BSM

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KIAS

Beyond Standard Model

Below

Advanced

From A to B.

Is SM the end of story?

Very successful but still problematic

→ TC

i) Higgs vacuum $\langle H \rangle \ll M_{NP} \ll M_{pl}$

10^{2} GeV 10^{10-16} GeV 10^{19} GeV

Vacuum stability

ii) Too many parameters, too hierarchical.

g_1, g_2, v, m_h m_ν m_e m_t

$m_q, M_\ell, V_{CKM}, V_{PMNS}$ 10^{-10} 10^{-3} 10^{2} GeV

6 6 4 4+2

→ flavor changing neutral processes? ✓

iii) Strong CP problem: $|\theta| \lesssim 10^{-10}$? ✓

→ axion & ALP

iv) Neutrino masses and mixing? ✓

v) Dark matter? → Andreas

vi) Baryon Asymmetry of Universe: $\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-9}$?

→ Leptogenesis, ALP-genesis.

EXD

Z',W'

X

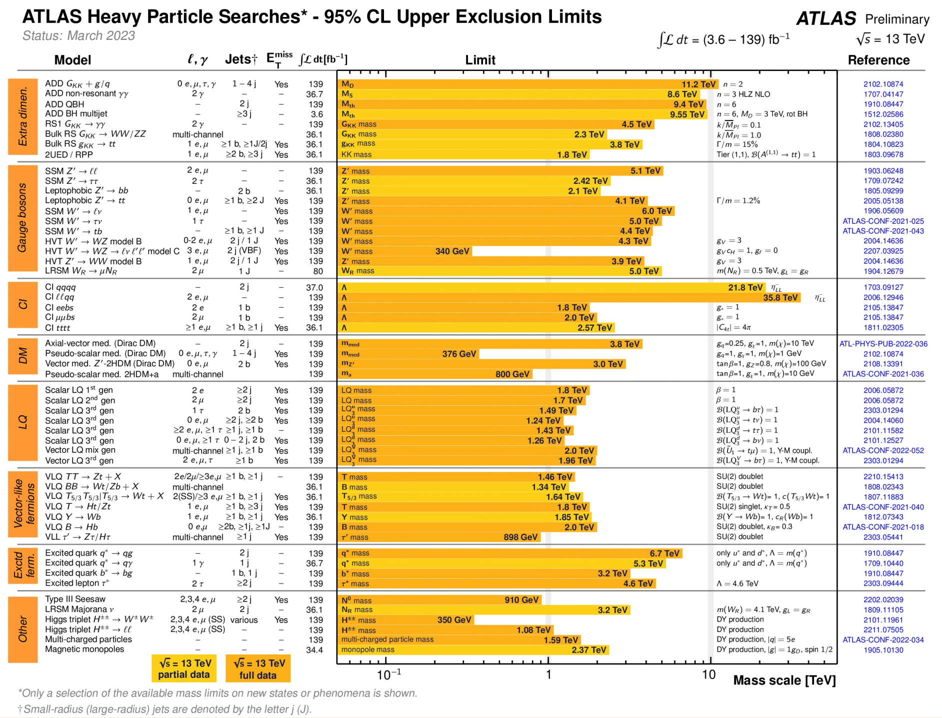
DM

LQ

VLQ

q'

Seesaw



h'

X

DS

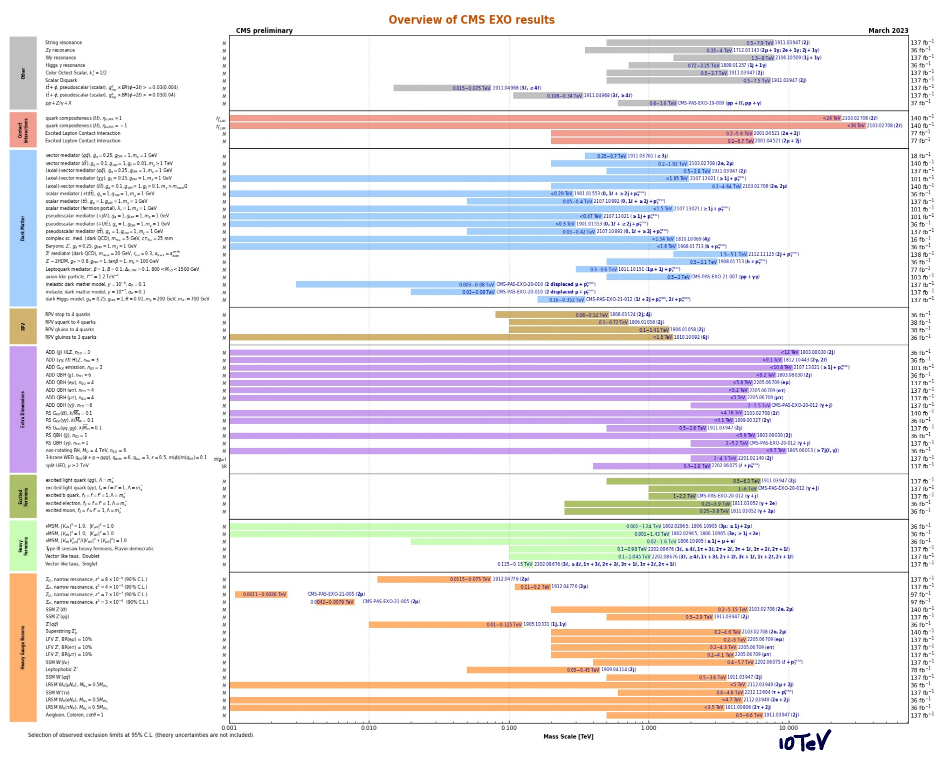
RPV

EXD

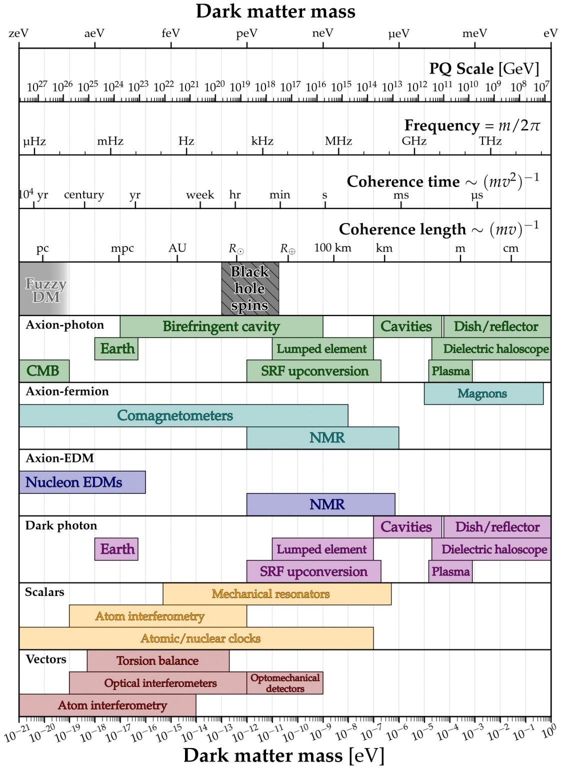
q'

N

Z',W'



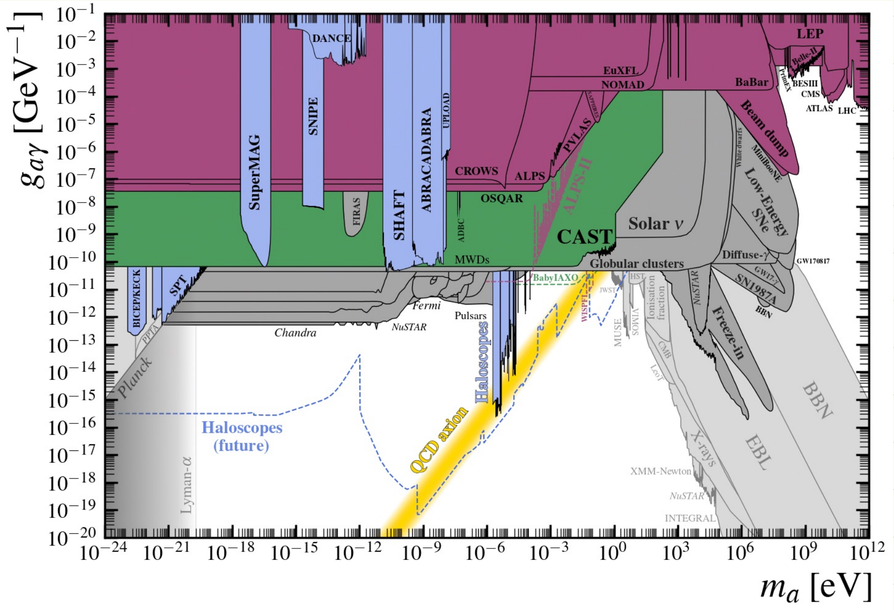
10TeV



[github.com/cajohare]

ULDM

ALP



A. 4 component $\leftrightarrow$ 2 component

chiral representation

[Haber-Kane, 1985 Appendix A.]

[Peskin, QFT]

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar\sigma^\mu & 0 \end{pmatrix}, \quad \sigma^\mu = (1, \vec\sigma), \quad \bar\sigma^\mu = (1, -\vec\sigma)$$

$$\gamma_5 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}$$

"anticommuting"

$\Uparrow$

ξ, η 2-component chiral fermion

$$\psi = \begin{pmatrix} \xi \\ \bar\eta \end{pmatrix}, \quad \bar\eta \equiv i\sigma^2\eta^*$$

Dirac $\xi \neq \eta$

Majorana $\xi = \eta$

$$\psi^c = C\bar\Psi^T = -i\gamma^2\psi^* = \begin{pmatrix} \eta \\ \bar\xi \end{pmatrix}$$

$$\begin{cases} \bar\Psi \equiv \psi^\dagger\gamma^0 \\ C = -i\gamma^2\gamma^0 \end{cases}$$

$$\overset{h.c.}{\longleftrightarrow}$$

Mass: $$\bar\Psi\Psi = \bar\Psi_R\Psi_L + \bar\Psi_L\Psi_R$$

$$= \eta^T(-i\sigma^2)\xi + \xi^\dagger(i\sigma^2)\eta^*$$

$$\left(\equiv \eta\cdot\xi + \bar\xi\cdot\bar\eta\right.$$

$$\left.= \xi\cdot\eta + \bar\eta\cdot\bar\xi\right)$$

(HW)

Current: $$\bar\Psi\gamma^\mu\Psi = \bar\Psi_L\gamma^\mu\Psi_L + \bar\Psi_R\gamma^\mu\Psi_R$$

$$= \xi^\dagger\bar\sigma^\mu\xi - \eta^\dagger\bar\sigma^\mu\eta$$

$$\left(\equiv \bar\xi\bar\sigma^\mu\xi - \bar\eta\bar\sigma^\mu\eta\right.$$

(HW)

$$\left.= -\xi\sigma^\mu\bar\xi + \eta\sigma^\mu\bar\eta\right)$$

$$\bar\Psi\gamma^\mu\gamma_5\Psi = -\bar\xi\bar\sigma^\mu\xi - \bar\eta\bar\sigma^\mu\eta$$

Tensor: $$-\frac{i}{2}\bar\Psi\Sigma^{\mu\nu}\Psi = \eta\sigma^{\mu\nu}\xi - \bar\eta\bar\sigma^{\mu\nu}\bar\xi$$

$$\Sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu,\gamma^\nu] = 2i\begin{pmatrix}\sigma^{\mu\nu} & 0\\ 0 & \bar\sigma^{\mu\nu}\end{pmatrix}$$

$$-\frac{i}{2}\bar\Psi\Sigma^{\mu\nu}\gamma_5\Psi = -\eta\sigma^{\mu\nu}\xi - \bar\eta\bar\sigma^{\mu\nu}\bar\xi$$

$$\left(= \xi\sigma^{\mu\nu}\eta + \bar\xi\bar\sigma^{\mu\nu}\bar\eta\right)$$

Majorana fermion

$$\psi = \begin{pmatrix} \xi \\ \bar{\xi} \end{pmatrix} = \psi^c \qquad \begin{cases} \psi_L = \xi = (\psi_R)^c \\ \psi_R = \bar{\xi} = (\psi_L)^c \end{cases}$$

$$\mathcal{L}_{maj} = \left[\bar{\Psi} i \gamma^\mu \partial_\mu \psi - m \bar{\Psi} \psi \right] \frac{1}{2} \qquad \text{(HW)}$$

$$= \bar{\xi} \cdot i \bar{\sigma}^\mu \partial_\mu \xi - \frac{m}{2} \left(\xi \cdot \xi + \bar{\xi} \cdot \bar{\xi} \right)$$

Ex) Neutrino : $\psi = \begin{pmatrix} \nu \\ \bar{\nu} \end{pmatrix}$

Ex) Electron

$$\psi = \begin{pmatrix} e \\ \bar{e}^c \end{pmatrix} \qquad \bar{\Psi}\psi = e e^c + \bar{e} \bar{e}^c \qquad U(1)_{em} \quad U(1)_L$$

$$\bar{\Psi} \gamma^\mu \psi = \bar{e} \bar{\sigma}^\mu e - \bar{e}^c \bar{\sigma}^\mu e^c$$

$$\psi^c = \begin{pmatrix} e^c \\ \bar{e} \end{pmatrix}$$

(*) Majorana mass : $\cancel{U(1)}_{e.m}$, $\cancel{U(1)}_L$

$$\overline{(\Psi^c)_R} \psi_L = e e \,, \qquad \overline{(\Psi^c)_L} \psi_R = \bar{e}^c \bar{e}^c$$

SM

- $SU(3)_C \times SU(2)_L \times U(1)_Y$
- Chiral structure
- Fundamental scalar to break $SU(2)_L \times U(1)_Y \to U(1)_{em}$

Chiral (Weyl) notation

$$q = \begin{pmatrix} u \\ d \end{pmatrix}, \quad u^c, \quad d^c, \quad l = \begin{pmatrix} \nu \\ e \end{pmatrix}, \quad e^c; \quad H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$$

$$Y = \quad \frac{1}{6} \quad -\frac{2}{3} \quad \frac{1}{3} \quad -\frac{1}{2} \quad 1 \quad +\frac{1}{2}$$

$$Q = T_3 + Y.$$

$$\tilde{H} \equiv -\varepsilon H^* \equiv \begin{pmatrix} -H^{0*} \\ +H^- \end{pmatrix}$$

$$-\mathcal{L}_{Yuk} = \underset{\frac{1}{6}\ +\frac{1}{2}\ -\frac{2}{3}}{y_u^{ij}\, q_i \cdot H\, u^c_j} + \underset{\frac{1}{6}\ -\frac{1}{2}\ \frac{1}{3}}{y_d^{ij}\, q_i \cdot \tilde{H}\, d^c_j} + \underset{-\frac{1}{2}\ -\frac{1}{2}\ 1}{y_e^{ij}\, l_i \cdot \tilde{H}\, e^c_j}$$

$$+ h.c.$$

$$q \cdot H = (u, d)\,\varepsilon \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = +uH^0 - dH^+$$

$$q \cdot \tilde{H} = (u, d)\,\varepsilon \begin{pmatrix} -H^{0*} \\ +H^- \end{pmatrix} = +uH^- + dH^0$$

$$H \cdot \tilde{H} = (H^+, H^0)\,\varepsilon \begin{pmatrix} -H^{0*} \\ H^- \end{pmatrix} = |H|^2$$

$$V_H = -\mu^2 |H|^2 + \frac{\lambda}{2}|H|^4 = \frac{\lambda}{2}\left(|H|^2 - \frac{\mu^2}{\lambda}\right)^2 + \cdots$$

$$\langle H \rangle = \begin{pmatrix} \frac{v}{\sqrt{2}} \\ 0 \end{pmatrix}$$

$$T_3 \langle H \rangle = +\frac{1}{2}\langle H \rangle \quad , \quad Q\langle H \rangle = 0$$

$$Y \langle H \rangle = -\frac{1}{2}\langle H \rangle$$

↑ unbroken $U(1)_{em}$

$$v^2 = \frac{2\mu^2}{\lambda} = (246.22\,\text{GeV})^2$$

$$m_h^2 = \lambda v^2 = (125\,\text{GeV})^2$$

$$H = \begin{pmatrix} \frac{v+h}{\sqrt{2}} \\ G^- \end{pmatrix}$$

$$V_H \Rightarrow \frac{1}{2} m_h^2 h^2 + \underline{\frac{1}{2}\frac{m_h^2}{v}} h^3 + \underline{\frac{1}{8}\frac{m_h^2}{v^2}} h^4$$

(*) Measure h-h-h and h-h-h-h couplings to confirm the EWSB in the *minimal* way.

$$-\mathcal{L}_{Yuk} = \frac{v+h}{\sqrt{2}} \left(y_u^{ij} u_i u_j^c + y_d^{ij} d_i d_j^c + y_e^{ij} e_i e_j^c \right)$$

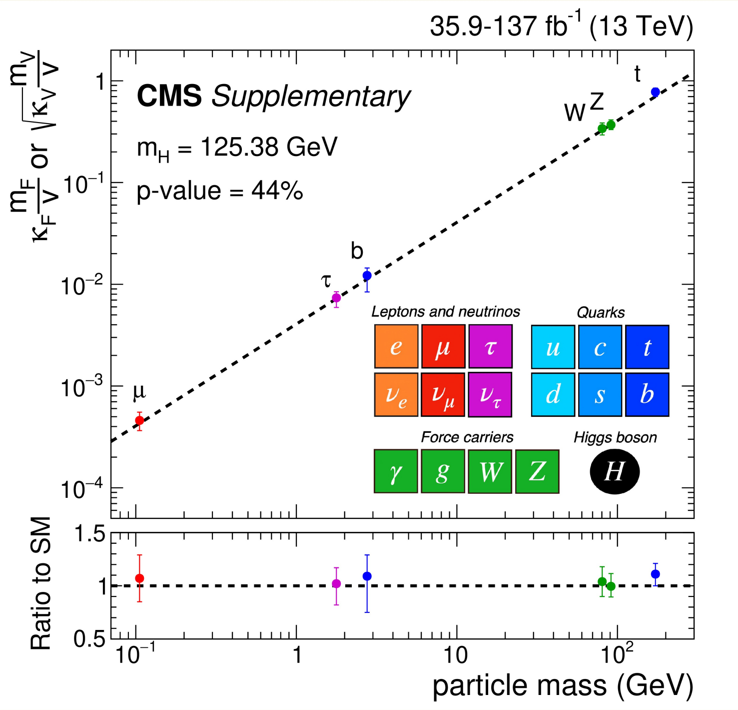
$+ h.c.$

Bi-unitary transformation (V_u, V_{u^c}), etc.

$$\Rightarrow \left(1+\frac{h}{v}\right)\left(m_{u_i} u_i u_i^c + m_{d_i} d_i d_i^c + m_{e_i} e_i e_i^c\right)$$

$+ h.c.$

(*1) Yukawa structure is tested at LHC!



(*2) No flavor changing neutral processes

NB) $W^+ \to u_i \bar{d}_j$ $\quad V_{CKM}^{ij} = (V_u V_d^\dagger)^{ij}$

$h \to e_i^\pm e_j^\mp \quad i \neq j$

$Z \to e_i^\pm e_j^\mp \quad i \neq j$

Gauge interaction is flavor universal.

$\Gamma(Z \to \mu^+\mu^-)/\Gamma(Z \to e^+e^-) = 1.0001 \pm 0.0024$

$\Gamma(Z \to \tau^+\tau^-)/\Gamma(Z \to e^+e^-) = 1.0020 \pm 0.0032.$

[PDG]

(*) lepton universality to be respected by New Physics.

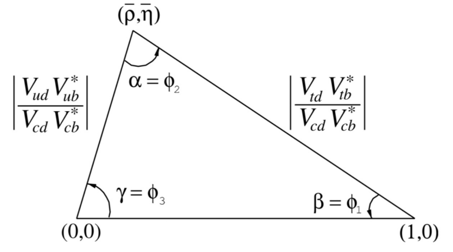
※3) Flavor & CPV phenomena
well described by CKM.

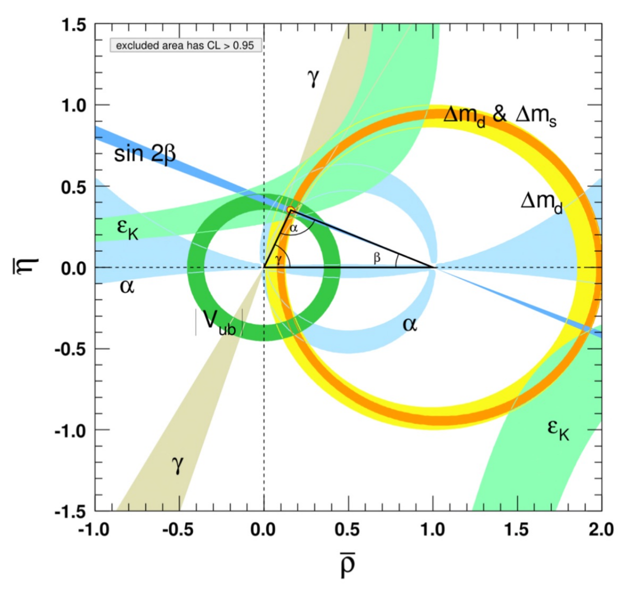
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

[PDG]

$$\lambda = 0.22501 \pm 0.00068\,, \qquad A = 0.826^{+0.016}_{-0.015}\,,$$
$$\bar\rho = 0.1591 \pm 0.0094\,, \qquad \bar\eta = 0.3523^{+0.0073}_{-0.0071}\,.$$

$$V_{ud}\,V_{ub}^* + V_{cd}\,V_{cb}^* + V_{td}\,V_{tb}^* = 0\,,$$

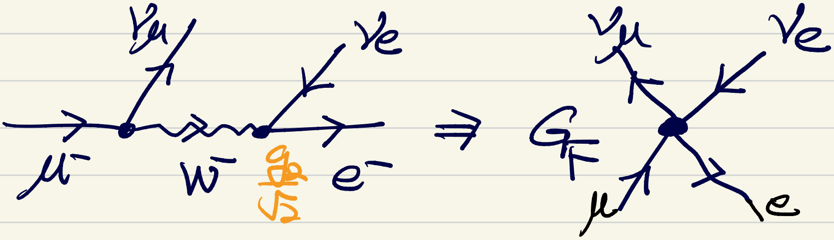




Electroweak Precision Measurement

[PDG]

Fermi constant (1933 Fermi theory)



$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}\, \bar{e}\gamma^\mu(1-\gamma_5)\nu_e \; \bar{\nu}_\mu \gamma_\mu(1-\gamma_5)\mu$$

$$\hookrightarrow \frac{g_2^2}{8m_W^2} \equiv \frac{G_F}{\sqrt{2}} = \frac{1}{2v^2} \sim \frac{1}{(300\,\text{GeV})^2}$$

$$\Gamma_\mu = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

$$G_F = 1.1663788(6) \times 10^{-5}\,\text{GeV}^{-2}$$

$$\Rightarrow v = 246.22\,\text{GeV}.$$

Fine structure constant

$$\alpha = \frac{e^2}{4\pi} = 1/137.035999180(10)$$

$$\alpha(M_Z) = 1/127.951(9)$$

Z, W boson masses

$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$

$$m_W = 80.377 \pm 0.012 \text{ GeV}$$

$$(*)\ \text{CDF}: m_W = 80.4335 \pm 0.0094 \text{ GeV}$$

Weak mixing angle

$$s_W^2(\ell) = 0.23104 \pm 0.00049 \quad (\text{LHC})$$

Three input parameters in the EW sector

$$v, g_1, g_2 \leftrightarrow v, e, s_W \leftrightarrow \underbrace{G_F, \alpha, m_Z}$$

most precisely measured

$$v \simeq (\sqrt{2} G_F)^{-\frac{1}{2}} = 246.22 \text{ GeV}$$

$$e = (4\pi\alpha)^{\frac{1}{2}} = 0.3184$$

$$\left(g_1 = e/c_W = 0.3580,\ g_2 = e/s_W = 0.6485\right)$$

$$s_W^2 = \frac{1}{2}\left(1 - \sqrt{1 - \frac{4\pi\alpha}{\sqrt{2} G_F m_Z^2}}\right) \leftarrow \left\{ \begin{aligned} m_Z^2 &= \frac{e^2 v^2}{4 s_W^2 c_W^2} \\ m_W^2 &= \frac{e^2 v^2}{4 s_W^2} = M_Z^2 c_W^2 \end{aligned} \right.$$

$$m_W^2 \simeq \pi\alpha G_F^{-1} / \sqrt{2} s_W^2$$

[Wells, 0512342]

SM prediction

Quantum corrections

$$m_W = \frac{1}{2} g_2 v = 79.83 \Rightarrow 80.36$$

$$s_W^2 = 0.2336 \Rightarrow 0.23155$$

[PDG]

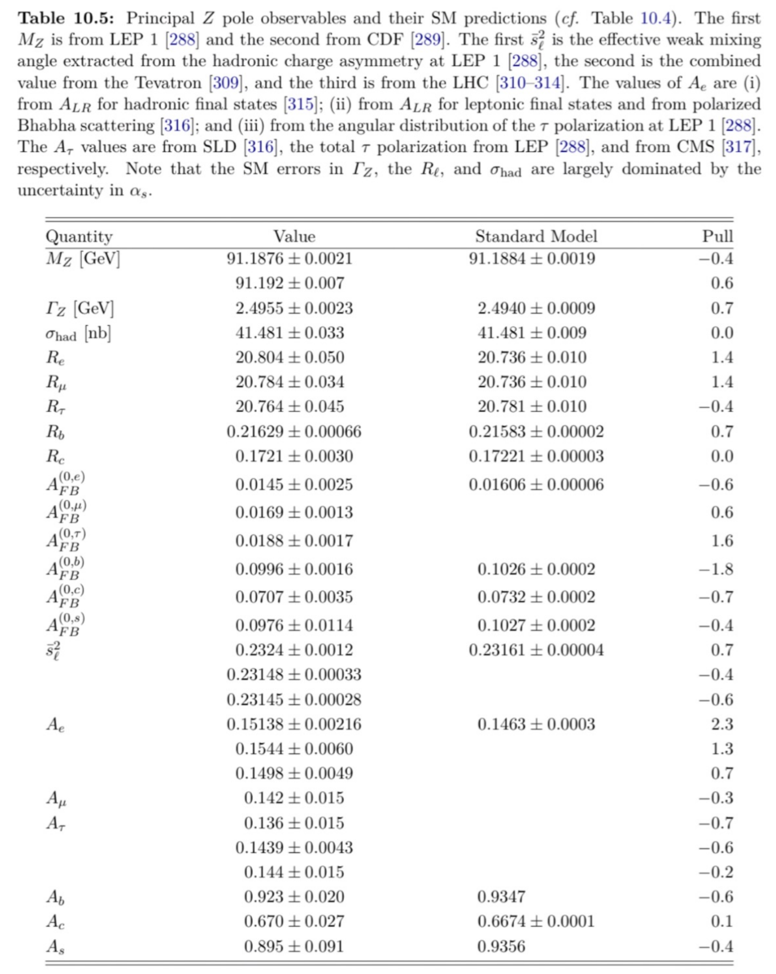


Table 10.5: Principal Z pole observables and their SM predictions (*cf.* Table 10.4). The first M_Z is from LEP 1 [288] and the second from CDF [289]. The first $\bar{s}_\ell^2$ is the effective weak mixing angle extracted from the hadronic charge asymmetry at LEP 1 [288], the second is the combined value from the Tevatron [309], and the third is from the LHC [310–314]. The values of A_e are (i) from A_{LR} for hadronic final states [315]; (ii) from A_{LR} for leptonic final states and from polarized Bhabha scattering [316]; and (iii) from the angular distribution of the τ polarization at LEP 1 [288]. The A_τ values are from SLD [316], the total τ polarization from LEP [288], and from CMS [317], respectively. Note that the SM errors in Γ_Z, the R_ℓ, and $\sigma_{\rm had}$ are largely dominated by the uncertainty in α_s.

Quantity	Value	Standard Model	Pull
M_Z [GeV]	91.1876 ± 0.0021	91.1884 ± 0.0019	-0.4
	91.192 ± 0.007		0.6
Γ_Z [GeV]	2.4955 ± 0.0023	2.4940 ± 0.0009	0.7
$\sigma_{\rm had}$ [nb]	41.481 ± 0.033	41.481 ± 0.009	0.0
R_e	20.804 ± 0.050	20.736 ± 0.010	1.4
R_μ	20.784 ± 0.034	20.736 ± 0.010	1.4
R_τ	20.764 ± 0.045	20.781 ± 0.010	-0.4
R_b	0.21629 ± 0.00066	0.21583 ± 0.00002	0.7
R_c	0.1721 ± 0.0030	0.17221 ± 0.00003	0.0
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01606 ± 0.00006	-0.6
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.6
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.6
$A_{FB}^{(0,b)}$	0.0996 ± 0.0016	0.1026 ± 0.0002	-1.8
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0732 ± 0.0002	-0.7
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1027 ± 0.0002	-0.4
$\bar{s}_\ell^2$	0.2324 ± 0.0012	0.23161 ± 0.00004	0.7
	0.23148 ± 0.00033		-0.4
	0.23145 ± 0.00028		-0.6
A_e	0.15138 ± 0.00216	0.1463 ± 0.0003	2.3
	0.1544 ± 0.0060		1.3
	0.1498 ± 0.0049		0.7
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.6
	0.144 ± 0.015		-0.2
A_b	0.923 ± 0.020	0.9347	-0.6
A_c	0.670 ± 0.027	0.6674 ± 0.0001	0.1
A_s	0.895 ± 0.091	0.9356	-0.4

<ρ parameter>

$$\rho \equiv \frac{m_W^2}{m_Z^2 c_W^2} = 1.00039 \pm 0.00019$$

SU(2) multiplets (T, Y)

Doublet $(\frac{1}{2}, \frac{1}{2})$ (H^+, H^0)

Triplet $(1, 0)$ $(\Sigma^+, \Sigma^0, \Sigma^-)$ real

$(1, 1)$ $(\Delta^{++}, \Delta^+, \Delta^0)$ complex

Septuplet $(3, 2)$ $(5+, 4+, 3+, 2+, +, 0, -)$

$$\rho = \frac{\sum_i c_i \left[T_i(T_i+1) - Y_i^2\right] v_i^2}{2 \sum_i Y_i^2 v_i^2}$$

$c_i = 1 \left(\frac{1}{2}\right)$ for complex (real)

i) $(\frac{1}{2}, \frac{1}{2})$

$$\rho = \frac{\sum_i \left(\frac{3}{4} - \frac{1}{4}\right) v_i^2}{2 \sum_i \frac{1}{4} v_i^2} = 1$$

ii) $(\frac{1}{2}, \frac{1}{2}) + (1, 1)$

$$\rho = \frac{\frac{1}{2} v_H^2 + v_\Delta^2}{\frac{1}{2} v_H^2 + 2 v_\Delta^2} \approx 1 - 2 \frac{v_\Delta^2}{v_H^2}$$

$$\Rightarrow v_\Delta \lesssim 10^{-2} v_H$$

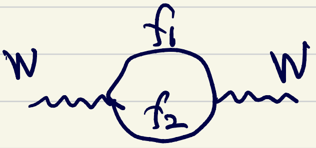
iii) $(\frac{1}{2},\frac{1}{2})+(1,1)+(1,0)$

$$\rho=\frac{\frac{1}{2}v_H^2+v_\Delta^2+v_\Sigma^2}{\frac{1}{2}v_H^2+2v_\Delta^2}=1 \quad \text{if} \quad v_\Delta=v_\Sigma$$

iv) $(3,2)$ $$\rho=\frac{(3\cdot4-4)\,v_{(3,2)}^2}{2\cdot4\,v_{(3,2)}^2}=1.$$

- Quantum correction to ρ

For a fermionic/bosonic doublet $\begin{pmatrix} f_1 \\ f_2 \end{pmatrix}$



[PDG]

$$\Rightarrow \delta\rho=\frac{N_c G_F}{8\sqrt{2}\pi^2}F(m_1^2,m_2^2)$$

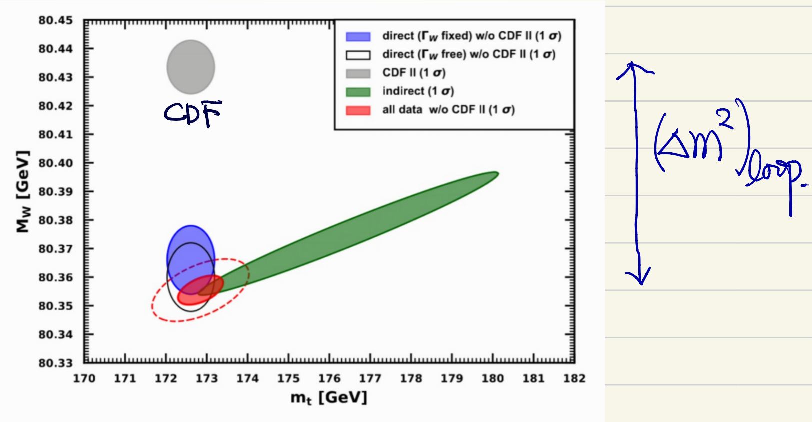
$$F=m_1^2+m_2^2-\frac{m_1^2m_2^2}{m_1^2-m_2^2}\ln\frac{m_1^2}{m_2^2}\geq(m_1-m_2)^2$$

$$\rightarrow \underbrace{0 \text{ if } m_1=m_2}$$ SU(2) symmetric

*) Control contribution from extra Higgses or fermions.

$$(16\,\mathrm{GeV})^2 < \sum_i \frac{N_c}{3} |\Delta m_i^2| < (48\,\mathrm{GeV})^2$$

Challenging the SM prediction?



< Custodial Symmetry >

EW gauge symmetry $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$

↳ global $SU(2)$

Gauge sector respects $SU(2)$ if $g_1 \rightarrow 0$.

$$M^2 = \frac{v^2}{4} \begin{array}{c} \begin{array}{cccc} W_1, & W_2 & W_3 & B \end{array} \\ \begin{pmatrix} g_2^2 & & & \\ & g_2^2 & & \\ & & g_2^2 & -g_1 g_2 \\ & & g_1 g_2 & g_1^2 \end{pmatrix} \end{array}$$

$g_1 \rightarrow 0$, $s_W \rightarrow 0$

$Z = W_3$

$m_{W^\pm}^2 = m_Z^2$

Higgs sector maintains an extended symmetry

$SU(2)_L \times SU(2)_R$

$$\Phi \equiv \begin{pmatrix} H^{0*} & H^+ \\ -H^- & H^0 \end{pmatrix} . \quad \frac{1}{2} \mathrm{Tr}(\Phi^\dagger \Phi) = |H|^2$$

$$V(\Phi) = -\frac{\mu^2}{2} \mathrm{Tr}(\Phi^\dagger \Phi) + \frac{\lambda}{8} \left[\mathrm{Tr}(\Phi^\dagger \Phi)\right]^2$$

invariant under $\Phi \rightarrow L^\dagger \Phi R$.

https://people.physics.carleton.ca/~logan/talks/cust-sym-TC2019.pdf

$$\langle \Phi \rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad \text{breaks} \quad SU(2)_L \times SU(2)_R \to SU(2)_V$$

$SU(2)_V$ remains to be a symmetry in the limit of $g_1=0$, & $y_u = y_d$.

$$\mathcal{L}_{Yuk} = y_u (u,d) H u^c + y_d (u,d) \tilde{H} d^c + h.c$$

$$\underset{y = y_u = y_d}{\Longrightarrow} \quad y\,(u,d)\,\Phi \begin{pmatrix} u^c \\ d^c \end{pmatrix} + h.c$$

That is, $m_u = m_d$ leading to $\delta\rho = 0$.

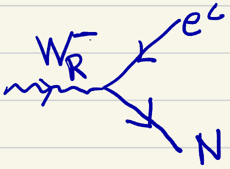
*) Safely go to the custodial symmetric limit for extra Higgses or fermions.

(ex) $m_{H^\pm} = m_H$ or m_A.

[Gerard, Herquet 0703051.]

**) $SU(2)_R$: remnant of gauge symmetry

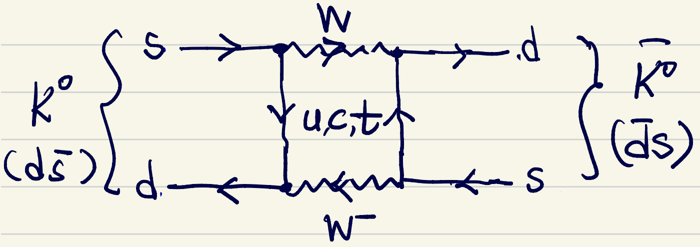
$$q^c \equiv \begin{pmatrix} u^c \\ d^c \end{pmatrix} \updownarrow W_R^\pm \updownarrow \begin{pmatrix} e^c \\ N \end{pmatrix} \equiv l^c$$



< Rare phenomena where BSM may hide. >

i) $K^0-\bar{K}^0$ ($B^0-\bar{B}^0$) mixing.

[Isidori 1302.0661]



$$\mathcal{L}_{eff} \approx \frac{G_F^2 m_W^2}{4\pi^2} \sum_{i,j=u,c,t} (V_{id}^* V_{is})(V_{jd}^* V_{js}) f(x_i, x_j)$$

$$(\bar{d}_L \gamma^\mu s_L)\cdot(\bar{d}_L \gamma_\mu s_L) \leftrightarrow (\bar{d}\,\bar{\sigma}^\mu s)^2$$

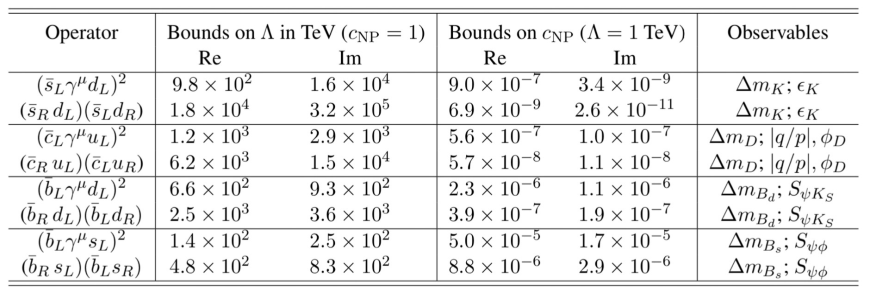
$$f(x_i, x_j) = f(x_j, x_i), \quad x_i = \frac{m_i^2}{m_W^2}.$$

$\to 0$ if $x_u = x_c = x_t$. "GIM mechanism".

$x_u \ll x_c \ll x_t$

$$\Rightarrow \frac{G_F^2 m_W^2}{4\pi^2} (\underbrace{V_{td}^* V_{ts}}_{\lambda^5})^2 F\left(\frac{m_t^2}{m_W^2}\right) (\bar{d}_L \gamma^\mu s_L)(\bar{d}_L \gamma^\mu s_L)$$

$$\equiv \frac{1}{\Lambda^2} (\bar{d}_L \gamma^\mu s_L)(\bar{d}_L \gamma_\mu s_L) \quad \Lambda \sim 10^3\,\text{TeV}$$ ✓

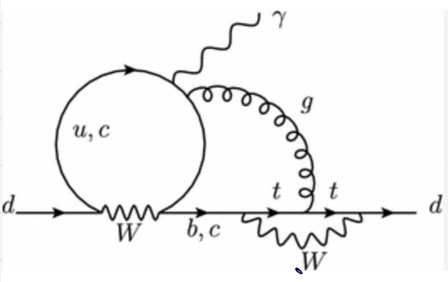


Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Bounds on Λ in TeV ($c_{\rm NP}=1$) Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\,\epsilon_K$
$(\bar{s}_R\,d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\,\epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\,\lvert q/p\rvert,\phi_D$
$(\bar{c}_R\,u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\,\lvert q/p\rvert,\phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_{B_d};\,S_{\psi K_S}$
$(\bar{b}_R\,d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_{B_d};\,S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\,S_{\psi\phi}$
$(\bar{b}_R\,s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\,S_{\psi\phi}$

ii) CPV & EDM

$$\mathcal{L}_{d_\psi} = -\frac{i}{2} d_\psi \bar{\Psi} \Sigma_{\mu\nu} \gamma_5 \psi F^{\mu\nu} \propto \vec{d}_\psi \vec{E}$$

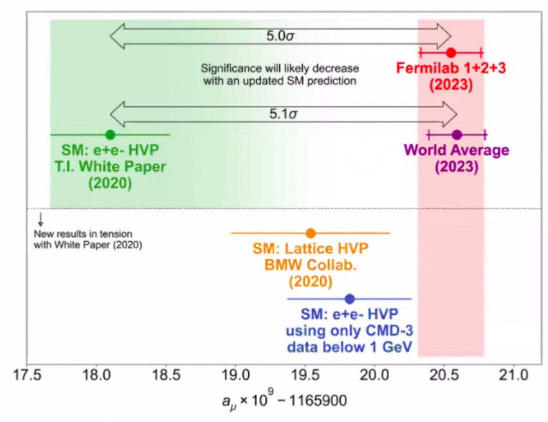
$$d_n \sim 10^{-32}\, ecm \ll 1.8 \times 10^{-26}\, ecm \;(PSI)$$

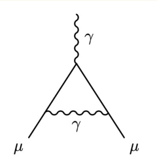


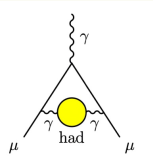
iii) Muon MDM

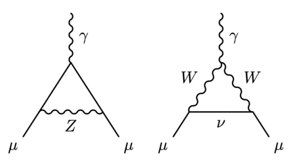
$$\mathcal{L}_{\mu_\psi} = \frac{i}{2} \mu_\psi \bar{\Psi} \Sigma_{\mu\nu} \Psi F^{\mu\nu} \propto \mu_\psi \vec{B}$$

$$\vec{\mu} = g \frac{e}{2m} \vec{S}, \quad a = \frac{g-2}{2}$$



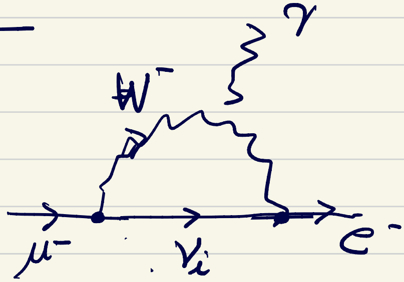






$$a_W \approx \frac{m_\mu^2}{16\pi^2 v^2} \sim 10^{-9}$$

iv) $\mu \to e\gamma$

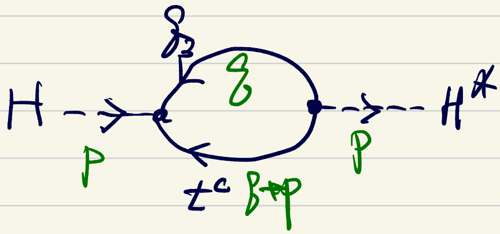


$$\propto \frac{3\alpha}{32\pi}\left|\sum_i \left(U^*_{ei}\frac{m_{\nu_i}^2}{m_W^2}U_{\mu i}\right)\right|^2 \lesssim \underset{\sim\sim}{10^{-53}}$$

(HW) $B(\mu \to e\gamma) \lesssim 10^{-48} \ll 4.2\times 10^{-13}$ (MEG)

Problems of Higgs boson

Quadratic divergencies in quantum correction to the Higgs mass



$$\propto y_t^2 \int \frac{d^4 q}{(2\pi)^4} \frac{\mathrm{Tr}[\not{q}(\not{q}+\not{p})]}{(q^2-m_t^2)((q+p)^2-m_t^2)}$$

$$\propto \frac{y_t^2}{(2\pi)^4} \int d^4 q \, \frac{1}{q^2}$$

$$\delta\mu^2 = \left[6 y_t^2 - \frac{3}{4}(3 g_2^2 + g_1^2) - 6\lambda\right] \frac{\Lambda^2}{8\pi^2}$$

- $\Lambda = M_{pl}$? "Hierarchy problem"

  $\mu^2 - \delta\mu^2 \sim m_h^2$

  $\hookrightarrow$ fine-tuning of $\frac{m_h^2}{M_{pl}^2} \sim 10^{-34}$.

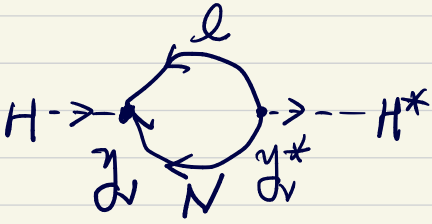
- $\Lambda \sim 4\pi m_h \sim$ TeV?

  New physics (SUSY, composite Higgs)

- No new physics $\Rightarrow$ renormalize away $\delta\mu^2$!

- Higgs mass is vulnerable to New Physics:

ex) Seesaw [Vissani. 1997]

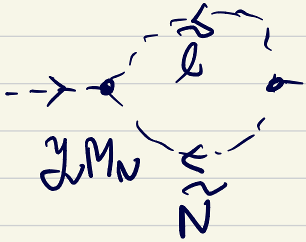
① 

$$\Rightarrow \delta\mu^2 \approx \underbrace{\frac{|y_\nu|^2}{(2\pi)^2} M_N^2}_{2} \ln\frac{M_N^2}{g^2}$$

$$\frac{m_\nu M_N^3}{(2\pi v)^2} \sim (100\text{GeV})^2$$

$$\Rightarrow \underline{M_N \lesssim 10^7 \text{ GeV}}$$

(*) With supersymmetry

② 

$$\Rightarrow \delta\mu^2 \approx -\frac{|y_\nu|^2 M_N^2}{(2\pi)^2} \ln\frac{M_{\tilde N}^2}{g^2}$$

$$(\delta\mu^2)_{susy} = ① + ② \approx \frac{|y_\nu|^2 M_N^2}{(2\pi)^2} \ln\left(\frac{M_N^2}{\boxed{M_{\tilde N}^2}}\right)$$

↳ $M_N^2 + m_{susy}^2$

$$\approx \frac{y_\nu^2}{(2\pi)^2} m_{susy}^2$$

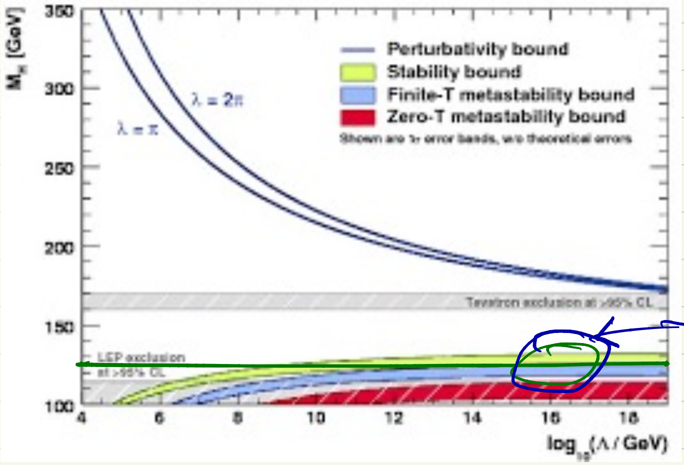
→ $m_{susy} \sim$ TeV even for $y_\nu \sim 1$.

• Instability of Higgs vacuum.

Running of the quartic coupling λ

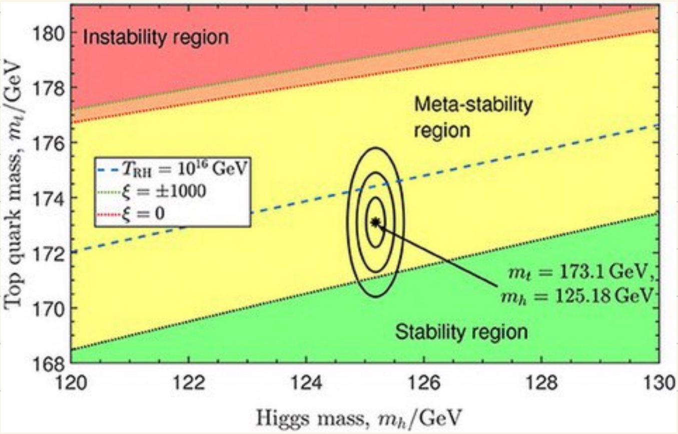
$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g_1^2 + 9g_2^2 - 24y_t^2)\lambda$$

$$+ \cdots$$



[Ellis, et.al. 0906.0954]

New Physics?



<Accidental Symmetries in SM>

Gauge symmetry: $SU(3)_c \times SU(2)_L \times U(1)_Y$

Particle content: $q, u^c, d^c, l, e^c, N, H$

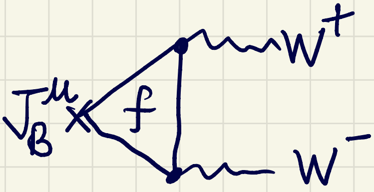
Write down most general gauge-invariant renormalizable Lagrangian: $7-4=\underset{\sim}{3}$

$$qHu^c, \quad q\tilde{H}d^c, \quad l\tilde{H}e^c, \quad lHN$$

B	$\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$	0	0	0	0
L	0	0	0	0	1	-1	1	-1

Anomalies

① $U(1)_B - SU(2)_L - SU(2)_L$



$(f=q)\ \frac{1}{3}\times 3\times 3 = 3$

$U(1)_L$

$(f=l)\ 1\times 3 = 3$

$\Rightarrow \begin{cases} B-L & \text{No } SU(2)_L \text{ anomaly} \\ B+L & \text{anomalous} \end{cases}$

② $\underline{U(1)_{BL} \times U(1)_Y \times U(1)_Y}$

$$\frac{1}{3}\cdot\left(\frac{1}{6}\right)^2 \times 3 \times 2 - \frac{1}{3}\left(-\frac{2}{3}\right)^2 \times 3 - \frac{1}{3}\left(+\frac{1}{3}\right)^2 \times 3 \qquad N_c$$

$$-1\cdot\left(\frac{1}{2}\right)^2 \times 2 + 1\cdot(+1)^2 - 1\cdot(0)^2 = 0$$ for each family.

doublet.

③ $\underline{U(1)^3_{BL}}$

$$\left(\frac{1}{3}\right)^3 \times 2 \times 3 + \left(-\frac{1}{3}\right)^3 \times 3 + \left(-\frac{1}{3}\right)^3 \times 3$$

$$+(-1)^3 \times 2 + (+1)^3 + (+1)^3 = 0$$

- $U(1)_{B-L}$ is totaly anomaly free and thus can be a new gauge symmetry.

Z'

	q	u^c	d^c	l	e^c	N
B-L	$\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	-1	$+1$	$+1$

d.o.f $\quad 6 + 3 + 3 + 2 + 1 + 1 = \underline{16}$

Fundamental rep of $\underline{SO(10)}$

$M_N \sim M_{GUT}$

"Seesaw"

$$-\mathcal{L}_{B-L} = y_\nu \underset{-1}{\ell} H \underset{+1}{N} + \frac{1}{2} y_N \underset{-2}{S} \underset{+1}{N} \underset{+1}{N} + h.c.$$

$$\Rightarrow \begin{cases} M_N = y_N \langle S \rangle & \text{B-L breaking} \\ M_{Z'} \sim g_{BL} \langle S \rangle \end{cases}$$

- <u>$SU(2)_R$ extension</u>

$$\mathcal{L}_{SM} \ni y_e \, \ell \cdot \tilde{H}_1 \cdot e^c + y_\nu \, \ell \cdot H_2 \cdot N + h.c. \longmapsto \mathcal{L}_{LR}$$

$$G_{LR} = \underset{T_{3L}}{SU(2)_L} \times \underset{T_{3R}}{SU(2)_R} \times \underset{B-L}{U(1)_{B-L}}$$

$$Q \simeq T_{3L} + \underbrace{T_{3R} + \frac{B-L}{2}}_{Y}$$

Fields: $\ell \equiv \begin{pmatrix} \nu \\ e \end{pmatrix}$, $\ell^c \equiv \begin{pmatrix} e^c \\ N \end{pmatrix}$, $\Phi = (\tilde{H}_1, H_2)$

$(\frac{1}{2}, 0, -1)$ $\quad (0, \frac{1}{2}, +1)$ $\quad (\frac{1}{2}, \frac{1}{2}, 0)$

$$\mathcal{L}_{LR} \ni y_D \, \underline{\ell \cdot \Phi \cdot \ell^c}$$

$$\hookrightarrow (\nu, e) \in (\tilde{H}_1, H_2) \in \begin{pmatrix} e^c \\ N \end{pmatrix}$$

$$\longmapsto e H_1^{0*} e^c + \nu H_2^0 N.$$

Further introduce,

$\Delta_L = (\Delta_L^{++}, \Delta_L^{+}, \Delta_L^{0})$; $\Delta_R = (\Delta_R^{0}, \Delta_R^{-}, \Delta_R^{--})$

$T_{3L} = (1, 0, -1)$ $T_{3R} = (1, 0, -1)$

$B-L = +2$ $B-L = -2$

$$\Rightarrow \quad l_i \Delta_L l_j = \nu_i \nu_j \Delta_L^0 + (\nu_i e_j + e_i \nu_j) \Delta_L^+ + e_i e_j \Delta_L^{++}$$

$$l_i^c \Delta_R l_j^c = N_i N_j \Delta_R^0 + (N_i e_j^c + e_i^c N_j) \Delta_R^- + e_i^c e_j^c \Delta_R^{--}$$

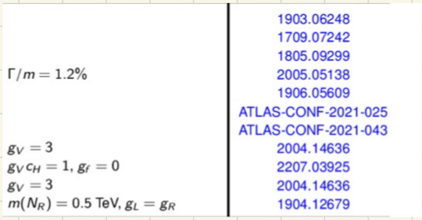
$\Rightarrow \quad m_\nu \propto \langle \Delta_L^0 \rangle$ $SU(2)_L \times U(1)_Y \to U(1)_{em}$

$M_N \propto \langle \Delta_R^0 \rangle$ $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$

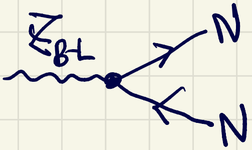
$M_{W_R^\pm} \propto \langle \Phi \rangle, \langle \Delta_R^0 \rangle$

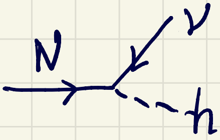
Searches for extra gauge bosons

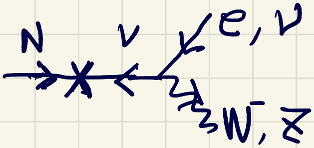
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z′ mass	5.1 TeV
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z′ mass	2.42 TeV
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z′ mass	2.1 TeV
	Leptophobic $Z' \to tt$	0 e, μ	≥1 b, ≥2 J	Yes	139	Z′ mass	4.1 TeV
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W′ mass	6.0 TeV
	SSM $W' \to \tau\nu$	1 τ	–	Yes	139	W′ mass	5.0 TeV
	SSM $W' \to tb$	–	≥1 b, ≥1 J	–	139	W′ mass	4.4 TeV
	HVT $W' \to WZ$ model B	0-2 e, μ	2 j / 1 J	Yes	139	W′ mass	4.3 TeV
	HVT $W' \to WZ \to \ell\nu\ell'\ell'$ model C	3 e, μ	2 j (VBF)	Yes	139	W′ mass	340 GeV
	HVT $Z' \to WW$ model B	1 e, μ	2 j / 1 J	Yes	139	Z′ mass	3.9 TeV
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass	5.0 TeV

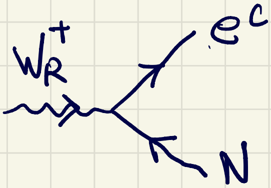


	1903.06248
	1709.07242
	1805.09299
$\Gamma/m = 1.2\%$	2005.05138
	1906.05609
	ATLAS-CONF-2021-025
	ATLAS-CONF-2021-043
$g_V = 3$	2004.14636
$g_V c_H = 1, g_f = 0$	2207.03925
$g_V = 3$	2004.14636
$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679







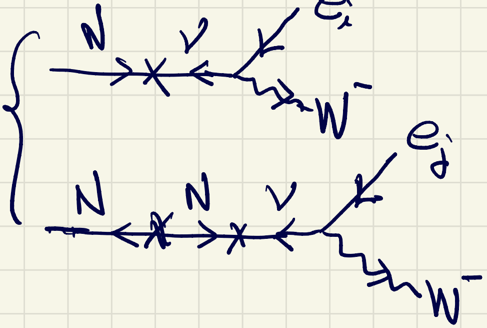


$$\begin{matrix} u^c & d^c & d^c \\ \frac{2}{3} & \frac{1}{3} & \frac{1}{3} \end{matrix}$$

(*) Majorana nature of N ⇒ same-sign di-leptons

$Z_{BL} \to N\bar{N}$

↳N



$\to e_i^\pm e_j^\pm + 4j$.

Q1) Origin of neutino masses?

i) Weinberg operator of dimension 5

$$-\mathcal{L}_W = \frac{\lambda_{ij}}{\Lambda}(l_i\cdot H)\cdot(l_j\cdot H)$$

$$\Rightarrow \lambda_{ij}\frac{(v+h)^2}{2\Lambda}\nu_i\nu_j + h.c.$$

$$\boxed{m^M_{\nu_{ij}} = \lambda_{ij}\frac{v^2}{\Lambda}\sim 0.1\,eV} \Rightarrow \boxed{\frac{\Lambda}{\lambda_{ij}} \lesssim 10^{15}\,GeV}$$

Neutrinos are Majorana.

ii) Dirac neutrinos

$$-\mathcal{L}_{Yuk} \ni y_\nu^{ij}\, l_i\cdot H N_j + h.c \Rightarrow \left(1+\frac{h}{v}\right) m_\nu^{ij}\,(\nu_i N_j + h$$

$$l\cdot H = (\nu, e)\,\varepsilon\begin{pmatrix}H^+\\ H^0\end{pmatrix}$$

$$= \nu H^0 - eH^+$$

$(Y=0,\ SU(2)_L\text{-singlet})$.

$$\boxed{y_\nu = \frac{m_\nu}{v} \sim \underline{10^{-13}}}$$

< Neutrino mixing matrix V_{PMNS} >

Dirac neutrino

$$-\mathcal{L}_{mass} = M_e^{ij}\, e_i e_j^c + M_\nu^{ij}\, \nu_i N_j$$

$$e \to U_e e \, , \quad \nu \to U_\nu \nu$$

$$e^c \to U_{e^c} e^c \quad N \to U_N N$$

$$\begin{cases} U_e^T M_e U_{e^c} = \mathrm{Diag}(m_e) \\ U_\nu^T M_\nu U_N = \mathrm{Diag}(m_\nu) \end{cases}$$

$$\begin{cases} W_\mu^+ \bar{\nu} \bar{\sigma}^\mu e \to W_\mu^+ \bar{\nu} \bar{\sigma}^\mu (\underbrace{U_\nu^\dagger U_e}_{U_{PMNS}}) e \\ -\mathcal{L}_{mass} = m_{e_i} e_i e_i^c + m_{\nu_i} \nu_i N_i \end{cases}$$

U_{PMNS} : 3×3 unitary = 9 parameters
= 3 angles + 6 phases.

⇒ 5 phases can be removed by 5 indep. phase rotations of ν & e (except $U(1)_L$). leaving m_{e_i}, m_{ν_i} unchanged by inverse rotations of e_i^c, N_i.

Majorana neutrino

Work in the diagonal basis of m_e

$$-\mathcal{L}_{mass} = m_\alpha \alpha \alpha^c + \frac{1}{2} M_\nu^{\alpha\beta} \nu_\alpha \nu_\beta + h.c.$$

$\alpha = e, \mu, \tau.$

M_ν : 3×3 complex symmetric

diagonalized by a unitary matrix U_{PMNS}

$$\nu_\alpha = U_{\alpha i} \nu_i \qquad U^T M_\nu U = \mathrm{Diag}[m_{\nu_i}]$$

$$-\mathcal{L}_{mass} = m_{e_i} e_i e_i^c + \frac{1}{2} m_{\nu_i} \nu_i \nu_i + h.c.$$

$$\mathcal{L}_W = W_\mu^- \bar{\alpha} \bar{\sigma}^\mu U_{\alpha i} \nu_i$$

$$U : 9 = 3\,\text{angles} + (1 + 2 + \cancel{3})\ \text{phases}$$

by α rotation

Neutrino parameters

3 masses, 3 angles, 3 phases

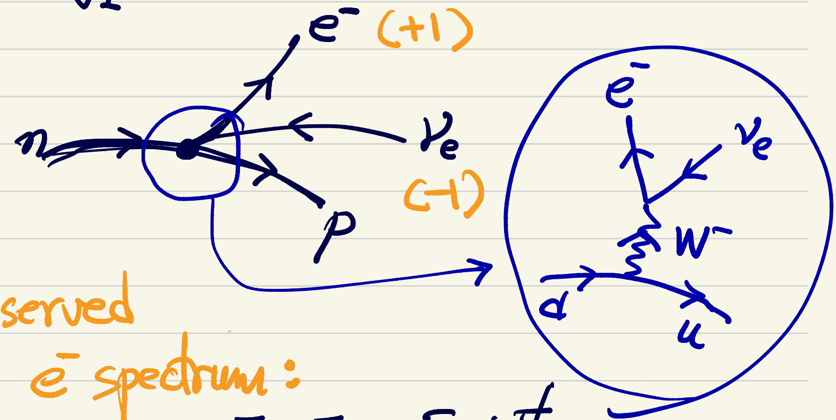
$$U_{PMNS} = \underset{\substack{\uparrow \\ \text{1 Dirac phase}}}{V_{CKM}} P, \quad P = \mathrm{Diag}[1, e^{i\varphi_2}, e^{i\varphi_3}]$$

2 Majorana phases.

< Are neutrinos Dirac or Majorana? >

Neutrinos appeared as missing energy in β-decays

$$\mathcal{L}_{Fermi} = \frac{G_F}{\sqrt{2}}(\bar{p}\bar{\sigma}^{\mu}n)\cdot(\bar{e}\bar{\sigma}_{\mu}\nu_e)$$



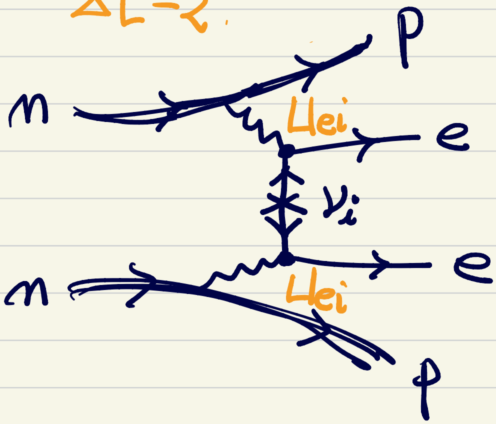
L conserved

Broad $\bar{e}$ spectrum:

$$E_n - E_p = E_e + \cancel{E}_\nu.$$

<u>0νββ</u> : no $\cancel{E}$ for majorana neutrinos,

ΔL=2.



"rare process"

$$\propto \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

$$m_{\beta\beta} \equiv U_{ei}^2 m_{\nu_i}.$$

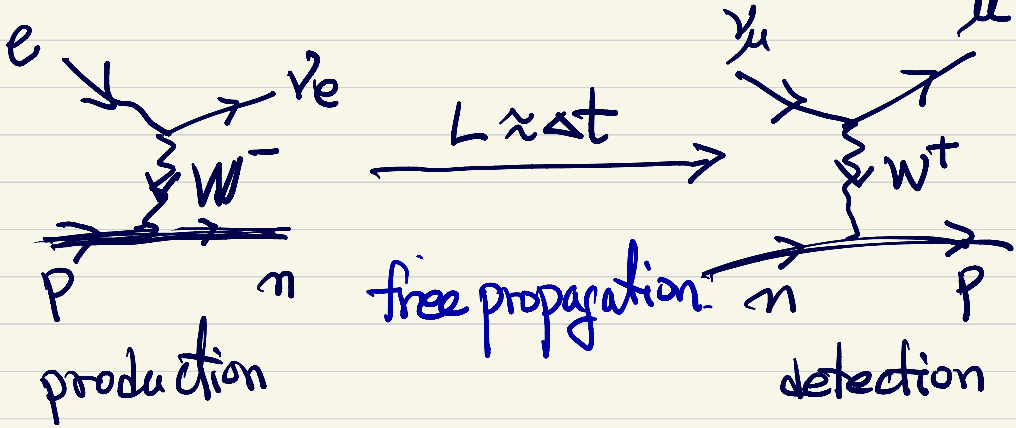
sharp peak

$$E_{2n} - E_{2p} = E_{2e^-}.$$

< Neutrino oscillation >

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu^+ \bar{\nu}_\alpha \bar{\sigma}^\mu \alpha + W_\mu^- \bar{\alpha} \bar{\sigma}^\mu \nu_\alpha$$

$$\nu_\alpha = U_{\alpha i} \nu_i$$



Transition amplitude

$$A_{\mu e} \equiv \langle \nu_\mu(t_2) | \nu_e(t_1) \rangle = \langle \nu_\mu | e^{-iH_0(t_2-t_1)} | \nu_e \rangle$$

$$= \sum_i \langle \nu_i | U_{\mu i}^* e^{-iH_0(t_2-t_1)} U_{ei} | \nu_i \rangle$$

$$\langle \nu_i | H_0 | \nu_i \rangle = \sqrt{\vec{p}^2 + m_{\nu_i}^2} \approx p + \frac{m_{\nu_i}^2}{2p} .$$

$$U_{\mu i}^* U_{ei} = V_{\mu i}^* P_i^* P_i V_{ei} = V_{\mu i}^* V_{ei}$$

No Majorana phase dependence.

$$A_{\mu e} \approx \sum_i U^*_{\mu i} U_{ei}\, e^{-i\left(p+\frac{m^2_{\nu_i}}{2p}\right)L}$$

$$|A_{\mu e}|^2 \approx \sum_{i,j} U^*_{\mu i} U_{ei} U_{\mu j} U^*_{ej}\, e^{-i\frac{m^2_{\nu_i}-m^2_{\nu_j}}{2p}L}$$

Two neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

The $\nu_e \to \nu_\mu$ transition probability

$$P_{\mu e} = |A_{\mu e}|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

$$\Delta m^2_{21} \equiv m^2_{\nu_2} - m^2_{\nu_1}.$$

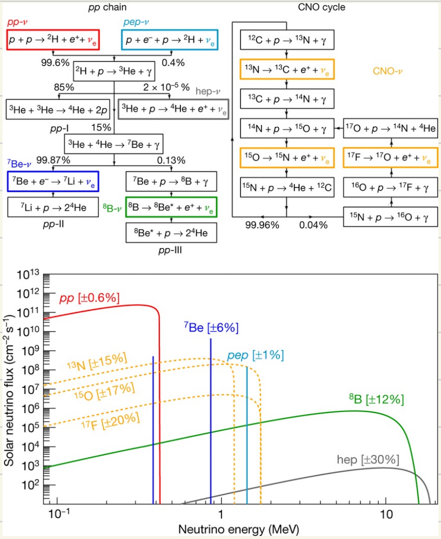
(*) $P_{\mu e} = P_{e\mu}$ (HW)

$P_{\mu e} + P_{ee} = 1.$

$$P_{\mu e} = \sin^2 2\theta \sin^2\left[1.267\, \frac{\Delta m^2_{21}(eV^2)\, L(km)}{E(GeV)}\right].$$

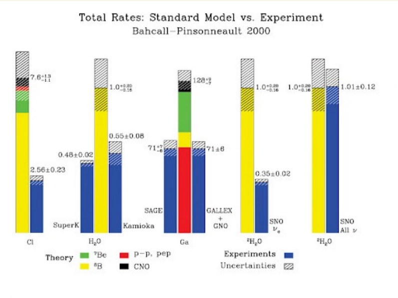
note) Indep. of sgn(Δm^2)

i) Neutrinos from the Sun.



Davis & Bachall 1966

"Solar neutrino problem"

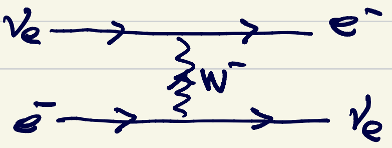


⇒ Solar neutrino transition $\nu_e \to \nu_{\mu,\tau}$

- vacuum oscillation:

$$\frac{E}{L} \sim \frac{\text{MeV}}{10^8\,\text{km}} \sim 10^{-11}\,\text{eV}^2$$

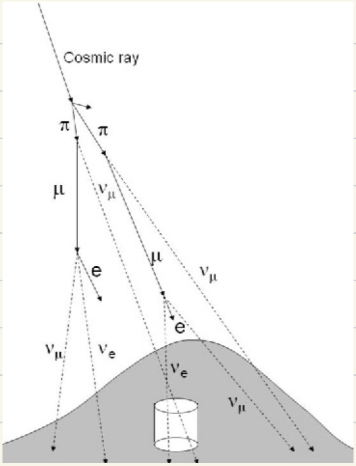
- MSW effect: $\Delta m^2_{sol} \sim 10^{-4}\,\text{eV}^2$

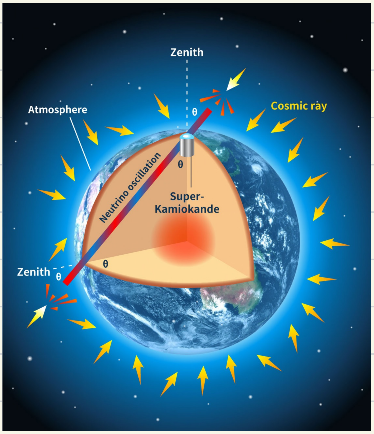


matter effect.

$V_W = \sqrt{2} G_F N_e$.

ii) Atmospheric neutrino





↓ 10km

↑ 10^4 km

$\nu_\mu \to \nu_\tau$ oscillation.

$$\frac{E}{L} = \frac{10\,\text{GeV}}{10^4\,\text{km}} \sim 10^{-3}\,\text{eV}^2 \simeq \Delta m^2_{\text{Atm}}.$$

iii) Reactor neutrinos

Nuclear fission

$\bar{\nu}_e \to \bar{\nu}_{\mu,\tau}$

$$\frac{E}{L} \sim \frac{\text{MeV}}{\text{km}} \sim \underset{\Delta m^2_{\text{Atm}}.}{\underset{\uparrow}{10^{-3}\,\text{eV}^2}}$$

(*) Three neutrino oscillation picture firmly established.

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric reactor solar

$\sin^2(\theta_{12}) = 0.307 \pm 0.013$

$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}$ eV^2

$\sin^2(\theta_{23}) = 0.553^{+0.016}_{-0.024}$ (S = 1.1) (Inverted order)

$\sin^2(\theta_{23}) = 0.558^{+0.015}_{-0.021}$ (Normal order)

$\Delta m^2_{32} = (-2.529 \pm 0.029) \times 10^{-3}$ eV^2 (Inverted order)

$\Delta m^2_{32} = (2.455 \pm 0.028) \times 10^{-3}$ eV^2 (Normal order)

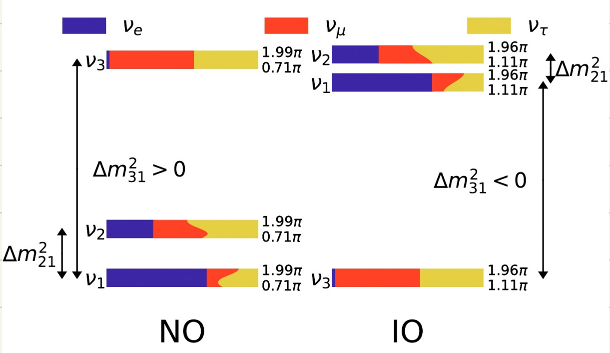
$\sin^2(\theta_{13}) = (2.19 \pm 0.07) \times 10^{-2}$ (S = 1.2)

δ, *CP* violating phase $= 1.19 \pm 0.22\ \pi$ rad (S = 1.2)

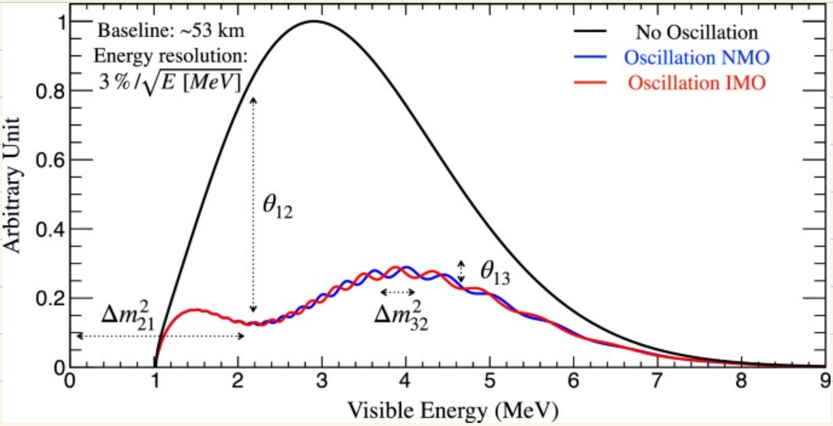
$\langle \Delta m^2_{21} - \Delta \overline{m}^2_{21} \rangle < 1.1 \times 10^{-4}$ eV^2, CL = 99.7%

$\langle \Delta m^2_{32} - \Delta \overline{m}^2_{32} \rangle = (-0.12 \pm 0.25) \times 10^{-3}$ eV^2

Neutrino mass ordering



Ref: https://doi.org/10.1038/s41598-022-09111-1



⇒ JUNO + NOVA + T2K

by 2028 ?

< New physics for ν masses >

i) Type I seesaw : (N = RHN = HNL)

$$-\mathcal{L}_I = y_\nu^{ij}\, \overset{1}{l_i} H \overset{-1}{N_j} + \frac{1}{2} M_k \overset{-1}{N_k}\overset{-1}{N_k} + h.c. \qquad U(1)_L$$

LNV

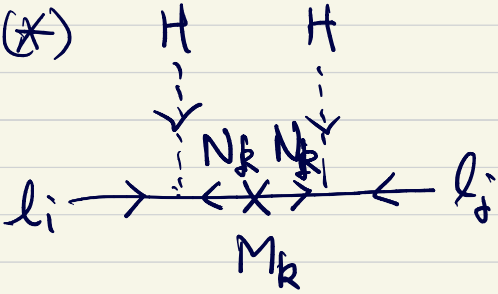
$$\Rightarrow \left(1+\frac{h}{v}\right)\frac{y_\nu^{ij} v}{\sqrt{2}}\, \nu_i N_j + \frac{1}{2} M_k N_k N_k + h.c.$$

ν–N mass matrix $\quad m_D = y\frac{v}{\sqrt{2}}$

$$\begin{pmatrix} 0 & m_D \\ m_D & M \end{pmatrix} \xRightarrow[m_D \ll M]{} \begin{pmatrix} -\frac{m_D^2}{M} & 0 \\ 0 & M+\frac{m_D^2}{M} \end{pmatrix}$$

$$\therefore \begin{cases} m_\nu \sim y_\nu^2 \frac{v^2}{2M} \\ \theta_{\nu N} \sim \frac{y_\nu v}{M} \sim \sqrt{\frac{m_\nu}{M}} \sim 10^{-6} \text{ for } M \sim v \end{cases}$$

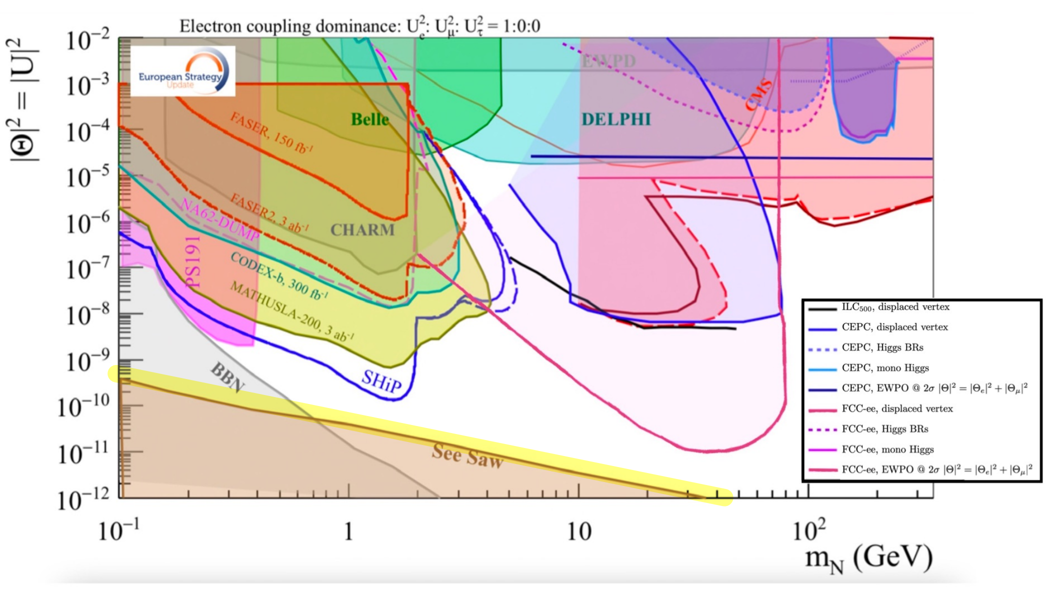
(*)

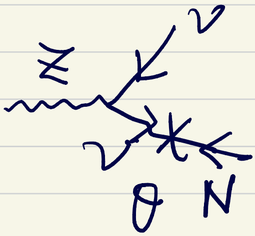


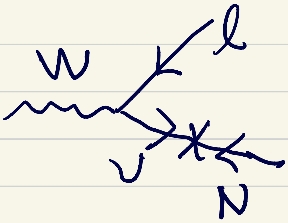
$$\Rightarrow \underbrace{(y_\nu M^{-1} y_\nu^T)_{ij}}\, l_i H\, l_j H$$

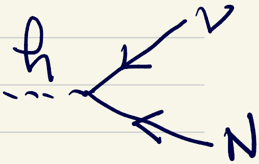
Searches for N in $(\theta_{\nu N}^2, M_N)$

[2203.05502]





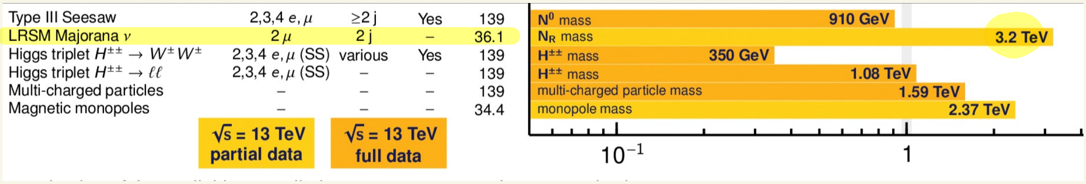




$$pp \to Z^*/W^* \xrightarrow[\theta^2]{} N \xrightarrow[\theta^2]{} \nu h, \ell W, \nu Z.$$

or

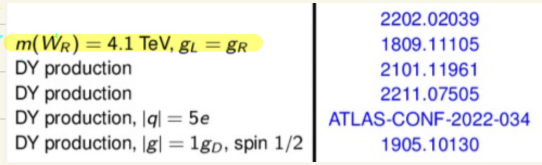
$$pp \to Z'_{BL}/W'_R \xrightarrow[g_R]{} N \xrightarrow[\theta^2]{} \uparrow$$



Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139
LRSM Majorana ν	2 μ	2 j	–	36.1
Higgs triplet $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	2,3,4 e, μ (SS)	various	Yes	139
Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	–	–	139
Multi-charged particles	–	–	–	139
Magnetic monopoles	–	–	–	34.4

$\sqrt{s}$ = 13 TeV partial data

$\sqrt{s}$ = 13 TeV full data



	2202.02039
$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
DY production	2101.11961
DY production	2211.07505
DY production, $\|q\| = 5e$	ATLAS-CONF-2022-034
DY production, $\|g\| = 1g_D$, spin 1/2	1905.10130

ii) Type II seesaw

$SU(2)_L$-triplet boson with $Y=1$.

$$\Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} \qquad Q = T_3 + Y.$$

$$-\mathcal{L}_{II} = \frac{1}{2}\lambda_{ij}\, \underset{1}{l_i}\cdot \underset{1}{l_j}\, \underset{-2}{\Delta} + \frac{1}{2}\mu_\Delta\, \overset{LNL}{\underset{0}{\tilde{H}}\, \underset{0}{\tilde{H}}\, \underset{-2}{\Delta}} + h.c. \qquad U(1)_L$$

$$+ M_\Delta^2 |\Delta|^2 + \cdots\cdots$$

$$l_i l_j \Delta = e_i e_j \Delta^{++} + (e_i \nu_j + \nu_i e_j)\Delta^{+} + \nu_i \nu_j \Delta^0$$

$Y = -\frac{1}{2} - \frac{1}{2} + 1.$

$$\tilde{H}\tilde{H}\Delta = H^- H^- \Delta^{++} + H^- H^{0*} \Delta^{+} + H^{0*} H^{0*} \Delta^0 .$$

$$\Rightarrow m_\nu^{ij} = \lambda_{ij} \langle \Delta^0 \rangle = \lambda_{ij}\, \mu_\Delta \frac{v^2}{4M_\Delta^2}$$

(*) $m_\nu \sim \underbrace{\lambda \cdot \frac{v_\Delta}{v}}_{10^{-12}} \cdot v \mapsto B(\Delta^{--} \to ee) \sim B(\Delta^{--} \to W^- W^-)$

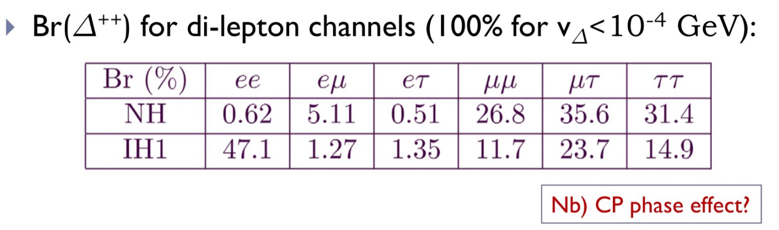
if $\lambda \sim \frac{v_\Delta}{v} \sim 10^{-6}$.

- Collider probe of neutrino mass matrix

$$pp \to \Delta^{++}\Delta^{--}$$
$$\Delta^{--} \to l_i^- l_j^-$$
$$\Delta^{++} \to l_i^+ l_j^+$$

[EJC, Lee, Park 0304069]

$$B(\Delta^{\pm\pm} \to l_i^\pm l_j^\pm) \propto |m_\nu^{ij}|^2$$



- Br(Δ^{++}) for di-lepton channels (100% for $v_\Delta < 10^{-4}$ GeV):

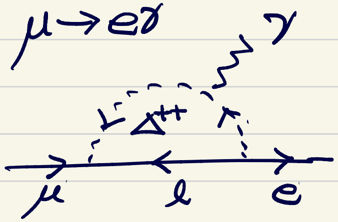
Br (%)	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
NH	0.62	5.11	0.51	26.8	35.6	31.4
IH1	47.1	1.27	1.35	11.7	23.7	14.9

Nb) CP phase effect?

- Lepton Flavor Violation in Type II Seesaw

LFV generic in neutrino mass models.

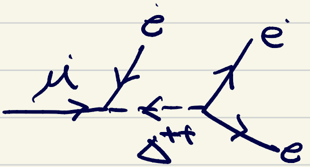
ex) $\mu \to e\gamma$



$B(\mu \to e\gamma) < 4.2\times10^{-13}$ MEG

$|(\lambda\lambda^\dagger)_{\mu e}| \lesssim 10^{-4}\left(\frac{M_\Delta}{\text{TeV}}\right)^2$

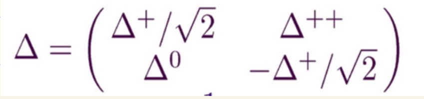
$\mu \to eee$



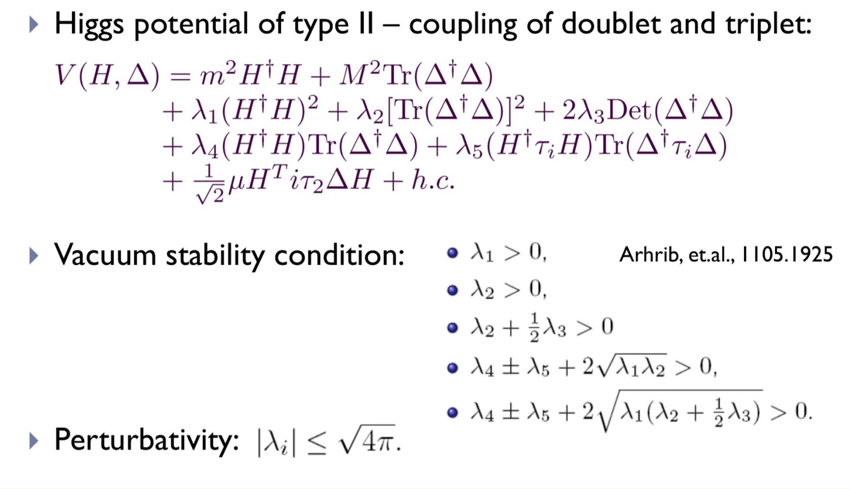
$B(\mu \to 3e) < 10^{-12}$ SINDRUM

$|\lambda_{ee}\lambda_{\mu e}| < 2\times10^{-5}\left(\frac{M_\Delta}{\text{TeV}}\right)^2$

- Higgs stability and sp bound in Type II Seesaw



$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$



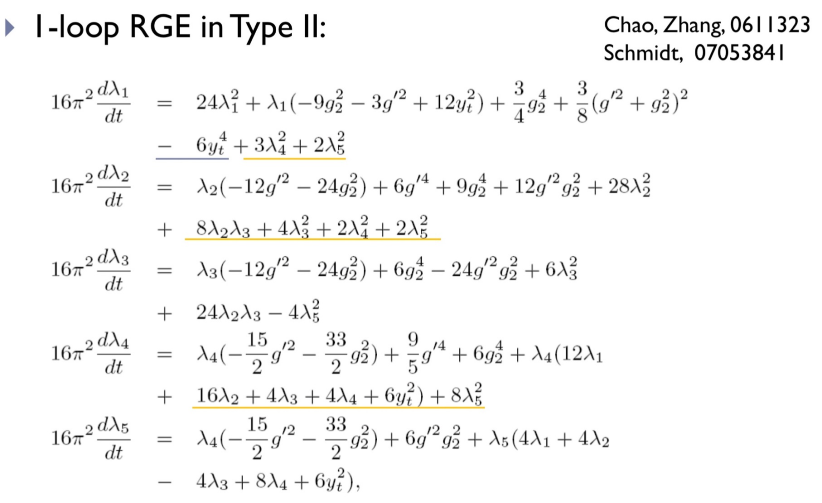
- Higgs potential of type II – coupling of doublet and triplet:

$$\begin{aligned} V(H,\Delta) = m^2 H^\dagger H + M^2 \mathrm{Tr}(\Delta^\dagger\Delta) \\ + \lambda_1 (H^\dagger H)^2 + \lambda_2 [\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + 2\lambda_3 \mathrm{Det}(\Delta^\dagger\Delta) \\ + \lambda_4 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_5 (H^\dagger \tau_i H)\mathrm{Tr}(\Delta^\dagger \tau_i \Delta) \\ + \frac{1}{\sqrt{2}}\mu H^T i\tau_2 \Delta H + h.c. \end{aligned}$$

- Vacuum stability condition:
  - $\lambda_1 > 0,$
  - $\lambda_2 > 0,$
  - $\lambda_2 + \frac{1}{2}\lambda_3 > 0$
  - $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1\lambda_2} > 0,$
  - $\lambda_4 \pm \lambda_5 + 2\sqrt{\lambda_1(\lambda_2 + \frac{1}{2}\lambda_3)} > 0.$

Arhrib, et.al., 1105.1925

- Perturbativity: $|\lambda_i| \leq \sqrt{4\pi}.$

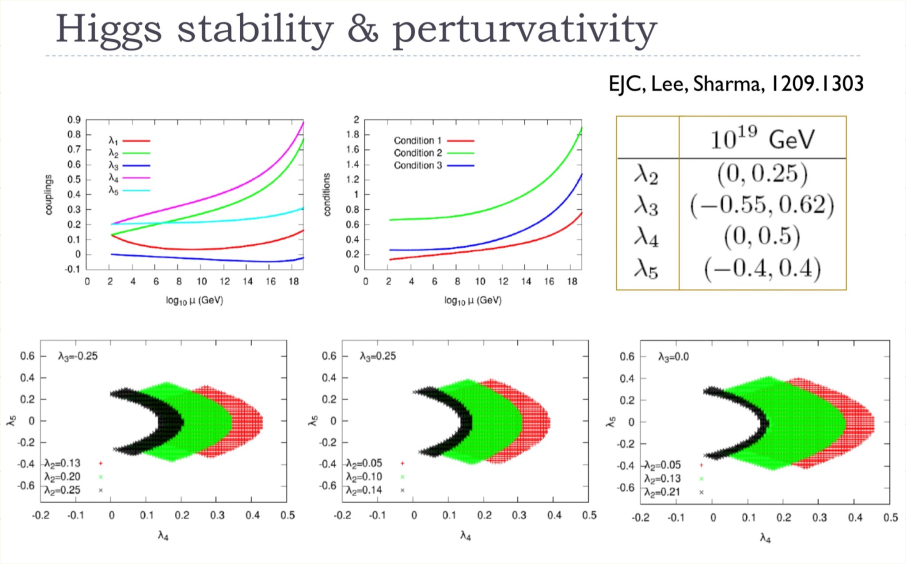


- 1-loop RGE in Type II:

Chao, Zhang, 0611323
Schmidt, 07053841

$$\begin{aligned} 16\pi^2 \frac{d\lambda_1}{dt} &= 24\lambda_1^2 + \lambda_1(-9g_2^2 - 3g'^2 + 12y_t^2) + \frac{3}{4}g_2^4 + \frac{3}{8}(g'^2 + g_2^2)^2 \\ &- \underline{6y_t^4} + \underline{3\lambda_4^2 + 2\lambda_5^2} \\ 16\pi^2 \frac{d\lambda_2}{dt} &= \lambda_2(-12g'^2 - 24g_2^2) + 6g'^4 + 9g_2^4 + 12g'^2 g_2^2 + 28\lambda_2^2 \\ &+ \underline{8\lambda_2\lambda_3 + 4\lambda_3^2 + 2\lambda_4^2 + 2\lambda_5^2} \\ 16\pi^2 \frac{d\lambda_3}{dt} &= \lambda_3(-12g'^2 - 24g_2^2) + 6g_2^4 - 24g'^2 g_2^2 + 6\lambda_3^2 \\ &+ 24\lambda_2\lambda_3 - 4\lambda_5^2 \\ 16\pi^2 \frac{d\lambda_4}{dt} &= \lambda_4(-\frac{15}{2}g'^2 - \frac{33}{2}g_2^2) + \frac{9}{5}g'^4 + 6g_2^4 + \lambda_4(12\lambda_1 \\ &+ \underline{16\lambda_2 + 4\lambda_3 + 4\lambda_4 + 6y_t^2) + 8\lambda_5^2} \\ 16\pi^2 \frac{d\lambda_5}{dt} &= \lambda_4(-\frac{15}{2}g'^2 - \frac{33}{2}g_2^2) + 6g'^2 g_2^2 + \lambda_5(4\lambda_1 + 4\lambda_2 \\ &- 4\lambda_3 + 8\lambda_4 + 6y_t^2), \end{aligned}$$

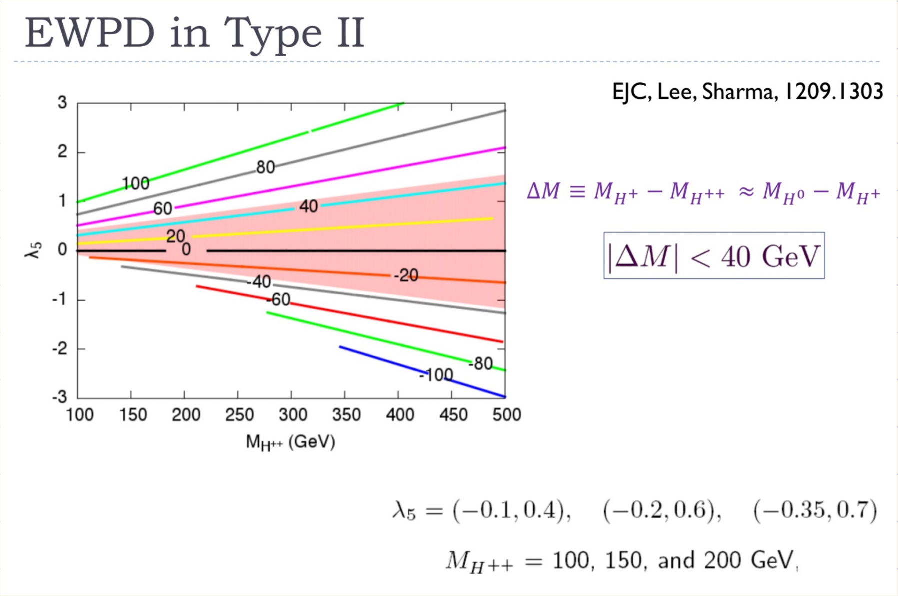
⇒ Higgs stability can be guaranteed.



Higgs stability & perturvativity

EJC, Lee, Sharma, 1209.1303

	10^{19} GeV
λ_2	$(0, 0.25)$
λ_3	$(-0.55, 0.62)$
λ_4	$(0, 0.5)$
λ_5	$(-0.4, 0.4)$



EWPD in Type II

EJC, Lee, Sharma, 1209.1303

$$\Delta M \equiv M_{H^+} - M_{H^{++}} \approx M_{H^0} - M_{H^+}$$

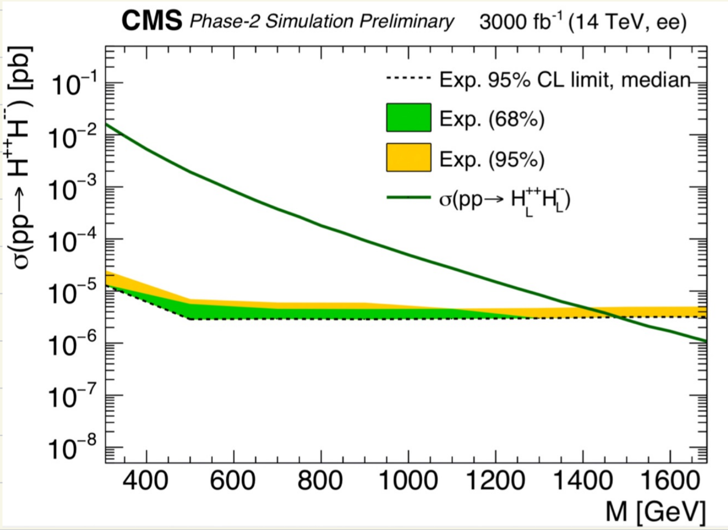
$$\boxed{|\Delta M| < 40 \text{ GeV}}$$

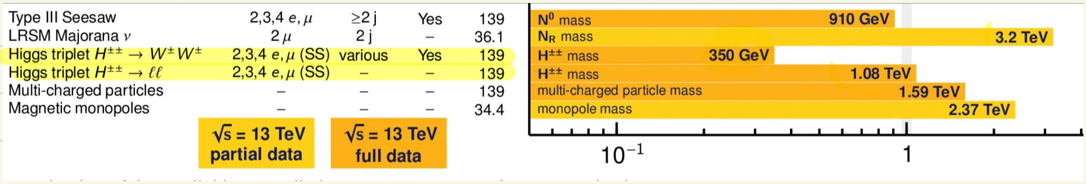
$$\lambda_5 = (-0.1, 0.4), \quad (-0.2, 0.6), \quad (-0.35, 0.7)$$

$$M_{H^{++}} = 100,\ 150,\ \text{and } 200 \text{ GeV},$$

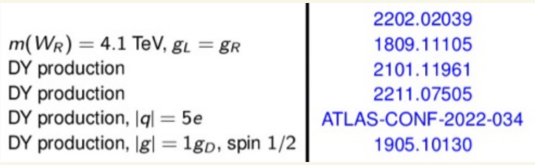
Discovering a douly-charged boson

$$pp \to Z^* \to \Delta^{++}\Delta^{--} \to \left\{ \begin{array}{c} l_i^\pm l_j^\pm \\ \hline W^\pm W^\pm \end{array} \right. \text{- - -} \left\{ \begin{array}{l} \lambda_{ij} \sim 10^{-6} \\ v_\Delta \sim 10^{-6} v_H \end{array} \right.$$





Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139
LRSM Majorana ν	2 μ	2 j	–	36.1
Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139
Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139
Multi-charged particles	–	–	–	139
Magnetic monopoles	–	–	–	34.4



	2202.02039
$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
DY production	2101.11961
DY production	2211.07505
DY production, $\lvert q \rvert = 5e$	ATLAS-CONF-2022-034
DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1905.10130

iii) Type III Seesaw : Triplet fermion $\Sigma = (\Sigma^+, \Sigma^0, \Sigma^-)$

$T_3 = +1, 0, -1$

$$-\mathcal{L}_{III} = y_\nu^{ij}\, l_i \Sigma_j H + \frac{1}{2} M_\Delta \Sigma \Sigma$$

$Y = -\frac{1}{2} \quad 0 \quad +\frac{1}{2}$

$2 \times 2 = 1 + \underline{3}$

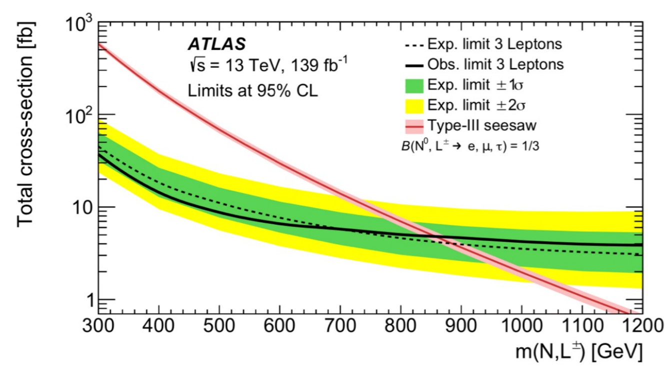
[Franceschini, et.al. 0805.1613]

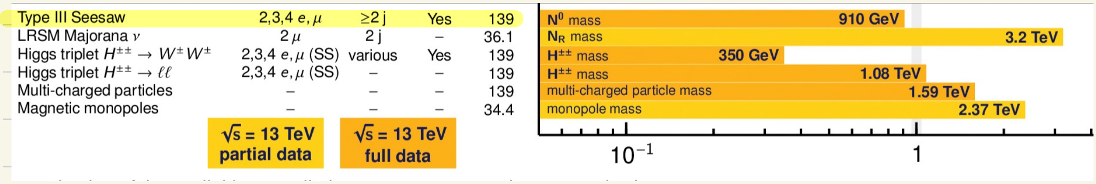
*) Search for Σ through its gauge production

$$pp \to W^* \to \Sigma_i^0 \, \Sigma_i^\pm$$

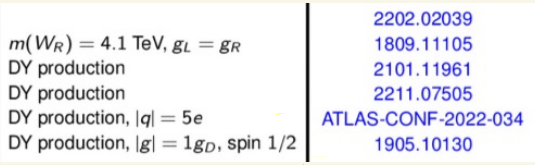
$\hookrightarrow l_j^\pm h, \; l_j^\pm Z, \; \nu_j W^\pm$

$\hookrightarrow \nu_j h, \; \nu_j Z, \; l_j^\mp W^\mp$





Type III Seesaw	2,3,4 e, μ	≥2 j	Yes	139	N^0 mass 910 GeV
LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV
Higgs triplet $H^{\pm\pm} \to W^\pm W^\pm$	2,3,4 e, μ (SS)	various	Yes	139	$H^{\pm\pm}$ mass 350 GeV
Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	139	$H^{\pm\pm}$ mass 1.08 TeV
Multi-charged particles	–	–	–	139	multi-charged particle mass 1.59 TeV
Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV



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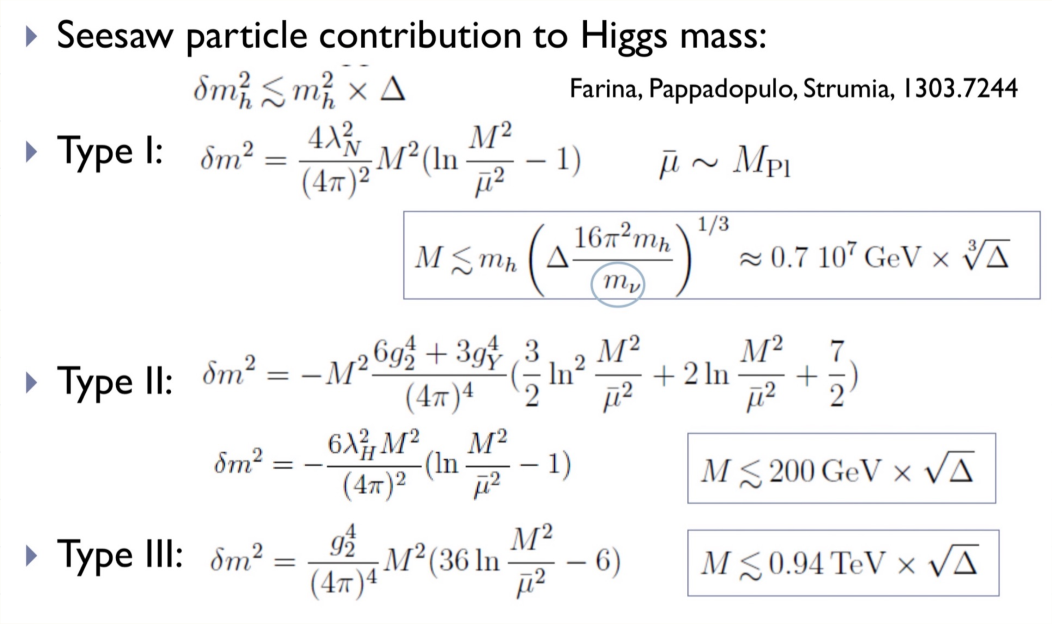
⟨ Fine-tuning bounds ⟩



- Seesaw particle contribution to Higgs mass:

$$\delta m_h^2 \lesssim m_h^2 \times \Delta$$

Farina, Pappadopulo, Strumia, 1303.7244

- Type I: $\delta m^2 = \frac{4\lambda_N^2}{(4\pi)^2} M^2 (\ln \frac{M^2}{\bar{\mu}^2} - 1)$ $\bar{\mu} \sim M_{\rm Pl}$

$$\boxed{M \lesssim m_h \left(\Delta \frac{16\pi^2 m_h}{m_\nu}\right)^{1/3} \approx 0.7\ 10^7\,\mathrm{GeV} \times \sqrt[3]{\Delta}}$$

- Type II: $\delta m^2 = -M^2 \frac{6g_2^4 + 3g_Y^4}{(4\pi)^4} (\frac{3}{2} \ln^2 \frac{M^2}{\bar{\mu}^2} + 2 \ln \frac{M^2}{\bar{\mu}^2} + \frac{7}{2})$

$$\delta m^2 = -\frac{6\lambda_H^2 M^2}{(4\pi)^2} (\ln \frac{M^2}{\bar{\mu}^2} - 1) \qquad \boxed{M \lesssim 200\,\mathrm{GeV} \times \sqrt{\Delta}}$$

- Type III: $\delta m^2 = \frac{g_2^4}{(4\pi)^4} M^2 (36 \ln \frac{M^2}{\bar{\mu}^2} - 6)$ $\boxed{M \lesssim 0.94\,\mathrm{TeV} \times \sqrt{\Delta}}$

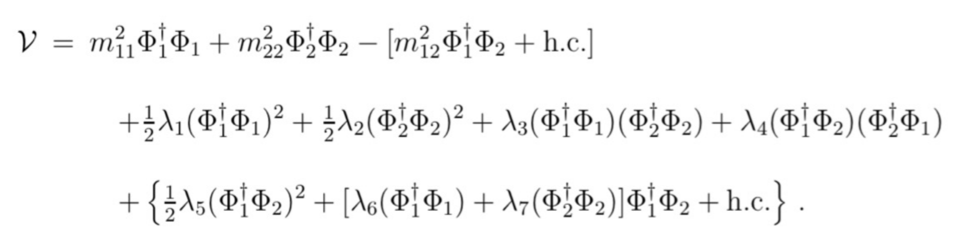
Q2) FCNC in the corner?

$h \to \mu\tau$ at LHC

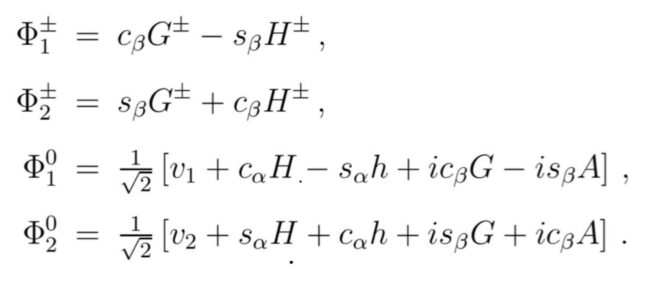
ex) 2HDM : Φ_1, Φ_2

Gunion, Haber
0207010

- Scalar potential.



$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$
$$+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} .$$



$$\Phi_1^\pm = c_\beta G^\pm - s_\beta H^\pm ,$$
$$\Phi_2^\pm = s_\beta G^\pm + c_\beta H^\pm ,$$
$$\Phi_1^0 = \frac{1}{\sqrt{2}}[v_1 + c_\alpha H - s_\alpha h + ic_\beta G - is_\beta A] ,$$
$$\Phi_2^0 = \frac{1}{\sqrt{2}}[v_2 + s_\alpha H + c_\alpha h + is_\beta G + ic_\beta A] .$$

$v^2 = v_1^2 + v_2^2$
$= (246\,\text{GeV})^2$

$t_\beta = \dfrac{v_2}{v_1}$

- $c_{\beta-\alpha} \approx \dfrac{\hat\lambda v^2}{m_H^2 - m_h^2}$, $\hat\lambda \equiv \frac{s_{2\beta}}{2}(\lambda_1 c_\beta^2 - \lambda_2 s_\beta^2 - \lambda_{345} c_{2\beta})$
$- \lambda_6 c_\beta c_{3\beta} - \lambda_7 s_\beta s_{3\beta}$.

$c_{\beta-\alpha} \to 0$ $(\alpha \approx \beta - \frac{\pi}{2})$ $\begin{cases} \text{Decoupling} & m_H \gg v \\ \text{Alignment} & m_H \sim v . \end{cases}$

• Yukawa

$$-\mathcal{L}_Y = \underbrace{\left(y_{e1}^{ij} \tilde{\Phi}_1 + y_{e2}^{ij} \tilde{\Phi}_2 \right)}_{\downarrow} l_i e_j^c + \text{h.c.}$$

$$\frac{v}{\sqrt{2}}\left(y_{e1}^{ij} c_\beta + y_{e2}^{ij} s_\beta\right) + \frac{h}{\sqrt{2}}\left(-y_{e1}^{ij} s_\alpha + y_{e2}^{ij} c_\alpha\right) + \frac{H}{\sqrt{2}}\left(y_{e1}^{ij} c_\alpha + y_{e2}^{ij} s_\alpha\right)$$

If $s_\alpha = -c_\beta,\ c_\alpha = s_\beta\ (c_{\beta-\alpha} = 0)$

$$-\mathcal{L}_Y = \left(1 + \frac{h}{v}\right) M_e^{ij} e_i e_j^c + \text{h.c}$$

$$\Rightarrow \left(1 + \frac{h}{v}\right) m_{e_i} e_i e_i^c + \text{h.c.}$$

No FCNC

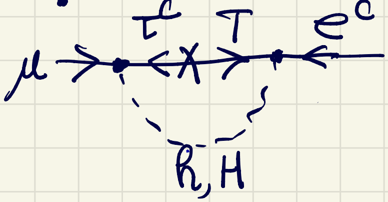
In general,

$$-\mathcal{L}_Y = m_{e_i} e_i e_i^c + y_{eh}^{ij} h e_i e_j^c + \text{h.c}$$

i) $h \to \mu\tau$? $\underline{\sqrt{|y_{eh}^{23}|^2 + |y_{eh}^{32}|^2}} \lesssim 10^{-3}$ (LHC)

$$\sim c_{\beta-\alpha} \frac{m_\tau}{v} \qquad c_{\beta\alpha} \lesssim 0.1 \ ?$$

ii) $\mu \to e\gamma$?



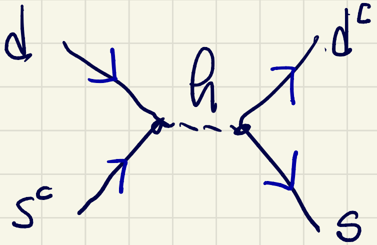
$$\propto y_{eh}^{\overset{13}{23}} y_{eh}^{\overset{32}{31}} m_\tau \qquad \text{(HW)}$$

$$\Rightarrow \left| y_{\underset{H}{eh}}^{23} y_{\underset{H}{eh}}^{31} \right| \lesssim 10^{-5} \left(\frac{m_H^2}{m_h^2}\right)$$

Similarly in the quark sector

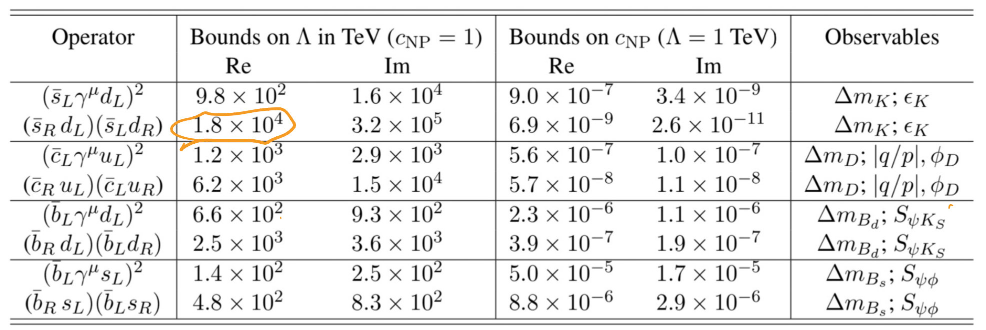
$$y^{ij}_{\varphi u}\, \varphi\, u_i u^c_j , \quad y^{ij}_{\varphi d}\, \varphi\, d_i d^c_j , \quad \varphi = h, H$$

Flavor-changing four-fermion operators



$$\Rightarrow \underbrace{\frac{y^{12}_{d\varphi}\, y^{21*}_{d\varphi}}{m_\varphi^2}}_{\hookrightarrow \frac{1}{\Lambda^2}} (d s^c)(\bar{d}^c \bar{s})$$

$$\left| y^{12}_{dh}\, y^{21}_{dh} \right|^{\frac{1}{2}} \lesssim \frac{m_h}{\Lambda} \sim 10^{-5} < \frac{\sqrt{m_d m_s}}{v} \sim 3\times 10^{-4}$$



Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$)		Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

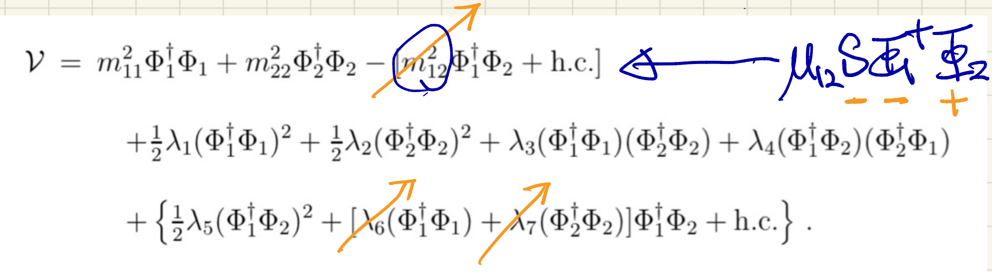
- FCNC can be totally forbidden if couple one Φ to each Yukawa

$\Phi_2 q u^c$,	$\tilde{\Phi}_2 q d^c$,		$\tilde{\Phi}_2 l e$		
2	2	+	2	+	(I)
2	1	−	1	−	(II)
2	2	+	1	−	(III)
2	1	−	2	+	(IV)

Assign Z_2 : Φ_2 , Φ_1

$+ \quad -$

2



$$\mathcal{V} = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [\cancel{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}]$$

$$+\tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$

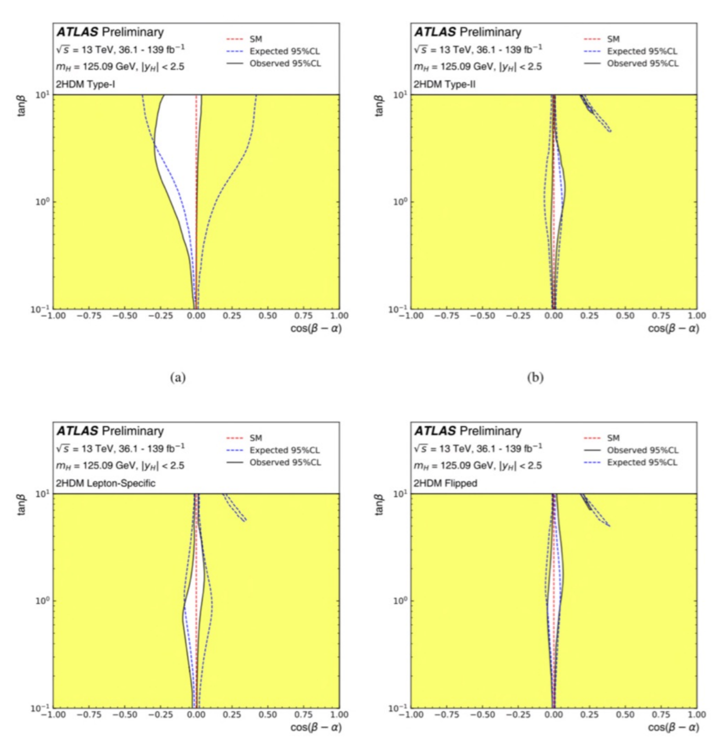
$$+\left\{\tfrac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\cancel{\lambda_6}(\Phi_1^\dagger\Phi_1) + \cancel{\lambda_7}(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} .$$

$\longleftarrow \underset{-\ -\ +}{\mu_{12} S \Phi_1^\dagger \Phi_2}$ Z_2

Note) $m_A^2 = \dfrac{m_{12}^2}{c_\beta s_\beta} - \dfrac{v}{2}\left[2\lambda_5 + \lambda_6 t_\beta^{-1} + \lambda_7 t_\beta\right]$ (HW)

< Testing 2HDM : $c_{\beta-\alpha} \neq 0$? >

$$\mathcal{L}_{\varphi VV} = (s_{\alpha-\beta} h + c_{\alpha-\beta} H) \frac{2}{v} (m_W^2 WW + m_Z^2 ZZ).$$



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- In the limit of $m_{12}^2, \lambda_{5,6,7} \longrightarrow 0$, there appears an additional U(1): Φ_2, Φ_1
  $+1 \quad -1$.
  Calculate its anomalies under $SU(3)_c, SU(2)_L, U(1)_Y$ for 2HDM (I, II, III, IV). (HW)

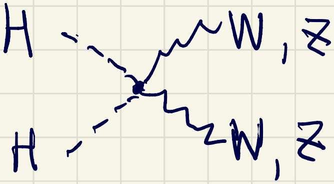
				SU(3) SU(2) U(1)
(II)	$\Phi_2 q u^c$	$\tilde{\Phi}_1 q d^c$	$\tilde{\Phi}_1 l e^c$	$(-2, 0, -\frac{8}{3}) N_g$
	1 0 -1	1 0 -1	1 0 -1	

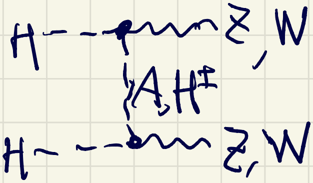
- **Inert doublet as DM candidate.**

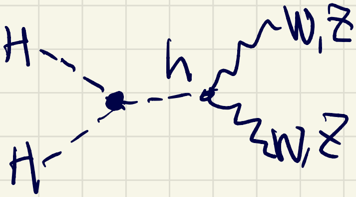
Archotype of WIMP. [0612275]

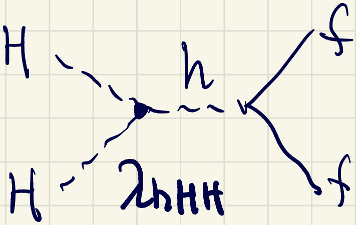
Φ_1 doesnot couple to fermions and gets no VEV.

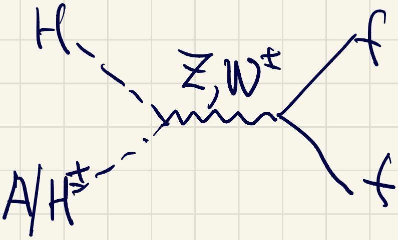
$$\Phi_1 = \begin{pmatrix} H^\pm \\ (H+iA)/\sqrt{2} \end{pmatrix}.$$











$$\text{WIMP}: \quad \langle \sigma v \rangle \sim \frac{\lambda^2}{4\pi m_{DM}^2} \sim \underline{10^{-9}\,\text{GeV}^{-1}}$$

$$\Rightarrow \underline{\Omega_H h^2 \sim 0.1} \text{ for } \lambda \sim 0.1,\ m_H \sim \text{TeV}$$

Viable ranges for IDM: $\begin{cases} m_H \gtrsim 500\,\text{GeV}. \\ m_H \sim \frac{1}{2} m_h \end{cases}$

(Q3) Why is strong CP well conserved?

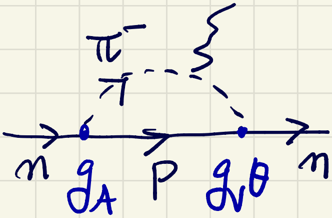
SM gauge symmetry allows [Peccei 0607268 Kim, Carosi 0807.3125]

$$\mathcal{L}_\theta = \theta \frac{g_3^2}{32\pi^2} G^a_{\mu\nu} \underbrace{\tilde{G}^{\mu\nu}_a}_{\frac{1}{2}\varepsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta}.}$$

$$\propto \theta \vec{E}\cdot\vec{B}$$

	$\vec{E}$	$\vec{B}$	$\vec{E}\cdot\vec{B}$
C	−	−	+
P	−	+	−
T	+	−	−

It leads to non-vanishing neutron EDM



$d_n \sim |\theta|\, 10^{-16}$ e·cm $\lesssim 10^{-26}$ e·cm (PSI)

$\Rightarrow \underline{|\theta| \lesssim 10^{-10}}$

Another small parameter in SM. Why?

PQWW mechanism

$\theta = 0$ due to the presence of a global $U(1)_{PQ}$ symmetry anomalous under $SU(3)_c$.

- Spontaneous breaking of $U(1)_{PQ}$ at f_a

$$P = \frac{1}{\sqrt{2}}(f_a + r)e^{ia/f_a}$$

predicts a pNGB "a" (axion).

- Since $U(1)_{PQ}$ current $J_{5\mu}^{PQ}$ is not conserved,

$$\partial^\mu J_{5\mu}^{PQ} = \frac{g_3^2}{32\pi^2} G\tilde{G} \,, \quad J_{5\mu}^{PQ} = \sum_f q_f \bar{f}\gamma_\mu\gamma_5 f .$$

there appear the coupling $aG\tilde{G}$:

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{1}{f_a}\partial^\mu a J_{5\mu}^{PQ} + \left(\frac{a}{f_a} + \theta\right)\frac{g_3^2}{32\pi^2} G\tilde{G}$$

- QCD condensates at $\Lambda_{QCD} \sim 100$ MeV, and generates the potential

$$V_{QCD} \sim \Lambda_{QCD}^4\left[1 - \cos\left(\frac{a}{f_a} + \theta\right)\right]$$

- Minimization of V_{QCD} gives us

$$\left\langle \frac{a}{f_a} + \theta \right\rangle = 0 \,, \quad m_a \approx \frac{\Lambda_{QCD}^2}{f_a} \sim 10^{-5}\,\text{eV}$$

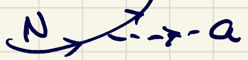
for $f_a \approx 10^{12}$ GeV.

- Widow for the axion:

$$10^{10}\,\text{GeV} \lesssim f_a \lesssim 10^{12}\,\text{GeV}$$

star cooling ↑ ↑ axion DM

$$\frac{1}{f_a}\partial_\mu a\, \bar{q}\gamma^\mu\gamma_5 q \Rightarrow \frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N \Rightarrow$$ energy loss radiating a

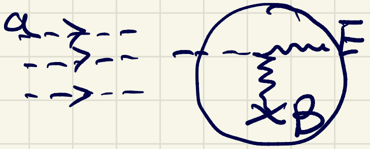


- Axion search via a-γ-γ coupling

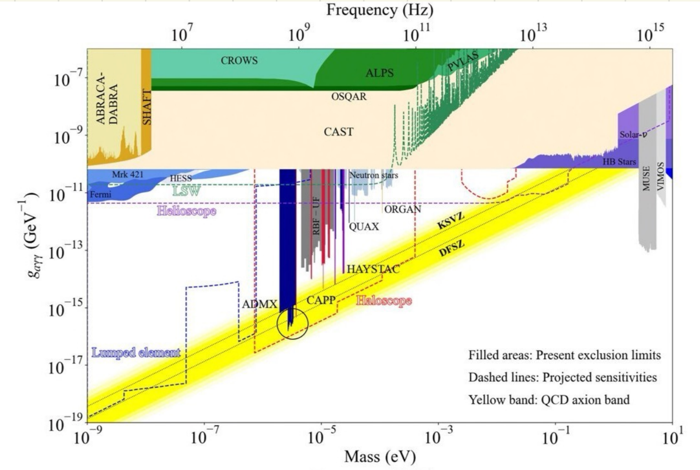
$$\mathcal{L}_{a\gamma\gamma} = C_{a\gamma\gamma} \frac{a}{f_a} \frac{1}{16\pi^2} F\tilde{F} \propto a\vec{E}\cdot\vec{B}$$

ex) Axion conversion to photon

DM



ADMX
CAPP

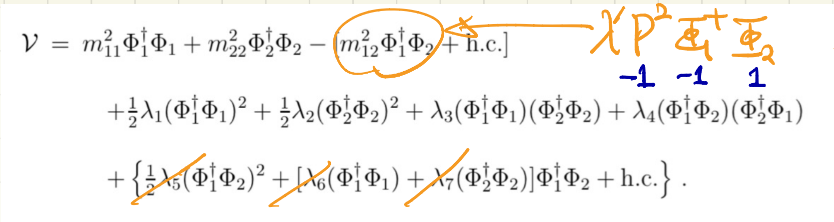


- { KSVZ model: $\lambda P Q Q^c$
  DFSZ model: 2HDM II

SU(3) SU(2) U(1)

(II) $\underset{1\ 0\ -1}{\Phi_2 q u^c}$ $\underset{1\ 0\ -1}{\tilde{\Phi}_1 q d^c}$ $\underset{1\ 0\ -1}{\tilde{\Phi}_1 l e^c}$ $(-2, 0, -\frac{8}{3})N_g$

$\lambda' P^2 \underset{-1}{\Phi_1^\dagger} \underset{-1}{\,} \underset{1}{\Phi_2}$ $\langle P\rangle \sim f_a$



$$\begin{aligned}\mathcal{V} = {} & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] \\ & + \tfrac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \tfrac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ & + \left\{\cancel{\tfrac{1}{2}\lambda_5}(\Phi_1^\dagger\Phi_2)^2 + \cancel{[\lambda_6}(\Phi_1^\dagger\Phi_1) + \cancel{\lambda_7}(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}.\end{aligned}$$