Dynamical scalegenesis via multiple seesaws

Shinya Matsuzaki

Department of Physics &
Institute for Advanced Research, Nagoya U.

Based on

Phys.RevD.95 (2017)
H.Ishida, S.M, S.Okawa, Y.Omura

and also
Phys.RevD.94(2016); 1610.07137,
H.Ishida, S.M, Y.Yamaguchi

@ PPP2017
07/31 - 08/04/2017

0. Introduction

☆ Discovery of Higgs boson in 2012

--- last piece of particles predicted in SM

--- very successful SM pheno. so far

☆ It's NOT the end of the story!...

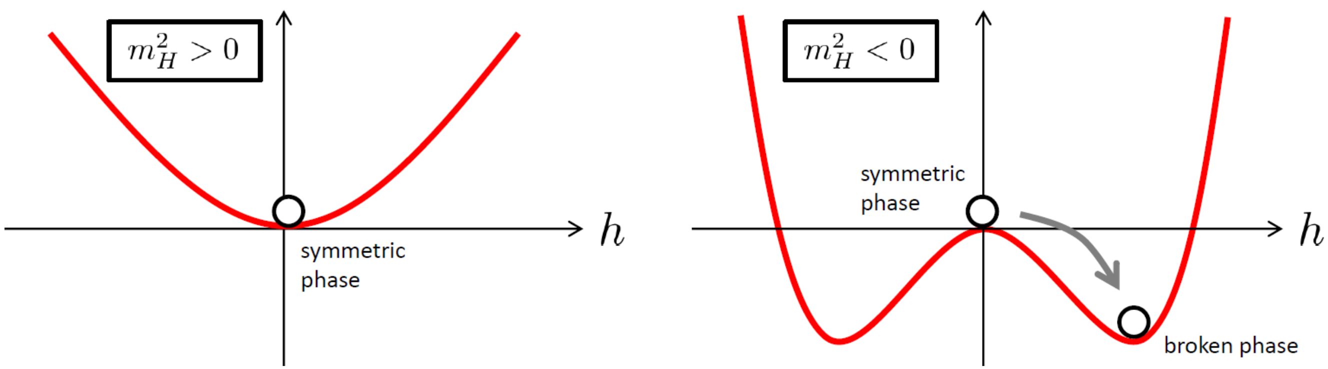
--- still lots of stuff left needed to account for

e.g. neutrino masses (mixing),
dark matter, baryon asymmetry, etc

☆ In particular,
unsatisfactory stuff on theoretical ground:

--- origin of mass is given "by hand"

Higgs potential: $V = \lambda_H (H^\dagger H)^2 + m_H^2 (H^\dagger H)$ $\quad H = (0, \frac{1}{\sqrt{2}}(v_H + h))^T$



--- why mH^2 <0 (dynamical origin?) and O(100 GeV)^2?
(related to gauge hierarchy problem)

--- No answer in SM

☆ Typical ideas to access the origin of mass
(or gauge hierarchy problem)

i) eliminate Higgs, replace fully by strong dynamics
e.g. Technicolor-like scenario

ii) protect Higgs by some symmetry
e.g. SUSY, composite Higgs, scale symmetry

☆ Typical ideas to access the origin of mass
(or gauge hierarchy problem)

Well… it's on break

i) eliminate Higgs, replace fully by strong dynamics
e.g. Technicolor-like scenario

ii) protect Higgs by some symmetry
e.g. SUSY, composite Higgs, scale symmetry

--- Today, let's take scale symmetry!
(classical scale-inv.)

☆ Then, how to generate “scales”, realize EWSB?

→ dimensional transmutation

i) Coleman-Weinberg mechanism

(Radiative sym. Breaking)

But, no way only within SM

(vacuum instability due to large top loop)

$$m^2_{h(125)} \sim \frac{1}{8\pi^2 v^2}(9m_W^4 - 12m_t^4)$$

--- Call for Beyond SM

☆ Then, how to generate "scales", realize EWSB?
→ dimensional transmutation

i) Coleman-Weinberg mechanism
(Radiative sym. Breaking)

Extensions w/ Higgs portal term

$$V = \kappa |\phi|^2 (H^\dagger H)$$

(a) κ = O(1), and >0; Φ loop effect included

-- assume Φ-symmetric phase: <Φ>=0
-- requires Φ mass > O(EW) or large # of Φ to stabilize EW vacuum:

$$m_\phi^2 \sim \kappa v^2 \qquad m^2_{h(125)} \sim \frac{1}{8\pi^2 v^2}(9m_W^4 - 12m_t^4 + N_\phi m_\phi^4)$$

K.Endo, et al (2016); K.Hashino, et al(2016)

☆ Then, how to generate "scales", realize EWSB?
→ dimensional transmutation

i) Coleman-Weinberg mechanism
(Radiative sym. Breaking)

Extensions w/ Higgs portal term

$$V = \kappa|\phi|^2(H^\dagger H)$$

(b) κ << O(1), and <0; Φ effect decoupled, but

-- if Φ is U(1)' (e.g. U(1)_B-L) charged,
then CW mechanism works for the U(1)' sector

-- nonzero Φ-VEV generates Higgs mass term <0,
triggers EWSB

$$V = -|\kappa|v_\phi^2(H^\dagger H)$$

S.Iso, et al (2009,2013); N.Okada, et al(2012,2016); I.Oda (2013); V.V.Khoze, et al(2013); M.Hashimoto, et al (2014); J.Guo, et al(2015)

☆ Then, how to generate “scales”, realize EWSB?

→ dimensional transmutation

ii) Strong gauge dynamics (hidden/dark QCD)

(nonperturbative sym. Breaking)

Extensions w/ Higgs portal term

$$V = \kappa|\phi|^2(H^\dagger H)$$

* κ <<O(1), and <0

* Φ = a scalar with strong coupling to hidden/dark QCD

--- below the dynamical scale, dark QCD generates scalar condensation:

$$\langle\phi^\dagger\phi\rangle \simeq \Lambda^2_{\rm dQCD}$$

$$\rightarrow V = -|\kappa|\Lambda^2_{\rm dQCD}(H^\dagger H)$$

F.Wilczek (2008); T.Hur, et al(2011); M.Holthausen, et al (2013); J.Kubo, et al(2014)

☆ Then, how to generate "scales", realize EWSB?

→ dimensional transmutation

iii) Strong gauge dynamics (vectorlike-SM gauging)

= vectorlike confinement (hypercolor: HC)

--- "bosonic seesaw mechanism"

N.Haba et al (2009,2016,2017); O.Antipin, et al (2015);
H.Ishida, S.M., Y.Yamaguchi (2016);
H.Ishida, S.M., S.Okawa, Y.Omura (2017)

Extensions w/ Yukawa term & HC fermions (F_{L/R})

$$\mathcal{L} = -y(\bar{\chi} H \psi) + \text{h.c.}$$

	$SU(N)_{\rm HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\chi_{L/R}$	N	1	2	1/2
$\psi_{L/R}$	N	1	1	0

N.Haba et al (2016,2017);
H.Ishida, S.M., Y.Yamaguchi (2016)

☆ Then, how to generate "scales", realize EWSB?

→ dimensional transmutation

iii) Strong gauge dynamics (vectorlike-SM gauging)

= vectorlike confinement (hypercolor: HC)

--- "bosonic seesaw mechanism"

N.Haba et al (2009,2016,2017); O.Antipin, et al (2015);
H.Ishida, S.M., Y.Yamaguchi (2016);
H.Ishida, S.M., S.Okawa, Y.Omura (2017)

Extensions w/ Yukawa term & HC fermions (F_{L/R})

$$\mathcal{L} = -y(\bar{\chi} H \psi) + \text{h.c.} \xrightarrow{@\Lambda_{\rm HC}} -\Lambda_{\rm HC}^2 (y \cdot \Theta^\dagger H + |\Theta|^2) + \cdots$$

	$SU(N)_{\rm HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$
$\chi_{L/R}$	N	1	2	1/2
$\psi_{L/R}$	N	1	1	0

$\Theta \sim \bar{\psi}\chi$ composite Higgs

$\Lambda_{\rm HC}$:

"chiral" $SU(3)_{F_{L/R}}$ breaking scale

N.Haba et al (2016,2017);
H.Ishida, S.M., Y.Yamaguchi (2016)

Slide of this part borrowed from Y.Yamaguchi

HC-quark condensate occurs at $\mu = \Lambda_{\rm HC}$.

⇨ $\langle \overline{F}F \rangle = \langle \overline{\chi}\chi \rangle = \langle \overline{\psi}\psi \rangle \neq 0$ $(\langle \overline{\chi}\psi \rangle = \langle \overline{\psi}\chi \rangle = 0$ by Vafa-Witten's theorem)

$\overline{\psi_L}\chi_R$ and $\overline{\psi_R}\chi_L$ couple to a composite Higgs doublet $\Theta \sim \overline{\psi}\chi$

Then, "bosonic seesaw mechanism" can work:

$$(H^\dagger,\ \Theta^\dagger) \begin{pmatrix} 0 & y\Lambda_{\rm HC}^2 \\ y\Lambda_{\rm HC}^2 & M_\Theta^2 \end{pmatrix} \begin{pmatrix} H \\ \Theta \end{pmatrix}$$

Classically scale invariance

HC-quark condensation

$$\approx \quad (H_1^\dagger,\ H_2^\dagger) \begin{pmatrix} -\frac{y^2}{M_\Theta^2}\Lambda_{\rm HC}^4 & 0 \\ 0 & M_\Theta^2 \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$$

where we have used $y << 1$. $(M_\Theta \simeq \Lambda_{\rm HC})$

Negative mass term is naturally generated: $m_H^2 \approx -\dfrac{y^2}{M_\Theta^2}\Lambda_{\rm HC}^4$

$$\approx -(y\Lambda_{\rm HC})^2$$

N.Haba et al (2009,2016,2017); O.Antipin, et al (2015);
H.Ishida, S.M., Y.Yamaguchi (2016);
H.Ishida, S.M., S.Okawa, Y.Omura (2017)

☆Constraint on scenarios of scalegenesis

~ asymptotic safety condition ~

-- scale/trace anomaly (quadratic, quartic divergence) should be generated at quantum level

-- which may, however, be cancelled by gravitational effects at Planck scale

M. Shaposhnikov, et al (2010); C. Wetterich, et al (2016); A. J. Helmboldt, et al (2016)

--- Hence, to keep the classical scale-inv. theory has to be safe up to Planck scale (i.e. free from Landau poles)

☆ This talk introduces a bosonic seesaw model, shows that

* single HC dynamics explains
  all masses for existing particles
  -- SM particles including 125 GeV Higgs,
  -- active (RH) neutrinos,
  -- dark matter candidate (composite or elementary),
     by EWSB and U(1)_{B-L} breaking

* rich pheno. at TeV is predicted:
  -- HC hadrons (pions, scalar mesons, baryons,...)
  -- B-L Higgs, gauge boson
  -- a “new” production process for DM in thermal history,
     DM detection exp. , etc.

More interesting than other scale-inv. models

Contents

0. Introduction

1. Bosonic seesaw model w/ multiple seesaws
   -- dynamical scalegeneration

2. Summary

1. Bosonic seesaw model w/ multiple seesaws
-- dynamical scalegeneration

Phys.RevD.95 (2017)
H.Ishida, S.M, S.Okawa, Y.Omura

* SM gauges x U(1)B-L
x SU(3)HC x CSI

		$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
quarks	q_L^α	3	2	1/6	−1/3
	u_R^α	3	1	2/3	−1/3
	d_R^α	3	1	−1/3	−1/3
leptons	l_L^α	1	2	−1/2	1
	e_R^α	1	1	−1	1
elementary EW Higgs	H	1	2	1/2	0
RHMν (3 generations)	N_R^α	1	1	0	1
elementary B-L Higgs	ϕ	1	1	0	−2

HC fermions (x4)	$F_{L/R}$	$SU(3)_{HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
SU(2) doublet	$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
SU(2) singlet	ψ_1	3	1	1	q	q'
SU(2) singlet	ψ_2	3	1	1	q	$-2 + q'$

* Criterion for modeling HC sector:

$F_{L/R}$	$SU(3)_{HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
ψ_1	3	1	1	q	q'
ψ_2	3	1	1	q	$-2 + q'$

Making "mirror" Higgses by HC strong dynamics

$$\Theta_1 \sim \overline{\psi_1}\chi, \qquad \Phi \sim \bar{\psi_1}\psi_2,$$

↑ ↑

H ~ (1,2,1/2,0) ϕ~ (1,1,0,-2)

to be seesaw partners via HC-fermion Yukawa terms:

$$y_H(\bar{\chi}H\psi_1 + \text{H.c.}) + y_\phi(\overline{\psi_2}\phi\psi_1 + \text{H.c.})$$

* Dynamical mass generation: sequence of seesaws

-- approximate "chiral"
SU(4) x SU(4) sym. in HC sector
(explicitly broken by gauges and
HC-fermion Yukawa ints.)

$F_{L/R}$	$\mathrm{SU}(3)_{\mathrm{HC}}$	$\mathrm{SU}(3)_c$	$\mathrm{SU}(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
ψ_1	3	1	1	q	q'
ψ_2	3	1	1	q	$-2 + q'$

up to HC-fermion axial U(1) (anomaly)

-- spontaneously broken at $\Lambda_{\rm HC}$ (say, O(TeV) – O(10TeV))

$$\langle \bar{F}^i F^j \rangle \sim \Lambda_{\rm HC}^3 \delta^{ij} \qquad SU(4)_{F_L} \times SU(4)_{F_R} \to SU(4)_{F_V}$$

-- as well as CSI, simultaneously

* Dynamical mass generation: sequence of seesaws

-- theory below HC scale, described by HC hadrons

-- (ref. QCD) low-lying spectra include:

- HC pions x 15 (pNG bosons) {+ HC eta'}
- HC scalar mesons x 16
- HC spin ½ baryons x 20 (→incl. DM), {and vector (axialvector) mesons}

HC baryon	constituent	$SU(2)_W$	I_3	Y	$B-L$
$p_{\rm HC}^{2+3q}$	$\chi_1\chi_1\chi_2$	2	1/2	$3/2+3q$	$3q'$
$n_{\rm HC}^{1+3q}$	$\chi_1\chi_2\chi_2$	2	$-1/2$	$3/2+3q$	$3q'$
$\Lambda_{(1)}^{1+3q}$	$\chi_1\chi_2\psi_1$	1	0	$1+3q$	$3q'$
$\Sigma_{(1)}^{2+3q}$	$\chi_1\chi_1\psi_1$	3	1	$1+3q$	$3q'$
$\Sigma_{(1)}^{1+3q}$	$\chi_1\chi_2\psi_1$	3	0	$1+3q$	$3q'$
$\Sigma_{(1)}^{3q}$	$\chi_2\chi_2\psi_1$	3	-1	$1+3q$	$3q'$
$\Xi_{(11)}^{1+3q}$	$\chi_1\psi_1\psi_1$	2	1/2	$1/2+3q$	$3q'$
$\Xi_{(11)}^{3q}$	$\chi_2\psi_1\psi_1$	2	$-1/2$	$1/2+3q$	$3q'$
$\Lambda_{(2)}^{1+3q}$	$\chi_1\chi_2\psi_2$	1	0	$1+3q$	$-2+3q'$
$\Omega_{(12)}^{3q}$	$\psi_1\psi_1\psi_2$	1	0	$3q$	$-2+3q'$
$\Sigma_{(2)}^{2+3q}$	$\chi_1\chi_1\psi_2$	3	1	$1+3q$	$-2+3q'$
$\Sigma_{(2)}^{1+3q}$	$\chi_1\chi_2\psi_2$	3	0	$1+3q$	$-2+3q'$
$\Sigma_{(2)}^{3q}$	$\chi_2\chi_2\psi_2$	3	-1	$1+3q$	$-2+3q'$
$\Xi_{(12)}^{1+3q}$	$\chi_1\psi_1\psi_2$	2	1/2	$1/2+3q$	$-2+3q'$
$\Xi_{(12)}^{3q}$	$\chi_2\psi_1\psi_2$	2	$-1/2$	$1/2+3q$	$-2+3q'$
$\Omega_{(22)}^{3q}$	$\psi_1\psi_2\psi_2$	1	0	$3q$	$-4+3q'$
$\Xi_{(22)}^{1+3q}$	$\chi_1\psi_2\psi_2$	2	1/2	$1/2+3q$	$-4+3q'$
$\Xi_{(22)}^{3q}$	$\chi_2\psi_2\psi_2$	2	$-1/2$	$1/2+3q$	$-4+3q'$

$\mathcal{M}=\mathcal{S}+i\mathcal{P}$	constituent	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
$(f_0^{\rm HC}, a_0^{\rm HC}+i\mathcal{P}_{a_0^{\rm HC}})_{ij}$	$\overline{\chi_i}\,\chi_j$	(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
$\varphi_1+i\mathcal{P}_{\varphi_1}$	$\overline{\psi_1}\,\psi_1$	1	0	0
$\varphi_2+i\mathcal{P}_{\varphi_2}$	$\overline{\psi_2}\,\psi_2$	1	0	0

* Dynamical mass generation: sequence of seesaws

Among HC hadrons, focus on "mirror" composite Higgses

$$\Theta_1 \sim \overline{\psi_1}\chi, \qquad \Phi \sim \bar{\psi_1}\psi_2,$$

via HC-fermion Yukawa terms:

$$y_H(\bar{\chi}H\psi_1 + \text{H.c.}) + y_\phi(\overline{\psi_2}\phi\psi_1 + \text{H.c.})$$

trigger two seesaws: $\begin{pmatrix} 0 & y_{H/\phi}\Lambda_{\text{HC}}^2 \\ y_{H/\phi}\Lambda_{\text{HC}}^2 & \Lambda_{\text{HC}}^2 \end{pmatrix}$ $y_{H/\phi} \ll 1$

$m_H^2 \simeq -y_H^2\Lambda_{\text{HC}}^2$ and $m_\phi^2 \simeq -y_\phi^2\Lambda_{\text{HC}}^2$ realize EWSB & U(1)B-L breaking w/

$$-\lambda_H(H^\dagger H)^2 - \lambda_\phi(|\phi|^2)^2$$

-- physical Higgs masses

$m_{h_1} \simeq \sqrt{2\lambda_H}v_{\text{EW}} \simeq 125\,\text{GeV}$

$m_{\phi_1} \simeq 2\sqrt{2\lambda_\phi}v_{\phi_1} = \mathcal{O}(10)\ \text{TeV}$

$v_\phi = \mathcal{O}(\Lambda_{\text{HC}})$ and $\lambda_\phi = O(1)$

* Dynamical mass generation: sequence of seesaws

Furthermore, via RH Majorana ν-Yukawa terms:

$$y_{lN}^{\alpha\beta}\overline{l_L^{\alpha}}\,\tilde{H}\,N_R^{\beta} + y_N^{\alpha\alpha}(\phi\overline{N_R^{c\alpha}}N_R^{\alpha} + \text{H.c.})$$

trigger neutrino seesaw (Type I):

$$\begin{pmatrix} 0 & y_{lN}v_{\text{EW}} \\ y_{lN}^T v_{\text{EW}} & m_{N_R} \end{pmatrix}$$

-- active and heavy RHM neutrino masses

$$m_\nu \simeq y_{lN}^2 v_{\text{EW}}^2 / m_{N_R} = \mathcal{O}(0.1\text{eV}) \qquad \text{for } y_{lN} = \mathcal{O}(10^{-5}).$$

$$m_{N_R}^{\alpha\alpha} = \mathcal{O}(y_N^{\alpha\alpha}\Lambda_{\text{HC}}) = \mathcal{O}(5\text{–}10\,\text{TeV}) \text{ with } y_N^{\alpha\alpha} = \mathcal{O}(1)$$

$$v_\phi = \mathcal{O}(\Lambda_{\text{HC}})$$

DM candidates

HC baryon	constituent	$SU(2)_W$	I_3	Y	$B-L$
(I) $\Lambda^{1+3q}_{(1)}$	$\chi_1\chi_2\psi_1$	1	0	$1+3q$	$3q'$
$\Lambda^{1+3q}_{(2)}$	$\chi_1\chi_2\psi_2$	1	0	$1+3q$	$-2+3q'$
(II) $\Omega^{3q}_{(12)}$	$\psi_1\psi_1\psi_2$	1	0	$3q$	$-2+3q'$
$\Omega^{3q}_{(22)}$	$\psi_1\psi_2\psi_2$	1	0	$3q$	$-4+3q'$

DM candidate = SM-gauge singlet, lightest HC baryons (TeV- O(10) TeV)

(I) $q=-1/3$ and (II) $q=0$.

* This charge choice is consistent w/ asymptotic safety

Other baryons decay to DMs + weak bosons(*) + HC pions (*)

$$p^+_{\rm HC} \to n^0_{\rm HC} + W^{+(*)} \qquad n^0_{\rm HC} \to \mathcal{P}^0_{\Theta_2} + \Lambda^0_{(2)}$$

DM production in early universe

* B-L singlet DM, for simplicity

-- lightest HC baryons (B= $\Lambda^0_{(1)}(q'=0)$ or $\Lambda^0_{(2)}(q'=2/3)$ for $q=-1/3$ case I)

-- generated @ T = HC baron mass scale O(1) – O(10) TeV:

DM=nonrelativistic; might have never been thermalized

(* HC pions can be as heavy as HC baryons;

HC pions might have never been in thermal EQ as well.)

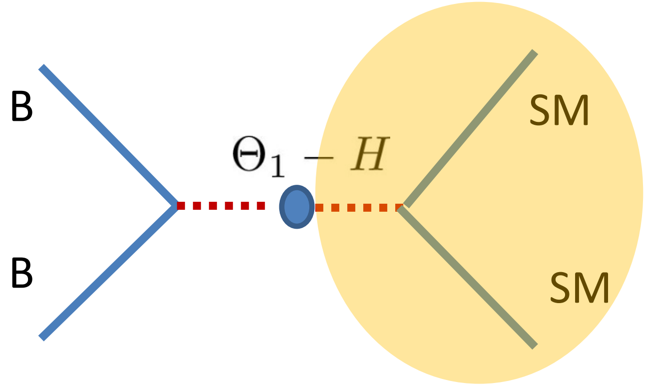
-- dominant source for DM production

= bosonic seesaw portal process

H.Ishida, S.M, Y.Yamaguchi (2016)

$$\frac{1}{\Lambda_{\rm HC}} \bar{B} B \Theta_1^\dagger \Theta_1 \to \frac{y_H^2}{\Lambda_{\rm HC}} \bar{B} B H^\dagger H$$

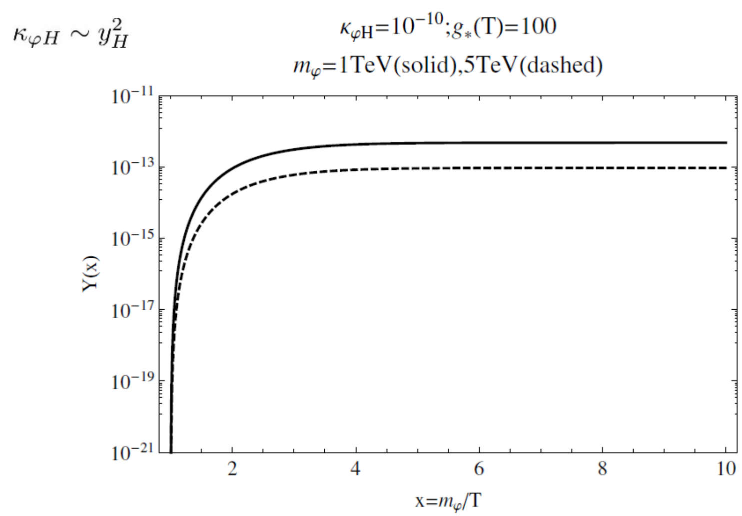
$\Theta_1 - H$ mixing $\quad y_H \ll 1$

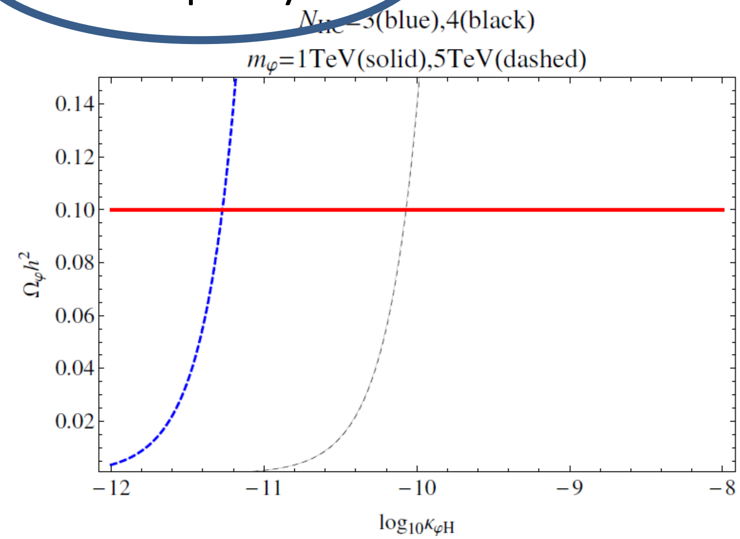


-- non-thermal production like "freeze-in" scenario (FIMP, E-WIMP)

DM production in early universe

* B-L singlet DM, for simplicity





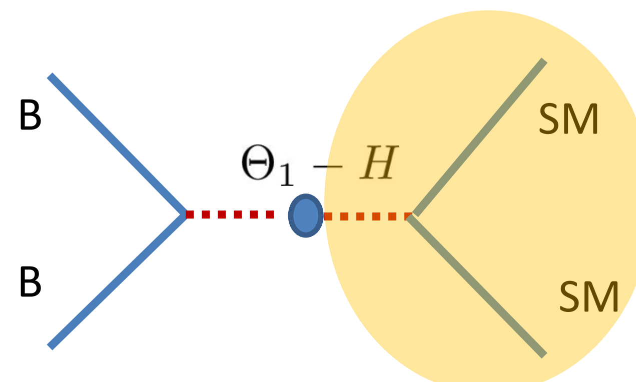
-- dominant source for DM production

= bosonic seesaw portal process

H.Ishida, S.M, Y.Yamaguchi (2016)

$$\frac{1}{\Lambda_{\rm HC}}\bar{B}B\Theta_1^\dagger\Theta_1 \to \frac{y_H^2}{\Lambda_{\rm HC}}\bar{B}BH^\dagger H$$

$\Theta_1 - H$ mixing $\quad y_H \ll 1$



-- non-thermal production like “freeze-in” scenario (FIMP, E-WIMP)

@ DM detection experiments

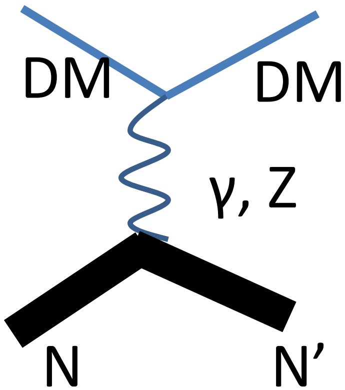
(I) $q = -1/3$ and (II) $q = 0$.

$F_{L/R}$	$SU(3)_{HC}$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{B-L}$
$\chi = (\chi_1, \chi_2)^T$	3	1	2	$1/2 + q$	q'
ψ_1	3	1	1	q	q'
ψ_2	3	1	1	q	$-2 + q'$

	HC baryon	constituent	$SU(2)_W$	I_3	Y	$B-L$
(I)	$\Lambda_{(1)}^{1+3q}$	$\chi_1\chi_2\psi_1$	1	0	$1+3q$	$3q'$
	$\Lambda_{(2)}^{1+3q}$	$\chi_1\chi_2\psi_2$	1	0	$1+3q$	$-2+3q'$
(II)	$\Omega_{(12)}^{3q}$	$\psi_1\psi_1\psi_2$	1	0	$3q$	$-2+3q'$
	$\Omega_{(22)}^{3q}$	$\psi_1\psi_2\psi_2$	1	0	$3q$	$-4+3q'$

Ref: q' = 0

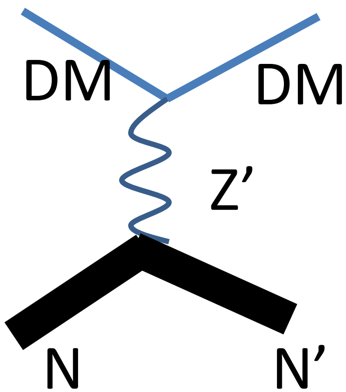
$$\frac{g \cdot g_Y}{2m_{\Lambda^0}} \bar{\Lambda}^0 \sigma_{\mu\nu} B^{\mu\nu} \Lambda^0$$



mag.moment int.
w/ g-factor: g ~ 1

Ref: q' = 1

$$g_{B-L} \bar{\Omega}^0 \gamma_\mu Z'^\mu \Omega^0$$



B-L gauge int.:
g_{B-L}^2/m_Z'^2
= 1/vϕ^2

Current bounds on SI cross sections
(LUX2016&XENON1T)

(I) $m_{\rm DM} > \mathcal{O}(10)$ TeV

(II) $m_{\rm DM} > \mathcal{O}(10)$ TeV for $v_\phi > 5$ TeV

preference to be clarified
in future exps.

3. Summary

* Bosonic seesaw models:
  -- interesting scenario giving
  dynamical explanation for origin of mass,
  solving gauge hierarchy problem

  -- can provide rich pheno. for TeV scale physics
  HC composite spectra: incl natural DM candidate

* We discussed a dynamical scalegenesis:
  -- all particle masses generated by a single HC

* Future direction --- HC hadron collider signatures at LHC
  --- effect on flavor physics
  -- GW detectability of HC phase transition, etc.
  → under consideration