Dynamical symmetry breaking via multiple seesaw mechanisms

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based on PRD 95, 075033 (2017),

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Introduction

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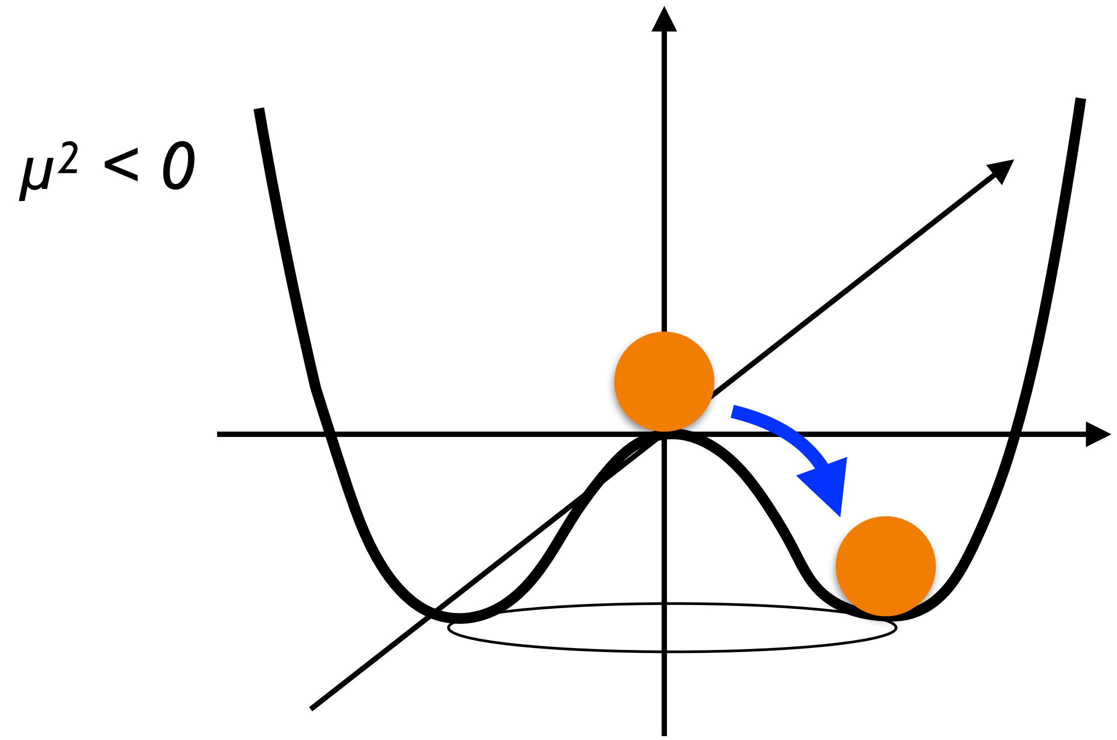
Higgs potential

✓ In the SM,

$$V = \mu^2 |H|^2 + \lambda |H|^4$$

VEV : $v^2 \sim -\mu^2/\lambda$

mass : $m_f \sim y_f v,\ m_V \sim g v,\ m_h^2 \sim \lambda v^2$



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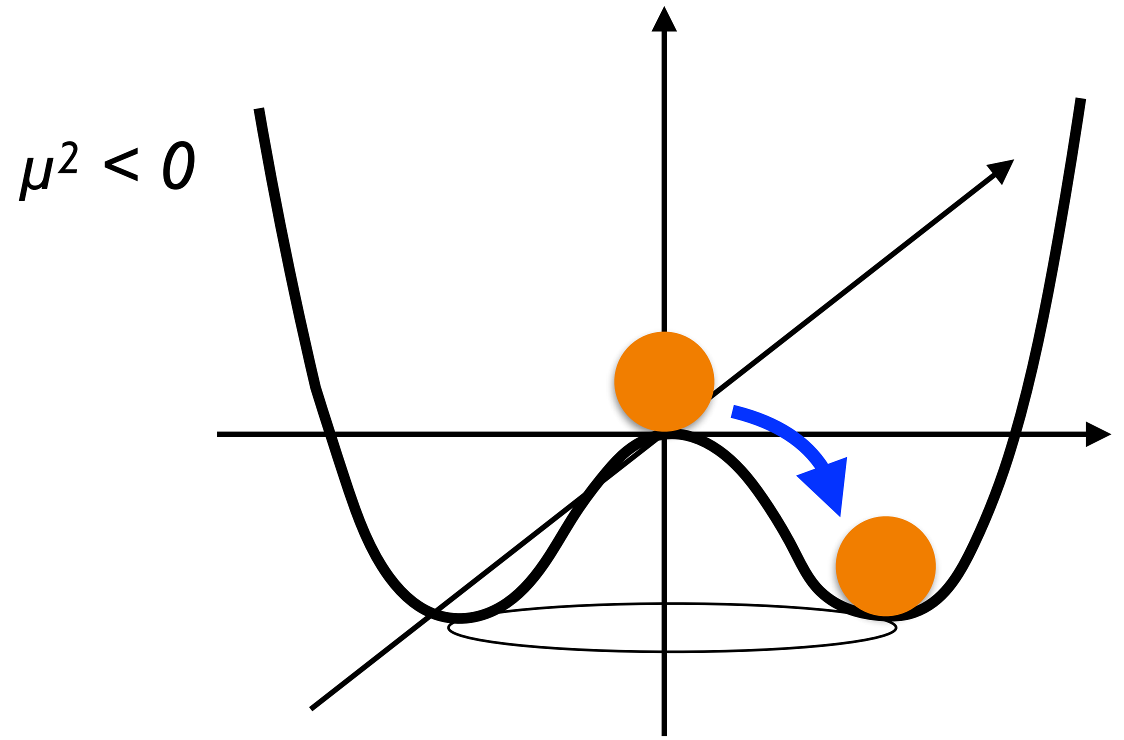

✓ it works well, but…it's tuning

$$1.\ |\mu^2| \ll \Lambda_{NP}^2$$

$$2.\ \mu^2 < 0$$

Classical scale invariance

✓ A simple way to avoid the tuning is to invoke classically scale invariance

(c.f. William A. Bardeen, '95, Summer Institute at Ontake)

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- related to Planck scale physics?
  - asymptotic safety of gravity *[Shaposhnikov-Wetterich, '10; Wetterich-Yamada, '17; etc.]*
  - multiple criticality point principle *[Froggatt-Nielsen, '95; Hamada-Kawai-Oda; etc.]*
  - solution to cosmological constant? *[Kugo's talk at Summer Institute 2017]*
  - etc.

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- ✓ How can we generate physical scale and retrieve the EWSB??

Scale generation in scale invariant theory

Scale invariance is broken at a quantum level and the scale is generated via

✓ Coleman-Weinberg mechanism *[Coleman and Weinberg, '73]*

- need bosonic d.o.f to directly generate EW scale *(e.g. Hashino et al., 1604.02069)*
- higher scale breaking triggers EW breaking *(e.g. Iso, Okada and Orikasa, 0909.0128; 0902.4050)*

  e.g.) a gauged U(1) extension at TeV scale

$$\mathcal{L} \supset \kappa|H|^2|\Phi|^2 \xrightarrow[\langle\Phi\rangle = v_\Phi]{} \kappa v_\Phi^2 |H|^2 \sim -\mu^2|H|^2$$

✓ Hidden strong dynamics *[Hur and Ko, 1103.2571; Holthausen, Kubo, Lim, Lindner, 1310.4423; Ametani, Aoki, Goto, Kubo, 1505.00128; etc.]*

- scale invariance is broken by the intrinsic strong scale
- "baryons" or "pions" can be dark matter as a bonus

$$\mathcal{L} \supset \bar{\psi}_i(i\not{D} - yS)\psi_i + \lambda_{HS}S^2|H|^2 \xrightarrow[\substack{\langle\bar{\psi}_i\psi_i\rangle \neq 0 \\ \langle S\rangle = v_S}]{} \lambda_{HS}v_S^2|H|^2 \sim -\mu^2|H|^2$$

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Bosonic seesaw mechanism

Haba, Kitazawa, Okada, '05; Calmet, '03; Kim, '05; Antipin, Redi, Strumia, '15; Haba, Ishida, Okada, Yamaguchi, '16; etc.

- Gauge group: $G = G_{SM} \times SU(N_{HC})$
- HC quarks

$F_{L/R}$	$SU(N_{\rm HC})$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$\chi = (\chi_1, \chi_2)^T$	$N_{\rm HC}$	1	2	$1/2 + q$
ψ	$N_{\rm HC}$	1	1	q

$$-\mathcal{L}_{\rm yukawa} = y(\overline{\chi} H \psi + h.c.)$$

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At E < Λ_{HC} scale,

$$\Theta \sim \overline{\psi}\chi = (2, 1/2)$$

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negative!

$$\approx \begin{pmatrix} H_1^\dagger & H_2^\dagger \end{pmatrix} \begin{pmatrix} -y^2\Lambda_{HC}^2 & 0 \\ 0 & \Lambda_{HC}^2 \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix} \qquad (y \ll 1)$$

Multiple seesaw model

Model of multiple seesaws

Ishida, Matsuzaki, SO and Omura, 1701.00598

Gauge groups: $G = G_{SM} \times SU(3)_{HC} \times U(1)_{B\text{-}L}$

Hypercolor quarks

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$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
ψ_1	3	1	1	q	q'
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B-L Higgs

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B\text{-}L}$
ϕ	1	1	0	-2

Three right-handed neutrinos:

$$N_R^\alpha \ (\alpha = 1, 2, 3)$$

$$-\mathcal{L}_{yukawa} = y_H(\overline{\chi} H \psi_1 + h.c.) + y_\phi(\overline{\psi_2}\phi\psi_1 + h.c.) + y_N^{\alpha\alpha}(\phi \overline{N_R^{c\alpha}} N_R^\alpha + h.c.)$$

+ SM yukawas

$$V = \lambda_H (H^\dagger H)^2 + \lambda_\phi (\phi^\dagger \phi)^2 + \kappa_\phi (\phi^\dagger \phi)(H^\dagger H)$$

HC hadrons

Ishida, Matsuzaki, SO and Omura, 1701.00598

Below HC confinement scale, a lot of HC hadrons appear;

✓ **Table of HC mesons:**

$\mathcal{M} = \mathcal{S} + i\mathcal{P}$	constituent	$SU(2)_W$	$U(1)_Y$	$U(1)_{B\text{-}L}$
$(f_0^{\rm HC}, a_0^{\rm HC} + i\mathcal{P}_{a_0^{\rm HC}})_{ij}$	$\overline{\chi_i}\ \chi_j$	(1, 3)	0	0
$(\Theta_1 + i\mathcal{P}_{\Theta_1})_i$	$\overline{\psi_1}\ \chi_i$	2	1/2	0
$(\Theta_2 + i\mathcal{P}_{\Theta_2})_i$	$\overline{\psi_2}\ \chi_i$	2	1/2	2
$\Phi + i\mathcal{P}_\Phi$	$\overline{\psi_1}\ \psi_2$	1	0	-2
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$\Theta_1 \sim \overline{\psi_1}\chi = (2, 1/2, 0)$ $\Phi \sim \overline{\psi_1}\psi_2 = (1, 0, -2)$

EW Higgs-like B-L Higgs-like

Seesaws in EW and B-L sector

Ishida, Matsuzaki, SO and Omura, 1701.00598

- ✓ EW and B-L Higgs-like scalar mesons;

$$\Theta_1 \sim \overline{\psi_1}\chi = (2, 1/2, 0) \qquad \Phi \sim \overline{\psi_1}\psi_2 = (1, 0, -2)$$

- ✓ Bosonic seesaw in each sector

EW sector	B-L sector
$y_H(\overline{\chi}H\psi_1 + h.c.)$	$y_\phi(\overline{\psi_2}\phi\psi_1 + h.c.)$
⇩	⇩
$y_H\Lambda_{HC}^2(\Theta_1^\dagger H + h.c.) + \Lambda_{HC}^2\Theta_1^\dagger\Theta_1$	$y_\phi\Lambda_{HC}^2(\Phi^\dagger\phi + h.c.) + \Lambda_{HC}^2\Phi^\dagger\Phi$

$$\Rightarrow \quad \mathcal{M}_{EW/B\text{-}L}^2 = \begin{pmatrix} 0 & y_{H/\phi}\Lambda_{HC}^2 \\ y_{H/\phi}\Lambda_{HC}^2 & \Lambda_{HC}^2 \end{pmatrix}$$

Neutrino seesaw

Ishida, Matsuzaki, SO and Omura, 1701.00598

In neutrino sector, ordinary type-I seesaw mechanism operates

$$-\mathcal{L}_{M_\nu} = (y_\nu \overline{l_L} H N_R + h.c.) + y_N(\phi \overline{N_R^c} N_R + h.c.)$$

$$\Downarrow \quad \langle H \rangle = v_{EW}, \ \langle \phi \rangle = v_{B\text{-}L}$$

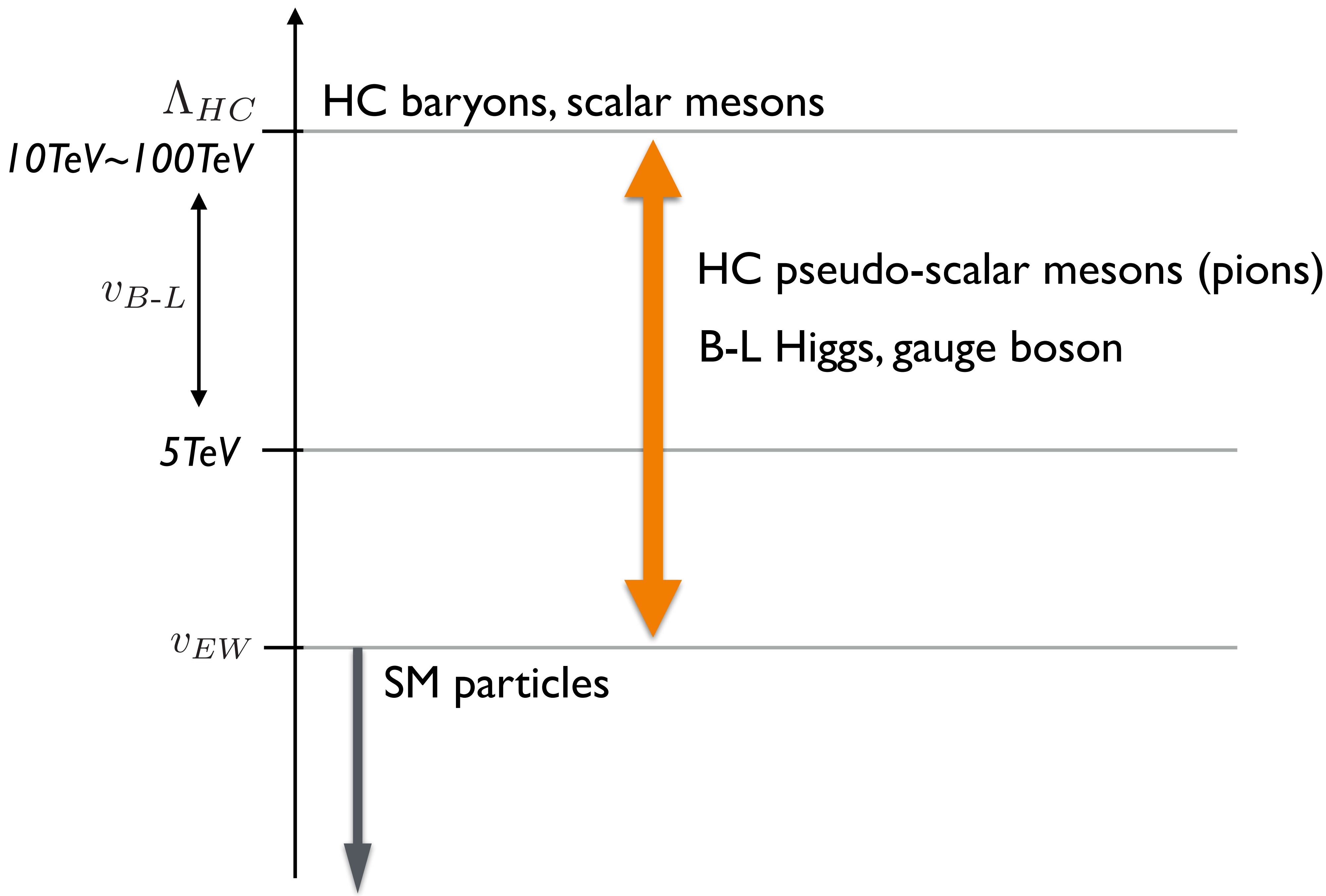
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & y_\nu v_{EW} \\ y_\nu^T v_{EW} & y_N v_{B\text{-}L} \end{pmatrix}$$

✓ active neutrino mass: $m_\nu \simeq y_\nu^2 v_{EW}^2 / y_N v_{B\text{-}L}$

$m_\nu = \mathcal{O}(0.1\text{eV}) \longrightarrow y_\nu = \mathcal{O}(10^{-5})$ *for* $v_{B\text{-}L} = \mathcal{O}(5\text{-}10\text{TeV}) = \mathcal{O}(\Lambda_{HC}),$
$y_N = \mathcal{O}(1)$

Phenomenology

Spectrum in multiseesaw model



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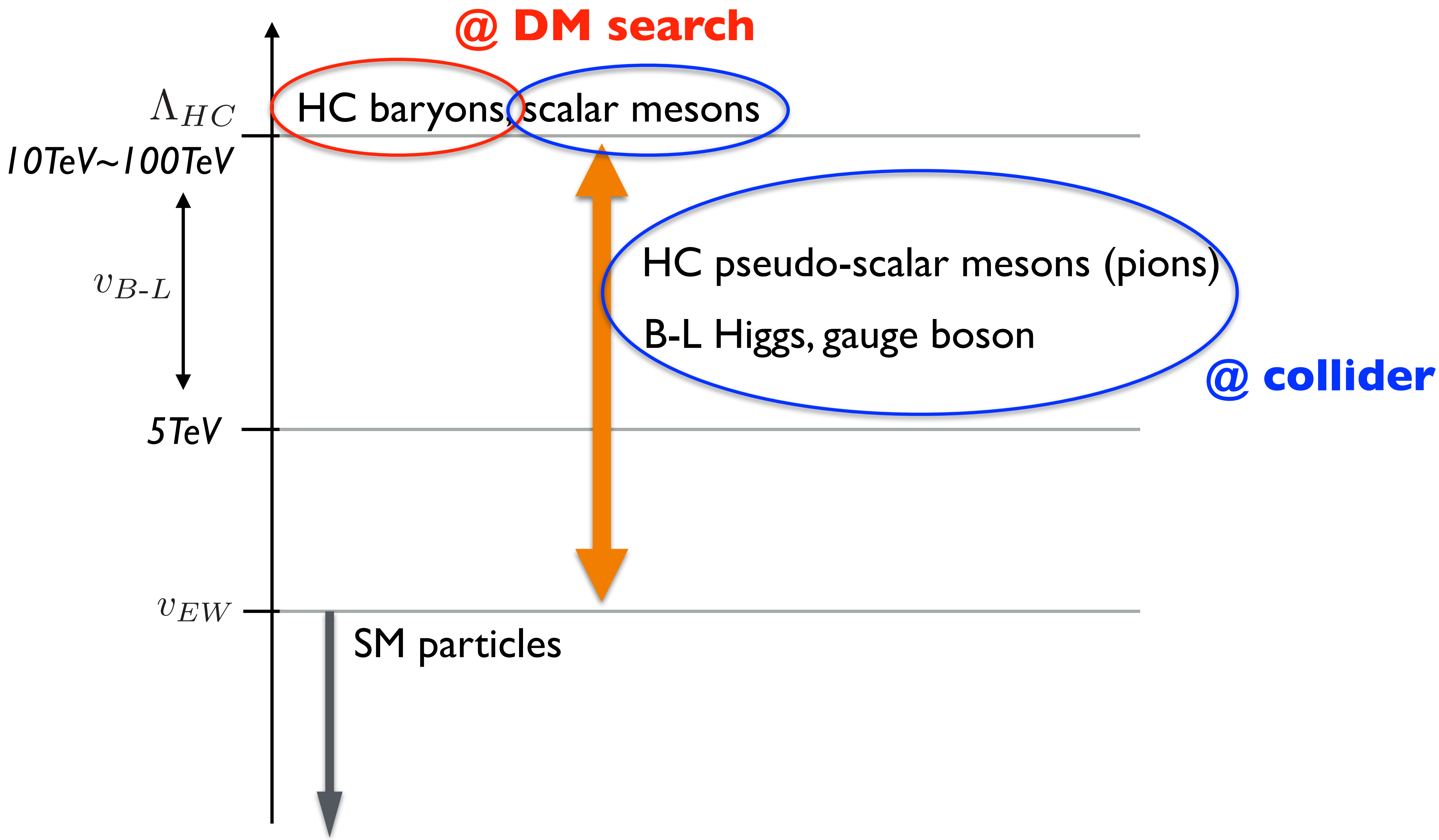

Collider search

✓ HC mesons:

- a HC meson looks like inert doublet Higgs at low energy
- however, it can decay to HC pions, subsequently decaying into dibosons etc.

[Ishida, Matsuzaki, Okawa, Omura, work in progress]

✓ B-L gauge:

- LEP constrains new physics contributions to four-fermi operators
- in particular, vector-type interaction is most severe

$$\mathcal{L}_{\rm eff} \supset \frac{c}{\Lambda^2}(\bar{f}\gamma_\mu f)(\bar{f}\gamma^\mu f) \Rightarrow \Lambda > \begin{cases} 6.12\ \mathrm{TeV} & (c=+1) \\ 5.64\ \mathrm{TeV} & (c=-1) \end{cases}$$

$\sim v_{B\text{-}L}$

[Carena, Daleo, Dobrescu, Tait, 0408098; Schael et al., 1302.3415]

Dark matter physics

DM candidate = HC baryons ~ FFF

$F_{L/R}$	$SU(3)_{\rm HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B\text{-}L}$
$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
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✓ If constituent HC fermions have electromagnetic charge, even the neutral baryons have large electromagnetic form factor

✓ There are two scenarios:
- HC baryon consists of charged HC fermions (q=-1/3)
- HC baryon consists of no charged HC fermions (q=0)

Dark matter physics

✓ **q=-1/3:**

- DM = neutral HC baryon consisting of charged HC fermion
- dominant DM-nuclei scattering is induced through magnetic moment operator
- bound (LUX): $m_{DM} \gtrsim 10 \text{ TeV}$

[Appelquist et al. (LSD collaboration), 1301.1693; Barbieri, Rychkov, Torre, 1001.3149; Banks, Fortin, Thomas, 1007.5515; etc.]

✓ **q=0:**

- neutral HC baryon consisting of ψ's is a DM candiate
- no large magnetic moment
- DM would show up in direct detection through B-L gauge boson exchanging

$$\frac{1}{v_{B\text{-}L}^2}(\bar{q}\gamma_\mu q)(\bar{\chi}\gamma^\mu \chi) \Rightarrow v_{B\text{-}L} > 5.1(4.3) \text{ TeV}$$ *for m_{DM}=5(10) TeV*

Summary

- **We study a (multiple) bosonic seesaw model for the dynamical EWSB:**
  - a new strongly coupled gauge sector, hypercolor (HC)
  - seesaw mechanism b/w an elementary Higgs and a HC meson
  - dynamically explains all of the masses (Higgs, RH neutrinos, etc.)

- **The model is testable:**
  - HC meson looks like inert Higgs boson, but is actually composite
  - neutral HC baryon = DM candidate with mass ~ O(5-10TeV)
  - etc.

Thanks for your attention