A Three-Loop Neutrino Model with Isolated Doubly-Charged Scalar

Kenji Nishiwaki (KIAS)

based on collaborations with

Hiroshi Okada (NCTS) &
Yuta Orikasa (KIAS & Seoul National Univ.)

(Ref: arXiv:1507.02412)

talk @ Kavli-IPMU-Durham-KIAS workshop: New particle searches confronting the first LHC run-2 data,
Kavli-IPMU (10th September 2015)

Intro: extended EW sector, required

SM (+ ν_R): its neutrino Yukawa sector is very unnatural :(

(At least) as small as 10^{-12} ! unnatural!!

$$\mathcal{L}_Y \supset -Y^{\nu}_{ij}\overline{L_{L_i}}\nu_{R_j}\tilde{H} + \text{h.c.}$$

i,j (=1,2,3): flavor/generation indices

$$\underline{(\text{Yukawa of } \nu)} \times \boxed{\frac{v}{\sqrt{2}}(= 174\,\text{GeV})} = \boxed{m_\nu\,(\sim \text{sub eV})}$$

- νs have large mixing angles.
- Also, no dark matter (DM) candidate in the SM...

These issues imply that the electroweak (EW) sector would be **extended with <u>flavor symmetry/structure</u>**.

neutrino large mixing, (also possibly) DM :)

<u>a naive Q: how the smallness of ν masses is explained???</u>

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<u>a naive Q: how the smallness of ν masses is explained???</u>

<u>(An) A: Don't worry! Flavor symmetry helps us also!</u>

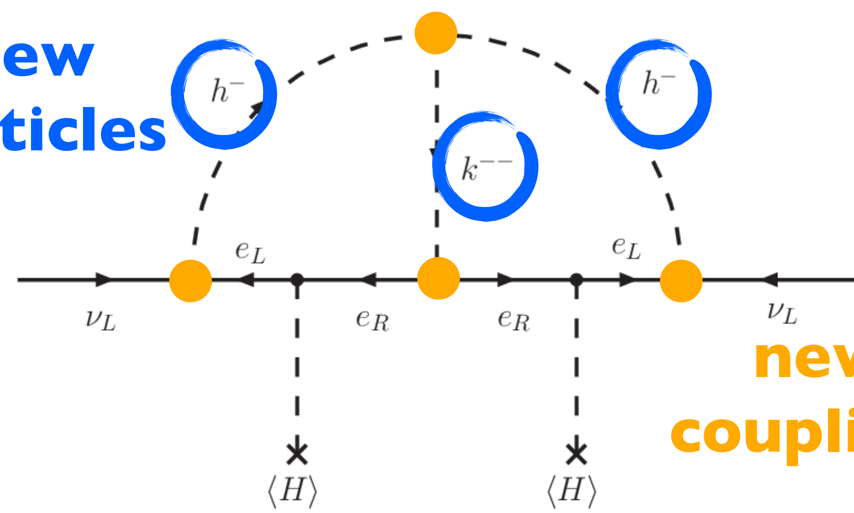
Intro: Flavor Symmetry → loop-induced ν mass

suitable assignment → (Majorana) ν masses become loop-induced

[Zee,NPB264-99(86); Babu,PLB203-132(88)]

a 2-loop example (Zee-Babu model)

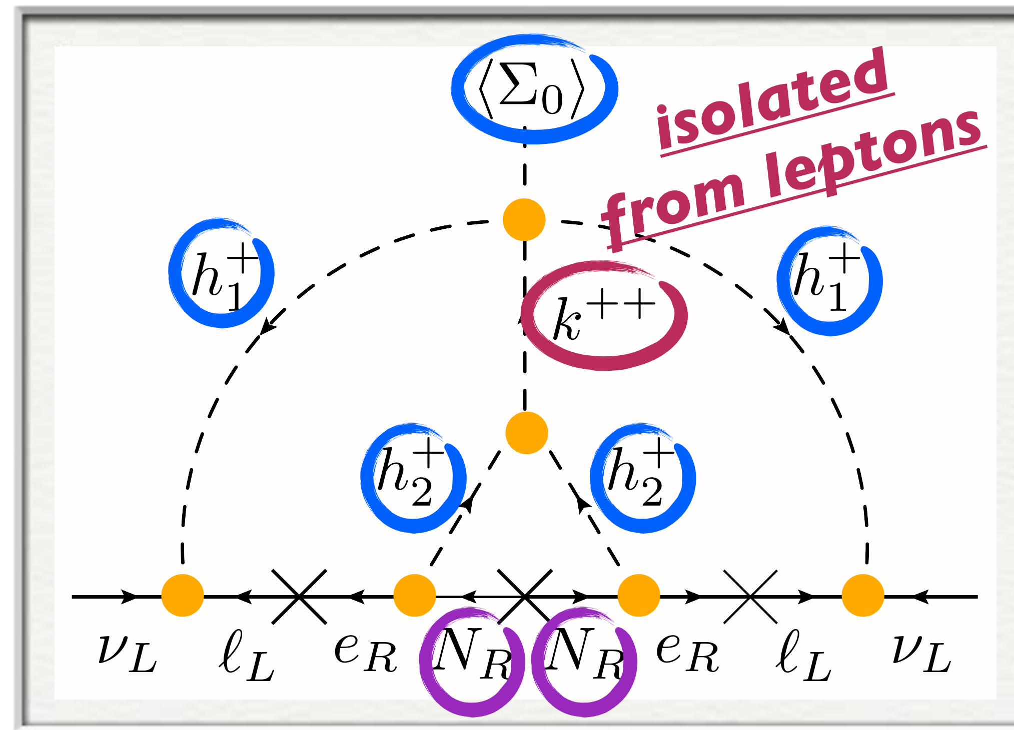
new particles



new couplings

alleviating unnaturalness!

[KN,Okada,Orikasa,arXiv:1507.02412] a **3-loop** example



DM included

radiative ν mass

$$\frac{1}{(16\pi^2)^{N_{\mathrm{loops}}}} \times (\text{loop function}) \times (\text{new couplings})$$

mass scale in the loop like (TeV-scale) see-saw

(see also talks by Seungwon & Yuta)

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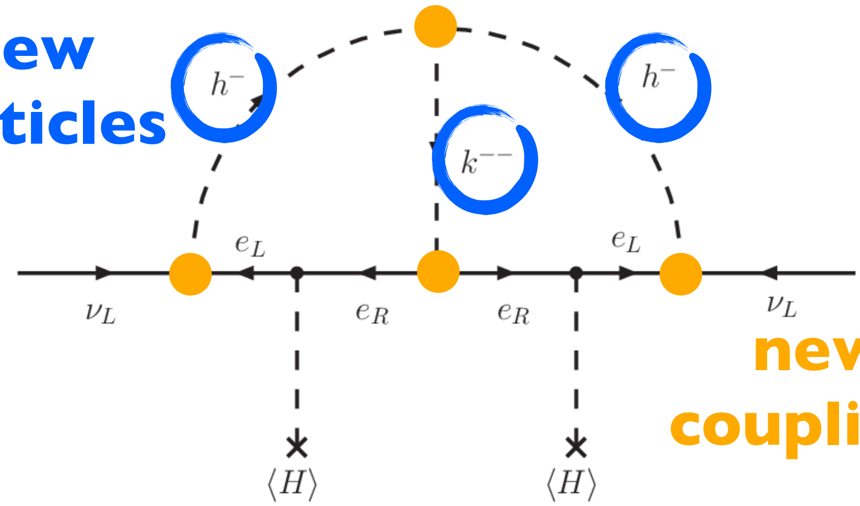

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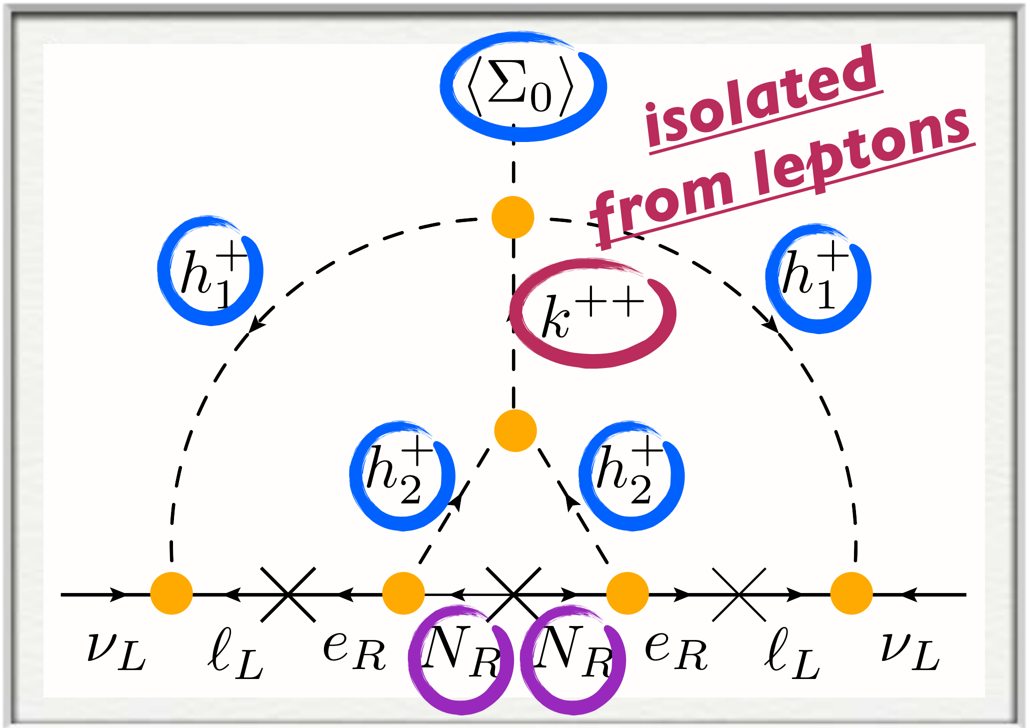

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higher loops, larger suppression

3-loop models can be more "natural" than 1- or 2-loop ones.
(Some new couplings can be close to unity.)

Intro: 3-loop model is predictive

On the other hand, sizable couplings would lead to

- enormous lepton flavor violation (LFV)
- rapid vacuum destabilization

couplings should be small

- too-suppressed ν masses

couplings should be large

complimentary

This means: valid parameter region is restricted (predictive)!!

(Careful model building is required.)

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This me… …dictive)!!

…l building …red.)

(picture from Web)

1: ν profile

$m_{k^{\pm\pm}}$	$(m_{h_1^\pm}, m_{h_2^\pm})$	$F_1^{(\zeta_2)}$	$F_1^{(\zeta_3)}$	# of allowed points
		loop functions		(out of 10^5 points, each)
500 GeV	$(4.8\,\mathrm{TeV}, 4.8\,\mathrm{TeV})$	-1.16818	-11.5428	2726
	$(4.0\,\mathrm{TeV}, 4.0\,\mathrm{TeV})$	-2.14198	-20.0287	422
	$(3.5\,\mathrm{TeV}, 3.5\,\mathrm{TeV})$	-3.30195	-29.6525	89
	$(3.0\,\mathrm{TeV}, 3.0\,\mathrm{TeV})$	-5.37518	-46.0932	16
250 GeV	$(4.8\,\mathrm{TeV}, 4.8\,\mathrm{TeV})$	-1.21466	-11.9695	1644
	$(4.0\,\mathrm{TeV}, 4.0\,\mathrm{TeV})$	-2.24746	-20.9444	190
	$(3.5\,\mathrm{TeV}, 3.5\,\mathrm{TeV})$	-3.49141	-31.2321	31
	$(3.0\,\mathrm{TeV}, 3.0\,\mathrm{TeV})$	-5.74153	-49.0141	2

considering requirements/constraints from

(1) suitable neutrino mass/mixing realization (3-loop),
(2) lepton flavor violations ($l_i \to l_j \gamma$, $l_i \to l_j l_k l_l$; 1-loop),
(3) gauge universalities (tree),
(4) vacuum stability (tree + primary 1-loop),

[right ν profiles fixed]

$$M_X = M_{N_1} \simeq m_{\mathrm{Higgs}}/2$$
$$M_{N_2} = 5\,\mathrm{TeV},\ M_{N_3} = 10\,\mathrm{TeV}$$

(note: other couplings are automatically fixed via neutrino profiles)

[scanned region]

$$\mu_{12} = \mu_{22}\ (\equiv \mu) \in [1\,\mathrm{TeV}, 20\,\mathrm{TeV}],\quad \delta \in [0, 2\pi],\quad \phi \in [0, 2\pi],\quad (y_L)_{23} \in [-1, 1],$$
$$(y_R)_{ij} \in [-0.01, -0.1] \cup [0.01, 0.1]\quad \Big(\text{for } (i,j) = (1,1), (1,2), (1,3), (2,1), (3,1)\Big).$$

1: ν profile

around (or heavier than) 3TeV

[current LHC bound] ~300GeV (when 100% branching ratio to e^+e^+, $\mu^+\mu^+$ or $e^+\mu^+$)

[ATLAS, EPJC72(2012)2244]

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loop functions **(out of 10^5 points, each)**

Also, (scalar trilinears) ~ 10TeV

$\mu_{11} = \lambda_{11} \langle \Sigma_0^* \rangle$

!

VEV of new singlet should be around a few TeV

!

sub-TeV $k^{\pm\pm}$ is consistent (isolation from lepton → less LFV)

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2: LHC Higgs search

LHC Higgs signal strengths are deviated (from the SM) via

- mixing effect between SM Higgs (Φ) & scalar for global U(1) breaking (Σ) ***primary!***
- loop effect via k^{++} (in $h \to 2\gamma$, $h \to \gamma Z$) **secondary ($m_k^{++} \geq$ 250GeV: via ν profile)**

$$\chi^2 = \sum_{\substack{f=\gamma\gamma, ZZ^*, WW^*,\\ b\bar{b}, \tau\bar{\tau}\ (\text{ATLAS})}} \left(\frac{\mu_f - \hat{\mu}_f}{\hat{\sigma}_f} \right)^2 + \sum_{\substack{f=\gamma\gamma, ZZ^*, WW^*,\\ b\bar{b}, \tau\bar{\tau}\ (\text{CMS})}} \left(\frac{\mu_f - \hat{\mu}_f}{\hat{\sigma}_f} \right)^2$$

[used data]

Process	ATLAS	CMS
$h \to \gamma\gamma$	$1.17^{+0.27}_{-0.27}$	1.12 ± 0.24
$h \to ZZ^* \to 4\ell$	$1.44^{+0.40}_{-0.33}$	1.00 ± 0.29
$h \to WW^* \to \ell\nu\ell\nu$	$1.09^{+0.23}_{-0.21}$	0.83 ± 0.21
$h \to b\bar{b}$	$0.5^{+0.4}_{-0.4}$	0.84 ± 0.44
$h \to \tau\bar{\tau}$	$1.4^{+0.4}_{-0.4}$	0.91 ± 0.28

[ATLAS: PRD90(2014)112015, PRD91(2015)012006, arXiv:1412.2641, JHEP1501(2015)069, ATLAS-CONF-2014-061]
[CMS: EPJC75(2015)212]

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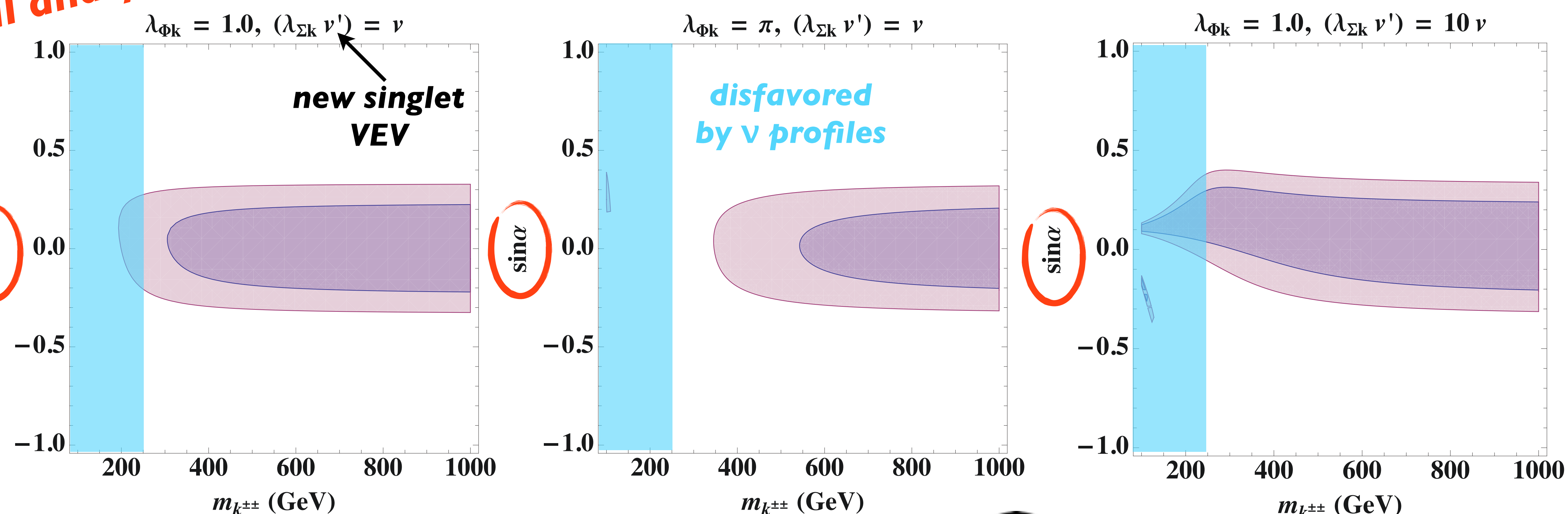
results of global analysis



CP-even part of Φ

CP-even part of Σ

$$\phi = h\cos\alpha + H\sin\alpha, \quad \sigma = -h\sin\alpha + H\cos\alpha.$$

125GeV Higgs

heavier Higgs

the mixing angle

$$\boxed{|\sin\alpha| \lesssim 0.3}$$

3: DM valid region

- Majorana DM can communicate with SM particles through two CP-even scalars

Higgs-portal DM

- DM-DM-portal couplings are suppressed by the TeV VEV of Σ

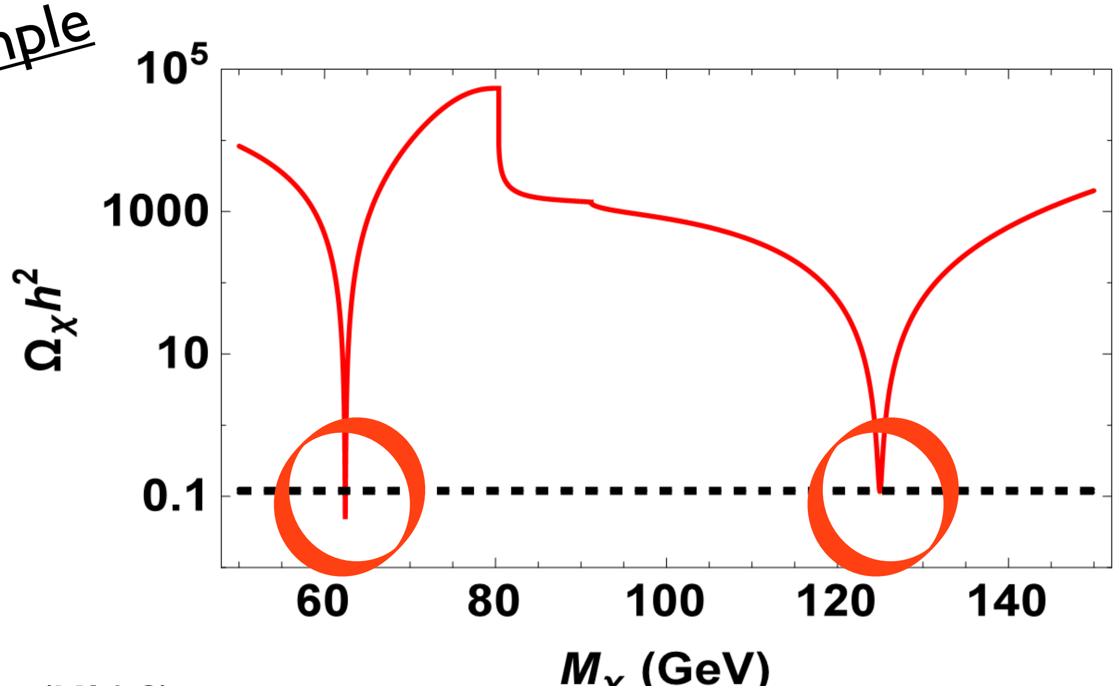
only two resonant points ($m_\chi \sim m_h/2$ or $m_H/2$) are viable

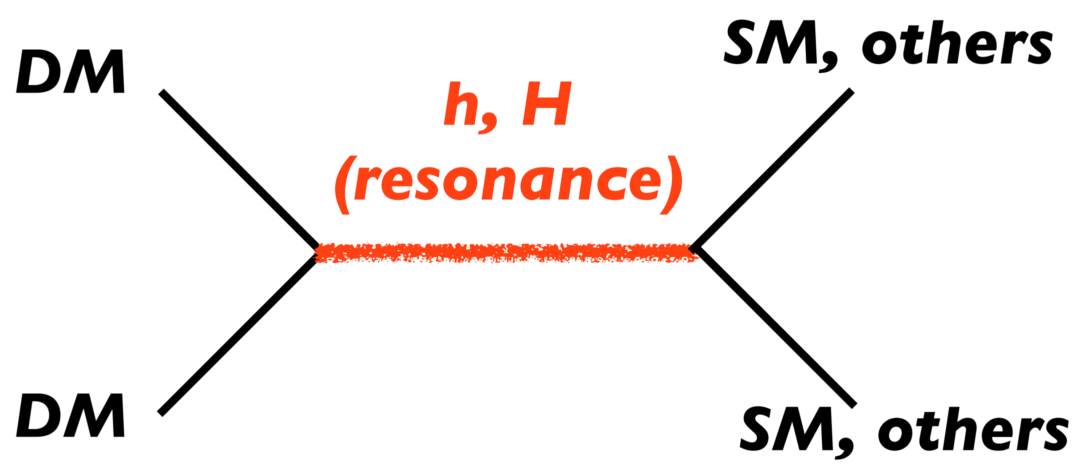
too heavy ($\gtrsim$ a few TeV), ineffective

$$(y_\ell)_{ij}\bar{L}_{L_i}\Phi e_{R_j} + \frac{1}{2}(y_L)_{ij}\bar{L}^c_{L_i}L_{L_j}h_1^+ + (y_R)_{ij}\bar{N}_{R_i}e^c_{R_j}h_2^- + \frac{1}{2}(y_N)_{ij}\Sigma_0\bar{N}^c_{R_i}N_{R_j} + \text{h.c.}$$

mix with the SM Higgs doublet

an example





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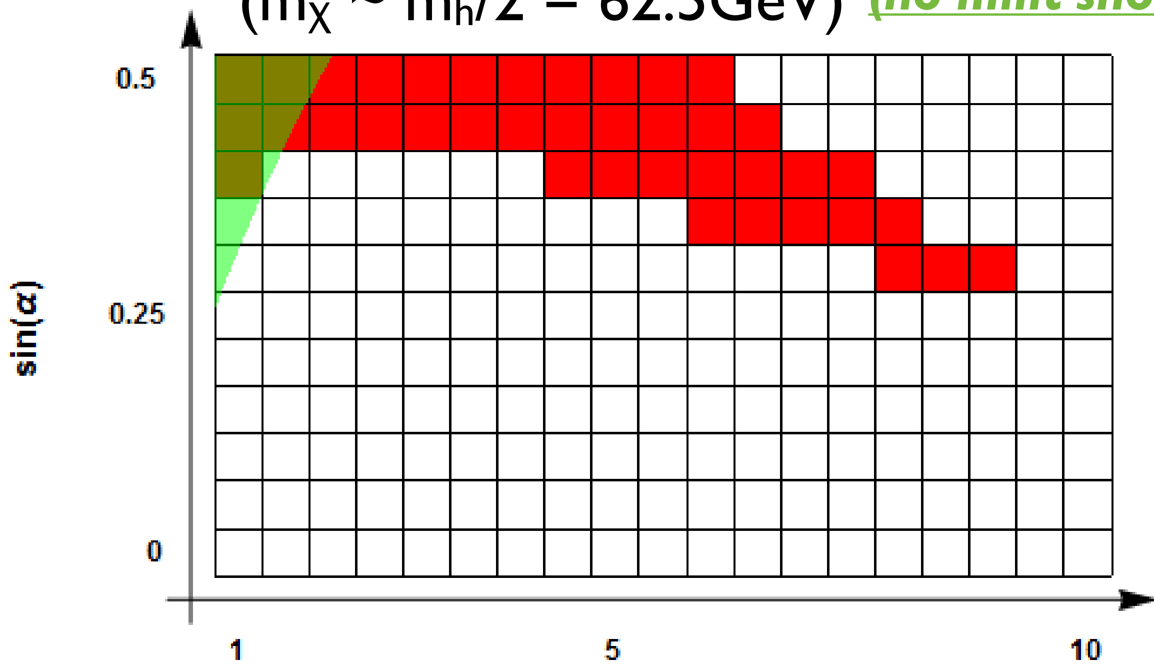
disfavored by invisible Higgs decay

(no limit shown via direct detection)

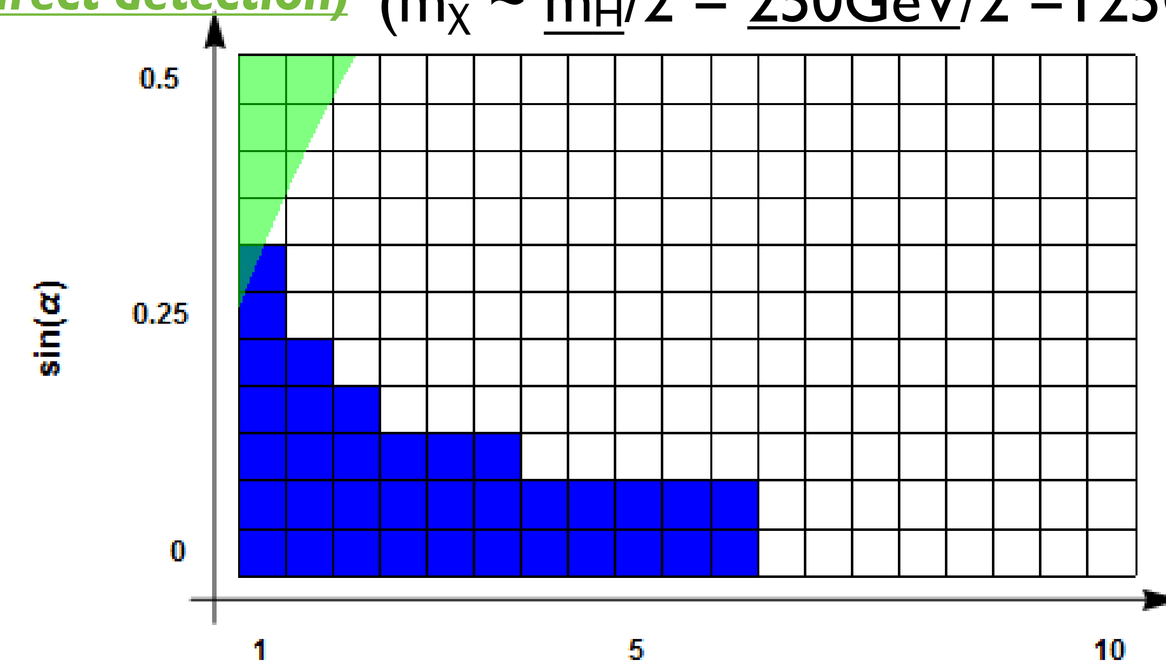
[ATLAS-CONF-2015-004]

($m_\chi \sim m_h/2$ = 62.5GeV)



v' (TeV)

($m_\chi \sim m_H/2$ = 250GeV/2 =125GeV)



v' (TeV)

[when m_k^{++} = 500GeV, $\lambda_{\Phi k}$ = 1, $\lambda_{\Sigma k}$ = 0.1]

(note: when m_H gets heavier as ~ 500GeV, propagator suppression → $m_\chi \sim m_H/2$ not valid)

$$|\sin\alpha| \gtrsim 0.3$$

or

heavier Higgs resonance (m_H < ~ 500GeV)

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[ATLAS-CONF-2015-004]

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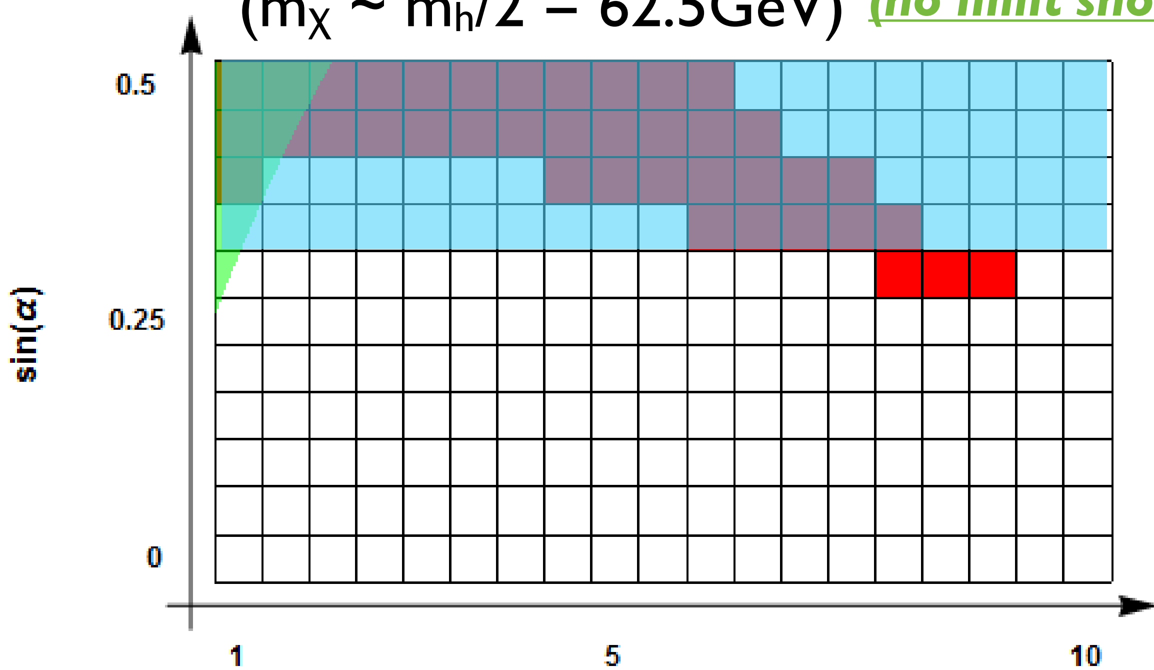

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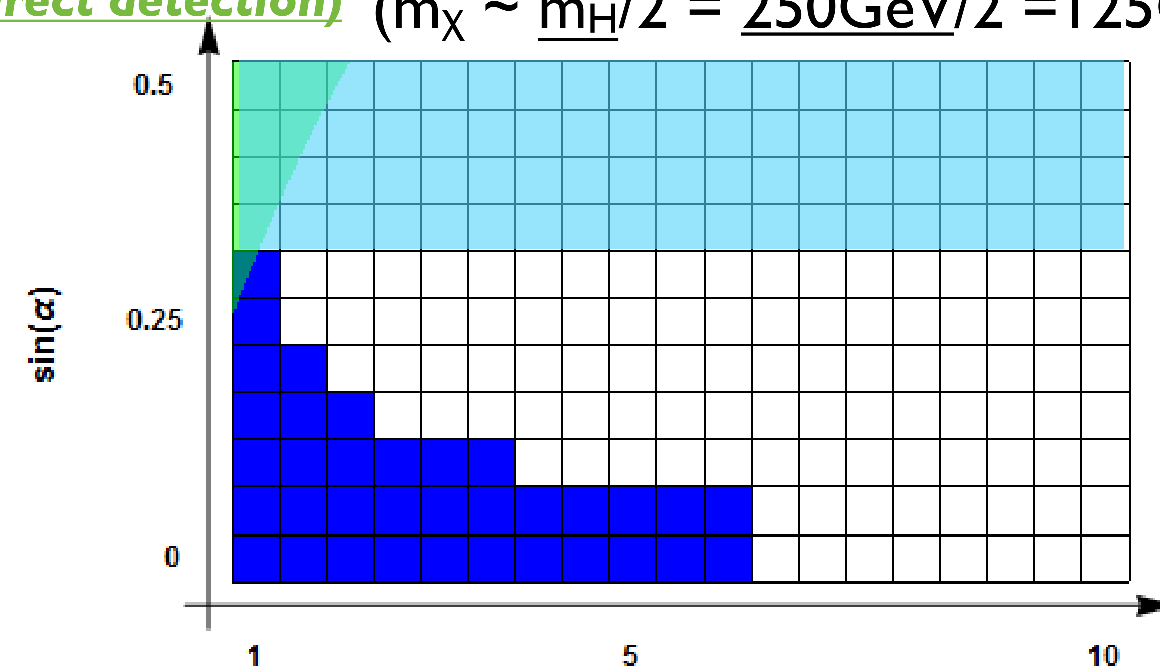

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Tensioned!

[conclusion in LHC issue]

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Summary

- In the three-loop neutrino model, ν profiles and DM are described very well.
- Allowed mass ranges are ***limited (predictive)***:

LHC bound approaching

☑ ***doubly-charged scalar (k^{++}): (more than) 250GeV***

☑ ***Majorana DM (χ): ~ $m_h/2$ (=62.5GeV) or $m_H/2$ (less than ~250GeV)***

tension with LHC Higgs search

small mixing with SM particles

The LHC experiment would test this direction!

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tension with LHC Higgs search

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The LHC experiment would test this direction!

thank you:-)

Backups

Status of Experiments

Recent significant achievements in experiments:

- confirmation of nonzero θ_{13}

[Gonzalez-Garcia,Maltoni,Schwetz,JHEP1411-052(2014)]

$$\sin^2\theta_{13} = 0.0218^{+0.0010}_{-0.0010}\ \text{(NH)}$$
$$\sin^2\theta_{13} = 0.0219^{+0.0011}_{-0.0010}\ \text{(IH)}$$

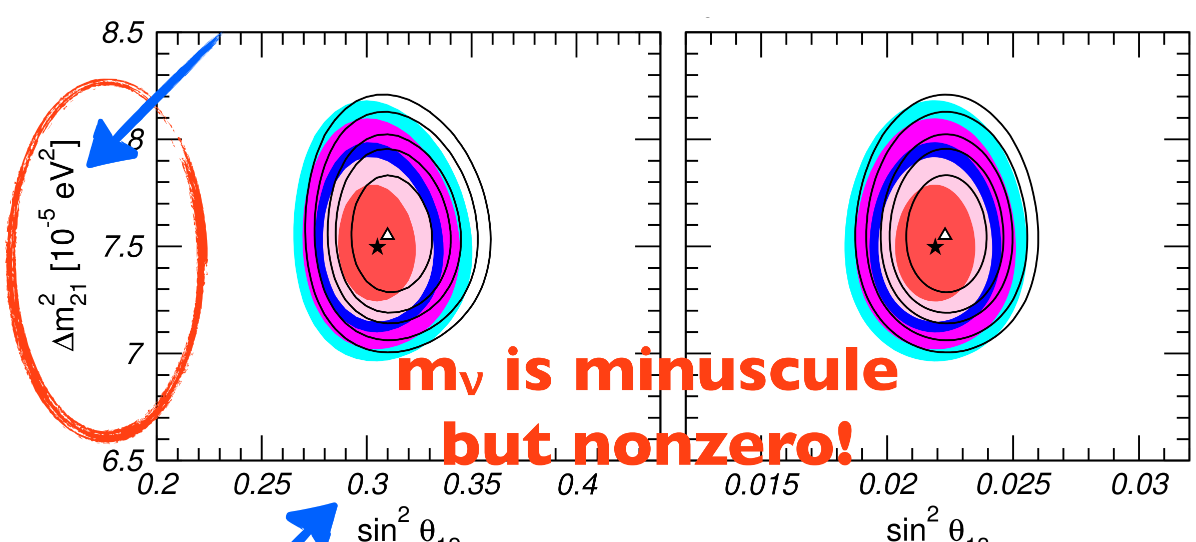
by global fit with data up to 2014 summer

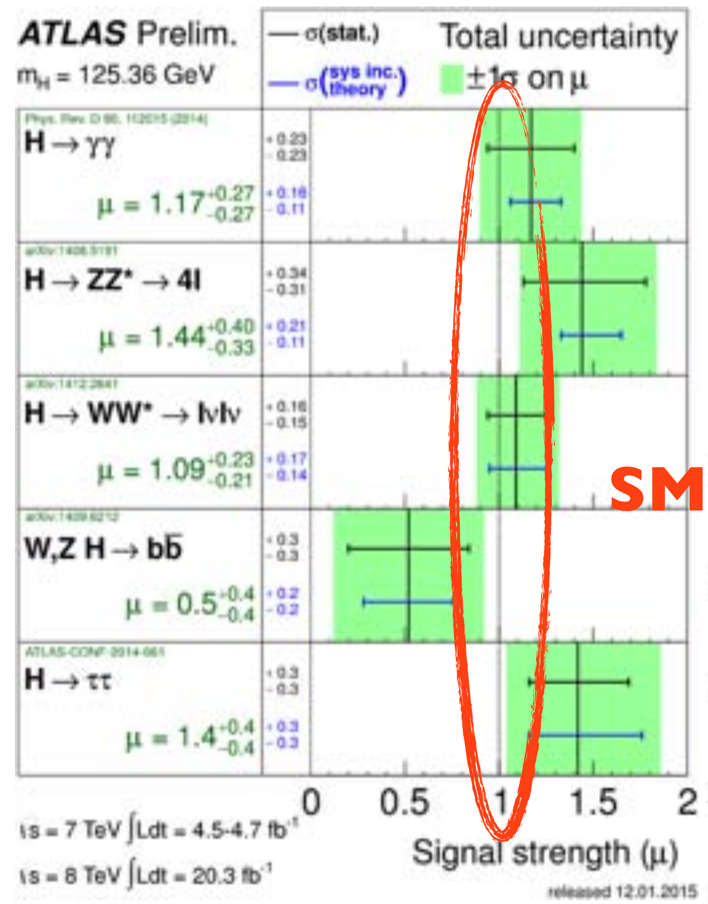
- discovery of SM-like Higgs boson

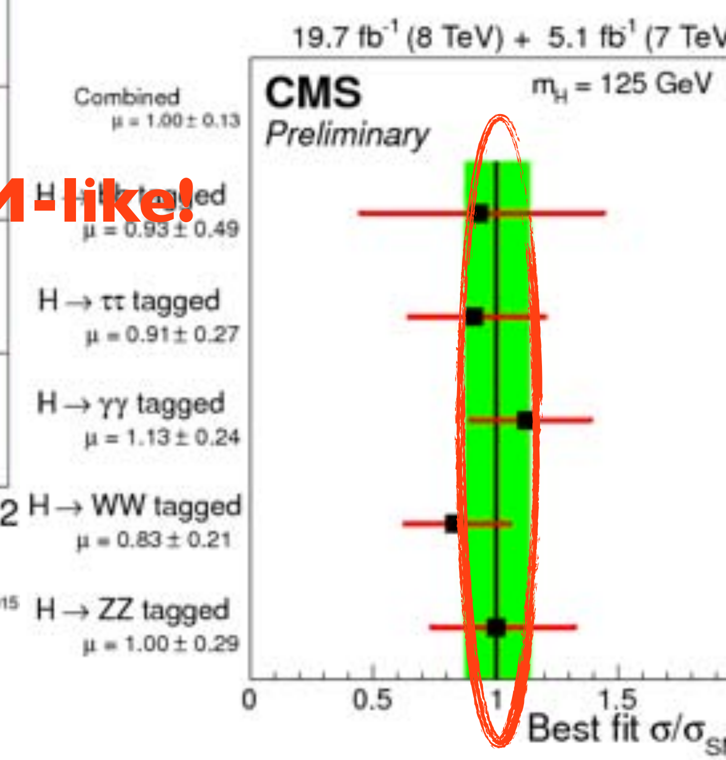
[CERN-PH-EP-2014-198,CMS-HIG-13-001]

$$m_H = 125.4\,\text{GeV},\ \ \mu_{\gamma\gamma} = 1.17 \pm 0.27\ \text{(ATLAS)}$$
$$m_H = 124.70\,\text{GeV},\ \ \mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23}\ \text{(CMS)}$$

based on data at 7 & 8 TeV







m_ν is minuscule but nonzero!

SM-like!

"lightest" particles with large mixing

What relationship?

an origin of masses

Details of our Neutrino Sector

	Lepton Fields			Scalar Fields				
Characters	L_{L_i}	e_{R_i}	N_{R_i}	Φ	Σ_0	h_1^+	h_2^+	k^{++}
$SU(3)_C$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	$-1/2$	-1	0	$1/2$	0	1	1	2
$U(1)$	0	0	$-x$	0	$2x$	0	x	$2x$

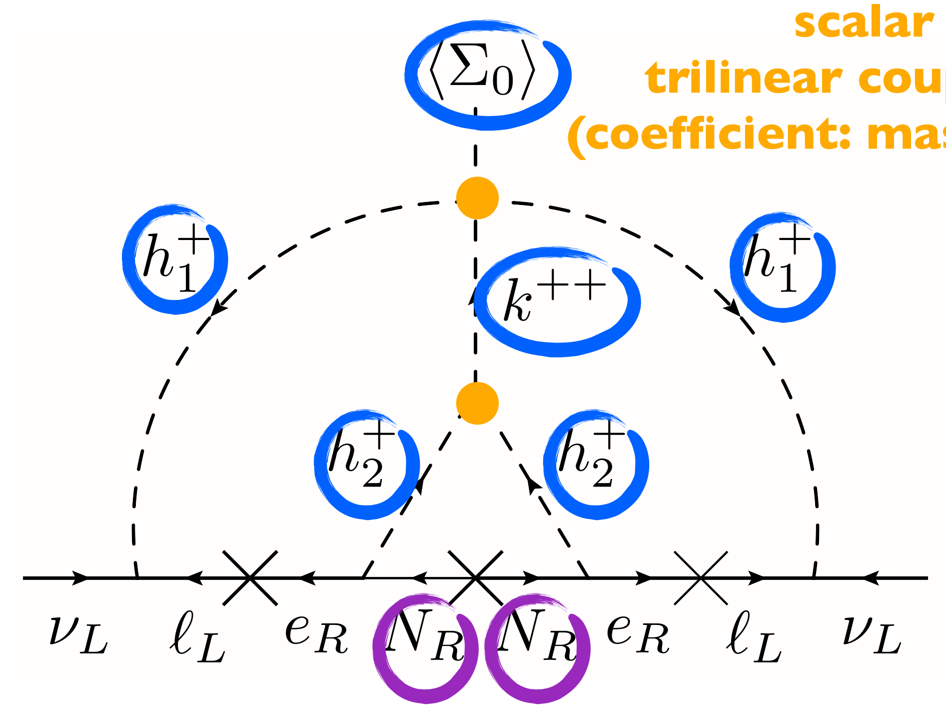
SM leptons

SM Higgs

global U(1) flavor sym.

negative parity remains after U(1) breaking (lightest one → DM)

origin of breakdown of global U(1) (including pseudo NG boson)



scalar trilinear couplings (coefficient: mass scales)

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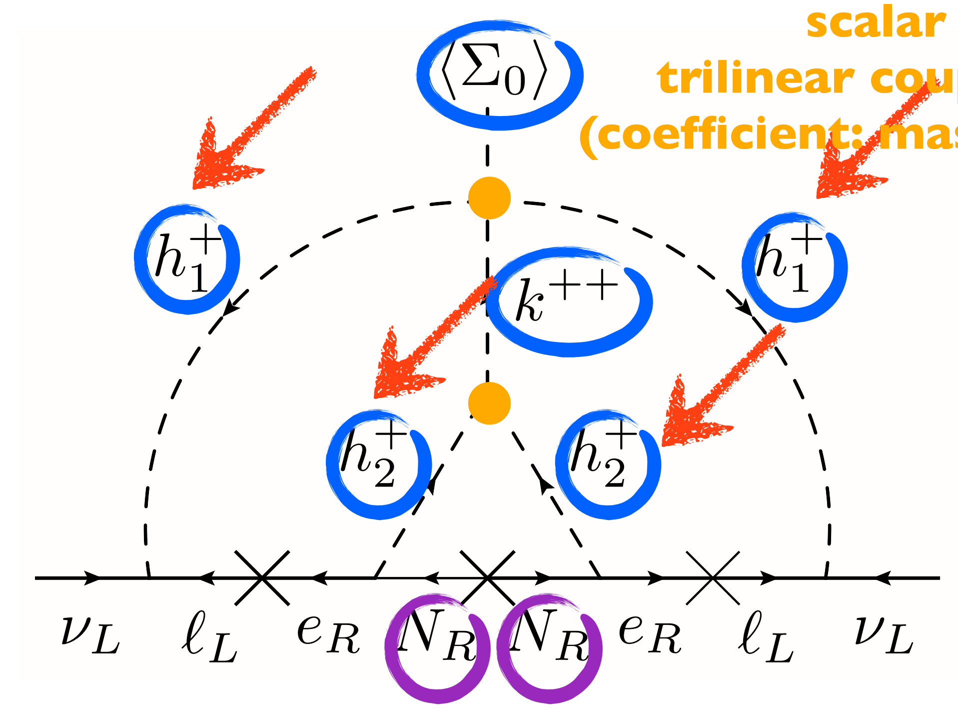

[points]

- **two singly-charged scalars are required (for 3-loop ν masses)**

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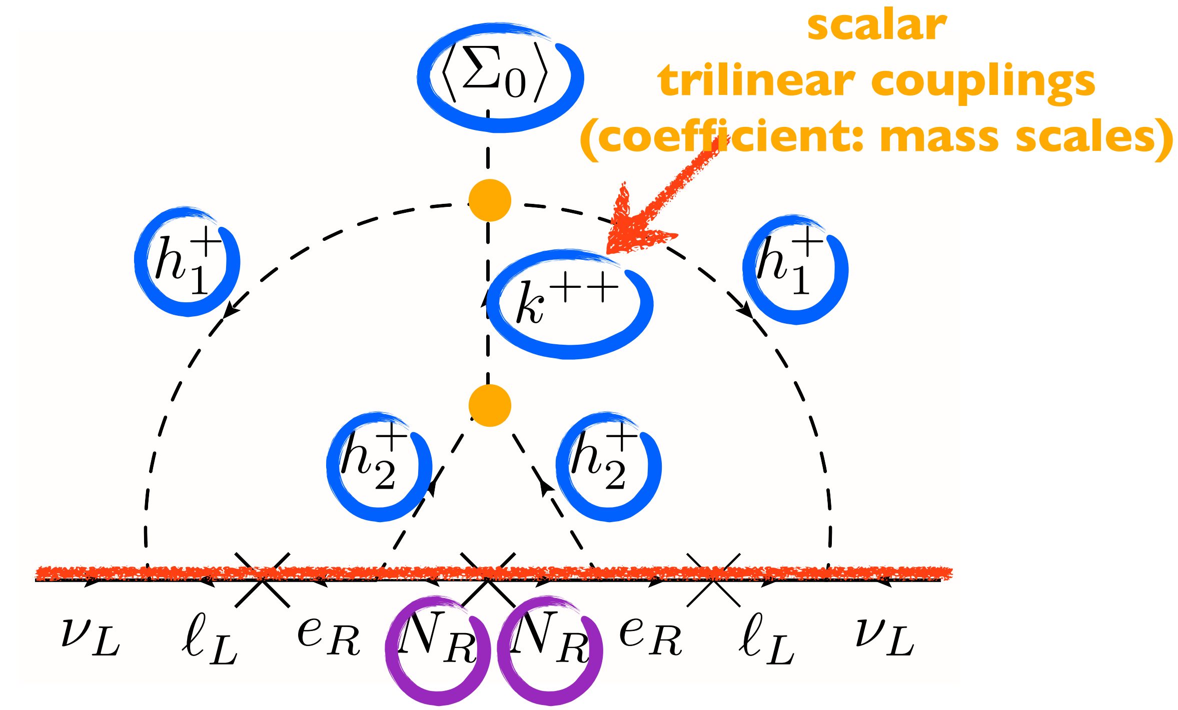

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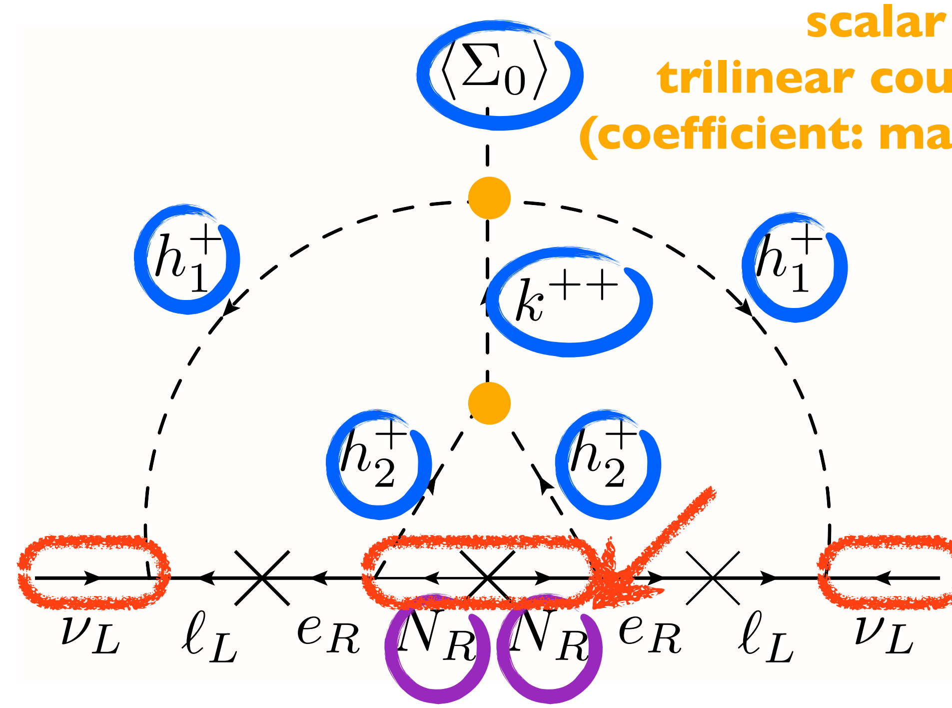


scalar trilinear couplings (coefficient: mass scales)

[points]

- **two singly-charged scalars are required (for 3-loop ν masses)**
- **a doubly-charged scalar should be isolated from leptons (for less LFV)**
- **right-handed neutrinos should be introduced (for Majorana ν mass & DM)**

Details of our Neutrino Sector

	Lepton Fields			Scalar Fields				
Characters	L_{L_i}	e_{R_i}	N_{R_i}	Φ	Σ_0	h_1^+	h_2^+	k^{++}
$SU(3)_C$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$SU(2)_L$	**2**	**1**	**1**	**2**	**1**	**1**	**1**	**1**
$U(1)_Y$	$-1/2$	-1	0	$1/2$	0	1	1	2
$U(1)$	0	0	$-x$	0	$2x$	0	x	$2x$

SM leptons

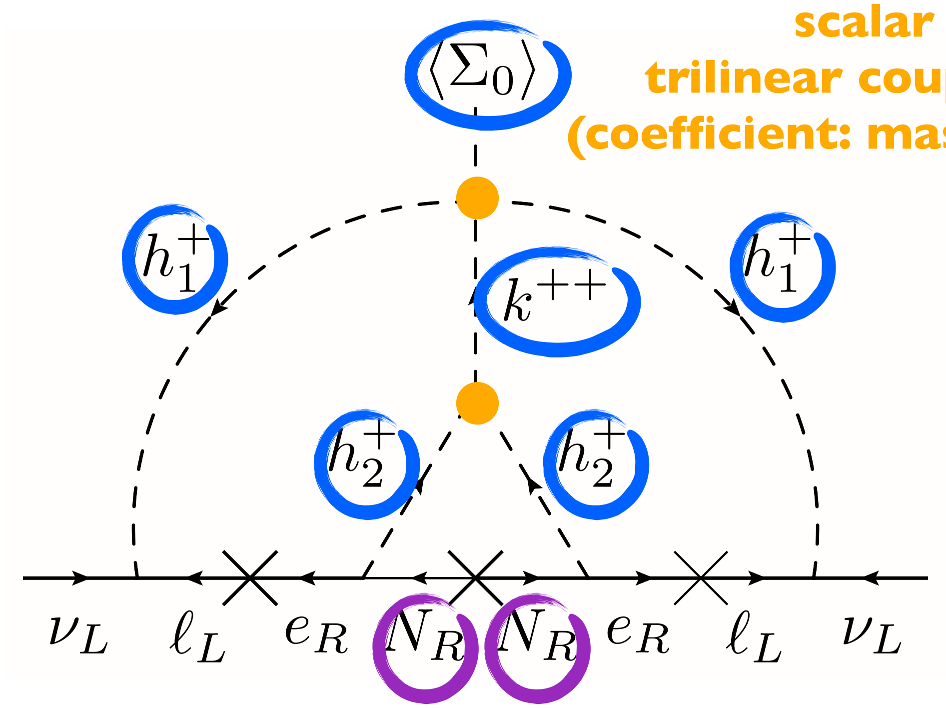
SM Higgs

global U(1) flavor sym.

negative parity remains after U(1) breaking (lightest one → DM)

origin of breakdown of global U(1) (including pseudo NG boson)

scalar trilinear couplings (coefficient: mass scales)

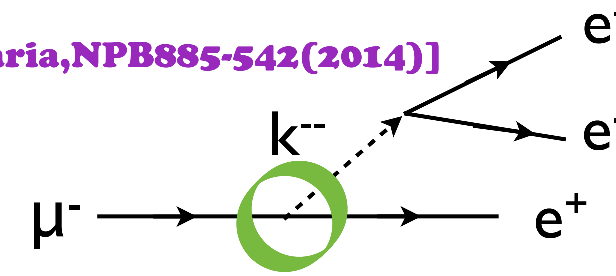


[points]

- **two singly-charged scalars are required (for 3-loop ν masses)**
- **a doubly-charged scalar should be isolated from leptons (for less LFV)**
- **right-handed neutrinos should be introduced (for Majorana ν mass & DM)**
- **pseudo NG boson does not couple to charged leptons (no limit via NG → 2γ)**

LFV, Vacuum Stability v.s. $k^{\pm\pm}$ Decoupling

In case of non-isolated k^{++}, e.g.,[Herrero-Garcia,Nebot,Ruis,Santamaria,NPB885-542(2014)]



direct couplings
to leptons

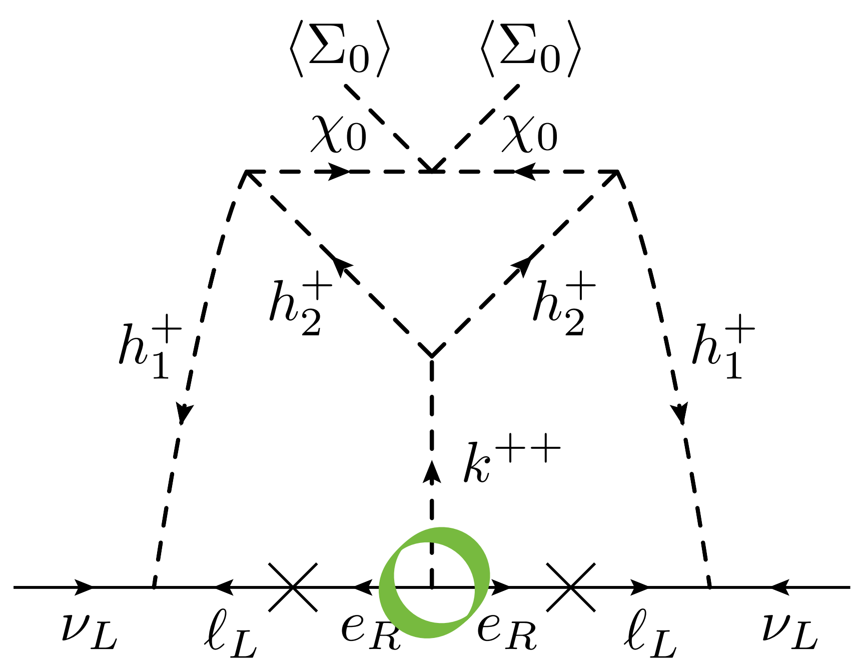
e.g., $\mu^- \to e^- e^+ e^-$ via k^{--} exchange (@ tree level)

$$|y_{R_{12}} y^*_{R_{11}}| < 2.3 \times 10^{-5} \left(\frac{m_{k^{\pm\pm}}}{\text{TeV}}\right)^2$$

should be small

[Hatanaka,KN,Okada,Orikasa,NPB894-268(2015)]

$$\boxed{[\nu \text{ mass}] = (\text{scalar trilinear couplings}) \times (\text{LFV couplings}) \times (\text{loop function})}$$



direct couplings
to leptons

Kenji Nishiwaki (KIAS)

LFV, Vacuum Stability v.s. $k^{\pm\pm}$ Decoupling

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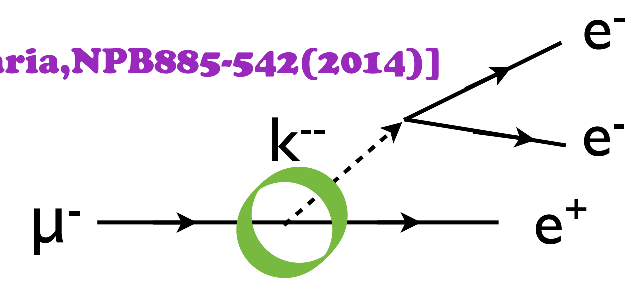

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[case (i)] **TeV** **(should be) small** **TeV inside**

$\longrightarrow$ **too small ν masses** ×

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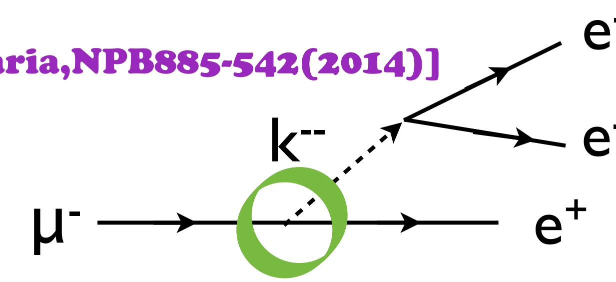

direct couplings
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[case (i)]	**TeV**	**(should be) small**	**TeV inside**
		$\longrightarrow$ **too small ν masses** ×	
[case (ii)]	**multi TeV**	**(should be) small**	**TeV inside**
		$\longrightarrow$ **vacuum destabilized** ×	

negative contrib. via scalar trilienars

$$\lambda^{(1)}_{h_1} = -\frac{1}{2}|\mu_{12}|^4 \sum_{i=R,I} F_0(m_{h_2^\pm}, m_{\chi_0(i)}),$$

$$\lambda^{(1)}_{h_2} = -3|\mu_{22}|^4 F_0(m_{h_2^\pm}, m_{k^{\pm\pm}}) - \frac{1}{2}|\mu_{12}|^4 \sum_{i=R,I} F_0(m_{h_1^\pm}, m_{\chi_0(i)}),$$

$$\lambda^{(1)}_{k} = -4|\mu_{22}|^4 F_0(m_{h_2^\pm}, m_{h_2^\pm}),$$

$$\left(F_0(m_1, m_2) = \frac{1}{(4\pi)^2}\int_0^1 dxdy\delta(x+y-1)\frac{xy}{(xm_1^2 + ym_2^2)^2}\right)$$

LFV, Vacuum Stability v.s. $k^{\pm\pm}$ Decoupling

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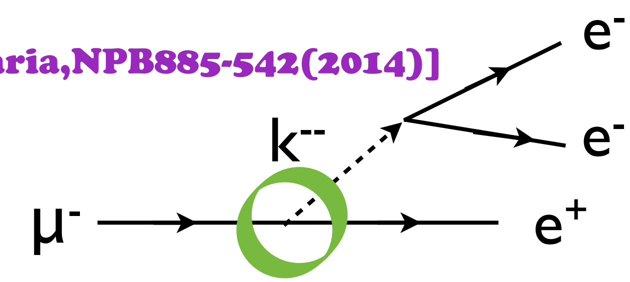

direct couplings to leptons

e.g., $\mu^- \to e^- e^+ e^-$ via k^{--} exchange (@ tree level)

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		$\longrightarrow$ **too small ν masses** ×	
[case (ii)]	**multi TeV**	**(should be) small**	**TeV inside**
		$\longrightarrow$ **vacuum destabilized** ×	
[case (iii)]	**multi TeV**	**(should be) small**	**multi TeV inside**
		$\longrightarrow$ **consistent ν profiles, but...**	

too heavy to be tested @ colliders...

$$10\ \text{TeV} \lesssim (\text{allowed masses}) \lesssim 100\ \text{TeV}$$

LFV, Vacuum Stability v.s. $k^{\pm\pm}$ Decoupling

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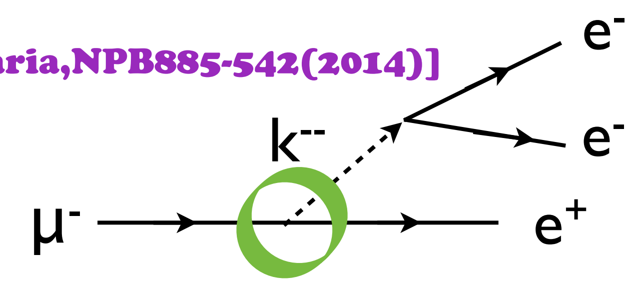

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[case (i)] **TeV** **(should be) small** **TeV inside**

→ **too small ν masses** ×

[case (ii)] **multi TeV** **(should be) small** **TeV inside**

→ **vacuum destabilized** ×

[case (iii)] **multi TeV** **(should be) small** **multi TeV inside**

→ **consistent ν profiles, but…**

[present case] **around TeV** **moderate** **TeV or less inside**

can be tested @ colliders

Relevant Lagrangian

$$-\mathcal{L}_Y = (y_\ell)_{ij}\bar{L}_{L_i}\Phi e_{R_j} + \frac{1}{2}(y_L)_{ij}\bar{L}^c_{L_i}L_{L_j}h_1^+ + (y_R)_{ij}\bar{N}_{R_i}e^c_{R_j}h_2^- + \frac{1}{2}(y_N)_{ij}\Sigma_0\bar{N}^c_{R_i}N_{R_j} + \text{h.c.}$$

$$\begin{aligned}
\mathcal{V} = {} & m_\Phi^2|\Phi|^2 + m_\Sigma^2|\Sigma_0|^2 + m_{h_1}^2|h_1^+|^2 + m_{h_2}^2|h_2^+|^2 + m_k^2|k^{++}|^2 \\
& + \left[\lambda_{11}\Sigma_0^* h_1^- h_1^- k^{++} + \mu_{22}h_2^+h_2^+k^{--} + \text{h.c.}\right] + \lambda_\Phi|\Phi|^4 + \lambda_{\Phi\Sigma}|\Phi|^2|\Sigma_0|^2 + \lambda_{\Phi h_1}|\Phi|^2|h_1^+|^2 \\
& + \lambda_{\Phi h_2}|\Phi|^2|h_2^+|^2 + \lambda_{\Phi k}|\Phi|^2|k^{++}|^2 + \lambda_\Sigma|\Sigma_0|^4 + \lambda_{\Sigma h_1}|\Sigma_0|^2|h_1^+|^2 + \lambda_{\Sigma h_2}|\Sigma_0|^2|h_2^+|^2 \\
& + \lambda_{\Sigma k}|\Sigma_0|^2|k^{++}|^2 + \lambda_{h_1}|h_1^+|^4 + \lambda_{h_1h_2}|h_1^+|^2|h_2^+|^2 + \lambda_{h_1k}|h_1^+|^2|k^{++}|^2 \\
& + \lambda_{h_2}|h_2^+|^4 + \lambda_{h_2k}|h_2|^2|k^{++}|^2 + \lambda_k|k^{++}|^4,
\end{aligned}$$

Lepton Flavor Violation processes

Process	(i,f)	Experimental bounds (90% CL)	C_{if}
$\mu^- \to e^-\gamma$	$(2,1)$	$\mathrm{Br}(\mu \to e\gamma) < 5.7 \times 10^{-13}$	1.6×10^{-6}
$\tau^- \to e^-\gamma$	$(3,1)$	$\mathrm{Br}(\tau \to e\gamma) < 3.3 \times 10^{-8}$	0.52
$\tau^- \to \mu^-\gamma$	$(3,2)$	$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$	0.7

Type of universality	Experimental bounds (90% CL)
lepton/hadron universality	$\sum_{q=d,s,b} \lvert V_{uq}^{\mathrm{exp}}\rvert = 0.9999 \pm 0.0006$
μ/e universality	$G_\mu^{\mathrm{exp}}/G_e^{\mathrm{exp}} = 1.0010 \pm 0.0009$
τ/μ universality	$G_\tau^{\mathrm{exp}}/G_\mu^{\mathrm{exp}} = 0.9998 \pm 0.0013$
τ/e universality	$G_\tau^{\mathrm{exp}}/G_e^{\mathrm{exp}} = 1.0034 \pm 0.0015$

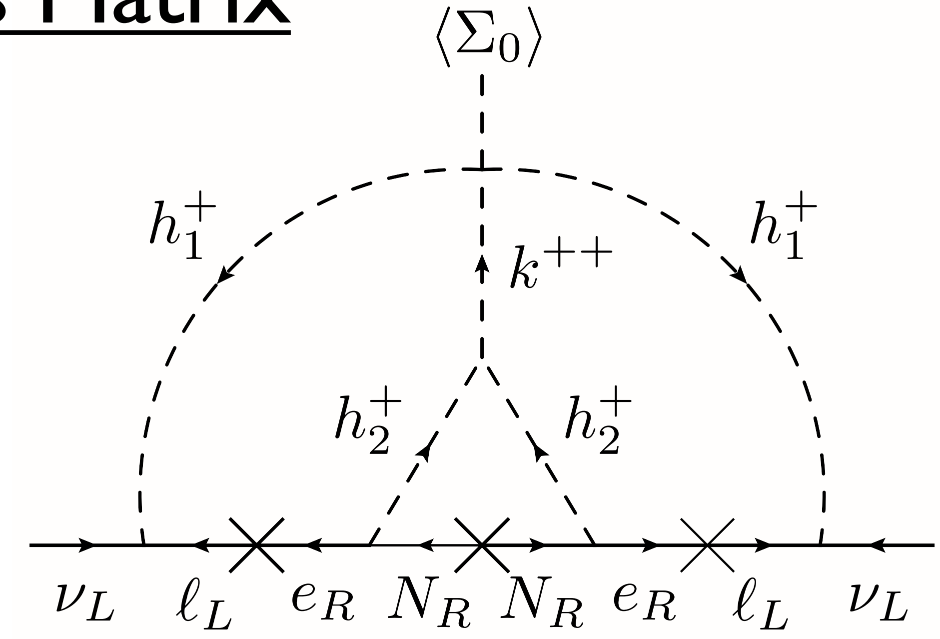
Process	(i,j,k,l)	Experimental bounds (90% CL)	A_{ijkl}
$\mu^- \to e^+e^-e^-$	$(2,1,1,1)$	$\mathrm{Br} < 1.0 \times 10^{-12}$	2.3×10^{-5}
$\tau^- \to e^+e^-e^-$	$(3,1,1,1)$	$\mathrm{Br} < 2.7 \times 10^{-8}$	0.009
$\tau^- \to e^+e^-\mu^-$	$(3,1,1,2)$	$\mathrm{Br} < 1.8 \times 10^{-8}$	0.005
$\tau^- \to e^+\mu^-\mu^-$	$(3,1,2,2)$	$\mathrm{Br} < 1.7 \times 10^{-8}$	0.007
$\tau^- \to \mu^+e^-e^-$	$(3,2,1,1)$	$\mathrm{Br} < 1.5 \times 10^{-8}$	0.007
$\tau^- \to \mu^+e^-\mu^-$	$(3,2,1,2)$	$\mathrm{Br} < 2.7 \times 10^{-8}$	0.007
$\tau^- \to \mu^+\mu^-\mu^-$	$(3,2,2,2)$	$\mathrm{Br} < 2.1 \times 10^{-8}$	0.008

Radiative Neutrino Mass Matrix

$$(m_\nu)_{ab} = \underline{\frac{\mu_{11}\mu_{22}}{(4\pi)^6}} \sum_{i,j,k=1}^{3} \underline{\frac{1}{M_k^4}} \left[(y_L)_{ai} m_{\ell_i} \underline{(y_R^T)_{ik}(M_{N_k})(y_R)_{kj}} m_{\ell_j} (y_L^T)_{jb}\right]$$

$$\underline{\times F_1\left(\frac{m^2_{h_1^+}}{M_k^2}, \frac{m^2_{h_2^+}}{M_k^2}, \frac{m^2_{\ell_i}}{M_k^2}, \frac{m^2_{\ell_j}}{M_k^2}, \frac{{M_{N_k}}^2}{M_k^2}, \frac{m^2_{k^{\pm\pm}}}{M_k^2}\right)},$$

$\mathbf{Y_R}$



$$F_1\left(X_1, X_2, X_3, X_4, X_5, X_6\right) = \int \mathbf{dX} \frac{1}{\Delta_1} \frac{1}{(\Delta_2)^2} \frac{\rho}{(\Delta_3)^2},$$

$$\int \mathbf{dX} = \int_0^1 dxdydz\, \delta(x+y+z-1) \int_0^1 d\alpha d\beta d\gamma d\delta\, \delta(\alpha+\beta+\gamma+\delta-1) \int_0^1 d\rho d\sigma d\omega\, \delta(\rho+\sigma+\omega-1),$$

with

$$\Delta_1 = y(y-1) + z(z-1) + 2yz,$$

$$\Delta_2 = (\alpha Y + \delta)^2 - \delta - \alpha Y^2 - \alpha X,$$

$$\Delta_3 = \rho A\left(X_1, X_2, X_3, X_5, X_6\right) - \sigma X_4 - \omega X_1,$$

$$A\left(X_1, X_2, X_3, X_5, X_6\right) = -\frac{\alpha((x+y)X_2 + zX_5)}{((\alpha Y+\delta)^2 - \delta - \alpha Y^2 - \alpha X)(y(y-1) + z(z-1) + 2yz)} + \frac{\beta X_1 + \gamma X_3 + \delta X_6}{((\alpha Y+\delta)^2 - \delta - \alpha Y^2 - \alpha X)},$$

$$X = -\left(\frac{y}{y+z}\right)^2 + \frac{y(y-1)}{y(y-1)+z(z-1)+2yz}, \quad Y = \frac{y}{y+z}.$$

y_R Structure

not important
for ν profiles

$$y_R = \begin{bmatrix} * & * & * \\ * & a & b \\ * & b & c \end{bmatrix}, \quad M_N = \mathrm{diag}\,(M_{N_1}, M_{N_2}, M_{N_3}),$$

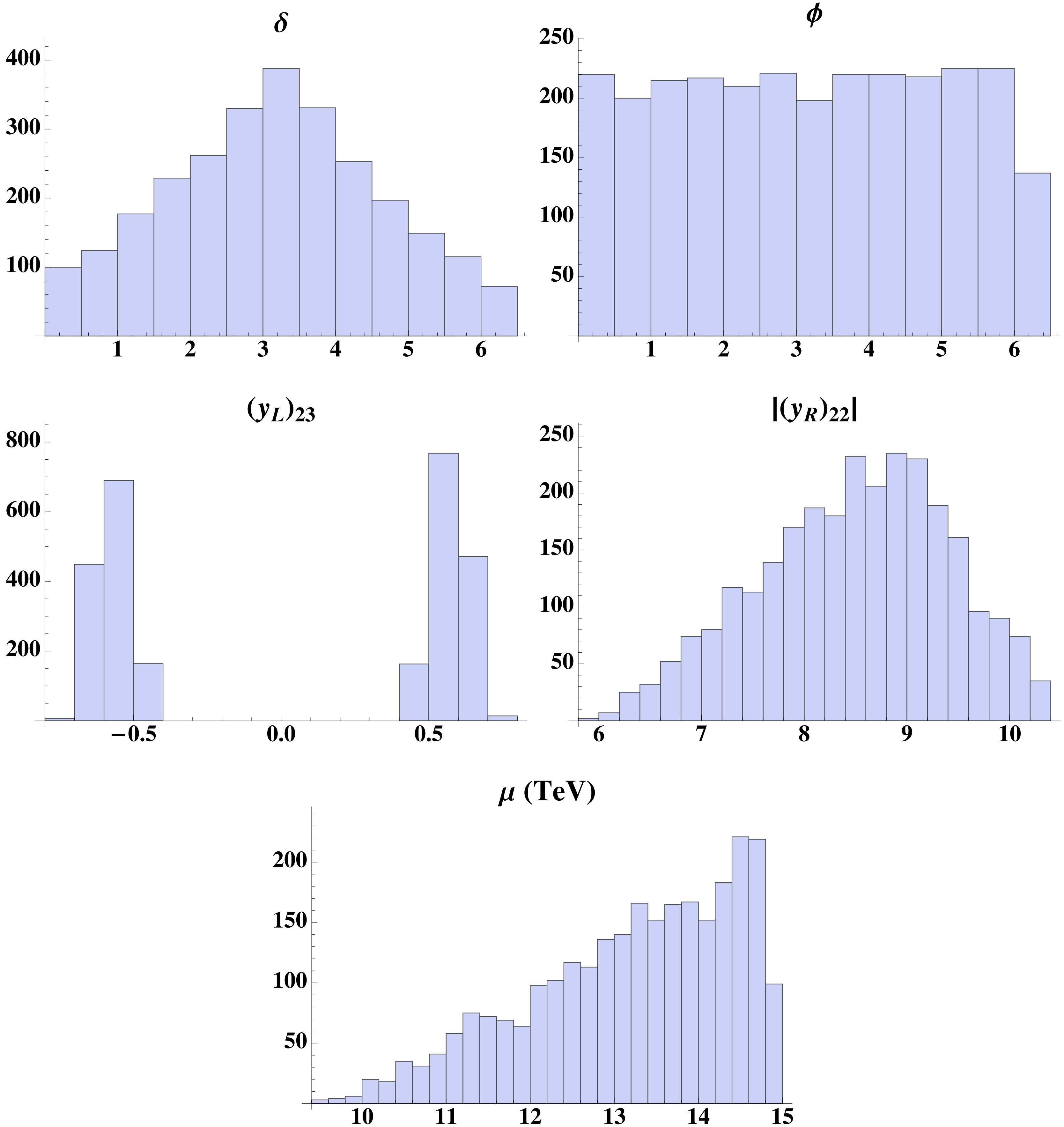
written by
observed values
(lepton & ν masses,
mixings)

$$\begin{aligned} \boxed{\frac{\omega_{22}}{m_{\ell_2}^2}} &= (Y_R)_{22} \simeq \left[a^2(\zeta_2 M_{N_2}) + b^2(\zeta_3 M_{N_3})\right], \\ \boxed{\frac{\omega_{23}}{m_{\ell_2} m_{\ell_3}}} &= (Y_R)_{23} \simeq \left[ab\,(\zeta_2 M_{N_2}) + bc\,(\zeta_3 M_{N_3})\right], \\ \boxed{\frac{\omega_{33}}{m_{\ell_3}^2}} &= (Y_R)_{33} \simeq \left[b^2(\zeta_2 M_{N_2}) + c^2(\zeta_3 M_{N_3})\right]. \end{aligned}$$

via
charged lepton
mass hierarchy

$$|(Y_R)_{33}| : |(Y_R)_{23}| : |(Y_R)_{22}| \sim \frac{m_\mu^2}{m_\tau^2} : \frac{m_\mu}{m_\tau} : 1$$

Distribution of Input Parameters



(2,726 points; m_k = 500GeV, m_{h1} = m_{h2} = 4.8TeV)