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The Compact Linear Collider: physics potential

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ACHEP 2023 Rabat Kénitra

Rabat - Salé - Kénitra Regional University Consortium Organizes

The First Edition of the African Conference on High Energy Physics

October
23rd-27th ,2023

Rabat & Kénitra
Morocco

2023

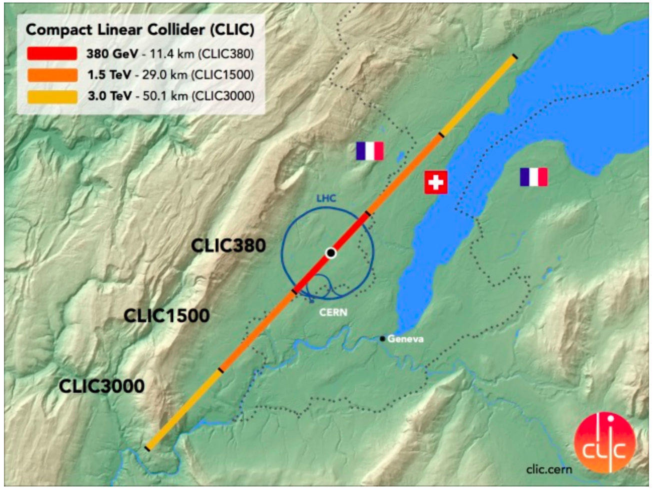
CLIC running scenarios

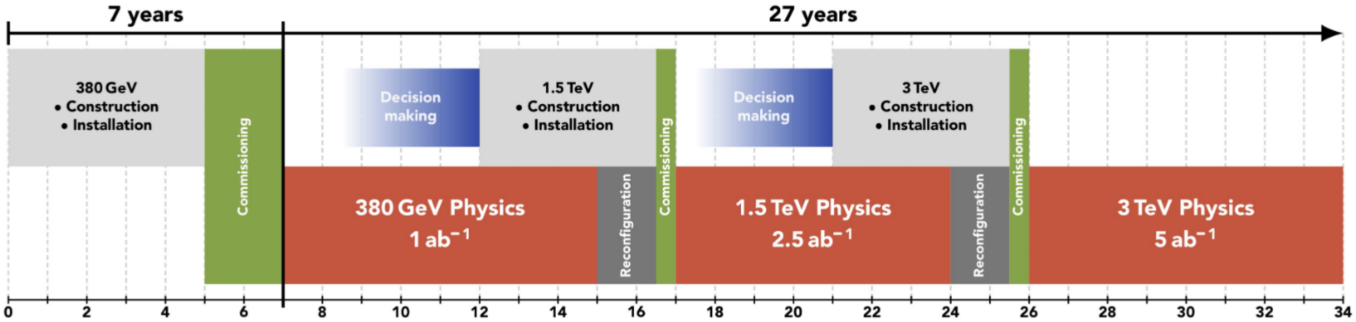
Staged implementation

→ Possible adjustments based on any potential discoveries

Three main areas of research:

- Higgs physics
- Top physics
- Beyond Standard Model searches





Baseline: several energy stages

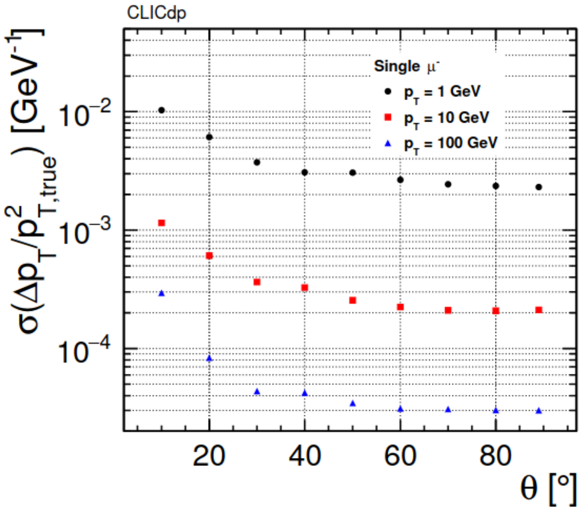
Stage	$\sqrt{s}$ [GeV]	$\mathcal{L}_{\text{int}}$ [fb^{-1}]
1	380	1000
top scan	350	100
2	1500	2500
3	3000	5000

Simulation and software framework

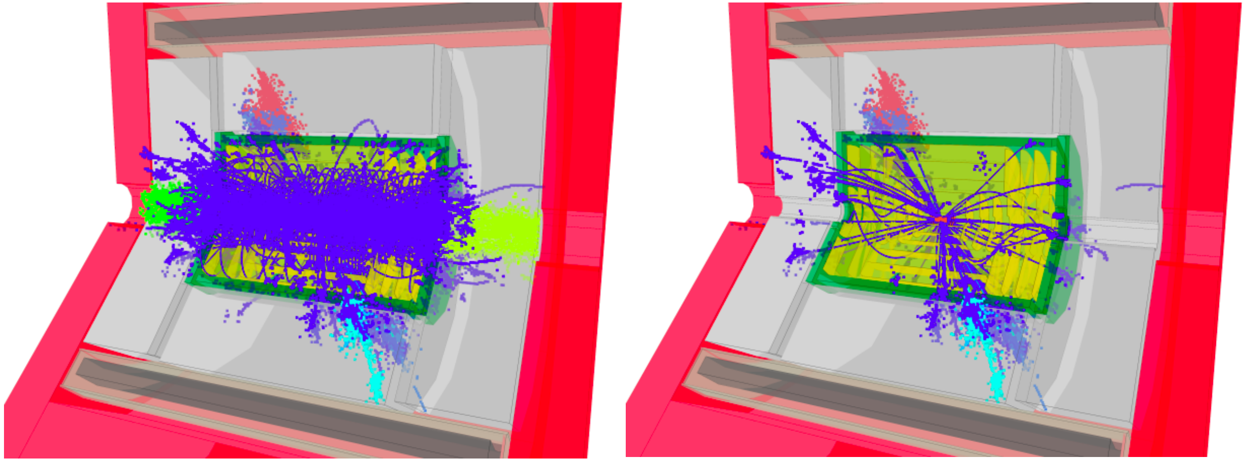
- **Whizard** (+Pythia) as the main generator
- Most of results based on **Geant4 full simulation**
- Comprehensive set of tools for reconstruction include:

  → Conformal Tracking, PandoraPFA libraries, VLC algorithm for jet reco.

  → tools for flavour tagging, isolation, and more
- Set of **Delphes cards** for fast simulation



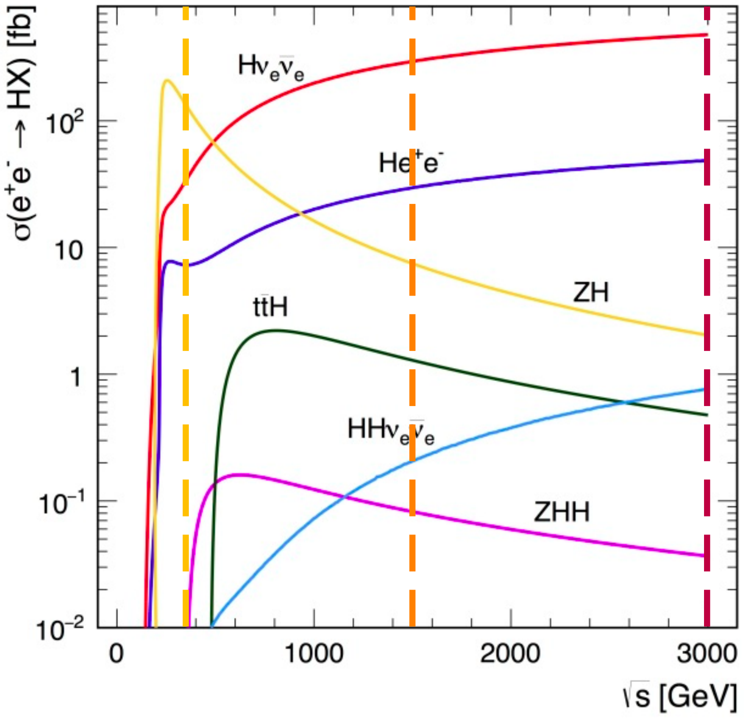
- **Beam-induced backgrounds** taken into account in full sim.
- Timing cuts applied to reduce $\gamma\gamma \to$ hadrons overlay events



tt events before and after cuts

Higgs boson

Higgs physics



ZH (Higgsstrahlung)

- At 380 GeV (close to max. cross section)
- Precise **mass** and **coupling** measurements

Production in Vector Boson Fusion (VBF)

- WW fusion dominant at high energies
- Allows complementary measurements increasing precision

Di-Higgss production

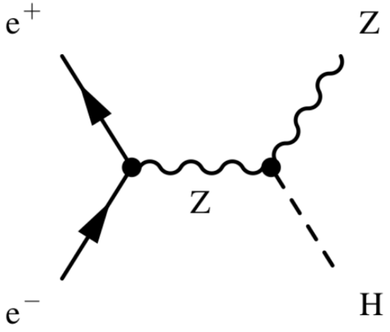
- Significant cross section in WW fusion at 3 TeV
- Self-coupling measurement

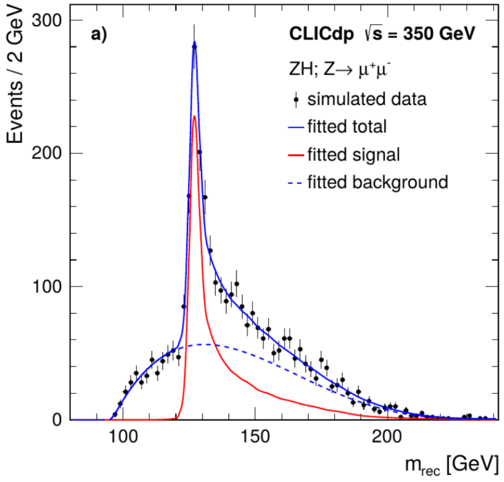
Higgsstrahlung and global fit

ZH (Higgsstrahlung)

- Use Z → ee, μμ, and **Z recoil mass** to identify HZ events

  → model-independent g_{HZZ} coupling determination
- Further improvement with Z → qq



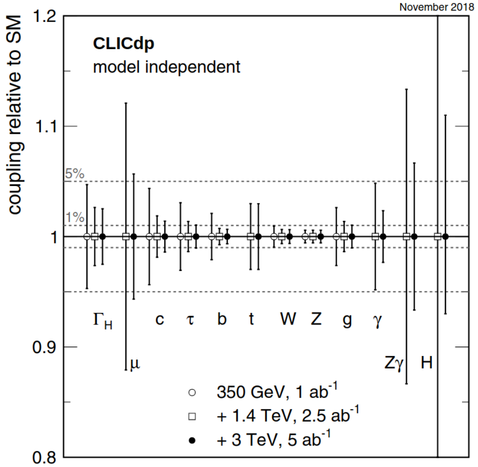


Invisible decays

- Model-independent measurement of BR(H→inv.)
- Can be constrained to **1%** at 95% C.L.

Model-independent global fit (no assumptions on BSM scenarios)

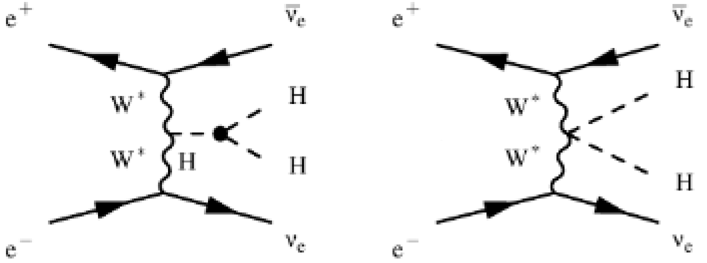
- Possible only at lepton colliders
- Fit to σ×BR measurements in HZ, VBF (different channels, energies)
- Precision ≲1% for most couplings
- Model-dependent fit also possible (see EPJ C 77 (2017) 475, arXiv:1812.01644)



Higgs self-coupling

Determines shape of the scalar potential

→ important for vacuum metastability, hierarchy problem, electroweak phase transition and baryogenesis



Direct access possible only above 500 GeV c.m. energy

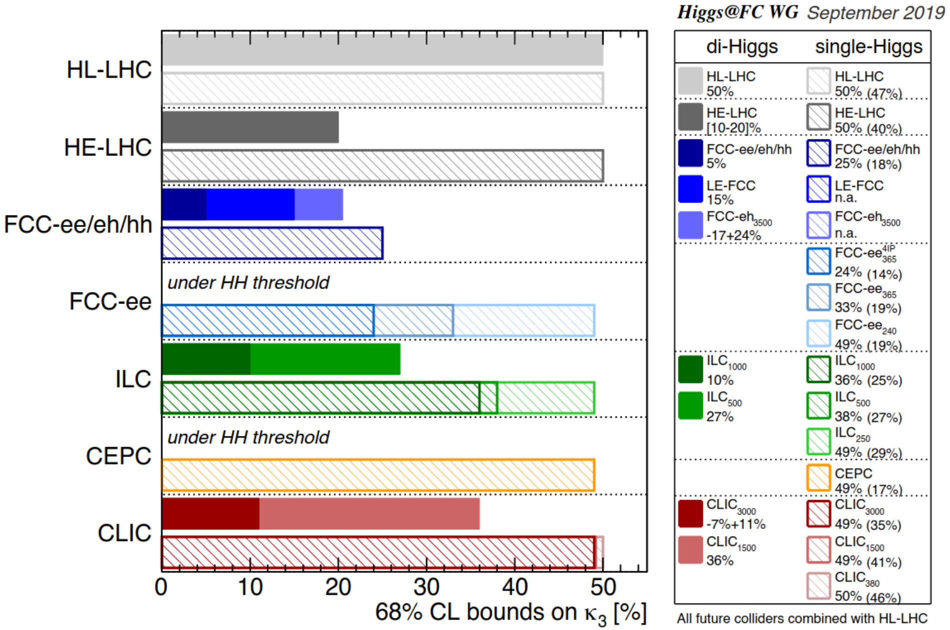
Cross section for HHνν grows with energy

→ g_{HHH} can be extracted using:

- 1.5 TeV (ZHH and HHνν) and 3 TeV (HHνν) data
- Cross section measurements and distributions of sensitive variables

→ leads to **-8%, +11% precision on g_{HHH}**

As g_{HHWW} also contributes to HHνν, simultanous fit can be performed to constrain both couplings



Top quark

Top physics

tt production

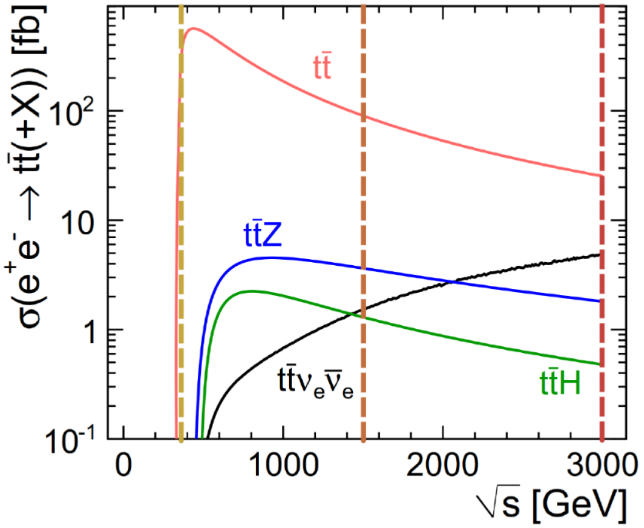
- At 380 GeV (close to max. cross section)
- Precise mass measurements

ttH production

- At 1.5 TeV (close to max. rate due to higher lumi)
- Top Yukawa coupling measurement

tt production in VBF

- At 3 TeV
- Sensitive to BSM effects



Other highlights in the top sector:

- Electroweak couplings
- CP properties (ttH)
- Forward-backward asymmmetry
- New physics searches (compositeness, FCNC, and more)

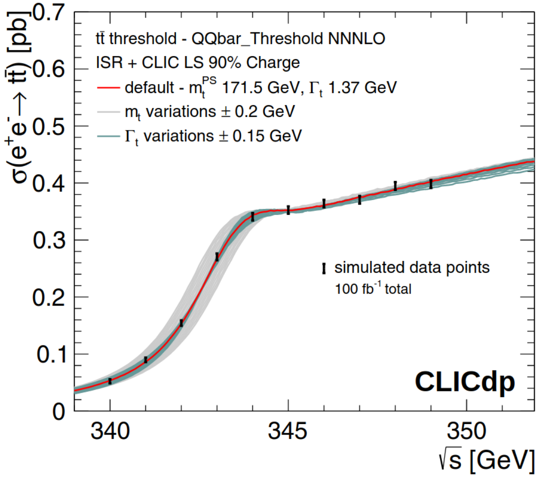
Top mass measurements

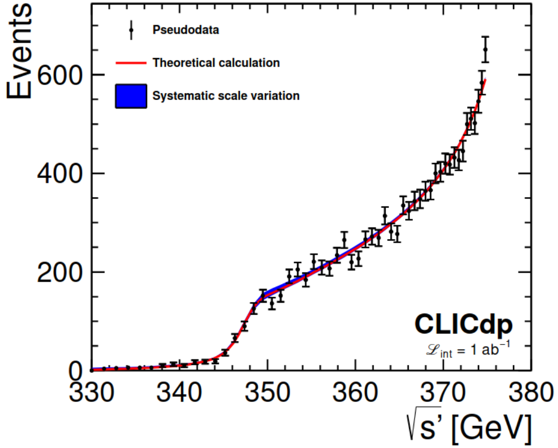
Top threshold scan:

- Dedicated runs at 10 points (10 fb^{-1} each) around 350 GeV with reduced charge lumi. spectrum → lower beamstrahlung
- Uncertainties from Yukawa and α_s couplings
- Most precise method for mass measurement
  → uncert. **20 MeV (stat.)** and **50 MeV (tot.)**

Complementary methods:

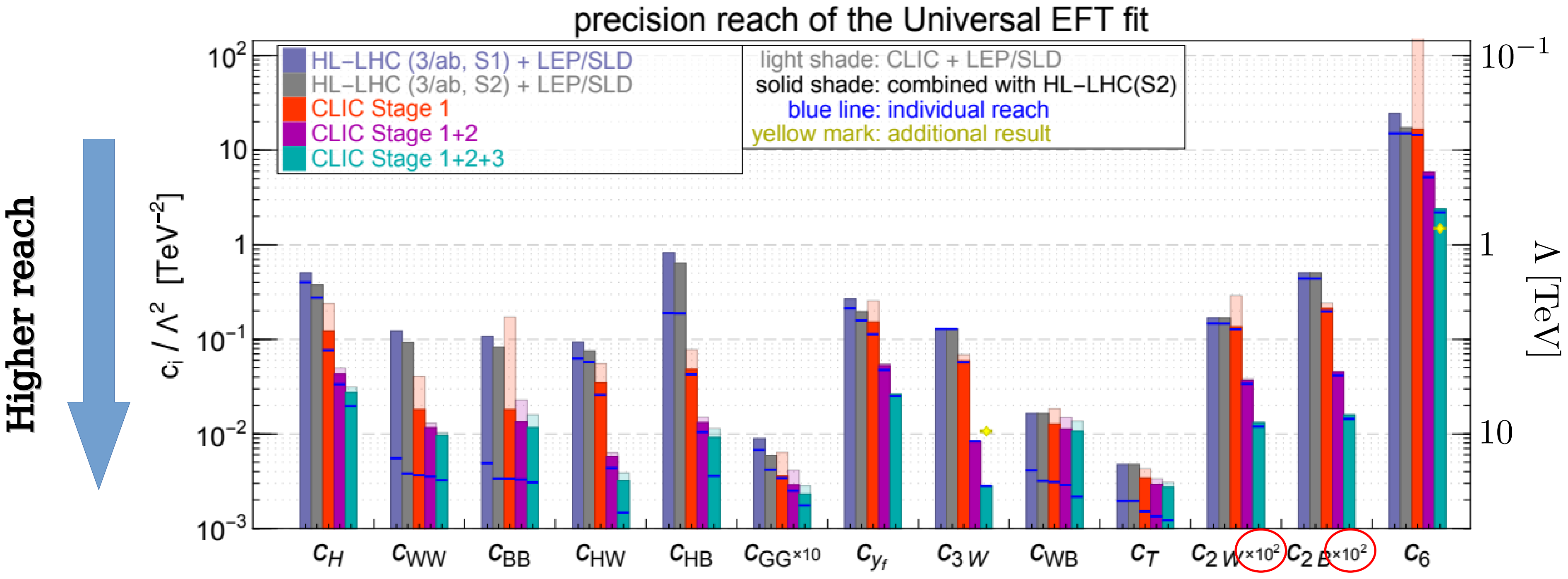
- Radiative events ($tt\gamma$) at 380 GeV
  → Similar method to threshold scan, ~140 MeV uncert.
- Direct mass reconstruction at 380 GeV
  → large theoretical uncert., experimentally challenging





BSM physics

EFT framework



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

Based on CLIC combined precision measurements of:

Higgs couplings, **top-quark observables**, **WW production** and **ee → ff**

Direct BSM searches

Process	**HL-LHC**	**CLIC**
Higgs mixing with heavy singlet	$\sin^2\gamma < 4\%$	$\sin^2\gamma < 0.24\%$
Higgs self-coupling $\Delta\lambda$	$\sim 50\%$ at 68% C.L.	$[-8\%, 11\%]$ at 68% C.L.
$\mathrm{BR}(\mathrm{H} \to \mathrm{inv.})$ (model-independent)		$< 1\%$ at 95% C.L.
Higgs compositeness scale m_*	$m_* > 3\,\mathrm{TeV}$ $(> 7\,\mathrm{TeV}$ for $g_* \simeq 8)$	Discovery up to $m_* = 10\,\mathrm{TeV}$ $(40\,\mathrm{TeV}$ for $g_* \simeq 8)$
Top compositeness scale m_*		Discovery up to $m_* = 8\,\mathrm{TeV}$ $(20\,\mathrm{TeV}$ for small coupling $g_*)$
Higgsino mass (disappearing track search)	$> 250\,\mathrm{GeV}$	$> 1.2\,\mathrm{TeV}$
Slepton mass		Discovery up to ~ 1.5 TeV
RPV wino mass $(c\tau = 300\,\mathrm{m})$	$> 550\,\mathrm{GeV}$	$> 1.5\,\mathrm{TeV}$
Z' mass (SM couplings)	Discovery up to $7\,\mathrm{TeV}$	Discovery up to $20\,\mathrm{TeV}$
NMSSM scalar singlet mass	$> 650\,\mathrm{GeV}$ $(\tan\beta \leq 4)$	$> 1.5\,\mathrm{TeV}$ $(\tan\beta \leq 4)$
Twin Higgs scalar singlet mass	$m_\sigma = f > 1\,\mathrm{TeV}$	$m_\sigma = f > 4.5\,\mathrm{TeV}$
Relaxion mass (for vanishing mixing)	$< 24\,\mathrm{GeV}$	$< 12\,\mathrm{GeV}$
Relaxion mixing angle $(m_\phi < m_\mathrm{H}/2)$		$\sin^2\theta \leq 2.3\%$
Neutrino Type-2 see-saw triplet		$> 1.5\,\mathrm{TeV}$ (for any triplet VEV) $> 10\,\mathrm{TeV}$ (for triplet Yukawa coupling $\simeq 0.1$)
Inverse see-saw RH neutrino		$> 10\,\mathrm{TeV}$ (for Yukawa coupling $\simeq 1$)
Scale $V_{LL}^{-1/2}$ for LFV $(\bar{\mathrm{e}}\mathrm{e})(\bar{\mathrm{e}}\tau)$		$> 42\,\mathrm{TeV}$

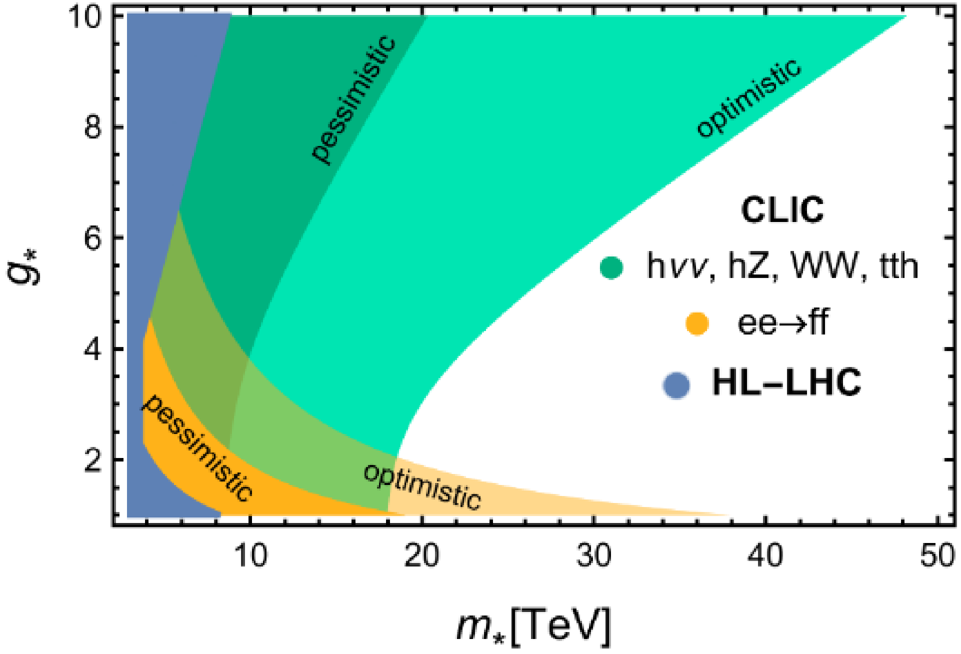
arXiv:1812.07986
arXiv:2111.04787

Outlook

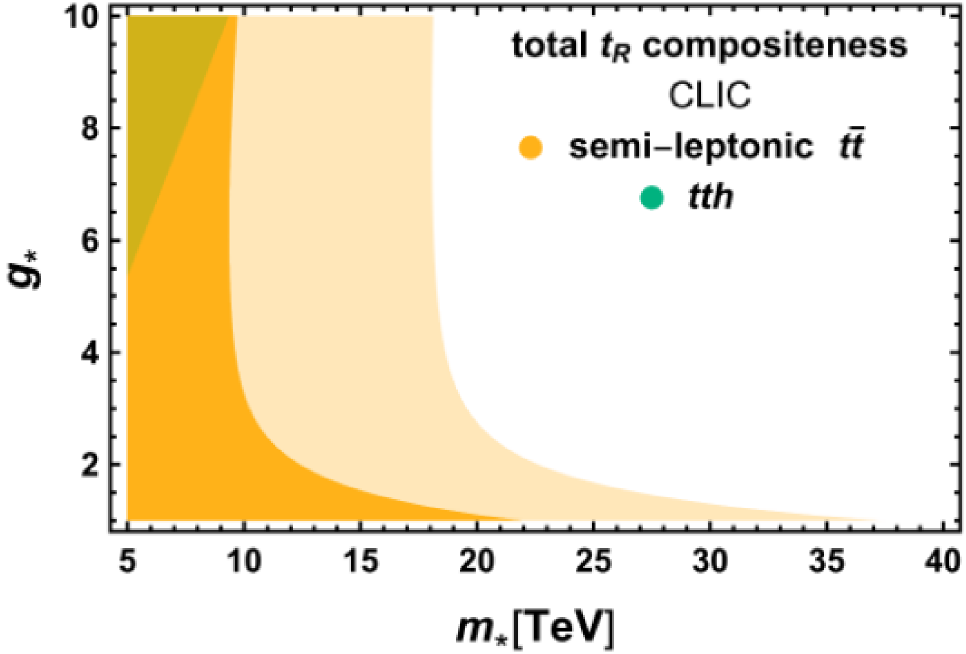
- CLIC, as a mature option for a future Higgs factory, has a broad physics programme for staged running at 380 GeV, 1.5 TeV, and 3 TeV
- Higgsstrahlung channel allows for Higgs measurements independent on its decay channels
- Higgs couplings can be measured at CLIC with unprecedented precision in a model-independent way
- CLIC is the earliest project where less than 10% presicion on Higgs self-coupling can be reached
- Top quark measurements include precise determination of mass and width (in the threshold scan), Yukawa and EW couplings
- CLIC high energy stages offers great possibility for direct BSM searches, in many cases surpassing HL-LHC reach

BACKUP

Higgs and top compositeness



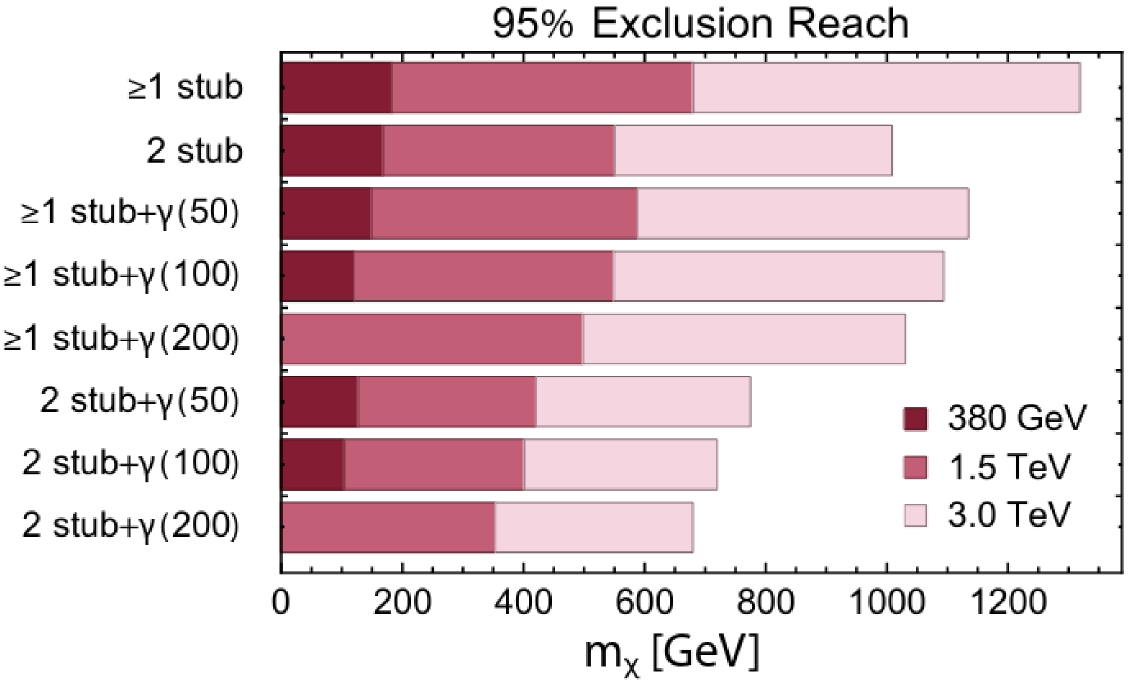
Higgs compositeness scale and coupling



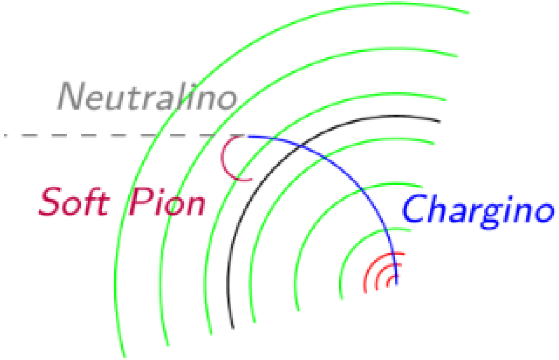
Top compositeness scale and coupling

arXiv:1812.02093

Disappearing tracks



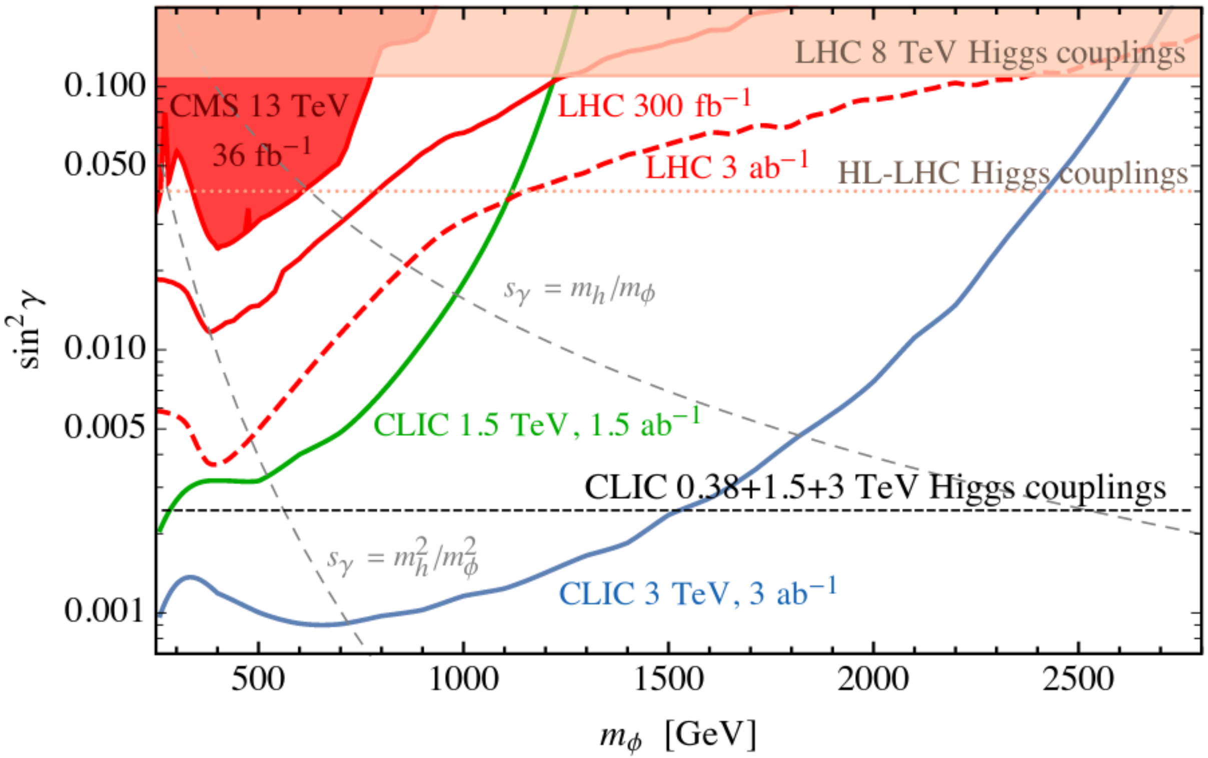
- Small mass difference between higgsino and neutralino
- At least 4 hits in tracker required



→ Reachable higgsino mass of 1.1 TeV required for exact DM relic density

arXiv:1812.02093

Heavy Scalar Singlets



Heavy scalar SM singlet mixing with the Higgs boson

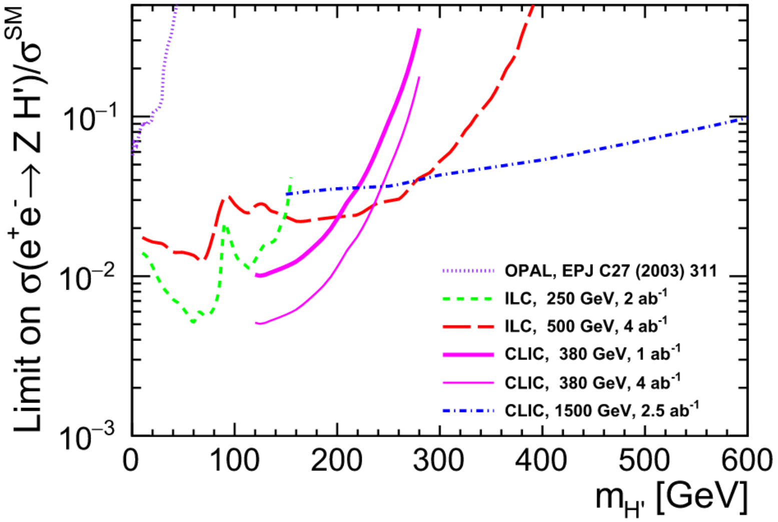
Limits from **direct** production and **indirect** from Higgs couplings

arXiv:1812.02093

Invisible scalar decays

$BR(H_{SM} \rightarrow \text{inv.}) < 1\%$ (95% CL.)

(380 GeV, 1 ab^{-1})



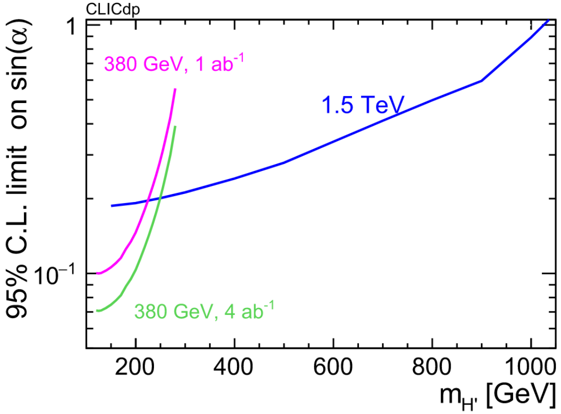
Higgs Portal

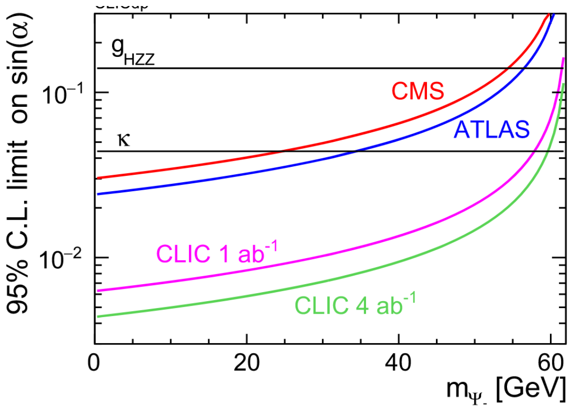
SM-like Higgs field

125 GeV state

$$\begin{pmatrix} H \\ H' \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

new scalar field



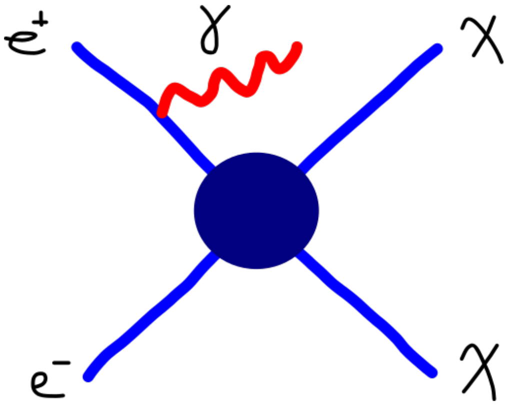


Interpretation in terms of
Vector-fermion DM Model

Much better constraints than current from ATLAS and **CMS**

Eur. Phys. J. Plus (2021) 136: 160

DM searches - mono-photon channel



<u>Most general approach for DM search</u>

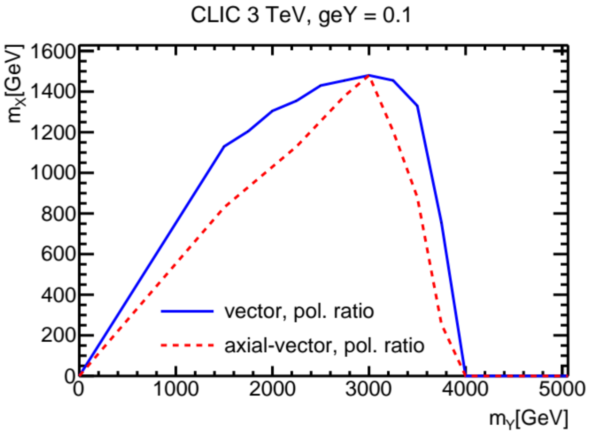
Simplified DM Models framework

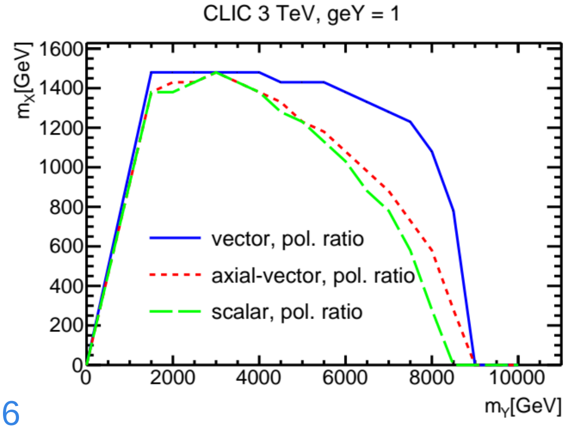
Vector, **axial-vector** and **scalar** mediators

Coupling **geY = 0.1, 1**

+80%, **-80%** and **no** beam **polarisation** considered
Best limits using: $\sigma(Pe{=}-80\%)/\sigma(Pe{=}+80\%)$
(sys. uncert. cancel)

<u>Discrimination between</u> vector and axial-vector mediators, with $m_Y = 3.5\,\mathrm{TeV}$, $m_X = 1\,\mathrm{TeV}$
WIMP mass determination with **1% accuracy**

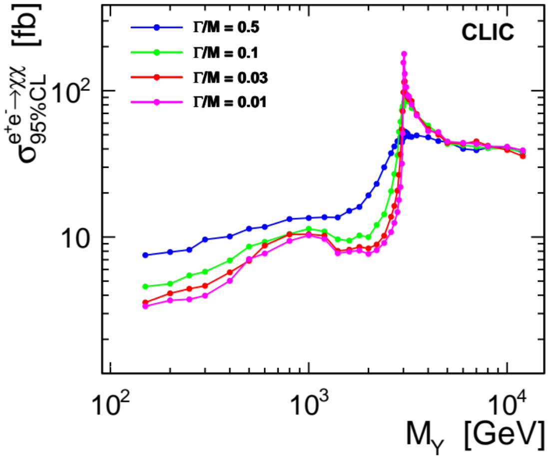




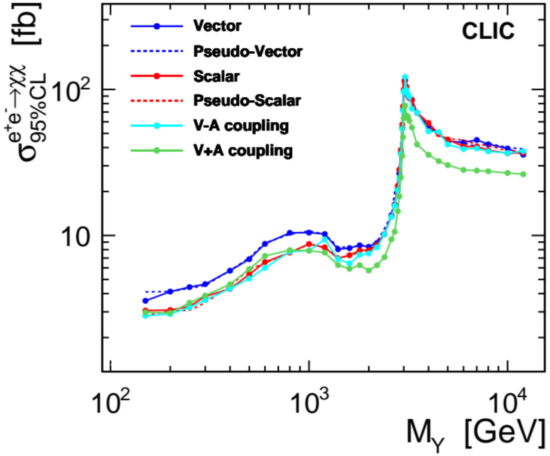
arXiv:2103.06006

Mono-photon – light mediator

Eur.Phys.J.C 81 (2021) 10, 955



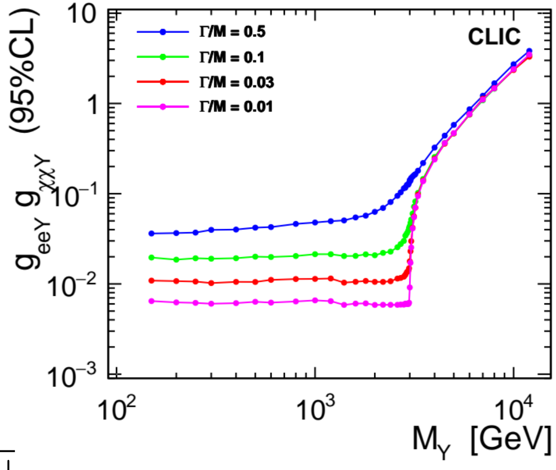
Light fermionic DM pair-production for vector mediator



Combined limits, Γ/M = 0.3

Small **masses** and **couplings**

„Experimental" approach – limits depending on width and mass



Weak dependence on the **model scenario**!

For high masses limits on EFT mass scale: **6-10 TeV**

$$\Lambda^2 = \frac{M_Y^2}{|g_{eeY}\, g_{\chi\chi Y}|}$$

Inert Doublet Model

Good agreement between **full** and **fast** simulation
→ **realistic predictions** for all scenarios

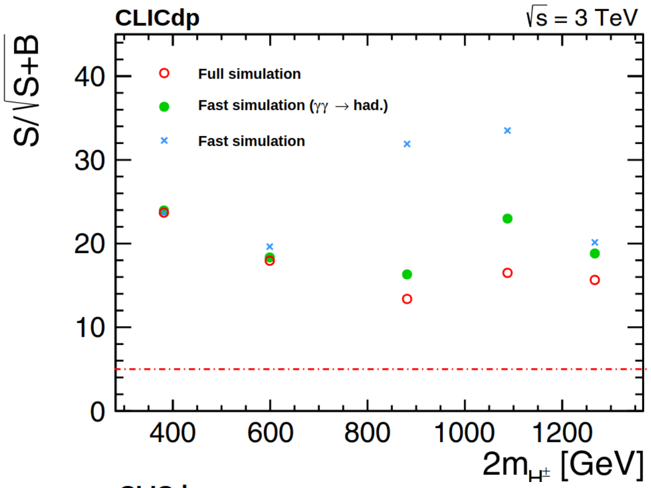
Wide range of scenarios at **1.5 TeV** and **3 TeV** CLIC analysed

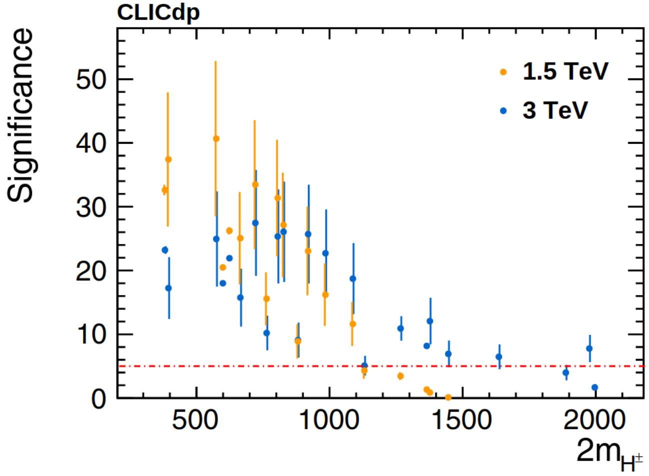
Almost all scenarios could be discovered

Scalars with **masses of 1 TeV accessible**
→ significant **increase** w.r.t. previous study
(based on leptonic channel)

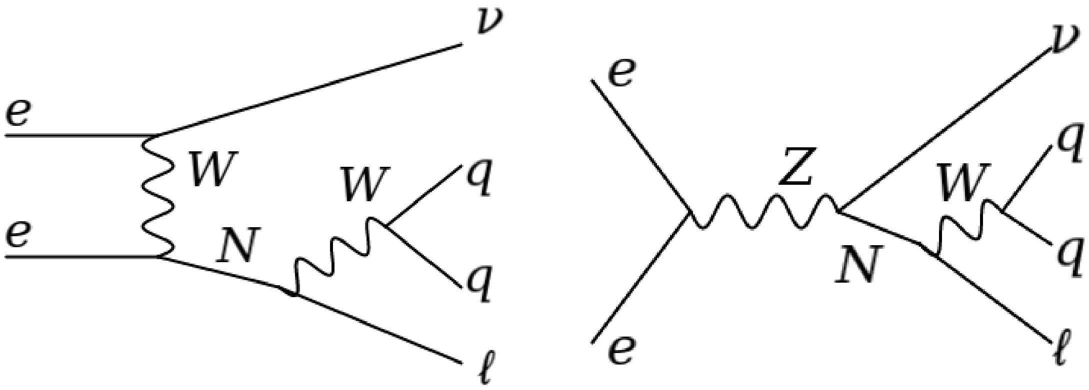
Significance reaching even **50σ**

EPJ C 82 (2022) 8, 738

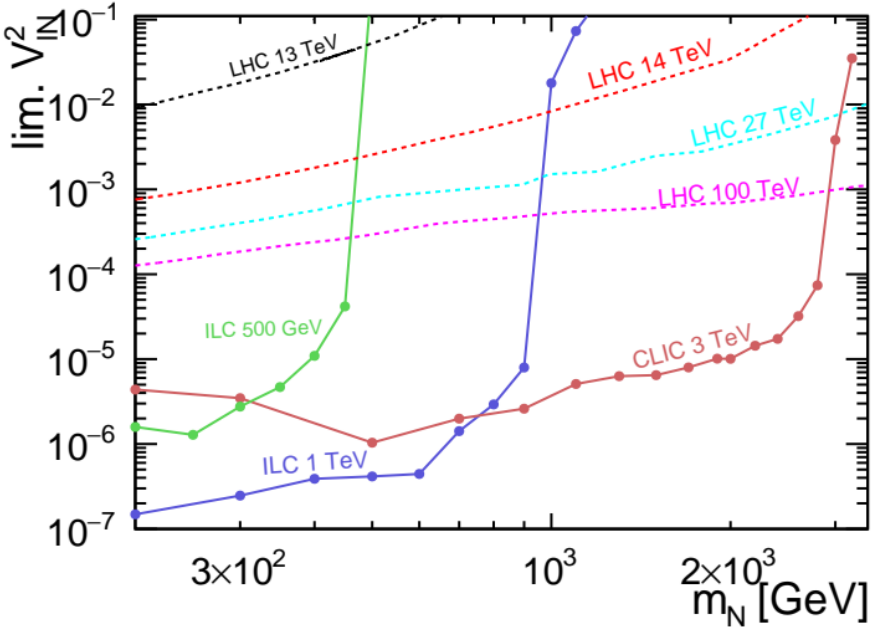




Heavy neutrinos



Semi-leptonic channel allows full neutrino reconstruction



JHEP 06 (2022) 010

Based on DELPHES simulation, with $e\gamma$, $\gamma\gamma$ backgrounds considered

Observation expected almost up to the **kinematic limit**

Limits stronger than from **LHC** and **FCC-hh**