

FERTILE NEUTRINOS

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OUTLINE

- ◆ INTRODUCTION & MOTIVATION
- A MODEL OF FERTILE NEUTRINOS
 - PHENO ◆ EW-SCALE / LHC
- ▲ FROM A DIFFERENT PERSPECTIVE
- ▼ FINAL REMARKS

"CANONICAL" MOTIVATION FOR BSM

- THERE IS A HIGGS
 - ◆ LIGHT, METASTABLE (?)
 - ◆ MASSES "EVERYWHERE"
- EVIDENCE FOR BSM PHYSICS :

MASSIVE NEUTRINOS

- CAN WE EXPLORE THE PHYSICS OF NEUTRINO MASSES AT COLLIDERS?

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→ WINDOW INTO BSM PHYSICS AT LHC

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- ◆ FERTILE NEUTRINOS : INTERACTING
ELECTROWEAK-SCALE NEUTRINOS

NEUTRINO MASS

$$\Delta M_{\text{atm}}^2 \sim 10^{-3} \text{ eV}^2$$

$$\Delta M_{\text{solar}}^2 \sim 10^{-5} \text{ eV}^2$$

COSMOLOGY: $\sum_i m_i < (0.17 - 2.0) \text{ eV}$

COSMO + OSCILLATION: $0.04 \text{ eV} < M_\nu < (0.07 - 0.7) \text{ eV}$

LIGHT ν -MASSES

■ SEESAW MECHANISM

$$m_\nu \sim \frac{m_D^2}{M_R}$$

LIGHT ν -MASSES

◆ SEESAW MECHANISM

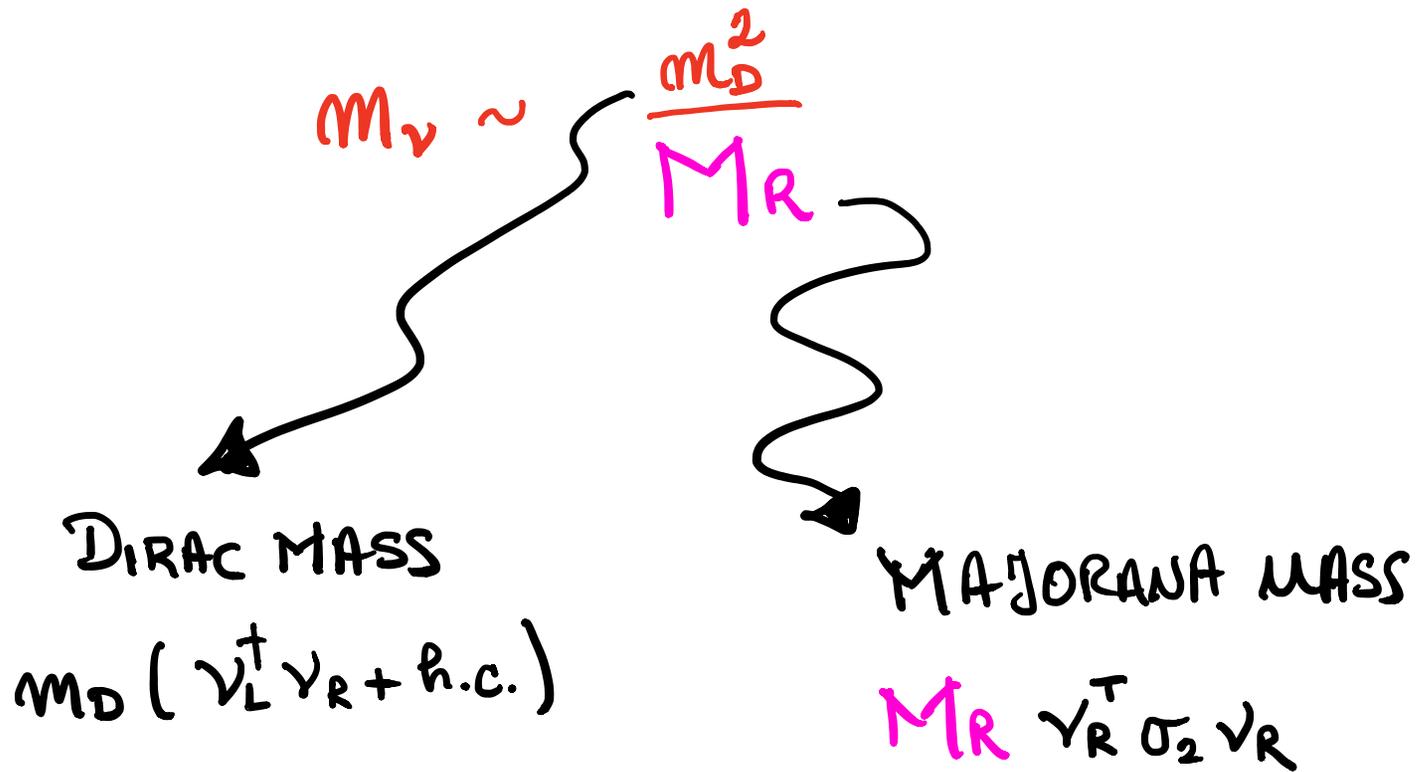
$$m_\nu \sim \frac{m_D^2}{M_R}$$

DIRAC MASS

$$m_D (\nu_L^\dagger \nu_R + \text{h.c.})$$

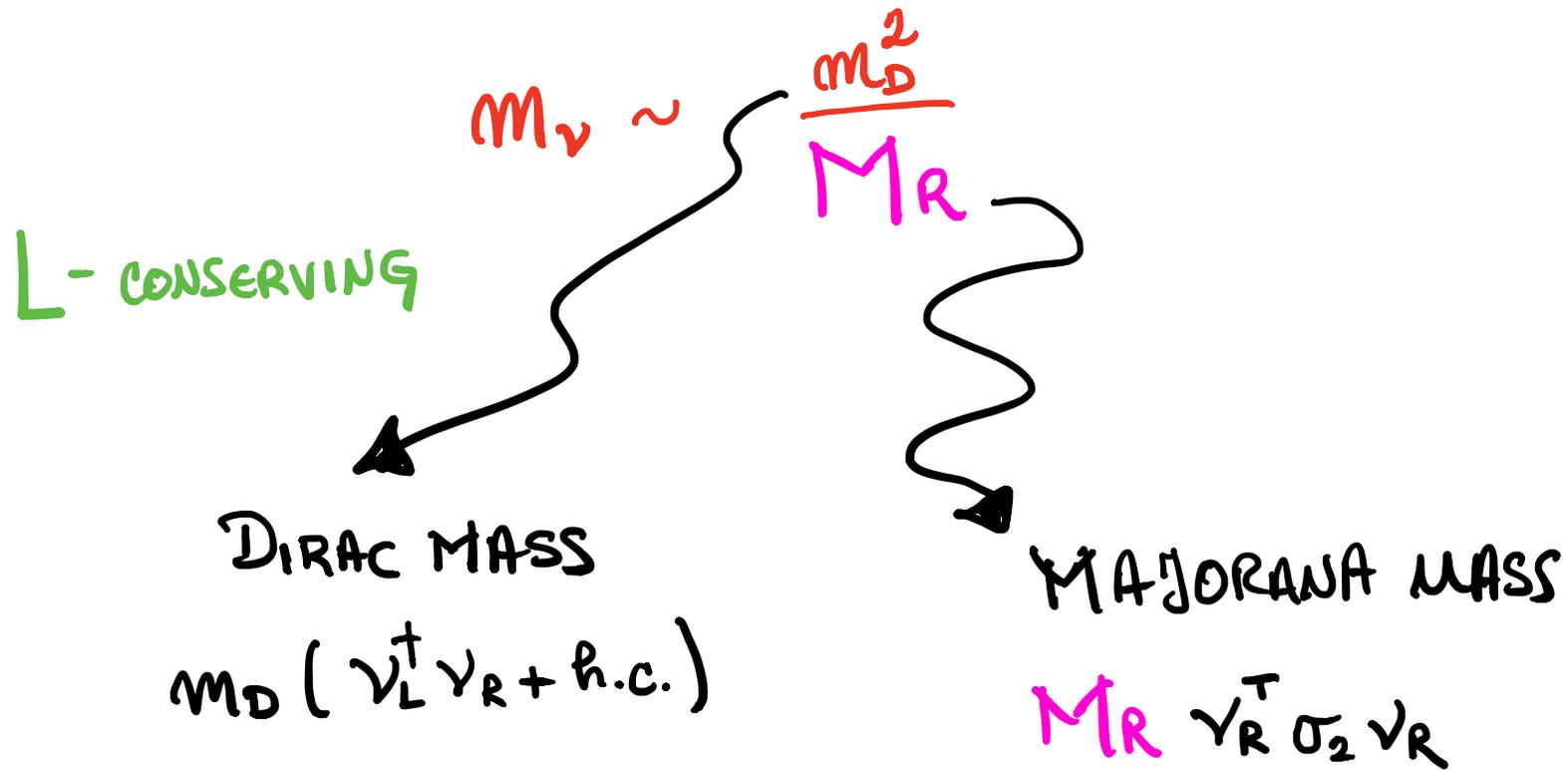
LIGHT ν -MASSES

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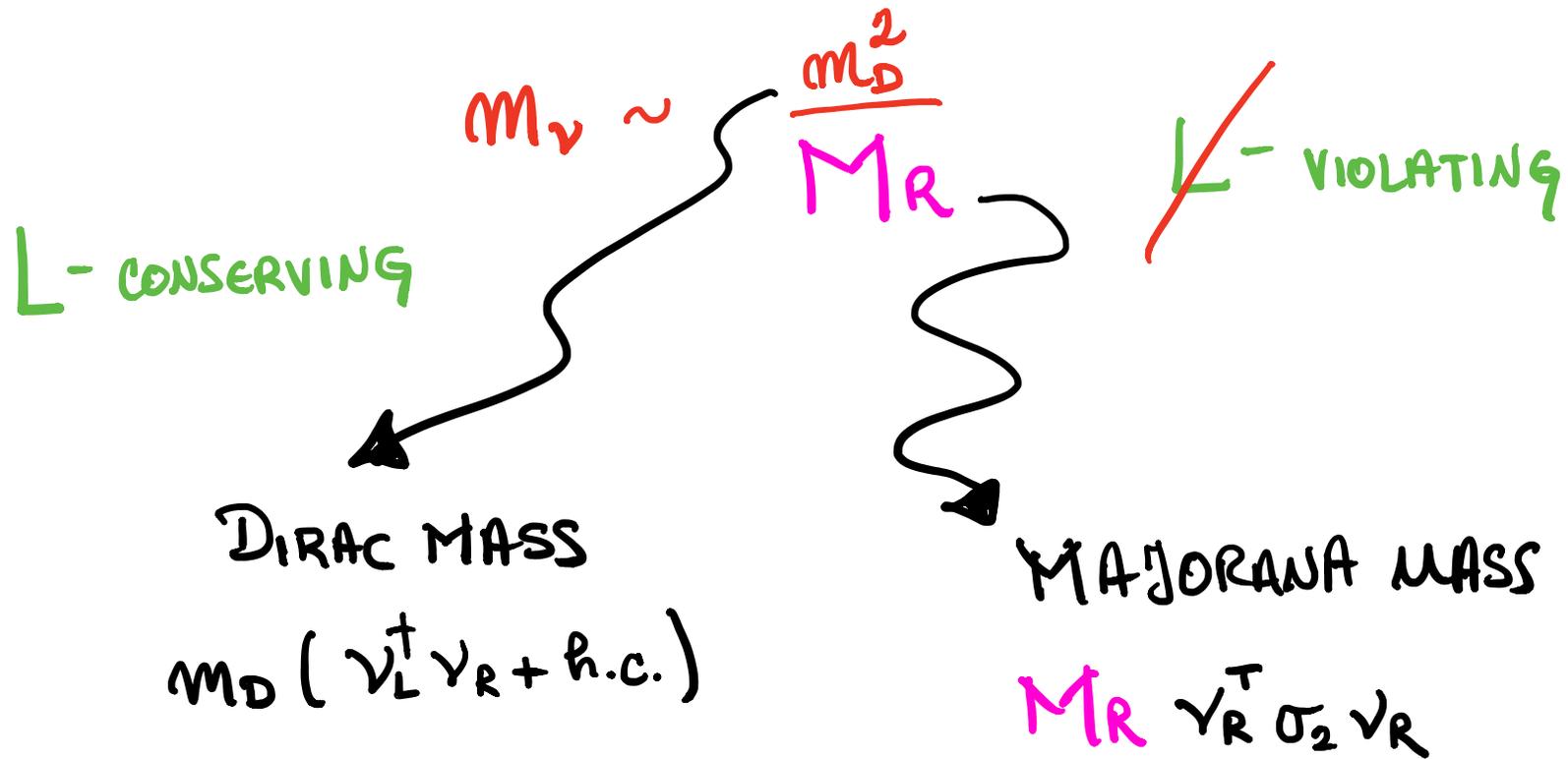
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LIGHT ν -MASSES

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EXPECTATIONS

- $m_D \lesssim \Lambda_{EW} ; M_R \gg \Lambda_{EW}$

- ◆ LEFT-RIGHT MODEL : $M_R \propto M_{WR}$

- GUT : $M_R \propto \Lambda_{GUT}$

▲ NEUTRINOS ARE **STERILE** IN
"STANDARD" SCENARIOS

DIRECT TEST OF SEESAW

⇒ DETECTION OF YR!

DIRECT TEST OF SEESAW

⇒ DETECTION OF VR!

• CAN $M_R \propto M_{EW}$?

↳ CAN V_R BE FERTILE?

◆ M_R RELATED TO SM BREAKING

↳ ν_R CANNOT BE A SM SINGLET

SIMPLEST POSSIBILITY

→ ν_R BELONGS TO A
 $SU(2)_W$ DOUBLET

THE MODEL

PQ HUNG

PLB 649,275 (2009)

GAUGE GROUP: $SU(3) \times SU(2) \times U(1)$

THE MODEL

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PLB 649,275 (2009)

GAUGE GROUP: $SU(3)_C \times SU(2)_L \times U(1)_Y$

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FERMION CONTENT:

INTRODUCE "MIRROR" FERMIONS

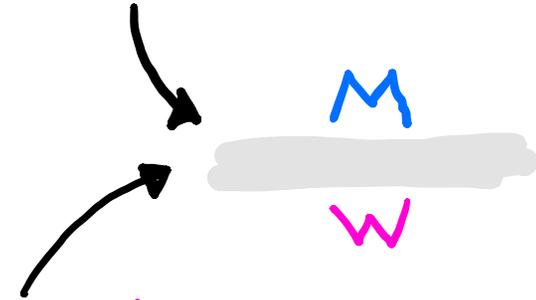
FOR EACH SM FERMION

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FERMION CONTENT:



INTRODUCE "MIRROR" FERMIONS

FOR EACH SM FERMION

SM

$$l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

e_R

$$q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

u_R

d_R

SM

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d_R



NEW

$$l_R = \begin{pmatrix} \nu_R \\ e_R^M \end{pmatrix}$$

e_L^M

$$q_R^M = \begin{pmatrix} u_R^M \\ d_R^M \end{pmatrix}$$

u_L^M

d_L^M

SCALAR SECTOR:

◆ IN ADDITION TO THE SM $SU(2)_W$ DOUBLET Φ

WE MUST INTRODUCE ADDITIONAL SCALARS

- TO GET A MAJORANA MASS FOR ν_R
A TRIPLET ($Y=2$) IS INTRODUCED:

$$\tilde{\chi} = \frac{1}{\sqrt{2}} \vec{T} \cdot \vec{\chi} = \begin{pmatrix} \frac{1}{\sqrt{2}} \chi^+ & \chi^{++} \\ \chi^0 & -\frac{1}{\sqrt{2}} \chi^+ \end{pmatrix}$$

$$\Rightarrow \mathcal{G}_M \mathcal{L}_R^{MT} \sigma_2 \mathcal{L}_R^M \tilde{\chi} \Rightarrow \mathcal{G}_M \mathcal{V}_R^T \sigma_2 \mathcal{V}_R \langle \chi^0 \rangle$$

CALLING $\mathcal{U}_M \equiv \langle \chi^0 \rangle$

$\rightarrow \mathcal{M}_R = \mathcal{G}_M \mathcal{U}_M > M_E/2$

$$\Rightarrow g_M \bar{l}_R^{MT} \sigma_2 l_R^M \tilde{\chi} \Rightarrow g_M \bar{\nu}_R^T \sigma_2 \nu_R \langle \chi^0 \rangle$$

CALLING $\nu_M \equiv \langle \chi^0 \rangle$

$$\rightarrow M_R = g_M \nu_M > M_E/2$$

BUT!! $\nu_M \sim \nu_{EW}$ SPOILS $g=1$

\rightarrow MUST INTRODUCE A $Y=0$ TRIPLET $\bar{\xi}$

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\rightarrow MUST INTRODUCE A $Y=0$ TRIPLET $\tilde{\Sigma}$

FINALLY THEN WE HAVE

$$\chi = \begin{pmatrix} \chi^0 & \tilde{\Sigma}^+ & \chi^{++} \\ \chi^- & \tilde{\Sigma}^0 & \chi^+ \\ \chi^{--} & \tilde{\Sigma}^- & \chi^{0*} \end{pmatrix}$$

- THE POTENTIAL HAS $SU(2)_L \times SU(2)_R$ SYMMETRY

$$\chi = (3, 3), \quad \bar{\Phi} = (2, 2)$$

- VACUUM ALIGNMENT $\langle \bar{\Phi} \rangle = \text{diag}(\frac{v_2}{\sqrt{2}}, \frac{v_2}{\sqrt{2}})$

$$\langle \chi \rangle = \text{diag}(v_m, v_m, v_m)$$

$$\Rightarrow M_Z = M_W / c_W; \quad v_{EW} = \sqrt{v_2^2 + 8v_m^2} \approx 246 \text{ GeV}$$

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- EWSB LINKED TO MAJORANA MASS OF FERTILE ν_R !

WE ARE NOT DONE WITH THE SCALAR SECTOR
(NOTHING IS FOR FREE!)

- WE NEED A DIRAC MASS TERM

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- INTRODUCE A SINGLET Φ_s

▶ $\mathcal{L}_s \supset g_{se} \bar{l}_L \Phi_s l_R^M + \text{h.c.}$

$$\Rightarrow m_D = g_{se} v_s$$

▶ $g_{se} \sim \mathcal{O}(10^{-3}) \Rightarrow v_s \sim \mathcal{O}(100 \text{ MeV})$



FINALLY * THE SCALAR SECTOR IS:

- ONE SINGLET
- ONE $SU(2)_W$ DOUBLET
- TWO $SU(2)_W$ TRIPLETS

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- } 10 PHYSICAL STATES
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IN TERMS OF THE CUSTODIAL $SU(2)_D$:

$$5 \rightarrow H_5^{++}, H_5^+, H_5^0$$

$$3 \rightarrow H_3^+, H_3^0$$

$$\text{Two } 1^0 \rightarrow H_1^0, H_1^{\prime 0}$$

AA, HERNANDEZ, HUNG
JHEP 0811, 092 (2008)

EW - PRECISION CONSTRAINTS

- EXTRA FERMION DOUBLETS

$$9 \text{ RH QUARK} \rightarrow \frac{1}{2}\pi \text{ TO } S \text{ (EACH)}$$

$$3 \text{ RH LEPTON} \rightarrow \frac{1}{6}\pi \text{ TO } S \text{ (EACH)}$$

- NEW PHYSICS CONTRIBUTION TO S & T ARE
CONSTRAINED TO BE

$$\tilde{S} = -0.02 \pm 0.14$$

$$\tilde{T} = 0.06 \pm 0.14$$

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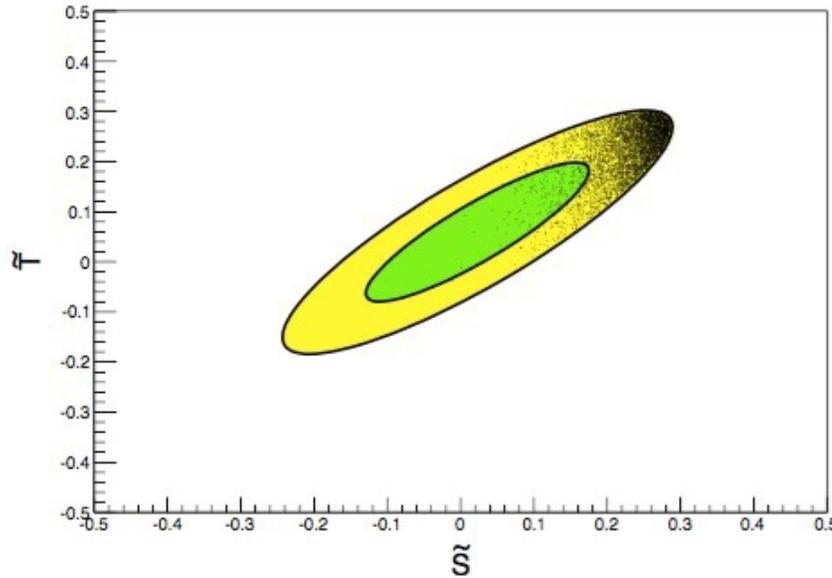
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MUST BE
CANCELLED



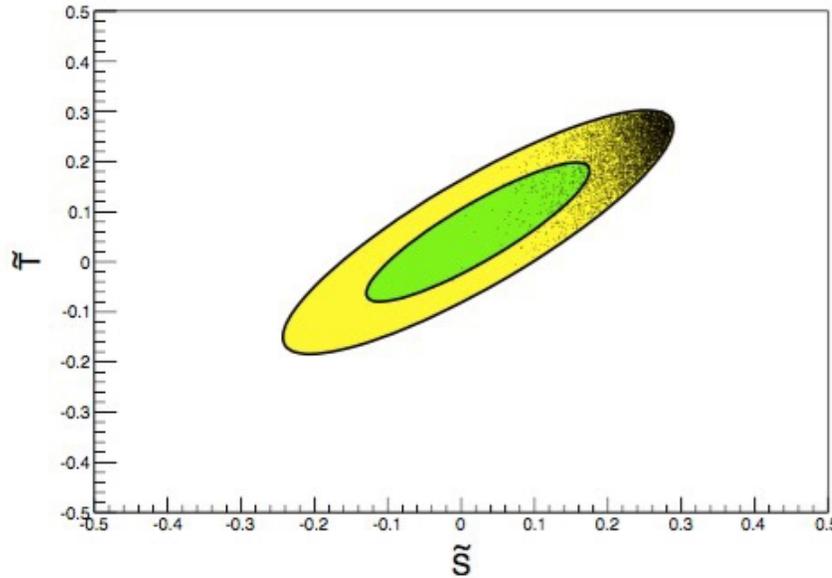
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HOANG, HUNG, KAMIAT, NUCL. PHYS. B 877 (2013)

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- ◆ REMEMBER THE "~~*~~" IN THE SCALAR SECTOR?
- THE HIGGS WAS DISCOVERED WITH $M_H = 125 \text{ GeV}$
- THE "MINIMAL" MODEL OVER PRODUCES AND IS NOT IN AGREEMENT WITH LHC RESULTS.

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- THE HIGGS WAS DISCOVERED WITH $M_H = 125 \text{ GeV}$
- THE "MINIMAL" MODEL OVER PRODUCES AND IS NOT IN AGREEMENT WITH LHC RESULTS.

▲ EXTENSION THAT WORKS :

HOANG, HUNG, KAMAT, NPB 896, 611 (2015)

NEED TO EXTEND TO TWO DOUBLETS

ONE FOR SM LEFT-HANDED FERMIONS

ONE FOR MIRROR RIGHT-HANDED ONES

★ 125 GeV Higgs is a combination

• • • MORE PHENO / MODEL-BUILDING

◆ LEPTONS AND PMNS MIXING MATRIX

HUNG, LE JHEP 1509 (2015) 007 & 134

◆ LFV PROCESSES ($\mu \rightarrow e\gamma$, $\mu \rightarrow e$)

HOANG, HUNG, KAMAT JHEP 1512, 169 (2015)

● INTERESTING POTENTIAL COLLIDER SIGNALS

◆ SEARCH OF MIRROR QUARKS @ LHC

CHAKRABARTY, GHOSH, HOANG, HUNG PRD 93, 2016

◆ SEARCH FOR ν_R AND MIRROR LEPTONS

CHAKRABARTY, GHOSH, HOANG, HUNG, NANDI, 1606.08502

• • • MORE PHENO / MODEL-BUILDING

@ PASICOS 2016

LEPTON FLAVOR VIOLATION {

CHRISNA	Radiative decays
VAN QUE	$li \rightarrow lj \gamma$
TRINH LE	$\mu \rightarrow e$ conversion

LHC SIGNATURES {

SUREYASHI	like-sign dileptons displaced vertices
-----------	---

A DIFFERENT TAKE

TAKE 1

- ◆ SUPPOSE THERE ARE NO QUARKS
- ◆ A MODEL OF LEPTONS: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; e_R ; $\bar{\Phi}$
 $\text{SU}(2)_L \times \text{U}(1)_Y$
- ◆ PROBLEMS?

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 - NO NEUTRINO MASS \longrightarrow SAME AS BEFORE
 - ANOMALOUS \longrightarrow MUST FIND A SOLUTION

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◆ SUPPOSE THERE ARE NO QUARKS

◆ A MODEL OF LEPTONS: $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$; e_R ; Φ
SU(2)_L × U(1)_Y

◆ PROBLEMS?

● NO NEUTRINO MASS → SAME AS BEFORE

● ANOMALOUS → MUST FIND A SOLUTION

■ "MUST" ADD NEW LEPTONS:

$l_R = \begin{pmatrix} \nu_R \\ e_R^+ \end{pmatrix}$, e_L^m WORKS!

CUTE!!

A DIFFERENT TAKE

TAKE 2

- EW PHASE TRANSITION IS INHERENTLY
A NON-PERTURBATIVE PHENOMENON
 - ➔ WOULD BE NICE TO STUDY IT AS SUCH
 - ↳ LATTICE ? ☺

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↳ LATTICE ? ☺

↳ NO

CAN'T PUT A CHIRAL MODEL ON

THE LATTICE ☹

NIELSEN - NINOMIYA NO-GO THM:

THERE MUST BE AN EQUAL NUMBER OF LEFT-HANDED
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It should be noticed that in our lattice no-go theorem the assumption (3) of the general no-go theorem, appearance of the (proper) anomalies, is not needed.

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THE MIRROR MODEL CAN BE PUT ON A LATTICE!

DARK MATTER

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LEPTON PORTAL BAI & BERGER, JHEP08(2014)153

DARK SECTOR WITH TWO MEMBERS

FERMION (MEDIATOR)

ψ^i

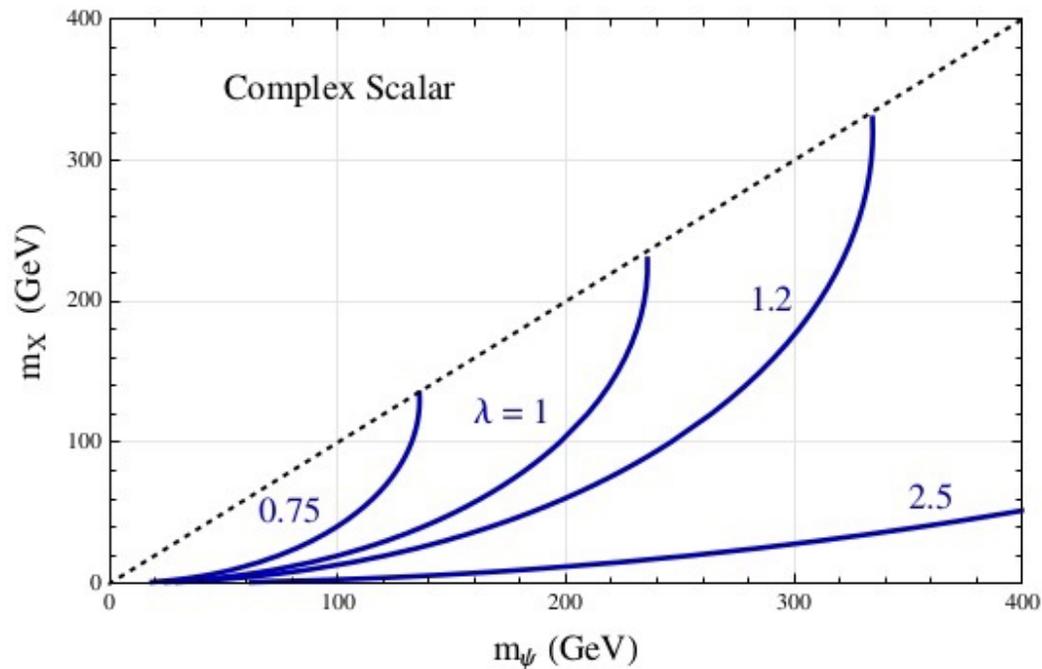
COMPLEX SCALAR (LIGHTEST)

X

$$\lambda_i X \bar{\psi}^i e_R^i$$

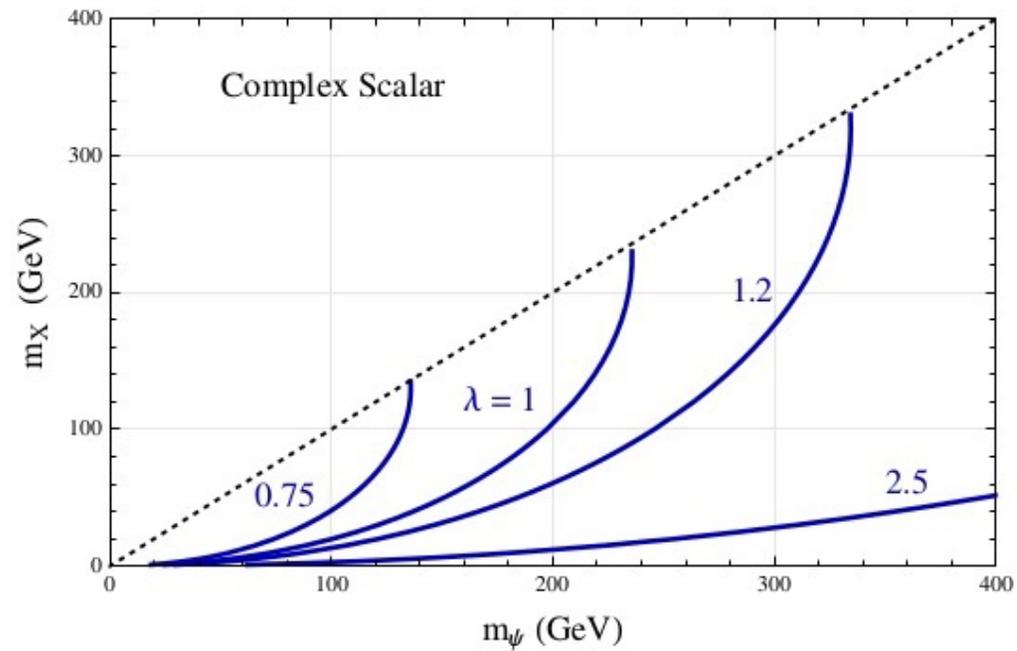
DARK MATTER

Assume $m_X < m_\psi \rightarrow \text{Br}(\psi^i \rightarrow X + \bar{e}^i) = 1$



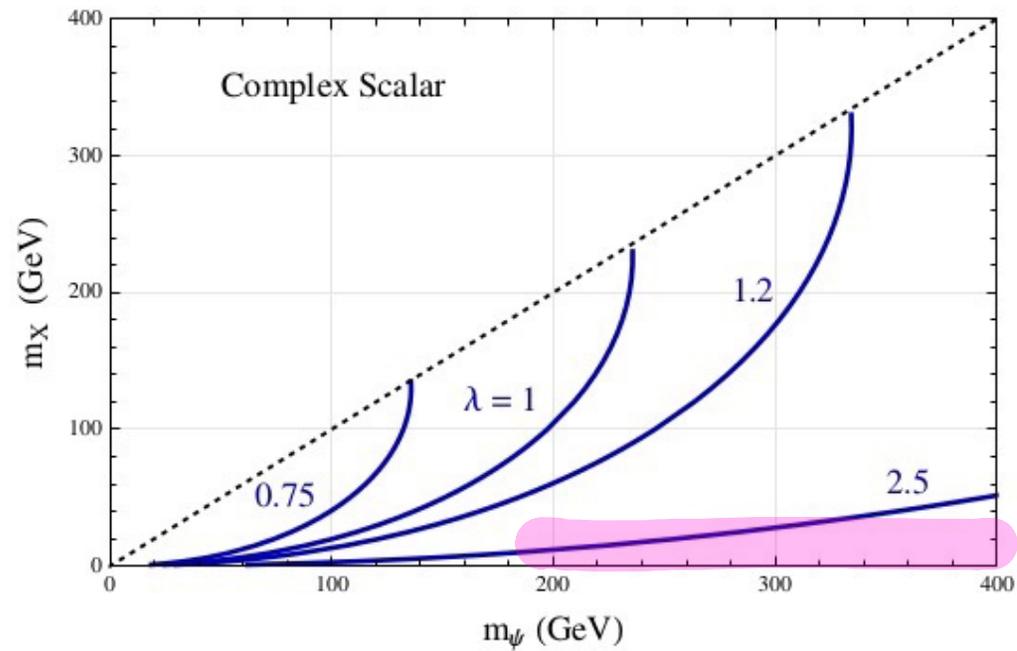
DARK MATTER

$$\Phi_S \bar{l}_L l_R^M \supset \Phi_S \bar{e}_L e_R^M$$



DARK MATTER

$$\phi_S \bar{l}_L l_R^M \supset \phi_S \bar{e}_L e_R^M$$



DARK MATTER

HIGGS PORTALS?

$$\mu_s \phi_s \bar{\Phi}^+ \bar{\Phi}_M$$

MULTI COMPONENT DARK MATTER?

EXTRA SINGLETs (A_4, \dots) ?

FINAL REMARKS

- NICE TO HAVE FERTILE NEUTRINOS
 - VIABLE MODEL WITH RICH & INTERESTING PHENO
 - NOT MORE "COMPLICATED" THAN STANDARD BSM EXTENSIONS
- INTERESTING THEORETICAL MOTIVATIONS
 - A DIFFERENT "TAKE" ON UNIFICATION (?)
 - POTENTIALLY ANALYZABLE ON THE LATTICE

THANK

YOU!