

Physics at the Compact Linear Collider (CLIC)

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Introduction to CLIC

CLIC collider and detector

Physics Programme

Top Higgs BSM searches

Summary

Compact Linear Collider: CLIC



- Based on normal-conducting acceleration structures and power supplied by a drive beam
- For a compact machine (~ 50 km) high accelerating gradient required (~ 100MV/m)
- ▶ e- beam polarisation $P_{e^-} = \pm 80\%$, positron beam polarisation as an option
- CLIC Collaborations (institutes/countries):
 CLIC (62/28): design and development of CLIC
 - CLICdp (30/18): detector optimisation and physics studies











Three stages: 380(350) GeV, 1.5 TeV, 3 TeV (benchmark studies at slightly different energies)

- 350/380 GeV: Precision SM Higgs and top physics
- 1.5 TeV: BSM searches, precision Higgs, ttH, HH, top physics
- 3 TeV: BSM searches, precision Higgs, HH, top physics





Top quarks: threshold scan



- Top pair production $\sqrt{s} = 380$ GeV and 350 GeV (dedicated to threshold scan).
- Cross section turn on sensitive to mass.
- \blacktriangleright 10-point scan with 10 ${\rm fb}^{-1},$ up to a year of data taking
- ▶ Resulting uncertainty (1S mass) $\Delta(m_t) \sim 50 \text{MeV}$ (dominated by NNNLO scale unc.)
- Transformed to MS scheme theoretical uncertainty of order of 10 MeV







Top quarks: precision measurements



Clear environment at CLIC allows for precision measurements and search for rare phenomena

New physics would modify the tt̄V vertex. Polarised beam measurement would disentangle γ and Z form factors

 $\Gamma^{t\bar{t}X}(k^2, q, \bar{q}) = ie \left\{ \gamma_{\mu} \left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2) \right) - \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^{\nu} \left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2) \right) \right\}$ vector axial tensor CPV

- Sensitivity 1-2 orders of magnitude better than at HL-LHC
- Interesting top physics programme at the first CLIC-380GeV stage



arXiv:1710.06737 arXiv:1608.07537



Flavour Changing Neutral Currents



Competitive limits for FCNC top decays

- ▶ $t \to cH$: Limits for CLIC 500 fb⁻¹ at 380 GeV Fully hadronic $B(t->cH) \times B(H->bb) < 1.4 \times 10^{-4}$ Semi-leptonic $B(t->cH) \times B(H->bb) < 2 \times 10^{-4}$ at 95%*C.L.* ATL-PHYS-PUB-2016-019 on $B(t->qH) \sim 2 \times 10^{-4}$
- ► $t \to c\gamma$: Limit for CLIC 500 fb⁻¹ at 380 GeV $B(t > c\gamma) \sim 4\times 10^{-5}$ at 95%*C.L.* Currently CMS: $B(t - > c\gamma) < 1.7\times 10^{-3}$ (arXiv:1511.03951) Expected 95% CL limits at HL-LHC $B(t - > c\gamma) < (2.0 - 3.4)\times 10^{-4}$ for 3 ab⁻¹ at 14 TeV (CMS-DP-2016-064)







Boosted top reconstruction



Hadronic decays of high-energy top quarks: "fat" jets -E [GeV] reconstruction of the top in a large/wide jet and identification of substructure $t \rightarrow Wb \rightarrow q\bar{q}b$



Higgs production



- **Higgsstrahlung**: $e^+e^- \rightarrow ZH$, dominant up to 450 GeV
- ▶ WW fusion: $e^+e^- \rightarrow H\nu_e\bar{\nu_e}$, dominant above 450 GeV, offers high statistic at high energy stages
- ▶ $t\bar{t}H$: $e^+e^- \rightarrow t\bar{t}H$, maximum around 800 GeV, top-Yukawa coupling measurement available
- HH $\nu\nu$ and ZHH processes contribute at $\sqrt{s} = 1$ TeV but $\sigma < 1$ fb







Higgsstrahlung at $\sqrt{s} = 350 \text{GeV}$



- ► **HZ** events with $Z \to e^+ e^-, \mu^+ \mu^-$ model-independent measurements of the g_{HZZ} coupling (2% uncertainty)
- ▶ Using $Z \rightarrow q\bar{q}$: almost model-independent measurements of g_{HZZ} coupling using hadronic Z decays with 0.9% uncertainty



The recoil mass technique can also be used to search for invisible and BSM Higgs decay modes



Higgs properties



Global fit using statistical uncertainties of all measurements to estimate Higgs couplings and width Γ by minimising $\chi_i^2 = \frac{(C_i/C_i^{SM}-1)^2}{\Delta F_i^2}$ where C_i : observables, ΔF_i : uncertainties



Model dependent LHC-like fit, SM decays-only





BSM physics at CLIC



Best discovery reach for higher energies in both cases of (in)direct searches

Direct searches: SUSY,Dark Matter, Hidden Valley,...

- Possible direct observations of new phenomena and precision measurements of masses and couplings
- Accessible up to kinematic limit
- Low background (no QCD): especially suitable for electroweak states
- Polarised beam and threshold scans might be useful to constrain underlying theory

\sqrt{s} (TeV)	Process	Decay mode	SUSY model	Observable	Unit	Gene- rator value	Stat. uncert ainty
3.0	Light Higgs production	$\begin{array}{l} h \rightarrow b\overline{b} \\ h \rightarrow c\overline{c} \\ h \rightarrow \mu^+\mu^- \end{array}$		$\sigma \times Bran-ching ratio$	ſb	285 13 0.12	0.22% 3.2% 15.7%
3.0	Heavy Higgs production	$HA \to b\overline{b} b\overline{b}$	I	Mass Width	GeV GeV	902.4	0.3% 31%
			П	Mass Width	GeV GeV	742.0	0.2% 17%
		$H^+H^- \to t \overline{b} b \overline{t}$	I	Mass Width	GeV GeV	906.3	0.3% 27%
			п	Mass Width	GeV GeV	747.6	0.3% 23%
3.0	Production of right-handed squarks	$\widetilde{q}_R\widetilde{q}_R \to q\overline{q}\overline{\chi}_1^0\overline{\chi}_1^0$	I	Mass σ	GeV fb	1123.7 1.47	0.52% 4.6%
		$\widetilde{\mu}_R^+ \widetilde{\mu}_R^- \to \mu^+ \mu^- \widetilde{\chi}_1^0 \widetilde{\chi}_1^0$		$\sigma_{\tilde{\ell} \text{ mass}}$ $\tilde{\chi}_1^0 \text{ mass}$	fb GeV GeV	0.72 1010.8 340.3	2.8% 0.6% 1.9%
3.0	Sleptons production	$\widetilde{e}^+_R \widetilde{e}^R \to e^+ e^- \widetilde{\chi}^0_1 \widetilde{\chi}^0_1$	п	$\sigma_{\tilde{\ell} \text{ mass}}$ $\tilde{\chi}_1^0 \text{ mass}$	fb GeV GeV	6.05 1010.8 340.3	0.8% 0.3% 1.0%
		$\begin{array}{l} \widetilde{e}^+_L \widetilde{e}^L \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 e^+ e^- hh \\ \widetilde{e}^+_L \widetilde{e}^L \rightarrow \tilde{\chi}^0_1 \tilde{\chi}^0_1 e^+ e^- Z^0 Z^0 \end{array}$		σ	ſb	3.07	7.2%
		$\widetilde{\nu}_e \widetilde{\nu}_e \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 e^+ e^- W^+ W^-$		$\sigma_{\tilde{\ell} \text{ mass}}$ $\tilde{\chi}_1^{\pm}$ mass	fb GeV GeV	13.74 1097.2 643.2	2.4% 0.4% 0.6%
3.0	Chargino and	$\tilde{\chi}_1^+\tilde{\chi}_1^-\rightarrow\tilde{\chi}_1^0\tilde{\chi}_1^0W^+W^-$	п	$\hat{\chi}_1^{\pm}$ mass σ	GeV fb	643.2 10.6	1.1% 2.4%
	neutralino production	$\tilde{\chi}_2^0 \tilde{\chi}_2^0 \rightarrow h^0/Z^0 h^0/Z^0 \tilde{\chi}_1^0 \tilde{\chi}_1^0$		$\hat{\chi}_2^0$ mass	GeV fb	643.1 3.3	1.5%



BSM physics at CLIC



Indirect searches: vector boson scattering, ee to $\gamma\gamma,\ldots$

- Precision measurements possible deviations of observables from SM predictions
- Possibility to reach for higher mass/energy scales (~ tens of TeV)
- e⁺e⁻ → µ⁺µ⁻: Z' test If discovered at LHC: precision measurements of the effective coupling
- Otherwise: Z' mass up to 50 TeV can be reached at 5σ with 1ab⁻¹ at 3 TeV (depending on coupling assumptions)

Composite Higgs: Higgs as a bound state of fermions.



 m_{ρ} : masses of vector resonances ξ : measures a strength of Higgs interactions (depends on scale of compositness)



Summary



Very active *R&D* projects for accelerator and extensive studies on physics/detector making CLIC a realistic option for post-LHC collider

Precision measurements of many observables through Higgs production (Higgsstrahlung and WW-fusion) and in the top quark threshold and continuum regimes

Energy staging optimal for physics:

- 380 GeV stage (optimised for precision SM Higgs and top physics) "affordable" and with guaranteed physics return
- Higher energies of 1.5/3 TeV will depend on LHC results. Best sensitivity for BSM searches, rare Higgs processes and decays



Backup Slides





CLIC layout at 3 TeV







CLIC parameters



Parameter	380 GeV	1.5 TeV	3 TeV	
Luminosity L (10 ³⁴ cm ⁻² sec ⁻¹)	1.5	3.7	5.9	
\mathscr{L} above 99% of Vs (10 $^{34} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$)	0.9	1.4	2.0	
Accelerator gradient (MV/m)	72	72/100	72/100	
Site length (km)	11.4	29	50	
Repetition frequency (Hz)	50	50	50	
Bunch separation (ns)	0.5	0.5	0.5	
Number of bunches per train	352	312	312	
Beam size at IP σ _x /σ _y (nm)	150/2.9	~60/1.5	~40/1	
Beam size at IP σ_z (µm)	70	44	44	
Estimated power consumption [*] (MW)	252 364		589	



CLIC detector







Beam-induced backgrd rejection





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Higgs parameters comparison with EFT







pp versus e+e-



Taken from Lucie Linssen presentation at CERN EP Seminar, January 24th, 2017





Other proposed e+e- machines







Other proposed e+e- machines



