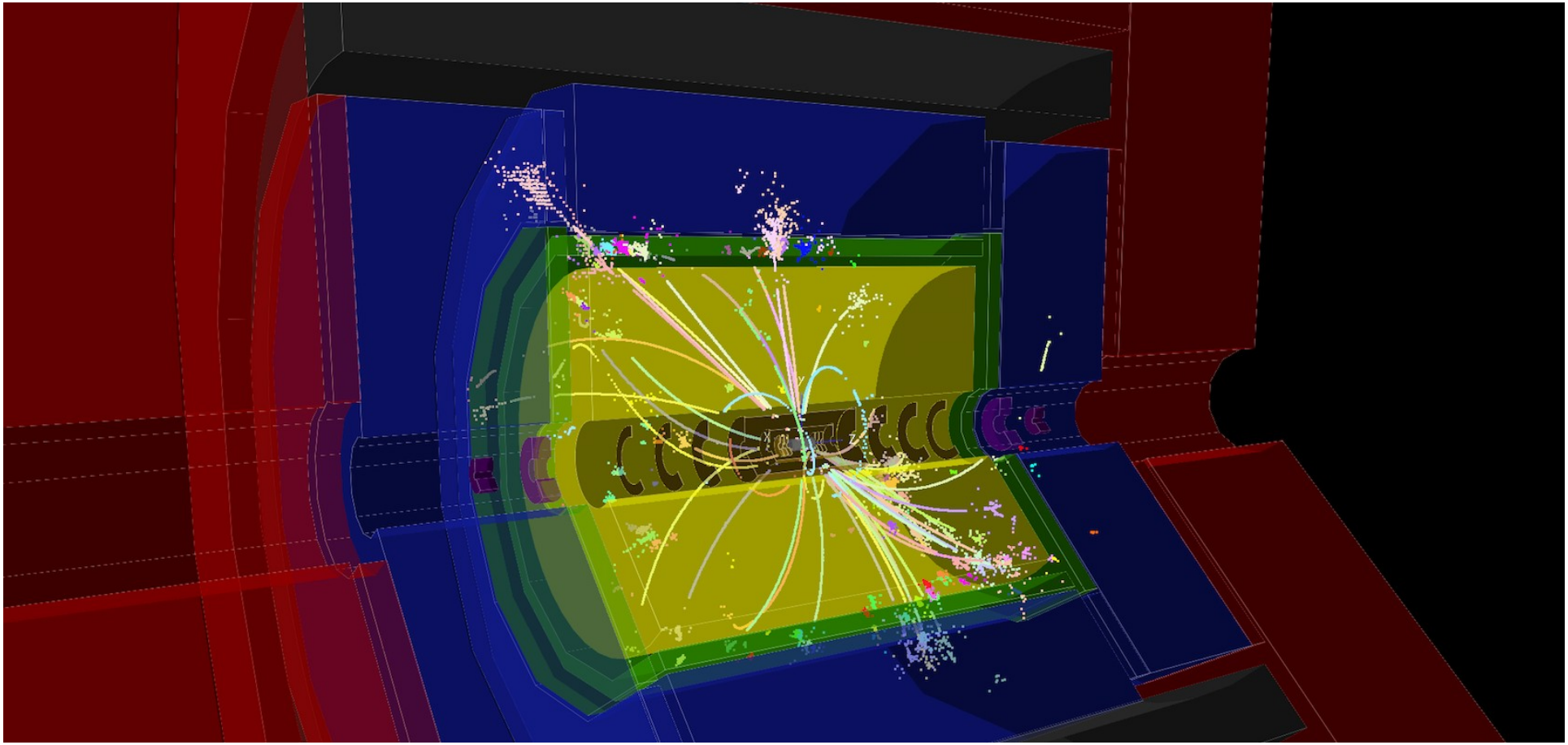
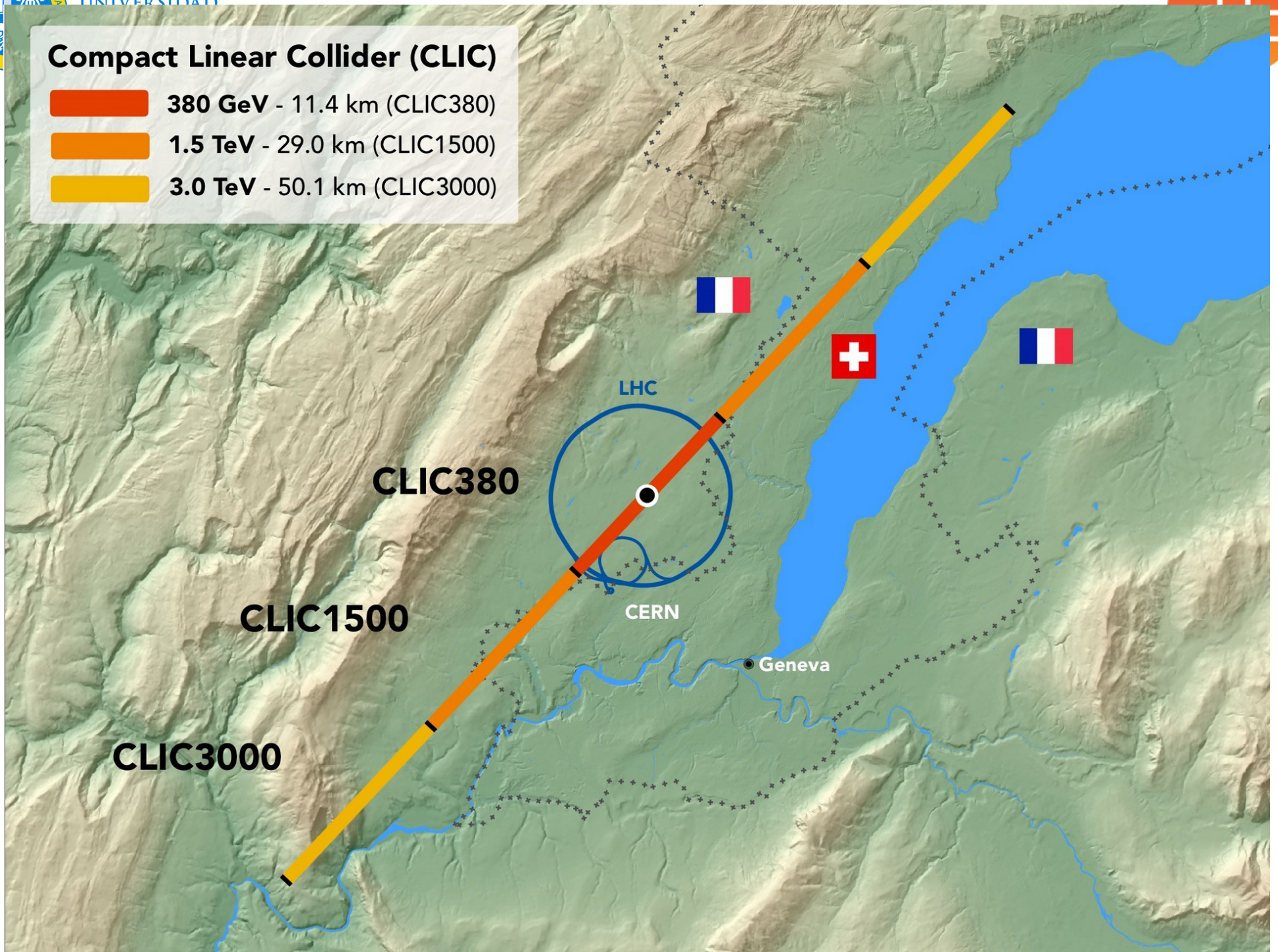
Physics at CLIC

7th international conference on High Energy Physics in the LHC era
UTFSM, Valparaiso, Chile

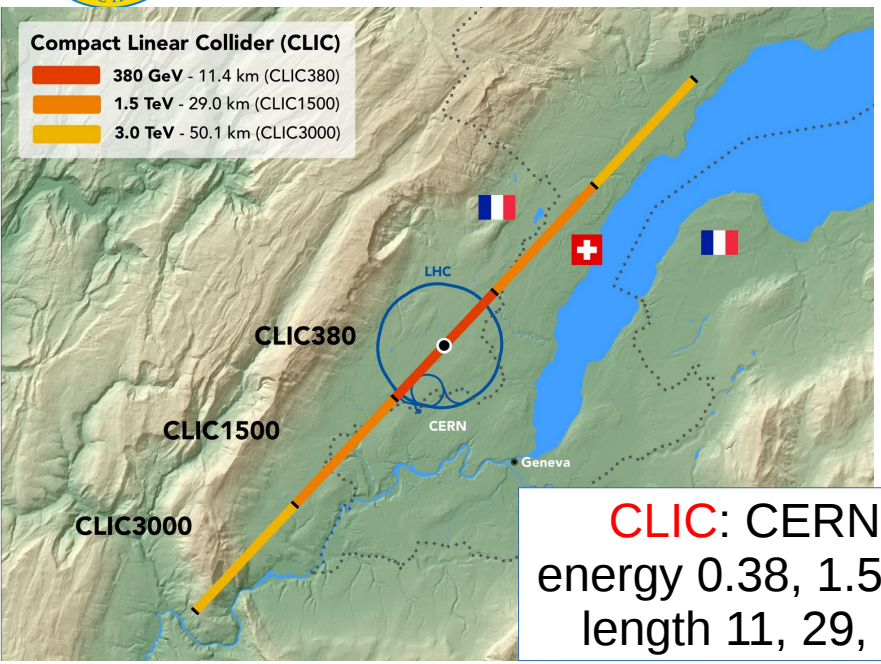


Marco Aurelio Díaz
on behalf of the CLICdp Collaboration
Pontificia Universidad Católica de Chile
Santiago, Chile

Thanks to my CLICdp colleages

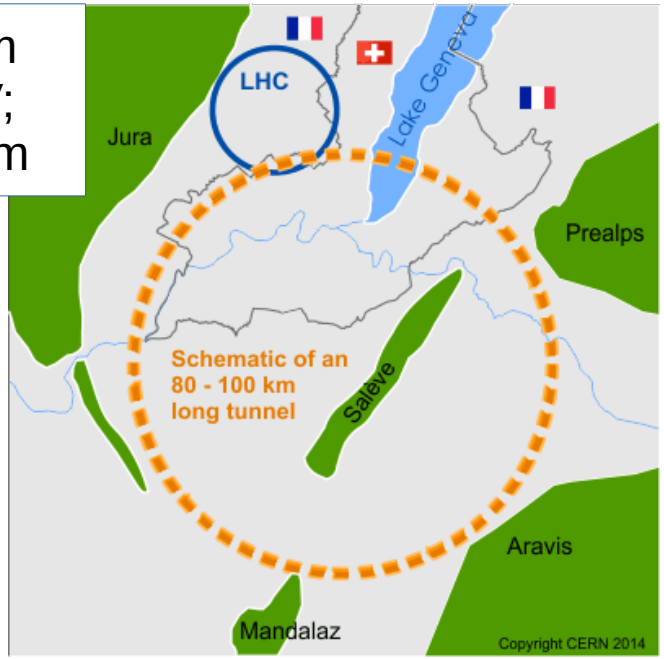

Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

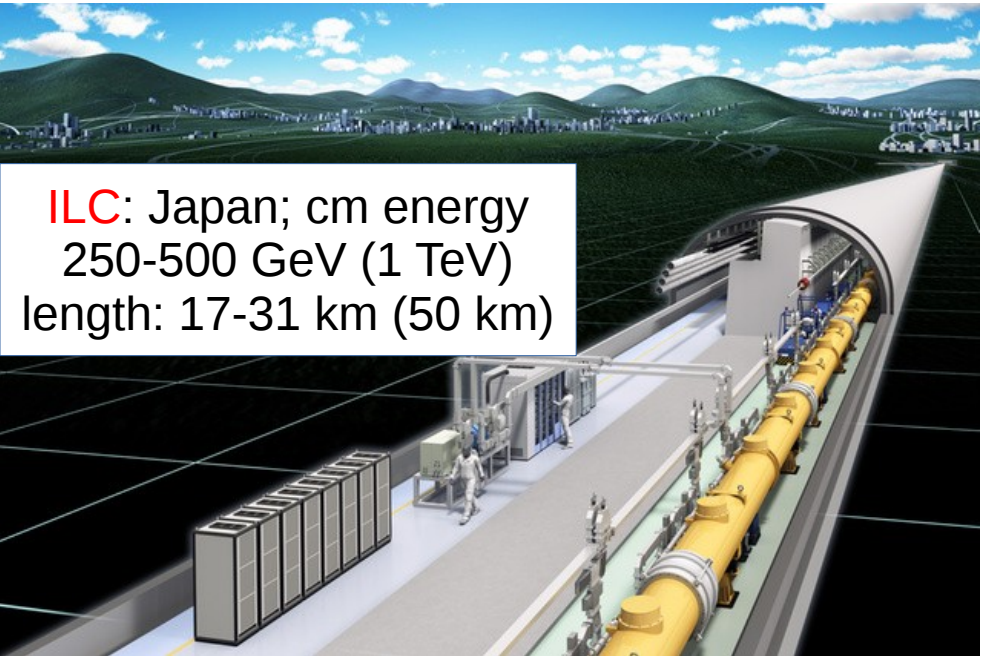
e+e- Colliders



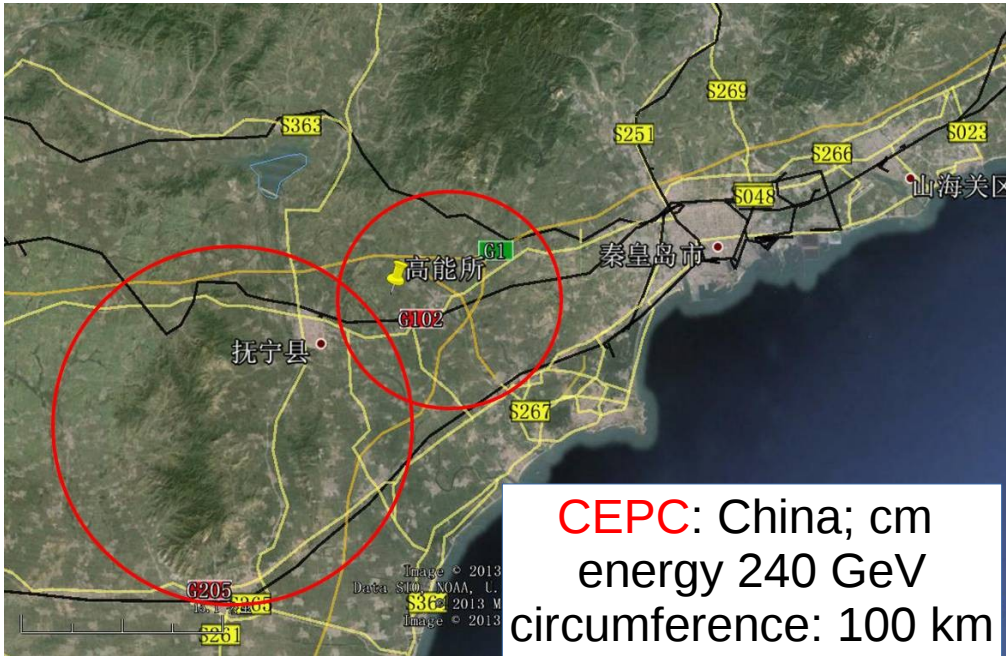
CLIC: CERN; cm energy 0.38, 1.5, 3 TeV; length 11, 29, 50 km

FCC-ee: CERN; cm energy 90-350 GeV; circumference 97 km





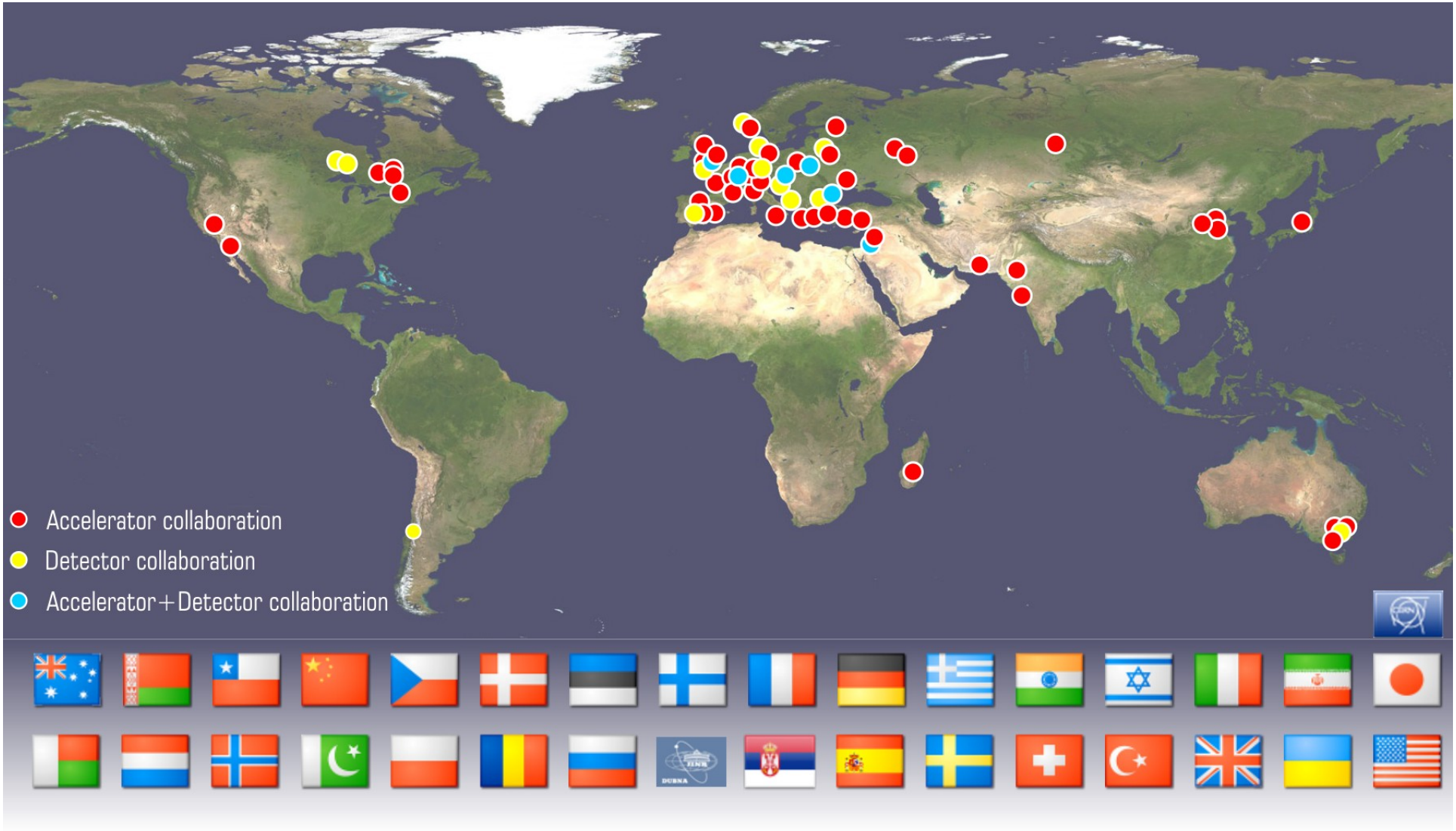
ILC: Japan; cm energy 250-500 GeV (1 TeV) length: 17-31 km (50 km)



CEPC: China; cm energy 240 GeV circumference: 100 km

CLIC Collaborations

- CLIC accelerator collaboration: http://clic-study.web.cern.ch/
- CLIC detector and physics collaboration (CLICdp): http://clicdp.web.cern.ch/



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CLIC timeline

2013 - 2019 Development Phase

Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase

Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase

Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions

Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start

Ready for construction; start of excavations

2035 First Beams

Getting ready for data taking by the time the LHC programme reaches completion

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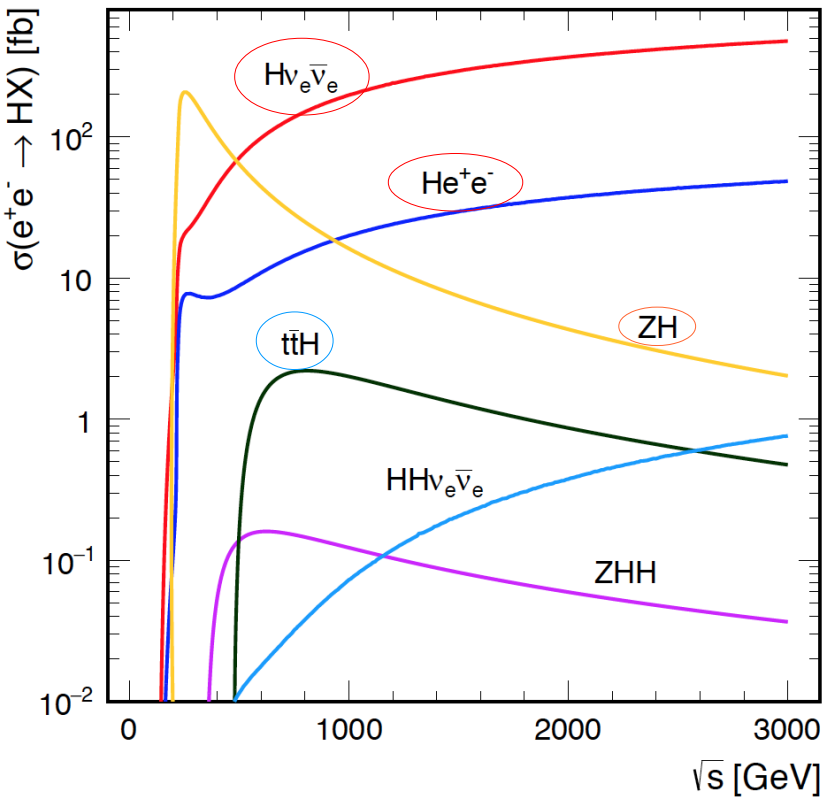
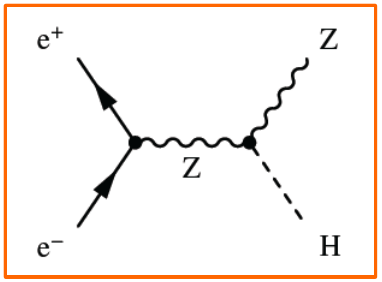
Higgs Physics

- Production
- Higgsstrahlung at 350 GeV
- Higgsstrahlung at 250, 350, and 420 GeV
- Higgs physics above 1 TeV
- Double Higgs production

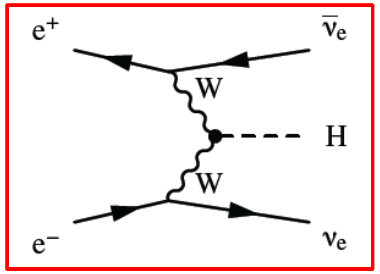
Higgs Physics at CLIC



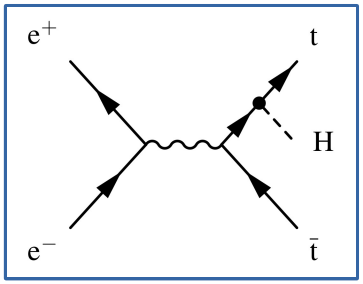
Dominant processes:



Higgsstrahlung
σ ~ 1/s
Dominant up to ~450 GeV



WW (ZZ) – fusion
σ ~ log(s)
Dominant above ~450 GeV

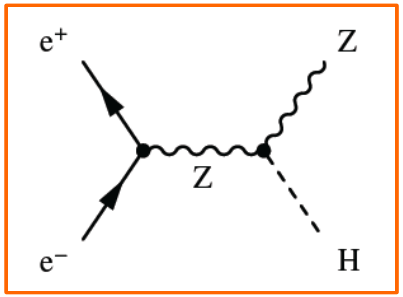


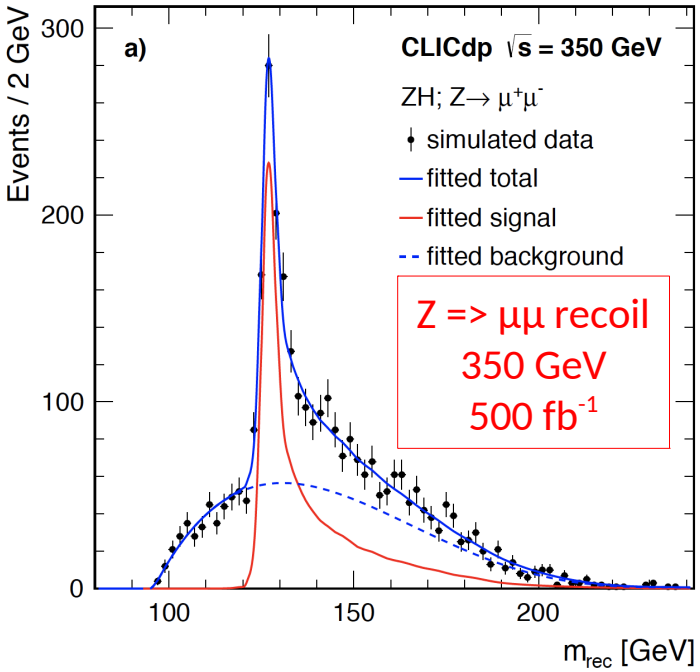
ttH Production
Accessible at above ~500 GeV
Maximum at ~800 GeV

	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
# ZH events	68 000	20 000	11 000
# $H\nu_e\bar{\nu}_e$ events	17 000	370 000	830 000
# He^+e^- events	3 700	37 000	84 000

For unpolarized beams.
Hνν increases ×1.8 for
-80% e- polarization
(CLIC baseline)

Higgsstrahlung $e^+e^- \to ZH$ at $\sqrt{s} \sim 350$ GeV





ZH events, identified through recoil mass against Z.

$$m_{rec}^2 = s + m_Z^2 - 2\sqrt{s}E_Z$$

Model independent measurement

$$\sigma(e^+e^- \to ZH) \sim g_{HZZ}^2$$

Decay mode	Branching ratio
$H \to b\bar{b}$	56.1 %
$H \to WW^*$	23.1 %
$H \to gg$	8.5 %
$H \to \tau^+\tau^-$	6.2 %
$H \to c\bar{c}$	2.8 %
$H \to ZZ^*$	2.9 %
$H \to \gamma\gamma$	0.23 %
$H \to Z\gamma$	0.16 %
$H \to \mu^+\mu^-$	0.021 %
Γ_H	4.2 MeV

$B(Z \to ee) \approx 3.5\%$, very clean; $\Delta(\sigma_{HZ}) = \pm 3.8\%$

$B(Z \to \mu\mu) \approx 3.5\%$, very clean; $\Delta(\sigma_{HZ}) = \pm 3.8\%$

$B(Z \to qq) \approx 70\%$, almost model independent; $\Delta(\sigma_{HZ}) = \pm 1.8\%$

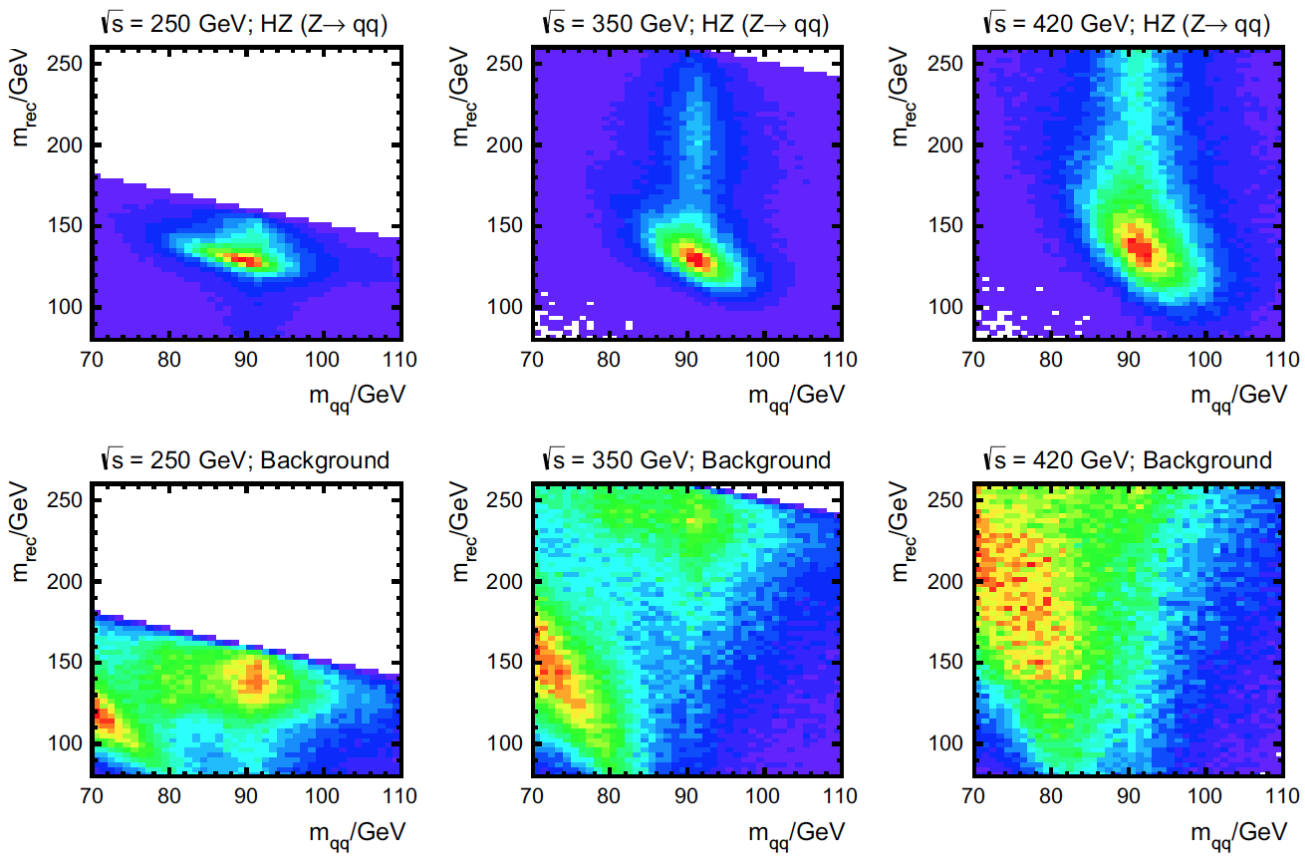
→ $\Delta(g_{HZZ}) = \pm 0.8\%$

EPJC 77, 475 (2017)

Higgsstrahlung $e^+e^- \rightarrow ZH$ at $\sqrt{s} \sim 250$, 350, 420 GeV

m(REC)

m(Z)



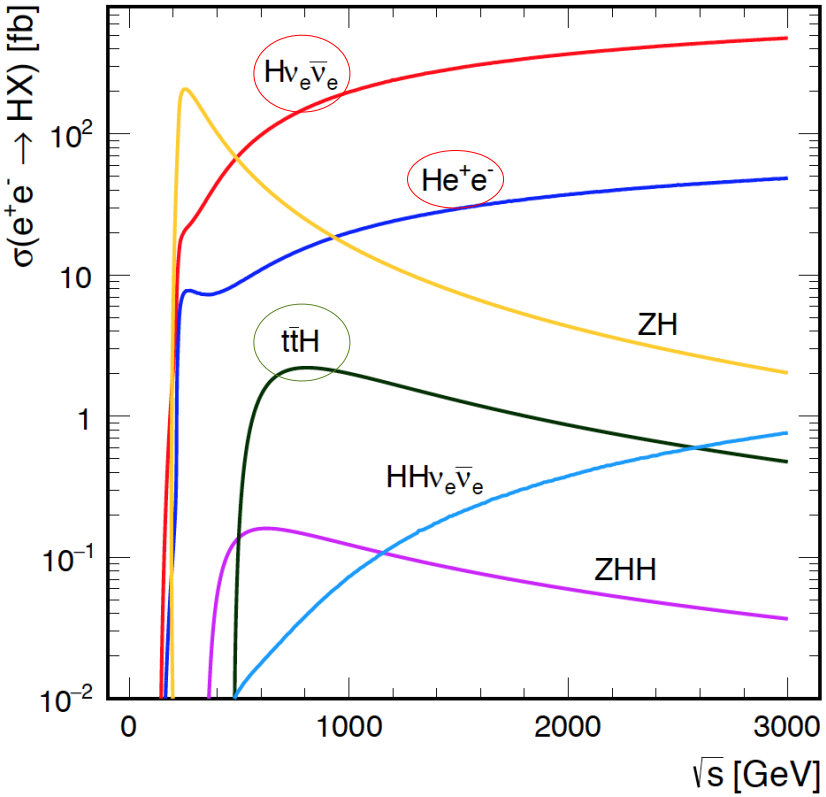
Signal

Background

$\sqrt{s}$	$\mathscr{L}$	σ(HZ)	$\Delta\,\sigma_{\text{vis.}}$	$\Delta\,\sigma_{\text{invis.}}$	$\Delta\,\sigma$(HZ)
250 GeV	500 fb^{-1}	136 fb	± 3.63 %	± 0.45 %	± 3.65 %
350 GeV	500 fb^{-1}	93 fb	± 1.71 %	± 0.56 %	± 1.80 %
420 GeV	500 fb^{-1}	68 fb	± 2.42 %	± 1.02 %	± 2.63 %

Eur.Phys.J. C76, 72 (2016)

Higgs Physics above 1 TeV



Vector boson fusion.
- e+e- → Hνν; e+e- → Hee
- High cross section.
- Combined with increased luminosity: access to rare Higgs decay.

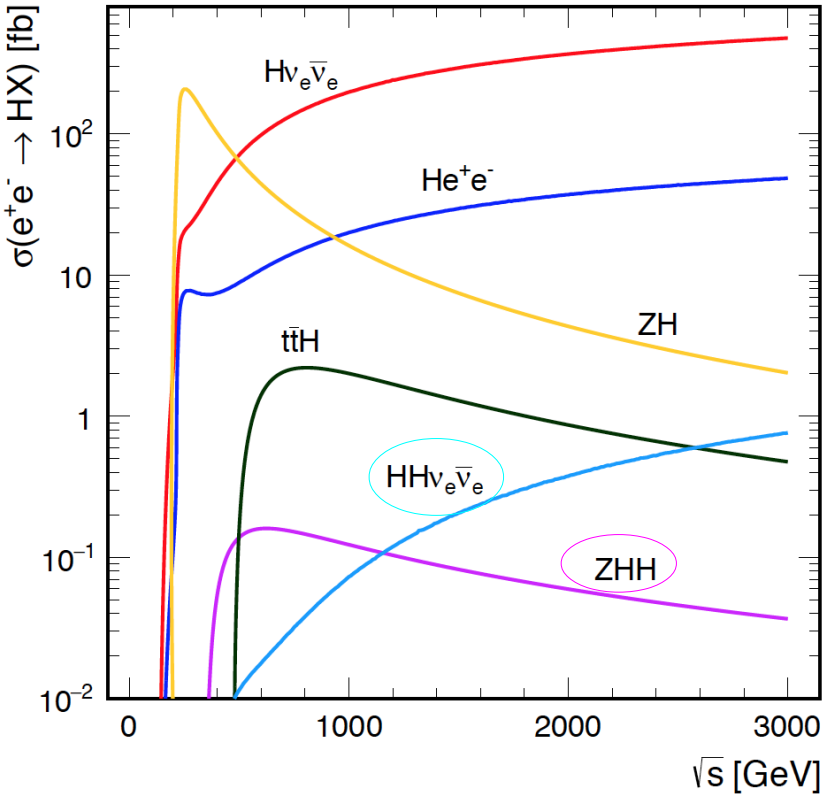
ttH production.
- Extraction of top quark Yukawa coupling
- Best above 700 GeV
- $\Delta(g_{Htt})=\pm 4.2\%$, 1.4 TeV, 1.5 ab^{-1}

$$\frac{g_{HWW}}{g_{HZZ}} = \cos^2\theta_W$$

Measured to ~1% level

EPJC 77, 475 (2017)

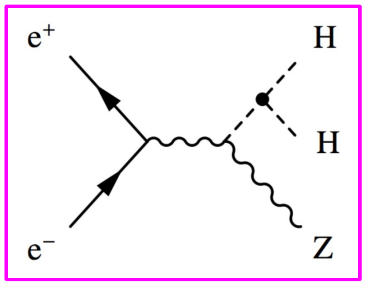
Double Higgs Production

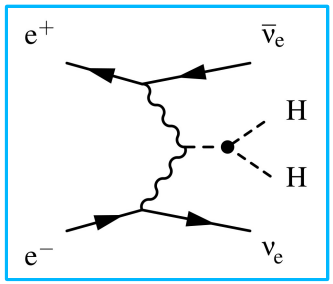


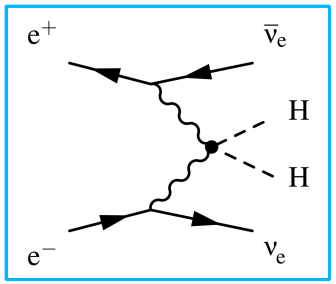
e+e- → ZHH: Cross section maximum at ~ 600 GeV, but very small number of events.

e+e- → HHνν: Allows simultaneous extraction of triple Higgs coupling λ, and quartic HHWW coupling. Benefits from high energy operation.

Expected precision: $\Delta(\lambda) = 16\%$ assuming 3 ab^{-1} at 3 TeV (10% using diferential distributions).

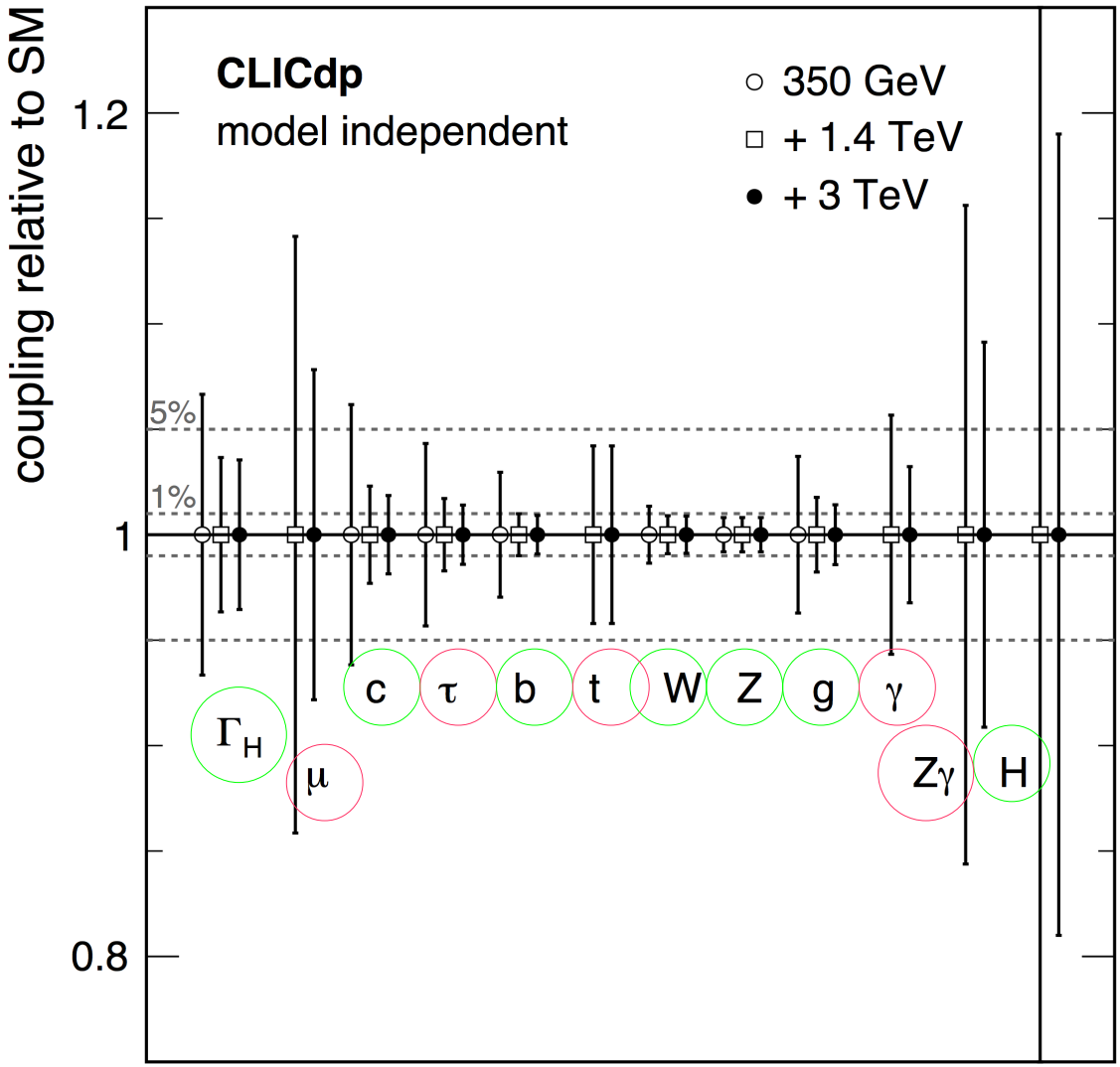






Eur. Phys. J. C 77, 475 (2017)

Combined Higgs Couplings



- Full CLIC program: ~5 years at each stage, 80% e- polarization above 1 TeV.
- Model independent measurements: 1-2% for most the couplings.
- Accuracy on the Higgs width: ~3.5%
- Green circles: accuracy significantly better than HL-LHC.
- Red circles: accuracy comparable to HL-LHC.

EPJC 77, 475 (2017)

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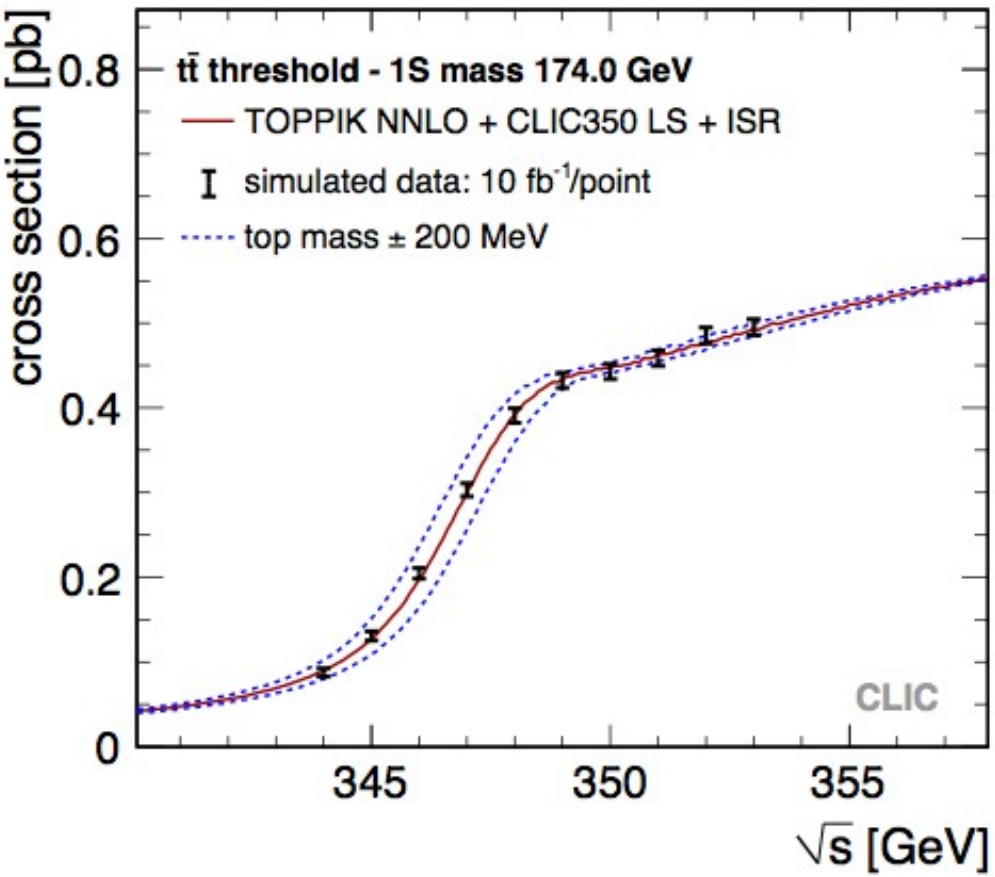
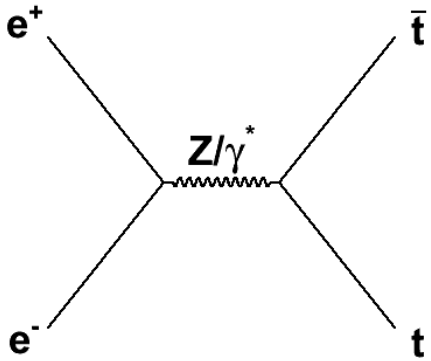
Top Physics

- Top quark mass
- Top quark electroweak couplings

Top Quark Mass

- CLIC will make a dedicated scan near the threshold for a top quark pair production.
- Cross section is very sensitive to the top quark pole mass.
- Uncertainty Δm_t~50 MeV (dominated by theory)
- In e+e- colliders top quark pairs appear through Z/γ* in the s-channel.



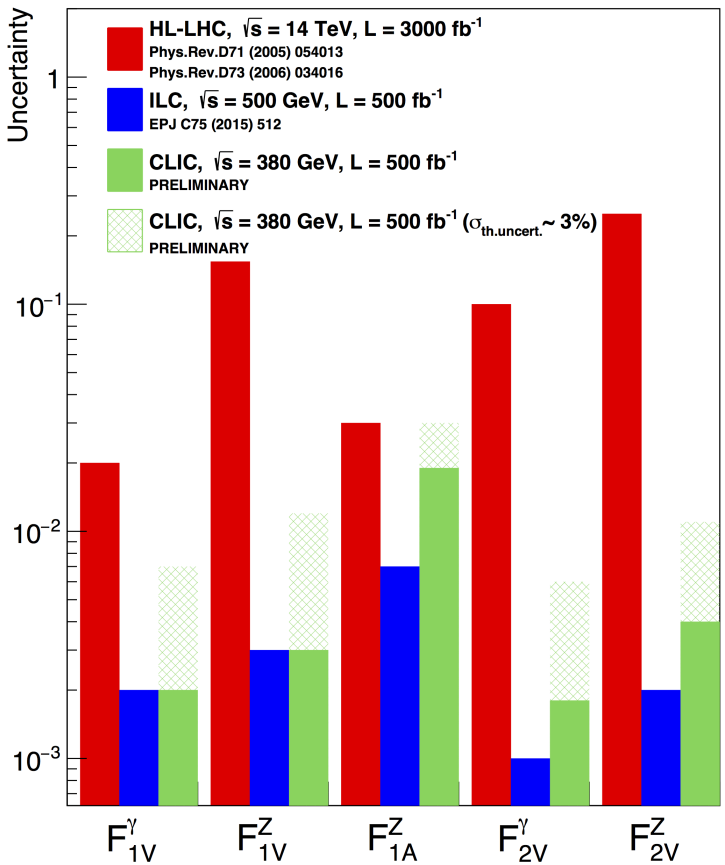


EPJC 73, 2550 (2013)

Top Quark Electroweak Couplings

- Top quark pairs are produced via Z/γ* in electron positron collisions
- New physics modifies the ttV coupling, whose general form is,

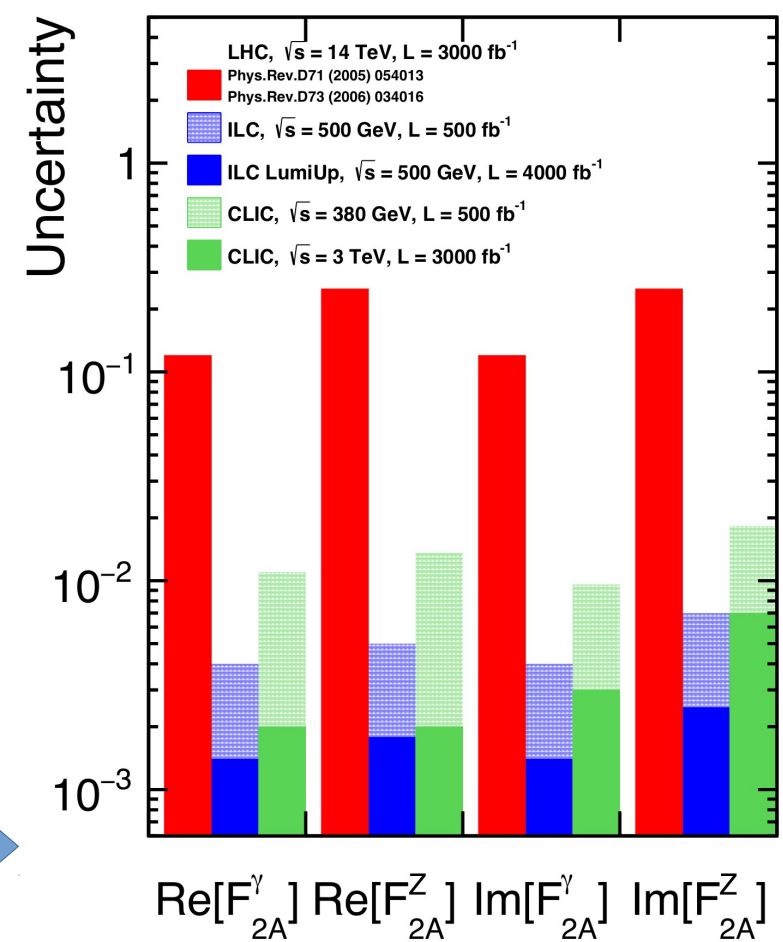
$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



Green: CP conserved
Red: CP violated

arXiv:1608.07537

arXiv:1710.06737



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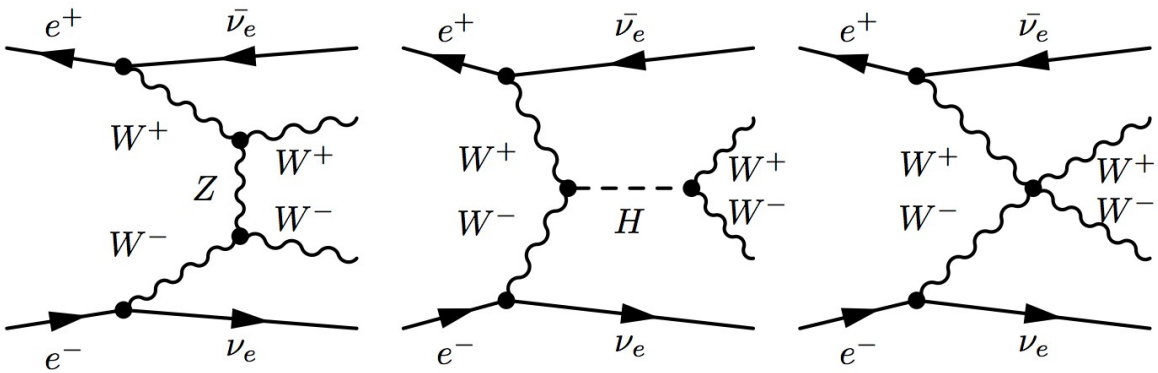
Beyond the Standard Model

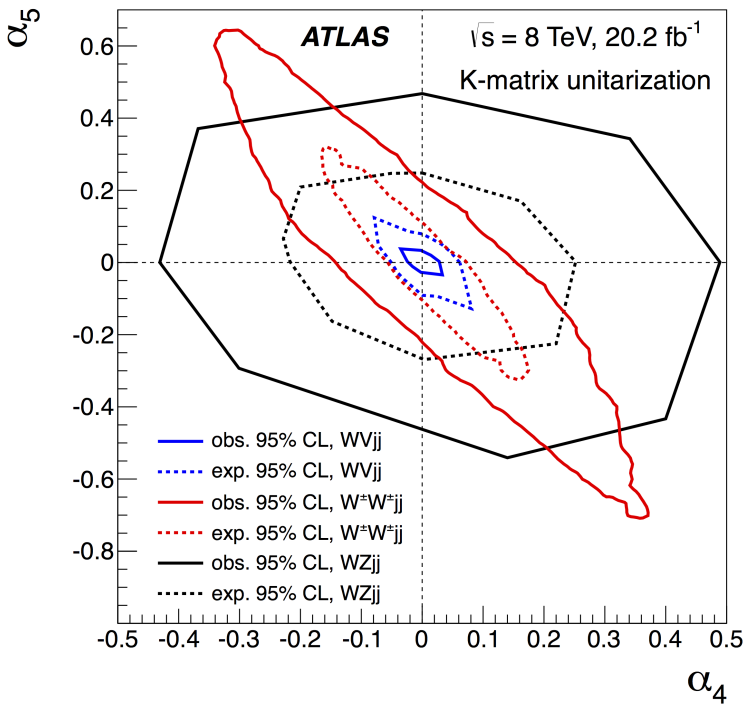
- Vector Boson Scattering
- Supersymmetry Direct Searches
- Non-doublet scalars

Vector Boson Scattering

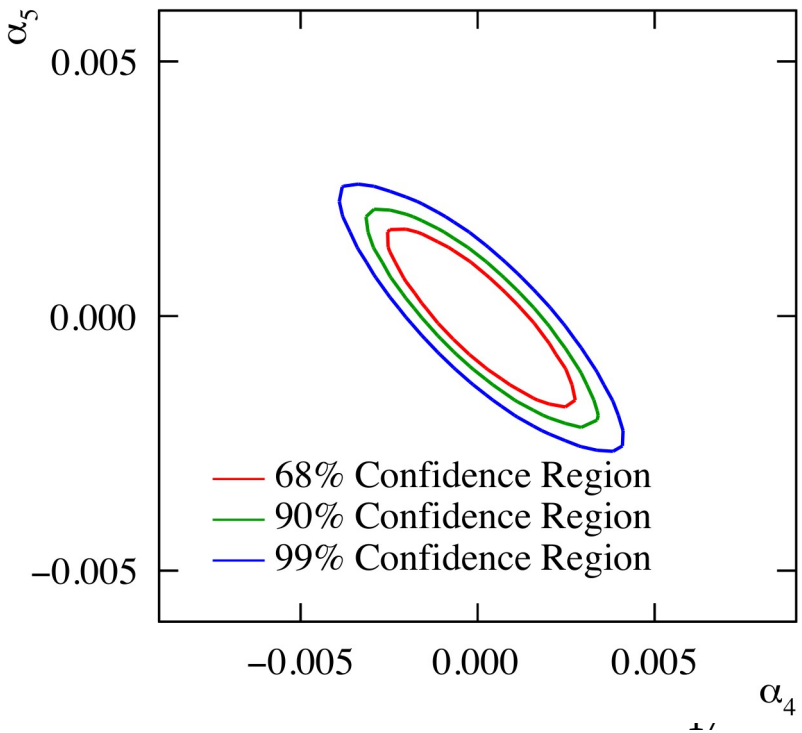
$$\alpha_4 \mathcal{L}_4 = \alpha_4 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}_\nu] \, \mathrm{tr}[\mathbf{V}^\mu \mathbf{V}^\nu] \,,$$
$$\alpha_5 \mathcal{L}_5 = \alpha_5 \, \mathrm{tr}[\mathbf{V}_\mu \mathbf{V}^\mu] \, \mathrm{tr}[\mathbf{V}_\nu \mathbf{V}^\nu] \,,$$



Anomalous couplings.



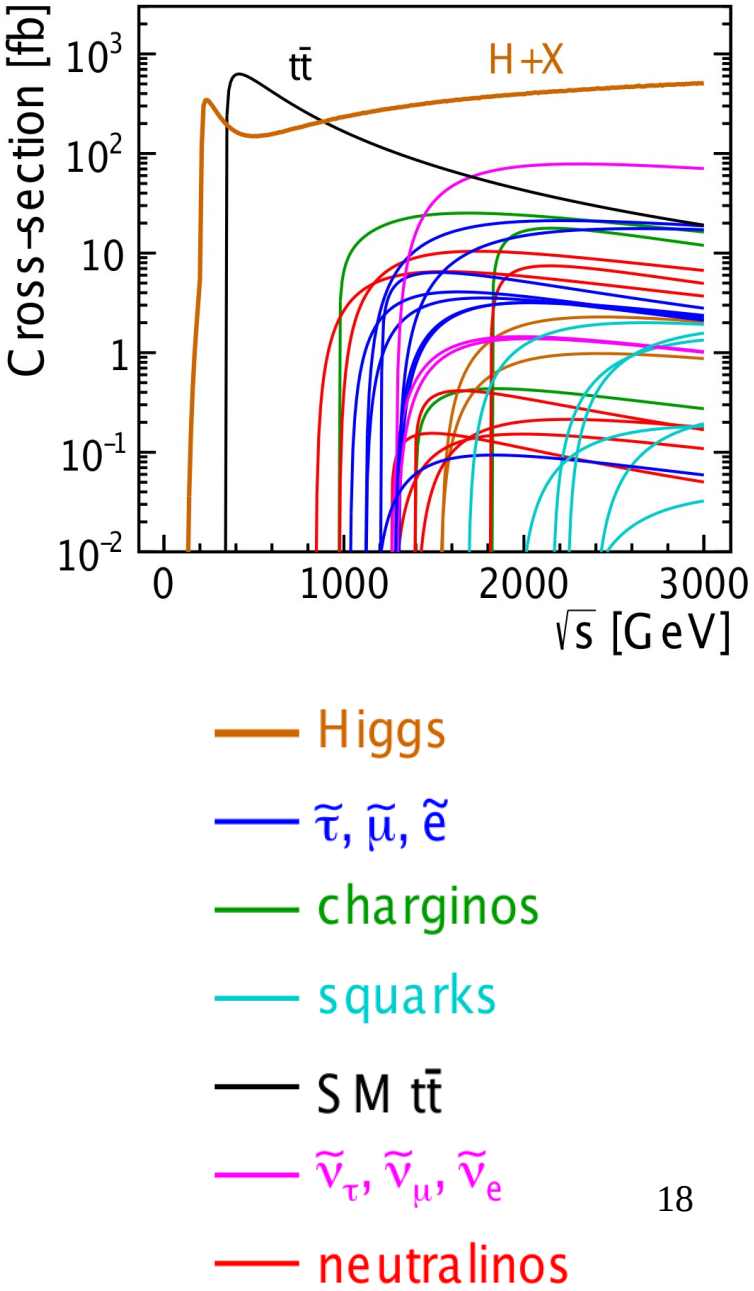
arXiv:1609.05122



CLIC, 3 TeV, 2 ab^{-1}

Supersymmetry Direct Searches

- Direct observation of susy particles couplings to γ/Z → precision measurements of susy particle masses and couplings.
- The sensitivity often extends up to the kinematic limit (e.g. up to √s/2 for the mass of the new particle in the case of pair production).
- Very rare processes accessible due to low backgrounds (no QCD). CLIC is specially equiped for electroweak states.
- The possibility for polarized electron beams and threshold scans can potentially constrain even more the underlying theory.



Supersymmetric Spectrum

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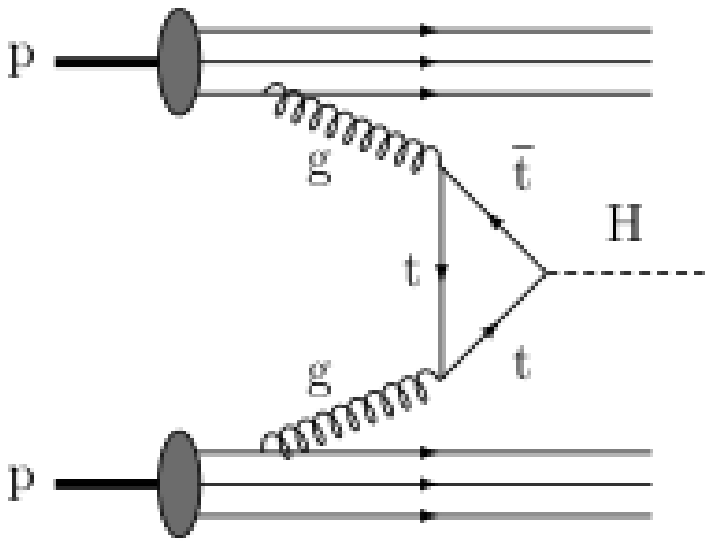
Table 8: Summary table of the CLIC SUSY benchmark analyses results obtained with full-detector simulations with background overlaid. All studies are performed at a center-of-mass energy of 3 TeV (1.4 TeV) and for an integrated luminosity of 2 ab^{-1} (1.5 ab^{-1}) [21, 22, 23, 24, 25, 26, 27].

$\sqrt{s}$ (TeV)	Process	Decay mode	SUSY model	Measured quantity	Generator value (GeV)	Stat. uncertainty
3.0	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\ell}$ mass	1010.8	0.6%
				$\tilde{\chi}_1^0$ mass	340.3	1.9%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	1010.8	0.3%
				$\tilde{\chi}_1^0$ mass	340.3	1.0%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	1097.2	0.4%
				$\tilde{\chi}_1^\pm$ mass	643.2	0.6%
3.0	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$ $\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$	II	$\tilde{\chi}_1^\pm$ mass $\tilde{\chi}_2^0$ mass	643.2 643.1	1.1% 1.5%
3.0	Squarks	$\tilde{q}_R\tilde{q}_R \to q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$	I	$\tilde{q}_R$ mass	1123.7	0.52%
3.0	Heavy Higgs	$H^0A^0 \to b\bar{b}b\bar{b}$ $H^+H^- \to t\bar{b}b\bar{t}$	I	H^0/A^0 mass $H^\pm$ mass	902.4/902.6 906.3	0.3% 0.3%
1.4	Sleptons	$\tilde{\mu}_R^+\tilde{\mu}_R^- \to \mu^+\mu^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\ell}$ mass	560.8	0.1%
				$\tilde{\chi}_1^0$ mass	357.8	0.1%
		$\tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$		$\tilde{\ell}$ mass	558.1	0.1%
				$\tilde{\chi}_1^0$ mass	357.1	0.1%
		$\tilde{\nu}_e\tilde{\nu}_e \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-W^+W^-$		$\tilde{\ell}$ mass	644.3	2.5%
				$\tilde{\chi}_1^\pm$ mass	487.6	2.7%
1.4	Stau	$\tilde{\tau}_1^+\tilde{\tau}_1^- \to \tau^+\tau^-\tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\tau}_1$ mass	517	2.0%
1.4	Chargino Neutralino	$\tilde{\chi}_1^+\tilde{\chi}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 W^+W^-$ $\tilde{\chi}_2^0\tilde{\chi}_2^0 \to h/Z^0\, h/Z^0\, \tilde{\chi}_1^0\tilde{\chi}_1^0$	III	$\tilde{\chi}_1^\pm$ mass $\tilde{\chi}_2^0$ mass	487 487	0.2% 0.1%

Large part of the SUSY spectrum measured at <1% level.

CERN-2012-007

Non-doublet scalar fields

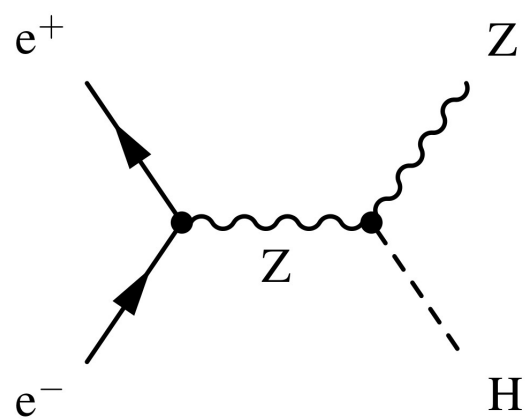


The largest production mechanism at a hadron collider only works for a scalar H with a large doublet component.

In particular, it does not work for a pure triplet commonly present in models that give mass to neutrinos.

This is an important production mode at an electron-positron collider.

It is not penalized if the field H is purely triplet.



Phys. Rev. D 95, 075038 (2017)

Conclusions

- CLIC is a mature option for a multi-TeV electron-positron collider
- It includes three stages, at 0.38, 1.5 and 3 TeV.
- It can study the Higgs boson with precision (relevant for physics beyond the SM).
- It can study the top quark mass and anomalous couplings.
- Double Higgs production can be achieved (relevant for the mechanism of SSB).
- Double vector boson fusion can be achieved, with anomalous coupling well determined.
- Supersymmetric partners can be studied with detail.
- Non doublet scalars are favored in electron-positron colliders

Thanks!