08th November 2023

KEK-PH2023

Light BSM physics search using radiative emission of neutrino pair

EPJC 82 (2022) 3, 208 , PLB 841 (2023) 137911 & arXiv:2306.12953

In Collaboration with:

Prof. Shao-Feng Ge

(pronouns: He/Him/His)

Pedro S. Pasquini

東京大学 THE UNIVERSITY OF TOKYO

Neutrino Pair Emission

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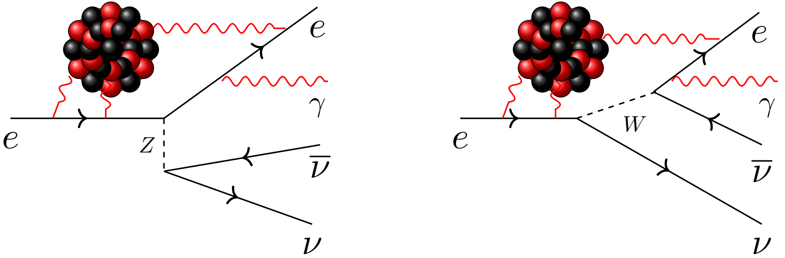

Low E_ν but hard experimentally

Advantages

Disadvantages

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- Atomic transition: $\mathcal{O}(1)$ eV
- Can measure the emitted photon
- Can be stimulated and coherently enhanced
- Tests ν physics in a different energy regime

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Benefits are great and can provide interesting results!
m_ν ordering and scale, non-unitary, BSM interactions and maybe neutrino mixing and nature

Neutrino LASER?

Radiative Emission of Neutrino Pair (RENP)

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Usual Laser beam:

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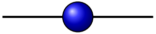

Excited (meta-stable) State ($|e>$)

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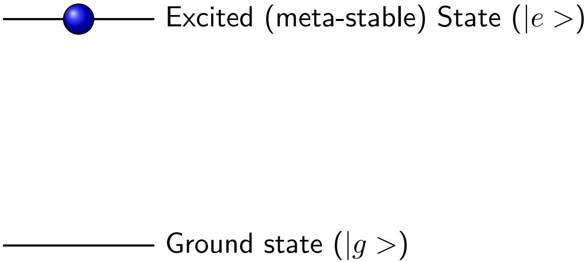

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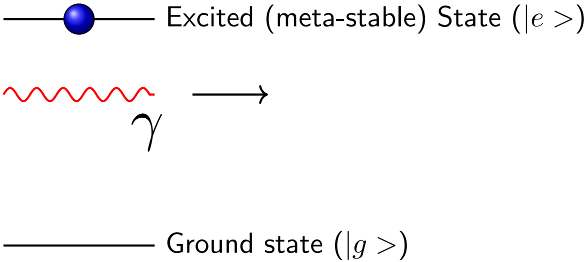

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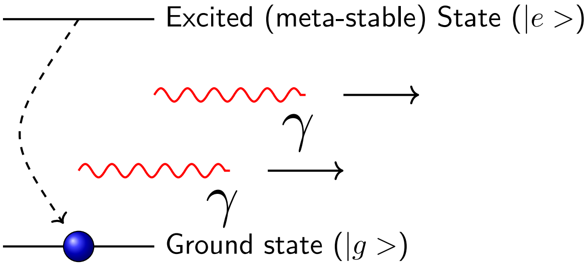

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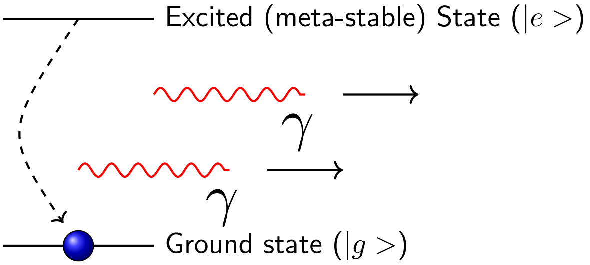

($E1$, $M1$ transition)

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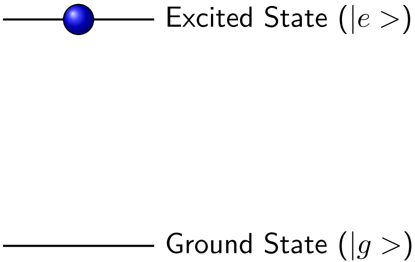

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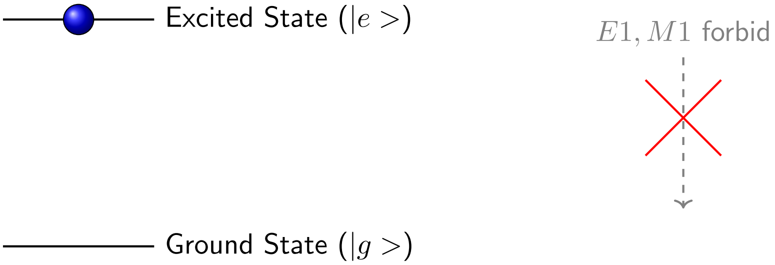

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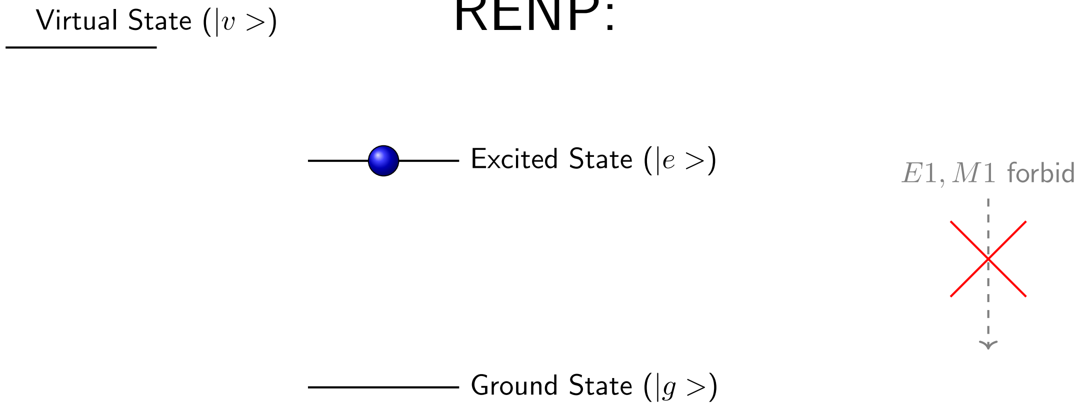

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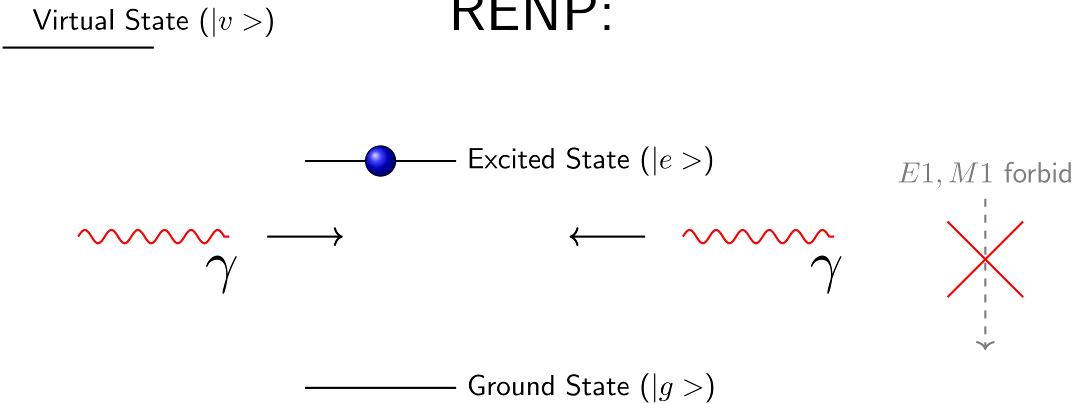

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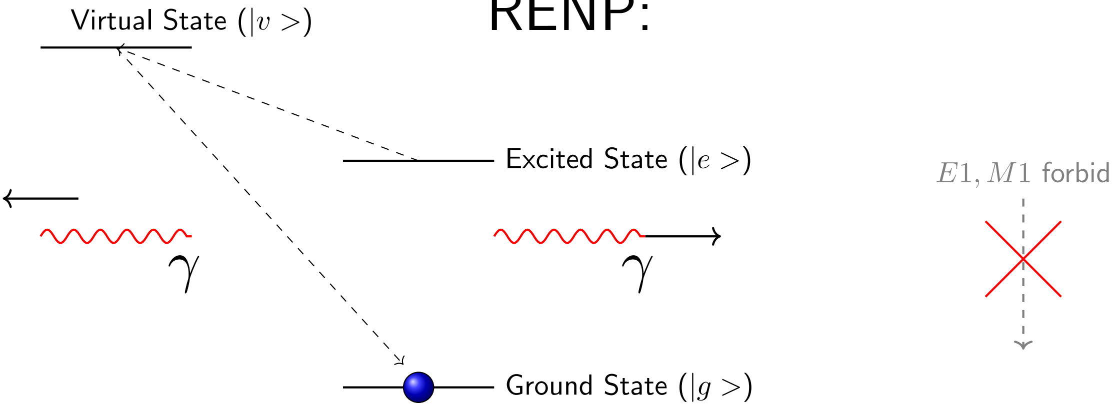

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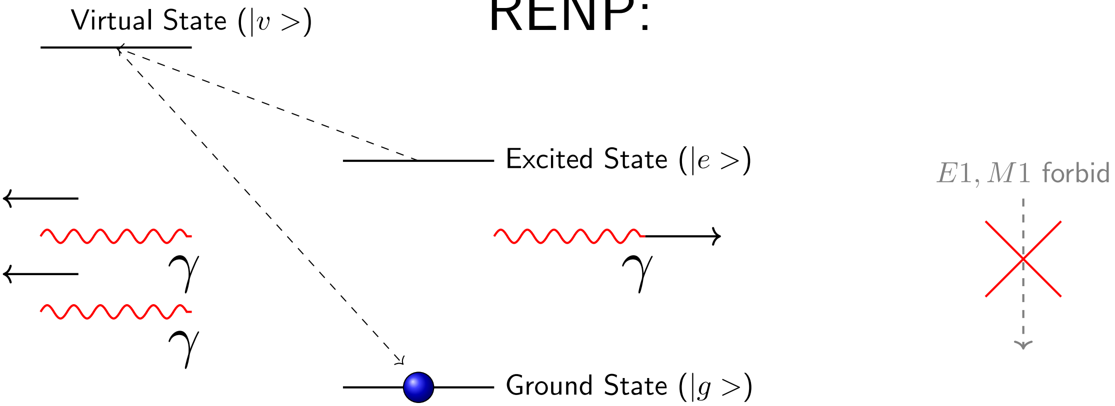

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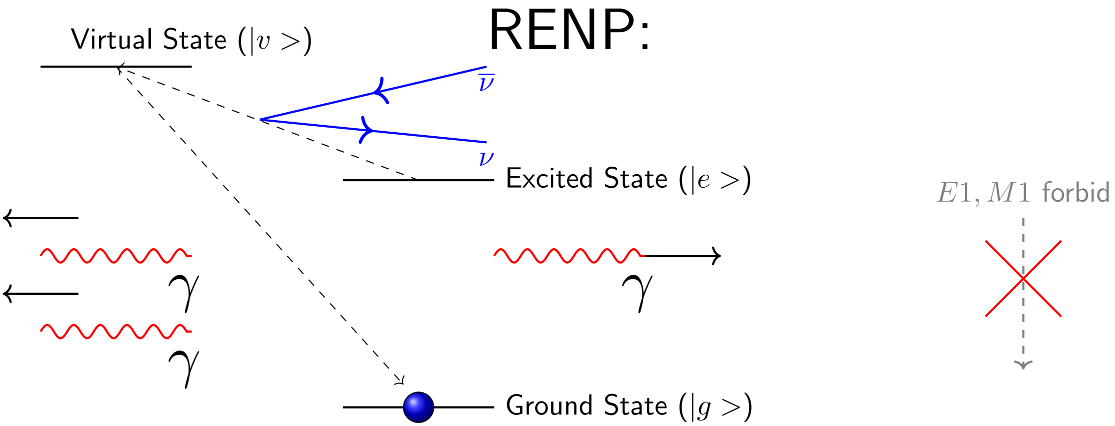

$E1 \times M1$ transition

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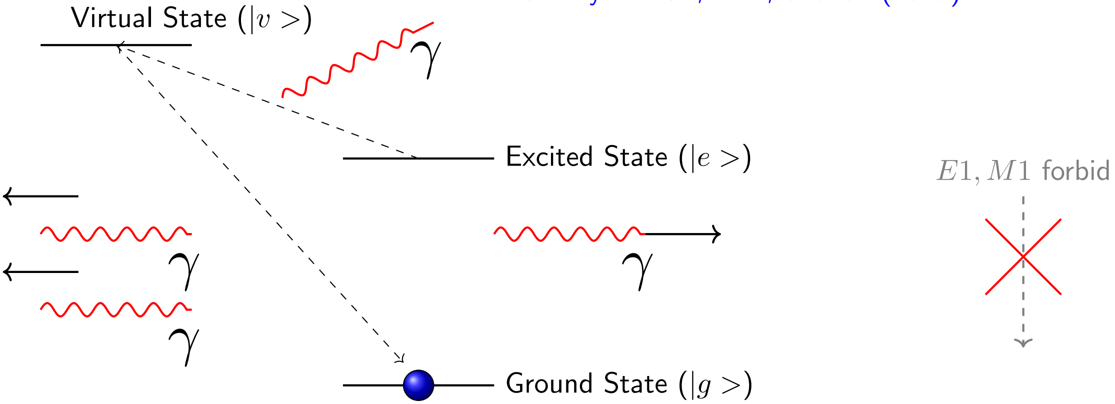
"Coherent two-photon emission from hydrogen molecules excited by counter-propagating laser pulses,"

T. Hiraki et al. J. Phys. B **52**, no.4, 045401 (2019)



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Current technology (probably) allows $\mathcal{O}(10)$ events/days of exposure

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Emitted photon contains information of the neutrino pair

from stimulation: $|\mathbf{p}_\gamma^{\text{emitted}}| = \omega$ (trigger LASER frequency)

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Two important information:
$\Rightarrow$ Spectral function: $I \equiv I(\omega)$
$\Rightarrow$ Thresholds: $\omega_{ij}^{\max}$

Threshold contain mass information

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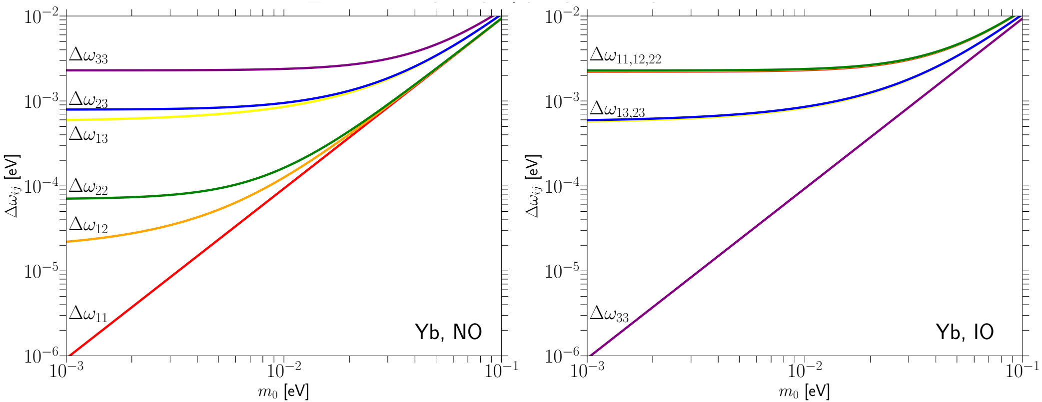
There is a total of 6 thresholds related to all combinations of m_i, m_j, $i, j = 1, 2, 3$.

Threshold contain mass information

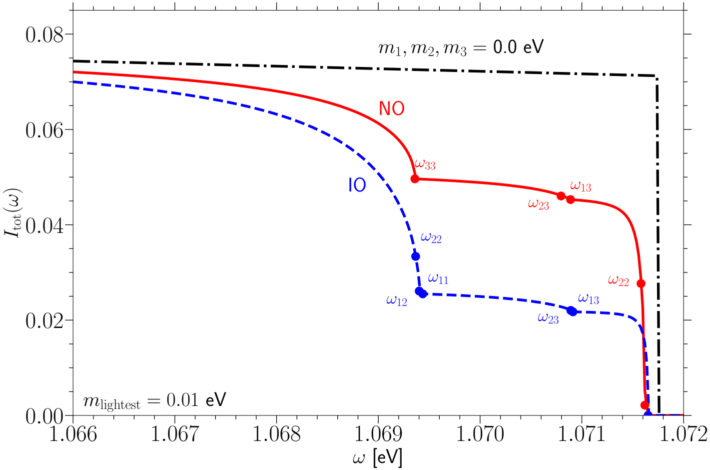
$$\Delta\omega_{ij} = \frac{(m_i+m_j)^2}{2\Delta E}$$



2, 3.

$\Delta\omega \sim \mathcal{O}(10^{-5})$ eV

Mass and hierarchy is observable!



N. Song, R. B. Garcia et.al.
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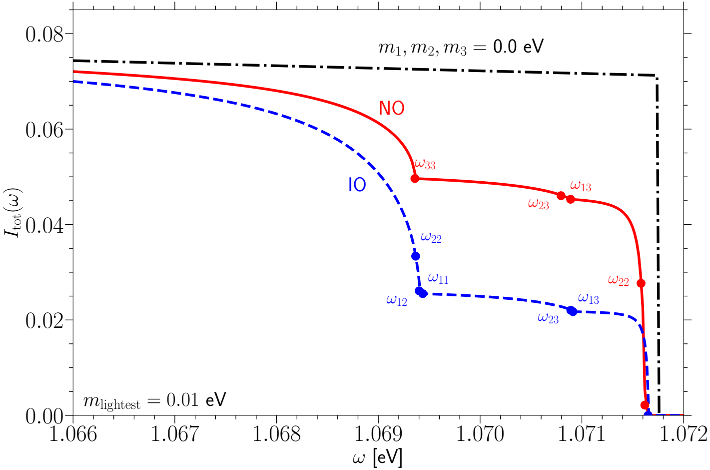

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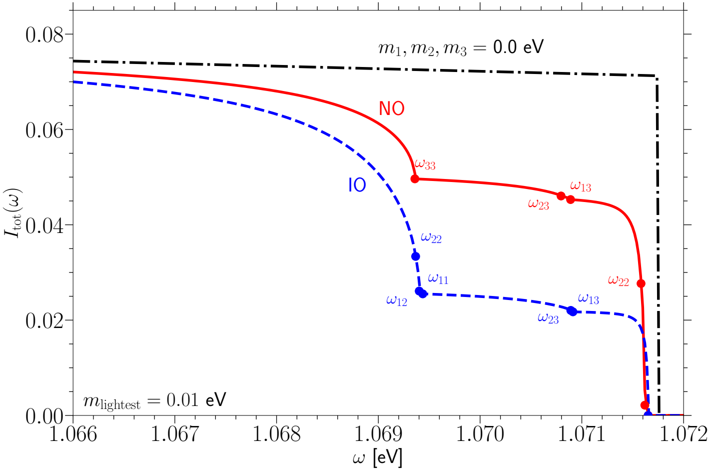

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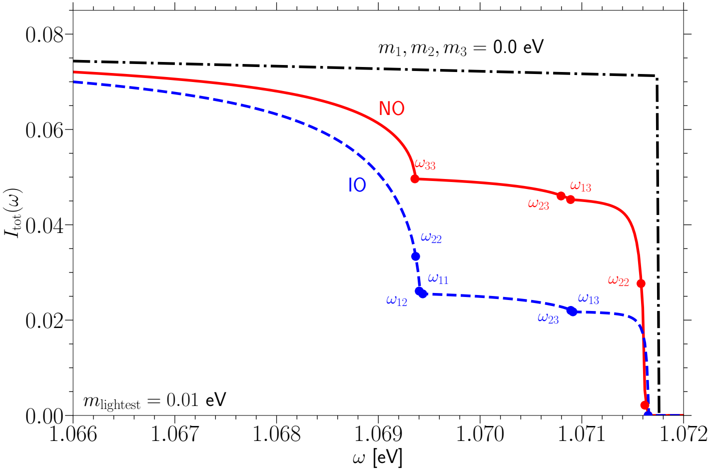

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Under reasonable assumptions:

3σ for $m_{\rm lightest}$ and mass ordering

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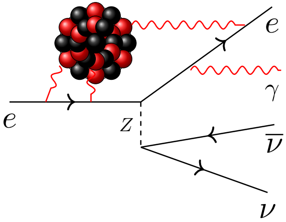

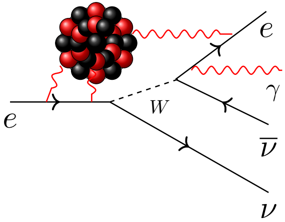

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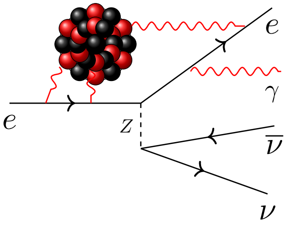

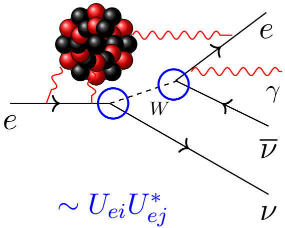

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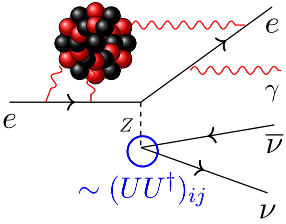

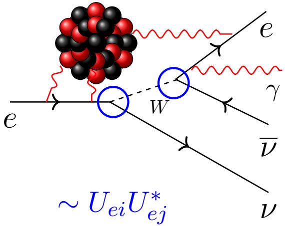

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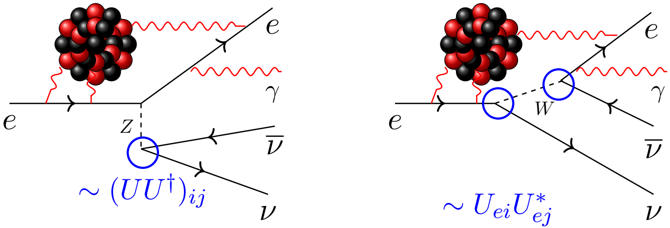

$$I(\omega) = \sum_{ij} \frac{\Delta_{ij}(\omega)}{(E_{vg} - \omega)^2} \Theta(\omega - \omega_{ij}^{\max}) \left[|a_{ij}|^2 I_{ij}^{(D)} - \delta_M \mathrm{Re}[a_{ij}^2] m_i m_j \right]$$

$$a_{ij} = U_{ei} U_{ej}^* + \frac{1}{2} (UU^\dagger)_{ij}$$

Require a large number of events...

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- Information on mixing angles

- Non-unitarity of U

- Even majorana phases

See: N. Song etal Phys. Rev. D **93**, no.1, 013020 (2016) and G. Y. Huang et al. Int. J. Mod. Phys. A **35**, no.01, 2050004 (2020)

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Caveat: Needs larger number of events ($\sim 10^3$ or larger).
But current technology $\mathcal{O}(10) \Rightarrow$ needs technological improvement

Possible to probe new interactions too!

BSM Interactions

S.-F. Ge & Pedro, Pasquini Eur.Phys.J.C 82 (2022) 3, 208

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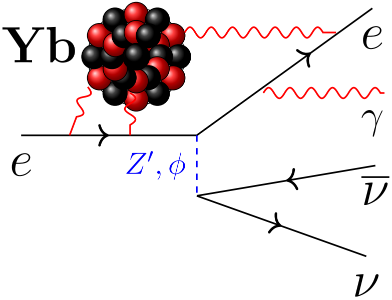

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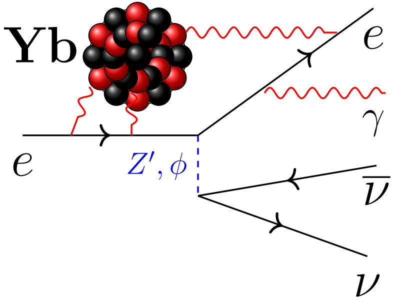

$$\mathcal{L}_V = g^e \bar{e}\gamma^\mu\gamma_5 e Z'_\mu + \bar{\nu}_i\gamma^\mu(g^\nu_{L,ij}P_L + g^\nu_{R,ij}P_R)\nu_j Z'_\mu.$$

$$\mathcal{L}_S = i y^e_P \bar{e}\gamma_5 e\phi + \bar{\nu}_i(y^\nu_{S,ij} + i\gamma_5 y^\nu_{P,ij})\nu_j\phi + h.c.,$$

Specially good for light mediators

Atomic transitions are great for probing light mediators

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$$\frac{1}{q^2 - M^2} \qquad \sim -\frac{1}{M^2} \text{ for } q^2 \ll M^2$$

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- Also, light mediators, the effect (and bounds) will be enhanced, specially for m_ϕ^2 around the eV scale: $\frac{m_W^2}{q^2 - m_{\phi,Z'}^2} \sim 10^{21}$

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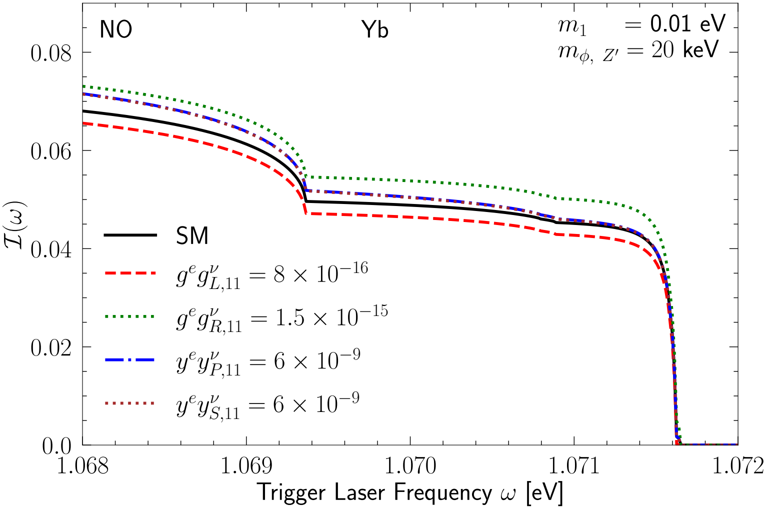
- The media

$$\frac{1}{q^2 - M^2}$$

- SM $M = I$
- Also, light ... or m_ϕ^2

around the e



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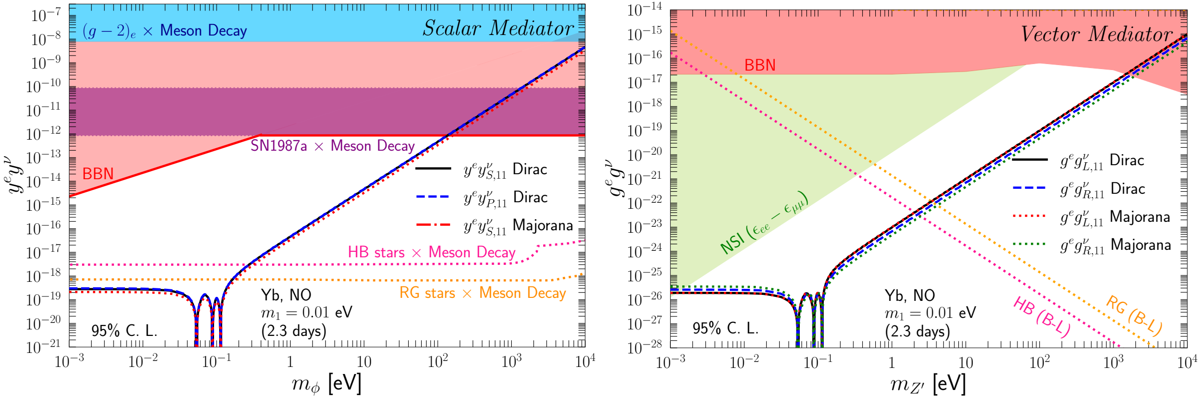

See S.-F. Ge & Pedro Pasquini Eur.Phys.J.C 82 (2022) 3, 208

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Surprisingly it can! Even in the SM!

Brief introduction to EM form factors

General ν/γ interaction: $\overline{u}(p_f)\Lambda^\mu u(p_i)A_\mu$

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General Lorentz Structure:

$$\Lambda_\mu^{ij} \equiv q_\mu(F_1^{ij} + F_2^{ij}\gamma_5) + \gamma_\mu(F_3^{ij} + F_4^{ij}\gamma_5) + i\sigma_{\mu\nu}q^\nu(F_5^{ij} + F_6^{ij}i\gamma_5)$$

Brief introduction to EM form factors

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$\Rightarrow$ Gauge symmetry: $q_\mu\overline{u}(p_f)\Lambda^\mu u(p_i) = 0$

$$F_1^{ij} = -F_3^{ij}(m_i - m_j)/q^2 \text{ and } F_2^{ij} = -F_4^{ij}(m_i + m_j)q^2$$

Brief introduction to EM form factors

$$\Lambda_\mu^{ij}(q) = \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right)\left[f_Q^{ij}(q^2) + f_A^{ij}(q^2)q^2\gamma_5\right] - f_M^{ij}(q^2)i\sigma_{\mu\nu}q^\nu + f_E^{ij}(q^2)\sigma_{\mu\nu}q^\nu\gamma_5$$

Charge $q_\nu^{ij} \equiv f_Q^{ij}(0)$
Anapole $a_\nu^{ij} \equiv f_A^{ij}(0)$
Magnetic moment $\mu_\nu^{ij} \equiv f_E^{ij}(0)$
Electric dipole $\epsilon_\nu^{ij} \equiv f_M^{ij}(0)$

$q_\nu^{ij} \approx 0$, thus we use

Charge radius $\langle r_\nu^2\rangle^{ij} \equiv \left.\frac{f_Q^{ij}}{dq^2}\right|_{q^2=0}$

(See C. Giunti and A. Studenikin RMP 85, 531, 2015)

Even SM has $f_A^{ij} \neq 0$

SM predicts non-zero for all moments ($\langle r_\nu^2 \rangle_{ij}, a_\nu^{ij}, \mu_\nu^{ij}, \epsilon_\nu^{ij}$)!

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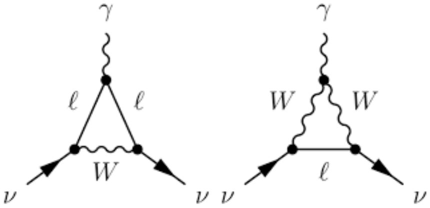

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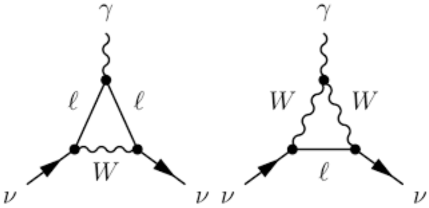
SM prediction

$$\mu_\nu, \epsilon_\nu \sim 3 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B$$

$$\langle r_\nu^2 \rangle, a_\nu \sim 4 \times 10^{-33} \text{cm}^2$$



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SM prediction	Current Bounds
$\mu_\nu, \epsilon_\nu \sim 3 \times 10^{-19} \left(\frac{m_\nu}{\text{eV}}\right) \mu_B$	$< 6 \times 10^{-12} \mu_B$
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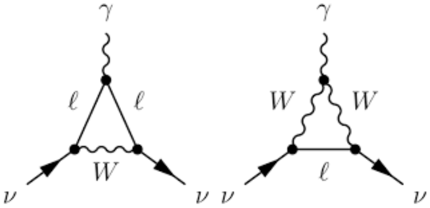

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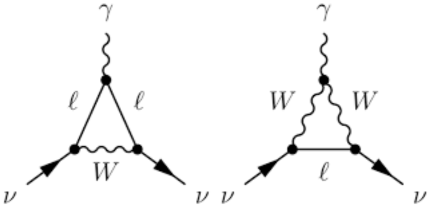
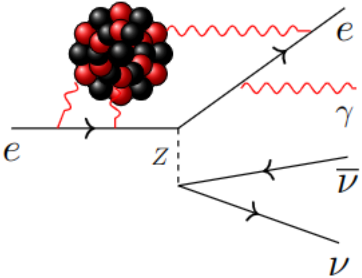


Fun Fact

SM predicts neutrino decay

$\nu_i \to \nu_j + \gamma \ (\tau_\nu \sim 10^{43} \left(\frac{eV}{m_\nu}\right)^5 s)$

Photon as mediator for RENP



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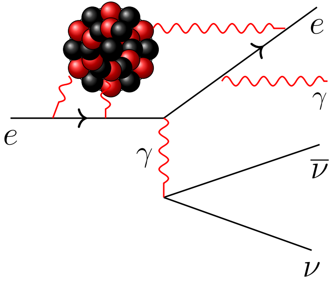

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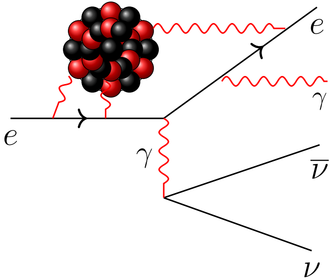
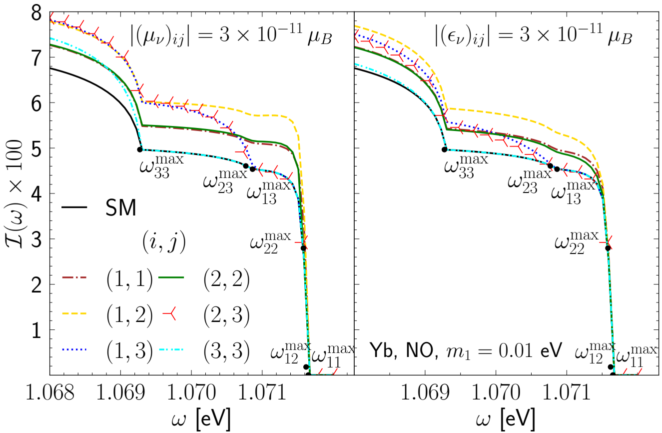
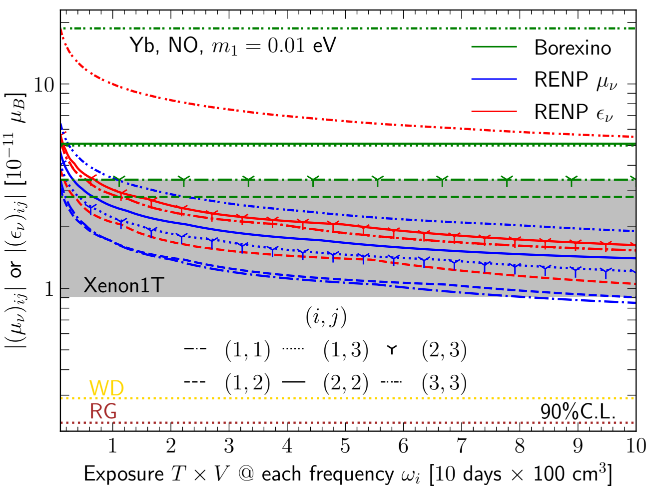
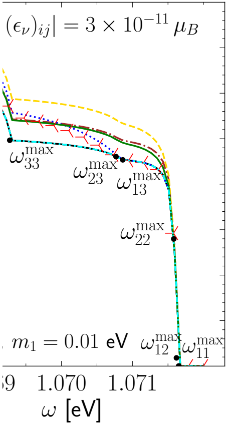




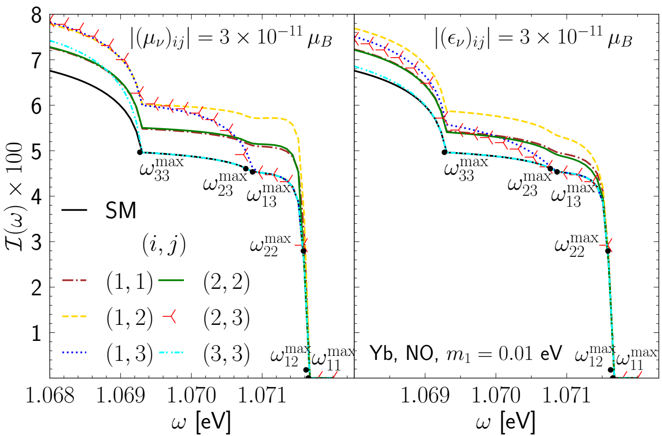
Photon as mediator for RENP

From S.-F. Ge & Pedro Pasquini EPJC 82 (2022) 3, 208





Notice

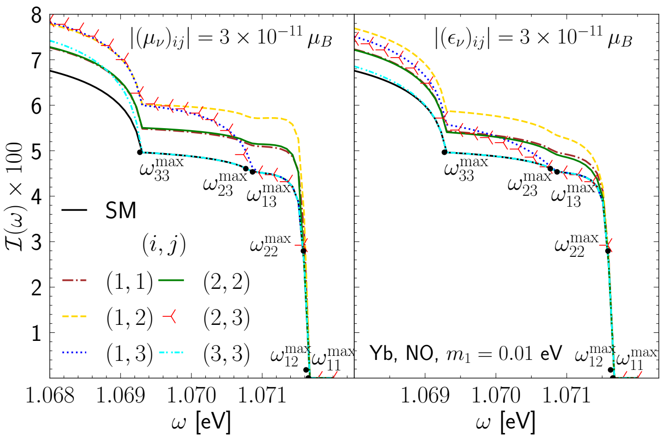


$|(\mu_\nu)_{ij}| = 3\times10^{-11}\,\mu_B$
$|(\epsilon_\nu)_{ij}| = 3\times10^{-11}\,\mu_B$
$\mathcal{I}(\omega)\times100$
ω [eV]
SM
(i,j)
$(1,1)$
$(2,2)$
$(1,2)$
$(2,3)$
$(1,3)$
$(3,3)$
ω_{33}^{max}
ω_{23}^{max}
ω_{13}^{max}
ω_{22}^{max}
ω_{12}^{max}
ω_{11}^{max}
Yb, NO, $m_1 = 0.01$ eV

Photon as mediator for RENP

Notice

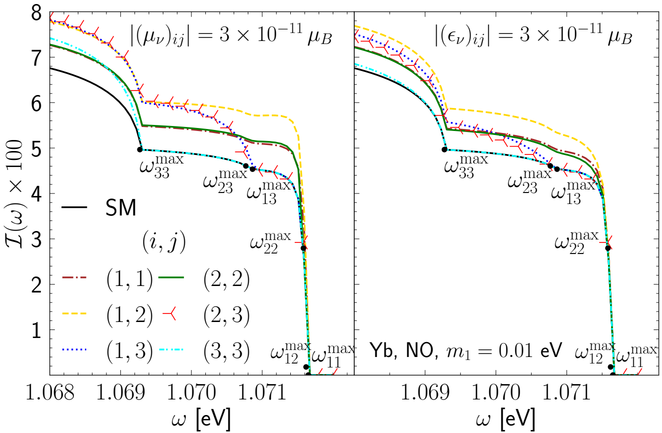
(1) Shape is different for μ_ν and ϵ_ν



Notice

(1) Shape is different for μ_ν and ϵ_ν

(2) ij contribution starts when $\omega < \omega_{ij}^{\max}$



Separate magnetic from electric dipoles

RENP can distinguish $\langle r^2 \rangle$, a, μ from ϵ!

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Has blind spots

D. A. Sierra et al.

Phys.Rev.D 105 (2022) 3, 035027

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Large system. uncertanties

R. J. Stancliffe et al.

A&A 586, A119 (2016)

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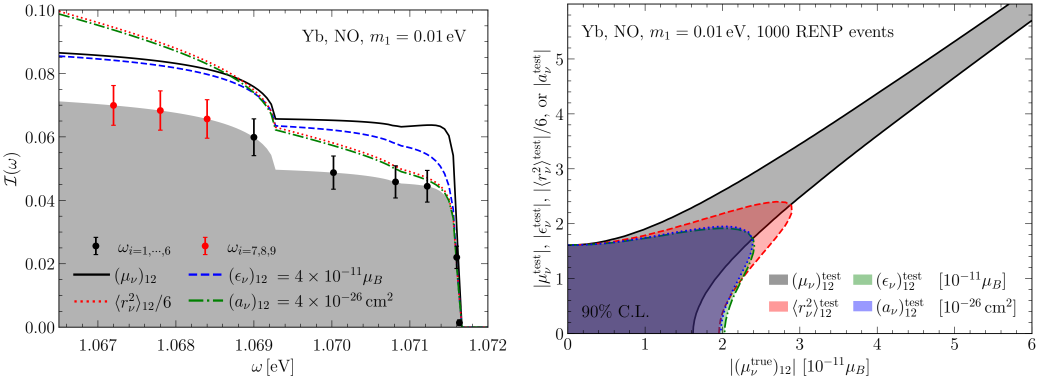
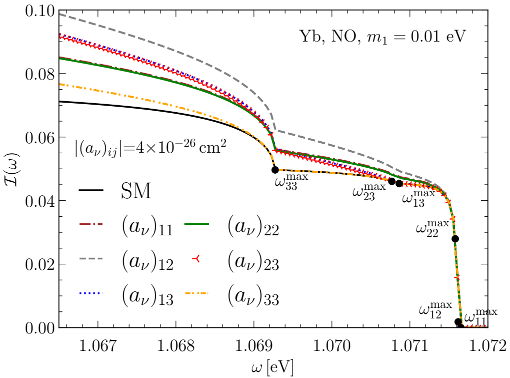
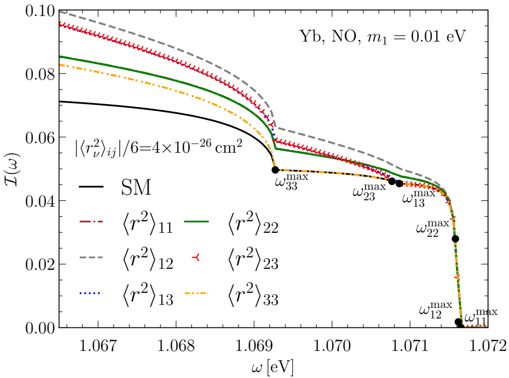


a_ν and r_ν are harder





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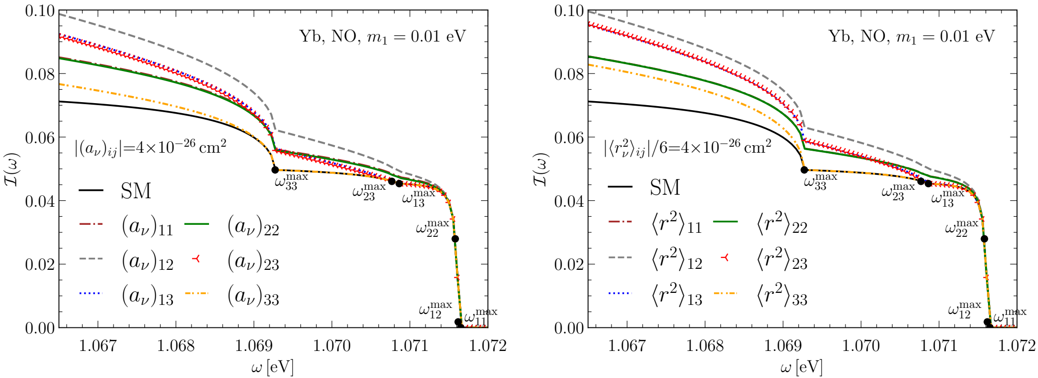

Current bound: $\langle r_\nu^2\rangle, a_\nu \lesssim 10^{-32}$ cm^2
(but suffer more from degeneracy)

We need $E_1 \times E_1$ transition!

Why sensitivity of a_ν,$\langle r_\nu^2 \rangle$ not so good?

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Note: $\frac{1}{m_e|\mathbf{d}_{ij}|} \sim 10^{-2}$

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νEM similar to EM, better use $E_1 \times E_1$
(increase $(10^2)^2$ and decrease SM bkg!)

Final thoughts

- Radiative emission of neutrino pair (RENP) is a novel and interesting idea.

- The RENP can obtain the neutrino mass scale and look for new physics.

- The low energy q^2 of RENP makes it specially powerful probe of light mediator.

- μ_ν, ϵ_ν, a_ν, and $\langle r_\nu^2 \rangle$ can be thoroughly explored

Thanks a lot!

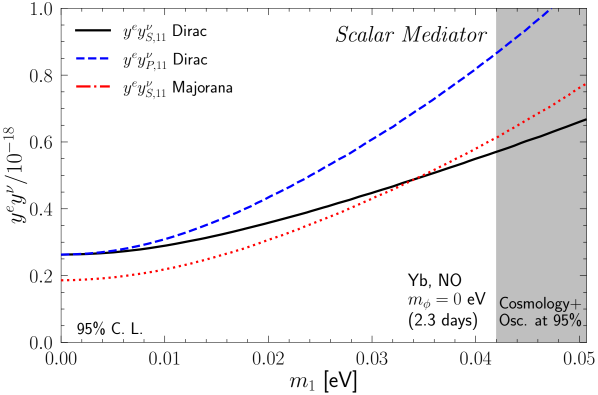
Any questions?

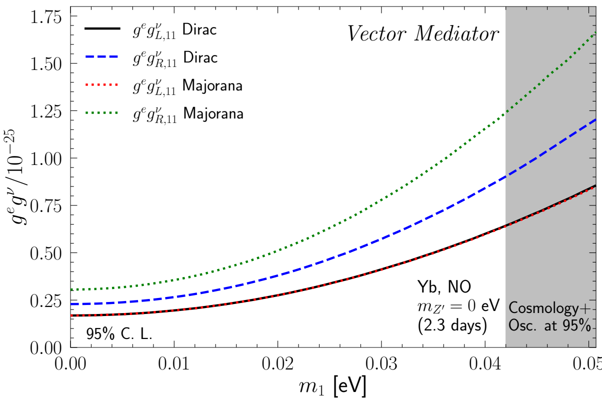
Founding Support:

Double First Class start-up fund (WF220442604), the Shanghai Pujiang Program (20PJ1407800), National Natural Science Foundation of China (No. 12090064), and Chinese Academy of Sciences Center for Excellence in Particle Physics (CCEPP). Grant-in-Aid for Innovative Areas No. 19H05810

Backup Slides

Backup slides





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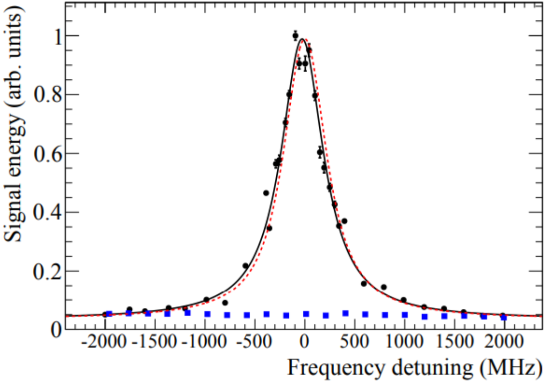

Source: T. Hiraki et al. J. Phys. B **52**, no.4, 045401 (2019)

Backup slides

$$\mathcal{I}_{Z'} = \sum_{ij} \frac{\Delta_{ij}(\omega)}{(E_{vg}-\omega)^2}\Theta(\omega-\omega_{ij}^{\max})\left[\left(|a_{ij}^L|^2+|a_{ij}^R|^2-2\delta_M \mathrm{Re}[a_{ij}^L a_{ij}^R]\right)I_{ij}^{(D)} + \left(\delta_M \mathrm{Re}\left[(a_{ij}^L)^2+(a_{ij}^R)^2\right]-2\mathrm{Re}\left[a_{ij}^{L*}a_{ij}^R\right]\right)\right.$$

$$\mathcal{I}_\phi = \sum_{ij}\frac{\Delta_{ij}(\omega)}{(E_{vg}-\omega)^2}\Theta(\omega-\omega_{ij}^{\max})\left[I_{ij}^{\mathrm{SM}}(\omega)+\delta I_{ij}(\omega)\right]$$

$$\delta I_{ij} = \frac{|y^e|^2\omega^2}{m_e^2 G_F^2}\frac{\left[|y_{S,ij}^\nu|^2+(1-\delta_M)|y_{P,ij}^\nu|^2\right]E_{eg}(E_{eg}-2\omega)-|y_{S,ij}^\nu|^2(m_i+m_j)^2-(1-\delta_M)|y_{P,ij}^\nu|^2(m_i-m_j)^2}{24[E_{eg}(E_{eg}-2\omega)-m_\phi^2]^2} \quad (29)$$

$$+\frac{y^e\omega^2}{6\sqrt{2}G_F}\left\{\frac{\mathrm{Re}\left[a_{ij}y_{S,ij}^\nu\right](m_i-m_j)\left[1-\frac{(m_i+m_j)^2}{E_{eg}(E_{eg}-2\omega)}\right]}{m_e[E_{eg}(E_{eg}-2\omega)-m_\phi^2]}-(1-\delta_M)\frac{\mathrm{Im}\left[a_{ij}y_{P,ij}^\nu\right](m_i+m_j)\left[1-\frac{(m_i-m_j)^2}{E_{eg}(E_{eg}-2\omega)}\right]}{m_e[E_{eg}(E_{eg}-2\omega)-m_\phi^2]}\right\}.$$

Coupling	$\mathcal{L}_{\text{new}}$	Non-Relativistic Transition	Type
scalar	$y_S^e \bar{e} e$	$\langle f \| i \rangle$	E1
pseudo-scalar	$i y_P^e \bar{e} \gamma_5 e$	$\frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \| i \rangle$	M1
vector	$g_V^e \bar{e} \gamma^\mu e$	$(\langle f \| i \rangle, \frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \boldsymbol{\sigma} \| i \rangle)$	E1
axial-vector	$g_A^e \bar{e} \gamma^\mu \gamma_\mu e$	$(\frac{\mathbf{q}}{2m_e} \cdot \langle f \| \boldsymbol{\sigma} \| i \rangle, \langle f \| \boldsymbol{\sigma} \| i \rangle)$	M1

	E1	M1
ΔJ	$0, \pm 1$	$0, \pm 1$
ΔM_J	$0, \pm 1$	$0, \pm 1$
Parity	$\pi_i = -\pi_f$	$\pi_i = \pi_f$

From: $\mathcal{L}_{EW} = \overline{e}\left[i\not{\partial} - e\not{A} - \sqrt{2}G_{\mathrm{F}}\not{j}^{(\nu)}\left(v + a\gamma_5\right) - m_e \right] e + \ldots .$

$$H_\gamma = -ie\boldsymbol{A}^{(\gamma)} \cdot [\hat{\boldsymbol{x}}, H_0] + \tfrac{e}{2m_e}\boldsymbol{\sigma} \cdot (\boldsymbol{\nabla} \times \boldsymbol{A}^{(\gamma)}).$$

$$H_{\nu\bar{\nu}} = -i\sqrt{2}G_{\mathrm{F}}\left(v\boldsymbol{j}^{(\nu)} + aj_0^{(\nu)}\boldsymbol{\sigma}\right) \cdot [\hat{\boldsymbol{x}}, H_0] + \sqrt{2}aG_{\mathrm{F}}\boldsymbol{j}^{(\nu)} \cdot \boldsymbol{\sigma}$$

$$H_{\nu EM} = -ie\boldsymbol{j}^{(\nu EM)} \cdot [\hat{\boldsymbol{x}}, H_0] + \tfrac{e}{2m_e}\boldsymbol{\sigma} \cdot (\boldsymbol{\nabla} \times \boldsymbol{j}^{(\nu EM)}).$$