University of Glasgow

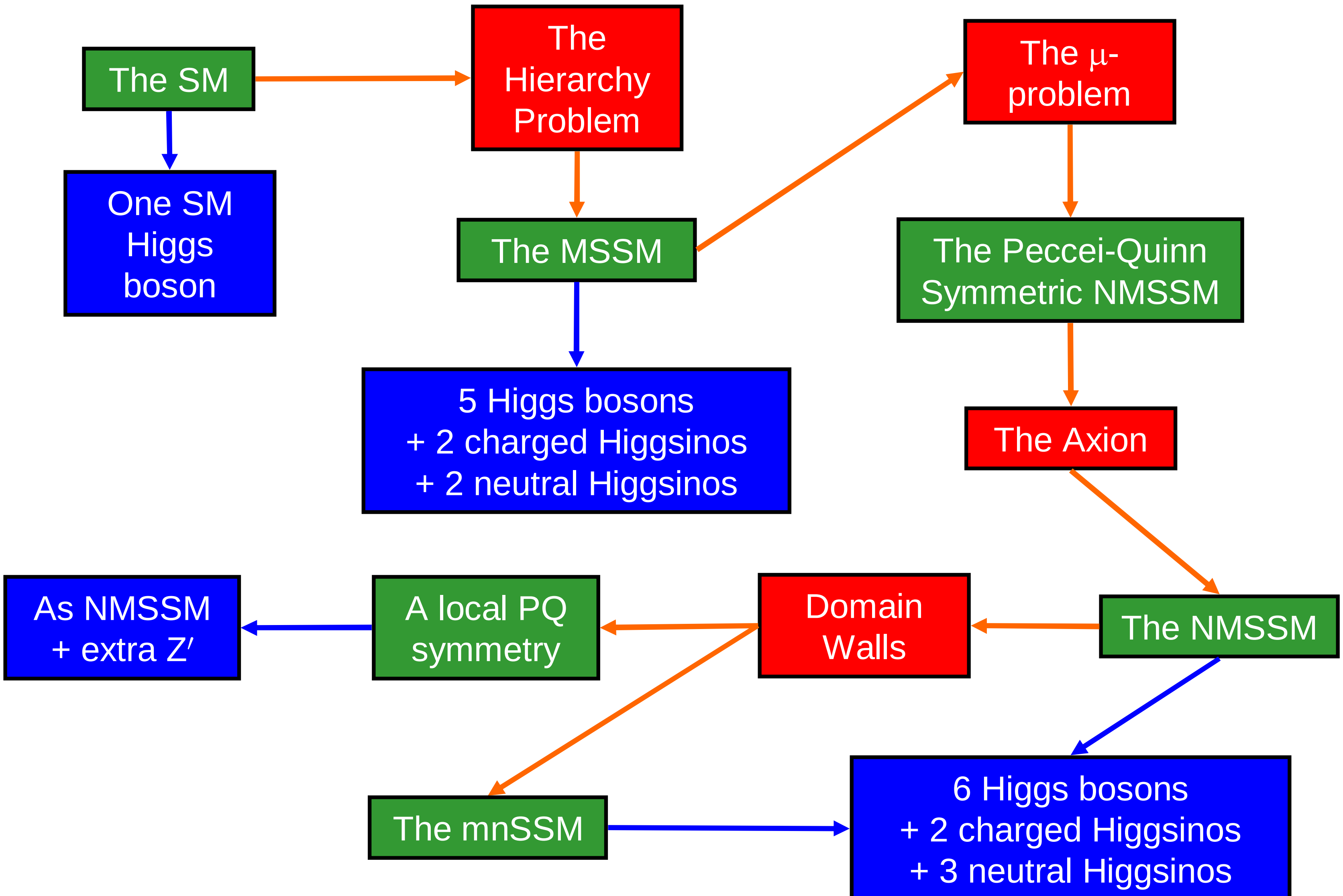
Breaking the electroweak symmetry in the Standard Model and beyond.

D.J. Miller

TeV scale physics and dark matter, Stockholm, June 2008

Outline:

- Introduction: The SM Higgs Sector
- The minimal SUSY Higgs sector
- The NMSSM
- The mnSSM
- A Local Peccei-Quinn Symmetry (and the E_6SSM)
- Conclusions and Summary


The SM
The Hierarchy Problem
The μ-problem
One SM Higgs boson
The MSSM
The Peccei-Quinn Symmetric NMSSM
5 Higgs bosons
+ 2 charged Higgsinos
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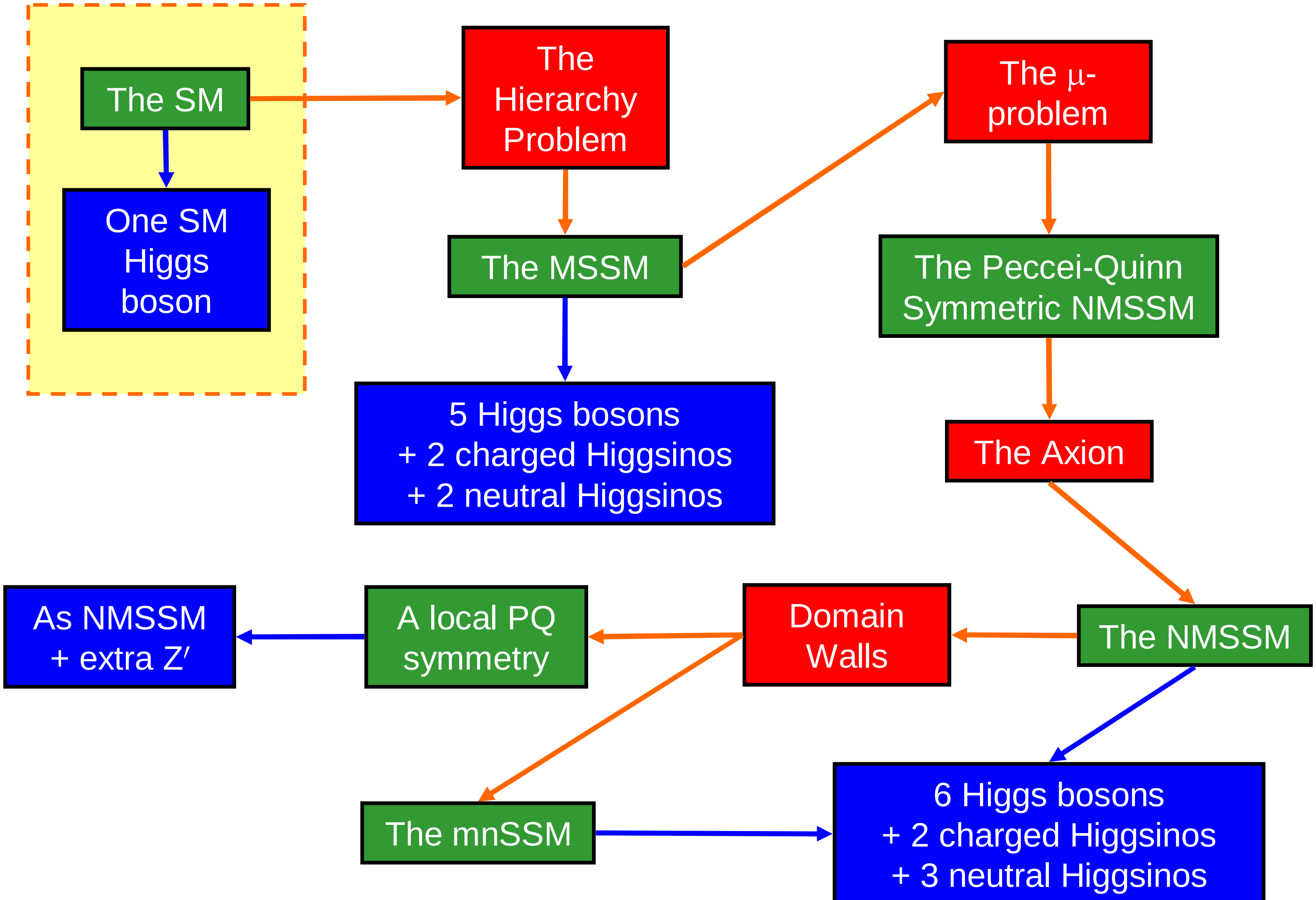
1. Introduction: The SM Higgs Sector



SM Higgs sector Lagrangian:

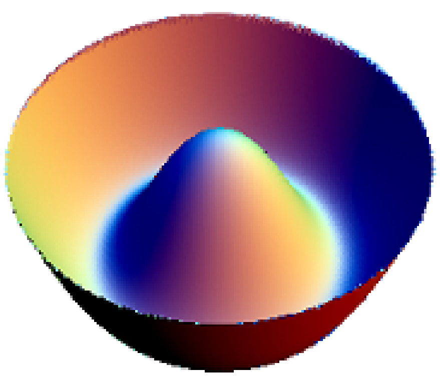
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$\mathcal{L}_{\text{Higgs}} = \mathcal{D}^\mu \Phi \mathcal{D}_\mu \Phi^* + V(\Phi) + \underbrace{Y_d\, \bar{Q}_L \cdot \Phi d_R + Y_u\, \bar{Q}_{L\,a} \epsilon^{ab} \Phi_b^\dagger u_R}_{} + \cdots$$

- Higgs potential

$$V(\Phi) = m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4$$

Minimum is at non-zero Φ if $m_\Phi^2 < 0$



- Yukawa interactions, provide mass terms for fermions when Φ gains a vacuum expectation value

Notice that we need to use the **conjugate** of the Higgs field for up type quarks to keep the terms hypercharge neutral.

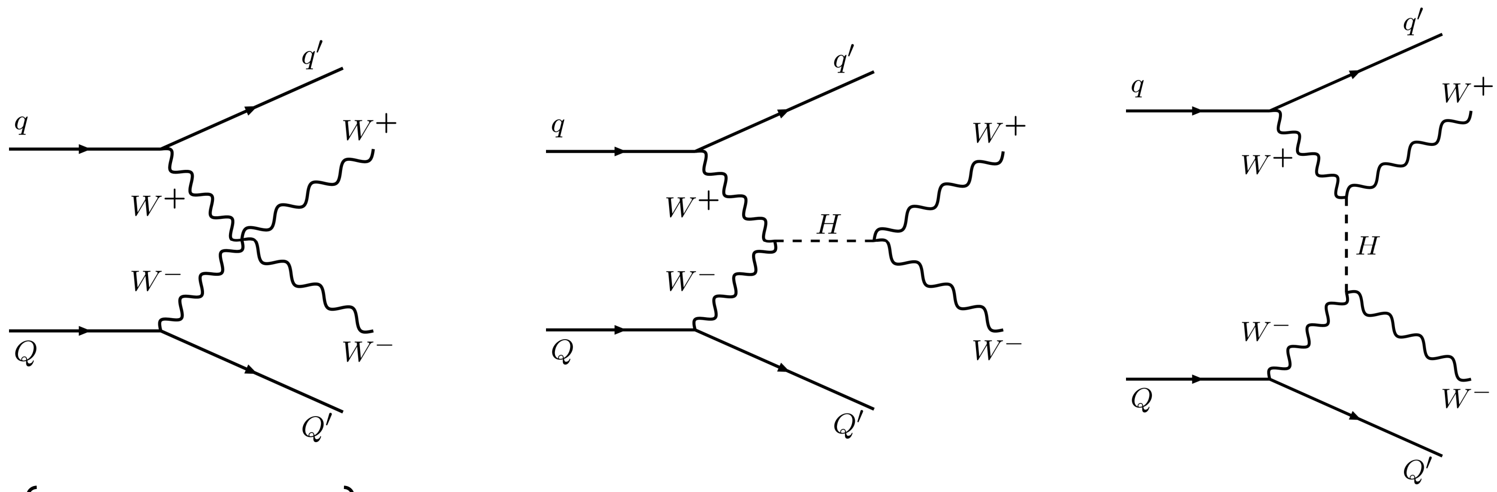
- Kinetic term $\rightarrow$ masses to W, Z bosons

$$\Rightarrow \quad \langle \phi^0 \rangle = \sqrt{\frac{-m_\Phi^2}{2\lambda}} \approx 174 \text{ GeV}$$

But the Higgs mass $\left(\sqrt{-2m_\Phi^2}\right)$ **is not predicted**

However, we have good reasons for expecting the Higgs boson to be **reasonably light**.

W-W scattering cross-sections rises very quickly with energy; without a Higgs boson they would **violate unitarity** before reaching a TeV



(+ γ/Z exchange)

The Higgs boson also contributes to this scattering, taming the violation.

$$\Rightarrow \quad M_H^2 \lesssim \frac{8\pi\sqrt{2}}{5G_F} \approx (780\ \text{GeV})^2$$

The coupling λ in the Higgs potential runs with energy.

$$t = \log Q^2/v^2$$

$$\langle \phi^0 \rangle = \frac{1}{\sqrt{2}} v$$

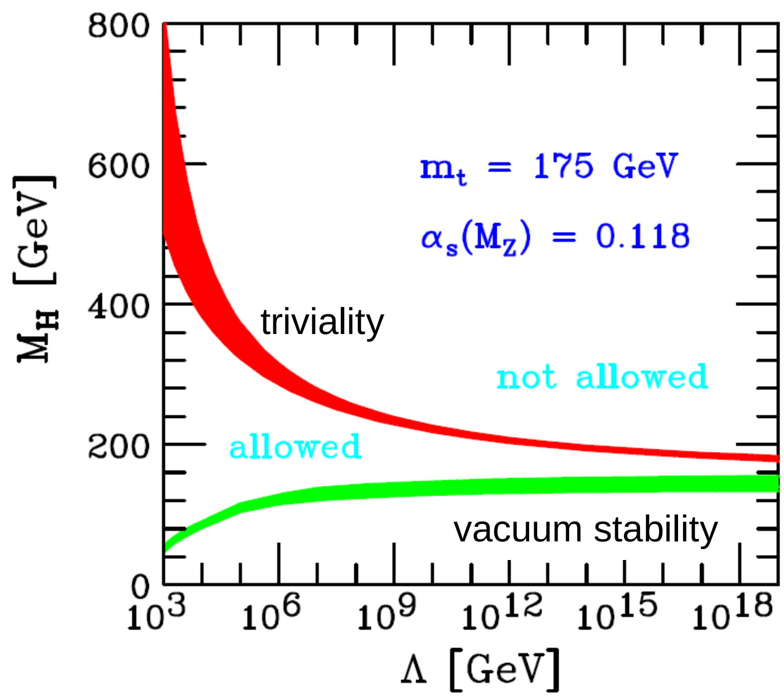
$$m_H = \sqrt{2\lambda}\, v$$

$$\frac{d\lambda}{dt} = \frac{3}{16\pi^2}\left(4\lambda^2 + \lambda m_t^2 v^2 - m_t^4 v^4/4\right)$$

- If λ is too big, then it blows up before the Planck scale

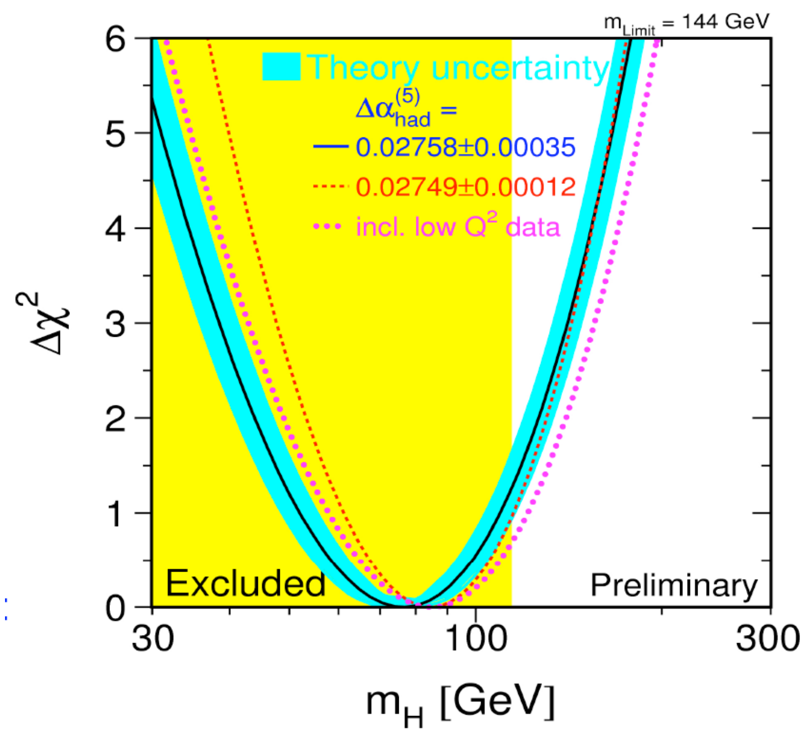
$$\lambda(Q^2) \approx \frac{\lambda(v^2)}{\left(1 - \frac{3}{4\pi^2}\lambda(v^2)t\right)} < \infty$$

$$\Rightarrow M_H^2 \lesssim \frac{8\pi^2 v^2}{3t}$$



- If λ is too small, the top mass pulls λ negative and the vacuum becomes unstable.

We also have good indications from experiment that the Higgs boson will be light:

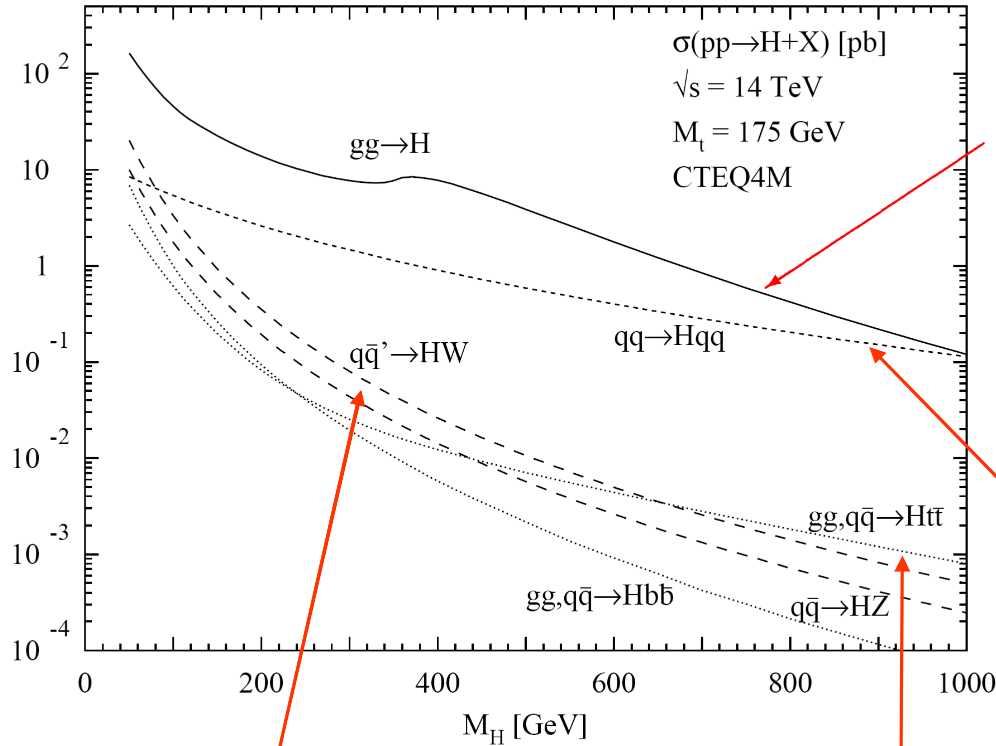


Electroweak precision data: $M_H = 76^{+33}_{-24}\,\mathrm{GeV}$ $\qquad M_H < 144\,\mathrm{GeV}$ (95% conf.)

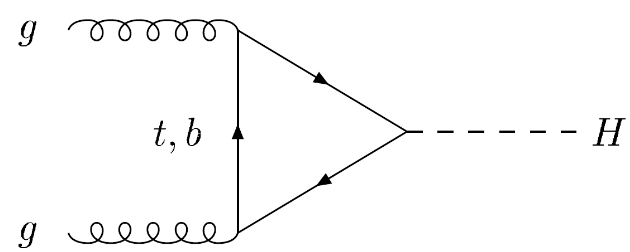
Folding in LEP limit $M_H > 114\,\mathrm{GeV}$ gives $M_H < 182\,\mathrm{GeV}$ (95% conf.)

[Numbers from Terry Wyatt's talk at EPS 07]

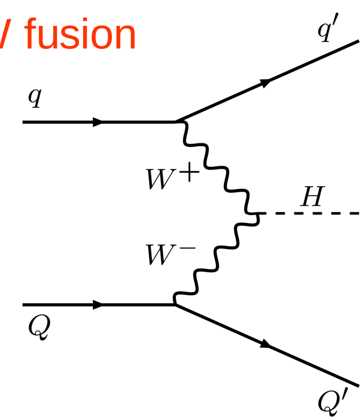
Production:



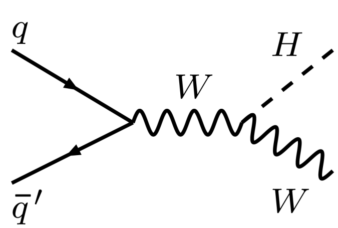
Main production channel is $gg \to H$



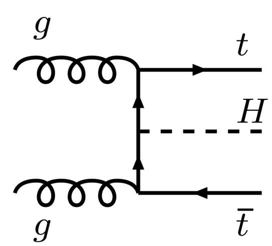
WW fusion



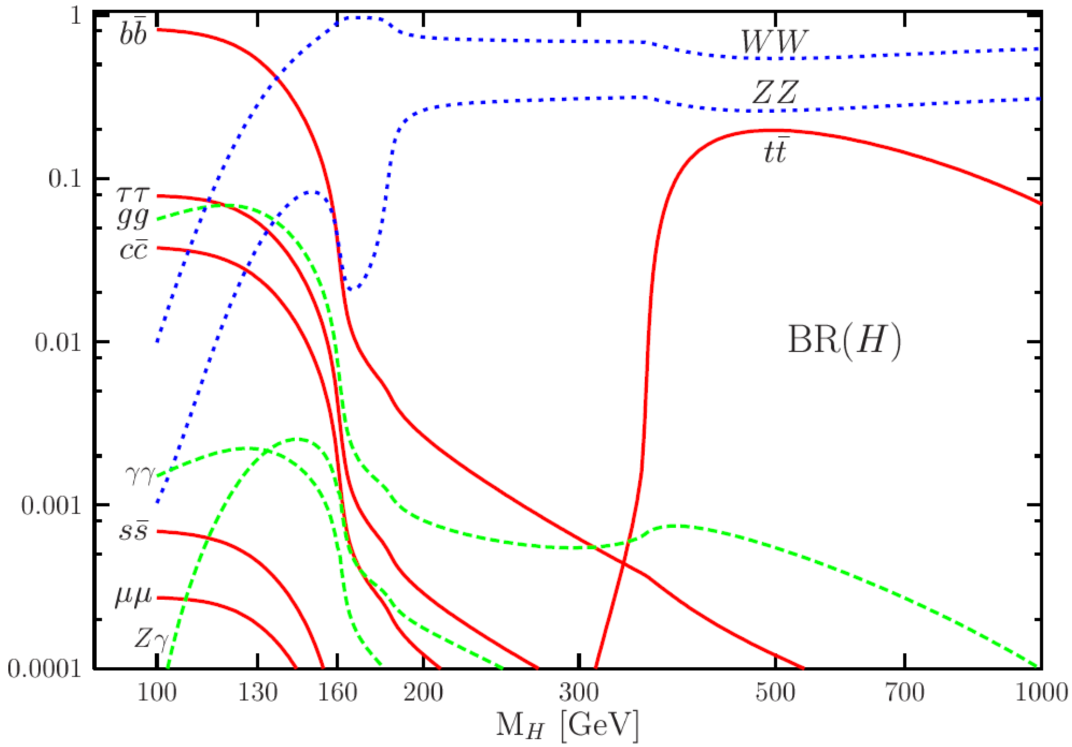
Higgs-strahlung



Associated production



Decay: Higgs branching ratios

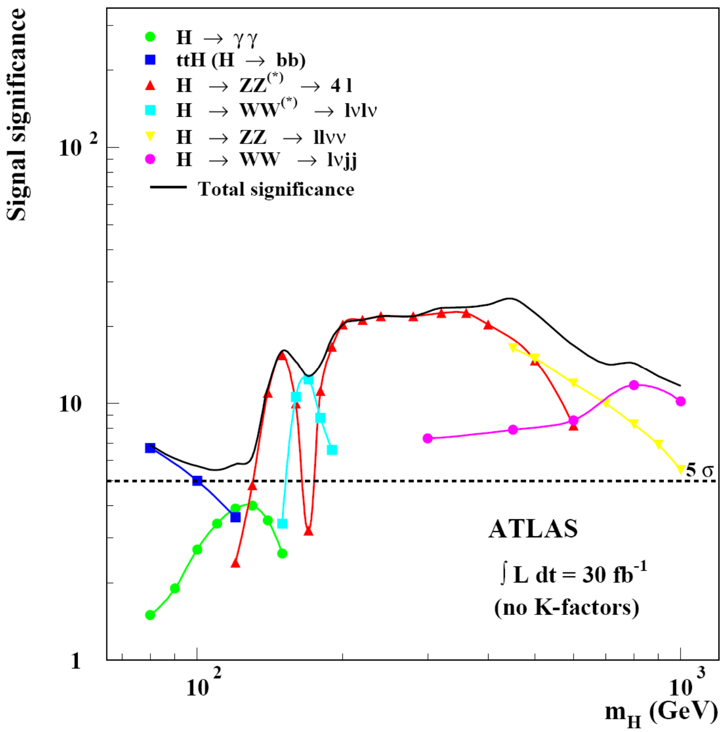


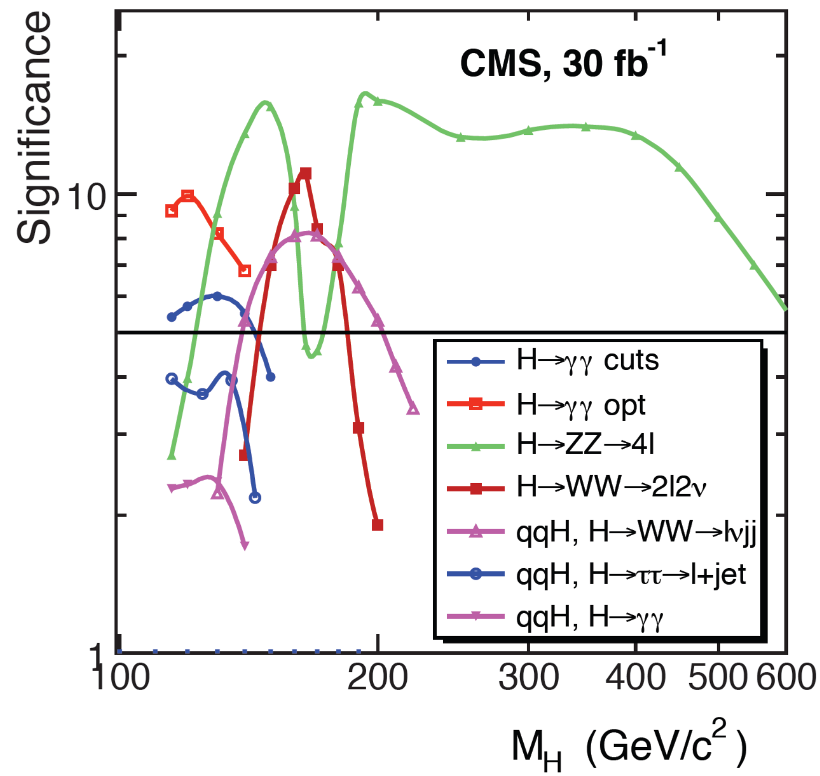
For low Higgs mass, the Higgs predominantly decays to b-quarks

For higher Higgs mass, the Higgs predominantly decays to gauge bosons.

(or Tevatron)

If the SM Higgs boson exists, it is almost certain that the LHC will see it within 10fb^{-1} or so:





After finding the “Higgs boson”, we are not yet done. We still need to prove it is the Higgs boson by measuring:

- Higgs CP and spin

  The Higgs is a pretty weird object – we have never seen a fundamental scalar before.

  Also should ensure it is not a pseudoscalar, or a mixture of scalar and pseudoscalar.

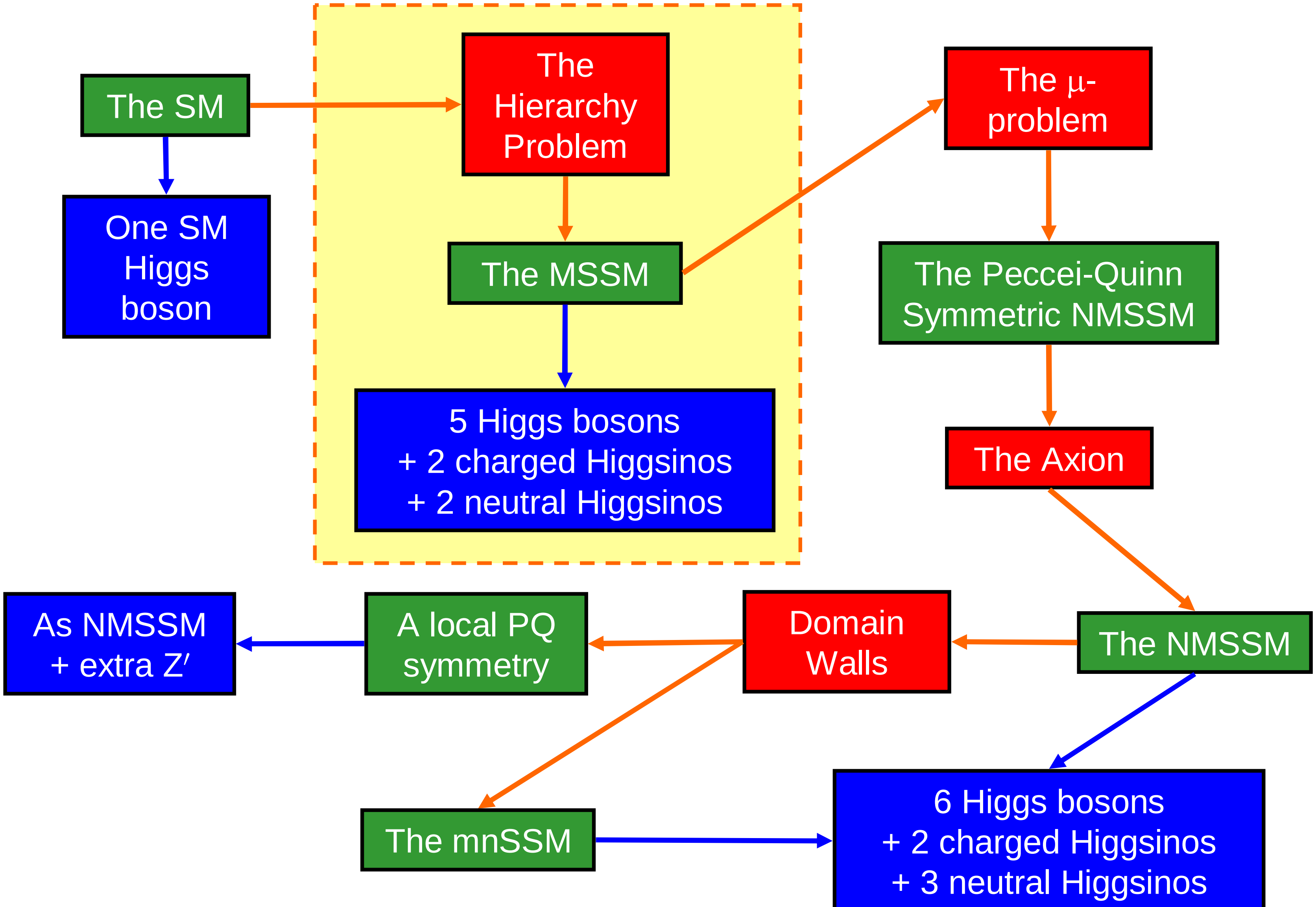
- Higgs couplings to fermions and gauge bosons

  Must be proportional to the particle masses

- Higgs self couplings

  In principle allows us to reconstruct the Higgs potential (out of reach of the LHC)

2. The minimal SUSY Higgs sector

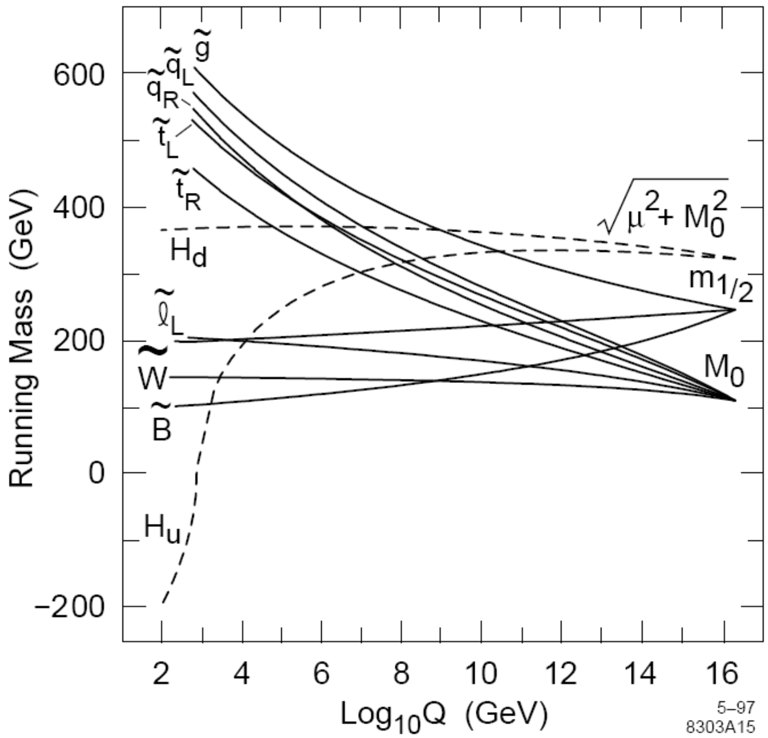


What is wrong with the SM Higgs?

- In the SM, there is no explanation of why $m_\Phi^2 < 0$. Why do we have a Mexican hat?

  In supersymmetry, this is caused by the large top Yakawa coupling.

$$16\pi^2 \frac{dm_{H_u}^2}{dt} \approx 6Y_t^2\left(m_{H_u}^2 + m_{Q_3}^2 + M_{u_3}^2\right) - 6g_2^2 M_2^2 - \frac{6}{5} g_1^2 M_1^2$$



With $m_{H_u}^2 > 0$ at the GUT scale,

the large top Yukawa coupling pulls it

negative as we run down to the

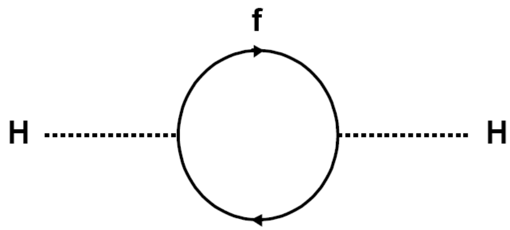
electroweak scale, triggering

electroweak symmetry breaking.

[Kane, Kolda, Roszkowski, Wells]

The Hierarchy Problem

In the SM, the Higgs mass obtains corrections from fermion (top quark) loops

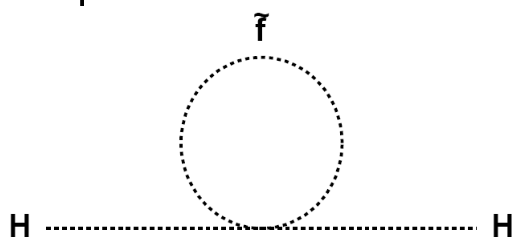


$$\delta M_H^2 = -2N_f \frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

This diagram is quadraticaly divergent, and must be cut off at some high scale Λ

$$\Lambda \approx \text{scale of new physics} \approx 10^{19}\,\text{GeV} \quad \Rightarrow \quad \delta m_H^2 \approx 10^{30}\,\text{GeV}^2$$

In supersymmetric models, one also has a contribution from the top quark's partner, the 'stop'



$$\delta M_H^2 = -2N_{\tilde f} \frac{\lambda_{\tilde f}}{16\pi^2}\Lambda^2 + \ldots$$

$$\text{SUSY} \Rightarrow N_f = N_{\tilde f},\ |\lambda_f|^2 = -\lambda_{\tilde f}$$

So the quadratic contributions exactly cancel out and the problem is solved.

The need for two Higgs doublets

The most striking difference between the SM and supersymmetric Higgs sectors is that supersymmetry has **two Higgs doublets** compared to the SM's **one**.

This is for two reasons.

- **Supersymmetry Algebra**

  One can generally show that any **Lagrangian** obeying supersymmetry can be derived from a **superpotential**, *W*, and gauge interactions:

$$V(\phi,\phi^*) = \sum_i \left|\frac{\partial W}{\partial \phi_i}\right|^2 + D \text{ terms} \qquad \text{and} \qquad \mathcal{L}_{\mathrm{Yuk}} = -\frac{1}{2}\frac{\partial^2 W}{\partial\phi_i \partial\phi_j}\psi_i\psi_j$$

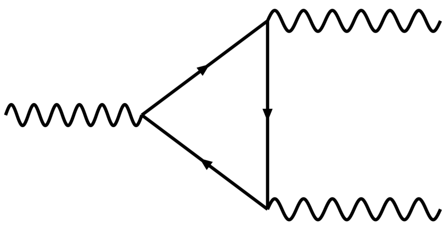
  Also, in order to obey supersymmetry, *W* must be analytic in the scalar fields ϕ_i, i.e. it cannot contain any complex conjugate fields ϕ_i^*.

  Our trick of using the complex conjugate of the Higgs field for the up-type Yukawa couplings doesn't respect supersymmetry. In supersymmetric models, we need to introduce a new Higgs doublet to give mass to up-type quarks.

$$W_{MSSM} = Y_u \bar{Q}_{L\,a}\epsilon^{ab} H_{u\,b} u_R - Y_d \bar{Q}_L \cdot H_d\, d_R - Y_e \bar{E} \cdot H_d\, d_R - \mu H_{u\,a}\epsilon^{ab} H_{d\,b}$$

Anomaly cancellation

Anomalies (which destroy renormalizability) can be caused by triangle diagrams.



The loop includes all fermions in the model, and there will be an anomaly unless

$$\mathrm{Tr}(Y_R^3 - Y_L^3) = 0$$

hypercharge

In the SM, for each generation:

$$\left.\begin{aligned} \mathrm{Tr}(Y_R^3) &= \underset{u_R}{3\left(\frac{2}{3}\right)^3} + \underset{d_R}{3\left(-\frac{1}{3}\right)^3} + \underset{e_R}{(-1)^3} = -\frac{2}{9} \\ \mathrm{Tr}(Y_L^3) &= \underset{u_L}{3\left(\frac{1}{6}\right)^3} + \underset{d_L}{3\left(\frac{1}{6}\right)^3} + \underset{e_L}{\left(-\frac{1}{2}\right)^3} + \underset{\nu_L}{\left(-\frac{1}{2}\right)^3} = -\frac{2}{9} \end{aligned}\right\} \Rightarrow \mathrm{Tr}(Y_R^3 - Y_L^3) = 0$$

In supersymmetry, we have extra fermions as the partners of the Higgs bosons (Higgsinos). The Higgsino contributes to the traingle loop, potentially creating an anomaly

To keep the theory anomaly free, we need two Higgs doublets, one with $Y = \frac{1}{2}$ and one with $Y = -\frac{1}{2}$, so that the contributions to the anomaly cancel.

Higgs bosons in the MSSM

5 Physical Higgs bosons: $\underbrace{h, H}_{\text{CP even}}$, A, $H^{\pm}$

CP odd

charged

Tree level parameters: M_{H_u}, M_{H_d}, μ, B

Supersymmetry is broken, so the Lagrangian also contains soft supersymmetry breaking terms such as $B\mu H_{u\,a}\epsilon^{ab}H_{d\,b}$

Vacuum minimization conditions: $\dfrac{\partial V}{\partial M^2_{H_u}} = \dfrac{\partial V}{\partial M^2_{H_u}} = 0 \;\rightarrow\; v_u, \quad v_d$

$M_Z \qquad \tan\beta \equiv v_u/v_d$

We find, at tree-level $M_A^2 = \dfrac{2\mu B}{\sin 2\beta}$, and it is

conventional to replace μB with M_A .

Finally have (tree-level) parameters: $\boxed{M_A \text{ and } \tan\beta}$

CP even Higgs bosons H_u^0 and H_d^0 mix to give $\boldsymbol{h}$ and $\boldsymbol{H}$: mixing angle α

not an independent parameter

Charged Higgs bosons mix with angle β

Couplings: $g_{\text{MSSM}} = \xi g_{\text{SM}}$

ξ	t	b/τ	W/Z
h	cosα/sinβ	-sinα/cosβ	sin(α-β)
H	sinα/sinβ	cosα/cos β	cos(α-β)
A	cotβ	tanβ	-

usually $\approx$ 0 (for largish M_A)

Large tanβ enhances coupling of Higgs bosons to b's and τ, and decreases coupling to t

- At **tree-level**:

$$M_{H}^{\pm} = M_A^2 + M_W^2$$
$$M_{h,H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{(M_A^2 + M_Z^2)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right)$$

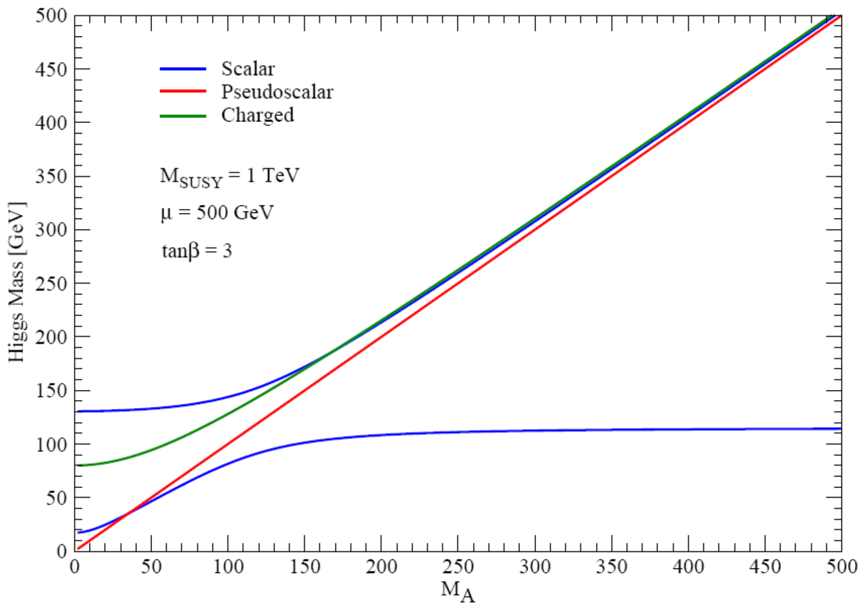
For large $\tan\beta$, or large M_A : $M_h \approx M_Z |\cos 2\beta|$, $M_H \approx M_A$

- In actuality, the lightest Higgs gains a significant mass contribution at one (and two) loops.

$$\Delta M_h^2 = \frac{3}{\pi^2}\frac{M_t^4}{v^2}\sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

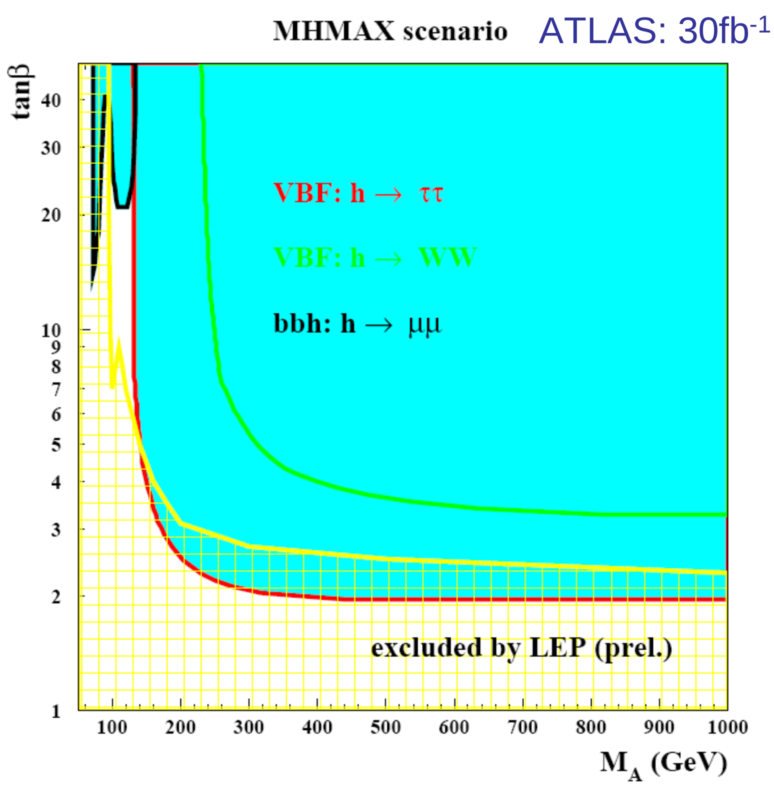
We have an upper bound on the MSSM lightest Higgs boson mass:

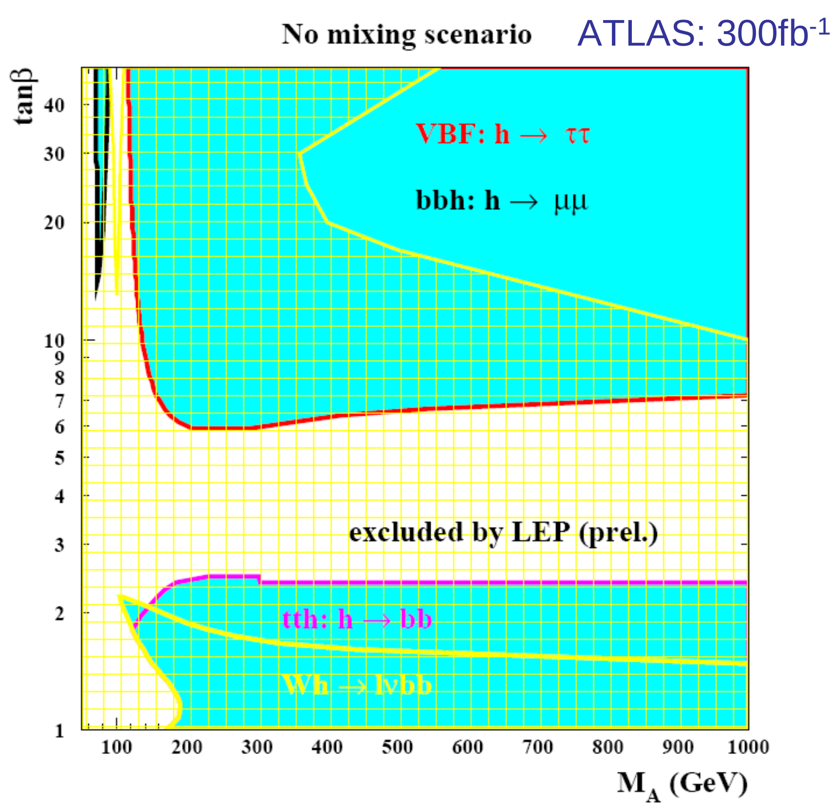
$$\boxed{M_h^2 \lesssim 135 \text{ GeV}}$$



These loop corrections are very sensitive to the mixing in the stop sector.

Large stop mixing is required over most of the parameter space to keep the lightest MSSM Higgs boson heavy enough to escape LEP limits.

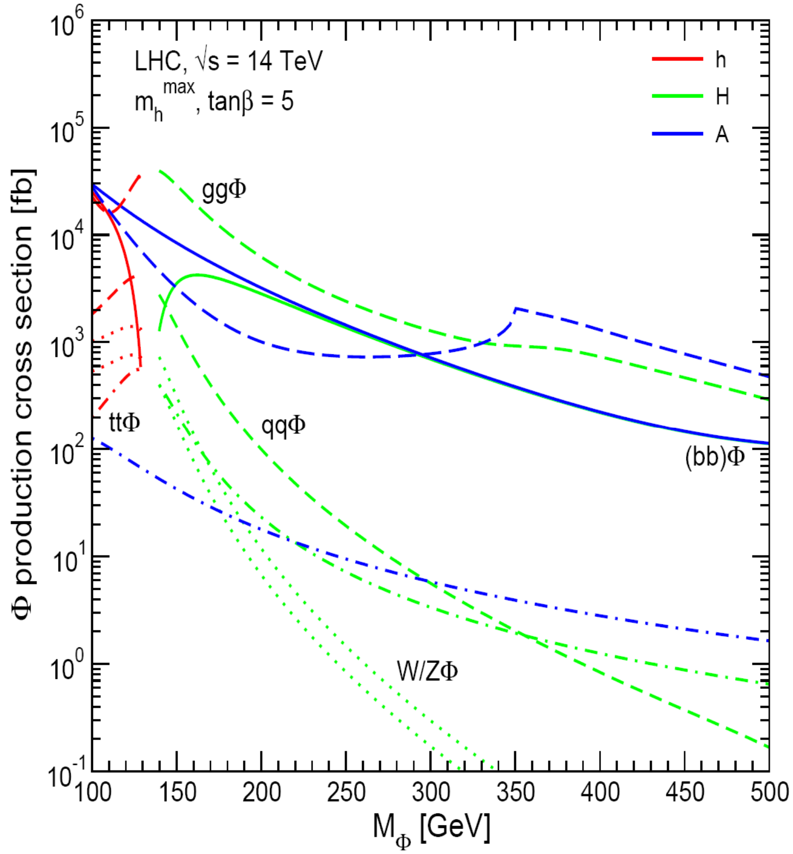


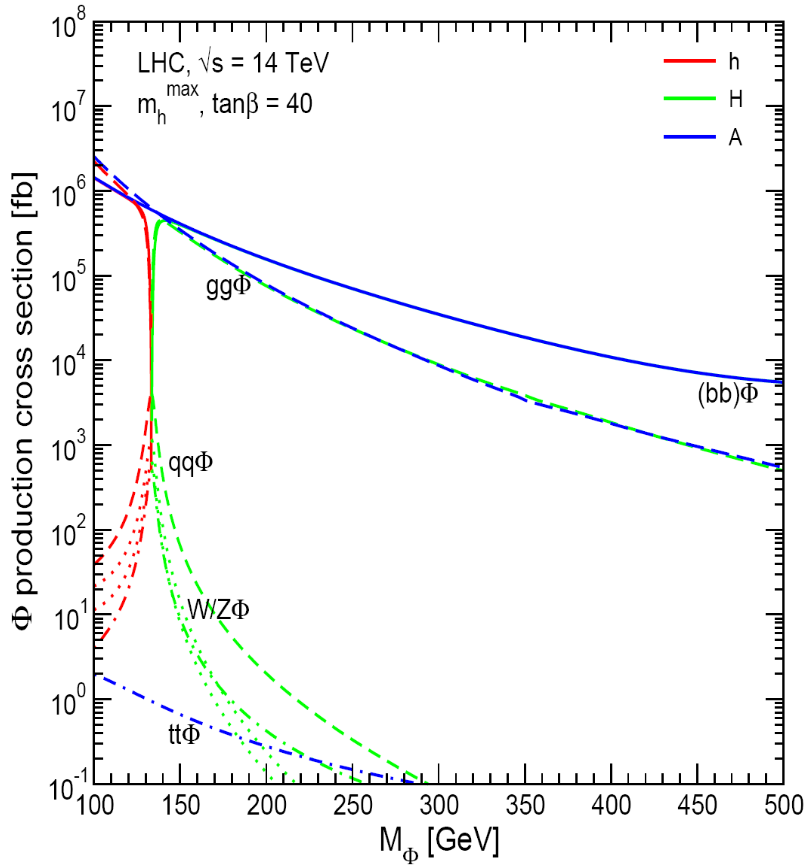


[Schumacher]

Neutral MSSM Higgs production

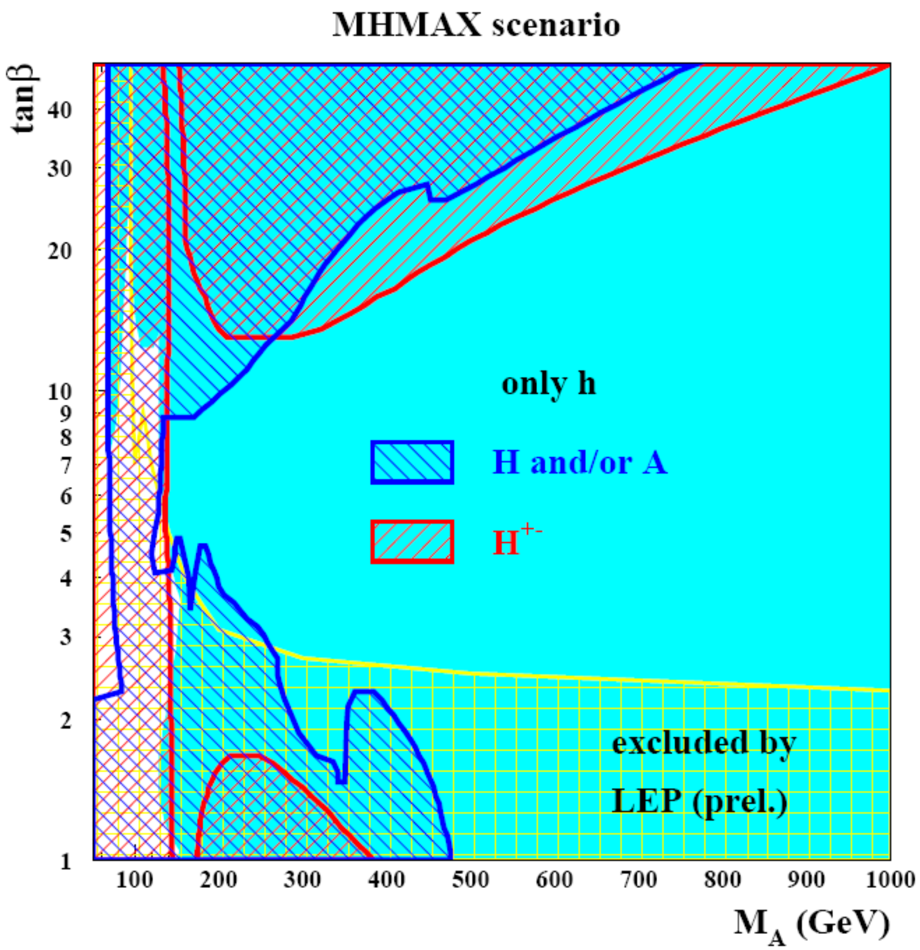
$$\Phi = h,\ H,\ A$$



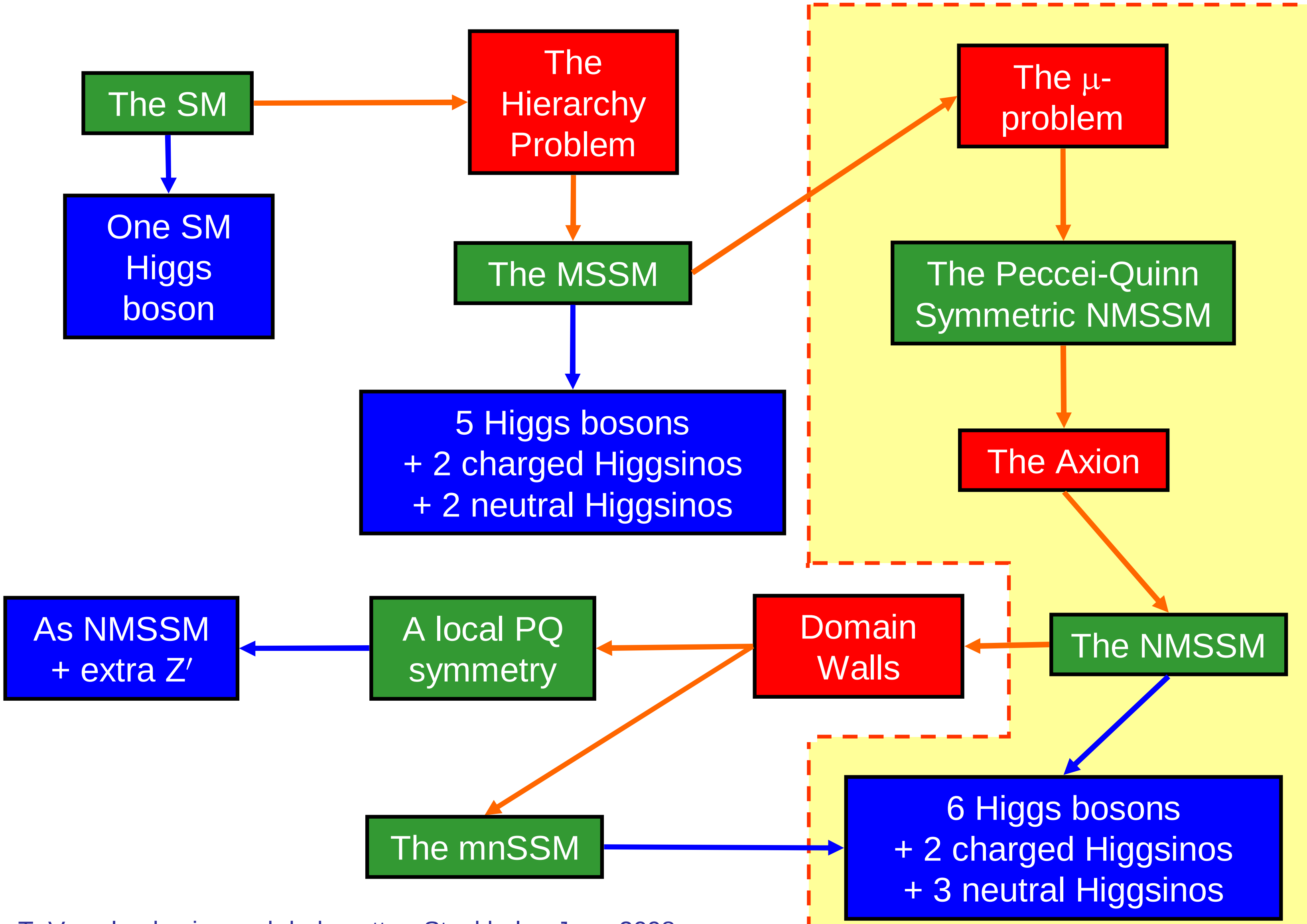


[Hahn, Heinemeyer, Maltoni, Weiglein, Willenbrock]

ATLAS discovery reach for 300fb^{-1}



3. The NMSSM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The μ problem

Recall the MSSM superpotential I wrote down earlier:

$$W_{MSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R - \mu H_u H_d$$

[now dropping ϵ's for simplicity]

This superpotential knows nothing (yet) about electroweak symmetry breaking, and knows nothing about supersymmetry breaking.

Notice that it contains a dimensionful parameter μ.

What mass should we use?

The natural choices would be **0** (forbidden by some symmetry) or $\mathbf{M_{Planck}}$ (or M_{GUT})

Therefore, it should know nothing about the electroweak scale.

- If $\mu = 0$ then there is no mixing between the two Higgs doublets. Any breaking of electroweak symmetry generated in the up-quark sector (by $M^2_{H_u} < 0$) could not be communicated to the down-quark sector

  $\Rightarrow$ the down-type quarks and leptons would remain massless.

- If $\mu = M_{\text{Planck}}$ then the Higgs bosons and their higgsino partners would gain Planck scale masses, in contradiction with upper bounds from triviality and precision electroweak data.

For phenomenologically acceptable supersymmetry, the μ-parameter must be of order the electroweak scale.

This contradiction is known as the μ-problem

Solving the μ-problem with an extra singlet

One way to link the μ-parameter with the electroweak scale is to make it a **vacuum expectation value**. [Another way is to use the Giudice-Masiero mechanism, which I won't talk about here.]

Introduce a new iso-singlet neutral colorless chiral superfield $\widehat{S}$, coupling together the usual two Higgs doublet superfields. The scalar part of this is

$$\lambda S H_u H_d$$

If S gains a vacuum expectation value we generate an **effective μ-term**

$$\mu_{\text{eff}} H_u H_d \qquad \text{with} \qquad \mu_{\text{eff}} = \lambda \langle S \rangle$$

We must also modify the **supersymmetry breaking terms** to reflect the new structure

$$\mu B H_u H_d \longrightarrow m_S^2 |S|^2 + \lambda A_\lambda S H_u H_d$$

The new scalar naturally picks up a VEV of order the SUSY breaking parameters, just as for the usual Higgs doublets.

Writing:

$$\langle H_d \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \qquad \langle H_u \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \qquad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

the minimization equations for the VEVs become:

$$m_{H_d}^2 = \frac{1}{8}\bar{g}^2(v_u^2 - v_d^2) - \frac{1}{2}\lambda^2 v_u^2 + \frac{1}{\sqrt{2}} A_\lambda \lambda v_s \frac{v_u}{v_d} - \frac{1}{2}\lambda^2 v_s^2$$

$$m_{H_u}^2 = \frac{1}{8}\bar{g}^2(v_d^2 - v_u^2) - \frac{1}{2}\lambda^2 v_d^2 + \frac{1}{\sqrt{2}} A_\lambda \lambda v_s \frac{v_d}{v_u} - \frac{1}{2}\lambda^2 v_s^2$$

$$m_S^2 = -\frac{1}{2}\lambda^2 v^2 + \frac{1}{\sqrt{2}} \lambda A_\lambda \frac{v_u v_d}{v_s}$$

So $\mu_{\text{eff}} = \frac{1}{\sqrt{2}} \lambda v_s$ is of the electroweak/SUSY scale, as desired.

So our superpotential so far is

$$W = \underbrace{Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R}_{\text{Yukawa terms}} - \lambda S H_u H_d$$

effective μ–term

But this too has a problem – it has an extra U(1) Peccei-Quinn symmetry

[Peccei and Quinn]

Setting U(1) charges for the states as:

$$\widehat{Q} : -1, \quad \widehat{u}^c : 0, \quad \widehat{d}^c : 0, \quad \widehat{L} : -1, \quad \widehat{e}^c : 0, \quad \widehat{H}_1 : 1, \quad \widehat{H}_2 : 1, \quad \widehat{S} : -2,$$

the Lagrangian is invariant under the (global) transformation $\widehat{\Psi}_i \to e^{iQ_i^{PQ}\theta}\widehat{\Psi}_i$

This extra U(1) is broken with electroweak symmetry breaking (by the effective μ-term)

$\Longrightarrow$ **massless axion**

(this is actually the extra pseudoscalar Higgs boson in S)

Removing the Peccei-Quinn axion

While the Peccei-Quinn axion would be nice to have around, we do not see it, so we have another problem.

There are (at least) three possible ways out, all of which introduce more problems.

- **Decouple the axion**

  We could just make λ very small, thereby decoupling the axion so that it would not have been seen in colliders.

  Unfortunately there are rather severe astrophysical constraints on λ from the cooling rate of stars in globular clusters, which constrain

  $$\lambda \lesssim 10^{-6}.$$

  There is (to my knowledge) no good reason why λ should be so small. (Though to be fair, this solution also solves the strong CP problem.)

Eat the axion

Making the U(1) Peccei-Quinn symmetry a **gauge symmetry** introduces a new gauge boson which will eat the PQ-axion when the PQ symmetry breaks and become massive (a Z′). Searches for a Z′ provide rather model dependent results but generally indicate that it must be heavier than a few hundred GeV.

To cancel anomalies one needs new chiral quark and lepton states too.

Explicity break the PQ symmetry

In principle, one can add **extra terms** into the superpotential of the form S^n with $n \in \mathbb{Z}$ but only for n=3 will there be a dimensionless coefficient. Any such term will break the PQ symmetry, giving the “axion” a mass so that it can escape experimental constraints.

How we break the PQ symmetry determines whether we have the NMSSM or the mnSSM or something else.

The superpotential of the **Next-to-Minimal Supersymmetric Standard Model (NMSSM)** is

[Dine, Fischler and Srednicki]
[Ellis, Gunion, Haber, Roszkowski, Zwirner]

$$W_{NMSSM} = \underbrace{Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R}_{\text{Yukawa terms}} - \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

effective μ–term

PQ breaking term

We also need soft supersymmetry breaking terms in the Lagrangian:

$$-\mathcal{L}_{\mathrm{soft}} \supset m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 + [\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \mathrm{h.c.}]$$

[Higgs sector SUSY breaking terms only]

- This model has the same particle content as the MSSM except:

  - one extra scalar Higgs boson
  - one extra pseudoscalar Higgs boson
  - one extra neutral higgsino

  for a total of

  - 3 scalar Higgs bosons
  - 2 pseudoscalar Higgs bosons
  - 5 neutralinos

  The charged Higgs boson and chargino content is the same as in the MSSM.

- The new singlets only couple to other Higgs bosons, so couplings to other particles are “shared out” by the mixing.

- Computer code for NMSSM: **NMHDECAY** by Ellwanger, Gunion & Hugonie

  http://higgs.ucdavis.edu/nmhdecay/mnhdecay.html

Parameters: $\lambda, \quad \kappa, \quad A_\lambda, \quad A_\kappa, \quad \underbrace{M_{H_u}, \quad M_{H_d}, \quad M_S,}$

$$\xrightarrow{\text{minimisation conditions}} \quad \overbrace{\underbrace{v_u, \quad v_d, \quad v_s}}$$

Top left entry of CP-odd mass matrix. Becomes MSSM M_A in MSSM limit.

$$M_A^2 = \frac{2\mu_{\text{eff}}}{\sin 2\beta}\left(A_\lambda + \frac{\kappa v_s}{\sqrt{2}}\right)$$

$$M_Z, \quad \tan\beta, \quad \mu_{\text{eff}}$$

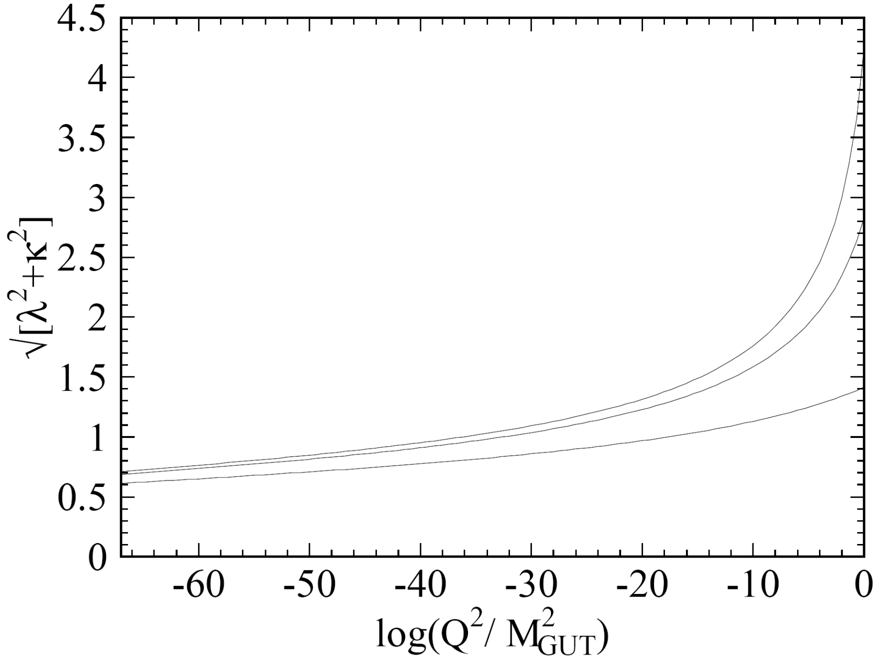
Will also sometimes use

$$\tan\beta_s = \frac{v_s}{v}$$

Finally: $\lambda, \quad \kappa, \quad M_A, \quad A_\kappa, \quad \tan\beta, \quad \mu_{\text{eff}}$

The MSSM limit is $\kappa \to 0$, $\lambda \to 0$, keeping κ/λ and μ fixed.

λ and κ are forced to be reasonably small due to **renormalisation group running**.



To stop them blowing up, we need to insist that $\lambda^2 + \kappa^2 \lesssim 0.6$

Lightest Higgs mass bound

- In the MSSM

$$M_h^2 \leq M_Z^2 \cos^2 2\beta + \frac{3}{\pi^2}\frac{m_t^4}{v^2} \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + ... \lesssim (130\mathrm{GeV})^2$$

- In the NMSSM

$$M_{H_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2}(\lambda v)^2 \sin^2 2\beta + \frac{3}{\pi^2}\frac{m_t^4}{v^2} \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + ... \lesssim (140\mathrm{GeV})^2$$

The extra contribution from the new scalar raises the lightest Higgs mass bound, but only by a little.

Approximate masses

[DJM, Nevzorov, Zerwas]

The expressions for the Higgs masses are rather complicated and unilluminating, even at tree level, but we can make some approximations to see some general features.

Regard both M_{EW}/M_A and $1/\tan\beta$ as small and expand as a power series.

CP-odd Higgs masses²: $M_A^2\,(1+\frac{1}{4}\cot^2\beta_s\sin^2 2\beta)$, $-\frac{3}{\sqrt{2}}\kappa v_s A_\kappa$

heavy pseudoscalar

one pseudoscalar whose mass depends on how well the PQ symmetry is broken

CP-even Higgs masses²:

$M_A^2(1+\frac{1}{4}\cot^2\beta_s\sin^2 2\beta)$, $M_Z^2\cos^2 2\beta$, $\frac{1}{2}\kappa v_s(4\kappa v_s+\sqrt{2}A_\kappa)$

heavy scalar

intermediate mass scalar

one scalar whose mass depends on how well the PQ symmetry is broken

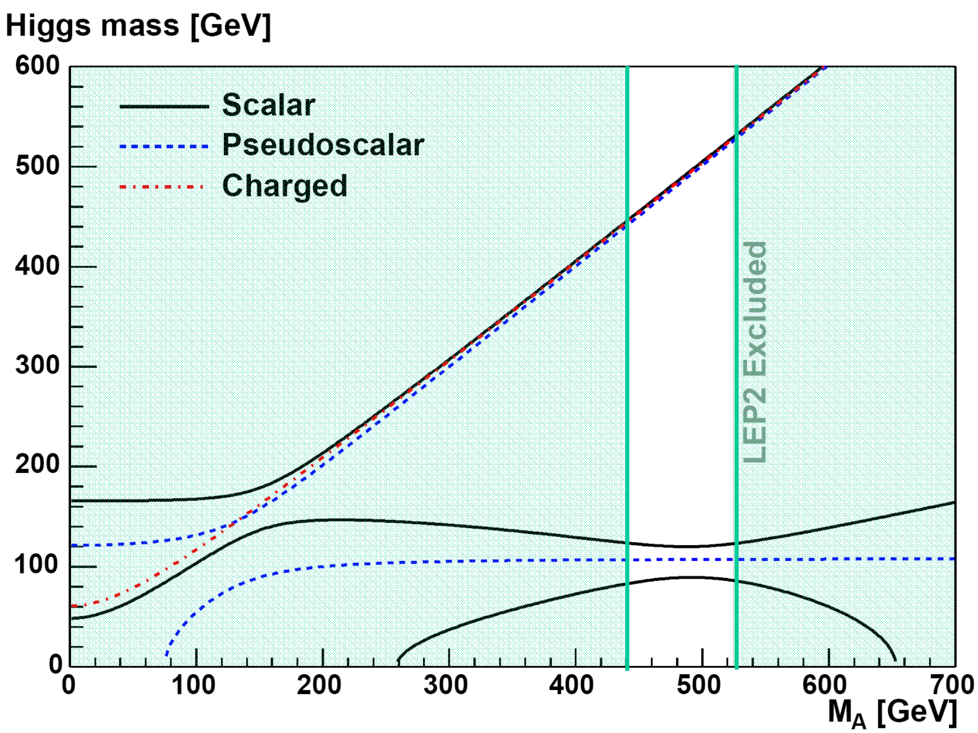
Charged Higgs masses²: $M_{H^\pm}^2 = M_A^2 + M_W^2 - \frac{1}{2}(\lambda v)^2$

Notice the different signs for A_κ $\Rightarrow -2\sqrt{2}\kappa v_s \lesssim A_\kappa \lesssim 0$

Two interesting scenarios

- **PQ symmetry only "slightly" broken** [DJM, S Moretti]

$$\lambda = 0.3,\ \kappa = 0.1,\ \tan\beta = \tan\beta_s = 3,\ A_\kappa = -60\mathrm{GeV}$$

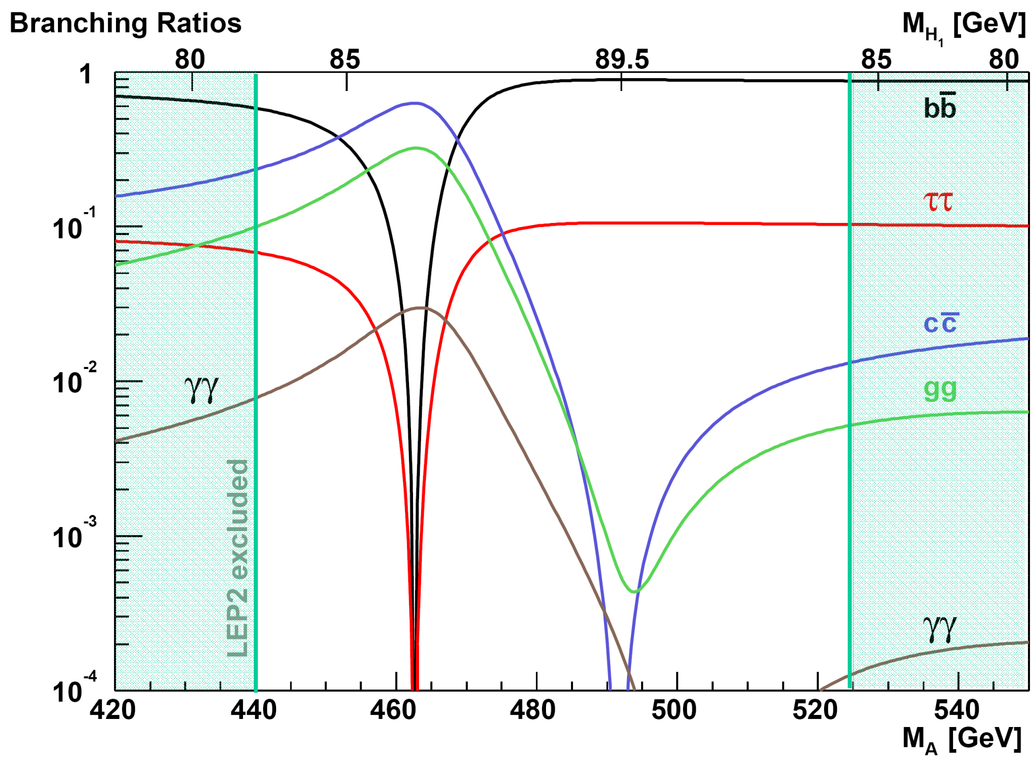


Most of the M_A range is excluded (at 95%) by LEP2 Higgs-strahlung but there is still a substantial region left.

Notice the rather light Higgs boson!

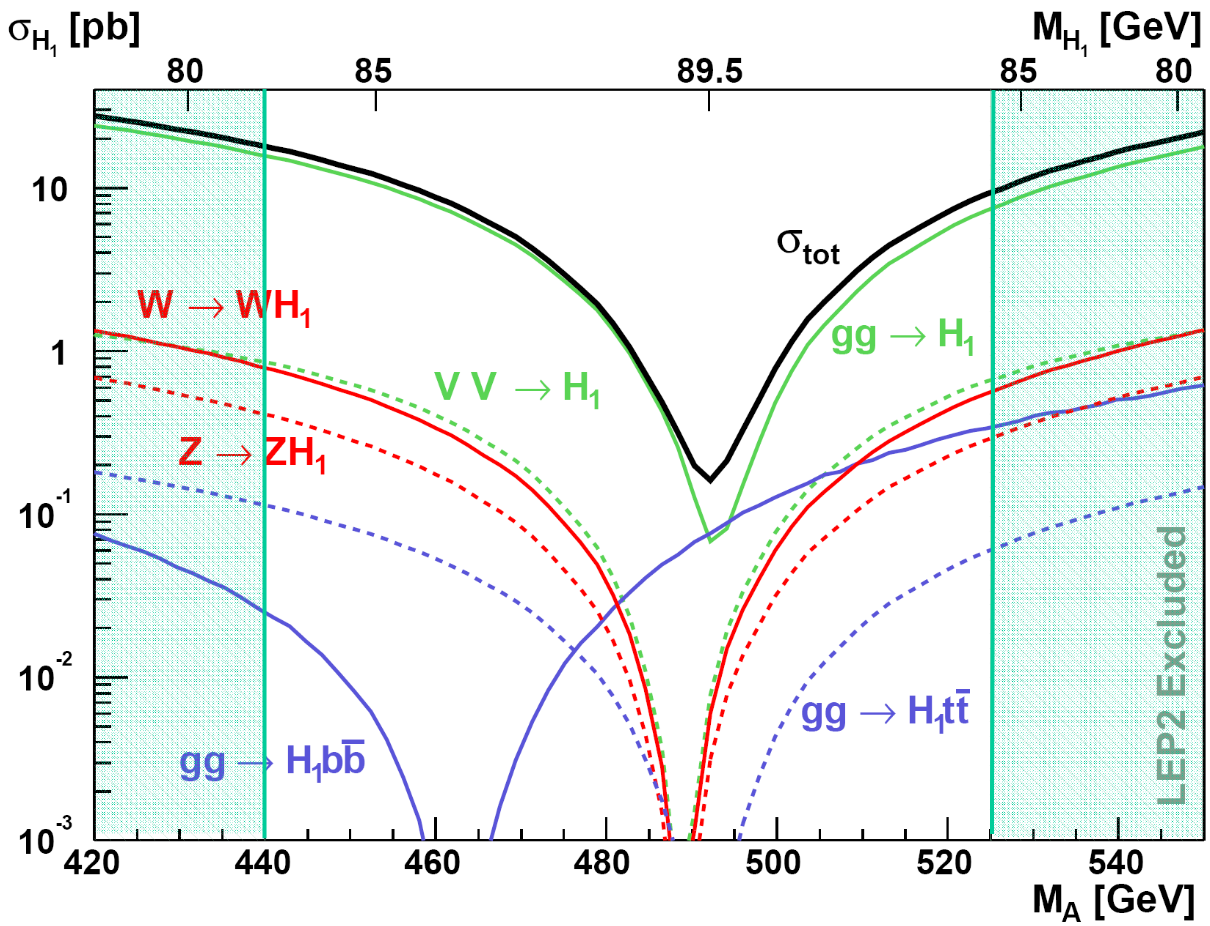
In the allowed region, the couplings of the lightest Higgs to gauge bosons is switching off, which is why LEP would not have seen it.

Branching ratios of lightest Higgs:



This Higgs decays mostly hadronically, so it will be difficult to see at the LHC, due to huge SM backgrounds.

LHC production rates are quite high, but many channels switch off.



A very light pseudoscalar

[Ellwanger, Gunion & Hugonie]

We could instead invoke approximate symmetries to keep one of the **pseudoscalar** Higgs bosons very light.

e.g. An approximate R symmetry when the NMSSM susy breaking parameters are small, $\lambda A_\lambda \to 0,\ \kappa A_\kappa \to 0$

Or an approximate Peccei-Quinn symmetry when the PQ breaking terms are kept small, $\kappa \to 0,\ \kappa A_\kappa \to 0$

Although a massless pseudoscalar (an axion) is ruled out a very light (few GeV) pseudoscalar is not.

For example:

$$\lambda = 0.27,\ \kappa = 0.15,\ \tan\beta = 2.9,$$

$$\mu_{\text{eff}} = -753\text{GeV},\ A_\lambda = 312\text{GeV},\ A_\kappa = 8.4\text{GeV}$$

very large $v_s \approx 4$ TeV

mainly singlet but approx. breaks down here

$$-\frac{3}{\sqrt{2}}\kappa v_s A_\kappa \approx (103\,\mathrm{GeV})^2$$

For these parameters,

h-like

$$\begin{aligned} M_{H_1} &= 95\mathrm{GeV}, & M_{A_1} &= 1\mathrm{GeV}, \\ M_{H_2} &= 483\mathrm{GeV}, & M_{A_2} &= 493\mathrm{GeV}, \\ M_{H_3} &= 831\mathrm{GeV}, \end{aligned}$$

$$\frac{1}{2}\kappa v_s \left(4\kappa v_s + \sqrt{2}A_\kappa\right) \approx (755\,\mathrm{GeV})^2$$

mainly singlet

$$M_A^2 = \frac{2\mu_{\mathrm{eff}}}{\sin 2\beta}\left(A_\lambda + \frac{\kappa v_s}{\sqrt{2}}\right) \approx (510\,\mathrm{GeV})^2$$

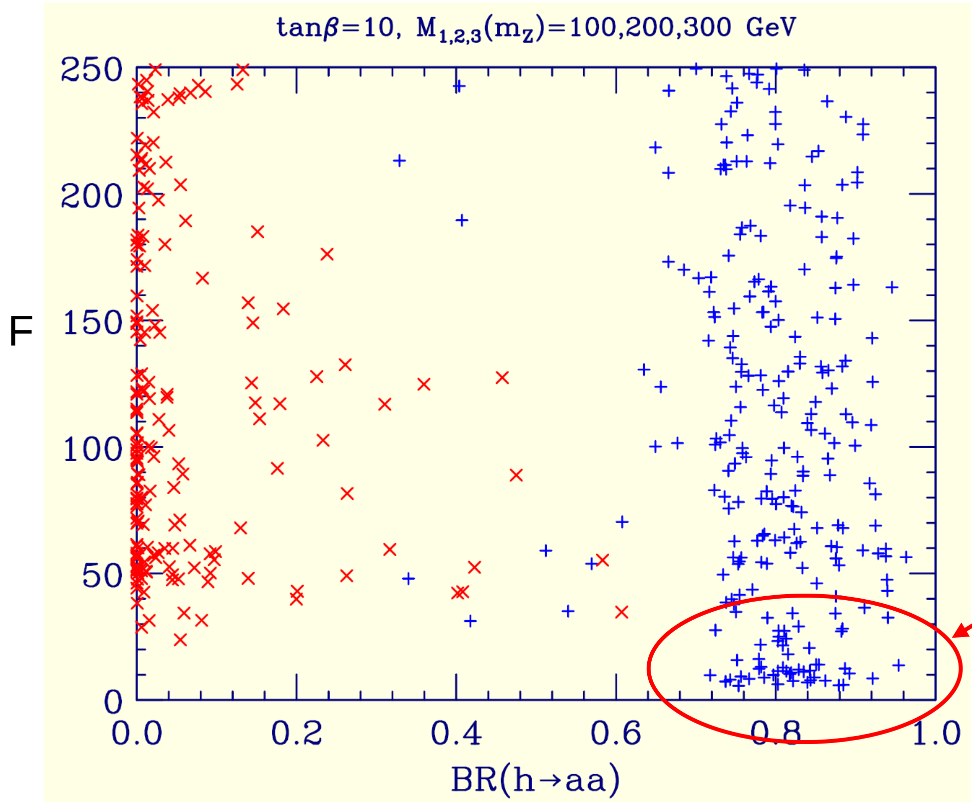
mainly MSSM heavy Higgses

The lightest pseudoscalar is now so light that $\sim$ 100% of H_1 decays are into pseudoscalar pairs: $H_1 \to A_1 A_1$,

$\Rightarrow$ the lightest scalar could be significantly lighter than 114GeV and have been missed by LEP

It is claimed that this model is less fine tuned too.

Taking $F = \max_a \left| \frac{d \log M_Z}{d \log a} \right|$ and scanning over parameter space



[From J. Gunion's talk at SUSY05]

× have M_{H_1} > 114GeV

+ have M_{H_1} < 114GeV

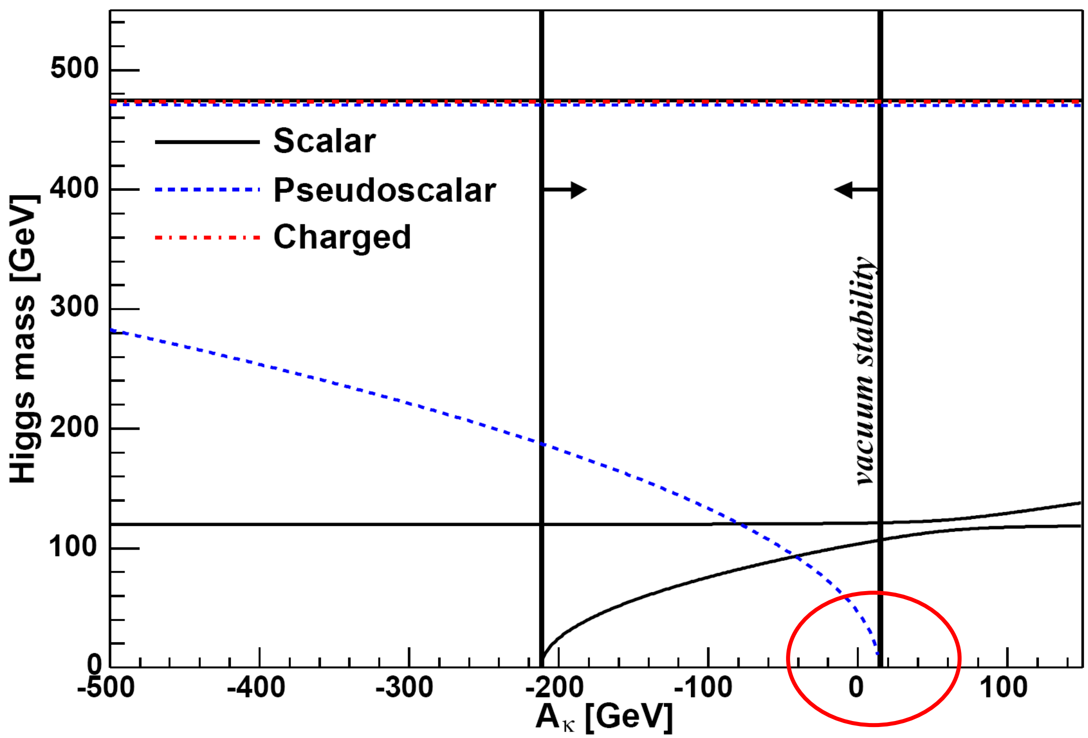
Points with high $H_1 \to A_1 A_1$ branching ratio have smaller fine tuning

If the pseudoscalar is heavy enough, it may be observable through decays to tau pairs:

$$A_1 \to \tau^+ \tau^-$$

A paper by Schuster & Toro pointed out that this point has fine tunings with respect to other observables,

e.g. the pseudoscalar mass with respect to A_κ



But this fine tuning is “explained” by the approximate symmetries.

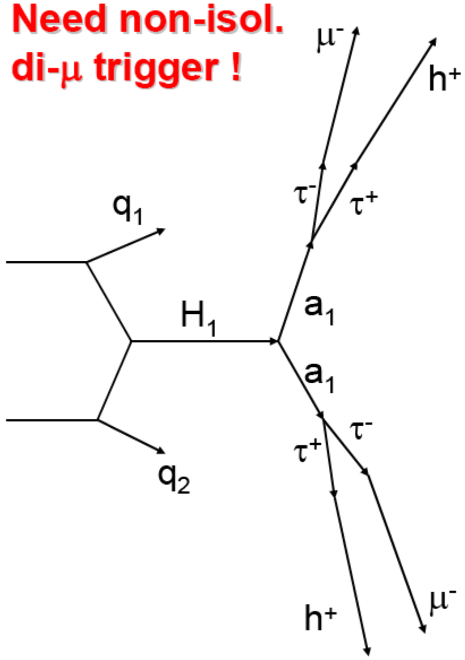
Les Houches 2007: (from A. Nikitenko's talk)

S. Lehti, I Rottlaender, A. Nikitenko, M. Schumacher, C. Shepard with S. Moretti, M. Mühlleitner, S. Hesselbach…

"Low fine-tuning" NMSSM points

qqH_1, $H_1 \to a_1 a_1 \to \tau\tau\tau\tau \to \mu\mu jj$

Need non-isol. di-μ trigger !

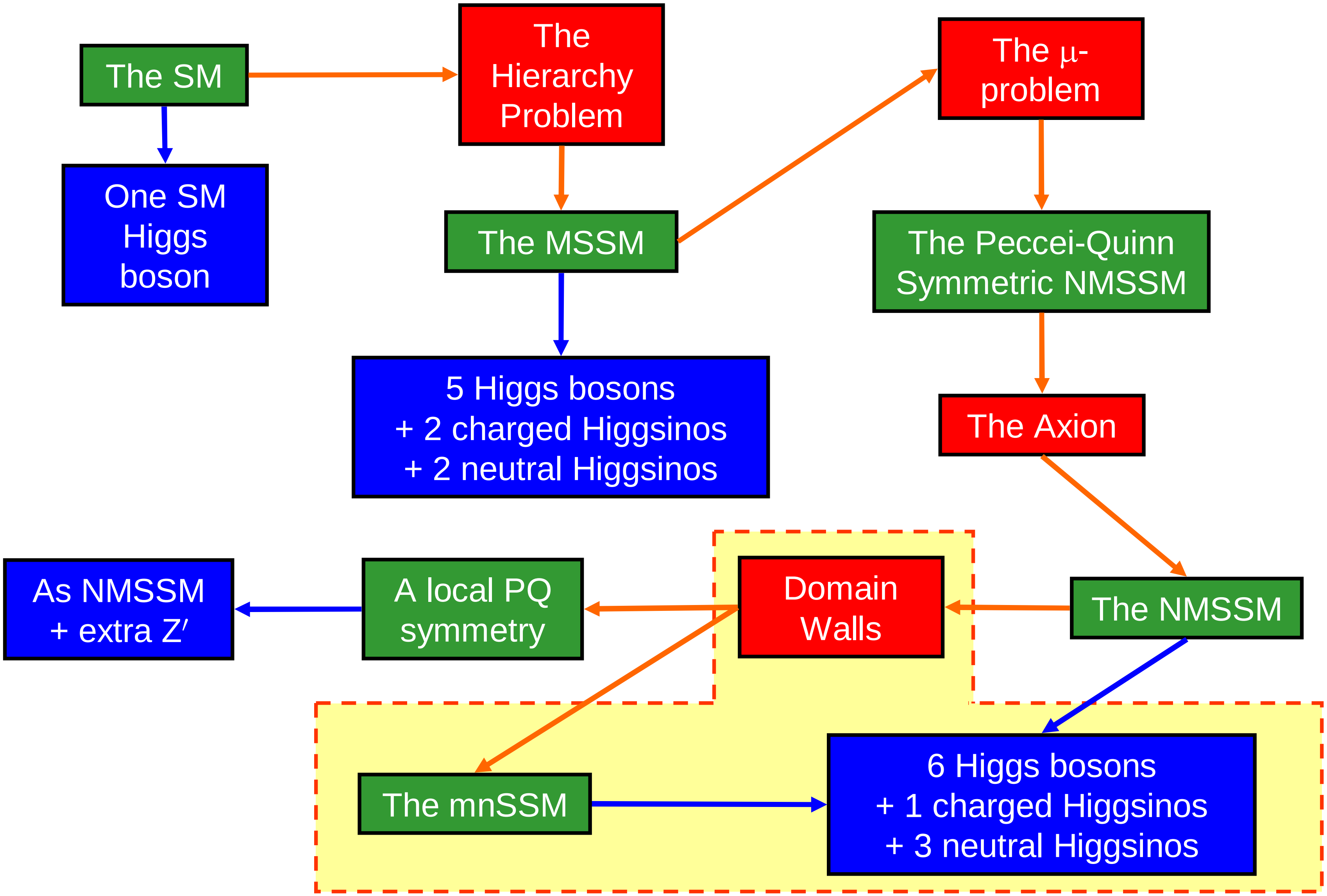


R. Dermisek and J.F. Gunion
See in CPNSH group report
hep-ph/0608079

M_{H_1}/M_{A_1} (GeV)	Branching Ratios $H_1 \to b\bar{b}$	$H_1 \to A_1 A_1$	$A_1 \to \tau\bar{\tau}$
98.0/2.6	0.062	0.926	0.000
100.0/9.3	0.075	0.910	0.852
100.2/3.1	0.141	0.832	0.000
102.0/7.3	0.095	0.887	0.923
102.2/3.6	0.177	0.789	0.814
102.4/9.0	0.173	0.793	0.875
102.5/5.4	0.128	0.848	0.938
105.0/5.3	0.062	0.926	0.938

This point is taken for analyses with $4\tau \to \mu\mu jj$ final state (CMS): qqH_1 and WH_1 (motivated by S. Moretti et al. hep-ph/0608233)

4. The mnSSM



The SM
The Hierarchy Problem
The μ-problem
One SM Higgs boson
The MSSM
The Peccei-Quinn Symmetric NMSSM
5 Higgs bosons
+ 2 charged Higgsinos
+ 2 neutral Higgsinos
The Axion
As NMSSM
+ extra Z′
A local PQ symmetry
Domain Walls
The NMSSM
The mnSSM
6 Higgs bosons
+ 1 charged Higgsinos
+ 3 neutral Higgsinos

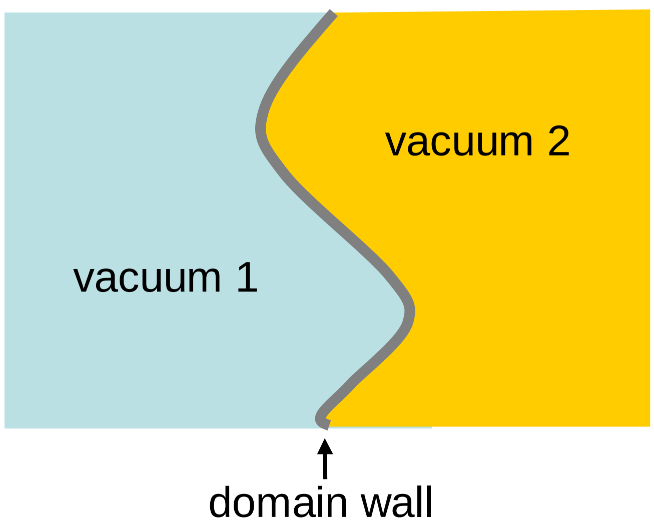
The Domain Wall Problem

Unfortunately we have yet another problem.

The NMSSM Lagrangian above has a (global) $\mathbb{Z}_3$ **symmetry** $\Psi \longrightarrow e^{i2\pi/3}\Psi$

$\Rightarrow$ the model has **3 degenerate vacua** separated by potential barriers

[This was an unavoidable consequence of having dimensionless couplings.]



We expect causally disconnected regions to choose different vacua and when they meet a **domain wall** will form between the two phases.

These domain walls are unobserved (they would be visible in the CMBR) so we need to remove them.

[Y.B.Zeldovich, I.Y.Kobzarev and L.B.Okun]

The degeneracy may be broken by the unification with gravity at the Planck scale. Introducing new higher dimensional operators raises the vacuum energies unequally, resulting in a preferred vacuum.

However, the same operators give rise at the loop level to **quadratically divergent tadpole terms** of the form

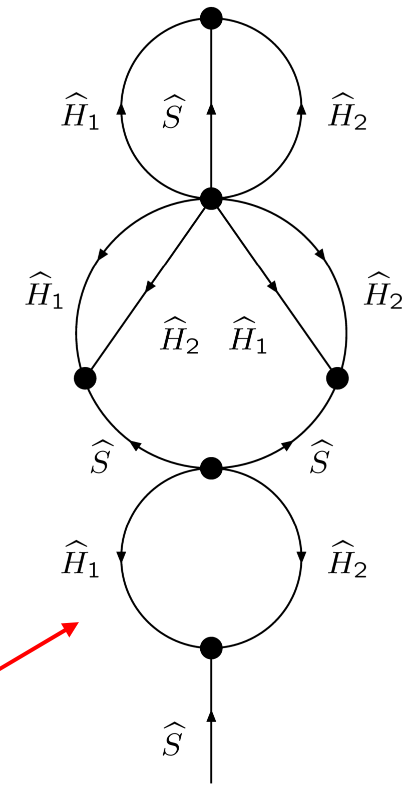
$$\mathcal{L}_{\mathrm{soft}} \supset t_s \sim \frac{1}{(16\pi^2)^n} M_P M_{\mathrm{SUSY}}^2 S$$

where $\boldsymbol{n}$ is the loop order they appear.

[S.A.Abel, S.Sarkar and P.L.White]

If such operators do break the degeneracy, then they must be suppressed to a high enough loop order that they don't cause a new hierarchy problem.

Use symmetries to suppress then to high loop order.



Example of a 6-loop tadpole contribution

[C.Panagiotakopoulos and K.Tamvakis;
[C.Panagiotakopoulos and A.Pilaftsis]

There are many different choices of symmetries to do this. Which you choose, changes the model.

The 2 most studied are:

- **Next-to-Minimal Supersymmetric Standard Model (NMSSM)**

  Choose symmetries to forbid divergent tadpoles to a high enough loop order to make them phenomenologically irrelevant but still large enough to break the degeneracy.

$$W_{NMSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R - \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

- **Minimal Non-minimal Supersymmetric Standard Model (mnSSM)**

  [Panagiotakopoulos, Pilaftsis]

  Choose symmetries to forbid also the S^3 term, but allow tadpoles which have a coefficient of the TeV scale.

$$W_{mnSSM} = Y_u \bar{Q}_L H_u u_R - Y_d \bar{Q}_L \cdot H_d d_R - Y_e \bar{E} \cdot H_d d_R - \lambda S H_u H_d + t_F S$$

radiatively induced tadpole

mnSSM parameters:

$$\lambda, \quad A_\lambda, \quad \mu_{\text{eff}}, \quad \tan\beta, \quad t_F, \quad t_S$$

can usually be neglected (v. small)

tadpole generated by sort SUSY breaking

The model is rather similar to the NMSSM, but has some distinctions.

e.g. the nmSSM has a **tree-level** sum-rule:

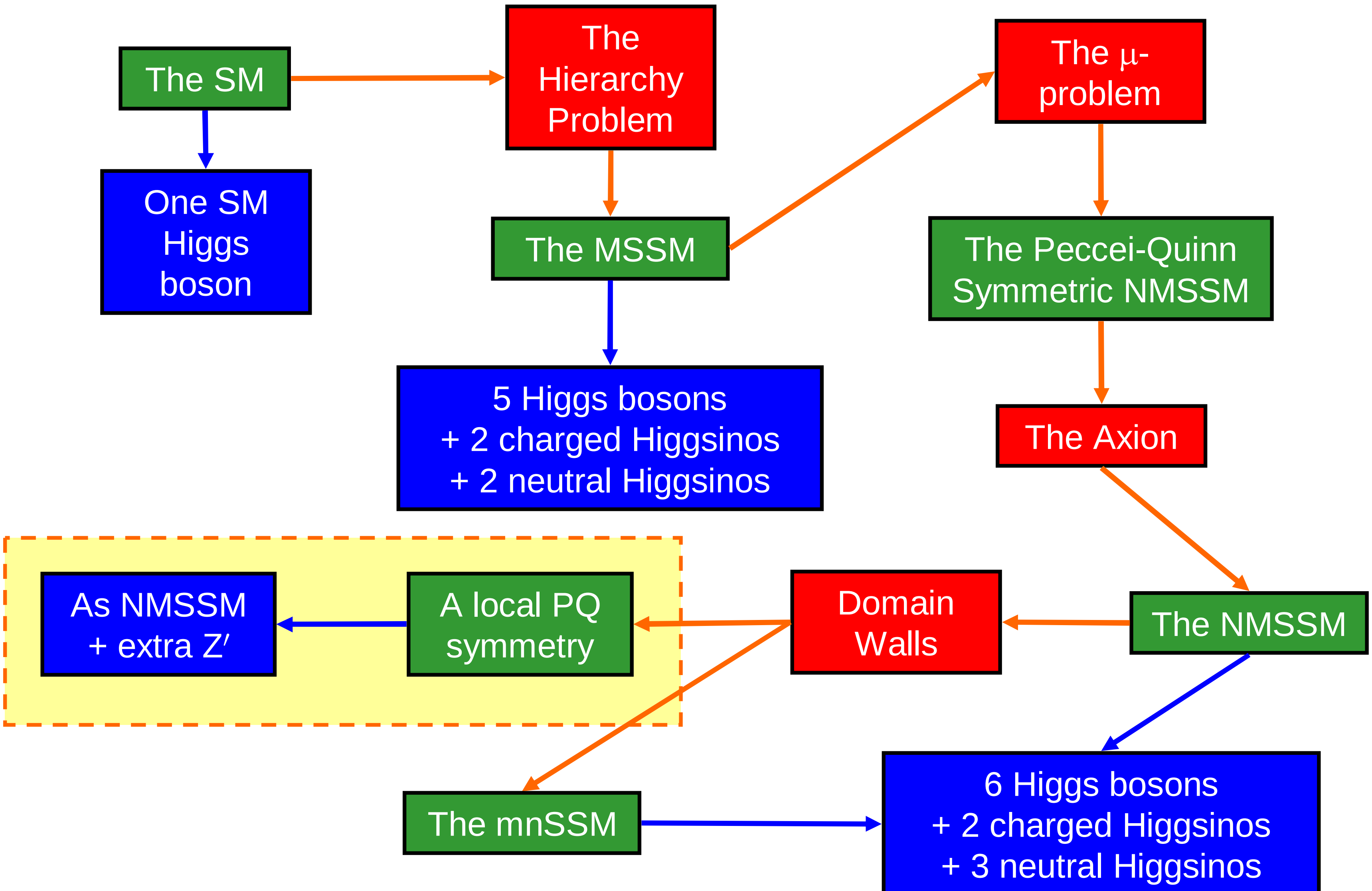
$$M_{H_1}^2 + M_{H_2}^2 + M_{H_3}^2 = M_Z^2 + M_{A_1}^2 + M_{A_2}^2$$

large deviations from this could distinguish the mnSSM from the NMSSM

Also, the mnSSM has an upper limit on the LSP mass $\lesssim 85$ GeV

[Hesselbach, DJM, Moortgat-Pick, Nevzorov, Trusov]

5. A Local Peccei-Quinn Symmetry



- The (nearly) massless axion appeared because we broke a **global** symmetry (the PQ symmetry) during electroweak symmetry breaking.

  But, if the PQ were **local**, instead of global, we would have an extra gauge boson which eats the axion to become massive, just like in the normal Higgs mechanism.

- This leads to a new heavy gauge boson Z' at some new energy scale $\gtrsim 1\ \mathrm{TeV}$

- However, field content needs to be extended by adding new chiral quark and lepton states in order to ensure anomaly cancellation related to the gauged $U(1)_{PQ}$ symmetry.

  Usually it is safest to base such theories on larger symmetry groups to ensure anomaly cancelation, Technical issues aside, there is a powerful aesthetic argument for new physics:

We want a unified model of all the forces (including gravity!)

While a unified theory is probably well beyond us still (especially gravity) we can ask what low energy phenomenology we might expect to see at the LHC as a consequence of unification.

For example, the E_6 inspired **Exceptional Supersymmetric Standard Model** (E_6SSM)

[S.F. King, S. Moretti, R. Nevzrov, Phys.Rev. D73 (2006) 035009]

Confession:

The E_6SSM is **not** really a GUT model, since it contains no mechanism of unification.

However, it does provide us with a glimpse of how a GUT model may affect the low energy phenomenology.

The E_6SSM

"Inspired" by the gauge group E_6 , breaking to the SM via

$$
\begin{aligned}
&E_6 \rightarrow SO(10) \times U(1)_\psi \\
&\qquad\qquad \hookrightarrow SU(5) \times U(1)_\chi \\
&\qquad\qquad\qquad \hookrightarrow SU(3)_C \times SU(2)_W \times U(1)_Y
\end{aligned}
$$

where only one linear superposition of the extra *U(1)* symmetries survives down to low energies:

$$U(1)_N = \frac{1}{4} U(1)_\chi + \frac{\sqrt{15}}{4} U(1)_\psi$$

This combination is required in order to keep the right handed neutrinos sterile.

So the E_6SSM is really a $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_N$ gauge theory.

All the SM matter fields are contained in one 27-plet of E_6 per generation.

$$[27]_i \Rightarrow [10, \tfrac{1}{\sqrt{40}}]_i + [5^*, \tfrac{2}{\sqrt{40}}]_i + [5^*, -\tfrac{3}{\sqrt{40}}]_i + [5, -\tfrac{2}{\sqrt{40}}]_i + [1, 5]_i + [1, 0]_i$$

SU(5) reps.

$U(1)_N$ charge

$Q_i,\ u_i^c,\ e_i^c$

$L_i,\ d_i^c$

$H_{1\,i} = \begin{pmatrix} H_{1\,i}^0 \\ H_{1\,i}^- \end{pmatrix},\ \bar{D}_i$

$H_{2\,i} = \begin{pmatrix} H_{2\,i}^+ \\ H_{2\,i}^0 \end{pmatrix},\ D_i$

S_i

N_i^c

3 generations of "Higgs"

exotic quarks

singlets

right handed neutrino

New States:

Placing each generation in a 27-plet forces us to have new particle states.

- Now have 3 generations of Higgs bosons. Only the third generation Higgs boson will gain a VEV, due to the large top Yukawa coupling. The others are neutral and charged scalars -- we will call them **"inert Higgs"**.

- New "exotic quarks" D_i and $\bar{D}_i$. These are colored SU(2) singlets, with charge $\pm{}^1/_3$.

- Three generations of singlets w.r.t. all SM groups, S_i (gen 3 becomes "Higgs-like").

(+ right handed neutrinos)

- Also require an additional SU(2) doublet H' and antidoublet $\bar{H}'$. These are the only part of an additional 27′ and $\overline{27}$′ which survive down to low energies.

  They are needed for gauge coupling unification, just as the normal Higgs doublets are needed for gauge unification in the MSSM.

  These extra states have a mass term $\mu' H' \bar{H}'$ which is not related to EWSB, so can in principle be anything. However, their masses should be less that about 100TeV for gauge unification.

- Extra U(1) $\rightarrow$ extra gauge boson, Z′.

  After electroweak symmetry breaking this will become massive (after eating the imaginary part of S_3)

Extra Symmetries

We have two potential problems:

- Rapid proton decay (just like most SuSy models)
- Large flavour changing neutral currents (FCNC)

Need extra symmetries to solve these problems.

For **proton decay**, we introduce Z_2^B or Z_2^L symmetries. This works just like R-parity except for the slightly surprising result that D has R_P = -1 while $\tilde{D}$ has R_P = +1 (so they are more like the Higgs/Higgsinos where the scalar has R_P =+1)

For **FCNC**, we must introduce an extra **approximate** "Z_2^H" symmetry, under which all superfields except the third generation of Higgs bosons and scalars are odd.

Writing $H_d \equiv H_{1,3}$, $H_u \equiv H_{2,3}$ and $S \equiv S_3$, the superpotential becomes:

$$\begin{aligned} W_{\mathrm{ESSM}} &= \textstyle\sum_{i=1}^{3}\left(\lambda_i \hat{S}(\hat{H}_{1i}\hat{H}_{2i}) + \kappa_i \hat{S}(\hat{D}_i\hat{\overline{D}}_i)\right) + \sum_{\alpha,\,\beta=1,2}\left[f_{\alpha\beta}\hat{S}_\alpha(\hat{H}_d\hat{H}_{2\beta})\right. \\ &+ \left.\tilde{f}_{\alpha\beta}\hat{S}_\alpha(\hat{H}_{1\beta}\hat{H}_u)\right] + \mu'(\hat{H}'\hat{\overline{H}}') + g_i\hat{e}_i^c(\hat{H}_d\hat{H}') + W_{\mathrm{MSSM}}(\mu=0), \end{aligned}$$

Notice that H′ have interactions like leptons

New parameters: $\lambda_i,\ \kappa_i,\ f_{\alpha\beta},\ \tilde{f}_{\alpha\beta},\ g_i \quad (i = 1\ldots 3,\ \alpha,\ \beta = 1,\ 2)$

Electroweak symmetry breaking

The third generation Higges H_d, H_u, gain VEVs and cause electroweak symmetry breaking, giving masses to quarks and leptons through Yukawa couplings.

The third generation S also gains a VEV:

- breaks $U(1)_N$, giving the Z' a mass
- provides an effective μ-term

The first and second generation remain "VEVless" (inert).

To achieve VEVs for only the third generation: $\lambda_3 \gtrsim \lambda_{1,2} \gg f_{\alpha\beta},\, \tilde{f}_{\alpha\beta},\, g_i$

$$W_{\rm ESSM} \simeq \lambda \hat{S}(\hat{H}_d \hat{H}_u) + \lambda_1 \hat{S}(\hat{H}_{1,1}\hat{H}_{2,1}) + \lambda_2 \hat{S}(\hat{H}_{1,2}\hat{H}_{2,2}) + \kappa \hat{S}(\hat{D}_3 \hat{\overline{D}}_3) + \kappa_1 \hat{S}(\hat{D}_1 \hat{\overline{D}}_1)$$
$$+\kappa_2 \hat{S}(\hat{D}_2 \hat{\overline{D}}_2) + h_t(\hat{H}_u \hat{Q})\hat{t}^c + h_b(\hat{H}_d \hat{Q})\hat{b}^c + h_\tau(\hat{H}_d \hat{L})\hat{\tau}^c + \mu'(\hat{H}' \hat{\overline{H}'})\,,$$

$$\left[\lambda \equiv \lambda_3,\ \kappa \equiv \kappa_3\right]$$

We also need to include soft SuSy breaking.

Scalar potential: $V = V_F + V_D + V_{\text{soft}}$

with: $$V_{soft} = \sum_{i=1}^{3}\Bigg(m_{S_i}^2|S_i|^2 + m_{H_{2\,i}}^2|H_{2\,i}|^2 + m_{H_{1\,i}}^2|H_{1\,i}|^2 + m_{D_i}^2|D_i|^2 + m_{\overline{D}_i}^2|\overline{D}_i|^2$$
$$+m_{Q_i}^2|Q_i|^2 + m_{u_i^c}^2|u_i^c|^2 + m_{d_i^c}^2|d_i^c|^2 + m_{L_i}^2|L_i|^2 + m_{e_i^c}^2|e_i^c|^2\Bigg) + m_{H'}^2|H'^2| + m_{\overline{H'}}^2|\overline{H'}|^2$$
$$+\Big[B'\,\mu'(H'\overline{H'}) + h.c.\Big] + \Bigg[\sum_{i=1}^{3}\Big(\lambda_i A_{\lambda_i} S(H_{1\,i}H_{2\,i}) + \kappa_i A_{\kappa_i} S(D_i\overline{D}_i)\Big)$$
$$+h_t A_t(H_u Q)t^c + h_b A_b(H_d Q)b^c + h_\tau A_\tau(H_d L)\tau^c + h.c.\Bigg].$$

Extra soft trilinear scalar couplings (e.g. $A_{\lambda_i},\ A_{\kappa_i}$) and 15 extra soft masses

The Constrained E6SSM

The E_6SSM has 43 new parameters compared with the MSSM (14 are phases).

But if we apply constraints at the GUT scale, this is drastically reduced.

Set:

$$g_1(M_X) = g_2(M_X) = g_3(M_X) = g_1'(M_X)$$

soft scalar masses $\longrightarrow$ m_0

gaugino masses $\longrightarrow$ $M_{1/2}$

$$A_{\lambda_i}(M_X) = A_{\kappa_i}(M_X) = A_{t,b,\tau}(M_X) = A(M_X)$$

Important parameters:

$$\lambda_i,\ \kappa_i,\ h_t,\ h_b,\ h_\tau,\ m_0,\ M_{1/2},\ A \quad \text{(at } M_X\text{)}$$

Renormalisation Group Running

We have derived the RGEs to 2 loops, and modified a verison of SoftSuSY [B. Allanach] to run down the GUT scale parameters to low energies.

Procedure:

Run in two stages, first for gauge and Yukawa couplings and later for soft parameters

Gauge and Yukawa couplings:

- Fix tanβ at EW scale and derive EW scale quark/lepton Yakawas

$$\left(\text{e.g. } m_t(M_t) = \frac{h_t(M_t) v}{\sqrt{2}} \sin\beta\right)$$

- Fix λ_i and κ_i (a guess) at SuSy scale and run all Yukawas and gauge couplings to M_X

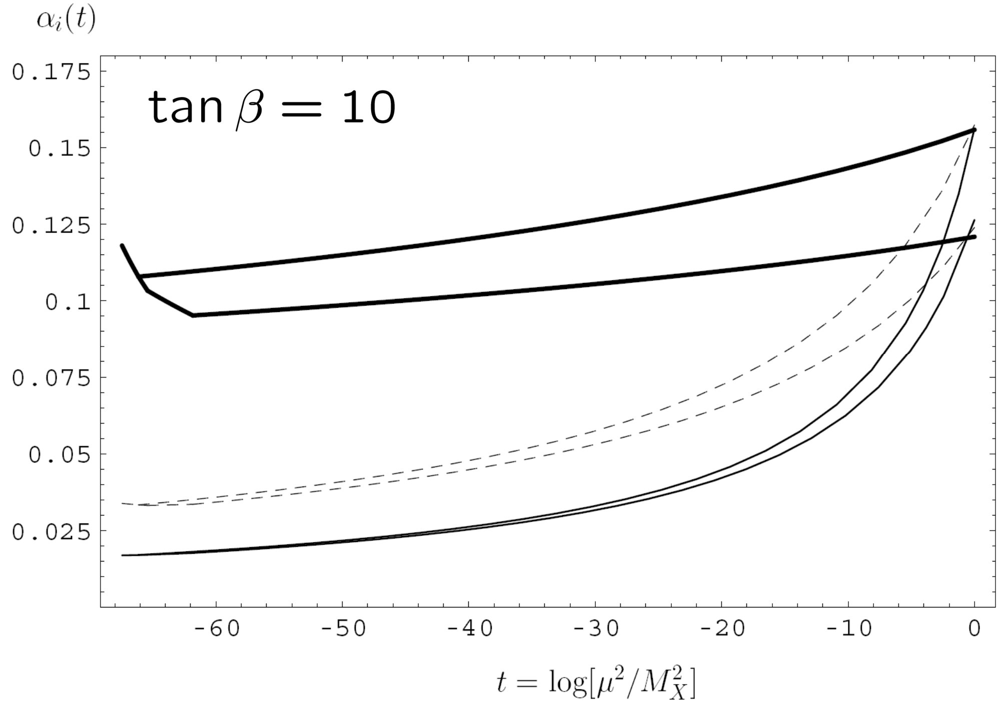
- Choose λ_i and κ_i at the High scale and fix gauge coupling unification
- Iterate until everything is consistent

Note:

Two loop running is essential since at one loop there is an accidental cancellation

making $\beta_3 \approx 0$

Running is very sensitive to thresholds



Soft SuSy breaking parameters

Since the gauge and Yukawa coupling RGEs don't involve soft SuSy breaking parameters, we can evolve these separately once we know the gauge and Yukawa couplings.

- For a particular scenario, put gauge and Yukawa coulpings into the soft SuSy RGEs
- This results in equations of the form, e.g.

$$M_3(\mu_S) = 0.705\, M_{1/2} + 0.0046\, A, \qquad M_2(\mu_S) = 0.274\, M_{1/2} + 0.0015\, A,$$

$$M_1(\mu_S) = 0.155\, M_{1/2} + 0.00088\, A, \qquad M_1'(\mu_S) = 0.159\, M_{1/2} + 0.0016\, A,$$

$$\begin{aligned} m_S^2(\mu_S) &= -0.535\, m_0^2 - 1.578\, M_{1/2}^2 - 0.085\, A^2 - 0.264\, AM_{1/2}, \\ m_{H_u}^2(\mu_S) &= 0.128\, m_0^2 - 1.145\, M_{1/2}^2 - 0.124\, A^2 - 0.481\, AM_{1/2}, \\ m_{H_d}^2(\mu_S) &= 0.940\, m_0^2 + 0.296\, M_{1/2}^2 - 0.013\, A^2 - 0.025\, AM_{1/2}, \end{aligned}$$

+ many more

- Use EWSB constraints to replace soft parameters with $\langle S\rangle = \frac{s}{\sqrt{2}}$, M_Z, $\tan\beta$

Note: only s is free choice now

$$
\begin{aligned}
\frac{\partial V}{\partial s} &= m_S^2 s - \frac{\lambda A_\lambda}{\sqrt{2}} v_1 v_2 + \frac{\lambda^2}{2}(v_1^2+v_2^2)s + \\
&\quad + \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_S s + \frac{\partial \Delta V}{\partial s} = 0\,, \\
\frac{\partial V}{\partial v_1} &= m_1^2 v_1 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_2 + \frac{\lambda^2}{2}(v_2^2+s^2)v_1 + \frac{\bar{g}^2}{8}\left(v_1^2 - v_2^2\right)v_1 + \\
&\quad + \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_1 v_1 + \frac{\partial \Delta V}{\partial v_1} = 0\,, \\
\frac{\partial V}{\partial v_2} &= m_2^2 v_2 - \frac{\lambda A_\lambda}{\sqrt{2}} s v_1 + \frac{\lambda^2}{2}(v_1^2+s^2)v_2 + \frac{\bar{g}^2}{8}\left(v_2^2 - v_1^2\right)v_2 + \\
&\quad + \frac{g_1^{'2}}{2}\left(\tilde{Q}_1 v_1^2 + \tilde{Q}_2 v_2^2 + \tilde{Q}_S s^2\right)\tilde{Q}_2 v_2 + \frac{\partial \Delta V}{\partial v_2} = 0\,,
\end{aligned}
$$

solve at tree-level $\longrightarrow$ gives tree-level m_0, $M_{1/2}$, A

- Iterate to include higher orders (ΔV)

Restrictions on solutions

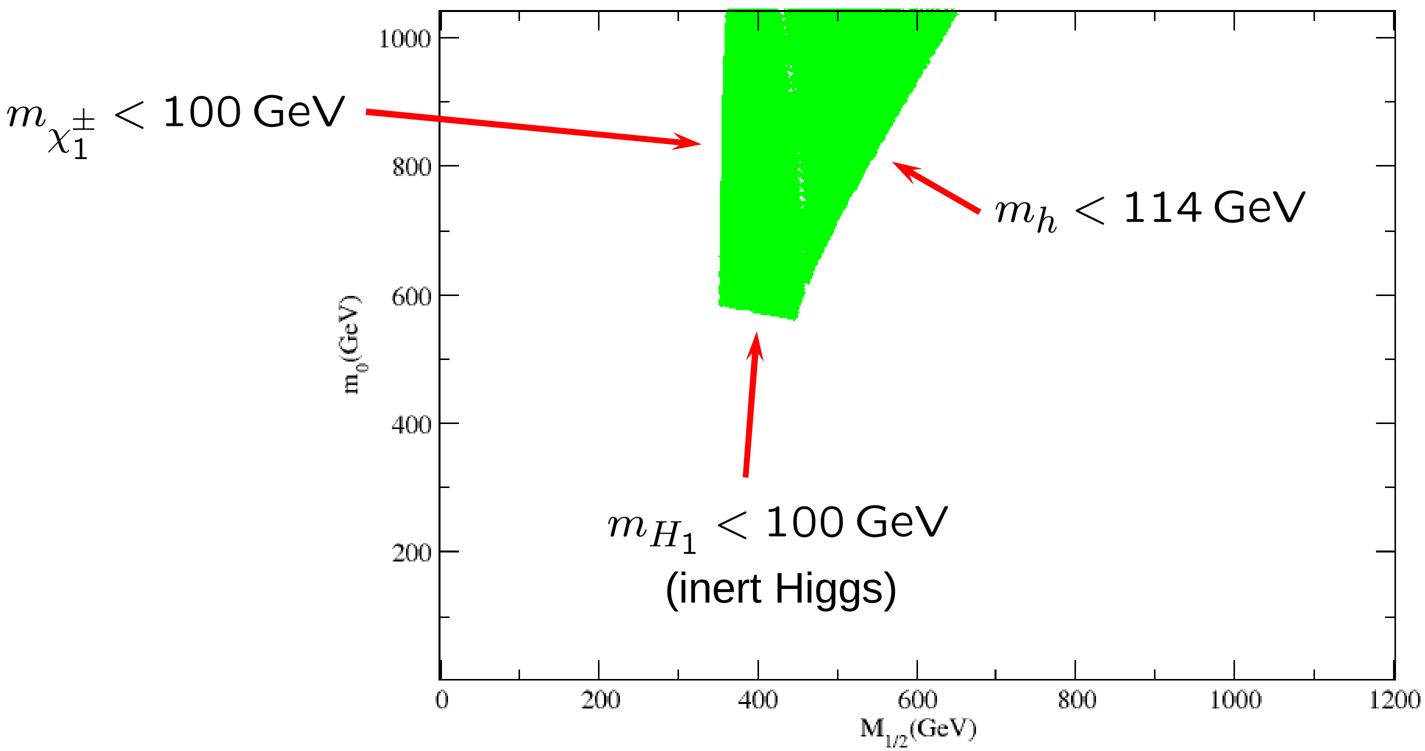
To ensure phenomenologically acceptable solutions, we require

- squarks and gluinos $\gtrsim$ 300 GeV
- exotic quarks and squarks $\gtrsim$ 300 GeV [HERA]
- $M_{Z'} \gtrsim$ 700 GeV (considering increasing to 900 GeV)
- Insist on neutralino LSP
- Keep Yukawa couplings $\lesssim 3$
- Inert Higgs and Higgsinos $\gtrsim$ 100 GeV

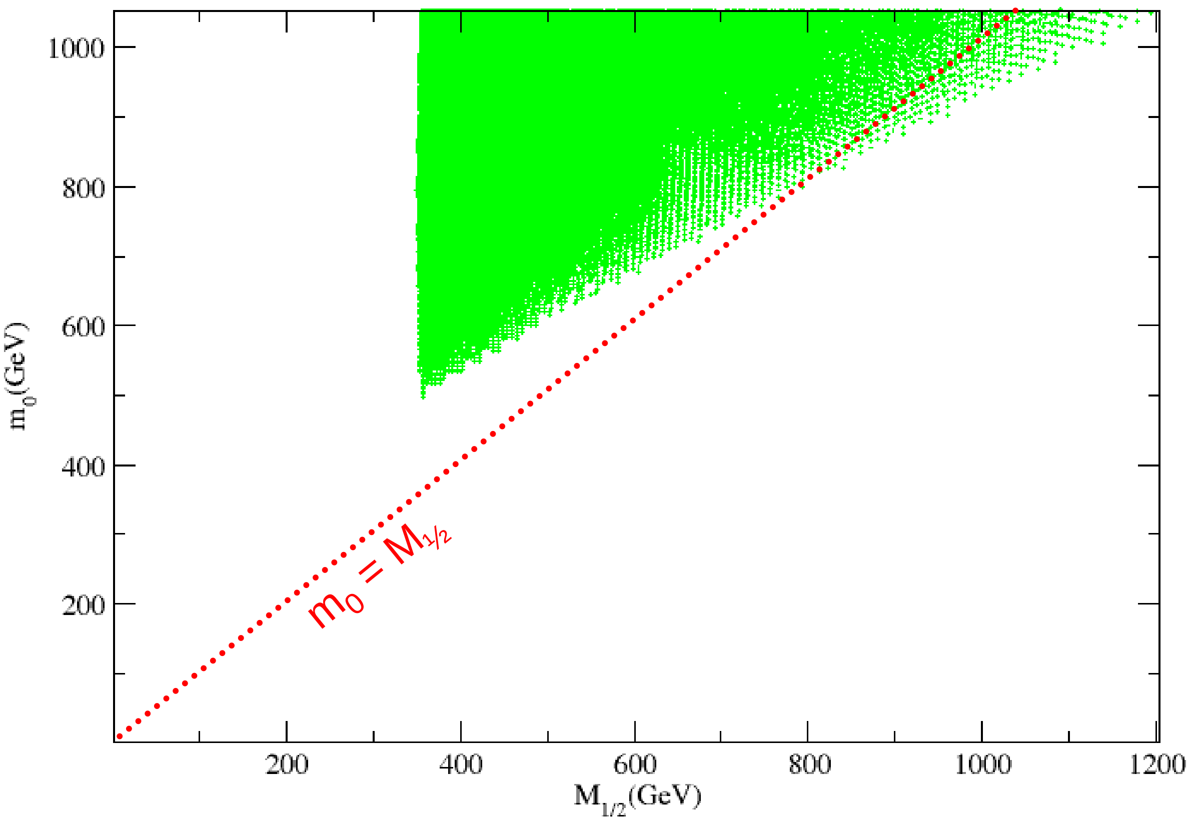
Allowed regions in the m_0 - $M_{½}$ plane

Fix $\tan\beta = 10,\ s = 3\,\text{TeV}$ and allow everything else to vary

Allowed points are in green.



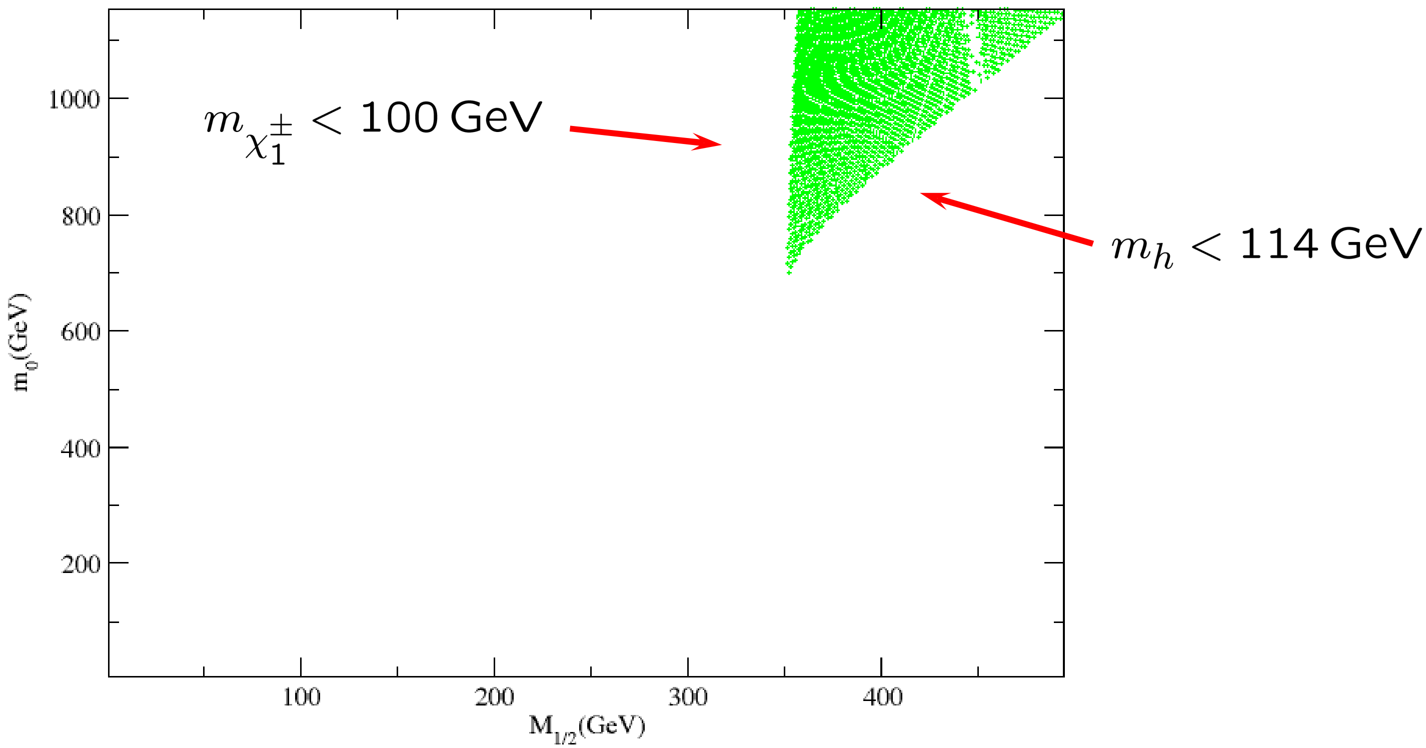
As previous, but now allowing s to vary too, i.e. only $\tan\beta = 10$ fixed



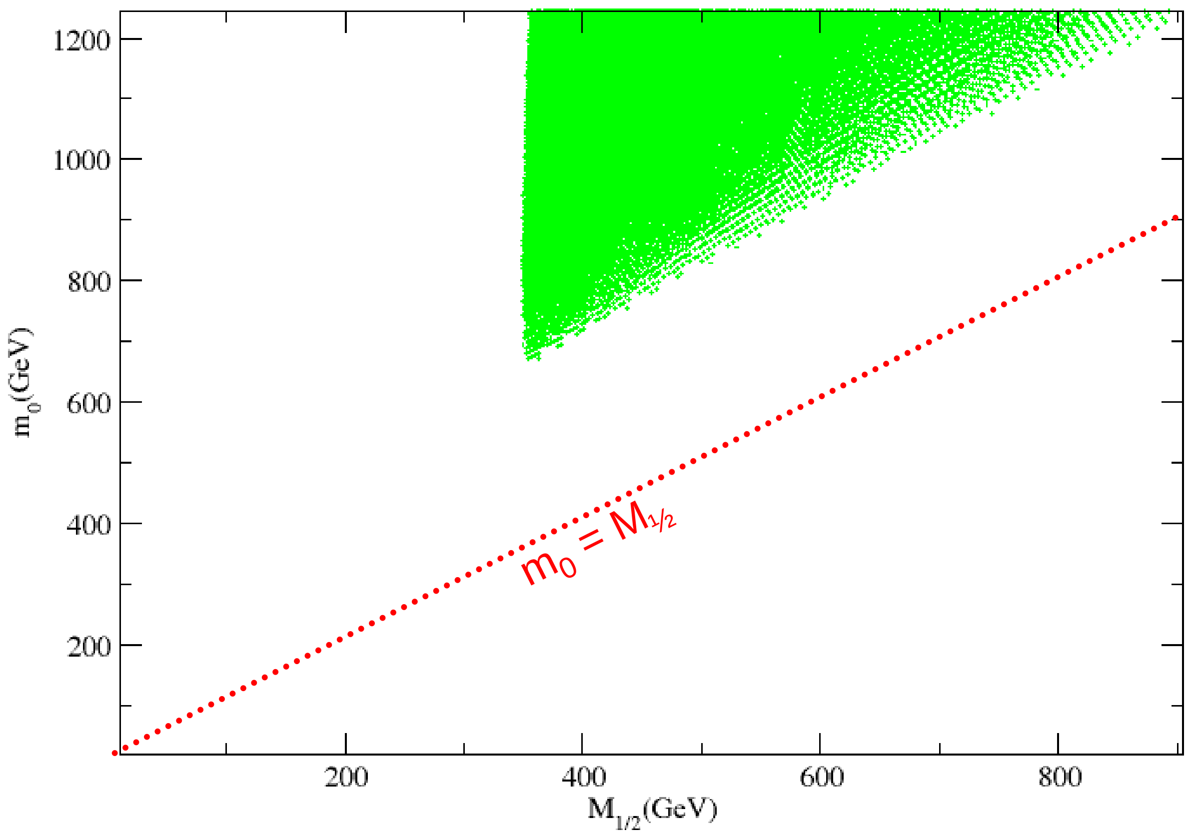
Note: since m_0, $M_{1/2}$ are derived, some possible regions are sparsely populated

Fix $\tan\beta = 30,\ s = 3\,\text{TeV}$ and allow everything else to vary

Allowed points are in green.



As previous, but now allowing s to vary too, i.e. only $\tan\beta = 30$ fixed



Particle Spectra and Benchmarks

- Firstly, notice that for most allowed scenarios $m_0 \gtrsim M_{1/2}$, so e.g. squarks tend to be heavier than the gluino

- Neutralinos, charginos and gluino:

$$m_{\tilde{\chi}_1^0} \approx M_1$$

$$m_{\tilde{g}} \approx M_3$$

$$m_{\tilde{\chi}_2^0} \approx m_{\tilde{\chi}_1^\pm} \approx M_2$$

$$m_{\tilde{\chi}_{3,4}^0} \approx m_{\tilde{\chi}_2^\pm} \approx \mu = \frac{\lambda s}{\sqrt{2}}$$

$$m_{\tilde{\chi}_{5,6}^0} \approx M_{Z'}$$

- Higgs bosons

$$m_{h_1} \approx M_Z + \Delta$$

$$m_{h_2} \approx m_{H^\pm} \approx m_A$$

$$m_{h_3} \approx M_{Z'}$$

- Exotic quarks have their mass set by $\frac{\kappa_i(M_S)}{\sqrt{2}}s$

  Exotic squarks are similar, but also have a contribution from the soft SuSy mass

  $$m^2_{\tilde{D}_i} \approx m^2_{D_i} + \frac{\kappa_i^2(M_S)}{2}\,s^2$$ + mixing and auxiliary D-terms

- Inert Higgses have contributions from the soft mass, auxiliary D-terms and $\frac{\lambda_i(M_S)}{\sqrt{2}}s$

  Inert Higgsinos are much simpler, $m_{\tilde{H}_i} \approx \frac{\lambda_i(M_S)}{\sqrt{2}}s$

  can be negative

Benchmark 1 (light spectra)

$$\tan\beta = 10, \quad s = 2.7\,\text{TeV},$$
$$M_{1/2} = 363\,\text{GeV}, \quad m_0 = 537\,\text{GeV}, \quad A = 711\,\text{GeV}$$
$$\lambda(M_X) = -0.368, \quad [\lambda(M_S) = -0.355]\,, \quad \lambda_{1,2}(M_X) = 0.1$$
$$\kappa_{1,2,3}(M_X) = 0.207, \quad \left[\kappa_{1,2,3}(M_S) = 0.538\right]$$

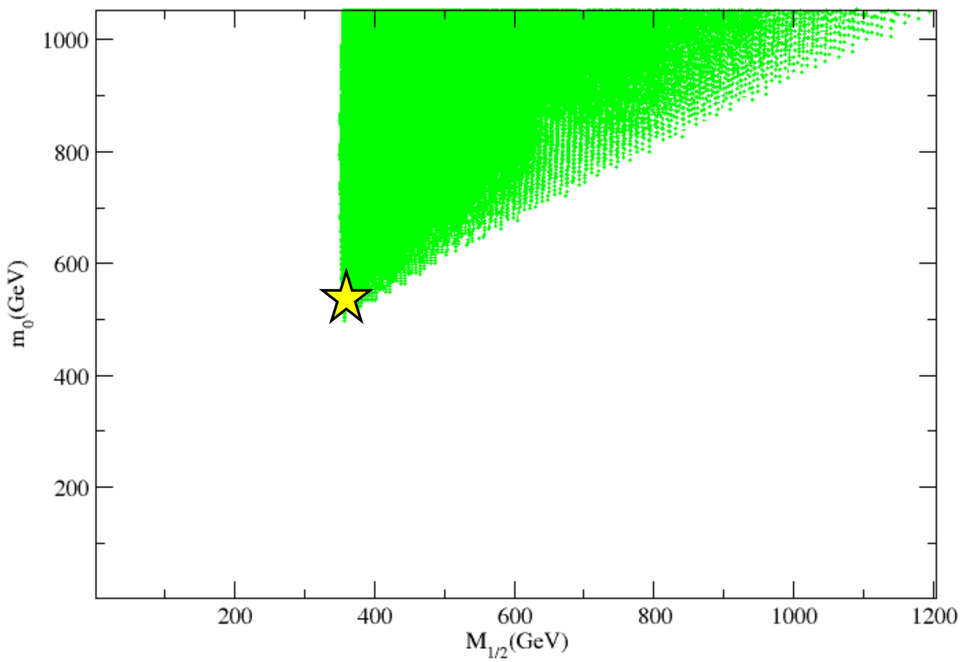
- κ's all equal, so exotic squarks all degenerate

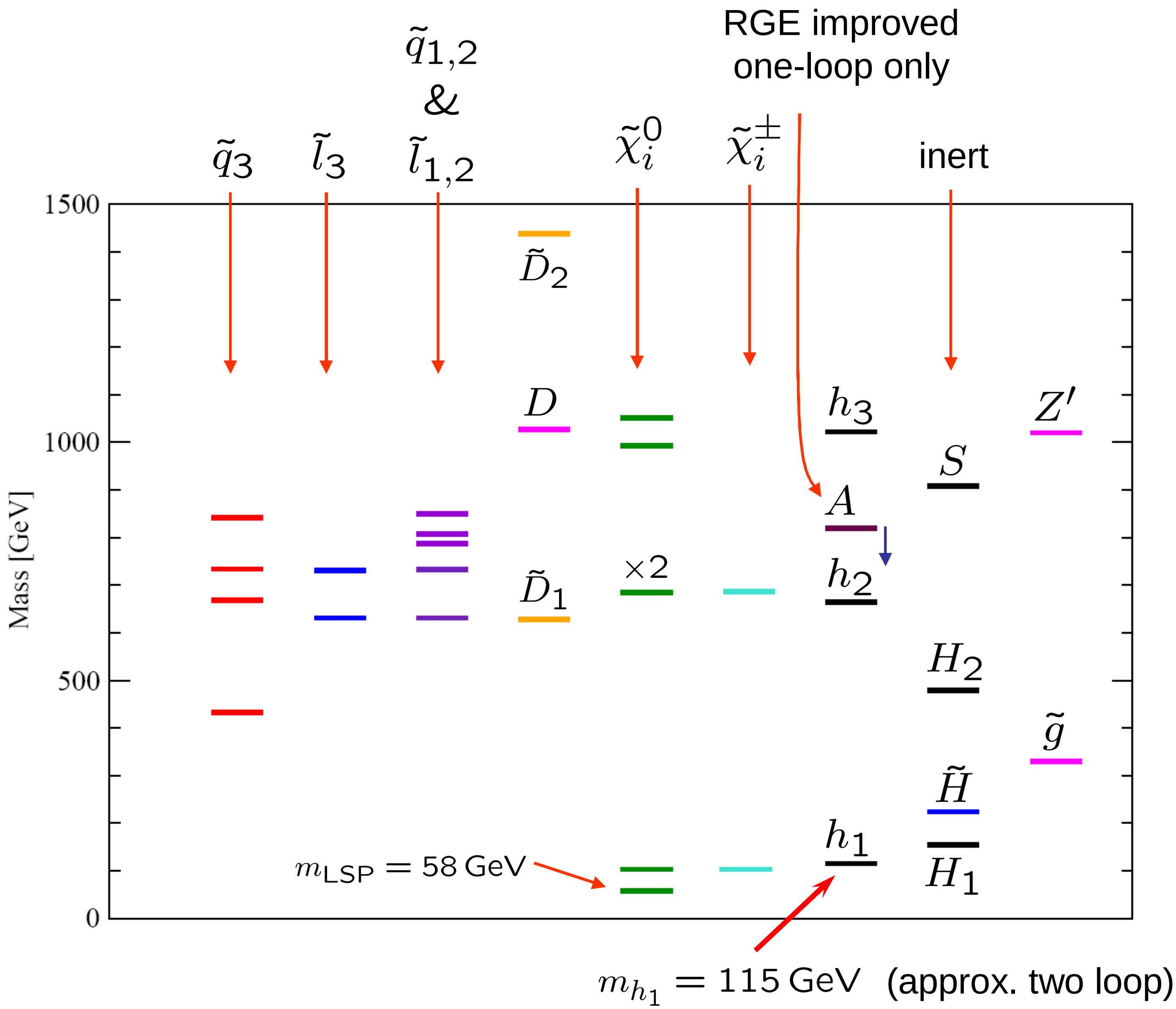
- Light Higgs and inert Higgs

$$m_{h_1} = 115\,\text{GeV}$$
$$m_{H_1} = 154\,\text{GeV}$$

- Light gluino and chargino

$$m_{\tilde{g}} = 330\,\text{GeV}$$
$$m_{\tilde{\chi}_1^\pm} = 103\,\text{GeV}$$



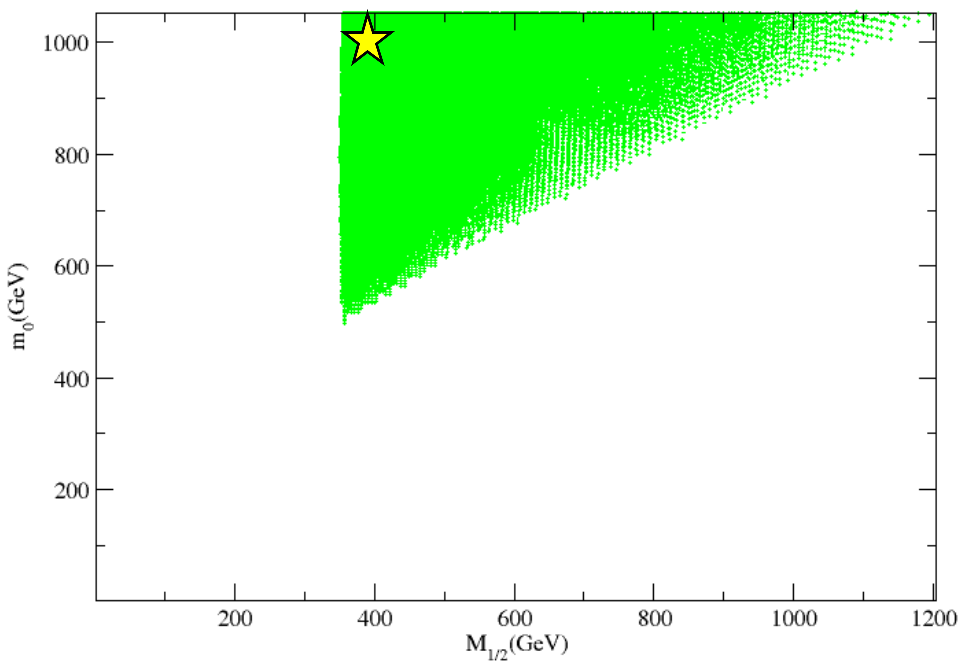


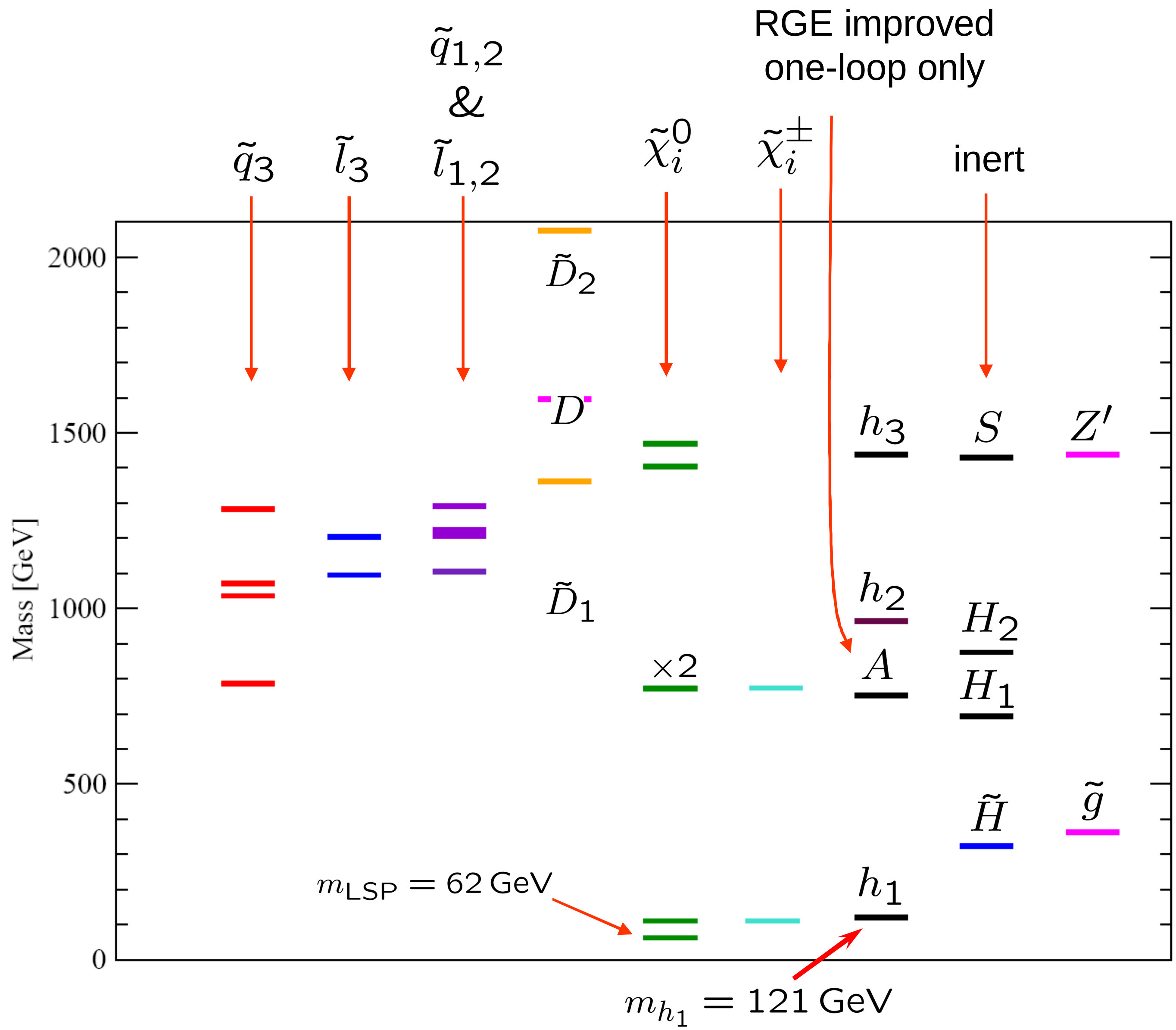
RGE improved
one-loop only
$\tilde{q}_{1,2}$ & $\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
1500
1000
500
0
Mass [GeV]
$\tilde{D}_2$
D
$\tilde{D}_1$
$\times 2$
h_3
A
h_2
h_1
S
H_2
$\tilde{H}$
H_1
Z'
$\tilde{g}$
$m_{\rm LSP} = 58$ GeV
$m_{h_1} = 115$ GeV (approx. two loop)

Benchmark 2 $\left(m_0 \gg M_{1/2}\right)$

$$
\begin{aligned}
&\tan\beta = 10, \quad s = 3.8\,\text{TeV}, \\
&M_{1/2} = 390\,\text{GeV}, \quad m_0 = 998\,\text{GeV}, \quad A = 768\,\text{GeV} \\
&\lambda(M_X) = -0.307, \quad [\lambda(M_S) = -0.285]\,, \quad \lambda_{1,2}(M_X) = 0.1 \\
&\kappa_{1,2,3}(M_X) = 0.246, \quad \left[\kappa_{1,2,3}(M_S) = 0.594\right]
\end{aligned}
$$

- Very split spectrum with light neutralinos/gauginos but very heavy scalars

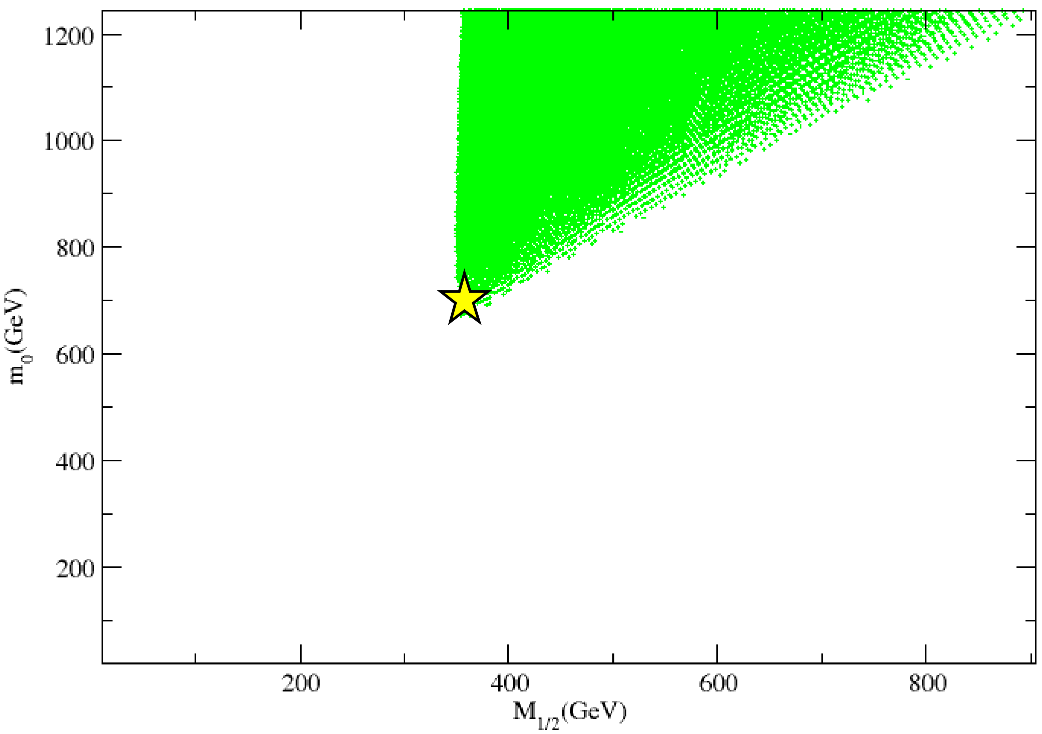


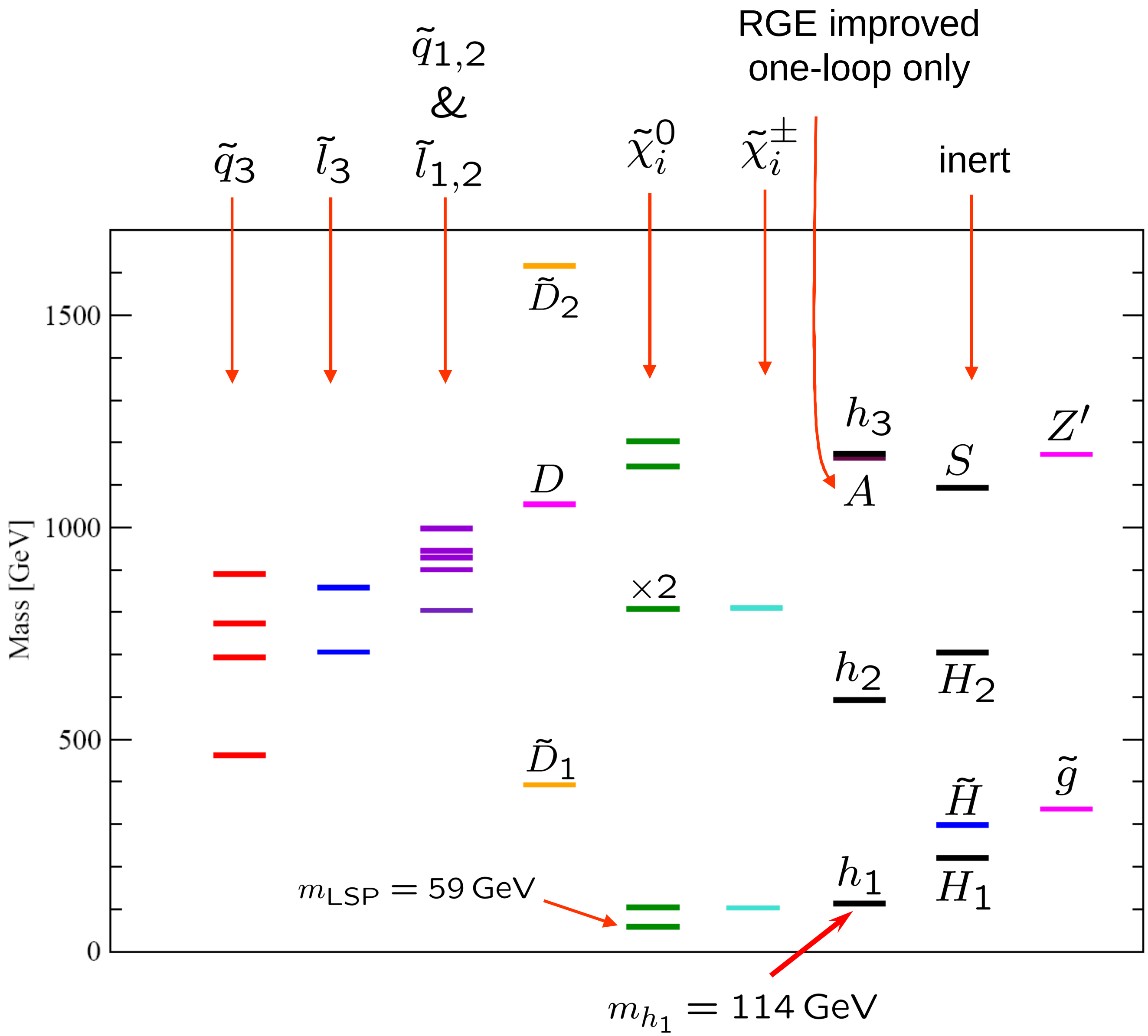


RGE improved
one-loop only
$\tilde{q}_{1,2}$ & $\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
$\tilde{D}_2$
D
$\tilde{D}_1$
h_3
S
Z'
h_2
H_2
$\times 2$
A
H_1
$\tilde{H}$
$\tilde{g}$
h_1
$m_{\mathrm{LSP}} = 62\,\mathrm{GeV}$
$m_{h_1} = 121\,\mathrm{GeV}$
Mass [GeV]
2000
1500
1000
500
0

Benchmark 3 (high $\tan\beta$ with light spectra)

$$\tan\beta = 30, \quad s = 3.1\,\text{TeV},$$
$$M_{1/2} = 365\,\text{GeV}, \quad m_0 = 702\,\text{GeV}, \quad A = 1148\,\text{GeV}$$
$$\lambda(M_X) = -0.378, \quad [\lambda(M_S) = -0.366]\,, \quad \lambda_{1,2}(M_X) = 0.1$$
$$\kappa_{1,2,3}(M_X) = 0.171, \quad [\kappa(M_S) = 0.481]$$





RGE improved
one-loop only
$\tilde{q}_{1,2}$
&
$\tilde{l}_{1,2}$
$\tilde{q}_3$
$\tilde{l}_3$
$\tilde{\chi}_i^0$
$\tilde{\chi}_i^\pm$
inert
1500
1000
500
0
Mass [GeV]
$\tilde{D}_2$
D
$\tilde{D}_1$
$\times 2$
h_3
A
S
Z'
h_2
H_2
$\tilde{H}$
$\tilde{g}$
h_1
H_1
$m_{\mathrm{LSP}} = 59$ GeV
$m_{h_1} = 114$ GeV

6. Conclusions and Summary

- The Higgs boson physics awaiting us at the LHC may be much more complicated than we expect!
- Supersymmetry requires at least two Higgs doublets, leading to a total of 5 Higgs bosons.
- The μ problem makes it desirable to increase the Higgs spectrum by adding an additional singlet, but this leads to a problem with an extra U(1) symmetry.
- How this symmetry is broken distinguishes the NMSSM, the mnSSM and models of local Peccei-Quinn symmetry.
- The NMSSM in particular presents interesting scenarios, where the lightest Higgs boson may have diluted couplings and have evaded LEP limits; or where the lightest scalar decays into a very light pseudoscalar.
- Models based on extended gauge groups may provide a more elegant solution by making the PQ symmetry local. I described one interesting scenario, the E_6SSM which predicts new states that will be found at the LHC.