Production and decays of supersymmetric Higgs bosons in SBRPM

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M. Hirsch, J. Romão, J. W. F. Valle and A. Villanova del Moral,
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Neutrino Physics Data

★ Neutrinos are massive

Allowed parameter region from all neutrino experimental data:

SM neutrinos are massless
SM neutrinos are massless since:
- Right-handed neutrinos do not exist
- Lepton number is “accidentally” conserved
- Higgs triplets do not exist
SM neutrinos are massless since:
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⇒ SM must be extended in some sector:
- Particles
- Symmetries
- or both
SUSY extension of the SM

The most general renormalizable and gauge invariant superpotential with minimal particle content is

\[ W = W_{\text{MSSM}} + W_\mathcal{L} + W_\mathcal{B} \]

where

\[ W_{\text{MSSM}} = \varepsilon_{ab} \left[ h_{ij}^U \, \hat{Q}_i^a \, \hat{U}_j \, \hat{H}_u^b + h_{ij}^D \, \hat{Q}_i^b \, \hat{D}_j \, \hat{H}_d^a + h_{ij}^E \, \hat{L}_i \, \hat{E}_j \, \hat{H}_d^a - \mu \hat{H}_d^a \hat{H}_u^b \right] \]

\[ W_\mathcal{L} = \varepsilon_{ab} \left[ \varepsilon_i \hat{L}_i^a \hat{H}_u^b + \lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{E}_k + \lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{D}_k \right] \]

\[ W_\mathcal{B} = \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k \]
SUSY extension of the SM

The most general renormalizable and gauge invariant superpotential with minimal particle content is

$$W = W_{\text{MSSM}} + W_\lambda + W_\beta$$

where

$$W_{\text{MSSM}} = \epsilon_{ab} \left[ h_{ij}^U \hat{Q}_i^a \hat{U}_j^b \hat{H}_u^b + h_{ij}^D \hat{Q}_i^b \hat{D}_j^b \hat{H}_d^a + h_{ij}^E \hat{L}_i^b \hat{E}_j^b \hat{H}_d^a - \mu \hat{H}_d^a \hat{H}_u^b \right]$$

$$W_\lambda = \epsilon_{ab} \left[ \epsilon_i^a \hat{L}_i^a \hat{H}_u^b + \lambda_{ijk} \hat{L}_i^a \hat{L}_j^b \hat{E}_k + \lambda'_{ijk} \hat{L}_i^a \hat{Q}_j^b \hat{D}_k \right]$$

$$W_\beta = \lambda''_{ijk} \hat{U}_i \hat{D}_j \hat{D}_k$$

It allows $L$ and $B$ violation $\Rightarrow$ Proton decay!!
Possible Solutions

Ad hoc postulation of R-parity conservation
$$\Rightarrow$$ MSSM

$$R_P = (-1)^{3B+L+2s}$$
Possible Solutions

Ad hoc postulation of R-parity conservation
\[ \Rightarrow \text{MSSM} \]

\[ R_P = (-1)^{3B+L+2s} \]

\[ W = W_{\text{MSSM}} + W_\ell + W_{\bar{B}} \]
Ad hoc postulation of R-parity conservation
⇒ MSSM

\[ R_P = (-1)^{3B+L+2s} \]

\[ W = W_{\text{MSSM}} = \]
\[ = \varepsilon_{ab} \left[ h^{ij}_{U} \hat{Q}^a_{i} \hat{U}^b_{j} \hat{H}^b_{u} + h^{ij}_{D} \hat{Q}^b_{i} \hat{D}^a_{j} \hat{H}^a_{d} + h^{ij}_{E} \hat{L}^b_{i} \hat{E}^a_{j} \hat{H}^a_{d} - \mu \hat{H}^a_{d} \hat{H}^b_{u} \right] \]
Possible Solutions

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⇒ MSSM

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\[ W = W_{\text{MSSM}} = \]
\[ = \varepsilon_{ab} \left[ h_{ij}^{i} \hat{Q}_{i} \hat{U}_{j} \hat{H}_{u}^{b} + h_{ij}^{i} \hat{Q}_{i} \hat{D}_{j} \hat{H}_{d}^{a} + h_{ij}^{i} \hat{L}_{i} \hat{E}_{j} \hat{H}_{u}^{a} - \mu \hat{H}_{d}^{a} \hat{H}_{u}^{b} \right] \]

Neutrinos remain massless
Possible Solutions

Ad hoc postulation of R-parity conservation
⇒ MSSM

\[ R_P = (-1)^{3B + L + 2s} \]

\[ W = W_{\text{MSSM}} = \]

\[ = \varepsilon_{ab} \left[ h_{ui}^{ij} \hat{Q}_i^{a} \hat{U}_j \hat{H}_u^b + h_{Dj}^{ij} \hat{D}_j \hat{H}_d^a + h_{Ei}^{ij} \hat{L}_i \hat{E}_j \hat{H}_d^a - \mu \hat{H}_d^a \hat{H}_u^b \right] \]

Neutrinos remain massless

★ Postulation of \( R_P \) conservation is not inevitable!
**Possible Solutions**

- **Ad hoc postulation of R-parity conservation**
  \[ R_P = (-1)^{3B+L+2s} \]
  \[ W = W_{\text{MSSM}} = \]
  \[ = \varepsilon_{ab} \left[ h_{U}^{ij} \hat{Q}^{a}_{i} \hat{U}^{b}_{j} \hat{H}^{b}_{u} + h_{D}^{ij} \hat{Q}^{b}_{i} \hat{D}^{j} \hat{H}^{a}_{d} + h_{E}^{ij} \hat{L}^{b}_{i} \hat{E}^{j} \hat{H}^{a}_{d} - \mu \hat{H}^{a}_{d} \hat{H}^{b}_{u} \right] \]

- Neutrinos remain massless

- Postulation of \( R_P \) conservation is not inevitable!

- Postulation of \( R_P \) as an exact symmetry of the \( W \), but which is spontaneously violated
  \[ \Rightarrow \text{SBRPM} \]
Neutrinos are electrically neutral particles.
They can have Majorana mass terms.

Lepton number would be violated.

How can $L$ be broken?
Explicitly
Spontaneously
The majoron

Spontaneous breaking of global $U(1)$ lepton number symmetry

⇒ Associated massless Nambu-Goldstone boson: $J$ (the majoron)
The majoron

- Spontaneous breaking of global $U(1)$ lepton number symmetry
  $\Rightarrow$ Associated massless Nambu-Goldstone boson: $J$ (the majoron)

- The majoron cannot be mainly doublet or triplet
  $\Leftarrow$ Ruled out by LEP measurement of $Z$ invisible decay
The majoron

- Spontaneous breaking of global $U(1)$ lepton number symmetry
  - Associated massless Nambu-Goldstone boson: $J$ (the majoron)
- The majoron must be mainly singlet
The majoron

- Spontaneous breaking of global $U(1)$ lepton number symmetry
  - Associated massless Nambu-Goldstone boson: $J$ (the majoron)
- The majoron must be mainly singlet
- New invisible Higgs boson decay channels

\[
H_i \rightarrow JJ \\
A_i \rightarrow H_j J \\
A_i \rightarrow JJJ
\]
Spontaneously Broken R-Parity Model

- The Model
- Particle Content
- Superpotential
- Non-Zero Vacuum Expectation Values
- Neutral Fermion Sector
- Neutral Higgs Boson Sector
  - Mass eigenstates
  - Production modes
  - Invisible decays
MSSM superfields

+ 3 Isosinglets

\[ L = \begin{array}{ccc}
\hat{\nu}^c & \hat{S} & \hat{\Phi} \\
-1 & +1 & 0
\end{array} \]

\[ \hat{\nu}^c \Rightarrow \text{neutrino Dirac mass term} \]

\[ \hat{S} \Rightarrow \text{large mass for } \hat{\nu}^c \]

\[ \hat{\Phi} \Rightarrow \text{it enlarges invisible Higgs boson decay} \]

\[ \Rightarrow \text{possible solution to the } \mu \text{ problem} \]
Superpotential

\[ W = \varepsilon_{ab} \left[ h^{ij}_{U} \hat{Q}^{a}_{i} \hat{U}_{j} \hat{H}_{u}^{b} + h^{ij}_{D} \hat{Q}^{b}_{i} \hat{D}_{j} \hat{H}_{d}^{a} + h^{ij}_{E} \hat{L}^{b}_{i} \hat{E}_{j} \hat{H}_{d}^{a} - \mu \hat{H}_{d}^{a} \hat{H}_{u}^{b} \right] + \\
+ \varepsilon_{ab} h_{0} \hat{H}_{d}^{a} \hat{H}_{u}^{b} \Phi - \delta^{2} \hat{\Phi} + \\
+ \varepsilon_{ab} h^{i}_{\gamma} \hat{L}^{a}_{i} \hat{\nu}^{c}_{\gamma} \hat{H}_{u}^{b} + h \hat{S} \hat{\nu}^{c} \hat{\Phi} + \\
+ M_{R} \hat{S} \hat{\nu}^{c} + \frac{1}{2} M_{\Phi} \hat{\Phi} \Phi + \frac{1}{3!} \lambda \hat{\Phi}^{3} \]
Superpotential

\[ W = \varepsilon_{ab} \left[ h^{ij}_{U} \hat{Q}^a_i \hat{U}_j \hat{H}^b_u + h^{ij}_{D} \hat{Q}^b_i \hat{D}_j \hat{H}^a_d + h^{ij}_{E} \hat{L}^b_i \hat{E}_j \hat{H}^a_d \right] + \\
+ \varepsilon_{ab} h_0 \hat{H}^a_d \hat{H}^b_u \Phi + \\
+ \varepsilon_{ab} h^i_{\nu} \hat{L}^a_i \hat{\nu}^c \hat{H}^b_u + h \hat{S} \hat{\nu}^c \Phi + \\
+ \frac{1}{3!} \lambda \hat{\Phi}^3 \]

Solution to the \( \mu \) problem
Vacuum Expectation Values

\[ \langle H^0_u \rangle \equiv \nu_u / \sqrt{2}, \quad \langle H^0_d \rangle \equiv \nu_d / \sqrt{2}, \]

\[ \langle \tilde{\nu}_i \rangle \equiv \nu_{Li} / \sqrt{2} \quad (i = 1 \ldots, 3), \]

\[ \langle \tilde{\nu}^c \rangle \equiv \nu_R / \sqrt{2}, \quad \langle \tilde{S} \rangle \equiv \nu_S / \sqrt{2}, \quad \langle \Phi \rangle \equiv \nu_\Phi / \sqrt{2} \]

\[ \nu_{Li} \ll \nu_d, \nu_u \ll \nu_R, \nu_S, \nu_\Phi \]
Neutral Fermion Sector

Non-zero VEVs ⇒

⇒ mixing of

- neutrinos
- gauginos
- higgsinos
- singlet fermions

In the basis

\[
(\psi^0)^T = \begin{pmatrix}
\nu_1, \nu_2, \nu_3, -i\lambda', -i\lambda^3, \tilde{H}^0_d, \tilde{H}^0_u, \nu^c, S, \tilde{\Phi}
\end{pmatrix}
\]

\[
\mathcal{L} \supset -\frac{1}{2} (\psi^0)^T M_N (\psi^0)
\]
Neutral Fermion Mass Matrix

\[ \mathbf{M}_N = \begin{pmatrix}
\bar{\mathbf{0}}_{3 \times 3} & \mathbf{m}_{\nu \chi^0} & \mathbf{m}_{\nu \nu^c} & \bar{\mathbf{0}}_{3 \times 1} & \bar{\mathbf{0}}_{3 \times 1} \\
\mathbf{m}^T_{\nu \chi^0} & \mathbf{M}_{\chi^0} & \mathbf{m}_{\chi^0 \nu^c} & \bar{\mathbf{0}}_{4 \times 1} & \mathbf{m}_{\chi^0 \Phi} \\
\mathbf{m}^T_{\nu \nu^c} & \mathbf{m}^T_{\nu \nu^c} & \bar{\mathbf{0}}_{3 \times 1} & \mathbf{0} & \mathbf{m}_{\nu \Phi} \\
\bar{\mathbf{0}}_{1 \times 3} & \bar{\mathbf{0}}_{1 \times 4} & \mathbf{m}_{\nu \Phi} & \mathbf{0} & \mathbf{m}_{S \Phi} \\
\bar{\mathbf{0}}_{1 \times 3} & \mathbf{m}^T_{\chi^0 \Phi} & \mathbf{m}_{\nu \Phi} & \mathbf{m}_{S \Phi} & \mathbf{M'}_{\Phi}
\end{pmatrix} \]

Mixing of the 10 neutral fermions
Effective Neutrino Mass Matrix

\[ m_{\nu\nu}^{\text{eff}} = -m_{3\times 7} \cdot M_7^{-1} \cdot m_{3\times 7}^T \]

Matrix elements:

\[ (m_{\nu\nu}^{\text{eff}})_{ij} = F^{\Lambda\Lambda} \Lambda_i \Lambda_j + F^{ee} \epsilon_i \epsilon_j + F^{\Lambda e} (\Lambda_i \epsilon_j + \Lambda_j \epsilon_i) \]

where

\[ \Lambda_i \equiv \epsilon_i \nu_d + \mu \nu_{Li} \]

\[ \epsilon_i \equiv \frac{1}{\sqrt{2}} h_i^\gamma \nu_R \]
Mass Eigenstates

\[ m_{\nu_1} = 0 \]
\[ m_{\nu_2} = \min(|m'_{\nu_2}|, |m'_{\nu_3}|) \Rightarrow \text{SOL scale} \]
\[ m_{\nu_3} = \max(|m'_{\nu_2}|, |m'_{\nu_3}|) \Rightarrow \text{ATM scale} \]

where, approximately,

\[ m'_{\nu_2} \propto |\vec{\lambda}|^2 \]
\[ m'_{\nu_3} \propto |\vec{\varepsilon}|^2 \]

Neutrino data constraints IMPOSED
Neutral CP-even Higgs Boson Sector

\[
(H'^0)^T = \left(H_{d}^{0R}, H_{u}^{0R}, \tilde{\nu}_1^R, \tilde{\nu}_2^R, \tilde{\nu}_3^R, \tilde{\nu}_c^R, S^R, \Phi^R\right)
\]

\[
\mathcal{L} \supset \frac{1}{2} (H'^0)^T \cdot M_{H^0}^2 \cdot H'^0
\]

Mass eigenstates are

\[
H^0 = R^{H^0} \cdot H'^0
\]

with the following mass eigenvalues

\[
\text{diag}(m_{H^0}^2, \ldots, m_{H^8}^2) = R^{H^0} \cdot M_{H^0}^2 \cdot (R^{H^0})^T
\]
Neutral CP-odd Higgs Boson Sector

\[(P'0)^T = (H^0_{dI}, H^0_{uI}, \tilde{v}_1^I, \tilde{v}_2^I, \tilde{v}_3^I, \tilde{c}_I, S^I, \Phi^I)\]

\[\mathcal{L} \supset \frac{1}{2} (P'0)^T \cdot M^2_{P0} \cdot P'0\]

Mass eigenstates are \(P^0_i\), where

\[(P^0)^T = (J, G^0, A_1, A_2, A_3, A_4, A_5, A_6)\]

\[P^0 = R^{P0} \cdot P'0\]

with the following mass eigenvalues

\[\text{diag}(0, 0, m^2_{A_1}, \ldots, m^2_{A_6}) = R^{P0} \cdot M^2_{P0} \cdot (R^{P0})^T\]
For
\[ \nu_{Li} \ll \nu_d, \nu_u \ll \nu_R, \nu_S, \nu_\Phi \]
the majoron is given by the imaginary part of
\[ \frac{\sum_i \nu_{Li}^2}{V \nu^2} (\nu_u H_u - \nu_d H_d) + \sum_i \frac{\nu_{Li}}{V} \tilde{\nu}_i + \frac{\nu_S}{V} \tilde{S} - \frac{\nu_R}{V} \tilde{\nu}^c \]

Majoron is mainly singlet
\[ \frac{1}{V} (\nu_S \tilde{S} - \nu_R \tilde{\nu}^c) \]
Neutral Higgs Boson Production

Direct Production (Bjorken process)

Associated production
\[ \mathcal{L}_{ZZH} = \sum_{i=1}^{8} \left( \sqrt{2} G_F \right)^{1/2} M_Z^2 Z_{\mu} Z^\mu \eta_i H_i^0 \]

Direct production parameter

\[ \eta_i \equiv \frac{g_{ZZH_i^0}}{g_{Z\bar{Z}H_i^0}^{SM}} = \frac{\nu_d}{\nu} R_{i1}^{H_0} + \frac{\nu_u}{\nu} R_{i2}^{H_0} + \sum_{j=1}^{3} \frac{\nu_{Lj}}{\nu} R_{ij+2}^{H_0} \]
Direct Production

\[ \mathcal{L}_{ZZH} = \sum_{i=1}^{8} (\sqrt{2} G_F)^{1/2} M_Z^2 Z_\mu Z^\mu \eta_i H_i^0 \]

Direct production parameter

\[ \eta_i \equiv \frac{g_{ZZH_i}^0}{g_{ZZH_i}^{SM}} = \frac{\nu_d}{\nu} R_{i1}^H + \frac{\nu_u}{\nu} R_{i2}^H + \sum_{j=1}^{3} \frac{\nu_{Lj}}{\nu} R_{ij+2}^H \]

- If \( \eta_i \sim 0 \) \( \Rightarrow \) \( H_i^0 \) mainly isosinglet
- If \( \eta_i \sim 1 \) \( \Rightarrow \) \( H_i^0 \) mainly isodoublet (like MSSM)
Upper bound on $m_{H_1^0}$

$$m_{H_1^0} \leq 150 \text{ GeV}, \quad \eta_1 \in [0, 1]$$

If $\eta_1 \sim 0 \Rightarrow H_1^0$ is NOT produced!

What about $H_2^0$?
If \( \eta_1 \sim 0 \) \( \Rightarrow \) What about \( \eta_2 \)?
If $\eta_1 \sim 0$ $\Rightarrow$ What about $\eta_2$?
If $\eta_1 \sim 0 \ \Rightarrow \ \eta_2 \sim 1$
i.e., if $H_1^0$ has small production, then $H_2^0$ is largely produced
Direct Production of $H_2^0$

If $\eta_1 \sim 0 \implies \eta_2 \sim 1$
i.e., if $H_1^0$ has small production, then $H_2^0$ is largely produced

If $\eta_2 \sim 1 \implies$ What about $m_{H_2^0}$?
Direct Production of $H_{2}^{0}$

- If $\eta_1 \sim 0 \Rightarrow \eta_2 \sim 1$
  i.e., if $H_{1}^{0}$ has small production, then $H_{2}^{0}$ is largely produced

- If $\eta_2 \sim 1 \Rightarrow$ What about $m_{H_{2}^{0}}$?

[Graph showing the relationship between $\eta_2$ and $m_{H_{2}^{0}}$ in [GeV].]
Direct Production of $H_2^0$

If $\eta_1 \sim 0 \Rightarrow \eta_2 \sim 1$

i.e., if $H_1^0$ has small production, then $H_2^0$ is largely produced

If $\eta_2 \sim 1 \Rightarrow m_{H_2^0} \leq 150$ GeV

i.e., for $H_2^0$ largely produced, its mass is bounded from above
Direct Production of $H^0_2$

- If $\eta_1 \sim 0 \Rightarrow \eta_2 \sim 1$
  i.e., if $H^0_1$ has small production, then $H^0_2$ is largely produced

- If $\eta_2 \sim 1 \Rightarrow m_{H^0_2} \leq 150$ GeV
  i.e., for $H^0_2$ largely produced, its mass is bounded from above

★ One Higgs boson, whose mass is bounded from above at around 150 GeV, will be produced, independently of whether this boson is the lightest or the next-to-lightest one
\[ \mathcal{L}_{ZHA} = \sum_{i,j=1}^{8} (\sqrt{2} G_F)^{1/2} M_Z \, \zeta_{ij} \left( Z^\mu H_i^0 \overleftrightarrow{\partial_\mu} P_j^0 \right) \]

Associated production parameter

\[ \zeta_{ij} \equiv R_{i1}^{S0} R_{j1}^{P0} - R_{i2}^{S0} R_{j2}^{P0} + \sum_{k=1}^{3} R_{ik+2}^{S0} R_{jk+2}^{P0} \]
\[ \mathcal{L}_{\text{ZHA}} = \sum_{i,j=1}^{8} (\sqrt{2}G_F)^{1/2} M_Z \zeta_{ij} \left( Z^\mu H^0_i \overleftrightarrow{\partial}_\mu P^0_j \right) \]

Associated production parameter

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Like in the MSSM, here we have an analogous but more complicated sum rule, which depends on the Higgs mass spectrum.
\[ \mathcal{L}_{ZHA} = \sum_{i,j=1}^{8} (\sqrt{2}G_F)^{1/2} M_Z \zeta_{ij} \left( Z^\mu H_i^0 \frac{\partial}{\partial \mu} P_j^0 \right) \]

Associated production parameter

\[ \zeta_{ij} \equiv R_{i1}^S R_{j1}^P - R_{i2}^S R_{j2}^P + \sum_{k=1}^{3} R_{i k+2}^S R_{j k+2}^P \]

Like in the MSSM, here we have an analogous but more complicated sum rule, which depends on the Higgs mass spectrum

★ At least one state will be produced
Main decay channels for either $H_1^0$ or $H_2^0$

\[ H_{1,2}^0 \rightarrow f_i \bar{f}_i \quad \text{if} \quad m_{H_{1,2}^0} > 2m_{f_i} \]

\[ H_{1,2}^0 \rightarrow JJ \]

Ratio between the invisible decay width and the visible one as

\[ R_{1,2} \equiv \frac{\Gamma(H_{1,2}^0 \rightarrow JJ)}{\sum_j \Gamma(H_{1,2}^0 \rightarrow f_j \bar{f}_j)} \]
Both can have dominant invisible decay for large values of their direct production parameters.
Both can have dominant invisible decay for large values of their direct production parameters.
Main decay channels for $A_1^0$

- $A_1^0 \rightarrow f_i \bar{f}_i$ \quad \text{if} \quad m_{A_1^0} > 2m_{f_i}$
- $A_1^0 \rightarrow H^0_j J$ \quad \text{if} \quad m_{A_1^0} > m_{H^0_j}$
- $A_1^0 \rightarrow JJJJ$
Problem: in most of the parameter space the lightest CP-odd Higgs boson that is largely produced via the associated production mechanism will have these invisible decay channels suppressed.
CP-odd Higgs Boson Decays

**Problem:** in most of the parameter space the lightest CP-odd Higgs boson that is largely produced via the associated production mechanism will have these invisible decay channels suppressed.

**Solution:** to find a compromise between its degree of "doubletness" (so that it will be produced) and "singletness" (so that it has a sizable invisible decay through majorons).
We can get a compromise of 10% invisible branching ratio and 0.1 associated production parameter. Masses are accessible for the next generation of colliders.
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We can get a compromise of 10% invisible branching ratio and 0.1 associated production parameter.

Masses are accessible for the next generation of colliders.
Conclusions

Experimental data: Neutrino oscillations
⇒ Neutrinos are massive
⇒ SM must be extended
Conclusions

The Spontaneously Broken R-Parity Model:

- Explains neutrino properties
- Masses
- Mixing angles
- Can give a solution to the problem
- A CP-even Higgs boson, whose mass is bounded from above at around 150 GeV, will be produced
- It can have dominant invisible decay
- Is it possible to have sizeable production and invisible decay for the CP-odd Higgs boson
Conclusions

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The Spontaneously Broken R-Parity Model:
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Conclusions

The Spontaneously Broken R-Parity Model:

- Explains neutrino properties
  - Masses
  - Mixing angles

- Can give a solution to the $\mu$ problem

- A CP-even Higgs boson, whose mass is bounded from above at around 150 GeV, will be produced

- It can have dominant invisible decay

- Is is possible to have sizeable both production and invisible decay for the CP-odd Higgs boson
The End