

Title: PSI 2018/2019 - Beyond Standard Model - Lecture 5

Speakers: Latham Boyle

Collection: PSI 2018/2019 - Beyond Standard Model (Boyle)

Date: March 29, 2019 - 11:30 AM

URL: <http://pirsa.org/19030067>

spin 1:

G_m	W_m	B_m
$SU(3)$	$SU(2)$	$U(1)$

$$W_m^\pm = \frac{1}{\sqrt{2}}(W_m^1 \pm iW_m^2)$$

$$\begin{pmatrix} Z_m \\ A_m \end{pmatrix} = \begin{pmatrix} \cos \Theta_W & -\sin \Theta_W \\ \sin \Theta_W & \cos \Theta_W \end{pmatrix}$$

spin $\frac{1}{2}$:

q_L	3	2	$1/6$
u_R	3	1	$2/3$
d_R	3	1	$-1/3$
l_L	1	2	$-1/2$
ν_R	1	1	0
e_R	1	1	-1

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

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

spin 0:

h	1	2	$1/2$
$\tilde{h} = i\sigma^2 h^*$	1	2	$-1/2$

$$h = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\tilde{h} = \frac{1}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}$$

L_{SM}

$-\sin \Theta_W$
 $\cos \Theta_W$

$$\begin{aligned}
 \mathcal{L}_{SM} = & -\frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a - \frac{1}{4} W_{\mu\nu}^a W_{\mu\nu}^a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} \\
 & - (D_\mu h)^\dagger (D^\mu h) + m^2 (h^\dagger h) - \frac{\lambda}{4} (h^\dagger h)^2 \\
 & + i [\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + \bar{e}_R \not{D} e_R] \\
 & - [\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \hat{h} u_R + \bar{l}_L y_e h e_R + \text{h.c.}]
 \end{aligned}$$

Bo

$$L_{SM} = -\frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a - \frac{1}{4} W_{\mu\nu}^a W_{\mu\nu}^a - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$- (D_\mu h)^\dagger (D^\mu h) + m^2 (h^\dagger h) - \frac{\lambda}{4} (h^\dagger h)^2$$

$$+ i [\bar{q}_L \not{D} q_L + \bar{u}_R \not{D} u_R + \bar{d}_R \not{D} d_R + \bar{l}_L \not{D} l_L + \bar{e}_R \not{D} e_R]$$

$$- [\bar{q}_L V_{CKM} y_d h d_R + \bar{q}_L y_u \hat{h} u_R + \bar{l}_L y_e h e_R + \text{h.c.}]$$

Bosonic
terms

fermionic
terms

$$h = 10 - h \parallel \begin{pmatrix} 1 & 1 & 2 & -1/2 \end{pmatrix} \rightarrow h = \sqrt{2} (0)$$

SSB in Bosonic Sector:

$$SU(3) \times SU(2) \times U(1) = 8 + 3 + 1 = 12 \text{ dim}$$

4D sub-algebra acts on $h: \{Y, T_1, T_2, T_3\}$

1D sub-algebra annihilates $\langle h \rangle: Q = Y + T_3$

4 red

4 real comps of h : $\begin{cases} \rightarrow 3 \text{ Goldstones} \\ \rightarrow 1 \text{ Higgs boson } H \end{cases}$

4 gauge bosons: $\{W_\mu^1, W_\mu^2, W_\mu^3, B_\mu\}$ $\begin{cases} \rightarrow 3 \text{ massive: } W_\mu^\pm, Z_\mu \\ \rightarrow 1 \text{ massless: } A_\mu \text{ (photon)} \end{cases}$

spin 1:

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spin $1/2$:

spin 0:

$W_m^\pm = \frac{1}{\sqrt{2}}(W_m^1 \pm iW_m^2)$
 $\begin{pmatrix} \bar{z}_m \\ \bar{a}_m \end{pmatrix} = \begin{pmatrix} \cos \Theta_W & -\sin \Theta_W \\ \sin \Theta_W & \cos \Theta_W \end{pmatrix}$
 $q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$
 $l_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$
 $h = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$
 $\tilde{h} = \frac{1}{\sqrt{2}} \begin{pmatrix} v + H' \\ 0 \end{pmatrix}$

$L_{SM} = -\frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a - (D_\mu h)^\dagger (D_\mu h) + i[\bar{q}_L D_\mu q_L - \bar{l}_L D_\mu l_L] - \sqrt{2} \bar{h} V_\mu h$

h	1	2	$\frac{1}{2}$	$\rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v+H \\ 0 \end{pmatrix}$
$\tilde{h} = i\sigma^2 h^*$	1	2	$-\frac{1}{2}$	$\rightarrow \tilde{h} = \frac{1}{\sqrt{2}} \begin{pmatrix} v+H \\ 0 \end{pmatrix}$

SSB in Bosonic Sector:

$$SU(3) \times SU(2) \times U(1) = 8 + 3 + 1 = 12 \text{ dim}$$

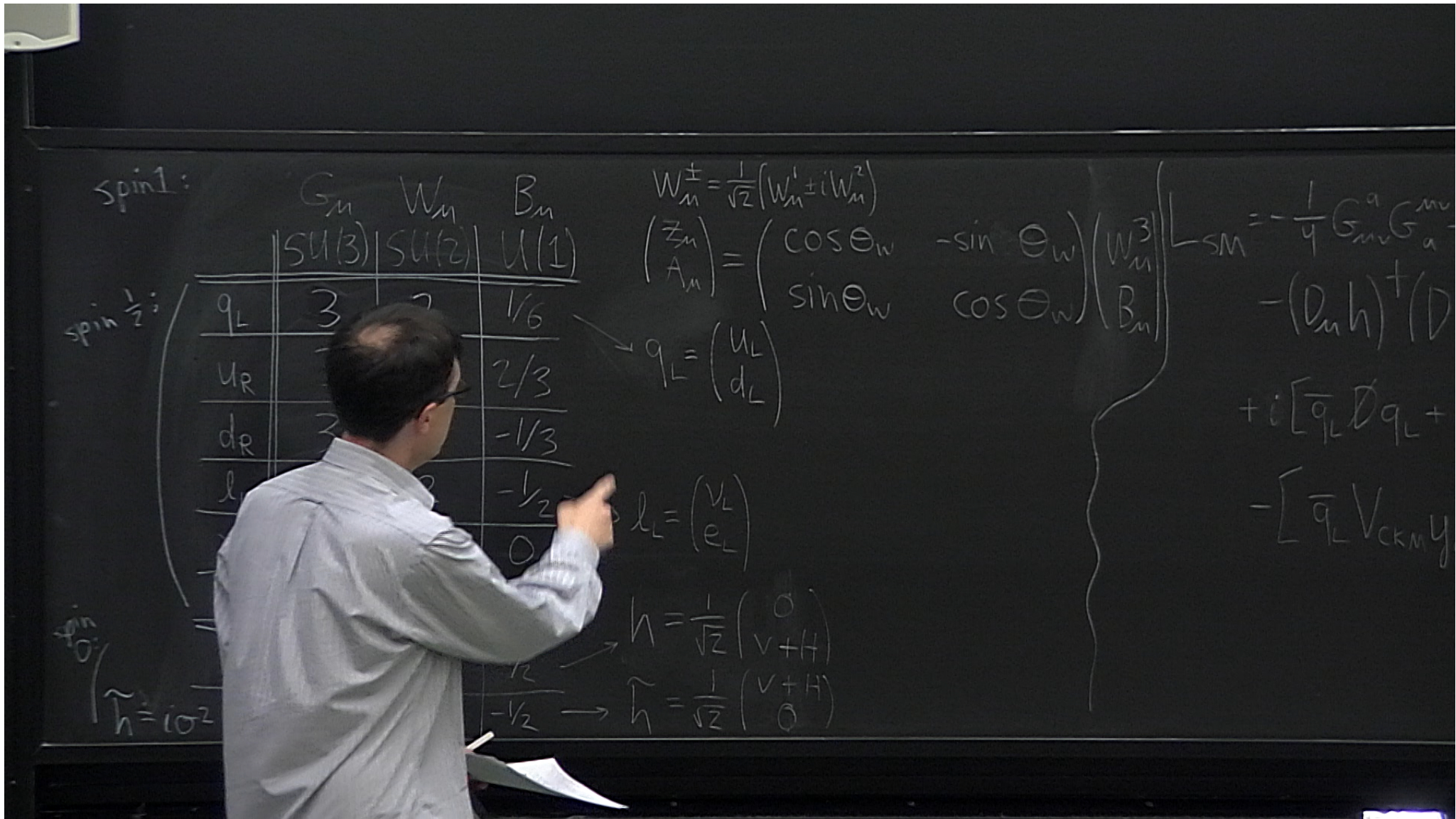
4D sub-algebra acts on h : $\{Y, T_1, T_2, T_3\}$

1D sub-algebra annihilates $\langle h \rangle$: $Q = Y + T_3$

$$\langle h \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

4 real comps

4 gauge b



Spin 1:

G_m W_m B_m
 $SU(3)$ $SU(2)$ $U(1)$

$$W_m^\pm = \frac{1}{\sqrt{2}}(W_m^1 \pm iW_m^2)$$

$$\begin{pmatrix} Z_m \\ A_m \end{pmatrix} = \begin{pmatrix} \cos \Theta_w & -\sin \Theta_w \\ \sin \Theta_w & \cos \Theta_w \end{pmatrix} \begin{pmatrix} W_m^3 \\ B_m \end{pmatrix}$$

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Spin $\frac{1}{2}$:

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e_R	1	1	-1

Spin 0:

$$\tilde{h} = i\sigma^2 h$$

$$\mathcal{L}_{SM} = -\frac{1}{4} G_{\mu\nu}^a G_{\mu\nu}^a - (D_\mu h)^\dagger (D_\mu h) + i[\bar{q}_L \not{D} q_L + \bar{l}_L \not{D} l_L] - [\bar{q}_L V_{CKM} q_R + \bar{l}_L V_{PMNS} l_R] + \dots$$

	1	-1
h	2	$1/2$
$i\sigma^2 h^*$	2	$-1/2$

 $\rightarrow h = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix}$
 $\rightarrow \hat{h} = \frac{1}{\sqrt{2}} \begin{pmatrix} v+H \\ 0 \end{pmatrix}$

$$-\frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - (D_\mu h)^\dagger (D^\mu h)$$

$$= \underbrace{-\frac{1}{4}W_{\mu\nu}^a W_a^{\mu\nu}}_{a=1,2} - \frac{1}{2}m_W^2 W_\mu^a W_a^\mu - \underbrace{\frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}m_Z^2 Z_\mu Z^\mu}_{m_Z = \frac{1}{2}(g_1^2 + g_2^2)^{1/2}V} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu}$$

$$m_W = \frac{1}{2}g_2 V$$

$$m_Z = \frac{1}{2}(g_1^2 + g_2^2)^{1/2} V$$

$$Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$$

spin 1:

spin $\frac{1}{2}$:

spin 0:

	G_m	W_m	B_m
	$SU(3)$	$SU(2)$	$U(1)$

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ν_R	1	1	0
e_R	1	1	0
h	1	1	0

$$\tilde{h} = i\sigma^2 h^*$$

$$W_m^\pm = \frac{1}{\sqrt{2}}(W_m^1 \pm iW_m^2)$$

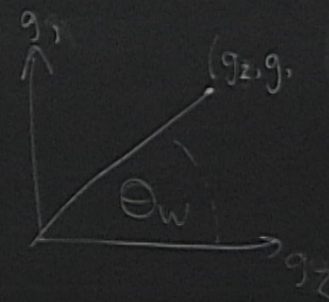
$$\begin{pmatrix} \bar{Z}_m \\ A_m \end{pmatrix} = \begin{pmatrix} \cos \Theta_w & -\sin \Theta_w \\ \sin \Theta_w & \cos \Theta_w \end{pmatrix} \begin{pmatrix} W_m^3 \\ B_m \end{pmatrix}$$

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

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$$h = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H \end{pmatrix}$$

$$\tilde{h} = \frac{1}{\sqrt{2}} \begin{pmatrix} v+H \\ 0 \end{pmatrix}$$



$$i[\bar{u}_L \not{\partial} u_L + \bar{d}_L \not{\partial} d_L + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R +$$

$$i[\bar{u}_L \not{\partial} u_L + \bar{d}_L \not{\partial} d_L + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R + \bar{\nu}_L \not{\partial} \nu_L + \bar{e}_L \not{\partial} e_L + \bar{e}_R \not{\partial} e_R]$$

$$- [\bar{d}_L V_{CKM} m_d d_R + \bar{u}_L m_u u_R + \bar{e}_L m_e e_R + \text{h.c.}]$$

$$m_d = \frac{V}{\sqrt{2}} y_d \quad m_u = \frac{V}{\sqrt{2}} y_u \quad m_e = \frac{V}{\sqrt{2}} y_e$$

$$i[\bar{u}_L \not{\partial} u_L + \bar{d}_L' \not{\partial} d_L' + \bar{u}_R \not{\partial} u_R + \bar{d}_R \not{\partial} d_R + \bar{\nu}_L \not{\partial} \nu_L + \bar{e}_L \not{\partial} e_L + \bar{e}_R \not{\partial} e_R]$$

$$- [\bar{d}_L' V_{CKM} m_d d_R + \bar{u}_L m_u u_R + \bar{e}_L m_e e_R + \text{h.c.}]$$

$$\bar{d}_L' \swarrow \\ m_d = \frac{V}{\sqrt{2}} y_d$$

$$\downarrow \\ m_u = \frac{V}{\sqrt{2}} y_u$$

$$m_e = \frac{V}{\sqrt{2}} y_e$$

$$\bar{d}'_L = \bar{d}_L V_{CKM}$$

$$d = \begin{pmatrix} d_R \\ d'_L \end{pmatrix}$$

$$u = \begin{pmatrix} u_R \\ u_L \end{pmatrix}$$

$$e = \begin{pmatrix} e_R \\ e_L \end{pmatrix}$$

$$i \left[\bar{u} \not{\partial} u + \bar{d} \not{\partial} d + \bar{e} \not{\partial} e + \bar{\nu}_L \not{\partial} \nu_L \right]$$

$$- \left[\bar{u} m_u u + \bar{d} m_d d + \bar{e} m_e e \right]$$

$[L, \bar{\psi} \psi]$

u, d, e, ν_L
massless

]

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u, d, e, ν_L
massless

$$- \left[\underbrace{\bar{u} m_u u}_{y_u H} + \underbrace{\bar{d} m_d d}_{y_d H} + \underbrace{\bar{e} m_e e}_{y_e H} \right]$$

$$i[\bar{u}\not{\partial}u + \bar{d}\not{\partial}d + \bar{e}\not{\partial}e + \bar{\nu}_L\not{\partial}\nu_L]$$

u, d, e, ν_L
massless

$$-[\bar{u}m_uu + \bar{d}m_dd + \bar{e}m_e e]$$

$y_u H$ $y_d H$ $y_e H$

d_L^i
 $d_L^{i'}$

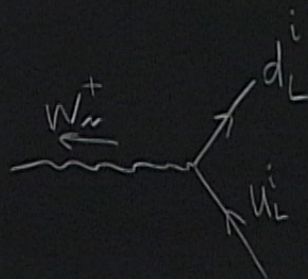
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$$i \bar{q}_L^i \not{D} q_L^i = i (\bar{u}_L \bar{d}_L) \left(\partial_\mu + i g_2 W_\mu^a \left(\frac{\sigma^a}{2} \right) \right) \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

d_L^i

$d_L^{i'}$



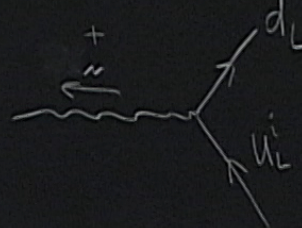
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d_L^i

$d_L^{i'}$

$$d_L^i = (V_{CKM})^i_{j'} d_L^{j'}$$


- i) predicts $m_\nu = 0$, don't oscillate. (expt disagrees)
- ii) no DM candidate
- iii) matter/anti-matter asymmetry.

(expt disagrees) {

- 1) only terms w/ $\dim \leq 4$.
- 2) only the fields in our table.

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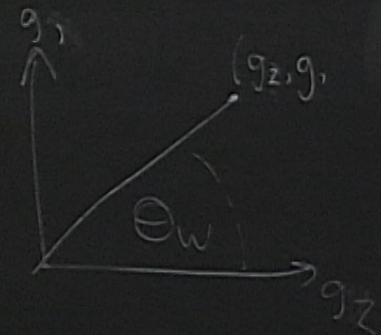
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Soln 1: 1) allow terms $\dim > 4$.

• SM EFT: leading BSM from $\dim 5$ (unique)

Soln 1: 1) allow terms $\dim > 4$.

- SM EFT: leading BSM from $\dim 5$ (unique)
- only solves mystery i)

Soln 2: 1) add ν_R

2) explains i) ii) iii)

3) recover Soln 1 when ν_R is heavy (see saw)

ii) no DM candidate

iii) ...

2) only the fit

$$\psi \rightarrow U\psi \quad \cancel{\psi^*} \quad \psi_c = -i\gamma^2 \psi^*$$

$$\gamma^2 = \begin{pmatrix} 0 & -\sigma^2 \\ \sigma^2 & 0 \end{pmatrix}$$

$$\psi_L = \begin{pmatrix} 0 \\ \vdots \end{pmatrix} \quad \psi_L^c = -i\gamma^2 \psi_L^* = \begin{pmatrix} \vdots \\ 0 \end{pmatrix}$$

$$\overline{\psi}_R \psi_L$$

$$\overline{\psi}_L^c \psi_L$$

$$\gamma^2 = \begin{pmatrix} 0 & -\sigma^2 \\ \sigma^2 & 0 \end{pmatrix}$$

$$\overline{\psi}_R \psi_L$$

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$$\tilde{h}_L^+$$

$$\frac{1}{2} + \frac{1}{2}$$

$$\psi_L \rightarrow$$

$$\psi_R \rightarrow$$