Production of Inert Scalars at e^+e^- Linear Colliders

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Outline

- Inert Doublet Model (IDM): a brief introduction
- Theoretical and experimental constraints
- Benchmark points
- Signatures at the linear collider
    - $e^+e^- \rightarrow H^+H^-$
    - $e^+e^- \rightarrow H\ A$
- Dark matter mass measurement
- Conclusion

Inert doublet model

- IDM is the simplest extension of the Standard Model (SM).
- Two scalar doublets Φ_S and Φ_D.
  - Φ_S is the SM like Higgs doublet.
  - Φ_D has four additional scalars H, A, $H^{\pm}$.
- Inert doublet is odd under Z_2 symmetry, i.e. $\Phi_D \to -\Phi_D$, hence
  - the lightest inert doublet particle is stable.
  - we consider H as the dark matter candidate.

Inert doublet model

Scalar potential

$$V(\Phi_S, \Phi_D) = -\frac{1}{2}\left[m_{11}^2(\Phi_S^\dagger\Phi_S) + m_{22}^2(\Phi_D^\dagger\Phi_D)\right] + \frac{\lambda_1}{2}(\Phi_S^\dagger\Phi_S)^2 + \frac{\lambda_2}{2}(\Phi_D^\dagger\Phi_D)^2$$
$$+ \lambda_3(\Phi_S^\dagger\Phi_S)(\Phi_D^\dagger\Phi_D) + \lambda_4(\Phi_S^\dagger\Phi_D)(\Phi_D^\dagger\Phi_S) + \frac{\lambda_5}{2}\left[(\Phi_S^\dagger\Phi_D)^2 + (\Phi_D^\dagger\Phi_S)^2\right]$$

- IDM has seven parameters $(m_{11}, m_{22}, \lambda_{1,2,3,4,5})$ which we take them to be real.
- Scalar masses:

$$m_h^2 = \lambda_1 v^2 = m_{11}^2 = (125\ \mathrm{GeV})^2, \qquad m_{H^\pm}^2 = \frac{1}{2}(\lambda_3 v^2 - m_{22}^2),$$
$$m_H^2 = \frac{1}{2}(\lambda_{345} v^2 - m_{22}^2), \qquad m_A^2 = \frac{1}{2}(\bar{\lambda}_{345} v^2 - m_{22}^2)$$

- where $\boxed{\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5}$, $\boxed{\bar{\lambda}_{345} = \lambda_3 + \lambda_4 - \lambda_5}$

Theoretical constraints

- The vacuum stability at tree level leads to the following conditions on the couplings:

$$\lambda_1 \geq 0, \qquad \lambda_2 \geq 0,$$
$$\sqrt{\lambda_1 \lambda_2} + \lambda_3 > 0, \qquad \sqrt{\lambda_1 \lambda_2} + \lambda_{345} > 0$$

- Perturbative unitarity.
- In order to have the global inert vacuum, we require

$$\frac{m_{11}^2}{\sqrt{\lambda_1}} \geq \frac{m_{22}^2}{\sqrt{\lambda_2}}$$

Experimental constraints

- The upper bound on the total width of h, $\Gamma_{total} \leq 22$ MeV.
- Total widths of W and Z boson imply the following bounds:

$$m_H + m_A \geq m_Z, \quad 2m_{H^\pm} \geq m_Z, \quad m_A + m_{H_\pm}, m_H + m_{H^\pm} \geq m_W.$$

- Direct bound by the dark matter nucleon scattering is by LUX experiment.
- A lower bound on mass of $m_{H^\pm} \geq 70$ GeV.
- Exclusion from LHC and SUSY LEP experiments.
- Agreement with electroweak precision observables (2σ).
- Upper limit on $H^\pm$, $\Gamma_{tot} \geq 6.58 \times 10^{-18}$ GeV.
- Planck experiment measurement leads to upper limit on relic density (2σ), $\Omega_c h^2 \leq 0.1241$.

Benchmark Points

BP	m_H	m_A	$m_{H^\pm}$
$BP1$	57.5	113.0	123
$BP2$	85.5	111.0	140
$BP3$	128.0	134.0	176.0

Benchmark Points: Ilnicka, Krawczyk and Robens 2015

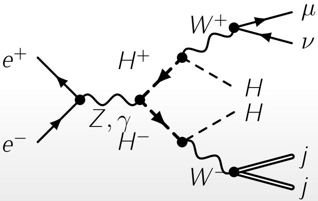
We analyse the following decay processes:

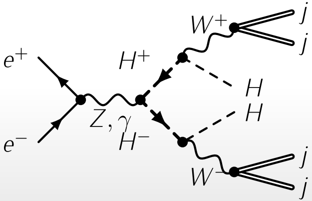
- $\boxed{e^+e^- \to H^+H^- \to W^+W^-HH \to \mu\nu jjHH, jjjjHH}$
- $\boxed{e^+e^- \to HA \to HHZ \to HH\mu\mu, HHjj}$

$e^+e^- \to H^+H^-$

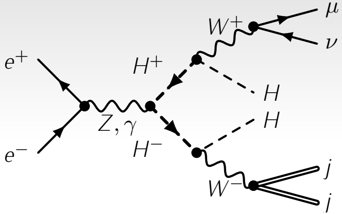
Signal and background cross sections

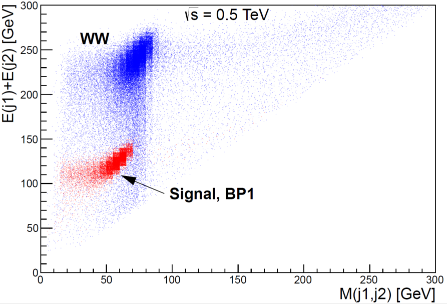
Process	Signal			Background			
	BP1	BP2	BP3	WW	ZZ	Z+jets	$t\bar{t}$
σ [fb] @ 500 GeV	164.4	141.8	89.2	7807	583	16790	595
σ [fb] @ 1 TeV	56.2	54.6	50.6	3180	233	4304	212

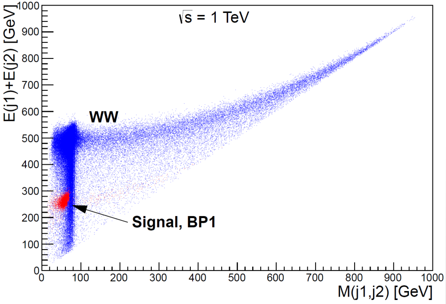




Correlation between the sum of energies of two jets and their invariant mass





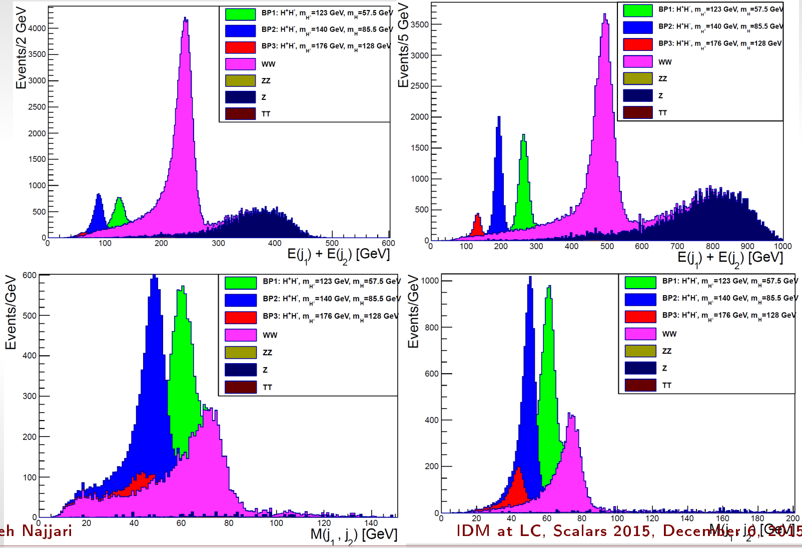


Selection cuts and Cut efficiencies for semi-leptonic final state

H^+H^- analysis, semi-leptonic final state selection		
Selection cut	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV
One lepton	$E_T > 10$ GeV	$E_T > 10$ GeV
Two jets	$E_T > 10$ GeV	$E_T > 10$ GeV
E_T^{miss}	$E_T^{\text{miss}} > 20$ GeV	$E_T^{\text{miss}} > 20$ GeV
$E(j_1) + E(j_2)$	$E(j_1) + E(j_2) < 150$ GeV	$E(j_1) + E(j_2) < 350$ GeV

H^+H^- analysis, semi-leptonic final state selection							
Cut eff.	BP1	BP2	BP3	WW	ZZ	Z	TT
Total eff.@ 500 GeV	0.5	0.64	0.2	0.014	0.00021	3.9e-05	0.0029
Total eff.@ 1 TeV	0.8	0.86	0.59	0.014	0.00035	9.6e-05	0.0032

Sum of the energies (up) and invariant mass (down) of two jets in semileptonic final state at $\sqrt{s} = 0.5$ TeV (left) and 1 TeV (right).



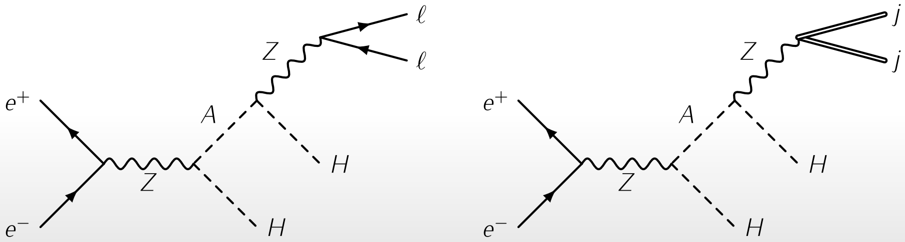
Number of events in signal and background processes after all selection cuts at integrated luminosity of 500 fb^{-1}.

H^+H^-, semi-leptonic final state at $\mathcal{L} = 500\ fb^{-1}$								
	$\sqrt{s}$ =0.5 TeV				$\sqrt{s}$ =1 TeV			
	S	B	S/B	$S/\sqrt{S+B}$	S	B	S/B	$S/\sqrt{S+B}$
BP 1	4887	3307	1.5	54	8709	2736	3.2	81
BP 2	5402	1342	4	66	8166	720	11	87
BP 3	478	1380	0.35	11	1534	602	2.5	33

$e^+e^- \to AH$

Signal and background cross sections

	$\sqrt{s} = 0.5$ TeV			$\sqrt{s} = 1$ TeV		
Process	$e^+e^- \to AH$			$e^+e^- \to AH$		
Benchmark point	BP1	BP2	BP3	BP1	BP2	BP3
Cross section [fb]	90	85.8	68.4	25	24.8	23.6

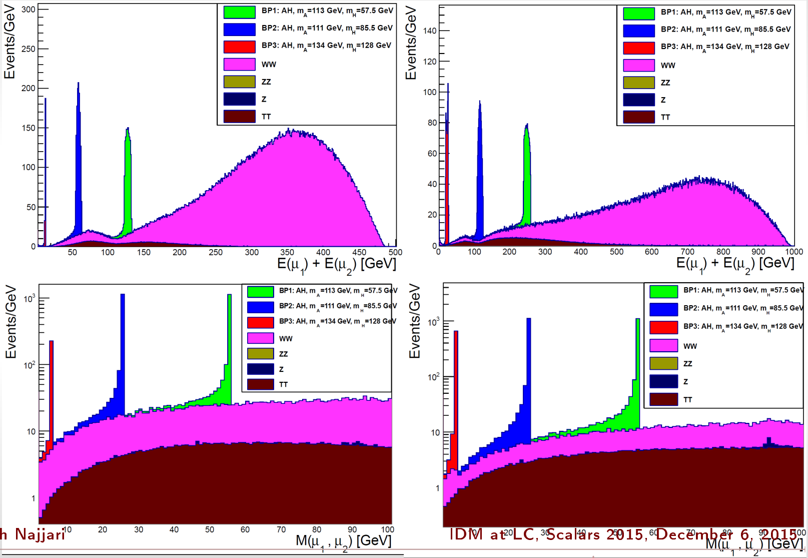


Selection cuts and cut efficiencies for fully leptonic final state

HA analysis, leptonic final state selection		
Selection cut	$\sqrt{s} = 0.5$ TeV	$\sqrt{s} = 1$ TeV
2 leptons	$E_T > 1$ GeV	$E_T > 5$ GeV
E_T^{miss}	$10 < E_T^{\text{miss}} < 120$ GeV	$10 < E_T^{\text{miss}} < 250$ GeV
$m_{\ell 1,\ell 2}$	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV	$\lvert m_{\ell 1,\ell 2} - m_Z \rvert > 20$ GeV

HA analysis, leptonic final state selection							
Cut eff.	BP1	BP2	BP3	WW	ZZ	Z	TT
Total eff.@ 0.5 TeV	0.99	1	0.22	0.67	0	1.5e–05	0.26
Total eff.@ 1 TeV	0.98	0.98	0.65	0.45	2e–06	4.2e–05	0.42

Sum of the energies (up) and invariant mass (down) of two lepton in leptonic final state at $\sqrt{s} = 0.5$ TeV (left) and 1 TeV (right).



Number of events in signal and background processes after all selection cuts at integrated luminosity of 500 fb^{-1}

HA, leptonic final state at $\mathcal{L} = 500\ fb^{-1}$								
	$\sqrt{s}$ =0.5 TeV				$\sqrt{s}$ =1 TeV			
	S	B	S/B	$S/\sqrt{S+B}$	S	B	S/B	$S/\sqrt{S+B}$
BP 1	1214	105	11.6	33	1220	55	22	34
BP 2	1223	71	17.2	34	1211	31	38.7	34
BP 3	225	34	6.6	14	666	13	50	26

Dark Matter Mass Measurement

- We can extract the DM mass by using the reconstructed peaks in the energy and invariant mass distributions.
- For this purpose, we assume that the off-shell W^* and Z^* are produced with their most probable virtuality.
- Let us consider the distribution of the sum of energies of the two jets, in the semi-leptonic final state of charged scalar production, $\sum_{i=1}^{2} E(j_i)$.
- In the W^* rest frame, the sum of jet energies is equal to the W^* mass and its most probable value is given by $m_{H^\pm} - m_H$.
- The Lorentz boost applied to jet energies can be related to scalar masses.

$$\boxed{\sum_{i=1}^{2} E(j_i) = E_{beam}\left(1 - \frac{m_H}{m_{H^\pm}}\right)}$$

- The invariant mass distribution for the two jets of the semi-leptonic final state in charged scalar production, $m(j_1, j_2)$, is expected to peak at the most probable W^* virtuality, i.e

$$\boxed{m(j_1, j_2) = m_{H^\pm} - m_H}$$

- By using the above two relations, we extract H and $H^\pm$ masses for each considered scenario.
- Similar procedure for two jet or two lepton invariant mass distribution for the neutral scalar pair production events, providing the value of $m_A - m_H$.
- This can be used to calculate the value of m_A.
- Hence, the IDM scalar mass spectrum can be reconstructed.

Conclusions

- The inert doublet model was studied for charged and neutral dark scalar production at linear colliders.
- For the charged scalar production, we considered $e^+e^- \to H^+H^-$, and for the neutral scalar production, we considered $e^+e^- \to AH$.
- Different benchmark scenarios where tested and detailed analyses were designed for each considered production channel with different final state.
- For the considered IDM benchmark scenarios, production of dark scalars should be observable at linear colliders running at center of mass energy of either 0.5 or 1 TeV.
- Using the reconstructed invariant mass and energy distributions of the visible decay products, the masses of dark matter particles can be extracted.