Prompt scalar searches at ILC and CLIC

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Standard and exotic Scalars at future HET factories

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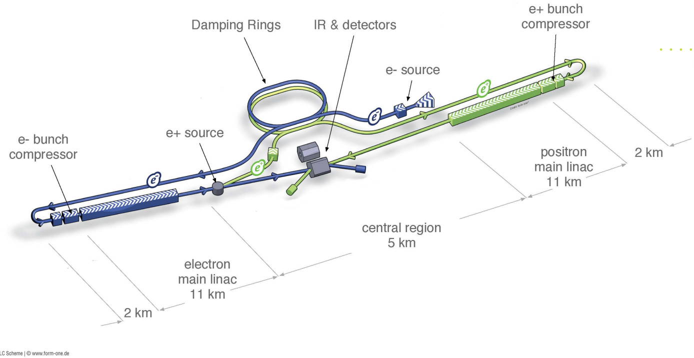
Outline

Presented is my personal, arbitrary selection of available results...

Introduction

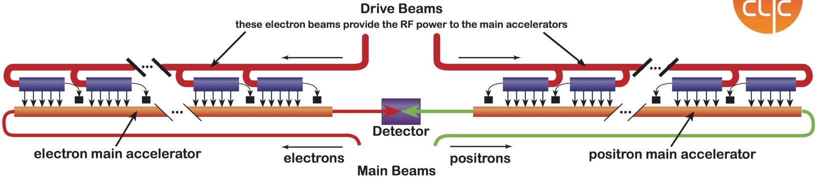
International Linear Collider



Technical Design (TDR) completed in 2013 arXiv:1306.6328

- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)

Compact LInear Collider



Conceptual Design (CDR) presented in 2012 CERN-2012-007

- high gradient, two-beam acceleration scheme
- staged implementation plan with energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^- polarisation (80%)

For details refer to arXiv:1812.07987

Running scenarios

Staged construction assumed for both ILC and CLIC.

ILC (H-20 scenario)

- total of $2000\,\mathrm{fb}^{-1}$ expected at 250 GeV
- $200\,\mathrm{fb}^{-1}$ assumed at 350 GeV
- total of $4000\,\mathrm{fb}^{-1}$ planned at 500 GeV

assuming polarisation of $\pm 80\%$ for electrons and $\pm 30\%$ for positrons

arXiv:1903.01629

CLIC

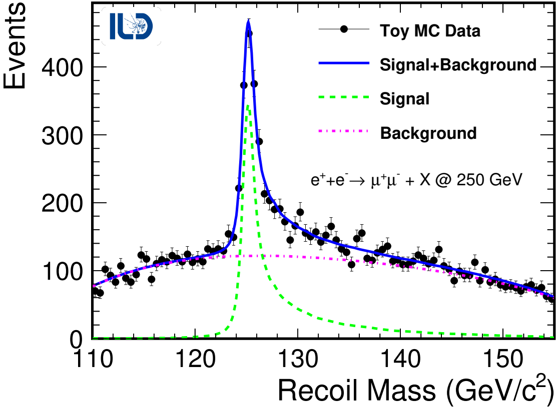
- total of $1000\,\mathrm{fb}^{-1}$ at 380 GeV (with 100 fb^{-1} at $t\bar{t}$ threshold)
  $4000\,\mathrm{fb}^{-1}$ possible with a longer first energy stage
- total of $2500\,\mathrm{fb}^{-1}$ expected at 1.5 TeV
- total of $5000\,\mathrm{fb}^{-1}$ expected at 3 TeV

assuming polarisation of $\pm 80\%$ for electrons

arXiv:1812.06018

Event reconstruction

In the ZH production channel (dominating below 450 GeV) we can use "Z-tagging" for unbiased selection of Higgs production events



arXiv:1604.07524

Avoid dependence on the Higgs decay channel ⇒ also invisible decays!

Beyond Standard Model example

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 $\sim \sin^2\alpha$)

$\Rightarrow$ search for invisible Higgs decays

Invisible Higgs decays

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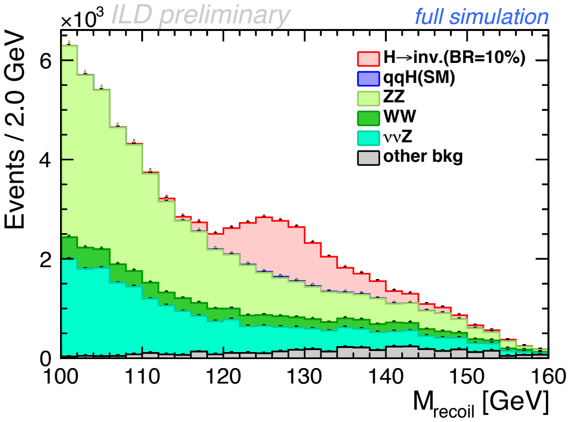
If h_2 is also light, it can be produced in e^+e^- collisions in the same way as the SM-like Higgs boson.

$\Rightarrow$ search for additional scalar states

Visible in recoil mass distribution even, if invisible decays dominate.

Constraining invisible decays

High sensitivity to invisible Higgs boson decays with recoil mass technique



Expected 95% C.L. limit for 2 ab^{-1} collected at 250 GeV ILC: 0.23%

arXiv:2002.12048

Expected limits

Summary of expected 95% CL limits on BR($H \rightarrow invisible$)

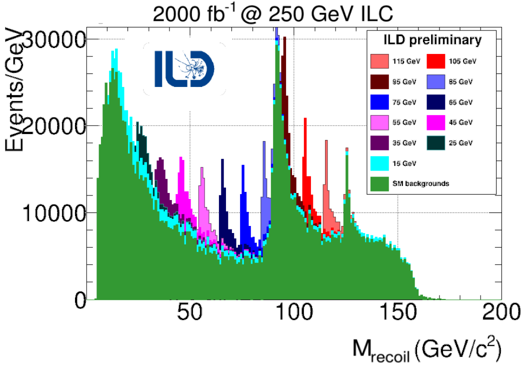
		$Z \rightarrow qq$	$Z \rightarrow ll$	Combined
ILC	250 GeV	0.25%	0.57%	0.25%
CLIC	380 GeV 4000 fb−1	0.5%		
ILC	500 GeV	0.78%	1.19%	0.65 %

arXiv:2002.12048, arXiv:2002.06034

Single scalar production

New scalars could be produced in the process similar to Higgs-strahlung...
Same approach used as in the search for invisible SM Higgs boson decays.

ILD search for production of new scalars: arXiv:1903.01629 arXiv:2005.06265



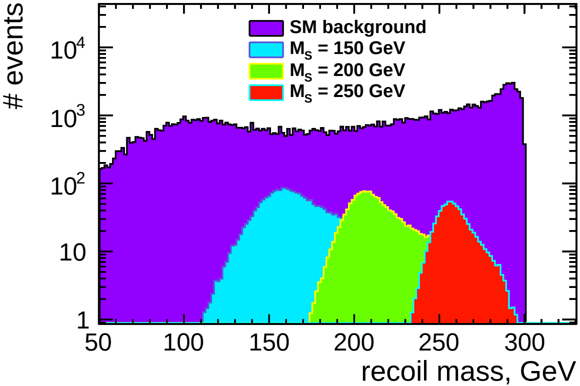
Search independent on the scalar decay: $e^+e^- \rightarrow Z\ S^0 \rightarrow \mu^+\mu^- + X$

Single scalar production

Assuming invisible decays of new scalar dominate, search for:

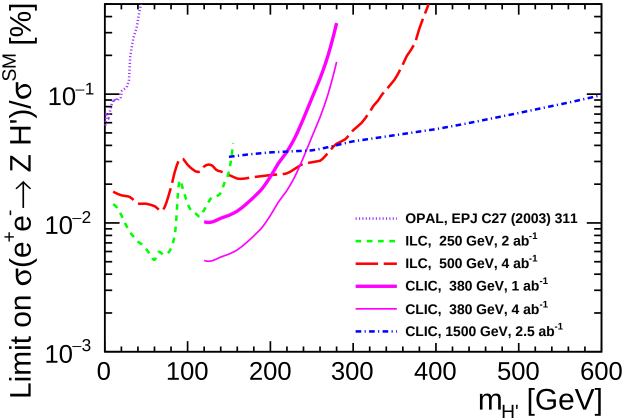
$$e^+e^- \rightarrow Z\ S \quad \rightarrow \quad q\ \bar{q}\ +\ \not{E}_T$$

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



Single scalar production

Expected sensitivity of ILC running at 250 GeV and 500 GeV, and CLIC running at 380 GeV and 1.5 TeV compared to the existing limit from LEP



EPJ Plus 136(2021)2, 160

Pair production: Inert Doublet Model example

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*: $\Phi_S \to \Phi_S$ (also other SM→SM)
- inert doublet Φ_D is *odd*: $\Phi_D \to -\Phi_D$.

⇒ Yukawa-type interactions only for Higgs doublet (Φ_S).
The inert doublet (Φ_D) does not interact with the SM fermions!

⇒ The lightest inert particle is stable: a natural candidate for dark matter!
We assume it is the neutral scalar H: $m_H < m_A, \ m_{H^\pm}$

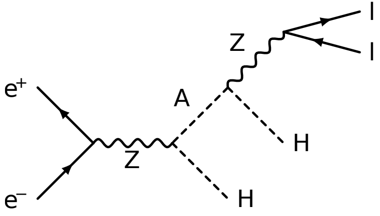
Pair production in the leptonic channel

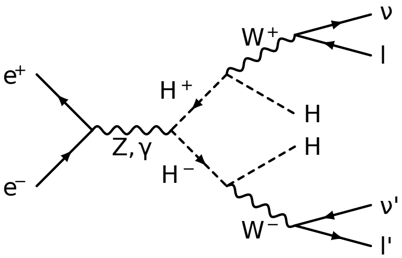
Same flavour lepton pair production can be considered a signature of the AH production process followed by the A decay:

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

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

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

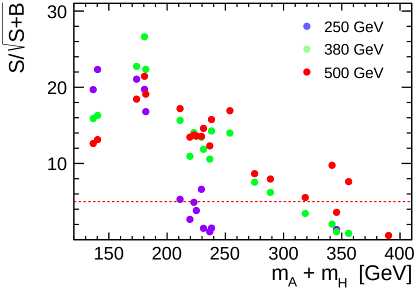




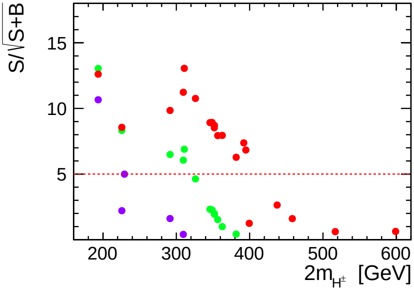
Pair production in the leptonic channel

Expected significance for IDM scalar pair-production arXiv:2203.07913

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

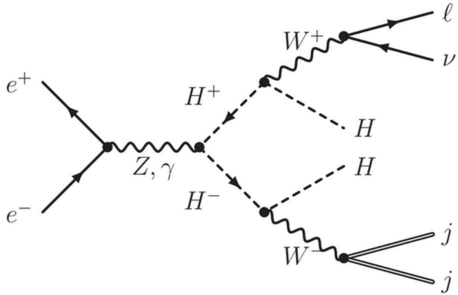
for 1000 fb^{-1} at $\sqrt{s} = 250,\ 380,\ 500$ GeV

Pair production in the semi-leptonic channel

For high scalar masses leptonic channel sensitivity limited by cross section

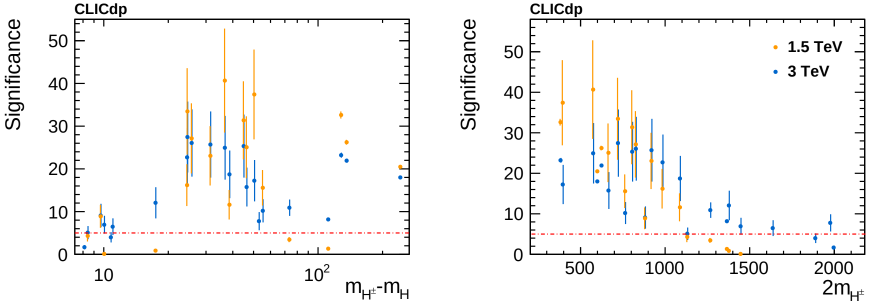
Much higher significance can be expected for H^+H^- production in the semi-leptonic final state (isolated lepton and two jets)

- 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



Pair production in the semi-leptonic channel

Expected statistical significance of IDM charged scalar pair-production



High mass benchmark scenarios only

arXiv:2201.07146

Error bars indicate systematic uncertainties attributed to fast simulation

Huge increase in signal significance over leptonic channel!

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

Conclusions

Prompt scalar searches at ILC and CLIC

ILC will offer many complementary options for BSM searches:

- different scenarios can be constrained via precision Higgs studies,
  see backup slides
- clean environment and kinematic constraints result in high sensitivity to new scalar production, including scenarios with DM decays,
- sensitivity to prompt scalar production mainly limited by energy,
- indirect constraints from precision measurements extend to the TeV mass scales, order of magnitude higher than the collision energy.
  see backup slides

References

- The International Linear Collider: A Global Project, arXiv:1903.01629
- The Compact Linear Collider (CLIC) - 2018 Summary Report, arXiv:1812.06018

- Measurement of the Higgs boson mass and $e^+e^- \to ZH$ cross section using $Z \to \mu^+\mu^-$ and $Z \to e^+e^-$ the ILC, arXiv:1604.07524
- Probing the dark sector via searches for invisible decays of the Higgs boson at the ILC, arXiv:2002.12048
- Search for Extra Scalars Produced in Association with Muon Pairs at the ILC, arXiv:1902.06118
- ILD Benchmark: Search for Extra Scalars Produced in Association with a Z boson at $\sqrt{s} = 500$ GeV, arXiv:2005.06265
- Sensitivity to invisible scalar decays at CLIC, arXiv:2002.06034, EPJ Plus 136(2021)2, 160

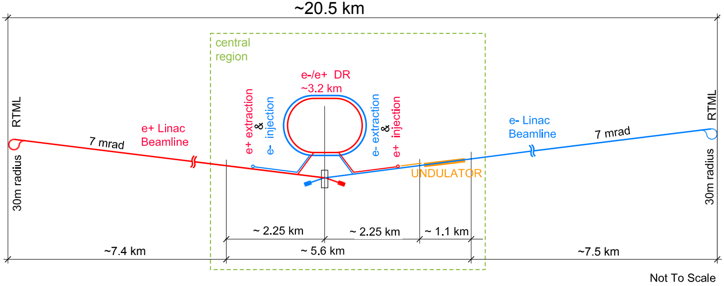
- Benchmarking the Inert Doublet Model for e^+e^- colliders, arXiv:1809.07712
- Exploring Inert Scalars at CLIC, arXiv:1811.06952
- New Physics with missing energy at future lepton colliders – Snowmass White Paper, arXiv:2203.07913
- Pair-production of the charged IDM scalars at high energy CLIC, arXiv:2201.07146

ILC-250

The discovery of a Higgs Boson with a mass of 125 GeV opened the possibility of reducing ILC cost by starting at a centre-of-mass energy of 250 GeV with the possibility of future upgrades to 500 GeV or even 1 TeV.

arXiv:1711.00568

"Higgs-factory" layout 250 GeV optimal for Higgs production



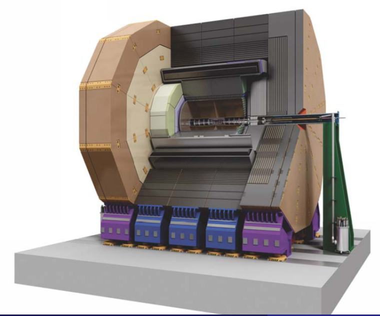
arXiv:1903.01629

Detector Requirements   same for ILC and CLIC

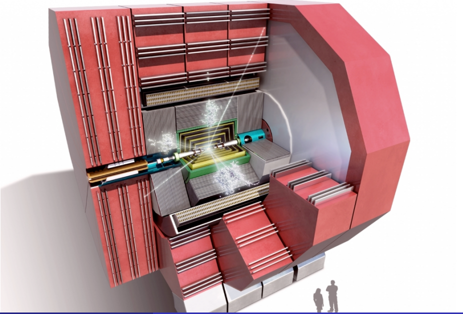
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Detailed detector concepts for ILC and CLIC:

ILD

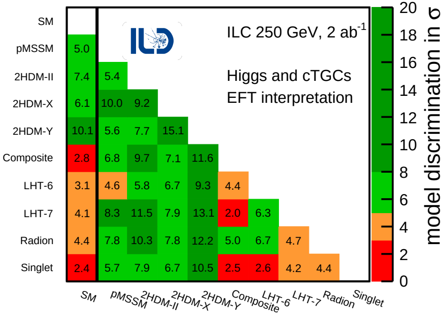


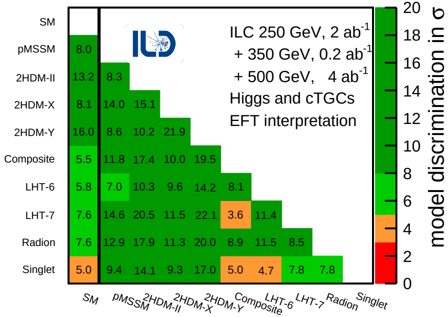
CLICdet



BSM sensitivity

Precision of e^+e^- colliders allows to distinguish the SM expectations and other models from the global analysis of the Higgs boson couplings





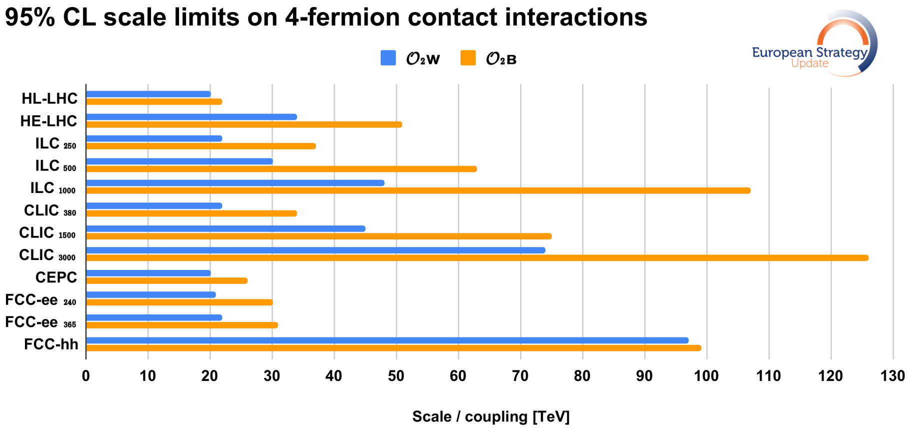
arXiv:1710.07621

Significant ($> 5\sigma$) differences between most scenarios already at 250 GeV

All considered scenarios identified at $\geq 5\sigma$ after full ILC programme (H-20)

BSM sensitivity EFT analysis

Summary of the sensitivity to SM-EFT operators from a global analysis of corresponding observables for different future colliders



ILC1000/CLIC3000 sensitivity exceeds that of FCC-hh