Pair production of charged IDM scalars at high energy CLIC

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Compact Linear Collider

- Novel two-beam acceleration technique
- Normal-conducting technology
- High 100 MeV/m gradient, 12 GHz accelerating structures
- ±80% electron beam polarisation
- Implementation in 3 energy stages
Compact Linear Collider

380 GeV stage (1 ab⁻¹):
- precision Higgs measurements
- precision top measurements
- top threshold scan

1.5 TeV (2.5 ab⁻¹), 3 TeV (5 ab⁻¹):
- Higgs self-coupling
- top Yukawa coupling
- more precision measurements: indirect BSM constraints

+ direct new physics searches at high energies
Inert Doublet Model

\[
\phi_{SM} = \left( \frac{1}{\sqrt{2}} (\nu + h + i\xi) \right) \quad \phi_D = \left( \frac{1}{\sqrt{2}} (H + iA) \right)
\]

"Higgs boson": \( h \)  
New scalars: \( H^\pm, H, A \)

- Additional scalars do not couple to fermions on tree level (\( Z_2 \) symmetry)
- The lightest of new particles is stable → **dark matter candidate**
- **5 free parameters** in the model with existing constraints
Inert Doublet Model

Considered 23 high-mass benchmark points from JHEP 1812 (2018) 081, arXiv:1809.07712 for two production scenarios:

- Mass difference affects virtuality of W boson!

![Diagram of production processes](image)
Strategy

IDM scalar production previously studied in leptonic channel (JHEP07 (2019) 053)

Discovery reach limited up to scalar masses $\sim 250$ GeV and $\sim 500$ GeV at 1.5 TeV and 3 TeV by production cross section.
Strategy

Order of magnitude higher cross section expected for **semi-leptonic** channel

Expected **signature** of the final state:

*One lepton*: $e^\pm$ or $\mu^\pm$ and a **pair of jets**

- cut-based preselection
- **multivariate analysis (BDTs)**
Strategy

Order of magnitude higher cross section expected for **semi-leptonic** channel

Expected **signature** of the final state:

**One lepton:** $e^\pm$ or $\mu^\pm$ and a **pair of jets**

- Use CLIC beam spectra for **1.5 TeV (2000 fb$^{-1}$)** and **3 TeV (4000 fb$^{-1}$)**
  - assumed -80% e$^-$ beam polarisation statistics

- Generate samples with **Whizard 2.7.0**

- Use **Geant4** CLICdet model to simulate detector response for 5 scenarios

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Extend to all 23 benchmarks using **fast simulation**
Scenarios with on-shell vs. off-shell $W^{\pm/-}$ (3 TeV)

Huge difference between scenarios with large and small $m_{H^{\pm}} - m_H$

5 scenarios used in full simulation study selected to cover wide range of mass splittings
Overlay background

Huge **beam-induced backgrounds** at CLIC

$\gamma\gamma \rightarrow \text{had.}$ most important (physics, performance)

Included in full sim., mitigated using timing cuts

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**Timing cuts not included** in Delphes CLICdet cards!

→ included in **approximate** way with **generator-level cuts**

Influence on the reconstruction if $W$ is virtual
\[ \gamma \gamma \rightarrow \text{had. influence} \]

- In **HP17 scenario** \( W^{+/−} \) is far **off-shell**
- **Overlay contribution** in **Delphes crucial** for reproducing full simulation results
Residual difference between **full simulation** and **fast simulation** (with overlay included)

- Dedicated correction introduced, depending on the scalar mass difference
Results (Delphes + $\gamma\gamma \rightarrow \text{had.}$)

- Two BDTs trained separately on the scenarios with off-shell $W^{+/−}$ and with on-shell $W^{+/−}$
- Conservative estimate of uncertainty: 100% uncertainty on the applied correction
- Most scenarios above $5\sigma$ discovery threshold
Summary

- CLIC sensitivity to **charged IDM scalar** pair-production studied with **full** and **fast simulation**

- Impact of the $\gamma\gamma \rightarrow \text{had.}$ **overlay events** crucial for the analysis. A method to include the overlay in **CLICdet model** for Delphes was developed

- Good agreement between full and fast simulation results (with overlay). **Dedicated correction applied** to take residual differences into account.

- Most IDM benchmark points, with scalar **masses** up to 1 TeV, accessible at high-energy CLIC

Thank you! arXiv:2201.07146
BACKUP
\( \gamma \gamma \rightarrow \text{had. influence} \)

Cut-based preselection + MVA with BDTs

(MVA optimised to particular scenario)

- **Agreement** between fast and full simulation **significantly improved** when overlay taken into account in Delphes.
- **Systematic differences remain** - most likely due to underestimated background contributions.
Results ($\sigma^{\text{slep}} = 1 \text{ fb}$)

- Final results scaled to 1 fb for all benchmark scenarios, assuming 4 ab$^{-1}$ luminosity at both energy stages.
- No visible dependence on the scalar mass or the energy.
  → the results depend on the signal cross section, not on the scalar mass.
Timing cuts

In full simulation we have BXs from 10 ns after the physical event.

0.5 ns

20 bunch crossings $\leftarrow \rightarrow$ 10 ns

Additional timing cuts on PFOs to reduce $\gamma \gamma \rightarrow$ had. backg.

Example: Accept tracks with $p_\text{T} < 1 \text{ GeV}$ with $t < 2 \text{ ns}$

2 ns

20 bunch crossings $\leftarrow \rightarrow$ 10 ns
Approximate timing cuts

Additional timing cuts on PFOs to reduce $\gamma\gamma \rightarrow \text{had.}$ backg.

Example: Accept tracks with $p_T < 1$ GeV with $t < 2$ ns

1. Take gen-level $\gamma\gamma \rightarrow \text{had.}$ events in batches of $N$
2. Accept specific particles with a probability $t/10$ ns, where a timing cut $t$ corresponds to number $n$ of BXs
   → e.g. for $t < 2$ ns one can accept $n=2$ out of $N=10$
3. Overlay selected events on physical sample