Signatures of new scalar particles at future e^+e^- colliders

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Outline

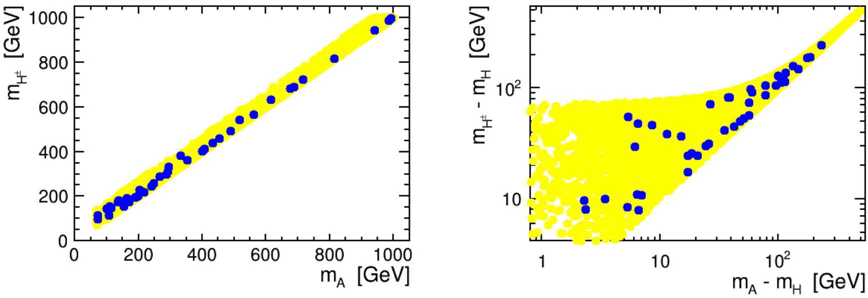
1. Inert Doublet Model analysis
   - Benchmark points
   - Leptonic analysis
   - Semi-leptonic analysis
2. Search for invisible scalar production
3. Future plans

For more details:

- IDM benchmark points: JHEP 1812 (2018) 081, arXiv:1809.07712
- IDM @ CLIC report: JHEP 1907 (2019) 053, arXiv:1811.06952
- Latest IDM results: arXiv:2002.11716
- Invisible scalar analysis: arXiv:2002.06034

IDM benchmark points

Out of about 15'000 points consistent with all considered constraints, we chose 41 benchmark points (including 20 "high mass") for detailed studies:



The selection was arbitrary, but we tried to

- cover wide range of scalar masses and the mass splittings
- get significant contribution to the relic density

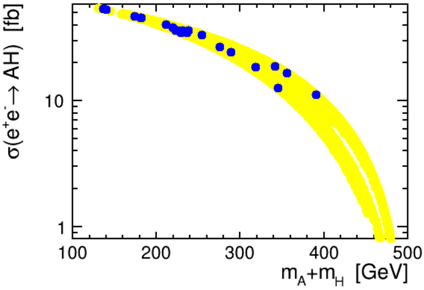
See previous presentation by Tania Robens for more details

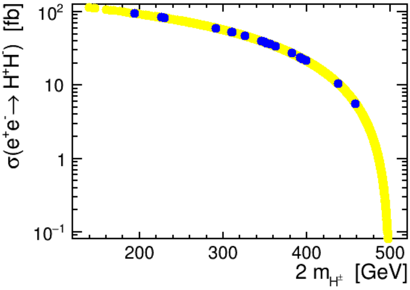
IDM production at e^+e^- colliders

Production of IDM scalars at e^+e^- colliders dominated by two processes:

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

Leading-order cross sections for IDM scalar production at 500 GeV:





Production via EW couplings ⇒ week dependence on IDM couplings

Beam luminosity spectra not taken into account

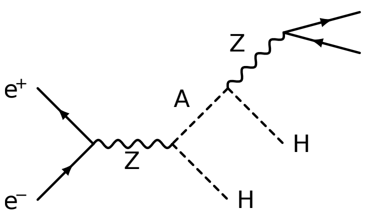
IDM scalars: leptonic analysis

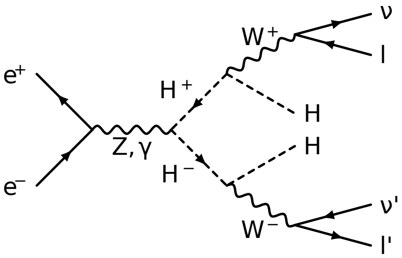
Same flavour lepton pair production can be considered a signature of the AH production process followed by the A decay:

$$e^+e^- \rightarrow HA \rightarrow HHZ^{(\star)} \rightarrow HH\mu^+\mu^-$$

while the production of the different flavour lepton pair is the expected signature for H^+H^- production:

$$e^+e^- \rightarrow H^+H^- \rightarrow HHW^{+(*)}W^{-(*)} \rightarrow HH\ell^+\ell'^-\nu\bar{\nu}'$$



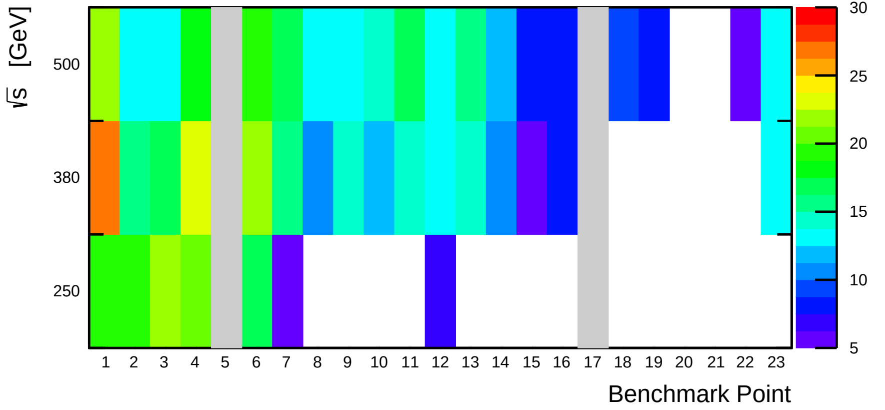


Neutral IDM scalar production

Significance of observation scenario-independent approach

Summary of results for multivariate analysis of $\mu^+\mu^-$ final state

(generator level analysis, cuts reflecting detector acceptance)



High significance of observation for scenarios accessible at given energy

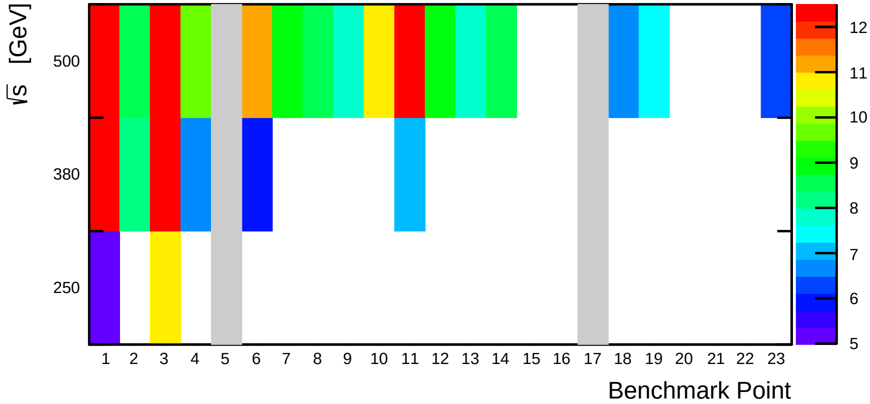
Significance mainly related to the *AH* production cross section ⇒ scalar masses

Charged IDM scalar production

Significance of observation scenario-independent approach

Summary of results for multivariate analysis of $e^{\pm}\mu^{\mp}$ final state

(generator level analysis, cuts reflecting detector acceptance)



Fewer scenarios can be observed, clear need for 500 GeV

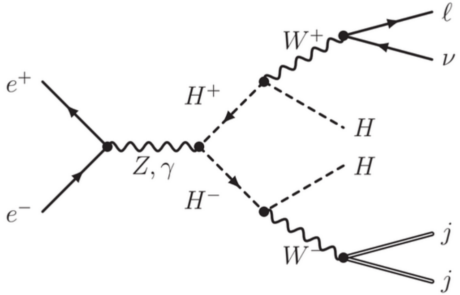
Significance mainly related to the H^+H^- production cross section $\Rightarrow$ scalar mass

IDM scalars: semi-leptonic analysis

For high scalar masses leptonic channel sensitivity limited by cross section

Much higher significance can be expected for H^+H^- production in the semi-leptonic final state (isolated lepton and two jets)

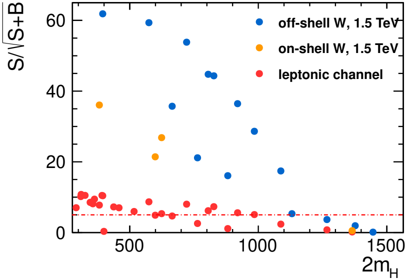
- energy and invariant mass recontruction for one of W bosons
  $\Rightarrow$ better signal-background separation
- much larger branching fraction compared to $e\mu$: 2.25% $\Rightarrow$ 28.6%
  $\Rightarrow$ discovery reach should increase significantly

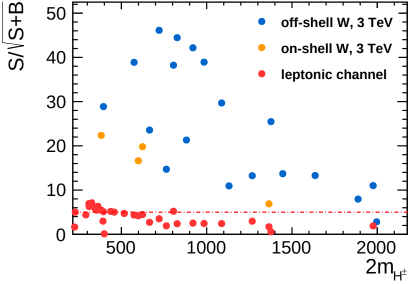


Results

Summary of results obtained for the semi-leptonic channel

compared with leptonic channel results for high mass benchmarks @ CLIC





Huge increase of signal significance!

Discovery reach extended up to $m_{H^{\pm}} \sim 1$ TeV for CLIC @ 3 TeV

Invisible scalar production

Motivation

In Higgs-portal models, new scalars fields ϕ coupling to dark matter particles can mix with the SM Higgs field h resulting in two mass eigenstates:

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

If $\alpha \ll 1$, h_1 is SM-like (the observed 125 GeV state),
but it can also decay invisibly via ϕ component (BR $\sim \sin^2\alpha$)

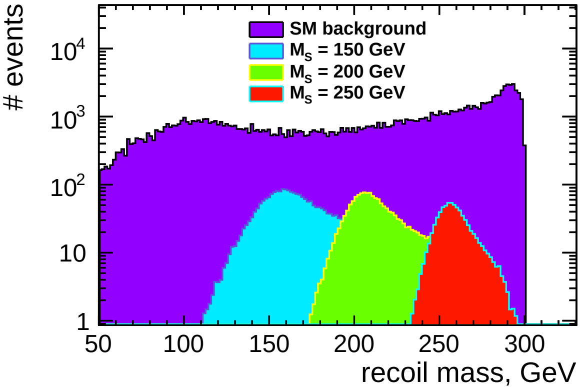
If h_2 is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson; invisible decays dominate.

We consider Vector-fermion dark matter model (VFDM) for simulation: arXiv:1710.01853

Same approach used as in the search for invisible SM Higgs boson decays.
Search for the process:

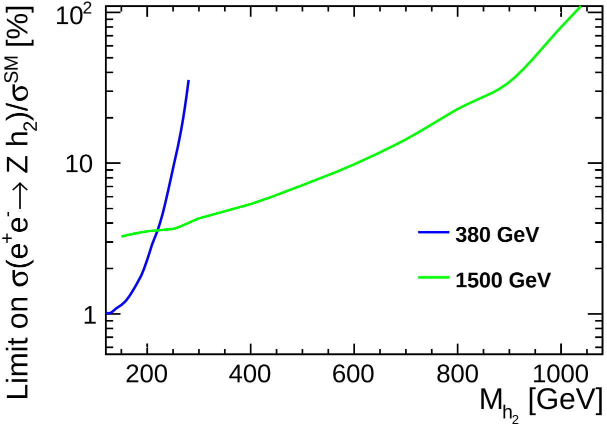
$$e^+e^- \to Z\ S \quad \to \quad q\ \bar{q}\ +\ \not{E}_T$$

Expected distribution of the recoil mass for CLIC running at 380 GeV:



Cross section limits

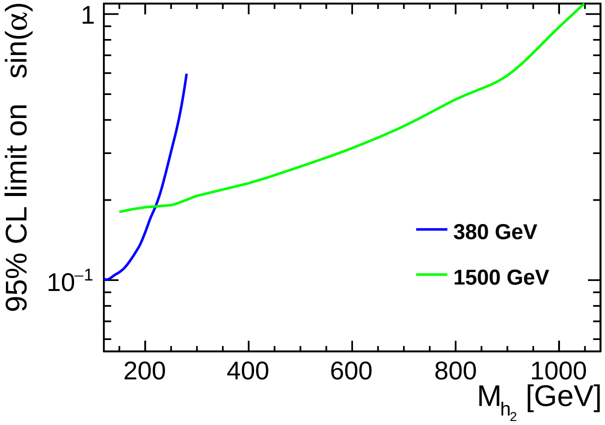
Expected CLIC limits on the h_2 production cross section, relative to SM for $1000\,\mathrm{fb}^{-1}$ at 380 GeV and $2500\,\mathrm{fb}^{-1}$ at 1500 GeV



assuming BR($h_2 \to inv$) ≈ 100%

Mixing angle limits

Corresponding CLIC limits on the sine of the mixing angle
for $1000\,\mathrm{fb}^{-1}$ at 380 GeV and $2500\,\mathrm{fb}^{-1}$ at 1500 GeV



assuming $BR(h_2 \to inv) \approx 100\%$

Experimental signatures

Covered in the presented studies (IDM and VFDM models)

final state	$\not{E}_T :$ 1 particle	$\not{E}_T : \geq 2$ particles
$Z + \not{E}_T$	$e^+e^- \to Z\ h_2$	$e^+e^- \to A\ H\ \to\ Z\ H\ H$
$W^+W^- + \not{E}_T$		$e^+e^- \to H^+H^-$

Future plans

Experimental signatures

Covered in the presented studies (IDM and VFDM models)
and considered for new study (possible Snowmass contribution)

final state	$\not{E}_T$: 1 particle	$\not{E}_T$: $\geq$ 2 particles
$Z + \not{E}_T$	$e^+e^- \to Z\ h_2$	$e^+e^- \to A\ H\ \to\ Z\ H\ H$
$W^+W^- + \not{E}_T$		$e^+e^- \to H^+H^-$
$h + \not{E}_T$		
$t\bar{t} + \not{E}_T$	e.g. $e^+e^- \to H\ a$	in 2HDM+a
$b\bar{b} + \not{E}_T$		

Conclusions

Signatures of new scalar production at future e^+e^- colliders

Production of Inert Doublet Model scalars can be observed with high significance in the di-lepton channels already with 250 GeV e^+e^- collider

Discovery reach increases for higher $\sqrt{s}$.
Semi-leptonic final state has to be considered for large masses!

Search for production and invisible decays of new scalars can give constraints complementary to precise 125 GeV Higgs boson measurements.

Experimentalist's point of view:

- Mono-Z and W-pair signatures considered so far.
  - Mono-h as well as $t\bar{t}$ and $b\bar{b}$ considered as next targets
    - Focusing on cross-section limits rather than particular models...

Thank you!

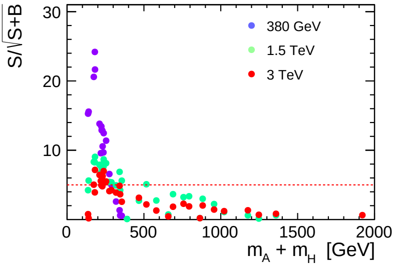
IDM: prospects at higher energies

JHEP 1907 (2019) 053, arXiv:1811.06952

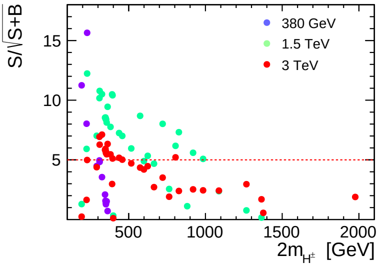
Leptonic channel sensitivity for CLIC running scenarios:

$1000\,fb^{-1}$ at 380 GeV $2500\,fb^{-1}$ at 1.5 TeV $5000\,fb^{-1}$ at 3 TeV

AH signature ($\mu^+\mu^-$)



H^+H^- signature ($\mu^\pm e^\mp$)



Only moderate increase in discovery reach for 1.5 TeV:

- neutral scalar production: $m_A + m_H < 450$ GeV (290 GeV @ 380 GeV)
- charged scalar production: $m_{H^\pm} < 500$ GeV (150 GeV @ 380 GeV)

Production cross sections too low at 3 TeV...

Backup slide

Analysis framework for semi-leptonic and invisible scalar analysis

Event samples generated with Whizard 2.7.0

based on the dedicated IDM and VFDM model implementations

fragmentation and hadronisation is simulated using PYTHIA 6.4

CLIC beam energy spectra taken into account

Consider running with ±80% electron beam polarisation,

with 2.5 ab^{-1} collected at 1.5 TeV and 5 ab^{-1} collected at 3 TeV

Fast simulation of CLIC detector response with DELPHES

dedicated CLICdet model cards

beam related backgrounds taken into account

by additional jet energy-momentum smearing