Higgs and supersymmetric Higgs phenomenology

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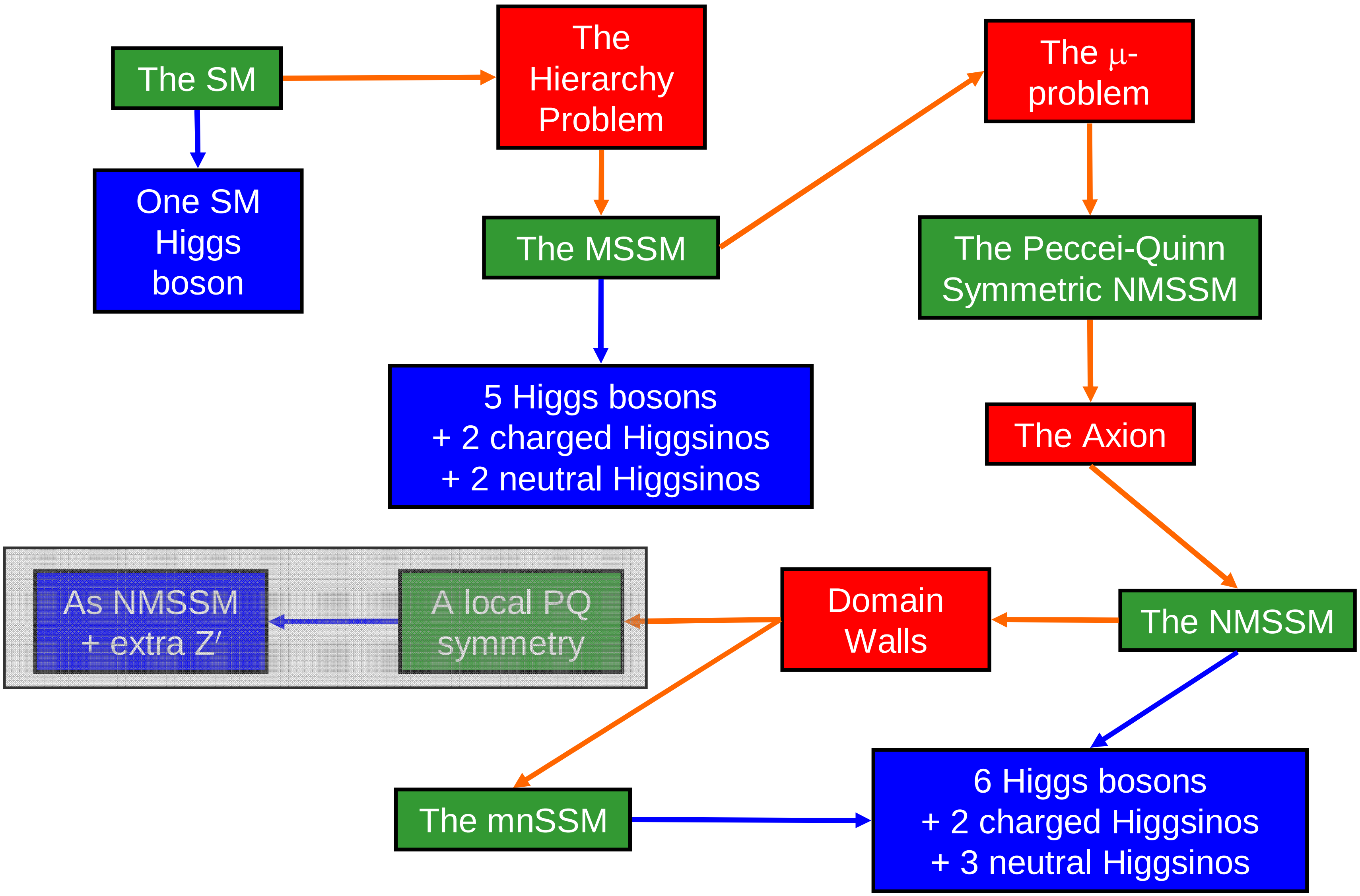
Outline:

- Introduction: The SM Higgs Sector
- The minimal SUSY Higgs sector
- The NMSSM
- The mnSSM
- Conclusions and Summary


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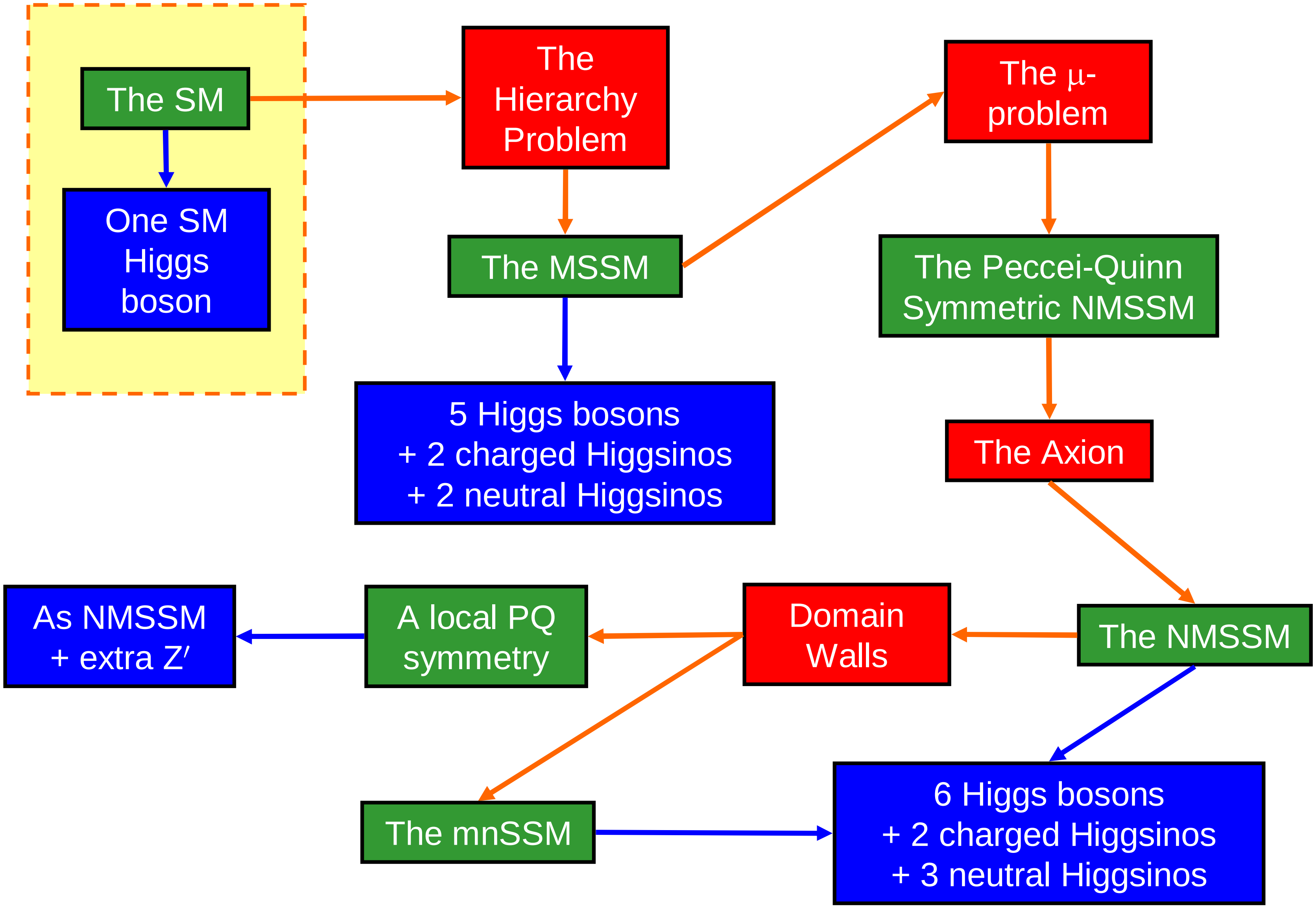
Domain Walls
A local PQ symmetry
As NMSSM
+ extra Z′
The mnSSM
6 Higgs bosons
+ 2 charged Higgsinos
+ 3 neutral Higgsinos

1. Introduction: The SM Higgs Sector



SM Higgs sector Lagrangian:

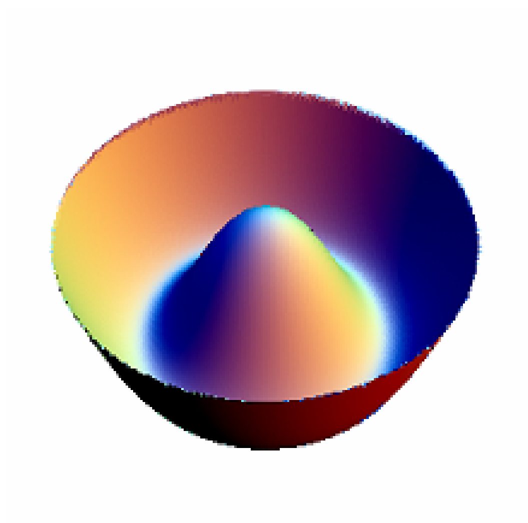
$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

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

- 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.

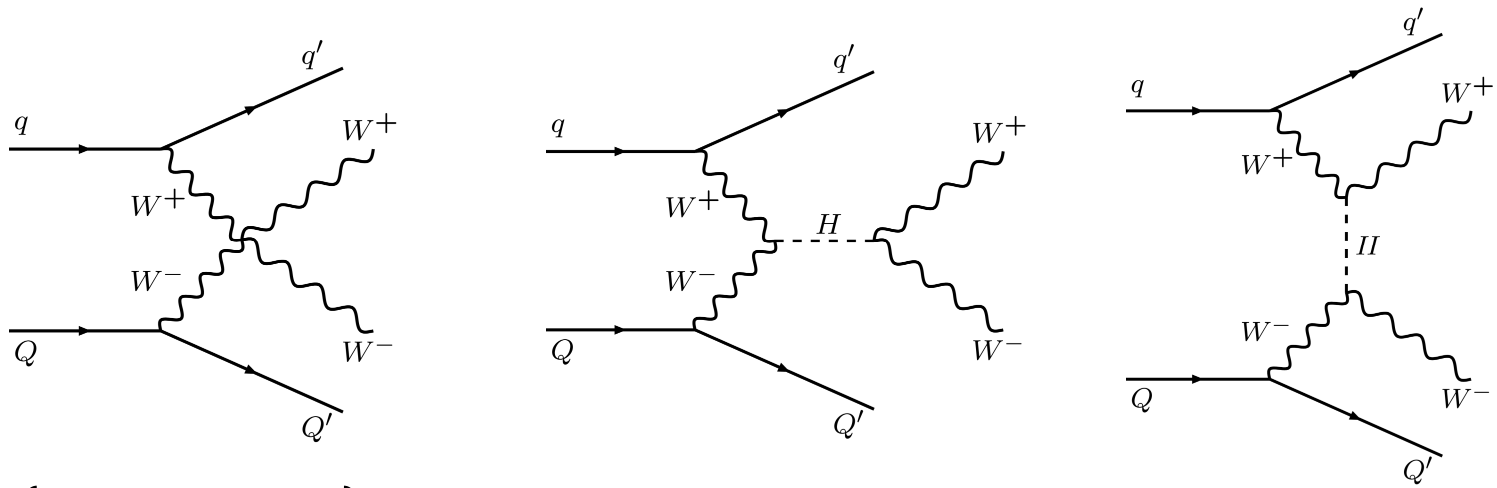
- Kinetic term $\rightarrow$ masses to W, Z bosons

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

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

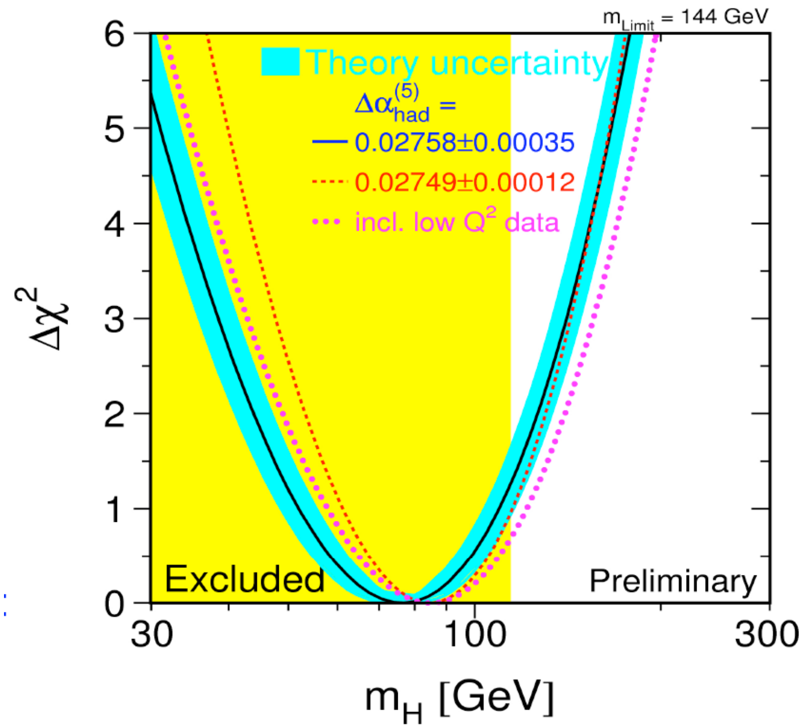


(+ γ/Z exchange)

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

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

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



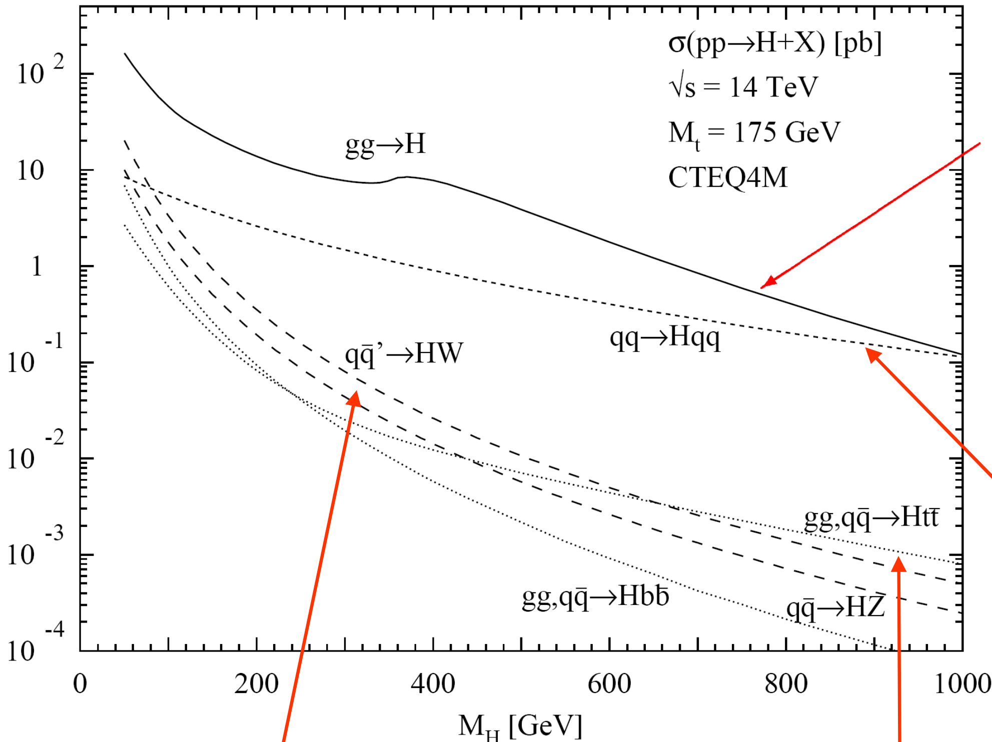
Electroweak precision data: $M_H = 76^{+33}_{-24}\,\mathrm{GeV}$ $\qquad M_H < 144\,\mathrm{GeV}$ (95% conf.)

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

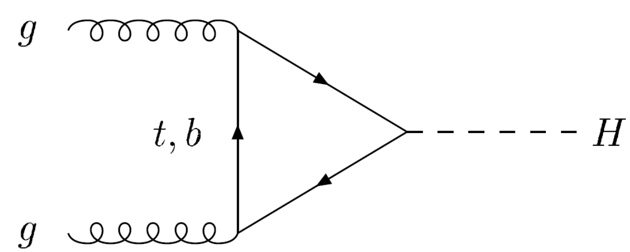
But see Jochum's talk!

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

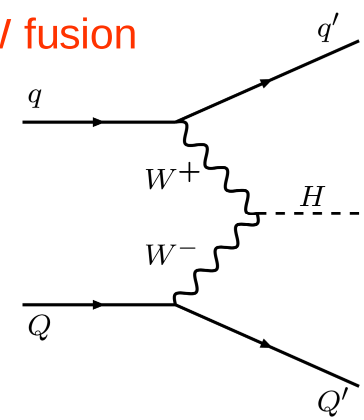
Production:



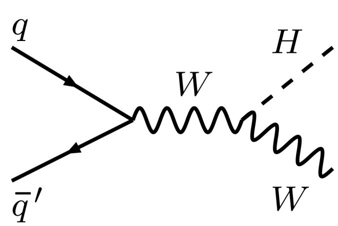
Main production channel is $gg \to H$



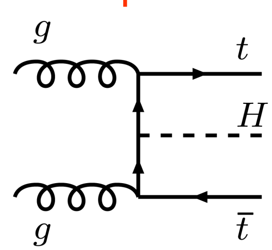
WW fusion



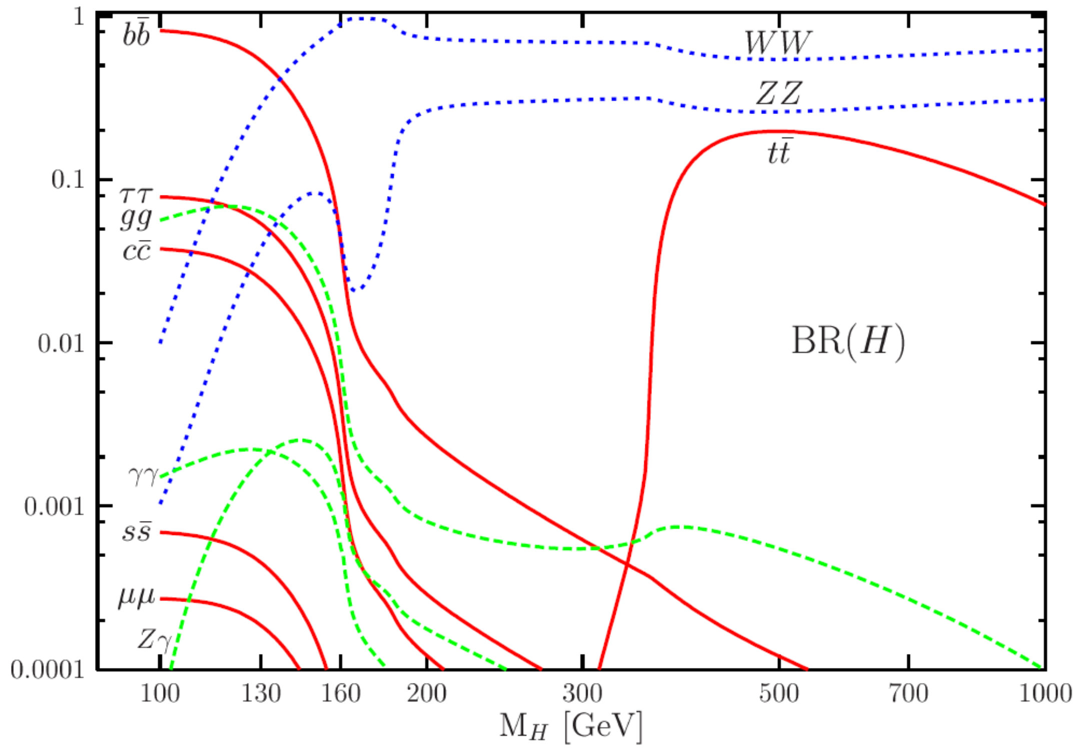
Higgs-strahlung



Associated production



Decay: Higgs branching ratios

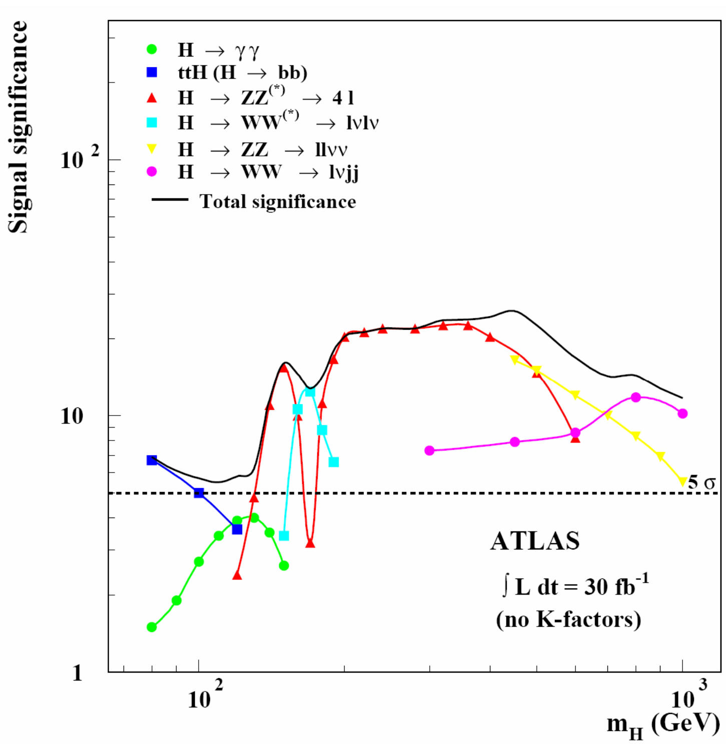


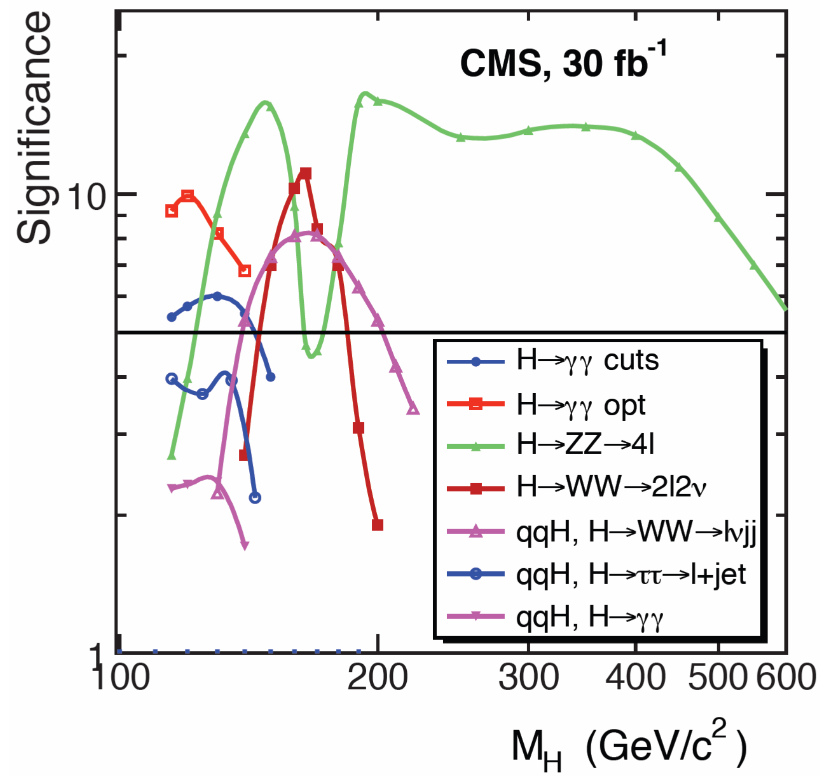
For low Higgs mass, the Higgs predominantly decays to b-quarks

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

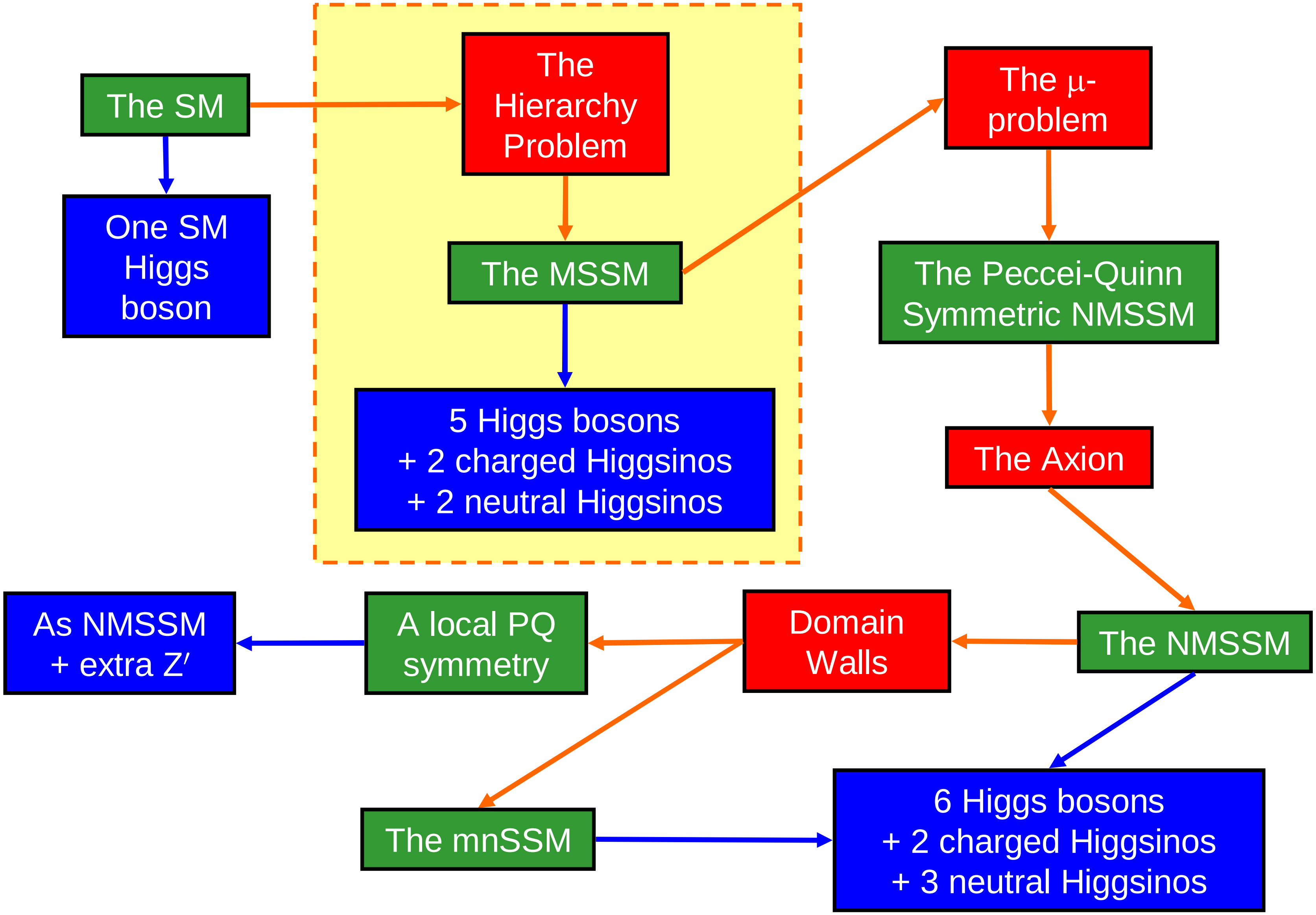
(or Tevatron)

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





2. The minimal SUSY Higgs sector

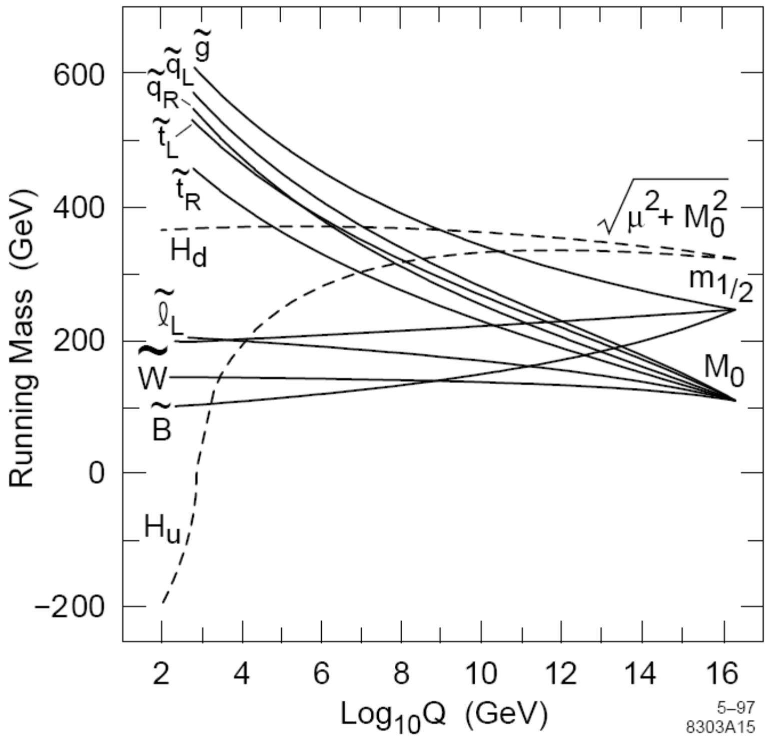


What is wrong with the SM Higgs?

- 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.

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

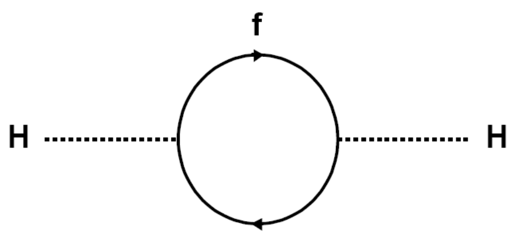


[Kane, Kolda, Roszkowski, Wells]

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.

The Hierarchy Problem

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

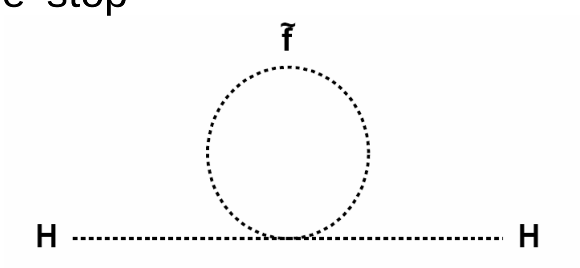


$$\delta M_H^2 = -2N_f \frac{|\lambda_f|^2}{16\pi^2}\Lambda^2 + \ldots$$

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:

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

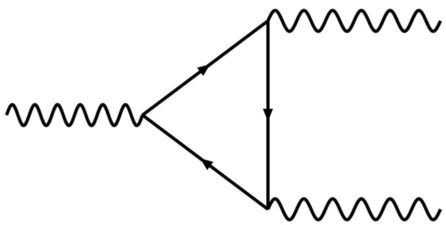
  Also, in order to obey supersymmetry, *W* must be analytic in the scalar fields ϕ_i, i.e. it cannot contain any complex conjugate fields ϕ_i^*.

  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 their will be an anomaly unless

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

hypercharge

In the SM, for each generation:

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

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 even

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: $\dfrac{\partial V}{\partial M_{H_u}^2} = \dfrac{\partial V}{\partial M_{H_u}^2} = 0 \;\rightarrow\; \underbrace{v_u, \quad v_d}$

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

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: $\boxed{M_A \quad \text{and} \quad \tan\beta}$

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**:

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

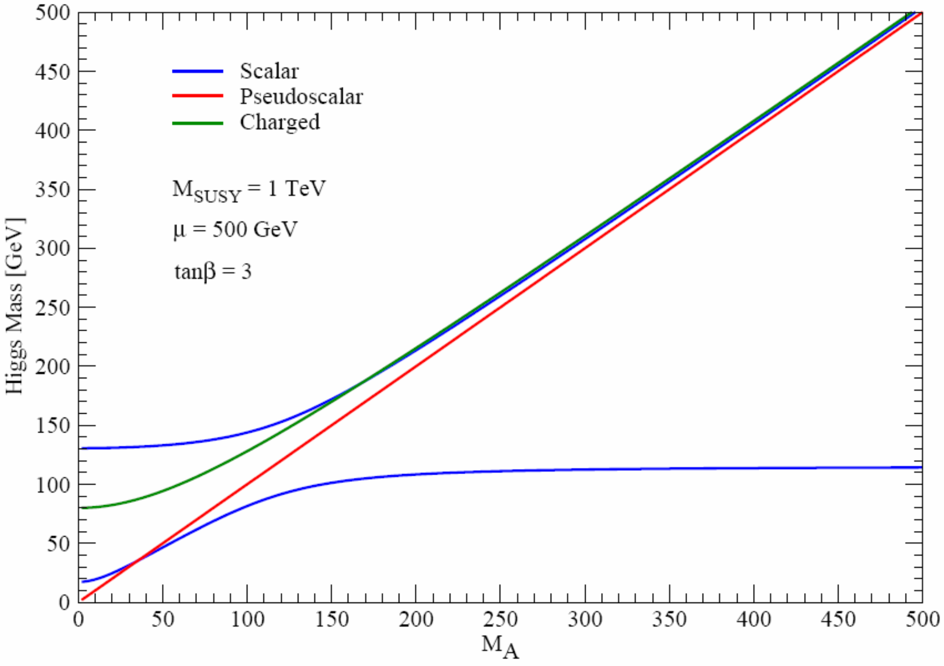
For large $\tan\beta$, or large M_A : $M_h \approx M_Z|\cos 2\beta|$, $M_H \approx M_A$

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

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

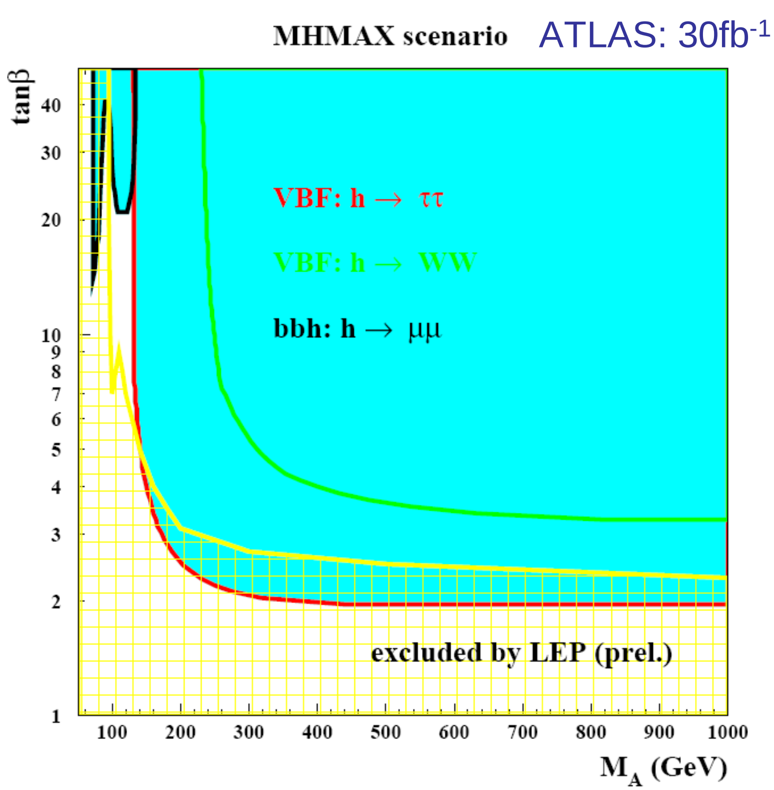
We have an upper bound on the MSSM lightest Higgs boson mass:

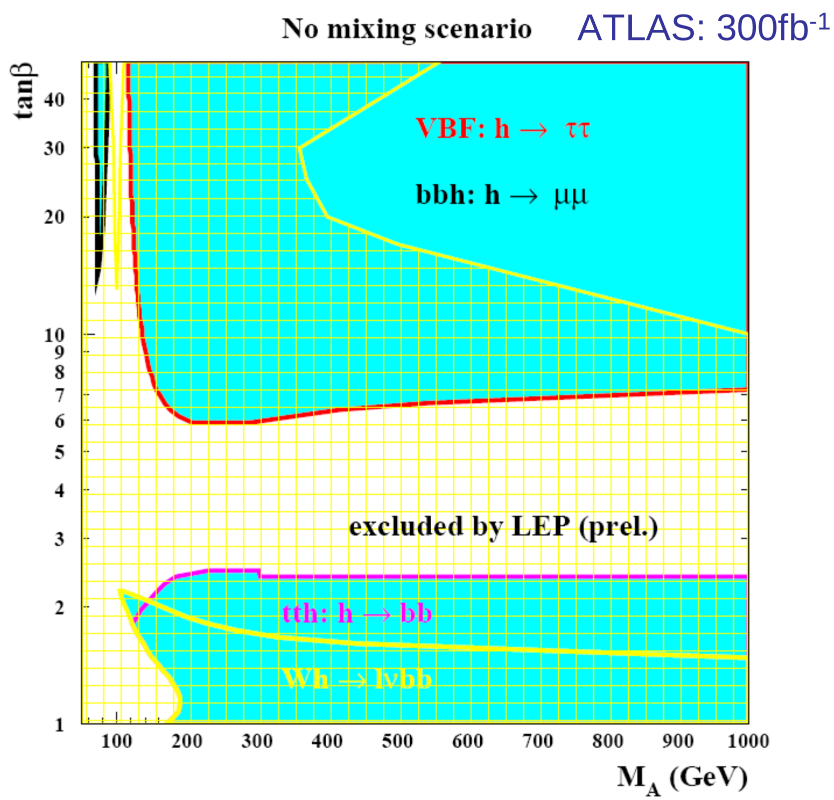
$$\boxed{M_h^2 \lesssim 135 \text{ GeV}}$$



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.

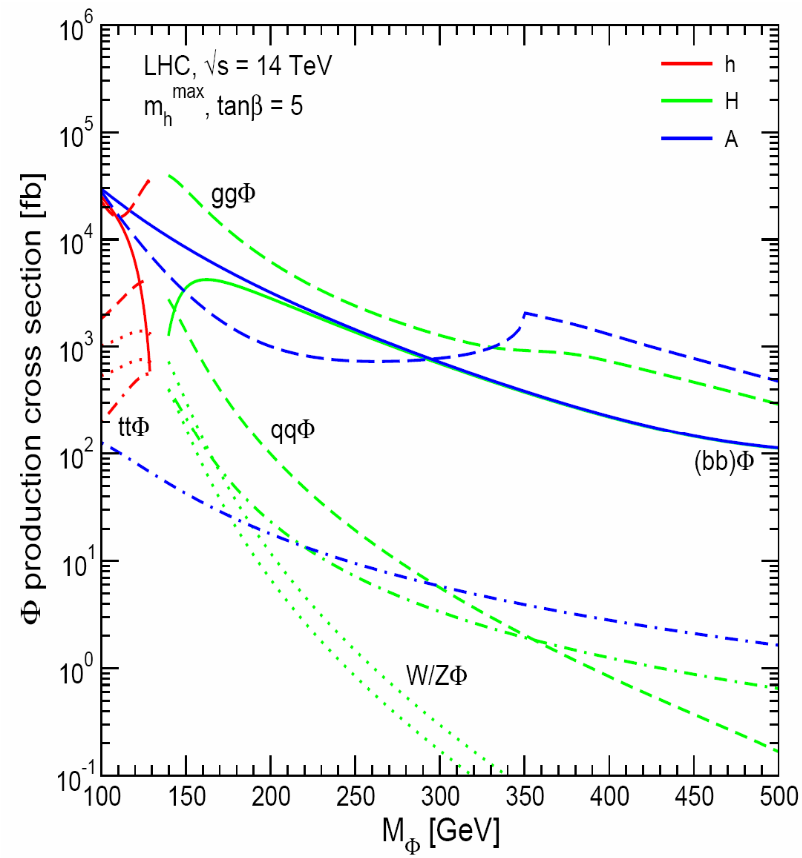


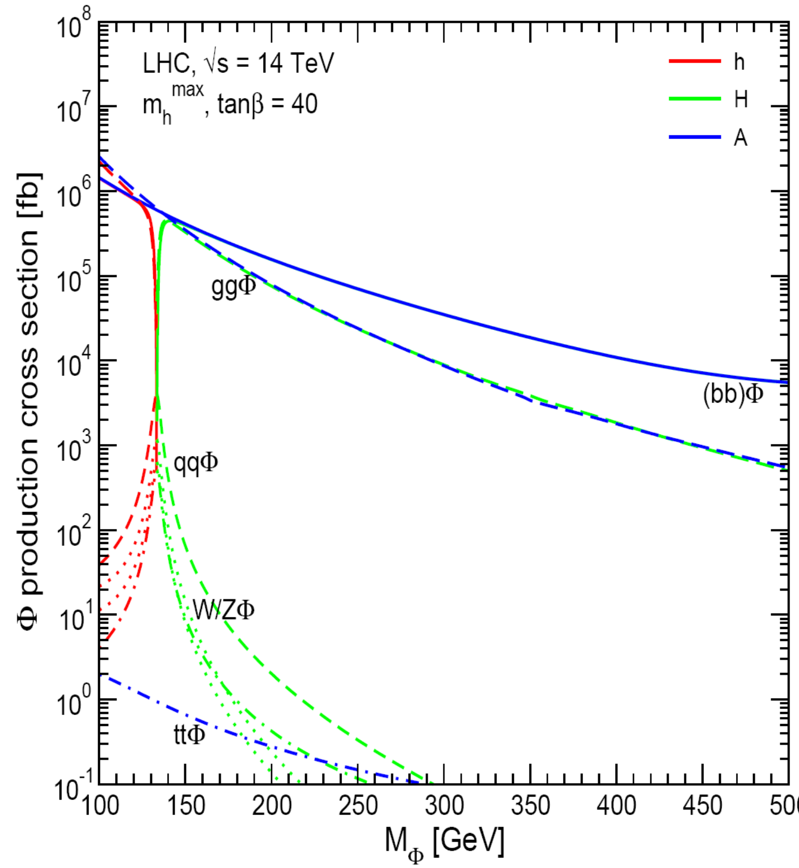


[Schumacher]

Neutral MSSM Higgs production

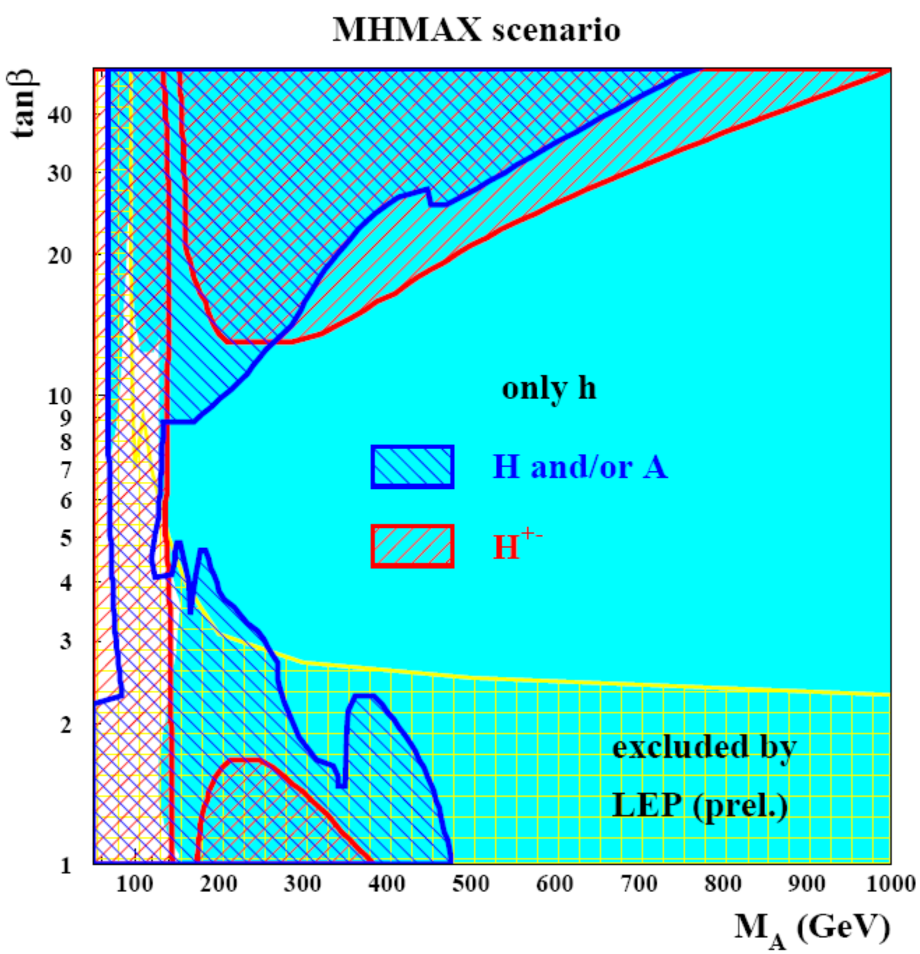
$$\Phi = h,\ H,\ A$$



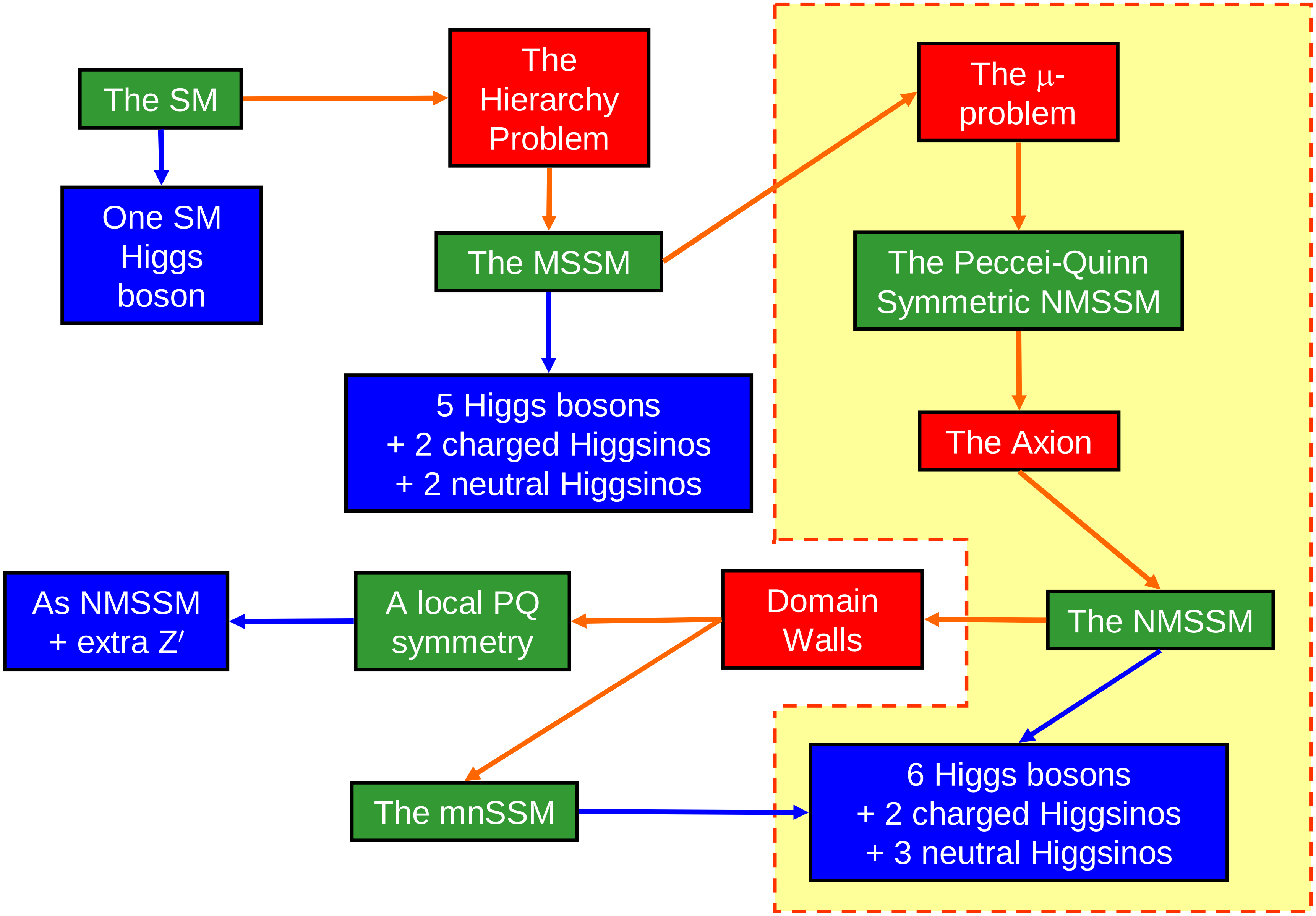


[Hahn, Heinemeyer, Maltoni, Weiglein, Willenbrock]

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 $\boldsymbol{\epsilon}$'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**.

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**

$$\mu_{\text{eff}} H_u H_d \qquad \text{with} \qquad \mu_{\text{eff}} = \lambda \langle S \rangle \qquad \left(\langle S \rangle = \frac{1}{\sqrt{2}} v_s \right)$$

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

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

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 $\widehat{\Psi}_i \rightarrow e^{iQ_i^{PQ}\theta}\widehat{\Psi}_i$

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:

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

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

minimisation conditions

$$\underbrace{\overbrace{v_u, \quad v_d, \quad v_s}}$$

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

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

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

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 $\kappa \rightarrow 0$, $\lambda \rightarrow 0$, keeping κ/λ and μ fixed.

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

$$\lambda^2 + \kappa^2 \lesssim 0.6$$

Lightest Higgs mass bound

- In the MSSM

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

- In the NMSSM

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

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

heavy pseudoscalar

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

CP-even Higgs masses²:

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

heavy scalar

intermediate mass scalar

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

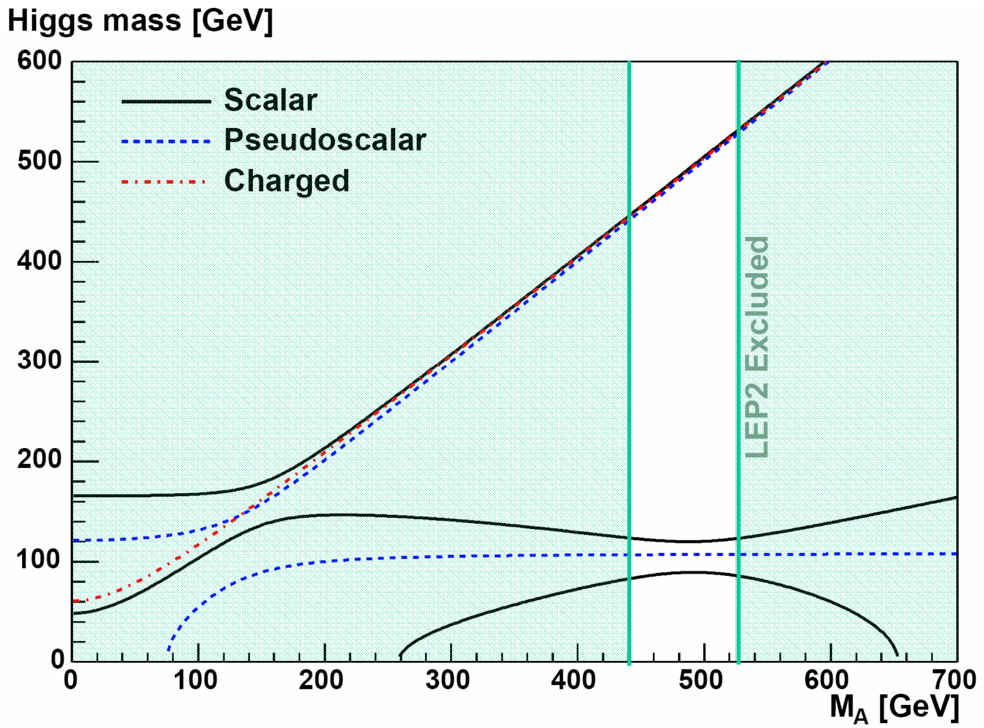
Charged Higgs masses²: $M_{H^\pm}^2 = M_A^2 + M_W^2 - \frac{1}{2}(\lambda v)^2$

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]

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

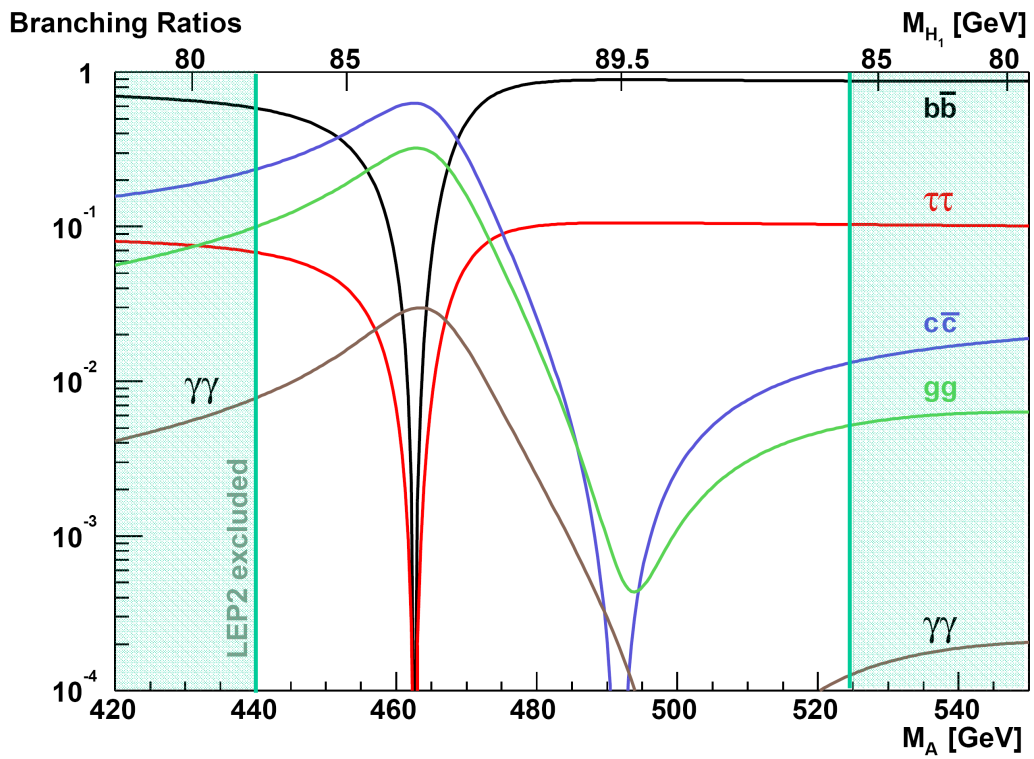


Most of the M_A range is excluded (at 95%) by LEP2 Higgs-strahlung but there is still a substantial region left.

Notice the rather light Higgs boson!

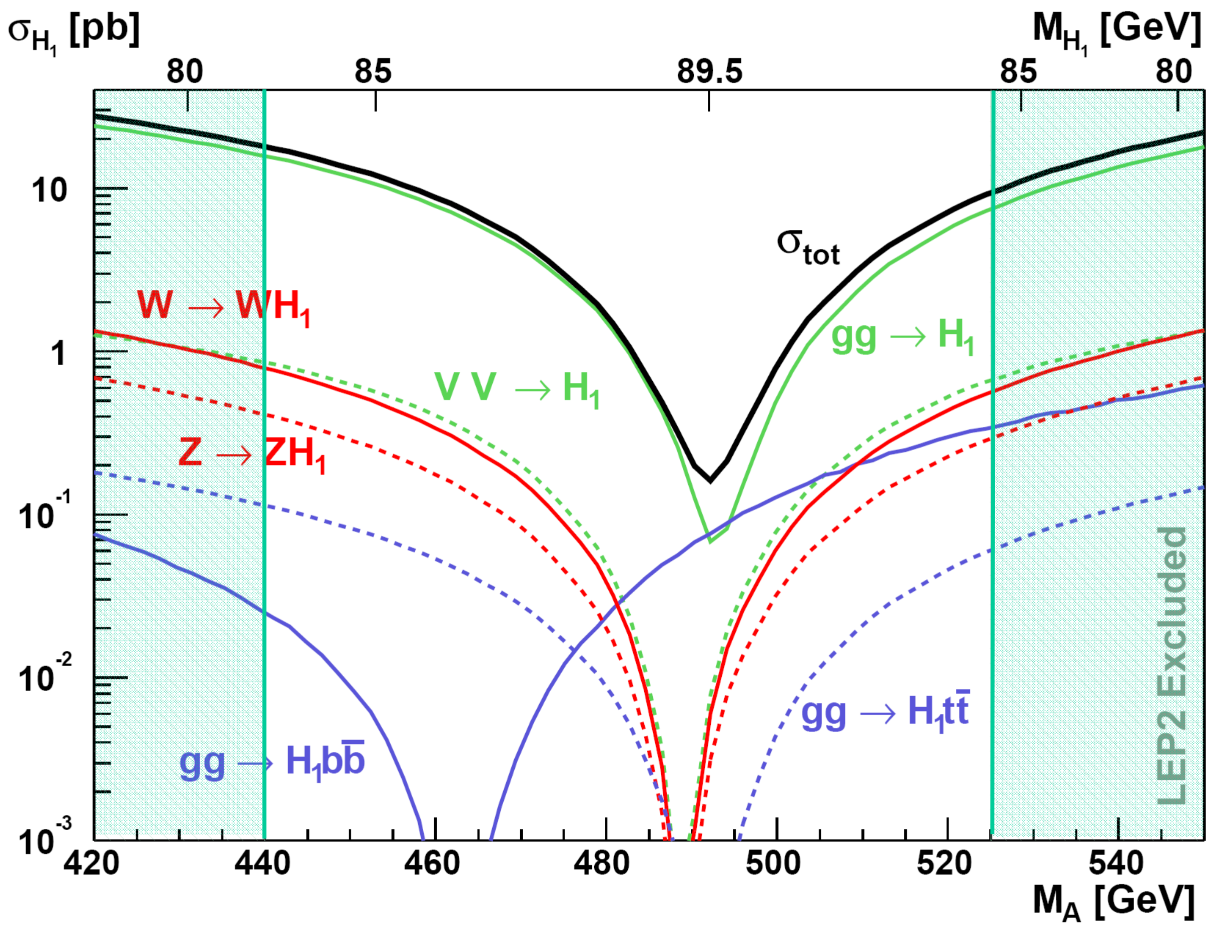
In the allowed region, the couplings of the lightest Higgs to gauge bosons is switching off, which is why LEP would not have seen it.

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:

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

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

very large $v_s \approx 4\ \mathrm{TeV}$

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

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

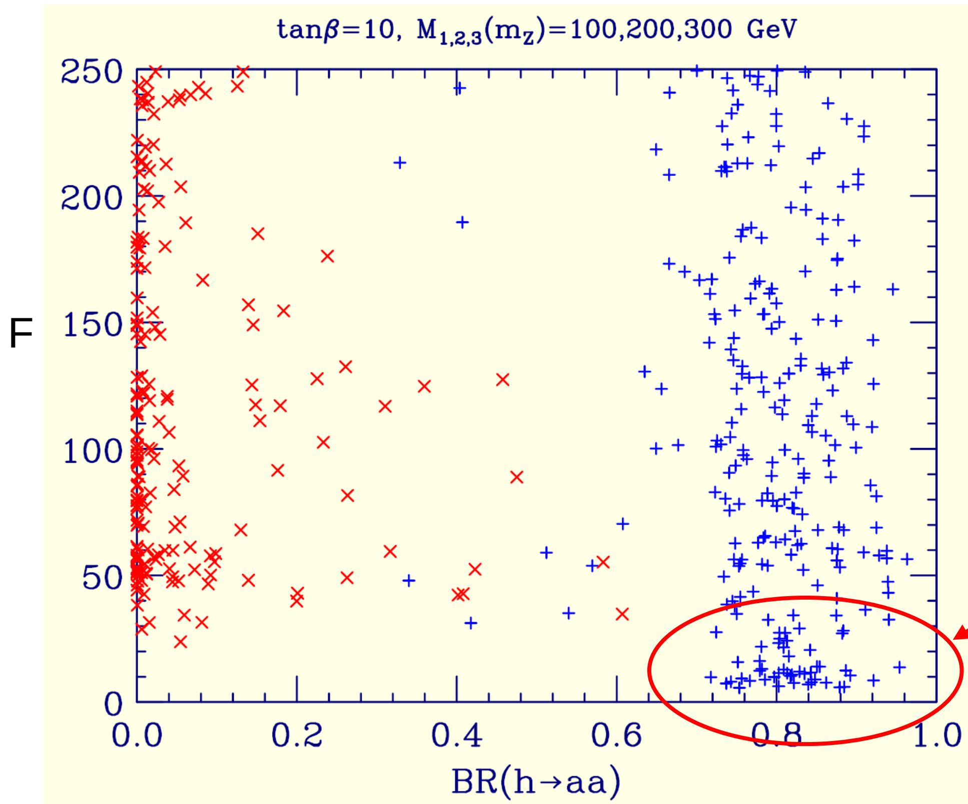
mainly MSSM heavy Higgses

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 $F = \mathrm{max}_a \left| \frac{d \log M_Z}{d \log a} \right|$ and scanning over parameter space



[From J. Gunion's talk at SUSY05]

× have M_{H_1} > 114GeV

+ have M_{H_1} < 114GeV

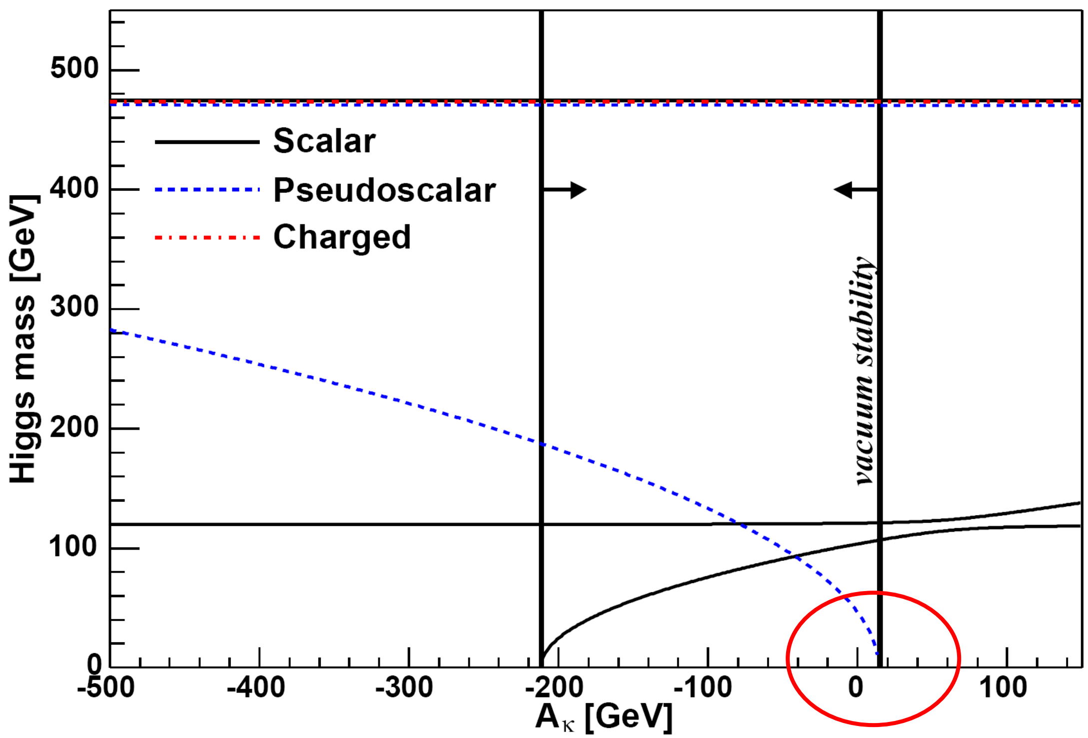
Points with high $H_1 \to A_1 A_1$ branching ratio have smaller fine tuning

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.

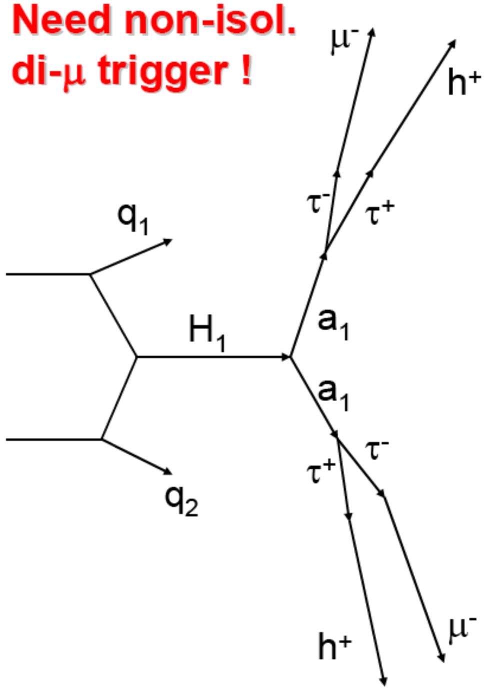
Les Houches 2007: (from A. Nikitenko's talk)

S. Lehti, I Rottlaender, A. Nikitenko, M. Schumacher, C. Shepard with S. Moretti, M. Muhlleitner, 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 !

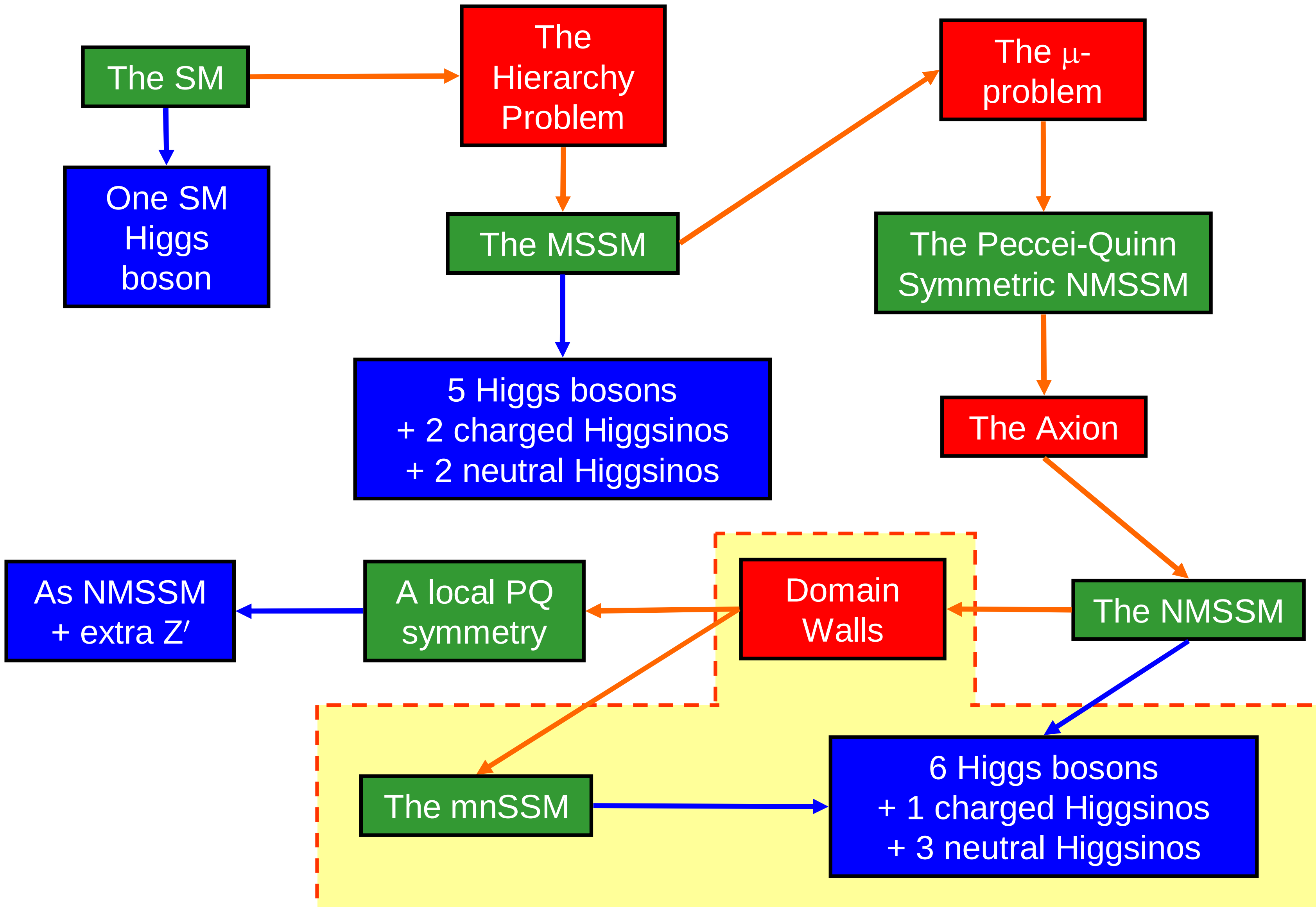


R. Dermisek and J.F. Gunion
See in CPNSH group report
hep-ph/0608079

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

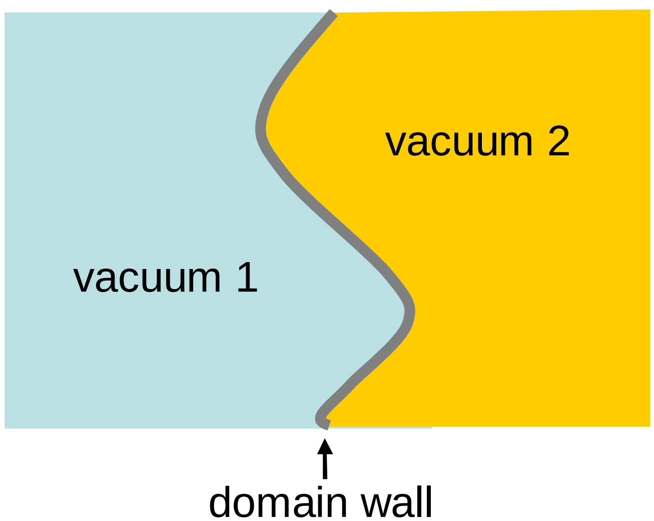
The Domain Wall Problem

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]

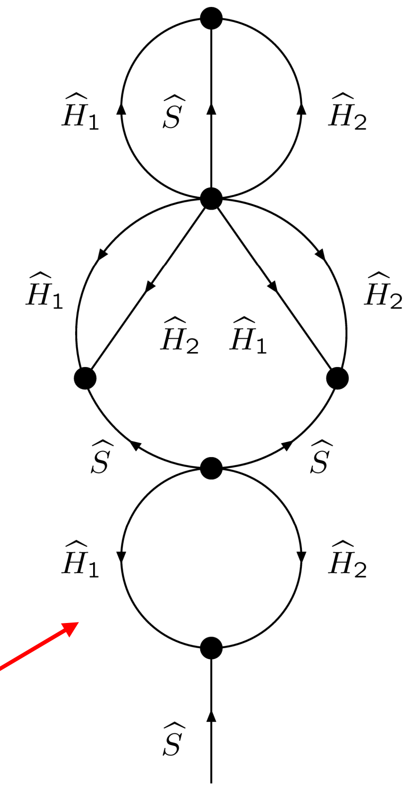
The degeneracy may be broken by the unification with gravity at the Planck scale. Introducing new higher dimensional operators raises the vacuum energies unequally, resulting in a preferred vacuum.

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

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

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]

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.