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

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Outline

1. Inert Doublet Model (IDM)
2. Analysis framework
3. Results
   - Charged scalar production
   - Neutral scalar production
   - Scalar mass reconstruction
4. Conclusions and Plans

Study done with Majid Hashemi, Maria Krawczyk and Saereh Najjari
Presented at “Scalars 2015” conference in Warsaw (December 2015)
arXiv:1512.01175

Inert Doublet Model

One of the simplest extensions of the Standard Model (SM).
The scalar sector consists of two doublets:

- Φ_S is the SM–like Higgs doublet,
- Φ_D (inert doublet) has four additional scalars H, A, $H^{\pm}$.

$$\Phi_S = \begin{pmatrix} G^{\pm} \\ \frac{v+h+iG^0}{\sqrt{2}} \end{pmatrix} \qquad \Phi_D = \begin{pmatrix} H^{\pm} \\ \frac{H+iA}{\sqrt{2}} \end{pmatrix}$$

The most general scalar potential:

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

has seven parameters $(m_{11,22}, \lambda_{1,2,3,4,5})$ that are assumed to be real.

Inert Doublet Model

Two parameters fixed from Standard Model (v, M_h)
$\Rightarrow$ 5 new, free parameters: M_H, M_A, $M_{H^\pm}$ + 2 couplings.

We assume a discrete Z_2 symmetry under which

- SM Higgs doublet Φ_S is *even*: $\Phi_S \to \Phi_S$ (also other SM→SM)
- inert doublet Φ_D is *odd*: $\Phi_D \to -\Phi_D$.

$\Rightarrow$ Yukawa-type interactions only for Higgs doublet (Φ_S).
The inert doublet (Φ_D) does not interact with the SM fermions!

$\Rightarrow$ The lightest inert particle is stable: a natural candidate for dark matter!
We assume the neutral scalar H is the dark matter particle.

Inert scalars couplings to γ, $W^\pm$ and Z determined by SM parameters
$\Rightarrow$ well established predictions for production and decay rates!

Inert Doublet Model

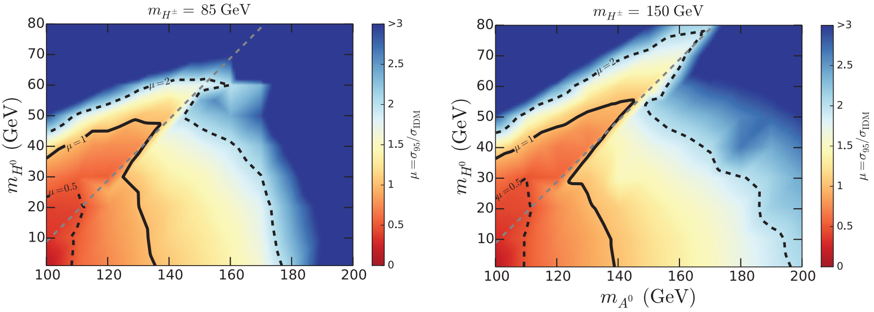
Constraints on inert scalar masses and couplings
see: A. Ilnicka, M. Krawczyk, and T. Robens, arXiv:1508.01671

- Theoretical
  - vacuum stability at tree level
  - perturbative unitarity
  - global minimum of the potential
- Experimental
  - The mass of the SM-like Higgs boson h
  - The upper bound on the total width of h
  - Total widths of W and Z boson
  - A lower bound from LEP on mass of $H^{\pm}$
  - Exclusion from SUSY searches at LEP and LHC experiments.
  - Agreement with electroweak precision observables
  - Lower limit on $H^{\pm}$ width from long-lived charged particle searches
  - Direct bound by the dark matter nucleon scattering is by LUX
  - Planck limit on relic density

Inert Doublet Model

Inert scalars can be pair-produced at LHC via virtual *Z* or *W* exchange.
Recasting the results of ATLAS Run I dilepton analyses:

- SUSY-2013-11: Chargino, neutralino and slepton [arXiv:1403.5294]
- HIGG-2013-03: $ZH \to l^+l^- +$ inv. [arXiv:1402.3244]



Sabine Kraml, presented at “Scalars 2015”, Warsaw, December 2015
G. Belanger et al., arXiv:1503.07367

Inert Doublet Model

Benchmark points (BP) for investigation at LHC Run II arXiv:1508.01671

- Benchmark point 1: low scalar mass

$$M_H = 57.5\,\mathrm{GeV},\ M_A = 113.0\,\mathrm{GeV}, M_{H^\pm} = 123\,\mathrm{GeV}$$

- Benchmark point 2: low scalar mass

$$M_H = 85.5\,\mathrm{GeV},\ M_A = 111.0\,\mathrm{GeV}, M_{H^\pm} = 140\,\mathrm{GeV}$$

- Benchmark point 3: intermediate scalar mass

$$M_H = 128.0\,\mathrm{GeV},\ M_A = 134.0\,\mathrm{GeV}, M_{H^\pm} = 176.0\,\mathrm{GeV}$$

- Benchmark point 4: high scalar mass, mass degeneracy

$$M_H = 363.0\,\mathrm{GeV}, M_A = 374.0\,\mathrm{GeV}, M_{H^\pm} = 374.0\,\mathrm{GeV}$$

- Benchmark point 5: high scalar mass, no mass degeneracy

$$M_H = 311.0\,\mathrm{GeV}, M_A = 415.0\,\mathrm{GeV}, M_{H^\pm} = 447.0\,\mathrm{GeV}$$

H is DM candidate, A decays always to $Z\,H$, $H^\pm$ decays mainly to $W^\pm\,H$

Analysis framework

- Signal events generated using CompHEP 4.5.2
  - based on IDM model files prepared using LanHEP 3.2,
  - final state showering and multi-particle interactions in PYTHIA 8.1.53.
- Background events generated with PYTHIA.
- Jet reconstruction with FASTJET 2.4.1
  - anti-kt algorithm with a cone size of 0.4.

- Running scenarios considered
  - $\sqrt{s} = 380, 500, 1000$ GeV
  - luminosity of 500 fb^{-1}

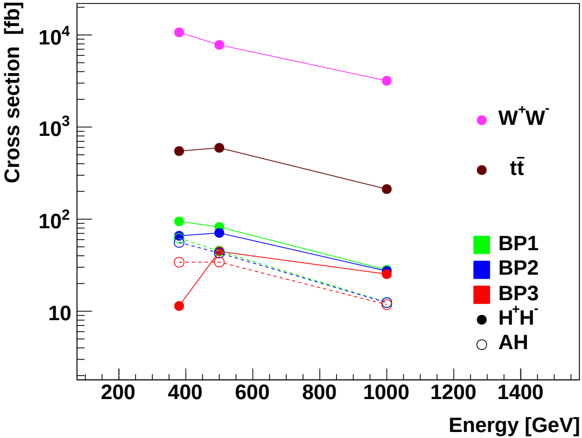
- No simulation of detector effects. Results corrected only for
  - angular acceptance
  - jet energy resolution $(\sigma_E = 50\%/\sqrt{E[GeV]})$

Analysis framework

CompHEP cross sections for charged and neutral scalar production

$$e^+e^- \to H^+H^- \,, \qquad e^+e^- \to AH$$

for three benchmark points considered:



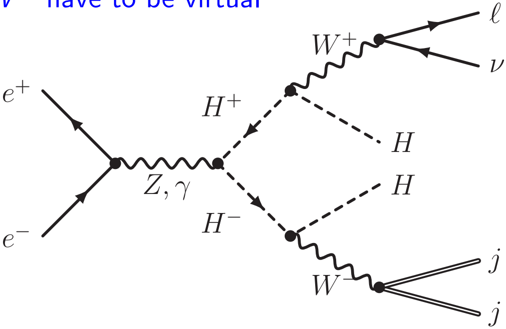
Charged scalar production

For the charged scalar pair production we focus on the decay channel

$$H^{\pm} \longrightarrow W^{\pm(\star)}\, H$$

For the considered benchmark scenarios $M_{H^{\pm}} < M_W + M_H$

$\Rightarrow$ produced $W^{\pm}$ have to be virtual

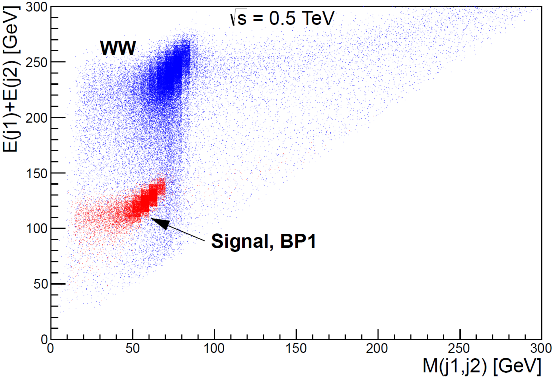


Final state topology depends on the $W^{\pm}$ decays (as for $t\bar{t}$ events)
Most promising channel: semi-leptonic decay

Charged scalar production

Jet energy sum vs invariant mass distribution for semi-leptonic channel:

- one lepton ($p_t > 10 GeV$)
- two jets ($E_T > 10 GeV$)
- a missing transverse momentum ($p_T^{miss} > 20 GeV$)



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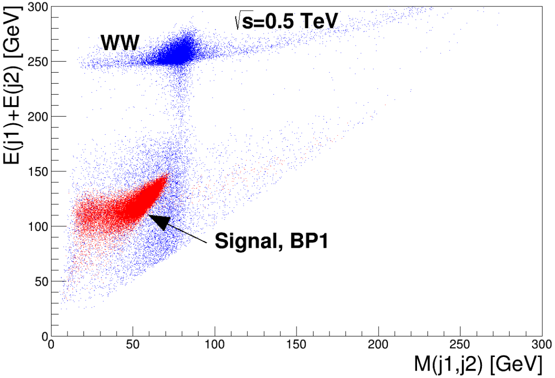


Dominant W^+W^- background can be further suppressed with cut on missing mass

Plot shown for $M_{miss} > 250 GeV$

Charged scalar production

How to interpret the maximum observed in $E_{j_1} + E_{j_2}$ vs $M_{j_1\,j_2}$ distribution

Semi-leptonic channel ⇒ two jets come from single off-shell $W^\pm$ decay

- two-jet invariant mass: $M_{j_1\,j_2} = M_{W^\star}$
- sum of jet energies: $E_{j_1} + E_{j_2} = E_{W^\star} = \gamma_{W^\star}\ M_{W^\star}$

where $\gamma_{W^\star}$ is the $W^\star$ Lorentz boost factor

We expect that $W^\star$ production with the highest virtuality is most likely
⇒ expect maximum at $M_{W^\star} \approx M_{H^\pm} - M_H$

With maximum virtuality $W^\star$ is almost at rest in the $H^\pm$ reference frame
⇒ we can approximate $W^\star$ boost by that of $H^\pm$: $\gamma_{W^\star} \approx \gamma_{H^\pm}$

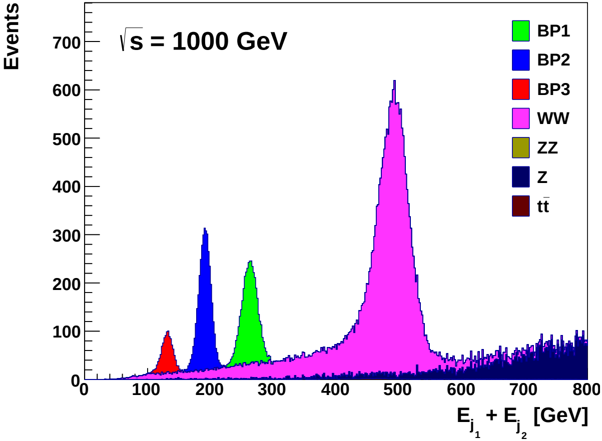
Energies of the charged scalars are given by the beam energy
⇒ their Lorentz boost factor: $\gamma_{H^\pm} = E_{beam}/M_{H^\pm}$

Therefore we expect to observe maximum at:

$$M_{j_1\,j_2} \approx M_{H^\pm} - M_H \qquad E_{j_1} + E_{j_2} = E_{beam}\left(1 - \frac{M_H}{M_{H^\pm}}\right)$$

Charged scalar production

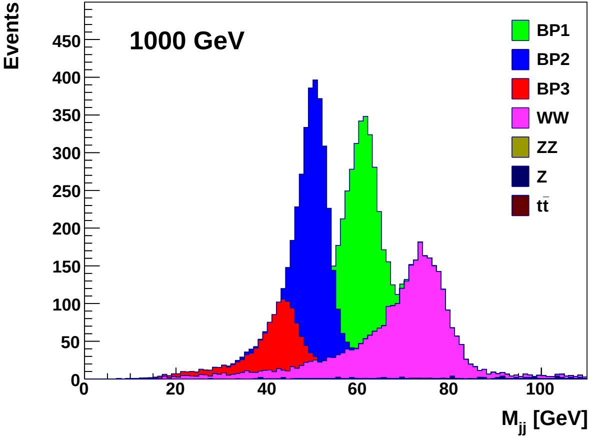
Distribution of the jet energy sum



Clear signal separation for all considered benchmark scenarios

Charged scalar production

Distribution of the two-jet invariant mass, after cut on jet energy sum



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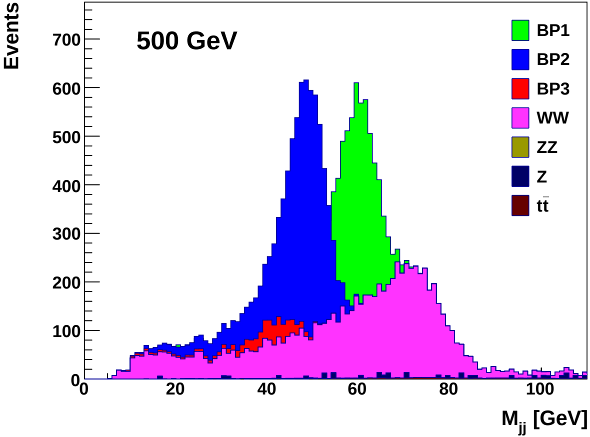

Clear signal separation for low mass benchmark scenarios

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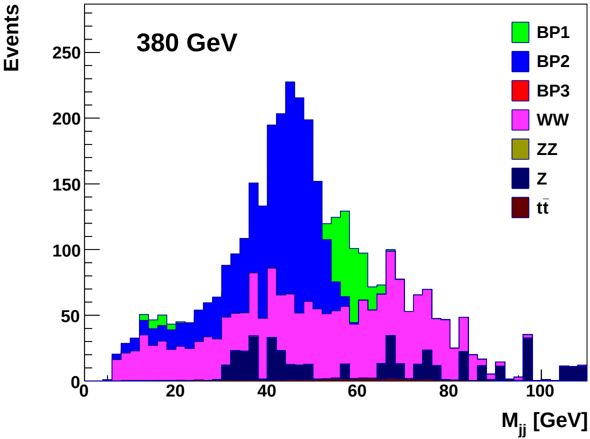


Clear signal separation for low mass benchmark scenarios

Charged scalar production

Unique kinematic constraints ⇒ high signal selection efficiency:

- 12 – 28% for $\sqrt{s}$=0.38 TeV (BP1 and BP2 only)
- 20 – 64% for $\sqrt{s}$=0.5 TeV
- 59 – 86% for $\sqrt{s}$=1 TeV

and good background suppression
⇒ signal to background ratio S/B after mass window cut:

- 1.44 – 3.7 for $\sqrt{s}$=0.38 TeV (BP1 and BP2 only)
- 0.35 – 4 for $\sqrt{s}$=0.5 TeV
- 2.5 – 11 for $\sqrt{s}$=1 TeV

Final statistical significance $S/\sqrt{S+B}$

- 25 – 39 for $\sqrt{s}$=0.38 TeV (BP1 and BP2 only)
- 11 – 66 for $\sqrt{s}$=0.5 TeV
- 33 – 87 for $\sqrt{s}$=1 TeV

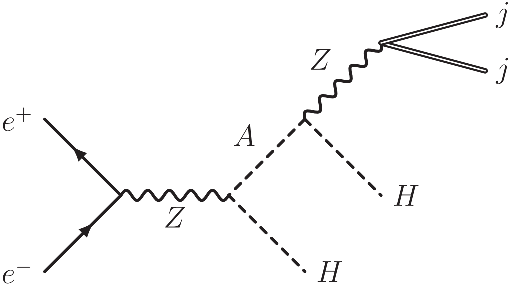
Neutral scalar production

For the neutral scalar pair production there is only one decay channel:

$$A \longrightarrow Z^{\star} H$$

For the considered benchmark scenarios $M_A < M_Z + M_H$

⇒ produced Z have to be virtual

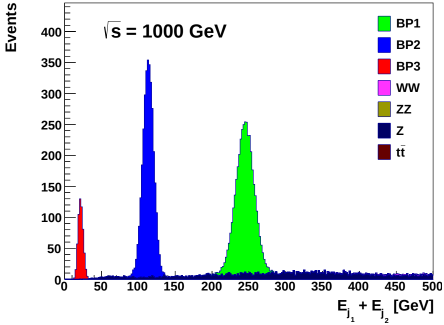


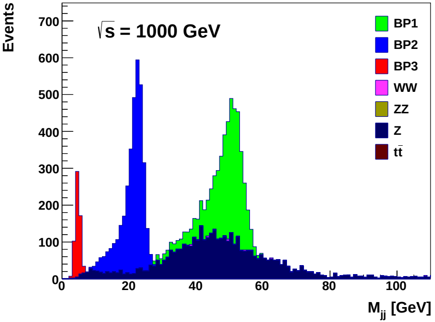
Both hadronic and leptonic Z decays can be considered.
Event statistics much higher in the hadronic channel.

Neutral scalar production

Final state is not symmetric ⇒ kinematic relations more complicated

However, we still expect to observe maxima for signal events in
jet energy sum and jet invariant mass distributions:





hadronic channel

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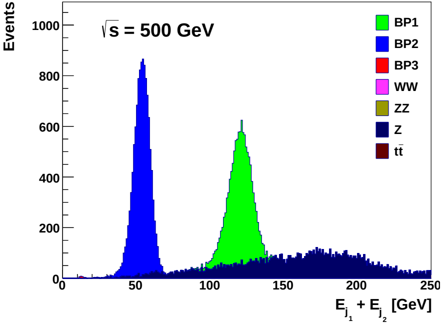

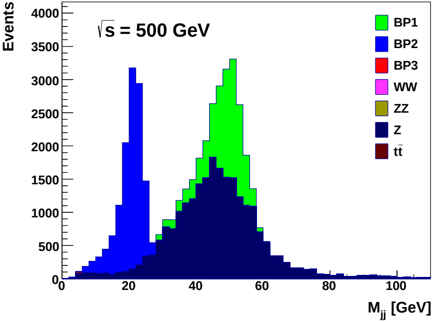

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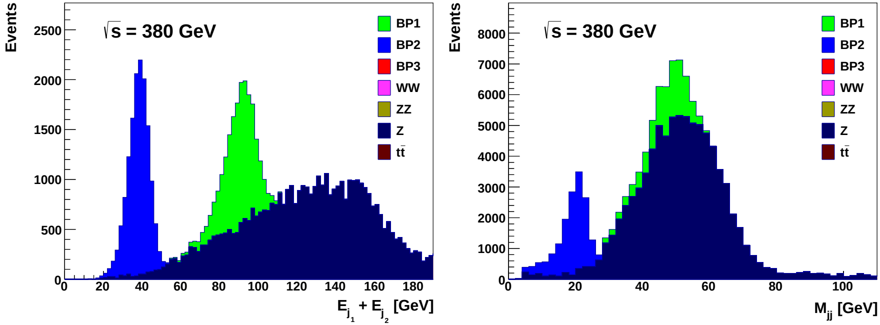

hadronic channel

Clear signal separation for low mass benchmark scenarios

Scalar mass reconstruction

For the charged scalar production $e^+e^- \rightarrow H^+H^-$

- Semi-leptonic channel $e^+e^- \rightarrow l\nu jjHH$
  - two jet invariant mass: $m_{jj} = m_{W^\star} \approx m_{H^\pm} - m_H$
  - sum of two jet energies: $E_{jj} = E_{beam}\,(1 - R)$, where $R = m_H/m_{H^\pm}$
- Fully hadronic channel $e^+e^- \rightarrow jjjjHH$

  As both $W^\star$ have the same Lorentz boost, jet with the highest energy (lab) comes from the same $W^\star$ as the jet with the lowest energy

  $\Rightarrow$ we can reconstruct both $W^\star$ easily
  - two jet invariant masses: $m_{14} = m_{23} = m_{W^\star} \approx m_{H^\pm} - m_H$
  - sum of four jet energies: $E_{4j} = 2\,E_{beam}\,(1 - R)$

For the neutral scalar production $e^+e^- \rightarrow HA$

- For leptonic channel $e^+e^- \rightarrow llHH$

  two lepton invariant mass: $m_{ll} = m_{Z^\star} \approx m_A - m_H$
- For hadronic channel $e^+e^- \rightarrow jjHH$

  two jet invariant mass: $m_{jj} = m_{Z^\star} \approx m_A - m_H$

Scalar mass reconstruction

Expected statistical precision of scalar mass determination with 500 fb^{-1}

Scalar	$\sqrt{s}$ [TeV]	BP1	BP2	BP3
$m_{H^\pm}$	theo.	123	140	176
	0.38	125.85 ± 0.17	136.53 ± 0.25	
	0.5	119.00 ± 0.10	138.43 ± 0.14	170.03 ± 0.38
	1	114.20 ± 0.06	130.45 ± 0.05	164.36 ± 0.23
m_H	theo.	57.5	85.5	128
	0.38	66.70 ± 0.09	92.69 ± 0.17	
	0.5	60.01 ± 0.05	89.78 ± 0.06	129.92 ± 0.30
	1	54.21 ± 0.04	80.72 ± 0.03	121.33 ± 0.17
m_A	theo.	113	111	134
	0.38	121.91 ± 0.10	117.52 ± 0.18	
	0.5	115.02 ± 0.06	114.27 ± 0.07	135.78 ± 0.38
	1	109.02 ± 0.05	105.39 ± 0.04	126.34 ± 0.19

The systematic shifts observed between the assumed (theo.) scalar masses and the fit results are due to the simplified approach used.

Can be corrected for based on the simulation results.

Conclusions

- Inert Doublet Model is one of the simplest extensions of the Standard Model providing a candidate for dark matter.
  - Second scalar doublet is not involved in mass generation and does not couple to fermions
  - IDM with inert scalar masses of the order of M_Z still in agreement with all existing data

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  - Run 1 limits on m_H extend to $\sim$50 GeV only
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- IDM should be clearly visible at high energy e^+e^- collider for low and intermediate mass scenarios
    - Well constrained kinematics allows for efficient selection
    - Scalar masses can be reconstructed with statistical precision of the order of 100 MeV

Plans

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  - Finalize 380 GeV results
  - Consider high mass benchmark points (at 1.5 or 3 TeV)

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- Proceed with detector level analysis