Electroweak Baryogenesis and Dark Matter in the nMSSM

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Based work done in collaboration with

Arjun Menon and Carlos Wnagner

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The nMSSM (MNSSM)

The MSSM

- The minimal supersymmetric standard model (MSSM) is a well-motivated extension of the SM.

- Even, so there are good reasons to extend the model.

1. μ problem:

$$W \supset \mu\, H_1 \cdot H_2,$$

   $\mu \sim M_w \sim m_{soft}$ is needed to break the electroweak symmmetry. Why not $\mu \sim M_{\text{Pl}}$ or M_{GUT}? (See however [Giudice+Masiero '88].)

2. LEP II Higgs mass bound:

$$m_h > 114\,\text{GeV},$$

   but at tree-level, $m_h^2 < M_Z^2 \cos^2 2\beta$.

3. Electroweak baryogenesis (EWBG):

   It is difficult to obtain a strong first-order electroweak phase transition required for EWBG if $m_h > 114\,\text{GeV}$.

Adding a Singlet S

- These difficulties can be avoided by replacing the μ term with a singlet S that gets a VEV,

$$W \supset \lambda\, S\, H_1 \cdot H_2.$$

- μ problem:

$$\mu_{eff} = \lambda\, \langle S \rangle\, .$$

The VEV of S is usually determined by the soft terms.

- Higgs mass:

$$m^2_{h_{tree}} \leq M_Z^2 \left(\cos^2 2\beta + \frac{2\lambda^2}{\bar{g}^2} \sin^2 2\beta \right).$$

- EWBG: A new $S\, H_1 \cdot H_2$ trilinear soft term can make the electroweak phase transition more strongly first-order.

  [Pietroni '92, Davies *et al* '96, Schmidt+Huber '00, Kang *et al* '04.]

But...

- The singlet should be charged under an additional symmtry to avoid generating new dimensionful ($d < 4$) couplings.

- The most popular choice is a $\mathbb{Z}_3$ symmetry, which yields the superpotential

$$W = \lambda\, S\, H_1 \cdot H_2 + \kappa\, S^3 + (\text{MSSM terms}).$$

  This model is called the NMSSM,
  the Next-to-Minimal Supersymmetric Standard Model.

- When S gets a VEV, the $\mathbb{Z}_3$ symmetry is broken producing cosmologically unacceptable domain walls.

- The domain wall problem can be avoided by including non-renormalizable operators that break $\mathbb{Z}_3$. However, these generate a large singlet VEV which destabilizes the hierarchy.
  [Abel,Sarkar,+White '95]

A way out: the nMSSM

- Both problems can be avoided by imposing discrete R-symmetries on both the superpotential and the Kähler potential.

  [Pangiotakopoulos+Tamvakis '98/'99, Pangiotakopoulos+Pilaftsis '00, Dedes *et al* '00]

- Such symmetries are broken (softly) in the course of supersymmetry breaking.

- A singlet tadpole can be generated as a result.

- With a $\mathbb{Z}_5^R$ or $\mathbb{Z}_7^R$ discrete symmetry, a singlet tadpole is only generated at six or seven loop order,

$$\delta V \sim \left(\frac{1}{16\pi^2}\right)^n \frac{F_x^2}{M_{\text{Pl}}} S + h.c., \quad \text{with } n = 6, 7.$$

  For $F_x \sim M_W \, M_{\text{Pl}}$ as in gravity mediation, this is about electroweak size.

- The resulting model is the nMSSM, the not-quite MSSM. (Also called the MNSSM.)
  - Superpotential:

$$W = \frac{m_{12}^2}{\lambda^2}\,S + \lambda\,S\,H_1\cdot H_2 + \text{(MSSM matter terms)},$$

  - Soft-breaking potential:

$$\begin{aligned} V_{soft} &= t_s(S + h.c.) \;+\; m_s^2|S|^2 \\ &\quad + a_\lambda(S\,H_1\cdot H_2 + h.c.) \;+\; \text{(MSSM terms)}. \end{aligned}$$

- All dimensionful couplings can be taken to be of electroweak size.
- The same superpotential and soft-breaking terms also arise in the low-energy limit of the Fat Higgs model. [Harnik *et.al.* '03]

- Does the nMSSM help with electroweak baryogenesis?

Electroweak Baryogenesis in the nMSSM

Electroweak Baryogenesis

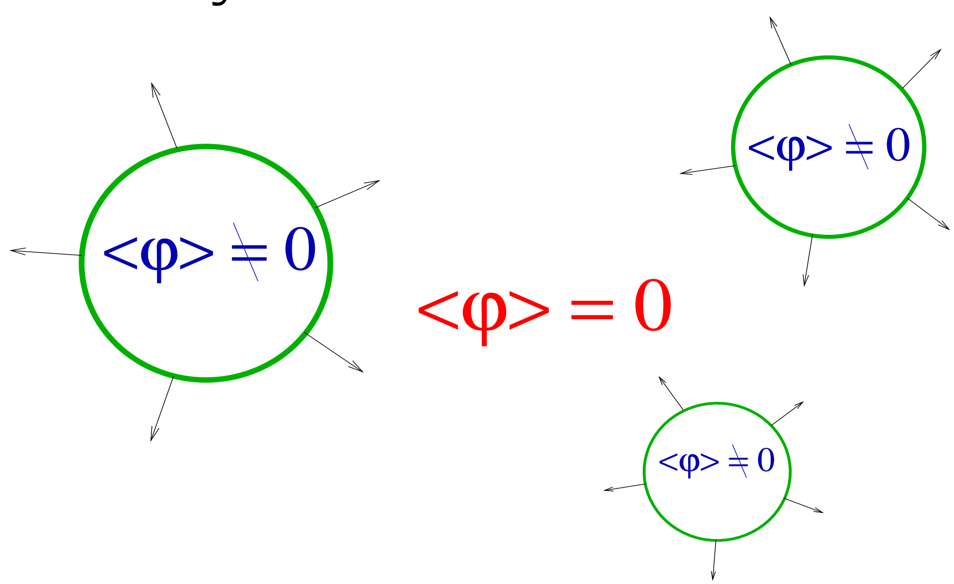
- EWBG $\rightarrow$ generation of the baryon asymmetry during the electroweak phase transition.

- At high temperatures, the EW symmetry is restored. It is broken as the Universe cools.

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{em}.$$

- If this phase transition is first order, it proceeds by the nucleation of bubbles of broken phase.

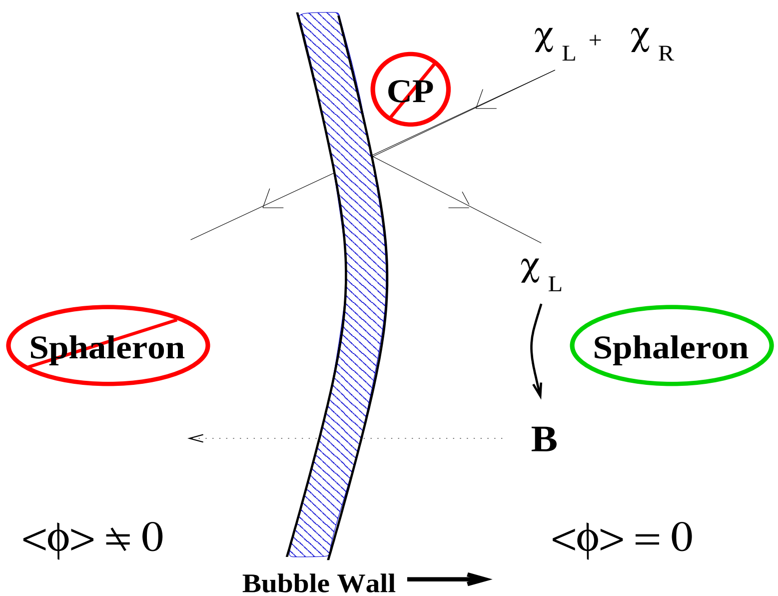
- Baryons are produced by reactions near the bubble walls.



Producing Baryons

- CP violating interactions within the bubble wall produce a net chiral fermion charge outside the bubble.
- Sphaleron transitions convert the chiral charge into baryons.
- The baryons are swept into the bubbles, where they are stable provided

$$\frac{\langle \phi_c \rangle}{T_c} \gtrsim 1.$$



EWBG in the SM and the MSSM

- In the SM and MSSM, the Higgs effective potential has the form:

$$V_{eff} \simeq (-\mu^2 + \alpha T^2)\phi^2 - \gamma T \phi^3 + \frac{\lambda}{4}\phi^4 + \dots .$$

- The coupling γ makes the electroweak phase transition first-order:

$$\frac{\phi_c}{T_c} \simeq \frac{\gamma}{\lambda}.$$

- In the SM and MSSM, γ is generated by *bosonic* loops.

- SM: $\gamma \sim g^3$
  $\Rightarrow$ the phase transition is strong only for $m_h \lesssim 70\,\text{GeV}$.

  [Kajantie, Laine, Rummukainen, Shaposhnikov '98]

- MSSM: $\gamma \sim y_t^3$ (if there is a light stop)
  $\Rightarrow$ the phase transition is strong only for $m_h \lesssim 120\,\text{GeV}$.

  [Carena *et al* '96, Laine '96, Losada '97, Laine+Rummukainen '00]

EWBG in the nMSSM

- The trilinear soft term $a_\lambda S H_1 \cdot H_2$ contributes to γ at tree level.
  $\longrightarrow$ potentially stronger first-order phase transition.

- CP violation can be generated by a common gaugino phase.
  The bubble wall dynamics will work much like in the MSSM.
  [Huet+Nelson '95, Carena *et al.* '97,. . . , Huber *et al.* '06]

- New possibilities for CP violation via the singlet are also possible.
  [Huber+Schmidt '00, Huber *et al.* '06, Ham *et al.* '07, Freitas *et al.* '07]

The Electroweak Phase Transition in the nMSSM

Approximate Analysis:

- Consider the effective tree-level potential at fixed $\tan\beta$ including the leading thermal corrections:

$$V(\varphi,\varphi_s,T) \simeq (-m^2+\xi^2 T^2)\,\varphi^2 + \tilde{\lambda}^2\,\varphi^4 + m_s^2\,\varphi_s^2 + 2t_s\,\varphi_s + 2\tilde{a}\,\varphi^2\varphi_s + \lambda^2\,\varphi^2\varphi_s^2.$$

- Along the trajectory with $\partial V/\partial\varphi_s = 0$, the potential becomes

$$\tilde{V}(\varphi,T) \simeq (-m^2+\xi^2 T^2)\,\varphi^2 - \frac{(t_s+\tilde{a}\varphi^2)^2}{m_s^2+\lambda^2\varphi^2} + \tilde{\lambda}^2\,\varphi^4.$$

- A sufficient condition for a first-order phase transition is

$$|D| > 1$$

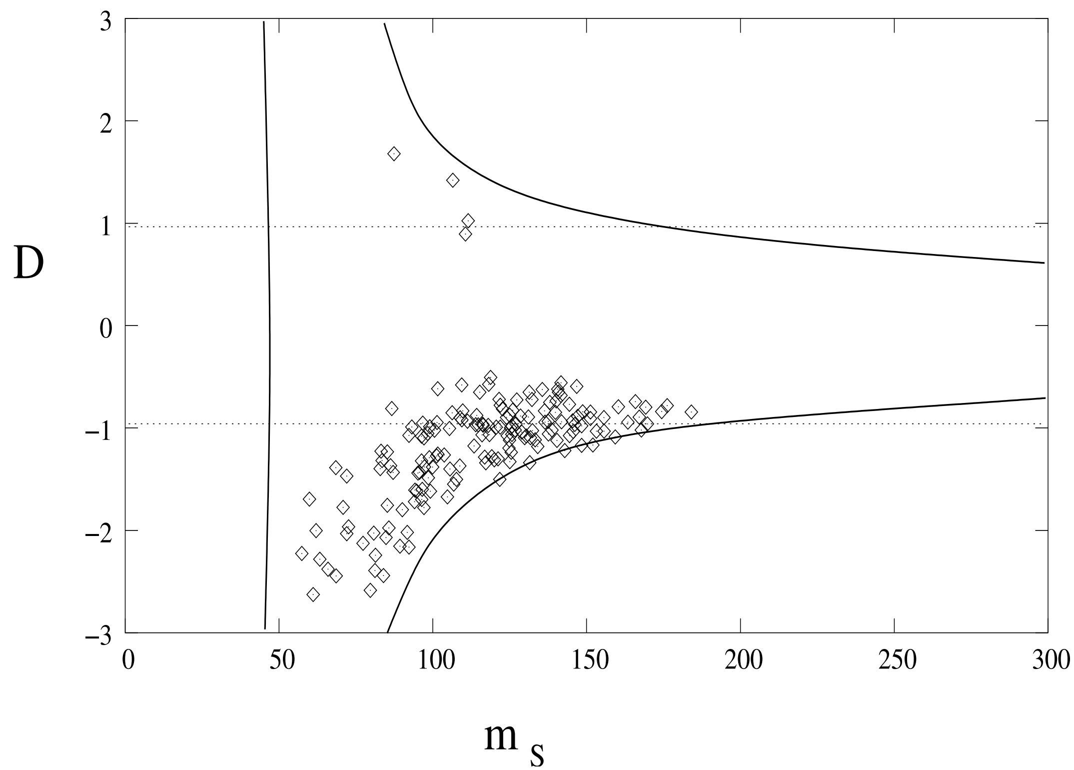
where

$$D := \frac{1}{\tilde{\lambda} m_s^2}\left(\frac{\lambda^2 t_s}{m_s} - m_s\,a_\lambda\,s_\beta c_\beta\right).$$

- Numerical scans using the one-loop effective potential support the approximate analysis.

- We scan over model parameters with universal gaugino masses, as well as $m_{Q_3}^2 = m_{U_3}^2 = (500\,\mathrm{GeV})^2$ and $y_t A_t = 100\,\mathrm{GeV}$.

- Points with $\varphi_c/T_c > 1$ (for $\lambda < 0.7$):



- Viable points seem to have:
  $a_\lambda = (300-600)\,\mathrm{GeV}$, $t_s = (50 - 200\,\mathrm{GeV})^3$, $|m_s^2| < (200\,\mathrm{GeV})^2$.

Dark Matter in the nMSSM

Charginos and Neutralinos

- The chargino mass matrix is identical to the MSSM, but with $\mu \to -\lambda\, v_s$.

- The fermion component of S, the singlino,

  produces a fifth neutralino state.

$$\mathcal{M}_{\tilde{N}} = \begin{pmatrix} M_1 & \cdot & \cdot & \cdot & \cdot \\ 0 & M_2 & \cdot & \cdot & \cdot \\ -c_\beta s_w M_Z & c_\beta c_w M_Z & 0 & \cdot & \cdot \\ s_\beta s_w M_Z & -s_\beta c_w M_Z & \lambda v_s & 0 & \cdot \\ 0 & 0 & \lambda v_2 & \lambda v_1 & 0 \end{pmatrix}$$

- We relate M_1 to M_2 by universality and allow for a common phase;

$$M_2 = |M_2|\, e^{i\phi} \simeq \frac{\alpha_2}{\alpha_1}\, M_1.$$

- $\lambda(M_Z) \lesssim 0.8$ for perturbative unification.

  $\Rightarrow$ there is always a light neutralino

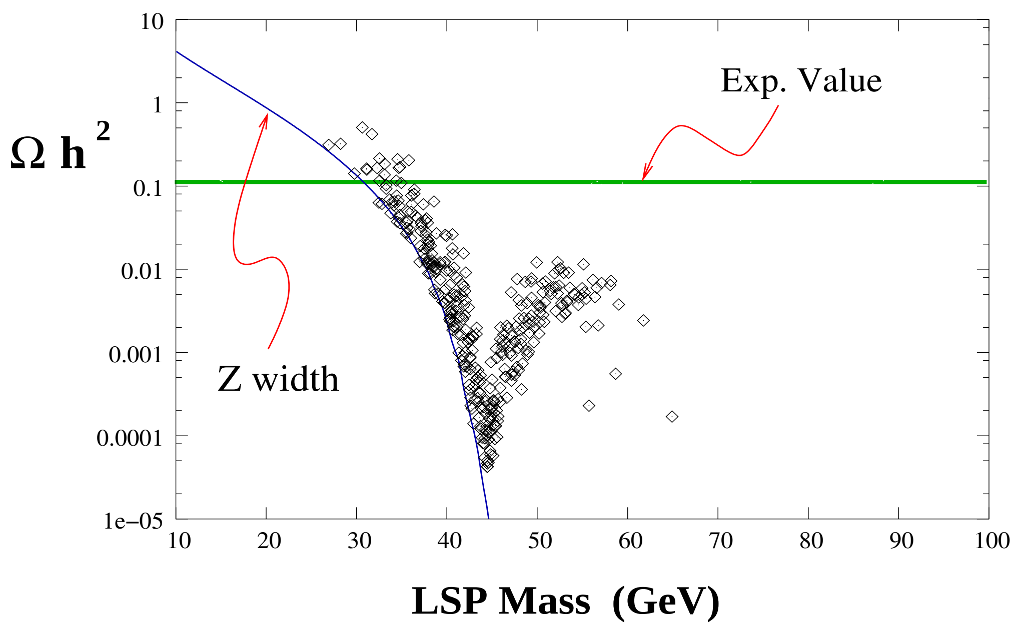
  e.g. $$m_{\tilde{N}_1} \simeq \frac{2\,\lambda\, v_1\, v_2\, v_s}{v_1^2 + v_2^2 + v_s^2},$$

  for M_1, $M_2 \to \infty$, and $\tan\beta \gg 1$ or $v_s \gg v$.

- This state is mostly singlino, with a small mixture of higgsino.

DM (and EWBG) Results

- Neutralino relic densities consistent with EWBG ($\lambda < 0.7$):



- Dots = parameter sets consistent with EWBG.
- Green line = WMAP result:

$$\Omega_{DM}\, h^2 = 0.113^{+0.016}_{-0.018}.$$

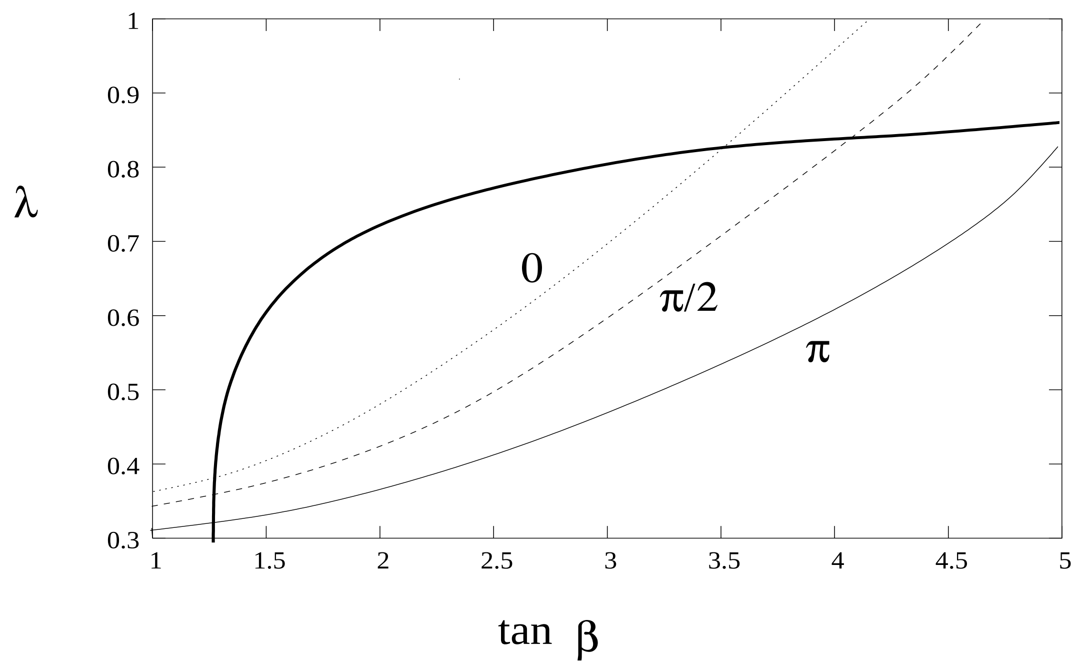
- Blue line = LEP Z-width constraint:

$$\Gamma(Z \to \tilde{N}_1 \tilde{N}_1) < 2.0 \text{ MeV}.$$

DM Parameter Constraints

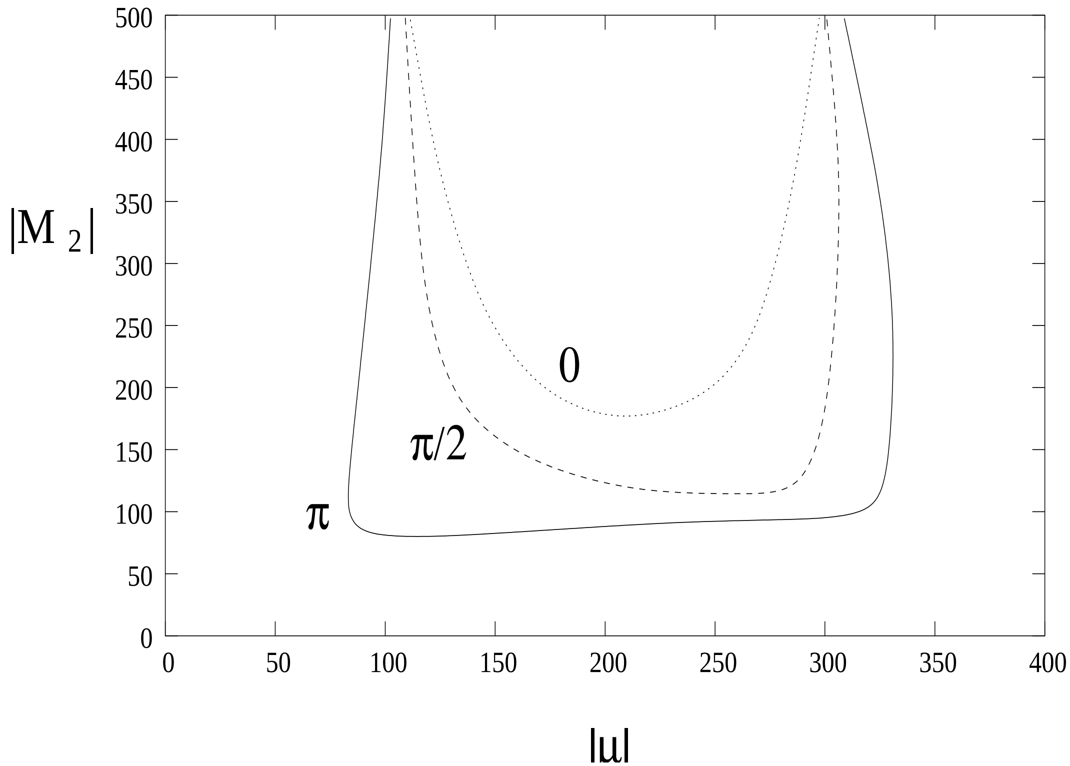
- The neutralino LSP for $\lambda < 0.7$ is mostly singlino with $m_{\tilde{N}_1} \lesssim 60\,\text{GeV}$.
- Z-pole annihilation is the dominant LSP channel.
  $\Rightarrow$ a small higgsino component is needed for a $\tilde{N}_1 \tilde{N}_1 Z^0$ coupling.
- This coupling can still be small enough that $\Gamma(Z^0 \to \tilde{N}_1 \tilde{N}_1)$ is consistent with LEP II for $m_{\tilde{N}_1} \gtrsim 25\,\text{GeV}$.
- Demanding $m_{\tilde{N}_1} > 25\,\text{GeV}$ (+ perturbativity) constrains parameters.

- $m_{\tilde{N}_1} > 25\,\text{GeV}$ (+perturbativity) requires smaller $\tan\beta$:



- Varying the gaugino phase alters the neutralino mixing.

- $m_{\tilde{N}_1} > 25$ GeV also bounds $|\mu_{eff}| = |\lambda\, v_s|$ from above:



- $|M_2|$ and μ_{eff} are also bounded from below by $m_{\chi^+} > 104$ GeV.

Summary

- The nMSSM is a minimal singlet extension of the MSSM that is consistent with the observed cosmology.
- This model solves the μ problem, and has an additional F-term contribution to the Higgs boson mass.
- New singlet soft terms help to make the electroweak phase transition strongly first order, even with heavier stops.
  $\longrightarrow$ can accomodate EWBG
- The LSP is usually a mostly singlino neutralino.
  $\longrightarrow$ acceptable dark matter relic density with $m_{\tilde{N}_1} \simeq 30\,\mathrm{GeV}$.
- New collider phenomenology $\longrightarrow$ Ayres' talk.

Extra Slides

Higgs Bosons

- Physical states: 3 CP-even, 2 CP-odd, 1 charged.
- For $M_a^2 \to \infty$, the charged state, one CP-even state, and one CP-odd state decouple.
- The remaining CP-odd state is pure singlet with mass

$$m_P^2 = m_s^2 + \lambda^2 v^2.$$

- The remaining CP-even states have mass matrix

$$M_S^2 = \begin{pmatrix} M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta & \cdot \\ v(a_\lambda \sin 2\beta + 2\,\lambda^2 v_s) & m_s^2 + \lambda^2 v^2 \end{pmatrix}.$$

  This is in the basis (S_1, S_2), where S_1 is SM-like, and S_2 is a singlet.

- EWBG $\Rightarrow \sqrt{m_s^2 + \lambda^2 v^2} \lesssim 250$ GeV.
- If so, there are two light CP-even and one light CP-odd Higgs bosons.
- The lightest CP-even and CP-odd states usually decay invisibly into pairs of the neutralino LSP.
- The CP-even states can still be detected at the LHC through vector boson fusion channels. Define

$$\eta = BR(h \to inv) \, \frac{\sigma(VBF)}{\sigma(VBF)_{SM}}.$$

- The luminosity needed for a 5σ discovery is then [Eboli+Zeppenfeld '00]

$$\mathcal{L}_{5\sigma} \simeq 8\text{fb}^{-1}/\eta^2.$$

  - $\eta \simeq 0.5 - 0.9$ for the SM-like state.
  - $\eta \simeq 0.0 - 0.3$ for the mostly singlet state .

Spurions and Tadpoles

- Let $X = M_{\text{Pl}} + F_x\,\theta^2$ parametrize SUSY (and R) breaking.
- The dangerous tadpole operators are (schematically)

$$\int d^4\theta\,(X^\dagger + \frac{X^\dagger X}{M_{\text{Pl}}} + \ldots)\,N \to \int d^2\theta\,F_x\,N + \frac{F_x^2}{M_{\text{Pl}}}\,n$$

- Even if we get rid of them as a matching condition at M_{Pl}, they are regenerated by loops. [Bagger+Poppitz '95, Abel '96]

- Two classes:

  1. N is charged under a non-R global symmetry that is explicitly broken by higher dimensional operators.

  2. N is charged under an R symmetry that is spontaneously broken in the course of SUSY breaking.