Higgs physics at CLIC

Matthias Weber (CERN)

on behalf of the CLIC detector and physics (CLICdp) collaboration

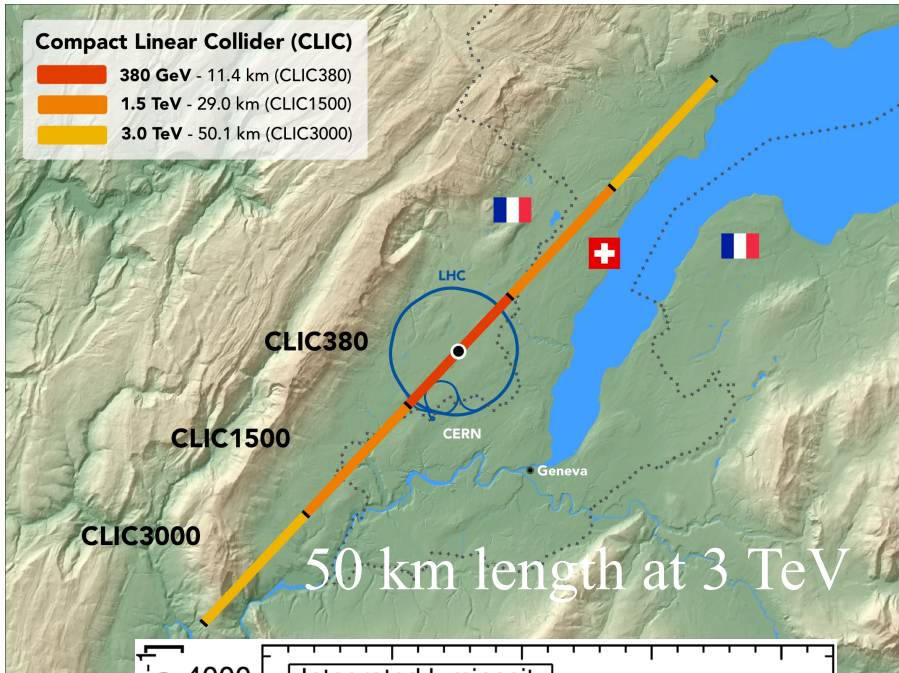
Compact Linear Collider

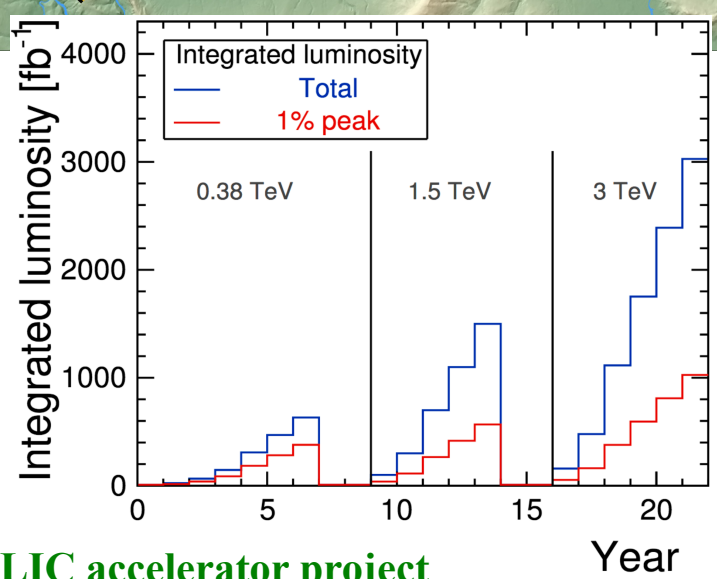
Proposed e^+e^- linear collider

- High acceleration gradient 100 MV/m
- Two beam acceleration scheme
- Staged construction up to 3 TeV
  - High precision physics
  - Higgs, top, BSM

Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

Slightly different energies assumed in physics performance studies for first two stages
380 → 350 GeV, 1.5 TeV →1.4 TeV





CLIC accelerator project #884 by D. Schulte

Higgs bosons in e^+e^- collisions

Energy stage	# Higgs produced
350 GeV	100000
1.4 TeV	430000
3 TeV	1400000

Numbers for unpolarised beams

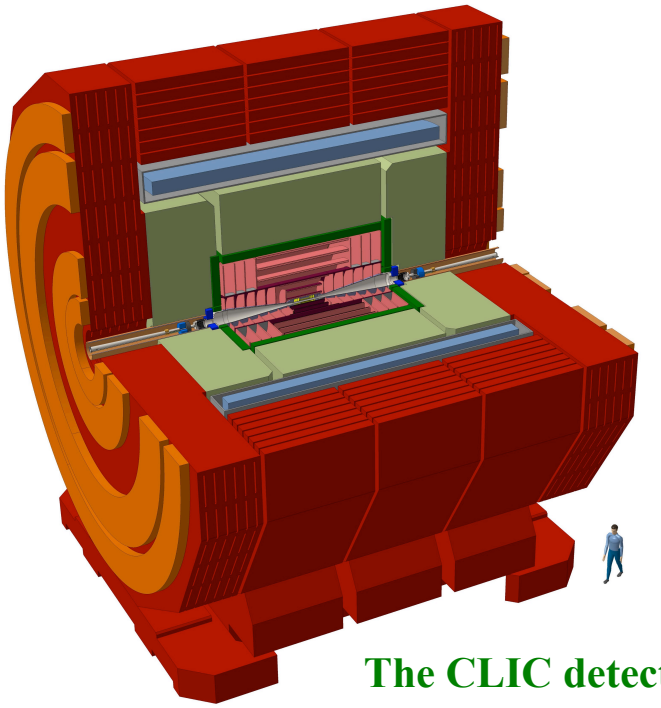
No triggers
→all Higgs events used

Event selection efficiency
20-60 %

Polarised beams can enhance production modes significantly

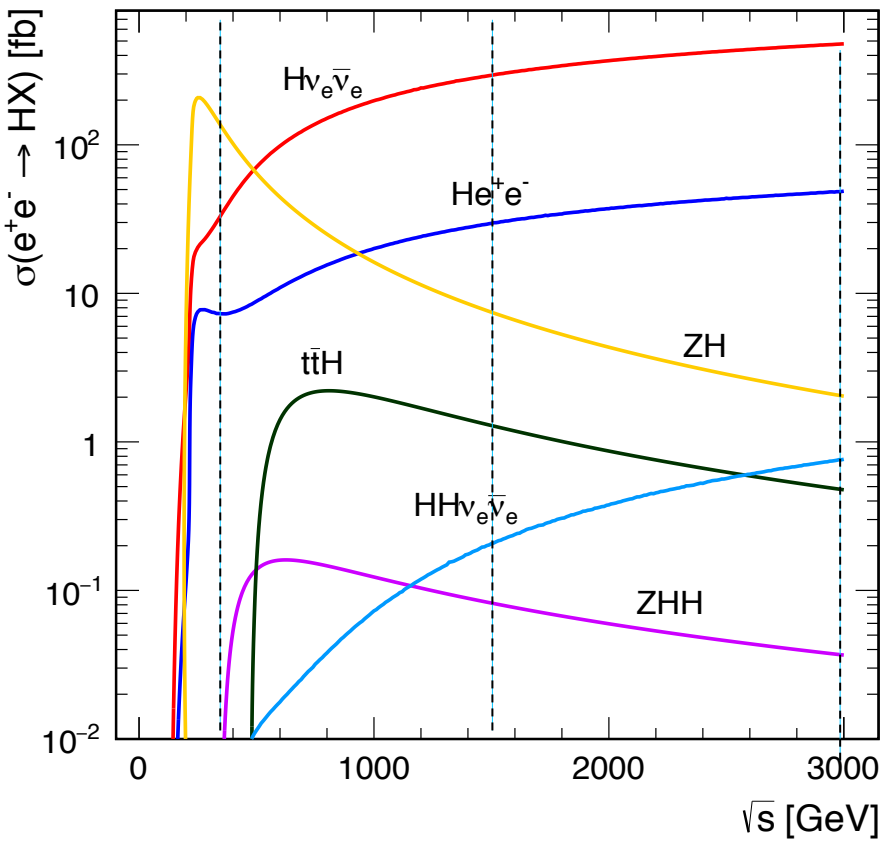
Polarisation	Scaling factor		
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$	$e^+e^- \to He^+e^-$
unpolarised	1.00	1.00	1.00
$-80\,\% : \quad 0\,\%$	1.12	1.80	1.12

All results shown in the following are based on realistic full detector simulations including the impact of beam-beam effects



The CLIC detector #528 by E. Sicking

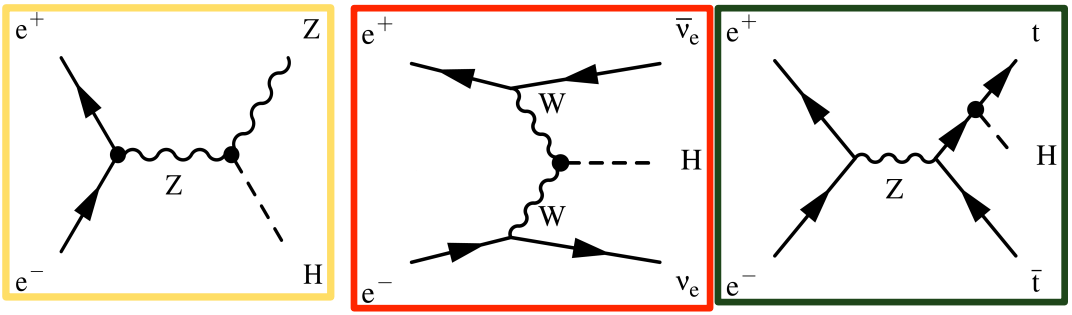
Higgs production

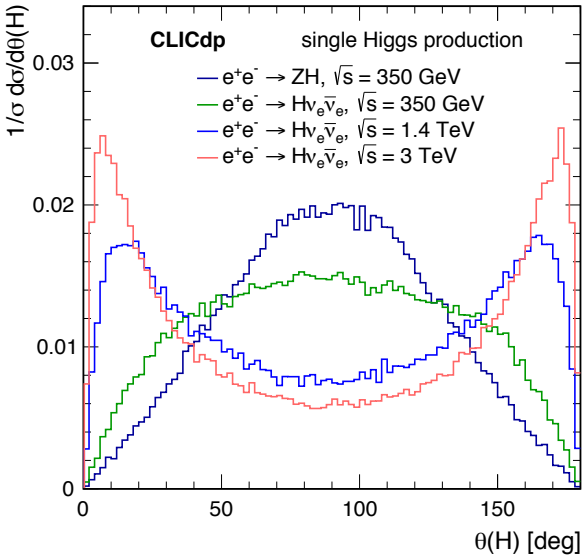


Higgsstrahlung $e^+e^- \rightarrow ZH$
Dominant at first energy stage $\sigma \sim 1/s$

WW fusion $e^+e^- \rightarrow H\nu_e\nu_e$
Dominant above 500 GeV, large statistics at high energy stages $\sigma \sim \log(s)$

ttH production $e^+e^- \rightarrow ttH$
Accessible at second energy stage
Direct extraction of top Yukawa coupling

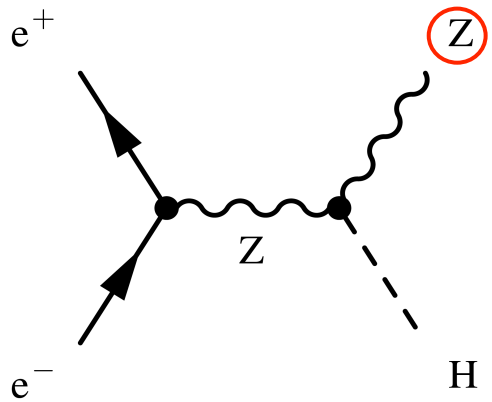




Recoil Method: ZH with $Z \rightarrow l^+l^-$ ($l=e,\mu$)

Higgsstrahlung dominant production process at 380 GeV:

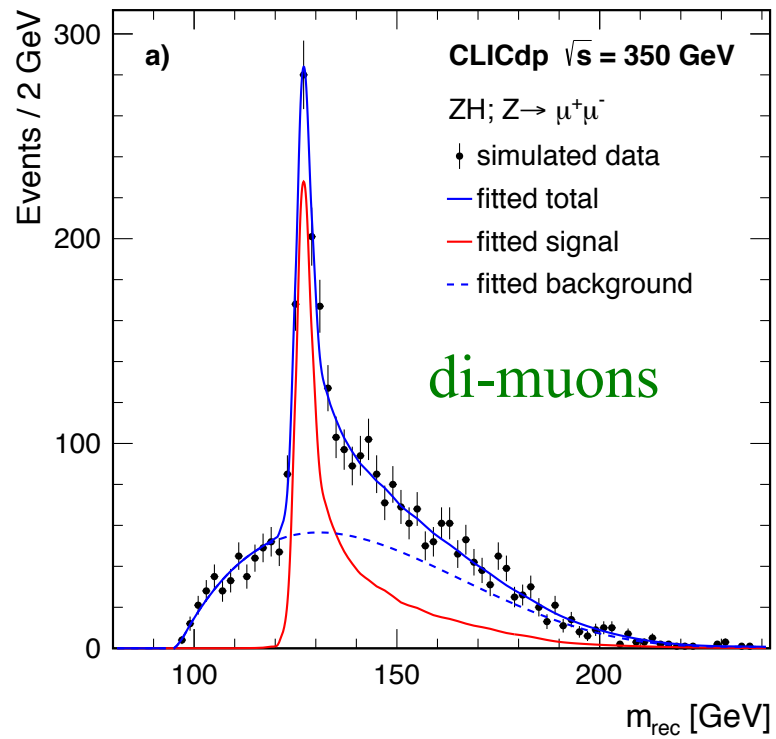
Recoil mass measurement only possible in e^+e^- collisions



ZH event identified from Z-recoil mass

→ Model independent measurement of $\sigma(ZH)$ and m_H

$\Delta\sigma\,(HZ)/\sigma\,(HZ) = \pm\, 3.8\,\%$



EPJC 76, 72 (2016)
arXiv:1708.08912

$$m_{\rm rec}^2 = (\sqrt{s} - E_Z)^2 - p_Z^2$$

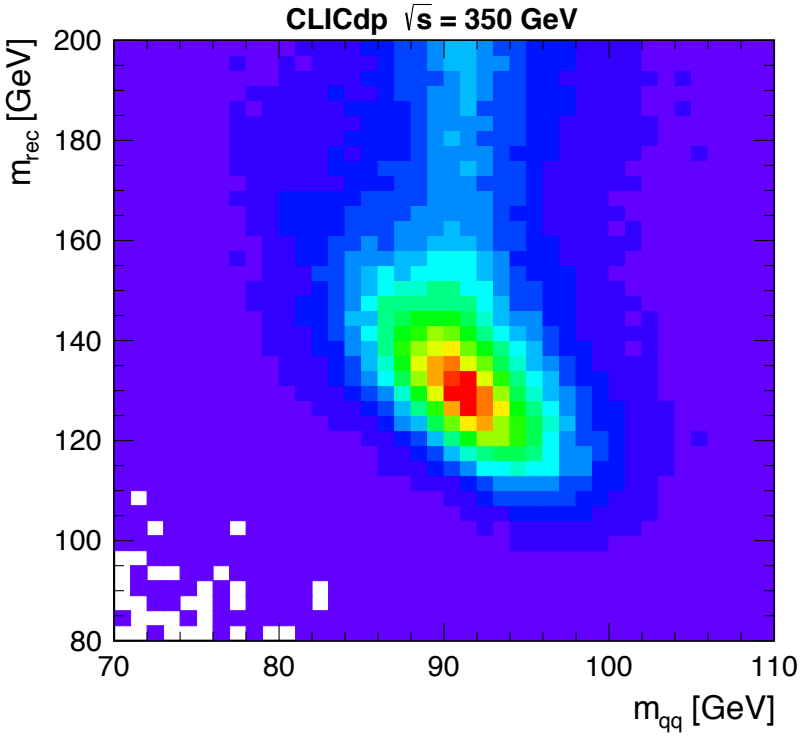
Known at lepton colliders

Recoil Method with Z→qq

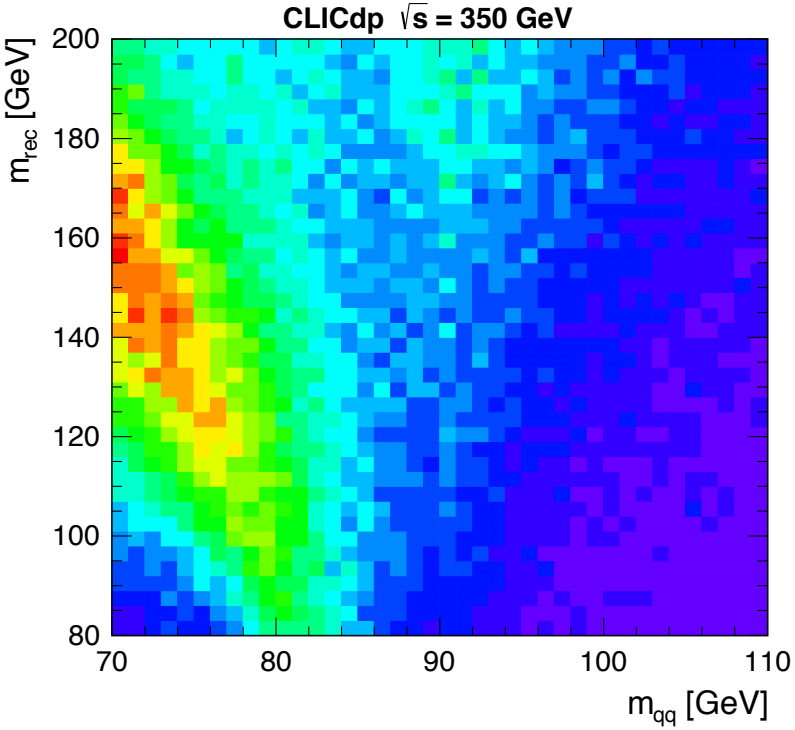
Fine grain calorimetry of CLIC detector ideal for particle flow reconstruction → achieve high precision in hadronic channels

$\Delta\sigma$ (HZ) /σ (HZ) = ± 1.8 % (Z→qq, 350 GeV)

signal



background



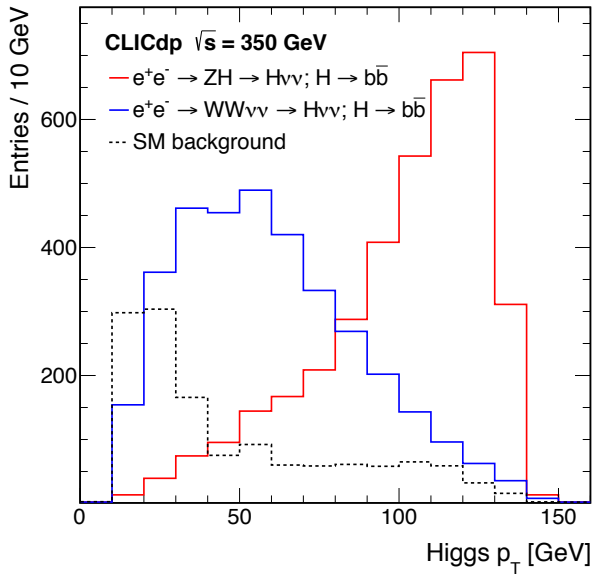
H→bb/cc/gg at √s = 350 GeV

Simultaneous extraction:

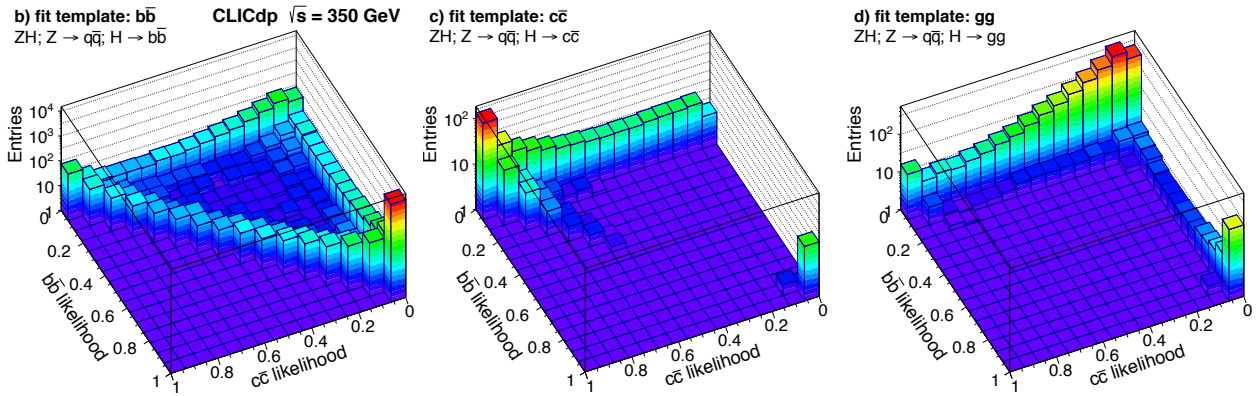
- Three decay modes bb/cc/gg
  → precise flavour tagging
- Production Mode: ZH or WW fusion
  →Higgs p_T spectrum

√s =350 GeV, L=500 fb^{-1}

Decay	Statistical uncertainty Higgsstrahlung	WW-fusion
$H \to b\bar{b}$	0.86 %	1.9 %
$H \to c\bar{c}$	14 %	26 %
$H \to gg$	6.1 %	10 %



H→bb **H→cc** **H→gg**



Fit templates using 2D distributions of bb vs cc likelihoods

EPJC 76, 72 (2016)
arXiv:1708.08912

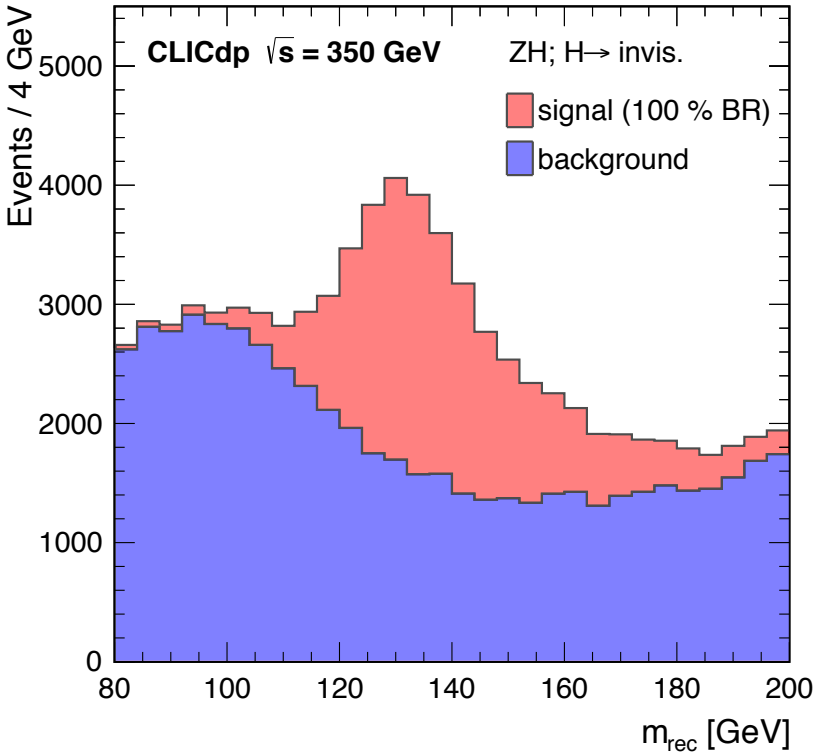
Invisible Higgs Decays

Invisible Higgs decays identified with recoil mass technique in a model independent way

At first energy stage
350 GeV, L=500 fb^{-1}

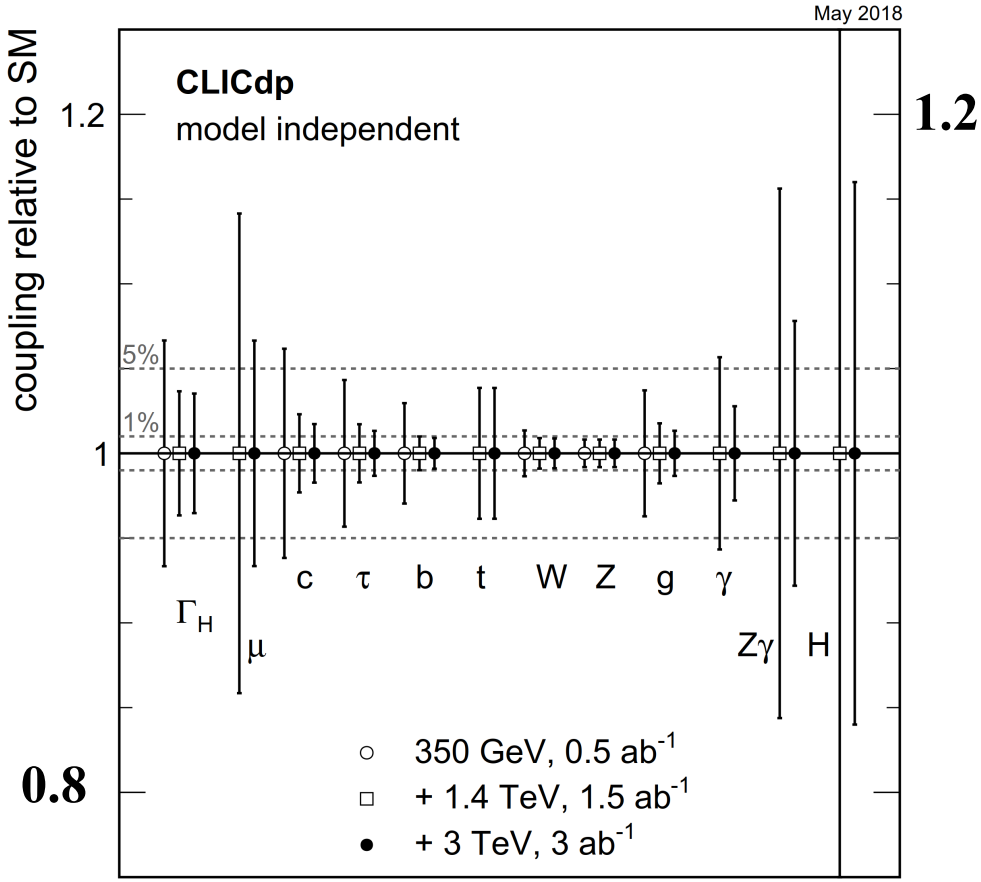
BR(H→inv) < 0.97 % at 90 % CL

EPJC 76, 72 (2016)
arXiv:1708.08912



Example: Recoil mass from Z→qq, assuming 100 % invisible Higgs decays

Higgs coupling: projected sensitivity



- Precision of all results limited by 0.8 % of σ(ZH) cross section measurement
- No assumptions on additional Higgs decays
- Relevant correlations included
- Higgs width extracted with 6.7 (350 GeV) – 3.5 % precision (all three stages)

$\sigma(ZH) \sim g^2_{HZZ}$

$\sigma(ZH) \times BR(H \rightarrow VV/ff) \sim g^2_{HZZ} g^2_{HVV/Hff}/\Gamma_H$

$\sigma(H\nu_e\nu_e) \times BR(H \rightarrow VV/ff) \sim g^2_{HWW} g^2_{HVV/Hff}/\Gamma_H$

based on EPJC 76, 72 (2016)

Higgs coupling: projected sensitivity (2)

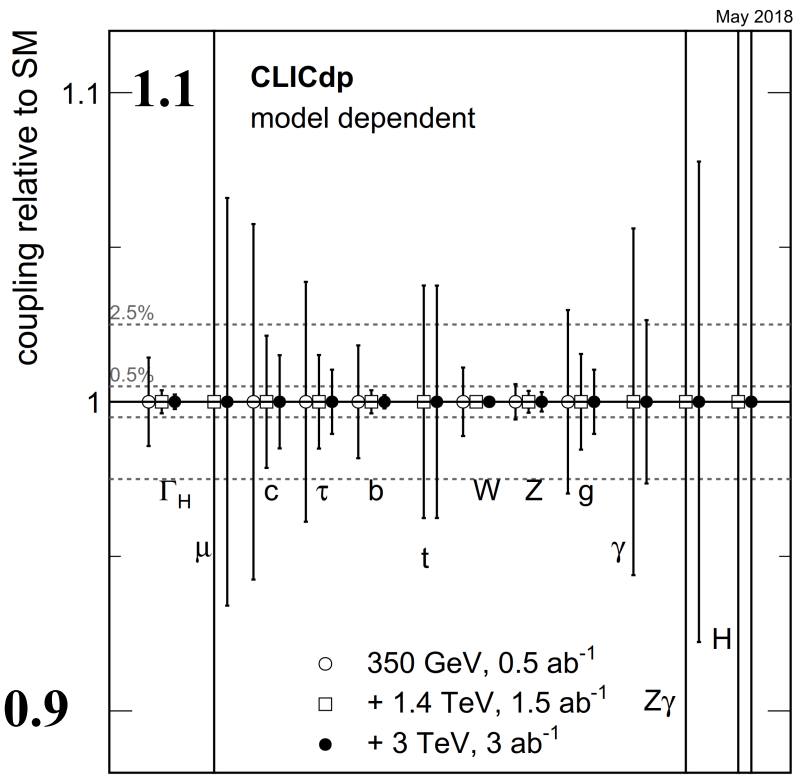
Model dependent fit:

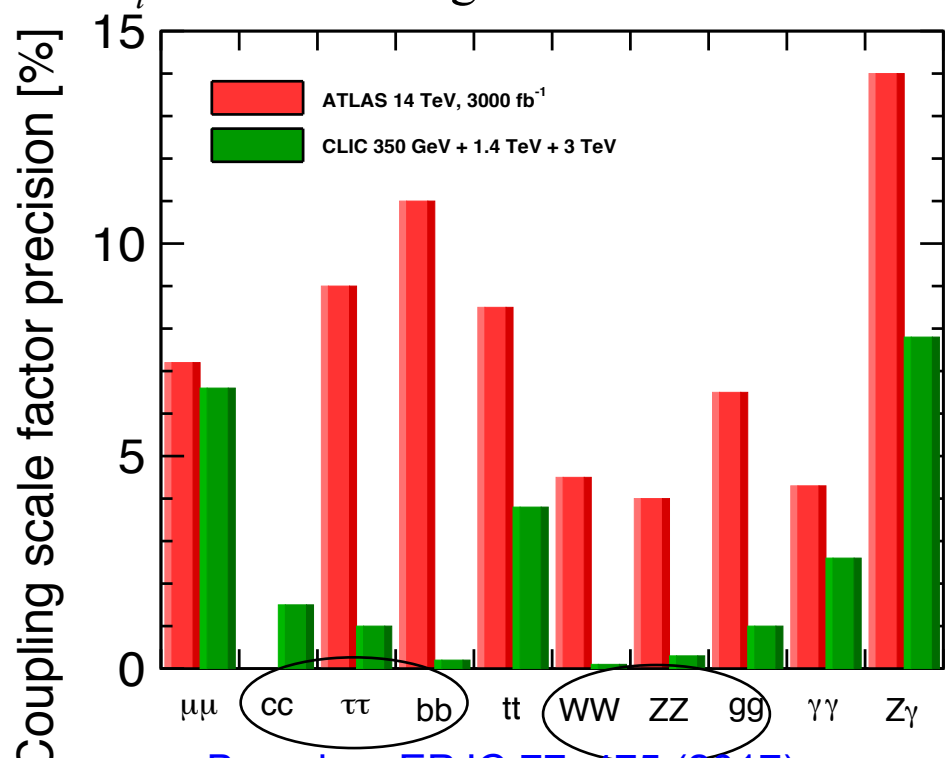
$$\kappa_i^2 = \Gamma_i / \Gamma_i^{\mathrm{SM}}$$

Assume SM decays Higgs only:

$$\frac{\Gamma_{\mathrm{H,md}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \Sigma_i \kappa_i^2 BR_i$$

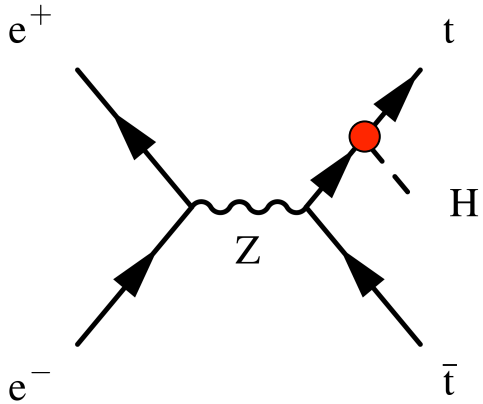
BR_i: SM branching fractions



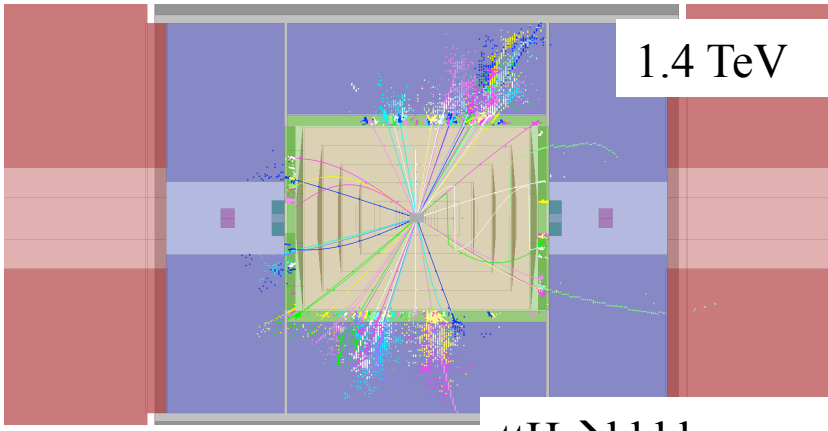


Based on EPJC 77, 475 (2017)
ATLAS-PHYS-PUB-2014-016

Top Yukawa coupling



σ(ttH) directly sensitive to top Yukawa coupling g_{ttH}



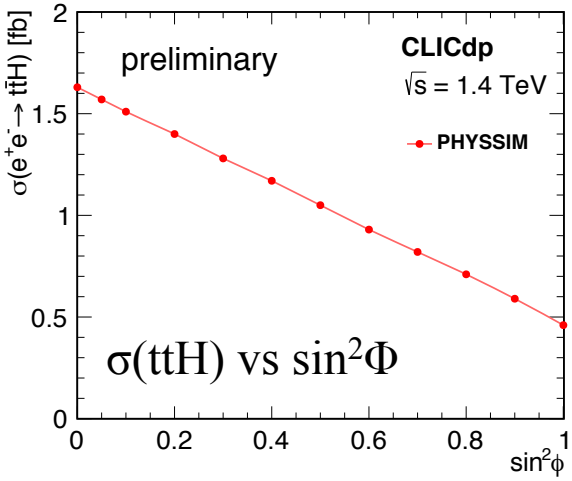
ttH→bbbbqqτν

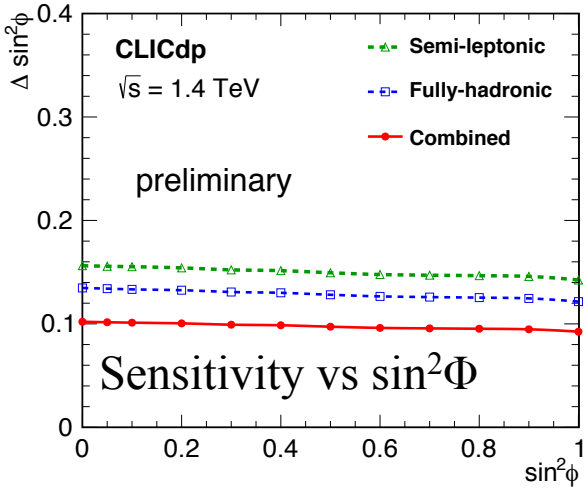
Studied in two final states:
ttH→bqq blν bb
ttH→bqq bqq bb
→similar sensitivity

$\sqrt{s}$ = 1.4 TeV, L = 1.5 ab^{-1}
$\Delta g_{ttH}/g_{ttH}$ = 3.8 %

σ(ttH) sensitive to CP mixing in ttH coupling

$$-ig_{ttH}(\cos\phi + i\sin\phi\,\gamma_5)$$

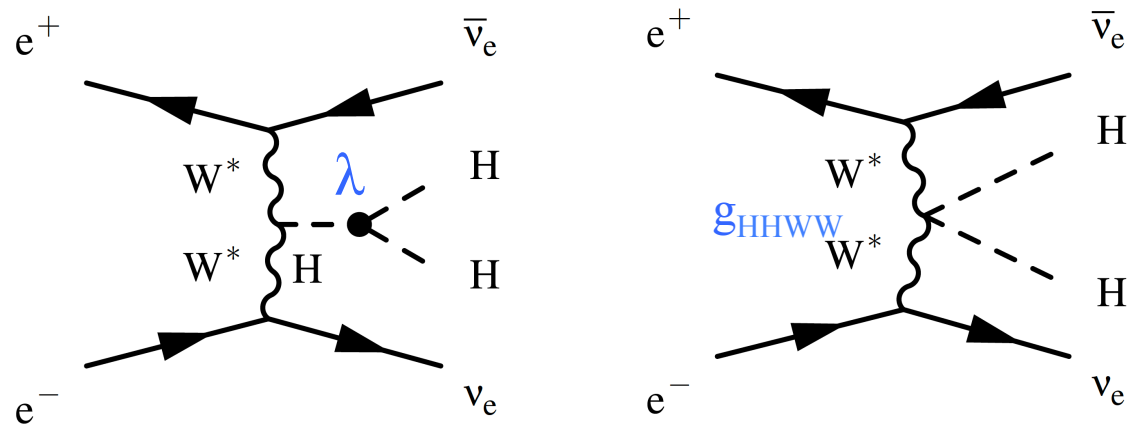




Top physics at high-energy CLIC # 527 by U. Schnoor

Double Higgs Production

$e^+e^- \rightarrow HH\nu\nu$: sensitive to quartic coupling g_{HHWW} and Higgs self-coupling λ, profits from operation at high energy



L=1.4 ab^{-1} at $\sqrt{s}$=1.4 TeV + 3 ab^{-1} at $\sqrt{s}$=3 TeV:

$\Delta\lambda/\lambda$ = 16% for P(e^-) = -80% from the total cross section

$\Delta\lambda/\lambda \approx$ 10% for P(e^-) = -80% from diff. distributions

Measurement performed in HH→bbbb final state

Sizeable deviations of Higgs self-coupling from SM expectation in several BSM scenarios

Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $-15\,\%^b$
NMSSM	$-25\,\%$

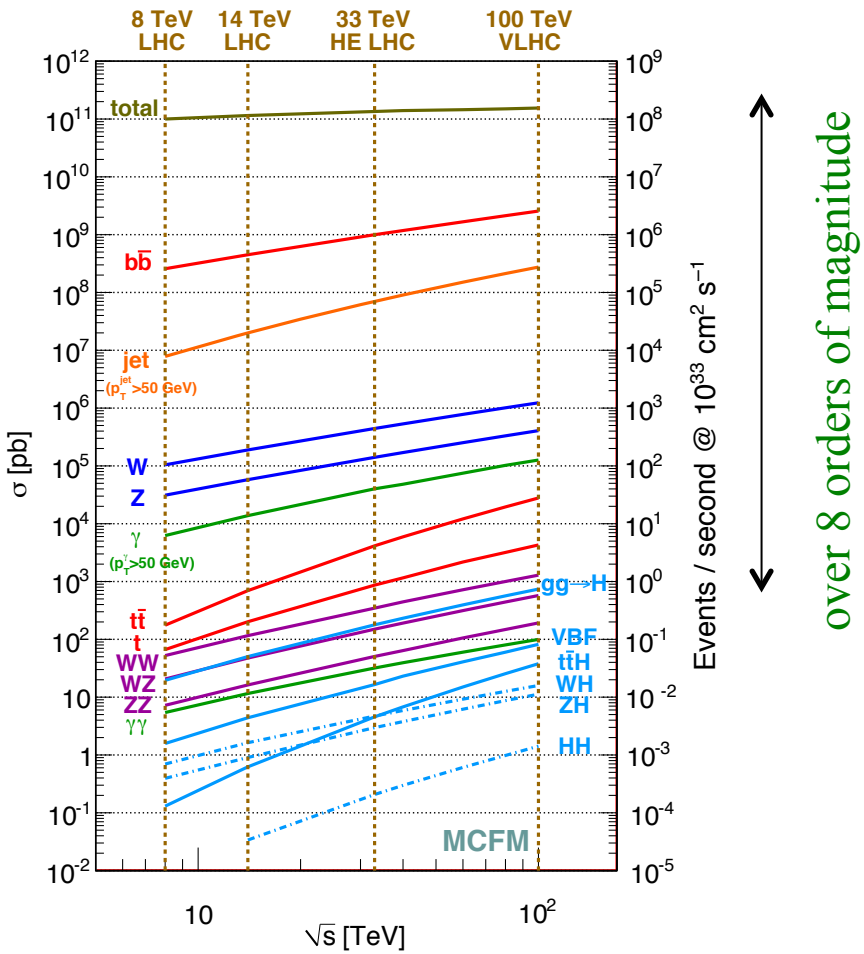
Phys. Rev. D 88, 055024 (2013)

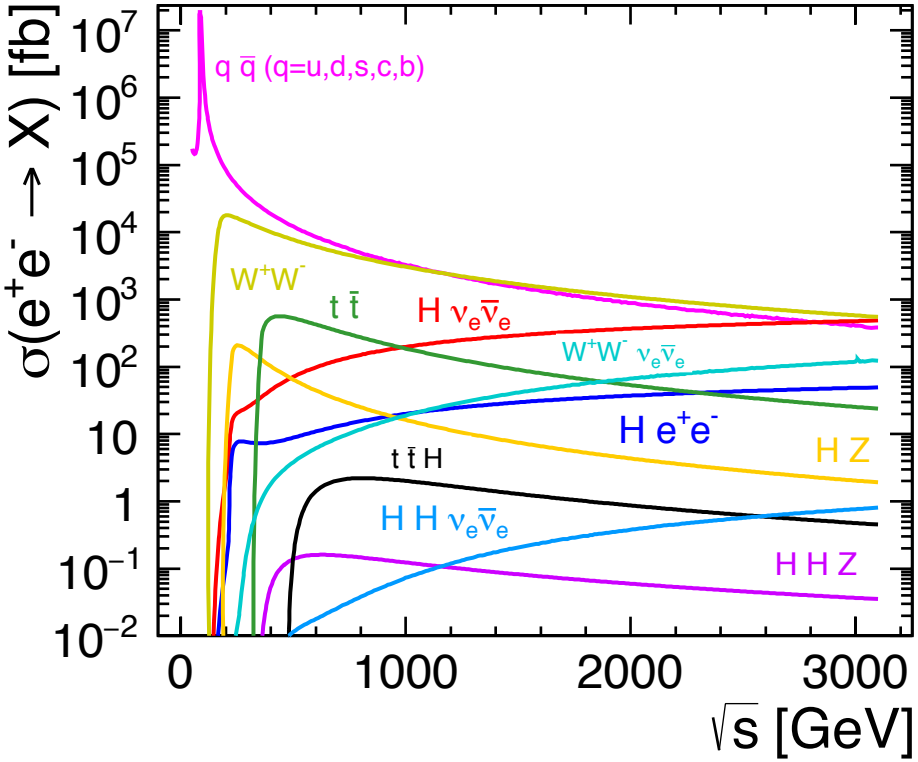
Conclusion and Summary

- A lepton collider is capable to enhance the understanding of the Higgs boson significantly beyond the precision of the HL-LHC
- Precise measurements of many Higgs couplings, Higgs mass and Higgs width using Higgsstrahlung and WW fusion processes
- Cross section and total Higgs width measured in a model-independent way
- Access to ttH at second energy stage at CLIC
- Double Higgs production measurement profits from highest possible energies

BACKUP

pp and e^+e^- production cross sections

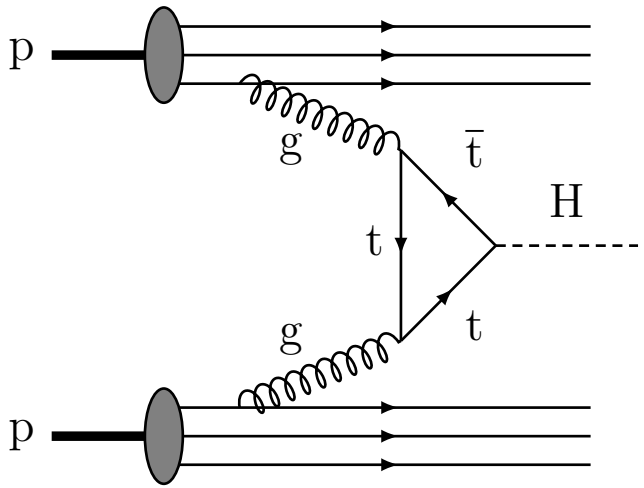


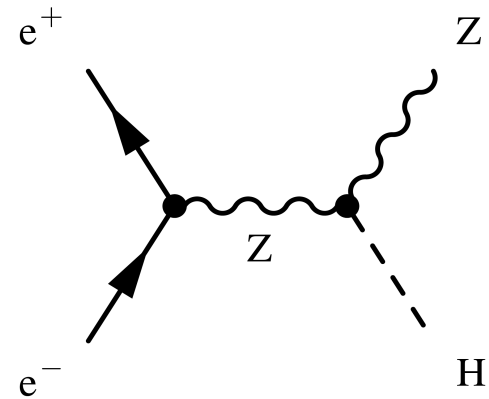


pp collisions:
Small signal in vast amount of background, triggers needed

e^+e^- collisions:
Less amount of background, no need for triggers, "clean" environment

Lepton vs Hadron colliders





Protons are compound objects:
- Unkown initial state
- Limits achievable precision

High QCD background rates
- Triggers needed
- High levels of radiation

High energy circular colliders feasible

e^+e^- point like
- Well defined initial state (polarisation, √s)
- High precision measurements

Cleaner experimental environment
- Triggers less readout possible
- Low levels of radiation

High energies (√s > 350 GeV) require linear collider

CLIC related contributions at ICHEP

Daniel Schulte: “The CLIC accelerator project status and plans” #884

Eva Sicking: “The CLIC detector” #528

Ulrike Schnoor: “Top-quark physics at high-energy CLIC operation” #527

Aleksander Zarnecki: “Top quark physics at the first CLIC stage” #526

Roberto Franceschini: “BSM searches at CLIC” #525

CLIC project 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

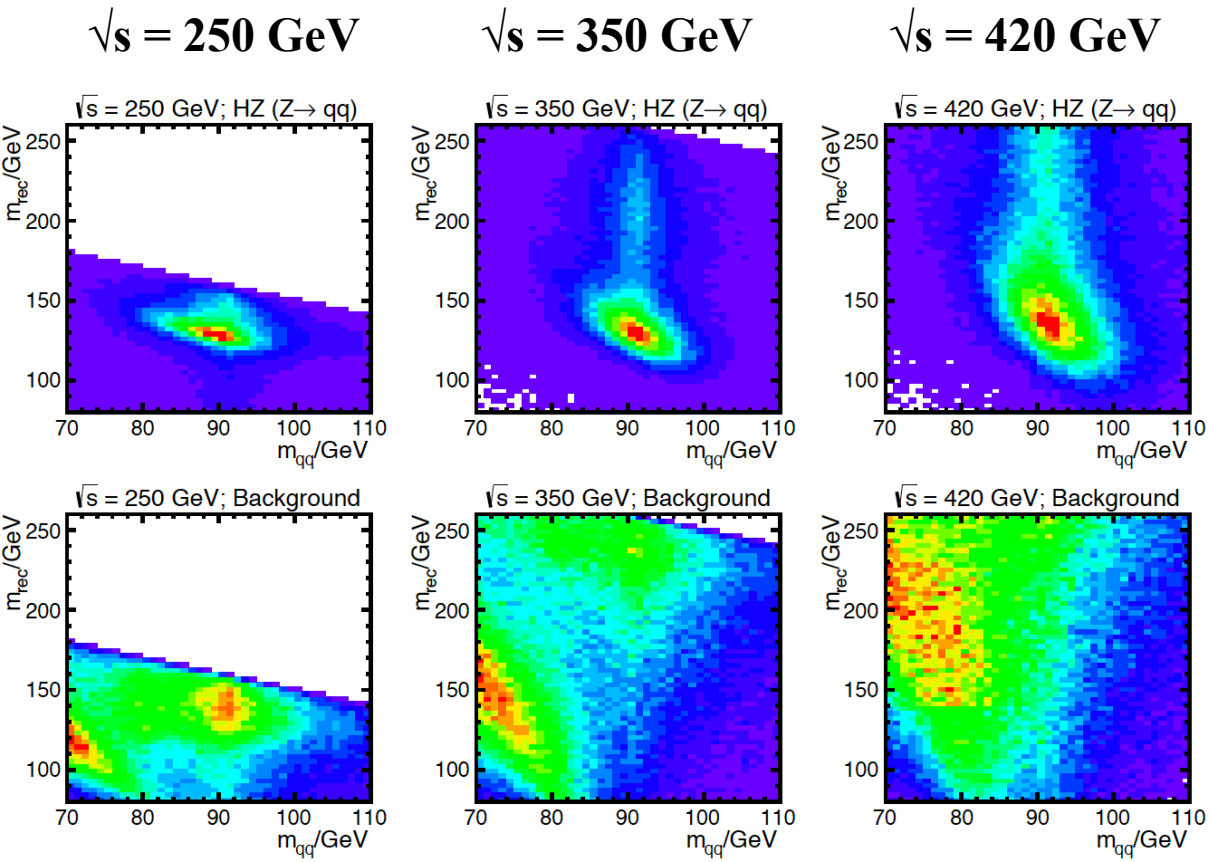
Getting ready for data taking by the time the LHC programme reaches completion

Systematic uncertainties

Example: analysis $\sigma(H\nu_e\nu_e)$ x $BR(H\rightarrow bb)$ statistical uncertainty 0.3 %

- Luminosity spectrum reconstructed from Bhabha scattering events → expected uncertainties lead to 0.15 % syst on $\sigma(H\nu_e\nu_e)$ x $BR(H\rightarrow bb)$
- Total luminosity: luminometer expected to reach accuracy of a few permille
- Beam polarisation: expected to be controlled to 0.2% using single W,Z,γ events with missing energy → syst uncertainty of 0.1 % on $\sigma(H\nu_e\nu_e)$ x $BR(H\rightarrow bb)$
- Jet energy scale: calibrated using $e^+e^-\rightarrow Z\nu_e\nu_e$, with $Z\rightarrow bb$
  biggest challenge for mass measurement, statistical uncertainty at 3 TeV is 44 MeV, systematic error of that scale requires JES uncertainty of 0.035 %
- Flavour tagging efficiency mostly affects the event rate → b-tagging uncertainties lead to an syst uncertainty of 0.25 %

Recoil Method with Z→qq



$\sqrt{s}$	$\mathscr{L}$	$\sigma(\mathrm{HZ})$	$\Delta\sigma_{\mathrm{vis.}}$	$\Delta\sigma_{\mathrm{invis.}}$	$\Delta\sigma(\mathrm{HZ})$
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 %

Optimization study for first CLIC stage

At 350 GeV highest precision in Hadronic Z decays

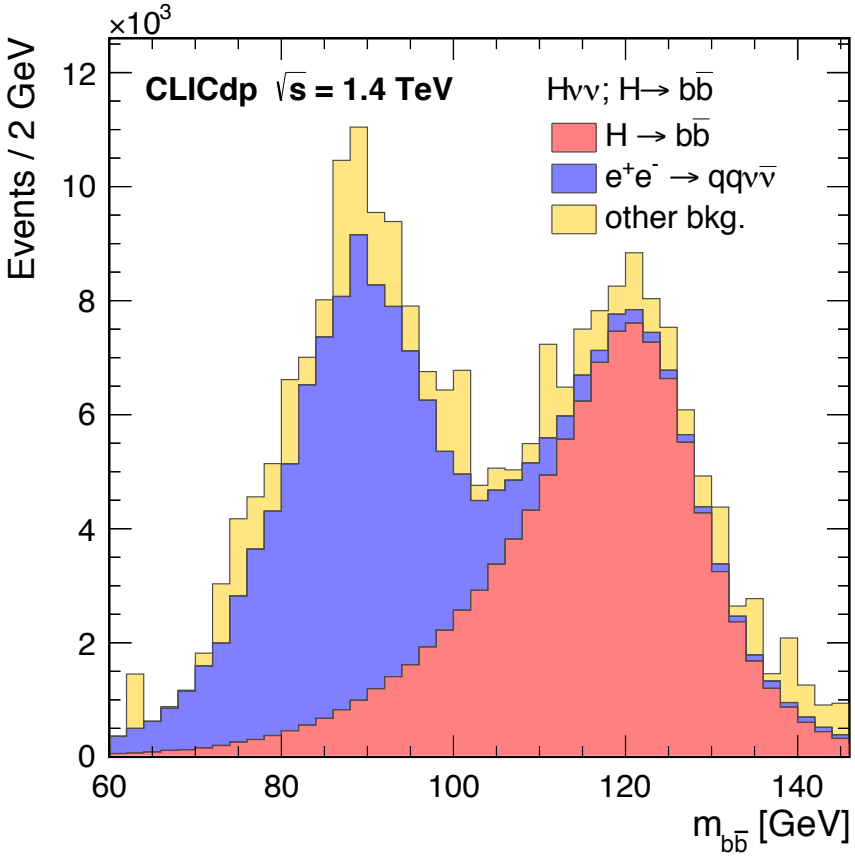
At 250 GeV largest signal cross-section, but background more signal like

At 450 GeV lower cross-section and worse jet energy resolution

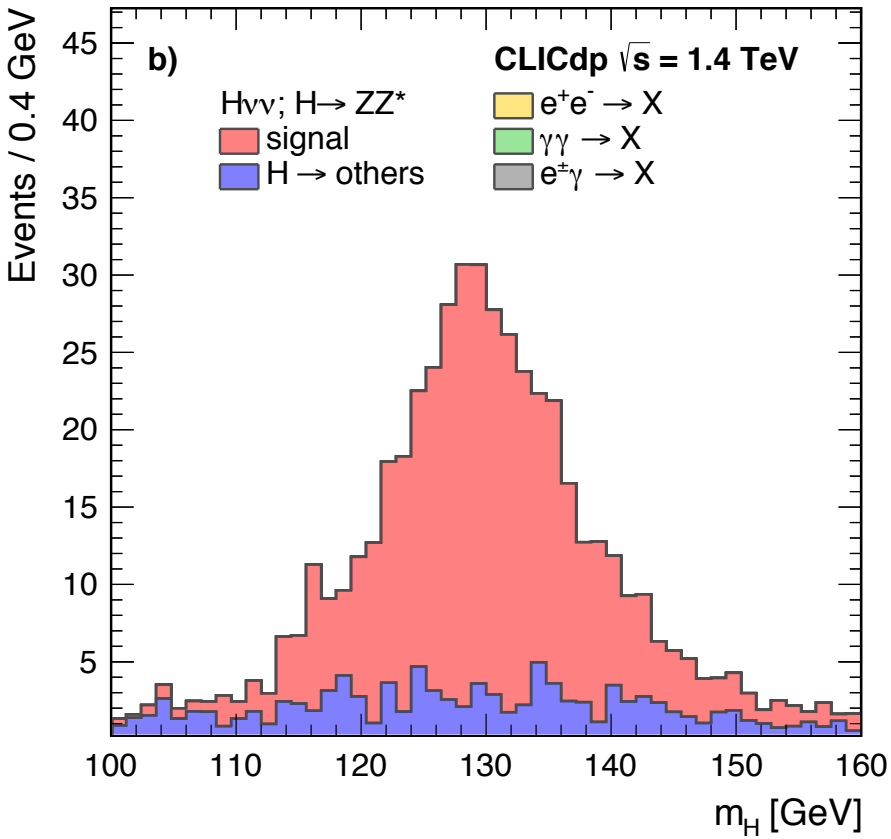
Slightly beyond 350 GeV optimal for top physics as well

EPJC 76, 72 (2016)
arXiv:1509.02853

Higgs mass measurements



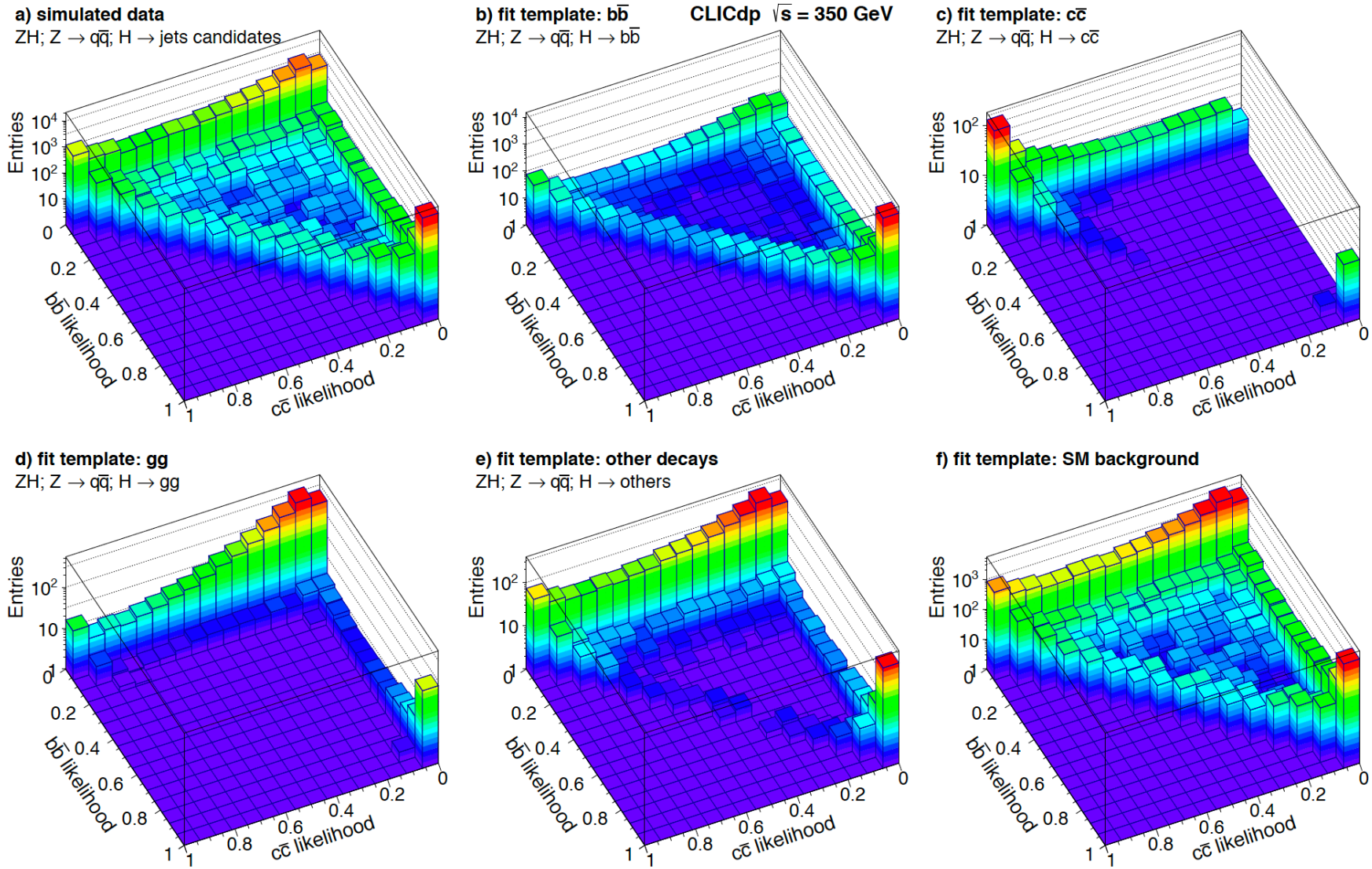
Di-jet invariant mass for H→bb selection at √s = 1.4 TeV



Reconstructed invariant mass for $H \rightarrow ZZ^* \rightarrow qql^+l^-$ selection at √s = 1.4 TeV

Signal & background templates for hadronic H decays

bb likelihood vs cc likelihood for $e^+e^- \rightarrow ZH$ hadronic Higgs decay study



Overview: CLIC projections

$\sqrt{s}$ = 350 GeV

Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_H	110 MeV
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.6 %
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	3.8 %
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.8 %
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	0.86 %
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ} g^2_{Hcc}/\Gamma_H$	14 %
ZH	$\sigma(ZH) \times BR(H \to gg)$		6.1 %
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ} g^2_{H\tau\tau}/\Gamma_H$	6.2 %
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ} g^2_{HWW}/\Gamma_H$	5.1 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	1.9 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	26 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		10 %

$\sqrt{s}$ = 1.4 & 3 TeV

Channel	Measurement	Observable	Statistical precision 1.4 TeV 1.5 ab^{-1}	3 TeV 3.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	36 MeV
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	3.3 %†	5.6 %†
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb}/\Gamma_H$	0.4 %	0.3 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW} g^2_{Hcc}/\Gamma_H$	6.1 %	5.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0 %	3.5 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau}/\Gamma_H$	4.2 %	3.6 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu}/\Gamma_H$	38 %	20 %
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15 %	8 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42 %	24 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	1.0 %	0.6 %*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ}/\Gamma_H$	5.6 %	3.2 %*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb}/\Gamma_H$	1.8 %	1.9 %*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb}/\Gamma_H$	7.3 %	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54 %	24 %
$HH\nu_e\bar{\nu}_e$	with −80 % e^- polarisation	λ	40 %	18 %

Unpolarised electron beam

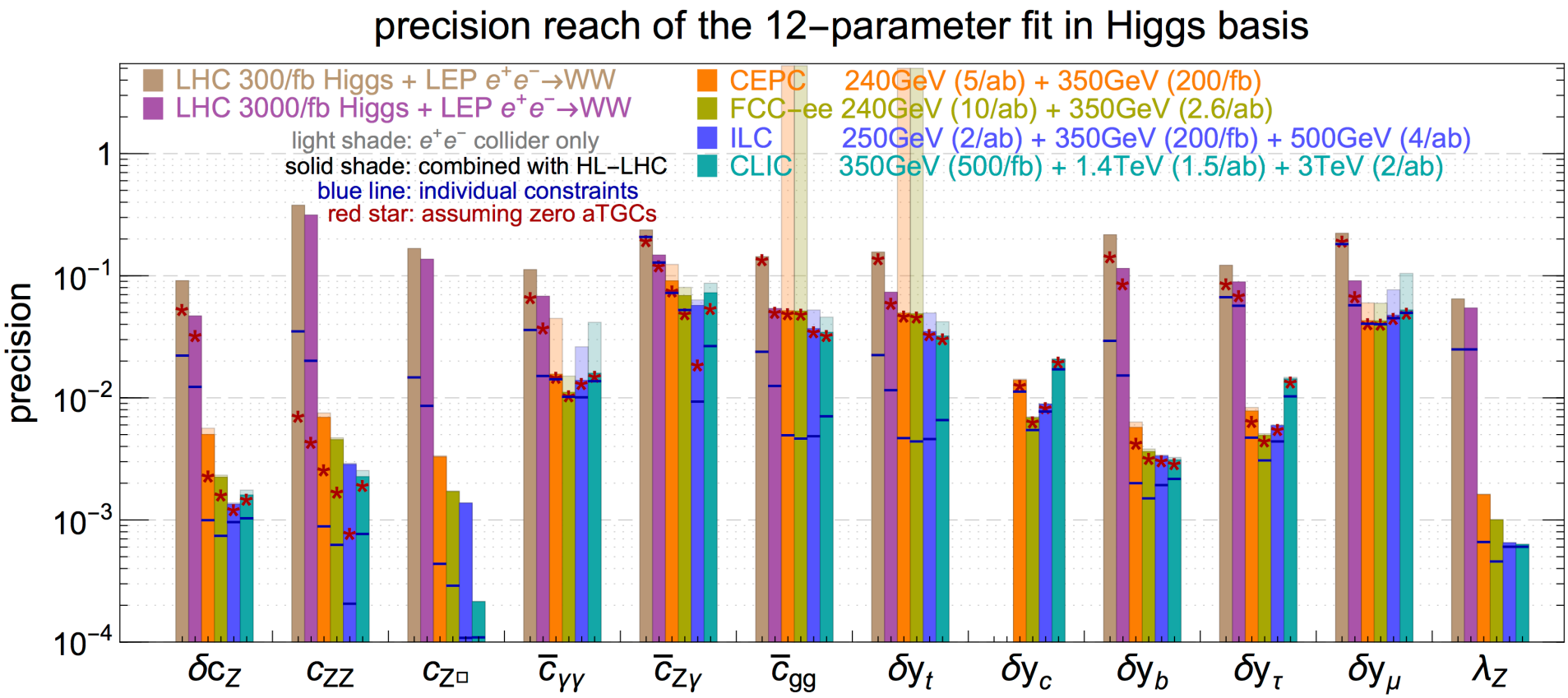
- Expected to collect more data with $P(e^-)$ = -80% at high energy

†: fast simulation

*: extrapolated from 1.4 to 3 TeV

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

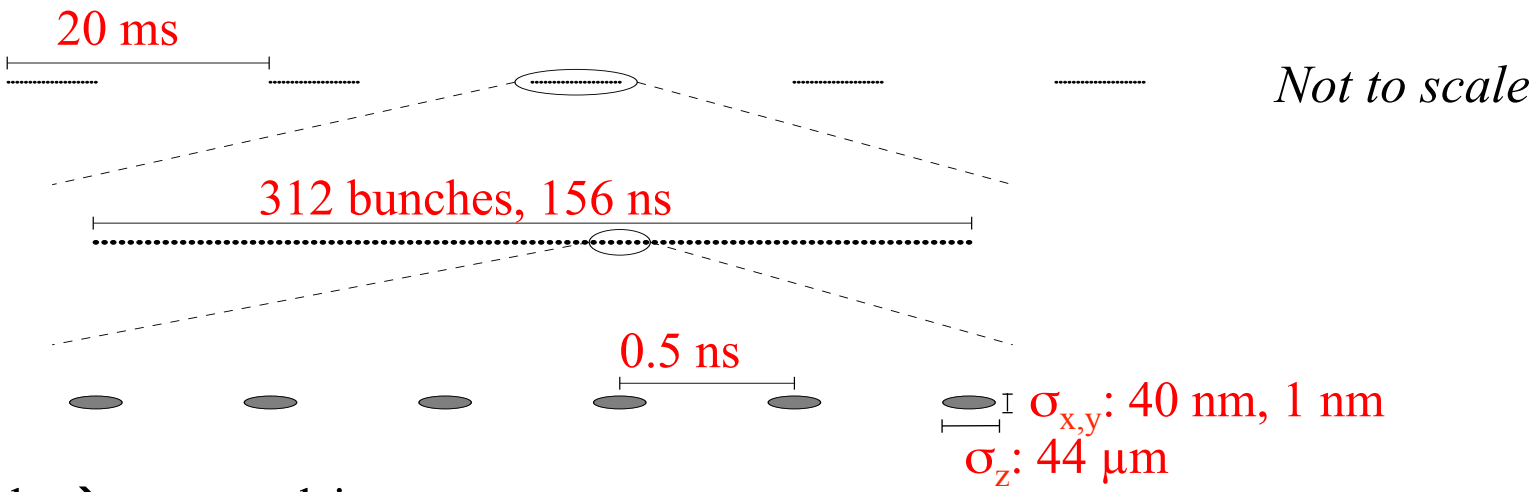
Comparison of different collider options



- Many EFT parameters can be measured significantly better at CLIC compared to the HL-LHC
- H→cc only accessible in at lepton colliders

arXiv:1704.02333
see also JHEP 1705, 096 (2017)

CLIC beam environment



Low duty cycle →power pulsing
High luminosity
Very small bunch size at IP
Very strong electromagnetic field from opposite beam →Beamstrahlung

- **Coherent** and **trident** e^+e^- pairs very forward
- Contribution from **incoherent** e^+e^- pairs (3×10^5 per BX) in detector region
- Main background in calorimeters and tracker from **$\gamma\gamma$→hadrons**
  (3.2 evts per BX at 3 TeV)

→beam background reduced by p_T and timing cuts