Inert Doublet Model signatures at Future e^+e^- Colliders

Jan Kalinowski[a], Jan Klamka[a], Wojciech Kotlarski[b], Tania Robens[c,d], Dorota Sokolowska[a,e], Pawel Sopicki[a], **Aleksander Filip Żarnecki**[a]

FACULTY OF PHYSICS UNIVERSITY OF WARSAW

[a] Faculty of Physics, University of Warsaw
[b] Institut für Kern- und Teilchenphysik, TU Dresden
[c] MTA-DE Particle Physics Research Group, University of Debrecen
[d] Theoretical Physics Division, Rudjer Boskovic Institute, Zagreb
[e] International Institute of Physics, Universidade Federal do Rio Grande do Norte, Brasil

Research supported by NATIONAL SCIENCE CENTRE POLAND

An Alpine LHC Physics Summit 2019

Outline

For more details:

- on benchmark points: JHEP 1812 (2018) 081, arXiv:1809.07712
- results submitted to CLIC Physics Potential report: arXiv:1811.06952

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, $H^{\pm}$.

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

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, $H^\pm$.

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

We assume a discrete Z_2 symmetry under which

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

$\Rightarrow$ 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.

$$m_H < m_A,\ m_{H^\pm}$$

Inert Doublet Model

After EWSB, the model contains a priori seven free parameters.

Two parameters can be fixed from the Standard Model (v, m_h).

We are left with five free parameters, which we take as:

$\Rightarrow$ three inert scalar masses: m_H, m_A, $m_{H^\pm}$

$\Rightarrow$ two couplings, eg. λ_2 and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

Inert Doublet Model

After EWSB, the model contains a priori seven free parameters.

Two parameters can be fixed from the Standard Model (v, m_h).

We are left with five free parameters, which we take as:

$\Rightarrow$ three inert scalar masses: m_H, m_A, $m_{H^\pm}$
$\Rightarrow$ two couplings, eg. λ_2 and $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

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

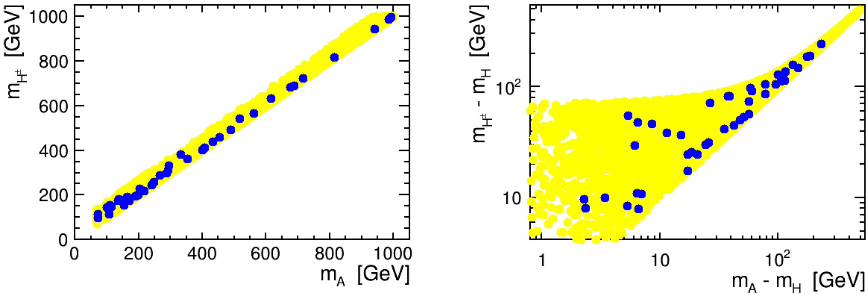
We scanned the IDM parameter space looking for scenarios consistent with current theoretical and experimental constraints, for masses up to 1 TeV.

For details and previous IDM parameter scan results see:

- Agnieszka Ilnicka, Maria Krawczyk, and Tania Robens, *Inert Doublet Model in light of LHC Run I and astrophysical data*, Phys. Rev. D93(5):055026, 2016, arXiv:1508.01671.
- Agnieszka Ilnicka, Tania Robens, and Tim Stefaniak, *Constraining Extended Scalar Sectors at the LHC and beyond*, Mod. Phys. Lett. A33(10n11):1830007, 2018, arXiv:1803.03594.

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

For details see: JHEP 1812 (2018) 081, arXiv:1809.07712

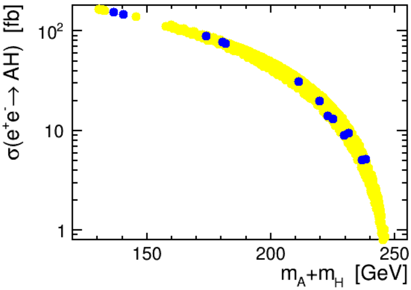
For list of benchmark point parameters, see backup slides

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

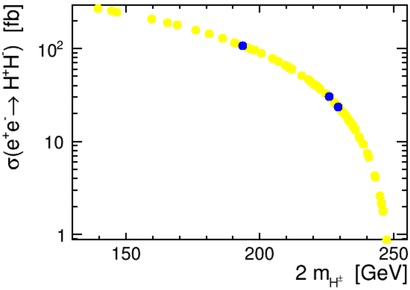
$$e^+e^- \to A \;\; H \qquad\qquad e^+e^- \to H^+H^-$$

Leading-order cross sections for inert scalar production processes at 250 GeV:

13 benchmarks



3 benchmarks



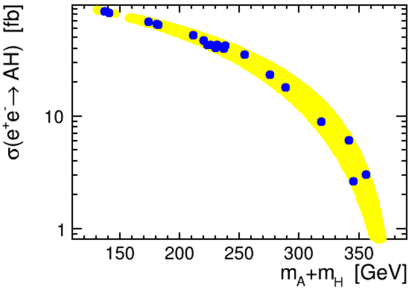
Beam luminosity spectra not taken into account

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

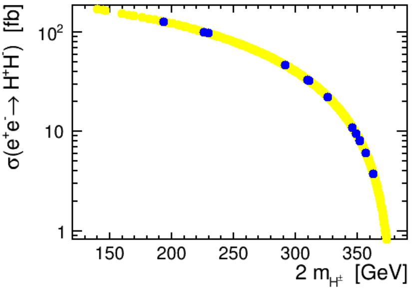
$$e^+e^- \to A\ H \qquad\qquad e^+e^- \to H^+H^-$$

Leading-order cross sections for inert scalar production processes at 380 GeV:

20 benchmarks



15 benchmarks



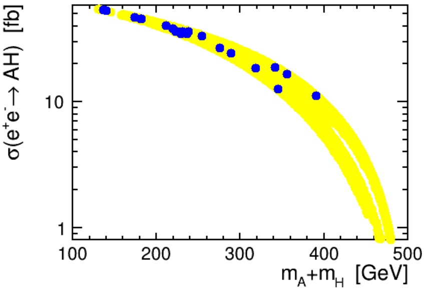
Beam luminosity spectra not taken into account

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

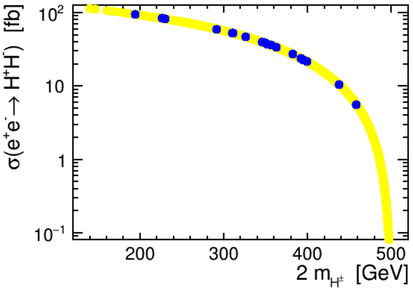
$$e^+e^- \to A\ H \qquad\qquad e^+e^- \to H^+H^-$$

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

21 benchmarks



21 benchmarks



Beam luminosity spectra not taken into account

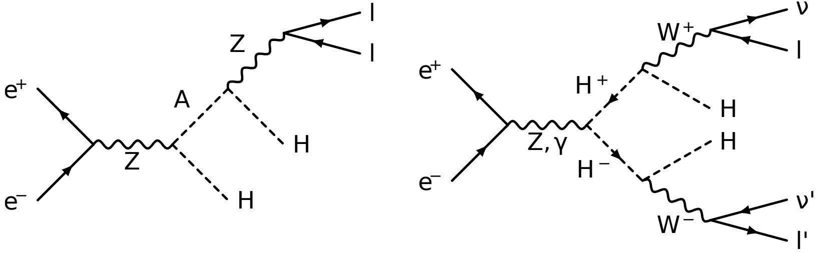
Analysis strategy

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:

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



Analysis strategy

We consider two possible final state signatures:

- muon pair production, $\mu^+\mu^-$, for AH production
- electron-muon pair production, μ^+e^- or $e^+\mu^-$, for H^+H^- production

Both channels include contributions from AH and H^+H^- production!
In particular due to leptonic tau decays.

Signal and background samples were generator with WHizard 2.2.8
based on the dedicated IDM model implementation in SARAH,
parameter files for benchmark scenarios were prepared using SPheno 4.0.3

Generator level cuts reflecting detector acceptance:

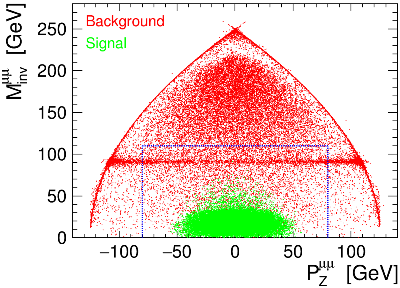
- require lepton energy $E_l > 5\,\text{GeV}$ and lepton angle $\Theta_l > 100\,\text{mrad}$
- no ISR photon with $E_\gamma > 10\,\text{GeV}$ and $\Theta_\gamma > 100\,\text{mrad}$

No detector resolution/efficiency taken into account
(but only electrons and muons in the final state)

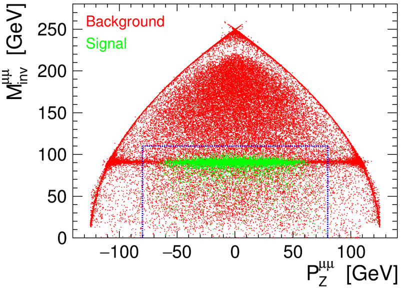
Neutral scalar production @ 250 GeV

Muon pair invariant mass, $\mathrm{M}_{inv}^{\mu\mu}$, as a function of the lepton pair long. momentum, $\mathrm{P}_{\mathrm{Z}}^{\mu\mu}$, for IDM signal and SM background, at 250 GeV

BP1



BP9

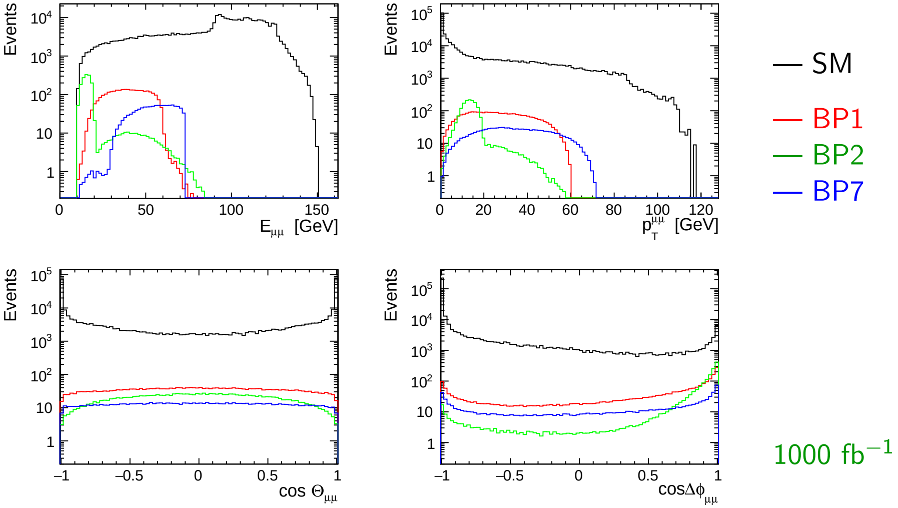


Background dominated by muon pair production $(e^+e^- \to \mu^+\mu^-)$ at nominal energy and radiative events $(e^+e^- \to \mu^+\mu^-\gamma)$

$\Rightarrow$ apply pre-selection cuts: $\mathrm{M}_{\mu\mu} < 0.33\sqrt{s}$ and $|\mathrm{P}_{\mathrm{Z}}^{\mu\mu}| < 0.44\sqrt{s}$

Neutral scalar production @ 250 GeV

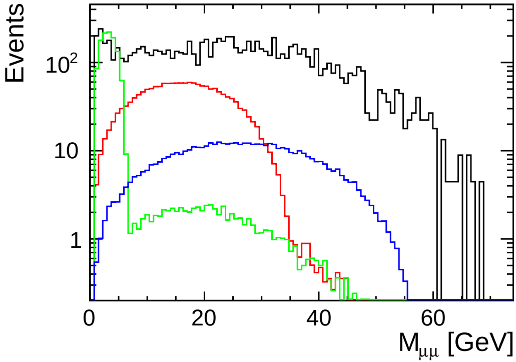
Distributions of the kinematic variables describing the leptonic final state



Cut based approach

Lepton pair invariant mass distribution after selection cuts 1000 fb^{-1}

- pair energy
  $E_{\mu\mu} < 75\,\mathrm{GeV}$
- transverse momentum
  $p_T^{\mu\mu} > 10\,\mathrm{GeV}$
- production angle
  $45^\circ < \Theta_{\mu\mu} < 135^\circ$
- azimuthal distance
  $|\Delta\varphi_{\mu\mu}| < \frac{\pi}{2}$



IDM signal would result in the visible excess in $M_{\mu\mu}$ distribution

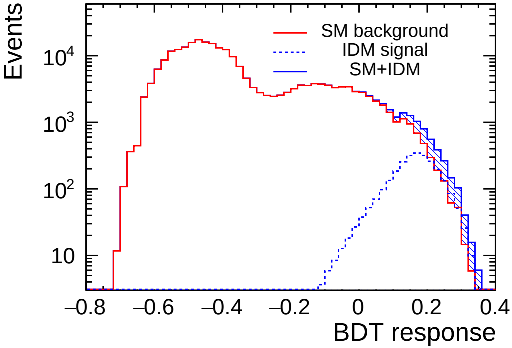
15.9σ, 11.6σ and 5.4σ, for BP1, BP2 and BP7

(without any cut on $M_{\mu\mu}$)

Multivariate analysis

BDT classifier with 8 input variables used for selection of signal events

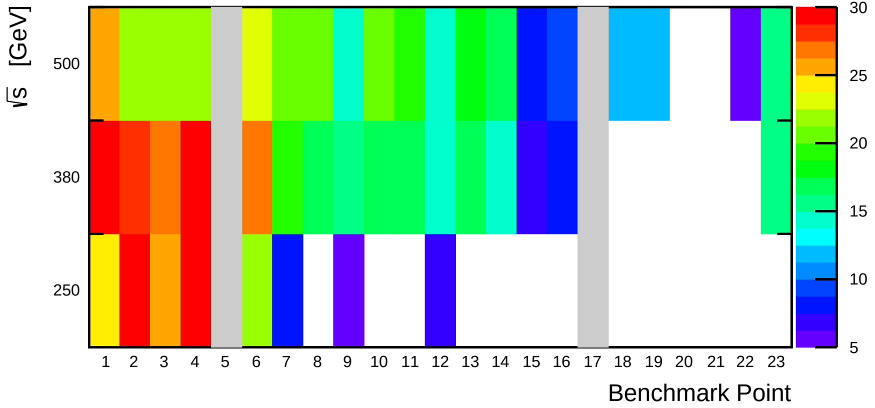
Response distribution for $\mu\mu$ channel: BP1 scenario and SM background
unpolarised 1000 fb^{-1} at $\sqrt{s} = 250$ GeV



$\Rightarrow$ signal significance of about 24 σ for BDT> 0.11

Significance of observation from multivariate analysis

Summary of results for the considered benchmark scenarios



High significance of observation for scenarios accessible at given energy

Expected significance mainly related to the *AH* production cross section

Wait !!!

We trained BDTs to separate the considered signal from the background

But we will not know in advance what to look for!

We will not know details of the model (scalar masses)

Wait !!!

We trained BDTs to separate the considered signal from the background
But we will not know in advance what to look for!
We will not know details of the model (scalar masses)

Modified approach

Divide the considered BP scenarios in two groups:

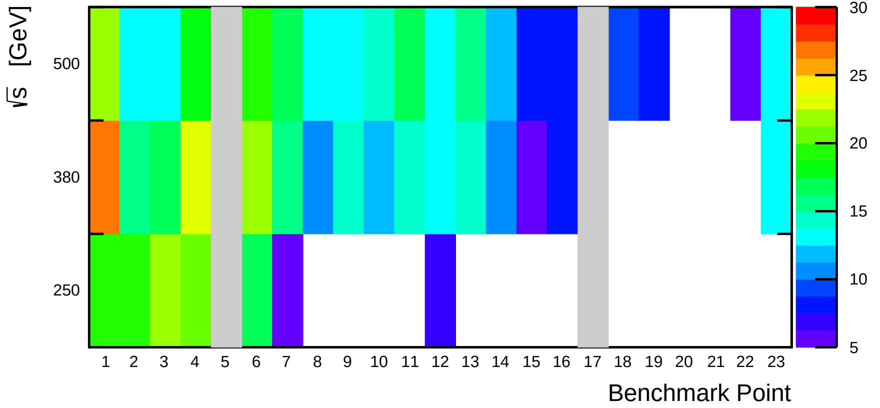
- scenarios with real Z (or real W) production
- scenarios with virtual Z (or virtual W) in intermediate state

For each group: search for given BP (test sample)
while using all other scenarios to train BDT (training samples)

Corresponds to the assumption that two independent BDTs will be used in the analysis for the two cases...

Significance of observation from modified approach

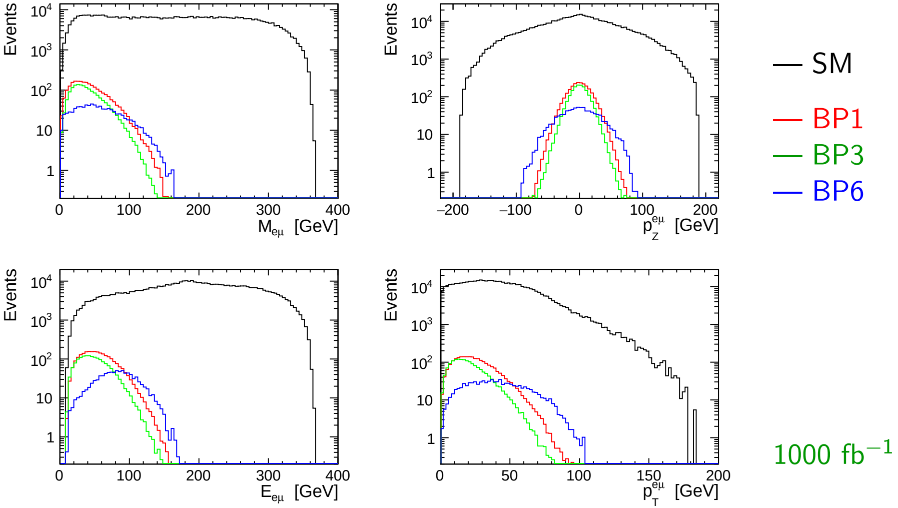
Summary of results for the considered benchmark scenarios



Significance reduced by about 20% but still high for accessible scenarios

We can perform general search for neutral IDM scalar pair-production

Distributions of the kinematic variables describing the leptonic final state

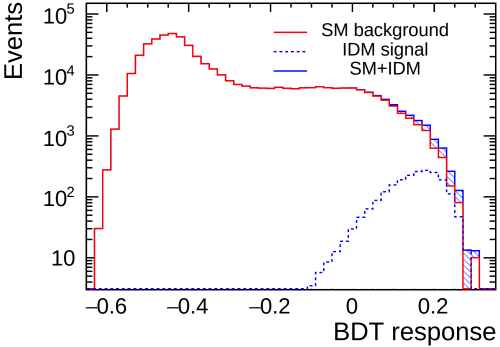


Multivariate analysis

BDT classifier with 8 input variables used for selection of signal events

Response distribution for $e\mu$ channel: BP1 scenario and SM background

unpolarised 1000 fb^{-1} at $\sqrt{s} = 380$ GeV

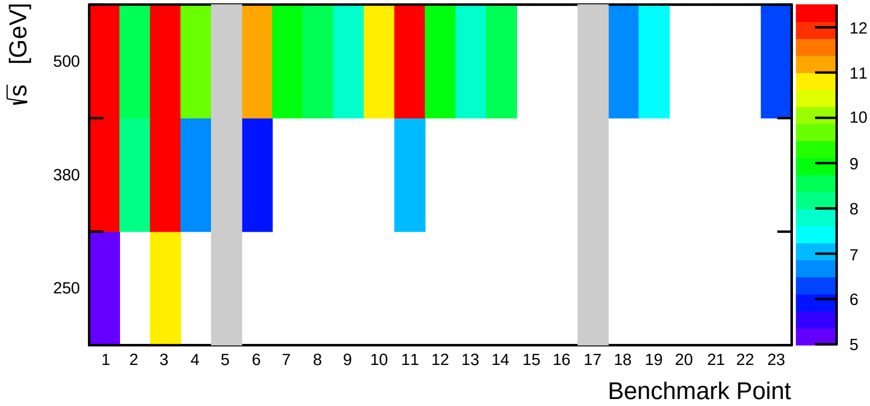


$\Rightarrow$ signal significance of about 17 σ for BDT> 0.12

Charged scalar production

Significance of observation scenario-independent approach

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



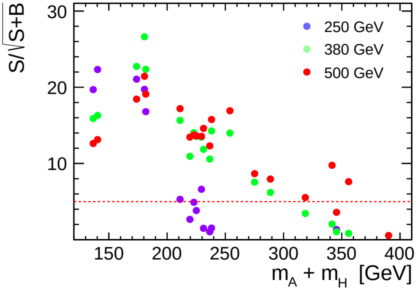
Fewer scenarios can be observed, clear need for 500 GeV

Significance reduced by about 10% by modified BDT training procedure

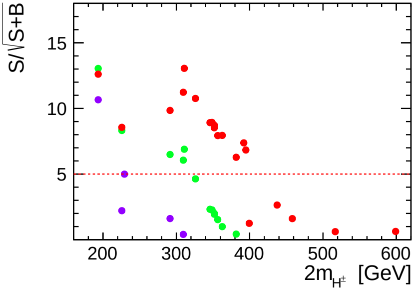
Expected significance

Search for pair-production of IDM scalars, for different $\sqrt{s}$

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



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



Discovery reach mainly depends on the scalar masses!

- $m_A + m_H < 220, 300, 330$ GeV
- $m_{H^\pm} < 110, 160, 200$ GeV

for 1000 fb^{-1} at $\sqrt{s} = 250, 380, 500$ GeV

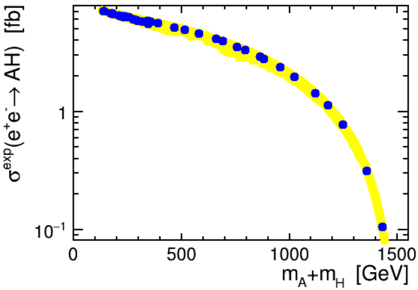
Prospects at higher energies

Production of IDM scalars considered also for high energy stages of CLIC

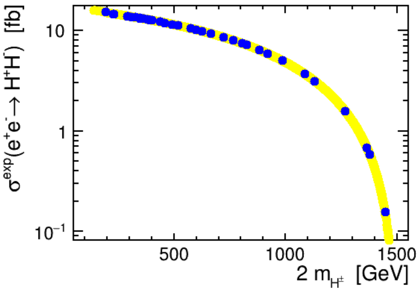
See arXiv:1811.06952 for results submitted to CLIC Physics Potential report

Leading-order cross sections for inert scalar production at 1.5 TeV:

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



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



Much smaller cross sections for light IDM scalar production ($\sim \frac{1}{s}$)!

Beam luminosity spectra not taken into account

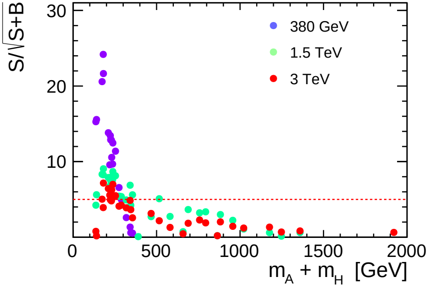
IDM study for CLIC

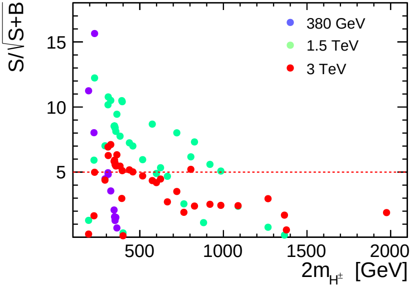
including luminosity spectra

Comparing CLIC running scenarios:

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

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





Only moderate increase in discovery reach for 1.5 TeV:

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

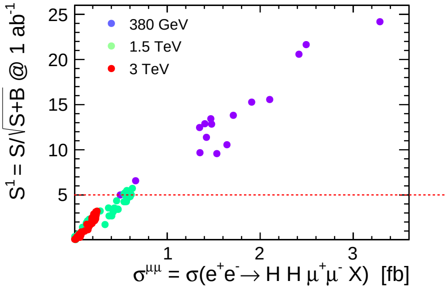
Prospects at higher energies

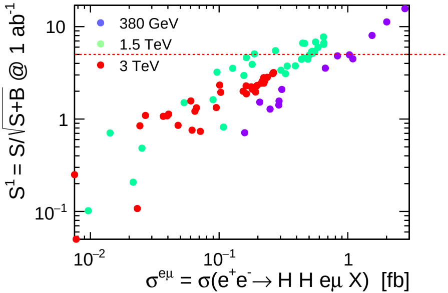
IDM study for CLIC

including luminosity spectra

Significance scaled to the same integrated luminosity of $1000\,\mathrm{fb}^{-1}$ as a function of the signal channel cross section

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





Expected significance mainly related to the signal channel cross section!

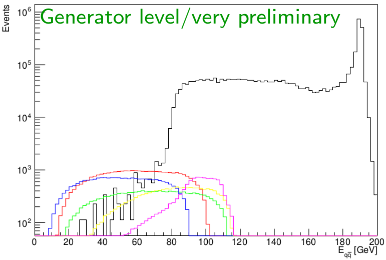
$\sim$ 0.5 fb sufficient for the discovery...

Prospects at higher energies

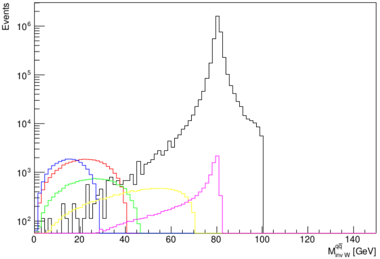
Much higher significance can be expected for H^+H^- production in the semi-leptonic final state (isolated lepton and two jets)

- 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%
  $\Rightarrow$ estimated discovery reach up to $m_{H^\pm} \sim 700$ GeV at 3 TeV

Hadronic $W^{(*)}$ energy



Hadronic $W^{(*)}$ mass



Considered benchmarks: BP1 BP2 BP3 BP4 BP6 @ 380 GeV

Analysis framework

Additional samples were generated with 100% polarised beams:

	P_{ele}	P_{pos}
LR	-100%	$+100\%$
RL	$+100\%$	-100%

These samples are mixed to obtain realistic polarisation levels:

Setup	P_{ele}	P_{pos}	$P_{pos} - P_{ele}$
$-+$	-80%	$+30\%$	$+1.1$
$-\,0$	-80%	0%	$+0.8$
$0\;0$	0%	0%	0
$+\,0$	$+80\%$	0%	-0.8
$+-$	$+80\%$	-30%	-1.1

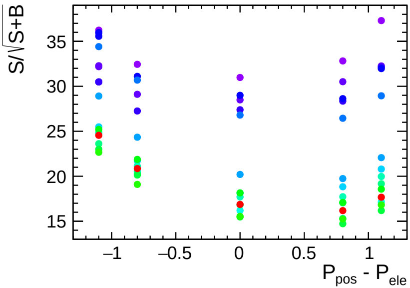
$P_{pos} - P_{ele}$ is used as 'polarisation label'

Luminosity spectra not taken into account

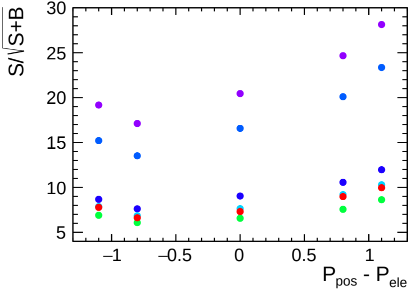
BDT analysis

Significance after BDT selection optimised for each BP and polarisation

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



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



Color indicates BP number

Selected BPs at 380 GeV

RL slightly better for *AH* signature, while LR better for H^+H^-

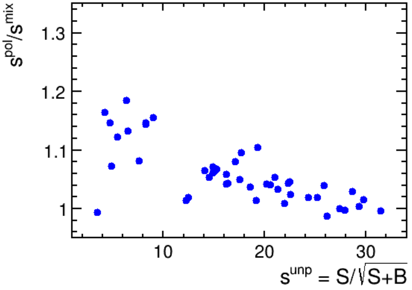
Final impact

Assume equal luminosity for two polarisations

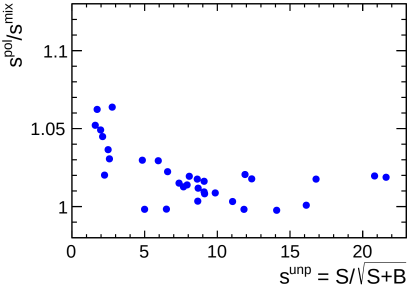
for CLIC running at 380 GeV: $P_{ele} = \pm 80\%$, $P_{pos} = 0$

Significance ratio for BDT analysis with and without polarisation input

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



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



Only marginal improvement, when using polarisation information

Conclusions

Inert Doublet Model is one of the simplest SM extensions
providing natural candidate for dark matter

Light IDM scenarios (masses in 0(100 GeV) range) are still not excluded

Low mass IDM scenarios can be observed with high significance in the di-lepton channels already with 250 GeV e^+e^- collider

Discovery reach increases for higher $\sqrt{s}$, but not above 1 TeV
Significant improvement expected when looking at semi-leptonic final state

Polarisation has only a marginal influence on the measurement
for 50:50 luminosity sharing

Thank you!

Additional references

Inert Doublet Model

- A. Ilnicka, M. Krawczyk, T. Robens, *Inert Doublet Model in light of LHC Run I and astrophysical data*, Phys. Rev. D93:055026, 2016, 1508.01671.
- Nilendra G. Deshpande and Ernest Ma, *Pattern of Symmetry Breaking with Two Higgs Doublets*, Phys. Rev. D18:2574, 1978.
- Laura Lopez Honorez and Carlos E. Yaguna, *The inert doublet model of dark matter revisited*, JHEP 09:046, 2010, 1003.3125.
- Ethan Dolle, Xinyu Miao, Shufang Su, and Brooks Thomas, *Dilepton Signals in the Inert Doublet Model*, Phys. Rev. D81:035003, 2010, 0909.3094.
- A. Goudelis, B. Herrmann, and O. Stål, *Dark matter in the Inert Doublet Model after the discovery of a Higgs-like boson at the LHC*, JHEP 09:106, 2013, 1303.3010.

Software

- Wolfgang Kilian, Thorsten Ohl, and Jurgen Reuter, *WHIZARD: Simulating Multi-Particle Processes at LHC and ILC*, Eur. Phys. J. C71:1742, 2011, arXiv:0708.4233.
- Florian Staub, *Exploring new models in all detail with SARAH*, Adv. High Energy Phys. 2015:840780, 2015, arXiv:1503.04200.
- Werner Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e+ e- colliders*, Comput. Phys. Commun. 153:275–315, 2003, hep-ph/0301101.
- Andreas Hoecker, Peter Speckmayer, Joerg Stelzer, Jan Therhaag, Eckhard von Toerne, and Helge Voss, *TMVA: Toolkit for Multivariate Data Analysis*, PoS ACAT:040, 2007, physics/0703039.

IDM benchmark points

Constraints on inert scalar masses and couplings

- Theoretical
  - vacuum stability at tree level
  - perturbative unitarity
  - global minimum of the potential
- Experimental
  - (SM-like) Higgs boson mass and signal strenghts from LHC
  - Total widths of W and Z boson
  - Agreement with electroweak precision observables
  - Exclusion from SUSY searches at LEP and LHC experiments
    we use whatever is available, but not all recasts are done yet
  - Lower limit on $H^{\pm}$ width from long-lived charged particle searches
  - Direct bound by the dark matter nucleon scattering (LUX, XENON1T)
  - Planck upper limit on relic density

Low mass IDM benchmark points

No.	M_H	M_A	$M_{H\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
BP1	72.77	107.8	114.6	1.445	-0.004407	0.1201
BP2	65	71.53	112.8	0.7791	0.0004	0.07081
BP3	67.07	73.22	96.73	0	0.00738	0.06162
BP4	73.68	100.1	145.7	2.086	-0.004407	0.08925
BP6	72.14	109.5	154.8	0.01257	-0.00234	0.1171
BP7	76.55	134.6	174.4	1.948	0.0044	0.0314
BP8	70.91	148.7	175.9	0.4398	0.0051	0.124
BP9	56.78	166.2	178.2	0.5027	0.00338	0.08127
BP10	76.69	154.6	163	3.921	0.0096	0.02814
BP11	98.88	155	155.4	1.181	-0.0628	0.002737
BP12	58.31	171.1	173	0.5404	0.00762	0.00641
BP13	99.65	138.5	181.3	2.463	0.0532	0.001255
BP14	71.03	165.6	176	0.3393	0.00596	0.1184
BP15	71.03	217.7	218.7	0.7665	0.00214	0.1222
BP16	71.33	203.8	229.1	1.03	-0.00122	0.1221
BP18	147	194.6	197.4	0.387	-0.018	0.001772
BP19	165.8	190.1	196	2.768	-0.004	0.002841
BP20	191.8	198.4	199.7	1.508	0.008	0.008494
BP21	57.48	288	299.5	0.9299	0.00192	0.1195
BP22	71.42	247.2	258.4	1.043	-0.00406	0.1243
BP23	62.69	162.4	190.8	2.639	0.0056	0.06404

Note that BP5 and BP17 were excluded by the updated XENON1T limits, arXiv:1805.12562

High mass IDM benchmark points

No.	M_H	M_A	$M_{H^\pm}$	λ_2	λ_{345}	$\Omega_c h^2$
HP1	176	291.4	312	1.49	-0.1035	0.0007216
HP2	557	562.3	565.4	4.045	-0.1385	0.07209
HP3	560	616.3	633.5	3.38	-0.0895	0.001129
HP4	571	676.5	682.5	1.98	-0.471	0.0005635
HP5	671	688.1	688.4	1.377	-0.1455	0.02447
HP6	713	716.4	723	2.88	0.2885	0.03515
HP7	807	813.4	818	3.667	0.299	0.03239
HP8	933	940	943.8	2.974	-0.2435	0.09639
HP9	935	986.2	988	2.484	-0.5795	0.002796
HP10	990	992.4	998.1	3.334	-0.051	0.1248
HP11	250.5	265.5	287.2	3.908	-0.1501	0.00535
HP12	286.1	294.6	332.5	3.292	0.1121	0.00277
HP13	336	353.3	360.6	2.488	-0.1064	0.00937
HP14	326.6	331.9	381.8	0.02513	-0.06267	0.00356
HP15	357.6	400	402.6	2.061	-0.2375	0.00346
HP16	387.8	406.1	413.5	0.8168	-0.2083	0.0116
HP17	430.9	433.2	440.6	3.003	0.08299	0.0327
HP18	428.2	454	459.7	3.87	-0.2812	0.00858
HP19	467.9	488.6	492.3	4.122	-0.252	0.0139
HP20	505.2	516.6	543.8	2.538	-0.354	0.00887

Signal processes for $\mu^+\mu^-$ final state

$$
\begin{aligned}
e^+e^- &\rightarrow \mu^+\mu^- \; HH, \\
&\rightarrow \mu^+\mu^-\nu_\mu\bar{\nu}_\mu \; HH, \\
&\rightarrow \tau^+\mu^-\nu_\tau\bar{\nu}_\mu \; HH, \;\; \mu^+\tau^-\nu_\mu\bar{\nu}_\tau \; HH, \\
&\rightarrow \tau^+\tau^- \; HH, \;\; \tau^+\tau^-\nu_\tau\bar{\nu}_\tau \; HH. \\
& \quad \text{with} \tau^\pm \rightarrow \mu^\pm\nu\nu
\end{aligned}
$$

Signal processes for $e^\pm\mu^\mp$ final state

$$
\begin{aligned}
e^+e^- &\rightarrow \mu^+\nu_\mu \, e^-\bar{\nu}_e \; HH, \;\; e^+\nu_e \, \mu^-\bar{\nu}_\mu \; HH, \\
&\rightarrow \mu^+\nu_\mu \, \tau^-\bar{\nu}_\tau \; HH, \;\; \tau^+\nu_\tau \, \mu^-\bar{\nu}_\mu \; HH, \\
&\rightarrow e^+\nu_e \, \tau^-\bar{\nu}_\tau \; HH, \;\; \tau^+\nu_\tau \, e^-\bar{\nu}_e \; HH, \\
&\rightarrow \tau^+ \, \tau^- \; HH, \;\; \tau^+\nu_\tau \, \tau^-\bar{\nu}_\tau \; HH,
\end{aligned}
$$

BDT input variables

Input variables describing the kinematics of the dilepton final state:

- total energy of the muon pair, E_{ll};
- dilepton invariant mass, M_{ll};
- dilepton transverse momentum, $\mathrm{p}_{\mathrm{T}}^{ll}$;
- polar angle of the dilepton pair, Θ_{ll} ;
- Lorentz boost of the dilepton pair, $\beta_{ll} = \mathrm{p}_{ll}/\mathrm{E}_{ll}$;
- ℓ^- production angle with respect to the beam direction, calculated in the dilepton center-of-mass frame, $\Theta_l^\star$
- ℓ^- production angle with respect to the dilepton pair momentum direction, calculated in the dilepton center-of-mass frame, $\angle^\star(\ell, \ell\ell)$,
- reconstructed missing (recoil) mass M_{miss} (calculated assuming nominal e^+e^- collision energy),