BSM Higgs boson searches at LHC

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Introduction

• Higgs boson searches beyond the SM: Important aspect of Higgs physics program at LHC

• Complimentary to the SM interpretations/investigation of properties of the observed 125 GeV scalar particle

• BSM searches include:
  • Search for exotic decays not expected within the SM.
  • Searches for more complex Higgs sector
    □ Prediction of additional Higgs bosons from many models beyond SM

Rich program to search for NEW physics in the Higgs sector

Due to time constraint I will discuss results only from a few prominent searches performed using pp collision data collected at $\sqrt{s} = 13$ TeV
Higgs boson in MSSM

- Two Higgs doublet => 5 physical bosons
  - Three neutrals: h, H (CP even), A (CP odd)
  - Two charged: H±
- Controlled by two parameters at tree level
  - \( m_A \) and \( \tan \beta \)

\[
\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1^+ \\ v_1 + \phi_1^0 \end{pmatrix}
\]
\[
\Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_2^+ \\ v_2 + \phi_2^0 \end{pmatrix}
\]

\[
\tan \beta = \frac{v_2}{v_1}
\]
\[
M_{H^+}^2 = M_A^2 + M_W^2
\]
\[
M_{h/H}^2 = \frac{1}{2} \left( M_A^2 + M_Z^2 + \sqrt{(M_A^2 + M_Z^2)^2 - 4 M_A^2 M_Z^2 \cos^2 2\beta} \right)
\]
\[
\tan \alpha = \frac{-(m_A^2 + m_Z^2) \sin 2\beta}{(m_Z^2 - m_A^2) \cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}}
\]

Mixing angle between h & H

Other SUSY parameters are important at higher order corrections
Higgs boson in MSSM

- Approximately 30% of h mass due to higher order corrections

\[
(\Delta m_h^2)^{t/i}_{\text{loop}} \approx \frac{3 m_t^4}{2 \pi^2 v^2} \left( \log \frac{m_{\text{SUSY}}^2}{m_t^2} + \frac{X_t^2}{m_{\text{SUSY}}^2} - \frac{X_t^4}{12 m_{\text{SUSY}}^4} \right)
\]

\[X_t = A_t - \mu \cot \beta\]

- Due to large \( m_t \), large \( m_{\tilde{t}} \), large \( X_t \), and large \( \tan \beta \)

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

\[
\tan \alpha = \frac{-(m_A^2 + m_Z^2) \sin 2\beta}{(m_Z^2 - m_A^2) \cos 2\beta + \sqrt{(m_A^2 + m_Z^2)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}}
\]

LHCHXSWG-2015-002

Mixing angle between h & H

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MSSM Neutral Higgs at LHC

- Neutral Higgs production:

- Dominant decay mode in MSSM: $b\bar{b}$ and $\tau\tau$
Charged Higgs at LHC

- Charged Higgs production and decay:

For $M_{H^+} \leq m_{top}$:

$$pp \rightarrow t\bar{t} \rightarrow bH^+\bar{b}W^\mp \quad \text{with} \quad t \rightarrow bH^+$$

For $M_{H^+} \geq m_{top}$:

$$pp \rightarrow tbH^\pm$$

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Next-to-MSSM Higgs sector

- Extend the MSSM Higgs sector by one more singlet field:

\[ W_{\text{NMSSM}} = W_{\text{MSSM}} + \lambda S \phi_u \phi_d + \frac{1}{3} \kappa S^3 \]

- Solves “µ-problem”
- Additional term to \( m_h^2 \) at LO
- Adds more degrees of freedom:

5 + 2 = 7 Higgs bosons:

\( h_1, h_2, H_3, A_2, a_1, H^\pm \)

\[ m_h^2 \approx m_Z^2 \left( \cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta \right) + \Delta m_h^2 \]

6 parameters @ LO: tan\( \beta \), \( \lambda \), \( \kappa \), \( A_\kappa \), \( A_\lambda \), \( \mu_{\text{eff}} \)

- More complex phenomenology (14 benchmark points in YR-4).
- Higgs bosons with large singlet admixture can become undetectable.
Summary of Run-1 Searches

Searches for heavy Higgs bosons in down-type fermions final states

Searches for $h \rightarrow aa$ decays in various final states

- Huge parameter space in MSSM systematically explored, NMSSM exploration ramping up.
- Also more general model independent limits and effective 2HDM(+S) interpretations.
Run-2 Searches

2HDM / MSSM Searches:

\[ h / H / A \rightarrow \tau\tau \quad (JHEP 01 (2018) 055, arXiv:1803.06553) \]

\[ h / H / A \rightarrow \mu\mu \quad (JHEP 08 (2018) 113, arXiv:1805.12191) \]

\[ h / H / A \rightarrow \tau\nu \quad (CMS-PAS-HIG-16-031, PLB 759 (2016), ATLAS-CONF-tbp) \]

\[ h / H / A \rightarrow WZ \quad (PRL 119 (2017) 141802) \]

\[ h / H / A \rightarrow tb \quad (ATLAS-CONF-tbp) \]

\[ h / H / A \rightarrow cb \quad (CMS-HIG-16-030) \]

\[ h / H / A \rightarrow cs \quad (JHEP 12 (2015) 1, EPJC 73 6 (2013) 2465) \]

NMSSM-like searches:

Low mass \( h \rightarrow \gamma\gamma \quad (CMS-PAS-HIG-17-013, ATLAS-CONF-2018-025) \)

\[ h(125) \rightarrow aa \quad (arXiv:1806.07355) \]

\[ h(125) \rightarrow (bb)(bb) \quad (arXiv:1807.00539) \]

\[ h(125) \rightarrow (bb)(\mu\mu) \quad (PLB 782 (2018) 750) \]

\[ h(125) \rightarrow (\gamma\gamma)(gg) \quad (CMS-PAS-HIG-16-035, arXiv:1812.00380) \]

\[ h(125) \rightarrow (\mu\mu)(\mu\mu) \quad JHEP 11 (2018) 018 \]

\[ h(125) \rightarrow (\mu\mu)(\tau\tau) \quad (arXiv:1805.04865) \]

\[ h(125) \rightarrow (bb)(\tau\tau) \quad PLB 785 (2018) 462 \]

\[ h(125) \rightarrow (bb)(\tau\tau) \quad (arXiv:1805.10191) \]
MSSM H/A → bb

\[ pp \rightarrow \phi b, \phi \rightarrow bb, \quad \phi : h, H, A \]

**Event Selection:**
- **Trigger:**
  \(-2\, b\)-tagged jets, \( p_T > 100\ \text{GeV}, \left| \Delta \eta \right| < 1.6 \)

- **Offline:**
  \(-3\, b\)-tagged jets (Thresholds vary according to analysis)

One of the jet contains a muon in semi-leptonic analysis.

**Backgrounds:**
- Major background: qcd \(bb\bar{b}\bar{b}\), Measured from data

**Final Discriminant:**
- Invariant mass of two leading b-jets

The natural width of the mass peak for a mass of 600 GeV is found to be <19% of the full width at half maximum of the reconstructed mass distribution.

Different shapes of signal and background motivate separation into three (overlapping) categories in
Upper Limit on $pp \to \phi b$, $\phi \to bb$ production by fitting observed $M_{12}$ distribution. Interpretations provided in many MSSM as well as 2HDM scenarios.
MSSM Higgs → ττ

pp → φ, φ → ττ, φ : h, H, A

Flagship analysis for MSSM Higgs search at LHC
- Enhanced coupling
- Better separation of signal from backgrounds compared to bb channel

Event categories exploit topological and kinematic peculiarities of MSSM motivated production

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Resonance</th>
<th>B (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic decays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>τ⁻ → e⁻ ν_e ν_τ</td>
<td>35.2</td>
<td></td>
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<tr>
<td>τ⁻ → μ⁻ ν_μ ν_τ</td>
<td>17.8</td>
<td></td>
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<tr>
<td>Hadronic decays</td>
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<tr>
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<tr>
<td>τ⁻ → h⁻ \pi_0 ν_τ</td>
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<td></td>
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<tr>
<td>τ⁻ → h⁻ \pi_0^0 ν_τ</td>
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<td>τ⁻ → h⁻ h⁻ ν_τ</td>
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<td></td>
</tr>
<tr>
<td>τ⁻ → h⁻ h⁻ \pi_0 ν_τ</td>
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</tr>
<tr>
<td>τ⁻ → h⁻ h⁻ \pi_0^0 ν_τ</td>
<td>9.8</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>4.8</td>
</tr>
</tbody>
</table>
| ~90% of all ττ final states contain at least one τ_h

Signal extraction based on
\[ m_T^{\text{tot}} = \sqrt{m_T^2(p_T^{\tau_1}, p_T^{\tau_2}) + m_T^2(p_T^{\tau_1}, p_T^{\text{miss}}) + m_T^2(p_T^{\tau_2}, p_T^{\text{miss}})}. \]
$\varphi \rightarrow \tau\tau$ Exclusion Limit

- b associated production
- gluon fusion
Large part of parameter space already excluded
\( M_A > 1 \text{ TeV} \)
for \( \tan\beta > 20 \)

\[ m_{h}^{\text{mod+ scenario}} \]

\[ m_{h}^{\text{hMSSM scenario}} \]
Charged Higgs

Search Channels:

- $H^\pm \rightarrow \tau\nu$ (Low & High mass)
  - JHEP 09 (2018) 139, CMS-PAS-HIG-18-014

- $H^\pm \rightarrow t\bar{b}$ (High mass)
  - JHEP 11 (2018) 085

- $H^\pm \rightarrow c\bar{s}$ (Low mass)
  - JHEP 12 (2015) 1

- $H^\pm \rightarrow c\bar{b}$ (Low mass)
  - CMS-HIG-16-030

- $H^\pm \rightarrow WZ$ (High mass)
  - PRL 119 (2017) 141802

CMS: Reconstruct $\tau\nu$ transverse mass in both leptonic and hadronic $\tau$ decays

$$m_T(\tau_h/\ell) = \sqrt{2p_T(\tau_h/\ell)p_{T\text{miss}}^\ell (1 - \cos \Delta \phi(p_T(\tau_h/\ell), p_{T\text{miss}}^\ell))}$$

ATLAS: BDT distributions in 5 bins of $m_{H^+}$ in $\tau+\ell$ channel

Lepton(s) + jets final states
- Categorize in number of b-Tagged jets
- Extract signal from BDT discriminant

Reconstruct full $tt$ events with kinematic fit, use invariant mass of two jets assigned to $H^\pm$ as the final discriminant

VBF $H^\pm$ production predicted by Georgi Machacek model
- Events selected requiring 3 leptons from decay of $W$ and $Z$ bosons
- $m_T(WZ)$ used as the final discriminant to extract signal
Charged Higgs Results

$H^{\pm} \rightarrow \tau \nu$ (Low & High mass)

JHEP 09 (2018) 139, CMS-PAS-HIG-18-014

$H^{\pm} \rightarrow \tau \nu$ (High mass) (JHEP 11 (2018) 085)

$H^{\pm} \rightarrow tb$ (High mass)

CMS Preliminary

$\sigma_{H^{\pm}} \times B(H^{\pm} \rightarrow \tau \nu)$ (fb)

CMS Preliminary

$\tan \beta$

ATLAS

$\sigma_{H^{\pm}} \times B(H^{\pm} \rightarrow \tau \nu)$ (fb)

CMS Preliminary

$\tan \beta$

ATLAS

$H^{\pm} \rightarrow WZ$ (High mass) (PRL 119 (2017) 141802)

CMS

$\sigma_{H^{\pm} \rightarrow WZ}$ (fb)

CMS

$S_{H^{\pm} \rightarrow WZ}$

ATLAS

$H^{\pm} \rightarrow \tau \nu$ (High mass)

CMS

$S_{H^{\pm} \rightarrow \tau \nu}$ (fb)

ATLAS

$95\%$ CL exclusions

$H^{\prime} \rightarrow \tau \nu, tb$

CMS

$S_{H^{\prime} \rightarrow \tau \nu, tb}$ (fb)

ATLAS

$H^{\prime} \rightarrow \tau \nu, tb$

$95\%$ CL exclusions

$95\%$ CL upper limits

$\tan \beta$

$m_{H^{\prime}}$ (GeV)

$m_{H^{\prime}}$ (GeV)

$m_{H^{\prime}}$ (GeV)

$m_{H^{\prime}}$ (GeV)

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PRL 119 (2017) 141802
Doubly Charged Higgs boson

Higgs Triplet Models:

- Addition of scalar triplet(s)
  - **Georgi-Machacek model:**
    Add one real and one complex SU(2) triplet
  - $H^+$ phenomenology different from the doublet models
- $H^+WZ$ couplings at tree level
- Double-charged Higgs bosons ($H^{++}$)

- ATLAS considered pair production: $pp \to H^{++}H^-$
- CMS considered VBF production: $pp \to qqH^{++}$
- Decay pre-dominantly to EWK bosons $H^{\pm\pm} \to W^\pm W^\pm$
- Signal Categories: $2\ell^ss, 3\ell, 4\ell$
- Additional selections on $p_T^{miss}$, nJets, b-Jet veto etc..
- Signal Extraction:
  - ATLAS did a rectangular cut optimization using TMVA
  - CMS used simultaneous fit to $(m_{\ell\ell}, m_{jj})$ 2D distribution and $m_{jj}$ in WZ control region

CMS result is also interpreted in Georgi-Machacek model

arXiv:1808.01899

PRL 120 (2018) 081801
h(125) → aa

- Constraint on $BR(h \rightarrow BSM)$ from fits for couplings still allows for up to 20-30% decays into unobserved particles.
- $h(125) \rightarrow aa$ decay mode possible in NMSSM scenarios, where “a” stands for just a Higgs boson that could be scalar or pseudo-scalar.
- Many final states analyzed for varying $m_a$ values, up to $m_a \leq m_h/2$.
- The decay products of “a” boson boosted for low $m_a$ values:
  - Challenging final states
  - Special care needed to reconstruct and identify leptons
- Results are presented in terms of upper limits on cross section times branching fractions.
**h(125) $$\rightarrow$$ aa $$\rightarrow$$ 4b**

$h(125)$ production in association with a vector boson, where $W/Z$ decays to leptons

Search mass region: $20 \text{ GeV} \leq m_a \leq 60 \text{ GeV}$

BDT discriminant to extract signal

Event Categories

Upper limits are obtained on $\sigma \times \text{BR}$ as a function of mass and lifetime.
h(125) \rightarrow aa \rightarrow bb\mu\mu

- For $m_a \geq 10$ GeV this means the “a” boson decays preferentially into $bb$
- However, in models with enhanced lepton couplings such as the Type-III 2HDM, the $a \rightarrow \mu\mu$ branching ratio can also be relatively large
- Presence of a clean dimuon resonance provides a distinctive signature
  - Used for triggering and precision mass reconstruction
  - Helps to suppress background
- A kinematic-likelihood (KL) fit exploiting the symmetry of $H \rightarrow aa$ decays is performed
  - Tests the compatibility of an event with the $m_{bb} \approx m_{\mu\mu}$ hypothesis
  - Improve the $m_{bb\mu\mu}$ resolution in signal events

Event Categories

Background normalizations are obtained from Control regions and validated in Validation regions

Search mass region: 20 GeV $\leq m_a \leq$ 60 GeV
VBF $h(125) \rightarrow aa \rightarrow \gamma\gamma gg$

- Much larger branching fractions than $h \rightarrow aa \rightarrow 4\gamma$, assuming same ratio of photon and gluon couplings SM $h$ and "a" bosons.
- VBF production mode to suppress overwhelming $\gamma\gamma$+multi-jet background

Upper limits are obtained on $\sigma \times BR$ as function of mass

![Graph showing upper limits on $\sigma \times BR$ as a function of mass](image)

Search mass region: $20 \text{ GeV} \leq m_a \leq 60 \text{ GeV}
Generic search for non-SM decay of Higgs boson to a pair of new light bosons (a), which subsequently decay to boosted pairs of oppositely charged muons.

Predicted in models like NMSSM, dark SUSY etc..

- Benchmark Scenarios:
  - NMSSM Higgs Sector:
    - Possible Signature at LHC: \( h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu \)
    - Typical Higgs masses: \( 90 \leq m_{h1} \leq 120–135 \text{ GeV} \)
  - Dark Susy: New light dark boson \( \gamma_D \)
    - Possible Signature at LHC:
      \[ h_1 \rightarrow 2n_1 \rightarrow 2n_D + 2\gamma_D \rightarrow 2n_D + 4\mu \]

Search assumption
\[ 0.25 < m_{\alpha_1} < 3.55 \text{ GeV} \]
\[ 2m_\mu \leq m_{\alpha_1} \leq 2m_\tau \]

Significant improvement in limits wrt 8 TeV results.

Limits also interpreted in Dark-SUSY scenario.
The signal combines two decay modes:

\[ h \rightarrow aa \rightarrow 2\mu 2\tau \]
\[ h \rightarrow aa \rightarrow 4\tau \]
(two of the \(\tau\)s decay to \(\mu\)s)

Assuming 2HDM-like scenarios

\[
\frac{B(a \rightarrow 2\mu)}{B(a \rightarrow 2\tau)} = \frac{m_{\mu}^2 \sqrt{1-(2m_{\mu}/m_a)^2}}{m_{\tau}^2 \sqrt{1-(2m_{\tau}/m_a)^2}} \approx \frac{m_{\mu}^2}{m_{\tau}^2}
\]

Four different final states are studied, depending on \(\tau\) decay modes

\[ \mu\mu + e\mu, \mu\mu + e\tau_h, \mu\mu + \mu\tau_h, \mu\mu + \tau_h\tau_h \]

Signal extracted by unbinned maximum likelihood fit to \(M(\mu\mu)\)

Probed mass region:

\[ 15 \text{ GeV} \leq m_a \leq 62.5 \text{ GeV} \]

Result improved (w.r.t 8 TeV) by a factor of \(\geq 2\)
h(125) → aa → bbττ

- Br(aa → 2b2τ) = 10 – 50% depending on scenarios and parameters
- signature: 1b + 1ℓ +1τ or 1b + 2ℓ
  - 3 different ττ final states: eμ, eτh, μτh
- 4 m_{vis}^{ττ} categories
- probed mass range: 15<m_a<60 GeV
- Binned maximum likelihood to m_{vis}(ττ)
• Forbidden in SM, but allowed in many BSM models
• Search performed in two decay channels: \( h \to \ell \tau, \mu \tau \)
  • 2 tau decay modes: \( \tau_h \) or \( \tau_{\mu/e} \)
  • 4 event categories designed to enhance the contribution of different Higgs production mechanisms: 0-jet, 1-jet, 2-jets (ggH), and VBF
• BDT classifier to extract signal
• Collinear mass fit as a cross check

\[ B(h \to \mu \tau) < 0.25\% \ (0.25\%) \]
\[ B(h \to e \tau) < 0.61\% \ (0.37\%) \]
Summary

- Rich program to search for new physics in the Higgs sector at LHC
- Both ATLAS and CMS experiments search for non-SM decays of the observed 125 GeV scalar as well as presence of additional Higgs bosons
- Many models such as MSSM, NMSSM, See-Saw etc., predict additional neutral as well as charged Higgs bosons
- Large parameter space of the MSSM benchmark scenarios are already excluded. However, analyses are not yet sensitive to exclude parameter space in NMSSM.
- Results are presented mostly for 13 TeV data collected during 2016.
- Lot of improvements in the analysis search sensitivities compared to Run-1 results.
- ~4 times more data is already collected during run-2 and are being analyzed now
- Looking for more exciting results soon
BACKUP
MSSM Scenarios

Table 1: MSSM benchmark scenarios.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$m_h^{max}$</th>
<th>$m_h^{mod+}$</th>
<th>$m_h^{mod-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_A$</td>
<td>90–1000 GeV</td>
<td>90–1000 GeV</td>
<td>90–1000 GeV</td>
</tr>
<tr>
<td>$\tan \beta$</td>
<td>0.5–60</td>
<td>0.5–60</td>
<td>0.5–60</td>
</tr>
<tr>
<td>$M_{SUSY}$</td>
<td>1000 GeV</td>
<td>1000 GeV</td>
<td>1000 GeV</td>
</tr>
<tr>
<td>$\mu$</td>
<td>200 GeV</td>
<td>200 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$M_1$</td>
<td>$(5/3) M_2 \tan^2 \theta_W$</td>
<td>$(5/3) M_2 \tan^2 \theta_W$</td>
<td>$(5/3) M_2 \tan^2 \theta_W$</td>
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<tr>
<td>$M_2$</td>
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<td>200 GeV</td>
<td>200 GeV</td>
</tr>
<tr>
<td>$X_t$</td>
<td>$2 M_{SUSY}$</td>
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<td>$A_b, A_t, A_\tau$</td>
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<td>$A_b = A_t = A_\tau$</td>
<td>$A_b = A_t = A_\tau$</td>
</tr>
<tr>
<td>$m_{\tilde{g}}$</td>
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<td>1500 GeV</td>
<td>1500 GeV</td>
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<td>$m_{\tilde{\tau}_3}$</td>
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<table>
<thead>
<tr>
<th>Parameter</th>
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2DHM scenarios

arXiv: 1507:04281

1. Type-I Yukawa couplings: $h_1^U = h_1^D = h_1^L = 0$,
2. Type-II Yukawa couplings: $h_1^U = h_2^D = h_2^L = 0$.
3. Type-X Yukawa couplings: $h_1^U = h_1^D = h_2^L = 0$,
4. Type-Y Yukawa couplings: $h_1^U = h_2^D = h_1^L = 0$.

$\rho_F \propto \kappa_F = \frac{\sqrt{2}}{v} M_F$

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<th>Type</th>
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<th>$D_R$</th>
<th>$L_R$</th>
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<th>$\rho^D$</th>
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<td>+</td>
<td>+</td>
<td>+</td>
<td>$\kappa^U \cot \beta$</td>
<td>$\kappa^D \cot \beta$</td>
<td>$\kappa^L \cot \beta$</td>
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<tr>
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<td>+</td>
<td>-</td>
<td>-</td>
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<td>$-\kappa^D \tan \beta$</td>
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<tr>
<td>III</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>$\kappa^U \cot \beta$</td>
<td>$-\kappa^D \tan \beta$</td>
<td>$\kappa^L \cot \beta$</td>
</tr>
<tr>
<td>IV</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>$\kappa^U \cot \beta$</td>
<td>$\kappa^D \cot \beta$</td>
<td>$-\kappa^L \tan \beta$</td>
</tr>
</tbody>
</table>

Type III = Type Y = “Flipped”
Type IV = Type X = “Lepton-spec.”

Barger, Hewitt, Philips, PRD41 (1990)