Natural Seesaw in Warped/ Composite Higgs framework and its LHC Signals

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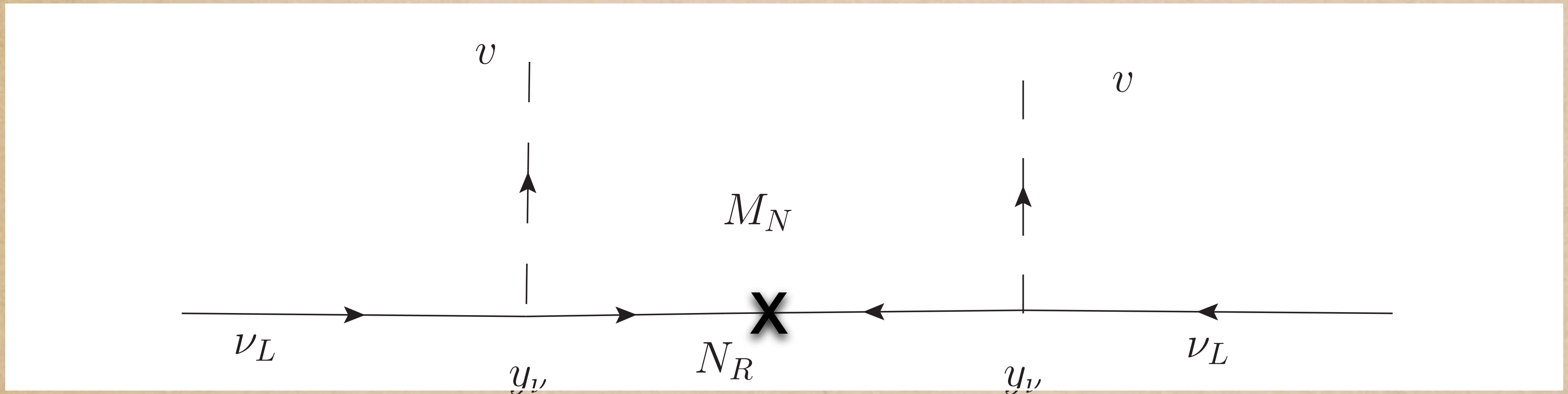
[Based on KA, Hong, Vecchi (1512.06742): theory; KA, Du, Hong (1612.04810 and 1703.07763): LHC signals]

Review of Seesaw for (Majorana) SM neutrino mass

$$\mathcal{L} \ni \begin{pmatrix} \overline{\nu_L} & \overline{(N_R)^c} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_N \end{pmatrix} \begin{pmatrix} (\nu_L)^c \\ N_R \end{pmatrix}$$



EWSB doublet-singlet Dirac mass term

$$\text{generic (type I): } m_\nu \sim \frac{m_D^2}{M_N}$$

Majorana mass term for SM singlet **neutrino**

Original (high-scale) seesaw

- Main idea:

$$\begin{aligned} m_D &\sim v \text{ or } m_\tau, \text{ i.e., } y_\nu \sim 1 \text{ or } y_\tau \ (\textit{no} \text{ tuning}) \\ M_N &\sim M_{\text{UV}} \ (\textit{no} \text{ tuning, but see next!}) \end{aligned}$$

GUT or
Planck scale

Too high a scale seesaw!

- observed:

$$m_\nu \sim 0.1 \text{ eV} \quad \Rightarrow \quad M_{\text{UV}} \sim 10^{10-14} \text{ GeV} \ll M_{\text{Pl}} \sim 10^{18} \text{ GeV}$$

(GUT/Planck scale gives too small m_ν)

- new UV scale: associated with breaking of new symmetry, e.g., (B - L)…but tuning (hierarchy)?

- difficult to test at colliders

TeV-scale seesaw

- **Main** idea:

weak scale

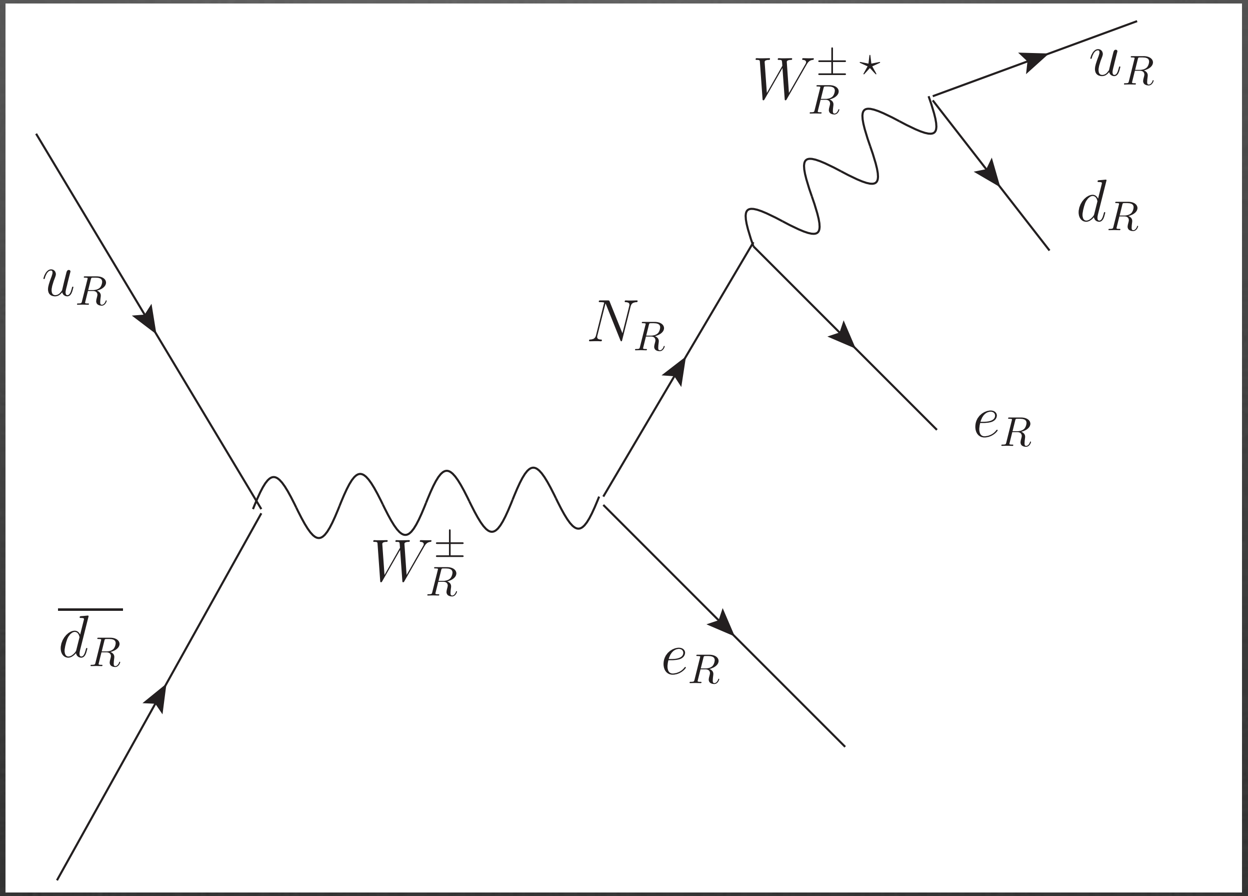
$$M_N \quad \sim \quad M_{\rm IR}\ (\sim \text{TeV})\ (\textit{no}\ \text{tuning, but see later!})$$

$$m_\nu \ll v \quad \Rightarrow \quad m_D \ll v, \text{i.e.,}\ \ y_\nu \ll 1\ (\text{tuning})$$

TeV-scale seesaw: LHC signals with left-right (LR) symmetry

[For a review, see Mohapatra (2016)]

- extend EW gauge symmetry to $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- spontaneous breaking $\sim$ TeV (also N_R mass): $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$
- smoking-gun: same-sign dileptons (due to Majorana N_R) from $W_R^\pm$ production/decay



doublet of $SU(2)_R$, with e_R

- Z' [extra $U(1)$] heavier than $W_R^\pm$, smaller signal

TeV-scale seesaw: summary

- LHC signals
- tuning of neutrino Yukawa
- extra model-building (coincidence?) to get $M_N \sim$ weak scale

Natural realization of seesaw in warped extra dimensional/composite Higgs framework (and LHC signals)

Outline

- (attempt at) 5D (warped) implementation of 4D high-scale seesaw

- what's underlying physical/dynamical picture (earlier analysis not in singlet mass basis)?

- LHC signals of TeV-mass singlet neutrinos:

    (I) similar to 4D LR models, but still different

    (II) from channels absent in 4D LR models

Snapshot of Warped Extra Dimensional Seesaw

(Try) 5D version of 4D high-scale type I seesaw

- add singlet in bulk, with (super-large) Majorana mass term (only) on UV/ Planck brane and coupled to Higgs and lepton doublet [Huber, Shafi (2003); Csaki et al (2003 and 2008); Perez, Randall (2008); Carena et al. (2009)]:

$$\mathcal{L}_{5\mathrm{D}} \ni \delta(y-L)\,(Yk)\,\overline{L}_L N_R H + (c_L k)\,\overline{L}_L L_R + (c_N k)\,\overline{N}_L N_R + \delta(y)\frac{M_N^{\mathrm{UV}}}{k}\overline{(N_R)^c}N_R$$

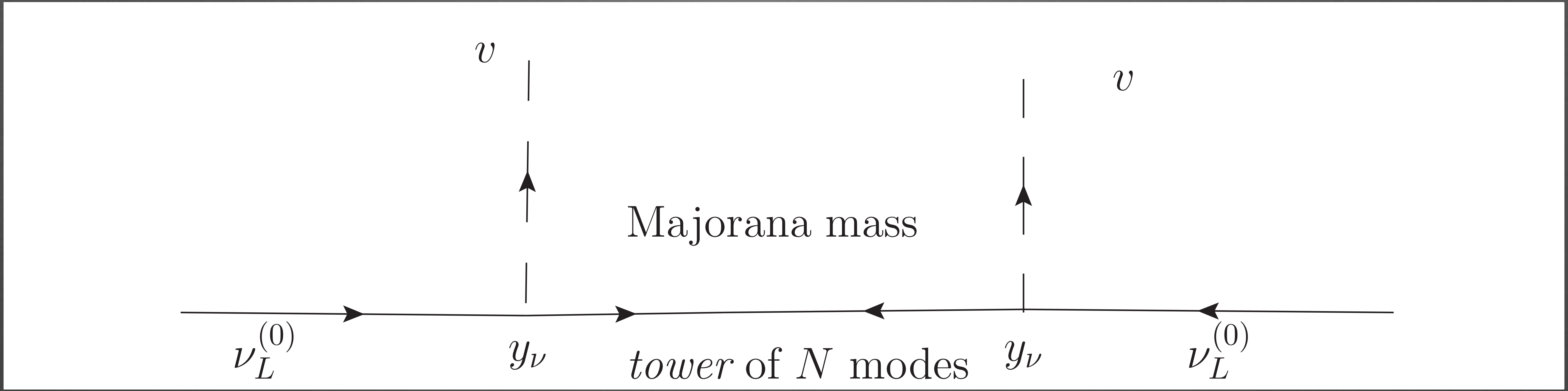
$SU(2)_L$ doublet

SM singlet

- hint of surprise: extra (vs. 4D) singlet d.o.f./chirality (N_L)!

Summary of past work

- SM neutrino mass (m_ν) from (usual) seesaw-type diagram:



- formula obtained earlier (mostly) using basis ("KK") for singlet tower which is not mass eigenstates [valid approach for observable defined at energies $\ll$ (lightest) singlet mass $\sim$TeV]

→ (impression of) high-scale seesaw

- …but physical/dynamical picture obscured: more to it than meets the eye?!

…On to Mass basis for Singlet Modes

- for on-shell production (colliders or early universe, e.g., leptogenesis)
- stick to 5D [KA, Hong, Vecchi (2015)]: tedious/not insightful…or…
- in this talk: simpler/intuitive picture using AdS/CFT duality [KA, Hong, Vecchi (2015)]

Detour on (usual) 4D strong dynamics (CFT) picture

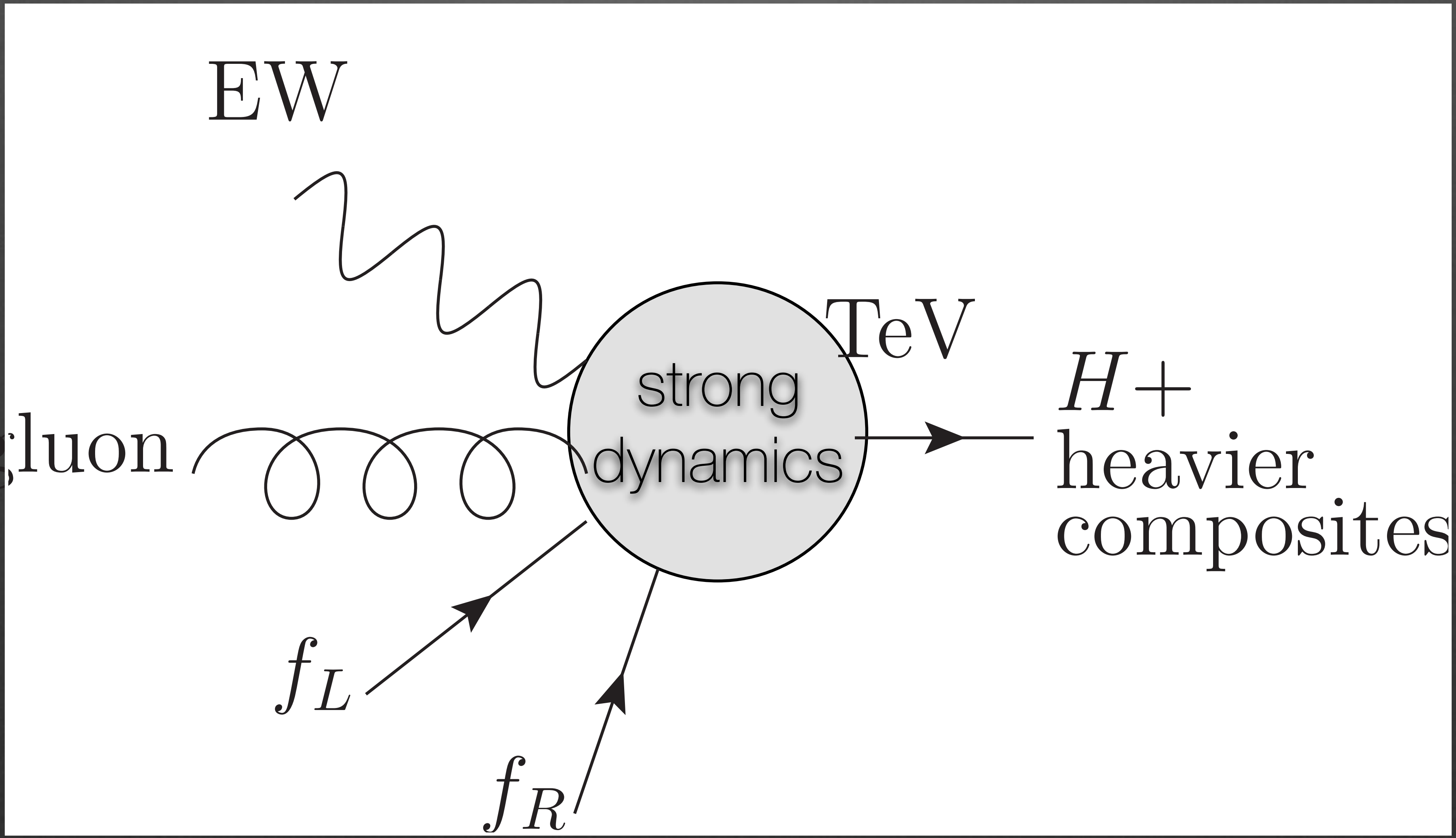
…without SM neutrino mass

Basic picture

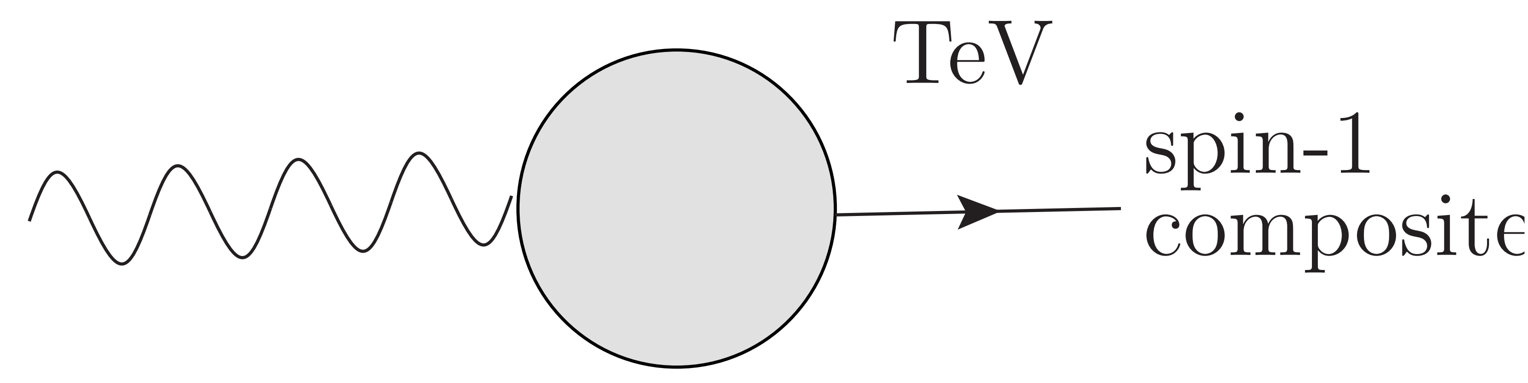
[For a review, see Panico, Wulzer (2015)]

- Higgs is (purely) composite of (new) strong dynamics

- rest of SM is admixture of elementary/external and composite, due to linear coupling (acquire mass by coupling to Higgs via composite component)



Elementary-Composite spin-1 ($\gamma - \rho$) mixing

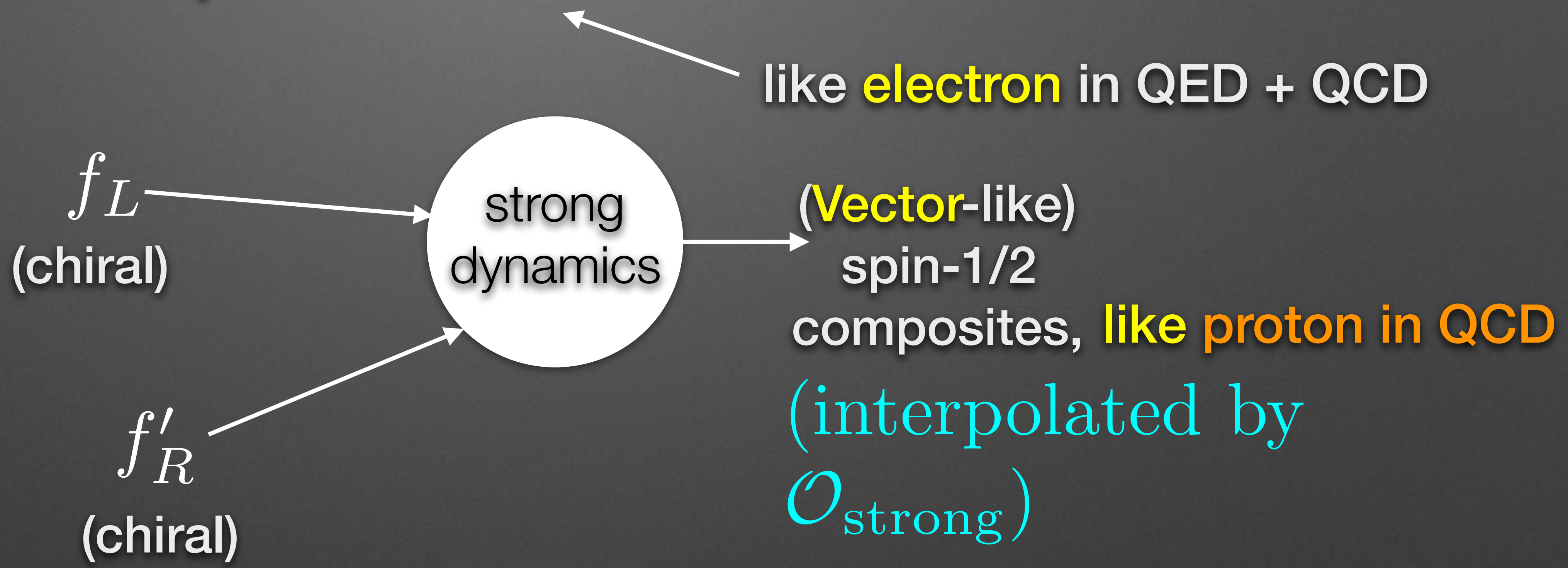


(interpolated by J^{μ}_{strong})

- (**SM**) subgroup of global symmetry of strong dynamics **externally** gauged: $g A_{\mu}^{\text{elem}} J^{\mu}_{\text{strong}}$
- a la **QCD** (2 flavors): $U(1)_{\text{EM}} \subset SU(2)_L \times SU(2)_R \times U(1)_B$
- W/Z **mass** via **composite** admixture

Elementary-composite fermion mixing: basic idea

- in “analogy” with spin-1: $\lambda \bar{f}_{\text{elem}} \mathcal{O}_{\text{strong}}$



like **electron** in QED + QCD

f_L

(chiral)

strong dynamics

f'_R

(chiral)

(**Vector**-like) spin-1/2 composites, **like proton in QCD**

(interpolated by $\mathcal{O}_{\text{strong}}$)

- **Two** (separate) **linear** couplings for each SM fermion [$SU(2)_L$ doublet and singlet]:

$$\lambda_L \bar{L}_L \mathcal{O}_L \;\; and \; \lambda_e \bar{e}_R \mathcal{O}_e$$

Elementary-composite fermion mixing: from UV to IR

- RGE with anomalous dimension

large/non-perturbative
wavefunction
renormalization for preons

$$\text{with } [\lambda] = 0; \; [\mathcal{O}] = 5/2 + \gamma,$$
$$\lambda(\text{IR}) \sim \lambda(\text{UV}) \left(\frac{\text{TeV}}{\text{M}_{\text{Pl}}} \right)^{\gamma} \; (\text{for } \gamma > 0)$$

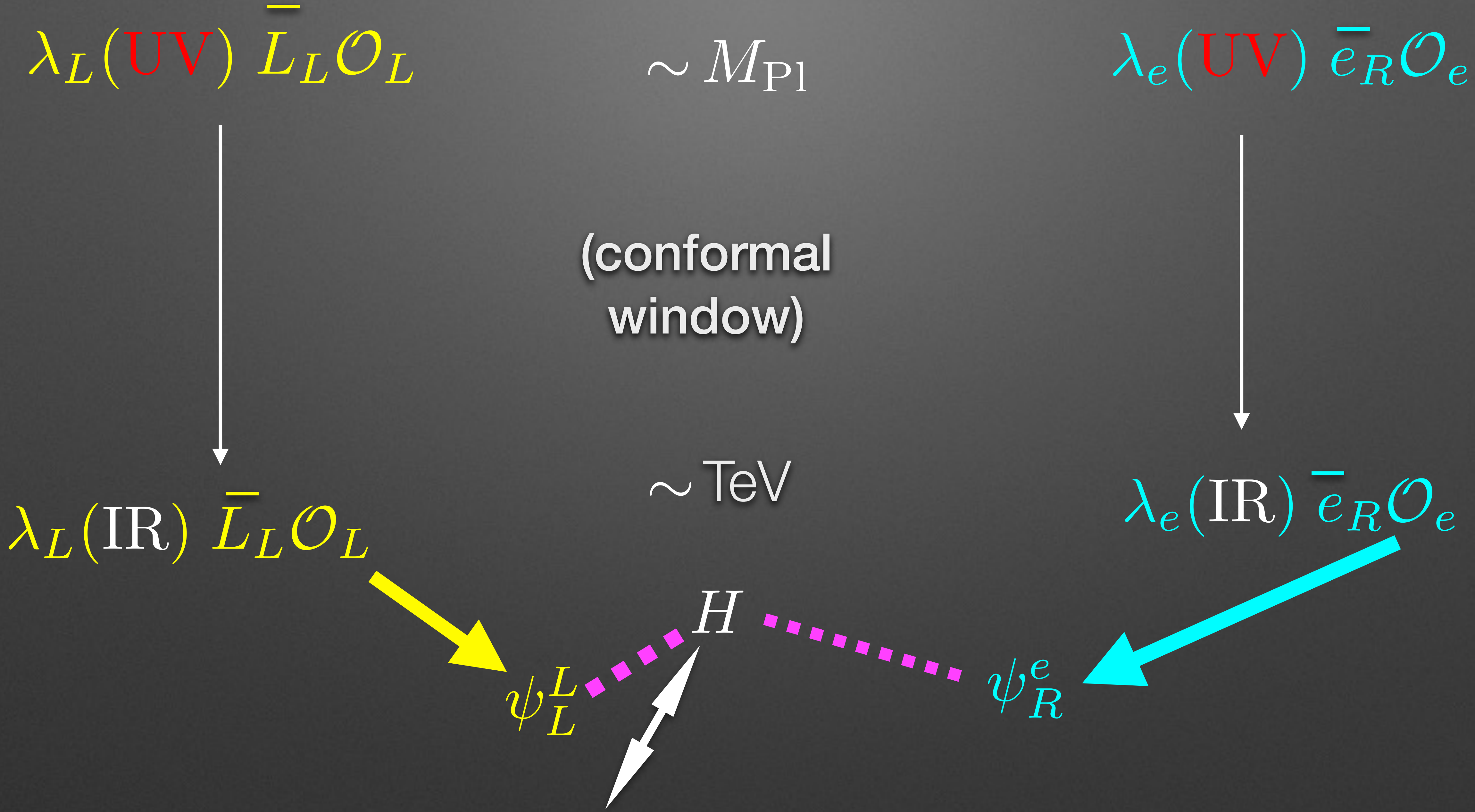
- SM fermion has $\propto \lambda(\text{IR})$ admixture of composite (ψ)

(λ's in IR hierarchical, even if not in UV +γ's similar)

- Dirac mass for composites $\sim$ TeV (dual to L, R chiralities in 5D)

SM fermion Yukawa/mass

- LH (doublet) and RH (singlet) only connect in IR:



$\lambda_L(\mathrm{UV})\ \bar{L}_L\mathcal{O}_L$

$\sim M_{\mathrm{Pl}}$

$\lambda_e(\mathrm{UV})\ \bar{e}_R\mathcal{O}_e$

(conformal window)

$\sim$ TeV

$\lambda_L(\mathrm{IR})\ \bar{L}_L\mathcal{O}_L$

$\lambda_e(\mathrm{IR})\ \bar{e}_R\mathcal{O}_e$

$$m_e \sim Y_e^{\mathrm{comp}}\ \lambda_L(\mathrm{IR})\ \lambda_e(\mathrm{IR})\ v$$

(flavor hierarchy from $\lambda(\mathrm{UV}),\gamma,\ Y^{\mathrm{comp}}$ anarchy)

...end detour on 4D strong dynamics (CFT)...

...back to SM neutrino mass using this picture
(follow one's nose)

Status of lepton-number

- preserved by strong dynamics

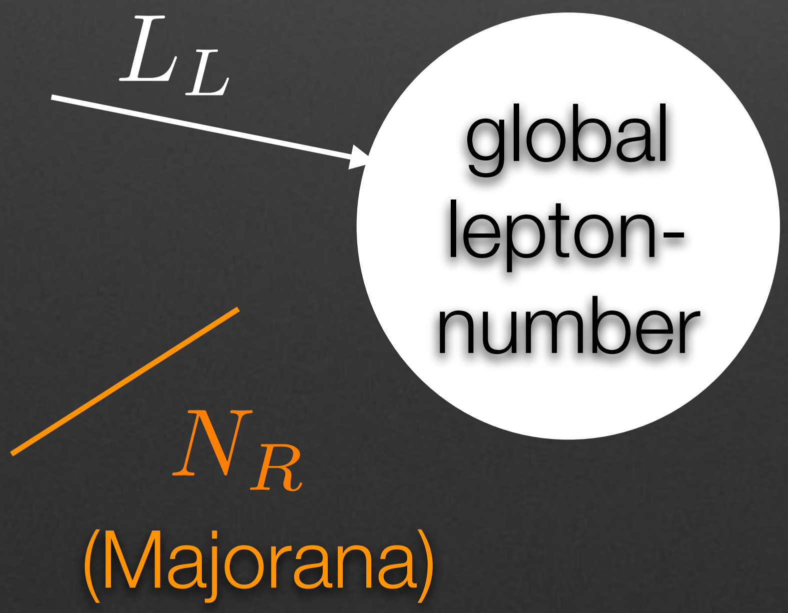
- broken in elementary sector at ~UV cut-off itself reminiscent of high-scale seesaw

- add singlet (aka RH neutrino), with Majorana mass:

$$\mathcal{L}_{\text{strong}} + \lambda_L \bar{L}_L \mathcal{O}_L + M_N^{\text{bare}} N_R^2$$

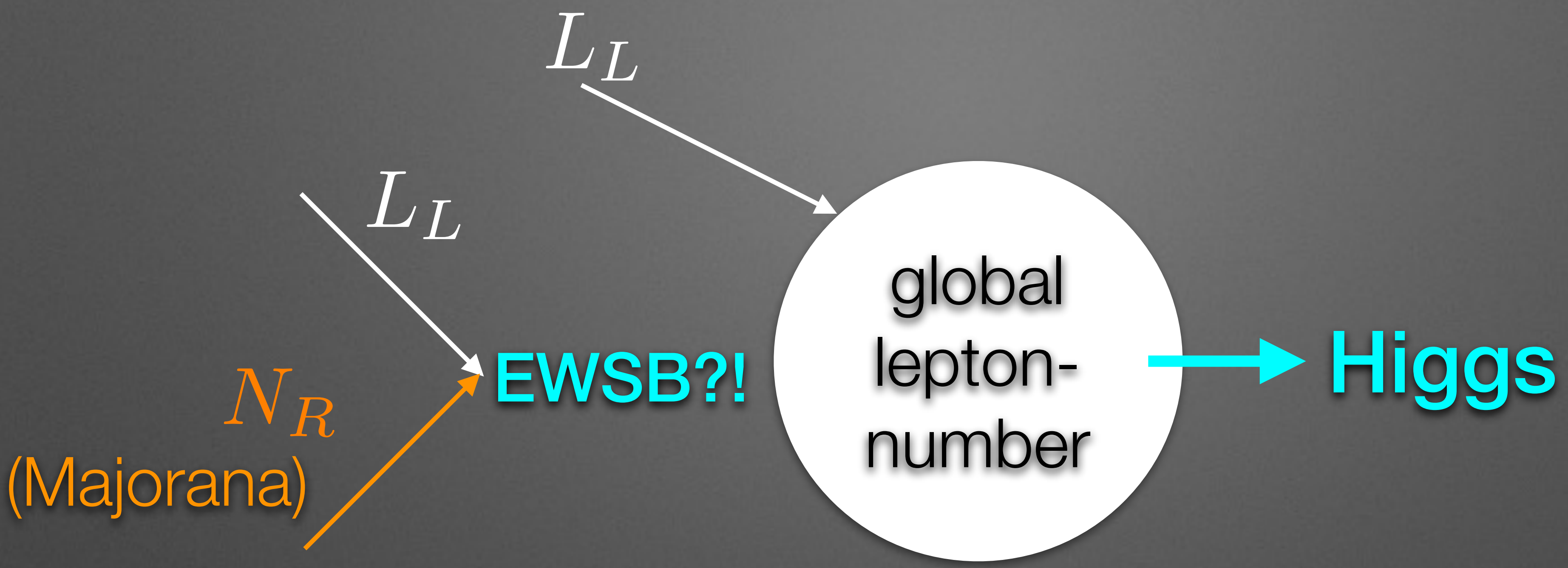
new

(dual to lepton-number broken only on UV/Planck brane)



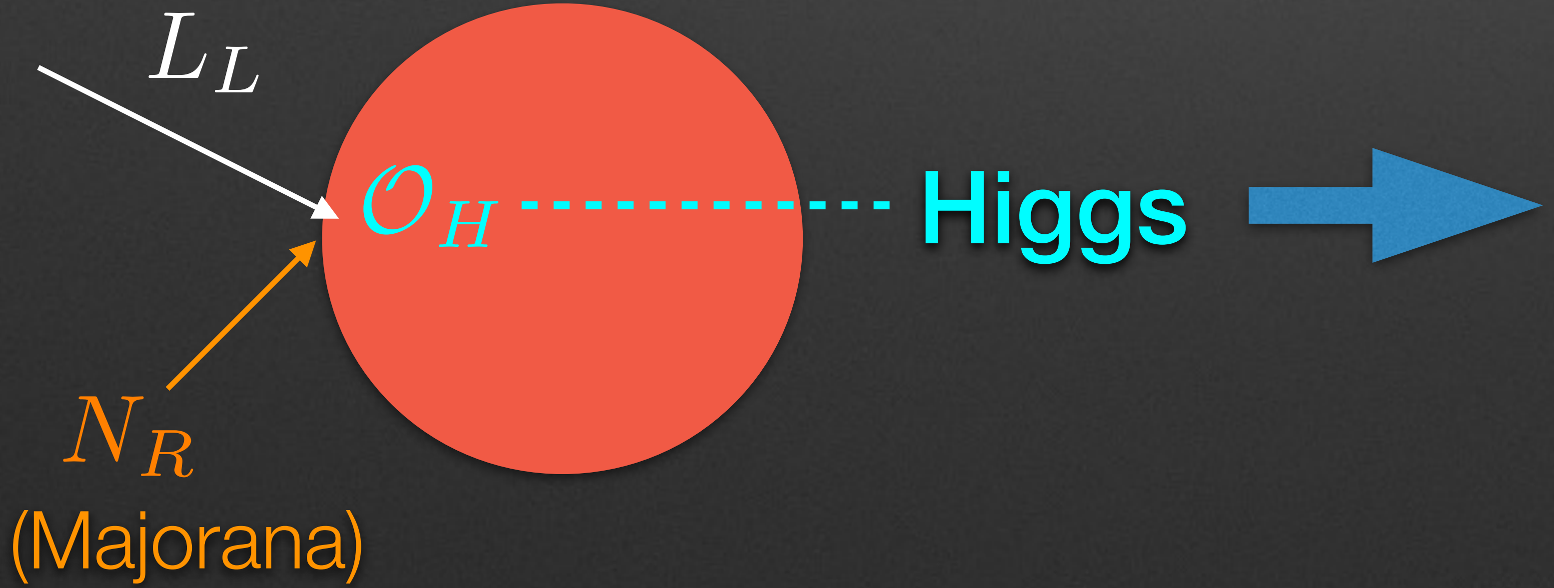
Need messenger…

- no EWSB at UV cut-off



- link 2 breakings/ingredients for SM neutrino (Majorana) mass: EWSB (IR) and lepton-number violation (UV)

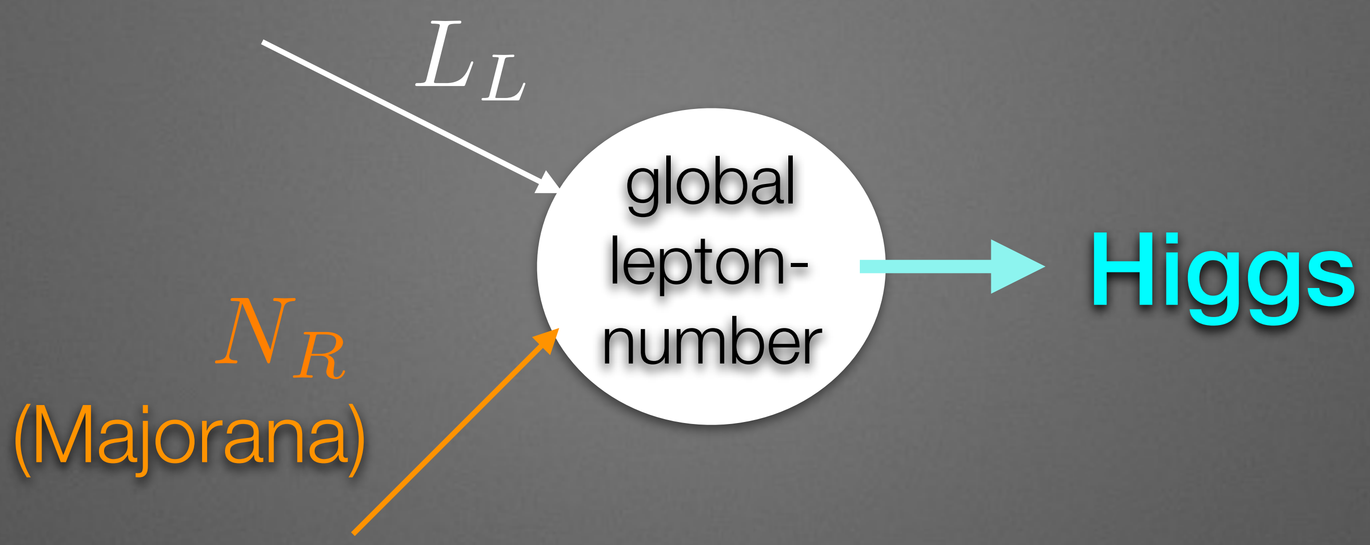
- fine-print: couple to Higgs operator in UV (highly irrelevant: neglect)



$$\text{(integrating out } N_R\text{)} \; L^2 \mathcal{O}_H^2$$

$$\Rightarrow \text{(given } \left[\mathcal{O}_H\right] \geq 2\text{)} \; \frac{L^2 H^2}{M_N^{\geq 7}}$$

Follow **charged** fermion…



L_L

N_R

(Majorana)

global lepton-number

Higgs

- couple N to SM **singlet** fermionic operator

$$\mathcal{L}_{\rm strong} + \lambda_L \bar{L}_L \mathcal{O}_L + M_N^{\rm bare} N_R^2 \quad + \lambda_N \bar{N}_R \mathcal{O}_N$$

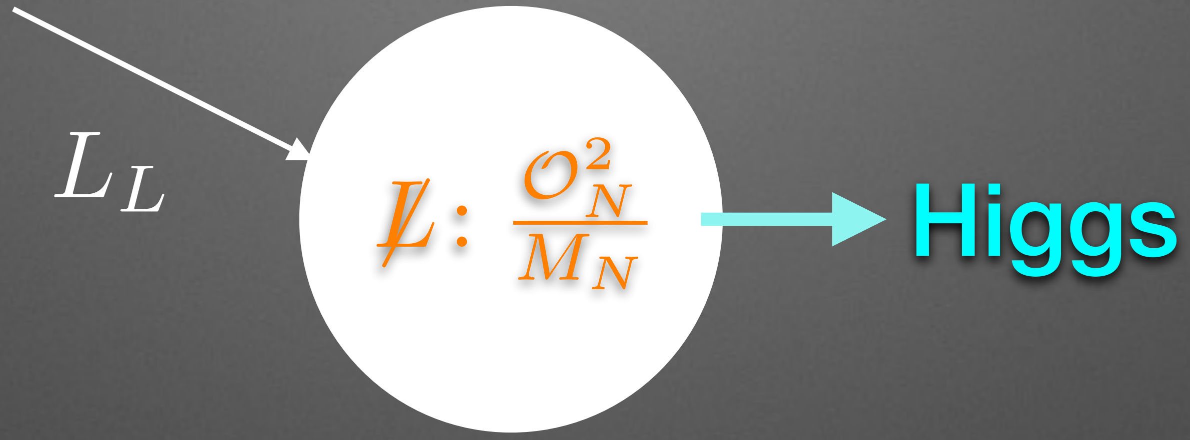
- fine-print: renormazliation of N_R mass term:

$$\text{for } \left[O_N \right] < 5/2 \ (\gamma_N < 0) \leftrightarrow c_N < 1/2,$$

$$M_N^{\rm phy} \quad \sim \quad M_N^{\rm bare} \left(\frac{M_N^{\rm bare}}{M_{\rm Pl}} \right)^{\frac{1}{2\left[\mathcal{O}_N\right]-4} - 1}$$

...but crucial difference

- integrate out N_R (in UV) to inject lepton-number breaking into strong dynamics:

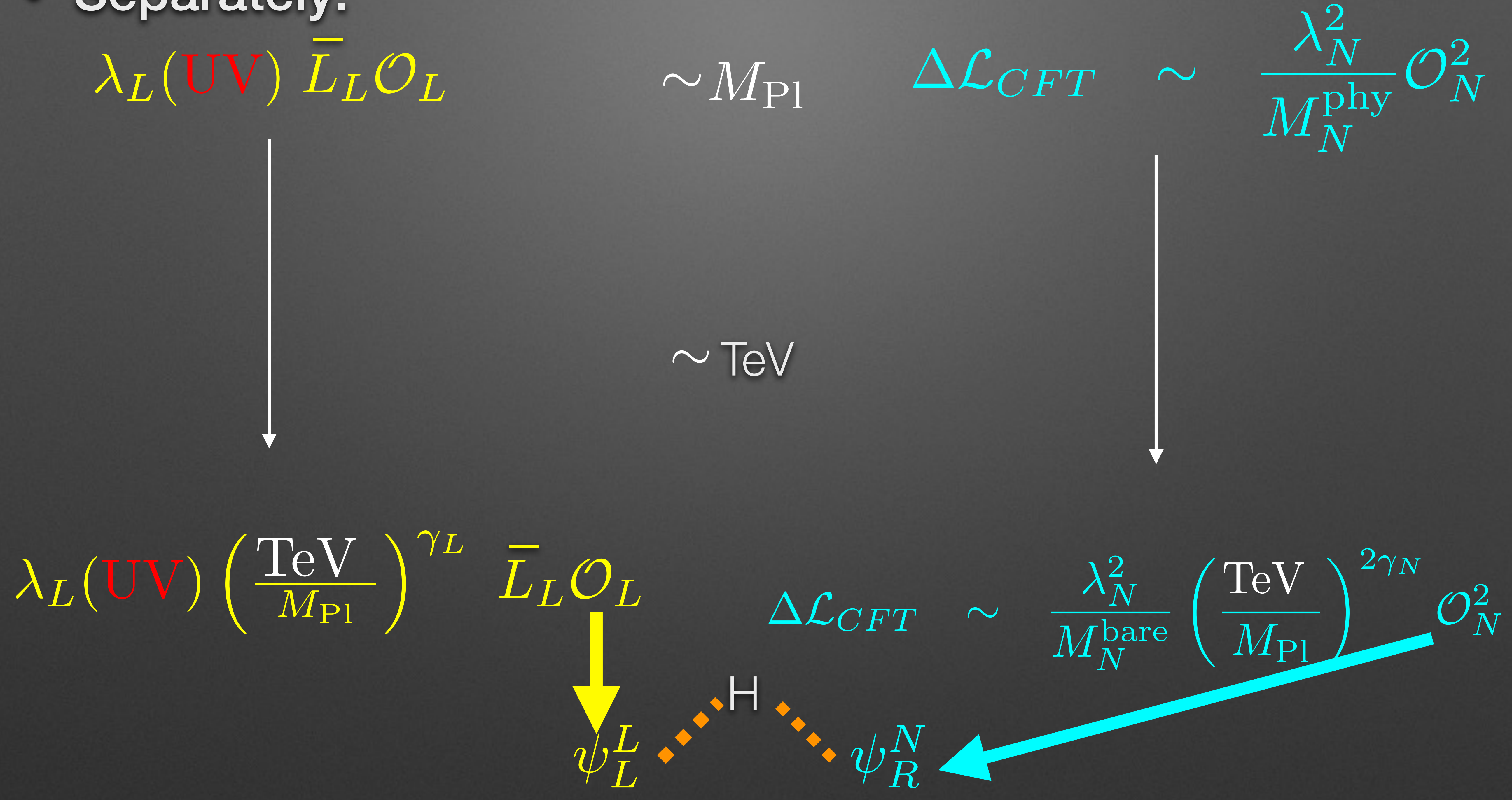


$$
\begin{aligned}
\Delta\mathcal{L}_{CFT} \quad &\sim \quad \lambda_N \bar{N}_R \mathcal{O}_N + \frac{1}{2} M_N^{\text{phy}} N_R^2 \\
&\rightarrow \quad \frac{\lambda_N^2}{M_N^{\text{phy}}} \mathcal{O}_N^2, \ \text{renormalized at } M_N^{\text{phy}}
\end{aligned}
$$

- ...no connection between L_L and $\mathcal{O}_N$ yet (UV): need EWSB...

RGE to IR

- Separately:



$\lambda_L(\mathrm{UV})\ \bar{L}_L \mathcal{O}_L$

$\sim M_{\mathrm{Pl}}$

$\Delta\mathcal{L}_{CFT} \sim \frac{\lambda_N^2}{M_N^{\mathrm{phy}}}\mathcal{O}_N^2$

$\sim$ TeV

$\lambda_L(\mathrm{UV})\left(\frac{\mathrm{TeV}}{M_{\mathrm{Pl}}}\right)^{\gamma_L}\ \bar{L}_L \mathcal{O}_L$

$\Delta\mathcal{L}_{CFT} \sim \frac{\lambda_N^2}{M_N^{\mathrm{bare}}}\left(\frac{\mathrm{TeV}}{M_{\mathrm{Pl}}}\right)^{2\gamma_N}\mathcal{O}_N^2$

(no elementary N_R)

Pseudo-Dirac TeV-mass singlets

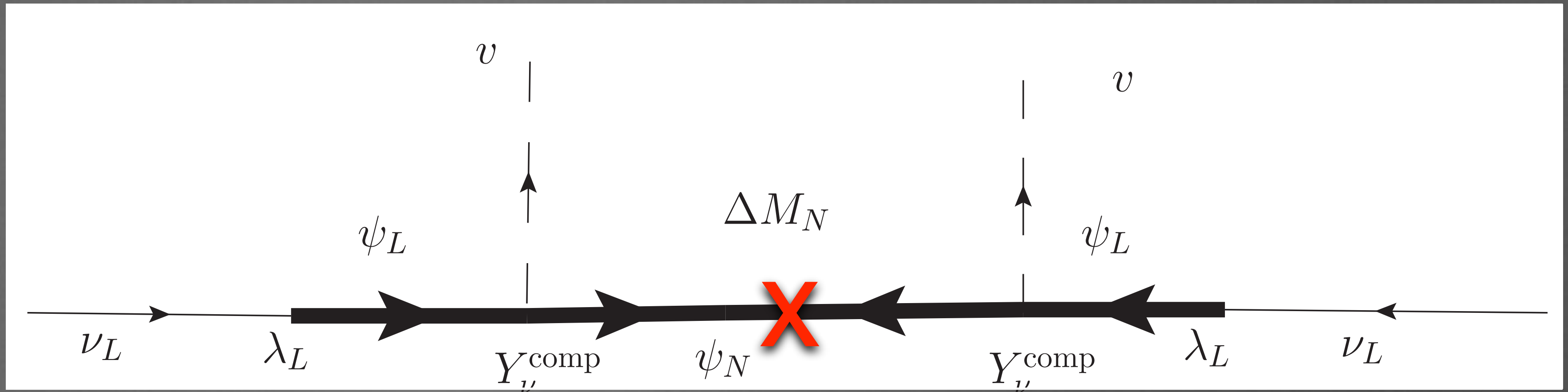
- tiny Majorana mass term for ψ_N (due to high-scale seesaw)

$$\Delta M_{\rm Maj} \text{ from } \mathcal{O}_N^2 \quad \sim \quad \frac{\rm TeV^2}{M_N^{\rm bare}} \left(\frac{\rm TeV}{M_{\rm Pl}} \right)^{2\gamma_N}$$

- Majorana mass term for LH chirality of ψ_N (coupled to N_R)

- Yukawa coupling of RH ψ_N to LH doublet lepton (like for case of charged fermion)

SM neutrino mass



- integrate out TeV-mass pseudo-Dirac singlets:

two ψ_N LR propagators

$$m_\nu \sim \left[Y_\nu^{\rm comp}\ \lambda_L(\mathrm{IR})\ v\right]^2 \times \left(\frac{1}{\mathrm{TeV}}\right)^2 \times \Delta M_{\rm Maj}$$

Dirac mass

$$\sim \frac{\left\{\left[Y_\nu^{\rm comp}\ v\left(\frac{\mathrm{TeV}}{M_{\rm Pl}}\right)^{\gamma_L}\right]^2\right.}{\left\{M_N^{\rm bare}\left(\frac{\mathrm{TeV}}{M_{\rm Pl}}\right)^{-2\gamma_N}\right.}$$

from $\lambda_L(\mathrm{IR})$

“effective” seesaw scale

from $\Delta M_{\rm Maj}$

- ...agrees with 5D/KK basis:

$$m_\nu \sim \frac{\left[Y_5\ v\left(\frac{\mathrm{TeV}}{M_{\rm Pl}}\right)^{\left(c_L-\frac{1}{2}\right)}\right]^2}{M_N^{\rm UV}\left(\frac{\mathrm{TeV}}{M_{\rm Pl}}\right)^{(1-2\,c_N)}}$$

- ...using dictionary:

$$(2+c) \leftrightarrow \left[\mathcal{O}\right] \equiv (5/2+\gamma);\ Y_5 \leftrightarrow Y^{\rm comp} \text{ and } M_N^{\rm UV} \leftrightarrow M_N^{\rm bare}$$

Warped/Composite seesaw is physically inverted!

cf. Inverse seesaw

[Mohapatra (1986);
Mohapatra, Valle (1986)]

from EWSB

(large) Dirac

add

- *4D model*

$$\mathcal{L} \ni m_D \, \overline{\nu_L} N_R + M_{NS} \, \overline{S_L} N_R + \mu \, \overline{S_L} \left(S^c \right)_R + \text{h.c.}$$

(tiny) Majorana

- *SM neutrino mass:* $m_\nu \sim \dfrac{m_D^2}{M_{NS}^2} \mu$

requires model-building/coincidence?

- *Choices of mass parameters:*

$$M_{NS} \sim M_{\text{IR}} \; (\sim \text{TeV}) \; (\textit{no} \text{ tuning})$$

$$m_\nu \ll v \quad \Rightarrow \quad \mu \ll M_{NS} \; (\text{tuning})$$

Warped/Composite Higgs seesaw:
(natural) hybrid of high-scale and inverse

- **tiny Majorana mass for singlet due to high-scale seesaw**
- **LH chirality "built-in" (Dirac composite singlets)**
- **TeV-mass natural (Higgs compositeness)**

Further using communication of lepton-number violation from UV to IR (I)

- messenger: $\mathcal{O}_N^2$ (from integrating out N_R)
- RGE ($M_{\rm Pl}$ to TeV!) + large anomalous dimensions (if strong dynamics is quasi-conformal) significantly modulate lepton-number violation (coefficient of $\mathcal{O}_N^2$) at TeV → (effective) seesaw scale: $\mathrm{TeV}^2/\Delta M_{\rm Maj} \sim M_N^{\rm bare} \left(\frac{\rm TeV}{M_{\rm Pl}}\right)^{-2\,\gamma_N}$
- naturally smaller than $M_{\rm Pl}$ ($\leftrightarrow$ would-be zero-mode profile at UV/Planck brane): $\sim 10^{12}$ GeV, with $M_N^{\rm bare} \sim M_{\rm Pl}$ and $\gamma_N \sim -0.2$
- no special physics at effective seesaw scale (cf. in usual case, invent new mechanism to get right seesaw scale)
- combined with $m_D^{\rm eff} \sim Y_\nu^{\rm comp}\, v \left(\frac{\rm TeV}{M_{\rm Pl}}\right)^{\gamma_L} \sim O(10)$ GeV

  for $Y_\nu^{\rm eff} \sim$ a few *and* $\gamma_L \sim +0.1$ (from *charged* lepton mass)

  $\Rightarrow m_\nu \sim O(0.1)$ eV

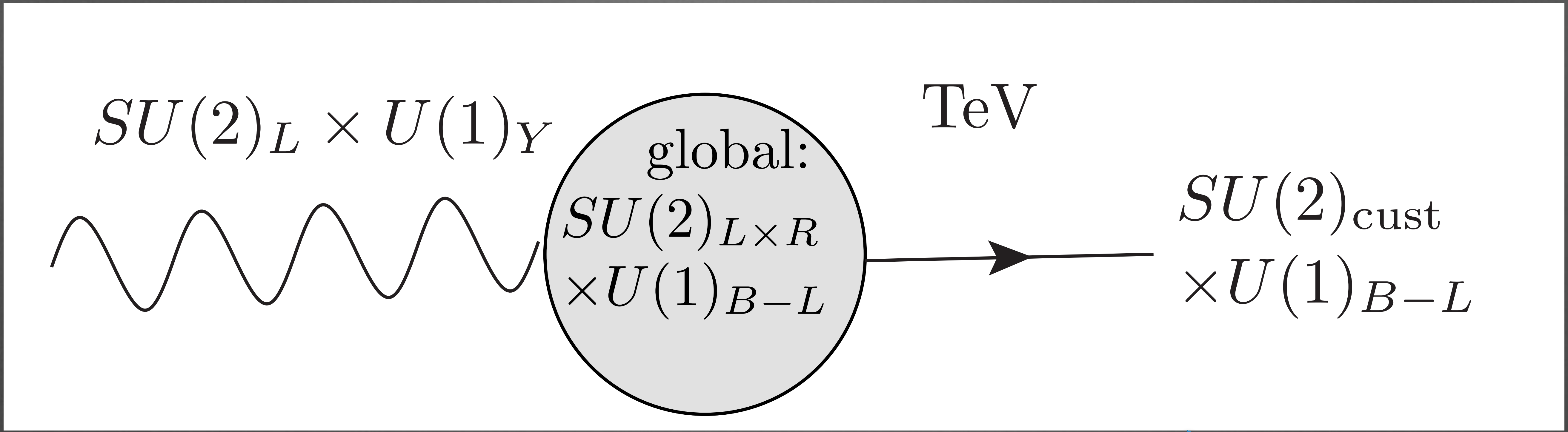
Further using communicator (II)

- Must have new states in IR (from $\mathcal{O}_N$): TeV-mass singlet neutrinos
- LHC signals for "source" of SM neutrino mass!
- 5D model: TeV-mass singlet neutrinos "always" present (even with high-scale seesaw impression from KK basis)
- ...but (physically) "switch" from "vestiges" to central players!

LHC Signals of SM Singlet Neutrinos?!

[KA, Du, Hong (2016 and 2017)]

Custodial symmetry for EW precision tests (strong dynamics picture)



- Global symmetry: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

  TeV mass Spin-1 composites: $\tilde{W}_L^{3,\,\pm}$; $\tilde{W}_R^{3,\,\pm}$ and $(B-L)$
- dynamically broken down (in IR) to $SU(2)_{\rm cust} \times U(1)_{B-L}$
- Only $SU(2)_L \times U(1)_Y$ subgroup gauged externally
- Only elementary sector (N_R) breaks lepton-number

of before

- Vector-like/Dirac composites: $\begin{pmatrix} \psi_N \\ \psi_e \end{pmatrix} \sim (1,2)_{-1} \cdots$ (dual to TeV-mass modes of N...)

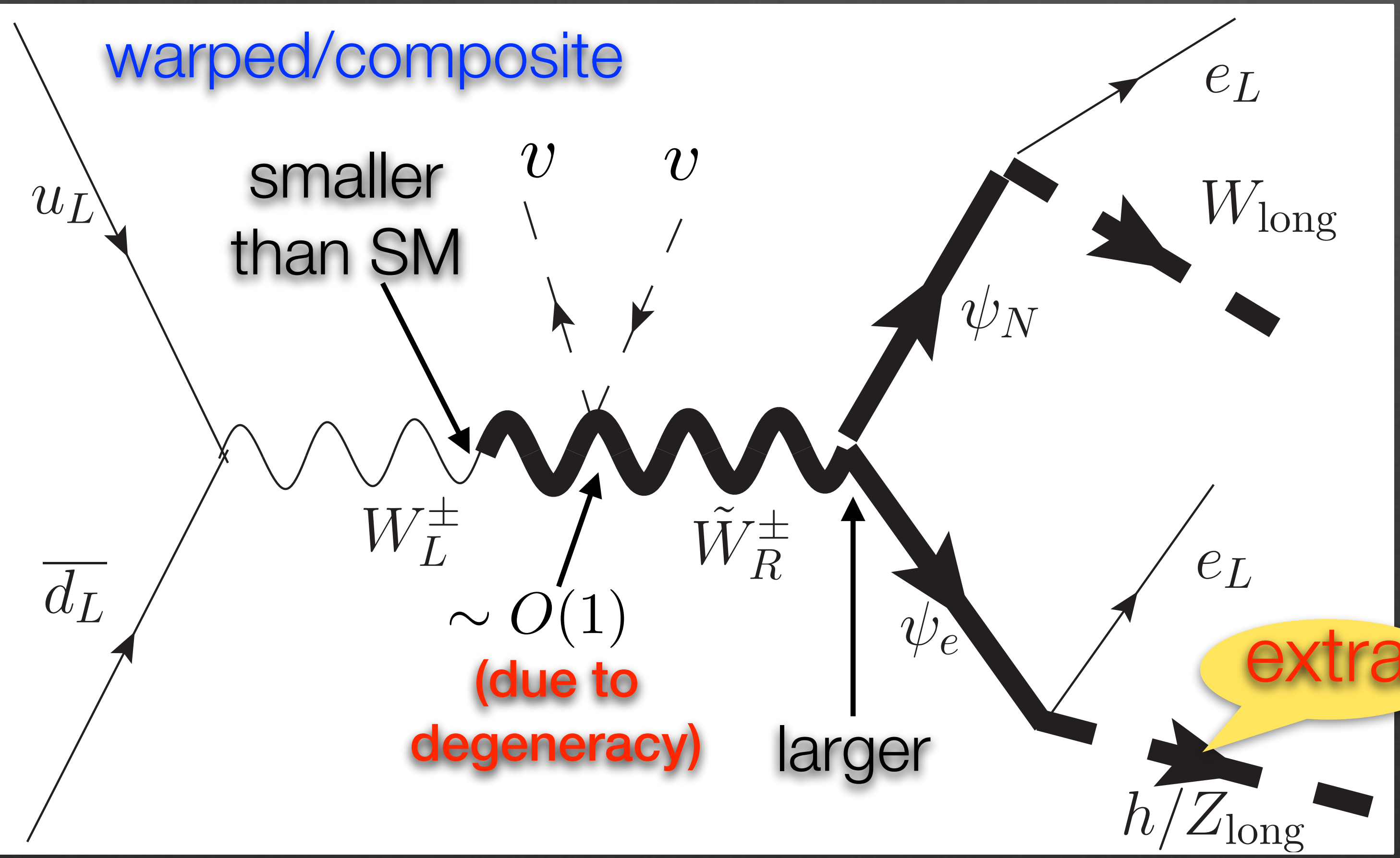
  [coupled to spin-1: $W_R^{3\;\pm}$ and $(B-L)$]

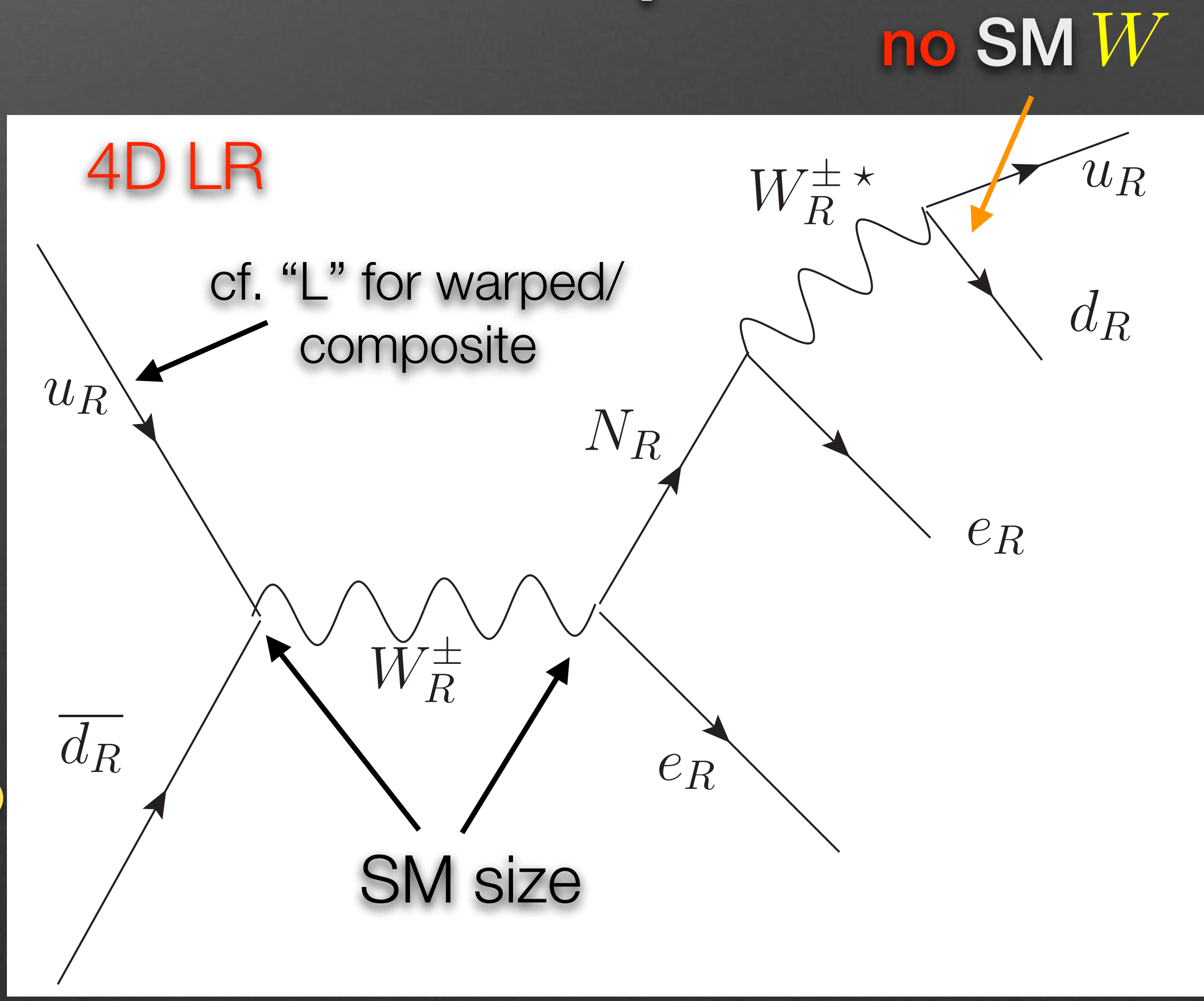
…4D LR symmetry model-like signals (?)

…not quite!

Summary: di and tri-lepton + boson(s) from $\tilde{W}_R^{\pm}$

- Extra boson(s) helps to reduce SM background
- (overall) production rate of $\tilde{W}_R^{\pm}$ smaller in warped/composite model (vs. 4D LR), BR to singlet neutrino larger
- 3-5σ with 300/fb for 2 TeV $\tilde{W}_R^{\pm}$ and 750 GeV ψ_N
- post-discovery: invariant mass distribution of dileptons different





Summary of (composite) neutral spin-1

(coupled to singlet neutrino)

Special case: $\tilde{W}_R^3$ and $(B-L)$ degenerate

- re-organize into $\tilde{Y}$ (couples to quarks via mixing with elementary, but not to singlet neutrino): vice versa for Z'

- use EWSB (composite mixing enhanced by same degeneracy) to couple (for production) Z' to quarks (decay into singlet neutrino): same mass/similar cross-section as $\tilde{W}_R^{\pm}$ (cf. Z' heavier in 4D LR)

Generically: $\tilde{W}_R^3$ and $(B-L)$ non-degenerate…

- cannot use $\tilde{Y}$ and Z' : $\tilde{W}_R^3$ and $(B-L)$ (separately) mass eigenstates (no analog in 4D LR), both couple to quarks via mixing with elementary hypercharge (no EWSB needed)

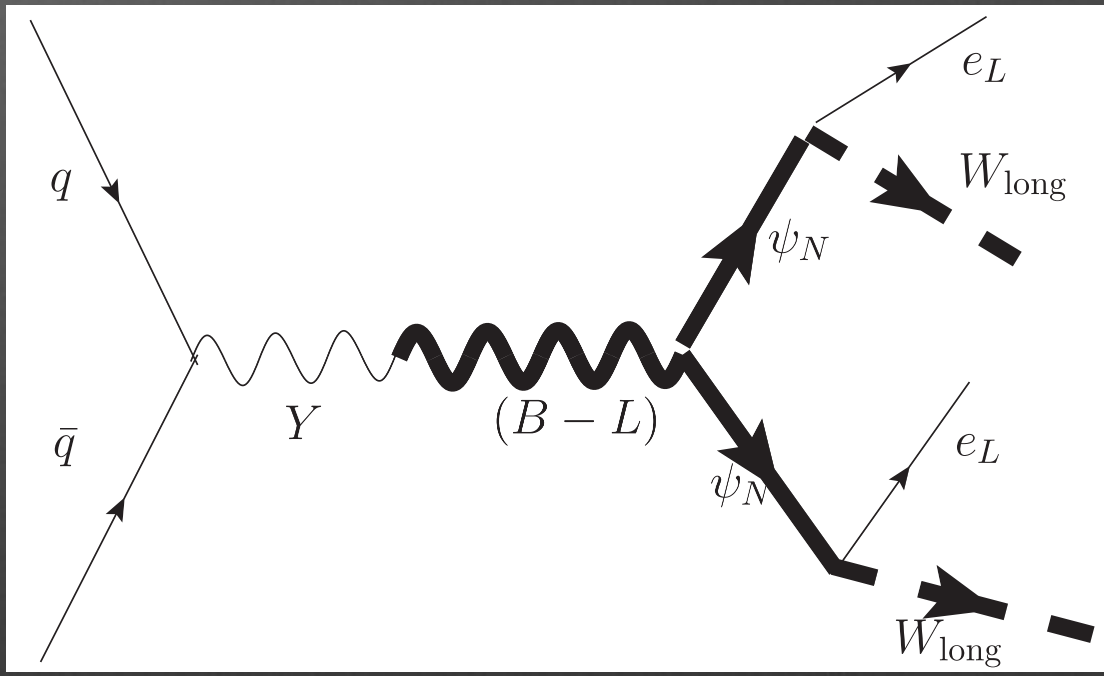
- $(B-L) \lesssim 2 \text{ TeV}$ striking (that's what's going on at weak scale/LHC?!): no charged counterpart (only spin-1 particle accessible, cf. 4D LR $\tilde{W}_R^{\pm}$ before Z'); discovery via decay into singlet neutrino [no diboson (cf. typical EW spin-1); di-top suppressed (rest of SM fermions negligible)]

Generic features of LHC signals from production of charged or neutral (a few TeV) spin-1, decay into pair of heavy leptons →

- final state: di-boson ($W/Z/h$) + di-charged/neutral "lepton"

leptons or jets
(but no di-boson peak
→ existing searches
inefficient)

di-lepton/(lepton + MET)/
(only) MET



- (boson + lepton) reconstructs heavy lepton

- Two heavy leptons form heavy spin-1

- bosons can be boosted (if heavy lepton $\gtrsim 500 \text{ GeV}$)
  → $W/Z/h$-jet

★ S small → use all of above features to beat B

Future

- Leptogenesis (at ~TeV temperatures from decay of pseudo-Dirac singlet neutrinos?!)
- reach of 100 TeV collider
- Flavor violation from TeV-mass composite leptons

Conclusions

Theory of SM neutrino mass in warped/composite Higgs framework

- implementation of high-scale seesaw morphs into a hybrid with inverse:
  SM neutrino mass from exchange of TeV-mass pseudo-Dirac SM singlet neutrinos, with high-scale seesaw giving tiny Majorana mass term
- observed size of SM neutrino mass/effective seesaw scale obtained naturally, without any hierarchies in fundamental parameters

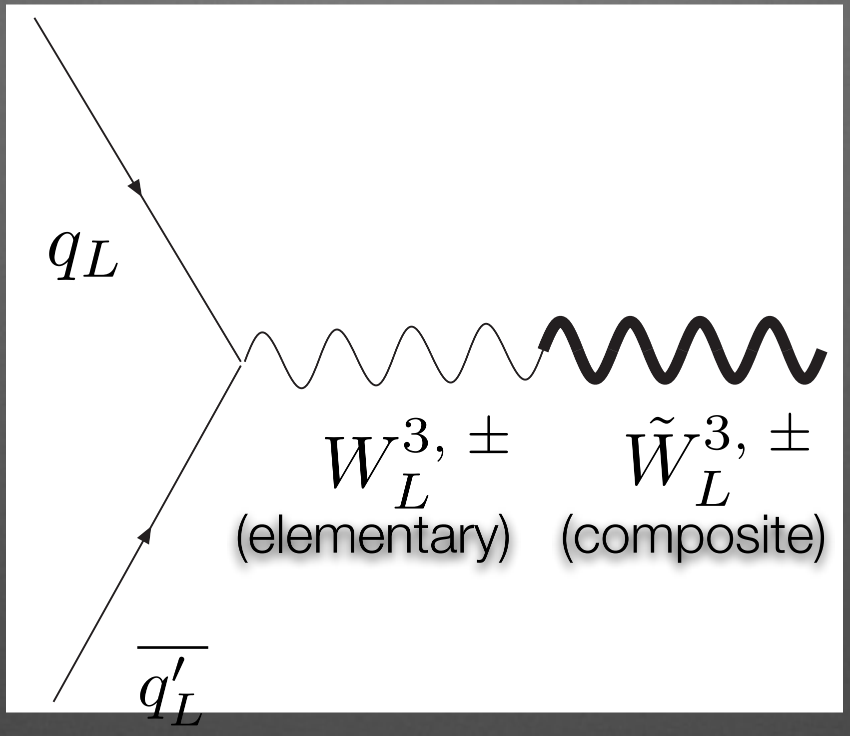
LHC Signals of TeV-mass singlet neutrinos

- Multi leptons + bosons
- similar to 4D LR models, although can be differentiated
- more importantly, acquire real motivation now

Back-up

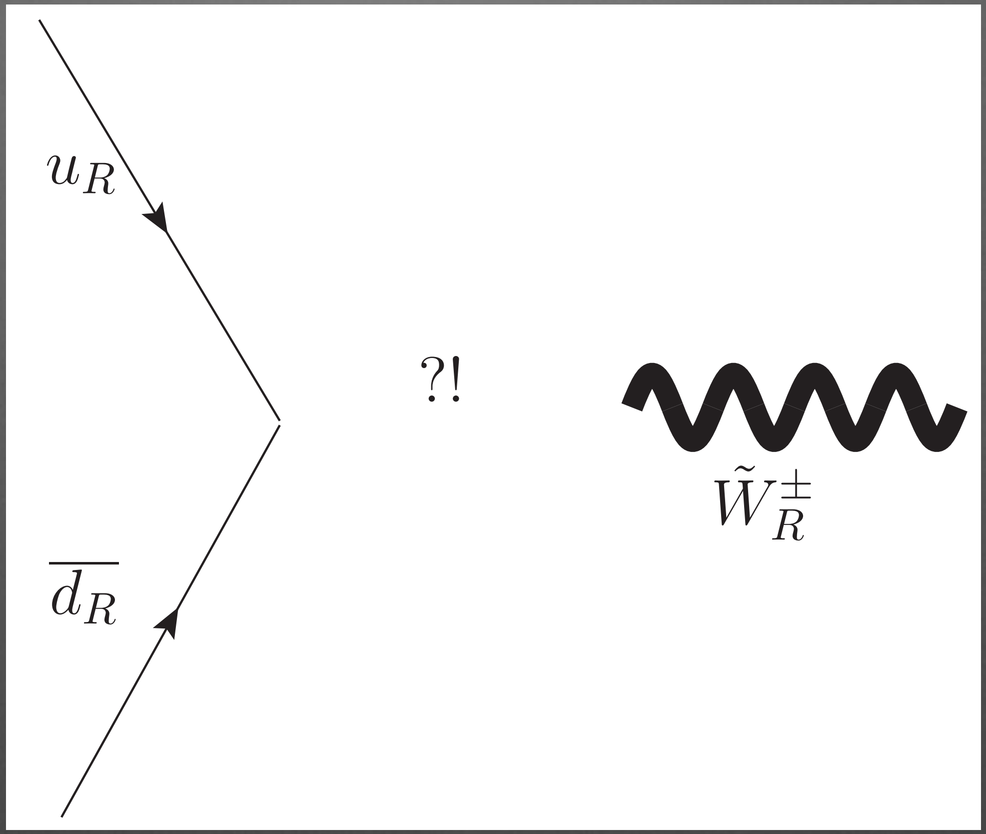
Details of signal from $\tilde{W}_R^{\pm}$

Coupling to (mostly elementary) light quarks: composite partner of SM gauge bosons



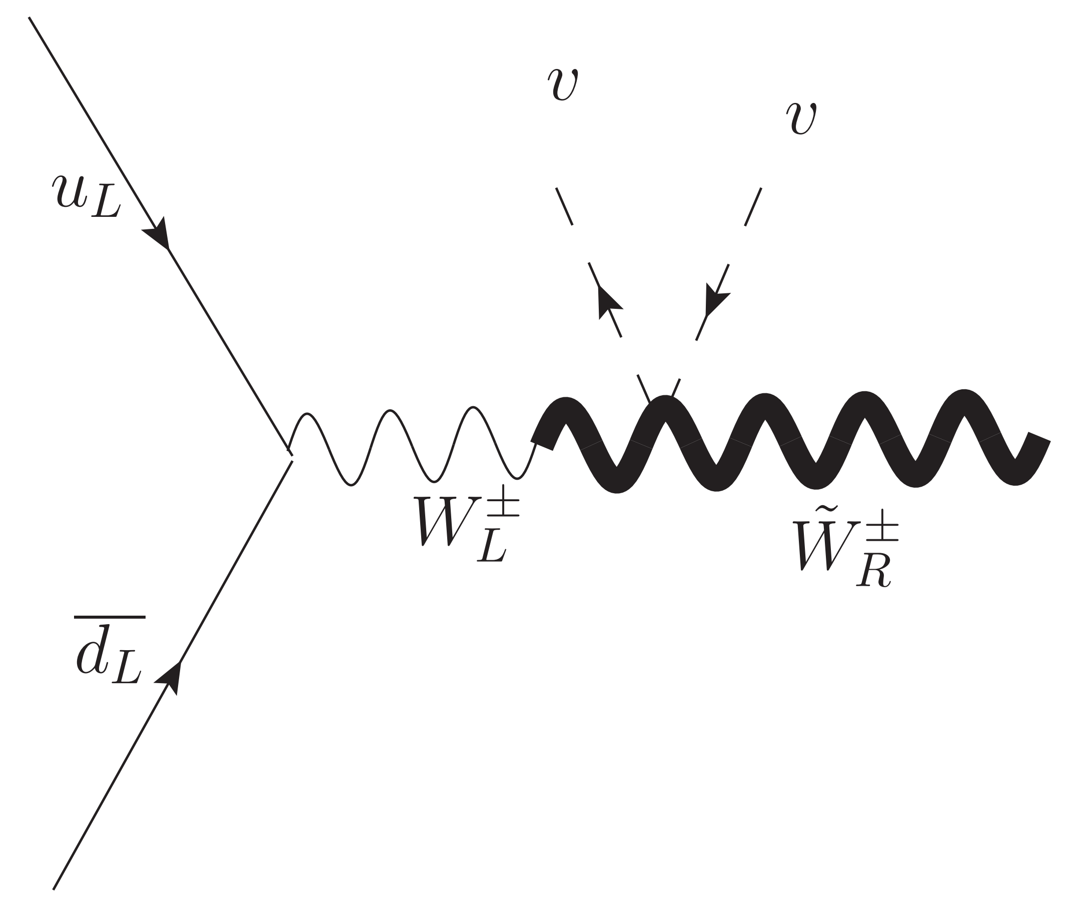
- Use spin-1 elementary-composite mixing: a la e^+e^- coupling to ρ^0 in QED+QCD
- …but singlet neutrino does not couple to W_L, only to $\tilde{W}_R^{\pm}$ and Z'

Coupling of $\tilde{W}_R^{\pm}$ to quarks (no/super-heavy elementary counterpart)?



- Like coupling of $e\ \nu$ to $\rho^{\pm}$ in EW +QCD via exchange of super-heavy $W^{\pm}$

Enter EWSB



- mixes $\tilde{W}_L$ and $\tilde{W}_R$

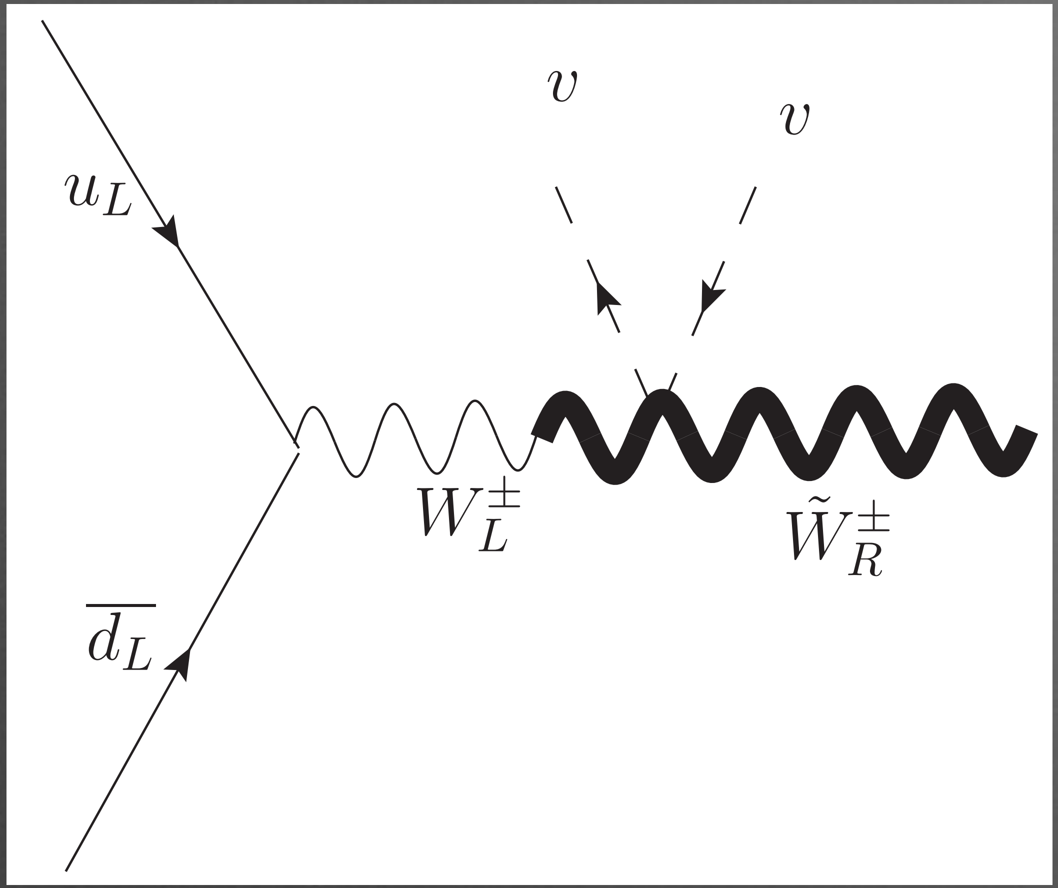
- ...but effect suppressed due to Higgs VEV vs. compositeness scale?!

a few

$$\text{mixing } angle \sim \frac{\left(g_W^{\text{comp}} v\right)^2}{\left(M^2_{\tilde{W}_L} - M^2_{\tilde{W}_R}\right)} \ll 1$$

$$if\ M_{\tilde{W}_{L,R}} \sim \text{a few TeV } and \sim O(1) \text{ different}$$

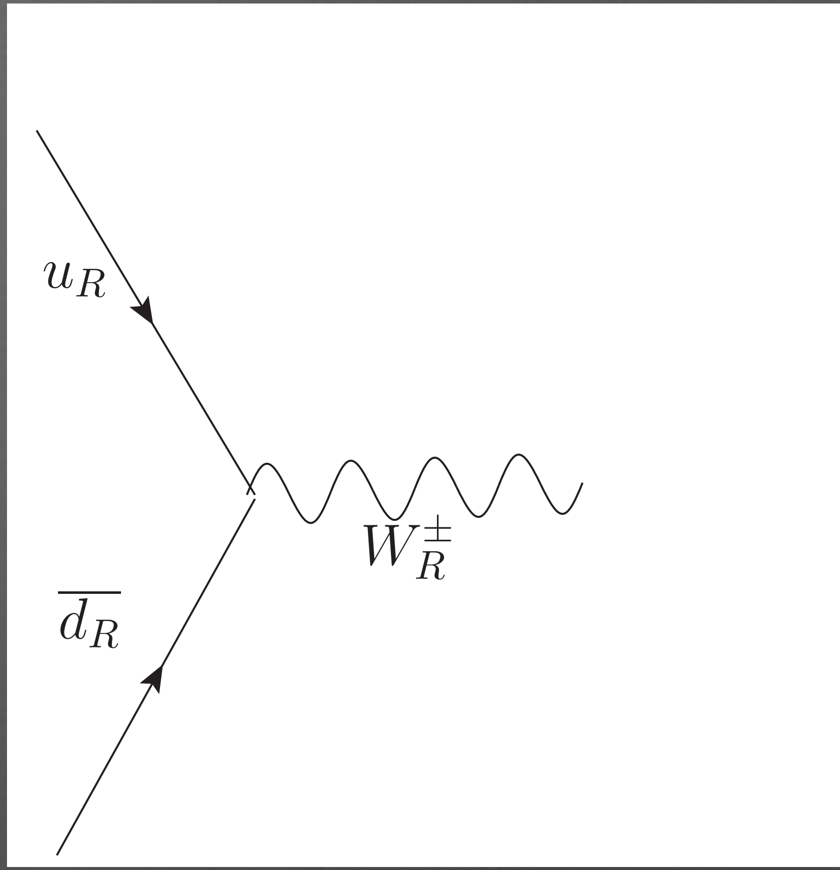
…followed by (quasi-)degeneracy



cf. direct coupling

in 4D LR →

(compare also chiralities of quarks!)



- L $\leftrightarrow$ R symmetry: (purely) composite mass identical, split (only) by mixing with elementary

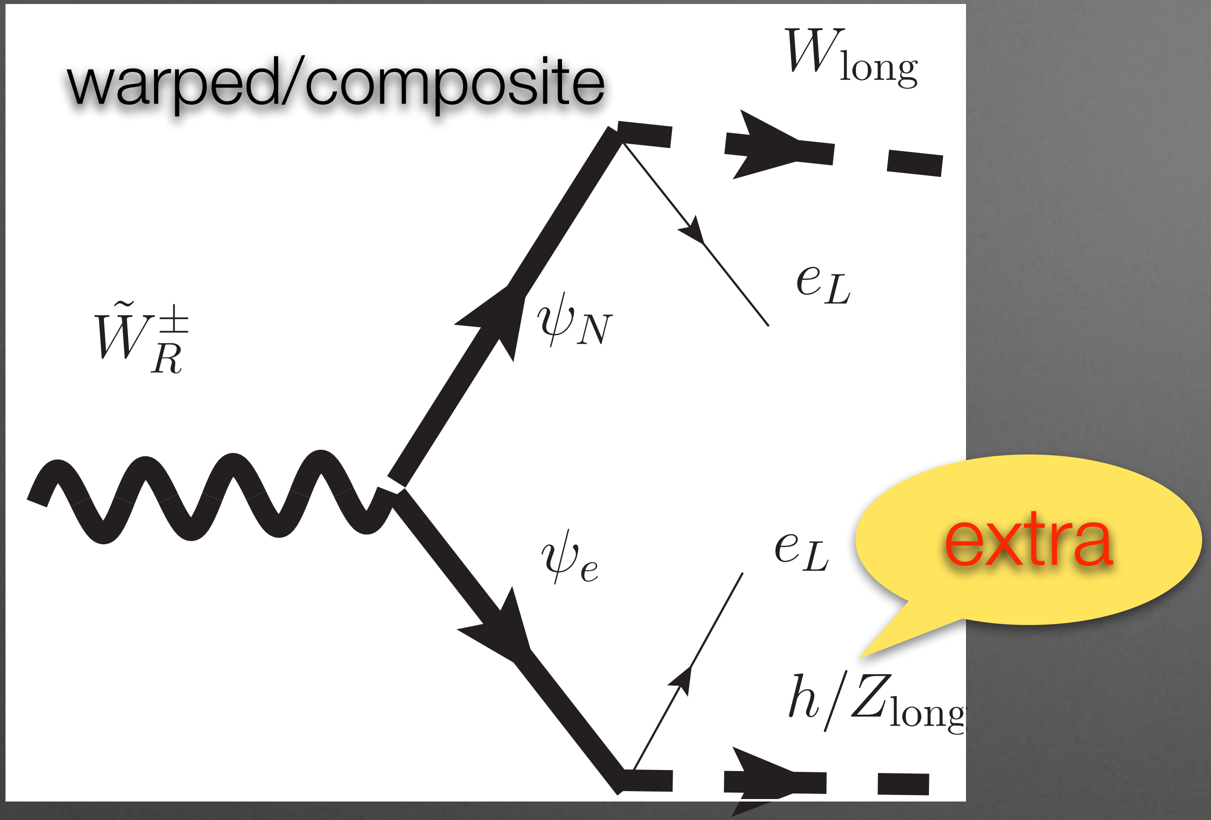
$$\text{mixing } \mathit{angle} \sim \frac{\left(g_W^{\text{comp}}\, v\right)^2}{\left(M^2_{\tilde{W}_L} - M^2_{\tilde{W}_R}\right)}$$

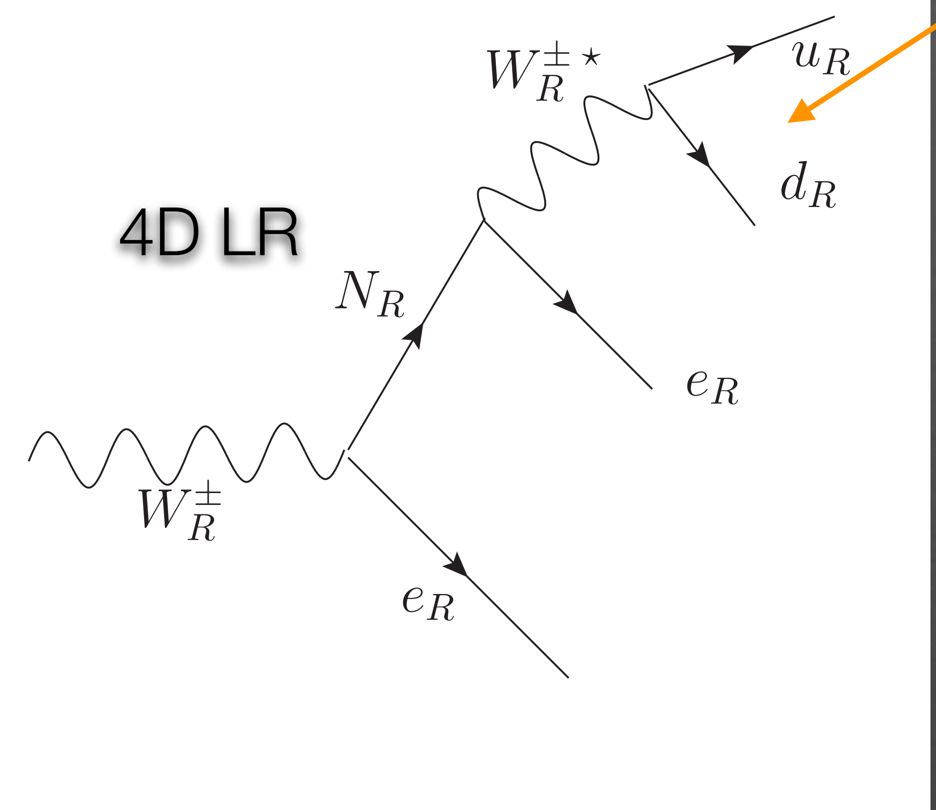
$$\sim O(1)$$

[KA, Davoudiasl, Gopalakrishna, Han, Huang, Perez, Si, Soni (2007); KA, Gopalakrishna, Han, Huang, Si, Soni (2008)]

$$\mathit{if}\ M_{\tilde{W}_{L,R}} \sim \text{a few TeV}\ \mathit{and}\ \Delta M^2_{\tilde{W}} \sim \left(\frac{g_W^{\text{elem}}}{g_W^{\text{comp}}}\right)^2 M^2_{\tilde{W}}$$

Decay also different (assume $M_{\tilde{W}_R^\pm} \gtrsim 2\, M_{\psi_{N,e}}$)





- via Yukawa coupling (involved also in SM neutrino mass generation)
- Opposite-sign dileptons in warped/composite model vs. same-sign for Majorana in 4D LR model
- Extra boson(s) vs. 4D LR models (2 jets do not form SM W)

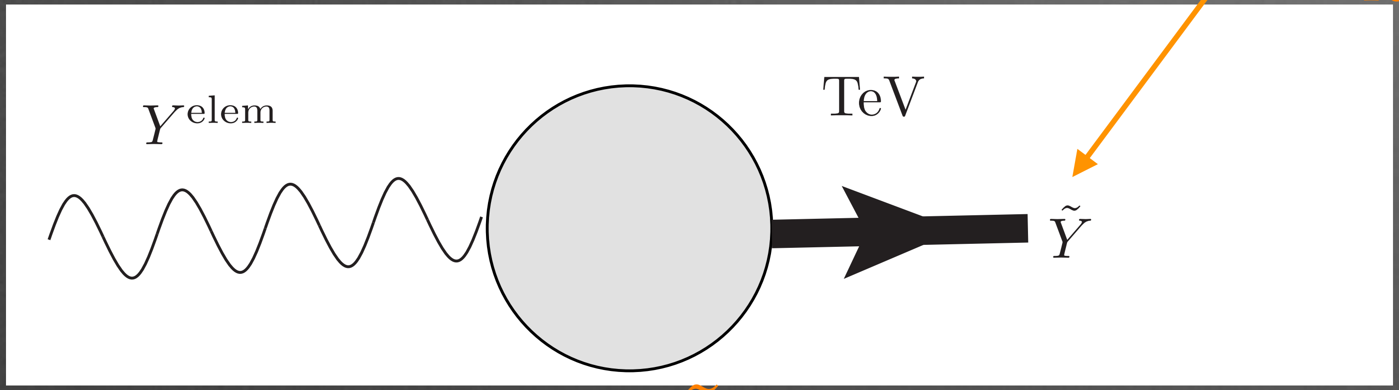
Neutral spin-1 sector…

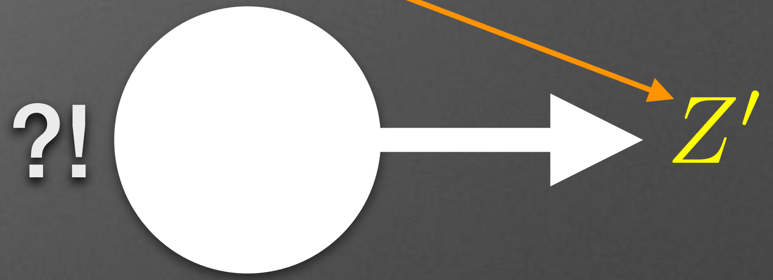
Neutral spin-1 sector carefully

- elementary hypercharge (Y) mixes with both $\tilde{W}_R^3$ and $(B-L)$

- assume degeneracy (special case) between $\tilde{W}_R^3$ and $(B-L)$

(combinations of $\tilde{W}_R^3$ and $(B-L)$)



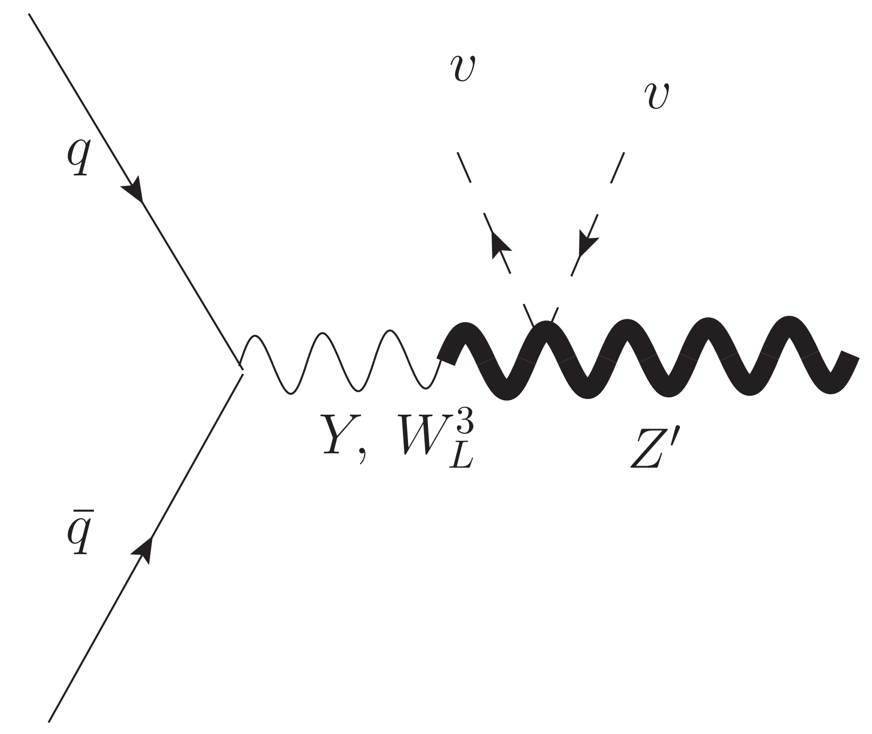


- Re-organize $\tilde{W}_R^3$ and $(B-L)$ into (mass eigenstates) $\tilde{Y}$ (mixing with elementary) and Z' (not mixing with elementary hypercharge)

- Singlet neutrino couples only to Z'…

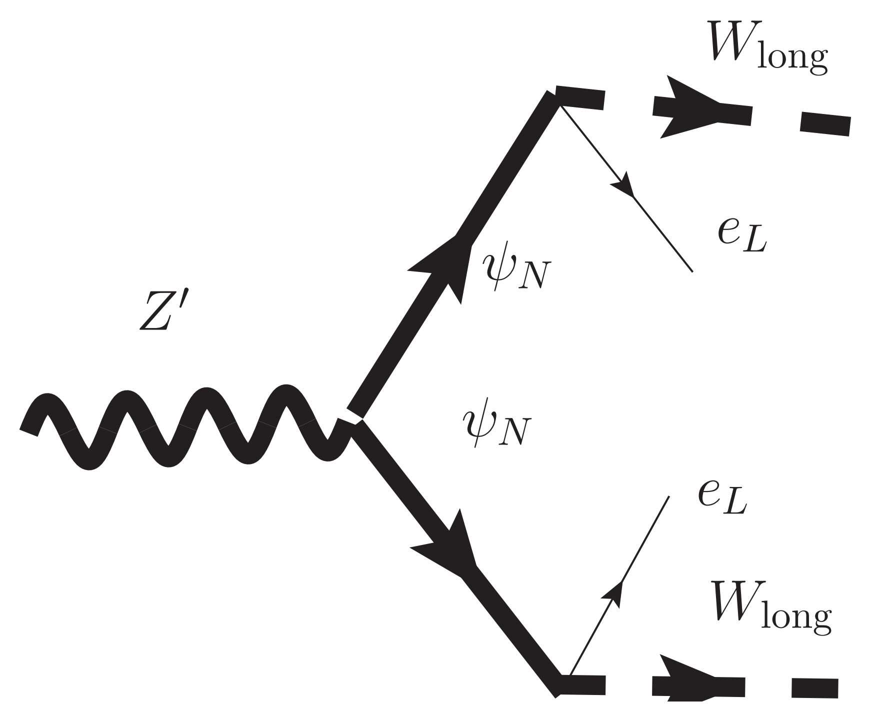
Coupling of quarks to Z' similarly to $\tilde{W}_R^{\pm}$ (no elementary counterpart)

- production

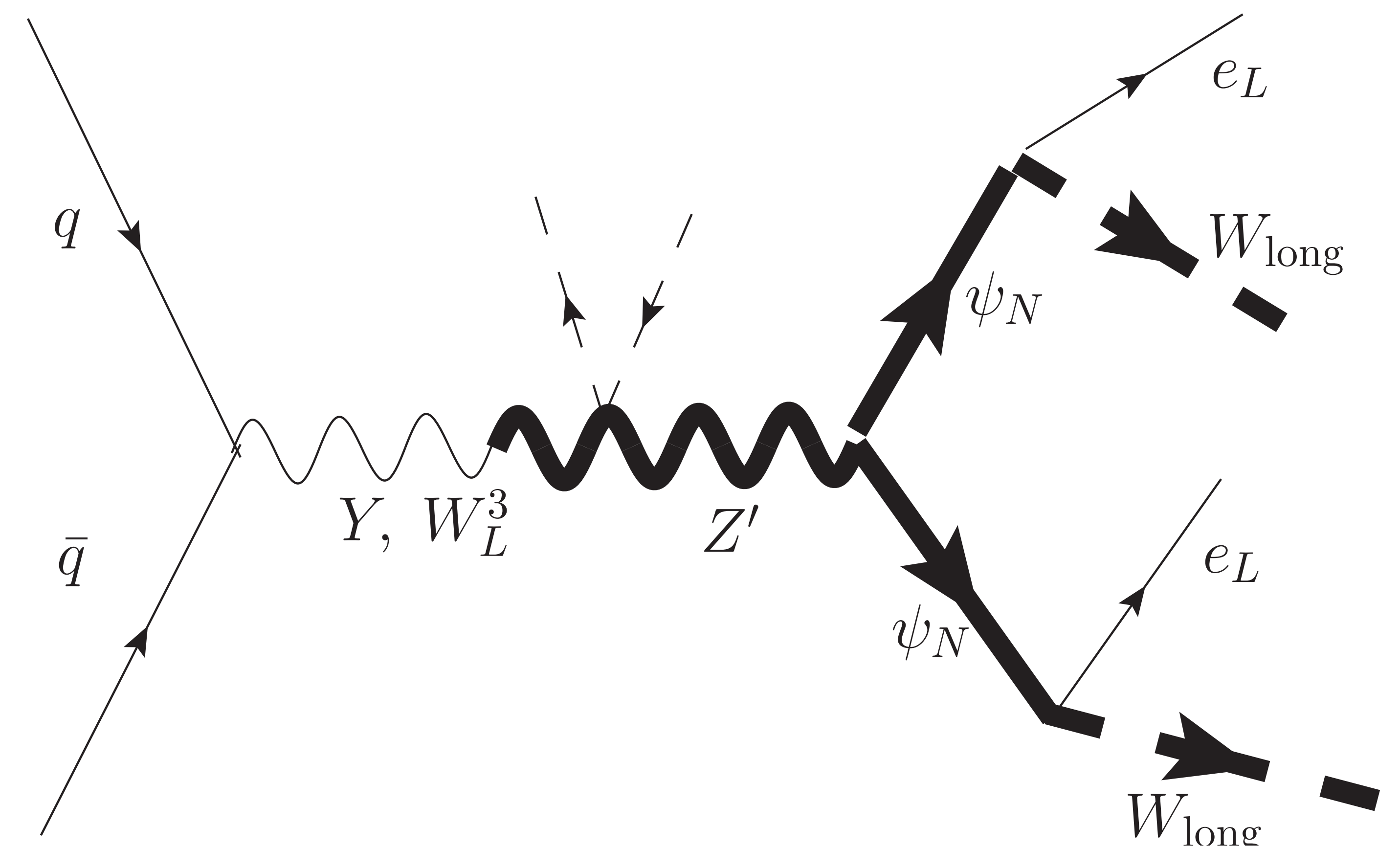


- use EWSB:
  mixing angle enhanced
  by (same) degeneracy
  [between $\tilde{W}_R^3$ and $(B - L)$]!

- decay



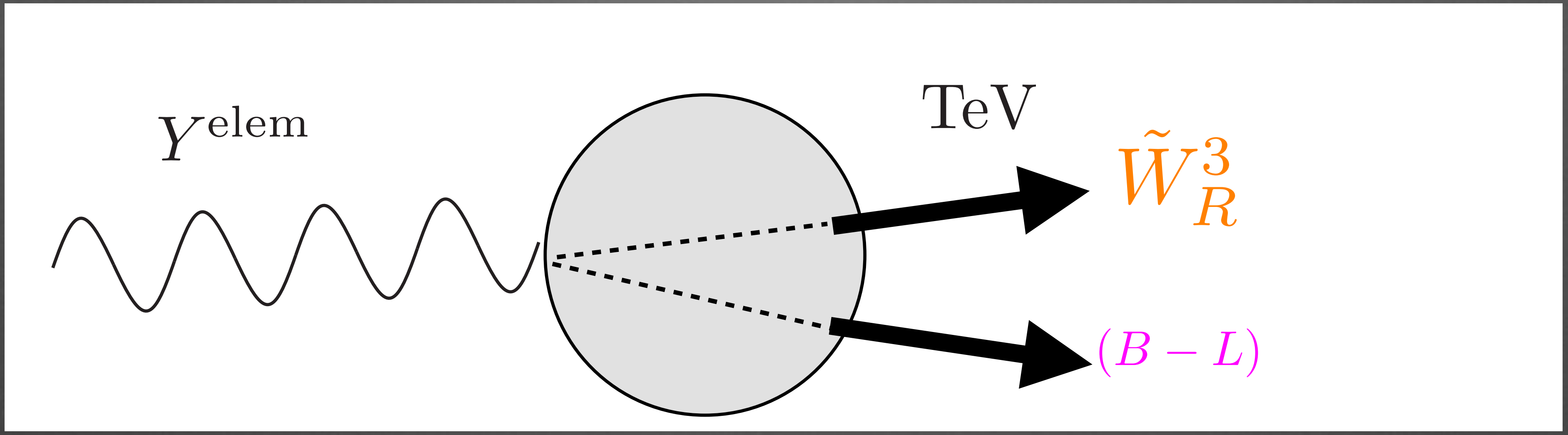
...and Z' **not** far behind



- **same** mass as $\tilde{W}_R^{\pm}$ in warped/composite model [due to $SU(2)_R$ **global** symmetry] vs. Z' **heavier** in 4D LR

Neutral spin-1 sector: non-degenerate case

- also lose neutral channel (Z'), like $W_R^{\pm}$?!

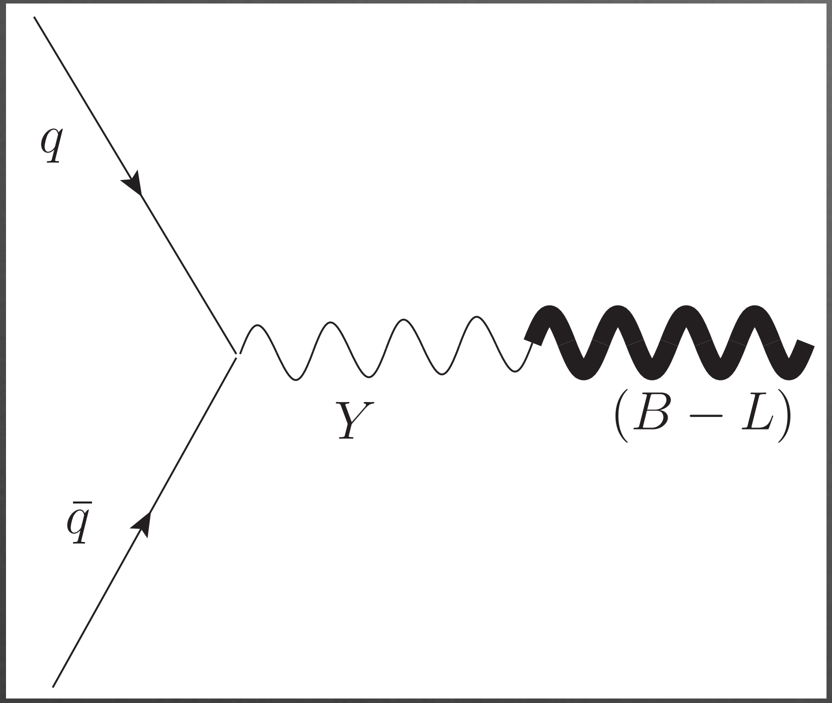


...not really!

- $\tilde{W}_R^3$ and $(B-L)$ are separately (non-degenerate) mass eigenstates ($\tilde{Y}$ and Z' not valid!)

- both $\tilde{W}_R^3$ and $(B-L)$ mix with elementary Y

Coupling of singlet neutrino to quarks (via neutral spin-1) without EWSB



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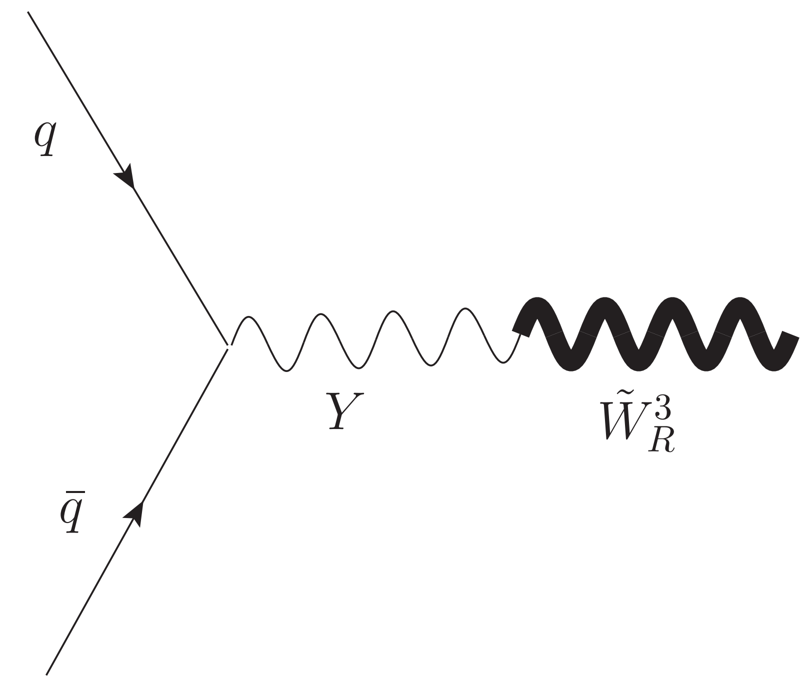


- SM singlet neutrino couples to both $\tilde{W}_R^3$ and $(B-L)$
- no analog in 4D LR model (only Z')

[Also in Low, Tesi, Wang (2015)]

(B - L) striking…

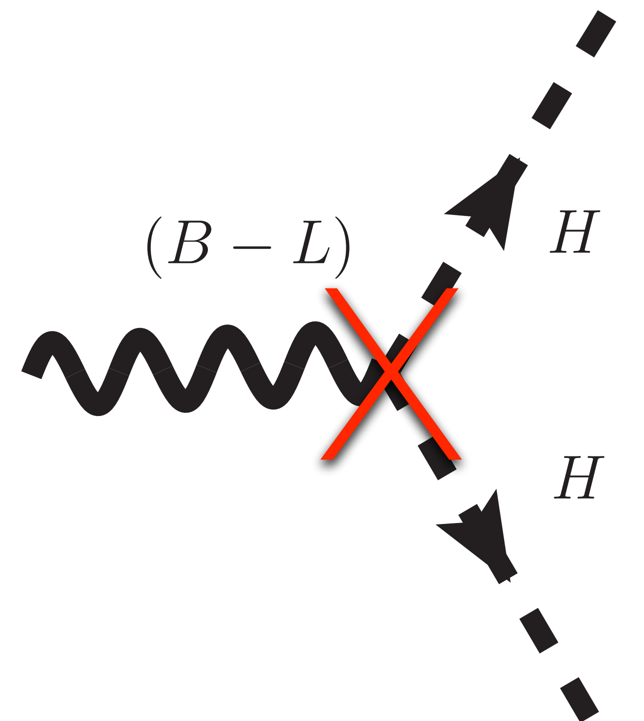
…maybe what’s going on at weak scale?!

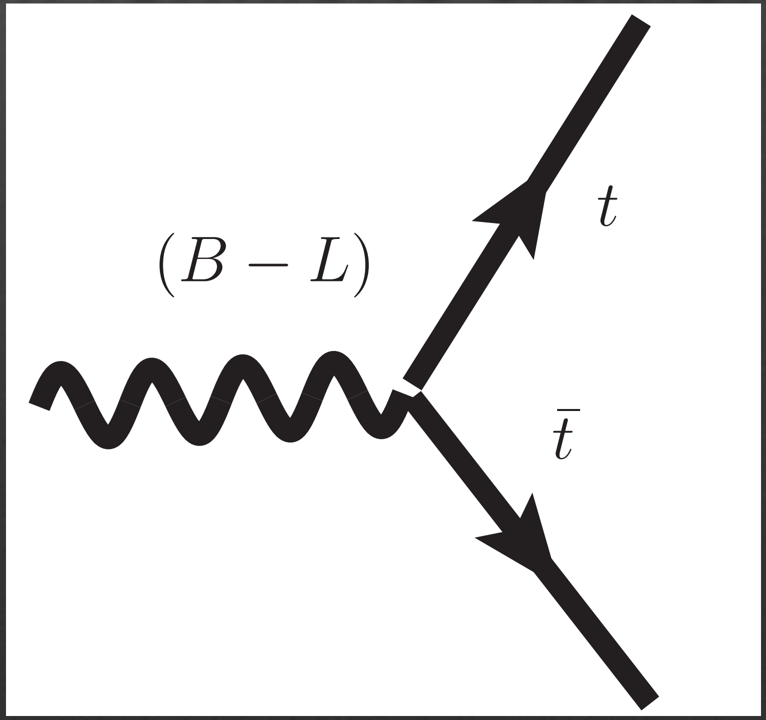
Only spin-1 signal: no charged counterpart

- Light $(B-L)$ ($\lesssim 2\ \mathrm{TeV}$): allowed by LHC direct searches (hypercharge coupling to light quarks via elementary-composite mixing) and EW precision tests (does not couple to EWSB)
- Others heavier ($\gtrsim 4\ \mathrm{TeV}$): production at LHC negligible
- 4D LR: see $W_R^{\pm}\ before\ Z'$

No (direct) decay di-boson, di-top BR suppressed (other SM fermions negligible)

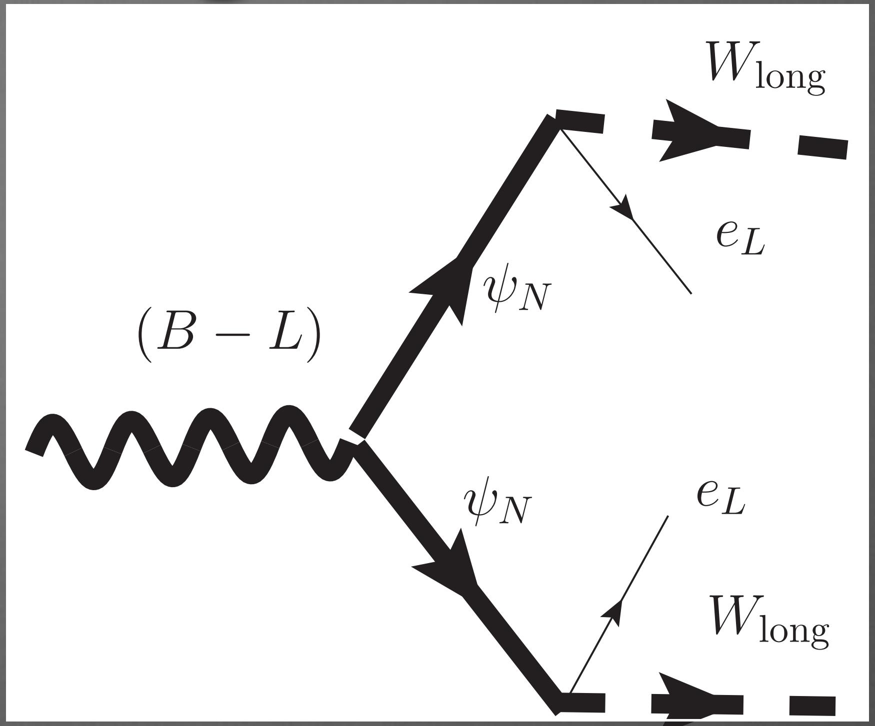
- $(B-L)$ does not couple of Higgs (including W/Z_{long})
- 4D LR: both $W_R^{\pm}$ and Z' decay into dibosons
- singlet neutrinos have larger charge and multiplicity than (composite) top (other SM fermions elementary)



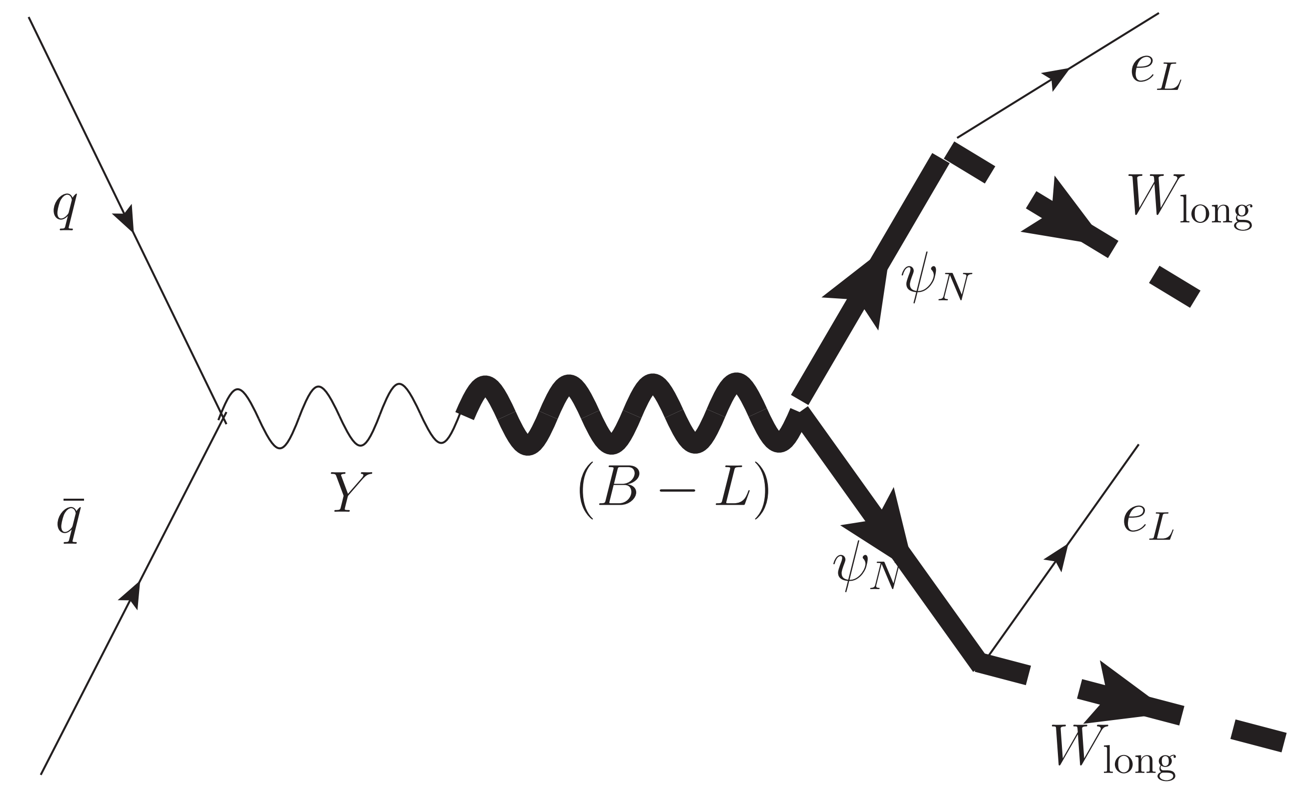


Discover via **singlet neutrino**

- decays like Z':



- overall process:

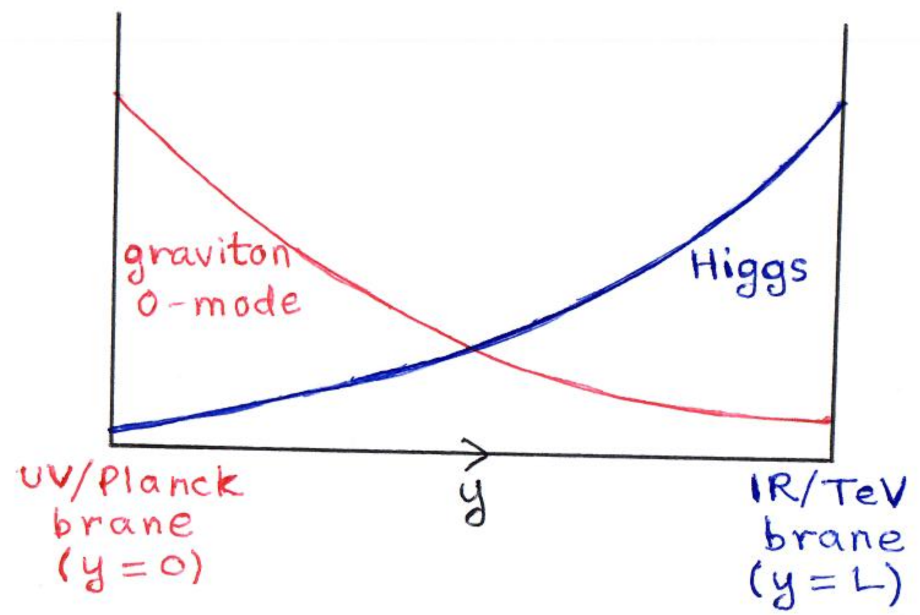


- 3-5 σ with 3000/fb for 2 TeV composite (B-L) and 750 GeV ψ_N

Basics of Warped Extra Dimension

Planck-weak hierarchy

[Randall, Sundrum, (1999)]



- **master formula:** $M_{\rm 4D}^{\rm eff}(y) \sim \boxed{e^{-ky}}\, M_{\rm 5D}^{\rm fund}$

warp factor

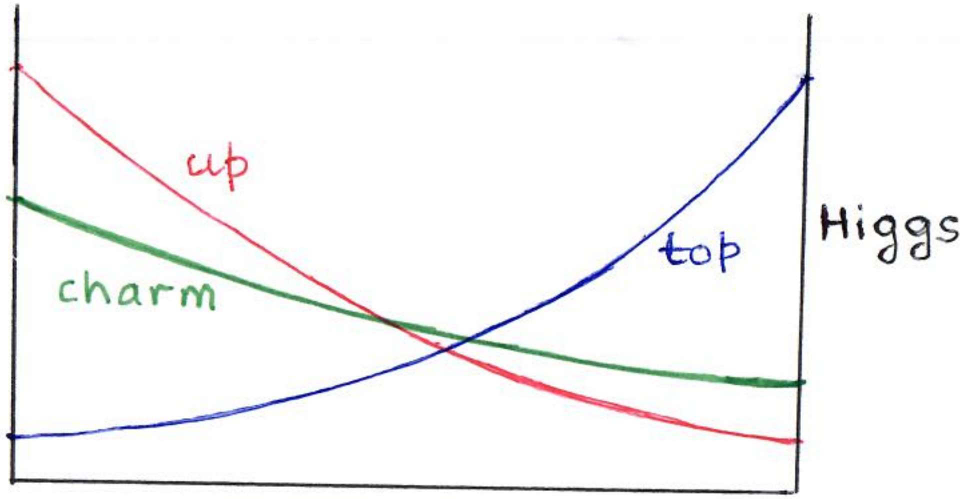
- **RS1:**

4D gravity (zero-mode graviton):
$y \sim 0 \Rightarrow M_{\rm 4D}^{\rm eff} \sim M_{\rm 5D}^{\rm fund}$
$\Rightarrow$ choose $M_{\rm 5D}^{\rm fund} \sim M_{\rm Pl}$

Weak scale/Higgs mass:
$y \sim L \Rightarrow M_{\rm 4D}^{\rm eff} \sim e^{-kL} M_{\rm 5D}^{\rm fund}$
$\Rightarrow$ choose $kL \sim 30$
(*mild* hierarchy, with $k \sim M_{\rm 5D}^{\rm fund}$)

4D Flavor hierarchy from 5D anarchy

[Grossman, Neubert (1999); Gherghetta, Pomarol (2000)]



SM particles are zero-modes of 5D fields

- Coupling of modes $\propto$ overlap of profiles (in general)

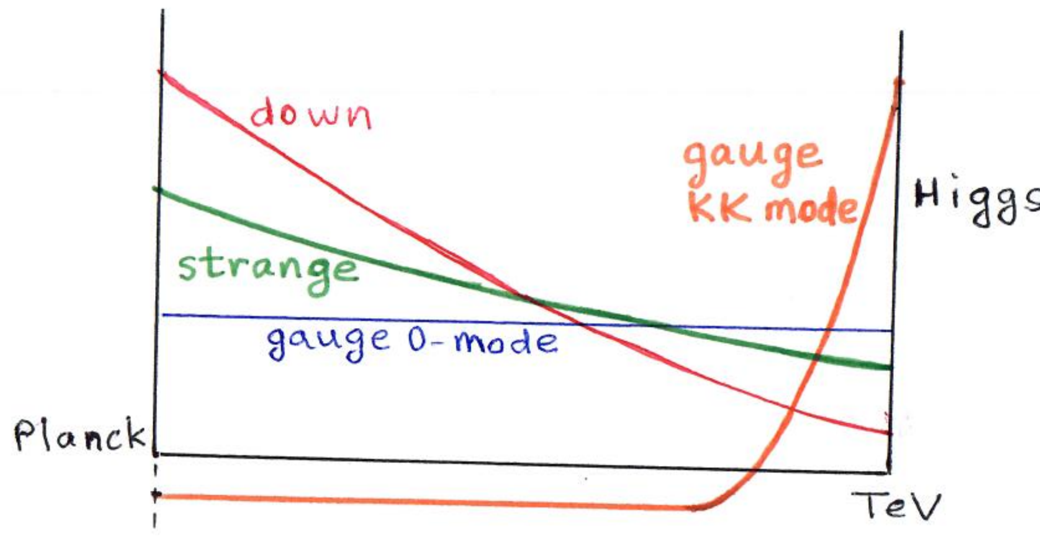
  $\text{profile of zero-mode fermion} \propto e^{-cky}$ $(ck$ is 5D mass parameter$)$

- Small variation in c suffices (5D Yukawa non-hierarchical):

  $$c > 1/2 \text{ for up, charm vs. } c < 1/2 \text{ for top}$$

Flavor/CP violation tests

[Gherghetta, Pomarol (2000); Huber, Shafi (2000); Huber (2003); KA, Perez, Soni (2004)]



- RS-GIM mechanism (flavor violation from KK $\propto$ quark masses)
- bound (much) weaker than generic $\sim O(10^5)$ TeV
- still $\sim O(10)$ TeV [Csaki, Falkowski, Weiler (2008); Buras et al. (2008); Bauer et al.]
- ameliorated by flavor symmetries: a few TeV allowed…

EW precision tests

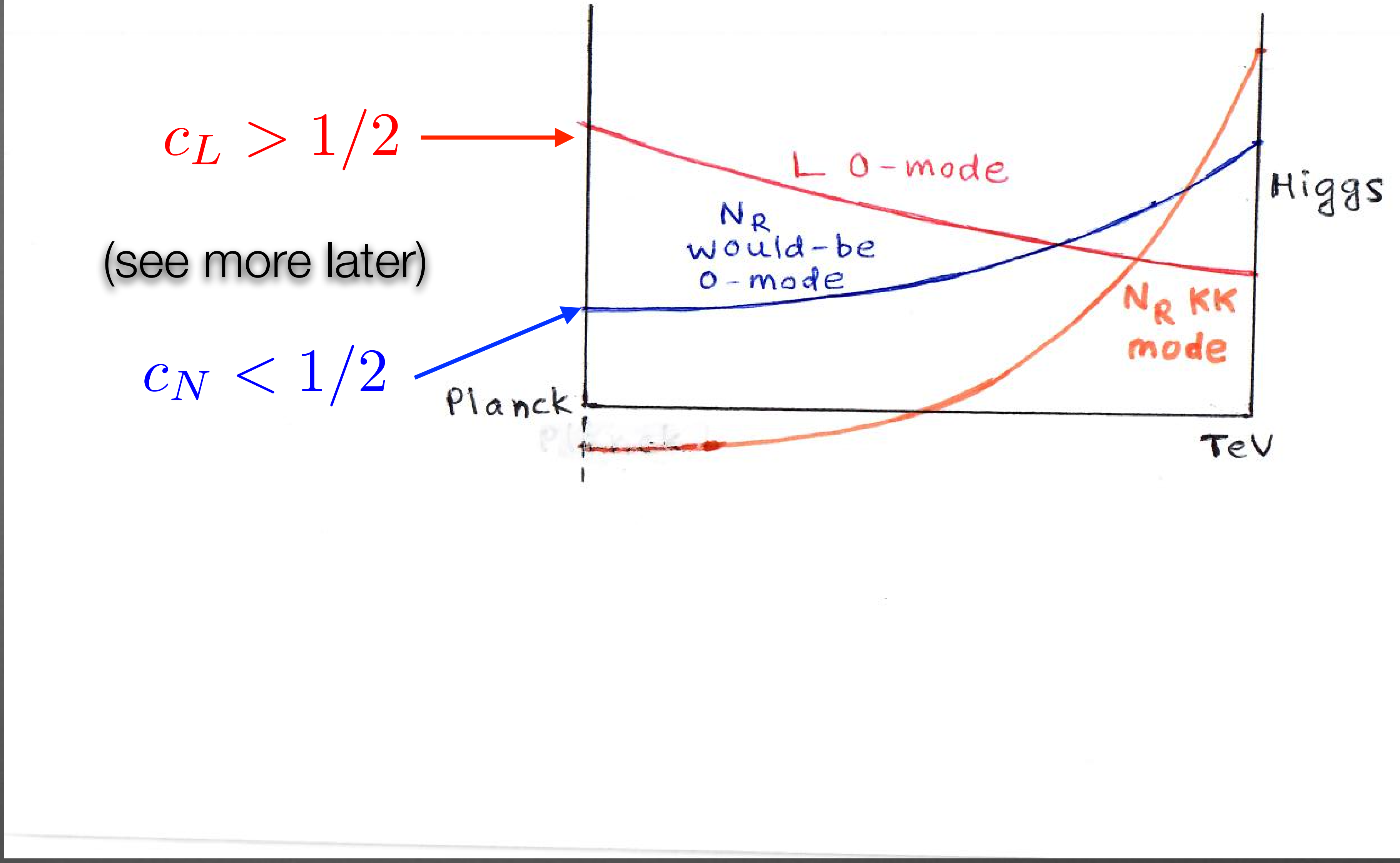
- Vanilla model: $\sim$ 5-10 TeV (from $\Delta\rho$ and $Zb\bar{b}$)
- custodial symmetries [KA, Delgado, May, Sundrum (2003); KA, Contino, Da Rold, Pomarol (2006)] relax it to $\sim$ 3 TeV [Carena et al, (2006); Delaunay et al. (2010)]

(assume a few TeV KK scale from here on)

Neutrino mass

KK basis: definition

- KK decomposition without Majorana mass term (familiar/ convenient)



- add effect of Majorana mass term: lifts (would-be) zero-mode and mixes all

KK/Dirac

from EWSB

$$\mathcal{L}_{\rm mass} = \sum_{n=1,2\ldots} m_n N_L^{(n)} N_R^{(n)} + \sum_{m=0,1\ldots} m_D^{(0,m)} \nu_L^{(0)} N_R^{(m)} + \sum_{n,m=0,1,2\ldots} \frac{1}{2} M_N^{(n,m)} \overline{\left[N^{(n)\,c}\right]_L} N_R^{(m)} + \text{h.c.}$$

Majorana

$$M_N^{(n,m)} \sim M_N^{\rm UV} \times \left(\text{profile of } n^{\rm th} \text{ mode}\right)\big|_{\rm UV} \times \left(\text{profile of } m^{\rm th} \text{ mode}\right)\big|_{\rm UV}$$

KK basis: SM neutrino mass (general)

- Even if not mass basis, can still use EOM (since heavy: $\gtrsim$ TeV)

$$\text{EOM for } N_L^{(n\neq 0)} \Rightarrow N_R^{(n\neq 0)} = 0$$

$$\text{EOM for } N_R^{(0)} \Rightarrow N_R^{(0)} = \nu_L^{(0)} \frac{m_D^{(0,0)}}{M_N^{(0,0)}}$$

(like usual seesaw)

- Plug back into Lagrangian:

$$\mathcal{L} \ni -\frac{1}{2} \frac{\left[m_D^{(0,0)} \right]^2}{M_N^{(0,0)}} \overline{\nu_L^{(0)}} \left[\nu^{(0)\ c} \right]_R$$

- general form: $m_\nu \equiv \dfrac{m_D^{\text{eff } 2}}{M_N^{\text{eff}}}$

KK basis: SM neutrino mass (specific)

- Modulation of Dirac and Majorana mass terms by profiles:

doublet profile at IR

for charged lepton mass

$$m_D^{\rm eff}\left[=m_D^{(0,0)}\right] \sim Y_5 v \left(\frac{\rm TeV}{M_{\rm Pl}}\right)^{c_L-\frac{1}{2}} \qquad \text{for } c_L > \frac{1}{2} \text{ and } c_N < \frac{1}{2}$$

$$M_N^{\rm eff}\left[=M_N^{(0,0)}\right] \sim M_N^{\rm UV} \times \left(\frac{\rm TeV}{M_{\rm Pl}}\right)^{1-2\,c_N} \qquad \text{for } c_N < \frac{1}{2}$$

singlet profile at UV

- **Observed** $[m_\nu \sim O(0.1)\ \text{eV}]$ *naturally*
  for $c_N \sim 0.3;\ c_L \sim 0.6$ and $M_N^{\rm UV} \sim M_{\rm Pl}$
  $[m_D^{\rm eff} \sim O(10)\ \text{GeV and } M_N^{\rm eff} \sim O\left(10^{12}\right)\ \text{GeV}]$

KK basis: high-scale seesaw?

- only singlet (would-be) zero mode with super-large (Majorana) mass term contributes
  “looks like” high-scale seesaw?
  physics of neutrino mass generation out of reach?
- …but, not mass basis: (would-be) zero-mode mixes with KK…
- physical/dynamical picture obscured: more to it than meets the eye?

…On to Mass basis for Singlet Modes

- for on-shell production (colliders or early universe, e.g., leptogenesis)
- can try diagonalization from KK basis, but ∞ -dimensional matrix (see back-up for toy model)
- or include Majorana mass term from get-go (as part of boundary condition) [KA, Hong, Vecchi (2015)]: tedious/not insightful
- simpler/intuitive picture using AdS/CFT duality [KA, Hong, Vecchi (2015)]

Diagonalization of KK basis

Basic set-up

- Singlet (only) zero and KK modes

Majorana

$$\mathcal{L} \ni M_N^{(0,0)} \left[N^{(0)\,c}\right]_L N_R^{(0)} + M_N^{(0,1)} \left[N^{(0)\,c}\right]_L N_R^{(1)} + M_N^{(1,1)} \left[N^{(1)\,c}\right]_L N_R^{(1)} + m_1 \overline{N_L^{(1)}} N_R^{(1)}$$
$$+ \text{ h.c. (as appropriate)}$$

KK/Dirac

- matrix form:

$$\left(\overline{\left[N^{(0)\,c}\right]_L} \quad \overline{\left[N^{(1)\,c}\right]_L} \quad \overline{N_L^{(1)}} \right) \begin{pmatrix} M_N^{(0,0)} & M_N^{(0,1)} & 0 \\ M_N^{(0,1)} & M_N^{(1,1)} & m_1 \\ 0 & m_1 & 0 \end{pmatrix} \begin{pmatrix} N_R^{(0)} \\ N_R^{(1)} \\ \left[N^{(1)\,c}\right]_R \end{pmatrix}$$

Relations between Majorana mass terms for zero and KK modes

- due to Majorana mass term for 5D field only on Planck/UV brane:

$$M_N^{(n,m)} \quad \sim \quad M_N^{\rm UV} \times \left(\text{profile of } n^{\rm th} \text{ mode}\right)\big|_{\rm UV} \times \left(\text{profile of } m^{\rm th} \text{ mode}\right)\big|_{\rm UV}$$

$$M_N^{(n,m)} \; M_N^{(p,q)} \quad = \quad M_N^{(n,q)} \; M_N^{(p,m)}$$

e.g., $M_N^{(0,0)} M_N^{(1,1)} \quad = \quad \left[M_N^{(0,1)}\right]^2$

Diagonalizing Majorana part

- One zero eigenvalue (`light”) and the other is trace (heavy)

$$\begin{aligned} N_R^{\text{heavy}} &= \cos\theta^{(0,1)} N_R^{(0)} + \sin\theta^{(0,1)} N_R^{(1)}, \text{ eigenvalue} = \left[M_N^{(0,0)} + M_N^{(1,1)}\right] \\ N_R^{\text{light}} &= \cos\theta^{(0,1)} N_R^{(1)} - \sin\theta^{(0,1)} N_R^{(0)}; \text{ eigenvalue} = 0 \end{aligned}$$

where $\sin\theta^{(0,1)} = \sqrt{\frac{M_N^{(1,1)}}{M_N^{(0,0)} + M_N^{(1,1)}}}$

- Re-write full Lagrangian in terms of Majorana mass eigenstates:

$$\mathcal{L} \ni \left[M_N^{(0,0)} + M_N^{(1,1)}\right] \overline{(N^{\text{heavy c}})_L} N_R^{\text{heavy}} + m_1 \sin\theta^{(0,1)} \overline{N_L^{(1)}} N_R^{\text{heavy}} + m_1 \cos\theta^{(0,1)} \overline{N_L^{(1)}} N_R^{\text{light}}$$

KK mass term mixes heavy and light

EWSB mass terms: general form

- KK basis:

$$\mathcal{L}_{\text{EWSBmass}} \quad = \quad \overline{\nu_L^{(0)}}\left[m_D^{(0,0)} N_R^{(0)} + m_D^{0,1)} N_R^{(1)}\right]$$

- Majorana-diagonal basis:

$$\mathcal{L}_{\text{EWSBmass}} \quad = \quad \overline{\nu_L^{(0)}}\Big[\left(\cos\theta^{(0,1)} m_D^{(0,0)} + \sin\theta^{(0,1)} m_D^{(0,1)}\right) N_R^{\text{heavy}} + \left(\cos\theta^{(0,1)} m_D^{(0,1)} - \sin\theta^{(0,1)} m_D^{(0,0)}\right) N_R^{\text{light}}\Big]$$

EWSB mass terms: N_R^{heavy} decouples

- Dirac mass terms from profiles on IR brane:

$$\frac{m_D^{(0,1)}}{m_D^{(0,0)}} \sim \frac{(\text{profile of 1st KK mode})|_{\text{IR}}}{(\text{profile of zero mode})|_{\text{IR}}}$$

$$\sim \begin{cases} \frac{1}{\sqrt{c_N - \frac{1}{2}}} \left(\frac{\text{TeV}}{M_{\text{Pl}}}\right)^{\frac{1}{2} - c_N}, & \text{for } c_N > 1/2 \\ \frac{1}{\sqrt{\frac{1}{2} - c_N}}, & \text{for } c_N < 1/2 \end{cases}$$

- Profiles on UV brane (gives singlet mixing angle):

$$\sqrt{\frac{M_N^{(1,1)}}{M_N^{(0,0)}}} \sim \begin{cases} \sqrt{c_N - \frac{1}{2}} \left(\frac{\text{TeV}}{M_{\text{Pl}}}\right)^{c_N - \frac{1}{2}}, & \text{for } c_N > 1/2 \\ \sqrt{\frac{1}{2} - c_N}, & \text{for } c_N < 1/2 \end{cases}$$

- Relation between above two ratios →

$$m_D^{(0,0)} \sim \textit{negative} \text{ of } \sin\theta^{(0,1)} m_D^{(0,1)}$$

→ N_R^{heavy} decouples from doublet

Integrating out N_R^{heavy} (still coupled via KK mass term to N_R^{light} !)

- pseudo-Dirac TeV-mass singlet + Dirac mass term with doublet

Dirac

Majorana

$$\begin{aligned}\mathcal{L} \;\ni\; & m_1 \cos\theta^{(0,1)}\, \overline{N_L^{(1)}}\, N_R^{\text{light}} + \frac{m_1^2 \sin^2\theta^{(0,1)}}{\left[M_N^{(0,0)} + M_N^{(1,1)}\right]}\, \overline{N_L^{(1)}} \left[N^{(1)\,c}\right]_R + \\ & \overline{\nu_L^{(0)}}\, N_R^{\text{light}} \left(\cos\theta^{(0,1)} m_D^{(0,1)} - \sin\theta^{(0,1)} m_D^{(0,0)}\right)\end{aligned}$$

EWSB

- …in agreement with CFT picture: $N_R^{\text{heavy}} \sim$ dual to elementary N_R

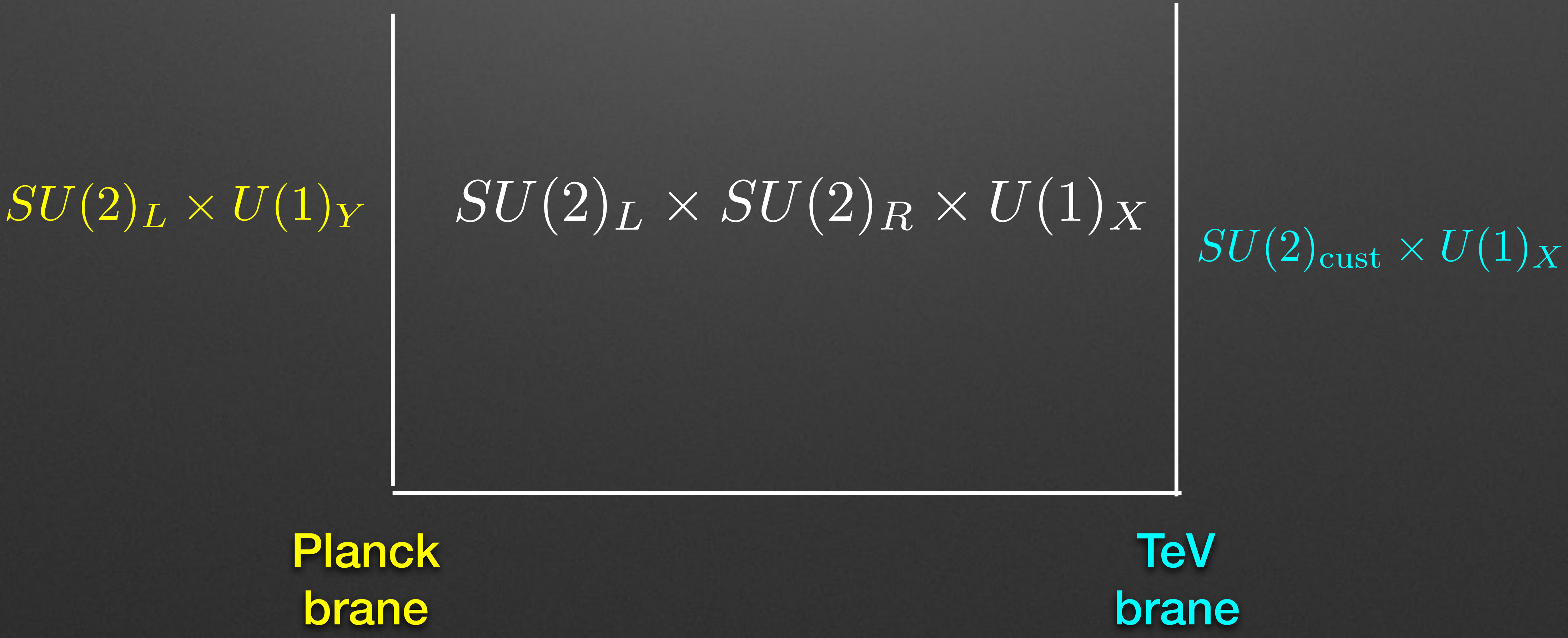
Custodial symmetry in 5D

- EW bulk gauge symmetry extended: $SU(2)_L \times SU(2)_R \times U(1)_X$
  (QCD also in bulk: neglect for leptonic sector here)
- On UV/Planck brane (by boundary condition):

$$SU(2)_R \times U(1)_X \to U(1)_Y$$

- On IR/TeV brane (by Higgs VEV):

$$SU(2)_L \times SU(2)_R \to SU(2)_{\rm cust}, \text{ with } U(1)_X \text{ unbroken}$$



$SU(2)_L \times U(1)_Y$

$SU(2)_L \times SU(2)_R \times U(1)_X$

$SU(2)_{\rm cust} \times U(1)_X$

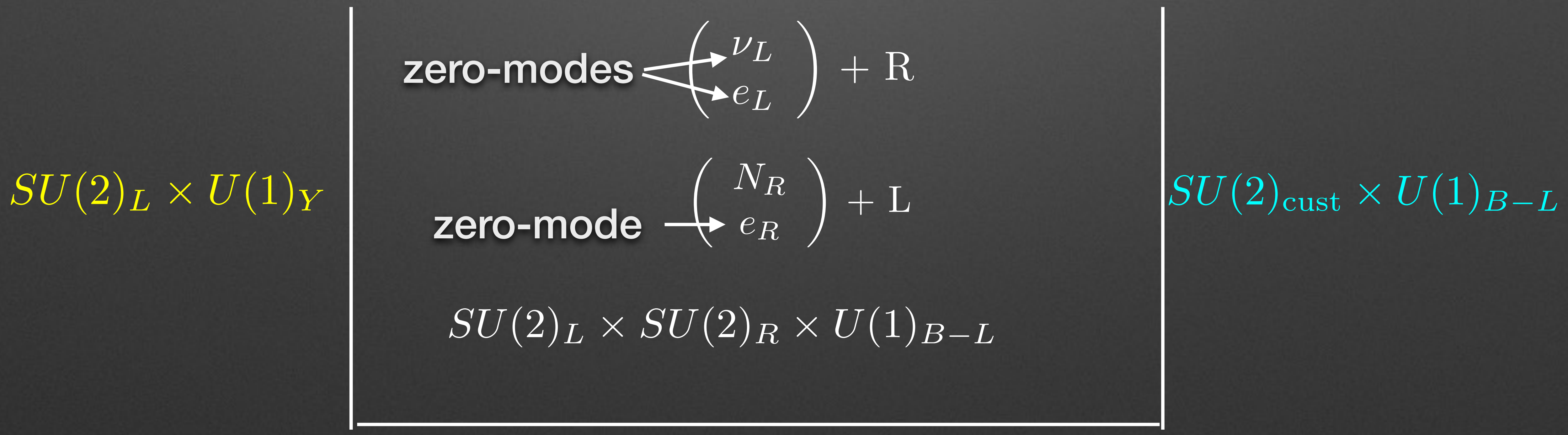
Planck brane

TeV brane

Simplest possibility: 2 X = (B - L)

- as in 4D LR symmetry models [$Y = T_{3R} + (B - L)/2$]:

SM L_L is zero-mode of 5D $L \sim (2,1)_{-1}$
SM e_R is zero-mode of 5D $e \in (1,2)_{-1} \Rightarrow$
$SU(2)_R$ *partner* of $e \sim N$ of 5D seesaw model ("built-in"):
SM gauge singlet
★ Majorana mass term only on UV/Planck brane
Yukawa with L_L



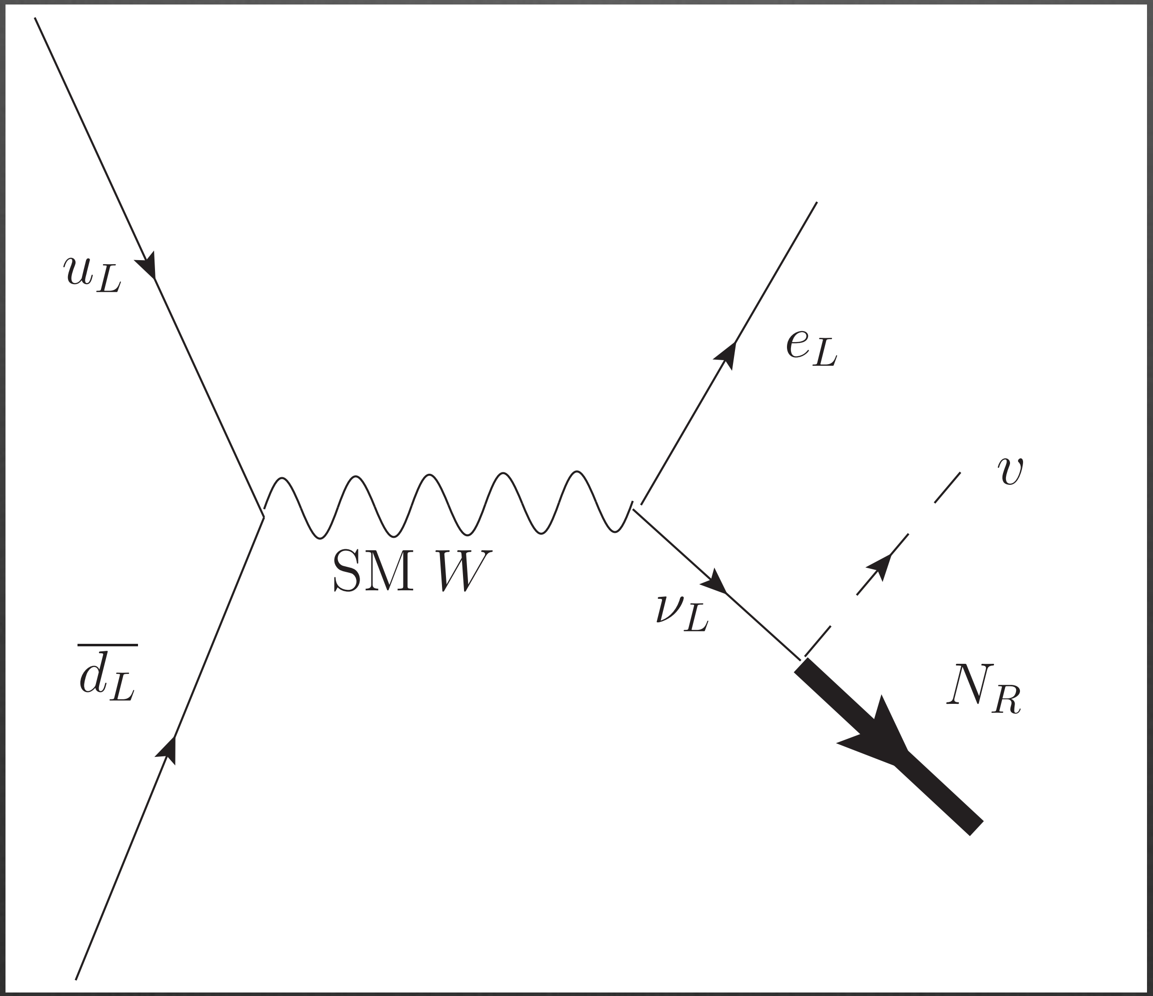
- N_R modes produced via **extra** gauge bosons, $W_R^{\pm}$ and Z'(?)

What if SM singlet neutrino also singlet of $SU(2)_R \times U(1)_X$?

...no $\tilde{W}_R^{\pm}$ or $(B-L)$ of before

4D option

- EWSB-induced mixing (same coupling as for SM neutrino mass) between doublet and singlet neutrinos
- SM W exchange
- …negligible for singlet neutrino mass $\gtrsim 500$ GeV



[For example, Das, Okada (2015)]

New in warped/composite model: singlet neutrinos from other spin 1/2 composites

Couplings at both ends are guaranteed

- (mandatory) composite $SU(2)_L$ doublet lepton (assumed heavy so far):

$$M_{\tilde{W}_L} \gtrsim 2\ M_{\psi_L} \gtrsim 2\ M_{\psi_{N,e}}$$

- production: elementary-composite mixing only
- decay: same Yukawa as for SM neutrino mass
- 3-5 σ with 3000/fb for 2.5 TeV composite W_L, 1 TeV ψ_L & 500 GeV ψ_N
- no analog in 4D LR model