Inert Doublet Model at CLIC

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Outline

1. Inert Doublet Model (IDM) benchmark points
2. Summary of results prepared for CLIC YR
3. Recent developments
   - Scenario independent search
   - Impact of beam polarisation
4. Conclusions and Plans

See also:

- presentation at the CLICdp Workshop, August 28, 2018
- benchmark points: JHEP 1812 (2018) 081 (arXiv:1809.07712)
- CLIC analysis write-up: arXiv:1811.06952

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, $H^{\pm}$.

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

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We assume a discrete Z_2 symmetry under which

- SM Higgs doublet Φ_S is *even*: $\Phi_S \to \Phi_S$ (also other SM$\to$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.

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

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 scalars couplings to γ, $W^\pm$ and Z determined by SM parameters

$\Rightarrow$ well established predictions for production and decay rates!

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

Out of about 15'000 points consistent with all considered constraints, we chose 43 benchmark points (23 accessible at 380 GeV) for detailed studies.

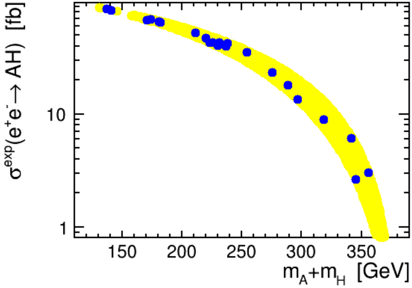
For details see: JHEP 1812 (2018) 081 (arXiv:1809.07712)

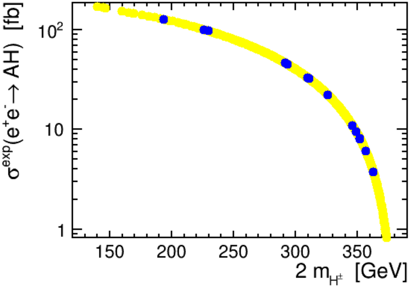
List of benchmark point parameters included in backup slides

Production of IDM scalars at CLIC 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:





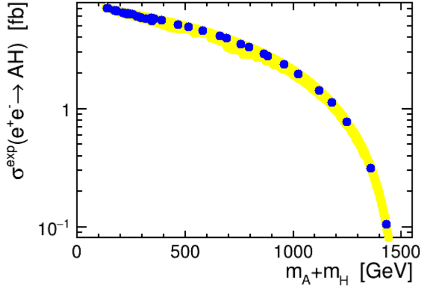
Beam luminosity spectra not taken into account

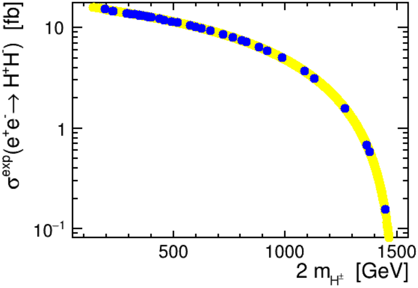
Analysis strategy

Production of IDM scalars at CLIC 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 1.5 TeV:





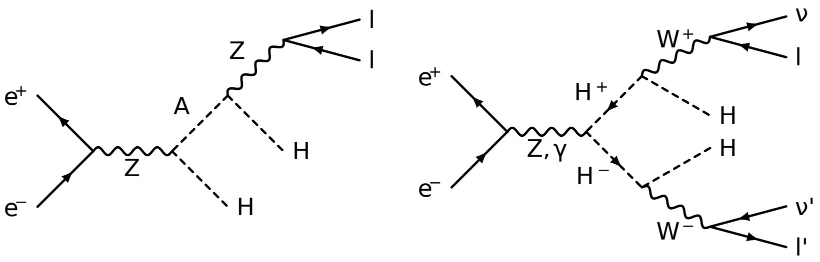
Beam luminosity spectra not taken into account

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.

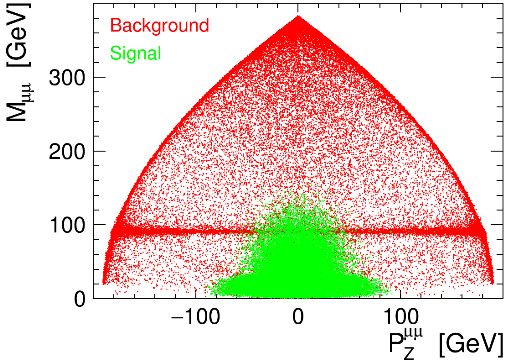
Signal and background samples were generator with WHizard 2.2.8
based on the dedicated IDM model implementation in SARAH,
parameter files for benchmark scenarios were prepared using SPheno 4.0.3

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)

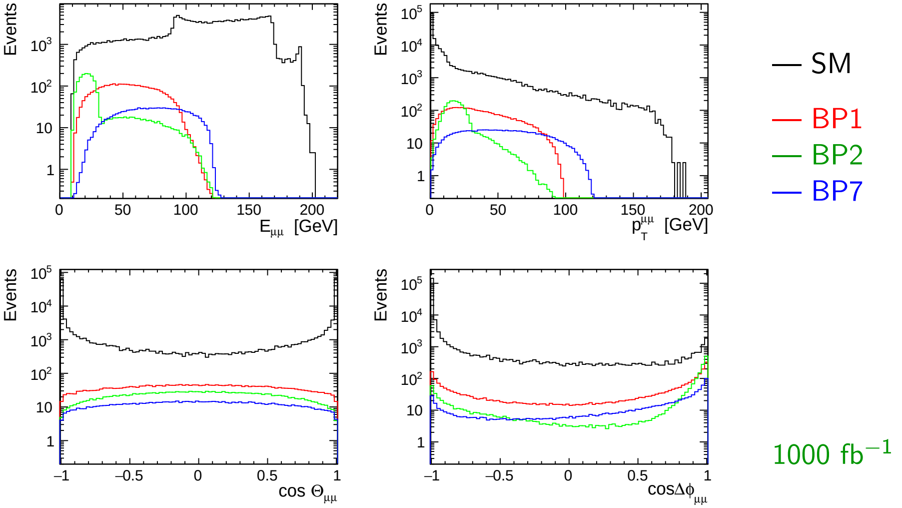
Muon pair invariant mass, $M_{\mu\mu}$, as a function of the lepton pair longitudinal momentum, $P_Z^{\mu\mu}$, for BP1 scenario and SM background, at 380 GeV



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: $M_{\mu\mu} < 100\,\text{GeV}$ and $|P_Z^{\mu\mu}| < 140\,\text{GeV}$

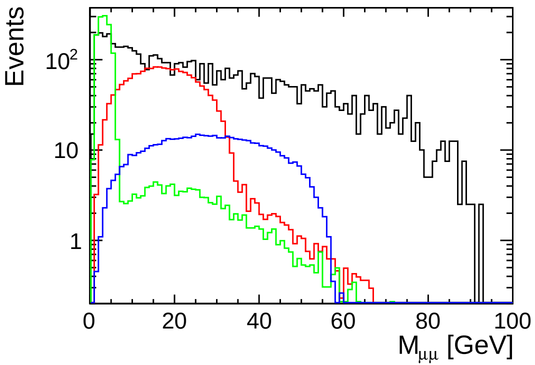
Distributions of the kinematic variables describing the leptonic final state



Cut based approach

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

- pair energy $E_{\mu\mu} < 100\,\mathrm{GeV}$
- transverse momentum $p_T^{\mu\mu} > 10\,\mathrm{GeV}$
- production angle $30^\circ < \Theta_{\mu\mu} < 150^\circ$
- azimuthal distance $|\Delta\varphi_{\mu\mu}| < \frac{\pi}{2}$

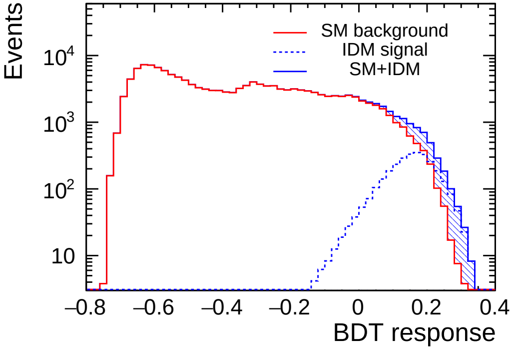


Considered IDM scenarios result in the visible event excess 21σ, 16σ and 7σ, for BP1, BP2 and BP7

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

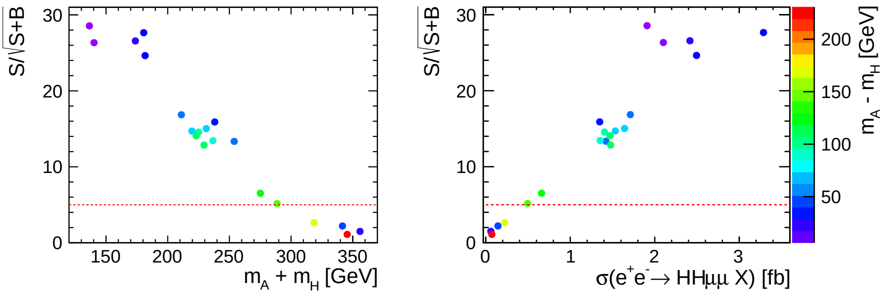


$\Rightarrow$ signal significance of about 28 σ for BDT> 0.12

Neutral scalar production @ 380 GeV

Multivariate analysis

Summary of results for the considered benchmark scenarios



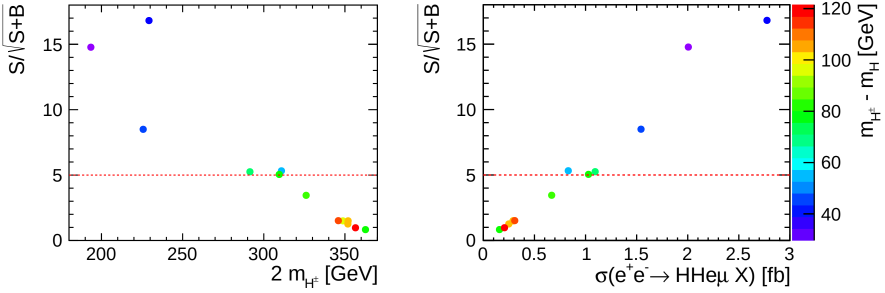
Expected significance mainly related to the *AH* production cross section

$5\,\sigma$ observation possible for signal cross section above about 0.5 fb (in the $\mu^+\mu^-$ channel)

$\Rightarrow$ neutral inert scalar mass sum below about 290 GeV

Multivariate analysis

Summary of results for the considered benchmark scenarios



Expected significance mainly related to the H^+H^- production cross section

$5\,\sigma$ observation possible for signal cross section above about 1 fb

(in the $e^\pm\mu^\mp$ channel after preselection)

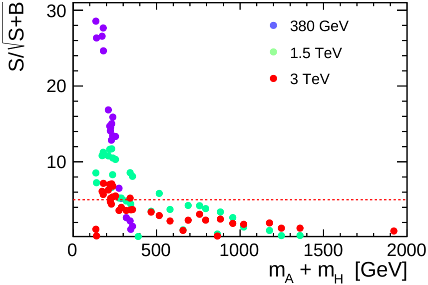
$\Rightarrow$ charged scalar masses up to about 150 GeV

Prospects for high energy running

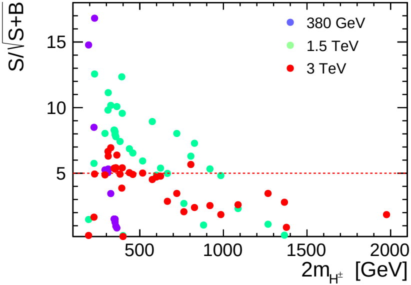
Same analysis procedure applied for high energy CLIC running:

$2500\,\mathrm{fb}^{-1}$ at 1.5 TeV and $5000\,\mathrm{fb}^{-1}$ at 3 TeV

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



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

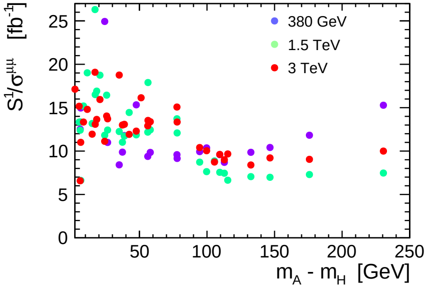


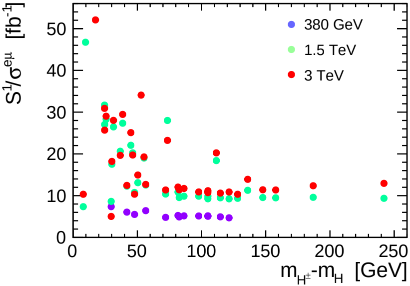
Moderate increase in discovery reach for 1.5 TeV:

- neutral scalar production: $m_A + m_H < 550$ GeV (290 GeV @ 380 GeV)
- charged scalar production: $m_{H^\pm} < 500$ GeV (150 GeV @ 380 GeV)

Prospects for high energy running

Ratio of the expected significance (scaled to $1000\,\text{fb}^{-1}$) to the signal cross section in the considered channel, as a function of the scalar mass splitting





For both channels: sensitivity tends to be better at low mass splittings when virtual Z or W boson produced in decay chain

For AH search: sensitivity decreases with energy for large mass splittings

For H^+H^-: sensitivity increases with energy for all mass differences

For more details see YR analysis write-up: arXiv:1811.06952

Recent developments

BDT training

Results presented so far were obtained for each BP separately.
BDT was trained to recognize exactly the correct model...

This is clearly too optimistic. We can not search for all possible scenarios one by one. We need a more general approach...

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BDT was trained to recognize exactly the correct model...

This is clearly too optimistic. We can not search for all possible scenarios one by one. We need a more general approach...

New approach

Devide the considered BP scenarios in three groups:

- scenarios with real Z (or real W) production
- low mass scenarios with virtual Z (or virtual W)
- high mass scenarios with virtual Z (or virtual W)

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

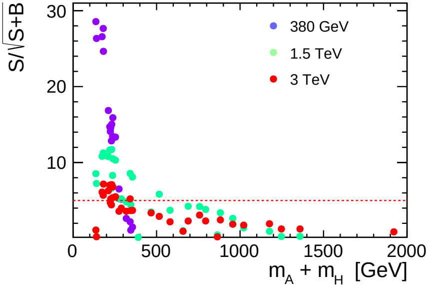
Corresponds to the assumption that three independent BDTs will be used for the three cases...

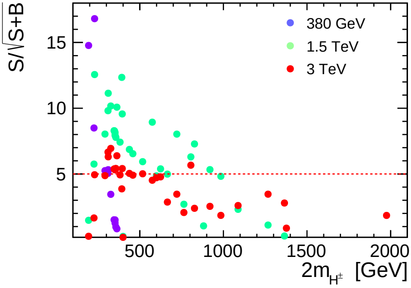
Same scenario used for BDT training (YR results)

$2500\,\mathrm{fb}^{-1}$ at 1.5 TeV and $5000\,\mathrm{fb}^{-1}$ at 3 TeV

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

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





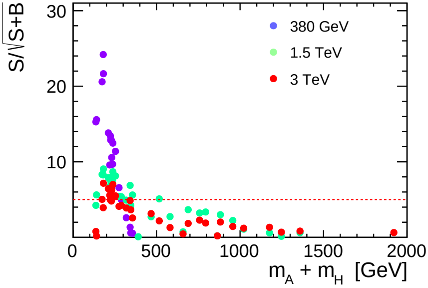
Moderate increase in discovery reach for 1.5 TeV:

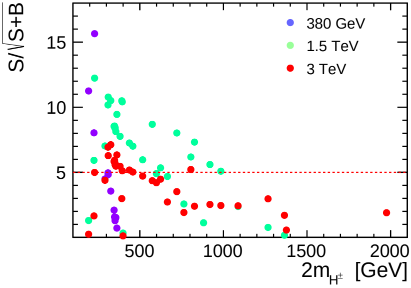
- neutral scalar production: $m_A + m_H < 550\,\mathrm{GeV}$
- charged scalar production: $m_{H^\pm} < 500\,\mathrm{GeV}$

Other scenarios used for BDT training (new results)

$2500\,\mathrm{fb}^{-1}$ at 1.5 TeV and $5000\,\mathrm{fb}^{-1}$ at 3 TeV

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





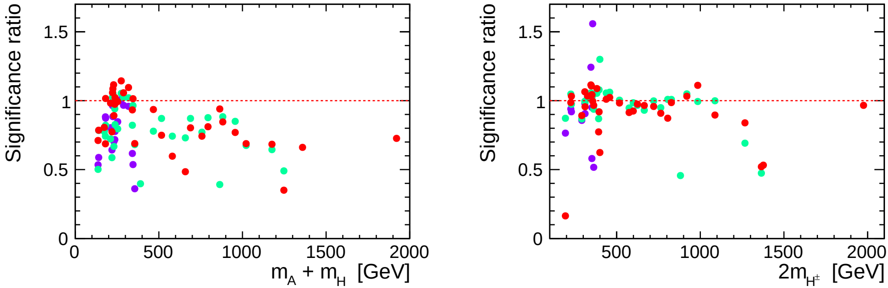
Moderate increase in discovery reach for 1.5 TeV:

- neutral scalar production: $m_A + m_H < 450\,\mathrm{GeV}$
- charged scalar production: $m_{H^\pm} < 500\,\mathrm{GeV}$

Scenario independent search

Ratio of the scenario independent to scenario optimised significance:

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



Moderate decrease of significance for same flavour lepton channel (*AH*)

Hardly any influence for different flavour lepton pairs (H^+H^-)

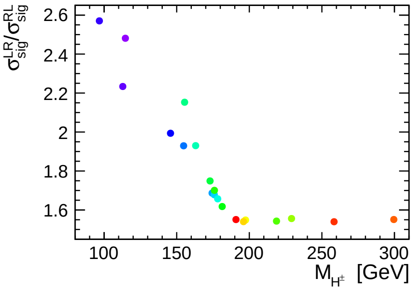
Impact of polarisatrion

Polarised cross section

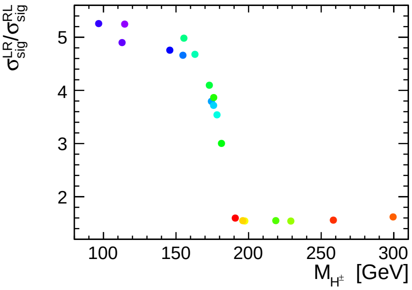
Ratio of $e_L^- e_R^+$ to $e_R^- e_L^+$ signal cross sections @ 380 GeV

Color indicates BP number

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



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



For background: 3.1

10.3

AH and H^+H^- production contribute to both final states.
Ratio of contributions depends on the $H^\pm$ mass (H^+H^- fraction).

Analysis framework

Dedicated 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

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

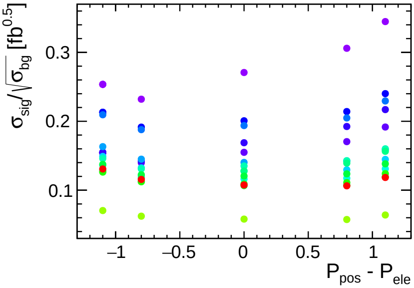
Luminosity spectra NOT taken into account for these studies

Impact of polarisatrion

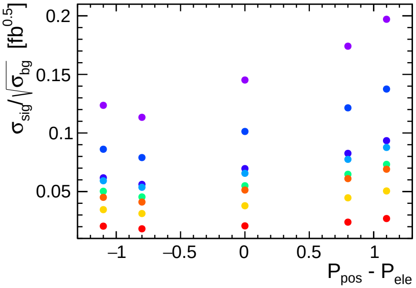
Polarised cross section

Signal significance: $S/\sqrt{S+B} \approx S/\sqrt{B} \sim \sigma_{sig}/\sqrt{\sigma_{bg}}$ for $S \ll B$

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



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



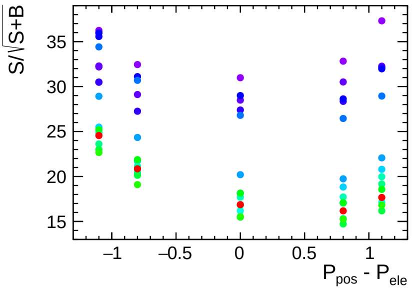
Color indicates BP number

For most BPs expected significance better for LR type configurations.
But dependence on the BP choice significant

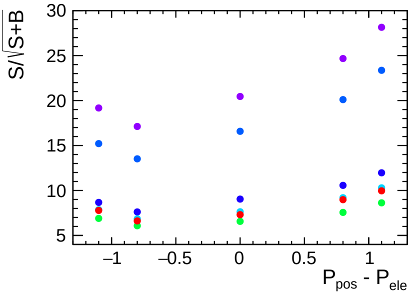
BDT analysis

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

BPs with high significance

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

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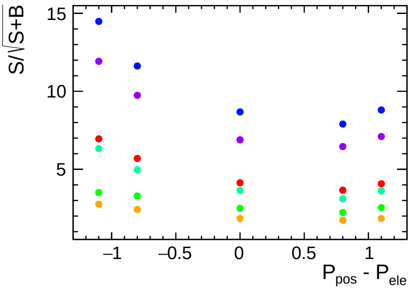
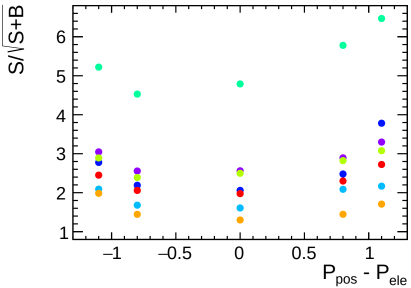
Significance after BDT selection optimised for each BP and polarisation

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



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



Color indicates BP number

BPs with lower significance

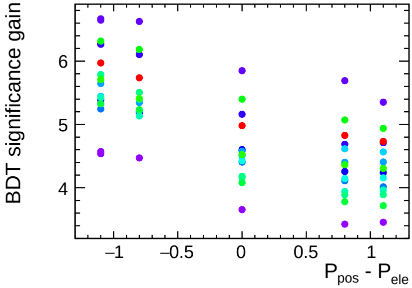
RL slightly better for AH signature, while LR better for H^+H^-

Impact of polarisatrion

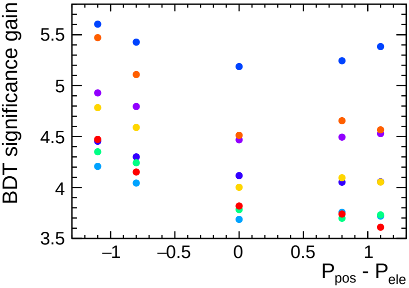
BDT analysis

Ratio of significance after and before applying BDT selection

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



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



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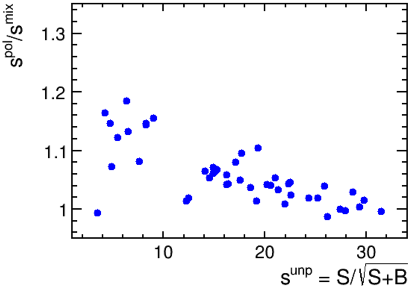
BDT selection more efficient for RL polarisation,
Influence of the polarisation stronger for *AH* signature

Analysis of combined samples

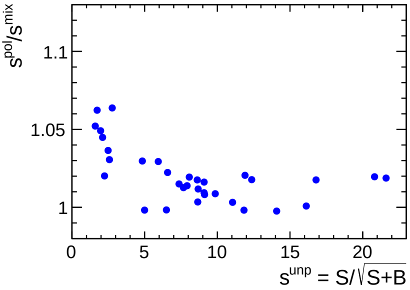
New baseline: $2x500\,\mathrm{fb}^{-1}$ @ 380 GeV with $P_{ele} = \pm 80\%$, $P_{pos} = 0$

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

Low mass IDM scenarios can be observed with high significance in the di-lepton channels already at the first stage of CLIC, up to $m_A + m_H \sim 290\,\mathrm{GeV}$ or $m_{H^\pm} \sim 150\,\mathrm{GeV}$

The discovery reach is extended to $\sim$500 GeV when running at 1.5 TeV
No improvement with 3 TeV running (cross sections too low)

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Going to scenario independent limits reduces the expected significance only for same-flavour lepton pair signature, by 20-30%

Polarisation does influence the signal to background ratio and the expected significance of observation:

- For AH signature: right-handed electrons slightly prefered
- For H^+H^- signature: left-handed electrons prefered

When the polarisation sharing is fixed (50:50 for 380 GeV assumed), using polarisation information has only a marginal influence on the measurement
One can ignore the polarisation and combine both samples for the analysis.

IDM model

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

- 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%
  $\Rightarrow$ significance increase by at least a factor of 3
  $\Rightarrow$ estimated discovery reach up to $m_{H^\pm} \sim 700\,\mathrm{GeV}$

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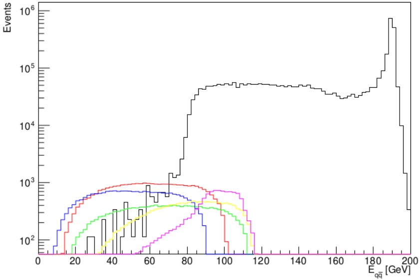
Possible extensions

We are also considering other BSM models with light DM candidates and relatively simple final states...

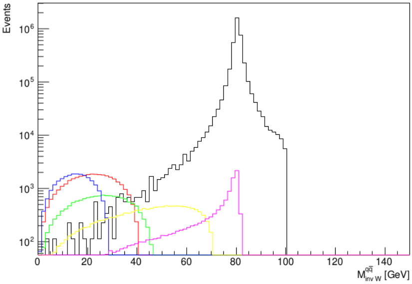
IDM model

First look at H^+H^- production in the semi-leptonic final state
(generator level results)

Hadronic $W^{(*)}$ energy



Hadronic $W^{(*)}$ mass



Considered benchmarks: BP1 BP2 BP3 BP4 BP6

Thank you!

Inert Doublet Model

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- 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

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

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

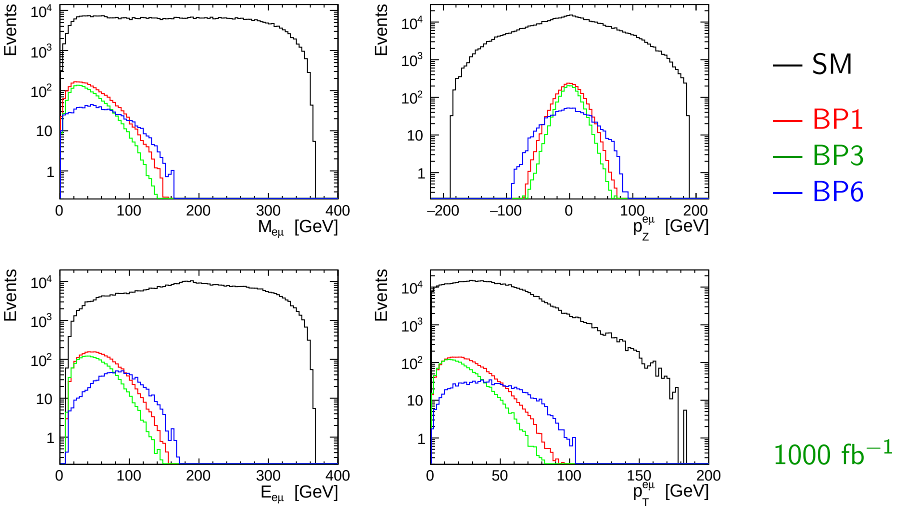
BDT input variables

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),

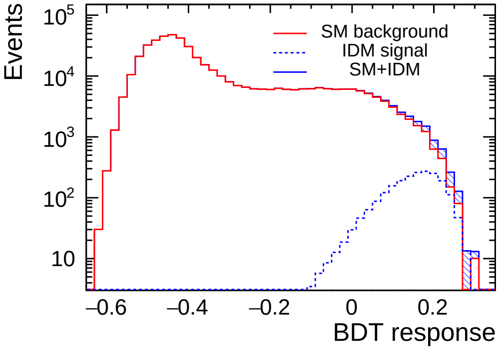
Charged scalar production @ 380 GeV

Distributions of the kinematic variables describing the leptonic final state



Charged scalar production @ 380 GeV

BDT classifier response distribution for $e\mu$ channel:
BP1 scenario and SM background 1000 fb^{-1} at $\sqrt{s} = 380$ GeV



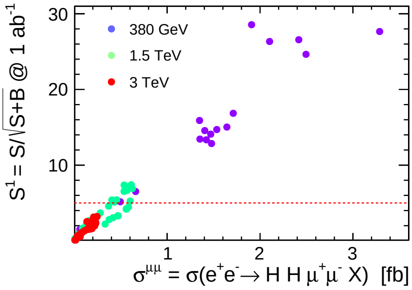
$\Rightarrow$ signal significance of about 17 σ for BDT> 0.12

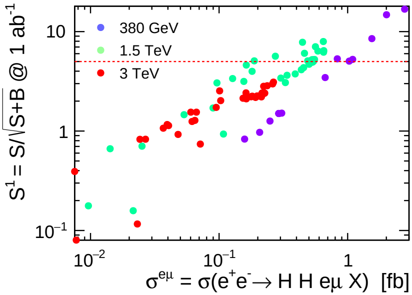
Backup slide

Prospects for high energy running

As for 380 GeV, significance of the observation mainly driven by the signal production cross section (in $\mu\mu$ or $e\mu$ channel) + integrated luminosity

Significance scaled to the same integrated luminosity of $1000\,\mathrm{fb}^{-1}$



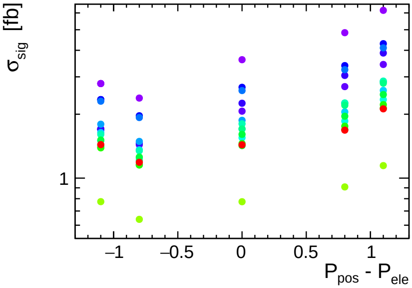


Slope of the significance vs cross section dependence can be used as a measure of the experimental sensitivity

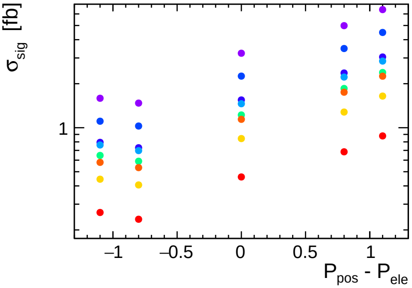
Impact of polarisatrion

Signal cross sections @ 380 GeV

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



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



Color indicates BP number

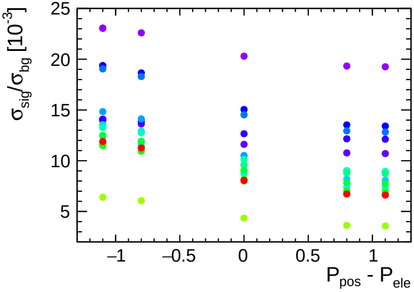
All cross sections higher for LR type polarisations...

Dependence even stronger for the background.

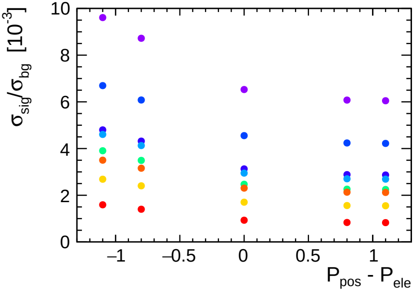
Impact of polarisatrion

Ratio of signal to background cross sections @ 380 GeV

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



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



Color indicates BP number

Signal to background ratio better for RL type configurations...

But the cross section much smaller (see previous page)!