Leptonic BSM,

Magnetic Moments and Majorana Masses

(things I learned when thinking about reconstructing new physics chez les leptons)

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IPN de Lyon

(ambitious) motivation (= daydreaming)

- we need New Physics to generate $[m_\nu]$
- Plethora of models — differing at high energy scale ?$\gtrsim$? ... E_{cm} of colliders within τ_{sacha}?

$\Rightarrow$ what can we reconstruct from the data? ??

...suppose (!)...$0\nu 2\beta$ but no info on new leptonic physics from the LHC... then:

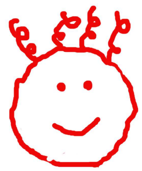
"if at the weak scale, we know the coupling of every possible interaction involving SM particles, of dim $< N$, what can we learn about the physics at higher energies?"

?? ?? ??

- toy model
  - suppose 3 light ν
  - suppose know coefficients of some $\Delta L = 2$ interactions of dim ≤ 7 :$[m_\nu]$, $[a]$

get distracted $\rightarrow$ 1. run coeffs of effective operators *up* in scale (SU(2) $\times$ U(1) RGEs ... what happens?)

2. suppose $[a]$, $[m_\nu]$ from 1-loop New Physics— solve (algebra) for masses and couplings ?
3. suppose generated at 2-loop, etc...



...it “works” in the SUSY seesaw

SD+Ibarra

Suppose usual $\mathcal{L}$ with 3 added singlets N (in N_K, charged lepton mass bases) :

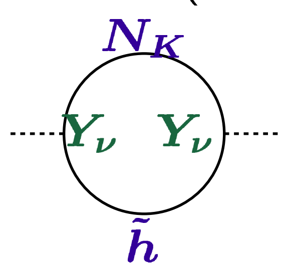
$$\mathcal{W} = \mathcal{W}_{MSSM} + N\mathbf{Y}_\nu L \cdot H_u - \frac{1}{2} N \mathcal{M} N$$

$\Rightarrow$ weak-scale neutrino mass matrix:

$$[m_\nu]_{ij} = [\mathbf{Y}_\nu{}^T]_{iK} \frac{1}{M_K} [\mathbf{Y}_\nu]_{Kj} \langle H_u^0 \rangle^2$$

flavour violation in sneutrino mass matrix (leading log):

$$[\tilde{m}^2]_{\mu e} \sim \tilde{\nu}_\mu$$



$$\tilde{\nu}_e \sim \frac{3m_0^2 + A_0^2}{8\pi^2} (\mathbf{Y}_\nu^\dagger)_{\mu K} (\mathbf{Y}_\nu)_{Ke} \log \frac{M_{GUT}}{M_K}$$

if universal soft masses, and ≤ 3 gen. of N, then:

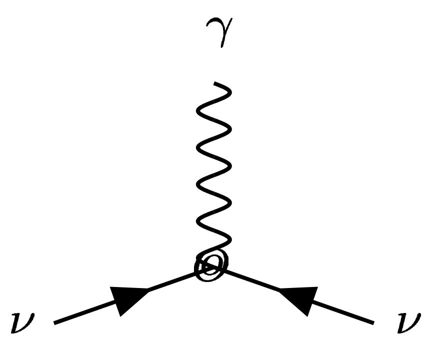
1. extract $Y^\dagger Y$ from $[m_{\tilde{\nu}}^2]$, $Y^\dagger Y = V_L^\dagger D_Y^2 V_L$
2. peal Y off outside of $[m_\nu]$: $D_Y^{-1} V_L^* [m_\nu] V_L^\dagger D_Y^{-1} = V_R^* D_{\mathcal{M}}^{-1} V_R^\dagger$

from masses at m_W, extract $D_{\mathcal{M}} = \{M_1, M_2, M_3\}$ and $\mathbf{Y}_\nu = V_L^\dagger D_Y V_R$ in “$D_{\mathcal{M}}, D_{me}$” basis

Constraints on operators responsable for

Magnetic Moments *from* *Majorana Masses*

S D + M Gorbahn + A Santamaria



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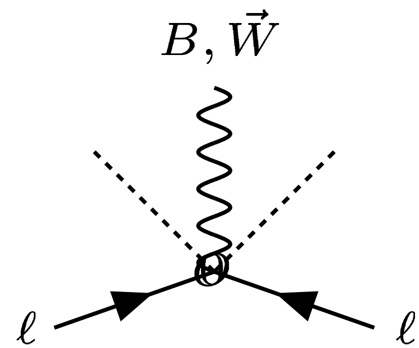
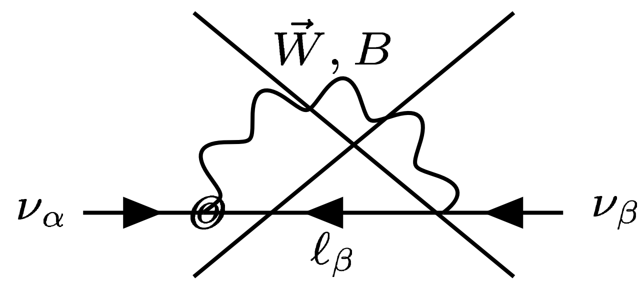
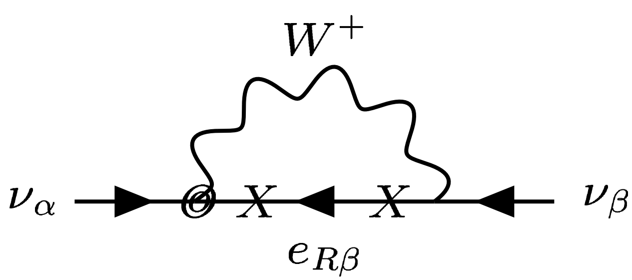
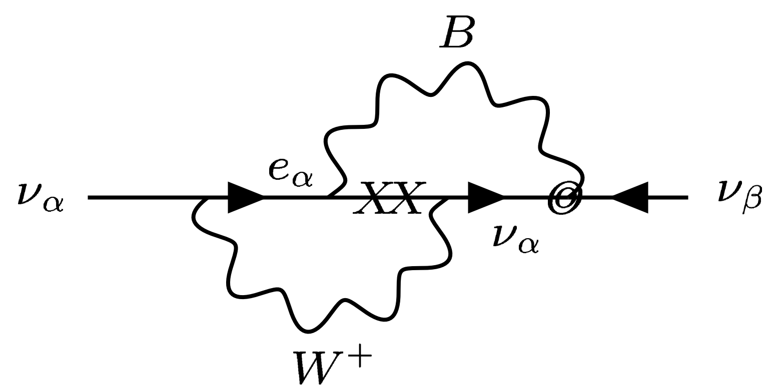


$\Rightarrow$ (?)







hep-ph/0505...

Outline

1. (ambitious) motivation...to more manageable project:

2. transition magnetic moments $a_{\alpha\beta}$: (from MeV $\rightarrow \Lambda_{NP}$)
   - notation
   - experimental bounds
   - SM operators
   - "theoretical expectations"

3. "bottom-up" pheno:
   - SM loops: $a \rightarrow \delta m_\nu$
   - for certain parameters, $[\delta m_\nu] > [m_\nu]$

4. detour: what do we know about $[m_\nu]$?

5. back to mag mo calculation: so what?
   - bounds on coefficients of non-renorm operators

6. summary

Transition magnetic moments (for majorana νs)

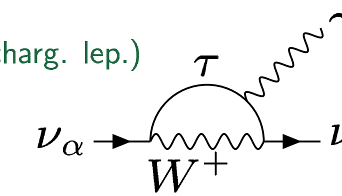
Nieves
Kayser
Shrock
Li+Wilcek

the magnetic moment interaction : $\frac{a}{2}\overline{\psi_R}\sigma^{\mu\nu}\psi_L F_{\mu\nu} + h.c.$ $\left\{ \begin{array}{l} \text{chirality flip} \\ \text{dimension 5} \end{array} \right.$

(for e^-: Gordon decomp. gives $a = \frac{2e}{2m_e} \equiv 2\mu_B$)

know: (small) neutrino masses $\rightarrow$ (smaller) magnetic moments $a \sim \frac{m_\nu m_\tau^2}{m_W^4}$ (τ = charg. lep.)

(veery small. forget)



question: mass? $\leftarrow$ LARGE magnetic moment

suppose neutrinos are majorana, then : $\frac{a_{\alpha\beta}}{2}\overline{\nu^c}_\alpha\sigma^{\mu\nu}\nu_\beta F_{\mu\nu} + h.c.$ $\left\{ \begin{array}{l} \Delta L = 2 \\ a_{\alpha\beta} = -a_{\beta\alpha} \end{array} \right.$

(so $a_{\alpha\alpha} = 0$)

Constraints

MUNU / LSND / DONUT

Raffelt

no evidence for a in $t \to 0$ $\bar{\nu}e$ scattering in the lab:

$$a_{e\beta} \leq 0.9 \times 10^{-10} \mu_B, \qquad a_{\mu\beta} \leq 6.8 \times 10^{-10} \mu_B$$

a induces $\gamma \to \nu\nu$ cooling of stars. From the lifetime of red giants:

$$a_{\alpha\beta} \quad \leq \quad 3 \times 10^{-12} \mu_B$$

if $a \neq 0$, in the solar $\vec{B}$ field $\Rightarrow$ time dependence of solar ν_α fluxes, also $\bar{\nu}_\beta$ flux from sun. Upcoming experiments could be sensitive to

$$a_{\alpha\beta} \quad \gtrsim \quad 10^{-13} \mu_B$$

Balantekin+Volpe

$\Rightarrow$ suppose $a \sim$ upper bound — does it give an " interesting" contribution to $[m_\nu]$?

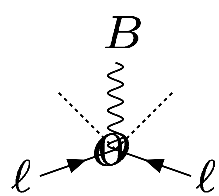
in the SM above m_W...

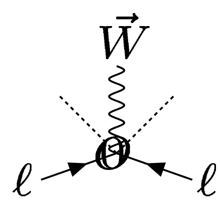
Transition magnetic moment: $\frac{a_{\alpha\beta}}{2}\overline{\nu^c}_\alpha \sigma^{\mu\nu}\nu_\beta F_{\mu\nu} + h.c.$

Suppose there is New Physics at $\Lambda_{NP} \gg m_W$, that produces $[a]$. Then below Λ_{NP}, have possible effective operators in the SM:

$$C_B \ (\bar{\ell}^c H)\sigma^{\mu\nu}(H\ell)B_{\mu\nu}$$
$$C_W \ \varepsilon_{abd}(\bar{\ell}^c\tau^a\ell)(H\tau^b H)W^d_{\mu\nu}$$

where ℓ = lepton doublet. $C_J \sim 1/\Lambda^3_{NP}$





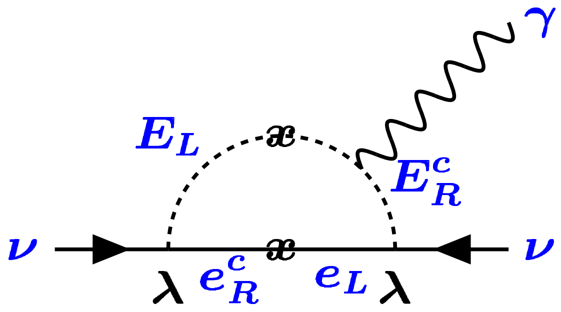
$\Rightarrow a \sim \frac{v^2}{\Lambda^3_{NP}}$

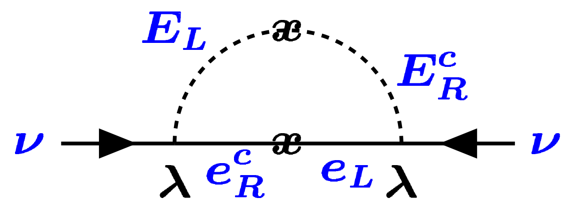
$N.B.$ $10^{-12}\mu_B$ is **BIG** : $\qquad \frac{v^2}{\Lambda^3_{NP}} = 10^{-12}\mu_B \Rightarrow \Lambda_{NP} \lesssim 10TeV$

model-building intermission: some possibilities (inside the blob)

Voloshin
BabuMohapatra
GeorgiRandall
Chang+...
Barr+...

$a \sim 10^{-12}\mu_B$ for ν_{sun} (?), but $m_\nu \lesssim$ eV $\Rightarrow$ problem for models ($e.g.$ in RPV SUSY):





$$a \sim \frac{\lambda^2 m_f^2 A}{m_S^4} \qquad m \sim \frac{\lambda^2 m_f^2 A}{m_S^2}$$

$$\text{so}\ \ a \sim 10^{-12}\mu_B \Rightarrow m_\nu \sim m_S^2 a \sim \text{MeV}\left(\frac{m_S}{\text{TeV}}\right)^2$$

"natural" solutions:

- Voloshin, ...: $a_{\alpha\beta}$ is flavour *antisymmetric*, arrange cancellations among the diagrams contributing to the flavour *symmetric* mass matrix

- Barr Freire,Zee: forbid by angular momentum conservation (spin) the magnetic moment diagram with its photon removed.

I am $\mathcal{NOT}$ building a model ! I do effective theory below Λ_{NP}

Outline (...again...where are we?)

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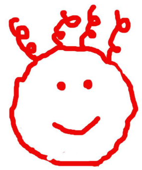
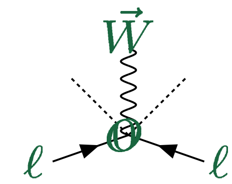
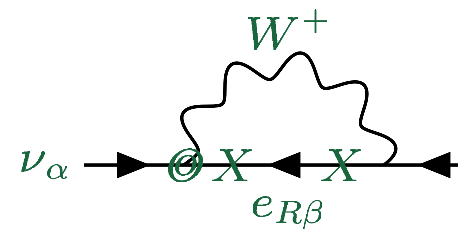


contribution to $[m_\nu]$ of $a \sim 10^{-12}\mu_B$ (large)...

1. Suppose $a_{\alpha\beta}$ is generated by $O^W = \varepsilon_{abd}(\bar{\ell}^c \tau^a \ell)(H\tau^b H)W^d_{\mu\nu}$:



2. leading log contribution of O_W to the dim 7 mass operator $O^M = (\overline{\ell^c}H)(H\ell)(H^\dagger H)$ from:



3. approximate solution:

$$\begin{aligned}[\delta m]_{\alpha\beta} &\simeq \frac{6g}{16\pi^2 s_W}(m_\alpha^2 - m_\beta^2)a_{\alpha\beta}\ln\left(\frac{\Lambda_{NP}}{m_W}\right) \\ &\sim 0.1\text{eV} \quad (\text{for } a_{\alpha\tau} = 10^{-12}\mu_B)\end{aligned}$$

results

O_W contributes to mag mo:

$$[a] = 2v^2 s_W [C_W]$$

and to the neutrino mass matrix ($a_{\alpha\beta} = \tilde{a}_{\alpha\beta} \cdot 10^{-12} \mu_B$):

$$[\delta m] \quad = \quad \left[\begin{array}{ccc} 0 & 0.004\tilde{a}_{e\mu} & \tilde{a}_{e\tau} \\ 0.004\tilde{a}_{e\mu} & 0 & \tilde{a}_{\mu\tau} \\ \tilde{a}_{e\tau} & \tilde{a}_{\mu\tau} & 0 \end{array} \right] \times .1\text{eV}$$

large atm mixing!
...but not pheno. viable
: (

$\Delta m^2_{atm} = (0.049eV)^2$, $\Delta m^2_{sol} = (0.0089eV)^2$, $\theta_{23} \simeq \pi/4$, $\theta_{12} \simeq \pi/6$, $s \equiv \sin\theta_{13} \leq .2$

- if $a_{\alpha\tau} \gtrsim 10^{-12}\mu_B$ and non- degen m_ν, then mild cancellation $\delta m \leftrightarrow [m_\nu]$ required.
- if $a_{e\tau} \sim 10^{-12}\mu_B$ and hierarchical m_ν,

$$[m_\nu]^{hier} \sim \left[\begin{array}{ccc} .06 & .06 + .35s & -.06 + .35s \\ .06 + .35s & .06 + .25 & -.06 + .25 \\ -.06 + .35s & -.06 + .25 & .06 + .25 \end{array} \right] \times .1\text{eV} \quad .$$

$$\Rightarrow \frac{[\delta m_\nu]_{e\tau}}{[m_\nu]_{e\tau}} \sim 10$$

$\Rightarrow a_{e\tau} < 10^{-13}\mu_B$, or cancellation (peculiar, unexpected, not impossible)

- $[\delta m]_{\mu e} \ll m_{\mu e}$

detour: what do we know about $[m_\nu]$?

not enough ν_μ arrive from the atmosphere, deficit consistent with KEK to SK deficit (K2K)
($\pi \to \mu\bar{\nu}_\mu \to e\nu_\mu\bar{\nu}_e$) ($\nu_\mu$ beam)

not enough ν_e arrive from the sun (MSW) , *and* deficit of $\bar{\nu}_e$ at KamLAND (vacuum osc)
(ν_e from nuclear fusion) ($\bar{\nu}_e$ from fission reactors)

$\Rightarrow$ ν have small masses and "oscillate":

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{(m_\alpha^2 - m_\beta^2)L}{2E}\right) \qquad \text{(2 flavour)}$$

(*NOT* seeing decays, precession due to mag mos, non-standard interactions...)

combined fit numbers

in "flavour" basis (charged lepton mass basis):

$$[m_\nu^2]_{\alpha\beta} = V D_{m\nu}^2 V^\dagger \qquad D_{m\nu}^2 = diag\{m_1^2, m_2^2, m_3^2\}$$

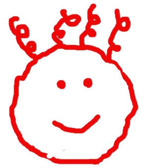
$$V_{fm} = \begin{bmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta} & c_{13}c_{23} \end{bmatrix}.$$

energies/baselines for $\Delta m_{31}^2 = m_3^2 - m_1^2$ (atm, K2K, CHOOZ):

$$\begin{aligned} \Delta m_{31}^2 &= (0.049\mathrm{eV})^2 \quad \pm 0.6 \times 10^{-3}\ eV^2 \\ \sin^2\theta_{23} &= 0.45 \pm \sim .15 \quad (\text{incident } \nu_\mu) \\ \theta_{13} &\lesssim 0.18 \quad (\text{incident } \bar{\nu}_\mathrm{e}) \end{aligned}$$

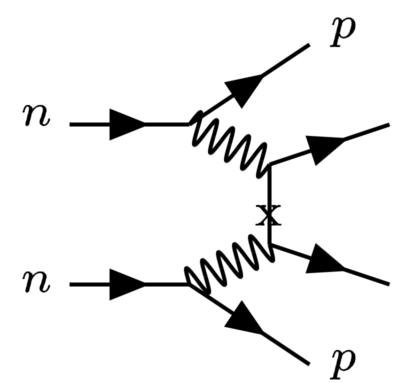
energies/baselines for $\Delta m_{21}^2 = m_2^2 - m_1^2$ (sun, KamLAND):

$$\begin{aligned} \Delta m_{21}^2 &\simeq (0.0089\mathrm{eV})^2 \quad \pm 0.6 \times 10^{-5} eV^2 \\ \sin^2\theta_{12} &\simeq 0.31 \pm + 0.05 \end{aligned}$$



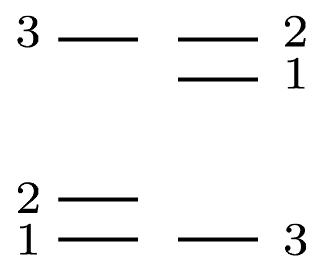
what we don't know...

1. how many Δm^2? — are there sterile mass eigenstates?
   test LSND ($\Delta m^2 \sim eV^2$) with MiniBoone— results $\nu_\mu \to \nu_e$ late 2005?
2. are ν masses majorana ($\Delta L = 2$) or Dirac (6 light 2-comp ν)
   ΔL process...*e.g.* $0\nu 2\beta$



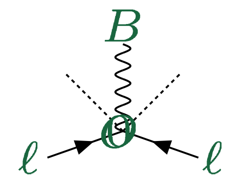
3. mass pattern:
   - hierarchical: $m_3 > m_2 > m_1$
   - inverted :$m_1, m_2 > m_3$

   $0\nu 2\beta$, ν beams under discussion



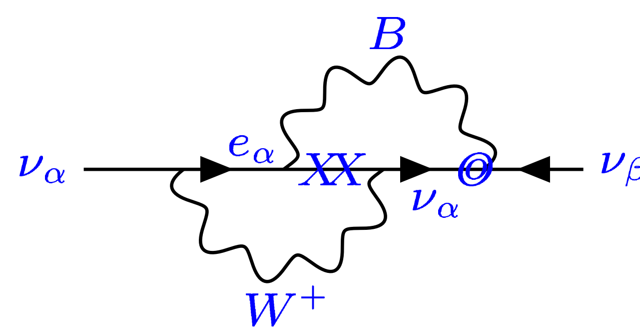
4. absolute mass scale
   - spectrum endpoint in β decay $|U_{ei}|^2 |m_i|^2$, $\lesssim 1$ eV
   - $0\nu 2\beta$: $\mathcal{M}_{nucl} |U_{ei}^2 m_i|$, !! $.2 \to 1$ eV
   - cosmology $\sum_i m_i \lesssim 0.46$ eV ($\to\sim 2$ eV)
5. θ_{13}, δ...

what about O_B



1. Suppose $a_{\alpha\beta}$ is generated by $O^B = (\bar{\ell}^c H)\sigma^{\mu\nu}(H\ell)B_{\mu\nu}$:

2. *could* calculate contribution to $[m_\nu]$ by operator mixing during RG running $\Lambda_{NP} \to m_W$:
   - match $[C_B]$ onto $[a]$ at $\mu \sim m_W$
   - Run $[C_B]$: $m_W \to \Lambda_{NP}$ (order 1 change, so forget)
   - run back to m_W: O^B can mix with O_W and other dim 7 operators...
   - calculate anomalous dim matrix $[\gamma]$ for $\{O_B$, ops it mixes into at one loop which also mix into O^M at one loop, $O^M\}$



3. but... estimate:

$$[\delta m]_{\alpha\beta} \sim \frac{6g'\alpha_W|m_\alpha^{e2} - m_\beta^{e2}|}{64\pi^3} a_{\alpha\beta} \log^2\left(\frac{\Lambda_{NP}}{m_W}\right)$$

$$\sim \frac{\alpha_{em}}{\pi} \cdot (1 - \text{loop estimte})$$

$$\Rightarrow \quad [\delta m]_{\alpha\beta} \leq [m]_{\alpha\beta}$$

better bound on $[C_B]_{\alpha\beta}$ from mag mos than masses

so what? Back to motivation...

...umm...no progress, going backwards:

another source of confusion in reconstruction: $[m_\nu]/v^2$ is the coefficient of of

$$(H\ell)(H\ell)\left(C^0 + C^1\frac{v^2}{\Lambda_{NP}^2} + ...\right)$$

I want to set $C^0 = [m_\nu]/v^2$. But is it?? If $C^0 = 0$ by some symmetry, how could I tell??

Summary

current bounds on neutrino magnetic moments are $a \lesssim 10^{-10}\mu_B$ (lab), $3 \cdot 10^{-12}\mu_B$ (astro).
Upcoming expts and solar physics could be sensitive to $a \gtrsim 10^{-13}\mu_B$. $[\mu_B = e/(2m_e)]$.

neutrino mass differences and mixing angles we know form oscillation expts:
$\Delta m^2_{atm} = (0.049eV)^2$, $\Delta m^2_{sol} = (0.0089eV)^2$, $\theta_{23} \simeq \pi/4$, $\theta_{12} \simeq \pi/6$, $\sin\theta_{13} \leq .2$

It is well known that a majorana mass induces a (small) transition magnetic moment

but...small m_ν as observed $\Rightarrow$ undetectable a

Converse is also true: operators generating mag. mo. $a_{\alpha\beta}$ contribute via loops to $[m_\nu]_{\alpha\beta}$.

large a near current bound $\Rightarrow$ contribution $[\delta m_\nu] \sim [m_\nu]$

two SU(2)×U(1) invariant, dimension 7 operators that could induce the transition mag moment.
Operator coefficients are bounded by $[a]$, $[\delta m_\nu] <$ expt:

$C_W\ \varepsilon_{abd}(\bar{\ell}^c \tau^a \ell)(H\tau^b H)W^d_{\mu\nu}$ (so $e\nu W^+$ exists)

- *if* non-degen m_ν, then $[\delta m_\nu] \lesssim [m_\nu] \Rightarrow a_{\alpha\tau} \lesssim 3 \times 10^{-13}\mu_B$
- *if* hierarchical m_ν, then $[\delta m_\nu] \lesssim [m_\nu] \Rightarrow a_{e\tau} \lesssim 10^{-13}\mu_B$
- strongest bounds on $[C_W]_{e\mu}$ are from $a_{e\mu}$

$C_B\ (\bar{\ell}^c H)\sigma^{\mu\nu}(H\ell)B_{\mu\nu}$ (only $\nu\nu Z/\gamma$ mag mo interaction),

- best limit on $[C_B]_{\alpha\beta}$ is astro mag mo