Neutrino Physics, and Other Intense Matters

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Outline

1. Neutrinos: What We Know;
2. Neutrinos: What We Are Trying to Understand;
3. Why Are Neutrino Masses Small? – Ideas, Consequences;
4. How Do We Learn More? Segue to Muons;
5. Brief Comment on Rare Kaon Decays;
6. Concluding Remarks

Three Flavor Mixing Hypothesis Fits All* Data Really Well.

⇒ Good Measurements of Oscillation Observables

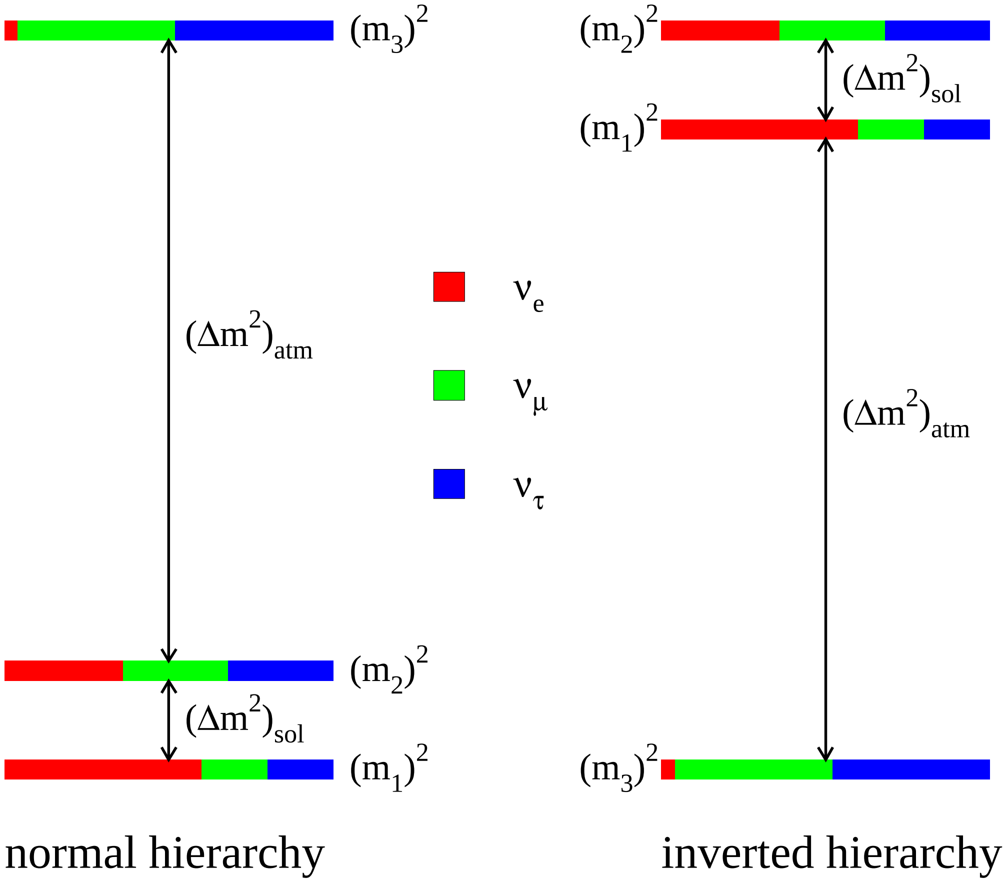
GS98 with Gallium cross-section from [24]	AGSS09 with modified Gallium cross-section [16]
$\Delta m^2_{21} = 7.59 \pm 0.20 \ \left({}^{+0.61}_{-0.69}\right) \times 10^{-5}\ \text{eV}^2$	Same
$\Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2 \\ +2.46 \pm 0.12\ (\pm 0.37) \times 10^{-3}\ \text{eV}^2 \end{cases}$	Same
$\theta_{12} = 34.4 \pm 1.0 \ \left({}^{+3.2}_{-2.9}\right)^\circ$	$34.5 \pm 1.0 \ \left({}^{+3.2}_{-2.8}\right)^\circ$
$\theta_{23} = 42.8\,{}^{+4.7}_{-2.9} \ \left({}^{+10.7}_{-7.3}\right)^\circ$	Same
$\theta_{13} = 5.6\,{}^{+3.0}_{-2.7} \ (\leq 12.5)^\circ$	$5.1\,{}^{+3.0}_{-3.3} \ (\leq 12.0)^\circ$
$\left[\sin^2\theta_{13} = 0.0095\,{}^{+0.013}_{-0.007} \ (\leq 0.047)\right]$	$\left[0.008\,{}^{+0.012}_{-0.007} \ (\leq 0.043)\right]$
$\delta_{\text{CP}} \in [0,\ 360]$	Same

[Gonzalez-Garcia, Maltoni, Salvado, arXiv:1001.4524]

* Modulo "Anomalies". Comments Later.

What We Know We Don't Know: Missing Oscillation Parameters

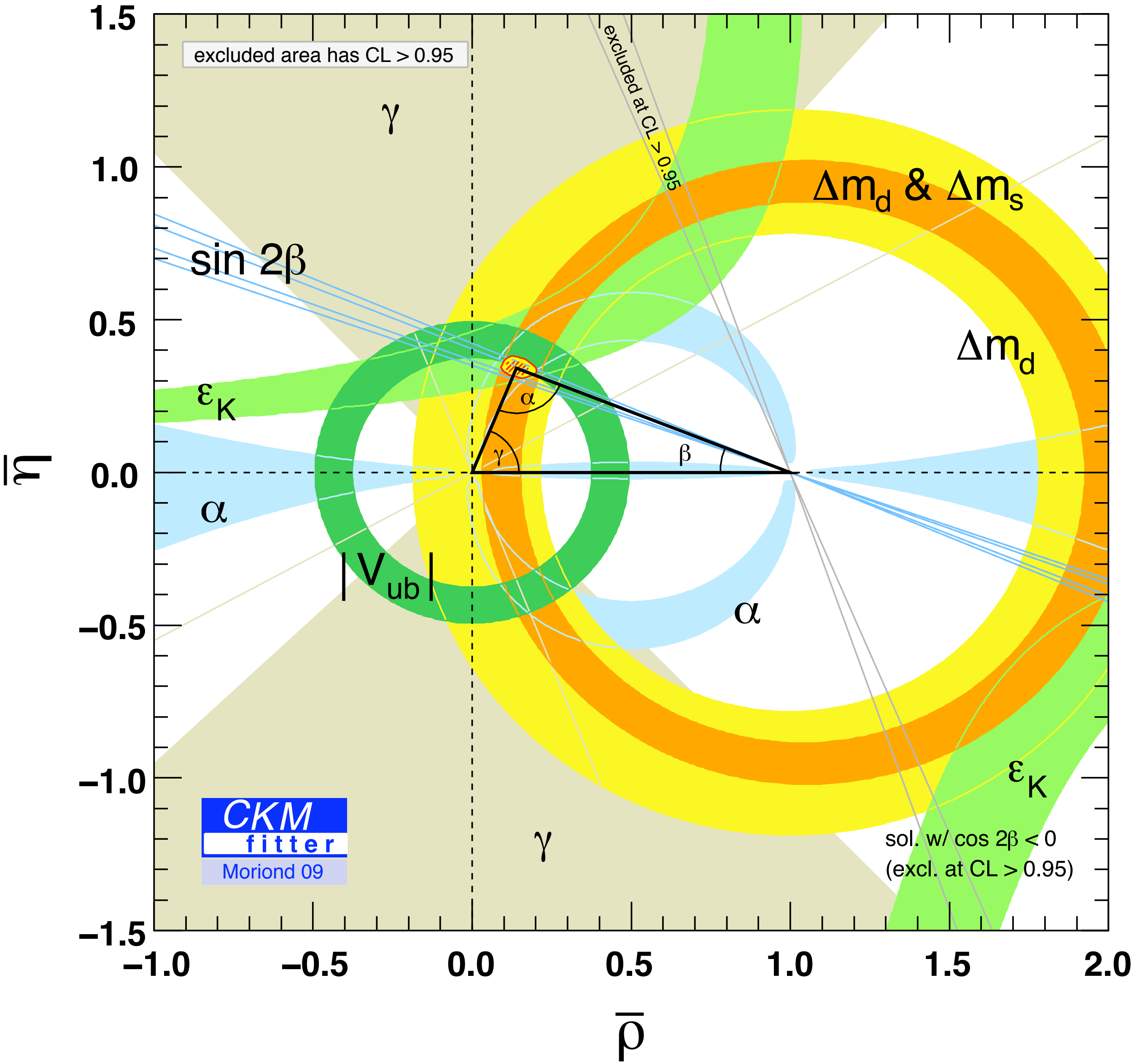
[Driving Force of Next-Generation Oscillation Program]



- What is the ν_e component of ν_3? ($\theta_{13} \neq 0$?)
- Is CP-invariance violated in neutrino oscillations? ($\delta \neq 0, \pi$?)
- Is ν_3 mostly ν_μ or ν_τ? ($\theta_{23} > \pi/4$, $\theta_{23} < \pi/4$, or $\theta_{23} = \pi/4$?)
- What is the neutrino mass hierarchy? ($\Delta m^2_{13} > 0$?)

⇒ All of the above can "only" be addressed with new neutrino oscillation experiments

Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)



We need to do this in the lepton sector!

Strawman New Physics: New Neutrino–Matter Interactions

These are parameterized by effective four-fermion interactions, of the type:

$$L^{NSI} = -2\sqrt{2}G_F\left(\bar{\nu}_\alpha\gamma_\mu\nu_\beta\right)\left(\epsilon_{\alpha\beta}^{f\tilde{f}L}\bar{f}_L\gamma^\mu\tilde{f}_L + \epsilon_{\alpha\beta}^{f\tilde{f}R}\bar{f}_R\gamma^\mu\tilde{f}_R\right) + h.c.$$

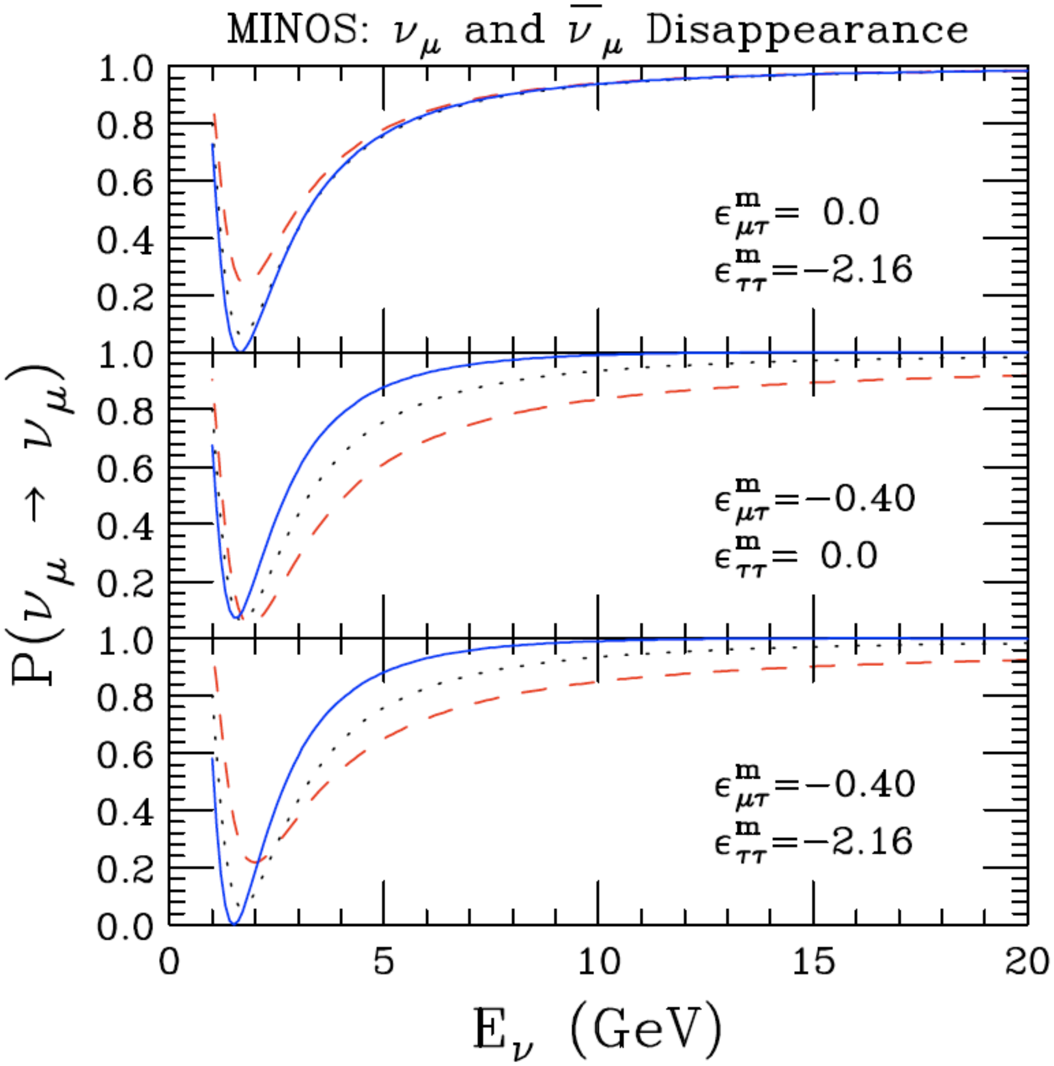
where $f, \tilde{f} = u, d, \dots$ and $\epsilon_{\alpha\beta}^{f\tilde{f}}$ are dimensionless couplings that measure the strength of the four-fermion interaction relative to the weak interactions.

While some of the ϵs are well constrained (especially those involving muons), some are only very poorly known. These are best searched for in neutrino oscillation experiments, where they mediate anomalous matter effects:

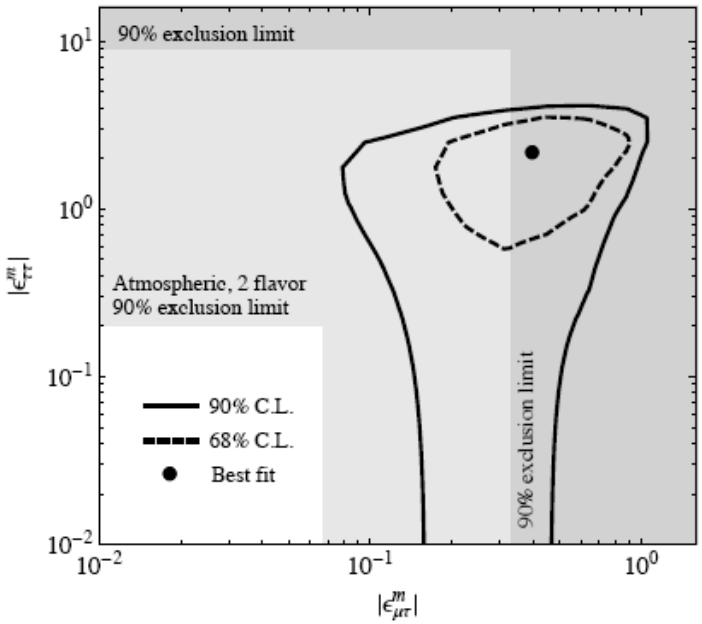
$$H_{\rm mat} = \sqrt{2}G_F n_e \left(\begin{array}{ccc} 1+\epsilon_{ee} & \epsilon_{e\mu}^* & \epsilon_{e\tau}^* \\ \epsilon_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}^* \\ \epsilon_{e\tau} & \epsilon_{\mu\tau} & \epsilon_{\tau\tau} \end{array}\right), \qquad \epsilon_{\alpha\beta} = \sum_{f=u,d,e} \epsilon_{\alpha\beta}^{ff}\frac{n_f}{n_e}$$

Anomalous matter effects are CPT violating (in a simple, benign way):

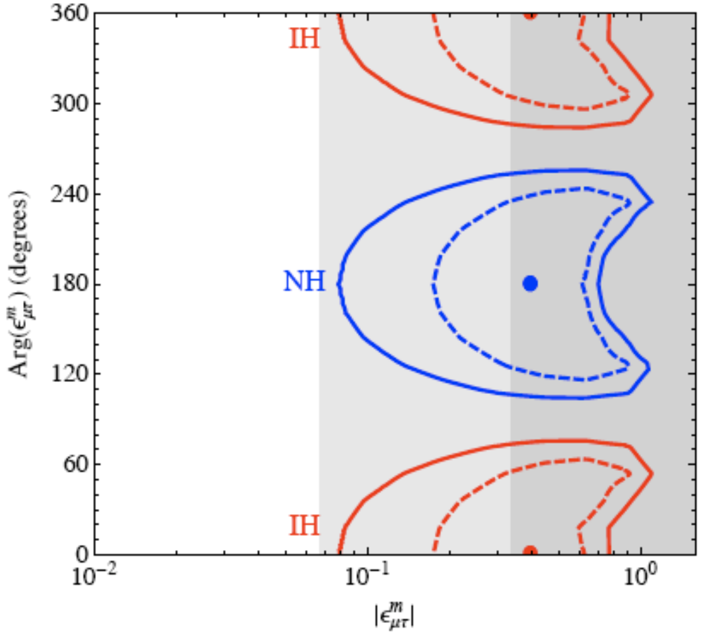
neutrinos and antineutrinos behave differently!

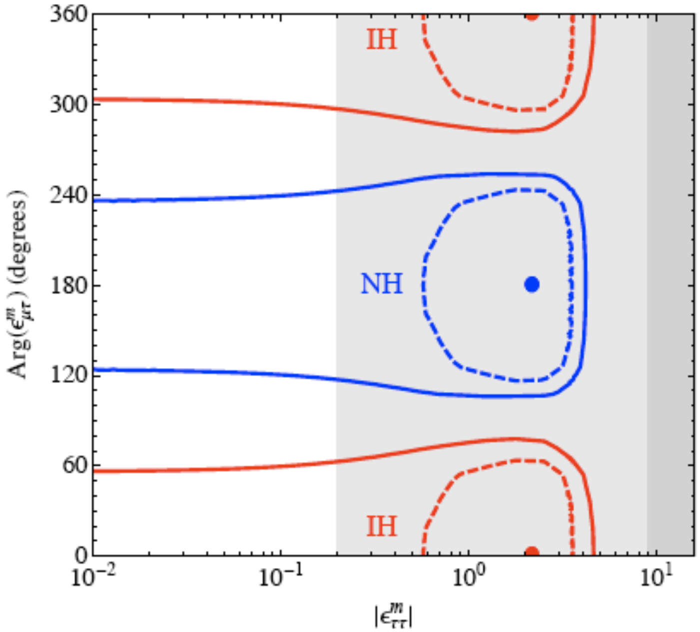


[Kopp, Machado, Parke, 1009.0014]



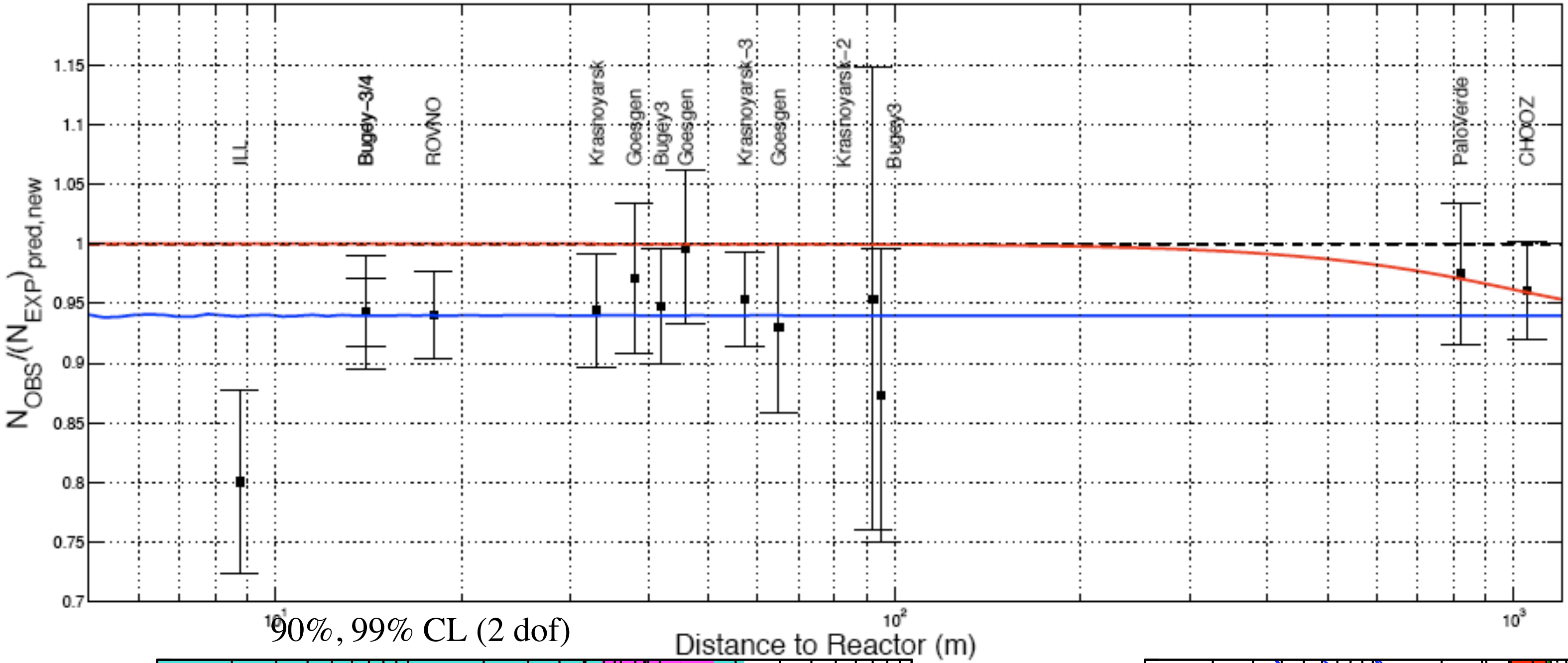
[Kopp, Machado, Parke, 1009.0014]

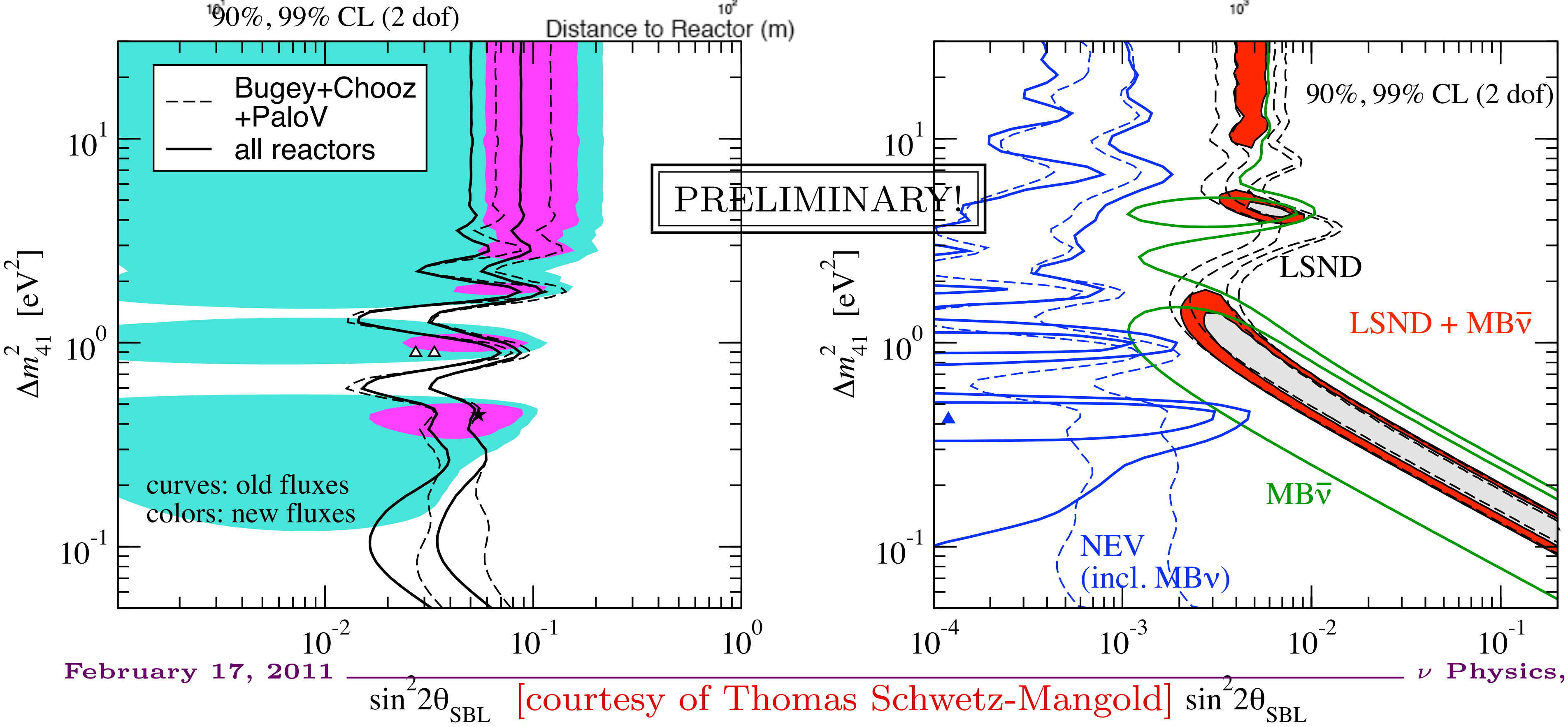




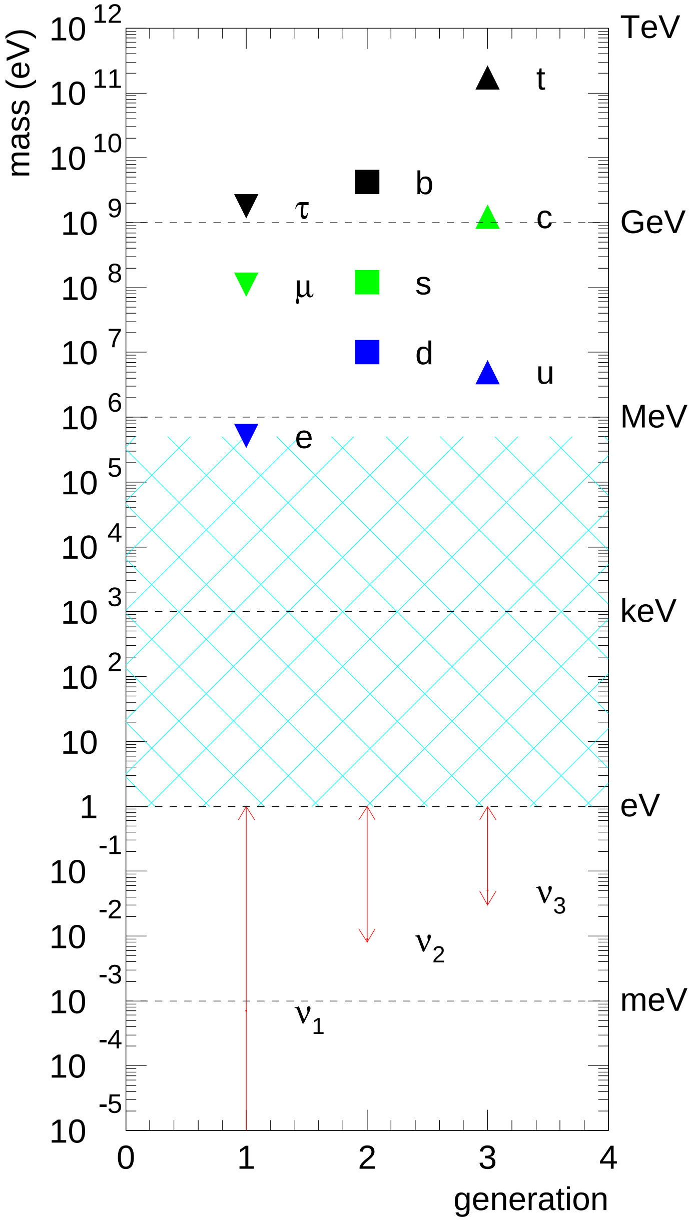
More Room For

New Neutrinos?





[courtesy of Thomas Schwetz-Mangold]



What We Are Trying To Understand:

⇐ NEUTRINOS HAVE TINY MASSES

⇓ LEPTON MIXING IS "WEIRD" ⇓

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & {\scriptstyle 0.001} \\ 0.2 & 1 & 0.01 \\ {\scriptstyle 0.001} & 0.01 & 1 \end{pmatrix}$$

What Does It Mean?

First Question: What Is The Lagrangian of The New Standard Model [νSM]?

The short answer is – WE DON'T KNOW. Not enough available info!

$\Updownarrow$

Equivalently, there are several completely different ways of addressing neutrino masses. The key issue is to understand what else the νSM candidates can do. [are they falsifiable?, are they "simple"?, do they address other outstanding problems in physics?, etc]

We need more experimental input.

Candidate νSM

SM as an effective field theory – non-renormalizable operators

$$\mathcal{L}_{\nu\rm SM} \supset -y_{ij}\frac{L^iHL^jH}{2\Lambda} + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + H.c.$$

There is only one dimension five operator [Weinberg, 1979]. If $\Lambda \gg 1$ TeV, it leads to only one observable consequence...

$$\text{after EWSB: } \mathcal{L}_{\nu\rm SM} \supset \frac{m_{ij}}{2}\nu^i\nu^j; \quad m_{ij} = y_{ij}\frac{v^2}{\Lambda}.$$

- Neutrino masses are small: $\Lambda \gg v \rightarrow m_\nu \ll m_f$ ($f = e, \mu, u, d$, etc)
- Neutrinos are Majorana fermions – Lepton number is violated!
- νSM effective theory – not valid for energies above *at most* Λ/y.
- Define $y_{\rm max} \equiv 1 \ \Rightarrow$ data require $\Lambda \sim 10^{14}$ GeV.

What else is this “good for”? Depends on the ultraviolet completion!

The Seesaw Lagrangian

A simple[a], renormalizable Lagrangian that allows for neutrino masses is

$$\mathcal{L}_\nu = \mathcal{L}_{\rm old} - \lambda_{\alpha i} L^\alpha H N^i - \sum_{i=1}^{3} \frac{M_i}{2} N^i N^i + H.c.,$$

where N_i ($i = 1, 2, 3$, for concreteness) are SM gauge singlet fermions.

$\mathcal{L}_\nu$ is the most general, renormalizable Lagrangian consistent with the SM gauge group and particle content, plus the addition of the N_i fields.

After electroweak symmetry breaking, $\mathcal{L}_\nu$ describes, besides all other SM degrees of freedom, six Majorana fermions: **six neutrinos.**

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[a] Only requires the introduction of three fermionic degrees of freedom, no new interactions or symmetries.

What We Know About M:

- $M = 0$: the six neutrinos "fuse" into three Dirac states. Neutrino mass matrix given by $\mu_{\alpha i} \equiv \lambda_{\alpha i} v$.

  The symmetry of $\mathcal{L}_\nu$ is enhanced: $U(1)_{B-L}$ is an exact global symmetry of the Lagrangian if all M_i vanish. Small M_i values are 'tHooft natural.

- $M \gg \mu$: the six neutrinos split up into three mostly active, light ones, and three, mostly sterile, heavy ones. The light neutrino mass matrix is given by $m_{\alpha\beta} = \sum_i \mu_{\alpha i} M_i^{-1} \mu_{\beta i}$ $[m \propto 1/\Lambda \;\Rightarrow\; \Lambda = M/\mu^2]$.

  This the **seesaw mechanism.** Neutrinos are Majorana fermions. Lepton number is not a good symmetry of $\mathcal{L}_\nu$, even though L-violating effects are hard to come by.

- $M \sim \mu$: six states have similar masses. Active–sterile mixing is very large. This scenario is (generically) ruled out by active neutrino data (atmospheric, solar, KamLAND, K2K, etc).

High-Energy Seesaw: Brief Comments

- This is everyone's favorite scenario.
- Upper bound for M (e.g. Maltoni, Niczyporuk, Willenbrock, hep-ph/0006358):

$$M < 7.6 \times 10^{15}\ \text{GeV} \times \left(\frac{0.1\ \text{eV}}{m_\nu}\right).$$

- Hierarchy problem hint (e.g., Casas, Espinosa, Hidalgo, hep-ph/0410298):

$$M < 10^{7}\ \text{GeV}.$$

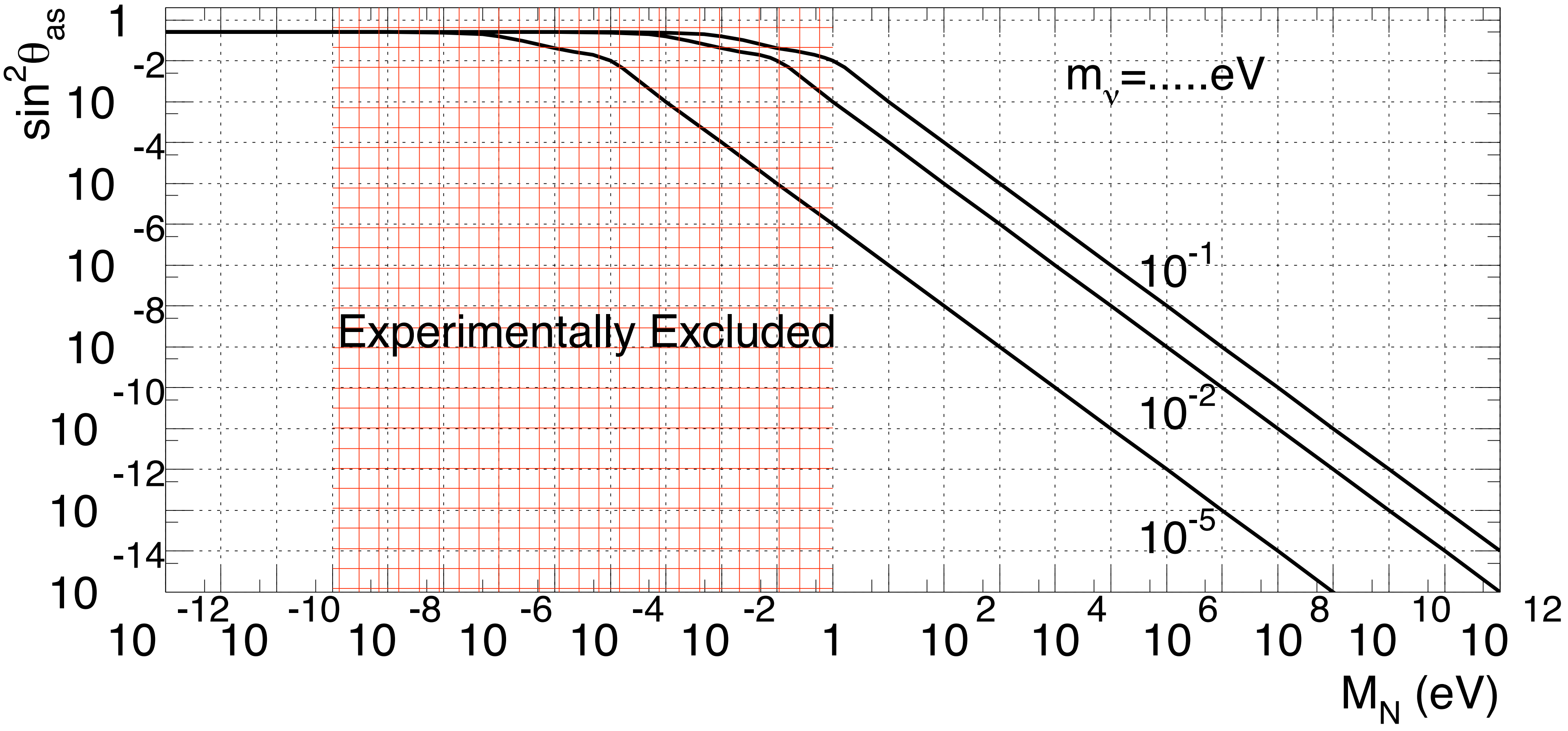
- Physics "too" heavy! No observable consequence other than leptogenesis. From thermal leptogenesis $M > 10^9$ GeV. Will we ever convince ourselves that this is correct? (e.g., Buckley, Murayama, hep-ph/0606088)

Low-Energy Seesaw [AdG PRD72,033005)]

The other end of the M spectrum ($M < 100$ GeV). What do we get?

- Neutrino masses are small because the Yukawa couplings are very small $\lambda \in [10^{-6}, 10^{-11}]$;
- No standard thermal leptogenesis – right-handed neutrinos way too light? [For a possible alternative see Canetti, Shaposhnikov, arXiv: 1006.0133 and reference therein.]
- No obvious connection with other energy scales (EWSB, GUTs, etc);
- Right-handed neutrinos are propagating degrees of freedom. They look like sterile neutrinos ⇒ sterile neutrinos associated with the fact that the active neutrinos have mass;
- sterile–active mixing can be predicted – hypothesis is falsifiable!
- Small values of M are natural (in the 'tHooft sense). In fact, theoretically, no value of M should be discriminated against!

Constraining the Seesaw Lagrangian



[AdG, Huang, Jenkins, arXiv:0906.1611]

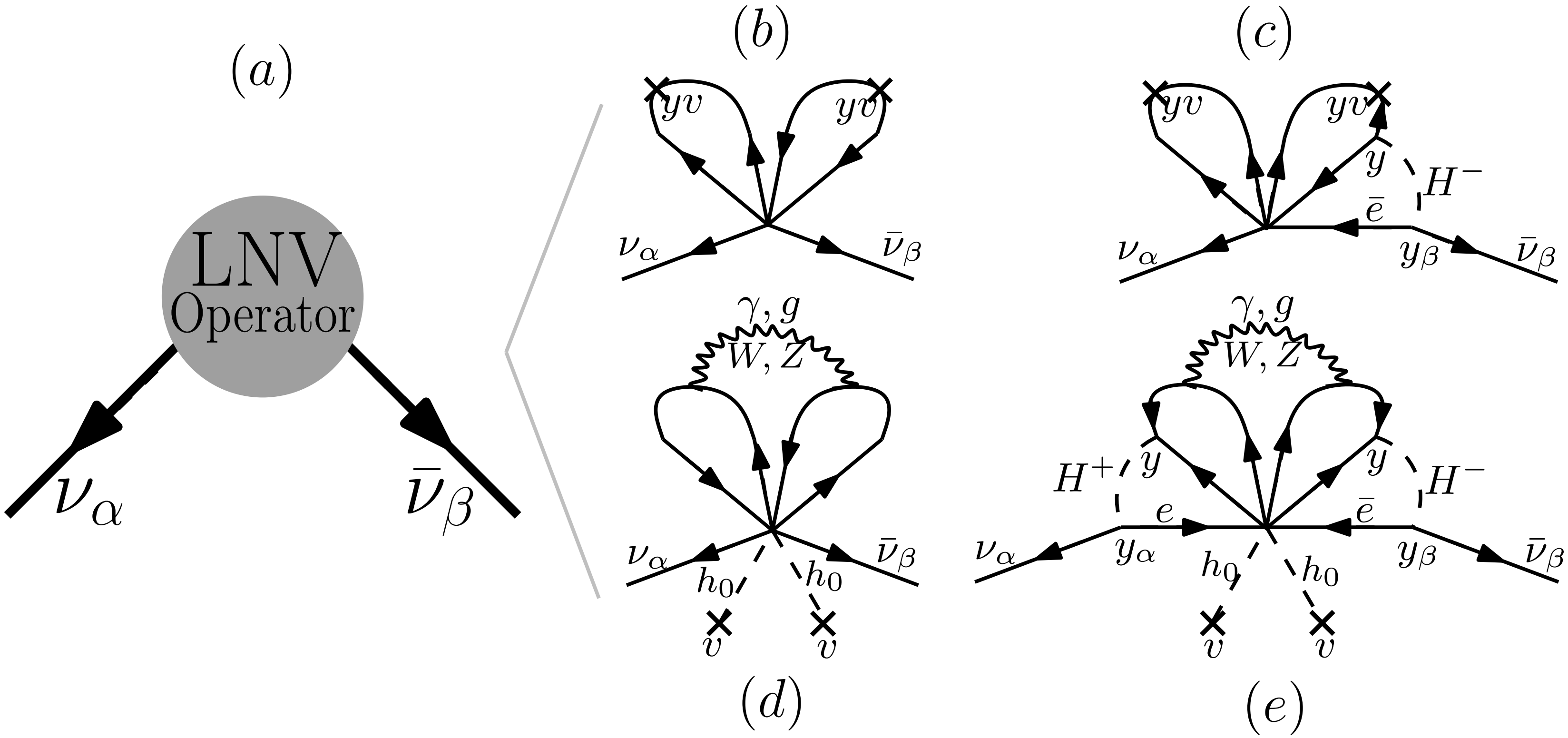
AdG, Jenkins,
0708.1344 [hep-ph]

Effective Operator Approach

(there are 129 of them if you discount different Lorentz structures!)

classified by Babu and Leung in NPB**619**,667(2001)

13	$L^iL^j\overline{Q}_i\overline{u^c}L^le^c\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	2×10^5	$\beta\beta0\nu$
14_a	$L^iL^j\overline{Q}_k\overline{u^c}Q^kd^c\epsilon_{ij}$	$\frac{y_d y_u g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
14_b	$L^iL^j\overline{Q}_i\overline{u^c}Q^ld^c\epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}$	6×10^5	$\beta\beta0\nu$
15	$L^iL^jL^kd^c\overline{L}_i\overline{u^c}\epsilon_{jk}$	$\frac{y_d y_u g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^3	$\beta\beta0\nu$
16	$L^iL^je^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
17	$L^iL^jd^cd^c\overline{d^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
18	$L^iL^jd^cu^c\overline{u^c}\overline{u^c}\epsilon_{ij}$	$\frac{y_d y_u g^4}{(16\pi^2)^4}\frac{v^2}{\Lambda}$	2	$\beta\beta0\nu$, LHC
19	$L^iQ^jd^cd^c\overline{e^c}\overline{u^c}\epsilon_{ij}$	$y_{\ell_\beta}\frac{y_d^2 y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1	$\beta\beta0\nu$, HElnv, LHC, m
20	$L^id^c\overline{Q}_i\overline{u^c}\overline{e^c}\overline{u^c}$	$y_{\ell_\beta}\frac{y_d y_u^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	40	$\beta\beta0\nu$, mix
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
22	$L^iL^jL^ke^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
23	$L^iL^jL^ke^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	40	$\beta\beta0\nu$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$	$\frac{y_d^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	1×10^2	$\beta\beta0\nu$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	4×10^3	$\beta\beta0\nu$
26_a	$L^iL^jQ^kd^c\overline{L}_i\overline{e^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{y_\ell y_d}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	40	$\beta\beta0\nu$
26_b	$L^iL^jQ^kd^c\overline{L}_k\overline{e^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_\ell y_d}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	40	$\beta\beta0\nu$
27_a	$L^iL^jQ^kd^c\overline{Q}_i\overline{d^c}H^lH^m\epsilon_{jl}\epsilon_{km}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
27_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{d^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
28_a	$L^iL^jQ^kd^c\overline{Q}_j\overline{u^c}H^l\overline{H}_i\epsilon_{kl}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
28_b	$L^iL^jQ^kd^c\overline{Q}_k\overline{u^c}H^l\overline{H}_i\epsilon_{jl}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
28_c	$L^iL^jQ^kd^c\overline{Q}_l\overline{u^c}H^l\overline{H}_i\epsilon_{jk}$	$\frac{y_d y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^3	$\beta\beta0\nu$
29_a	$L^iL^jQ^ku^c\overline{Q}_k\overline{u^c}H^lH^m\epsilon_{il}\epsilon_{jm}$	$\frac{y_u^2}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^5	$\beta\beta0\nu$
29_b	$L^iL^jQ^ku^c\overline{Q}_l\overline{u^c}H^lH^m\epsilon_{ik}\epsilon_{jm}$	$\frac{g^2}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	4×10^4	$\beta\beta0\nu$
30_a	$L^iL^j\overline{L}_i\overline{e^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$	$\frac{y_\ell y_u}{(16\pi^2)^3}\frac{v^2}{\Lambda}$	2×10^3	$\beta\beta0\nu$
30_b	$L^iL^j\overline{L}_m\overline{e^c}\overline{Q}_n\overline{u^c}H^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$	$\frac{y_\ell y_u}{(16\pi^2)^2}\frac{v^2}{\Lambda}\left(\frac{1}{16\pi^2}+\frac{v^2}{\Lambda^2}\right)$	2×10^3	$\beta\beta0\nu$
31_a	$L^iL^j\overline{Q}_i\overline{d^c}\overline{Q}_k\overline{u^c}H^kH^l\epsilon_{jl}$		4×10^3	$\beta\beta0\nu$


(a)
LNV
Operator
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ν_α
h_0
h_0
$\bar{\nu}_\beta$
v
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γ, g
W, Z
H^+
y
y
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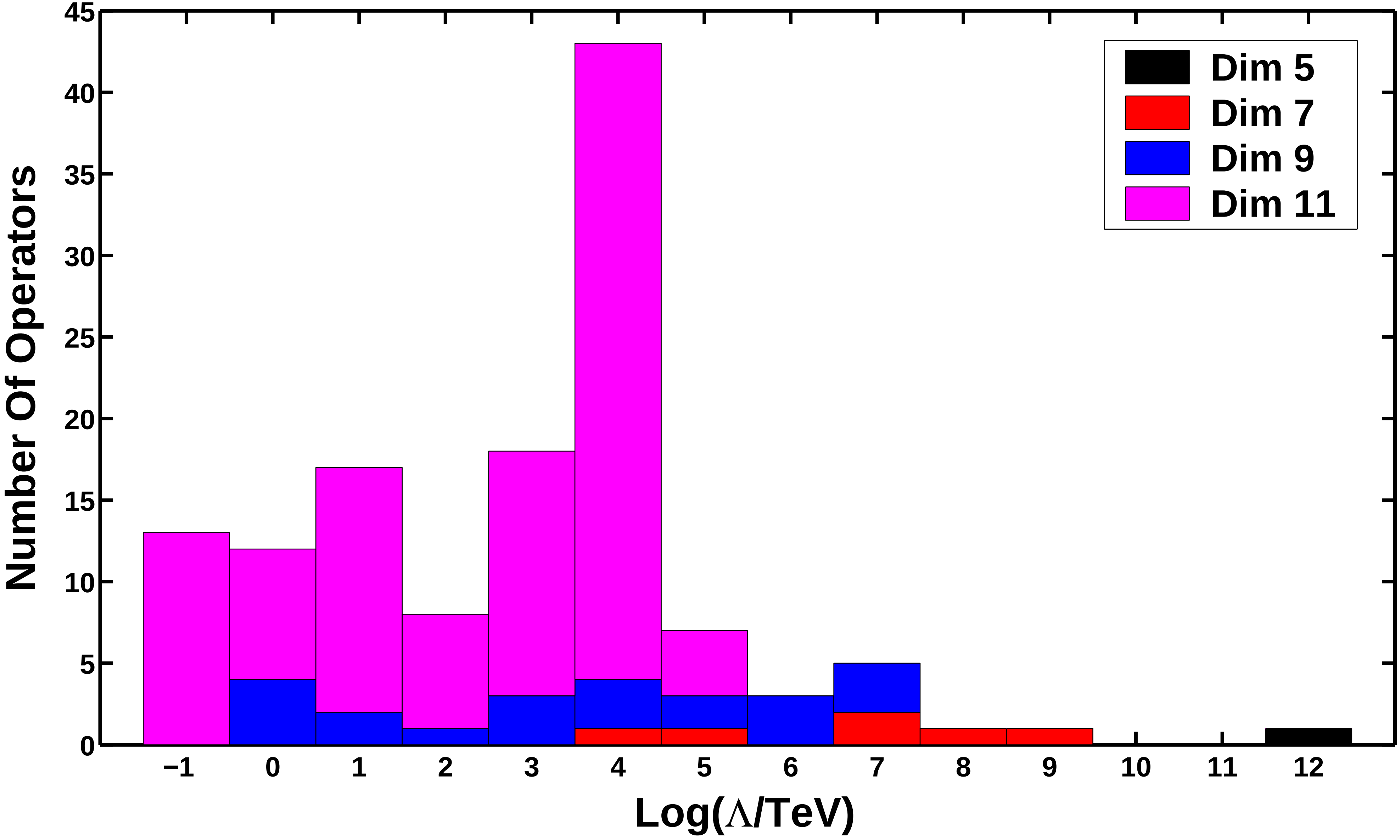
Number Of Operators
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Log(Λ/TeV)
Dim 5
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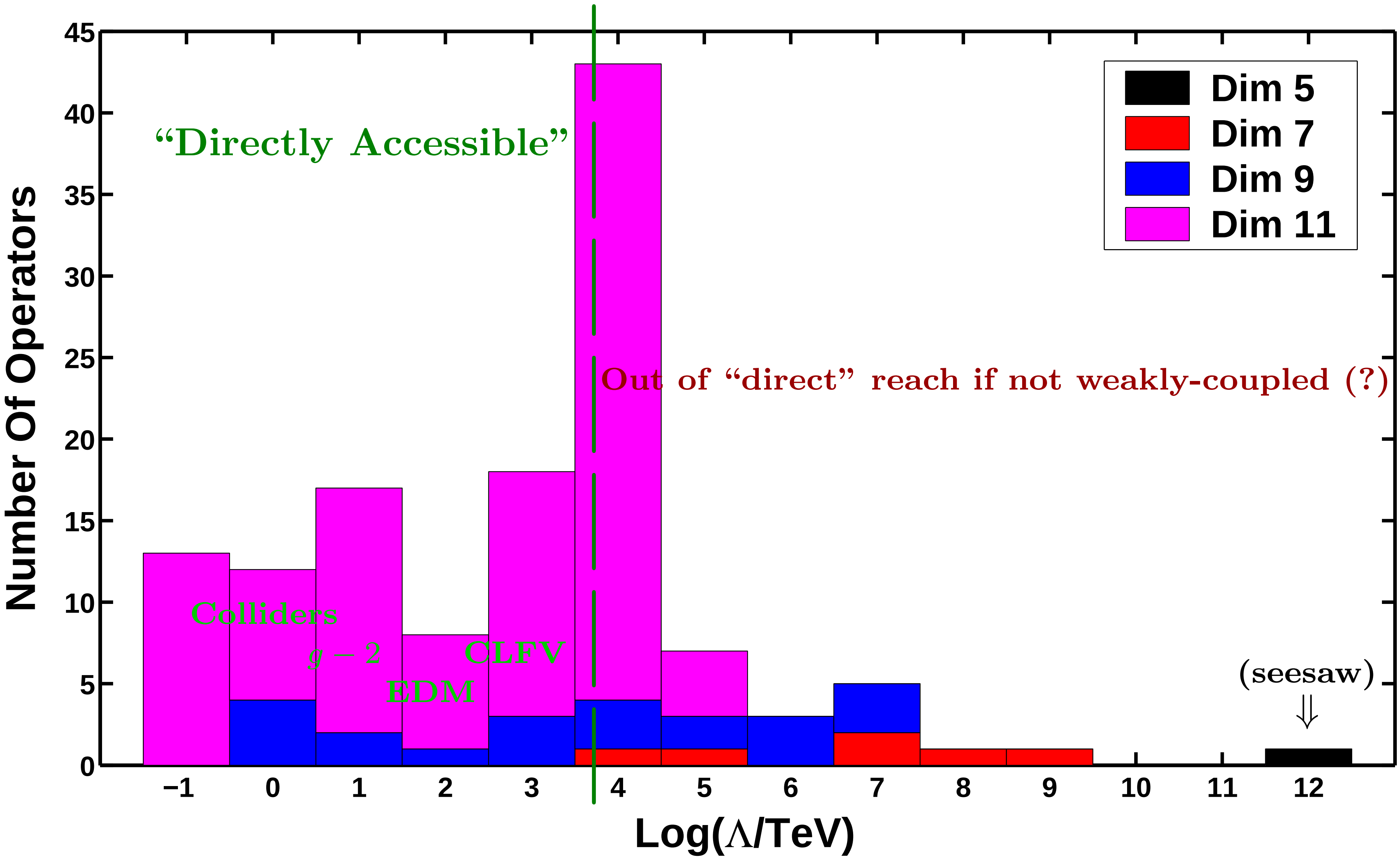
Dim 11


“Directly Accessible”
Out of “direct” reach if not weakly-coupled (?)
Colliders
$g-2$
EDM
CLFV
(seesaw)
⇓
Dim 5
Dim 7
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Dim 11
Number Of Operators
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Log(Λ/TeV)

How Do We Learn More?

In order to learn more, we need more information. Any new data and/or idea is welcome, including

- searches for charged lepton flavor violation;
  ($\mu \to e\gamma$, $\mu \to e$-conversion in nuclei, etc)
- searches for lepton number violation;
  (neutrinoless double beta decay, etc)
- neutrino oscillation experiments;
  (Daya Bay, NOνA, etc)
- searches for fermion electric/magnetic dipole moments
  (electron edm, muon $g-2$, etc);

- precision studies of neutrino – matter interactions;

  (Minerνa, NuSOnG, etc)

- collider experiments:

  (LHC, etc)

  - *Can* we "see" the physics responsible for neutrino masses at the LHC? – YES!

    Must we see it? – NO, but we won't find out until we try!
  - we need to understand the physics at the TeV scale before we can really understand the physics behind neutrino masses (is there low-energy SUSY?, etc).

Segue to Charged-Lepton Flavor Violation:

Neutrino Oscillations have revealed that individual lepton-flavor numbers are NOT conserved!

Hence, in the νSM (the old Standard Model plus operators that lead to neutrino masses) $\mu \to e\gamma$ is allowed (along with all other charged lepton flavor violating processes).

These are Flavor Changing Neutral Current processes, observed in the quark sector ($b \to s\gamma$, $K^0 \leftrightarrow \bar{K}^0$, etc).

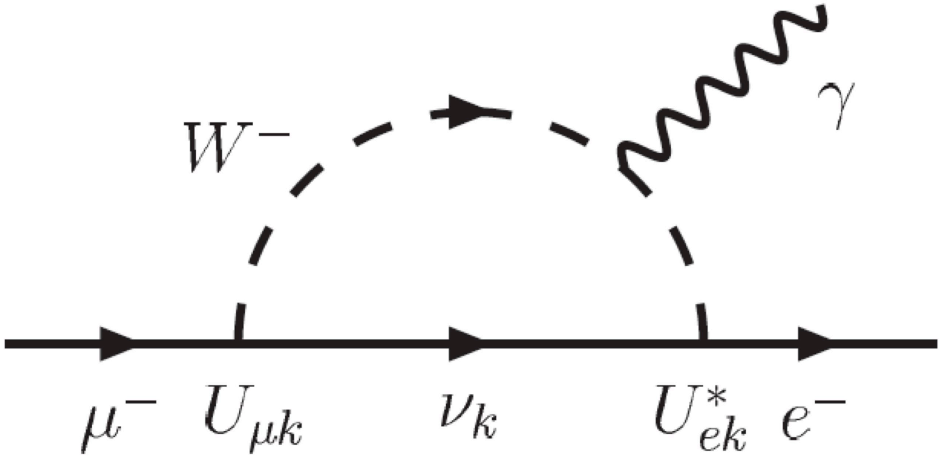
Unfortunately, we do not know the νSM expectation for charged lepton flavor violating processes → **we don't know the νSM Lagrangian !**

One contribution known to be there: active neutrino loops (same as quark sector).

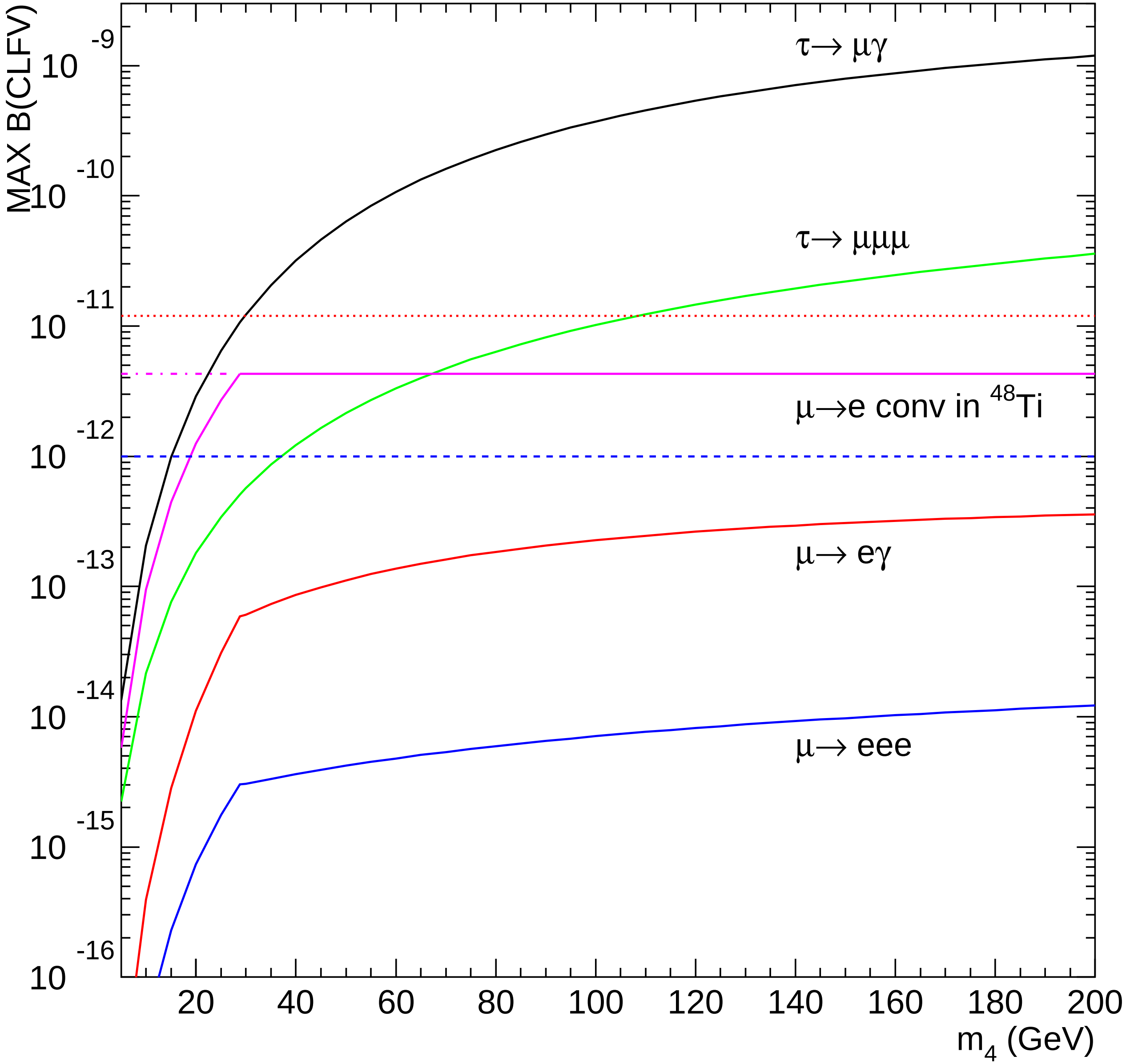
In the case of charged leptons, the **GIM suppression is very efficient**…

e.g.: $$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

[$U_{\alpha i}$ are the elements of the leptonic mixing matrix,
$\Delta m^2_{1i} \equiv m_i^2 - m_1^2$, $i = 2, 3$ are the neutrino mass-squared differences]



In The SeeSaw Mechanism. . . [minus "Theoretical Prejudice"]



arXiv:0706.1732 [hep-ph]

Independent from neutrino masses, there are strong theoretical reasons to believe that the expected rate for flavor changing violating processes is much, much larger than naive νSM predictions and that discovery is just around the corner.

Due to the lack of SM “backgrounds,” searches for rare muon processes, including $\mu \to e\gamma$, $\mu \to e^+e^-e$ and $\mu + N \to e + N$ (μ-e–conversion in nuclei) are considered ideal laboratories to probe effects of new physics at or even above the electroweak scale.

Indeed, if there is new physics at the electroweak scale (as many theorists will have you believe) and if mixing in the lepton sector is large “everywhere” the question we need to address is quite different:

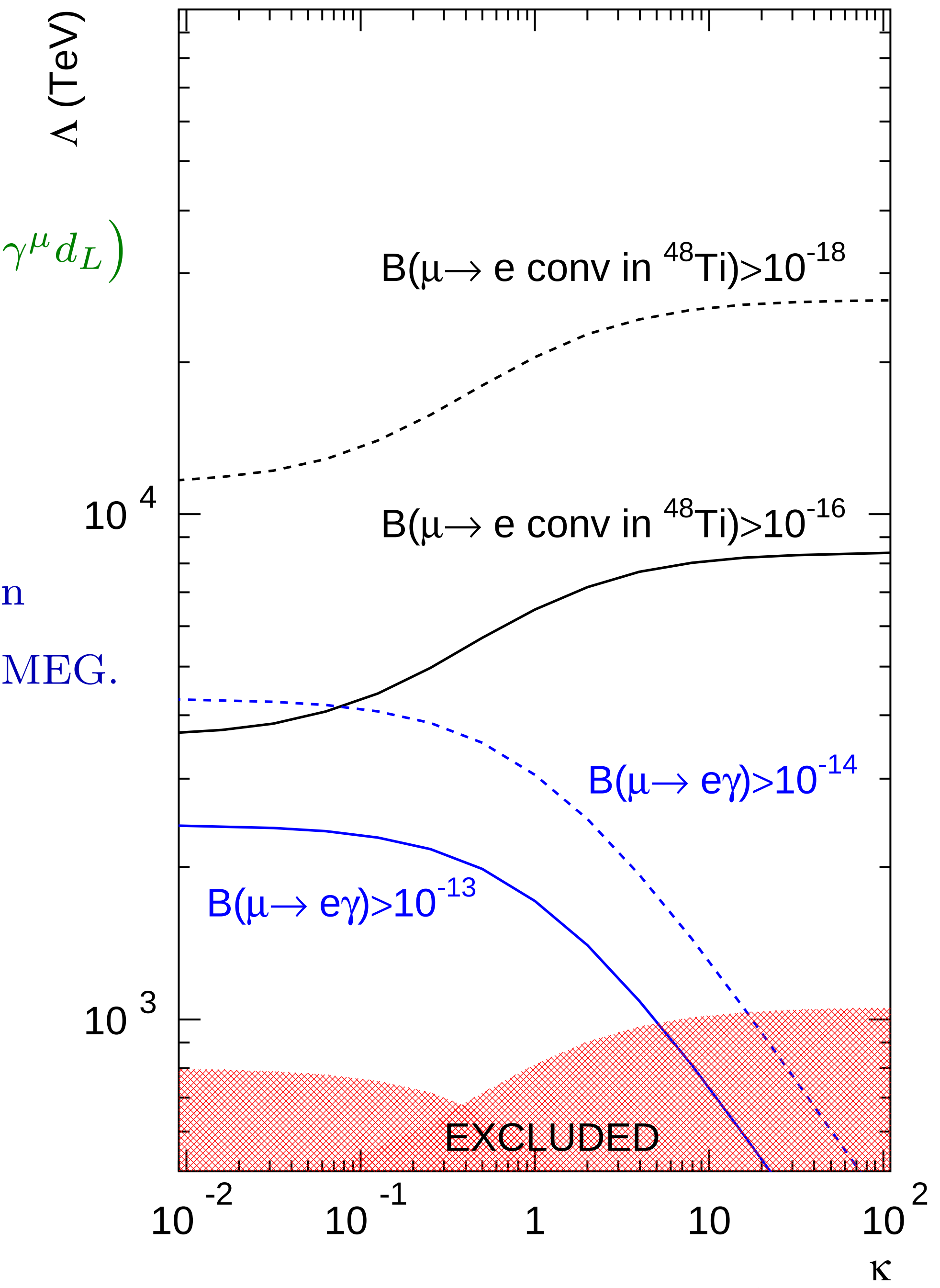
Why haven’t we seen charged lepton flavor violation yet?

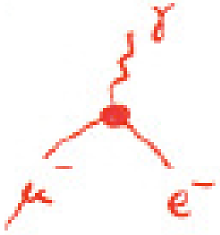
Model Independent Considerations

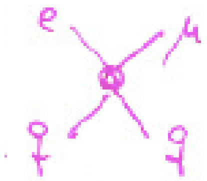
$$L_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} +$$

$$+\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L\right)$$

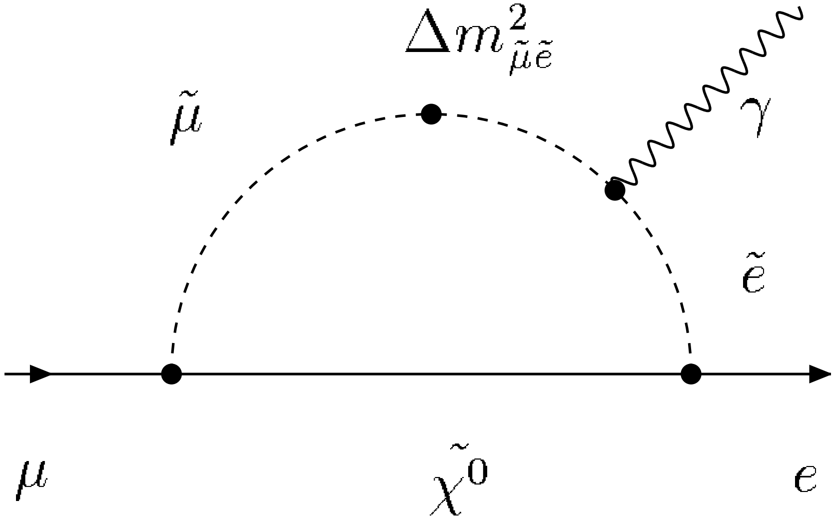
- $\mu \to e$-conv at 10^{-17} “guaranteed” deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- We don’t think we can do $\mu \to e\gamma$ better than 10^{-14}. $\mu \to e$-conv “only” way forward after MEG.
- If the LHC does not discover new states $\mu \to e$-conv among very few process that can access 1000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.







"Bread and Butter" SUSY plus High Energy Seesaw



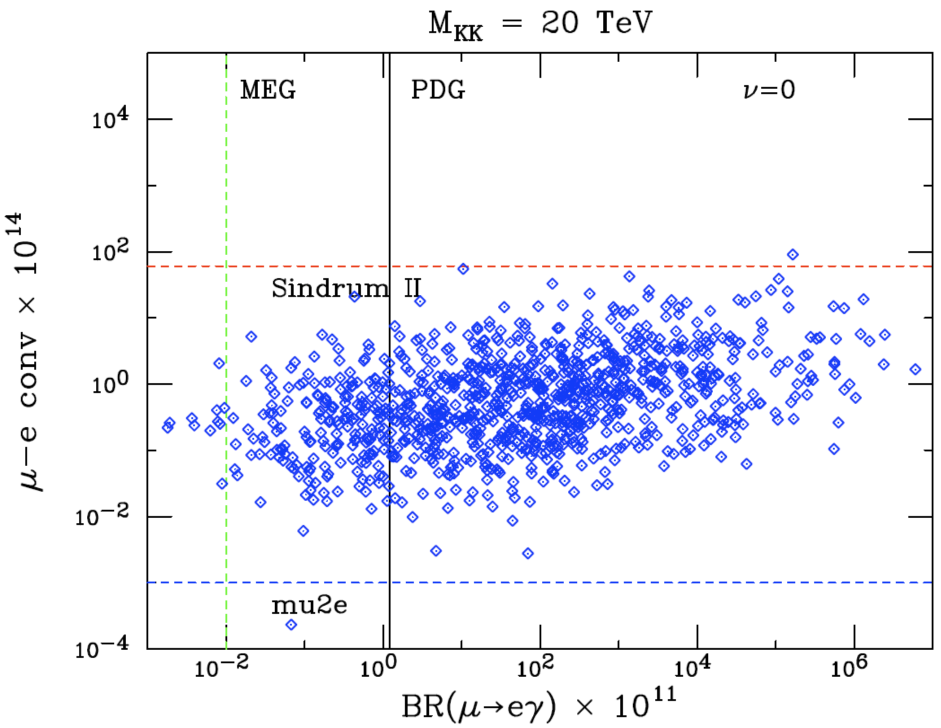
$$\rightarrow \quad \theta_{\tilde{e}\tilde{\mu}} \sim \frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}}$$

$Br(\mu \rightarrow e\gamma) \simeq \frac{\alpha^3\pi}{G_F^2\tilde{m}^4}\theta^2_{\tilde{e}\tilde{\mu}}$, $\tilde{m}^2$ is a typical supersymmetric mass.

$\theta_{\tilde{e}\tilde{\mu}}$ measures the "amount" of flavor violation.

For $\tilde{m}$ around 1 TeV, $\theta_{\tilde{e}\tilde{\mu}}$ is severely constrained. Very big problem.

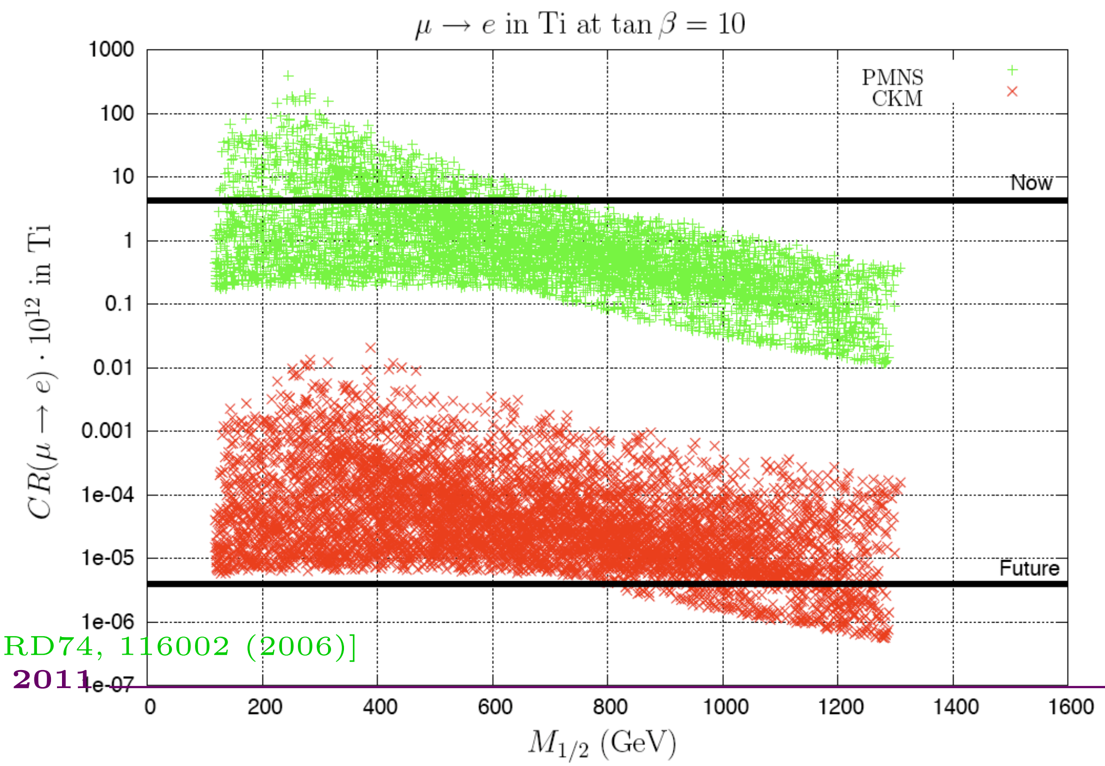
"Natural" solution: $\boxed{\boxed{\theta_{\tilde{e}\tilde{\mu}} = 0}}$ → modified by quantum corrections.



Randall-Sundrum Model (fermions in the bulk)

- dependency on UV-completion(?)
- dependency on Yukawa couplings
- "complementarity" between $\mu \to e\gamma$, $\mu - e$ conv

[Agashe, Blechman, Petriello, hep-ph/0606021]



SUSY GUT

- dependency on choice for neutrino Yukawa couplings
- scan restricted to scenarios LHC discovers new states.

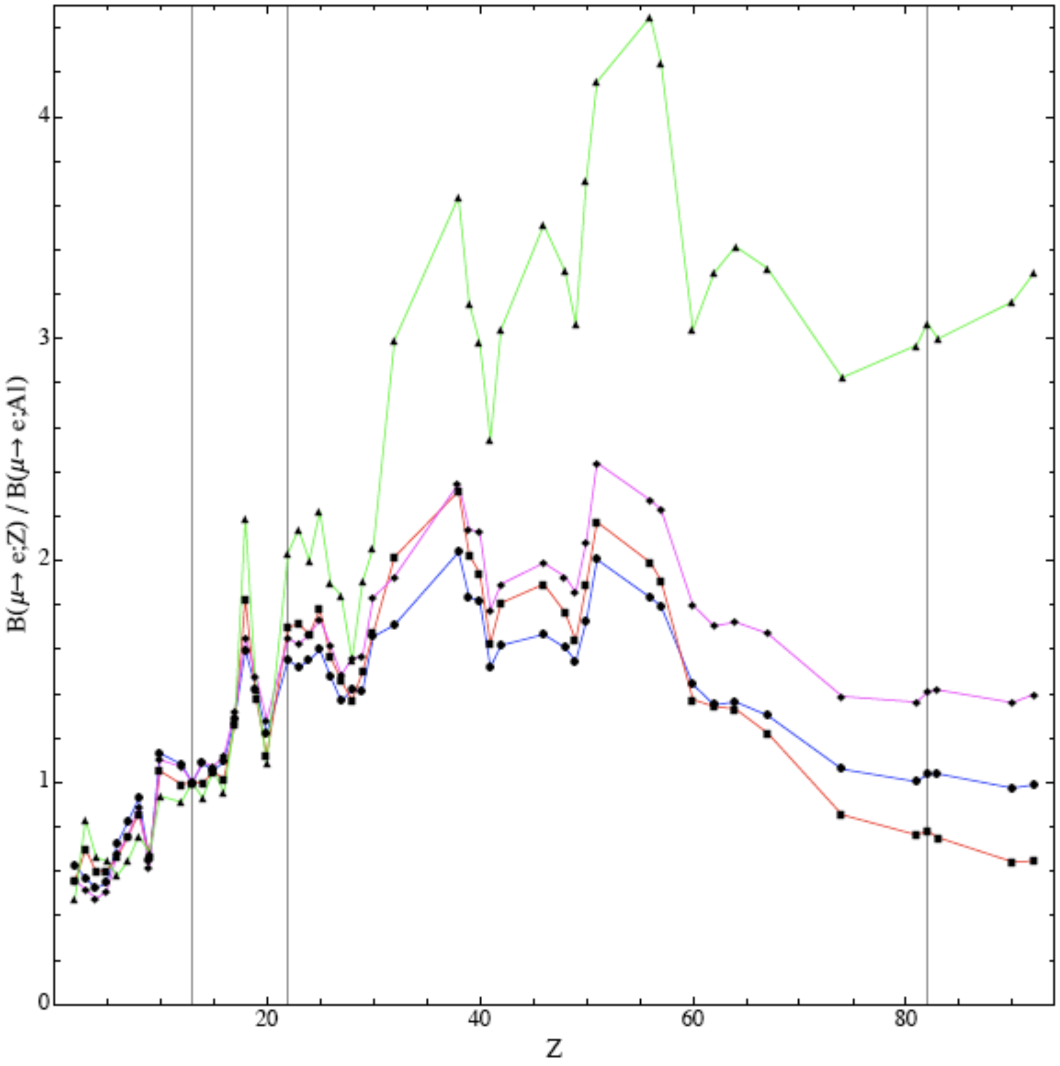
[Calibbi et al, PRD74, 116002 (2006)]

What is This Good For?

While specific models (see last slide) provide estimates for the rates for CLFV processes, the observation of one specific CLFV process cannot determine the underlying physics mechanism (this is always true when all you measure is the coefficient of an effective operator).

Real strength lies in combinations of different measurements, including:

- kinematical observables (e.g. angular distributions in $\mu \to eee$);
- other CLFV channels;
- neutrino oscillations;
- measurements of $g-2$ and EDMs;
- collider searches for new, heavy states;
- etc.



Vector 4-Fermion Interaction (Z)

$\propto (\bar{\mu}\gamma_\alpha e)(\bar{q}\gamma^\alpha q)$

Vector 4-Fermion Interaction (γ)

Dipole $(\propto \bar{\mu}\sigma_{\alpha\beta} e F^{\alpha\beta})$

Scalar 4-Fermion Interaction

$\propto (\bar{\mu}e)(\bar{q}q)$

Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum $(Z = 13)$ versus the atomic number Z for the four theoretical models described in the text: D (blue), S (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13\,$(Al), $Z = 22\,$(Ti), and $Z = 83\,$(Pb).

[Cirigliano, Kitano, Okada, Tuzon, 0904.0957]

Model Independent Comparison Between $g-2$ and CLFV:

The dipole effective operators that mediate $\mu\to e\gamma$ and contribute to a_μ are virtually the same:

$$\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}\mu F_{\mu\nu} \qquad \times \qquad \theta_{e\mu}\frac{m_\mu}{\Lambda^2}\bar{\mu}\sigma^{\mu\nu}eF_{\mu\nu}$$

$\theta_{e\mu}$ measures how much flavor is violated. $\theta_{e\mu}=1$ in a flavor indifferent theory, $\theta_{e\mu}=0$ in a theory where indiviadual lepton flavor number is exactly conserved.

If $\theta_{e\mu}\sim 1$, $\mu\to e\gamma$ is a much more stringent probe of Λ.

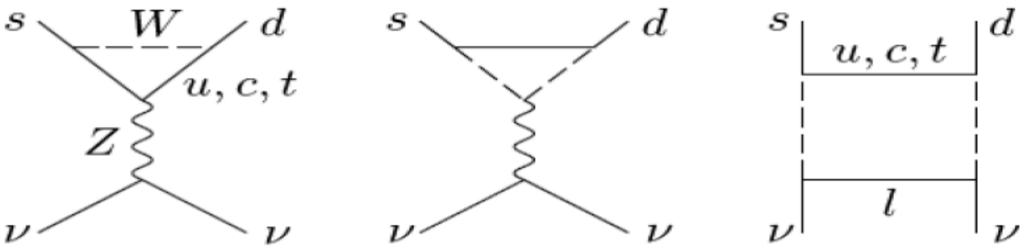
On the other hand, if the current discrepancy in a_μ is due to new physics, $\theta_{e\mu}\ll 1$ ($\theta_{e\mu}<10^{-4}$). [Hisano, Tobe, hep-ph/0102315]

e.g., in SUSY models, $Br(\mu\to e\gamma)\simeq 3\times 10^{-5}\left(\frac{10^{-9}}{\delta a_\mu}\right)\left(\frac{\Delta m^2_{\tilde{e}\tilde{\mu}}}{\tilde{m}^2}\right)^2$

Comparison restricted to dipole operator. If four-fermion operators are relevant, they will "only" enhance rate for CLFV with respect to expectations from $g-2$.

$K \to \pi\nu\bar{\nu}$ in the SM

2nd order weak: proceeds very slowly!



Standard Model (*Buras*):

$\text{Im}\,\lambda_t = \text{Im}V^*_{ts}V_{td} = \eta A^2\lambda^5$

$$B(K^0_L \to \pi^0\nu\bar{\nu}) = 1.8x10^{-10}\left(\frac{\text{Im}\,\lambda_t}{\lambda^5}X(x_t)\right)^2 = 2.5 \pm 0.40\,x10^{-11}$$

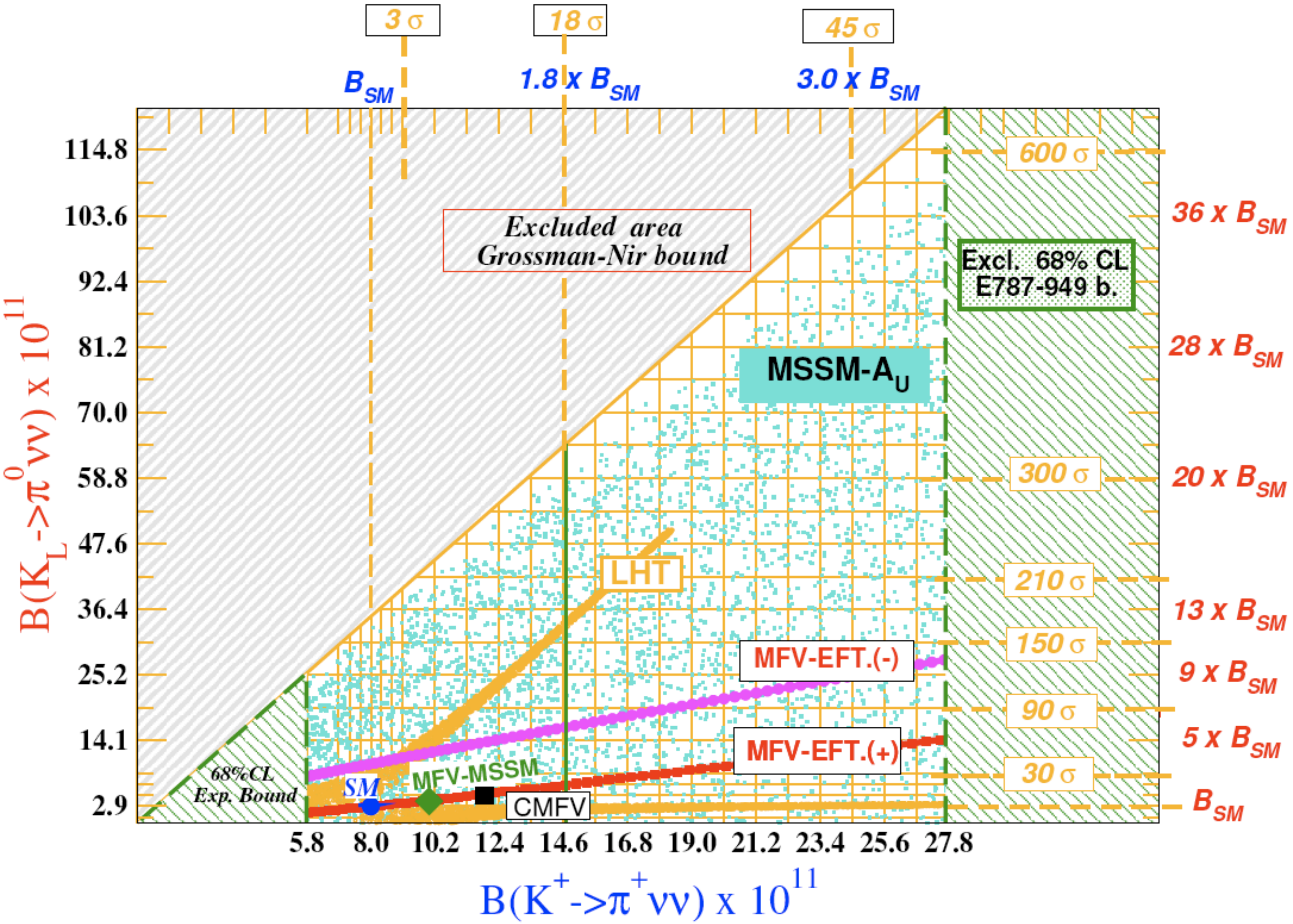
$(\pm 16\% \to \pm 12\%)$

$$B(K^+ \to \pi^+\nu\bar{\nu}) \sim 1.0x10^{-10}A^4\left[\eta^2 + (\rho_0 - \rho)^2\right] = 8.5 \pm 0.7\,x10^{-11}$$

$(\pm 8\% \to \pm 6\%)$

(From Talk by D. Bryman)

New Physics: Exchange $10^{-4}(M_W)^{-2}$ by $C_{\rm new}(M_{\rm new})^{-2}$

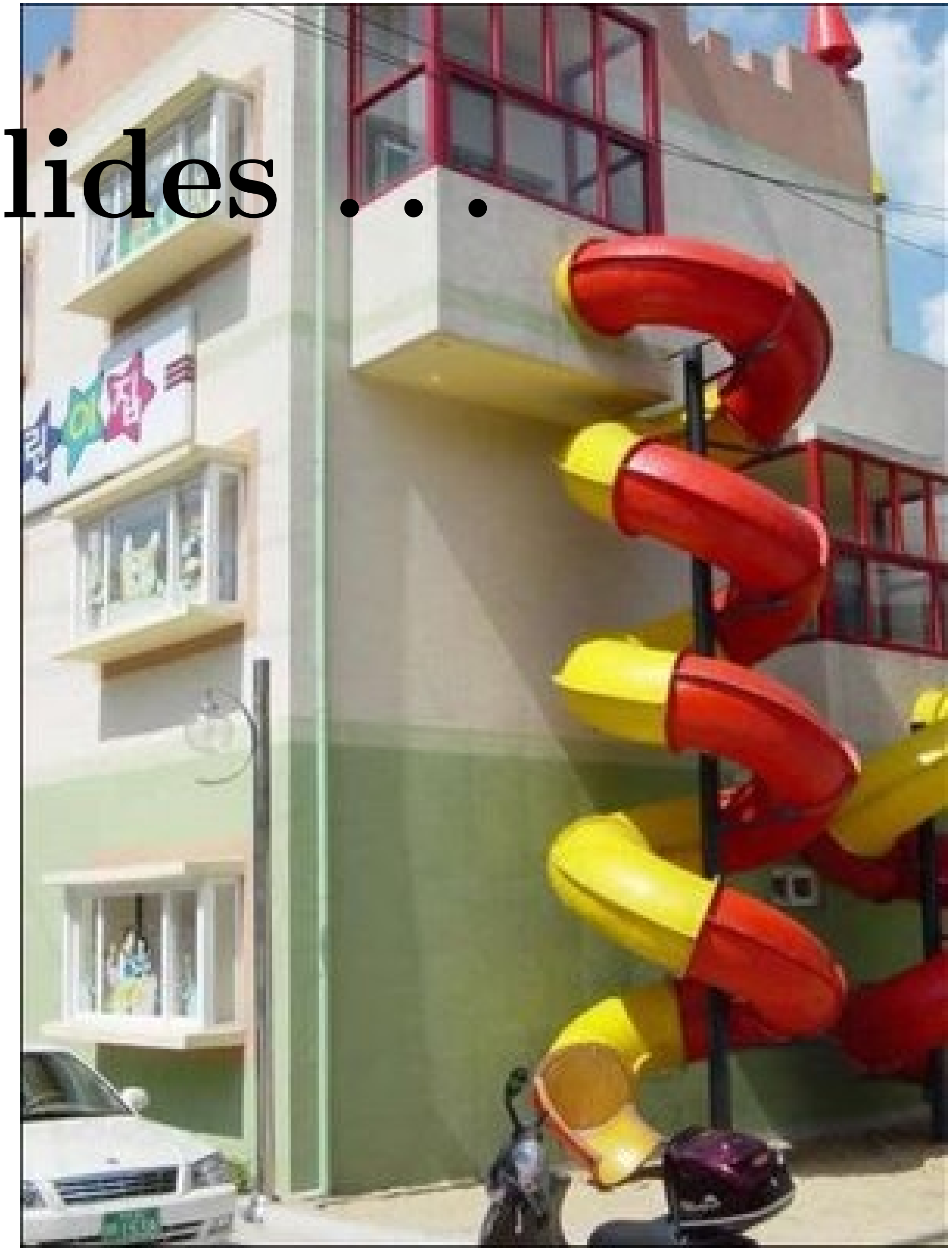


large data samples may teach us a lot . . . depending on where we are in (2017±?)

CONCLUSIONS

1. we have a very successful parametrization of the neutrino sector, but we still don't understand where neutrino masses (and lepton mixing) come from;
2. neutrino masses are very small – we don't know why, but we think it means something important. What are neutrinos trying to tell us?;
3. **we need more experimental data!** And there are some intriguing hints here and there. Help may come from many different sources: colliders, neutrino experiments, experiments with charged-leptons, etc.
4. Intensity Frontier experiments provide a very powerful probe of new physics (reach well beyond the TeV scale), whether or not this new physics has anything to do with neutrino masses.

Backup Slides . . .



Understanding Fermion Mixing

The other puzzling phenomenon uncovered by the neutrino data is the fact that Neutrino Mixing is Strange. What does this mean?

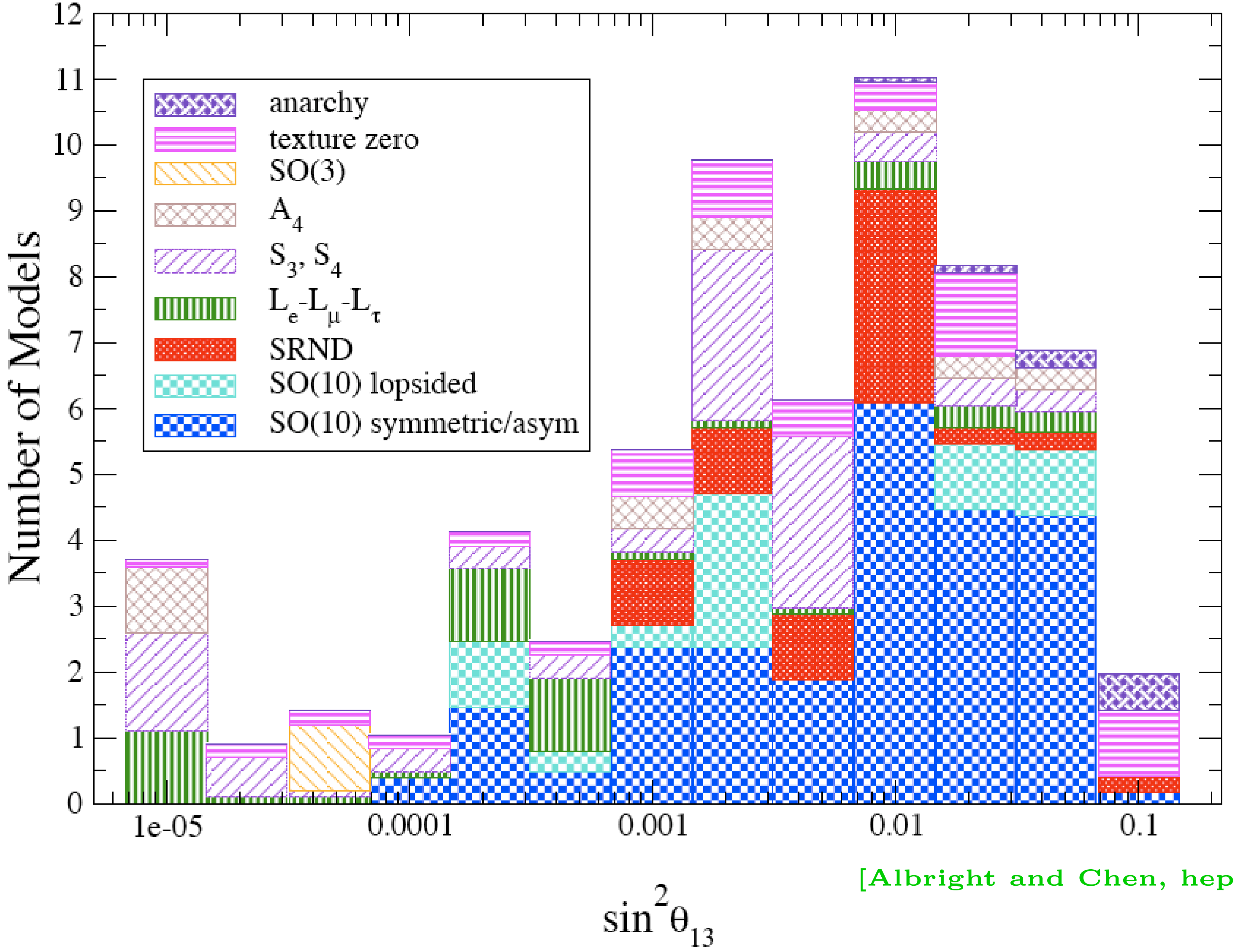
It means that lepton mixing is very different from quark mixing:

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & \mathbf{0.2} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \qquad V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

$[|(V_{MNS})_{e3}| < 0.2]$

$\boxed{\boxed{\text{WHY?}}}$

They certainly look VERY different, but which one would you label as “strange”?



[Albright and Chen, hep-ph/0608137]

pessimist – “We can’t compute what $|U_{e3}|$ is – must measure it!”

(same goes for the mass hierarchy, δ)

Comments On Current Flavor Model-Building Scene:

- VERY active research area. Opportunity to make *bona fide* prediction regarding parameters that haven't been measured yet but will be measured for sure in the near future → θ_{13}, δ, mass hierarchy, etc;
- For flavor symmetries, more important than determining the values of the parameters is the prospect of establishing non-trivial relationships among several interesting unkowns;

  e.g.,

  $$\sin^2\theta_{13} \sim \Delta m^2_{12}/|\Delta m^2_{13}| \text{ if hierarchy is normal,}$$
  $$\sin^2\theta_{13} \sim (\Delta m^2_{12}/|\Delta m^2_{13}|)^2 \text{ if hierachy is inverted}$$

  is common "prediction" of many flavor models (often also related to $\cos 2\theta_{23}$).

On very small Yukawa couplings

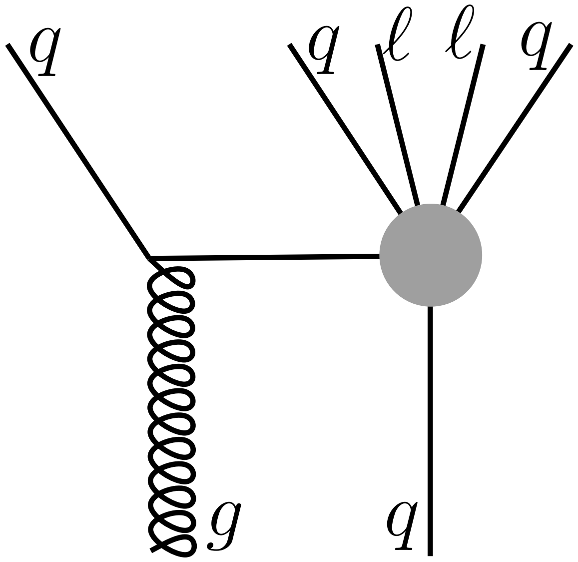
We would like to believe that Yukawa couplings should naturally be of order one.

Nature, on the other hand, seems to have a funny way of showing this. Of all known fermions, only one (1) has a “natural” Yukawa coupling – the top quark!

Regardless there are several very different ways of obtaining “naturally” very small Yukawa couplings. They require more new physics.

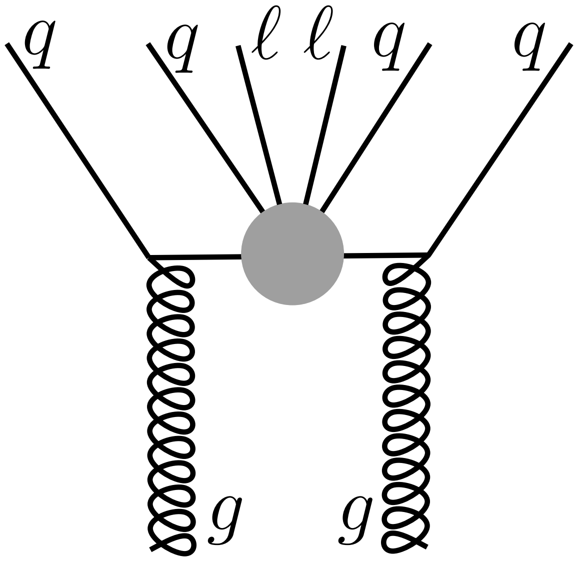
“Natural” solutions include flavor symmetries, extra-dimensions of different “warping,” . . .

LNV at Colliders ⇒ LHC: $pp \to \ell^\pm \ell^\pm +$ multi-jets



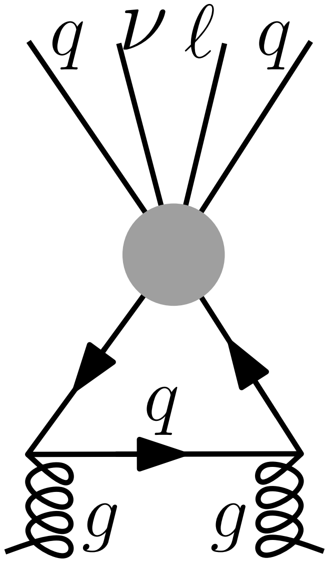
(a)

OK



(b)

OK



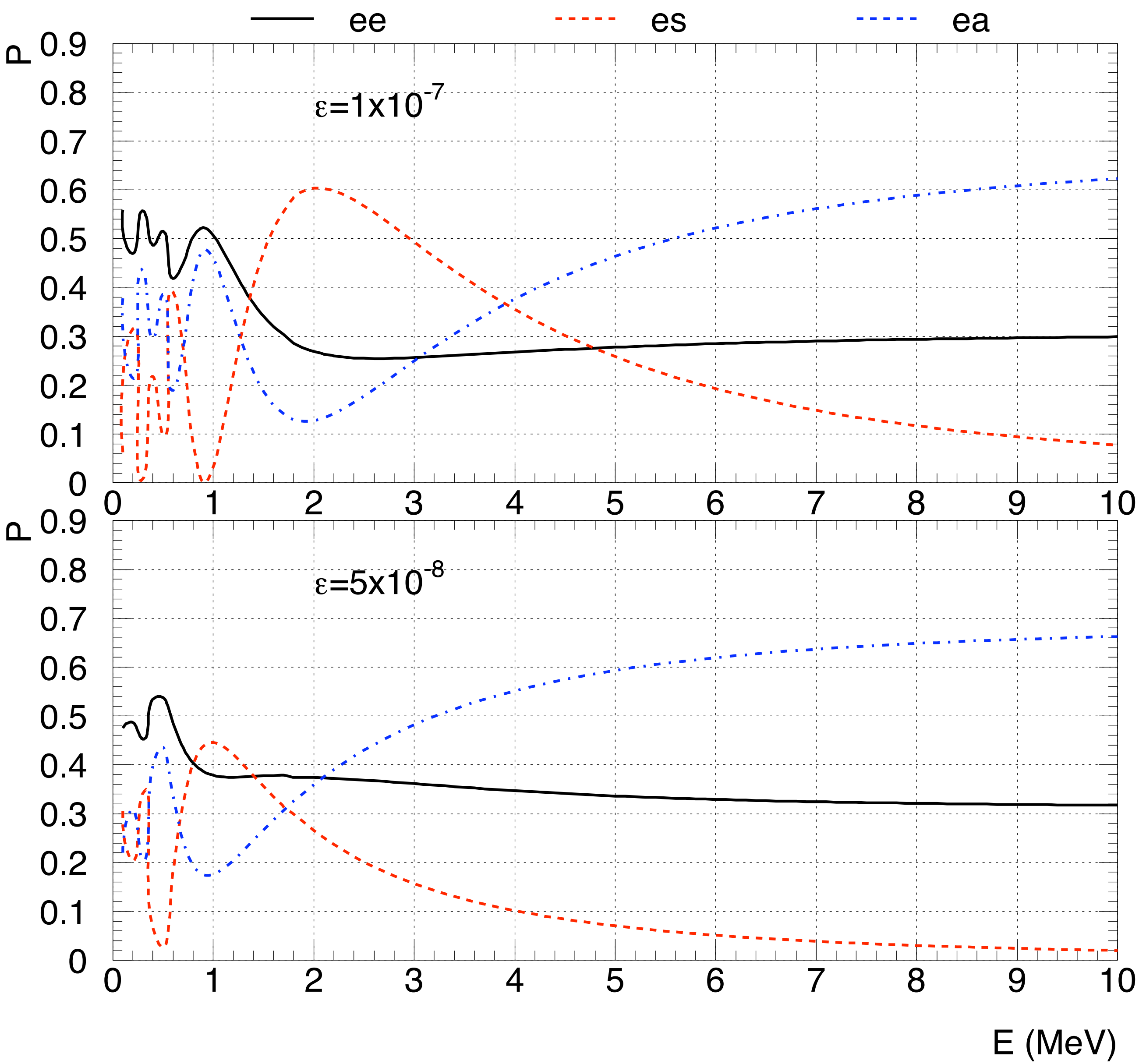
(c)

ν in final state

Going All the Way: What Happens When $M \ll \mu$?

In this case, the six Weyl fermions pair up into three quasi-degenerate states ("quasi-Dirac fermions").

These states are fifty–fifty active–sterile mixtures. In the limit $M \to 0$, we end up with Dirac neutrinos, which are clearly allowed by all the data.

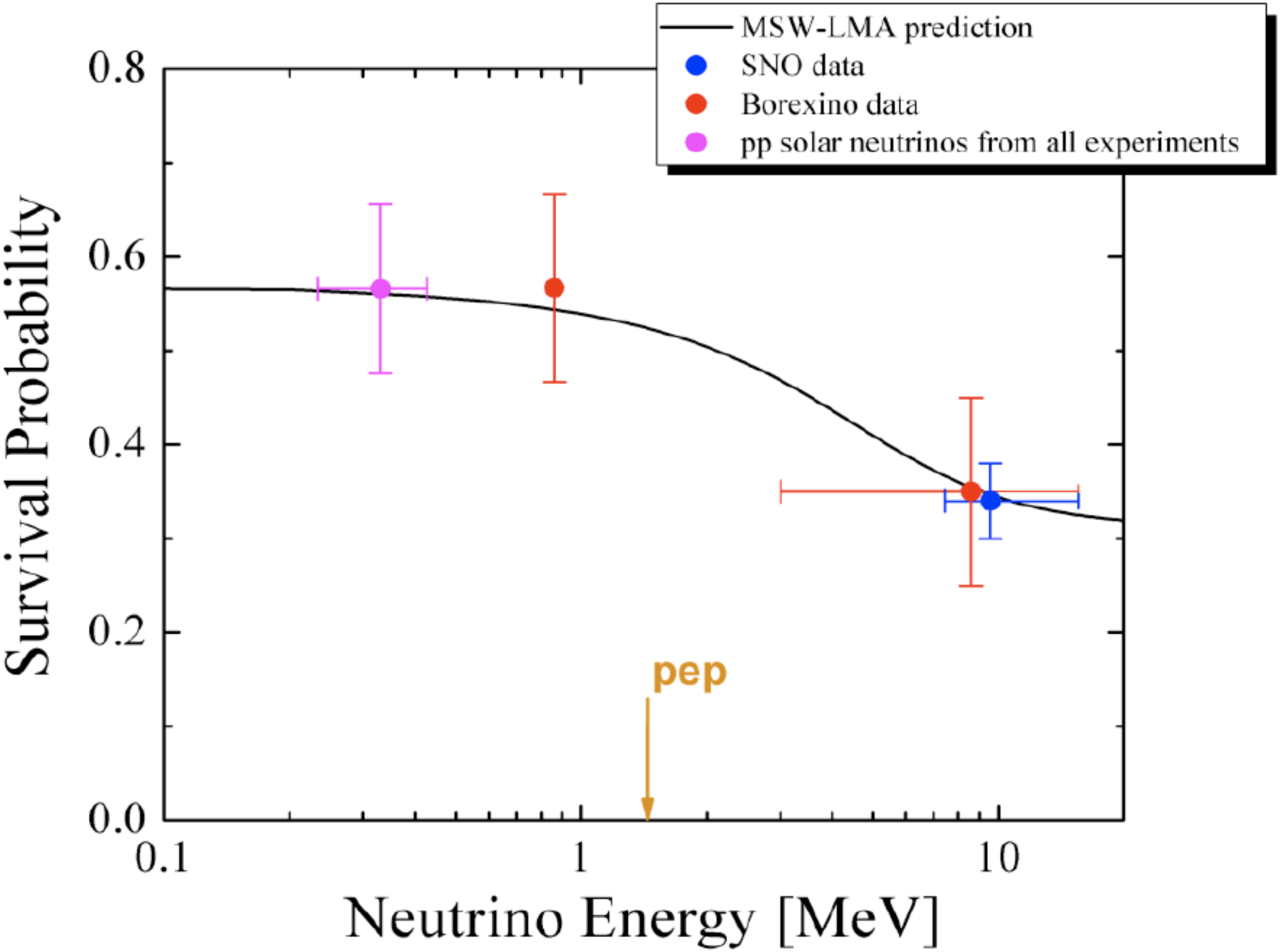


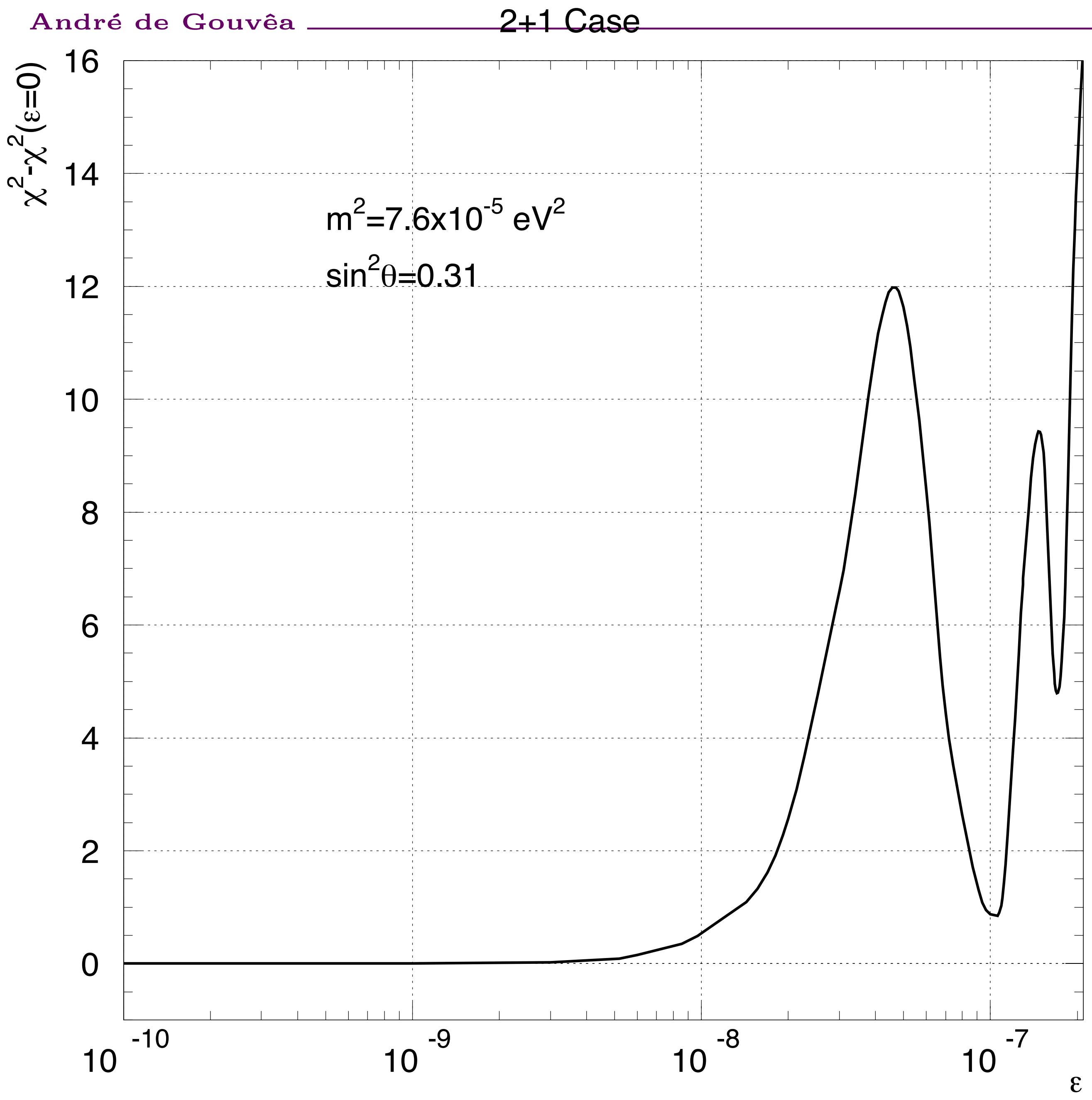
Quasi-Sterile Neutrinos

- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
- maximal mixing!
- Effects in Solar νs

[AdG, Huang, Jenkins, arXiv:0906.1611]

(Almost) All We Know About Solar Neutrinos





[AdG, Huang, Jenkins, arXiv:0906.1611]

Quasi-Sterile Neutrinos

- tiny new $\Delta m^2 = \epsilon \Delta m^2_{12}$,
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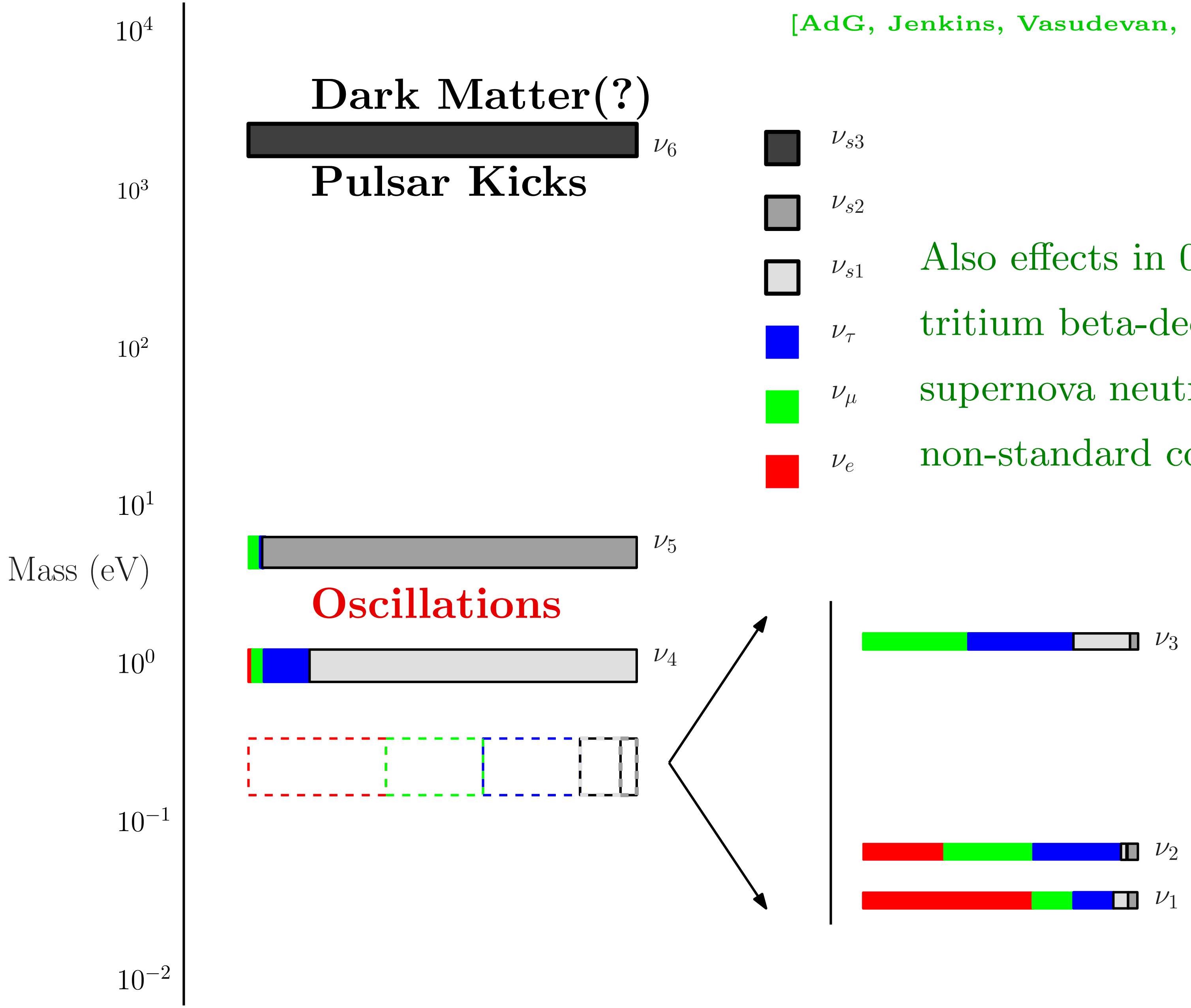
[AdG, Jenkins, Vasudevan, PRD75, 013003 (2007)]



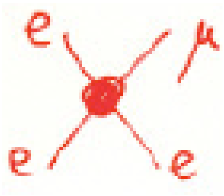
Also effects in $0\nu\beta\beta$,
tritium beta-decay,
supernova neutrino oscillations,
non-standard cosmology.

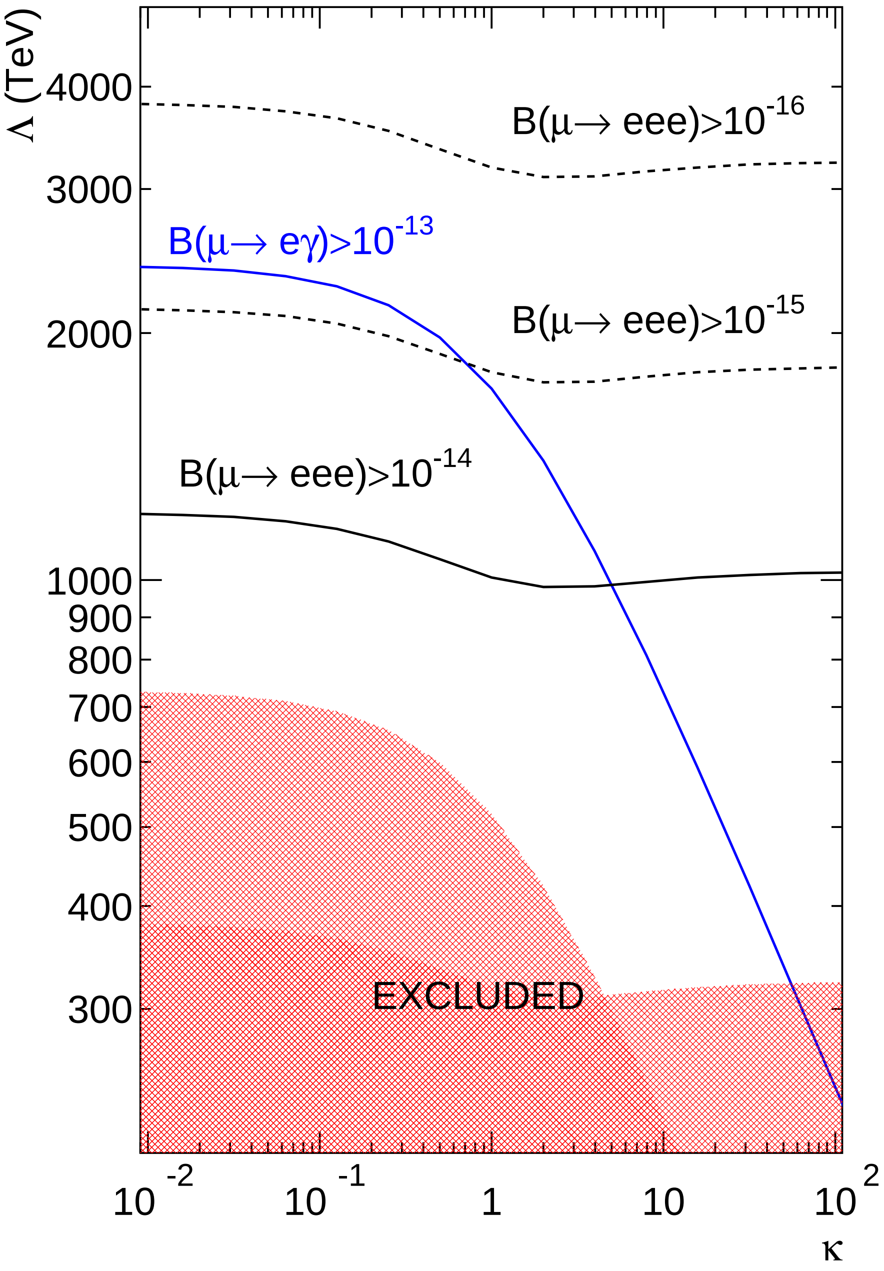
Other Example: $\mu \to e e^+ e^-$

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + $$

$$+ \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \bar{e}\gamma^\mu e$$

- $\mu \to eee$-conv at 10^{-16} “guaranteed” deeper probe than $\mu \to e\gamma$ at 10^{-14}.
- $\mu \to eee$ another way forward after MEG?
- If the LHC does not discover new states $\mu \to eee$ among very few process that can access 1,000+ TeV new physics scale: tree-level new physics: $\kappa \gg 1$, $\frac{1}{\Lambda^2} \sim \frac{g^2\theta_{e\mu}}{M^2_{\rm new}}$.





Who Cares About Neutrino Masses: Only* "Palpable" Evidence of Physics Beyond the Standard Model

The SM we all learned in school predicts that neutrinos are strictly massless. Massive neutrinos imply that the the SM is incomplete and needs to be replaced/modified.

Furthermore, the SM has to be replaced by something qualitatively different.

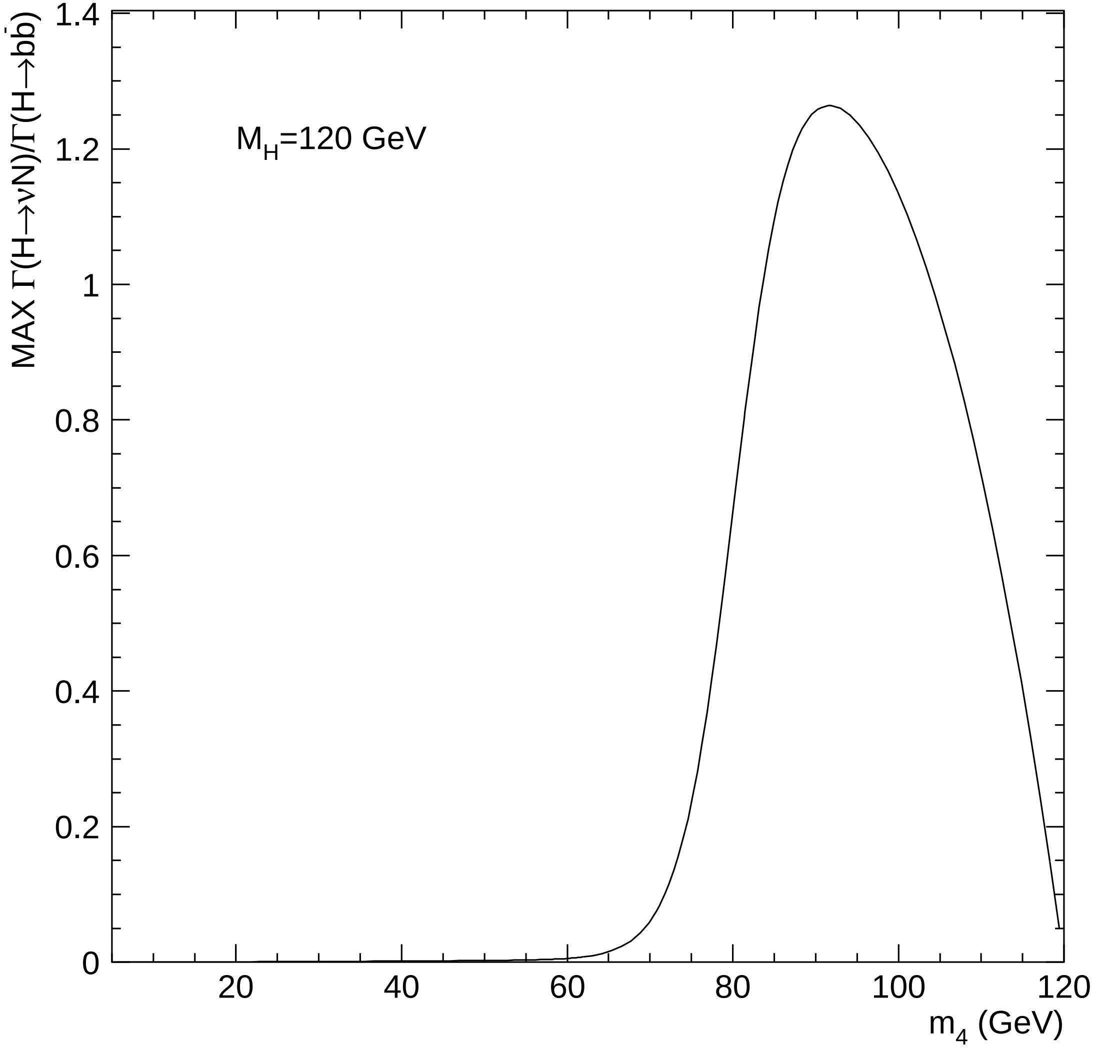
---

* There is only a handful of questions our model for fundamental physics cannot explain properly. These are, in order of "palpability" (my opinion):

- What is the physics behind electroweak symmetry breaking? (Higgs *or* not in SM).
- What is the dark matter? (not in SM).
- Why does the Universe appear to be accelerating? Why does it appear that the Universe underwent rapid acceleration in the past? (not in SM – is this "particle physics?").

Weak Scale Seesaw, and Accidentally Light Neutrino Masses

[AdG arXiv:0706.1732 [hep-ph]]



What does the seesaw Lagrangian predict for the LHC?

Nothing much, unless...

- $M_N \sim 1 - 100$ GeV,
- Yukawa couplings larger than naive expectations.

$\Leftarrow$ $H \to \nu N$ as likely as $H \to b\bar{b}$!

$\Big($NOTE: $N \to \ell q'\bar{q}$ or $\ell\ell'\nu$ (prompt)

"Weird" Higgs decay signature! $\Big)$

["No" Lepton Number Violation at Colliders]

Why are Neutrino Masses Small in the $M \neq 0$ Case?

If $\mu \ll M$, below the mass scale M,

$$\mathcal{L}_5 = \frac{LHLH}{\Lambda}.$$

Neutrino masses are small if $\Lambda \gg \langle H \rangle$. Data require $\Lambda \sim 10^{14}$ GeV.

In the case of the seesaw,

$$\Lambda \sim \frac{M}{\lambda^2},$$

so neutrino masses are small if either

- they are generated by physics at a very high energy scale $M \gg v$ (high-energy seesaw); or
- they arise out of a very weak coupling between the SM and a new, hidden sector (low-energy seesaw); or
- cancellations among different contributions render neutrino masses accidentally small ("fine-tuning").