Full next-to-leading-order corrections to the Higgs strahlung process from electron-positron collisions in the Inert Higgs Doublet Model

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Outlines

- A scalar particle with a mass of approximately 125 GeV was discovered in 2012[1],[2] by ATLAS and CMS that is so far compatible with SM Higgs boson ...

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- λ_{hhh}, λ_{hhhh} and $H \to Z\gamma$ are still not reached at the LHC.
- IDM can describe dark matter.
- The need of new physics is motivated by : Dark matter, baryon asymmetry, neutrino masses, among other.
- Future generation of e^+e^- colliders will provide clean environment and precised measurement.

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Motivations

- The high precision measurement at ILC [3].

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- The high precision measurement at ILC [3].
- The $e^+e^- \rightarrow h^0 Z$ dominates near the production threshold for ILC@250 .
- The range of radiative corrections to Higgsstrahlung in IDM is in the same range of the precision measurement at ILC.
- The Higgs boson mass can be precisely measured independently of the decay modes by using the recoil mass spectrum against the Z

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Inert Higgs Model

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- Extensively used also to explain Dark matter of the universe.

Inert Higgs Model

- The IDM consist of the SM, including its Higgs doublet $\Phi_1 = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$ and an additional Lorentz scalar SU(2) doublet $\phi_2 = \begin{pmatrix} H^+ \\ (H^0 + A^0)/\sqrt{2} \end{pmatrix}$.

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- The difference between IDM and the General Two Higgs Doublet Model is its potential has an exact (unbroken by the vacuum state) discrete symmetry Z_2.
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  Z_2 symmetry : $\Phi_1 \Longleftrightarrow \Phi_1, \Phi_2 \Longleftrightarrow -\Phi_2$.
- Z_2 guarantees the absence of the couplings between the SM fermions and inert doublet Φ_2 : no FCNC.

- The scalar Potential :

$$V = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \lambda_1^2|\Phi_1|^4 + \lambda_2^2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\{(\Phi_1^\dagger\Phi_2)^2 + h.c\},$$

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- The parameter λ_i are all real.
- The news scalar Boson are : H^0, A^0, H^+ and H^-, their masses are given by:

$$m_{h^0}^2 = -2\mu_1^2 = 2\lambda_1 v^2; \quad m_{H^0}^2 = \mu_2^2 + \lambda_L v^2$$
$$m_{A^0}^2 = \mu_2^2 + \lambda_S v^2; \quad m_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2 \tag{1}$$

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- After minimisation: we left with 7 Free parameters. v and M_h are fixed $\Rightarrow$ 5 free parameters $\mu_2^2, \lambda_2, M_{H^0}, M_{A^0}$ and $M_{H^\pm}$.

Constraints

Theoretical constraints

- Vacuum Stability :

$$\lambda_{1,2} > 0, \lambda_3 + \lambda_4 + |\lambda_5| + 2\sqrt{\lambda_1 \lambda_2} > 0 \tag{2}$$

- Perturbativity and unitarity
- Charge breaking minima: The conservation of the neutral charge of the vacuum can be reached by imposing :

$$\lambda_4 - |\lambda_5| \leq 0 \tag{3}$$

Constraints

Experimental constraints

- Contraints from Higgs data at LHC : In our analysis we toke into account two constraints from LHC data
  - $h^0 \rightarrow \gamma\gamma$
  - $Br(h^0 \rightarrow invisible) < 11\%$ at 95% CL
- Direct search from LEP : These constraints are summarized as follows :
  - $m_{H^+} > 80 GeV$
  - $Max(m_{A^0}, m_{H^0}) > 100 GeV$
  - $m_{A^0} + m_{H^0} > m_Z$ and $m_{A^0} + m_{H^\pm} > m_W$
- Electro Weak Precision : these constraints require a small split between charge Higgs mass and one of the heavy neutral Higgs $m_{H^+} \simeq m_{H^0}$ or $m_{H^+} \simeq m_{A^0}$.
- DM relic density, direct, indirect and collider searche

Constraints

Allowed Parameter space

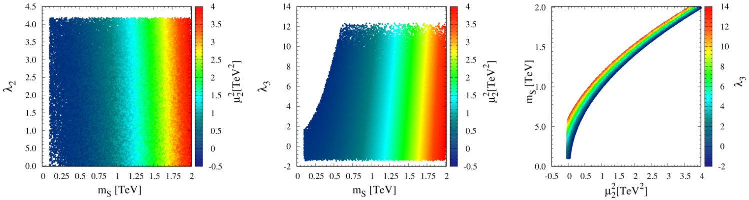

Figure 1: Allowed parameter space in the degenerate IDM spectra are shown, where the various theoretical constraints and experimental bounds.

Constraints

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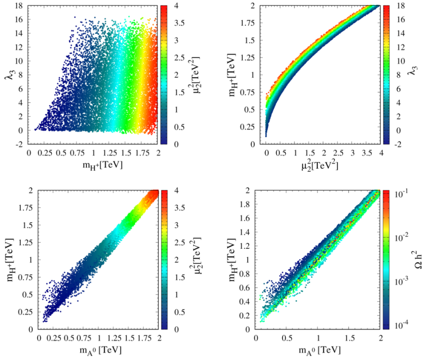
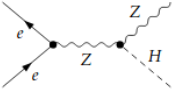
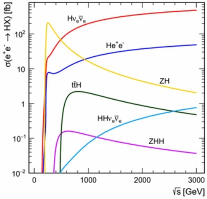


Figure 2: Allowed parameter space in the non-degenerate IHDM spectra satisfying all theoretical and experimental constraints are shown.

Higgs strahlung

Motivation





- By using the recoil mass spectrum against the Z, the Higgs boson mass can be precisely measured independently of the decay modes.

$e^+e^- \rightarrow H^+H^-$
Leading Order

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Leading Order

- The Higgs Strahlung at tree level both in SM and IDM is leading by the same Feynman diagram .
- The dynamic of the Higgs Strahlung processes is driven at leading order by the tree-level interaction Lagrangian

$$\mathscr{L}_{Z^0Z^0h^0} = \frac{eM_Z}{s_w c_w} g^{\mu\nu} Z^0_\mu Z^0_\nu h^0 \tag{4}$$

Higgs Strahlung

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- We redefine the Higgs field and masses as follows We redefine the Higgs fields and masses as follows:

$$\begin{aligned} h &\to Z_h^{1/2} h = (1 + \frac{1}{2}\delta Z_h) h \\ m_h^2 &\to m_h^2 + \delta m_h^2 \end{aligned} \quad (5)$$

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$$m_h^2 \rightarrow m_h^2 + \delta m_h^2 \quad (5)$$

- Inserting these redefinitions into the above Lagrangian we obtain the conter-term for the ZZh^0 diagrams :

$$\delta\mathscr{L}_{ZZh^0} = i\frac{em_W}{s_W c_W^2}(\delta Z_e + \frac{\delta Z_{H^0}}{2} + \delta Z_{ZZ} - \frac{\delta s_W(c_W^2 - 2s_W^2)}{c_W^2 s_W} + \frac{\delta m_W^2}{2m_W^2}) Z^\mu Z_\mu h^0 \quad (6)$$

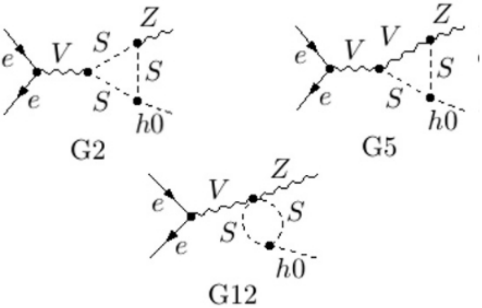

Figure 3: Some interesting Feynman diagrams .

Higgs Strahlung

Next-to-leading-order

- At one-loop order, the cross section can be obtained by the interference of tree level diagrams and those arising at the one-loop.

$$\mathcal{M} = \mathcal{M}_{tree} + \mathcal{M}_{loop} \tag{7}$$

Higgs Strahlung

Next-to-leading-order

The total cross section at NLO, σ^{NLO}, is the sum of LO cross section σ^0, and NLO corrections σ^1, namely

$$\sigma^{NLO} = \sigma^0 + \sigma^1 \equiv \sigma^0(1 + \Delta), \quad (8)$$

where Δ is the relative correction. Thus Δ can be decomposed into two gauge-invariant parts,

$$\Delta = \Delta_{\text{weak}} + \Delta_{\text{QED}} \quad (9)$$

In order to illustrate the pure effect of IHDM radiative corrections , we define the following ratio given as:

$$\delta = \frac{\sigma^{IHDM}_{Zh^0} - \sigma^{SM}_{Zh^0}}{\sigma^{SM}_{Zh^0}}, \quad (10)$$

Results

Scenarios and their conditions.

	Sc I	Sc II	Sc III	Sc IV	Sc V
Theoretical constraints	✓	✓	✓	✓	✓
Degenerate spectrum	✓				
Higgs Data	✓	✓	✓	✓	✓
Higgs Invisible decay open				✓	✓
Direct searches from LEP	✓	✓	✓	✓	✓
Electroweak precision tests	✓	✓	✓	✓	✓
Dark matter constraints			✓		✓

Table 1: Scenarios and their conditions.

Results

Angular distribution.

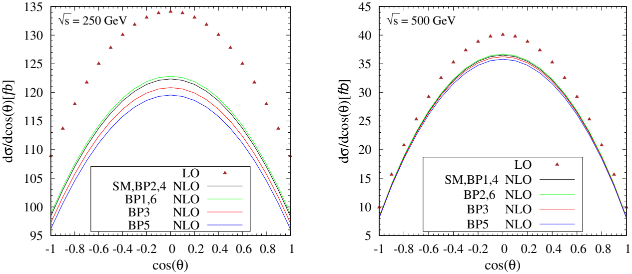

Figure 4: Angular distribution with three different collision energies: $\sqrt{s} = 250$ and 500 GeV .

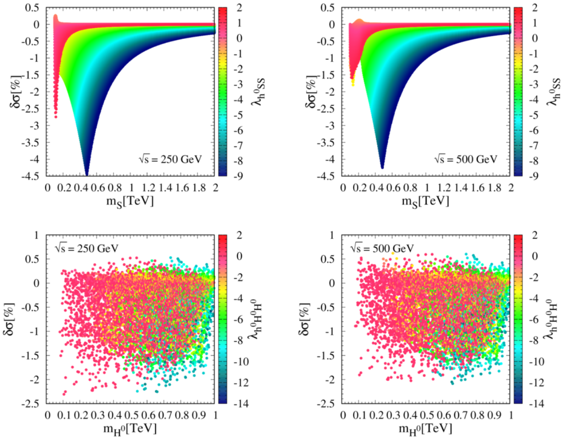

Figure 5: The results for new physics contribution to $e^+e^- \rightarrow Zh^0$ for collision energies 250 and 500 GeV, are shown for Scenario I, III respectively from upper panels to lower panels.

Results

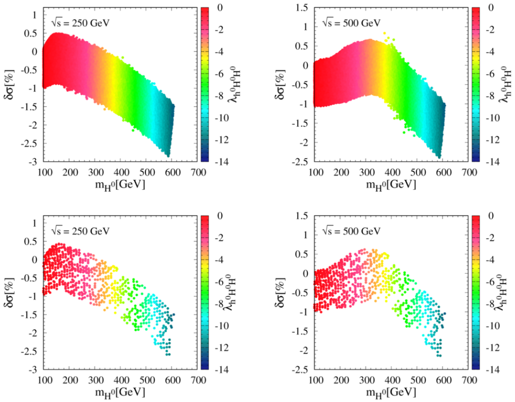

Figure 6: The results for new physics contribution to $e^+e^- \to Zh^0$ for collision energies 250,500 GeV, are shown for Scenario IV in the upper panels and V in the lower one.

Results

- After all constraints we can still find a significant contribution of new physics bigger than two percent $\delta\sigma \geq 2$.
- At 250 GeV and 500GeV the radiative correction of the Higgs Strahlung process are not bigg enough to be significant at ILC but they will be more useful at FCC-ee and CEPC .

Thank you!