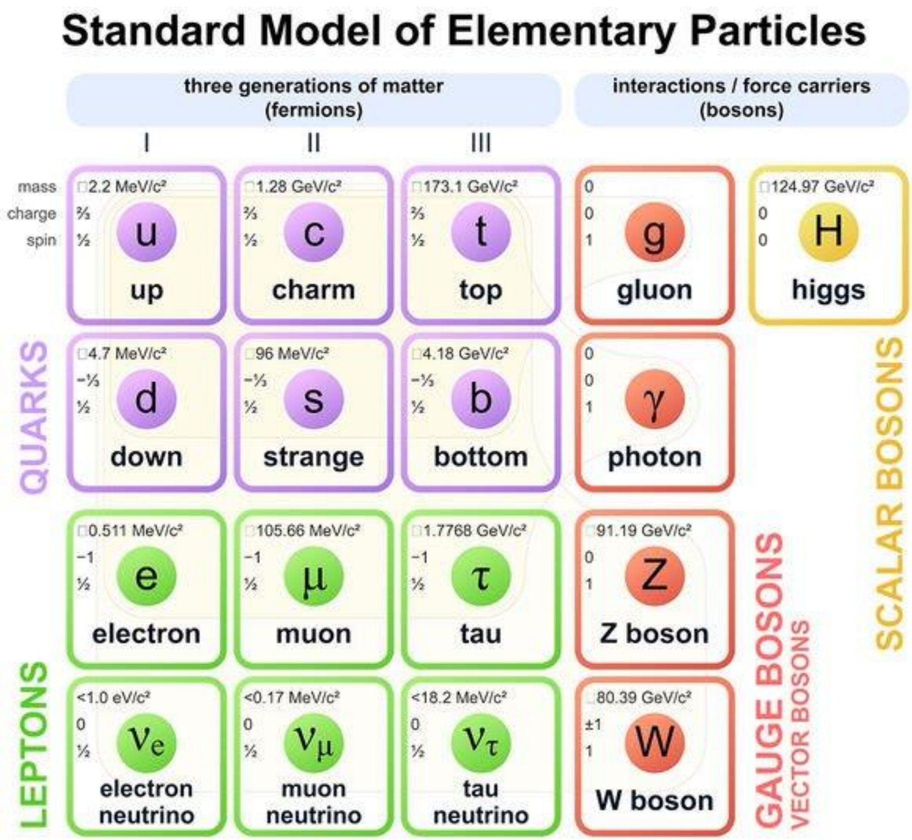
Beyond the Standard Model

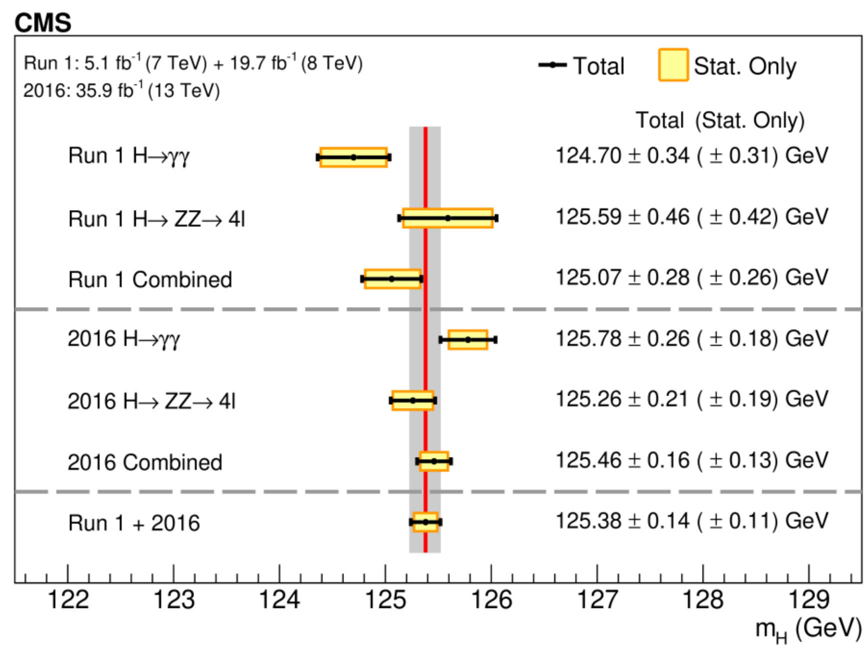
1. Electroweak theories

LHC discovered the Higgs boson

[2013]



The SM zoo is now complete



and so far *h* looks very [SM-like]

Go beyond the SM: where is the lead?

- Theory motivations

  Hierarchy problem(s), origin of SM symmetries, unification, particle mass hierarchies, etc.

- Experimental `issues'

  strong CP problem, neutrino oscillations, flavor `anomalies'

- Astronomy/cosmology

  Dark matter, dark energy, matter-antimatter asym.

- SM predictions

  electroweak phase transition, precision tests,

Topics

- Higgs fine tuning problem (susy, composite, relaxation)
- BSM Exotics & collider search
- Neutrino mass (seesaw models)
- Strong CP problem & axion

Fine tuning issues

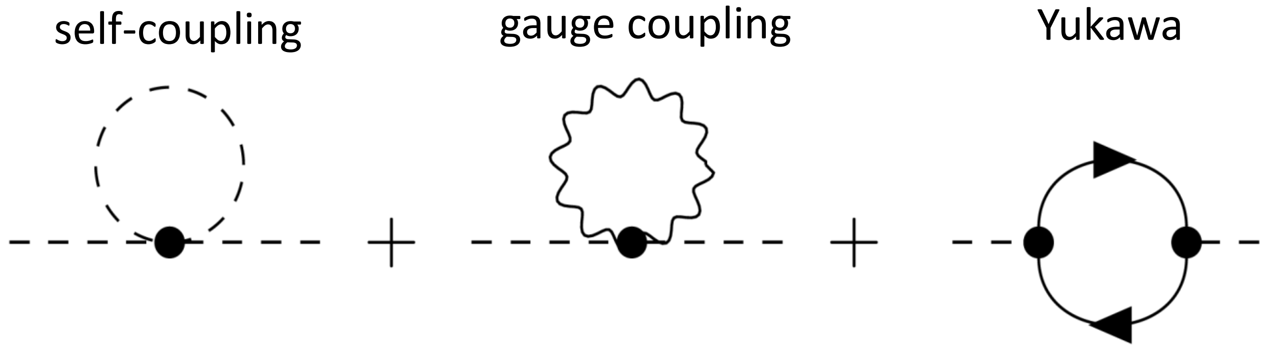
- Cosmological: $\rho_\Lambda \sim 10^{-122}\,\Lambda_{Pl}{}^4$
- Gauge: $\Lambda_{EW} \sim 10^{-16}\,\Lambda_{Pl}$
- Masses $m_e \sim 10^{-6}\, m_t$

  $m_\nu \sim 10^{-(12+)}\, m_t$

The Higgs' fine tunning problem

- Large correction to the Higgs potential

$$V(H) = -\mu^2|H|^2 + \lambda|H|^4 \qquad \langle H \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}, \quad v^2 = \frac{\mu^2}{\lambda}$$



Higgs mass correction has quadratic divergence with Λ, exceeds μ^2 for Λ >> TeV

$$-\mu^2 \to -\mu^2 + \frac{\Lambda^2}{32\pi^2}\left[-6y_t^2 + \frac{1}{4}(9g^2 + 3g'^2) + 6\lambda\right]$$

Note: Quadratic divergence explained π^0 π^+ mass difference

- Veltman condition not easy: $\delta m_H^2 = \sum_i c_i \frac{g_{i,\star}^2}{16\pi^2}\Lambda_i^2 = 0$
- Unnatural if a new physics scale exists ($\Lambda^2_{UV} >> m_h^2$).

Severe `tuning' must occur to guarantee a `small' Higgs boson mass

- Scalars generally not symmetry-protected against large corrections

fermion : $\delta m_f \sim m_f \log(\Lambda / m_f)$ chiral sym.

gauge boson : $\delta m_V^2 \sim m_V^2 \log(\Lambda / m_V)$ gauge sym.

scalar(s): $\lambda_S |H|^2 |S|^2 \longrightarrow \delta\mu^2 = \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 - m_S^2 \log\frac{\Lambda_{UV}^2}{m_S^2} + \mathcal{O}(m_S^2)\right]$

Many proposed solutions

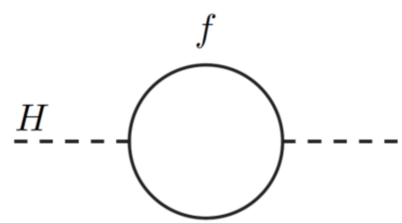
- Supersymmetry (cancellation by susy-partner)
- Composite Higgs (as a Nambu-Goldstone boson)
- Anthropics (give up)
- Warped extra dimension (dual to composite model)
- Relaxation (Dynamically rolling to bottom)
- + many others …

For exotics, see:
N.Craig. "20 ways to solve the hierarchy problem",
https://indico.cern.ch/event/550030/contributions/2417761/

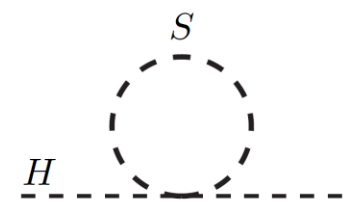
A supersymmetric solution

If some symmetry **requires** the presence of fermions and scalars, with correlated couplings $\lambda_S = |\lambda_f|^{2}$t provide cancellation.

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle$$
$$Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$



$$-\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\rm UV}^2$$



$$\frac{\lambda_S}{16\pi^2}\left[\Lambda_{\rm UV}^2 - 2m_S^2\ln(\Lambda_{\rm UV}/m_S)\right]$$

fields of definite spin → supermultiplets

chiral

$$\delta\phi_i = \epsilon\psi_i$$
$$\delta\psi_{i\alpha} = -i(\sigma^\mu\epsilon^\dagger)_\alpha\,\nabla_\mu\phi_i + \epsilon_\alpha F_i$$
$$\delta F_i = -i\epsilon^\dagger\overline{\sigma}^\mu\nabla_\mu\psi_i \;+\; \sqrt{2}g(T^a\phi)_i\,\epsilon^\dagger\lambda^{\dagger a}.$$

gauge

$$\delta A^a_\mu = -\frac{1}{\sqrt{2}}\left(\epsilon^\dagger\overline{\sigma}_\mu\lambda^a + \lambda^{\dagger a}\overline{\sigma}_\mu\epsilon\right),$$
$$\delta\lambda^a_\alpha = \frac{i}{2\sqrt{2}}(\sigma^\mu\overline{\sigma}^\nu\epsilon)_\alpha\,F^a_{\mu\nu} + \frac{1}{\sqrt{2}}\epsilon_\alpha\,D^a,$$
$$\delta D^a = \frac{i}{\sqrt{2}}\left(-\epsilon^\dagger\overline{\sigma}^\mu\nabla_\mu\lambda^a + \nabla_\mu\lambda^{\dagger a}\overline{\sigma}^\mu\epsilon\right).$$

Supersymmetric Q are (1/2,0) or (0,1/2) operators under Lorentz algebra, as extension to CM- theorem

$$\{Q_\alpha\,,\,Q^\dagger_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta}P_\mu \qquad \{Q_\alpha\,,\,Q_\beta\} = \{Q^\dagger_{\dot\alpha}\,,\,Q^\dagger_{\dot\beta}\} = 0$$
$$[Q_\alpha\,,\,P^\mu] = [Q^\dagger_{\dot\alpha}\,,\,P^\mu] = 0$$
$$\{Q_\alpha\,,\,Q_\beta\} = \{Q^\dagger_{\dot\alpha}\,,\,Q^\dagger_{\dot\beta}\} = 0$$
$$[Q_\alpha\,,\,J^{\mu\nu}] = (\sigma^{\mu\nu})_\alpha{}^\beta Q_\beta \qquad \left[Q^\dagger_{\dot\alpha}\,,\,J^{\mu\nu}\right] = -Q^\dagger_{\dot\beta}(\overline{\sigma}^{\mu\nu})^{\dot\beta}{}_{\dot\alpha}$$

Haag, J. Lopuszanski, and M. Sohnius, 75'
S. Coleman and J. Mandula, 67'

The supersymmetric Lagrangian.

chiral: fermions and scalars & susy partners
gauge: gauge boson & susy partners

	ϕ	ψ	F
on-shell ($n_B = n_F = 2$)	2	2	0
off-shell ($n_B = n_F = 4$)	2	4	2

	A_μ	λ	D
on-shell ($n_B = n_F = 2$)	2	2	0
off-shell ($n_B = n_F = 4$)	3	4	1

$$\mathcal{L} = \mathcal{L}_{\text{chiral}} + \mathcal{L}_{\text{gauge}} \\ -\sqrt{2}g(\phi^* T^a \psi)\lambda^a - \sqrt{2}g\lambda^{\dagger a}(\psi^\dagger T^a \phi) + g(\phi^* T^a \phi)D^a.$$

gaugino to matter

$$\mathcal{L}_{\text{chiral}} = -\partial^\mu \phi^{*i}\partial_\mu \phi_i + i\psi^{\dagger i}\overline{\sigma}^\mu \partial_\mu \psi_i - \frac{1}{2}\left(W^{ij}\psi_i\psi_j + W^*_{ij}\psi^{\dagger i}\psi^{\dagger j}\right) - W^i W^*_i.$$

free fields
(cov. deriv. for gauged interaction)

scalar-fermion interactions

scalar interactions

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a} + i\lambda^{\dagger a}\overline{\sigma}^\mu \nabla_\mu \lambda^a + \frac{1}{2}D^a D^a$$

$$\nabla_\mu \lambda^a = \partial_\mu \lambda^a + g f^{abc} A^b_\mu \lambda^c$$

covariant deriv.

The Superpotential (scalars)

$$W = L^i \phi_i + \frac{1}{2}M^{ij}\phi_i\phi_j + \frac{1}{6}y^{ijk}\phi_i\phi_j\phi_k.$$

$$W^{ij} = \frac{\delta^2}{\delta\phi_i \delta\phi_j}W$$

The scalar potential

$$V(\phi, \phi^*) = W^*_i W^i + \frac{1}{2}\sum_a g_a^2 (\phi^* T^a \phi)^2.$$

"F-term" ~ $F^{*i}F_i$

"D-term": ~ $D^a D^a/2$

$$F_i = -W^*_i \qquad D^a = -g(\phi^* T^a \phi)$$

Supersymmetric particle content

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times 3$ families)	$\overline{u}$	$\widetilde{u}_R^*$	$u_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}_R^*$	$d_R^\dagger$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times 3$ families)	$\overline{e}$	$\widetilde{e}_R^*$	$e_R^\dagger$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H_u^+\ \ H_u^0)$	$(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H_d^0\ \ H_d^-)$	$(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Each SM chiral fermion component has a sfermion partner.

Two Higgs multiplets with fermionic partners (ensures no gauge anomaly)

SM gauge boson acquires gaugino parnters

Minimal Supersymmetric Standard Model

The MSSM superpotential

$$W_{\rm MSSM} = \overline{u}\mathbf{y_u}QH_u - \overline{d}\mathbf{y_d}QH_d - \overline{e}\mathbf{y_e}LH_d + \mu H_u H_d \, .$$

The μ term: gives higgs(ino) mass

$$-\mathcal{L}_{\rm higgsino} = \mu(\widetilde{H}_u^+ \widetilde{H}_d^- - \widetilde{H}_u^0 \widetilde{H}_d^0) + {\rm c.c.}$$

Higgs mass-square terms

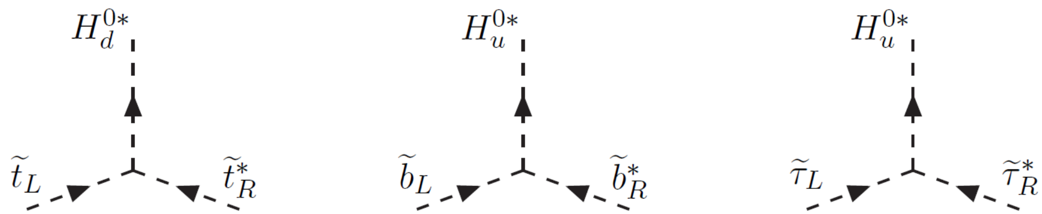
$$= |\mu|^2(|H_u^0|^2 + |H_u^+|^2 + |H_d^0|^2 + |H_d^-|^2).$$

H^0: non-negative & min. at H^0=0
Need additional (soft) terms to
make non-zero min.

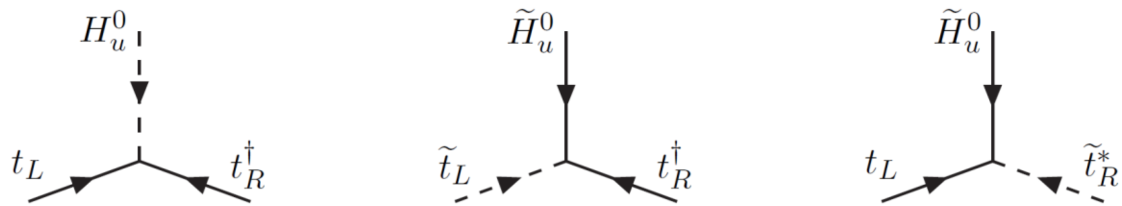
S^4 vertices $\sim y_t^2$

S^3 vertices

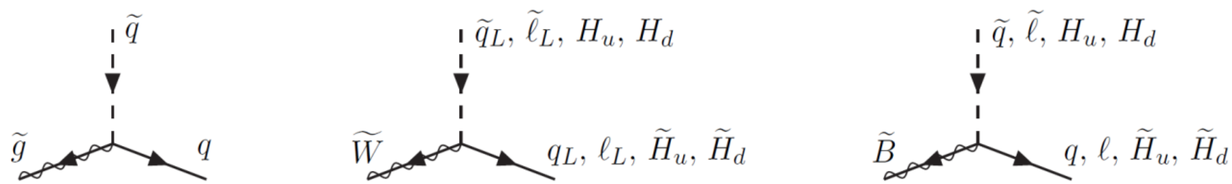
(sfermion mixing)



`yukawa'



gauge

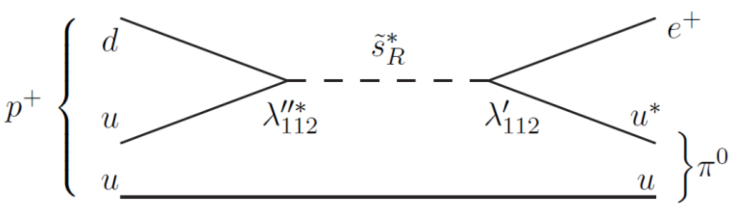


R-parity

B, L # violating superpotential terms:

$$W_{\Delta L=1} = \frac{1}{2}\lambda^{ijk}L_iL_j\overline{e}_k + \lambda'^{ijk}L_iQ_j\overline{d}_k + \mu'^i L_iH_u$$
$$W_{\Delta B=1} = \frac{1}{2}\lambda''^{ijk}\overline{u}_i\overline{d}_j\overline{d}_k$$

proton decay:



$$\Gamma_{p\to e^+\pi^0} \sim m^5_{\rm proton}\sum_{i=2,3}|\lambda'^{11i}\lambda''^{11i}|^2/m^4_{\tilde{d}_i}$$

Impose a $U(1)_R$ that breaks to discrete Z_2

$$P_R = (-1)^{3(B-L)+2s}$$

$$R = \begin{cases} +1\,, & \text{for all SM particle particles}\,, \\ -1\,, & \text{for all superpartners}\,. \end{cases}$$

Lightest Sparticle Particle (LSP), L=-1 becomes stable and can be dark matter (if neutral)

Susy is broken.

- Unbroken susy requires SM particle & partner have the same mass (unobserved)

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

Soft susy-breaking terms contain mass terms & positive dimensional coupling terms

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

gaugino mass — scalar cubic — non-holomorphic

- Susy restores m_{soft} ->0, expected contribution:

L_{soft} maintains quadratic div. cancellation

Girardello & Grisaru, 82'

$$\Delta m_H^2 = m_{\rm soft}^2\left[\frac{\lambda}{16\pi^2}\ln(\Lambda_{\rm UV}/m_{\rm soft}) + \ldots\right]$$

MSSM soft breaking terms

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$
$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right)$$
$$-\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger$$
$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.$$

$$M_1,\ M_2,\ M_3,\ \mathbf{a_u},\ \mathbf{a_d},\ \mathbf{a_e}\ \sim\ m_{\text{soft}},$$
$$\mathbf{m_Q^2},\ \mathbf{m_L^2},\ \mathbf{m_{\overline{u}}^2},\ \mathbf{m_{\overline{d}}^2},\ \mathbf{m_{\overline{e}}^2},\ m_{H_u}^2,\ m_{H_d}^2,\ b\ \sim\ m_{\text{soft}}^2,$$

105 new independent masses, phases & mixing angles in MSSM
Dimopoulos, Sutter, 95'

`soft susy-breaking universality'

$$\mathbf{m_Q^2} = m_Q^2\mathbf{1},\quad \mathbf{m_{\overline{u}}^2} = m_{\overline{u}}^2\mathbf{1},\quad \mathbf{m_{\overline{d}}^2} = m_{\overline{d}}^2\mathbf{1},\quad \mathbf{m_L^2} = m_L^2\mathbf{1},\quad \mathbf{m_{\overline{e}}^2} = m_{\overline{e}}^2\mathbf{1}.$$

no flavor mixing (avoid large FCNC)

$$\mathbf{a_u} = A_{u0}\,\mathbf{y_u},\qquad \mathbf{a_d} = A_{d0}\,\mathbf{y_d},\qquad \mathbf{a_e} = A_{e0}\,\mathbf{y_e},$$

$$\text{Im}(M_1),\ \text{Im}(M_2),\ \text{Im}(M_3),\ \text{Im}(A_{u0}),\ \text{Im}(A_{d0}),\ \text{Im}(A_{e0})\ =\ 0,$$

no additional CPV

EWSB in MSSM

The MSSM Higgs potential (neutral fields, with soft terms)

b & vevs are chosen real and positive

$$V = (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b\, H_u^0 H_d^0 + \text{c.c.}) + \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2.$$

`D-flat': quartic vanishes if $|H_u^0| = |H_d^0|$

Sensible EWSB requires:

Positive quadratic in D-flat: $$2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2.$$

Existence of a negative square-mass at $H_u^0=H_d^0=0$ $$b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2).$$

$m^2_{Hu} \neq m^2_{Hd}$ at least @ EW scale

Potential minimization $\partial V/\partial H_u^0 = \partial V/\partial H_d^0 = 0$ gives

$$m_{H_u}^2 + |\mu|^2 - b\cot\beta - (m_Z^2/2)\cos(2\beta) = 0,$$
$$m_{H_d}^2 + |\mu|^2 - b\tan\beta + (m_Z^2/2)\cos(2\beta) = 0.$$

$$\sin(2\beta) = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2},$$
$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1-\sin^2(2\beta)}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2.$$

$$2m_Z^2/(g^2+g'^2) = v_u^2 + v_d^2$$
$$v_u = \langle H_u^0\rangle \quad v_d = \langle H_d^0\rangle$$
$$\tan\beta \equiv v_u/v_d$$

large tanβ limit:

$$m_Z^2 = -2(m_{H_u}^2 + |\mu|^2) + \frac{2}{\tan^2\beta}(m_{H_d}^2 - m_{H_u}^2) + \mathcal{O}(1/\tan^4\beta)$$

Cancellation is again needed if $-m_{H_u}^2$, $\mu^2 >> m_Z^2$ → `μ problem'

The Higgs masses (tree)

$$V = \frac{1}{2}m^2_{h^0}(h^0)^2 + \frac{1}{2}m^2_{H^0}(H^0)^2 + \frac{1}{2}m^2_{G^0}(G^0)^2 + \frac{1}{2}m^2_{A^0}(A^0)^2$$
$$+m^2_{G^\pm}|G^+|^2 + m^2_{H^\pm}|H^+|^2 + \ldots,$$

$$\begin{pmatrix} H_u^+ \\ H_d^{-*} \end{pmatrix} = R_{\beta_\pm}\begin{pmatrix} G^+ \\ H^+ \end{pmatrix}$$

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}}R_\alpha\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}}R_{\beta_0}\begin{pmatrix} G^0 \\ A^0 \end{pmatrix}$$

Physical scalars:
h^0, H^0, A^0, H^+

generally heavy except h^0.
At tree-level:

$$m_{h^0} < m_Z|\cos(2\beta)|$$

At tree level, $m_{G0}{}^2=0$, $\beta_0 = \beta_\pm = \beta$

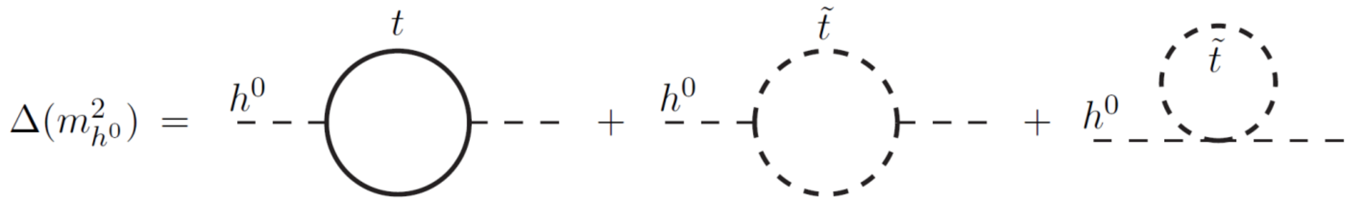
h^0 mass needs a lift.
(measured at 125 GeV)

$$m^2_{A^0} = 2b/\sin(2\beta) = 2|\mu|^2 + m^2_{H_u} + m^2_{H_d}$$
$$m^2_{h^0,H^0} = \frac{1}{2}\Big(m^2_{A^0} + m^2_Z \mp \sqrt{(m^2_{A^0} - m^2_Z)^2 + 4m^2_Z m^2_{A^0}\sin^2(2\beta)}\Big),$$
$$m^2_{H^\pm} = m^2_{A^0} + m^2_W.$$

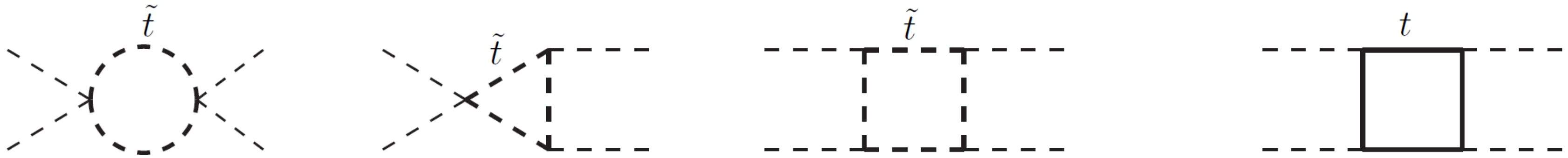
μ & soft masses

Loop correction

stop correction
to h^0 mass



stop correction to quartic



Large stop contribution limit:

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2} \cos^2\alpha \; y_t^2 m_t^2 \left[\ln(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2) + \Delta_{\rm threshold}\right],$$

Last term from stop mixing,
maximize with large $\tilde{t}_L$ $\tilde{t}_R$ mixing.
For TeV sparticles, $m_{h^0} \lesssim 135$ GeV

$$\Delta_{\rm threshold} = c_{\tilde{t}}^2 s_{\tilde{t}}^2 [(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)/m_t^2] \ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2) + c_{\tilde{t}}^4 s_{\tilde{t}}^4 \left[(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4) \ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2)\right]/m_t^4$$

For review, see P. Draper and H. Rzehak,1601.01890

`Next to' MSSM (NMSSM)

Nilles, Srednicki, Wyler, 83',
Fr`ere, Jones, Raby, 83'
Derendinger,Savoy, 84'

Addition of a singlet to the MSSM.
SH_uH_d term + self couplings

$$W_{\rm NMSSM} = W_{\rm MSSM} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 + \frac{1}{2}\mu_S S^2$$

and extra soft-terms

$$\mathcal{L}_{\rm soft}^{\rm NMSSM} = \mathcal{L}_{\rm soft}^{\rm MSSM} - (a_\lambda S H_u H_d - \frac{1}{3}a_\kappa S^3 + \frac{1}{2}b_S S^2 + tS + {\rm c.c.}) - m_S^2|S|^2$$

A solution to the mu-problem:

in the limit of $\mu_{MSSM} = \mu_S = 0$, $b_{MSSM} = b_S = 0$, $t=0$
(can be enforced by a Z_3 on all chiral multiplets)
Spontaneous EWSB occurs at nonzero $\langle s \rangle = v_S$
`Dynamically' generating an effective $\mu_{eff} = \lambda v_S$.

tree level correction to h^0 mass
(via singlet $|F|^2$)

$$\Delta(m_{h^0}^2) \leq \lambda^2 v^2 \sin^2(2\beta)$$

Bonus: a global $U(1)_{PQ}$ emerges when setting $\mu=0$. EWSB ↔ Strong CP

some features in NMSSM…

- Additional (to MSSM) singlet H,A and singlino

→Self-interacting DM

light as $\kappa \to 0$, dark as $\lambda \to 0$ (S decouples)

- Large λ gets a Landau pole

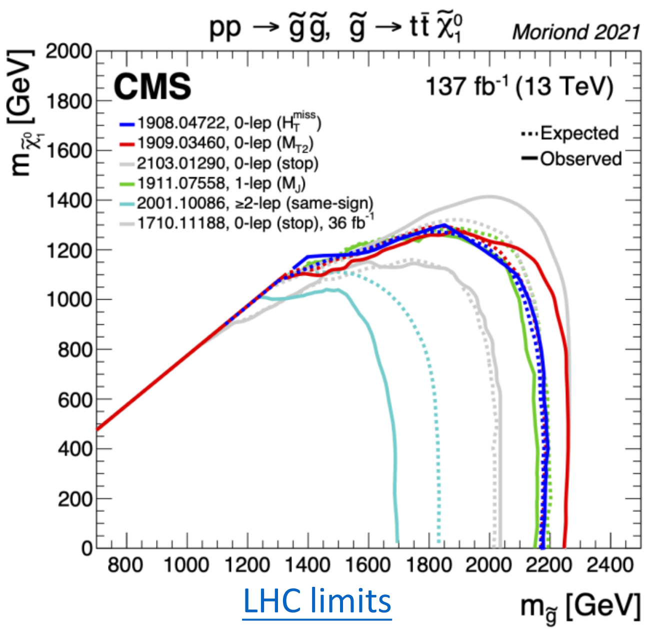
"λ-susy"

$\lambda \sim 0.7$ for $\Lambda_{pole} \sim \Lambda_{GUT}$ $\lambda \sim 2$ for $\Lambda_{pole} \sim 10$ TeV

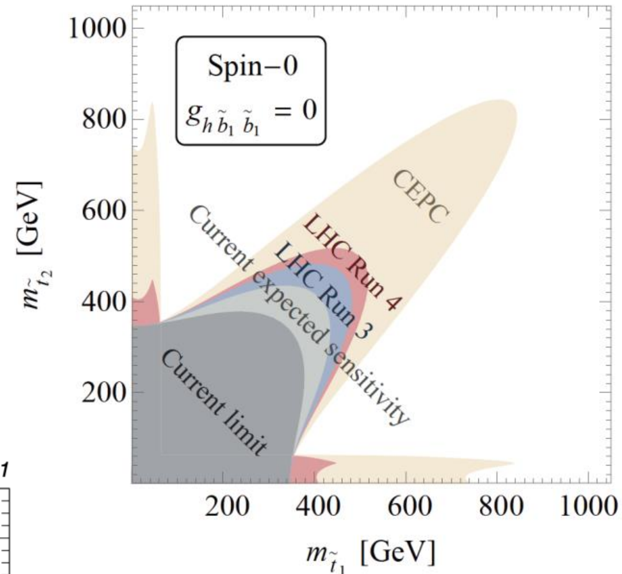
- Singlet scalar may give mass to neutrinos (via seesaw)
- Higgs coupling to SM (g_{hVV}, g_{hff}), suppressed by doublet-singlet mixing.

Where is susy?

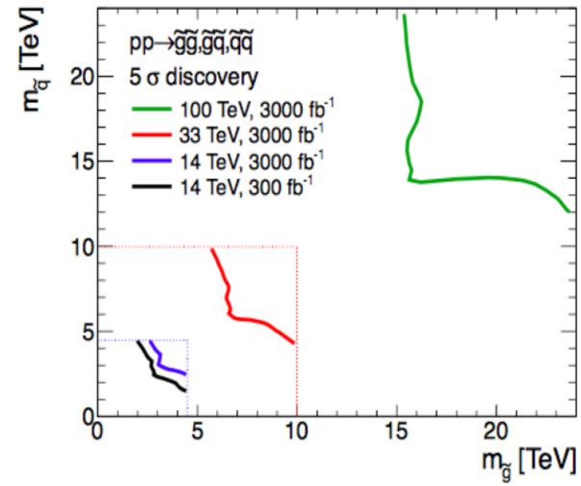
- Lots of sparticles.
- Extra (pseudo)/scalars.
- Dark matter candidate?
- Virtual corrections?
  (g-2, Higgs precisions, etc.)



LHC limits



CEPC: stop correction to effective hgg, hγγ couplings.
Essig,Meade,Ramani, Zhong, 1707.03399

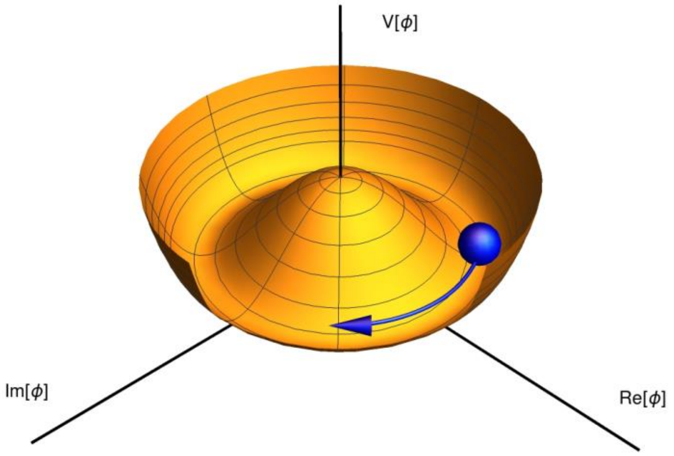


Future collider reach,
J.Ellis, 2015

The composite Higgs solution

Georgi, Kaplan `84

- A global symmetry **G** breaks to a subgroup **H** at some scale f , the Higgs boson lives in the coset **G/H**.
- h is a Nambu-Goldstone boson, shift symmetry protects m_h.
- $m_h \neq 0$ requires breaking of **G**.



Sketch of (Goldstone) mode in degenerate vacua (C.Csáki 18)

A toy composite scenario

SU(3)/SU(2) : Global SU(3) breaks into SU(2) by a vac. condensate Σ_0

$$\Sigma_0 = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

One NGB for each broken generator:

SU(3): 8 → SU(2): 3

5 NGBs π^a (a=1~5) → one SU(2) doublet H and one singlet S

Dynamics below $\Lambda=4\pi f$ described a nonlinear sigma model (nlsm)

$$\Sigma(x) = \frac{1}{f} \exp\left(\frac{2i\pi^a(x)X^a}{f}\right)\Sigma_0$$

X^a: broken generators

$$2\pi^a(x)X^a = \begin{pmatrix} 0 & H(x) \\ H^\dagger(x) & 0 \end{pmatrix} + \frac{s(x)}{2\sqrt{2}}\begin{pmatrix} \mathbb{1} & 0 \\ 0 & -2 \end{pmatrix}$$

Has only derivatives if the global SU(3) is exact. Leading term contains lowest derivative terms:

$$\mathcal{L}_{\rm kin} = f^2\, \partial_\mu \Sigma^\dagger \partial^\mu \Sigma$$

see M.Perelstein, 05’

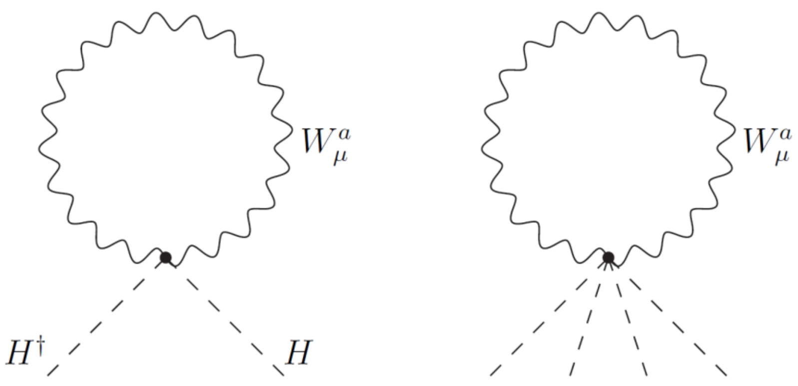
- Gauging the SU(2) subgroup to break global SU(3)

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu - igW^a_\mu(x)Q^a$$

Now the SU(3)/SU(2) effective nlsm Lagrangian contains SU(2) gauge interactions for H, and derives quadratic and quartic diagrams at loop level

W^a_μ are the SU(2) gauge fields, Q^a (a=1...3) are gauged generators:

$$Q^a = \begin{pmatrix} \sigma^a/2 & 0 \\ 0 & 0 \end{pmatrix}$$



Both diagrams are quadratic with cut-off Λ~4πf

$$\mu^2 = c\frac{g^2}{16\pi^2}\Lambda^2 \sim cg^2 f^2, \quad \lambda = c'\frac{g^2}{f^2}\frac{1}{16\pi^2}\Lambda^2 \sim c'g^2$$

→ EWSB induced by physics at scale f.

$$m_H = \sqrt{2}|\mu| \approx \sqrt{c}gf$$

for large f, natural Higgs mass seems heavy. $m_H = \sqrt{2}|\mu| \approx \sqrt{c}gf$

$$\mathcal{O}_1 = \frac{1}{\Lambda^2}\left|H^\dagger D_\mu H\right|^2, \quad \mathcal{O}_2 = \frac{1}{\Lambda^2}\left(H^\dagger \sigma^a H\right) W^a_{\mu\nu} B^{\mu\nu}$$

+ Problem terms:
EW precision test: $\Lambda > O(10)$ TeV

The `little hierarchy' problem

Collective Symmetry Breaking:

Consider a product of multiple global G_1xG_2x..., each has an SU(2)xU(1) subgroup.
Each G_i commutes with one subgroup of G that acts nonlinearly on the Higgs.

→ All G_i subgroups must be collectively gauged to avoid leaving an unbroken global symmetry that makes the Higgs massless.

→ Non-derivative terms proportional to the product of all G_i's gauge subgroup couplings

→ Can also fix the fermion contribution: must involve all Yukawa(s) if each preserves some global symmetry.

The littlest Higgs model SU(5)/S0(5)

N. Arkani-Hamed, A.Cohen, E.Katz and A.E.Nelson, 2002’

- An SU(5)/SO(5) non-linear sigma model, SU(5) spontaneoulsy breaks to SO(5) by

$$\Sigma_0 = \begin{pmatrix} 0 & 0 & \mathbb{1} \\ 0 & 1 & 0 \\ \mathbb{1} & 0 & 0 \end{pmatrix}$$

24 − 10 = 14 broken generators, thus 14 NGBs,

$$\Sigma(x) = e^{i\Pi/f}\Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f}\Sigma_0$$

$$\Pi(x) = \sum_{a=1}^{14} \pi^a(x) X^a$$

$$Q_1^a = \begin{pmatrix} \sigma^a/2 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

global symmetry is explicitly broken by gauging $[SU(2)\times U(1)]^2$ subgroup of the SU(5)

$$Q_2^a = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*}/2 \end{pmatrix}$$

$$\mathcal{L}_{\rm kin} = \frac{f^2}{8}\mathrm{Tr}(D_\mu\Sigma)(D^\mu\Sigma)^\dagger$$

$$\partial_\mu\Sigma \to D_\mu\Sigma = \partial_\mu\Sigma - i\sum_{j=1}^{2}\left[g_j W_{j\mu}^a(Q_j^a\Sigma + \Sigma Q_j^{aT}) + g_j' B_{j\mu}(Y_j\Sigma + \Sigma Y_j)\right]$$

[SU(2)xU(1)]^2 first breaks into diagonal SU(2)xU(1).
Then the latter breaks at EW scale.

$$g = \frac{g_1 g_2}{\sqrt{g_1^2 + g_2^2}}, \quad g' = \frac{g_1' g_2'}{\sqrt{g_1'^2 + g_2'^2}} \qquad \tan\psi = \frac{g_2}{g_1}, \quad \tan\psi' = \frac{g_2'}{g_1'}$$

One copy of heavy gauge bosons acquire f-scale masses (B_H and W_H)

$$M(W_H) = \frac{g}{\sin 2\psi} f, \quad M(B_H) = \frac{g'}{\sqrt{5}\sin 2\psi'} f$$

$$W_H^a = -\cos\psi\, W_1^a + \sin\psi\, W_2^a, \quad B_H = -\cos\psi'\, B_1 + \sin\psi'\, B_2$$

and a copy of light gauge bosons

$$W_L^a = \sin\psi\, W_1^a + \cos\psi\, W_2^a, \quad B_L = \sin\psi'\, B_1 + \cos\psi'\, B_2$$

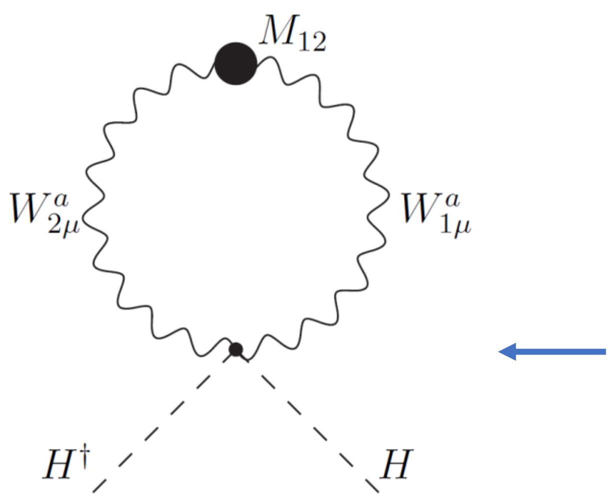
The pNGBs:

$$\Pi = \begin{pmatrix} -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\omega^+/\sqrt{2} & H^+/\sqrt{2} & -i\phi^{++} & -i\frac{\phi^+}{\sqrt{2}} \\ -\omega^-/\sqrt{2} & \omega^0/2 - \eta/\sqrt{20} & H^0/\sqrt{2} & -i\frac{\phi^+}{\sqrt{2}} & \frac{-i\phi^0+\phi_P^0}{\sqrt{2}} \\ H^-/\sqrt{2} & H^{0*}/\sqrt{2} & \sqrt{4/5}\eta & H^+/\sqrt{2} & H^0/\sqrt{2} \\ i\phi^{--} & i\frac{\phi^-}{\sqrt{2}} & H^-/\sqrt{2} & -\omega^0/2 - \eta/\sqrt{20} & -\omega^-/\sqrt{2} \\ i\frac{\phi^-}{\sqrt{2}} & \frac{i\phi^0+\phi_P^0}{\sqrt{2}} & H^{0*}/\sqrt{2} & -\omega^+/\sqrt{2} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} \end{pmatrix},$$

	SU(2)	U(1)
η^*	1	0
ω^*	3	0
H	2	½
ϕ	3	1

Collective breaking:

each Q^a_i, Y_i (i=1,2) generator commutes with an SU(3) inside SU(5).



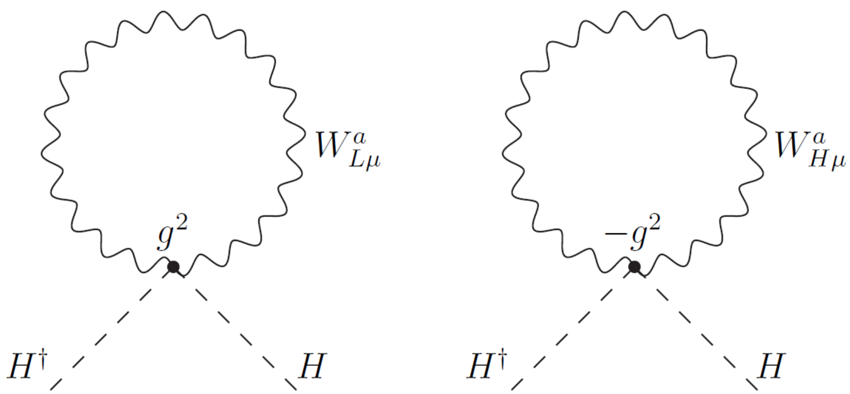
$$\frac{1}{4} H^\dagger H \left(g_1 g_2 W_1^{\mu a} W^a_{2\mu} + g_1' g_2' B_1^\mu B_{2\mu} \right)$$

~ log divergence with Λ

Any diagram renormalizing the Higgs mass vanishes unless involves both g_1 and g_2.

Couplings written in mass eigenstates W_L, W_H :

$$\frac{1}{4}\,H^\dagger\,H\Big(\underline{g^2(W^a_{L\mu}W^{\mu a}_L}\;\underline{-\,W^a_{H\mu}W^{\mu a}_H}-2\cot 2\psi\,W^a_{H\mu}W^{\mu a}_L)+ g'^2(B_{L\mu}B^\mu_L-B_{H\mu}B^\mu_H-2\cot 2\psi'\,B_{H\mu}B^\mu_L)\Big)\,.$$



quadratic ~ Λ^2 cancel
due to removal of diagonal (W_iW_i)
couplings by collecting breaking

Fixing the top loop

Extend top Yukawa to incorporate CSB.

$$q_{3L} = (u_L, b_L)^T \quad \chi_L = \begin{pmatrix} \sigma_2 q_{3L} \\ U_L \end{pmatrix}$$

$$\mathcal{L}_{\rm top} = -\frac{\lambda_1}{2} f\, \chi^\dagger_{Li} \epsilon_{ijk} \epsilon_{mn} \Sigma_{jm} \Sigma_{kn} u_{3R} - \lambda_2 f\, U^\dagger_L U_R + \text{h.c.}$$

Σ_{jm} denotes the 3×2 upper-right block of Σ, (i, j, k =1,2,3; m,n = 4,5),

T acquires f scale mass. Higgs decouples if λ_1=0; Higgs is NGB if λ_2=0

$$t_L = u_L, \qquad t_R = \frac{\lambda_2 u_{3R} - \lambda_1 U_R}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

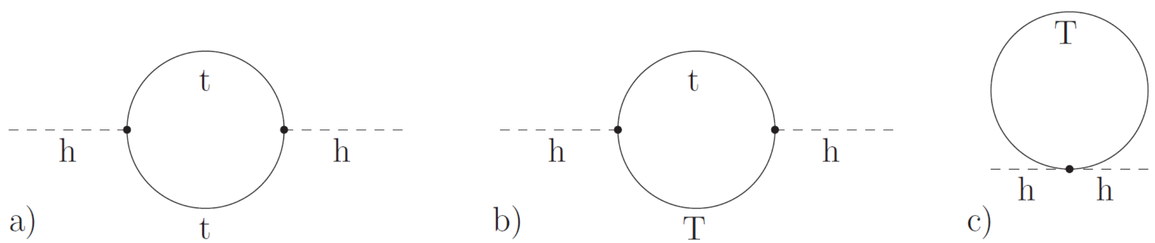
$$T_L = U_L, \qquad T_R = \frac{\lambda_1 u_{3R} + \lambda_2 U_R}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

Top Yukawas, etc.

$$\lambda_1\left(\sqrt{2}q_L^\dagger\tilde{H}-\frac{1}{f}H^\dagger H U_L^\dagger\right)u_{3R}\ +\ \text{h.c.}$$
$$=\lambda_t q_L^\dagger\tilde{H}t_R\ +\ \lambda_T q_L^\dagger\tilde{H}T_R-\frac{1}{\sqrt{2}f}(H^\dagger H)T_L^\dagger\left(\lambda_T T_R+\lambda_t t_R\right)\ +\ \text{h.c.}$$

$$\lambda_t=\frac{\sqrt{2}\lambda_1\lambda_2}{\sqrt{\lambda_1^2+\lambda_2^2}},\qquad \lambda_T=\frac{\sqrt{2}\lambda_1^2}{\sqrt{\lambda_1^2+\lambda_2^2}}.$$

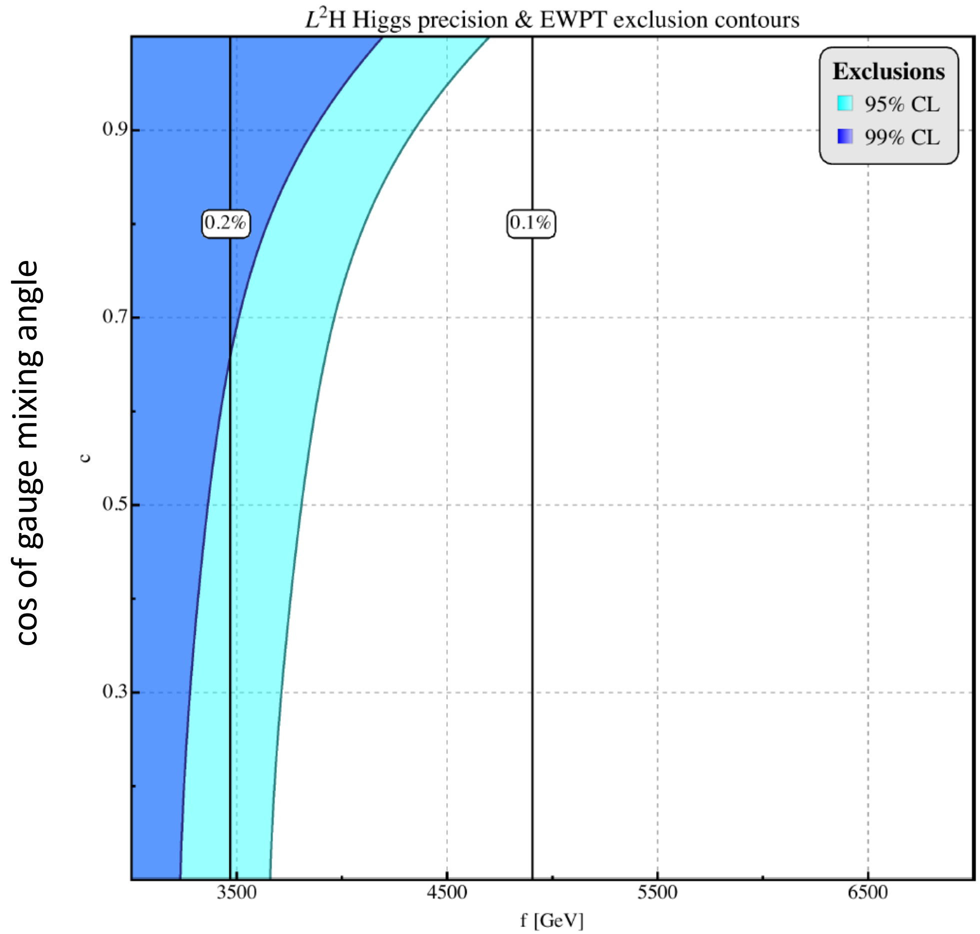
Mass eigenstate diagrams



$$-6\lambda_t^2\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2}\qquad -6\lambda_T^2\int\frac{d^4k}{(2\pi)^4}\frac{1}{k^2-M_T^2}\qquad +6\frac{\sqrt{2}\lambda_T}{f}\int\frac{d^4k}{(2\pi)^4}\frac{M_T}{k^2-M_T^2}$$

cancel as $\dfrac{M_T}{f}=\dfrac{\lambda_t^2+\lambda_T^2}{\sqrt{2}\lambda_T}$

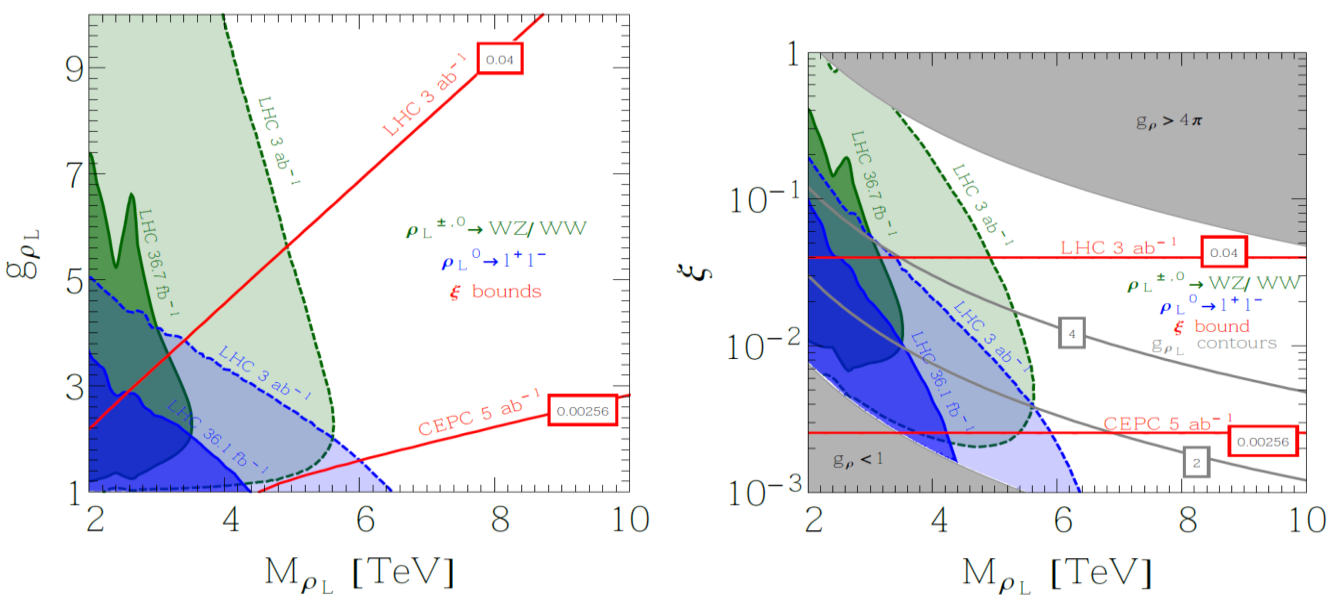
hep-ph/0310039



Littlest Higgs (L^2H) limits, snowmass 2013
Less constrained in LH with T-parity

- For composite Higgs reviews, see [1512.00468](), [2002.04914](), etc

- Intriguing application of the pion's success story for the EW sector
- as a pNGB, generally not too far below Λ. (LHC: m_h=125 GeV)
- New physics at Λ: Heavy composites, heavy gauge bosons, etc. 1805.01476
- EW precision tests. (LEP: typically Λ > 5-10 TeV) → less with discrete T-parity
- Higgs precision tests? (coming with future lepton colliders) 1709.06103, 1502.01701



minimal SO(5)/SO(4) coset

$$\xi = \frac{g_\rho^2}{m_\rho^2} v^2$$

$$m_\rho \sim g_\rho f$$

from CEPC whitepaper

A cosmic relaxation of hierarchy?

Graham, Kaplan, Rajendran,15'

$$V(H,\phi) = \mu^2(\phi)H^\dagger H + \lambda(H^\dagger H)^2 + V(\phi) + \Delta V_{\rm br}(h,\phi)$$

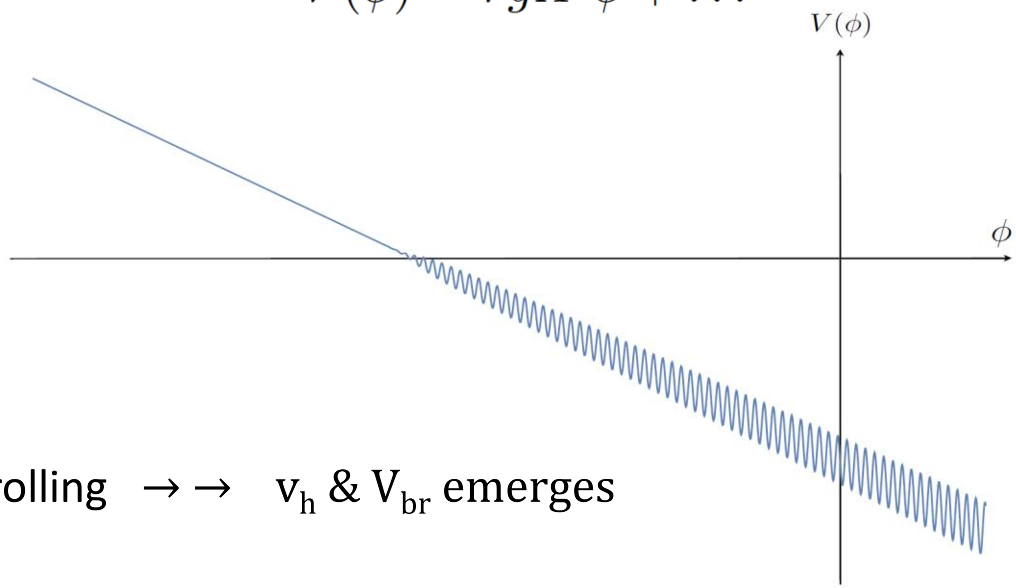
the `problem' term.
ϕ is a field at high scale Λ

$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi + \ldots$$

ϕ rolls downs its own potential

$$V(\phi) = rg\Lambda^3\phi + \ldots$$

`back-reaction' puts up barriers as v_h increases



ϕ rolling → → v_h & V_{br} emerges

SSB: Rolling of ϕ makes quadratic term more negative and causes Higgs vev ≠ 0.

Why EW scale: V_{br} must `know' exactly where to hit brake.

$$\Delta V_{\rm br}(h,\phi) = -\tilde{M}^{4-j}\hat{h}^j \cos\left(\frac{\phi}{f}\right)$$

ϕ gets an axionic potential from a strong sector (QCD or new physics), where the fermions get mass from v_h.

axionic potential magnitude increases with v_h, so at some point ϕ gets stuck.

QCD-axion model: $$\Delta V_{\rm br} \simeq -m_u \cos\frac{\phi}{f}\langle\bar{q}q\rangle \simeq -4\pi f_\pi^3 m_u \cos\frac{\phi}{f}$$

issue: relaxation doesn't guarantee stopping at ϕ/f ->0

New strong sector near EW scale?

see 1610.02025 for review

techniquarks $$\Lambda_{\rm br}^4 \simeq \frac{y v'^3 v_H}{\sqrt{2}}$$

EW symmetric condensates $$\Delta V_{\rm br} \simeq -\frac{4\pi f_{\pi'}^3 y_1 y_2 \hat{h}^2}{m_L}\cos\frac{\phi}{f}$$

A new light boson mode (relaxion)

minimizing the potential

$$V = \left[-\Lambda^2 + g\Lambda\phi + \ldots\right]\hat{h}^2 + \lambda\hat{h}^4 + rg\Lambda^3\phi + rg^2\Lambda^2\phi^2 - \tilde{M}^3\hat{h}\cos\left(\frac{\phi}{f}\right)$$

(j=1 model)

near expected vev(s) yields:

$$\phi = \phi_0 + \phi', \qquad \hat{h} = \frac{v_H + h'}{\sqrt{2}}$$

$$\lambda v_H^2 - \Lambda^2 + g\Lambda\phi_0 - \frac{\tilde{M}^3}{\sqrt{2}v_H}\cos\left(\frac{\phi_0}{f}\right) = 0$$

$$rg\Lambda^3 + 2rg^2\Lambda^2\phi_0 + \frac{g\Lambda v_H^2}{2} + \frac{\tilde{M}^3 v_H}{\sqrt{2}f}\sin\left(\frac{\phi_0}{f}\right) = 0$$

The mass matrix

$$M^2_{h'h'} \equiv \frac{\partial^2 V}{\partial h'\partial h'} = 3\lambda v_H^2 - \Lambda^2 + g\Lambda\phi = 2\lambda v_H^2 + \frac{\tilde{M}^3}{\sqrt{2}v_H}\cos\left(\frac{\phi_0}{f}\right),$$ → weak scale mass

$$M^2_{h'\phi'} \equiv \frac{\partial^2 V}{\partial h\partial\phi'} = g\Lambda v_H + \frac{\tilde{M}^3}{\sqrt{2}f}\sin\left(\frac{\phi_0}{f}\right) \simeq \frac{\tilde{M}^3}{\sqrt{2}f}\sin\left(\frac{\phi_0}{f}\right),$$ → small off-diag

$$M^2_{\phi'\phi'} \equiv \frac{\partial^2 V}{\partial\phi'\partial\phi'} = \frac{\tilde{M}^3 v_H}{\sqrt{2}f^2}\cos\left(\frac{\phi_0}{f}\right) + 2rg^2\Lambda^2 \simeq \frac{\tilde{M}^3 v_H}{\sqrt{2}f^2}\cos\left(\frac{\phi_0}{f}\right)$$ → smaller diag

Extended Higgs - Singlet

Scalar potential with an additional SM singlet scalar

$$V(\phi, S) = \mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2 + a_1 S + \mu_2^2 S^2 + \kappa S^3 + \lambda_2 S^4 + \lambda_3 (\phi^\dagger \phi) S^2$$

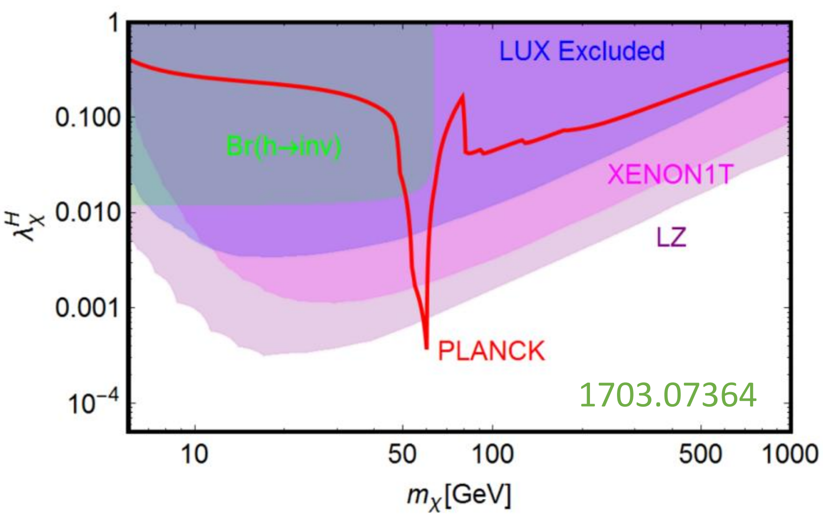
*Additional h^0 and A emerge. The 125 GeV eigenstate's coupling to SM reduces due to mixing ~ $\cos^2 \alpha$, branching ratios are unchanged.
*If additional h0 and A are light, $h_2(125) \to h_1 h_1$, AA are possible.

Z_2 version:

Silveira, Zee, 85'

Singlet can be stable if S -> -S under Z_2, S-Higgs is forbidden and requires <S>=0. Only three singlet parameters: Higgs portal λ_3, mass μ_2, and quartic λ_2.

S contain DM candidate(s).



Extended Higgs – 2HDM

*m_{12}, $\lambda_{5,6,7}$ may be complex:
mass eigenstates not CP eigenstates.

The 2HDM potential (CP-invariant)

$$V(\phi_1,\phi_2) = m_{11}^2\,\phi_1^\dagger\phi_1 + m_{22}^2\,\phi_2^\dagger\phi_2 - \left[m_{12}^2\,\phi_1^\dagger\phi_2 + \text{h.c.}\right]$$
$$+\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4\,|\phi_1^\dagger\,\phi_2|^2$$
$$+\left[\frac{\lambda_5}{2}(\phi_1^\dagger\phi_2)^2 + \lambda_6(\phi_1^\dagger\phi_1)(\phi_1^\dagger\phi_2) + \lambda_7(\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \text{h.c.}\right]$$

*Additional physical states: one neutral scalar, charged scalar, one pseudoscalar

$$h^0 = \sqrt{2}\left[-\text{Re}(\phi_1^0 - v_1)\sin\alpha + \text{Re}(\phi_2^0 - v_2)\cos\alpha\right]$$
$$H^0 = \sqrt{2}\left[\text{Re}(\phi_1^0 - v_1)\cos\alpha + \text{Re}(\phi_2^0 - v_2)\sin\alpha\right]\ ,$$

$$\tan\beta \equiv t_\beta = v_2/v_1$$

$$m_{H^\pm}^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \frac{v^2}{2}\left[\lambda_4 + \lambda_5 + \frac{\lambda_6}{t_\beta} + \lambda_7 t_\beta\right]$$
$$m_{A^0}^2 = \frac{m_{12}^2}{s_\beta c_\beta} - \frac{v^2}{2}\left[2\lambda_5 + \frac{\lambda_6}{t_\beta} + \lambda_7\,t_\beta\right]\ ,$$

2HDM: rich pheno with collider & precision tests.

The light Higgs coupling to gauge bosons scales as

$$\frac{g_{VVh^0}}{g_V^{\rm SM}} = \sin(\beta - \alpha)$$

	h^0	H^0	A^0
$\frac{g_{VV\phi}}{g_V^{\rm SM}}$	$s_{\beta-\alpha}$	$c_{\beta-\alpha}$	0
$\frac{y_t}{y_t^{\rm SM}}$	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{1}{t_\beta}$
$\frac{y_b}{y_b^{\rm SM}}$	$-\frac{\sin(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$	$\frac{\cos(\alpha-\gamma_b)}{\cos(\beta-\gamma_b)}$	$\tan(\beta-\gamma_b)$
$\frac{y_\tau}{y_\tau^{\rm SM}}$	$-\frac{\sin(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$	$\frac{\cos(\alpha-\gamma_\tau)}{\cos(\beta-\gamma_\tau)}$	$\tan(\beta-\gamma_\tau)$

Natural flavor conservation requires one fermion family couple to only one doublet. Canonical schemes:

	u-type	d-type	leptons
type I (T1)	Φ_2	Φ_2	Φ_2
type II (T2)	Φ_2	Φ_1	Φ_1
lepton-specific	Φ_2	Φ_2	Φ_1
flipped	Φ_2	Φ_1	Φ_2

- type-I, where all fermions only couple to ϕ_2;
- type-II, where up-type (down-type) fermions couple exclusively to ϕ_2 (ϕ_1);
- lepton–specific, with a type-I quark sector and a type-II lepton sector;
- flipped, with a type-II quark sector and a type-I lepton sector.

Extended Higgs – Triplet

Two $U(1)_Y$ assignments:

$$\xi = \begin{pmatrix} \xi^+ \\ \xi^0 + v_\xi \\ \xi^- \end{pmatrix}$$

real scalar, $U(1)_Y = 0$

$$\chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 = v_\chi + (h_\chi + i a_\chi)/\sqrt{2} \end{pmatrix}$$

complex, $U(1)_Y = 1$

Triplet vevs contribute to gauge boson masses

$$M_W^2 = \frac{g^2}{4}\left(v_\phi^2 + 4v_\chi^2 + 4v_\xi^2\right)$$

$$M_Z^2 = \frac{g^2}{4c_W^2}\left(v_\phi^2 + 8v_\chi^2\right) \ ,$$

breaks custodial $SU(2)_V$

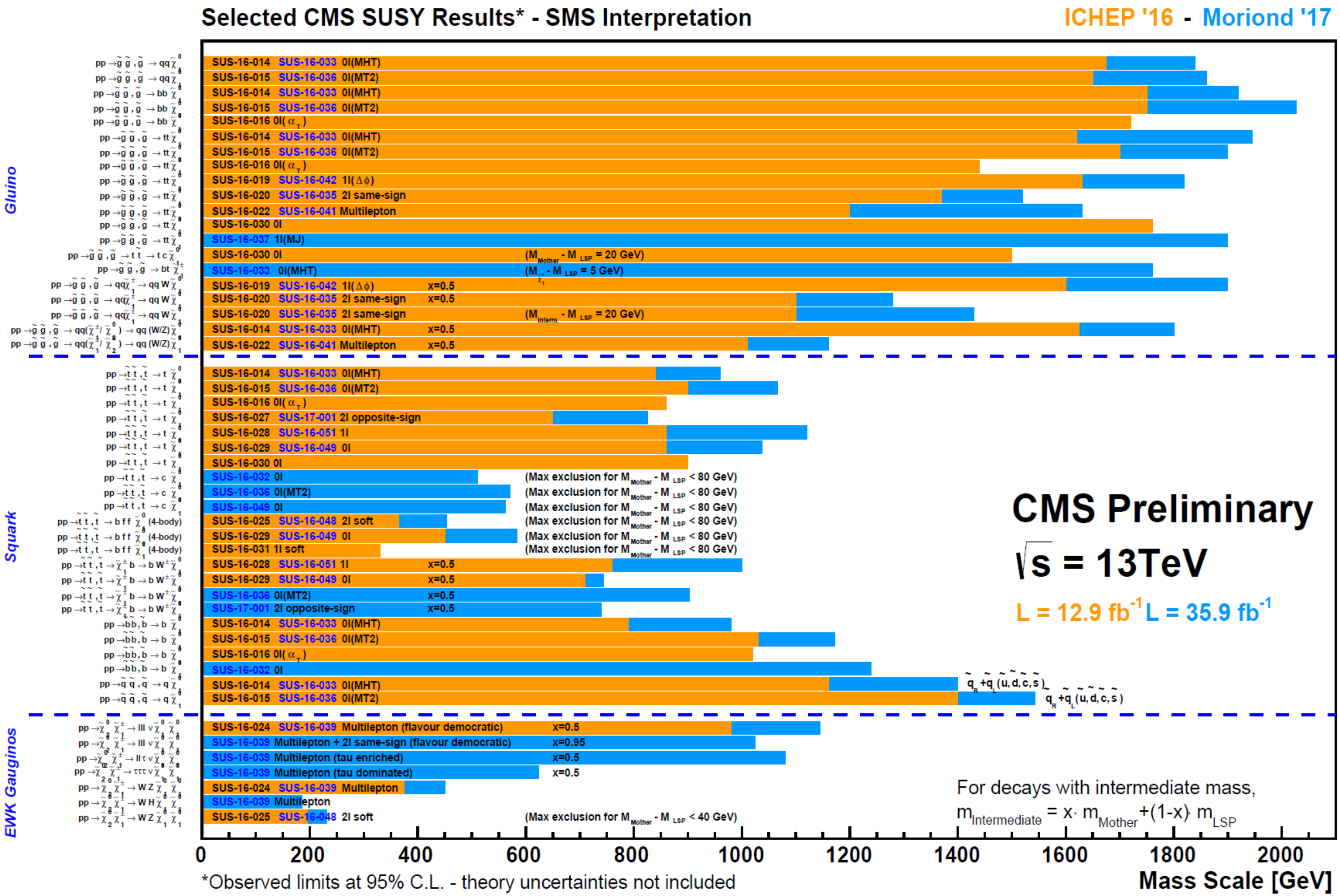
$$\rho = \frac{M_W^2}{c_W^2 M_Z^2} = \frac{v^2 + 4(v_\xi^2 + v_\chi^2)}{v^2 + 8v_\chi^2}$$

(likely) in tension with EWPD

Georgi-Machacek,85'

A $v_\xi = v_\chi$ scenario protects custodial sym. and evades EWPD.

Can generate neutrino mass – appears in Type-II seesaw.



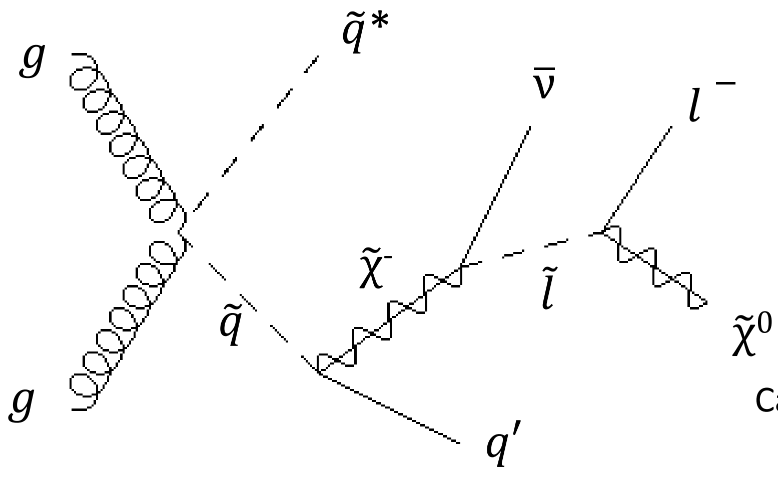
*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{LSP} \approx 0$ GeV unless stated otherwise

SUSY search @ pp

- Colored sparticles: squarks/gluino   -> strong production.
- EW gauginos, sleptons   -> weak production.
- Extra Higgs -> strong production (via loop), weak VBF, decays, etc.
- LSP dark matter -> weak production/decays. (missing energy)

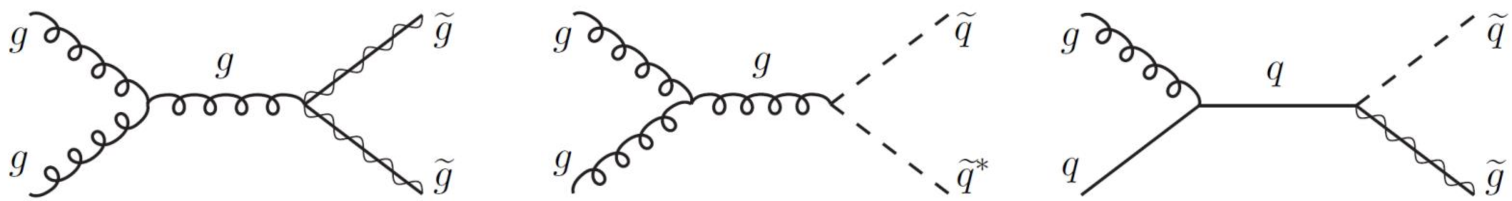
A susy cascade event



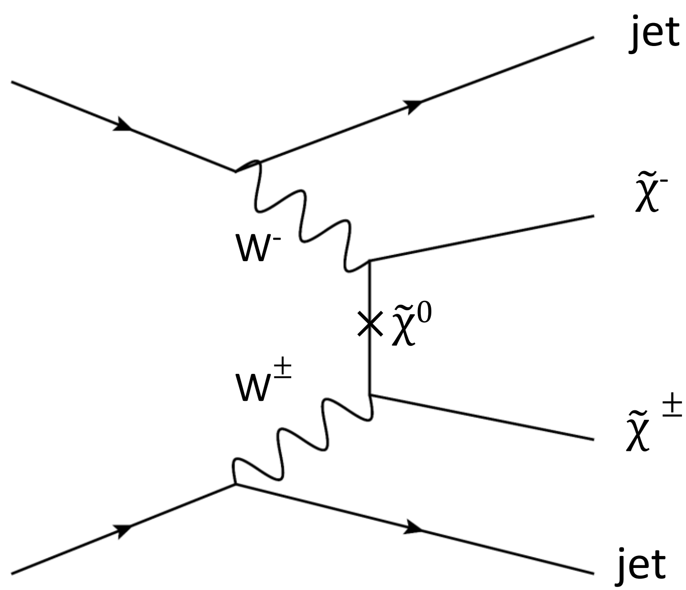
Cascade decay finds
a way to the LSP

Squark diagram in QCD production

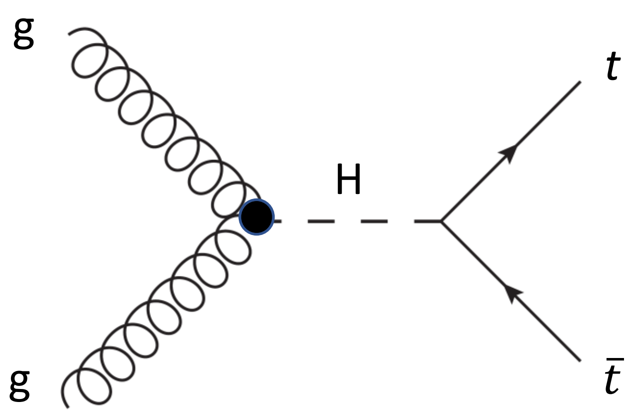
+ t-channel diagrams, etc



Weak VBF production of charginos

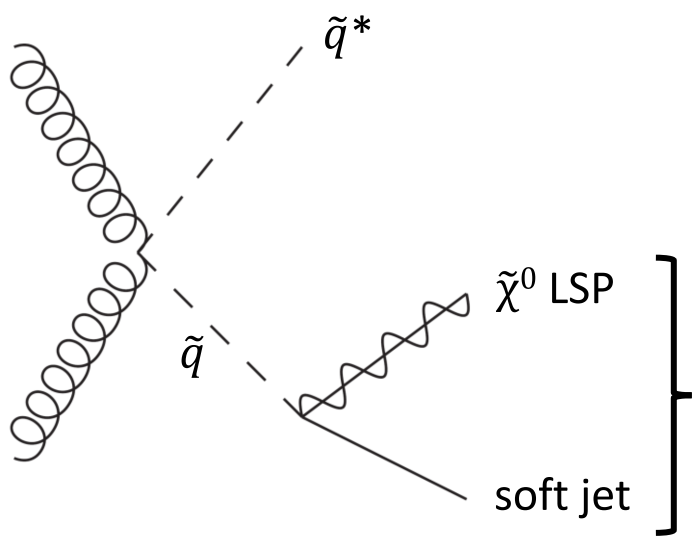


Heavy resonance



Large top Yukawa leads to large resonance width

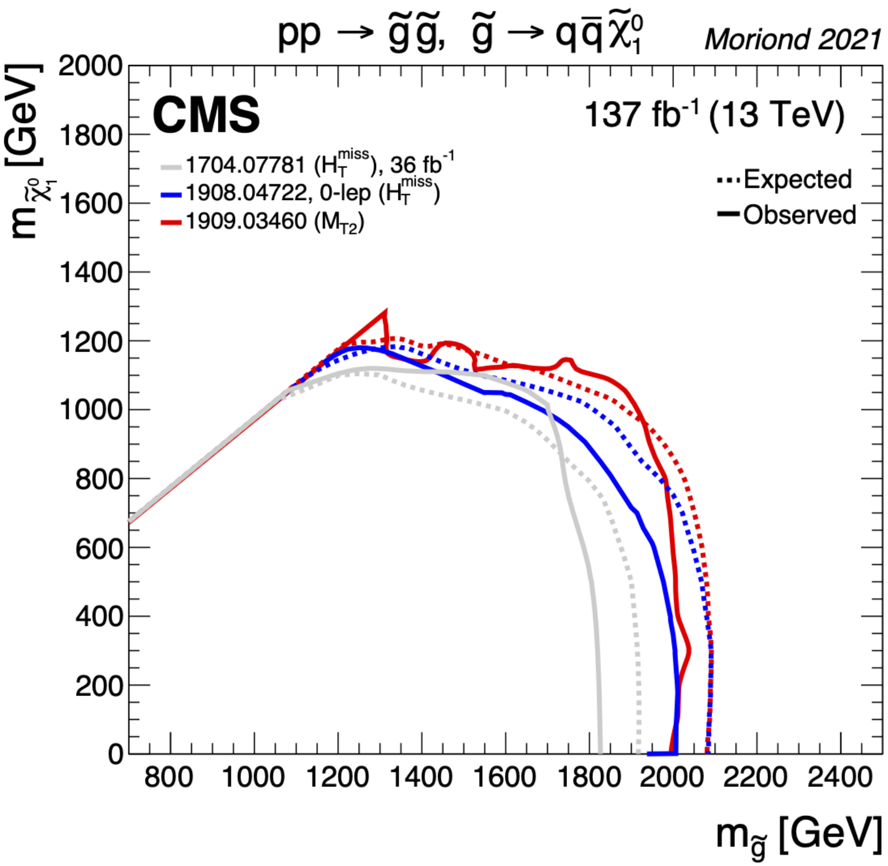
Issue with LSP: `Compressed' scenario



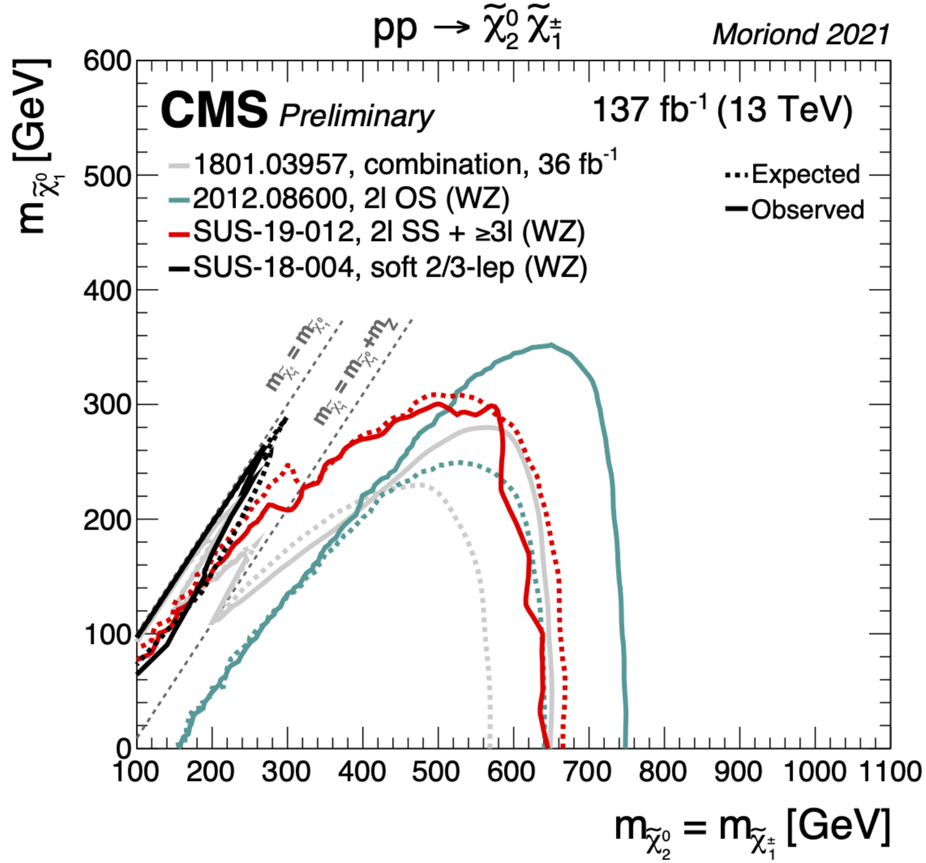
if LSP mass too close to squark's, jet has very low energy.

Entire system will be missing.

sparticle limits

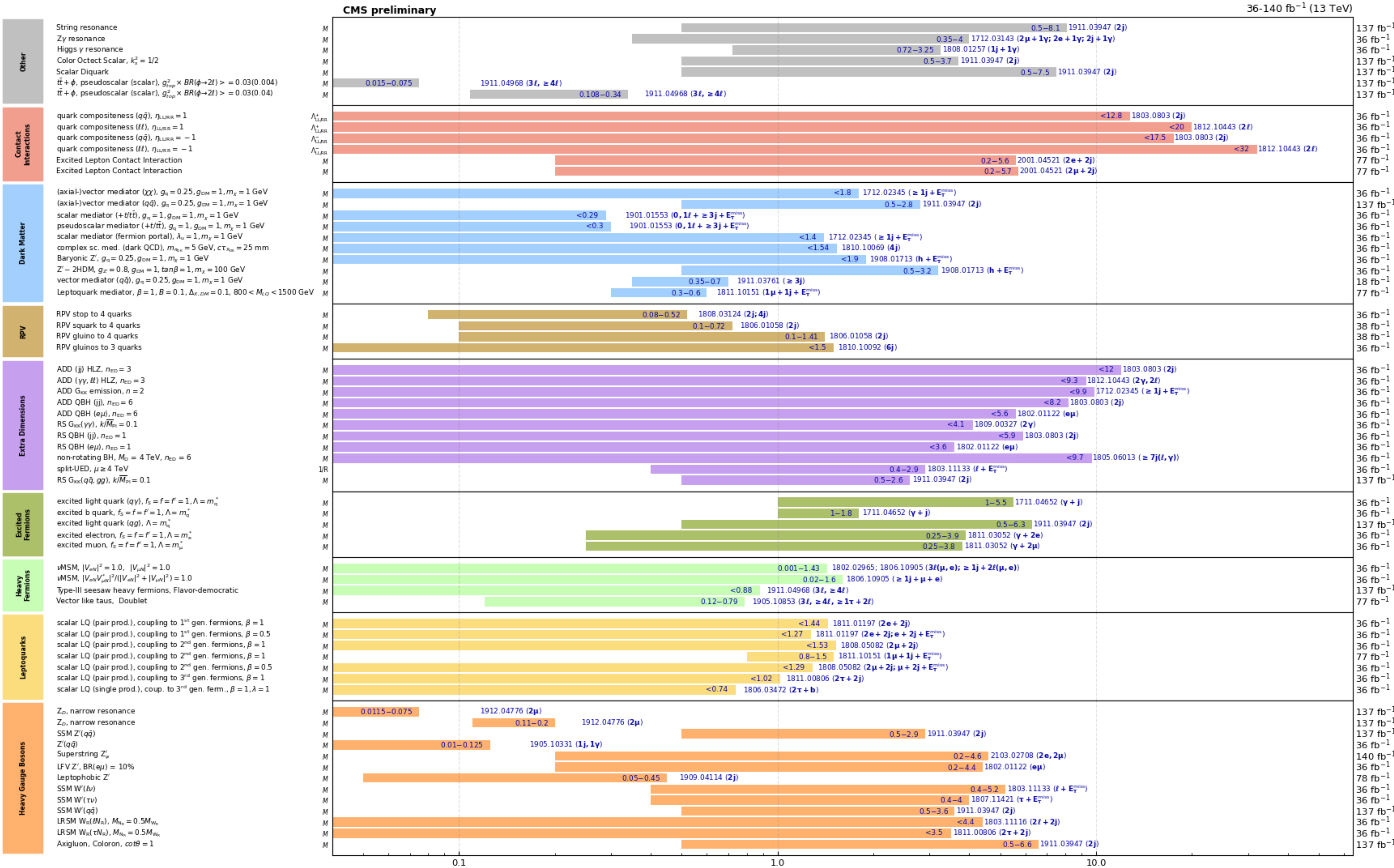


gluino-squark



weak gauginos

Overview of CMS EXO results



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Moriond 2021