Potential of the Compact Linear Collider (CLIC) to measure branching fraction of the Higgs to ZZ* decays at 350 GeV and 3 TeV center-of-mass energies

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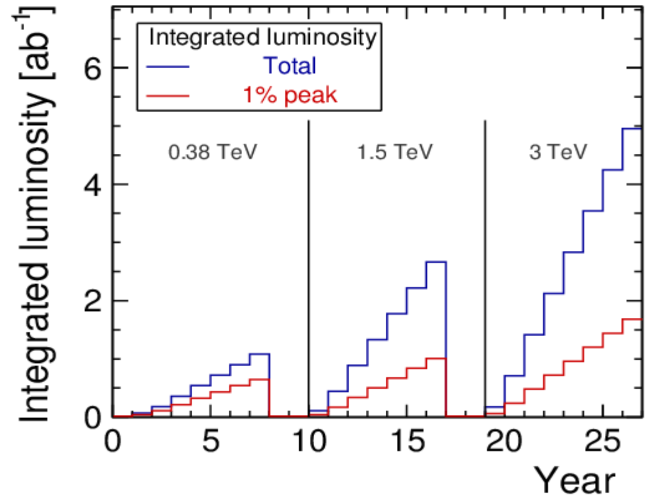
Overview

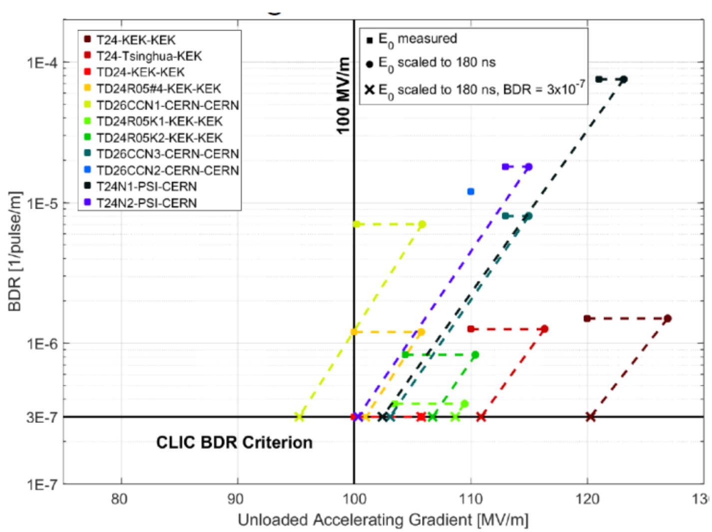
- CLIC project
- CLIC physics programme
- Introduction to $H \rightarrow ZZ^{*}$ analyses @ 350 GeV and 3 TeV
- Method
- Results
- Summary

Compact LInear Collider

- Feasible and attractive option for an e^+e^- collider at CERN (Higgs factory & beyond)
- CLIC is a mature project: ready for construction starting ~2026, with first collisions ~2035



- Demonstrated two-beam acceleration [arXiv:1812.07987]
- With 100 MV/m gradient in main-beam cavities



- Electron polarisation:
- enhances Higgs production at high-energy stages
- provides additional observables sensitive to NP
- helps to characterize new particles in case of discovery

Baseline polarization scenario

Stage	$\sqrt{s}$ [TeV]	$\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = -80\%$ $\mathscr{L}_{int}$ [ab^{-1}]	$P(e^-) = +80\%$ $\mathscr{L}_{int}$ [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 Compact Linear e+e− Collider (CLIC): Accelerator and Detector, arXiv:1812.07987

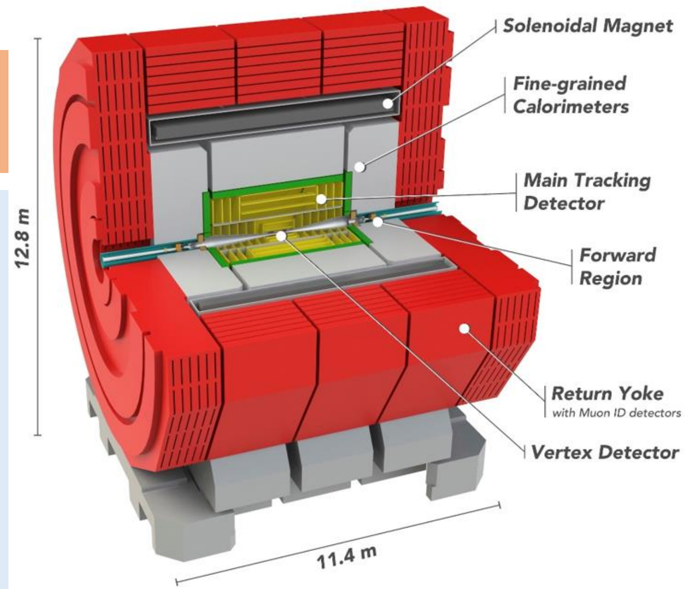
Detector for CLIC

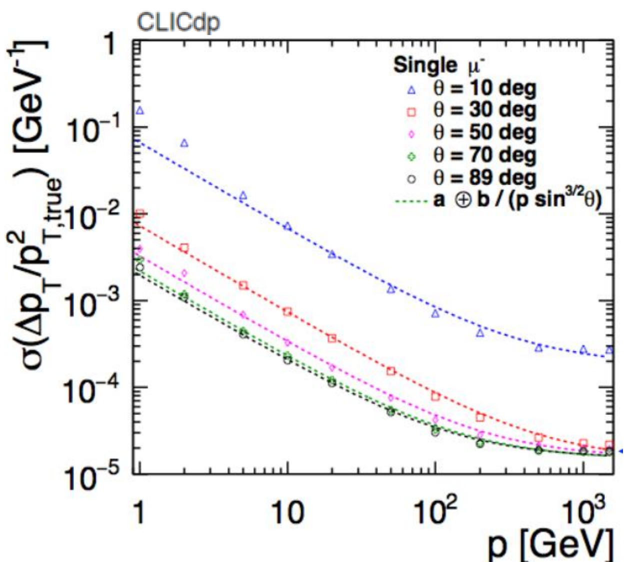
Detector for CLIC is optimized for a staged physics program addressing SM and beyond

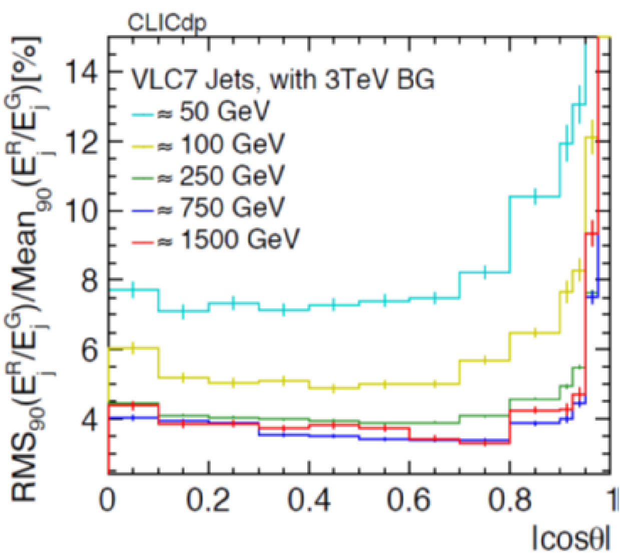
Excellent particle ID and reconstruction proven through experimental testing and detailed simulations:

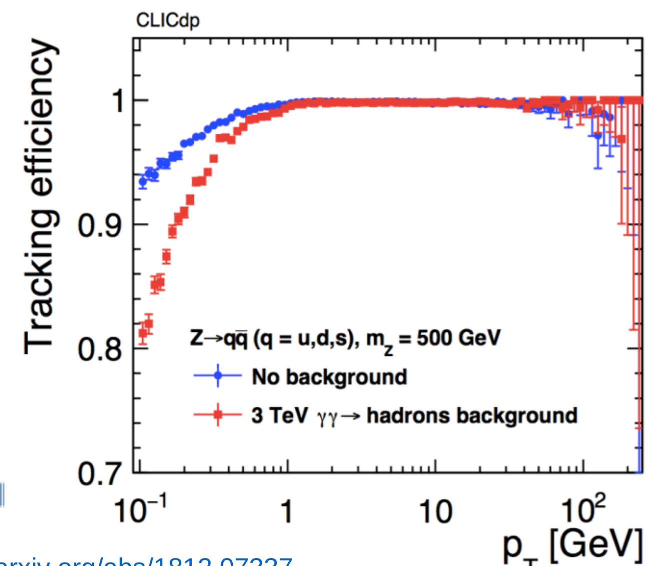
- $\sigma_{p_T}/p_T^2 \sim 2 \cdot 10^{-5}$ GeV^{-1}
- separation of H/W/Z jets, $\sigma_E/E \sim$ 5% - 3.5%
- lepton identification efficiency > 95%

*Our *analyses are done with the CLIC ILD [CLIC CDR], but difference in performance is not such to affect the results*



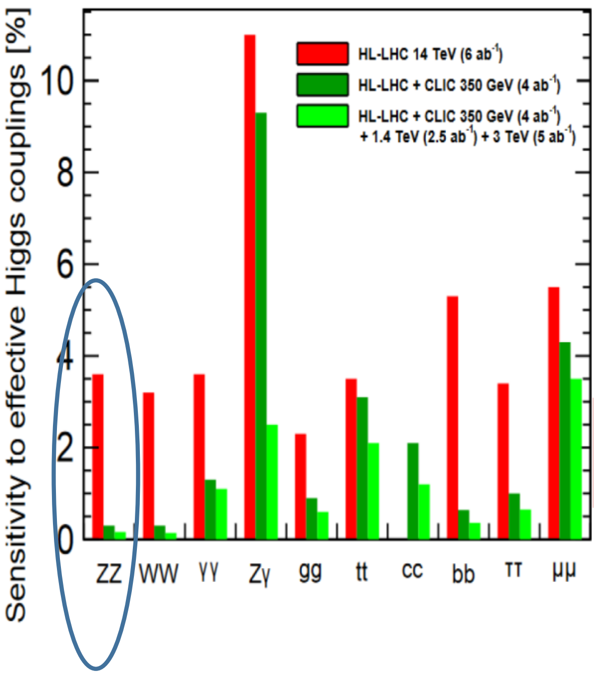


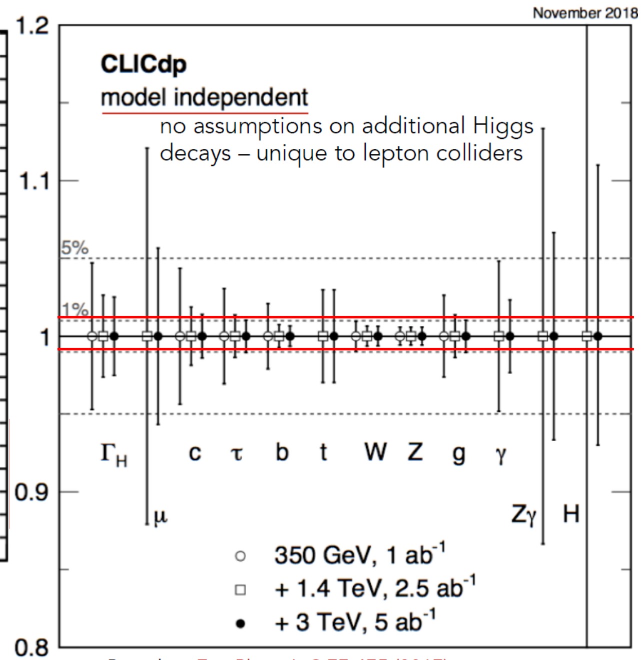




A detector for CLIC: main parameters and performance, arxiv.org/abs/1812.07337

Higgs to ZZ measurements at CLIC





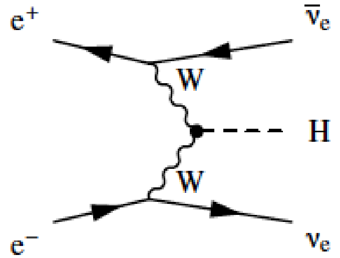
Based on Eur. Phys. J. C 77 475 (2017)
updated to new luminosity scenario arXiv:1812.01644

- 380 GeV stage is optimized to exploit HZ, WW-fusion and ttbar threshold production
- 3 TeV energy stage already produces $3.4 \cdot 10^6$ Higgs bosons standalone, including polarization
- All stages combined in global fits - each contributes significantly
- Detailed studies: full detector simulation of physics and background processes including beam-beam interactions, global fit including correlations

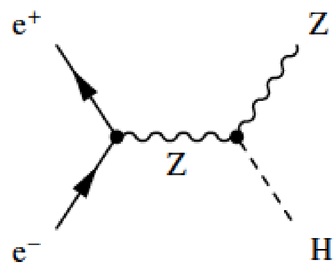
Already at the first stage better precision than at HL-LHC, in particular for c/b/W/Z couplings

H to ZZ couplings can be measured below 1% stat. uncertainty from a global fit (model indent/dependent)

Introduction to H → ZZ* analyses @ 350 GeV and 3 TeV



- H → ZZ has not been studied before at 350 GeV and 3 TeV



- Full simulation of CLIC_ILD detector, realistic beam spectrum, overlay of beamsstrahlung background
- Estimates of the relative statistical uncertainties based on the statistical significance

BR(H → ZZ*) = 2.9%

BR(Z → qq) ≈ 70%

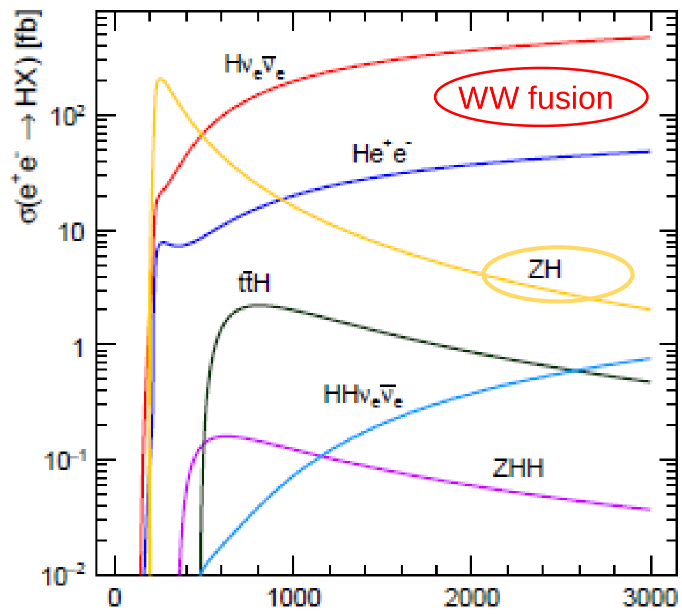
BR(Z → e^+e^- ($\mu^+\mu^-$)) ≈ 3.4%

@ 3 TeV

$\sigma(e^+e^- \to H\nu\nu)$ ~ 415 fb, in 5 ab^{-1} ~ 6000 signal evt.

@ 350 GeV

$\sigma(e^+e^- \to HZ, Z \to q\bar{q})$ ~ 93.44 fb, in 1 ab^{-1} ~ 240 signal evt.



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

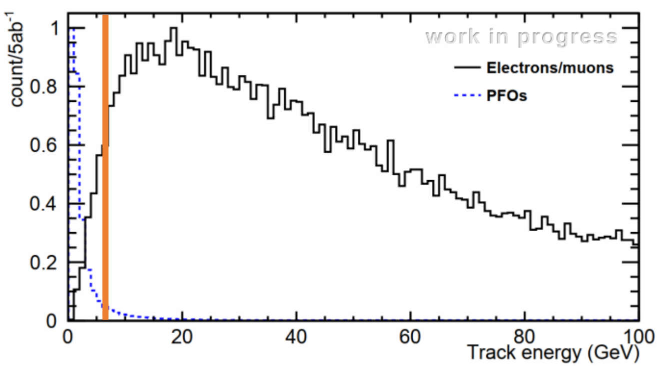
Overview of the method

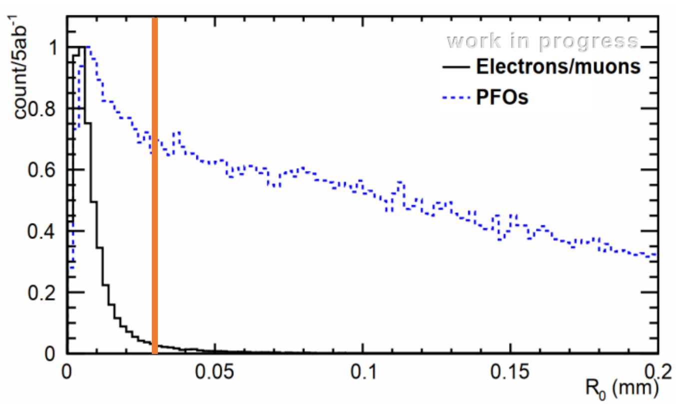
- **Lepton Isolation with Bremsstrahlung recovery**
  First the 2 isolated electrons or muons are found
- **Jet Reconstruction**
  Events are then grouped in 2 (4) jets by k_T algorithm, with cone radius of R = 0.7 at 3 TeV and R = 1.1 at 350 GeV
- **Z reconstruction**
  Larger of two fermion invariant masses is considered as on-shell Z boson
- **LCFI Vertexing (heavy flavors)**
  Helps to reduce background processes $\mathrm{e}^+\mathrm{e}^- \to \mathrm{H}\nu_e\bar{\nu}_e$, $\mathrm{H} \to \mathrm{b}\bar{\mathrm{b}}$ and $\mathrm{H} \to \mathrm{c}\bar{\mathrm{c}}$
- **Preselection (reduce large cross-section backgrounds)**
  Exactly 2 isolated leptons per event
- **MVA Selection**
  Maximizing statistical significance (S) of signal to background separation

Preselection

@ 3 TeV

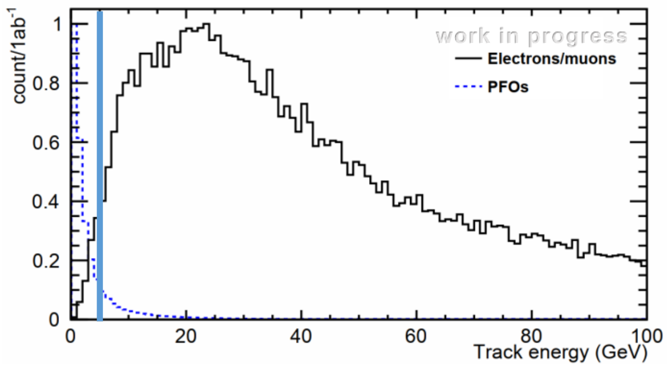
- $E_{\text{track}} > 6$ GeV – remove PFOs
- $d_0 < 0.02$ mm, $z_0 < 0.02$ mm, $R_0 < 0.03$ mm
  tracks only from primary vertex

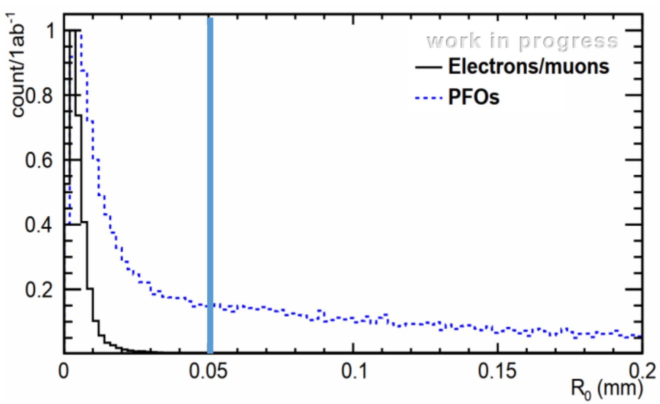




@ 350 GeV

- $E_{\text{track}} > 5$ GeV remove PFOs
- $d_0 < 0.02$ mm, $z_0 < 0.02$ mm $R_0 < 0.05$ mm
  tracks only from primary vertex

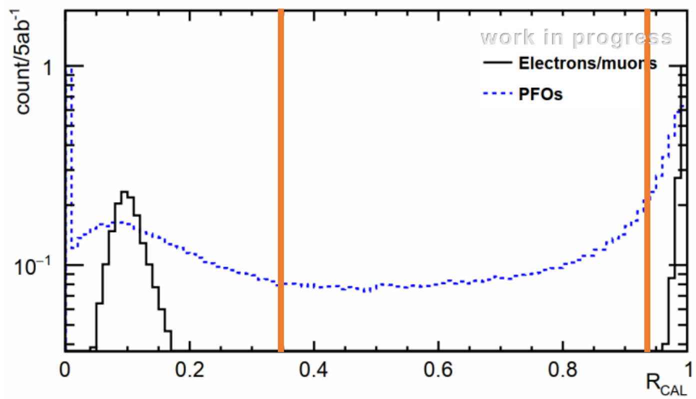


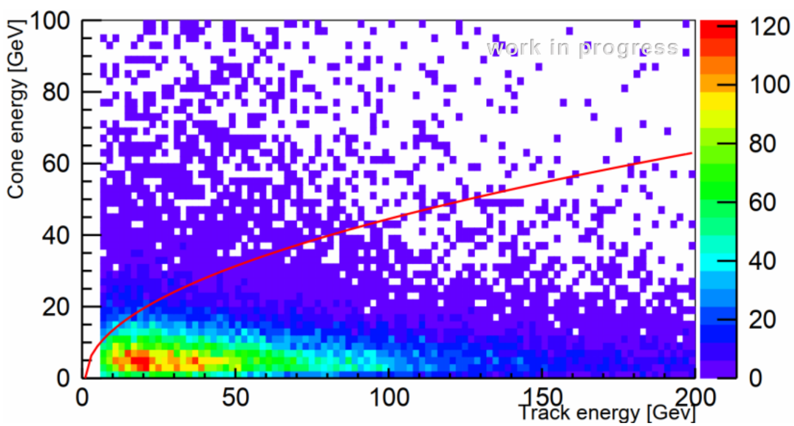


Preselection

@ 3 TeV

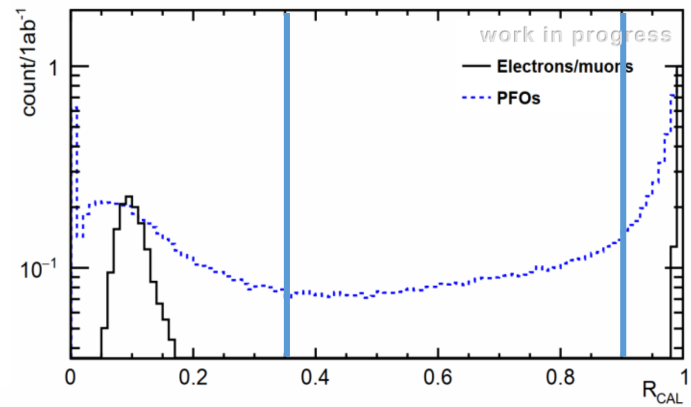
- $R_{CAL} = 0.02 - 0.35, R_{CAL} > 0.94$ – select e and μ
- $E^2_{\text{cone}} < 0 * E^2_{\text{track}} + 20\ \text{GeV} * E_{\text{track}} - 20\ \text{GeV}^2$ – isolate lepton
- p_T cut in Tight Pandora Collection – remove cone contamination from Beamstrahlung

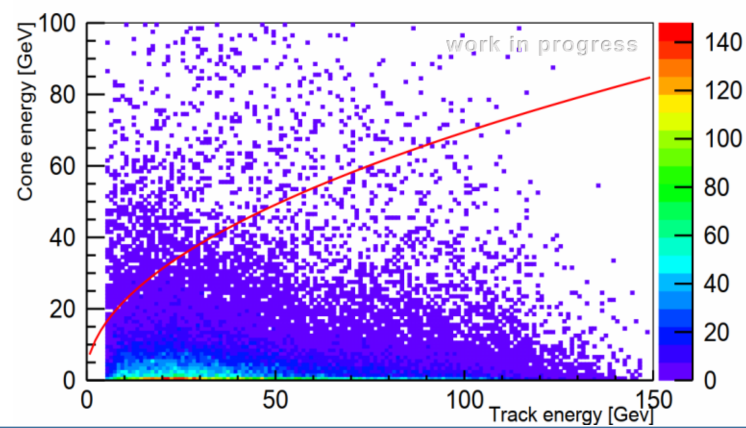




@ 350 GeV

- $R_{CAL} < 0.35, R_{CAL} > 0.9$ – select e and μ
- $E^2_{\text{cone}} < 0 * E^2_{\text{track}} + 48\ \text{GeV} * E_{\text{track}} + 16\text{GeV}^2$ – isolate lepton

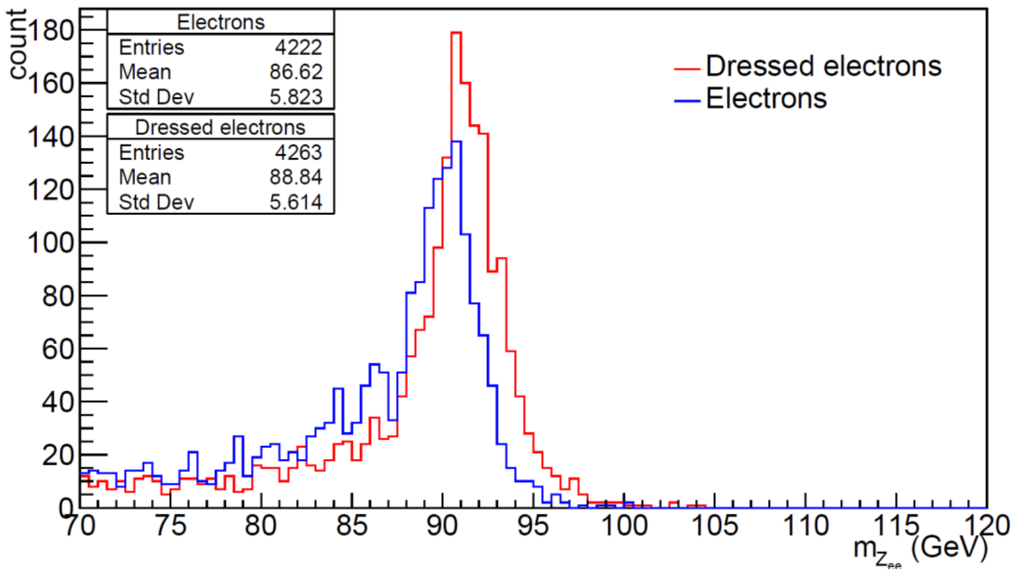




Preselection

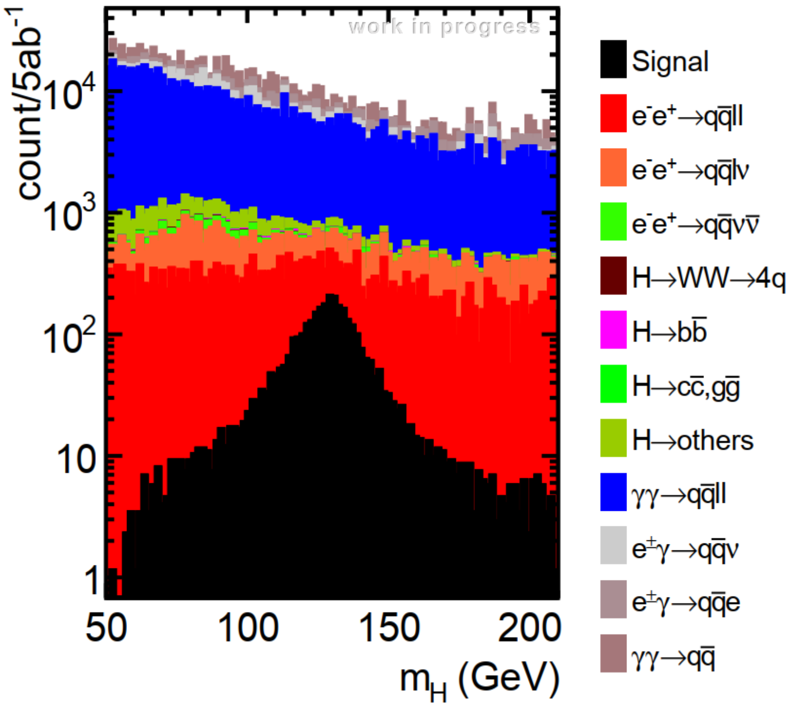
Z reconstruction and lepton dressing

- Before preselection, leptons are dressed with photons found in a 3 deg. cone, to recover for the Bremsstrahlung
- The above impacts Z reconstruction, when Z decays to leptons (e in particular)
- Invariant mass di-electron system forming the on-shell (heavier) Z boson is illustrated before and after Bremstrahlung recovery at 350 GeV

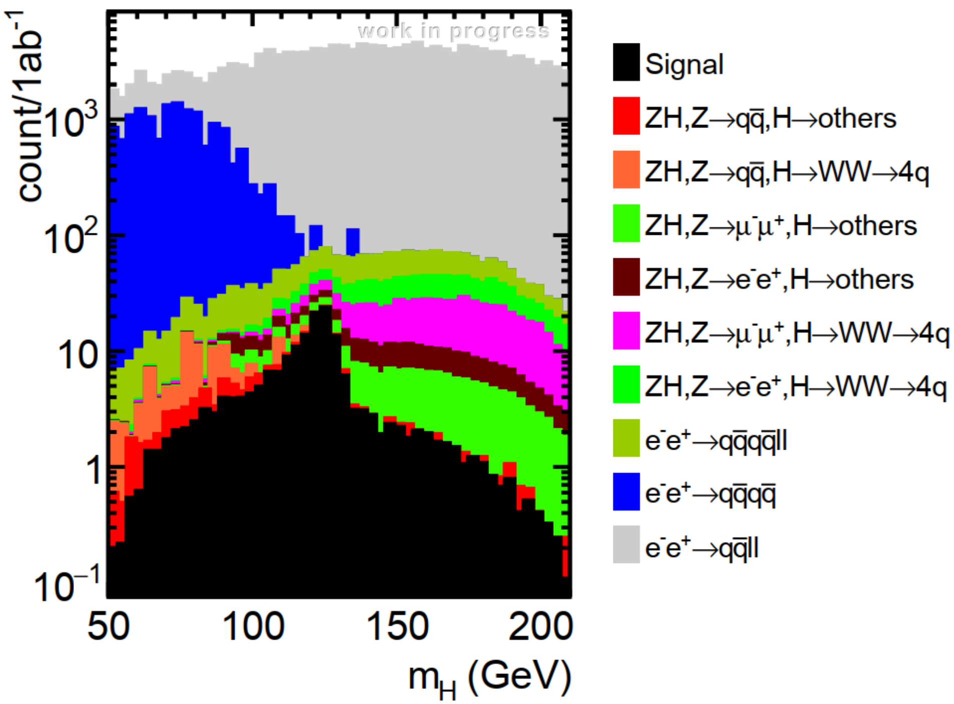


Preselection

@ 3 TeV



@ 350 GeV



Signal preselection efficiency*:

67% **77%**

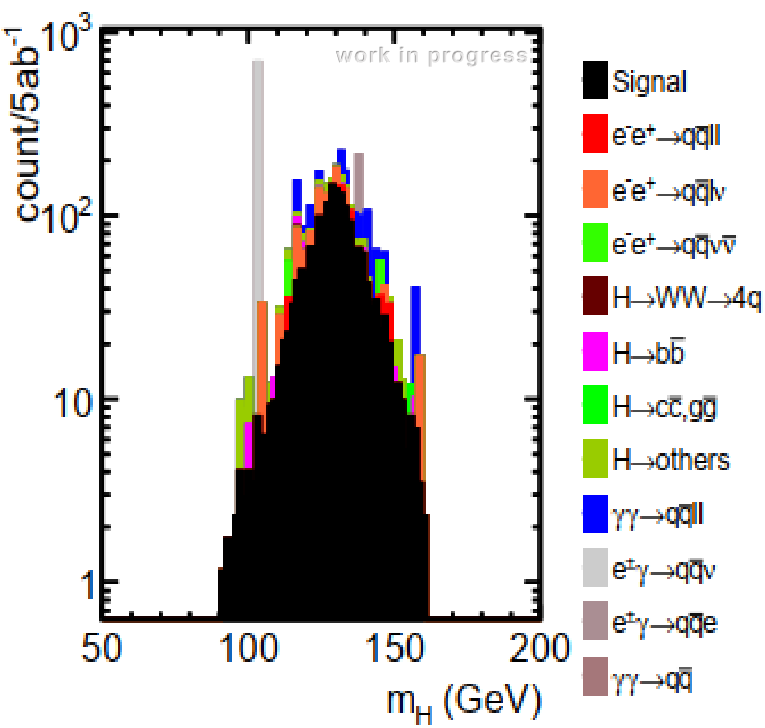
**Preselection efficiencies have not been reviewed by the Collaboration*

MVA

@ 3 TeV

- 16 sensitive observables:

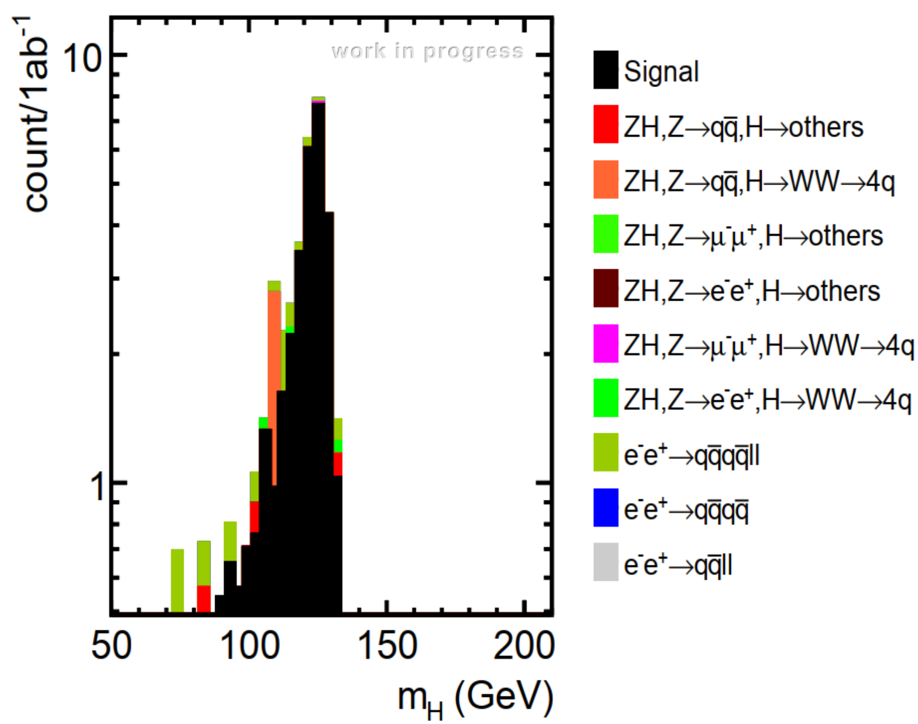
$m_Z, m_{Z^*}, m_{l^+l^-}, m_{q\bar{q}}, m_{\mathrm{H}}$ (90,160 GeV), $E_{\mathrm{vis}}, E_{\mathrm{vis}} - E_{\mathrm{H}}, -\log y_{23}, -\log y_{12}, P(\mathrm{b})^{\mathrm{jet}_1}, P(\mathrm{b})^{\mathrm{jet}_2}, P(\mathrm{c})^{\mathrm{jet}_1}, P(\mathrm{c})^{\mathrm{jet}_2}, p_{\mathrm{T}}^{\mathrm{miss}}, \theta_{\mathrm{H}}, N_{\mathrm{PFO}}$



@ 350 GeV

- 20 sensitive observables:

$m_{primaryZ}, m_{Z^*}, m_Z, m_{l^+l^-}, m_{q\bar{q}}, m_{\mathrm{H}}, E_{\mathrm{vis}}, E_{\mathrm{vis}} - E_{\mathrm{H}}, -\log y_{12}, -\log y_{23}, -\log y_{45}, P(\mathrm{b}), P(\mathrm{c}), \theta_{\mathrm{H}}, \varphi_{ZZ^*}, N_{\mathrm{PFO}}, p_{T_1}, p_{T_2}, E_1, E_2$



MVA efficiency and background rejection

@ 3 TeV

Process at 5 ab^{-1}	ε_{BDT}	N_{BDT}
Signal		
$\mathbf{e^+e^- \to H\nu_e\bar{\nu}_e, H \to ZZ^*, ZZ^* \to q\bar{q}l^+l^-, (l = e, \mu)}$	**47 %**	**1793**
Background		
$e^{\pm}\gamma \to q\bar{q}\nu$	3.5 ‰	678
$\gamma\gamma \to q\bar{q}l^+l^-$	0.3 ‰	444
$e^+e^- \to q\bar{q}l\nu$	3.4 ‰	281
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to \text{others}$	1 %	211
$e^{\pm}\gamma \to q\bar{q}e$	0.2 ‰	116
Processes with BDT < 100	1.2 ‰	152

@ 350 GeV

Process at 1 ab^{-1}	ε_{BDT}	N_{BDT}
Signal		
$\mathbf{e^+e^- \to HZ, Z \to q\bar{q}, H \to ZZ^*, ZZ^* \to q\bar{q}l^+l^-\ (l = e, \mu)}$	**19 %**	**35**
Background		
$e^+e^- \to q\bar{q}q\bar{q}l^+l^-$	3 ‰	3
$e^+e^- \to ZH, Z \to q\bar{q}, H \to WW \to q\bar{q}q\bar{q}$	4.5 %	2

Total signal efficiency:

32% (@ 3 TeV)

15% (@ 350 GeV)

Results & discussion

- Relative statistical uncertainty $\frac{\Delta\sigma}{\sigma}$ is estimated as $\frac{\Delta\sigma}{\sigma}$=1/S= $\frac{\sqrt{N_S+N_B}}{N_S}$
- @ 3 TeV $\frac{\Delta\sigma}{\sigma} = 3.4\%$
- @ 350 GeV $\frac{\Delta\sigma}{\sigma} = 18.2\%$

- Preselection efficiency is lower at 3 TeV due to more dominant Beamsstrahlug background (than at 350 GeV) that contaminates isolation cone
- Relatively low MVA efficiency at 350 GeV is due to the fact that signal is relatively rare in Nature (< 200 preselected events in 1 ab^{-1})
- Proposed polarization scheme would improve statistical precision at least for a factor $\sqrt{1.48}$ while 350 GeV result wouldn't be relevantly influenced [CLICdp-Note-2018-002]

The draft of the paper is currently under Collaboration discussion and thus all figures and numbers should be taken as preliminary

Summary

- First study at 350 GeV CLIC with 1 ab^{-1} of data, shows that σ_{HZ} x BR($H \rightarrow ZZ^*$) can be measured with the relative statistical uncertainty of ~18.2%.
- $\sigma_{H\nu\nu}$ x BR($H \rightarrow ZZ^*$), at 3 TeV CLIC and 5 ab^{-1} of data can be measured with the relative statistical uncertainty of ~3.4%, with unpolarized beams. Proposed polarization scheme would improve statistical precision at least for a factor $\sqrt{1.48}$.
- Measurements in these individual channels complete input for global fits of the CLIC data to be collected in various energy stages.

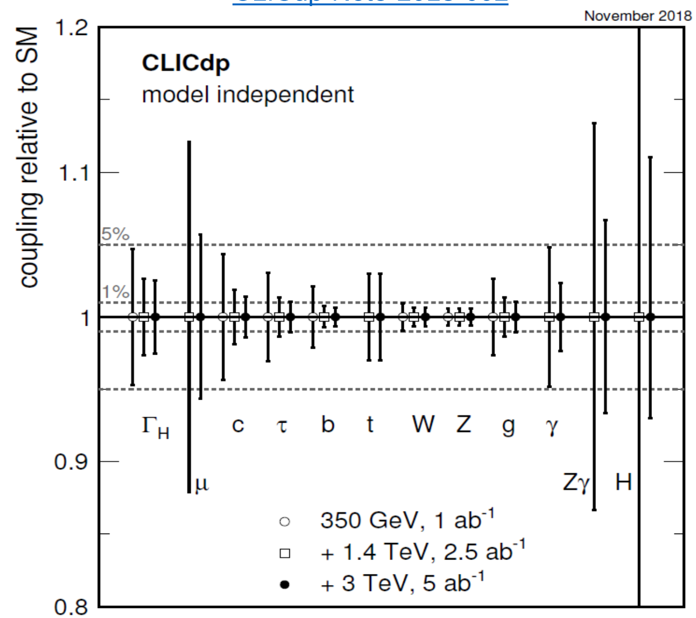
Backup

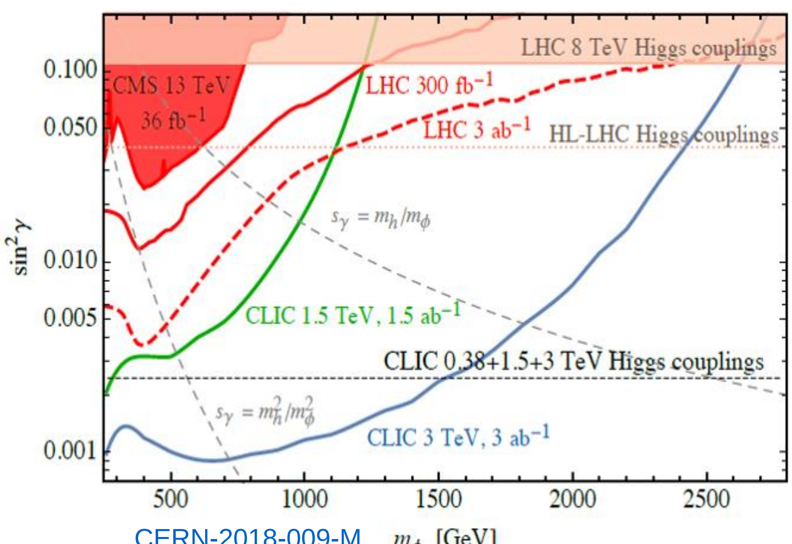
CLIC Physics program

- CLIC is a Higgs factory with the largest Higgs statistics among proposed e^+e^- colliders of $4.5 \cdot 10^6$ Higgs bosons

- Determination of the most of the Higgs couplings below 1% from global model-independent or model-dependent fit
- Unrivalled sensitivity to Higgs self-coupling measurement λ (-8%, 11%)
- Significant discovery potential for BSM physics in the Higgs sector(e.g. compositness, heavy singlet state, CPV) … and elsewhere (Z' mass, NMSSM scalar singlet, relaxion DM,…)

CLICdp-Note-2018-002





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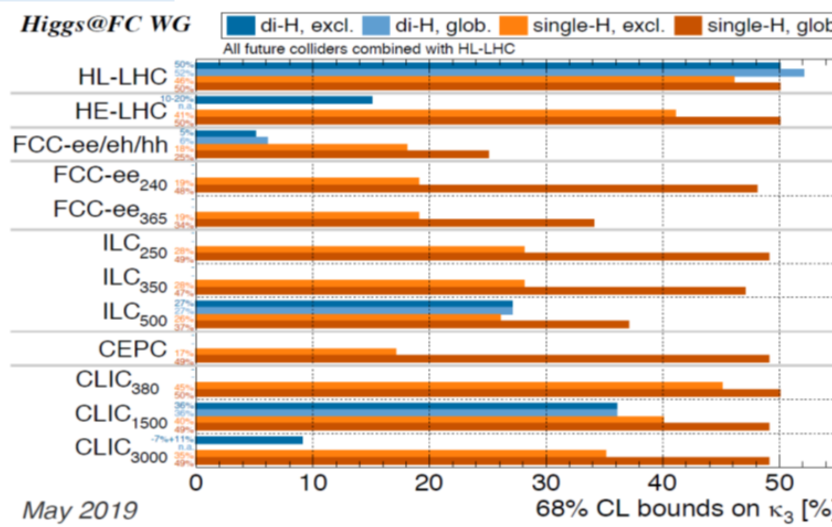


JHEP 01 (2020) 139

Background

@ 3 TeV

Background	σ (fb)	ε_{presel} (‰)
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to WW, WW \to q\bar{q}q\bar{q}$	43	1.7
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to b\bar{b}$	233	0.6
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to c\bar{c}$	11.7	0.6
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to gg$	35.2	0.9
$e^+e^- \to H\nu_e\bar{\nu}_e, H \to \text{others}$	91	45
$e^+e^- \to q\bar{q}l^+l^-$	3320	7.5
$e^+e^- \to q\bar{q}l\nu$	5561	3
$e^+e^- \to q\bar{q}\bar{\nu}_e\nu_e$	1317	0.7
$\gamma\gamma \to q\bar{q}l^+l^-$	20293	11
$\gamma\gamma \to q\bar{q}$	112039	1
$e^\pm\gamma \to q\bar{q}e$	20661	8.8
$e^\pm\gamma \to q\bar{q}\nu$	36832	1.4

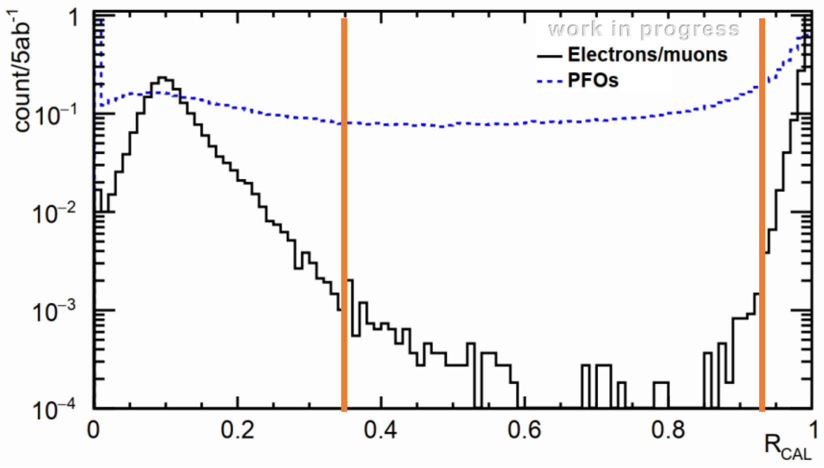
@ 350 GeV

Background	σ (fb)	ε_{presel} (%)
$e^+e^- \to ZH, Z \to q\bar{q}, H \to \text{others}$	6.96	0.37
$e^+e^- \to ZH, Z \to q\bar{q}, H \to WW \to q\bar{q}q\bar{q}$	10.5	0.42
$e^+e^- \to ZH, Z \to \mu^+\mu^-, H \to \text{others}$	2.33	61
$e^+e^- \to ZH, Z \to e^+e^-, H \to \text{others}$	2.33	62
$e^+e^- \to ZH, Z \to \mu^+\mu^-, H \to WW \to q\bar{q}q\bar{q}$	0.723	60
$e^+e^- \to ZH, Z \to e^+e^-, H \to WW \to q\bar{q}q\bar{q}$	0.723	60
$e^+e^- \to q\bar{q}q\bar{q}l^+l^-$	4.47	21
$e^+e^- \to q\bar{q}q\bar{q}$	5842	0.32
$e^+e^- \to q\bar{q}l^+l^-$	1704	11.4

Preselection

@ 3 TeV

- $R_{CAL} = 0.02 - 0.35, R_{CAL} > 0.94$ – select e and μ



@ 350 GeV

- $R_{CAL} < 0.35, R_{CAL} > 0.9$ – select e and μ