Precision measurements at CLIC

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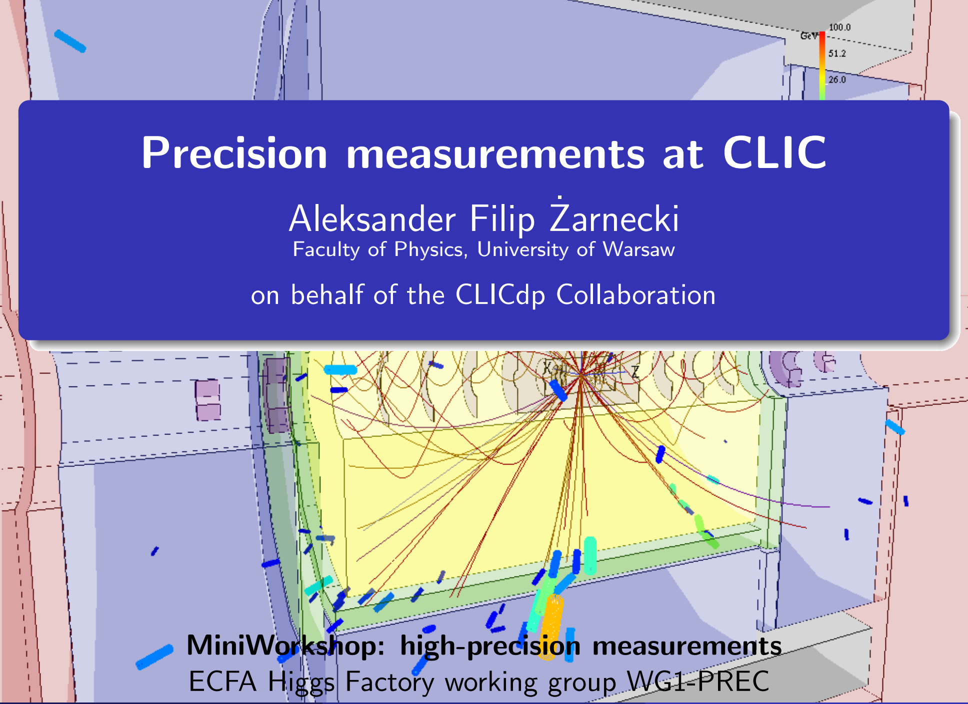
on behalf of the CLICdp Collaboration



MiniWorkshop: high-precision measurements

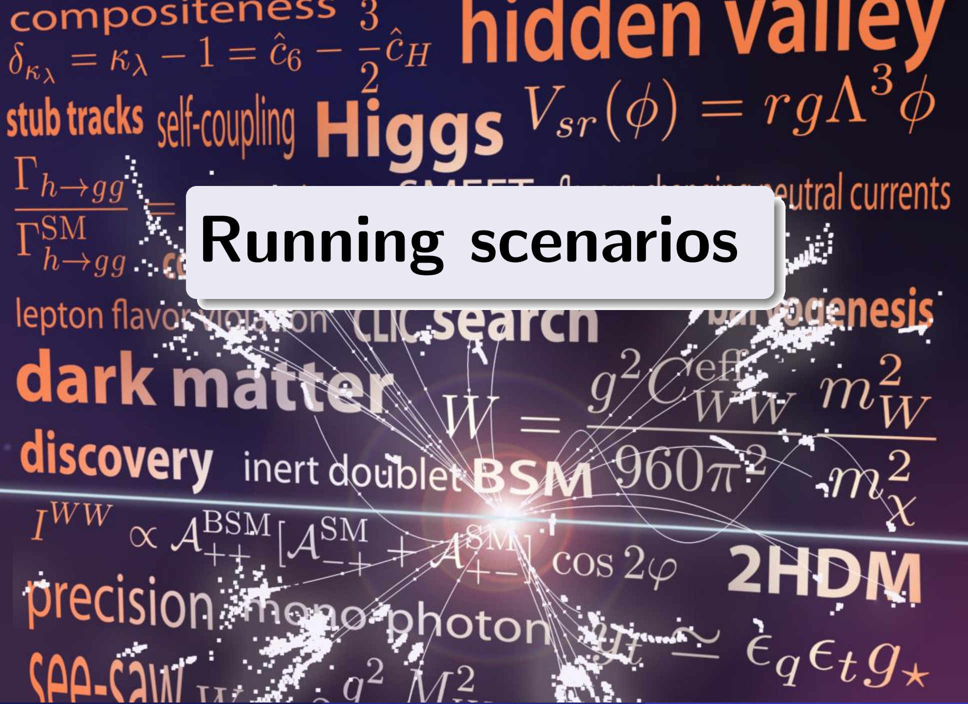
ECFA Higgs Factory working group WG1-PREC

Outline

1. Running scenarios
2. Higgs precision measurements
3. Top precision measurements
4. EW precision measurements
5. Conclusions

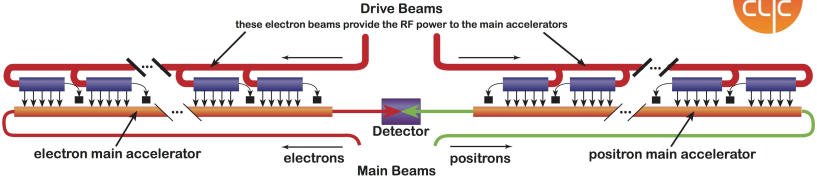
Please note this is a personal choice of CLICdp results...

Running scenarios



Running scenarios

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%)

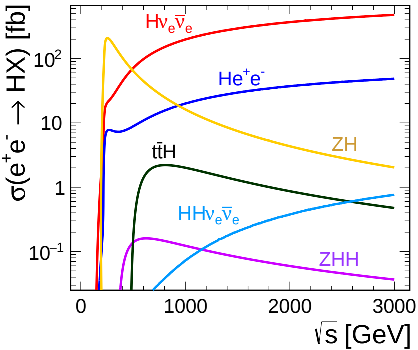
For details refer to arXiv:1812.07987

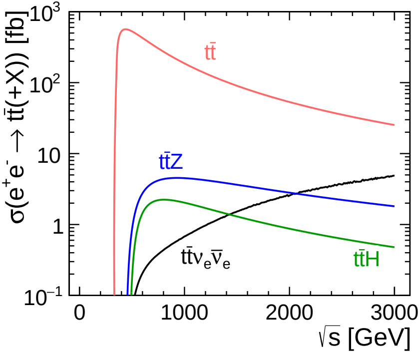
Baseline scenario

arXiv:1812.06018

Three construction stages (each 7 to 8 years of running)
for an optimal exploitation of its physics potential

- $\sqrt{s} = 380$ GeV with 1 ab^{-1} including 100 fb^{-1} at $t\bar{t}$ threshold
  focus on precision Standard Model physics,
  optimised for **Higgs boson** and **top-quark** measurements





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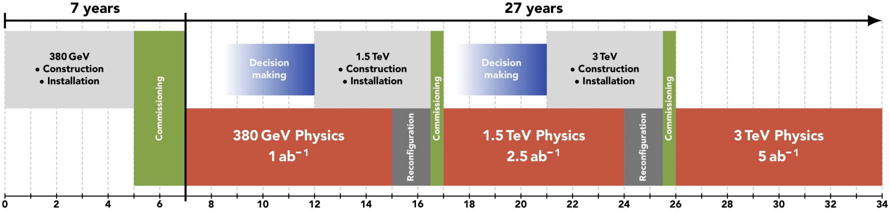
- $\sqrt{s} = 380$ GeV with $1\,\text{ab}^{-1}$ including 100 fb^{-1} at $t\bar{t}$ threshold
  focus on precision Standard Model physics,
  optimised for **Higgs boson** and **top-quark** measurements
- $\sqrt{s} = 1.5$ TeV with $2.5\,\text{ab}^{-1}$
- $\sqrt{s} = 3$ TeV with $5\,\text{ab}^{-1}$
  focus on direct and indirect **BSM searches**,
  but also additional **Higgs boson** and **top-quark** studies

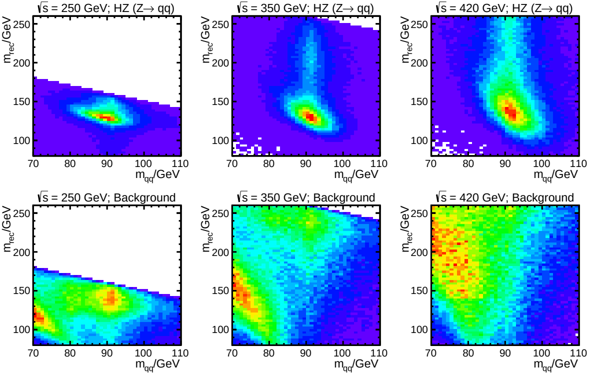


Energy choice

arXiv:1509.02853

Energy of 380 GeV (350 GeV) was selected as providing the best precision for Higgs coupling measurement in $e^+e^- \rightarrow ZH$ with hadronic Z decays.

This choice allows also to study top physics at the first stage...



My personal opinion: if optimised for running at 250 GeV, CLIC performance should be similar to that of ILC (but for positron polarisation)

Running options

Extended first stage

CERN-ACC-2019-0051

With two modifications to the baseline scenario:

- 100 Hz bunch train repetition rate (instead of 50 Hz)
  5% increase of cost, 30% increase of power consumption
- Initial stage increase from 8 to 13 years

$\Rightarrow$ Integrated luminosity at 380 GeV increased by factor 4, to 4 ab^{-1}

Running options

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- 100 Hz bunch train repetition rate (instead of 50 Hz)
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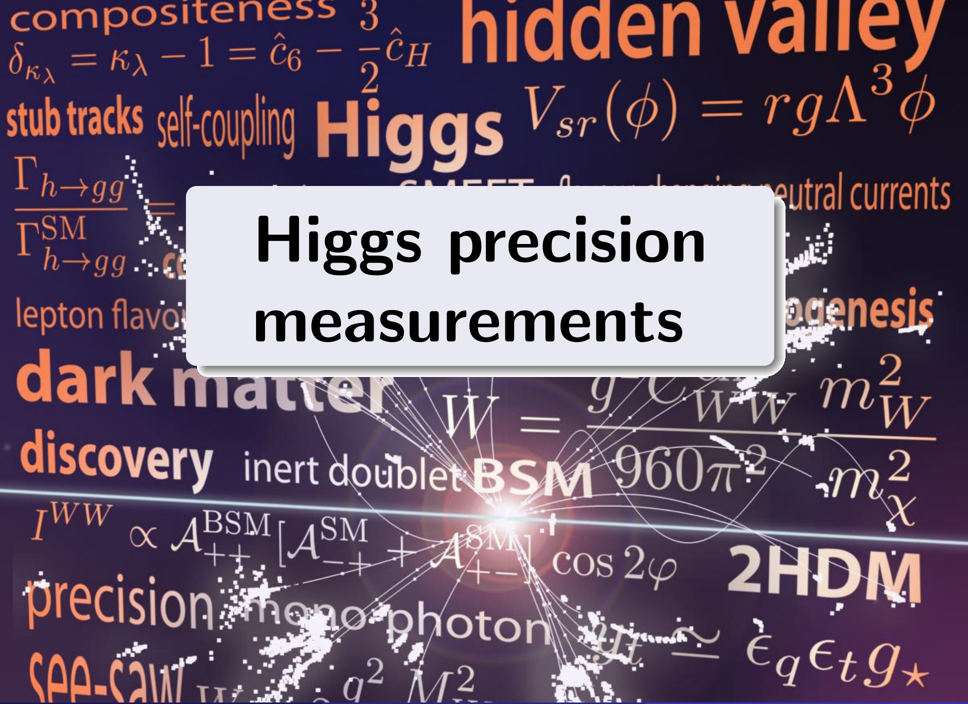
$\Rightarrow$ Integrated luminosity at 380 GeV increased by factor 4, to 4 ab^{-1}

Z-pole running

CERN-ACC-2019-0051

- 380 GeV collider running at Z-pole:
  $\mathcal{L} = 2.3 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$
  $\Rightarrow$ very useful for calibration, but not for precision measurements
- Shorter liniac for Z-pole energy with adapted beam delivery system:
  $\mathcal{L} = 0.36 \cdot 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ (for 50 Hz)
  $\Rightarrow$ 100 fb^{-1} can be collected in a few years, 4.5 billion Z bosons
  50:50 splitting of -80% and +80% polarisations assumed

Higgs precision measurements



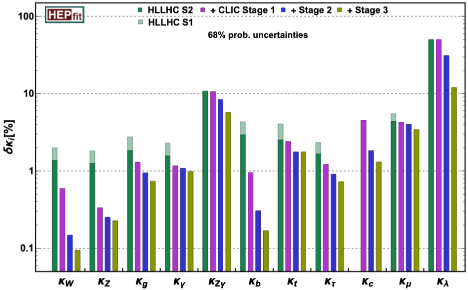
Higgs couplings

CLIC sensitivity to the different Higgs boson couplings
compared with the HL-LHC projections

Model-dependent analysis

Parameter	Relative precision		
	350 GeV 1 ab^{-1}	+ 1.4 TeV + 2.5 ab^{-1}	+ 3 TeV + 5 ab^{-1}
κ_{HZZ}	0.4 %	0.3 %	0.2 %
κ_{HWW}	0.8 %	0.2 %	0.1 %
κ_{Hbb}	1.3 %	0.3 %	0.2 %
κ_{Hcc}	4.1 %	1.8 %	1.3 %
$\kappa_{H\tau\tau}$	2.7 %	1.2 %	0.9 %
$\kappa_{H\mu\mu}$	–	12.1 %	5.6 %
κ_{Htt}	–	2.9 %	2.9 %
κ_{Hgg}	2.1 %	1.2 %	0.9 %
$\kappa_{H\gamma\gamma}$	–	4.8 %	2.3 %
$\kappa_{HZ\gamma}$	–	13.3 %	6.6 %

arXiv:1812.01644



arXiv:1812.02093

Sub-percent level precision already at the first energy stage

Higgs couplings

CLIC sensitivity to the different Higgs boson couplings
compared with the HL-LHC projections

Model-dependent analysis

Parameter	Relative precision		
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arXiv:1812.01644

Parameter	Relative precision		
	350 GeV $4\,ab^{-1}$	+ 1.4 TeV + $2.5\,ab^{-1}$	+ 3 TeV + $5\,ab^{-1}$
κ_{HZZ}	0.2 %	0.1 %	0.1 %
κ_{HWW}	0.4 %	0.1 %	0.1 %
κ_{Hbb}	0.6 %	0.3 %	0.2 %
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arXiv:2001.05278

Measurement dominated by statistical uncertainties

Higgs couplings

CLIC sensitivity to the different Higgs boson couplings

Model-independent analysis

Parameter	Relative precision		
	350 GeV $1\,ab^{-1}$	+ 1.4 TeV + $2.5\,ab^{-1}$	+ 3 TeV + $5\,ab^{-1}$
g_{HZZ}	0.6 %	0.6 %	0.6 %
g_{HWW}	1.0 %	0.6 %	0.6 %
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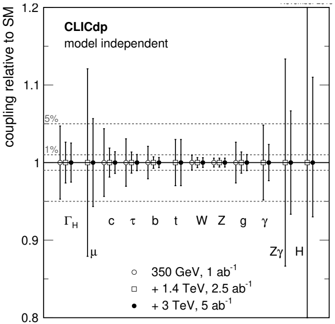
Γ_H	4.7 %	2.6 %	2.5 %



arXiv:1812.01644

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arXiv:1812.01644

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Γ_H	2.4 %	1.5 %	1.3 %

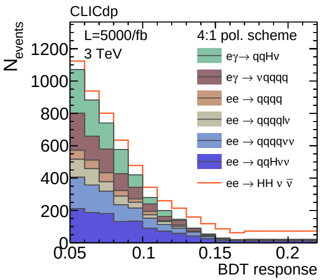
arXiv:2001.05278

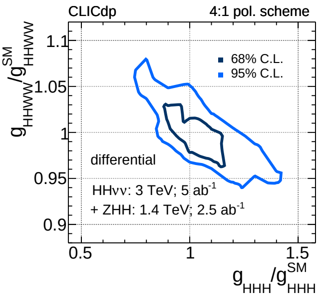
Measurement dominated by statistical uncertainties

Higgs self-coupling

arXiv:1901.05897

Extracted from the measurement of double Higgs boson production at CLIC, at energies of $\sqrt{s} = 1.5$ and 3 TeV.





Both trilinear Higgs self-coupling and the quartic HHWW coupling can be constrained.

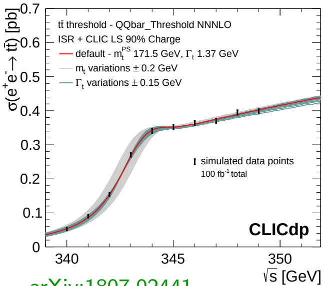
$$\delta\lambda/\lambda = -7\%/+11\% \qquad (68\%\ \text{C.L.})$$

Top precision measurements

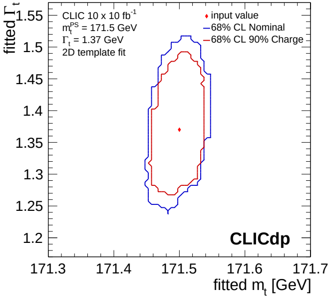
Threshold scan

Precision top mass measurement possible already with 100 fb^{-1}

Baseline scan scenario: 10 cross section measurements, 10 fb^{-1} each



arXiv:1807.02441



About 20 MeV uncertainty on mass expected from mass and width fit (2D)

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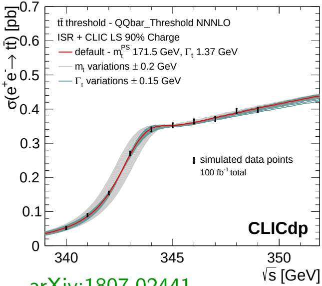
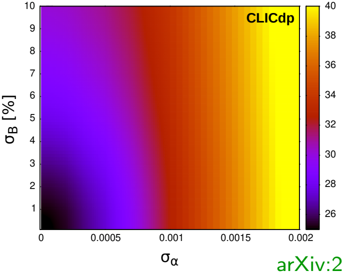


arXiv:1807.02441

top Yukawa uncertainty of 10%



arXiv:2103.00522

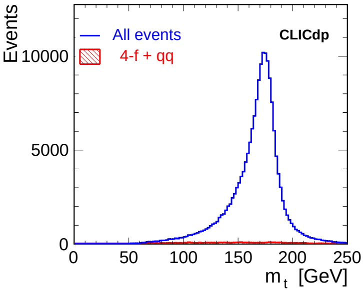
About 20 MeV uncertainty on mass expected from mass and width fit (2D)

Parametric uncertainties: α_s and top-quark Yukawa coupling need to be constrained from independent measurements

$\Rightarrow$ total systematic uncertainty $\sim$ 50 MeV

Direct mass measurement

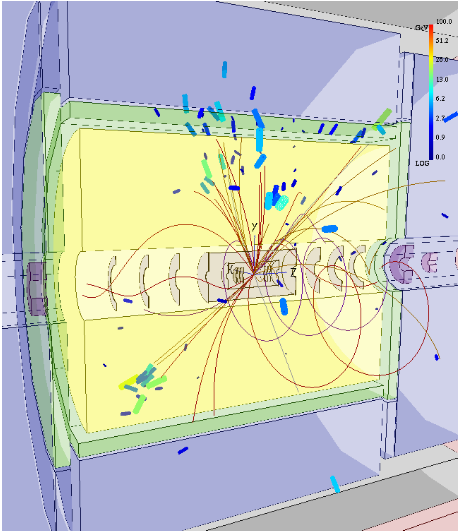
From reconstruction of hadronic top-quark decays



Statistical precision ∼ 30 MeV

Needs excellent control of JES
Large theoretical uncertainties

arXiv:1807.02441

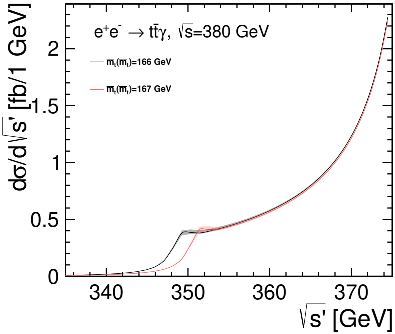


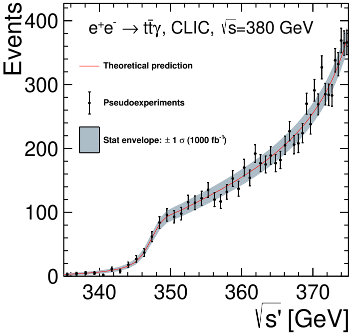
Mass from radiative events

arXiv:1912.01275

$$e^+e^- \rightarrow t\,\bar{t} + \gamma_{ISR}$$

Threshold from reconstructed $t\bar{t}$ invariant mass distribution



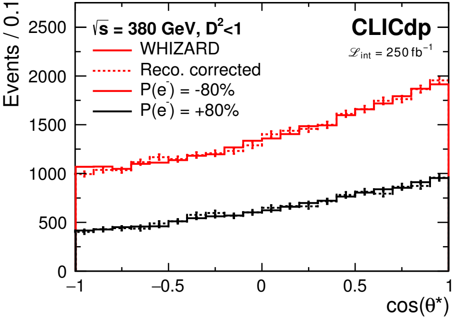


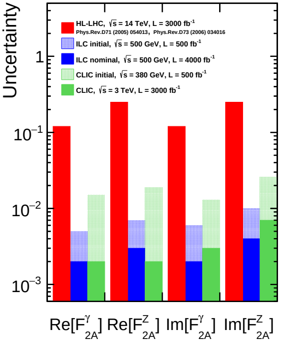
Statistical unc. on m_t: 90 MeV Total unc. 110 MeV

Top EW couplings

Can be constrained from the measurements of top-quark pair-production cross sections and angular distributions

CP-violating form factors



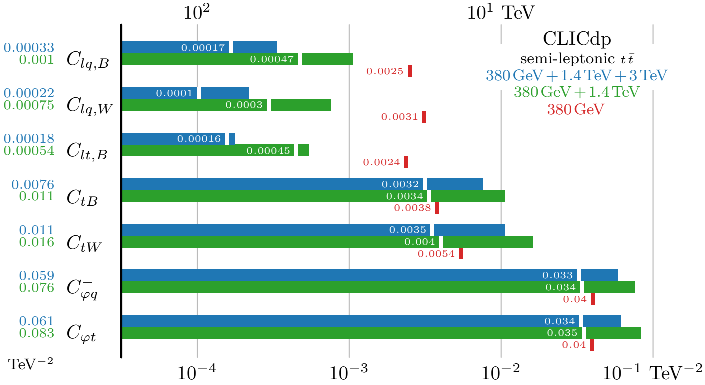


arXiv:1710.06737

Top EW couplings

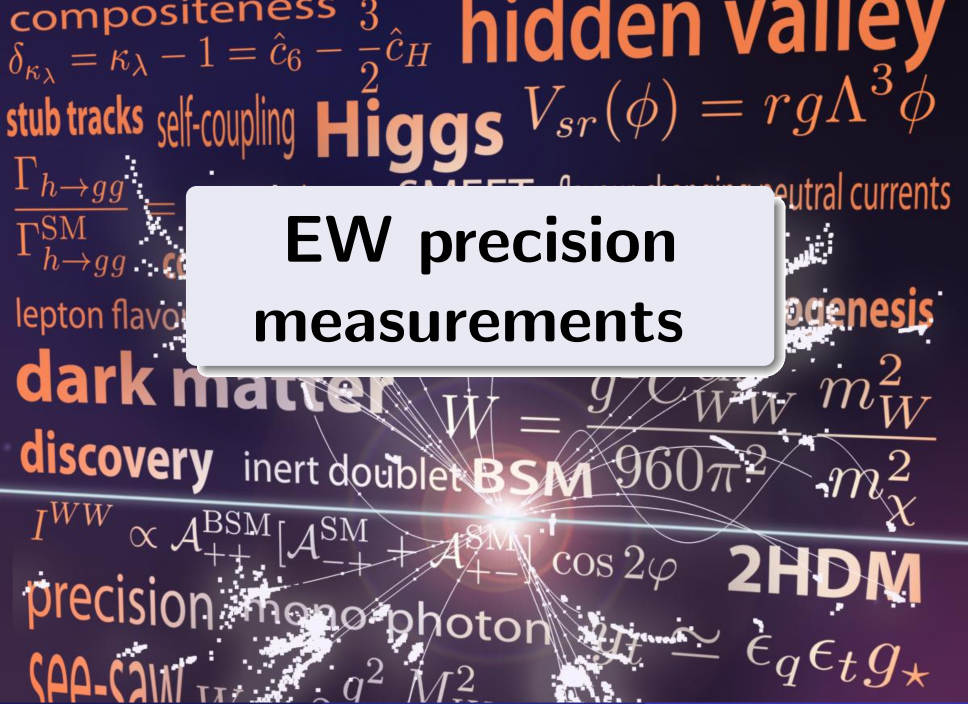
Global EFT analysis of CLIC measurements involving top quark

Results based on statistically optimal observables arXiv:1807.02441



High energy CLIC can reach “new physics” scales in the 100 TeV range

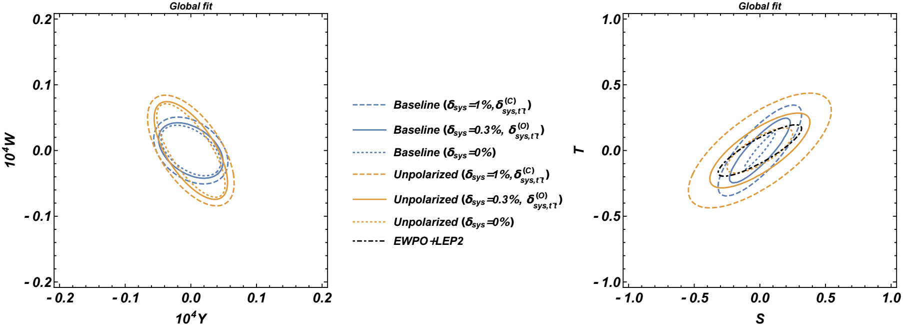
EW precision measurements



EWPO

arXiv:1812.02093

Expected errors on the different oblique parameters from combined analysis of $e^+e^- \to f\bar{f}$ angular distributions (non-radiative events)

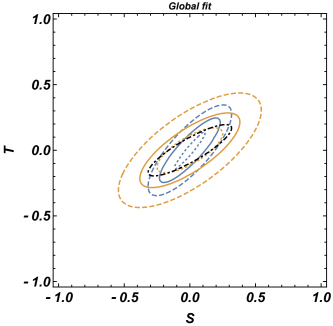


EWPO

arXiv:1812.02093

Expected errors on the different oblique parameters from combined analysis of $e^+e^- \to f\bar{f}$ angular distributions (non-radiative events)

Scenario (P_{e^-}, P_{e^+})	Current	CLIC Baseline $(\mp 80\%, 0\%)$	CLIC Unpolarized $(0\%, 0\%)$
S	0.13	0.09 (0.05)	0.16 (0.10)
T	0.08	0.10 (0.05)	0.12 (0.07)
$W\,[\times 10^6]$	600	1.7 (1.5)	3.0 (2.2)
$Y\,[\times 10^6]$	900	2.0 (1.8)	2.3 (1.7)



In parenthesis: the results assuming the other oblique parameters are set to 0.

Return-to-Z events

J.-J. Blaising, Ph. Roloff, 2019

The energy loss due to ISR and beamstrahlung
$\Rightarrow$ large samples of return-to-Z events at 380 GeV ($\sim$5 M in 1 ab^{-1})
$\Rightarrow$ Significant improvement compared to LEP / SLD possible

Asymmetry parameters

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.0006	0.00015
A_μ	0.142	0.0039	0.00014
A_τ	0.143	0.0055	0.00014
A_c	0.670	0.0019	0.00067
A_b	0.923	0.0036	0.00092

Relative branching ratios

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_e$	0.0481	0.00012	0.00005
$1/R_\mu$	0.0481	0.00012	0.00005
$1/R_\tau$	0.0482	0.00016	0.00024
R_c	0.172	0.00042	0.00086
R_b	0.216	0.00031	0.00022
R_ν	0.286	0.0027	0.00029

Direct measurement of R_ν possible!

Largly dominated by statistical uncertainties

Z-pole running

J.-J. Blaising, Ph. Roloff, 2019

100 fb^{-1} with polarised electron beam (50:50) for dedicated design

⇒ ∼4.5 billion Z events

⇒ another order of magnitude improvement possible

Asymmetry parameters

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
A_e	0.1515	0.00002	0.00015
A_μ	0.142	0.00014	0.00014
A_τ	0.143	0.00021	0.00014
A_c	0.670	0.00013	0.00067
A_b	0.923	0.00007	0.00092

Relative branching ratios

Observable	PDG value [4]	$\Delta_{stat.}$	$\Delta_{syst.}$
$1/R_e$	0.0481	4×10^{-6}	2×10^{-5}
$1/R_\mu$	0.0481	4×10^{-6}	1×10^{-5}
$1/R_\tau$	0.0482	6×10^{-6}	2×10^{-5}
R_c	0.172	1.5×10^{-5}	4×10^{-4}
R_b	0.216	1.1×10^{-5}	1.5×10^{-4}

Most measurements dominated by systematic uncertainties

More detailed study of systematic effects still pending...

Conclusions

Precision measurements at CLIC

CLIC program allows for a wide range of precision measurements:
Higgs couplings, top-quark properties, WW & two-fermion production...

Return-to-Z events at 380 GeV provide some improvement to the knowledge of the Z-boson couplings

Significant improvement expected from running at 91 GeV with dedicated design (Giga-Z stage)

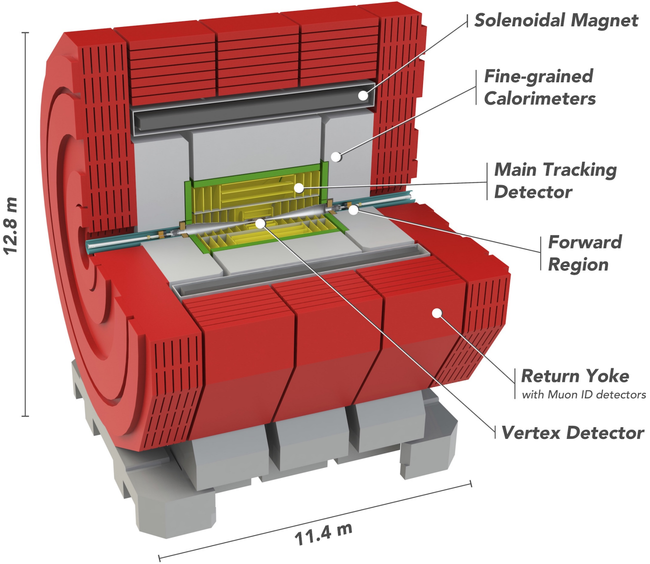
CLIC detector model: CLICdet

Based on detailed simulation studies, detector R&D and beam tests.

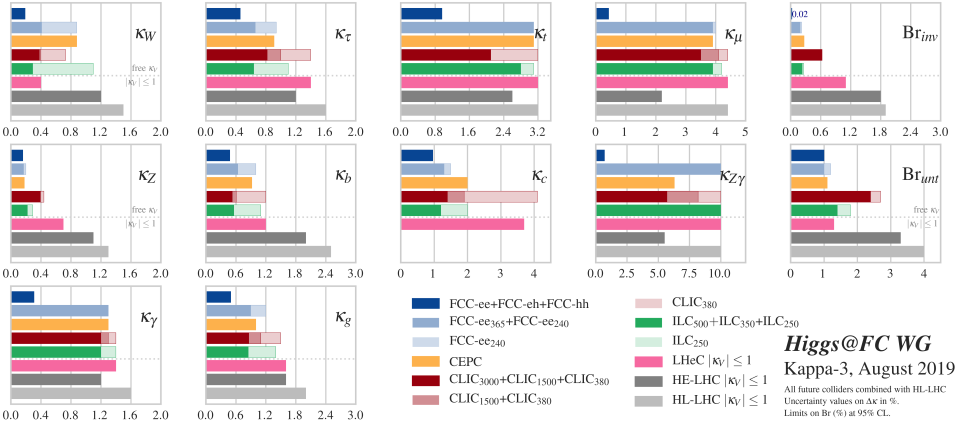
Optimised for Particle Flow reconstruction

Full exploitation of physics potential from 380 GeV to 3 TeV

For details refer to arXiv:1812.07337



Higgs couplings at future colliders

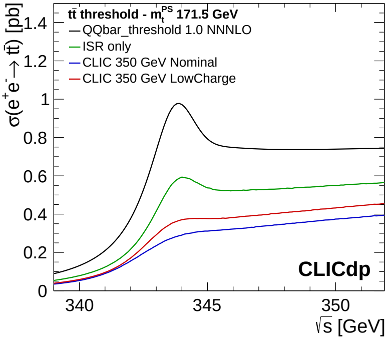


Threshold scan

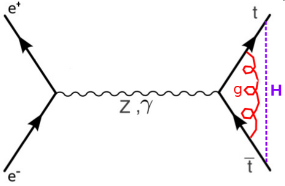
Top pair production cross section around threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



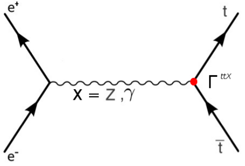
Significant cross section smearing due to luminosity spectra and ISR

Smearing due to luminosity spectra can be reduced by using dedicated running configuration

Top-quark pair production

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics" contribution



New physics effects can be constrained through measurement of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

Additional constraints obtained by:

- using electron beam polarisation
- measurements at different $\sqrt{s}$