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Inert Doublet Model at future e^+e^- colliders

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ECFA Higgs Factories WG1:
1st Workshop of the WG1-SRCH group
25 May 2022

References

- Jan Kalinowski, Wojciech Kotlarski, Tania Robens, Dorota Sokolowska, and Aleksander Filip Zarnecki. Benchmarking the Inert Doublet Model for e+e- colliders. JHEP 12(2018)081, arXiv:1809.07712.
- Jan Kalinowski, Wojciech Kotlarski, Tania Robens, Dorota Sokolowska, Aleksander Filip Zarnecki, Exploring Inert Scalars at CLIC, JHEP 1907 (2019) 053, arXiv:1811.06952.
- Aleksander Filip Zarnecki, Jan Kalinowski, Jan Klamka, Pawel Sopicki, Wojciech Kotlarski, Tania Robens, Dorota Sokolowska, Inert Doublet Model Signatures at Future e+e- Colliders, PoS(ALPS2019)010, arXiv:1908.04659.
- Dorota Sokolowska, Jan Kalinowski, Jan Klamka, Wojciech Kotlarski, Pawel Sopicki, Tania Robens, Aleksander Filip Zarnecki, Inert Doublet Model signatures at future e+e- colliders, PoS(EPS-HEP2019)570, arXiv:1908.04659.
- Aleksander Filip Zarnecki, Jan Kalinowski, Jan Klamka, Pawel Sopicki, Wojciech Kotlarski, Tania Robens, Dorota Sokolowska, Searching Inert Scalars at Future e+e- Colliders, arXiv:2002.11716.
- Jan Kalinowski, Tania Robens, Dorota Sokolowska, and Aleksander Filip Zarnecki. IDM Benchmarks for the LHC and Future Colliders. Symmetry, 13(6):991, 2021, arXiv:2012.14818.
- Jan Klamka, Aleksander Filip Zarnecki, Pair-production of the charged IDM scalars at high energy CLIC, arXiv:2201.07146.
- Jan Kalinowski, Tania Robens, Aleksander Filip Zarnecki, New Physics with missing energy at future lepton colliders - Snowmass White Paper, arXiv:2203.07913.

Inert Doublet Model

$$\phi_{SM} = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + h + i\xi) \end{pmatrix} \qquad \phi_D = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

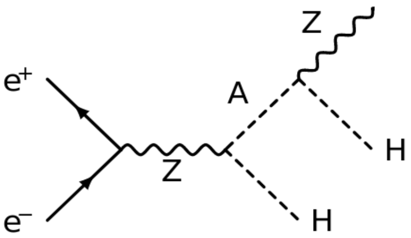
„Higgs boson”: h

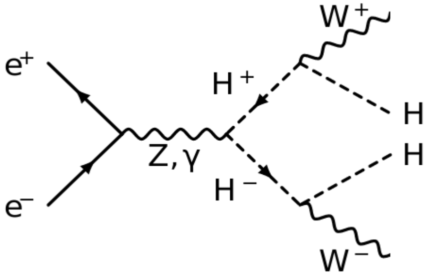
New scalars: $H^{\pm}$, H, A

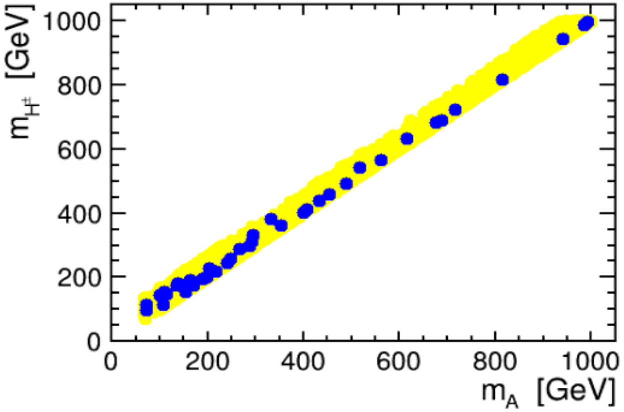
- Additional scalars do not couple to fermions on tree level (Z_2 symmetry)
- The lightest of new particles is stable → **DM candidate**
- **5 free parameters** in the model with existing constraints

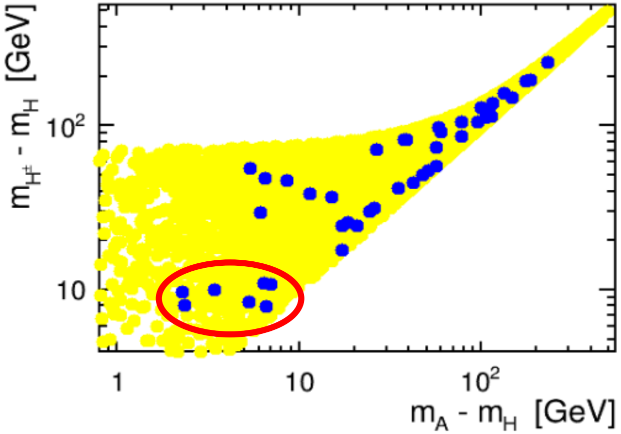
Benchmark scenarios

23 benchmark points selected in JHEP 1812 (2018) 081, arXiv:1809.07712 for the two production scenarios:







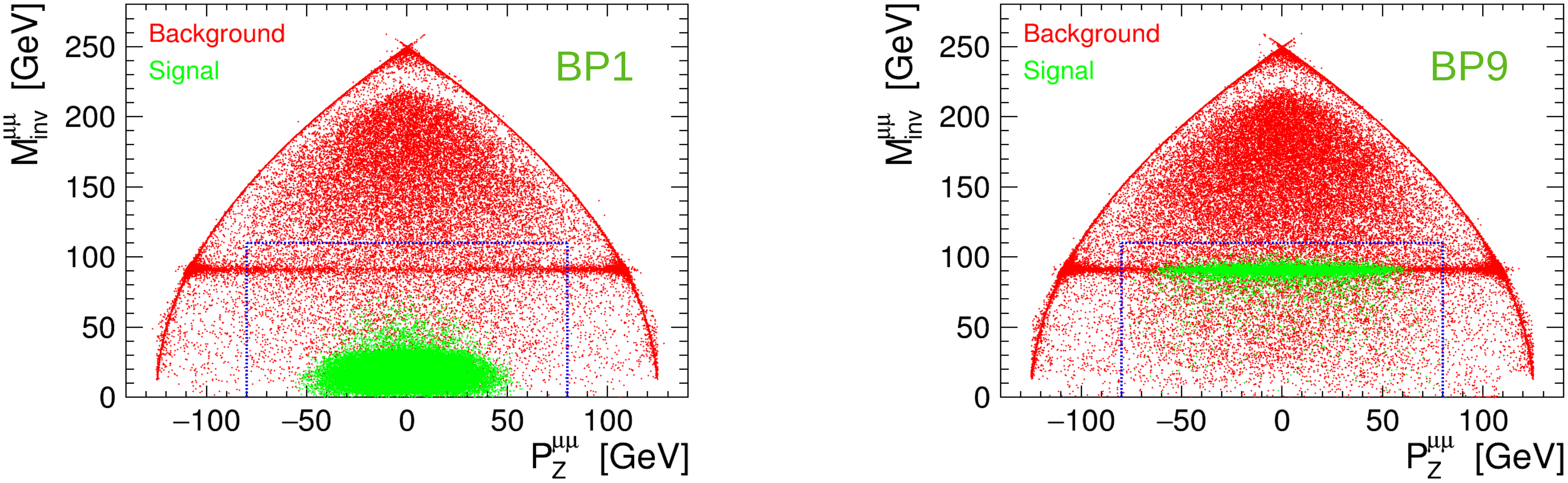


Mass difference affects virtuality of W boson!

Leptonic channel analysis

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

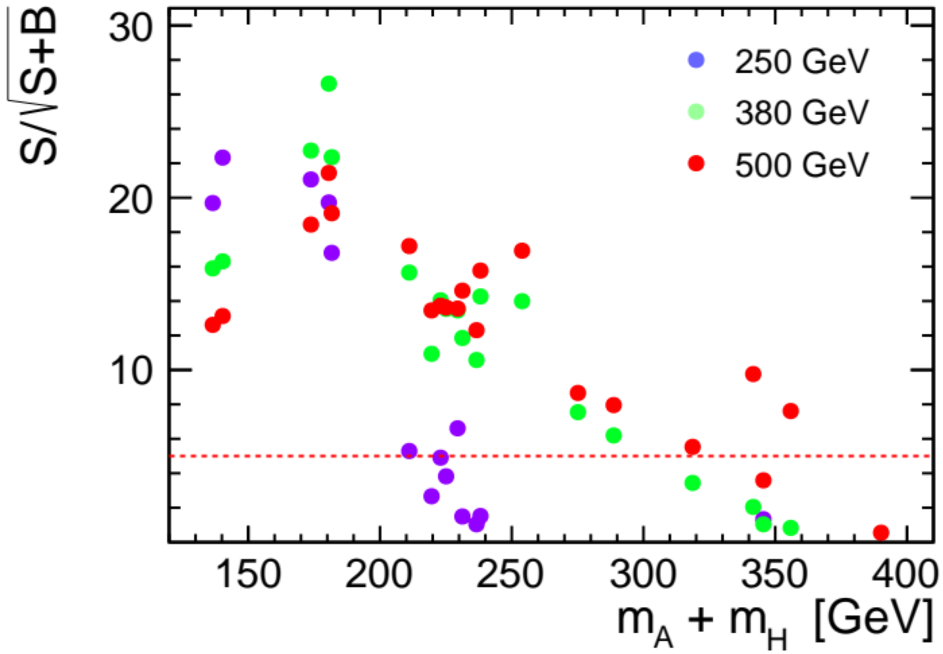
$$e^+e^- \to HA \to HHZ^{(*)} \to HH\mu^+\mu^-$$

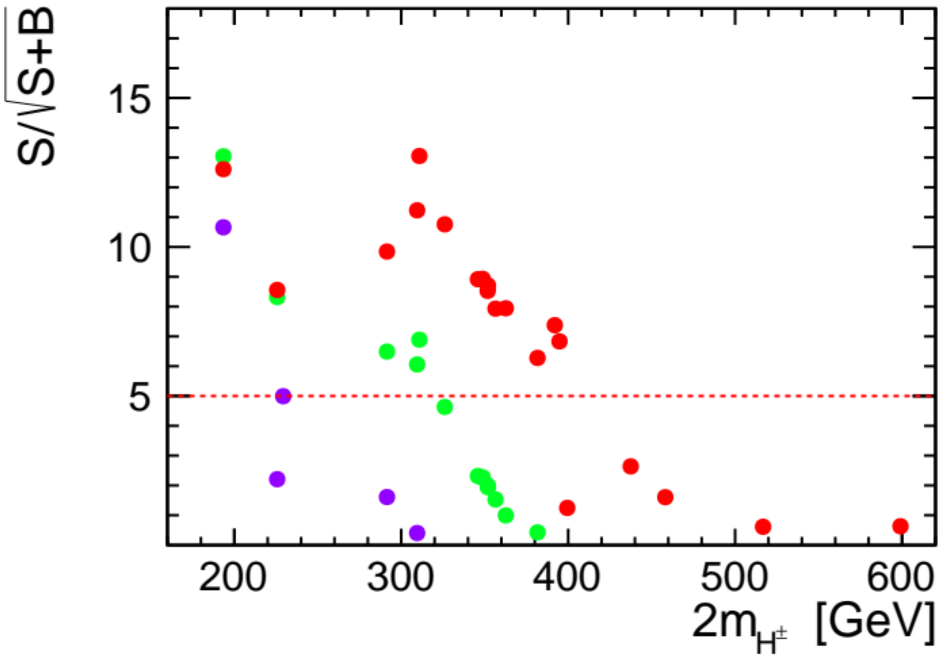


Generator-level analysis, preselection cuts on $M_{\mu\mu}$ and $P_z^{\mu\mu}$ + final classification based on BDTs.

Sensitivity at low energies

IDM scalar production studied in leptonic final state: expected significance with 1000 fb^{-1}

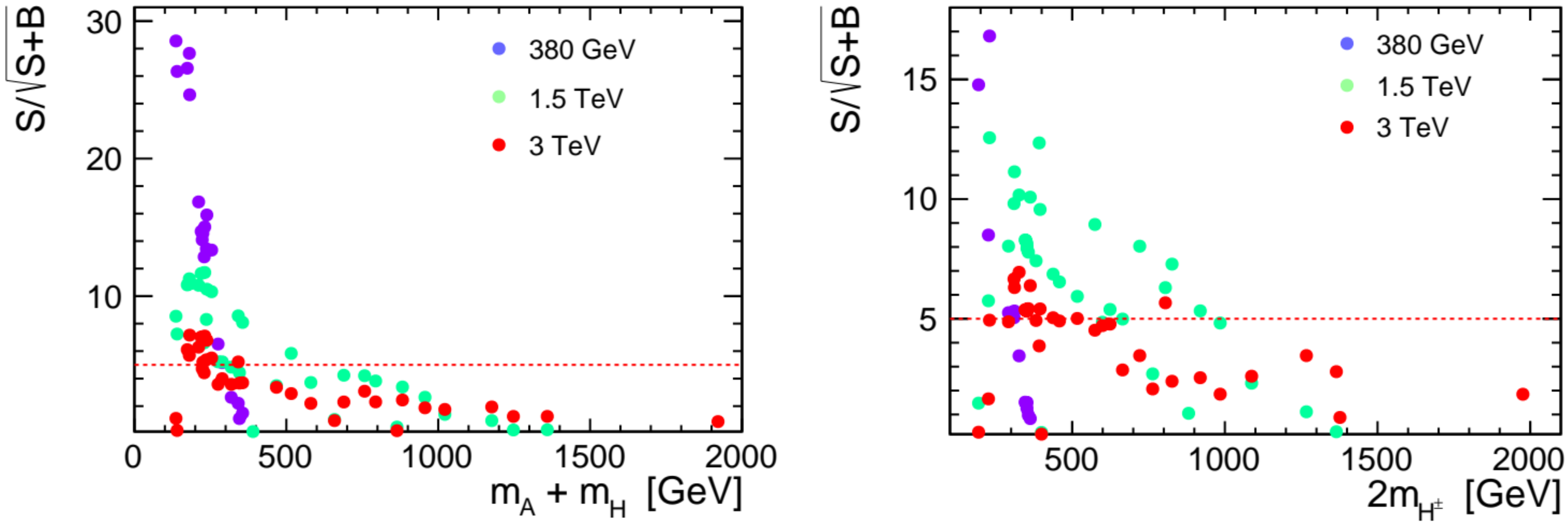




Sensitivity up to total mass ~350 GeV and ~400 GeV at 500 GeV ILC

Sensitivity at higher energies

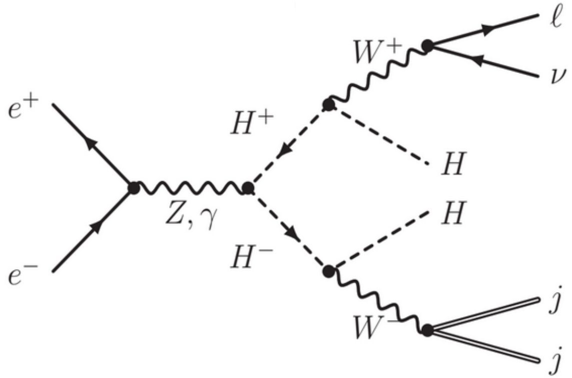
20 high-mass additional scenarios considered for high collision energies:



Discovery reach at 3 TeV CLIC, up to total mass ~500 GeV and ~1000 GeV, **limited** by production cross section

Semi-leptonic channel

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

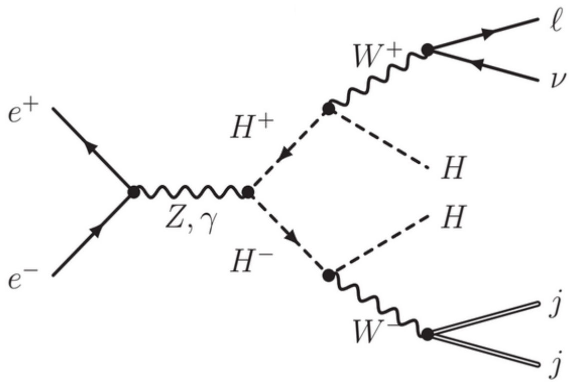


Expected **signature** of the final state:
One lepton: $e^{\pm}$ or $\mu^{\pm}$ and a **pair of jets**

cut-based preselection
+
multivariate analysis (BDTs)

Semi-leptonic channel

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



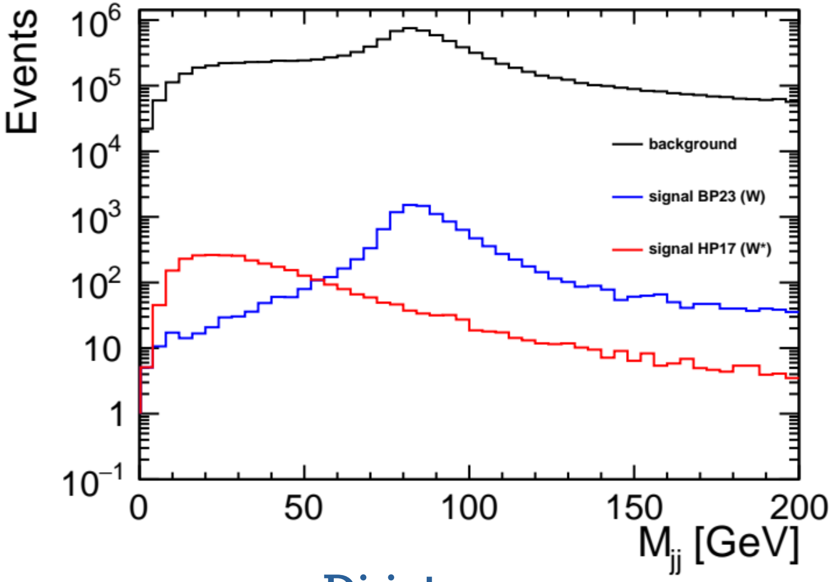
Expected **signature** of the final state:
One lepton: $e^{\pm}$ or $\mu^{\pm}$ and a **pair of jets**

cut-based preselection
+
multivariate analysis (BDTs)

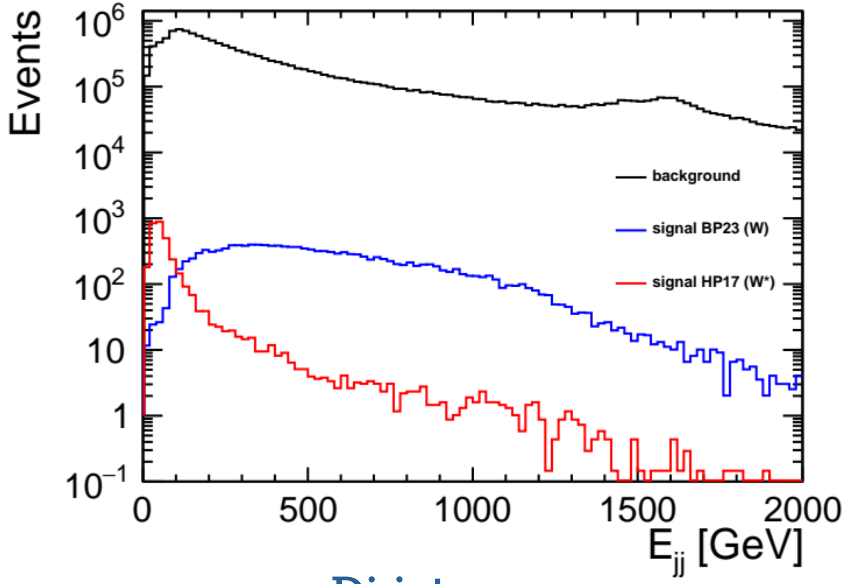
- Use CLIC beam spectra for **1.5 TeV (2000 fb^{-1})** and **3 TeV (4000 fb^{-1})**
- Generate samples with **Whizard 2.7.0**
- Use **Geant4** CLICdet model to simulate detector response for 5 scenarios

→ Extend to all 23 benchmarks using **fast simulation**

Scenarios with on-shell vs. off-shell $W^{+/-}$ (3 TeV)



Di-jet mass

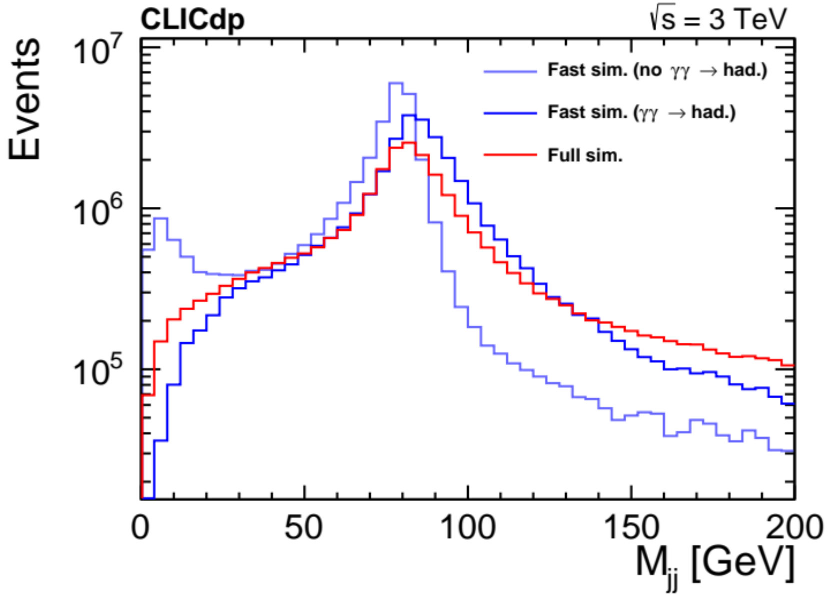


Di-jet energy

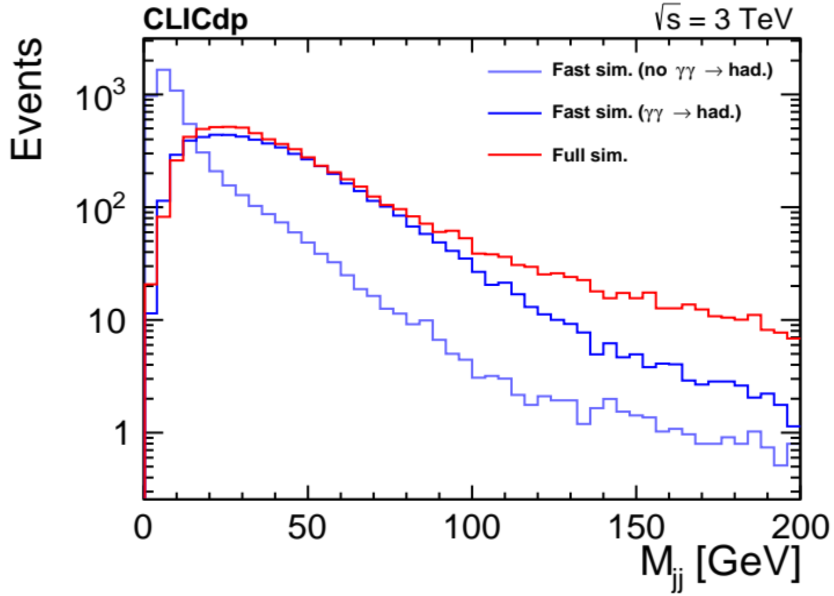
Huge difference between scenarios with large and small $m_{H^\pm} - m_H$

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

$\gamma\gamma \rightarrow$ had. influence



Background ($qql\nu$)

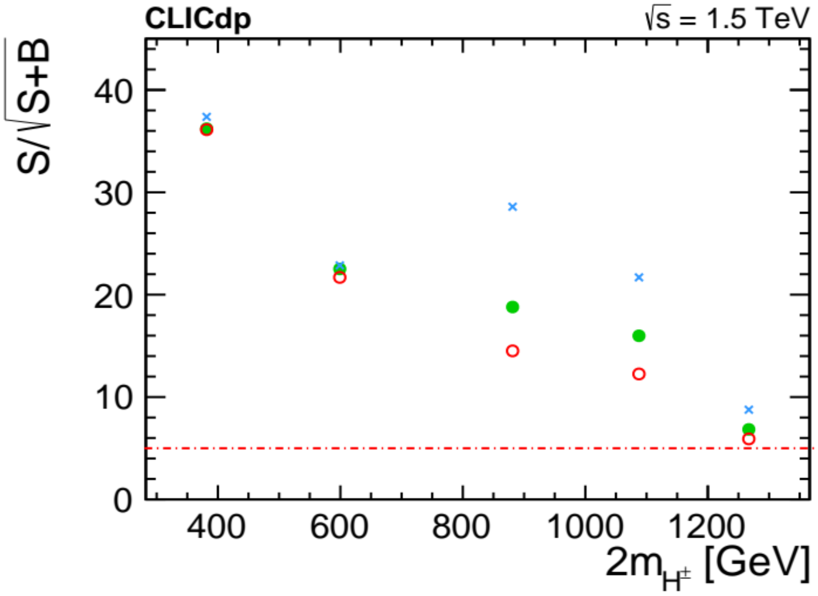


Signal (HP17)

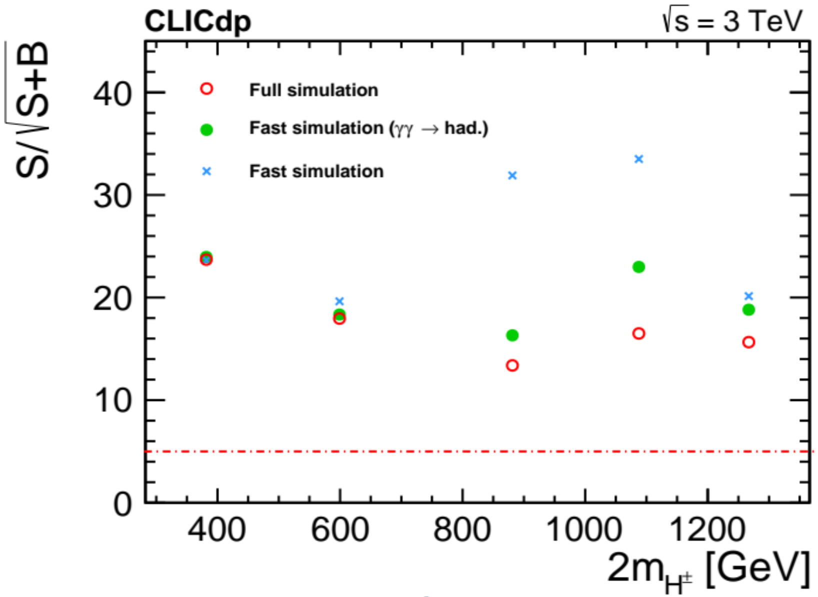
- In **HP17 scenario** $W^{+/-}$ is far off-shell
- **Delphes with overlay** performs much better

$\gamma\gamma \rightarrow$ had. influence

Cut-based preselection + MVA with BDTs



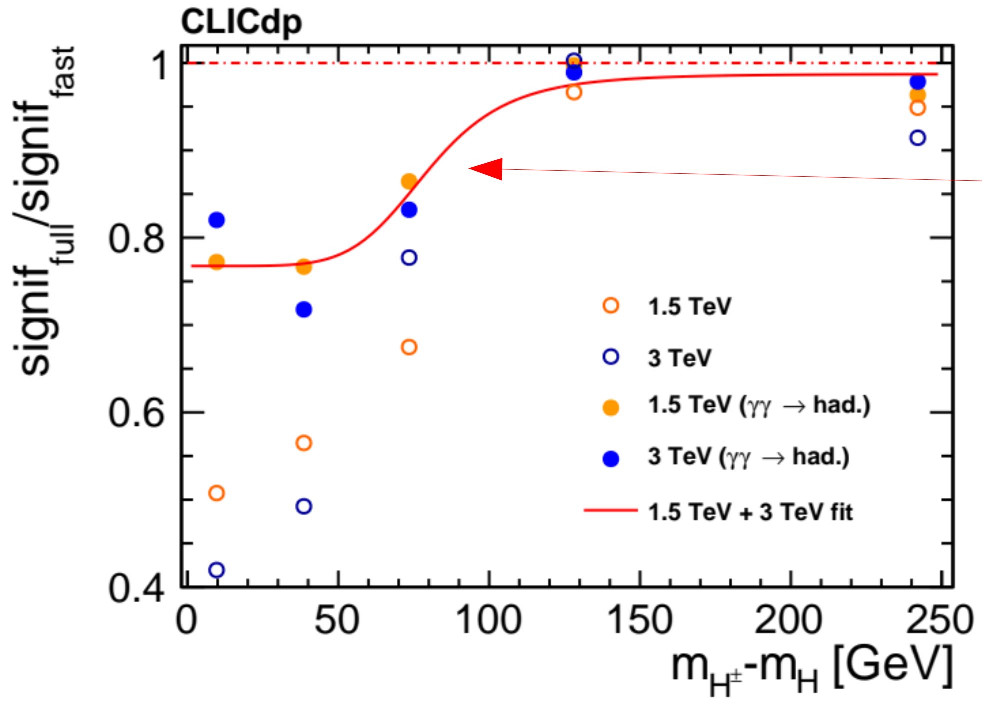
1.5 TeV



3 TeV

Background contribution still **underestimated**.

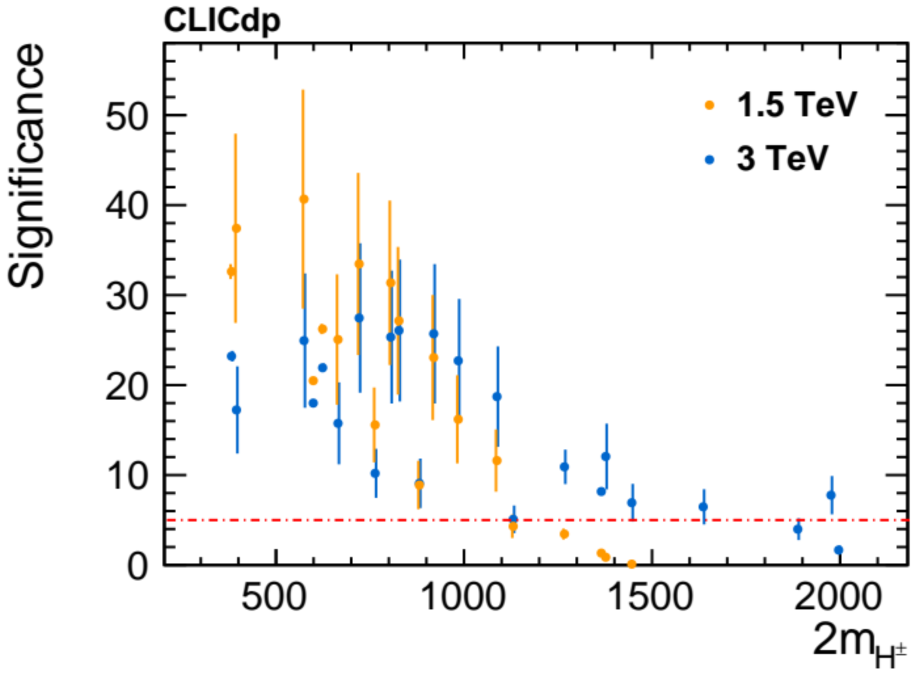
Further results correction

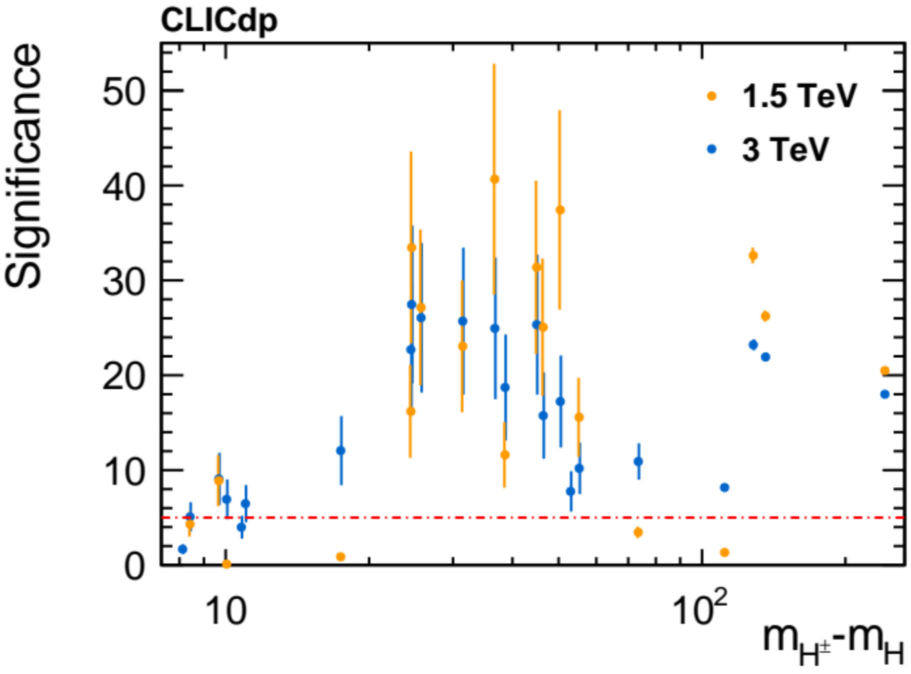


Inflection of the curve corresponds to W mass!

- Fit a curve to ratio of full sim. to fast sim. + overlay results
- Use the function to scale the rest of fast sim. results

Results





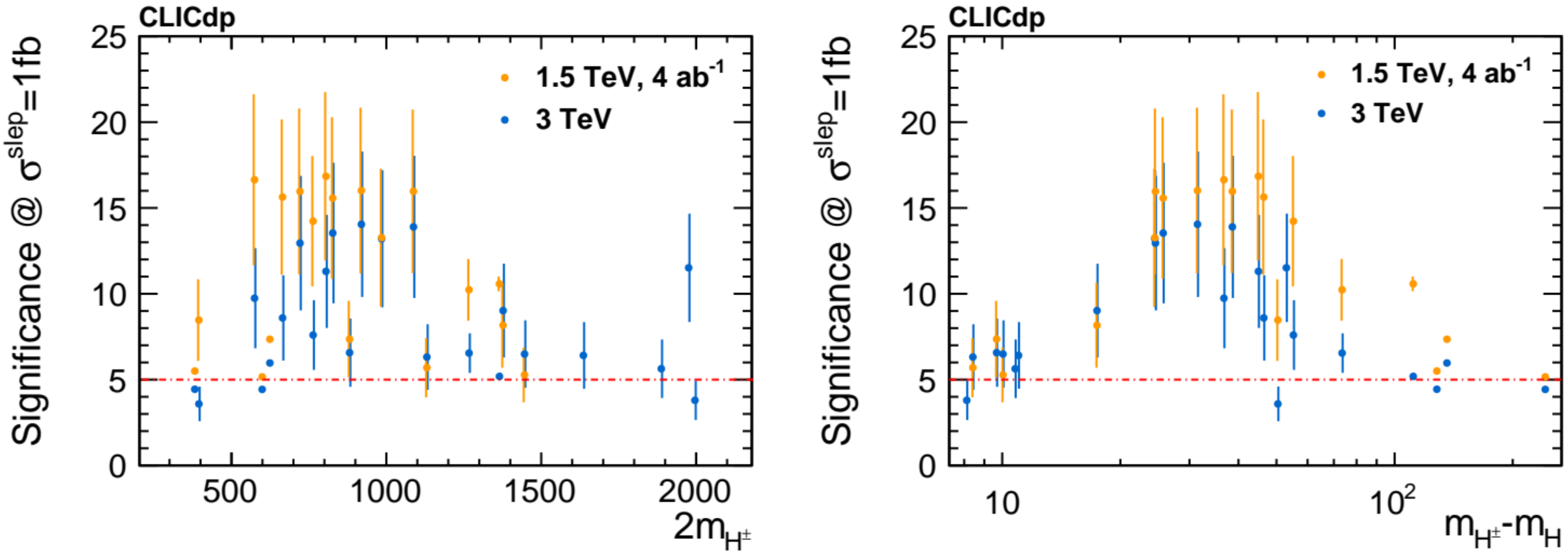
- Conservative estimate of uncertainty: **100% uncertainty** on the applied correction
- Most benchmarks **above 5σ** discovery threshold

Summary

- Sensitivity to **pair-production of the IDM scalars** at future linear e+e- colliders studied in **leptonic** and **semi-leptonic** channels
- A set of **23 low-mass** + **20 high-mass benchmarks** analysed
- Discovery reach mostly driven by the production cross-section
- High sensitivity in leptonic channel up to 500 GeV c.m.s. energy
  → Semi-leptonic channel has to be used at high energy CLIC to extend discovery reach
- Semi-leptonic channel analysis performed using **full** and **fast detector simulation** methods
- Impact of the $\gamma\gamma \rightarrow \mathrm{had.}$ **overlay events** crucial for the analysis
- Charged IDM scalars with masses of up to about 1 TeV can be discovered at CLIC

BACKUP

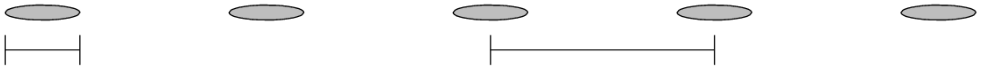
Results ($\sigma^{slep} = 1$ fb)



- 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

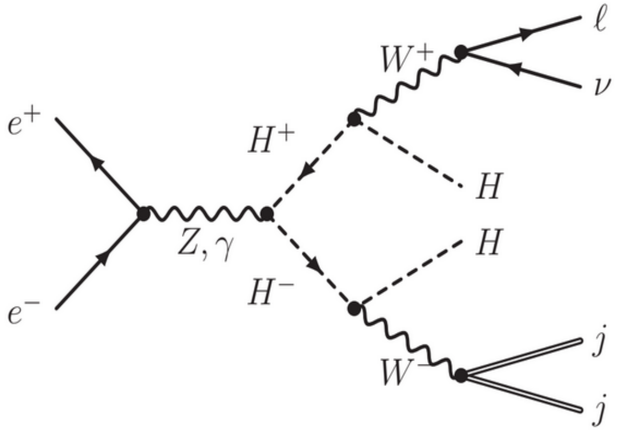
Overlay background

LCD-Note-2011-006



CLIC: 44 μm
ILC: 300 μm

CLIC: 0.5 ns, 0.15 m
ILC: 369 ns, 111 m



Huge **beam-induced backgrounds** at CLIC

$\gamma\gamma \to \boldsymbol{had.}$ most important (physics, performance)

Mitigation using timing cuts

Timing cuts not existing in DELPHES CLICdet cards!

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

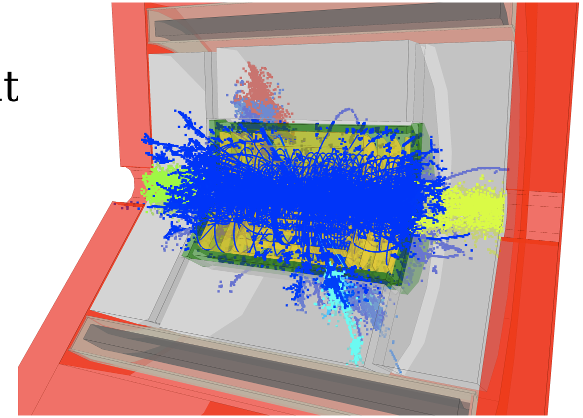
Influence on the reconstruction if W is virtual

Timing cuts

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

0.5 ns

20 bunch crossings ◄—► 10 ns

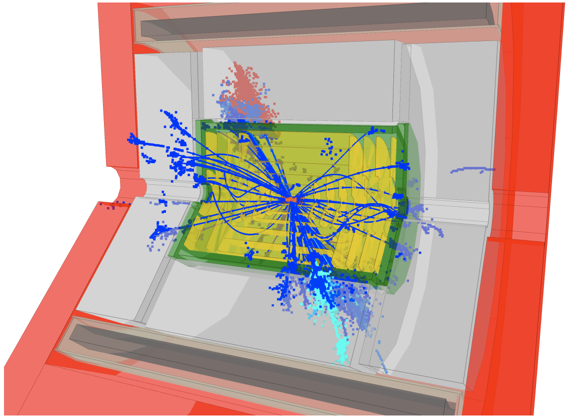


Additional timing cuts on PFOs to reduce $\gamma\gamma \to \text{had. backg.}$

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

2 ns

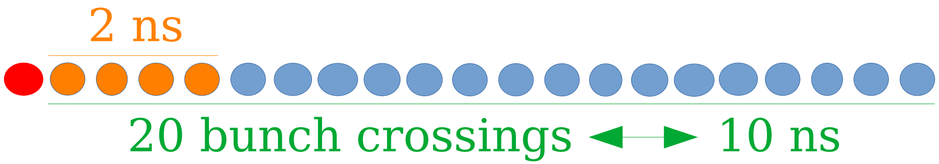
20 bunch crossings ◄—► 10 ns



Approximate timing cuts

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

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



1. Take gen-level $\gamma\gamma \rightarrow \mathrm{had.}$ 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