Physics Beyond the Standard Model

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Beyond the Standard Model

Lecture 1
- Why do we need to go Beyond the SM ?
- The Hierarchy Problem: what do we need to solve it ?

Lecture 2
- Supersymmetry and the Hierarchy Problem

Lecture 3
- New Dynamics at the TeV scale: the Higgs as a (pseudo) Nambu-Goldstone Boson

Beyond the Standard Model I

- Status of the SM

- Why do we want to go beyond the SM ?

The Standard Model Today

- A gauge theory: $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\begin{pmatrix} u \\ d \end{pmatrix}_L, \quad u_R, \quad d_R \qquad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad e^-_R$$

$$\begin{pmatrix} c \\ s \end{pmatrix}_L, \quad c_R, \quad s_R \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad \mu^-_R$$

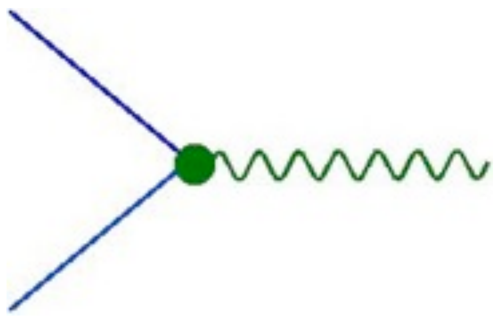
$$\begin{pmatrix} t \\ b \end{pmatrix}_L, \quad t_R, \quad b_R \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \quad \tau^-_R$$

} 3 generations of matter

Coupled through $g, W^\pm, Z^0, \gamma$

Gauge Sector

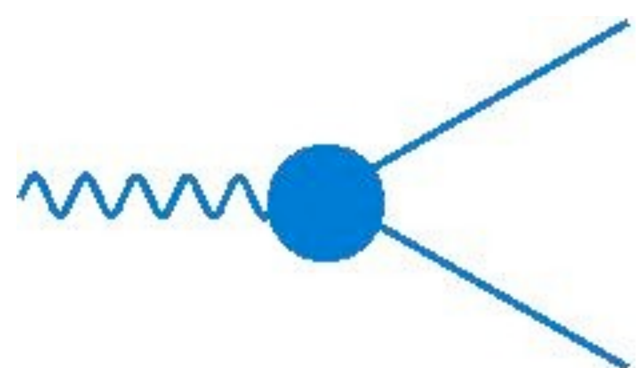
- Couplings of fermions to gauge bosons



determined by gauge symmetry

- Tested with sub-percent precision at LEP, Tevatron, SLD

Oblique



Vertex

Symmetry Breaking Sector

- M_Z, M_W, m_f require spontaneous symmetry breaking

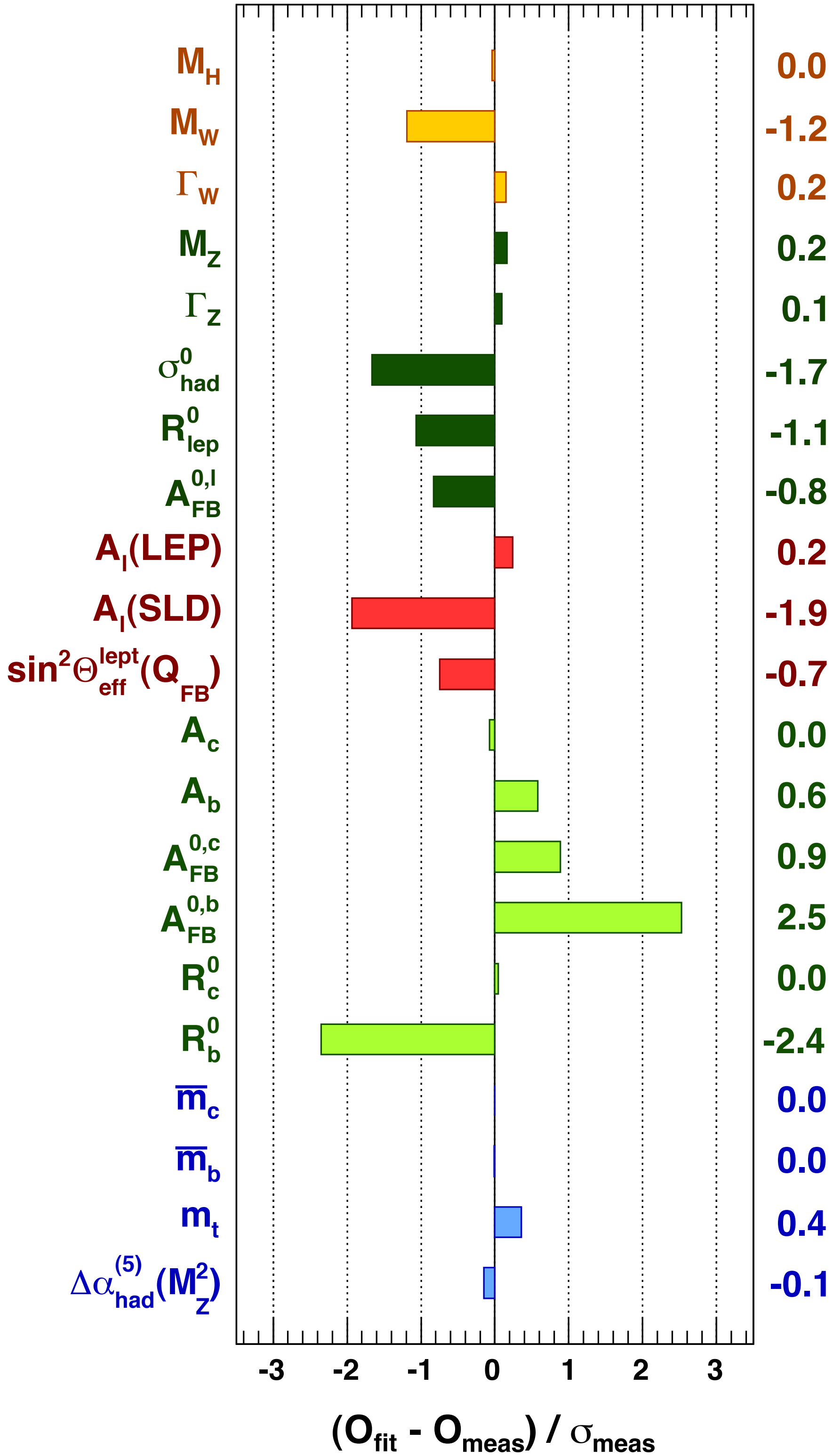
$$(D_\mu \Phi)^\dagger \; D^\mu \Phi \;\Longrightarrow\; g^2 \frac{v^2}{2} W_\mu^+ W^{-\mu} + \frac{(g^2 + g'^2)\, v^2}{4} Z_\mu Z^\mu$$

when $\langle \Phi \rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix}$

Also $Y_f \bar{f}_L \Phi f_R \;\Longrightarrow\; Y_f \frac{v}{\sqrt{2}}$

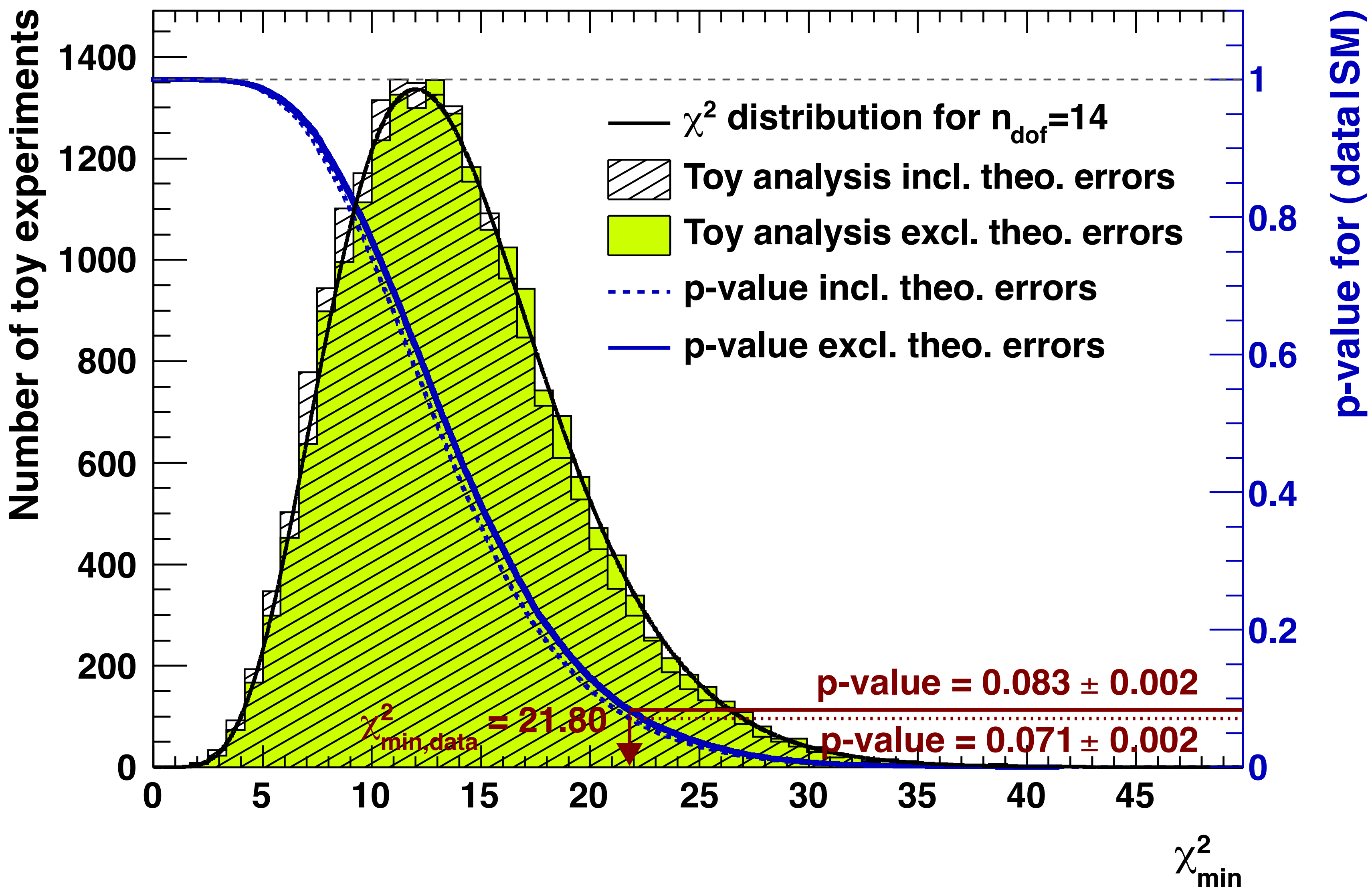
But SB sector much more open than gauge sector of the SM

The Standard Model Today

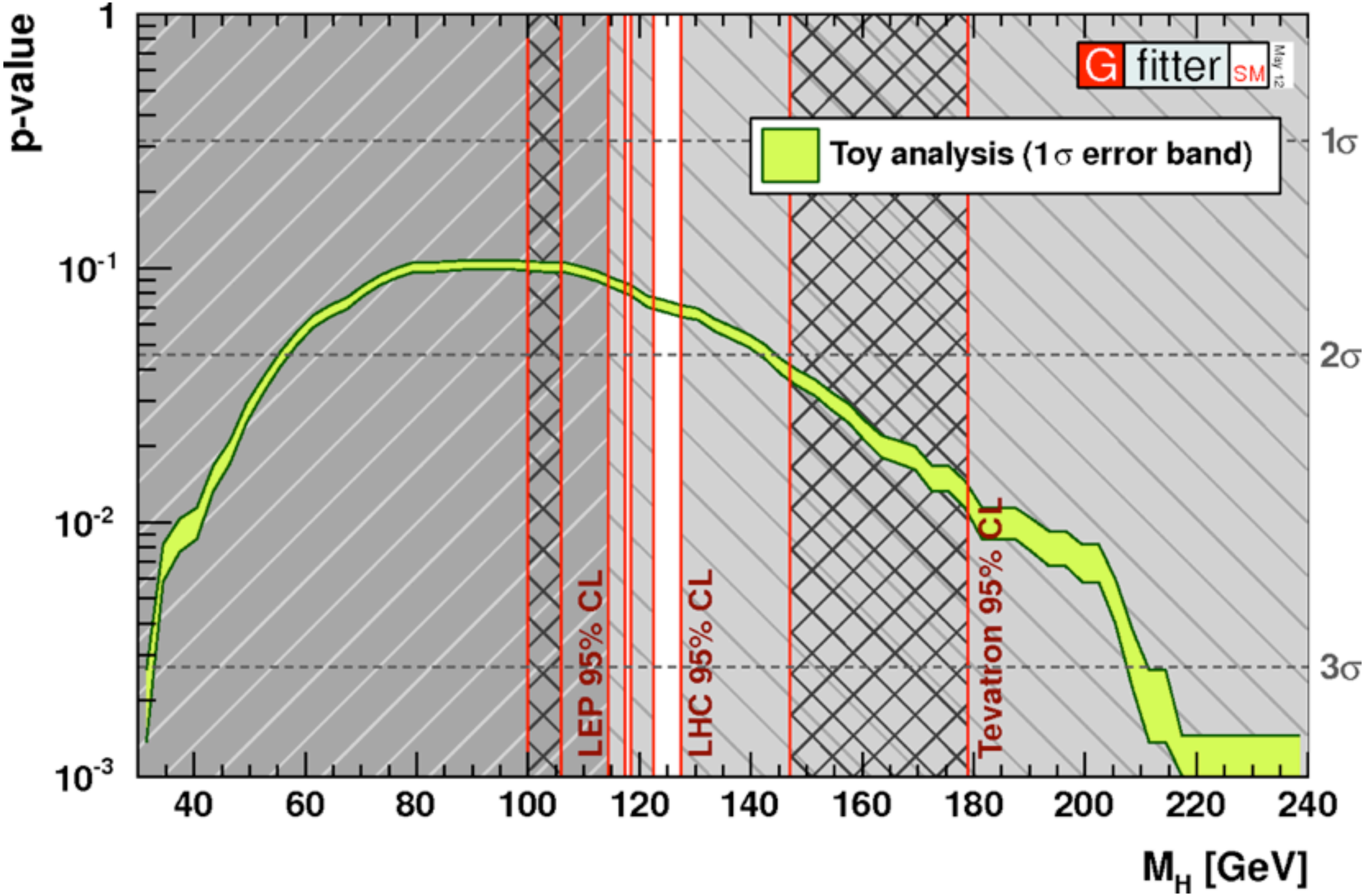


Fit with $m_h = 126 \text{ GeV}$

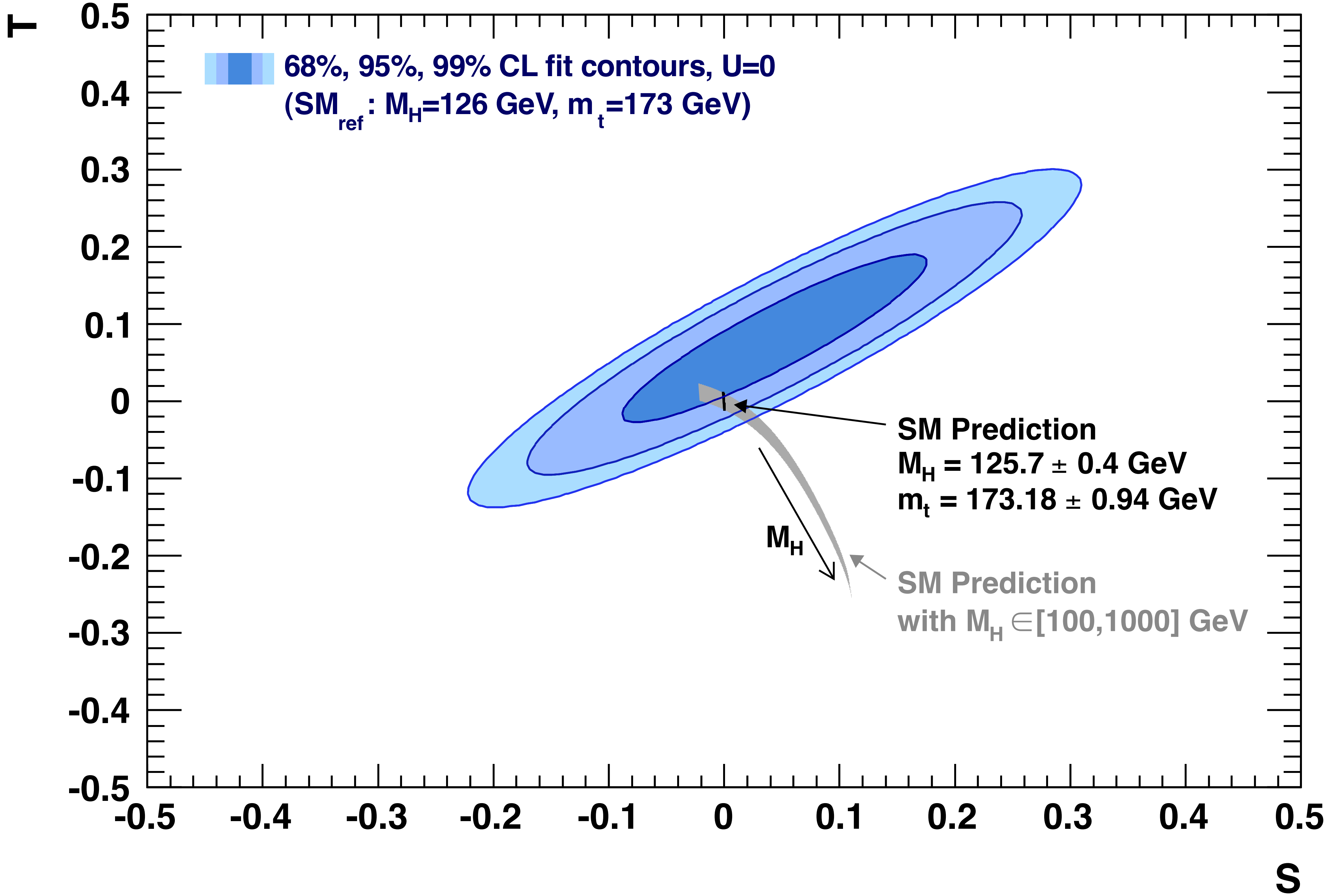
The Standard Model Today



The Standard Model Today



Oblique Corrections



→ Not where the tension is

The Problem(s) with the Standard Model

I. Where is the scalar sector coming from ?

- EWSB requires Higgs sector

- SM corresponds to minimal choice

$$\mathcal{L}_\Phi = (D_\mu \Phi)^\dagger \; D^\mu \Phi + V(\Phi^\dagger \Phi)$$

with

$$V(\Phi^\dagger \Phi) = -m^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

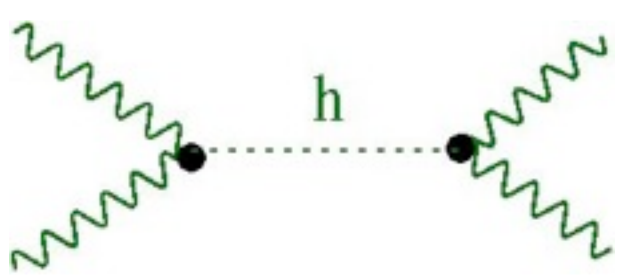
Symmetry Breaking Sector

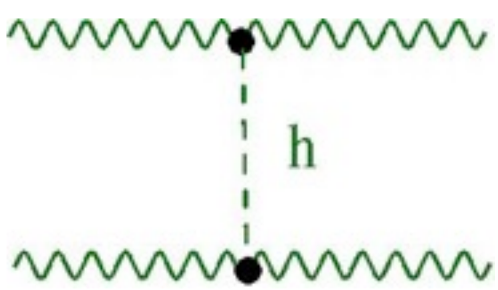
<u>Higgs mass</u>

$$m_h = \sqrt{2\lambda} v$$

Needs to be $m_h \leq O(1)$ TeV

to unitarize theory with $M_Z, M_W \simeq O(100)$ GeV





Where is the Scalar Sector Coming From

- But what determines m and λ ?

- Is the scalar sector resulting from some underlying dynamics ?

E.g. Superconductivity:

Cooper pairs $\Rightarrow \langle\Phi\rangle \neq 0$

$\mathcal{L}_\Phi$ is the Ginzburg-Landau theory $\left\{\right.$
EM broken in the SC
Meissner effect
penetration depth
⋮

But microscopic description is BCS

The Higgs Mechanism and Superconductivity

Electromagnetism in a Superconductor

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + (\partial_\mu + 2ieA_\mu)\Phi^\dagger (\partial_\mu - 2ieA_\mu)\Phi - V(\Phi^\dagger\Phi)$$

Complex scalar field Φ with $U(1)$ gauge symmetry

$$\left.\begin{array}{l} \Phi \to e^{i\,\alpha(x)}\,\Phi \\ A_\mu \to A_\mu + \partial_\mu\alpha \end{array}\right\} \Rightarrow \quad \delta\mathcal{L} = 0$$

At $T < T_c$ $\qquad V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$

The Higgs Mechanism and Superconductivity

Spontaneous breaking of $U(1)$

At $T < T_c$ $\langle \Phi \rangle \neq 0$ breaks EM

Photon acquires effective mass in the superconductor

In reality Φ is a condensate of electron pairs (Cooper)

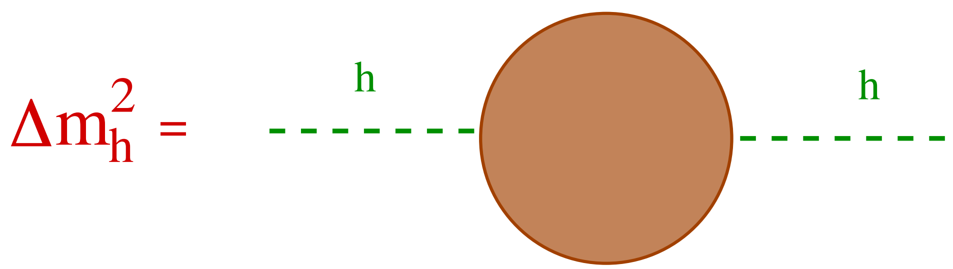
$$\epsilon_{\alpha\beta}\,\Phi(x) = \langle 0|\psi_\alpha(x)\,\psi_\beta(x)|0\rangle$$

The Landau-Ginzburg description can be obtained from the microscopic theory of SC: BCS

The Problem(s) with the Standard Model

II. Why is the Higgs so Light ?

m_h not stable under radiative corrections

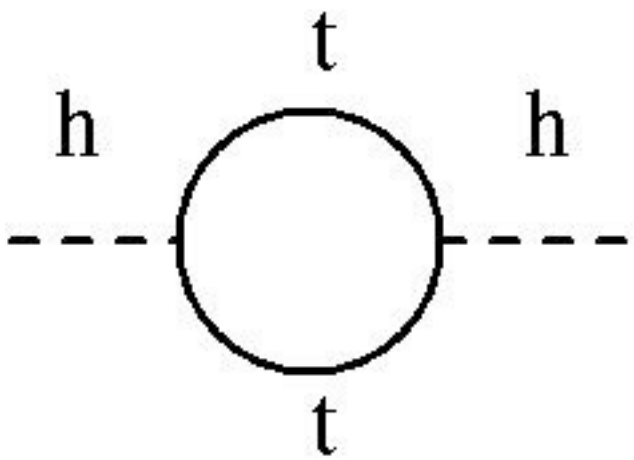


$$\Delta m_h^2 \simeq \frac{c}{16\pi^2}\,\Lambda^2$$ quadratically divergent

c determined by SM states: $t, W^{\pm}, Z^0, h$

The Hierarchy Problem

E.g. : The top quark contribution



$$= (-1) N_c \int \frac{dp^4}{(2\pi)^4} \mathrm{Tr} \left[\frac{-iy_t}{\sqrt{2}} \frac{i}{\not{p} - m_t} \frac{-iy_t}{\sqrt{2}} \frac{i}{\not{p} - m_t} \right]$$

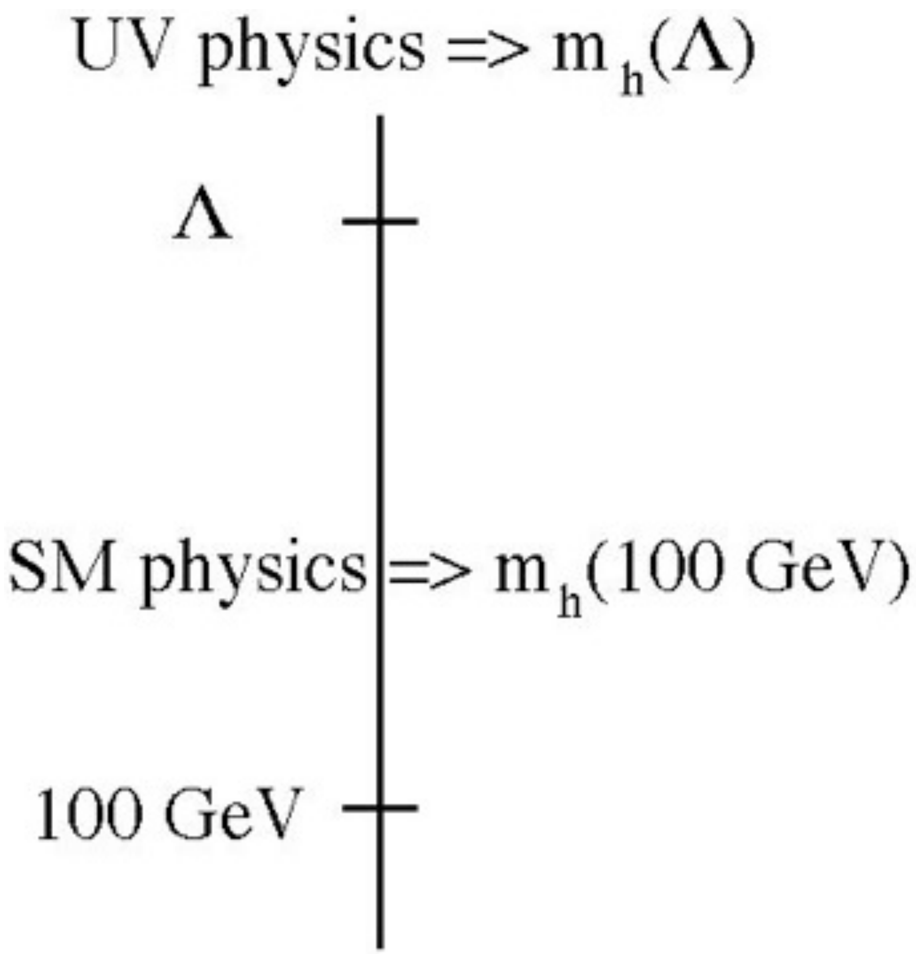
$$\simeq -\frac{3}{8\pi^2} y_t^2 \Lambda^2 + \frac{3 N_c y_t^2}{8\pi^2} m_t^2 \ln\left(\frac{\Lambda^2}{m_t}\right)$$

Contributions from gauge bosons and h itself have similar form

The Hierarchy Problem

Renormalization group evolution of the Higgs mass

$$m_h^2(100\ \mathrm{GeV}) = m_h^2(\Lambda) + \Delta m_h^2$$



The Problem(s) with the Standard Model

But c is determined by SM fields at the EW scale

Need to adjust bare parameters (e.g. λ, m) to cancel these

$$\left(m^2_{h\text{bare}} - \frac{c}{16\pi^2}\Lambda^2\right) \simeq O(100\ \text{GeV})^2$$

$\Longrightarrow$ Need fine tuning for $\Lambda \gg 1\ TeV$

But physics that determines $m_{h\text{bare}}$ lives above Λ

$\Longrightarrow$ Hierarchy Problem

The Problem(s) with the Standard Model

III. Why are the fermion masses so different ?

Fermion masses come from Yukawa couplings

$$Y_f \, \bar{f}_L \Phi f_R$$

But why $Y_t \simeq 1, \quad Y_c \simeq 10^{-2}, \quad Y_u \simeq 10^{-5}$

$$Y_b \simeq 10^{-2}, \quad Y_s \simeq 10^{-3}, \quad Y_d \simeq 10^{-5}$$

$$Y_\tau \simeq 10^{-2}, \quad Y_\mu \simeq 10^{-3}, \quad Y_e \simeq 10^{-6}$$

The Problem(s) with the Standard Model

IV. How do neutrinos get masses ?

If we want m_ν from $Y_\nu \, \bar{\nu}_L \, \Phi \, \nu_R$ we need ν_R

But $Y_{\nu_R} = 0, \; T^3_{\nu_R} = 0, \; Q(\nu_R) = 0$

$\Rightarrow$ ν_R has no SM interactions !

The Problem(s) with the Standard Model

IV. How do neutrinos get masses ? (cont.)

If neutrinos are Majorana particles we can have

$$-m_\nu \, \bar{\nu}_L^c \, \nu_L + \text{h.c.}$$

From the dim-5 operator $\frac{k}{\Lambda} \, \bar{L} \, \tilde{\Phi} \, \tilde{\Phi} \, L$

leading to $\frac{k}{\Lambda} \, v^2 \;\, \bar{\nu}_L^c \, \nu_L$

New physics scale $\Lambda \simeq O(10^{15}) \;\text{GeV}$ to get m_ν

The Problem(s) with the Standard Model

III. Dark Matter

We know that

$$\left.\begin{array}{l}\Omega_\Lambda \simeq 0.73 \\ \Omega_{CDM} \simeq 0.23 \\ \Omega_b \simeq 0.04\end{array}\right\} \Rightarrow$$

- Most of matter is non-baryonic cold dark matter

- The SM does not have a suitable DM candidate

- Need new physics beyond the SM to explain CDM

Dark Matter

If DM is a particle $\left\{ \begin{array}{l} \text{• Neutral} \\ \text{• Stable (or long-lived)} \\ \text{• Weakly interacting (at most)} \end{array} \right.$

- Neutrinos: too light and hot
- Axions: very light ($m_a \simeq 10^{-5}\mathrm{eV}$), very little interaction
- Weakly Interacting Massive Particles (WIMPs):

$$m_\chi \simeq (1 - 1000)\mathrm{GeV}$$

Dark Matter

WIMP Coincidence

- If WIMPs are thermal relics

$$\chi + \bar{\chi} \leftrightarrow \text{SM} \qquad \text{for} \quad \Gamma \gg H$$

- Freeze out:

for $\Gamma < H$ annihilation of χ's stops

$$n_\chi \simeq a^{-3}$$

- WIMP Relic Density:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 3 \times 10^{-27} \text{cm}^3 \text{ s}^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

Dark Matter

WIMP Relic Density:

$$\Omega_\chi h^2 = \frac{m_\chi n_\chi}{\rho_c} \simeq 0.1\mathrm{pb}\cdot\mathrm{c}\,\frac{1}{\langle\sigma_A v\rangle}$$

For a typical weakly interacting particle

$$\langle\sigma_A v\rangle \simeq \frac{\alpha^2}{m_\chi^2}\,c \simeq 1\,\mathrm{pb}\cdot\mathrm{c} \quad \text{for} \quad m_\chi \sim 100\ \mathrm{GeV}$$

$\Longrightarrow$ WIMPS are natural CDM candidates

Other Problems

What's the origin of the baryon asymmetry ?

The Strong CP Problem

•

•

•

Not necessarily associated with the
Symmetry Breaking Sector

What Physics Beyond the Standard Model

- Solves a problem:

  Origin of the scalar sector

  Gauge hierarchy problem

  Fermion mass hierarchy

- Experimentally accessible

  We'll see it at the LHC or close

Organize by origin of Higgs sector or solution to HP

- Supersymmetry:

  Higgs is elementary

  SUSY protects m_h

- Higgs sector is composite:

  Technicolor. No Higgs. ✗

  Higgs is a pNGB ✓

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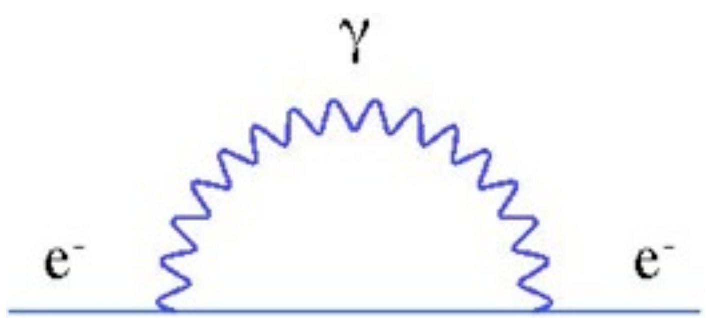
Beyond the Standard Model II - SUSY

- Supersymmetry: a solution to the Hierarchy Proble
- Basic elements of SUSY theories
- The MSSM
- The MSSM and the Higgs

Supersymmetry and the Hierarchy Problem

<u>Protecting Fermion Masses: Chiral Symmetry</u>

Fermion masses only log divergent. E.g. QED



$$\delta m_e \simeq \frac{\alpha}{4\pi} m_e^0 \ln\left(\frac{\Lambda}{m_e}\right)$$

Chiral symmetry protects m_e to all orders in PT

1. $\delta m_e \longrightarrow 0$ for m_e^0
2. Divergence is logarithmic

Supersymmetry and the Hierarchy Problem

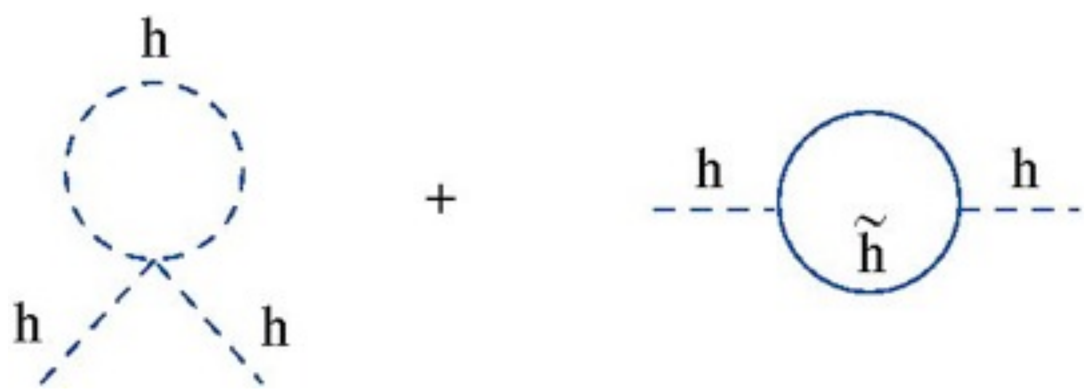
How to protect the Higgs mass ?

Introduce a fermionic partner of the Higgs: *Higgsino*

Need symmetry to relate Higgs (boson) to Higgsino (fermion)

$\Longrightarrow$ Supersymmetry

Higgs and Higgsino form a SUSY multiplet $(H, \tilde{H})$



no Λ dependence if SUSY exact

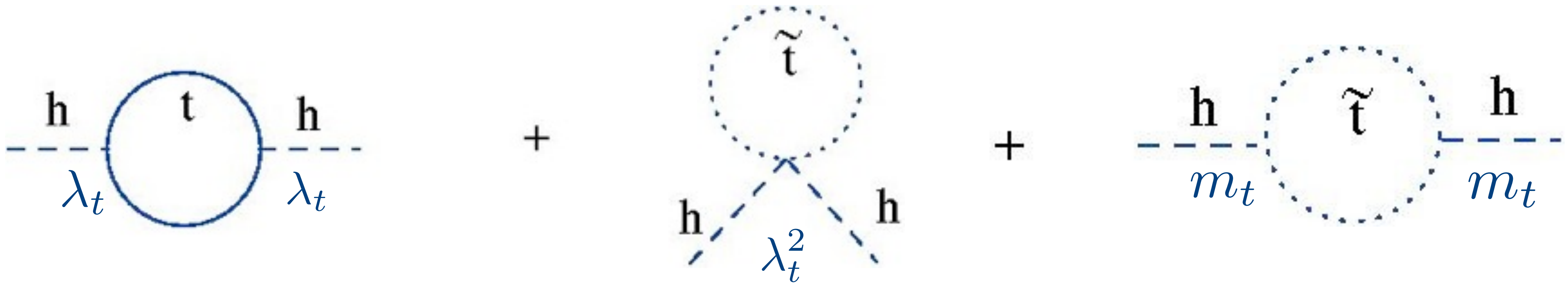
Supersymmetry and the Hierarchy Problem

What about the top quark Λ^2 divergence ?

All fermions will have a scalar partner and viceversa

stop quark $\tilde{t}$ forms SUSY multiplet with t

$$(t, \tilde{t})$$



No divergences in exact SUSY

Supersymmetric Theories

Matter in *Chiral Supermultiplets:* {
- Complex scalar
- Weyl fermion

Gauge in *Vector Supermultiplets:* {
- Vector field
- Weyl fermion

Supersymmetric Theories

SUSY transformations turn scalars into fermions and viceversa leaving the lagrangian invariant

$$\sigma_0 = \bar{\sigma}_0 = I$$
$$\sigma_i = -\bar{\sigma}_i$$

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi + i\psi^\dagger \bar{\sigma}_\mu \partial^\mu \psi$$

$$\Rightarrow \qquad \delta\phi = \epsilon\,\psi$$

with ϵ fermionic anti-commuting infinitesimal change

and

$$\delta\psi = i\sigma^\mu \epsilon \partial_\mu \phi$$

Supersymmetric Theories

Superspace

Coordinates $y^\mu = x^\mu - \theta\bar{\sigma}^\mu\bar{\theta}$

θ: two-component Grassmann spinor $\theta_\alpha, \quad \theta^\dagger_\alpha \equiv \bar{\theta}_{\dot{\alpha}}$

Chiral superfield

$$\Phi(y) = \phi(y) + \sqrt{2}\,\theta\psi(y) + \theta^2\,F(y)$$

$$= \phi(x) - i\theta\sigma^\mu\bar{\theta}\,\partial_\mu\phi(x) - \frac{1}{4}\,\theta^2\bar{\theta}^2\,\partial^2\phi(x)$$

$$+\sqrt{2}\theta\,\psi(x) + \frac{i}{\sqrt{2}}\,\theta^2\partial_\mu\psi(x)\sigma^\mu\bar{\theta} + \theta^2\,F(x)$$

SUSY in Superspace

- θ and $\bar{\theta}$ $\Rightarrow \theta^n = 0$ for $n \geq 3$

- $\int d^2\theta\, \theta^2 = 1$ selects coefficient of θ^2

- $d^4\theta \equiv d^2\theta\, d^2\bar{\theta}$ $\Rightarrow \int d^4\theta$ selects coefficient of $\theta^2\, \bar{\theta}^2$

- The θ^2 component of a CSF is a total derivative under SUSY

  $\Rightarrow \int d^2\theta\, W(\Phi)$ is SUSY invariant

- Same for $\theta^2\, \bar{\theta}^2$ components $\Rightarrow \int d^4\theta\, K(\Phi^\dagger, \Phi)$ invariant under SUSY

SUSY in Superspace

E.g. Kinetic terms in free theory

$$\int d^4\theta\,\Phi^\dagger\Phi = \partial_\mu\phi^*\partial^\mu\phi + i\psi^\dagger\bar{\sigma}^\mu\partial_\mu\psi + F^*F \quad \text{+ total derivatives}$$
$$= \mathcal{L}_{\rm free}$$

Superpotential $W(\Phi)$: Generates interactions through

$$\int d^2\theta\, W(\Phi) = \mathcal{L}_{\rm int.}$$

where $W(\Phi)$ is holomorphic function of Φ

SUSY in Superspace

Gauge Superfields

$$V_\mu^a = \theta\bar{\sigma}^\mu\bar{\theta}A_\mu^a + i\theta^2\bar{\theta}\lambda^{a\dagger} - i\theta\bar{\theta}^2\,\lambda^a + \frac{\theta^2\,\bar{\theta}^2}{2}\,D^a$$

Gauge transformation for gauge superfields

$e^{t^a V^a} \to e^{t^a \Lambda^{a\dagger}}\, e^{t^a V^a}\, e^{t^a \Lambda^a}$ $\quad\Lambda^a$: gauge parameter is superfield

$$\Rightarrow V^a \to V^a + \Lambda^{a\dagger} + \Lambda^a + O(V^a\Lambda^a)$$

For chiral superfields:

$$\Phi \to e^{-g t^a \Lambda^a}\,\Phi$$

SUSY Interactions

Gauge-invariant kinetic terms

$$\int d^4\theta\, \Phi^\dagger\, e^{g t^a V^a}\, \Phi \quad = (D_\mu \phi)^\dagger D^\mu \phi + i\psi^\dagger \bar{\sigma}^\mu\, D_\mu \psi$$

$$-\sqrt{2} g \left[(\phi^* t^a \psi)\, \lambda^a + \lambda^{a\dagger} (\psi^\dagger t^a \phi) \right]$$

$$+ g (\phi^* t^a \phi) D^a$$

In addition to usual gauge interactions

SUSY Interactions

Gauge fields kinetic terms: superfield strength

$$\mathcal{W}^a = -\sigma^{\mu\nu}\theta F^a_{\mu\nu}(y) - \theta^2\sigma_\mu\, D^\mu \lambda^a(y) - i\lambda^a(y) + \theta D^a(y)$$

is a chiral superfield

$$\int d^2\theta\, \mathcal{W}^a(y)\, \mathcal{W}^a(y) \quad \Longrightarrow \quad \text{Kinetic terms} \begin{cases} \text{gauge fields} \\ \text{gauginos} \end{cases}$$

Supersymmetric Theories

Summary

- Gauge and SUSY invariant kinetic terms for matter

$$\int d^4\theta\, \Phi^\dagger\, e^{g t^a V^a}\, \Phi$$

- Gauge and SUSY invariant kinetic terms for gauge fields

$$\int d^2\theta\, \mathcal{W}^a(y)\, \mathcal{W}^a(y)$$

- Gauge and SUSY invariant non-gauge interactions

$$\int d^2\theta\, W(\Phi)$$

Supersymmetry

Supersymmetric extension of the SM

$Q, \ \bar{u}, \ \bar{d}$	*quarks and squarks*	Chiral Superfields
$L, \ \bar{e}$	*leptons and sleptons*	
$H_u, \ H_d$	*Higgs and higgsinos*	

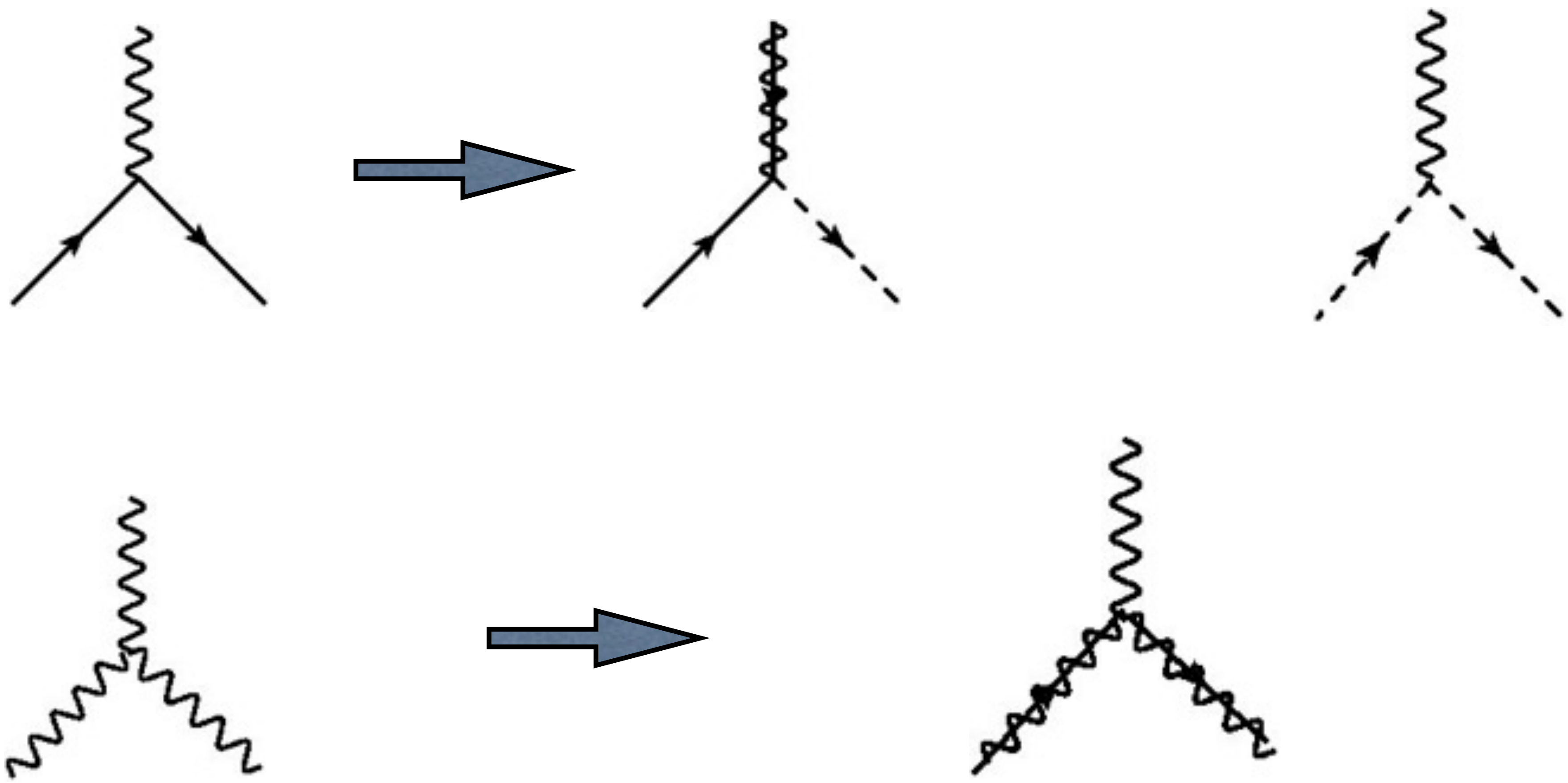
$(\tilde{g}, g)$	*gluinos and gluons*	Vector Superfields
$(\tilde{W}^{\pm,0}, W^{\pm,0})$	*winos and SU(2) gauge bosons*	
$(\tilde{B}, B)$	*binos and Y gauge bosons*	

Supersymmetry

MSSM

- Interactions still determined by SM gauge

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$



Supersymmetry

- <u>Superpotential</u>

$$W_{\rm MSSM} = \bar{u} Y_u Q H_u - \bar{d} Y_d Q H_d - \bar{e} Y_e L H_d + \mu H_u H_d$$

Y_u, Y_d, Y_e Yukawa matrix in flavor space

μ term

$g, g^{\prime}, v_u, v_d$

} *parameters*

Soft SUSY Breaking

- Need to break SUSY softly:

$$W_{\rm soft} = -\frac{1}{2}\Big(M_1 \tilde{B}\tilde{B} + M_2 \tilde{W}\tilde{W} + M_3 \tilde{g}\tilde{g} + {\rm h.c.}\Big)$$

$$-\tilde{Q}^\dagger\, m_Q^2\, \tilde{Q} - \tilde{L}^\dagger\, m_L^2\, \tilde{L} - \tilde{\bar{u}}\, m_u^2\, \tilde{\bar{u}}^\dagger - \tilde{\bar{d}}\, m_d^2\, \tilde{\bar{d}}^\dagger - \tilde{\bar{e}}\, m_e^2\, \tilde{\bar{e}}^\dagger$$

$$-\Big(\tilde{\bar{u}}\, A_u\, \tilde{Q} H_u - \tilde{\bar{d}}\, A_d\, \tilde{Q} H_d + \tilde{\bar{e}}\, A_e\, \tilde{L} H_d + {\rm h.c.}\Big)$$

$$-m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (b H_u H_d + {\rm h.c})$$

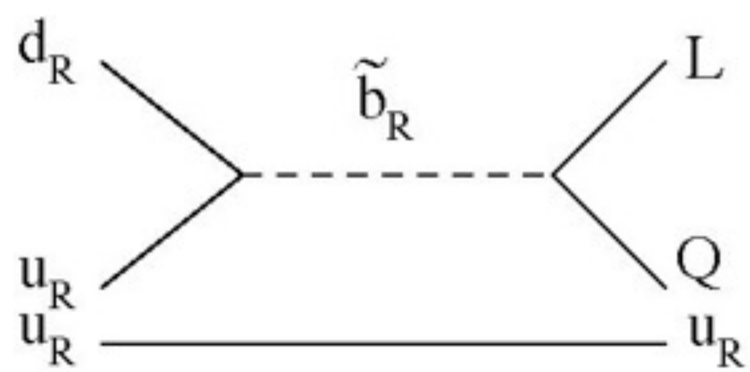
R Parity

- Additional SUSY-preserving terms in the superpotential

$$W_{\rm RPV} = \alpha^{ijk} Q_i L_j \bar{d}_k + \beta^{ijk} L_i L_j \bar{e}_k + \gamma^i L_i H_u + \delta^{ijk} \bar{d}_i \bar{d}_j \bar{u}_k$$

they violate B and L !

p^+



$(e^+, \mu^+)(\nu_e, \nu_\mu)$

$(\pi^0, K^0)(\pi^+, K^+)$

$$\tau_p > 10^{33} \text{ years} \quad \Longrightarrow \quad |\alpha\, \delta| < 10^{-25}$$

R Parity

- Introduce new discrete symmetry, M parity

$$P_M = (-1)^{3(B-L)}$$

Forbids terms W that violate B, L

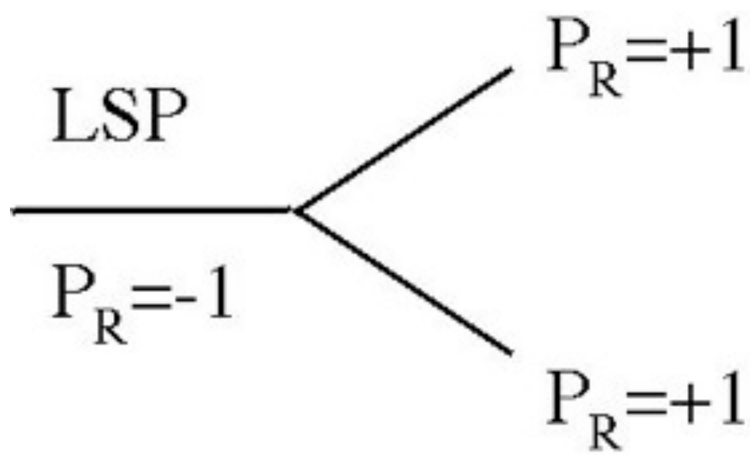
- Equivalent to R parity

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

$$\Rightarrow \begin{cases} \text{Superpartners have } P_R = -1 \\ \text{SM particles have } P_R = +1 \end{cases}$$

R Parity

Lightest Supersymmetric Particle (LSP) is stable



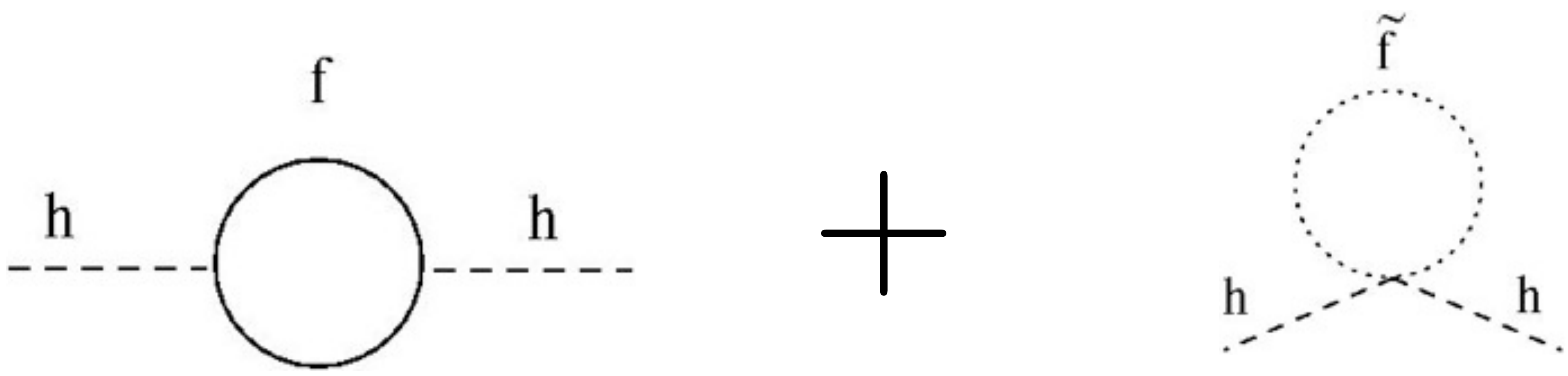
decay of LSP forbidden by R parity

Typical SUSY WIMP candidate:

neutralino: $\tilde{\chi}^0$ admixture of $\tilde{W},\ \tilde{B},\ \tilde{H}$

In generic SUSY models is possible to obtain the correct Ω_χ

Implications of m_h for SUSY



Superpartner loops cancel quadratic divergences

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ Stop mass scale

$X_t = A_t - \mu \cot\beta$ Stop mixing

SUSY Phenomenology

MSSM with R parity conservation

- E.g. $pp \to \tilde{g}\tilde{g},\ \tilde{q}\tilde{q}^*,\ \tilde{q}\tilde{q}$ with $\tilde{q} \to q\,\chi_1^0$ or $\tilde{g} \to \tilde{q}\,q$

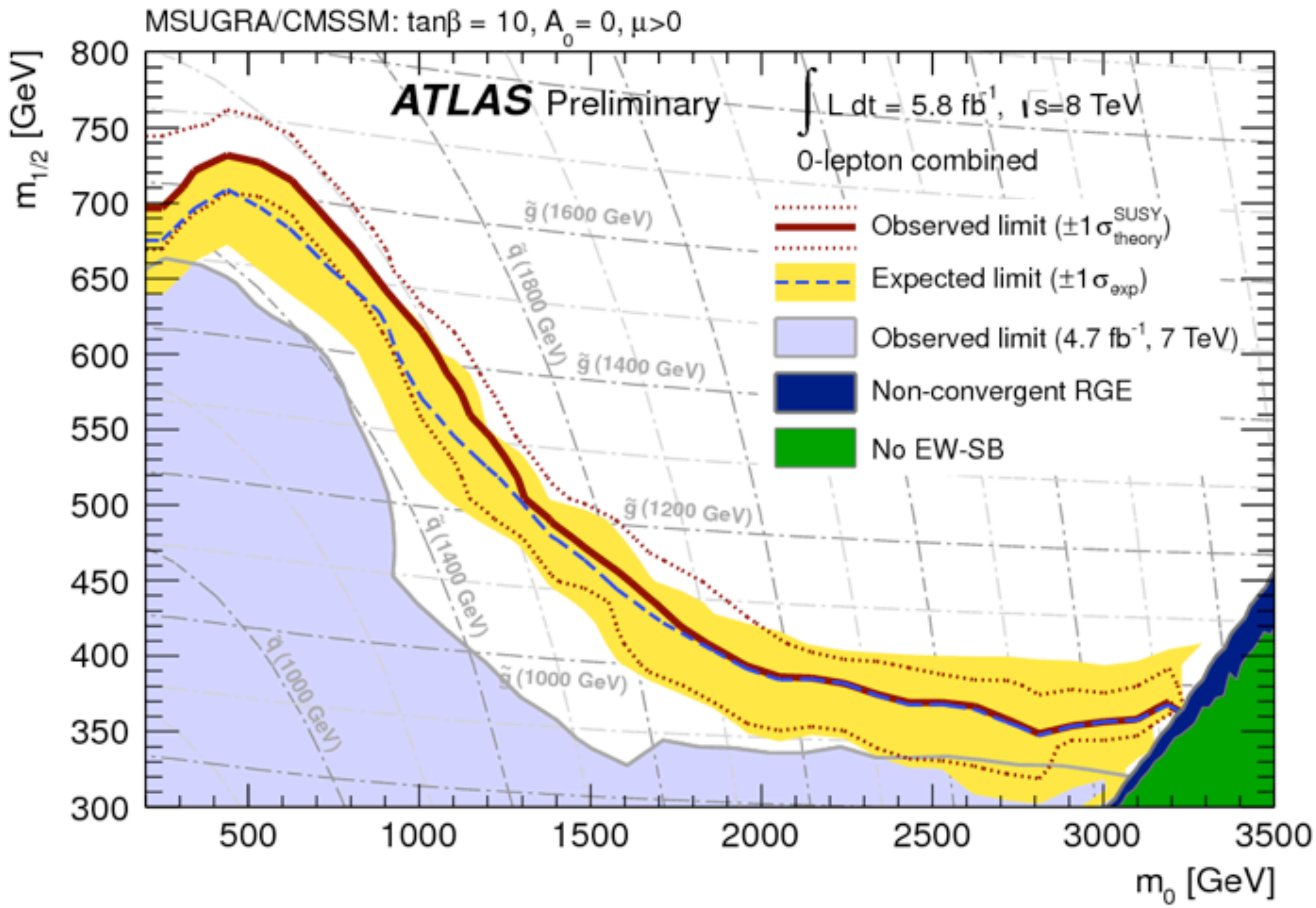
$\Longrightarrow$ jets + $E_T^{\mathrm{miss.}}$

- Or 3-body decays. E.g. $\tilde{g} \to q\,\bar{q}\,\chi_1^0$

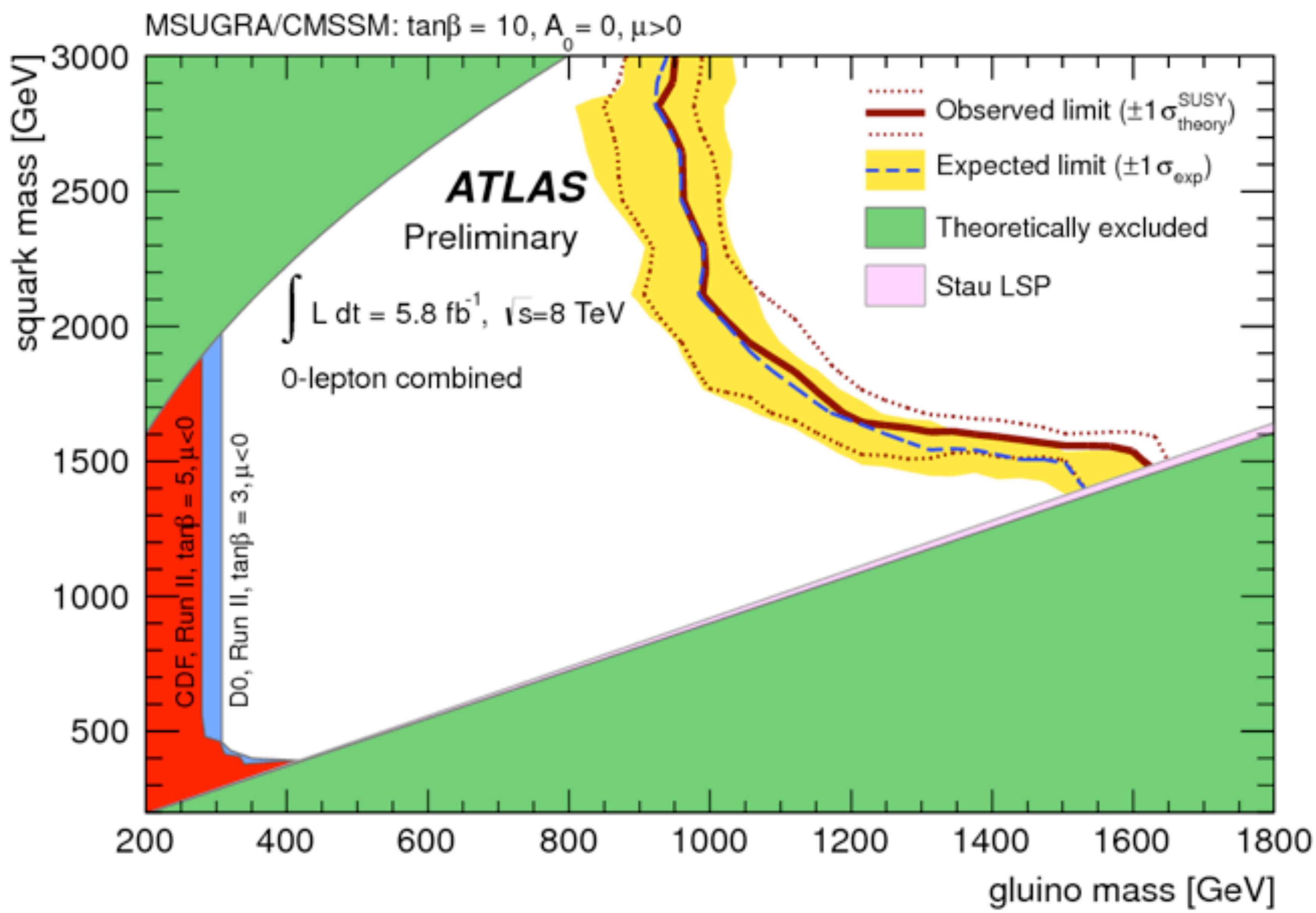
- Also decays with 1 or more leptons

- Bounds depend on decay channels/models

SUSY Searches at the LHC

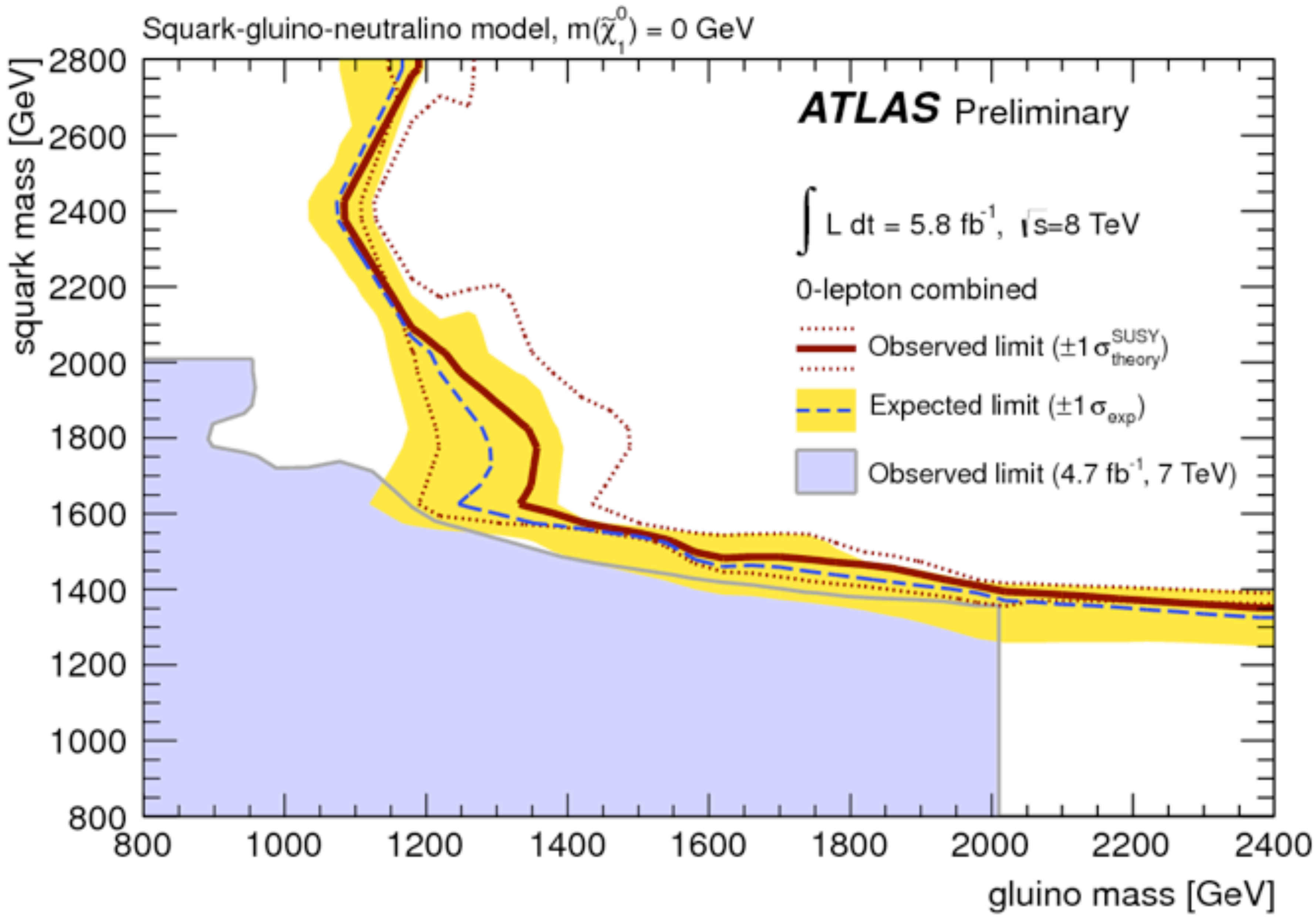


SUSY Searches at the LHC



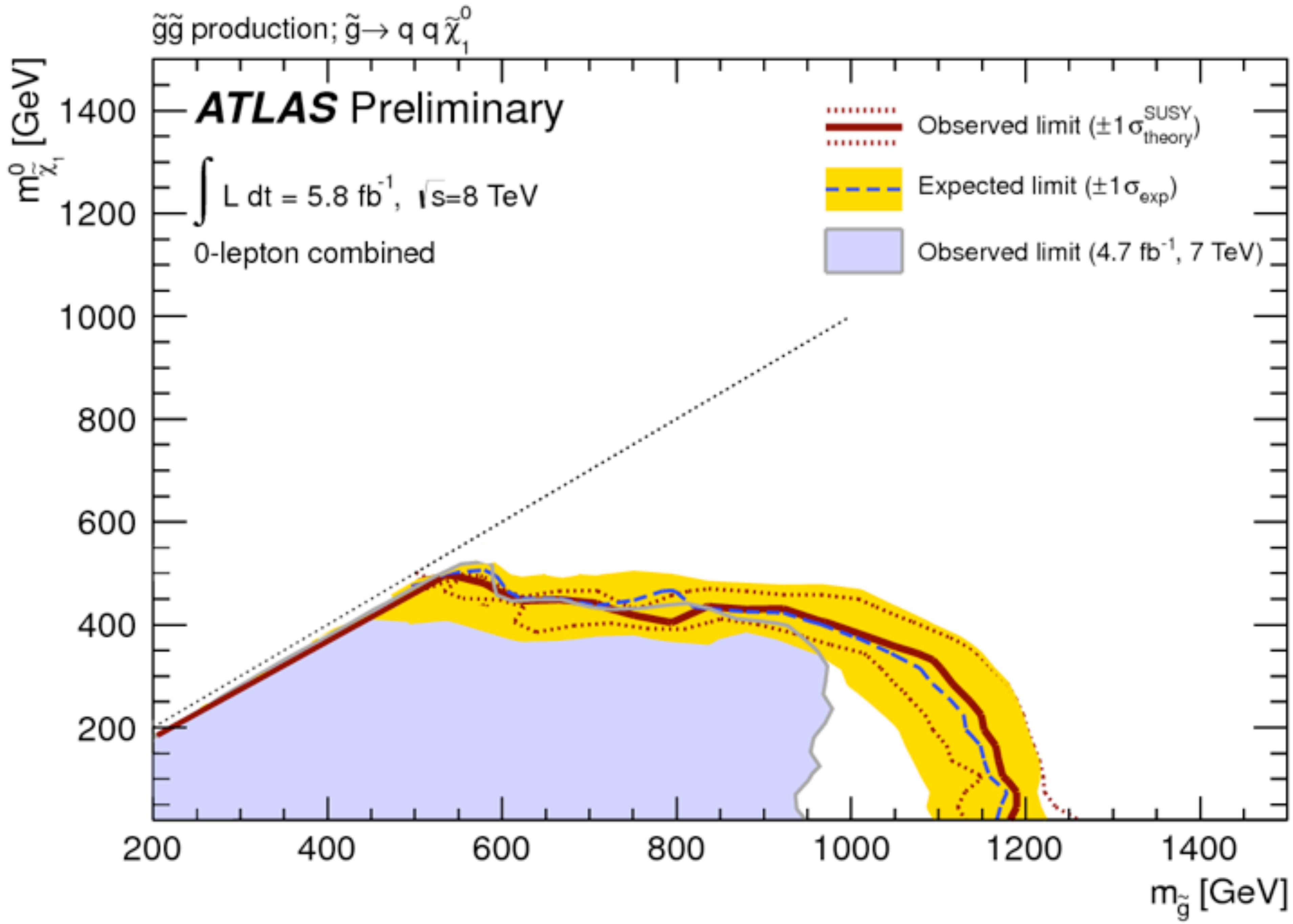
SUSY Searches at the LHC

- Assuming direct decays to jets

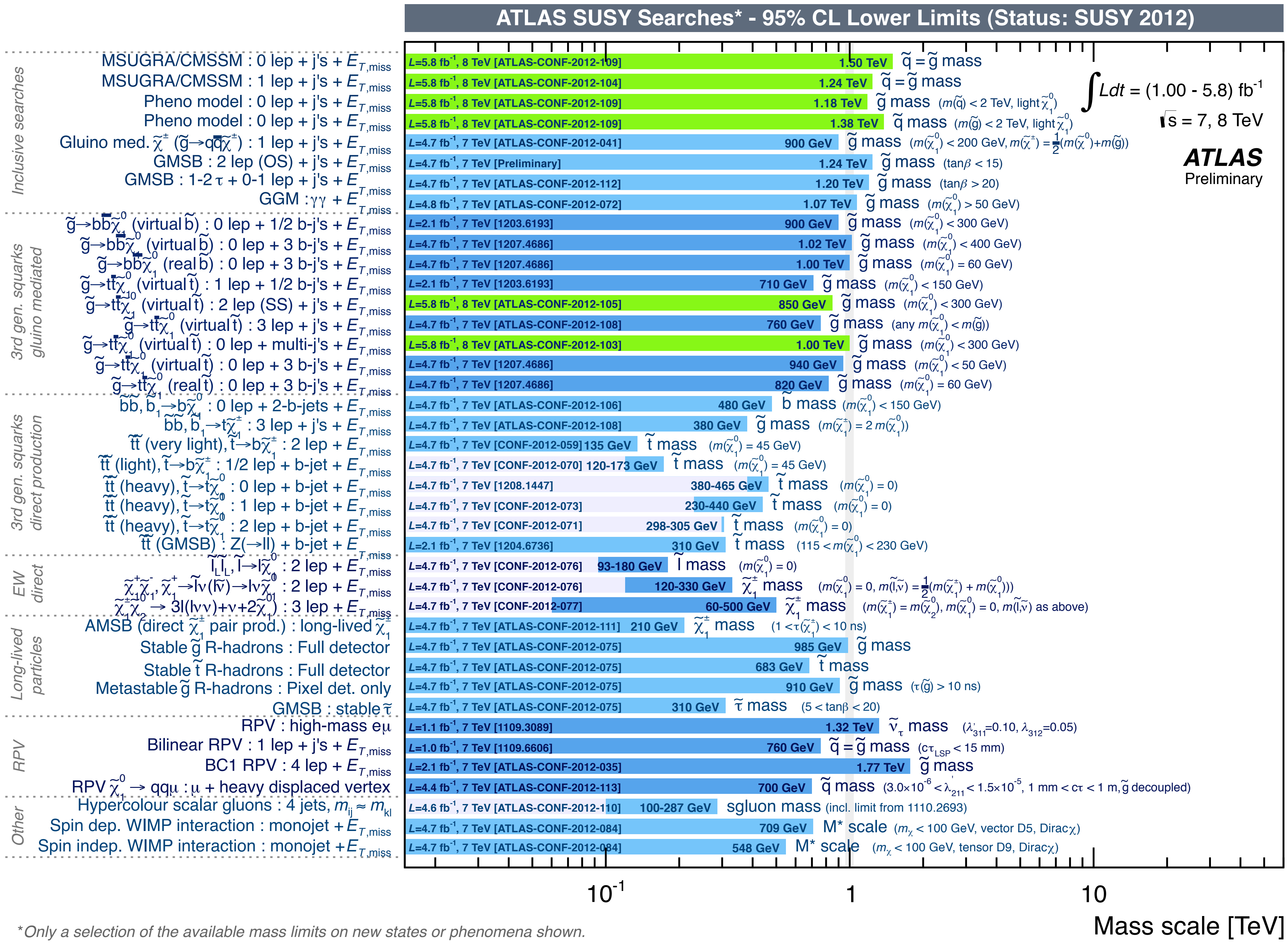


SUSY Searches at the LHC

- Assume $\tilde{g} \to q\,\bar{q}\,\chi_1^0$



SUSY Searches at the LHC



*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

Hiding SUSY

Why haven't we seen it ?

- *Compressed Spectrum*

  Not enough $E_T^{\text{miss.}}$

- *R-parity Violation*

  LSP not stable. Different decay modes. Not enough $E_T^{\text{miss.}}$

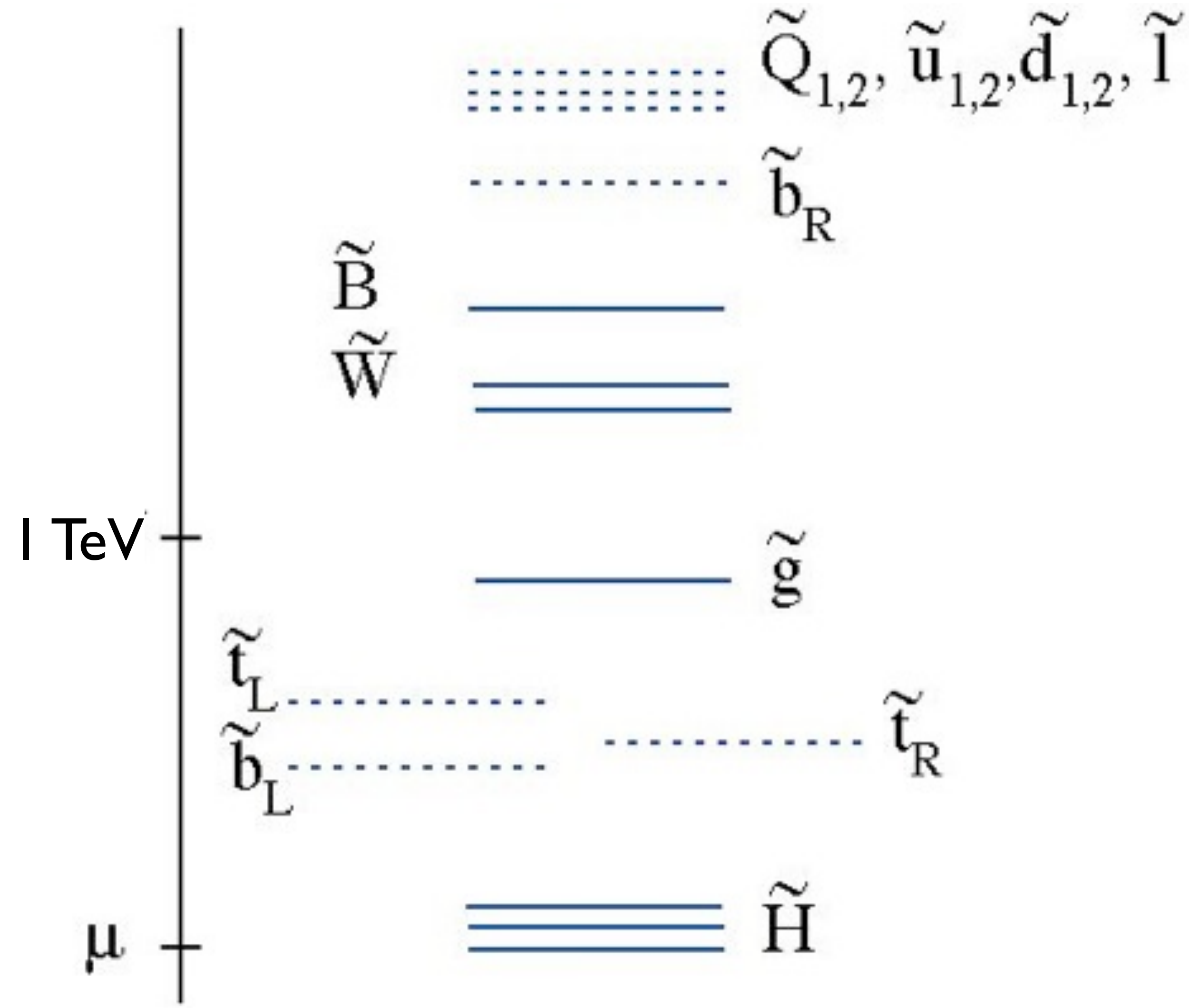
- *Natural SUSY*

  Light *higgsinos*, *3rd. gen. squarks*

  Everybody else heavy

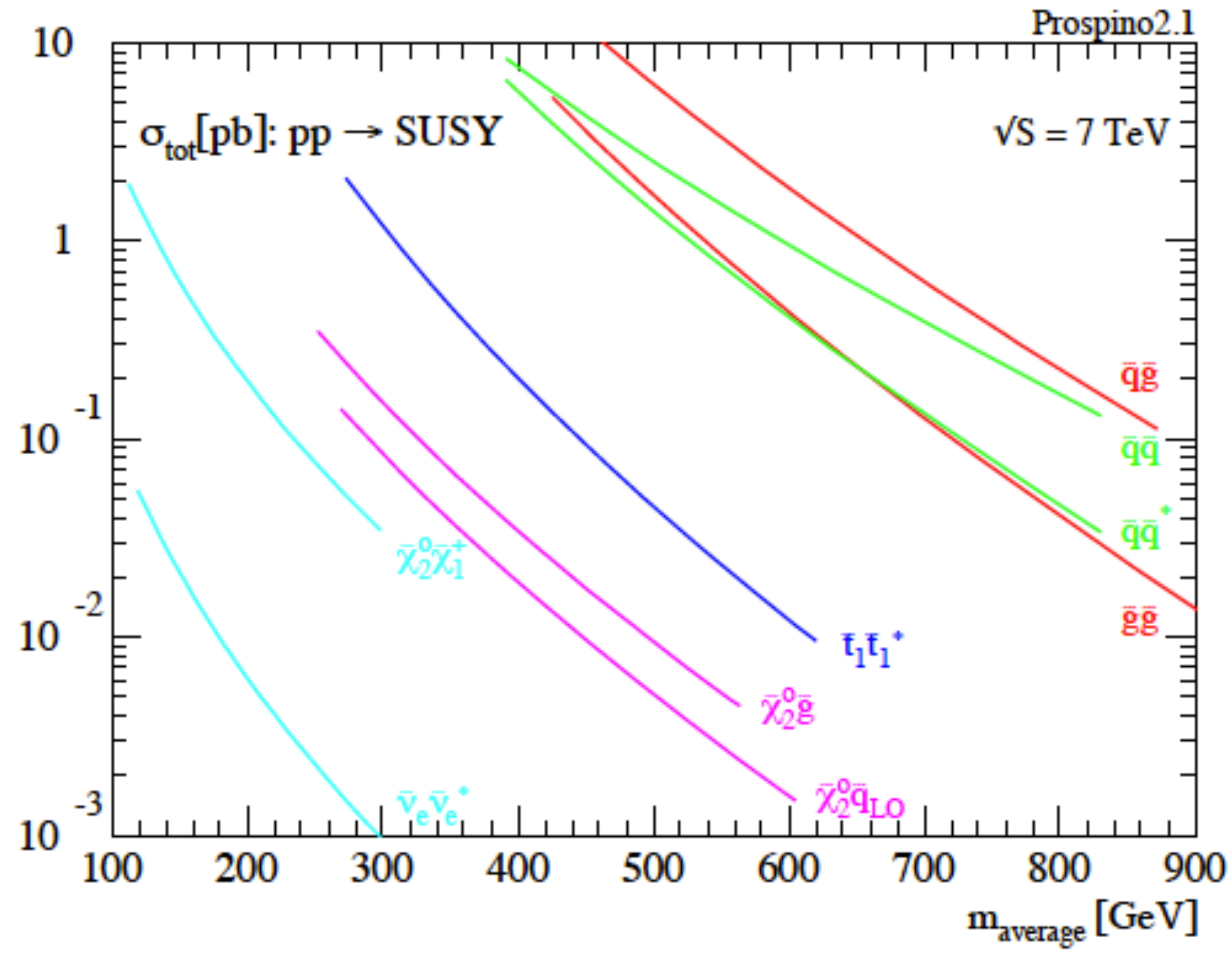
Natural SUSY

Naturalness only requires Higgsinos, stops and gluinos to be "light"



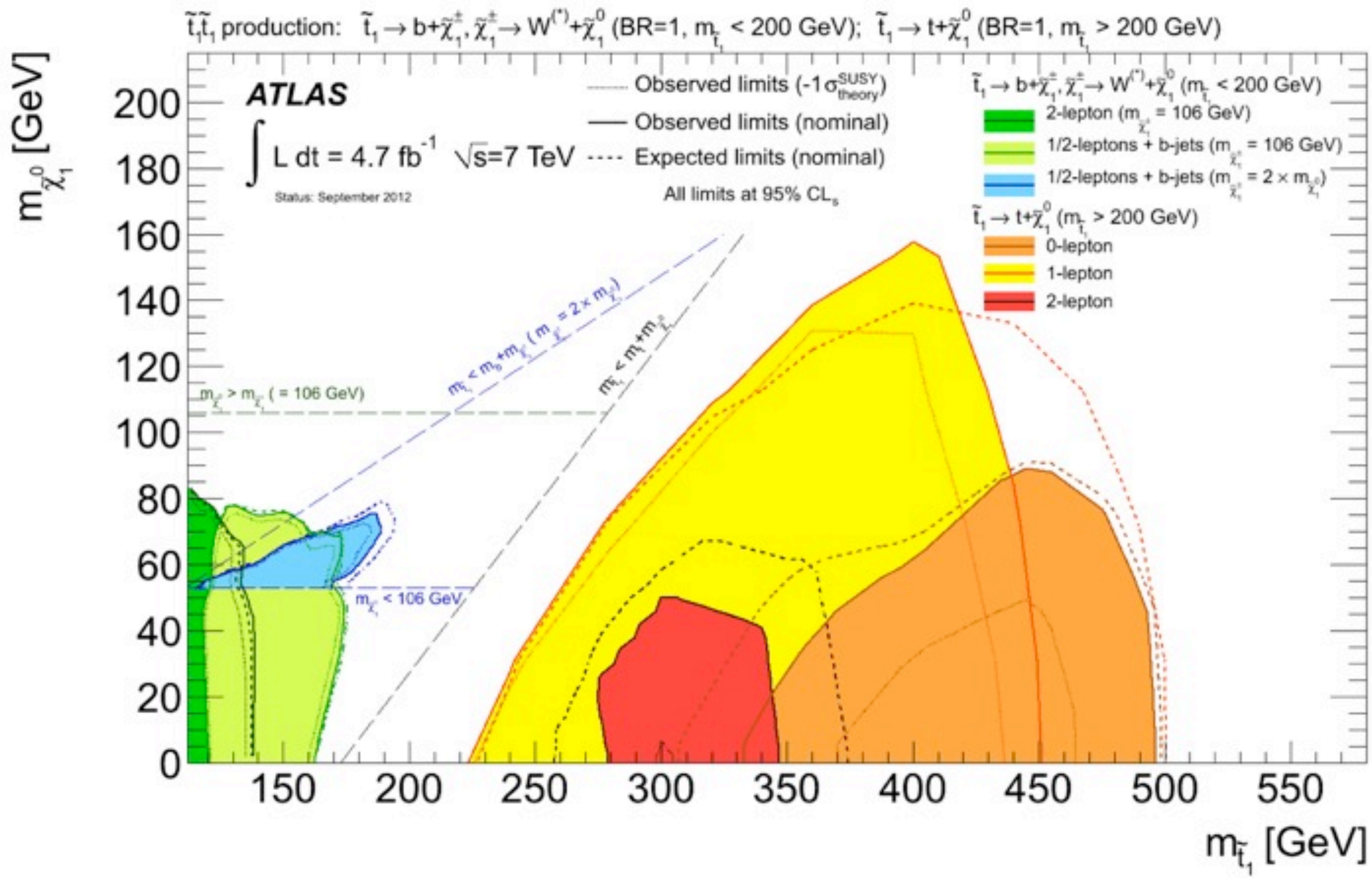
Natural SUSY

It's hard to produce light stops



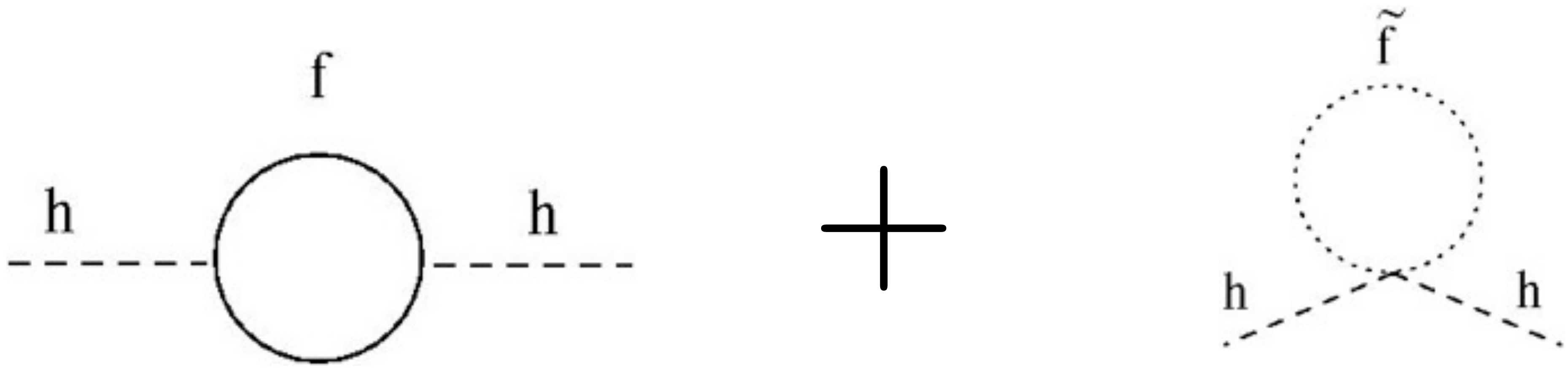
Hiding SUSY

Stop limits



Finding Natural SUSY is hard

Implications of m_h for SUSY



Superpartner loops to make Higgs heavier

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

$M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ Stop mass scale

$X_t = A_t - \mu \cot\beta$ Stop mixing

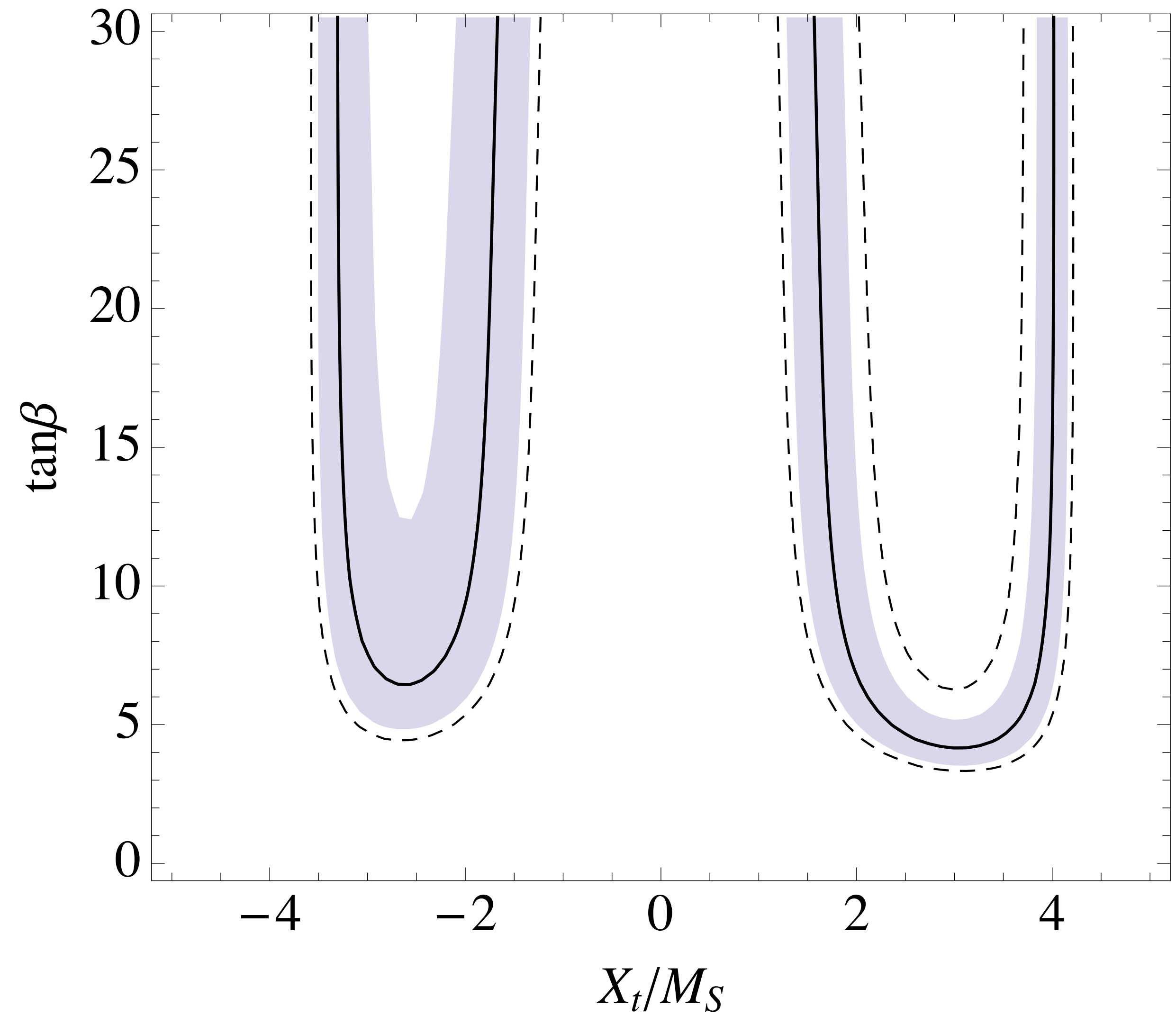
SUSY and the Higgs

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{M_S^2}\right)\right)$$

For $m_h = 125\ \mathrm{GeV}$

$\Rightarrow \tan\beta > 3.5$

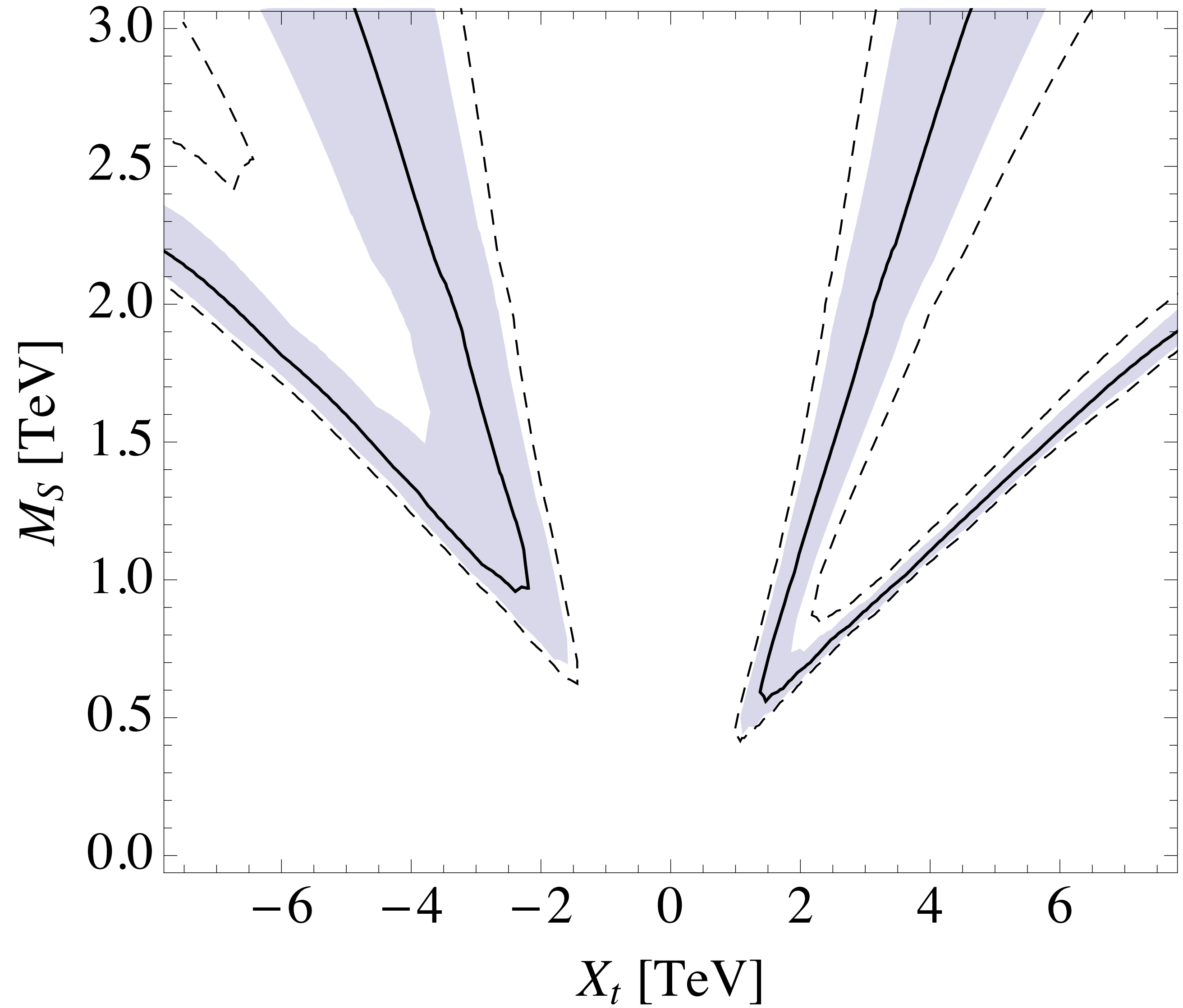
Draper, Meade, Reece, Shih '12



SUSY and the Higgs

For fixed $\tan\beta = 30$

$$\Rightarrow \begin{cases} |X_t| > 1\ \text{TeV} \\ M_S > 500\ \text{GeV} \end{cases}$$



$\Rightarrow$ Trouble for GMSB:

pressure on M_{mess} to be large

to get large enough superpartner masses

Beyond the MSSM

Problem in the MSSM:

$$V(H_u, H_d) = \frac{(g^2 + g'^2)}{2}\,(H_u^2 - H_d^2)^2 \qquad \Rightarrow m_h^2 = M_Z^2\, cos^2(2\beta)$$

NMSSM   Add a singlet chiral superfield

$$\lambda_S\, S\, H_u\, H_d$$

$$\langle S \rangle = v_s \quad \Rightarrow \quad \lambda_S v_s\, H_u H_d$$ gives μ term

and an extra quartic $\lambda_S^2\; H_u^2\, H_d^2$

$$\Longrightarrow \quad m_h^2 = M_Z^2\, cos^2(2\beta) + \lambda_S^2\, v^2\; \sin^2(2\beta) + \cdots$$

SUSY - Conclusions/Outlook

- SUSY is a beautiful solution to the Hierarchy Problem

- The MSSM spectrum is highly constrained if we want

$$\tilde{m}_Q \leq O(1)\ \mathrm{TeV}$$

- But natural spectrum very much viable

- Bottom-up approach: look for natural SUSY signals if we really want to exclude SUSY

- The measurement of m_h posses additional constraints.

- Extensions of the MSSM (NMSSM, extended gauge sectors) should be explored, as long as they remain natural solutions to the HP

Physics Beyond the Standard Model 3.1

Gustavo Burdman

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CERN - Latin American School of High Energy Physics

Arequipa, Peru, March 6-19 2013

Beyond the Standard Model

Lecture 1
- Why do we need to go Beyond the SM ?
- The Hierarchy Problem: what do we need to solve it ?

Lecture 2
- Supersymmetry and the Hierarchy Problem

Lecture 3
- New Dynamics at the TeV scale: the Higgs as a (pseudo) Nambu-Goldstone Boson

Beyond the Standard Model III

- Solve the Hierarchy problem with dynamics: QCD and the σ (Technicolor, ...)

- Dynamical (composite) *light* Higgs: is a (pseudo) Goldstone boson
  The example of the pion in QCD

- Composite Higgs Models:

  Little Higgs
  Twin Higgs
  Gauge-Higgs unification in AdS_5

Where is the Scalar Sector Coming From

- But what determines m and λ ?

- Is the scalar sector resulting from some underlying dynamics ?

E.g. Superconductivity:

Cooper pairs $\Rightarrow \langle \Phi \rangle \neq 0$

$\mathcal{L}_\Phi$ is the Ginzburg-Landau theory $\left\{ \begin{array}{l} \text{EM broken in the SC} \\ \text{Meissner effect} \\ \text{penetration depth} \\ \vdots \end{array} \right.$

But microscopic description is BCS

Physics Beyond the Standard Model

Organize by origin of Higgs sector or solution to HP

- Supersymmetry:

  Higgs is elementary

  SUSY protects m_h

- Higgs sector is composite:

  Technicolor. No Higgs. ✗

  Higgs is a pNGB ✓

Composite Scalars: the Example of QCD

Spontaneous breaking of chiral symmetry in QCD

QCD with 2 flavors:

$$\mathcal{L}_{\rm QCD} = \bar{Q}_L\, i\, \not{D} Q_L + \bar{Q}_R\, i\, \not{D} Q_R - \bar{Q}_L\, M Q_R + \text{h.c.}$$

with

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad M = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

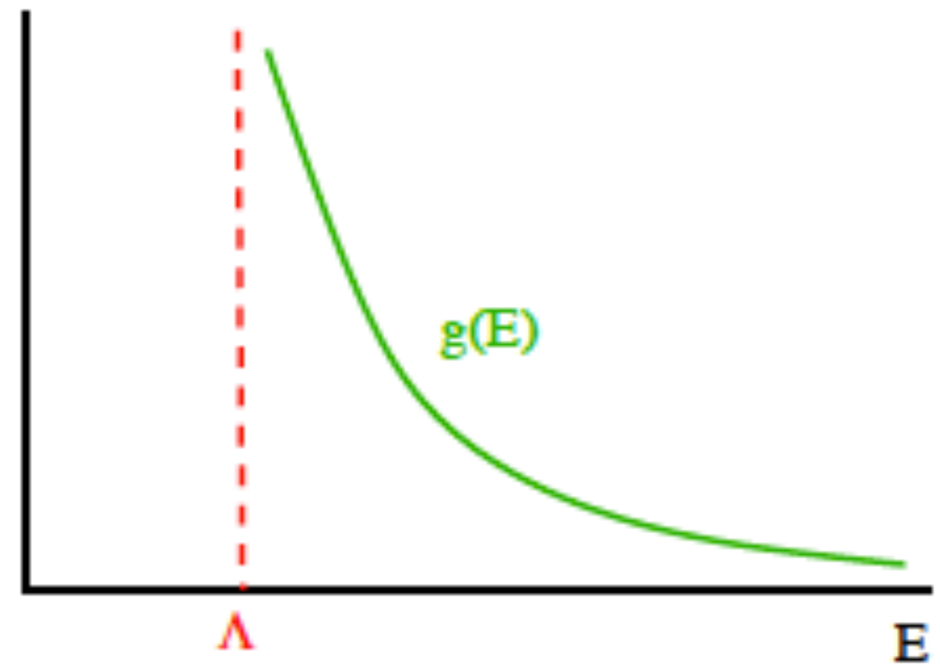
If $M = 0$, is invariant under $SU(2)_L \times SU(2)_R$

$$\begin{aligned} Q_L &\longrightarrow e^{i\ell^a t^a}\, Q_L \\ Q_R &\longrightarrow e^{i r^a t^a}\, Q_R \end{aligned}$$

with $\begin{cases} t^a = \dfrac{\sigma^a}{2}, \quad a = 1,2,3 \\ \ell^a,\ r^a \quad \text{free parameters} \end{cases}$

Chiral Symmetry Breaking

$SU(3)_c$ asymptotically free



At low energies, $\Lambda \simeq \Lambda_{\rm QCD}$, quark condensation

$$\langle \bar{Q}_L Q_R \rangle \neq 0 \;\; \Rightarrow SU(2)_L \times SU(2)_R \longrightarrow \;\; SU(2)_V$$

- Quarks acquire a dynamical mass

$$m_Q \sim \Lambda_{\rm QCD}$$

Chiral Symmetry Breaking

- 3 broken generators $\Longrightarrow$ 3 NGBs (π^+, π^-, π^0)

Since $SU(2)_L \times SU(2)_R = SU(2)_V \times SU(2)_A \longrightarrow SU(2)_V$

Axial current $\quad j_\mu^{a5} = \bar{Q}\gamma_\mu \gamma^5 Q$

does not annihilate the vacuum

$$\langle 0 | j_\mu^{a5} | \pi^b(p_\mu) \rangle = i f_\pi \, p_\mu \, \delta^{ab}$$

But still conserved if $m_\pi = 0$

$$\partial^\mu \, j_\mu^{a5} = f_\pi m_\pi^2$$

Spontaneous Breaking of Chiral Symmetry

Linear σ model

$$\mathcal{L} = \frac{1}{4}\mathrm{Tr}\left[\partial_\mu \Sigma^\dagger \partial^\mu \Sigma\right] + \frac{\mu^2}{4}\mathrm{Tr}\left[\Sigma^\dagger \Sigma\right] - \frac{\lambda}{16}\left(\mathrm{Tr}\left[\Sigma^\dagger \Sigma\right]\right)^2$$

with $\Sigma = \sigma + i\, t^a \pi^a$ and $\Sigma \to L^\dagger\, \Sigma\, R$

If $\mu^2 > 0 \quad \Rightarrow \langle \Sigma \rangle = v \neq 0$ $\qquad v = \sqrt{\dfrac{\mu^2}{\lambda}}$

$\Rightarrow$ {
Spontaneous breaking of chiral symmetry

$$m_\sigma = \sqrt{2\lambda}\, v$$

$$m_\pi = 0$$

Spontaneous Breaking of Chiral Symmetry

<u>In real QCD:</u>

- $\begin{cases} m_\sigma \sim \Gamma_\sigma \sim \ O(1) \ \mathrm{GeV} & \text{Cutoff of the effective theory} \\ \sigma & \text{is not a low energy state (too broad to be observable)} \end{cases}$

- $m_u, \ m_d \neq 0 \quad \Longrightarrow$ Explicit symmetry breaking

$m_\pi \neq 0 \qquad \pi' s$ are pseudo NGBs

But still light

$$m_\pi \simeq 0.14 \mathrm{GeV} \ll O(1) \ \mathrm{GeV}$$

GeV vs. TeV Scales

Build a TeV-scale model of *EWSB* in analogy with QCD

Two avenues:

- Fermionic sector breaks *EWS* just as in QCD

  Higgs (σ) is not is the light spectrum

- Strong sector breaks global symmetry

  Higgs is a (pseudo) NGB remnant

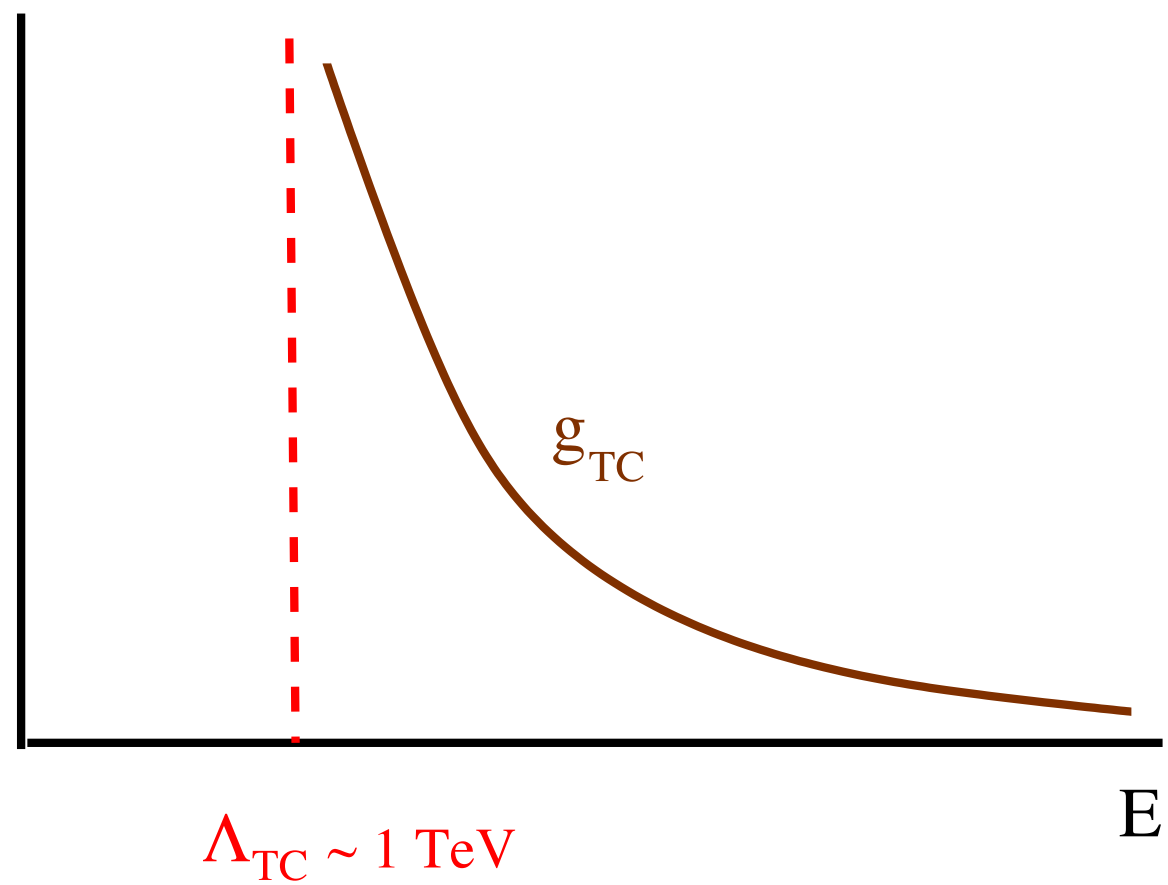
  just like the $\pi' s$

Strong Dynamics at the TeV Scale

Scaled up QCD

- New gauge interaction
- Strong at the TeV scale
- Breaks EWS by

$$\langle \bar{F} F \rangle \neq 0$$



Basic Technicolor Model

- Asymptotically-free interaction $SU(N_T)$
- New fermions: $SU(2)_L$ doublet

$$Q_L = \begin{pmatrix} T \\ B \end{pmatrix}_L \qquad (N_T, 1, 2, Y_Q)$$

$$T_R \qquad (N_T, 1, 1, Y_T)$$

$$B_R \qquad (N_T, 1, 1, Y_B)$$

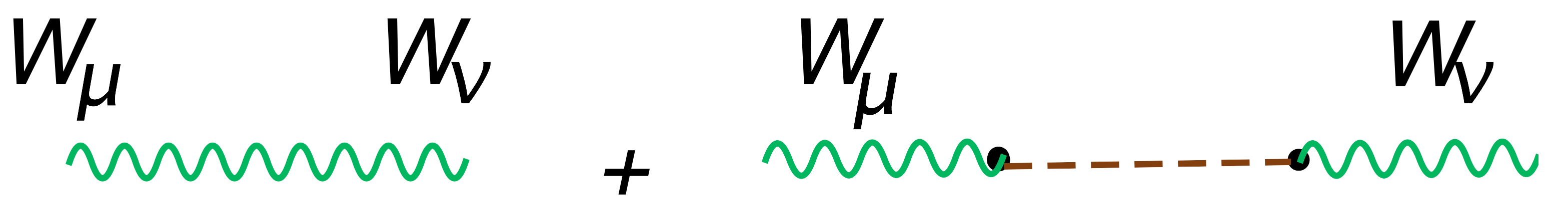
- At Λ_{TC} we have $\langle \bar{Q}_L Q_R \rangle \neq 0$

$\Rightarrow$
- Spontaneous breaking of global $SU(2)_L \times SU(2)_R$
- Also SB of the gauge $SU(2)_L \times U(1)_Y \to U(1)_{\text{EM}}$

Higgs Mechanism without a Higgs

$SU(2)_L \times SU(2)_R \to SU(2)_V \quad \Longrightarrow$ 3 Nambu-Goldstone bosons

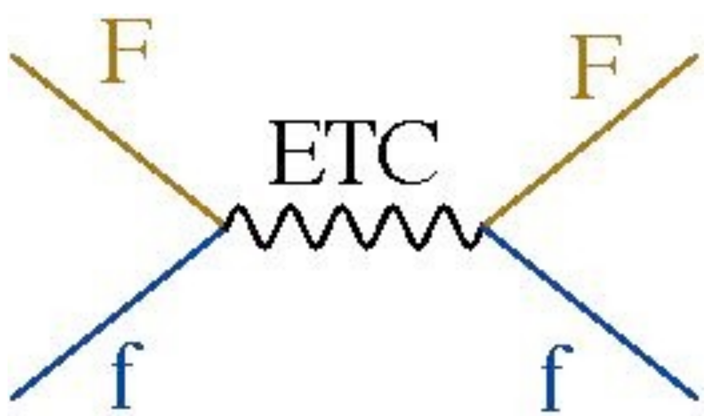
NGBs eaten as gauge boson longitudinal polarizations

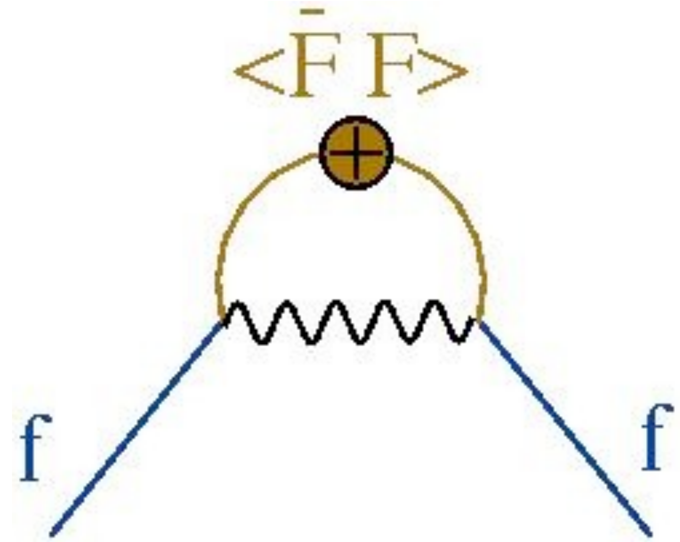


$$i\frac{g^2 F_T^2}{4}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)$$

Fermion Masses without a Higgs

Need extended interaction mixing SM fermions with tfermions





$$-\frac{g^2_{\rm ETC}}{M^2_{\rm ETC}}\,\bar{f} f\,\bar{F} F \qquad \Rightarrow \qquad m_f \sim \frac{g^2_{\rm ETC}}{M^2_{\rm ETC}}\,\Lambda^3_{\rm TC}$$

Extended Technicolor

<u>ETC requires more techni-fermions</u>

$\begin{pmatrix} T \\ B \end{pmatrix}_L^i \qquad T_R^i,\ B_R^i$ techni-quarks

$\begin{pmatrix} N \\ E \end{pmatrix}_L \qquad N_R,\ E_R$ techni-leptons

- Number of doublets higher $N_D = 4$

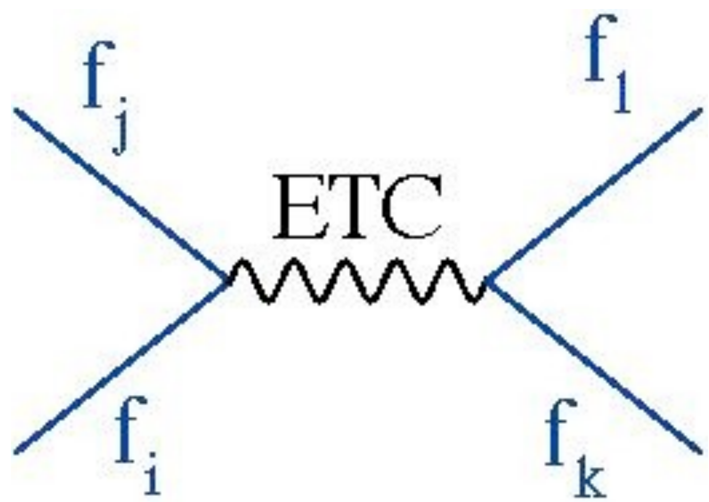
  Problems with EWPC

- Larger chiral symmetry broken $SU(8)_L \times SU(8)_R \longrightarrow SU(8)_V$

  63 -3 = 60 NGBs left in the spectrum!

Flavor Violation from ETC Interactions

ETC leads to tree-level flavor violation



$\Longrightarrow$ effects in $(K^0 - \bar{K}^0),\ (B^0 - \bar{B}^0),$ mixing, ...

$$\Longrightarrow\ M_{\rm ETC} > 1000\ {\rm TeV}$$

But $M_{\rm ETC}$ cannot be too large or it would suppress

m_t, m_b, m_c too much

Walking Technicolor and Separation of Scales

To get heavier masses need to enhance TC condensate

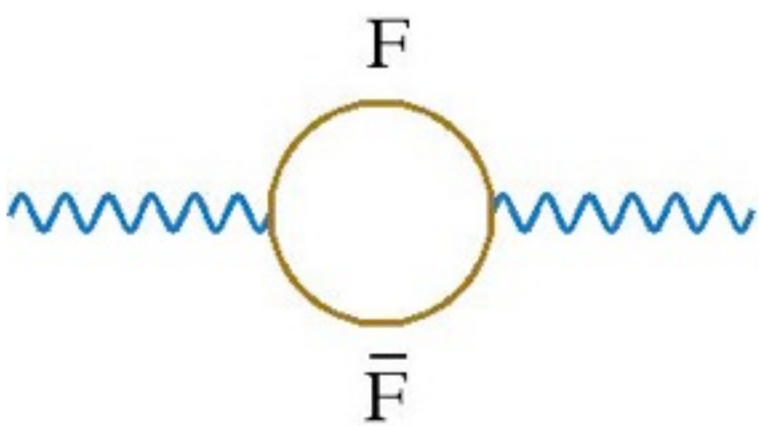
$$\Rightarrow \begin{cases} \text{Near-conformal behavior of TC interaction} \\ \text{Coupling walks} \end{cases}$$

But walking takes long time for coupling to become super-critical

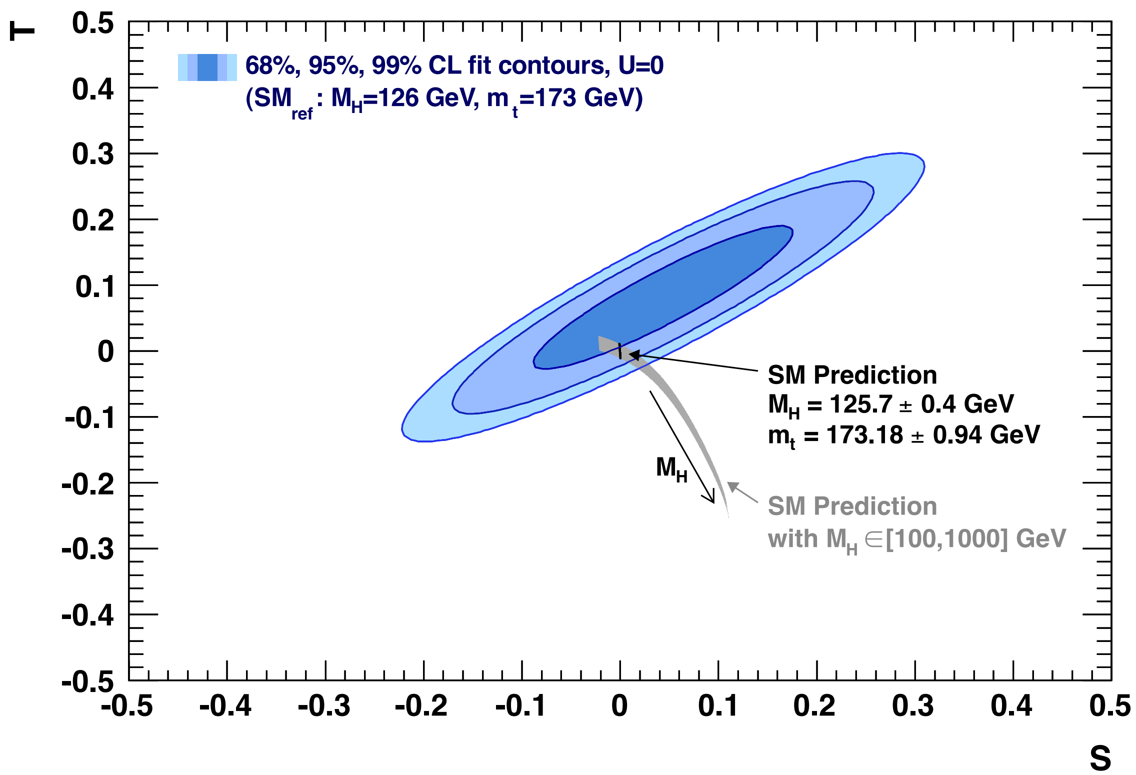
$\Longrightarrow$ Walking generates large separation of scale

Electroweak Precision Constraints

For the simple scaled up QCD scenario



$$\Rightarrow \qquad S \sim \frac{N_T\, N_D}{6\pi}$$



S is very large in QCD-like models

New Ideas in Techni-Color Models

- Minimal Walking Technicolor (F. Saninno *et al.*)

  $$N_T = 2, N_D = 1$$

  No flavor theory

  Not clear how to get a light Higgs

  Can be modeled in AdS_5

- Conformal Technicolor (M. Luty *et al.*)

  Strong sector is near a conformal fixed point in the UV

  Explicit conformal breaking $\rightarrow$ EWSB

  First basic models accommodate light Higgs as pNGB

Higgs is a pseudo Nambu-Goldstone Boson

Back to the analogy of QCD at low energies

- Build models where the Higgs is like π instead of σ

  Need to break global symmetry spontaneously

$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

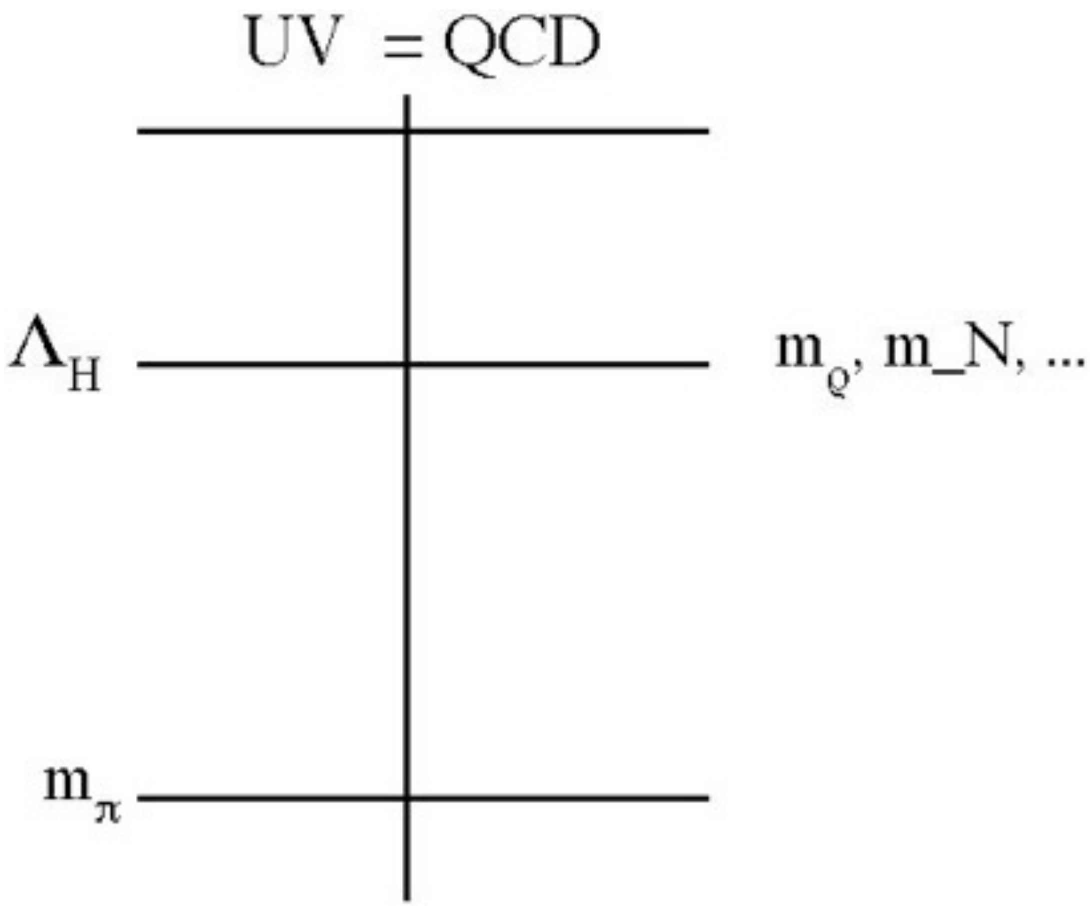
Number of NGBs: $3+3-3=3 \qquad (\pi^+, \pi^-, \pi^0)$

- Explicit symmetry breaking:

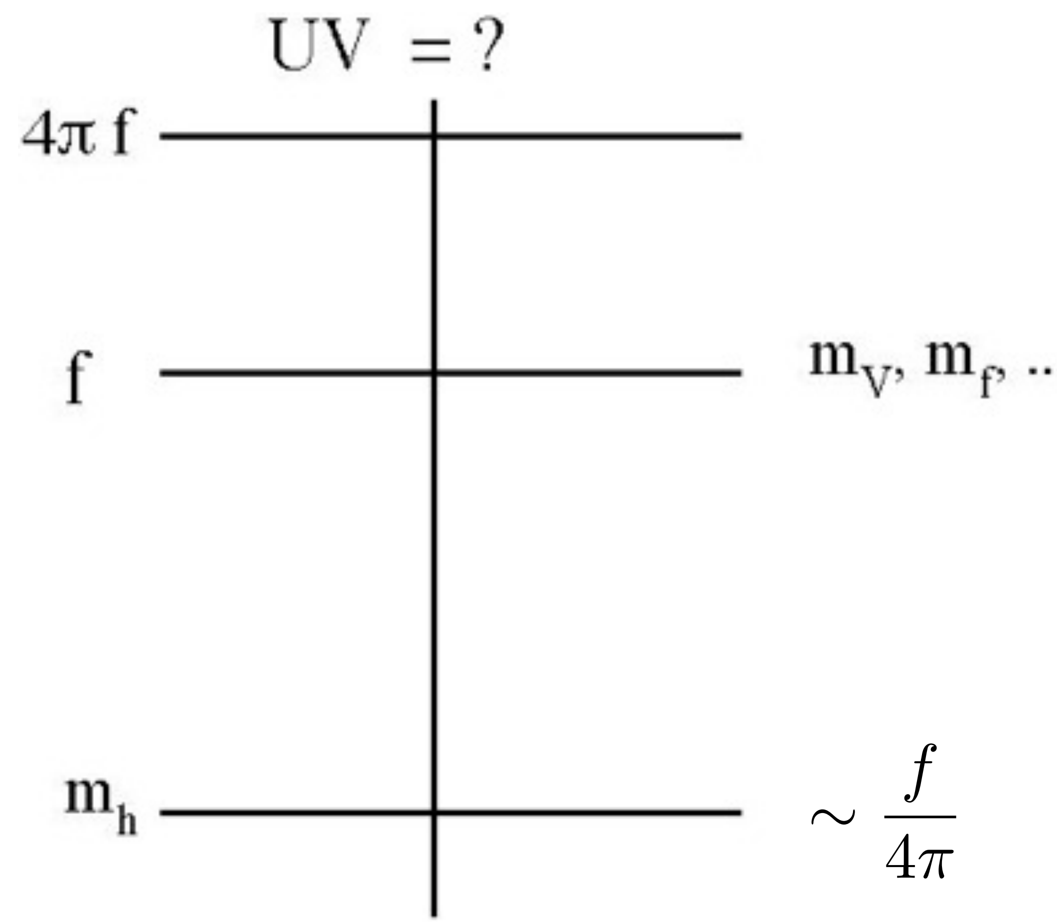
$$m_\pi^2 = B_0\, m_q$$

gives mass to the NGB

Higgs is a pNGB



QCD



Electroweak

Physics Beyond the Standard Model 3.2

Gustavo Burdman

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CERN - Latin American School of High Energy Physics

Arequipa, Peru, March 6-19 2013

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- The Hierarchy Problem: what do we need to solve it ?

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  The example of the pion in QCD

- Composite Higgs Models:

  Little Higgs
  Twin Higgs
  Gauge-Higgs unification in AdS_5

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Back to the analogy of QCD at low energies

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$$SU(2)_L \times SU(2)_R \to SU(2)_V$$

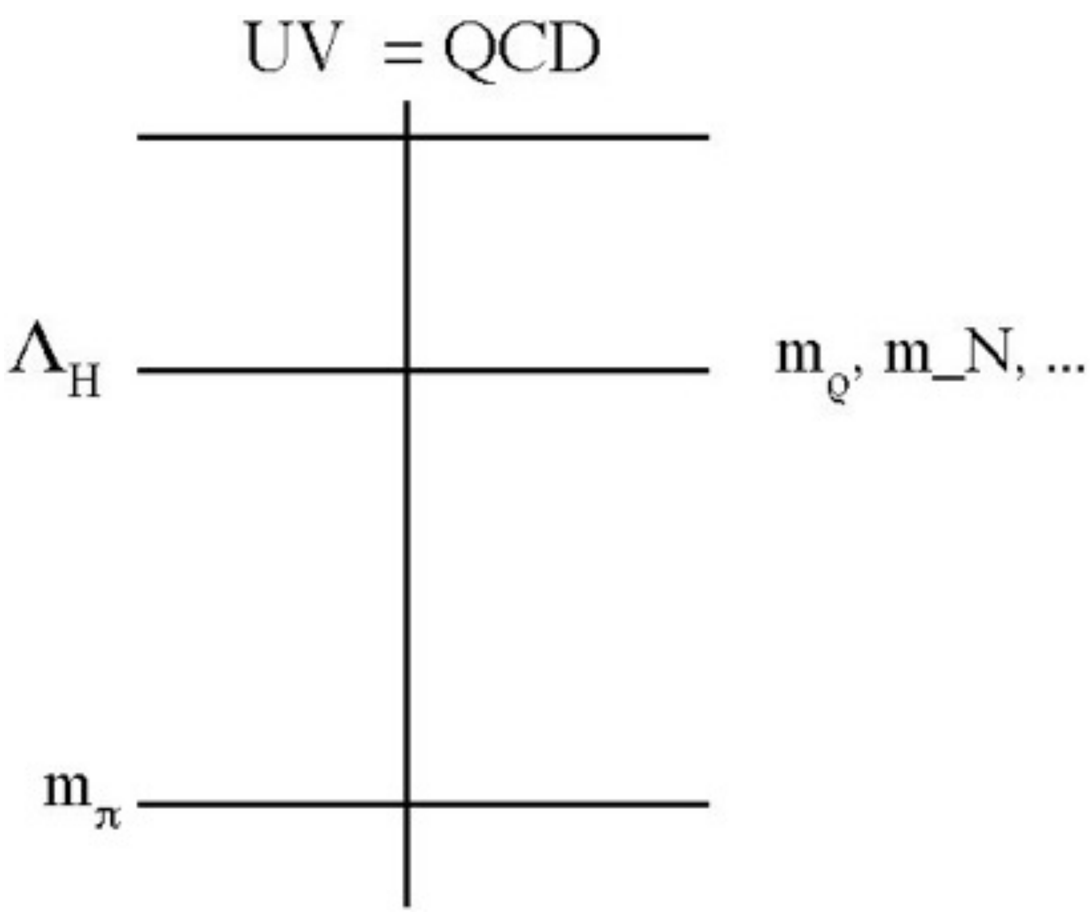
  Number of NGBs: $3+3-3=3 \qquad (\pi^+, \pi^-, \pi^0)$

- Explicit symmetry breaking:

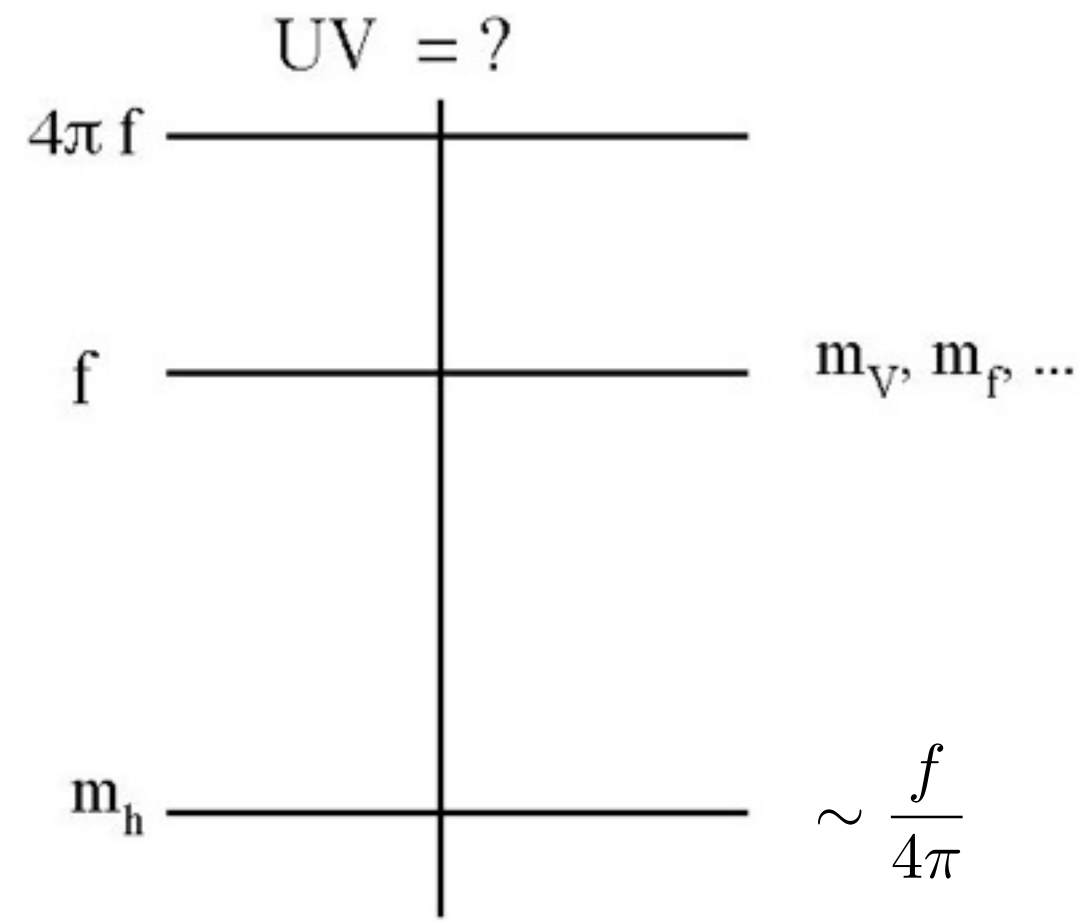
$$m_\pi^2 = B_0\, m_q$$

  gives mass to the NGB

Higgs is a pNGB



QCD



Electroweak

Higgs as a pNGB: Little Higgs Mechanism

- If the Higgs is (part of) a NGB then $m_h = 0$ and it can only have derivative interactions:

invariance under $h \to h + c$ shift symmetry

- In the SM $SU(2)_L \times U(1)_Y \to U(1)_{\rm EM}$

\# NGBs = # of broken generators = 3

But they're all eaten by $W_L^\pm, Z_L$

- To have NGBs left over need

Global symmetry > Gauge symmetry

Little Higgs Mechanism

- The spontanous breaking of a global symmetry gives massless NGBS
  One of them: doublet of $SU(2)_L$ h

- But we need to give h a mass

$\Longrightarrow$ Need explicit breaking of global symmetry

$$\Longrightarrow \quad m_h \neq 0$$

Simplest Little Higgs

Try with global symmetry $SU(3) \rightarrow SU(2)$

- # of broken generators = 8 - 3 = 5
- OK. We need 4 d.o.f. for h
- Explicit breaking to get $m_h \neq 0$

If we gauge part of $SU(3)$ (e.g. $SU(2)$)
we break explicitly $SU(3)$ global $\Longrightarrow$ quadratic divergences

If we gauge all of the $SU(3)$

Global symmetry is respected.

But now all of the NGBs are eaten
to give masses to gauge bosons.

Simplest Little Higgs

<u>Solution:</u> Enlarge the global symmetry to $SU(3) \times SU(3)$

$$SU(3) \times SU(3) \to SU(2) \times SU(2)$$

# of broken generators = 16 -6 = 10

But 5 eaten in the gauge breaking $SU(3) \to SU(2)$

So in the end: 5 NGBs left

Simplest Little Higgs

$$\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2$$

$$\Phi_1 = e^{i\pi/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \qquad , \Phi_2 = e^{-i\pi/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

with

$$\pi = \pi^a t^a = \eta/\sqrt{2} + \begin{pmatrix} 0 & 0 & h_1 \\ 0 & 0 & h_2 \\ h_1^* & h_2^* & 0 \end{pmatrix}$$

and

$$\begin{pmatrix} h1 \\ h2 \end{pmatrix} = h \qquad SU(2)_L \text{ doublet}$$

Simplest Little Higgs

Gauge interactions do respect global symmetry

$$\mathcal{L} = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2$$

They do lead to quadratic divergences, from terms like

$$A_\mu A^\mu \left(\Phi_1^\dagger \Phi_1 + \Phi_1^\dagger \Phi_1 \right)$$

$$\longrightarrow \qquad \frac{g^2}{16\pi^2}\Lambda^2 \left(\Phi_1^\dagger \Phi_1 + \Phi_2^\dagger \Phi_2 \right) = \frac{g^2}{16\pi^2}\Lambda^2 \left(f^2 + f^2 \right)$$

But they do not induce and $h^\dagger h$ term

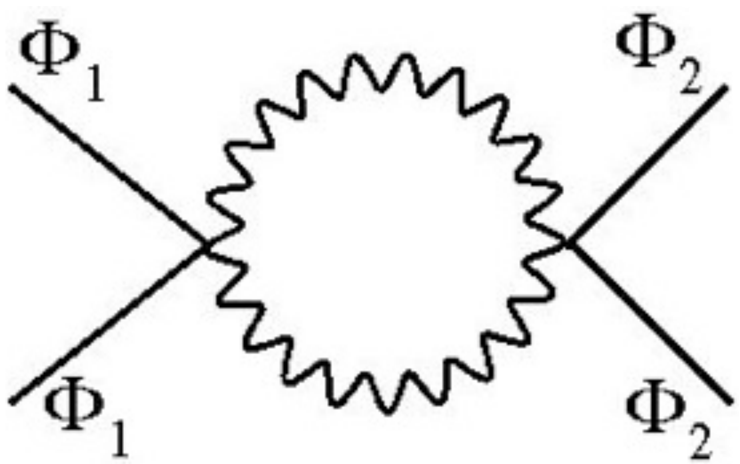
Do not contribute to m_h^2

Simplest Little Higgs

But at one loop we generate operators like $\Phi_1^\dagger \Phi_2$

$$\Phi_1 = e^{i\pi/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \qquad , \Phi_2 = e^{-i\pi/f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

that will depend on h



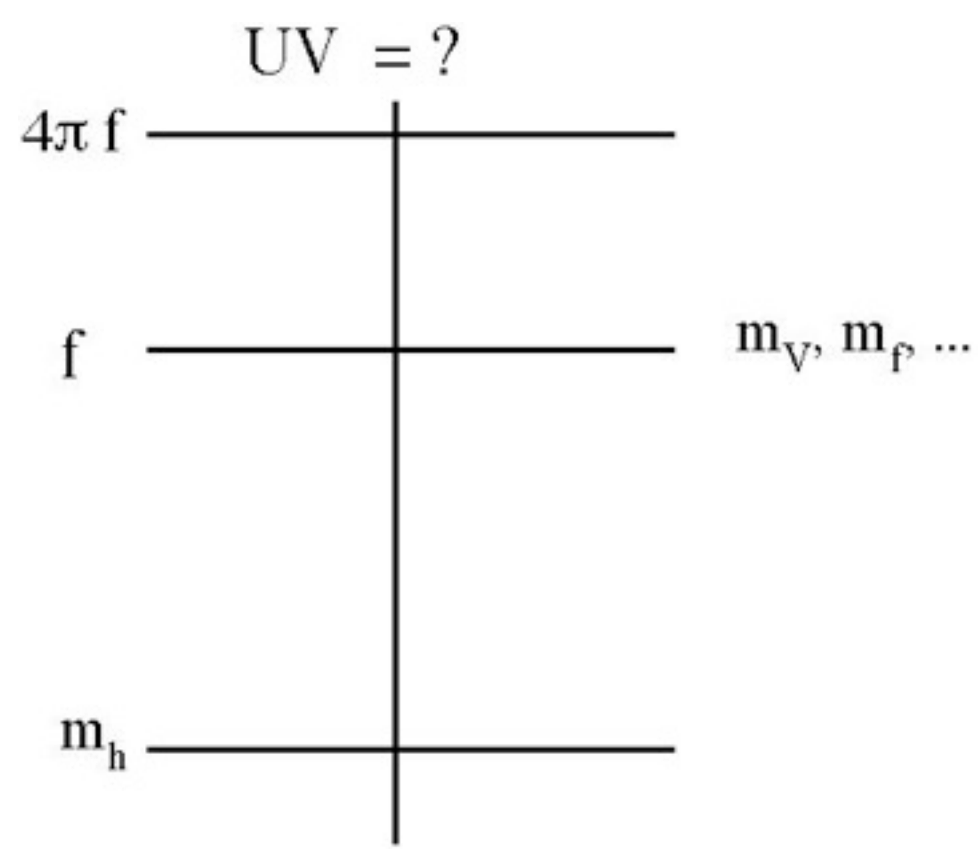
Two boson propagators $\Longrightarrow$ *only logarithmic divergence*

Simplest Little Higgs

$$\frac{g^4}{16\pi^2}\ln\left(\frac{\Lambda^2}{\mu^2}\right)|\Phi_1^\dagger\Phi_2|^2 \quad \Longrightarrow \quad \delta m_h^2 \simeq \frac{g^4}{16\pi^2}\ln\left(\frac{\Lambda^2}{\mu^2}\right) f^2$$

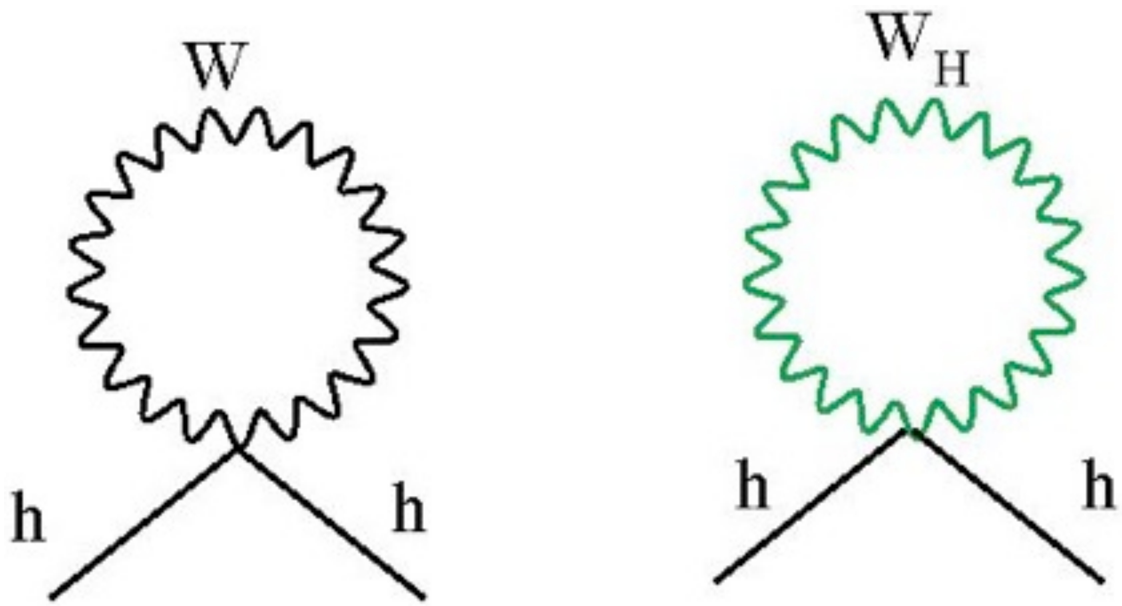
$\Longrightarrow$ generates $m_h \sim \dfrac{f}{4\pi}$

just as we needed



Simplest Little Higgs

But how are the quadratic divergences cancelled ?



Heavy gauge bosons cancel W quadratic divergence

Simplest Little Higgs: Fermions

We choose am anomaly-free model. Quarks:

$$\Psi_{Q_1} = \begin{pmatrix} d \\ u \\ D \end{pmatrix}_L \sim (\mathbf{3}^*, 0), \qquad \Psi_{Q_2} = \begin{pmatrix} s \\ c \\ S \end{pmatrix}_L \sim (\mathbf{3}^*, 0),$$

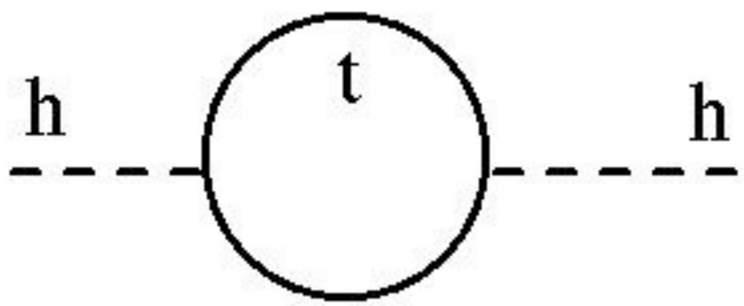
$$\Psi_{Q_3} = \begin{pmatrix} t \\ b \\ T \end{pmatrix}_L \sim (\mathbf{3}, 1/3),$$

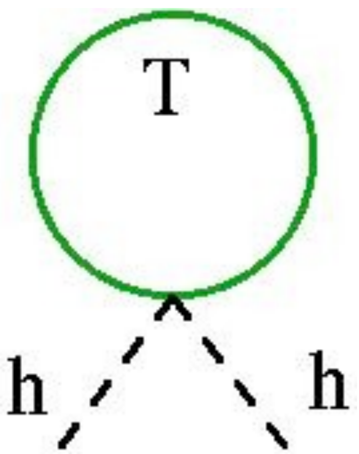
and right-handed singlets

$$u_R,\ c_R,\ t_R \sim (\mathbf{1}, 2/3), \qquad d_R,\ s_R,\ b_R \sim (\mathbf{1}, -1/3),$$

$$T_R \sim (\mathbf{1}, 2/3) \qquad\qquad D_R,\ S_R \sim (\mathbf{1}, -1/3)$$

Top Cancellation





Little Higgs

Electroweak Symmetry is broken radiatively

$$\delta V = \delta m^2 \, h^\dagger h + \lambda \, (h^\dagger h)^2$$

Tension: get a light Higgs with large enough f

EWPC want $f \gtrsim 2$ TeV

Many models other than this:

Littlest Higgs: $SU(5)/SO(5)$ with $SU(2) \times SU(2)$

T Parity: Better agreement with EWPC, Dark Matter

All require new fermions and new gauge bosons at f

Other pNGB Higgs Models

Twin Higgs

Gauge-Higgs unification in AdS_5

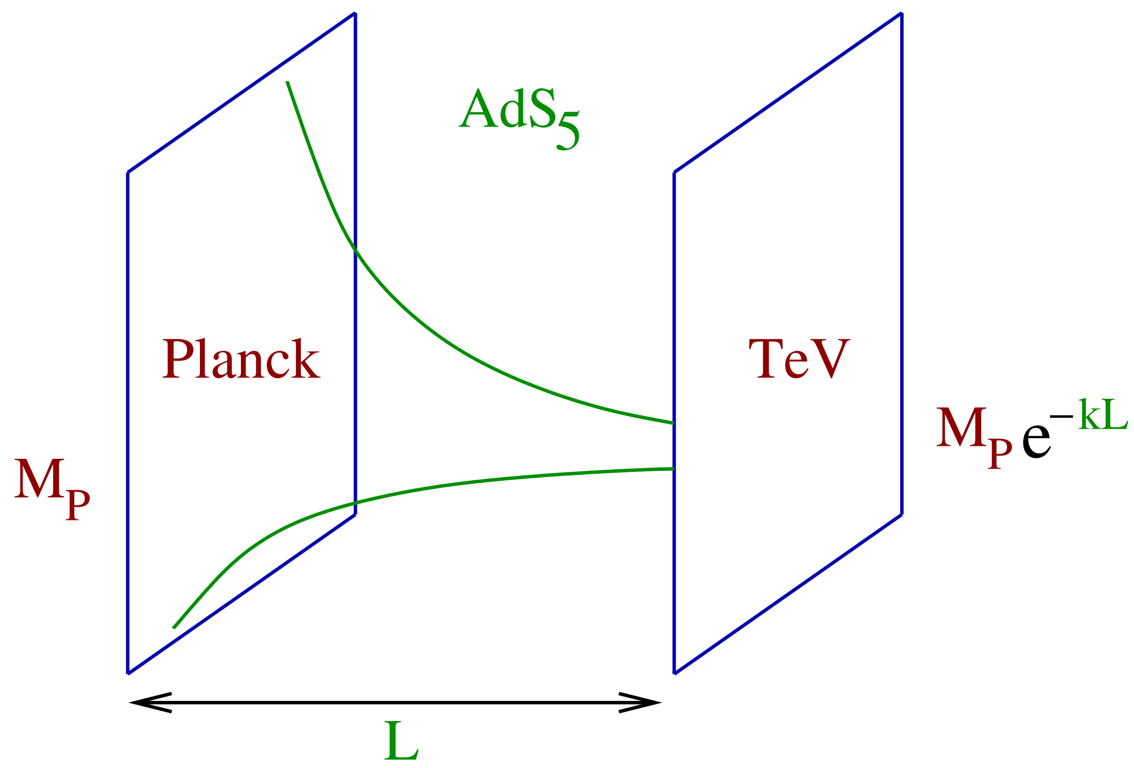
$\vdots$

In all cases Higgs is composite

Higgs couplings to SM particles is suppressed by powers of $\frac{v}{f}$

Separation of Scales in AdS_5

- One compact extra dimension. Non-trivial metric induces a small energy scale from a high one. (Randall, Sundrum '99)



- Geometry of extra dimension generates exponential hierarchy

$$\Lambda_{\text{TeV}} \sim M_{\text{Planck}}\, e^{-k\,L}$$

Separation of Scales in AdS5

- Warped 5D metric in RS

$$ds^2 = e^{-2k|y|}\,\eta^{\mu\nu}dx_\mu dx_\nu - dy^2$$

- Compactified on orbifold S_1/Z_2 with $L = \pi R$ and k the AdS_5 curvature

- Hierarchy problem: for $kR \simeq (11-12)$

$$k\,e^{-k\pi R} \simeq O(1)\ \mathrm{TeV}$$

The Hierarchy Problem in AdS

- If Higgs is localized in IR brane at $y = \pi R$

$$S_H = \int d^4x \int_0^{\pi R} dy \sqrt{-g}\,\delta(y - \pi R)\left[g_{\mu\nu}\partial^\mu H^\dagger \partial^\nu H - \lambda\left(|H|^2 - v_0^2\right)^2\right]$$

- Warp factor e^{ky} appears in $g_{\mu\nu}$ and $\sqrt{-g}$

$$S_H = \int d^4x \left[e^{-2k\pi R}\eta_{\mu\nu}\partial^\mu H^\dagger \partial^\nu H - e^{-4k\pi R}\lambda\left(|H|^2 - v_0^2\right)^2\right]$$

- Canonically normalize Higgs

$$e^{-k\pi R} H \to H$$

Hierarchy Problem in AdS$_5$

$$S_H = \int d^4x \, \left[\eta_{\mu\nu} \partial^\mu H^\dagger \partial^\nu H - \lambda \left(|H|^2 - e^{-2k\pi R} v_0^2 \right)^2 \right]$$

- If $v_0 \simeq M_P$, choosing $k\,R \simeq O(10)$ gives

$$v \simeq \text{weak scale}$$

$\Longrightarrow$ Higgs must be at or near IR brane

Bulk Fields in AdS

Bulk AdS models require

- Enlarge gauge symmetry to include custodial symmetry in bulk to avoid large T parameter

- Minimal choice: $SU(2)_L \times SU(2)_R \times U(1)_X$

- Expand bulk theory in Kaluza-Klein modes. Get effective 4D theory

Gauge Fields in AdS Bulk

- Gauge fields zero-modes are flat by gauge invariance

- KK modes have IR-localized wave functions

$$M_n \simeq (n - O(1)) \times \pi\, k\, e^{-k\pi R}$$

with masses starting at the TeV scale

Fermion Fields in AdS Bulk

- Massive fermion in curved 5D space

$$S_f = \int d^4x\, dy\, \sqrt{g} \left\{ \frac{i}{2} \bar{\Psi} \hat{\gamma}^M \left[\mathcal{D}_M - \overleftarrow{\mathcal{D}}_M \right] \Psi - \; M_f \bar{\Psi} \Psi \right\}$$

- To be natural $M_f \simeq O(1) k$

$M_f \equiv c_f\, k$ with $c_f \simeq O(1)$

- The parameter c_f determines the localization of the ZM fermion

Fermion Fields in AdS Bulk

- E.g.: Localization of left-handed ZM

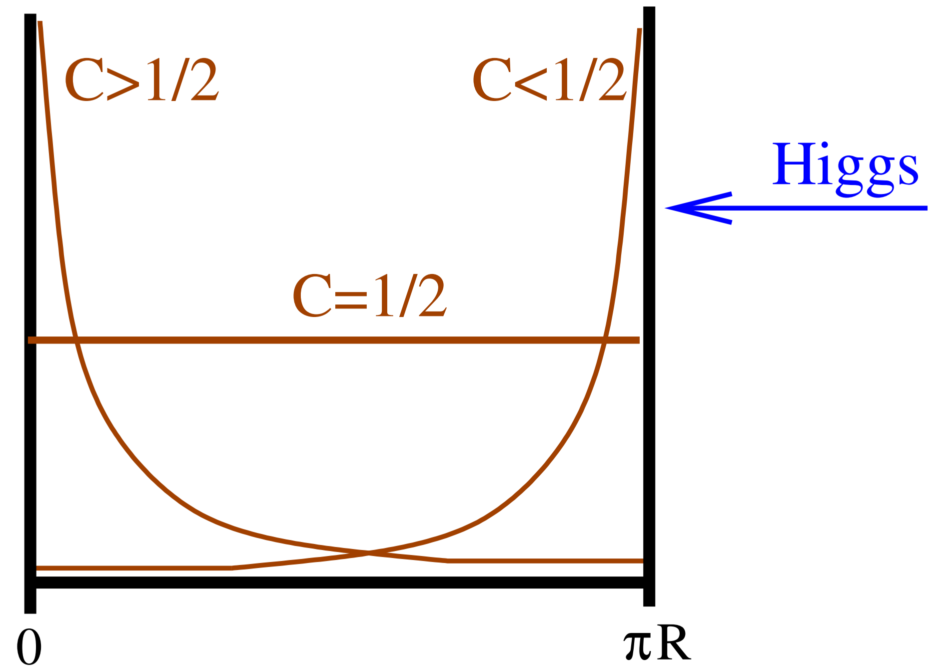
$$F^L_{\rm ZM}(y) = \frac{1}{\sqrt{2\pi R}}\, f^L_0(0) e^{(\frac{1}{2}-c_L)\,ky}$$

$c_L > \frac{1}{2} \Rightarrow$ ZM fermion localized near Planck brane

$c_L < \frac{1}{2} \Rightarrow$ ZM fermion localized near IR brane

Fermion Fields in AdS Bulk

• O(1) flavor breaking in bulk can give fermion mass hierarchy



Fermions localized near TeV brane have O(1) Yukawas

Those localized near the Planck brane have highly suppressed Yukawas

Dynamical Localization of the Higgs

- Gauge-Higgs unification: gauge filed in 5D has scalar A_5

- To extract Higgs from A_5 need to enlarge gauge symmetry

  E.g.: $SU(3) \to SU(2) \times U(1)$ broken by boundary conditions

$$A_\mu : \left(\begin{array}{cc|c} (+,+) & (+,+) & (-,-) \\ (+,+) & (+,+) & (-,-) \\ \hline (-,-) & (-,-) & (+,+) \end{array}\right)$$

$$A_5 : \left(\begin{array}{cc|c} (-,-) & (-,-) & (+,+) \\ (-,-) & (-,-) & (+,+) \\ \hline (+,+) & (+,+) & (-,-) \end{array}\right)$$

$\Longrightarrow$ Higgs doublet from $A_5 = A_5^a \, t^a$

Dynamical Localization of the Higgs

- In the dual 4D theory equivalent to Higgs as a NGB

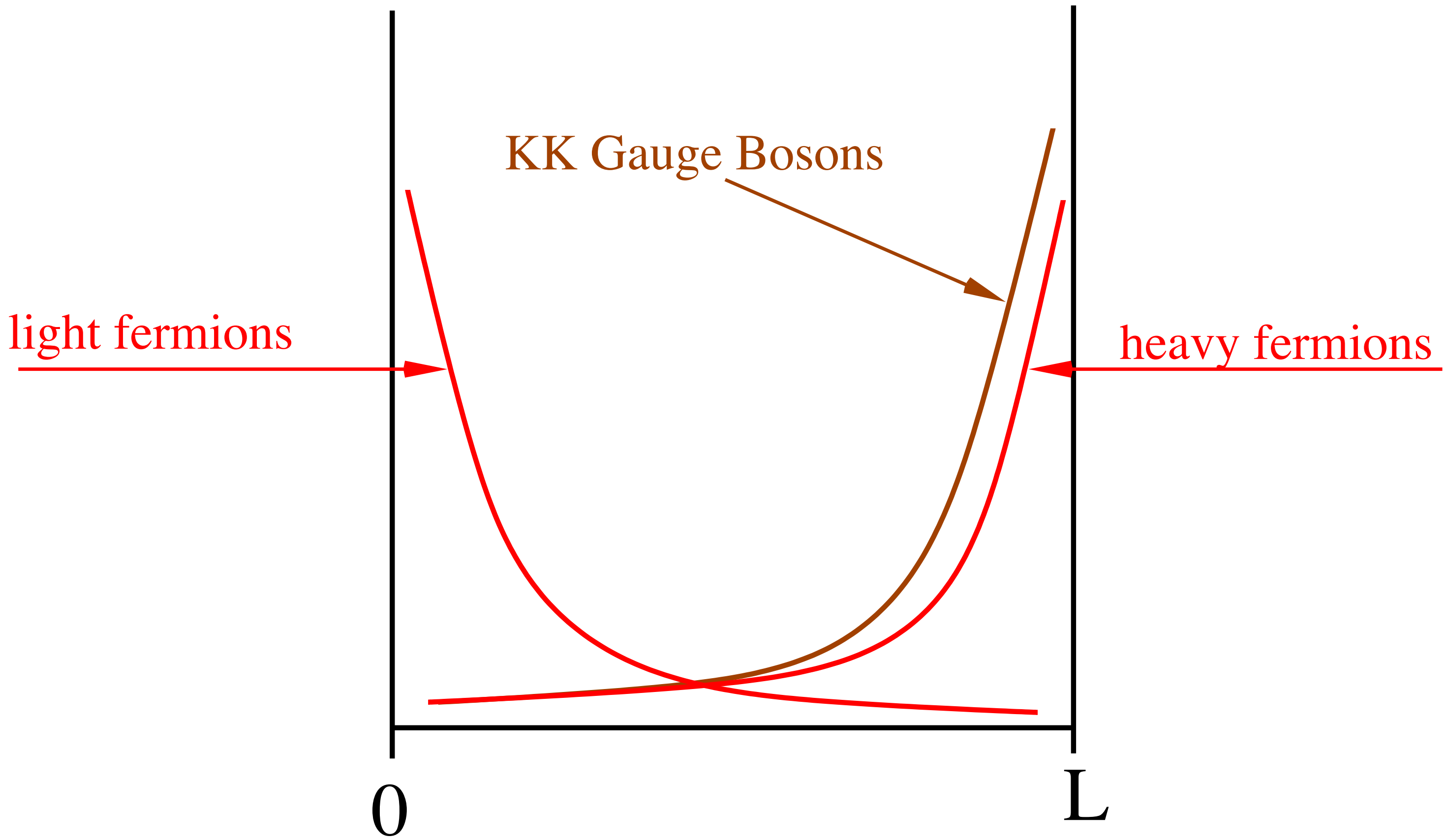
gauge symmetry in bulk $A_5 \to A_5 + \partial_y \chi$

$\Longrightarrow$ shift symmetry in 4D

Higgs is a (p)NGB

The Flavor Problem in AdS_5

- KK gauge bosons couple stronger to heavier fermions



- Tree-level flavor violation is hierarchical.
  only important with heavier generations.

The Flavor Problem in AdS$_5$

- Flavor bounds OK from most observables in K,D and B physics

- But one flavor observable is tough: ϵ_K

  mixed chirality operators $\bar{d}_R\, s_L\, \bar{d}_L\, s_R$

  have large enhancement $\left(\frac{m_K}{m_s}\right)^2 \eta_1^{-5} \simeq 100$

$$\Rightarrow M_{KK} > O(10)\ \mathrm{TeV}$$

- Requires flavor symmetries in the bulk

Conclusions

- Composite light Higgs require symmetry to protect m_h from being at the TeV scale (f)

- Models of pNGB Higgs generally work
  require new global and gauge symmetries at f
  Imply the existence of many new states above f

- They also imply a new strong interaction above $4\pi f$

- They replace a renormalizable theory with a non-renormalizable one ... but we've seen this before.