The CLIC potential for new physics

Philipp Roloff (CERN)
on behalf of the CLICdp collaboration

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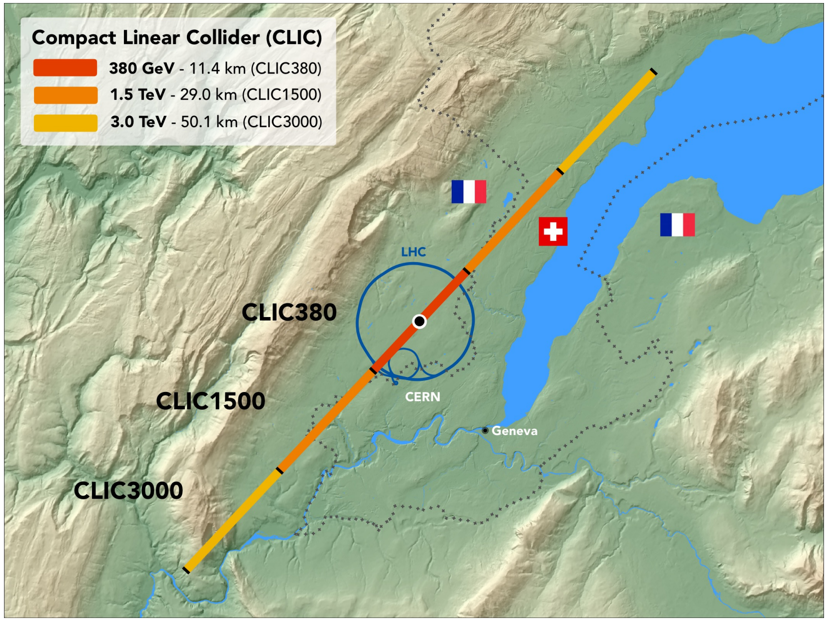
ICHEP 2020: 40th International Conference on High Energy Physics



CLIC portal:
https://clic.cern/

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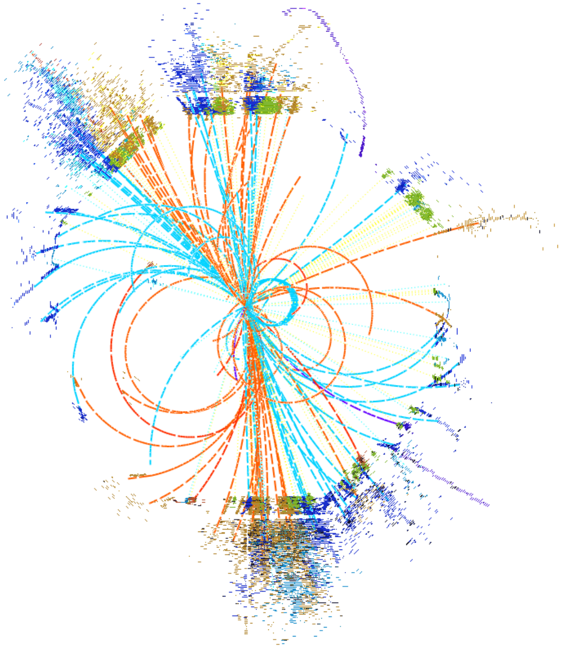
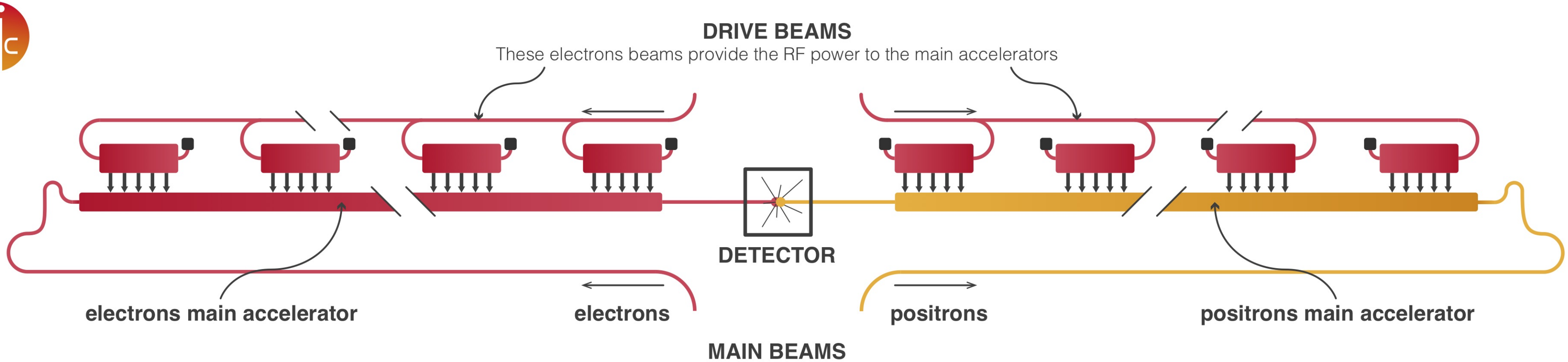
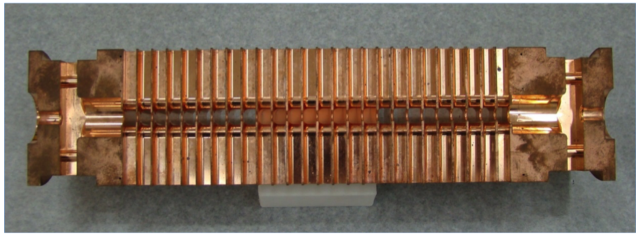


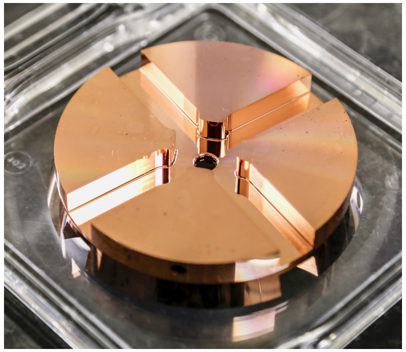
The Compact Linear Collider

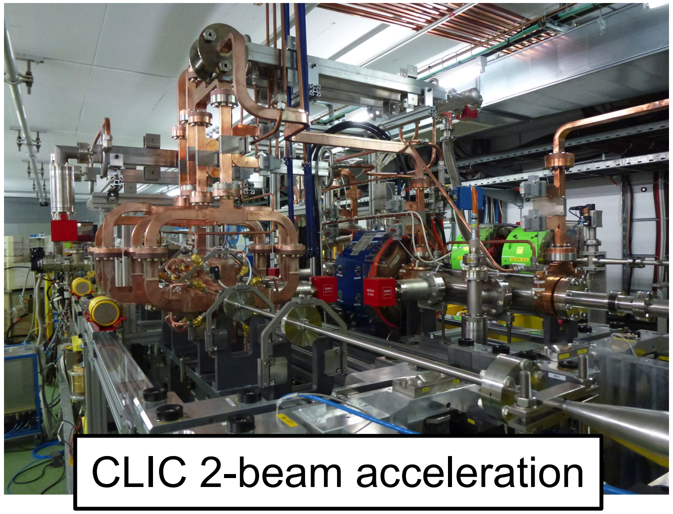


Compact Linear Collider (CLIC):

- Based on 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: 380 GeV - 3 TeV (in several stages)
- $P(e^-) = \pm 80\%$







CLIC 2-beam acceleration

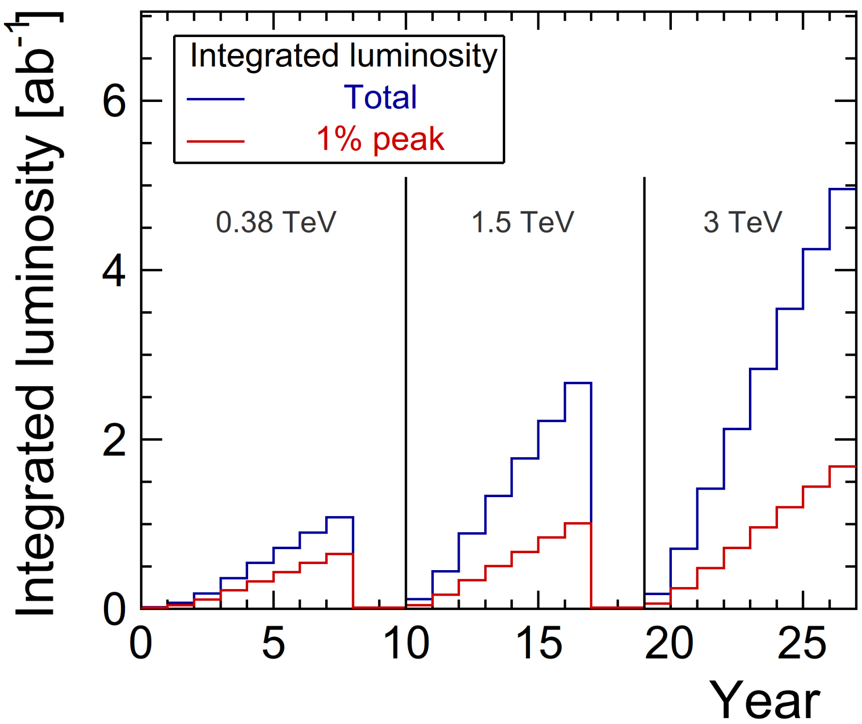
arXiv:1903.08655

CLIC staged implementation

• CLIC would be implemented in several energy stages

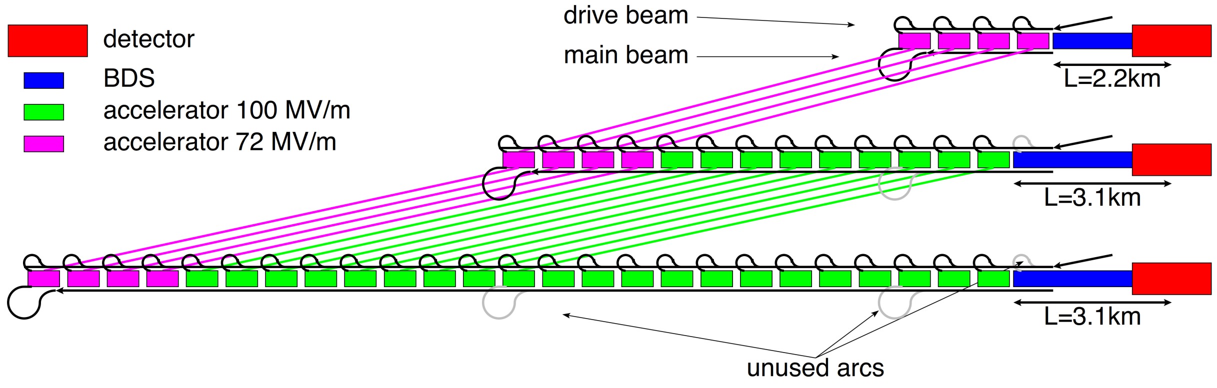
Baseline scenario:

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(e^-) = -80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]	$P(e^-) = +80\%$ $\mathscr{L}_{\text{int}}$ [ab^{-1}]
1	0.38 (and 0.35)	1.0	0.5	0.5
2	1.5	2.5	2.0	0.5
3	3.0	5.0	4.0	1.0



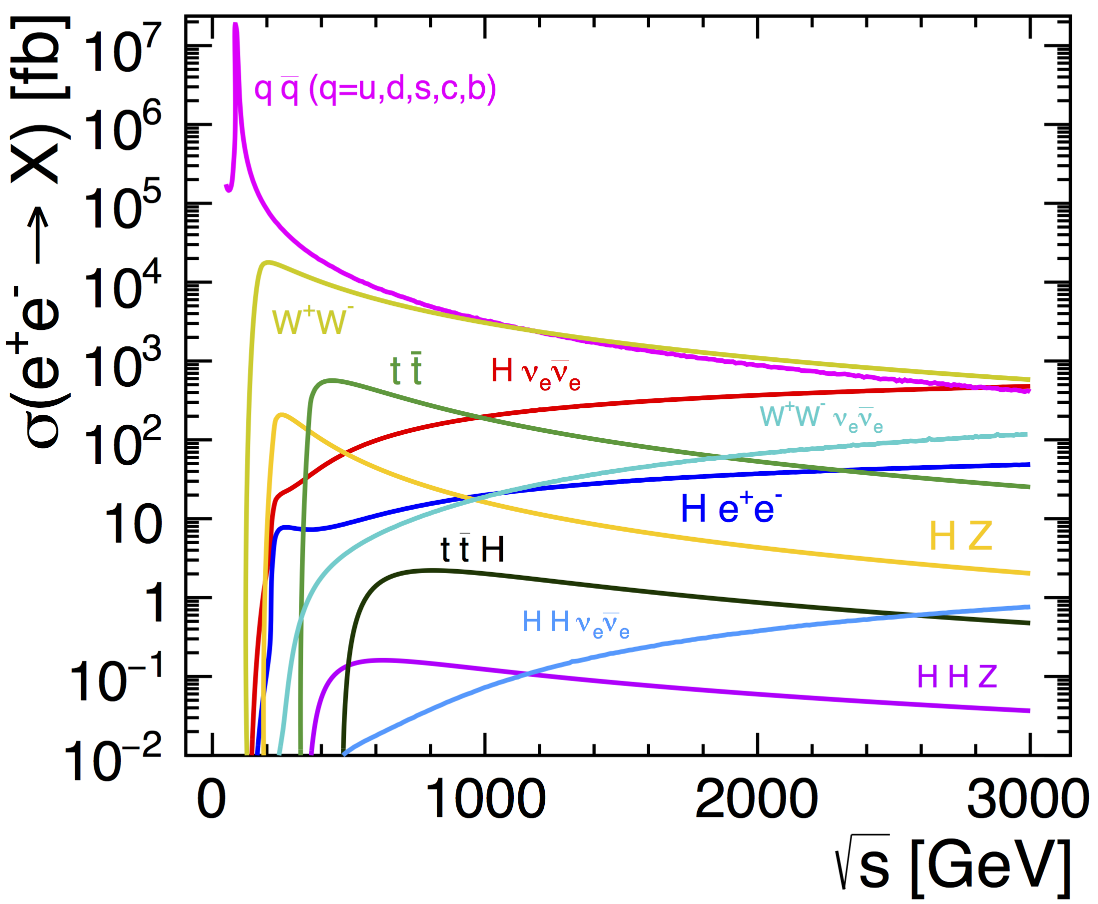
• The strategy can be adapted to possible discoveries at the (HL-)LHC or the initial CLIC stage(s)

• 1 year = 1.2×10^7 seconds (based on CERN experience)



arXiv:1812.01644
arXiv:1812.06018

Important processes in e^+e^- collisions

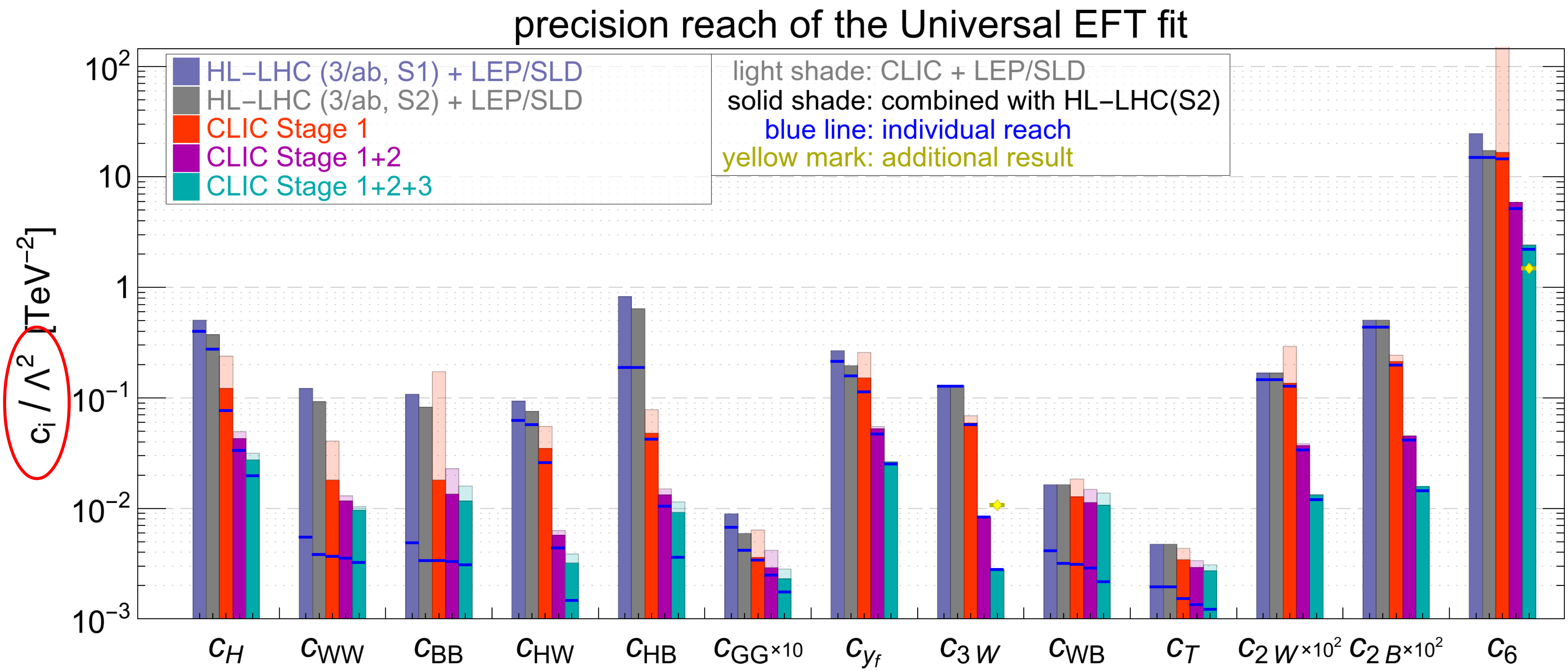


- **2-fermion production,** e.g. $q\bar{q}$
- **W-boson pair production (WW)**
- **Higgsstrahlung (HZ):** best at 240 - 380 GeV → "Higgs factory"
- **$t\bar{t}$ threshold:** 350 GeV
- **$t\bar{t}$ continuum:** ≥ 365 GeV
- **Double Higgsstrahlung (HHZ):** cross section maximum ≈ 600 GeV
- **Single and double Higgs in WW fusion ($H\nu_e\bar{\nu}_e$ and $HH\nu_e\bar{\nu}_e$):** cross section rises with energy

→ Wide range of physics opportunities, best explored in several energy stages

+ Direct searches for new particles: highest possible energy

Global Effective Field Theory fit

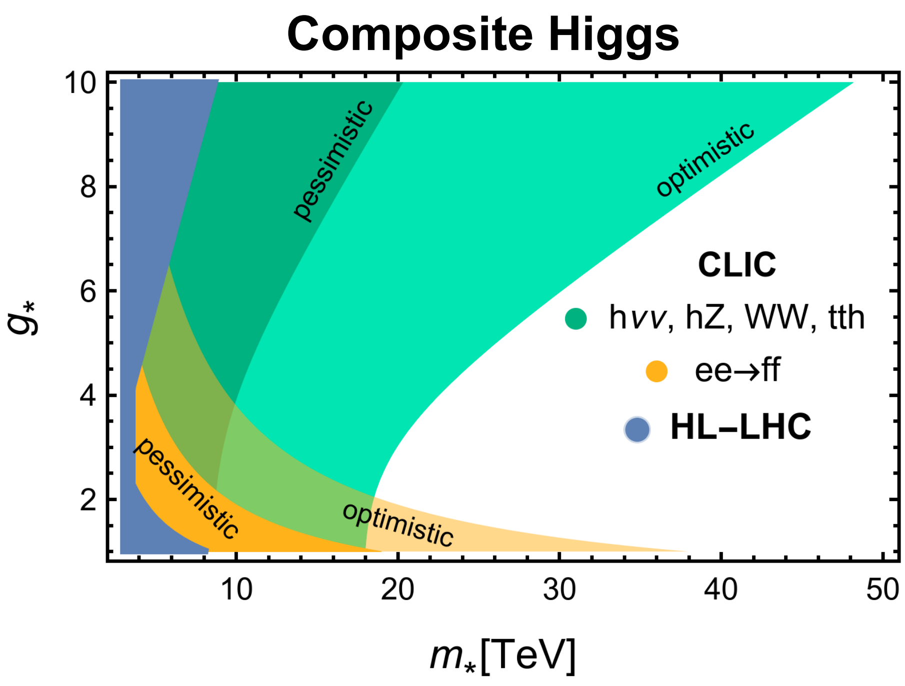


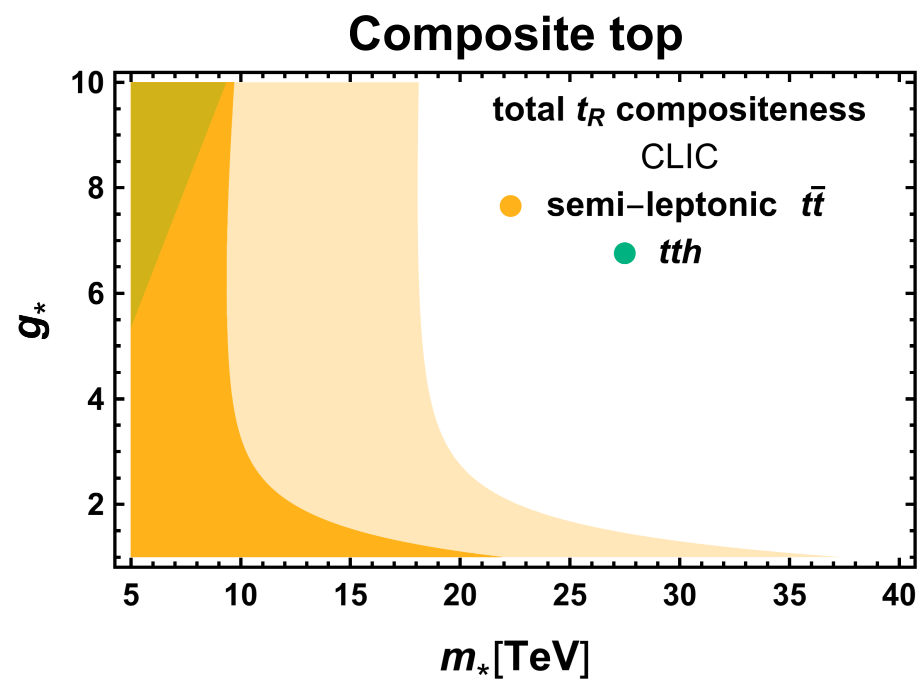
arXiv:1812.02093

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

Input to fit:
Higgs couplings, top-quark observables,
WW production, two-fermion production

Compositeness at CLIC





m_*: compositeness scale

g_*: coupling strength of the composite sector

Discovery of Higgs compositeness scale up to 10 TeV (40 TeV for $g_* \approx 8$)

Discovery of top compositeness scale up to 8 TeV (20 TeV for small g_*)

arXiv:1812.02093
JHEP **11**, 003 (2019)

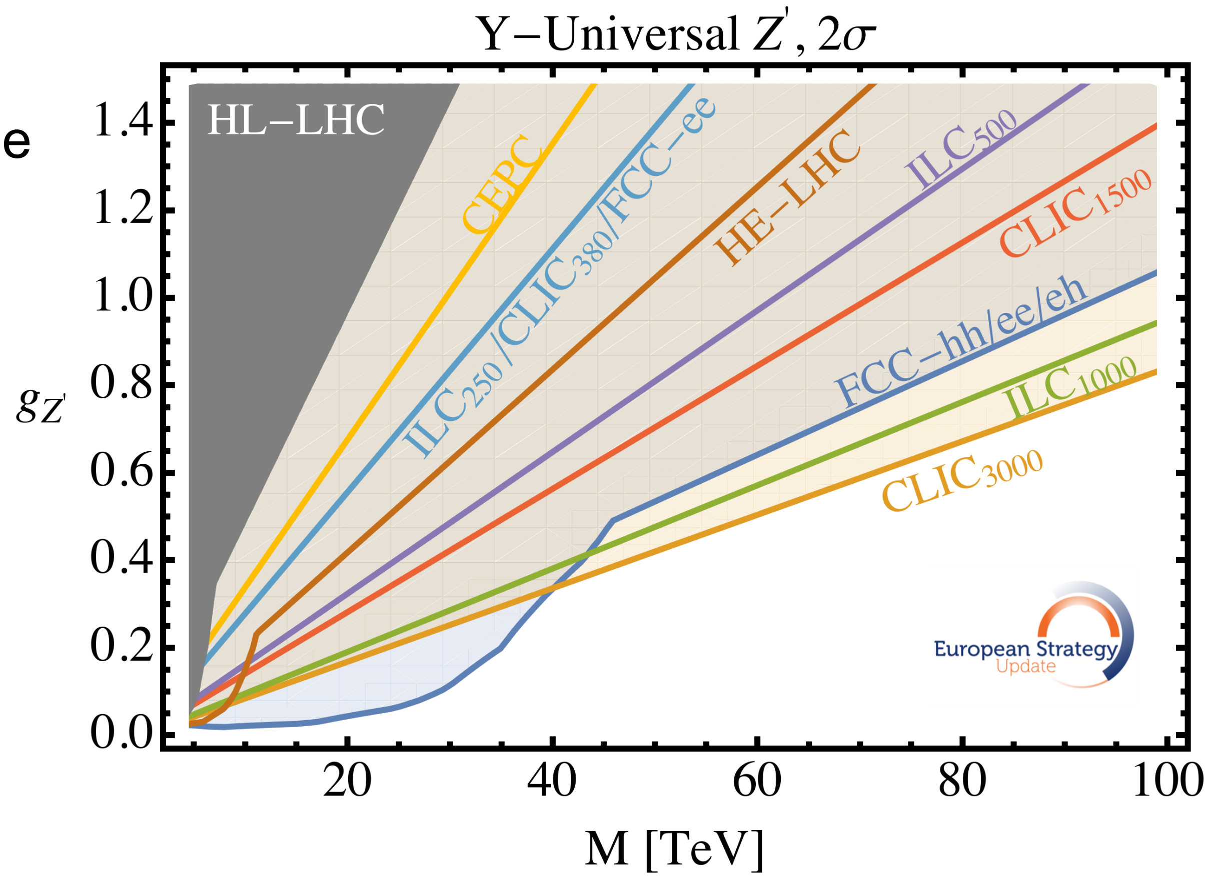
New heavy gauge boson: Y-Universal Z'

- New neutral gauge boson Z' with mass M and charges to SM particles equal to hypercharge

$$\frac{c_{2B}}{\Lambda^2} = \frac{g_{Z'}^2}{g'^4 M_{Z'}^2}$$

- Coupling $g_{Z'}$ (= force strength) and mass are free parameters

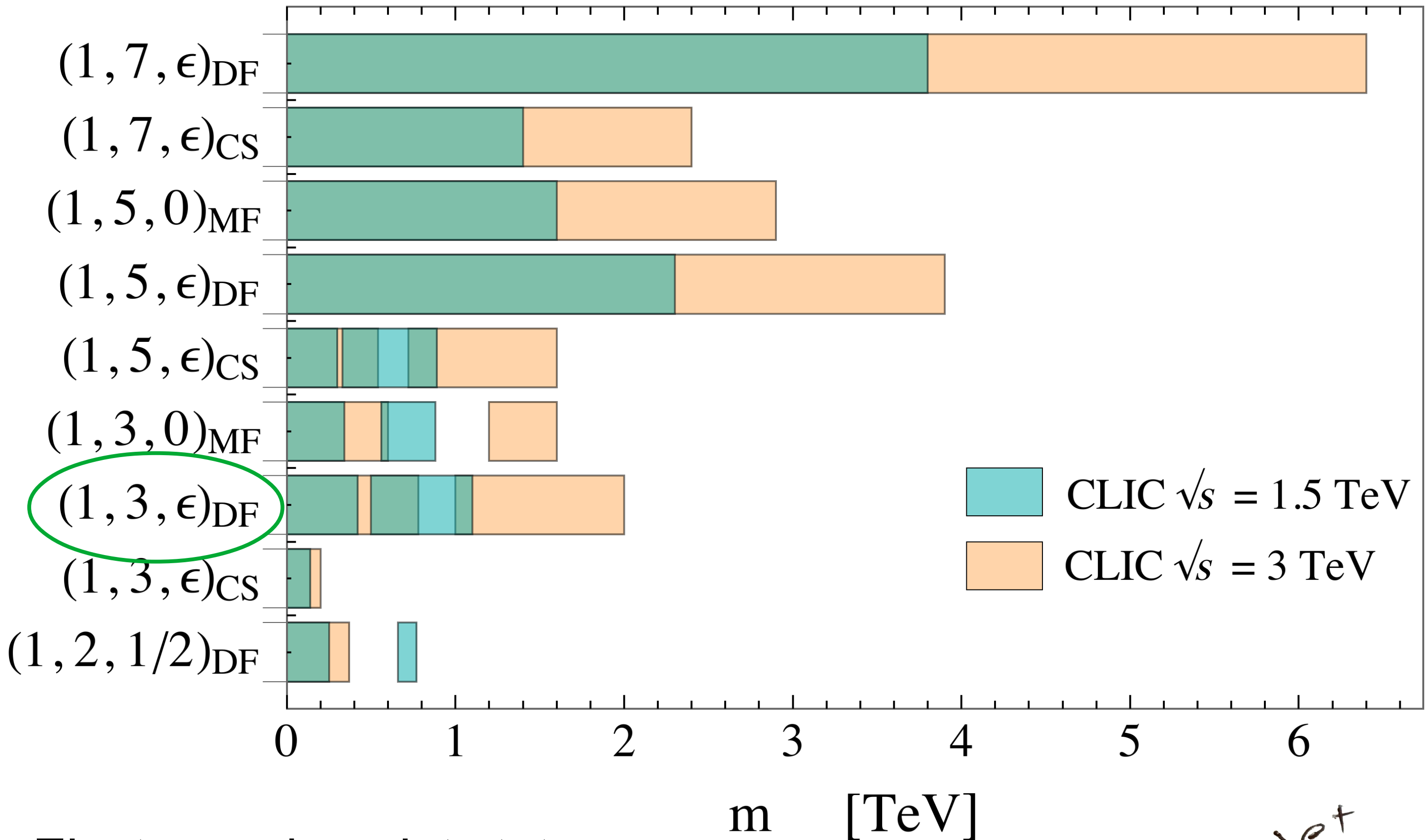
→ Indirect sensitivity to very high mass scales at CLIC



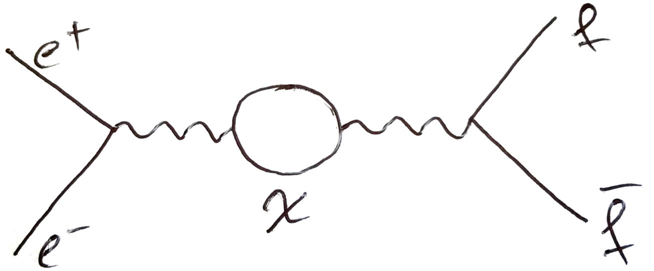
NB: $g_{Z'} > 1.5$ → width exceeds 30% of M

arXiv:1910.11775

Dark Matter in loops: $e^+e^- \rightarrow f\bar{f}$



Electroweak n-plet states
with hypercharge Y: (1,n,Y)



→ CLIC reaches thermal DM mass
in case of Dirac fermion triplet candidate

arXiv:1812.02093

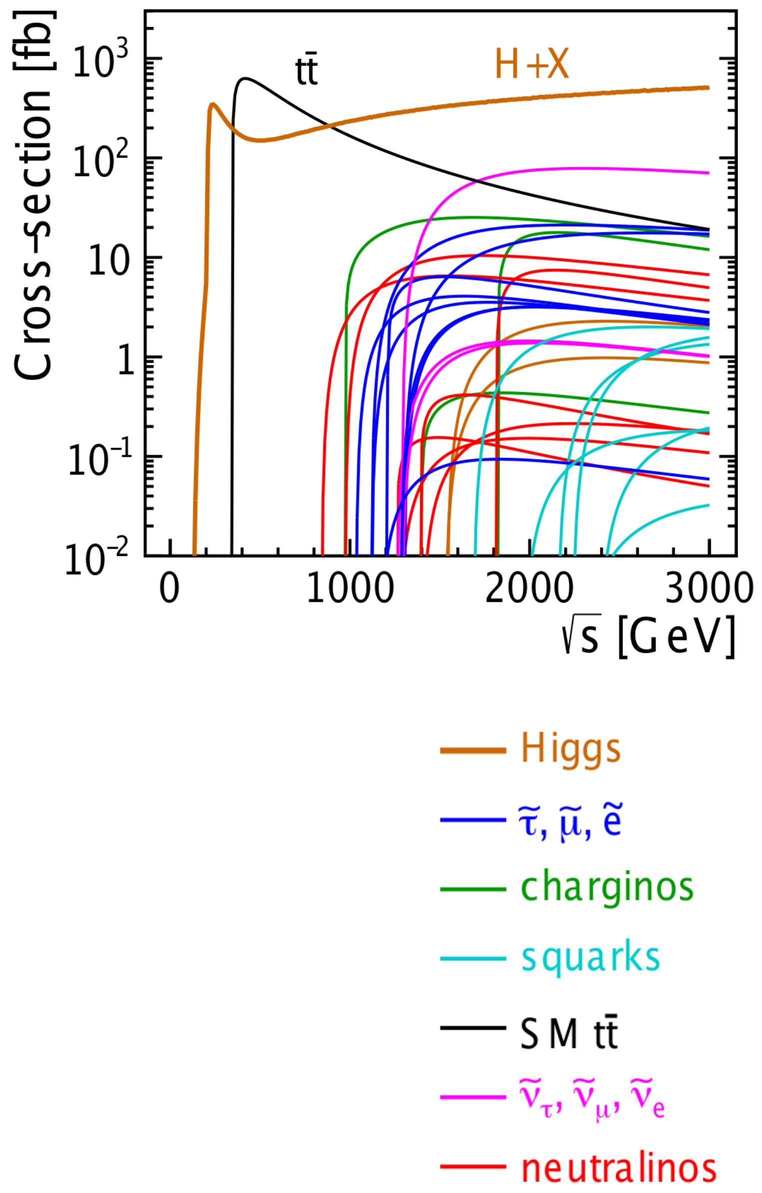
Direct new physics searches

• Direct observation of new particles coupling to γ*/Z/W → precision measurement of new particle masses and couplings

• The sensitivity often extends up to the kinematic limit (e.g. M ≤ √s / 2 for pair production)

• Very rare processes accessible due to low backgrounds (no QCD) → CLIC especially suitable for electroweak states

• Polarised electron beam and threshold scans are useful to constrain the underlying theory



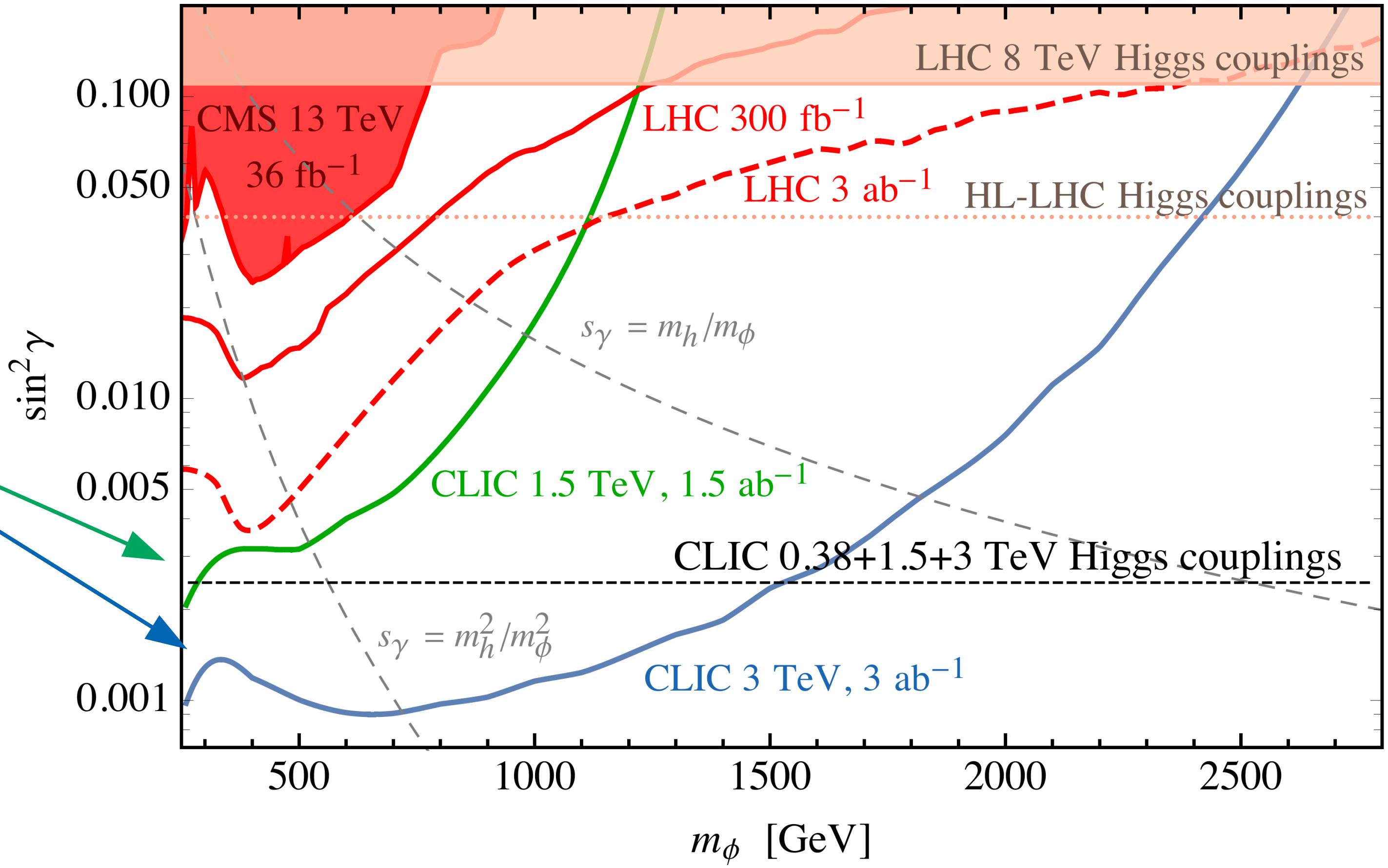
Higgs plus heavy singlet

Heavy singlet mixing with Higgs boson:
$h = h_0 \cos\gamma + S \sin\gamma$
$\phi = S \cos\gamma - h_0 \sin\gamma$

Direct production:
$e^+e^- \rightarrow \nu\bar{\nu}\phi,\ \phi \rightarrow hh$

Indirect sensitivity from Higgs couplings

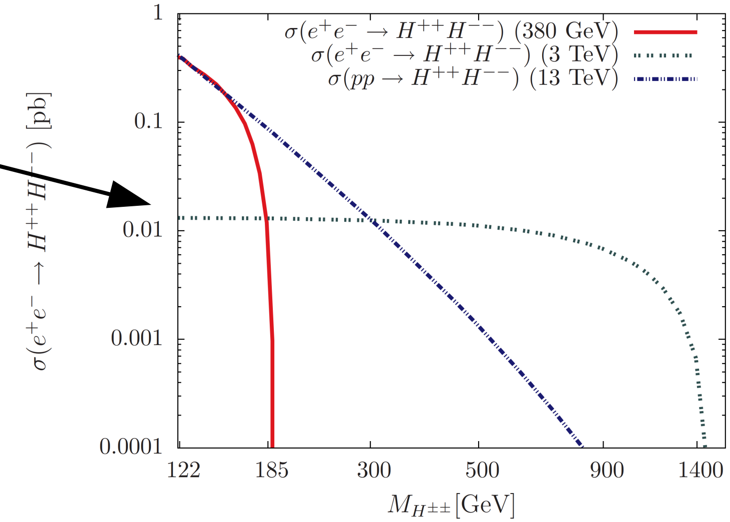
→ Both approaches are complementary



arXiv:1812.02093
JHEP **11**, 144 (2018)

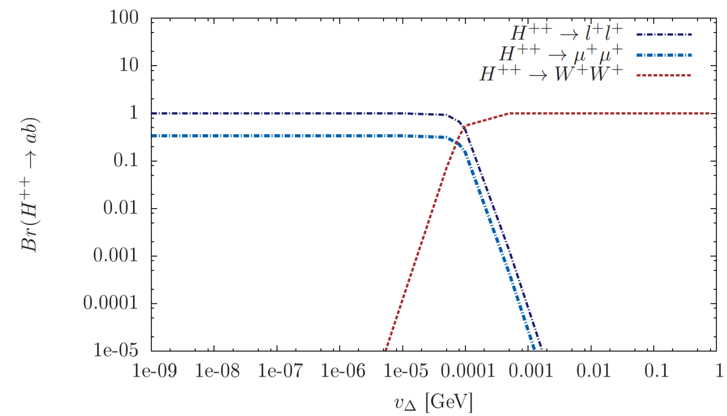
Doubly-charged Higgs: type II seesaw

- Pair production cross section almost flat up to the kinematic limit: $e^+e^- \rightarrow H^{++}H^{--}$



Benchmark: triplet vacuum expectation value $v_\Delta = 10^{-2}$ GeV
→ $BR(H^{++} \rightarrow W^+W^+) = 100\%$
(cross section in VBF at LHC very small)

- CLIC study for 380 GeV and 3 TeV shows sensitivity almost up to the kinematic limit



$\sqrt{s}$ = 380 GeV:

$e^+e^- \rightarrow H^{++}H^{--} \rightarrow N_j \geq 7j$		
Mass (GeV)	n_s	$\mathcal{L}$ (fb^{-1})
121	1.54	1054.14
137	4.48	124.56
159	10.48	22.76
172	10.15	24.26
184	2.69	345.48

$\sqrt{s}$ = 3 TeV:

$e^+e^- \rightarrow H^{++}H^{--} \rightarrow W^+W^+W^-W^- \rightarrow N j_{\text{fat}}$		
Masses (GeV)	n_s (2, 3-tagged $\mathcal{L} = 500$ fb^{-1})	$\mathcal{L}$(fb^{-1})(with 2,3-tagged)
800	17.96(2-tag)	38.75
1000	13.95(2-tag)	64.23
1120	11.49(2-tag)	94.68
1350	5.48(3-tag)	416.24
1400	3.95(3-tag)	801.15

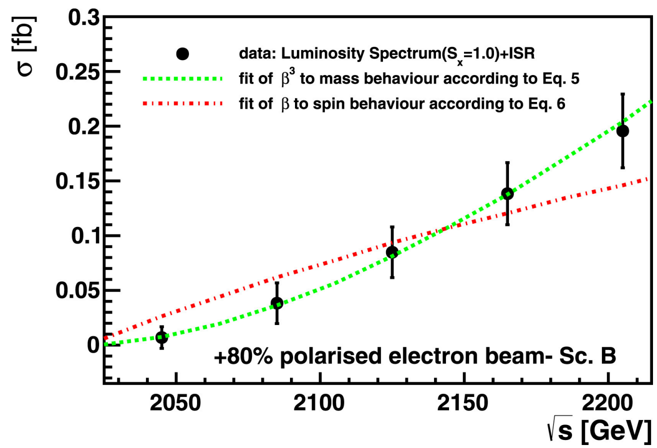
NB: $M(H^{++}) < M(H^+)$

→ Luminosity for 5σ discovery smaller than foreseen integrated luminosity at CLIC

Phys. Rev. **D 98**, 015024 (2018)
arXiv:1812.02093

Threshold scan for smuon pair production

Threshold scan:

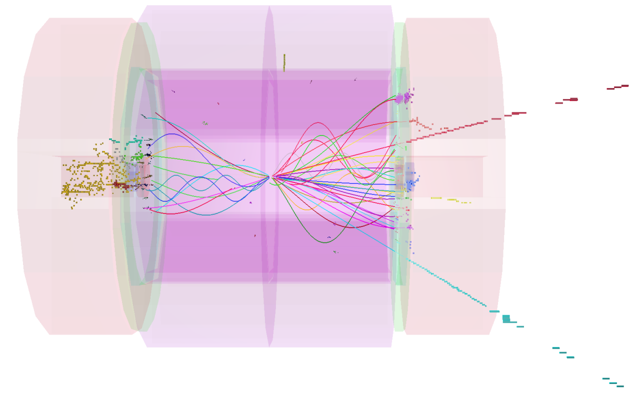


Threshold scans might help to characterise newly discovered particles

Example: spin determination

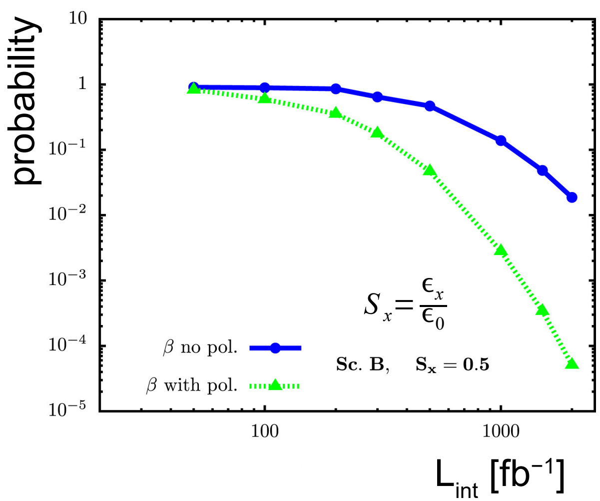
σ ~ β: spin ½

σ ~ β³: spin 0



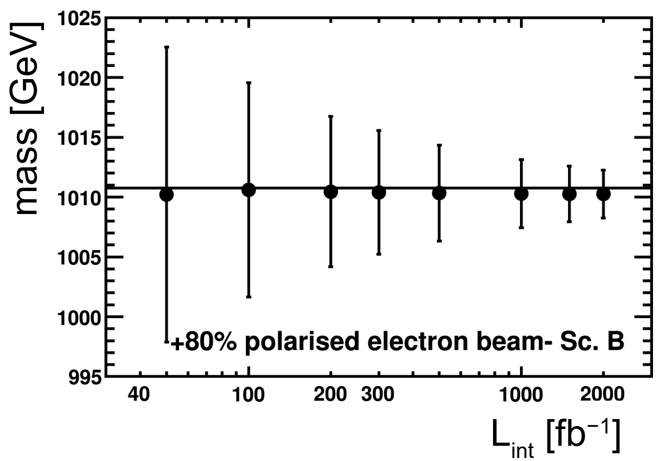
$$e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \,\tilde{\chi}_1^0\,\tilde{\chi}_1^0$$

Exclusion of spin-1/2 hypothsis:



→ Spin determination benefits from +80% electron beam polarisation and reduced horizontal emittance here

Precision on mass:



Nucl. Inst. Meth. **A 955**, 163327 (2020)

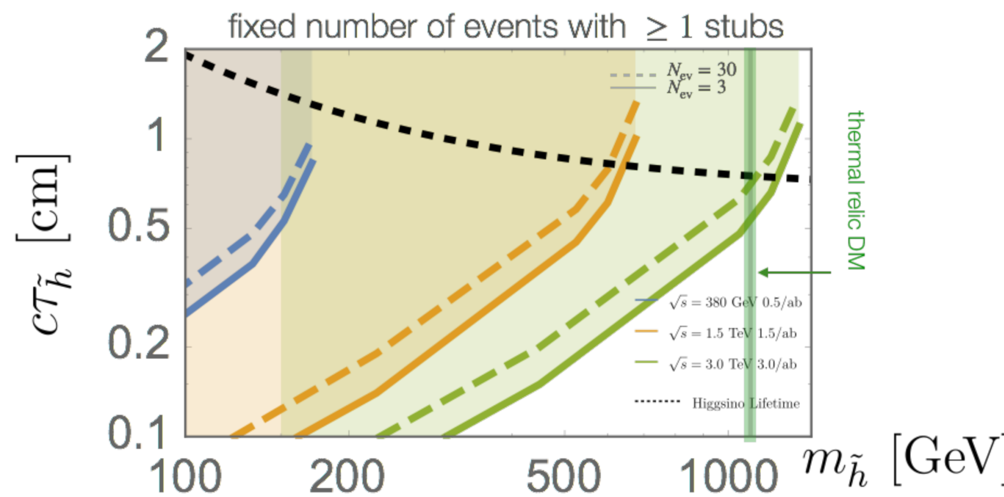
Dark Matter using stub tracks

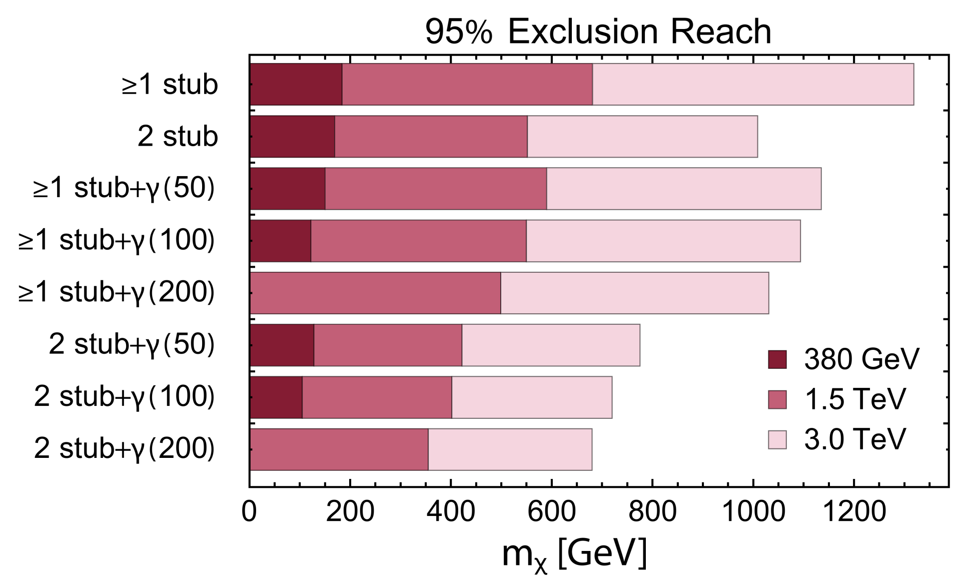
Benchmark: Higgsino pair production

$e^+e^- \rightarrow \chi^+\chi^-(+\gamma)$
Small mass difference: $\chi^\pm \rightarrow \chi^0\pi^\pm$
Long-lifetime: $\chi^\pm$ leaves disappearing ("stub") track in the detector

- Stub tracks required to have 4 hits in the detector

→ CLIC might discover the thermal Higgsino at 1.1 TeV





arXiv:1812.02093

Summary and additional projections

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.
BR(H $\to$ inv.) (model-independent)		$< 0.69\%$ at 90% C.L.
Higgs compositeness scale m_*	$m_* > 3\,\text{TeV}$ ($> 7\,\text{TeV}$ for $g_* \simeq 8$)	Discovery up to $m_* = 10\,\text{TeV}$ ($40\,\text{TeV}$ for $g_* \simeq 8$)
Top compositeness scale m_*		Discovery up to $m_* = 8\,\text{TeV}$ ($20\,\text{TeV}$ for small coupling g_*)
Higgsino mass (disappearing track search)	$> 250\,\text{GeV}$	$> 1.2\,\text{TeV}$
Slepton mass		Discovery up to ~ 1.5 TeV
RPV wino mass ($c\tau = 300\,\text{m}$)	$> 550\,\text{GeV}$	$> 1.5\,\text{TeV}$
Z$'$ mass (SM couplings)	Discovery up to 7 TeV	Discovery up to 20 TeV
NMSSM scalar singlet mass	$> 650\,\text{GeV}$ ($\tan\beta \leq 4$)	$> 1.5\,\text{TeV}$ ($\tan\beta \leq 4$)
Twin Higgs scalar singlet mass	$m_\sigma = f > 1$ TeV	$m_\sigma = f > 4.5$ TeV
Relaxion mass (for vanishing mixing)	$< 24\,\text{GeV}$	$< 12\,\text{GeV}$
Relaxion mixing angle ($m_\phi < m_\text{H}/2$)		$\sin^2\theta \leq 2.3\%$
Neutrino Type-2 see-saw triplet		$> 1.5\,\text{TeV}$ (for any triplet VEV) $> 10\,\text{TeV}$ (for triplet Yukawa coupling $\simeq 0.1$)
Inverse see-saw RH neutrino		$> 10\,\text{TeV}$ (for Yukawa coupling $\simeq 1$)
Scale $V_{LL}^{-1/2}$ for LFV $(\bar{\text{e}}\text{e})(\bar{\text{e}}\tau)$		$> 42\,\text{TeV}$

arXiv:1812.07986

Conclusions

- CLIC is a mature project, ready to provide a Higgs/top factory and a subsequent multi-TeV lepton collider

- Substantial improvement with respect to HL-LHC possible for all discussed physics topics

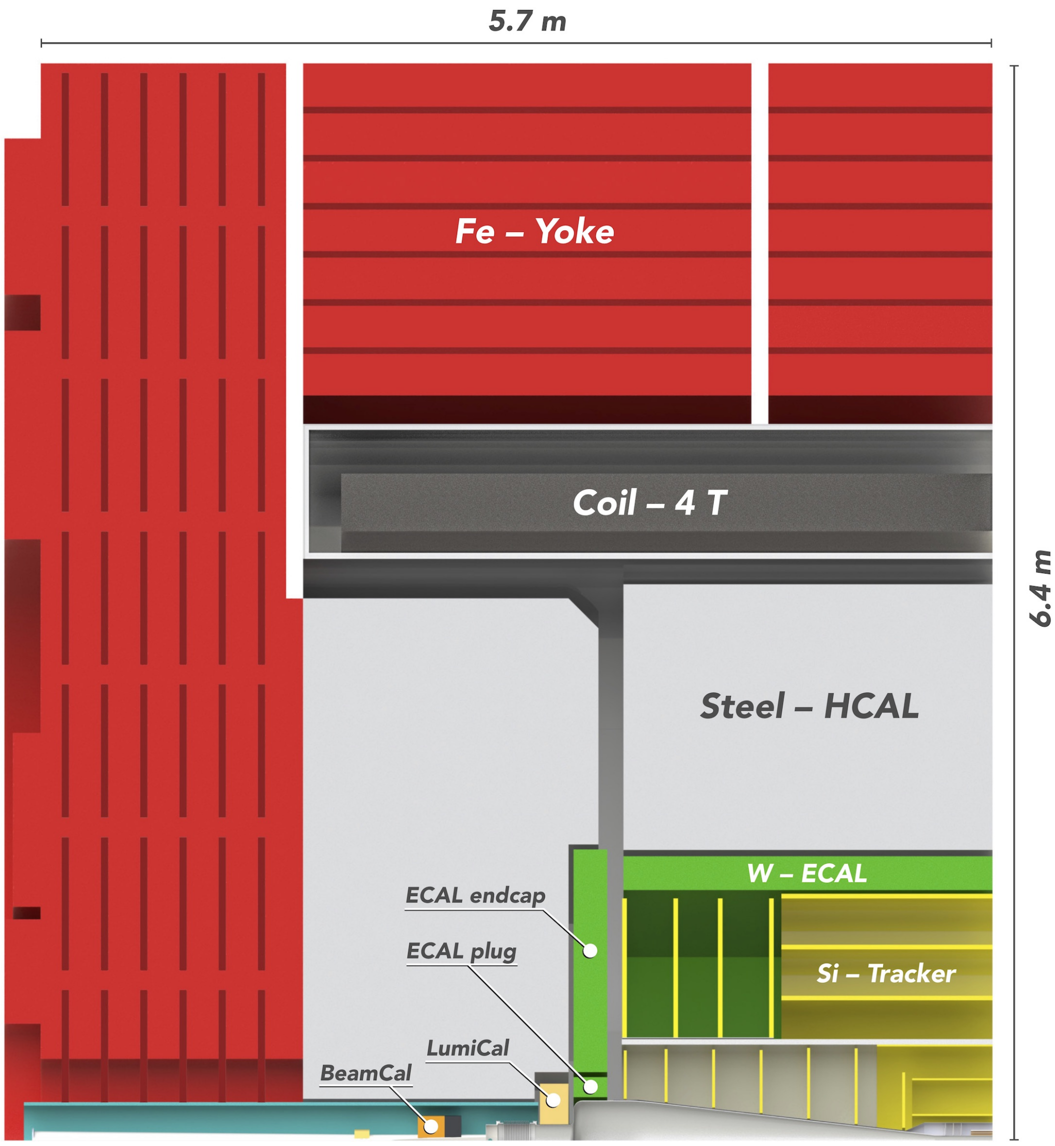
- Large amount of complementarity between direct and indirect searches for new particles and interactions (and between the different CLIC energy stages)

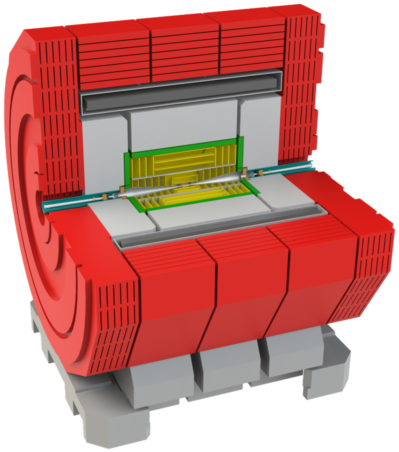
- Beam polarisation and threshold scans enhance the capability to characterise potential new discoveries further

Thank you!

Backup slides

CLIC detector concept





Basic characteristics:
- B-field: 4 T
- Vertex detector with 3 double layers
- Silicon tracking system (1.5 m radius)
- ECAL with 40 layers (22 X_0)
- HCAL with 60 layers (7.5 λ)

Precise timing for background suppression
(bunch crossings 0.5 ns apart)**:**
- ≈ 10 ns hit time-stamping in tracking
- 1 ns accuracy for calorimeter hits

CLICdp-Note-2017-001
arXiv:1812.07337