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

Hamza Abouabid

Faculté des sciences et techniques Tangier, Université Abdelmalek Assaadi, Morocco

In Collaboration with: A. Arhrib, J. EL Falaki, R. Benbrik, B.Gong, W. Xi, and Q. Yan Based on : JHEP05(2021)100

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Hamza Abouabid

hamza.abouabid@gmail.com

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Hamza Abouabid



Hamza Abouabid hamza.abouabid@gmail.com Université Abdelmalek Assaadi

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 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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- A scalar particle with a mass of approximately 125 GeV was discovered in 2012¹,² by ATLAS and CMS that is so far compatible with SM Higgs boson ...
- λ_{hhh} , λ_{hhhh} and $H \rightarrow Z\gamma$ are still not reached at the LHC.

¹ Phys.	Lett	В	716	(2012)	1-29
² Phys.	Lett	В	716	(2012)	30

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- The need of new physics is motivated by : Dark matter, baryon asymmetry, neutrino masses, among other.

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- A scalar particle with a mass of approximately 125 GeV was discovered in 2012¹,² by ATLAS and CMS that is so far compatible with SM Higgs boson ...
- λ_{hhh} , λ_{hhhh} and $H \rightarrow Z\gamma$ 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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<sup>1</sup>Phys. Lett B 716 (2012) 1-29
<sup>2</sup>Phys. Lett B 716 (2012) 30
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Motivations				

• The high precision measurement at ILC ³.

³T. K. Nelson,SLAC–PUB–12246

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hamza.abouabid@gmail.com

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Motivations				

- The high precision measurement at ILC 3 .
- The $e^+e^- \to h^0 Z$ dominates near the production threshold for ILC@250 .

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Motivations				

- The high precision measurement at ILC ³.
- The $e^+e^- \to h^0 Z$ 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 ${\it Z}$

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Inert Higgs	Model			

 Inert two Higgs Doublet Model (IDM, or i2HDM) was introduced at by Deshpande and Ma (1978), about same time as 2HDM.

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Inert Higgs	Model			

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Inert Higgs	Model			

- Inert two Higgs Doublet Model (IDM, or i2HDM) was introduced at by Deshpande and Ma (1978), about same time as 2HDM.
- Extensively used also to explain Dark matter of the universe.

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Inert Higgs	Model			

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

 Z_2 symmetry : $\Phi_1 \iff \Phi_1, \Phi_2 \iff -\Phi_2$.

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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 Z₂.

 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.

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

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• The parameter λ_i are all real.

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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:

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

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

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(1)

• After minimisation: we left with 7 Free parameters. v and M_h are fixed \Rightarrow 5 free parameters μ_2^2 , λ_2 , M_{H^0} , M_{A^0} and $M_{H^{\pm}}$.

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• 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 :

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

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- 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

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Allowed Parameter space



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

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Constraints Allowed Parameter space



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

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

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Leading-order				
$e^+e^- o H^+$ Leading Order	· <i>H</i> ⁻			

• The Higgs Strahlung at tree level both in *SM* and *IDM* is leading by the same Feynman diagram .

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Leading-order				
$e^+e^- ightarrow H^+$ Leading Order	·H ⁻			

- 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

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

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Higgs Strahlu NLO - ON-Shell F	ng Renormalization			

• In this work we used the On-shell renormalization scheme



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Higgs Strahlung					
NLO - ON-Shell Renormalization					

- In this work we used the On-shell renormalization scheme
- We redefine the Higgs field and masses as follows We redefine the Higgs fields and masses as follows:

$$h \rightarrow Z_h^{1/2} h = (1 + \frac{1}{2}\delta Z_h)h$$
$$m_h^2 \rightarrow m_h^2 + \delta m_h^2$$
(5)

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NLO - ON-She	Il Renormalization				

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$$h \rightarrow Z_h^{1/2} h = (1 + \frac{1}{2} \delta Z_h) h$$
$$m_h^2 \rightarrow m_h^2 + \delta m_h^2$$
(5)

Inserting these redefinitions into the above Lagrangian we obtain the conter-term for the ZZh⁰ diagrams :

$$\delta \mathscr{L}_{ZZh^{0}} = i \frac{em_{W}}{s_{W}c_{W}^{2}} (\delta Z_{e} + \frac{\delta Z_{H^{0}}}{2} + \delta Z_{ZZ} - \frac{\delta s_{W}(c_{W}^{2} - 2s_{W}^{2})}{c_{W}^{2}s_{W}} + \frac{\delta m_{W}^{2}}{2m_{W}^{2}}) Z^{\mu} Z_{\mu} h^{0}$$
(6)

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Figure 3: Some interesting Feynman diagrams .

Hamza Abouabid

hamza.abouabid@gmail.com

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

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

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

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

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

$$\Delta = \Delta_{\text{weak}} + \Delta_{\text{QED}} \tag{9}$$

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

$$\delta = \frac{\sigma_{Zh^0}^{IHDM} - \sigma_{Zh^0}^{SM}}{\sigma_{Zh^0}^{SM}}$$
(10)

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Results Scenarios and their conditions.

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Theoretical constraints	1	 Image: A set of the set of the	1	 Image: A set of the set of the	 Image: A second s
Degenerate spectrum	1				
Higgs Data	1	1	1	1	 Image: A start of the start of
Higgs Invisible decay open				 Image: A set of the set of the	 Image: A set of the set of the
Direct searches from LEP	1	 Image: A set of the set of the	1	 Image: A set of the set of the	 Image: A start of the start of
Electroweak precision tests	1	 Image: A set of the set of the	1	1	 Image: A second s
Dark matter constraints			1		 Image: A start of the start of

Table 1: Scenarios and their conditions.

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Angular distribution.



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

Hamza Abouabid

hamza.abouabid@gmail.com

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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.

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

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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 .

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