BSM Models with Gauge Unification and Hidden Strong Dynamics

Fang Ye
National Taiwan University

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Based on 1607. 05403 [hep-ph] with Cheng-Wei Chiang, and Sichun Sun

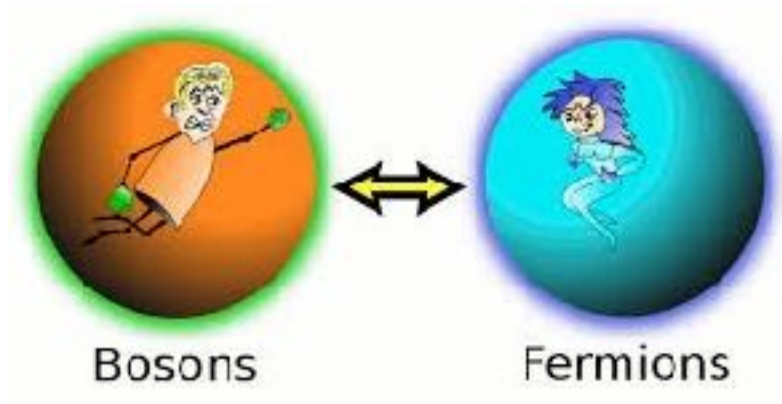
Introduction

A class of models targeting BSM scenarios:

- Extended gauge sector with strong dynamics
- Gauge unification of the visible sector
- SUSY

Introduction

- **SUSY**: spacetime symmetry that relates fermions and bosons



- SUSY has good motivations from both theoretical and phenomenological perspectives.

- Experiment ruled out a large portion of parameter/ model space for low scale SUSY

SUSY>TeV ?

Introduction

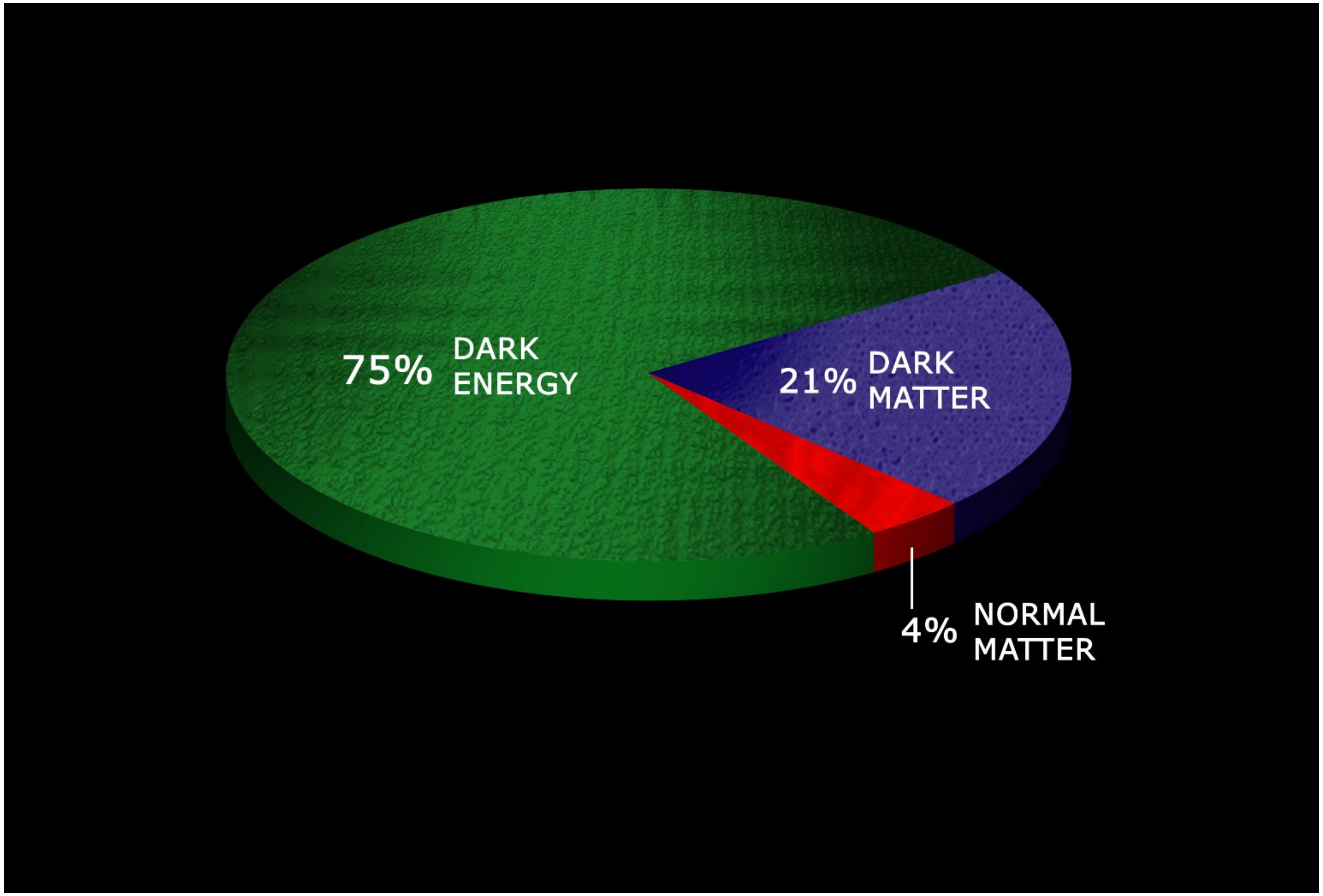
- Usually low/intermediate scale SUSY: perturbative (except QCD)
- **Strongly coupled sectors**: generic in fundamental theories
- The study of strongly coupled gauge theory has shed light on the non-perturbative calculations

Weak ←— **gauge/gravity duality** —→ **Strong**

e.g. Holographic gauge mediation: strongly coupled hidden sector talks to the visible sector via messengers

P. McGuirk, G. Shiu, Y. Sumitomo, Phys. Rev. D81 (2010) 026005 [arXiv:0911.0019[hep-th]].

Introduction



Introduction

- **DM**: strong evidence of BSM physics
- Much remains unknown about DM: candidate? elementary or composite?
- How DM interacts? Gravitationally? Non-gravitationally?
- DM -> Hidden sector w/ gauge fields, matter fields

  "Hidden valley scenario"
- If **hidden sector w/ strong force** -> **bound states** -> escape experimental bound?

Introduction

- To propose a type of models s.t.:
- W/ a hidden sector with strong force
- Alleviate naturalness problem in SM
- Its SUSY version w/ significant features different than the usual low scale SUSY
- Possible for GUT
- Various bound states
- W/ DM candidate

Setup

- SM+ hidden SU(N) gauge + new (scalar) particles

hidden $SU(N)_H$ gauge group with a confinement scale $\Lambda_H \sim \mathcal{O}(1)$ TeV

All SM particles are neutral under hidden SU(N)

New (scalar) particles are charged under both hidden SU(N) and SM

Only consider scalars at this stage

Setup

Complex scalars

 # generations not fixed; will be determined later

Messenger Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{Q} = (\tilde{Q}_U, \tilde{Q}_D)^T$	N	3	2	1/6	2/3, −1/3
$\tilde{U'}^\dagger$	N	$\overline{3}$	1	−2/3	−2/3
$\tilde{D}^\dagger$	N	$\bar{3}$	1	1/3	1/3
$\tilde{L} = (\tilde{L}_N, \tilde{L}_E)^T$	N	1	2	−1/2	0, −1
$\tilde{E}^\dagger$	N	1	1	1	1

Table 1: Representations of the new messenger fields. The dagger denotes the Hermitian conjugate. The electric charge is related to the hypercharge through $Q_{EM} = T_3 + Y$.

$$\bar{5} = \begin{pmatrix} \tilde{D}^\dagger \\ \tilde{L} \end{pmatrix},$$

$$10 = \begin{pmatrix} 0 & \tilde{U'}^\dagger_3 & \tilde{U'}^\dagger_2 & \tilde{Q}_{U1} & \tilde{Q}_{D1} \\ -\tilde{U'}^\dagger_3 & 0 & \tilde{U'}^\dagger_1 & \tilde{Q}_{U2} & \tilde{Q}_{D2} \\ -\tilde{U}^\dagger_2 & -\tilde{U}^\dagger_1 & 0 & \tilde{Q}_{U3} & \tilde{Q}_{D3} \\ -\tilde{Q}_{U1} & -\tilde{Q}_{U2} & -\tilde{Q}_{U3} & 0 & \tilde{E}^\dagger \\ -\tilde{Q}_{D1} & -\tilde{Q}_{D2} & -\tilde{Q}_{D3} & -\tilde{E}^\dagger & 0 \end{pmatrix}$$

$$\tilde{D}^\dagger = \begin{pmatrix} \tilde{D}^\dagger_1 \\ \tilde{D}^\dagger_2 \\ \tilde{D}^\dagger_3 \end{pmatrix}, \quad \tilde{L} = \begin{pmatrix} \tilde{L}_N \\ \tilde{L}_E \end{pmatrix}.$$

Higgs Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$H_u = (H_u^+, H_u^0)^T$	1	1	2	1/2	1, 0
$H_d = (H_d^0, H_d^-)^T$	1	1	2	−1/2	0, −1

Table 2: Representations of the Higgs doublets.

Neatly fit into visible SU(5)

Higgses are fundamental!

Different from technicolor/little Higgs/composite Higgs

A supersymmetric version

Visible
MSSM

Hidden
Vector multiplets

Chiral multiplets

Messenger Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{Q} = (\tilde{Q}_U, \tilde{Q}_D)^T$	$\mathbf{N}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$2/3, -1/3$
$\tilde{U}^\dagger$	$\overline{\mathbf{N}}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$-2/3$
$\tilde{D}^\dagger$	$\mathbf{N}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$1/3$
$\tilde{L} = (\tilde{L}_N, \tilde{L}_E)^T$	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$0, -1$
$\tilde{E}^\dagger$	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{1}$	1	1

Complex scalars

+

Superpartners

fields w/o tilde L.H

+ conjugate (R.H)

Vector-like fermions

Non-minimal SUSY

A supersymmetric version

Messenger Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{Q} = (\tilde{Q}_U, \tilde{Q}_D)^T$	N	**3**	**2**	1/6	2/3, −1/3
$\tilde{U}'^\dagger$	N	$\overline{\mathbf{3}}$	**1**	−2/3	−2/3
$\tilde{D}^\dagger$	N	$\bar{\mathbf{3}}$	**1**	1/3	1/3
$\tilde{L} = (\tilde{L}_N, \tilde{L}_E)^T$	N	**1**	**2**	−1/2	0, −1
$\tilde{E}^\dagger$	N	**1**	**1**	1	1

Table 1: Representations of the new messenger fields. The dagger denotes the Hermitian conjugate. The electric charge is related to the hypercharge through $Q_{EM} = T_3 + Y$.

to be embedded in another 10-plet

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{U}^\dagger$	$\overline{\mathbf{N}}$	$\overline{\mathbf{3}}$	**1**	−2/3	−2/3

$$W_{\text{hidden}} \supset \Phi_{\tilde{U}^\dagger} Y_U \Phi_{\tilde{Q}} \Phi_{H_u}$$

Only refer to their L.H. (holomorphic) components

$$V \supset -|Y_U|^2 \left(H_u^\dagger H_u \tilde{Q}^\dagger \tilde{Q} + H_u^\dagger H_u \tilde{U}^\dagger \tilde{U} + \tilde{Q}^\dagger \tilde{Q}\, \tilde{U}^\dagger \tilde{U} \right)$$

$$\mathcal{L}_{\text{Yukawa}} \supset -Y_U U^\dagger H_u Q + \text{c.c.}$$

Higgs Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$H_u = (H_u^+, H_u^0)^T$	**1**	**1**	**2**	1/2	1, 0
$H_d = (H_d^0, H_d^-)^T$	**1**	**1**	**2**	−1/2	0, −1

Table 2: Representations of the Higgs doublets.

e.g. F-term breaking in hidden sector ~~SUSY~~ mediation

→ mass splitting btw fermion and scalar in hidden chiral multiplet

→ loops of hidden particles

→ modify MSSM gaugino masses etc → visible mass splitting

A supersymmetric version

Take gaugino mediation for example

$$W_{mess1} = Y_s \Phi_S \Phi_\phi \bar{\Phi}_\phi, \quad \Phi_\phi : \text{ a messenger}, \quad < F_S > \neq 0,$$

$$V \ni \left| \frac{\partial (W_{mess1} + W_{mess2})}{\partial \phi} \right|^2 + \left| \frac{\partial (W_{mess1} + W_{break})}{\partial S} \right|^2,$$

$$W_{\text{hidden}} \supset \Phi_{\tilde{U}^\dagger} Y_U \Phi_{\tilde{Q}} \Phi_{H_u} = W_{mess2}$$

There may be other contribution to the scalar potential due to the existence of hidden strong dynamics.

-> possible that messenger scalar mass eigenvalues smaller than their superpartners

↑

Assume this is the case

Those messengers enter into 1-loop corrections to the SM gaugino masses as in the normal gaugino mediation, while the SM gauge bosons remain unaffected due to the gauge symmetries. Thus the mass splittings occur in the SM vector supermultiplets.

Fine-tunings of Higgs mass

SUSY case

SM Higgs: a linear combination of two Higgs doublets

with a mass of 125 GeV and vev 246 GeV.

Higgs mass loop correction from MSSM and hidden sector

assume from mass splitting, not considering different SUSY breaking schemes, etc

$\tilde{U}^\dagger Y_U \tilde{Q} H_u$

$$\delta m_{H_u}^2 \supset \frac{3 g_2^2 M_t^4}{8\pi^2 M_W^2} \log \frac{M_{\tilde{t}}^2}{M_t^2}$$

$$\delta m_{H_u}^2 \supset \frac{3 N g_2^2 M_Q^4}{4\pi^2 M_W^2} \log \frac{M_{\tilde{Q}}^2}{M_Q^2}$$

Gauge coupling unification

Messenger Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{Q} = (\tilde{Q}_U, \tilde{Q}_D)^T$	$\mathbf{N}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$2/3, -1/3$
$\tilde{U'}^\dagger$	$\mathbf{N}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$-2/3$
$\tilde{D}^\dagger$	$\mathbf{N}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$1/3$	$1/3$
$\tilde{L} = (\tilde{L}_N, \tilde{L}_E)^T$	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$0, -1$
$\tilde{E}^\dagger$	$\mathbf{N}$	$\mathbf{1}$	$\mathbf{1}$	1	1

Table 1: Representations of the new messenger fields. The dagger denotes the Hermitian conjugate. The electric charge is related to the hypercharge through $Q_{EM} = T_3 + Y$.

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{U}^\dagger$	$\overline{\mathbf{N}}$	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$	$-2/3$

$$\bar{\mathbf{5}} = \begin{pmatrix} \tilde{D}^\dagger \\ \tilde{L} \end{pmatrix},$$

$$\mathbf{10} = \begin{pmatrix} 0 & \tilde{U'}_3^\dagger & \tilde{U'}_2^\dagger & \tilde{Q}_{U1} & \tilde{Q}_{D1} \\ -\tilde{U'}_3^\dagger & 0 & \tilde{U'}_1^\dagger & \tilde{Q}_{U2} & \tilde{Q}_{D2} \\ -\tilde{U}_2^\dagger & -\tilde{U}_1^\dagger & 0 & \tilde{Q}_{U3} & \tilde{Q}_{D3} \\ -\tilde{Q}_{U1} & -\tilde{Q}_{U2} & -\tilde{Q}_{U3} & 0 & \tilde{E}^\dagger \\ -\tilde{Q}_{D1} & -\tilde{Q}_{D2} & -\tilde{Q}_{D3} & -\tilde{E}^\dagger & 0 \end{pmatrix}$$

Higgs Sector

	$SU(N)_H$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$H_u = (H_u^+, H_u^0)^T$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$1, 0$
$H_d = (H_d^0, H_d^-)^T$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$	$0, -1$

Table 2: Representations of the Higgs doublets.

$$\tilde{D}^\dagger = \begin{pmatrix} \tilde{D}_1^\dagger \\ \tilde{D}_2^\dagger \\ \tilde{D}_3^\dagger \end{pmatrix}, \quad \tilde{L} = \begin{pmatrix} \tilde{L}_N \\ \tilde{L}_E \end{pmatrix}.$$

- SM and new particles embedded into a visible SU(5)?

Assume no intermediate stage of SU(5)_V -> SM

Gauge coupling unification

GUT-Higgs mechanism to break SU(5)_V:

$$< \mathbf{24} >= \mathrm{diag}\,(2,\,2,\,2,\,-3,\,-3)\,v.$$

v around GUT scale

SU(5)_V multiplets (e.g. **5**, **10**) split into SM multiplets

e.g.

$$\mathbf{5} \to (3,\,\mathbf{1},\,-\frac{1}{3}) + (\mathbf{1},\,\mathbf{2},\,\frac{1}{2}),$$
$$\bar{\mathbf{5}} \to (\bar{\mathbf{3}},\,\mathbf{1},\,\frac{1}{3}) + (\mathbf{1},\,\mathbf{2},\,-\frac{1}{2}),$$

Gauge coupling unification

Goal: 1-loop gauge couplings unify at GUT scale M_{GUT}

$$\alpha_3(M_{GUT}) = \alpha_2(M_{GUT}) = \alpha_1(M_{GUT}) \equiv \alpha_{GUT}$$

1-loop beta function

b_i should not be smaller than SM values

$b_1 \geq \frac{41}{10}$, $b_2 \geq -\frac{19}{6}$, $b_3 \geq -7$

Conditions on gauge coupling unification

GUT remains within the perturbative region, i.e.

$$0 < \alpha_{\rm GUT}(M_{\rm GUT}) < 1.$$

The GUT scale is not too low or too high. We require the GUT scale is lower than the fundamental string scale M_s (which is lower than the reduced Planck mass M_P). On the other hand, the GUT scale should be high enough not to incur a fast proton decay. Practically speaking, we expect $\mathcal{O}(M_{GUT})$ to be within $\mathcal{O}(10^{15}) \sim \mathcal{O}(10^{16})$ GeV.

$\tau(p \to \pi^0 e^+) > 5.3 \times 10^{33}$ yr

$$M_{\rm GUT} > \left(\frac{\alpha_{\rm GUT}}{1/35}\right)^{1/2} \left(\frac{\alpha_N}{0.015\ {\rm GeV}^3}\right)^{1/2} \left(\frac{A_L}{5}\right)^{1/2} 6 \times 10^{15}\ {\rm GeV}$$

Gauge coupling unification

SUSY case

$$10: (Q, U'^{\dagger}, E^{\dagger}),$$
$$10': (U^{\dagger}, ...),$$
$$\bar{5}: (D^{\dagger}, L)$$

$(b_1, b_2, b_3)_{MSSM} = \left(\frac{33}{5}, 1, -3\right)$ unify at $(2-3) \times 10^{16}\,\mathrm{GeV}$

Assume SM super partners and new particles all at 1 TeV

If add **complete** SU(5) representations

Assume: all new scalars ~ 300 GeV,
all new fermions and SM super partners ~ 5 TeV

$$b_1 = \frac{33}{5} + N(n_5 + 3n_{10} + 3n_{10'})$$
$$b_2 = 1 + N(n_5 + 3n_{10} + 3n_{10'}) ,$$
$$b_3 = -3 + N(n_5 + 3n_{10} + 3n_{10'})$$

↓

hidden "multiplicity"

SU(N)_H

$W_{\mathrm{hidden}} \supset \Phi_{\bar{U}^{\dagger}} Y_U \Phi_{\bar{Q}} H_u$, → at least one $\Phi_{\bar{Q}}$ and one $\Phi_{\bar{U}^{\dagger}}$

↓

blow up running couplings

Added too many particles to low energy

Gauge coupling unification

SUSY case

$$10:\ (Q,\ U'^{\dagger},\ E^{\dagger}),$$
$$10':\ (U^{\dagger},\ ...),$$
$$\bar{5}:\ (D^{\dagger},\ L)$$

$(b_1, b_2, b_3)_{MSSM} = \left(\frac{33}{5}, 1, -3\right)$ unify at $(2-3)\times 10^{16}\,\mathrm{GeV}$

Assume SM super partners and new particles all at 1 TeV

If add **incomplete** SU(5) representations

Assume: all new scalars ~ 300 GeV,
all new fermions and SM super partners ~ 5 TeV

$W_{\rm hidden} \supset \Phi_{\bar{U}^\dagger} Y_U \Phi_{\bar{Q}} H_u$, → at least one $\Phi_{\bar{Q}}$ and one $\Phi_{\bar{U}^\dagger}$

→ **blow up running couplings**

Added too many particles to low energy

Still can't unify due to Landau pole

Gauge coupling unification

SUSY case

To preserve unification

to have fewer particles at low energies

Split-SUSY?

Only a few SM super partners and new particles remain at low energies; others are at/above GUT scale

Small rank hidden group? Focus on N=2

for the $SU(2)_H$ case the multiplet $\tilde{U'}^\dagger$ identifies with the one without tilde,

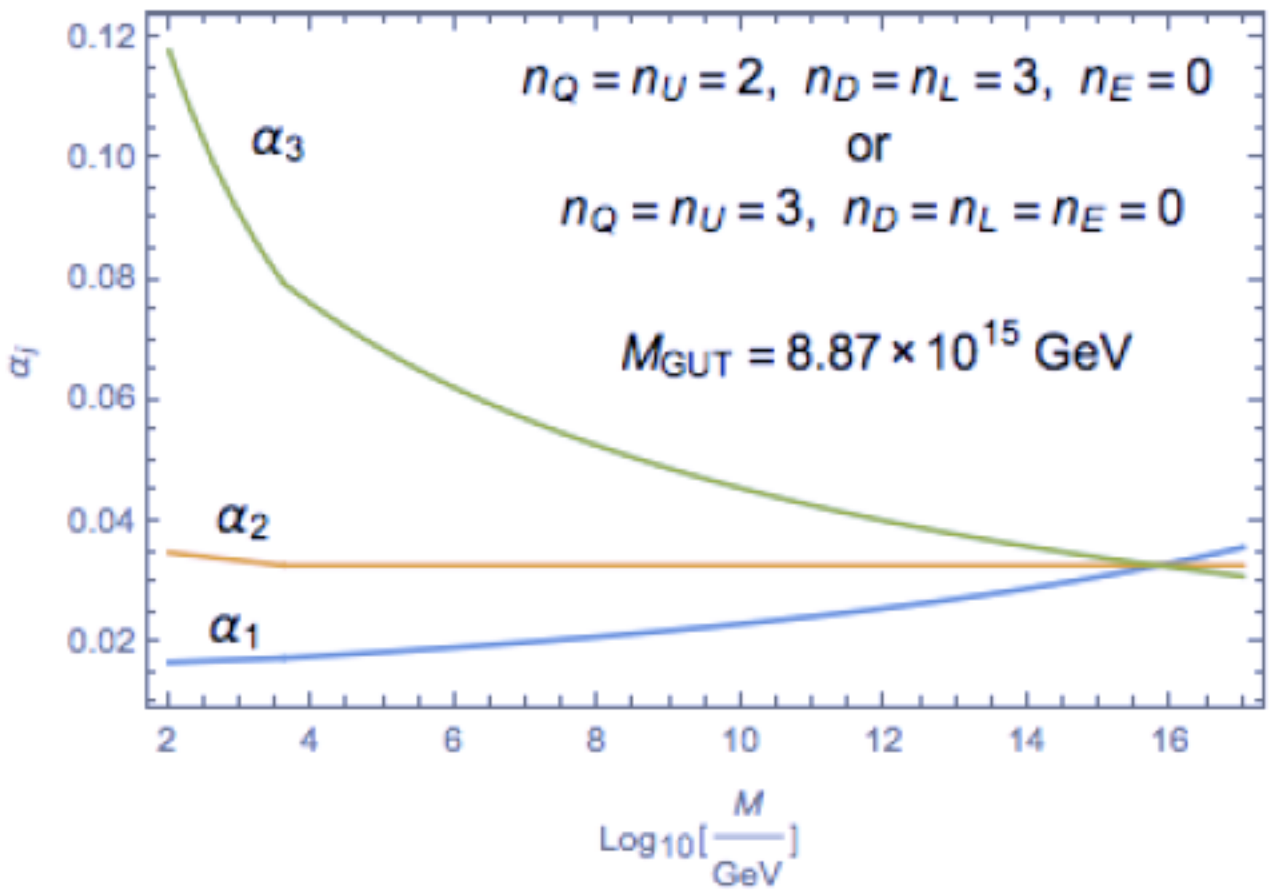
Agree with 1608.01675 [hep-ph] by Nima et al

Gauge coupling unification

Non-SUSY case

SU(2)_H

Setting:
hidden confinement scale ~ 4 TeV,
new scalars and the extra Higgs ~ 300 GeV,
bound states formed by new scalars >= 800 GeV



$$b_1 = \frac{41}{10} + \frac{1}{20} + \frac{1}{5}\left(\frac{n_Q}{6} + \frac{4n_U}{3} + \frac{n_D}{3} + \frac{n_L}{2} + n_E\right)$$

$$b_2 = -\frac{19}{6} + \frac{1}{6} + \frac{n_Q}{2} + \frac{n_L}{6}\,,$$

$$b_3 = -7 + \frac{n_Q}{3} + \frac{n_U + n_D}{6}\,,$$

↓

1 class of sol: $n_Q = n_U = 2\,,\ n_D = n_L = 3\,,\ n_E = 0\,,$ or
$n_Q = n_U = 3\,,\ n_D = n_L = n_E = 0\,,$

unification scale $M_{GUT} \sim 8.87 \times 10^{15}$ GeV,

Gauge coupling unification

Non-SUSY case

SU(2)_H

$$n_Q = n_U = 2\ ,\ n_D = n_L = 3\ ,\ n_E = 0\ , \quad \text{or}$$
$$n_Q = n_U = 3\ ,\ n_D = n_L = n_E = 0\ ,$$

unification scale $M_{GUT} \sim 8.87 \times 10^{15}$ GeV,

satisfy

$$\tau(p \to \pi^0 e^+) > 5.3 \times 10^{33}\ \text{yr}$$

$$M_{\rm GUT} > \left(\frac{\alpha_{\rm GUT}}{1/35}\right)^{1/2} \left(\frac{\alpha_N}{0.015\ \text{GeV}^3}\right)^{1/2} \left(\frac{A_L}{5}\right)^{1/2} 6 \times 10^{15}\ \text{GeV}$$

$A_L = A_R = 5.$ lattice result $\alpha_N = 0.015\ \text{GeV}^3$

No fast proton decay!

Gauge coupling unification

Non-SUSY case

SU(2)_H **Confining?**

$n_Q = n_U = 2$, $n_D = n_L = 3$, $n_E = 0$, or

$n_Q = n_U = 3$, $n_D = n_L = n_E = 0$,

unification scale $M_{GUT} \sim 8.87 \times 10^{15}$ GeV,

In the confining phase of SU(2)_H?

Need more details about the hidden sector, e.g. purely hidden particles

Find: 1-loop b_2H <0 (asymptotic free in UV),
if there are not too many particles only charged under SU(2)_H.

Gauge coupling unification

Non-SUSY case

$$10:\ (Q,\ U'^{\dagger},\ E^{\dagger}),$$
$$10':\ (U^{\dagger},\ ...),$$
$$\bar{5}:\ (D^{\dagger},\ L)$$

SU(2)_H $n_Q = n_U = 2\ ,\ n_D = n_L = 3\ ,\ n_E = 0\ ,$ or
$n_Q = n_U = 3\ ,\ n_D = n_L = n_E = 0\ ,$

incomplete SU(5) multiplets added

typical in 4d GUT theories.

In 4d field theory context

e.g. doublet-triplet splitting

$$W_5 = \lambda \bar{\mathbf{5}} \cdot \mathbf{24} \cdot \mathbf{5} + \mu \bar{\mathbf{5}} \cdot \mathbf{5}$$
$$\Rightarrow (2\lambda v + \mu)\, \bar{\mathbf{3}} \cdot \mathbf{3} + (-3\lambda v + \mu)\, \bar{\mathbf{2}} \cdot \mathbf{2}$$

v around GUT scale and doublets at $\mathcal{O}(100)$ GeV

tuning for mu parameter

General strategy: to **construct a super potential such that some components of the multiplets get masses around GUT scale** and thus decouple from the low energy spectrum. Requiring **careful arrangement of VEVS** of other fields (in particular singlets); often **complicated**

Gauge coupling unification

Non-SUSY case

SU(2)_H

incomplete SU(5) multiplets added

In the context of
extra spacial dimensions with orbifold

often in "local GUT" models

Fields localized at the fixed points of internal space survive the orbifold actions and remain as complete multiplets in 4d

Fields living in the bulk are partially projected out and form incomplete multiplets

A GUT multiplet at the fixed point or in the bulk: model-dependent

Assume: underlying mech. to generate mass splitting exists

Bounds from colliders and precision observables

New particles in **bound states**

Different than normal squark/slepton search

- Indirect bounds from **EW precision constraints** of LEPs (bounds for S, T, W, Y parameters for new scalars are **similar to the SUSY bounds**) -> lower bound O(100) GeV

may be relaxed by decoupling new scalars from SM Higgs

G. Marandella, C. Schappacher and A. Strumia, Nucl. Phys. B **715**, 173 (2005) doi:10.1016/j.nuclphysb.2005.03.001 [hep-ph/0502095].

- Indirect bounds from **Higgs data**: mostly from $H\gamma\gamma$, Hgg vertices

K. Cheung, J. S. Lee and P. Y. Tseng, Phys. Rev. D **92**, no. 9, 095004 (2015) doi:10.1103/PhysRevD.92.095004 [arXiv:1501.03552 [hep-ph]].

Mass of hidden scalars > 300 GeV: safe

Exotic bound states: mesons

SU(2)_H

Exotic Mesons
$\tilde{Q}\tilde{Q}^\dagger$, $\tilde{U}\tilde{U}^\dagger$, $\tilde{D}\tilde{D}^\dagger$, $\tilde{L}\tilde{L}^\dagger$, $\tilde{E}\tilde{E}^\dagger$

Lightest: CP-even (S-wave bound states of scalars)

SUSY setup: compared to composite/little Higgs, the neutral composite states can be lighter due to mixing with hidden glueballs

Diboson/Diphoton/Dijet Resonance

- Various hidden scalar contents -> Form various mesons -> Various diboson/diphoton/dijet resonances at different energy scales
- Different than the little Higgs/composite Higgs/technicolor models: fundamental Higgs, hidden sector not chiral
- For mesons at TeV, their existence may be tested in the near future

Possible other resonance (e.g. Higgs+dijet)?

Exotic bound states: baryons

SU(2)_H

Assume a hidden baryon number. Each scalar has hidden baryon number 1/2 (-1/2 for the conjugate).

baryons

AA',

A and A' denote distinct hidden scalars (or their conjugates) ($i.e.$, $A' \neq A^\dagger$).

AA'	$SU(2)_L$	$U(1)_Y$	$U(1)_{EM}$
$\tilde{Q}\tilde{U}^\dagger$	**2**	$-\frac{1}{2}$	$-1, 0$
$\tilde{Q}\tilde{D}^\dagger$	**2**	$\frac{1}{2}$	$0, 1$
$\tilde{L}\tilde{E}^\dagger$	**2**	$\frac{1}{2}$	$0, 1$
$\tilde{L}\tilde{E}$	**2**	$-\frac{3}{2}$	$-2, -1$
$\tilde{U}\tilde{D}^\dagger$	**1**	1	1

Hidden baryon number 1 ($\tilde{Q}\tilde{U}^\dagger$, $\tilde{Q}\tilde{D}^\dagger$, $\tilde{L}\tilde{E}^\dagger$, $\tilde{U}\tilde{D}^\dagger$)

Hidden baryon number 0 ($\tilde{L}\tilde{E}$)

Table 5: Exotic baryons as $SU(2)_L$ doublets and singlets and their Abelian charges. The conjugate particles are not listed.

Baryon masses are not roughly set by the confinement scale like in QCD.

Made by **scalars** instead of chiral fermions

Exotic bound states: baryons

SU(2)_H

Assume a hidden baryon number. Each scalar has hidden baryon number 1/2 (-1/2 for the conjugate).

baryons

$AA'a$

A and A' denote distinct hidden scalars (or their conjugates) (*i.e.*, $A' \neq A^{\dagger}$).
a refers to a SM quark.

$\tilde{Q}\tilde{Q}u_R$	singlet or triplet under $SU(2)_L$	hypercharge 1 and electric charge 0, ± 1, or ± 2.

Stability: QCD binds the hidden singlet AA' and a together

QCD confinement scale ~ O(100) MeV much lower than TeV hidden confinement scale

AA'a type much less stable than AA'

Decay of AA'a: need extra field?

Detailed discussion in follow-up work

Exotic bound states: DM candidates

SU(2)_H

Assume a hidden baryon number. Each scalar has hidden baryon number 1/2 (-1/2 for the conjugate).

baryons

AA',

A and A' denote distinct hidden scalars (or their conjugates) (*i.e.*, $A' \neq A^{\dagger}$).

DM: lightest, electrically neutral, with hidden baryon number 1

DM baryons **annihilate** into lighter scalar composite states

$$\Omega_B h^2 \sim 10^{-5} \frac{1}{F(M_B)^4} \left(\frac{M_B}{1\,\mathrm{TeV}} \right)^2$$

M_B is the mass of the DM baryon, denoted as B.

$F(M_B)$ is the form factor

Unitarity limit: F=1

For new scalar ~ 300 GeV, M_B ~ sub-TeV,
F not smaller than a certain value,
DM will not over close the universe

More exact calculation needs detailed knowledge of hidden strong dynamics, particularly the exact form of form factor

Exotic bound states: DM candidates

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baryons

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DM: lightest, electrically neutral, with hidden baryon number 1

Direct search: couplings to SM Higgs $\mathcal{L} \ni \lambda_B B^\dagger B H^\dagger H$,

hidden strong dynamics

spin-independent cross section $$\sigma_{SI} = \frac{\lambda_B^2}{4\pi m_h^4}\frac{m_N^4 f_N^2}{M_B^2} \approx 1.36 \times 10^{-44}\text{cm}^2 \times \lambda_B^2 \left(\frac{1\,\text{TeV}}{M_B}\right)^2,$$

$f_N \approx 0.326$ m_N is the nucleon mass

can satisfy LUX limit $\sigma_{SI} \lesssim 1 \times 10^{-44}\text{cm}^2 (M_B/1\,\text{TeV})$ for a suitable value of λ_B.

can be w/in reach of proposed LUX-Zeplin **But the unsuppressed Z-boson exchange will violate the LUX limit!**

No DM among the lowest baryons in SU(2)_H case.

SU(3)_H?

Yes, there is DM candidate. e.g. $\tilde{L}_N \tilde{L}_E \tilde{E}^\dagger$.

Summary

- We propose a type of models consisting of SM and a **strongly coupled hidden gauge sector**.
- W/ new matter fields charged under SM and hidden groups, SM gauge couplings can be unified at a reasonable scale w/o fast proton decay. -> Potential **GUT**
- Alleviate the EW hierarchy problem w/ or w/o SUSY.
- **Higgses as fundamental particles** whose EW breaking pattern largely remains intact at low energies -> different than little/composite/-Higgs/techni-color, suffering less from constraints
- Predict **exotic bound states** -> a wide range of spectrum, some maybe w/in detector search, some maybe **DM** (w/ various weak charges and spins), some maybe **diboson/diphoton/dijet resonance**

  Possible other resonance (e.g. Higgs+dijet)
- May exist an underling theory, e.g. string theory

Thank you!

Backup

Split SUSY

Spectrum

N. Arkani-Hamed and S. Dimopoulos, arXiv:hep-th/0405159.

SM + Higgsinos + gluinos, winos, bino

All the scalars of the supersymmetric SM except a finely tuned Higgs become ultra heavy.

Fermions can remain light, protected by (approx) chiral symmetry, and account for gauge coupling unification

Can solve:
absence of many particles,
dim-5 proton decay,
SUSY flavor and CP problems,
cosmological graviton and moduli problems

SUSY breaking and mediation

- SUSY: impose relations between **dimensionless** couplings to cancel Higgs mass quadratic divergence

- Soft SUSY breaking (w/o introducing quadratic divergence): SUSY relations btw dimensionless couplings must hold; **soft terms only contain couplings with positive mass dimension**

$$\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft}$$

Soft terms vanish in limit: soft mass ->0

$m_{\rm soft}$ largest mass scale in soft terms

$$\mathcal{L}_{\rm soft} = -\left(\frac{1}{2}M_a\,\lambda^a\lambda^a + \frac{1}{6}a^{ijk}\phi_i\phi_j\phi_k + \frac{1}{2}b^{ij}\phi_i\phi_j + t^i\phi_i\right) + \text{c.c.} - (m^2)^i_j\phi^{j*}\phi_i,$$

gaugino

$$\mathcal{L}_{\text{maybe soft}} = -\frac{1}{2}c_i^{jk}\phi^{*i}\phi_j\phi_k + \text{c.c.}$$

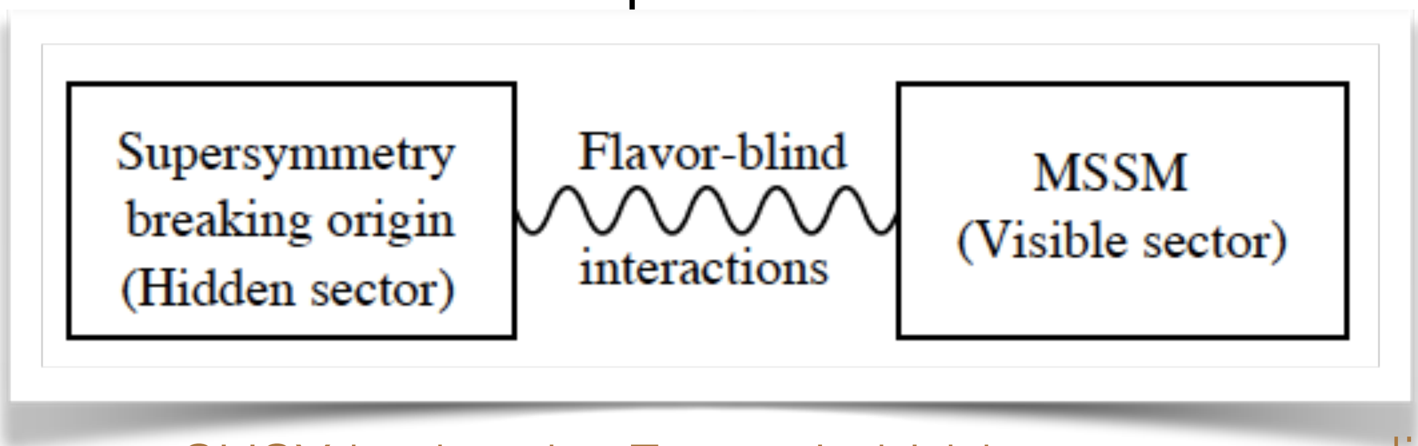
Soft mass terms for chiral multiplet fermion: from superpotential and

Soft parameters cannot be arbitrary either

SUSY breaking and mediation

- Spontaneous SUSY breaking: via non-vanishing F- and/or D-term(s)

- MSSM: a D-term VEV for U(1)_Y not leading to acceptable spectrum; no gauge singlet whose F-term with a VEV -> Need a separate SUSY breakdown sector



SUSY broken by F-term in hidden sector

mediated by ordinary weak & color gauge interactions

- Mediation: gravity, gauge, etc

MSSM soft terms from messenger loops

Dim-analysis: soft mass vanishing when F-term VEV -> 0, and also when the messenger mass -> infinity (decoupled) → $m_{\rm soft} \sim \frac{\alpha}{4\pi} \frac{< F >}{M_{\rm messager}}$

Gauge coupling unification

1-loop running couplings $\alpha_a = \frac{g_a^2}{4\pi}$

$$\alpha_a^{-1}(\mu) = \alpha_a^{-1}(\mu_0) + \frac{b_a}{4\pi} \ln\left(\frac{\mu_0^2}{\mu^2}\right)$$

field contents participating

$$b_a = -\frac{11}{3}\sum_V C(R_V^a) + \frac{2}{3}\sum_{Weyl} C(R_F^a) + \frac{1}{6}\sum_{Real} C(R_S^a),$$

Dynkin indices

$$\mathrm{Tr}\left(T_R^A T_R^B\right) = C(R)\delta^{AB}$$

$$C(\mathrm{N}) = \frac{1}{2}.$$

$$C(a) = N, \quad C(A_2) = \frac{N-2}{2}, \quad C(S_2) = \frac{N+2}{2},$$

Abelian group $\quad C(R_V^a) \to 0, \quad C(R_F^a) \to \frac{3}{5}Y_F^2$ and $C(R_S^a) \to \frac{3}{5}Y_S^2,$

EW precision constraints of LEPs

- SUSY affects the "universal" EW precision parameters S, T, W, Y

Heavy universal approx: new physics above weak scale (heavy), couples dominantly to vector bosons (universal)

Adimensional form factors			operators			custodial	$SU(2)_L$
$g^{-2}\widehat{S}$	$=$	$\Pi'_{W_3B}(0)$	$\mathcal{O}_{WB}$	$=$	$(H^\dagger\tau^a H)W^a_{\mu\nu}B_{\mu\nu}/gg'$	$+$	$-$
$g^{-2}M_W^2\widehat{T}$	$=$	$\Pi_{W_3W_3}(0)-\Pi_{W^+W^-}(0)$	$\mathcal{O}_H$	$=$	$\lvert H^\dagger D_\mu H\rvert^2$	$-$	$-$
$-g^{-2}\widehat{U}$	$=$	$\Pi'_{W_3W_3}(0)-\Pi'_{W^+W^-}(0)$		$-$		$-$	$-$
$2g^{-2}M_W^{-2}V$	$=$	$\Pi''_{W_3W_3}(0)-\Pi''_{W^+W^-}(0)$		$-$		$-$	$-$
$2g^{-1}g'^{-1}M_W^{-2}X$	$=$	$\Pi''_{W_3B}(0)$		$-$		$+$	$-$
$2g'^{-2}M_W^{-2}Y$	$=$	$\Pi''_{BB}(0)$	$\mathcal{O}_{BB}$	$=$	$(\partial_\rho B_{\mu\nu})^2/2g'^2$	$+$	$+$
$2g^{-2}M_W^{-2}W$	$=$	$\Pi''_{W_3W_3}(0)$	$\mathcal{O}_{WW}$	$=$	$(D_\rho W^a_{\mu\nu})^2/2g^2$	$+$	$+$
$2g_s^{-2}M_W^{-2}Z$	$=$	$\Pi''_{GG}(0)$	$\mathcal{O}_{GG}$	$=$	$(D_\rho G^A_{\mu\nu})^2/2g_s^2$	$+$	$+$

Table 1: *The first column defines the adimensional form factors. The second column defines the* $SU(2)_L$-*invariant universal dimension-6 operators, which contribute to the form-factors on the same row. We use non canonically normalized fields and* Π, *see eq.* (3). *The* $\widehat{S}$, $\widehat{T}$, $\widehat{U}$ *are related to the usual* S, T, U *parameters [5] as:* $S = 4s_W^2\widehat{S}/\alpha \approx 119\,\widehat{S}$, $T = \widehat{T}/\alpha \approx 129\,\widehat{T}$, $U = -4s_W^2\widehat{U}/\alpha$. *The last row defines one additional form-factor in the QCD sector.*

R. Barbieri, A. Pomarol, R. Rattazzi and A. Strumia, Nucl. Phys. B 703 (2004) 127 [hep-ph/0405040].

EW precision constraints of LEPs

$$\widehat{S} = \frac{g}{g'}\Pi'_{W_3Y}(0) \qquad \widehat{T} = \frac{\Pi_{W_3W_3}(0) - \Pi_{W^+W^-}(0)}{M_W^2} \qquad W = \frac{M_W^2}{2}\Pi''_{W_3W_3}(0) \qquad Y = \frac{M_W^2}{2}\Pi''_{YY}(0)$$

$$(H^\dagger \tau^a H)W^a_{\mu\nu}Y_{\mu\nu} \qquad |H^\dagger D_\mu H|^2 \qquad \frac{(D_\rho W^a_{\mu\nu})^2}{2} \qquad \frac{(\partial_\rho Y_{\mu\nu})^2}{2}$$

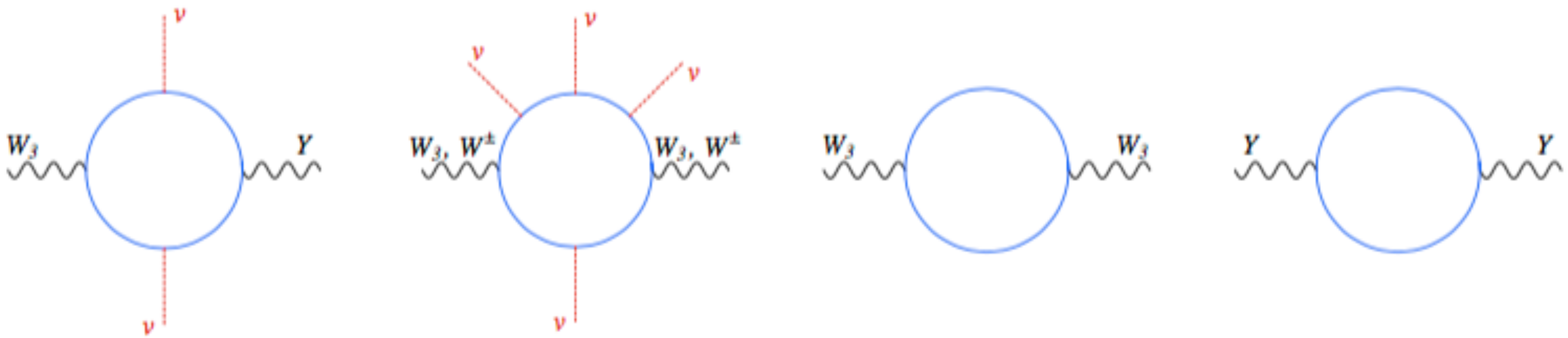


Figure 2: *Upper row: definition of $\hat{S}$, $\hat{T}$, W and Y in terms of canonically normalized inverse propagators Π. Middle row: the corresponding dimension 6 operators. Lower row: one-loop Feynman graphs that contribute to $\hat{S}$, $\hat{T}$, W and Y. Unspecified lines denote generic sparticles.*

G. Marandella, C. Schappacher and A. Strumia, Nucl. Phys. B **715**, 173 (2005) doi:10.1016/j.nuclphysb.2005.03.001 [hep-ph/0502095].

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Diboson/Diphoton/Dijet Resonance

SU(2)_H example

Assume

$$n_Q = n_U = 2\,,\; n_D = n_L = 3\,,\; n_E = 0\,, \quad \text{or}$$
$$n_Q = n_U = 3\,,\; n_D = n_L = n_E = 0\,,$$

- Both $\tilde{Q}$ and $\tilde{U}$ representations are respectively degenerate, *i.e.*,

$$m_{\tilde{Q}_1} = m_{\tilde{Q}_2} = \ldots\,, \quad m_{\tilde{U}_1} = m_{\tilde{U}_2} = \ldots\,,$$

  where the lower indices of $\tilde{Q}$ and $\tilde{U}$ refer to different generations.

- Both $\tilde{Q}$ and $\tilde{U}$ have similar masses, and are lighter than the other scalars,

$$m_{\tilde{Q}} \approx m_{\tilde{U}} < \text{ mass of any other hidden scalars.}$$

follows 1 examples with gauge coupling unification

$$n_Q = n_U = 2\,,\; n_D = n_L = 3\,,\; n_E = 0\,, \quad \text{or}$$
$$n_Q = n_U = 3\,,\; n_D = n_L = n_E = 0\,,$$

We haven't specified the mechanism to generate the hidden scalar masses

Diboson/Diphoton/Dijet Resonance

meson mass eigenstates S and T

$$\begin{pmatrix} S \\ T \end{pmatrix} = \frac{4\pi}{\kappa\Lambda_H}\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \tilde{Q}^\dagger\tilde{Q} \\ \tilde{U}^\dagger\tilde{U} \end{pmatrix}$$

$$n_Q = n_U = 2\ ,\ n_D = n_L = 3\ ,\ n_E = 0\ , \quad \text{or}$$
$$n_Q = n_U = 3\ ,\ n_D = n_L = n_E = 0\ ,$$

$\kappa \sim \mathcal{O}(1)$

$$\mathcal{L}_{eff} \ni \frac{\kappa}{4\pi\Lambda_H}\Big[(2\cos\theta + \sin\theta)SG^2 + 3\cos\theta\, SW^2 + (\frac{1}{3}\cos\theta + \frac{8}{3}\sin\theta)SB^2\Big] + ...,$$

suppression scales

$$\frac{1}{\Lambda_3} = \frac{\kappa(2\cos\theta + \sin\theta)}{4\pi\Lambda_H}\ ,$$
$$\frac{1}{\Lambda_2} = \frac{3\kappa\cos\theta}{4\pi\Lambda_H}\ ,$$
$$\frac{1}{\Lambda_Y} = \frac{3}{5}\frac{\kappa}{4\pi\Lambda_H}\left(\frac{1}{3}\cos\theta + \frac{8}{3}\sin\theta\right)$$

Diboson/Diphoton/Dijet Resonance

Effective interactions of a scalar S or a pseudoscalar P with the SM gauge bosons

messenger scalar formed meson

$$\mathcal{L}^S_{\rm eff} = \frac{\kappa_3^{(S)}}{\Lambda_H} S G^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2^{(S)}}{\Lambda_H} S W^i_{\mu\nu} W^{i\,\mu\nu} + \frac{5}{3}\frac{\kappa_Y^{(S)}}{\Lambda_H} S B_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{L}^P_{\rm eff} = \frac{\kappa_3^{(P)}}{\Lambda_H} P \tilde{G}^a_{\mu\nu} G^{a\,\mu\nu} + \frac{\kappa_2^{(P)}}{\Lambda_H} P \tilde{W}^i_{\mu\nu} W^{i\,\mu\nu} + \frac{5}{3}\frac{\kappa_Y^{(P)}}{\Lambda_H} P \tilde{B}_{\mu\nu} B^{\mu\nu}$$

$$\frac{1}{\Lambda_i} = \frac{\kappa_i^{(S/P)}}{\Lambda_H}, \quad i = Y,\,2,\,3.$$

S/P-dependent, O(1), characterizing details of strong dynamics

Narrow width approximation

Gluon fusion production

large gluon PDF for 13-TeV pp collisions

$$\sigma(p+p \to S/P) = \frac{\pi^2}{8}\left(\frac{\Gamma(S/P \to g+g)}{M_{S/P}}\right) \times \left[\frac{1}{s}\frac{\partial \mathcal{L}_{gg}}{\partial \tau}\right]$$

$$\frac{1}{s}\frac{\partial \mathcal{L}_{gg}}{\partial \tau} \simeq \begin{cases} 0.97 \times 10^3\ \text{pb}\ (\text{for}\sqrt{s} = 8\ \text{TeV})\,, \\ 4.4 \times 10^3\ \text{pb}\ \ (\text{for}\sqrt{s} = 13\ \text{TeV}) \end{cases}$$

$M_S \simeq 750$ TeV. renormalization scale at $\mu = M_S/2$

Diboson/Diphoton/Dijet Resonance

Focus on CP-even case

$$\Gamma(S \to g + g) = \frac{2}{\pi}\left(\frac{g_s^2}{\Lambda_3}\right)^2 M_S^3 \,,$$

$$\Gamma(S \to W^+ + W^-) = \frac{1}{2}\frac{1}{\pi}\left(\frac{g^2}{\Lambda_2}\right)^2 M_S^3 \,,$$

$$\Gamma(S \to Z + Z) = \frac{1}{4}\frac{1}{\pi}\left[\left(\frac{g^2}{\Lambda_2}\right) c_W^2 + \frac{5}{3}\left(\frac{g'^2}{\Lambda_1}\right) s_W^2\right]^2 M_S^3 \,,$$

$$\Gamma(S \to \gamma + \gamma) = \frac{1}{4}\frac{1}{\pi}\left[\left(\frac{g^2}{\Lambda_2}\right) s_W^2 + \frac{5}{3}\left(\frac{g'^2}{\Lambda_1}\right) c_W^2\right]^2 M_S^3 \,,$$

$$\Gamma(S \to Z + \gamma) = \frac{1}{2}\frac{1}{\pi}\left[\left(\frac{g^2}{\Lambda_2}\right) - \frac{5}{3}\left(\frac{g'^2}{\Lambda_1}\right)\right]^2 c_W^2 s_W^2 M_S^3 \,,$$

W, Z masses neglected

Diboson/Diphoton/Dijet Resonance

Coupling to Higgs

$$\mathcal{L} = \left(\lambda_Q \, \tilde{Q}^\dagger \tilde{Q} + \lambda_U \, \tilde{U}^\dagger \tilde{U}\right) H^\dagger H$$

↓ reparameterize $\lambda_{Q,D}$ and θ by λ.

$$\mathcal{L} = \frac{\lambda}{4\pi} \Lambda_H S H^\dagger H$$

$$\Gamma(S \to H + H^\dagger) = \frac{1}{8\pi M_S} \left(\frac{\lambda \Lambda_{\rm dyn}}{4\pi}\right)^2$$

Diboson/Diphoton/Dijet Resonance

$$n_Q = n_U = 2\ ,\ n_D = n_L = 3\ ,\ n_E = 0\ , \quad \text{or}$$
$$n_Q = n_U = 3\ ,\ n_D = n_L = n_E = 0\ ,$$

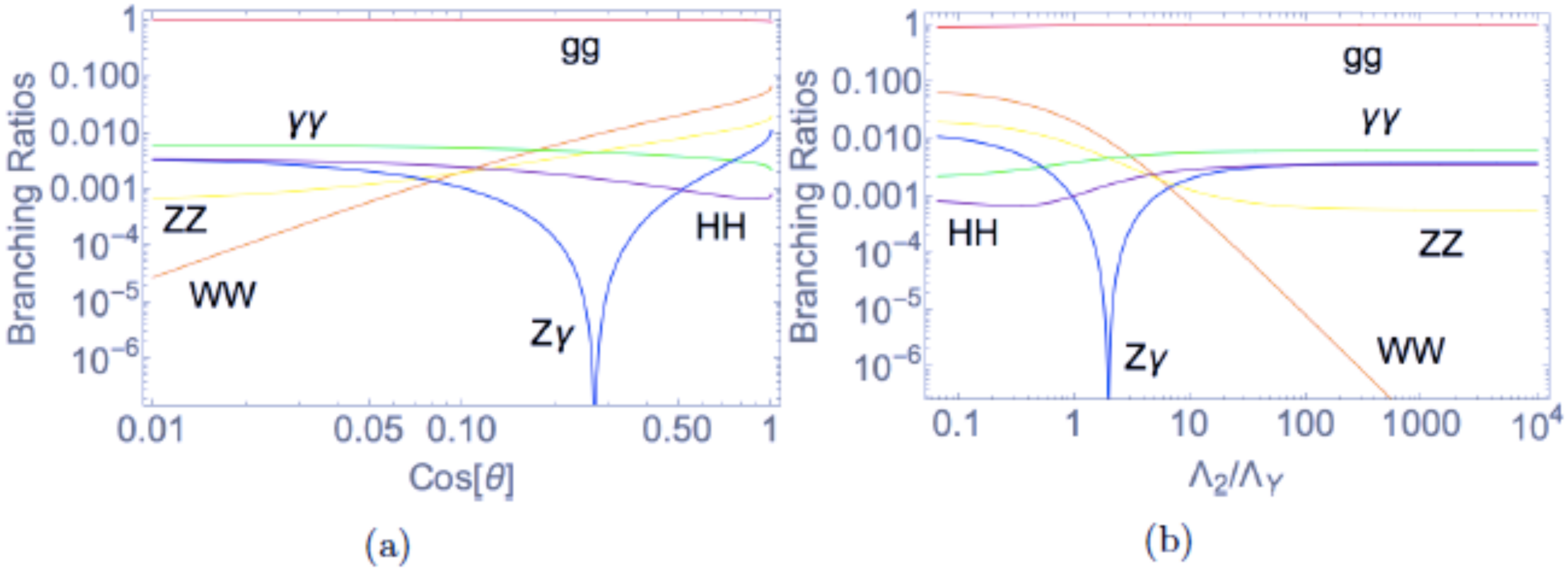

Figure 5: Branching ratios of the scalar resonance decaying into the gauge boson pairs and the Higgs boson pair as functions of $\cos\theta$ [plot (a)] and Λ_2/Λ_Y [plot (b)] for $M_S = 750$ GeV, and $\Lambda_H = 4$ TeV. (a) and (b) are depicted for $\lambda = 0.01$.

$$\mathcal{L} = \frac{\lambda}{4\pi}\Lambda_H S H^\dagger H$$

Large gluon-fusion production

Resonance is purely constructed by colored scalars

$$\Gamma(S \to H + H^\dagger) = \frac{1}{8\pi M_S}\left(\frac{\lambda\Lambda_{\rm dyn}}{4\pi}\right)^2$$

assuming $\lambda \to 0$, in the following