Topics in extended Higgs sector Models

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HPNP2017, 1-5 th March Toyama
Outlines

• General introduction
• Triple Higgs coupling in the Inert Higgs Doublet Model: Implications for LHC and $e^+e^-$ LC.
  A.A, R. Benbrik, J.ElFalaki and A.Jueid JHEP’16
• Triple Higgs couplings effect on $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$ in the 2HDM.
• Conclusions
Introduction

- The "Higgs like" discovery at $7 \oplus 8$ TeV LHC, is consistent with the SM Higgs boson
- BUT it will take further work to determine whether or not it is the Higgs boson predicted by the SM.
- The Higgs mechanism with *just one Higgs doublet* is the simplest one.
  Extended Higgs sector models are predicted by other theories that go beyond SM such as: more doublets, doublet & triplets, doublet & singlets
• The mission of the LHC run at 13 TeV is:
  • Improve the measurements of Higgs-like boson mass.
  • Improve the measurements of Higgs-like boson couplings to SM particles and perform new ones such as $h \rightarrow \gamma Z$ as well as the triple self coupling of the Higgs.
  • Find a clear hint of new physics beyond SM.
Accurate measurements of the scalar boson couplings to SM particles would help to determine if the Higgs-like boson is the SM Higgs or a Higgs that belongs to a higher representations: *more doublets, doublet & triplets, doublet & singlets*

So far, the precision measurements program of the LHC increasingly point to a SM like Higgs boson.

In several models beyond SM, such SM like Higgs boson could be obtained in the so called alignment/decoupling limit.
The Inert Model is an extension of SM, with two $SU(2)$ doublets $H_1$ and $H_2$ with $\mathbb{Z}_2$ symmetry. $H_1$ is the SM-Higgs:


The Scalar potential of this model is given by

$$
H_1 = \left( \frac{G^\pm}{\sqrt{2}} + \frac{v_1}{\sqrt{2}} + \frac{(h + iG^0)/\sqrt{2}}{\sqrt{2}} \right), \quad H_2 = \left( \frac{H^\pm}{(S + iA)/\sqrt{2}} \right)
$$

$$
V = \mu_1^2 |H_1|^2 + \lambda_1 |H_1|^4 + \mu_2^2 |H_2|^2 + \lambda_2 |H_2|^4 + \lambda_3 |H_1|^2 |H_2|^2
+ \lambda_4 |H_1^\dagger H_2|^2 + \frac{\lambda_5}{2} \left\{ (H_1^\dagger H_2)^2 + h.c. \right\}
$$

Spectrum: $h_{SM}$, S, A and $H^\pm$.

the free parameters are:

$m_h, m_S, m_A, m_{H^\pm}, \mu_2^2$ and $\lambda_L = \frac{1}{2}(\lambda_3 + \lambda_4 \pm \lambda_5)$
Scalar couplings

\[ hSS = (\lambda_3 + \lambda_4 - \lambda_5) \nu = \frac{2}{\nu} (m_S^2 - \mu_2^2) \]

\[ hAA = (\lambda_3 + \lambda_4 + \lambda_5) \nu = \frac{2}{\nu} (m_A^2 - \mu_2^2) \]

\[ hH^+ H^- = \lambda_3 \nu = \frac{2}{\nu} (m_{H^\pm}^2 - \mu_2^2) \]

- \( hSS \) and \( hAA \) can contribute to the invisible decay of the Higgs as well as to relic density
- \( hH^+ H^- \) can contribute to \( h \rightarrow \gamma\gamma \)
- \( hH^+ H^- \), \( hSS \) and \( hAA \) contribute to \( hh \) at one loop level
Theoretical constraints

- Electroweak Precision Tests: $S$, $T$, $U$
- All quartic couplings obey: $|\lambda_i| \leq 8\pi$
- Perturbative tree-level unitarity is preserved:
  
  $e_{1,2} = \lambda_3 \pm \lambda_4, \quad e_{3,4} = \lambda_3 \pm \lambda_5, \quad e_{5,6} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5$
  
  $e_{7,8} = -\lambda_1 - \lambda_2 \pm \sqrt{(\lambda_1 - \lambda_2)^2 + \lambda_4^2}$
  
  $e_{9,10} = -3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2}$
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  e_{9,10} &= -3\lambda_1 - 3\lambda_2 \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + (2\lambda_3 + \lambda_4)^2}
  \end{align*}

- The potential $V$ must be bounded from below:
  
  \begin{align*}
  \lambda_{1,2} &> 0, \\
  \lambda_3 + \lambda_4 - |\lambda_5| + 2\sqrt{\lambda_1 \lambda_2} &> 0, \quad \lambda_3 + 2\sqrt{\lambda_1 \lambda_2} > 0
  \end{align*}

- In order to have an inert vacuum as a global minima:
  
  $v^2 > -\mu_2^2 / \sqrt{\lambda_1 \lambda_2}$

I. Ginzburg, K. Kanishev, M. Krawczyk and D. Sokolowska PRD82’2010
\[ \Gamma (h \rightarrow \gamma \gamma) = \frac{\alpha^2 G_F m_h^2}{128\sqrt{2}\pi^3} \left| \text{top} + W + \frac{(m_{H^\pm}^2 - \mu_2^2)}{2s_W m_W} \frac{m_W^2}{m_{H^\pm}^2} F_0(\tau_{H^\pm}) \right|^2, \]

\[ \Gamma (h \rightarrow Z\gamma) = \frac{G_F^2 m_W^2 s_W^2}{64\pi^4} \alpha m_h^3 \left( 1 - \frac{m_Z^2}{m_h^2} \right)^3 \left| \text{top} + W + \right. \]

\[ \left. + \frac{1 - 2s_W^2}{s_W c_W} \frac{m_{H^\pm}^2 - \mu_2^2}{m_{H^\pm}^2} l_1(\tau_{H^\pm}, \lambda_{H^\pm}) \right|^2 \]

where \( \tau_i = 4m_i^2/m_h^2 \) and \( \lambda_i = 4m_i^2/m_Z^2, (i = t, W, H^\pm). \)

\( h \rightarrow \gamma \gamma, Z\gamma \) are controlled by:

\[ g_{hH^\pm H^\mp} = 2 \frac{m_W s_W}{e} \lambda_3 = \frac{e}{2s_W m_W} (m_{H^\pm}^2 - \mu_2^2) \]
$h \rightarrow \gamma \gamma$ and $h \rightarrow \gamma Z$ correlation

$$R_{V\gamma} = \frac{\sigma(gg \rightarrow h) \times Br(h \rightarrow V\gamma)}{\sigma(gg \rightarrow h)^{SM} \times Br(h \rightarrow V\gamma)^{SM}} = \frac{Br(h \rightarrow V\gamma)}{Br(h \rightarrow V\gamma)^{SM}}$$
If $R_{\gamma\gamma} > 1$, $R_{\gamma\gamma} > R_{\gamma Z}$:
$W^{\pm}$ and $H^{\pm}$ are constructive.

If $R_{\gamma\gamma} < 1$, $R_{\gamma\gamma} < R_{\gamma Z}$:
The destructive interference between $W^{\pm}$ and $H^{\pm}$ is more effective in $R_{\gamma\gamma}$ than in $R_{\gamma Z}$ ($W$ loops in $R_{\gamma Z}$ are larger than in $R_{\gamma\gamma}$).
In order to establish the Higgs mechanism for EWSB we need also to measure the **self-couplings $hh$ and $hhh$**.

The measurement of the triple couplings, if precise enough, can help distinguishing between various extensions of the SM.

$\lambda_{hhh} > 1.2\lambda_{hhh}^{SM}$ well motivated by electroweak baryogenesis.
In order to establish the Higgs mechanism for EWSB we need also to measure the **self-couplings hhh and hhhh**

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\[ \lambda_{hhh} > 1.2 \lambda_{hhh}^{SM} \] is well motivated by electroweak baryogenesis.

\[ \sigma_{hh}^{NLO} [\text{fb}] = 9.66 \lambda^2 y_t^2 - 49.9 \lambda y_t^3 + 70.1 y_t^4 + \mathcal{O}(y_by_t^2) \]

\[ \lambda = \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}} = 1 + \delta \] and \[ y_f = 1 \]

\[ \text{Out[74]} = \]

![Graph showing \( \sigma(gg \rightarrow hh) \) vs. \( \delta \)]

\( \sigma(gg \rightarrow hh) \) (fb)

- **NLO**
- **LO**
at 14 TeV with 3000 fb$^{-1}$, $gg \to h^* \to hh \to b\bar{b}\gamma\gamma$ leads to 8 event in the SM corresponding to a signal significance of 1.3 $\sigma$.

The analysis also foresee an exclusion of BSM with $\lambda_{hhh}/\lambda_{SM} \leq -1.3$ and $\lambda_{hhh}/\lambda_{SM} \geq 8.7$.

ATLAS note: ATL-PHYS-PUB-2014-019

At 14 TeV with 3000 fb$^{-1}$, $gg \to h^* \to hh \to b\bar{b}\tau^+\tau^-$, ATLAS can set an upper limit on the di-Higgs production of $4.3\times\sigma(hh \to b\bar{b}\tau^+\tau^-)$ which can be translated to an exclusion on $\lambda_{hhh}/\lambda_{SM} \leq -4$ and $\lambda_{hhh}/\lambda_{SM} \geq 12$.

ATLAS note: ATL-PHYS-PUB-2015-046
$h^* \rightarrow hh$ at 1-loop: On-shell renormalization

B.Spiesberger and W.Hollik, Fortsch. Phys.34,1988

- $hhh = 3\, e\, m_h^2/(2 m_W s_w)$

- on-shell renormalization for: Higgs field, $m_h$, $m_W$, $m_Z$

- All Higgs tadpole amplitudes $T$ are absorbed into $\delta t$ such that: $\hat{T} = \delta t + T = 0$

- on-shell definition for $s_W^2 = 1 - m_W^2/m_Z^2$

- renormalization of the electric charge: $e$

- $\delta \mathcal{L}_{hhh} =$

\[-\frac{3e^2}{2s_w} \frac{m_h^2}{m_W} \left( \delta Z_e - \frac{\delta s_W}{s_W} + \frac{\delta m_h^2}{m_h^2} + \frac{e}{2s_w} \frac{\delta t}{m_W m_h^2} - \frac{\delta m_W^2}{2m_W^2} + \frac{3}{2} \delta Z_h \right) h^3\]
\( h^* \rightarrow hh \) at 1-loop: On-shell renormalization

B. Spiesberger and W. Hollik, Fortsch. Phys. 34, 1988

- \( hhh = 3 \ e \ m_h^2/(2 m_W s_w) \)

- on-shell renormalization for: Higgs field, \( m_h, m_W, m_Z \)

- All Higgs tadpole amplitudes \( T \) are absorbed into \( \delta t \) such that: \( \hat{T} = \delta t + T = 0 \)

- on-shell definition for \( s_W^2 = 1 - m_W^2/m_Z^2 \)

- renormalization of the electric charge: \( e \)

- \( \delta L_{hhh} = \)
  \[
  \frac{-3e^2}{2s_W m_W} \left( \delta Z_e - \frac{\delta s_W}{s_W} + \frac{\delta m_h^2}{m_h^2} + \frac{e}{2s_W} \frac{\delta t}{M_W m_h^2} - \frac{\delta m_W^2}{2 m_W^2} + \frac{3}{2} \delta Z_h \right) h^3
  \]

http://www.feynArts.de, FormCalc, LoopTools
1-loop corrections to $hhh$ in SM


A.A, R. Benbrik, J. Elfalaki, A Jueid, JHEP'14

Bosonic, top-bottom, Total
1-loop corrections to $hhh$ in the Inert Higgs Model

- Need to implement FeynArts model file for the inert model.

\[ hSS = (\lambda_3 + \lambda_4 - \lambda_5) v = \frac{2}{v} (m_S^2 - \mu_2^2) \]

\[ hAA = (\lambda_3 + \lambda_4 + \lambda_5) v = \frac{2}{v} (m_A^2 - \mu_2^2) \]

\[ hH^+ H^- = \lambda_3 v = \frac{2}{v} (m_{H^\pm}^2 - \mu_2^2) \]

$\mu_2^2 < 0$ would be preferred.
Decoupling/non-decoupling effects in $hhh$

$$m_{\Phi} = m_S = m_A = m_{H^\pm}$$

![Graph showing decoupling/non-decoupling effects in $hhh$](image-url)
Decoupling/non-decoupling effects in $hh\bar{h}$

$m_\Phi = m_S = m_A = m_{H\pm}$
$m_Φ = m_Σ = m_A = m_{H±}$

Graphical representation showing the relationship between $m_Φ$ and $\Delta Γ_{hhh}$, with additional notes:

- $m_{H±}=m_A^0=m_Φ$
- $\text{Br}(h \rightarrow \text{invisible}) < 20\%$
- $\lambda_2 = 2$
- $\mu_γγ$ at $2σ$
Decoupling/non decoupling effects in $hhh$

$\Delta \Gamma_{HHH}$ vs $m_{\phi}$

$m_{H^\pm} = m_{A^0} = m_{H^0} = m_{\phi}$

$q = 300$ GeV

$\mu_{\gamma\gamma}$ at $2\sigma$
Large effects found in 2HDM:

S. Kanemura, Y. Okada, E. Senaha, C.-P. Yuan, PRD70’2004,
M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu, PRD87, 2013

At $e^+e^- \text{ LC}$ with $\sqrt{s} = 500$ GeV, $\sigma(e^+e^- \to Zhh) = 0.14\text{fb}$

At $e^+e^- \text{ LC}$ $e^+e^- \to Zhh \to l^+l^- b\bar{b}b\bar{b}$ or $e^+e^- \to W^*W^* \to h^*\nu\bar{\nu} \to hh\nu\bar{\nu}$: to extract the triple coupling $hhh$.

Luminosity upgrade is needed to get better precision. (See Fujii talk)
$hh = hh_{SM}(1 + \delta)$
Scan over $m_\Phi$ and $\mu_2^2$. 

\[ \Delta hhh \text{ and } \Delta \sigma(e^+e^- \rightarrow Zhh) \]
LHC will pin down the uncertainty of $h^0 \rightarrow b\bar{b}$ and $h^0 \rightarrow \tau^+\tau^-$ to 10-13% and 6-8% respectively for bottom quark and tau lepton.

With the High Luminosity option (HL-LHC), these measurements will be ameliorated down to 4-7% and 2-5%

At the $e^+e^-$ Linear Collider (LC), the uncertainties on $h \rightarrow b\bar{b}$ and $h^0 \rightarrow \tau^+\tau^-$ would reach 0.6% and 1.3%

<table>
<thead>
<tr>
<th>Observable</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>LC</th>
<th>HL-LHC+LC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Hbb$</td>
<td>10-13%</td>
<td>4-7%</td>
<td>0.6%</td>
<td>0.6%</td>
</tr>
<tr>
<td>$H_{\tau^+\tau^-}$</td>
<td>6-8%</td>
<td>2-5%</td>
<td>1.3%</td>
<td>1.2%</td>
</tr>
<tr>
<td>$R = \frac{Br(H \rightarrow bb)}{Br(H \rightarrow \tau^+\tau^-)}$</td>
<td>32-42%</td>
<td>12-24%</td>
<td>4%</td>
<td>3%</td>
</tr>
</tbody>
</table>


\[ S \rightarrow H^\pm, A^0, H^0 \text{ and } F \text{ represents } (b, t) \text{ for } h \rightarrow b\bar{b} \text{ and } (\tau, \nu) \text{ for } h \rightarrow \tau^+\tau^- \]
At one-loop order the amplitude can be written as follows,

$$M_1(h \to f \bar{f}) = -\frac{igm_f}{2m_W} \sqrt{Z_h} \left[ \xi_h^f (1 + \Delta M_1) + \xi^f_{H^0} \Delta M_{12} \right]$$

$$\Delta M_1 = V_1^{hf \bar{f}} + \frac{\delta m_f}{m_f} + \delta Z_f^f + \frac{\delta v}{v}$$

$$\Delta M_{12} = \frac{\Sigma_{hH^0}(m_h^2)}{m_h^2 - m_{H^0}^2} - \delta \alpha$$

$$Z_h = \left[ 1 + \Sigma'_h(m_h^2) + s^2_{\alpha} \delta Z_{\Phi_1}^{MS} + c^2_{\alpha} \delta Z_{\Phi_2}^{MS} \right]^{-1}.$$  

We use the on-shell scheme for determination of the counterterms, with the exception that $\delta Z_{\Phi_1}$ and $\delta Z_{\Phi_2}$ are determined in the $\overline{\text{MS}}$ scheme.

In order to get the counterterms for $v_1$, we take

$$\frac{\delta v_2}{v_2} = \frac{\delta v_1}{v_1} = \frac{\delta v}{v}$$

$$\frac{\delta v}{v} = \frac{1}{2} \left( c^2_{\beta} \delta Z_{\Phi_1}^{MS} + s^2_{\beta} \delta Z_{\Phi_2}^{MS} + \Sigma'_{\gamma\gamma}(0) + 2 \frac{s_W}{c_W} \frac{\Sigma_{\gamma Z}(0)}{M_Z^2} - \frac{c^2_W}{s_W^2} \frac{\Re \Sigma_{ZZ}(M_Z^2)}{M_Z^2} - \frac{c^2_W - s^2_W}{s_W^2} \frac{\Re \Sigma_{WW}(M_W^2)}{M_W^2} \right)$$
scalar couplings

\[
\lambda^{2HDM}_{h^0 h^0 h^0} = \frac{-3g}{2m_W s_{2\beta}^2} \left[ (2c_{\alpha+\beta} + s_{2\alpha}c_{\beta-\alpha})s_{2\beta}m_{h^0}^2 - 4c_{\beta-\alpha}^2c_{\beta+\alpha}m_{12}^2 \right]
\]

\[
\lambda^{2HDM}_{h^0 H^0 H^0} = \frac{g s_{\beta-\alpha}}{2m_W s_{2\beta}^2} \left[ (m_{h^0}^2 + 2m_{H^0}^2)s_{2\alpha}s_{2\beta} - 2(3s_{2\alpha} + s_{2\beta})m_{12}^2 \right]
\]

\[
\lambda^{2HDM}_{h^0 H^\pm H^\mp} = \frac{g}{2m_W} \left[ (m_{h^0}^2 - 2m_{H^\pm}^2)s_{\beta-\alpha} - \frac{2c_{\beta+\alpha}}{s_{2\beta}^2}(m_{h^0}^2s_{2\beta} - 2m_{12}^2) \right]
\]

in the decoupling limit:

\[
\lambda^{2HDM}_{h^0 h^0 h^0} = \frac{-3g}{2m_W} m_{h^0}^2 = \lambda_{hhh}^{SM},
\]

\[
\lambda^{2HDM}_{h^0 H^0 H^0} = \frac{g}{m_W} \left[ \left( \frac{2m_{12}^2}{s_{2\beta}} - m_{H^0}^2 \right) - \frac{m_{h^0}^2}{2} \right],
\]

\[
\lambda^{2HDM}_{h^0 H^\pm H^\mp} = \frac{g}{m_W} \left[ \left( \frac{2m_{12}^2}{s_{2\beta}} - m_{H^\pm}^2 \right) - \frac{m_{h^0}^2}{2} \right],
\]
At one-loop order the decay width of $h \rightarrow f \bar{f}$ is

$$
\Gamma_1(h \rightarrow f \bar{f}) = \frac{N_C G_F m_f^2}{4\sqrt{2}\pi} \beta^3 m_h (\xi_f^h)^2 Z_h \left[ 1 - \Delta r + 2\Re(\Delta M_1) \right]
$$

$$
= \Gamma_0(h \rightarrow f \bar{f}) Z_h \left[ 1 - \Delta r + 2\Re(\Delta M_1) \right],
$$

To parameterize the quantum corrections, we define

$$(f = b, \tau)$$

$$
\Delta_{ff} = \frac{\Gamma_1^{2HDM}(h \rightarrow f \bar{f})}{\Gamma_1^{SM}(h \rightarrow f \bar{f})} = \frac{Z_h(1 - \Delta r^{2HDM} + 2\Re(\Delta M_1^{2HDM}))}{(1 - \Delta r^{SM} + 2\Re(\Delta M_1^{SM}))},
$$
An other observable that could help in distinguishing between models is the ratio of branching fractions given by:

\[ R = \frac{BR(h \to b\bar{b})}{BR(h \to \tau^+\tau^-)} \; ; \; X = \frac{R^{2HDM}}{R^{SM}} = \frac{\Delta_{b\bar{b}}}{\Delta_{\tau\tau}} \]

\[ X^{\text{exp}} = \frac{R^{\text{exp}}}{R^{SM}} = \frac{\lambda_{bZ}^2}{\lambda_{\tau Z}^2} \; , \; \lambda_{xy} = \frac{\kappa_x}{\kappa_y} \]

\[ \lambda_{bZ}^{\text{CMS}} = 0.59^{+0.22}_{-0.23} \; , \; \lambda_{\tau Z}^{\text{CMS}} = 0.79^{+0.19}_{-0.17} \; , \\
\lambda_{bZ}^{\text{ATLAS}} = 0.60 \pm 0.27 \; , \; \lambda_{\tau Z}^{\text{ATLAS}} = 0.99^{+0.23}_{-0.19} \]

one can get the following experimental values for \( X \):

\[ X^{\text{CMS}} = 0.56^{+0.48}_{-0.52} \; , \; X^{\text{ATLAS}} = 0.37^{+0.36}_{-0.37} \]
The coupling $\lambda_{hhh}^{SM}$ is modified as $\lambda_{hhh}^{SM}(1 + \Delta)$.

In the SM $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+\tau^-$ are not very sensitive to the change in $\lambda_{hhh}^{SM}$.
Figure: Scatter plot in the decoupling limit for $\Delta_{ff}$ in the plane $(M_{H^{\pm}}, m_{12}^2)$ in 2HDM-I, III.


In 2HDM type I: $\tan \beta = 2$, $m_{H^{\pm}} > 200$ GeV, this limit get larger for small $\tan \beta$.

In 2HDM type II: $m_{H^{\pm}} > 580$ GeV, independent of $\tan \beta$. 
Results

Figure: Scatter plot in the decoupling limit for $\Delta_{ff}$ in the plane $(M_{H\pm}, m^2_{12})$ in 2HDM-I, III.

  In 2HDM type I: $\tan\beta = 2$, $m_{H\pm} > 200$ GeV, this limit get larger for small $\tan\beta$.

In 2HDM type II: $m_{H\pm} > 580$ GeV, independent of $\tan\beta$.
Figure: Scatter plot in the decoupling limit for $\Delta_{ff}$ in the plane $(M_{H^+}, m_{12}^2)$ in 2HDM-II, IV.
Figure: $X = \frac{R_{2HDM}^{\tan\beta=1}}{R_{SM}} = \frac{\Delta_{bb}}{\Delta_{\tau\tau}}$ in $(M_{H^\pm}, m_{12}^2)$ plane: type I and II.

$X^{CMS} = 0.56^{+0.48}_{-0.52}, \quad X^{ATLAS} = 0.37^{+0.36}_{-0.37}$. 
\begin{itemize}
  \item Note that in the MSSM \( \frac{R^{\text{MSSM}}}{R^{\text{SM}}} \) can reach values of 30%.
\end{itemize}

E. Arganda, J. Guasch, W. Hollik and S. Penaranda et al EPJC’2016
large radiative corrections to triple Higgs boson in the inert Higgs model, could exceed 100% in some case.

this large effects can effect also $pp \rightarrow gg \rightarrow hh$ and $e^+ e^- \rightarrow Zhh$

Precision Measurements of $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+ \tau^-$ can be used to distinguish between models. In the 2HDM, 1-loop radiative corrections to $h \rightarrow b\bar{b}$ and $h \rightarrow \tau^+ \tau^-$ are important in 2HDM type I and III, mild in type II.