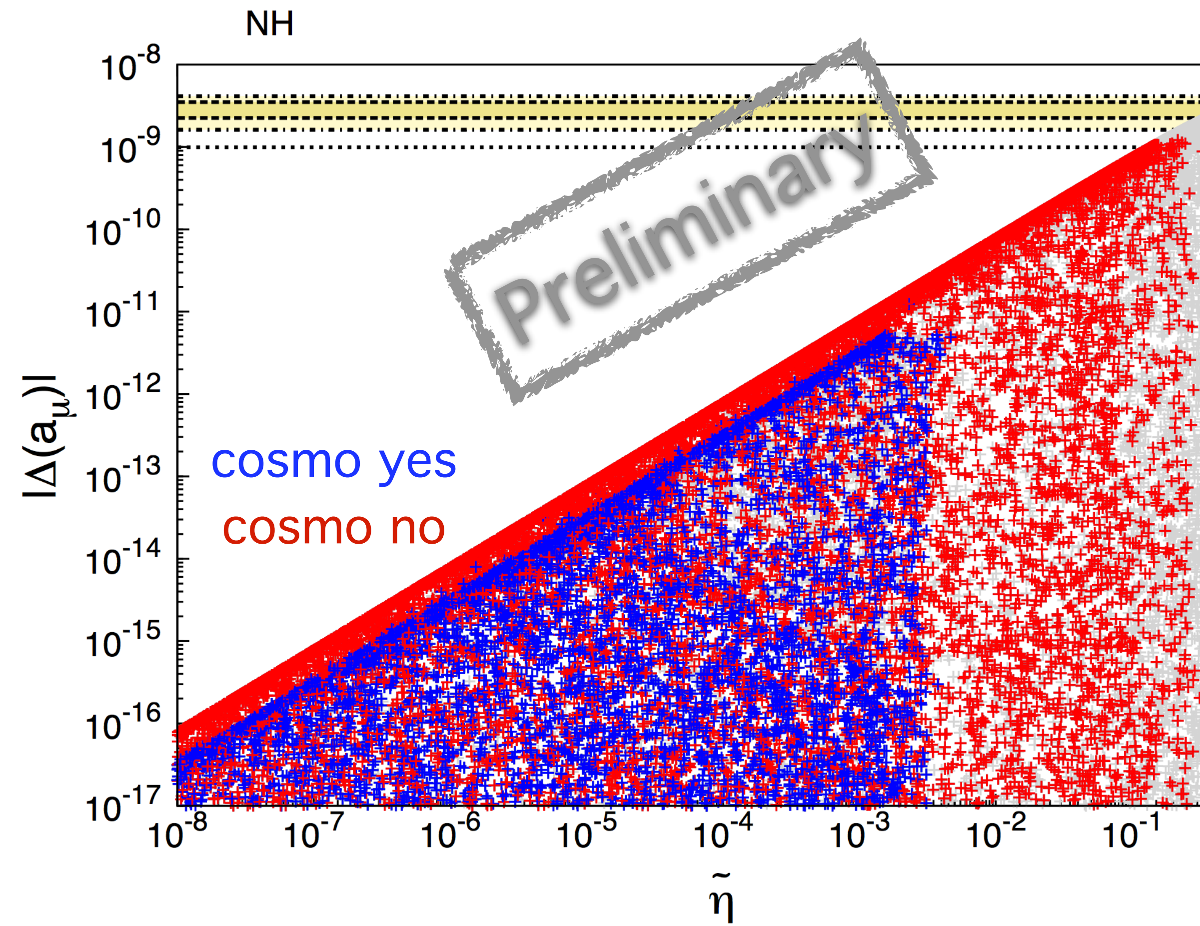
$$U_{4\times 4} = R_{34}.R_{24}.R_{14}.\boxed{R_{23}.R_{13}.R_{12}}\ U_{PMNS}$$

$$U_{4x4} = \left(\begin{array}{ccc|c} & & & U_{eS} \\ & \tilde{U}_{PMNS} & & U_{\mu S} \\ & & & \\ \hline U_{Se} & U_{S\mu} & & U_{\tau S} \end{array}\right)$$

Parameters:

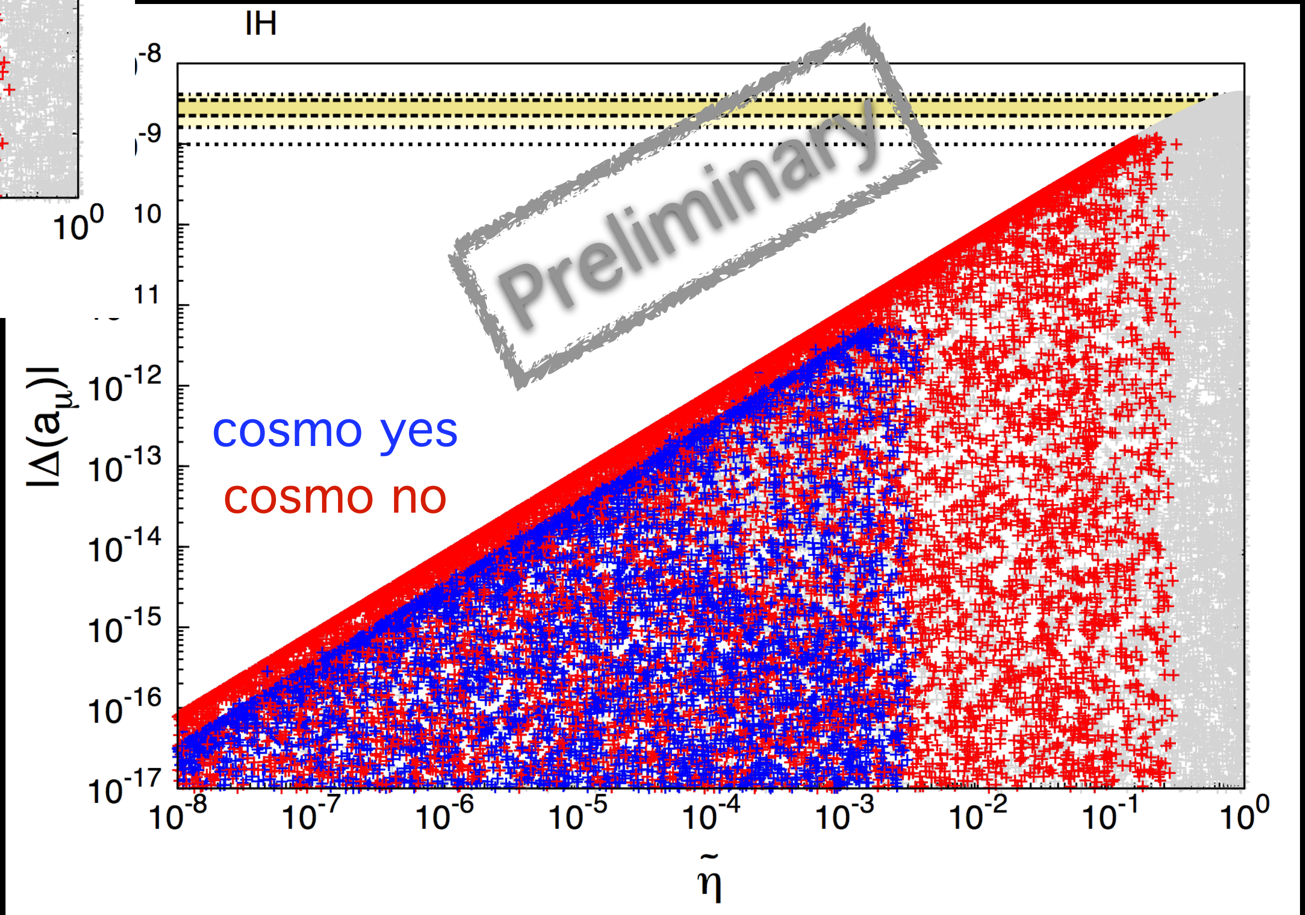
- $\theta_{14},\theta_{24},\theta_{34}$
- 3 Majorana and 3 Dirac phases
- Normal (NH) / Inverted (IH) hierarchy

Effective case: a_μ



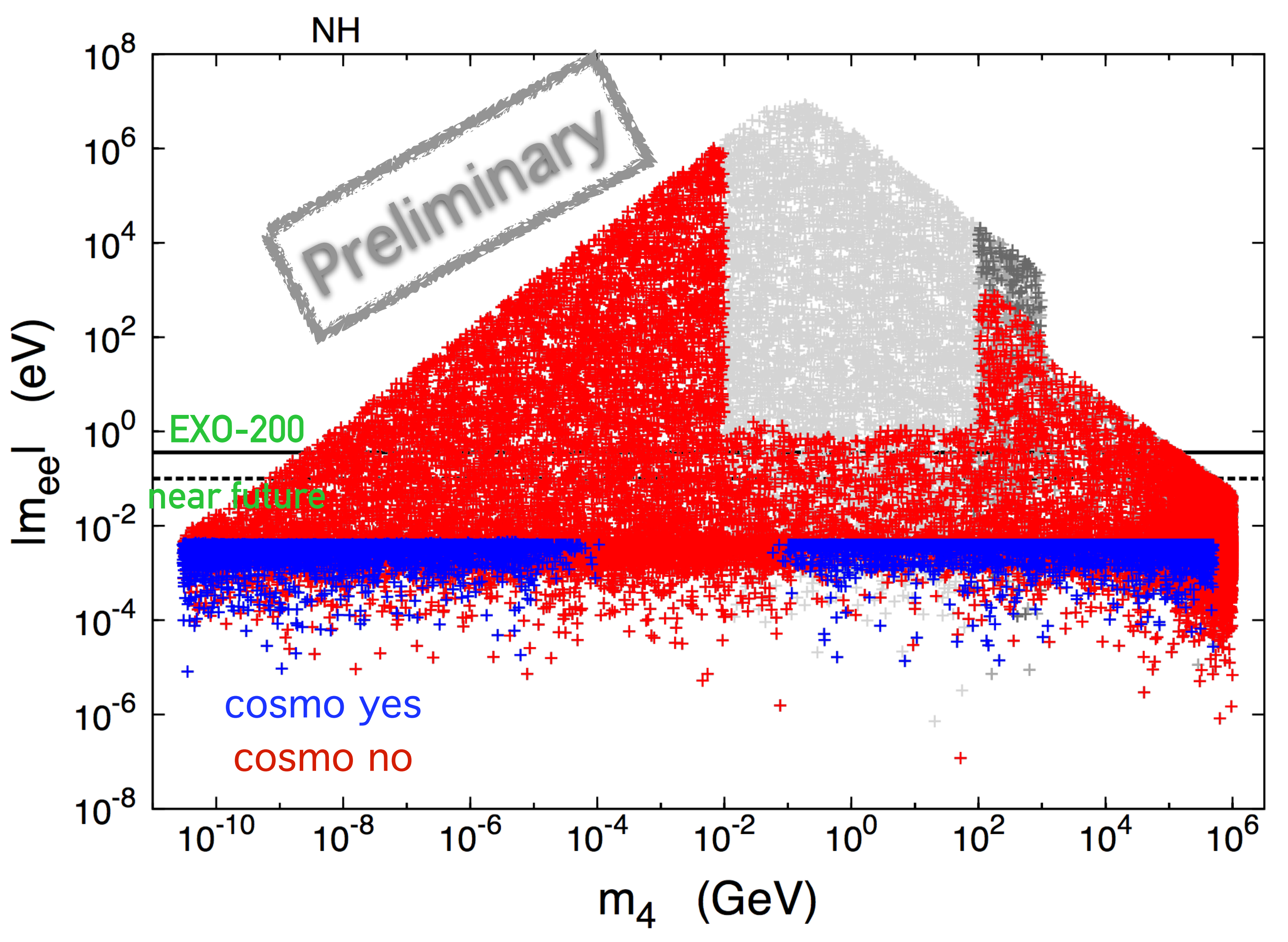
$$\tilde{\eta} = 1 - \det(\tilde{U}_{\rm PMNS})$$

measures the deviation from unitarity.



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

Effective case: 0νββ decay



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

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

Conclusions

Measurements of the electron and muon anomalous magnetic moments (g-2) have recently reached an extraordinary precision. The discrepancy between the theoretical and the measured values of the muon g-2 could unveil NP signals.

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 investigated the contribution of the sterile states to the anomalous magnetic moment of the leptons in these two classes of models and discussed them taking into account a number of experimental and theoretical constraints.

Even if the scale of such NP is low, its contribution to the anomalous magnetic moment of the leptons is generically smaller than the errors in theoretical calculation. However, for large η (deviation from unitarity) we can get solutions within 2σ of the expectation (ISS).
The largest mixing angles (active-sterile) which would give a sizeable contribution to the muon g-2 are indeed strongly constrained by other EW observables, e.g. $0\nu\beta\beta$.

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Thank you!