Higgs physics at CLIC

CLIC Detector and Physics Advisory Board, 17th April 2018

Rosa Simoniello, JGU Mainz
on behalf of the CLICdp collaboration

Overview

- Rich physics program across all centre-of-mass energy stages
- Higgs program to investigate electroweak symmetry breaking (and probe of new physics beyond SM → see next talks)
- High precision model-independent evaluation of Higgs couplings (including rare decays), Higgs mass and Higgs width

https://link.springer.com/article/10.1140%2Fepjc%2Fs10052-017-4968-5

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Regular Article - Experimental Physics

Higgs physics at the CLIC electron–positron linear collider

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Information on simulation

- All studies in this talk use a full Geant4 detector simulation
- Effect of ISR and beamstrahlung taken into account
- These studies use the 2 detector models based on ILC concepts and adapted to the CLIC operation condition, and the centre-of-mass energies and $\mathcal{L}$ as documented in the CDR CERN-2012-003
- Similar results expected with the recently optimised CLIC detector model and centre-of-mass energies baseline (+ profits from the increased $\mathcal{L}$ at 3 TeV)

CDR baseline

$\sqrt{s}$ [GeV]	$\mathcal{L}_{int}$ [fb^{-1}]
350	500
1400	1500
3000	2000

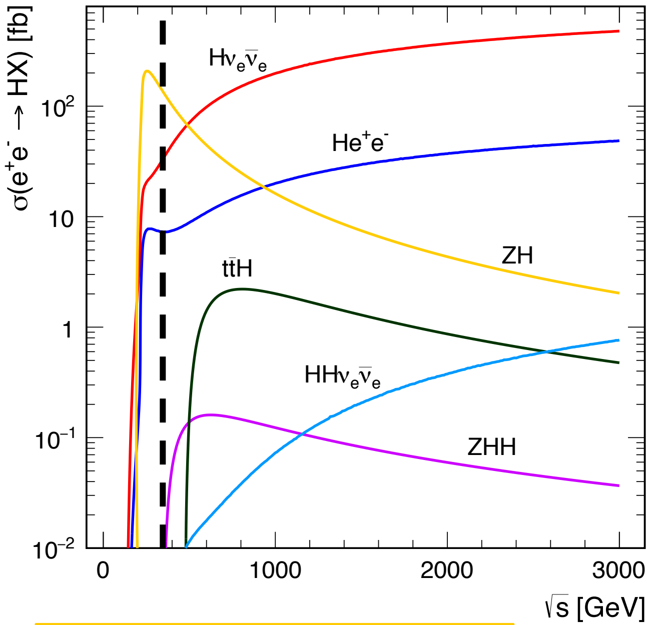
→

Updated baseline

$\sqrt{s}$ [GeV]	$\mathcal{L}_{int}$ [fb^{-1}]
380	500
1500	1500
3000	3000

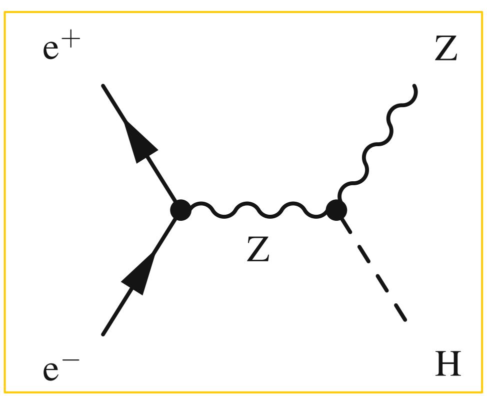
Higgs production at CLIC

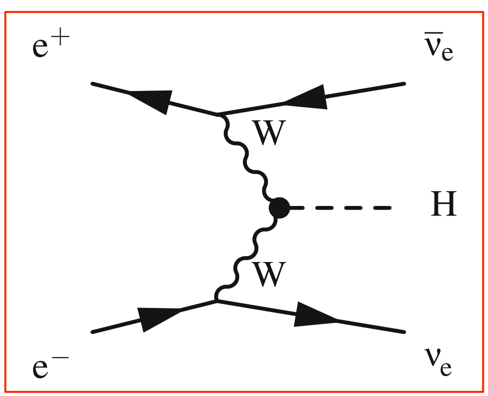
- Max of Higgsstrahlung at 250 GeV, operation at 350 (380) GeV compensates with higher $\mathcal{L}$ and boost, and contribution from VBF

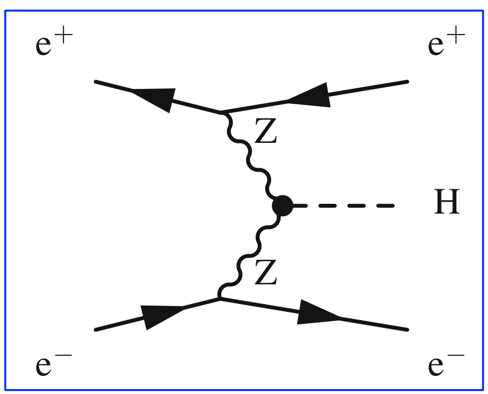


Numbers include beamstrahlung and ISR, no beam polarisation

$\sqrt{s} =$	350 GeV	1.4 TeV	3 TeV
$\int \frac{d\mathcal{L}}{ds'} ds'$	$500\,\text{fb}^{-1}$	$1.5\,\text{ab}^{-1}$	$2\,\text{ab}^{-1}$
$\sigma(e^+e^- \to ZH)$	133 fb	8 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	34 fb	276 fb	477 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	48 fb
No. ZH events	68,000	20,000	11,000
No. $H\nu_e\bar{\nu}_e$ events	17,000	370,000	830,000
No. He^+e^- events	3700	37,000	84,000

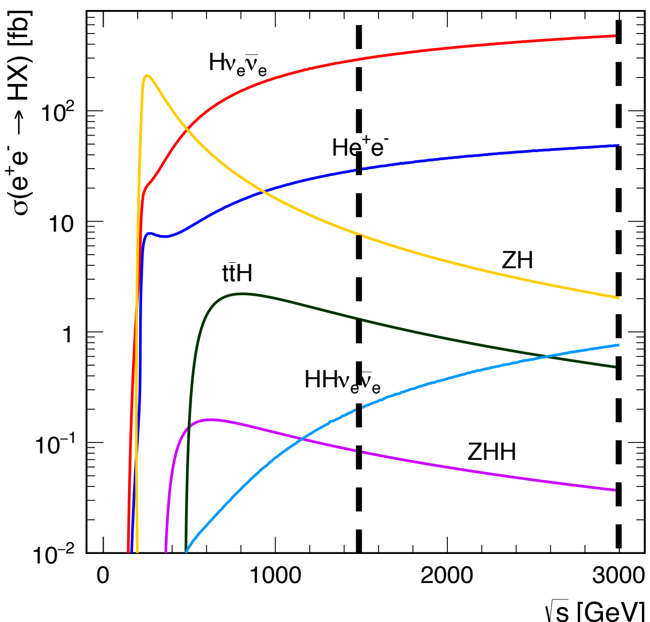






Higgs production at CLIC

- Higher energies and luminosity give access to rare Higgs processes (production and decay). VBF is the dominant production mode.



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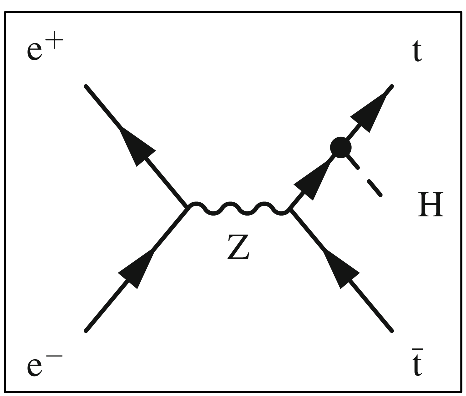
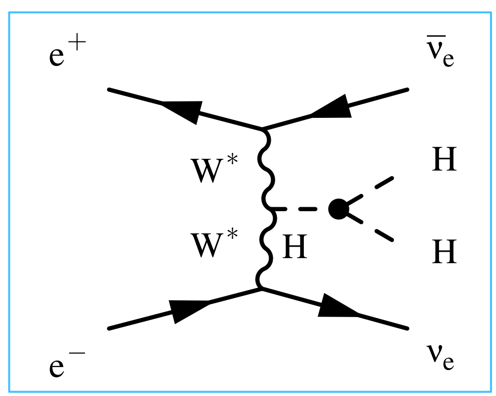
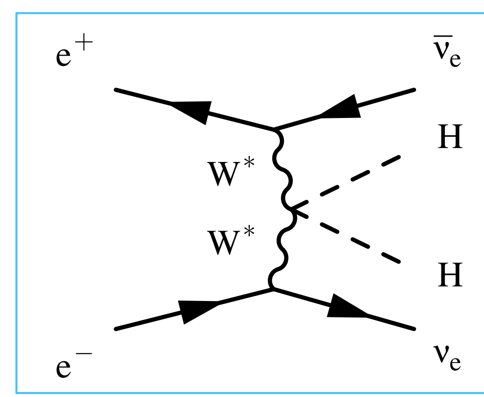


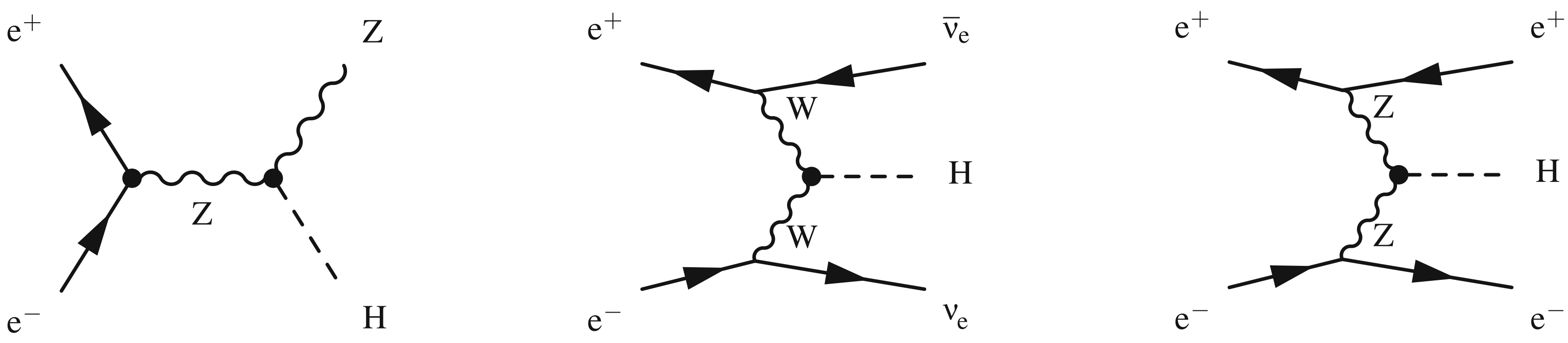




Beam polarisation

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% : 0%	1.12	1.80	1.12
−80% : +30%	1.40	2.34	1.17

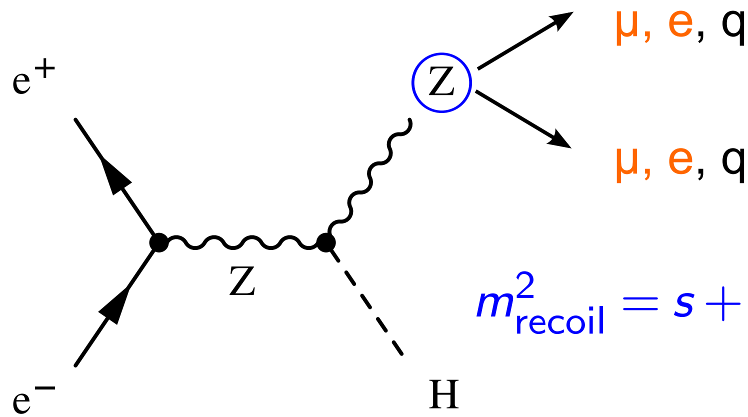
CLIC baseline design



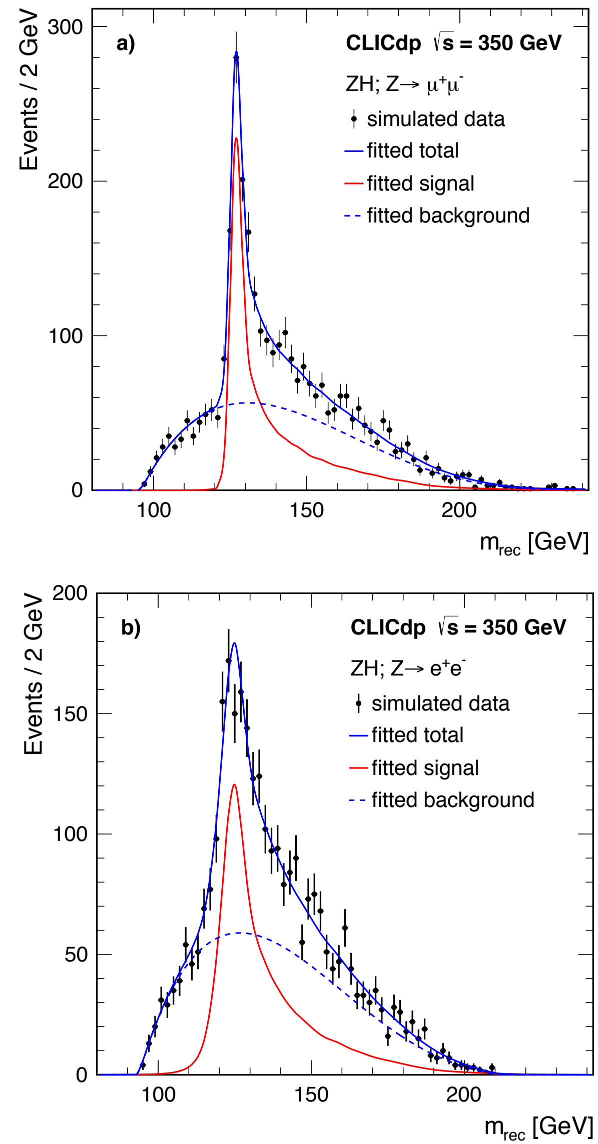
350 GeV

Higgsstrahlung: inclusive σ(ZH)

Unique at lepton colliders!



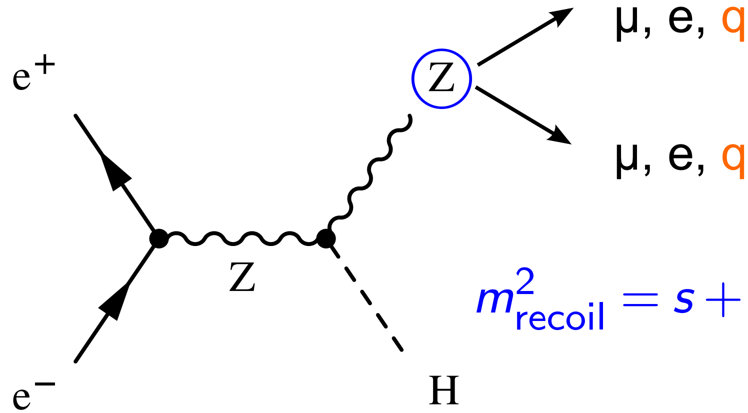
$$m^2_{recoil} = s + m^2_Z - 2E_z\sqrt{s}$$



- Evaluation of g_{HZZ} from measurement of the inclusive σ(ZH) (independently on the Higgs decay) exploiting knowledge of the centre-of-mass energy for the recoil mass
- Lepton channel very clean but small BR (~7%)
- Main background: 4 fermions final state
  - under control with cuts on m_{ll} and recoil mass
- Fit to extract precisely Higgs mass (~100 MeV)

Higgsstrahlung: inclusive σ(ZH)

Unique at lepton colliders!



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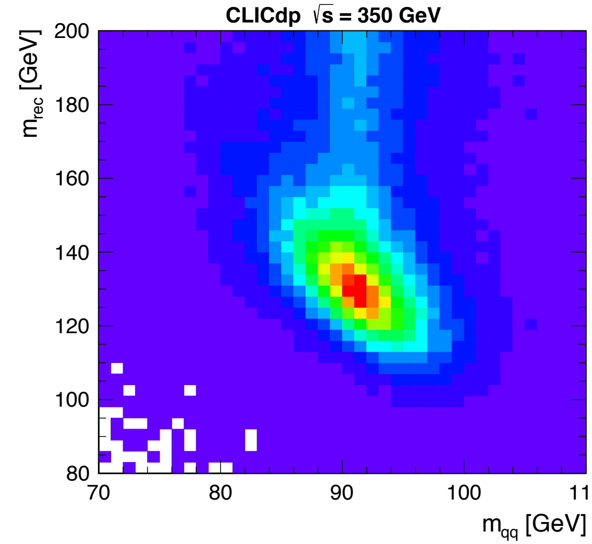
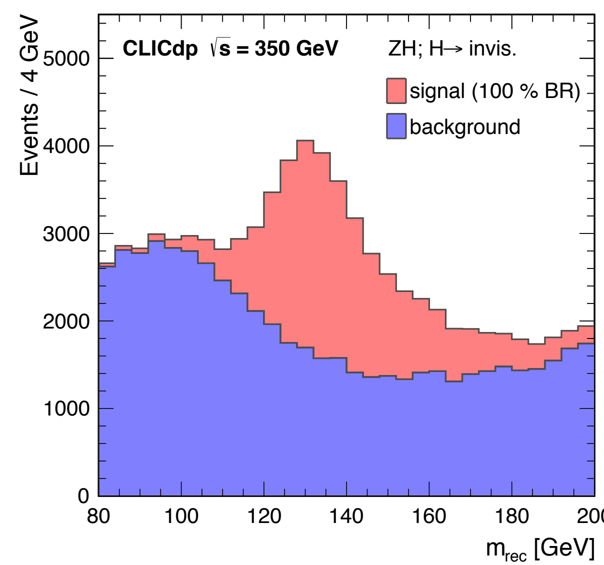
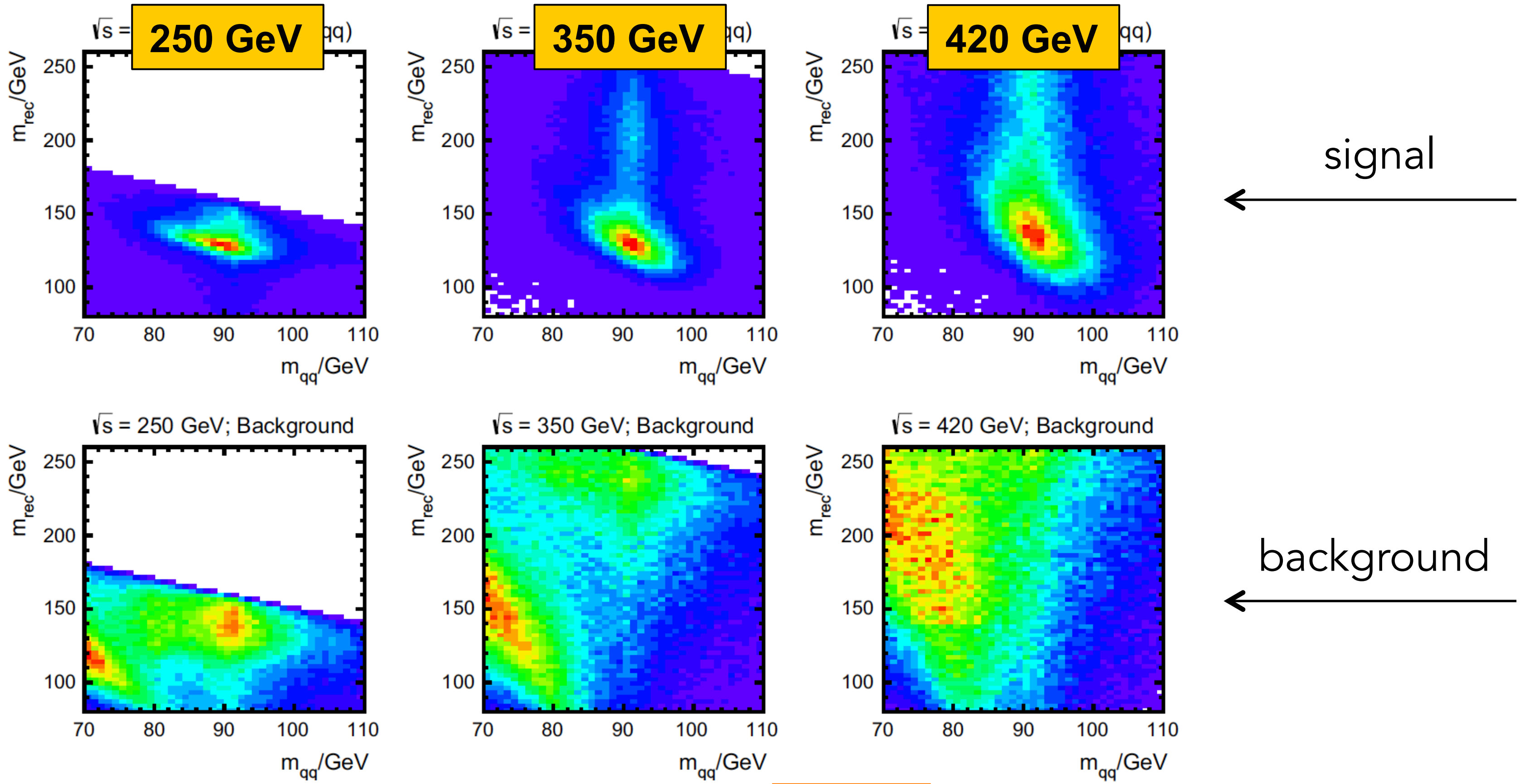


- Hadron decays have larger BR (~70%)
- Challenge in associating particles to jets, and jets to Z and H while keeping the selection independent on the Higgs decay mode (order per mille effect on the cross section)
- Δσ(ZH)/σ(ZH) = 1.65% → $\Delta g_{HZZ}/g_{HZZ}$ = 0.8%
- Investigation of Higgs invisible decays
  - constrains down to < 1%



Choice of centre-of-mass energy

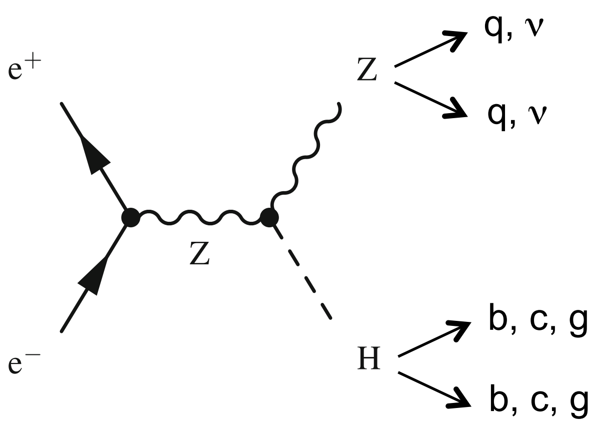


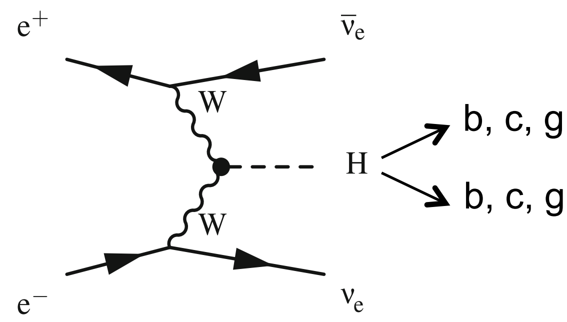
$\sqrt{s}$	$\mathcal{L}$	$\sigma(HZ)$	$\Delta\sigma_{vis.}$	$\Delta\sigma_{invis.}$	$\Delta\sigma(HZ)$
250 GeV	500 fb^{-1}	136 fb	±3.63 %	±0.45 %	±3.65 %
350 GeV	500 fb^{-1}	93 fb	±1.71 %	±0.56 %	±1.80 %
420 GeV	500 fb^{-1}	68 fb	±2.42 %	±1.02 %	±2.63 %

Together with top physics it drives the choice of CLIC initial energy stage at 380 GeV

Eur. Phys. J. C (2016) 76: 72

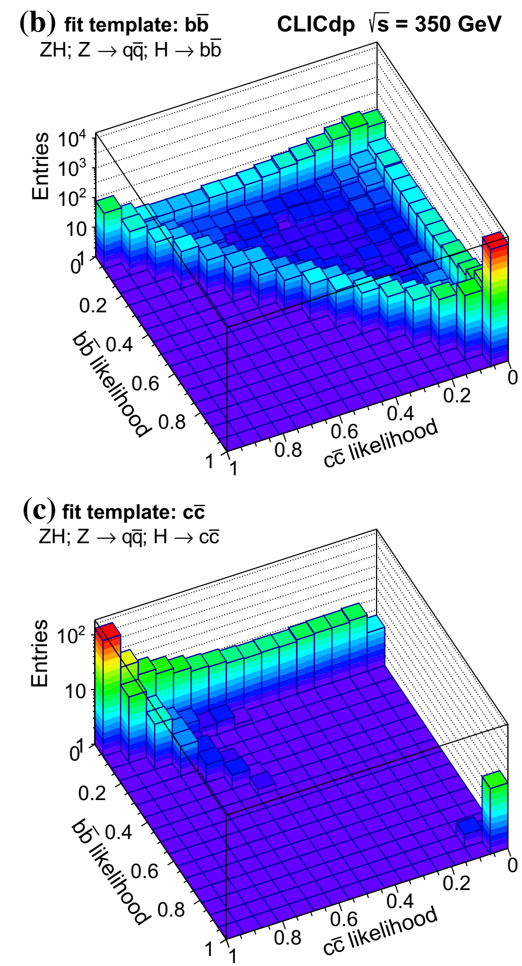
Exclusive σ×BR measurements





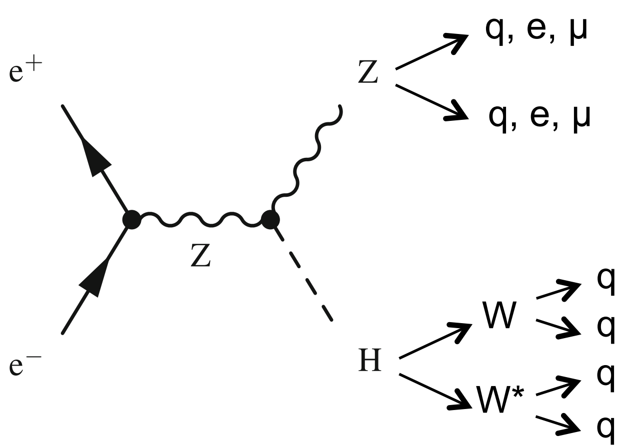
- Hadronic Higgs decay (b, c, gluon)
- Both Higgsstrahlung and VBF considered (same final state for Z to νν)
  - Global fit accounts for the correlation
- Events classified in 2/4 jets
  - Main backgrounds: WW, ZZ, Zνν
- Multidimensional template fit with tagging and P_T^H info to measure 2 production and 3 decay modes

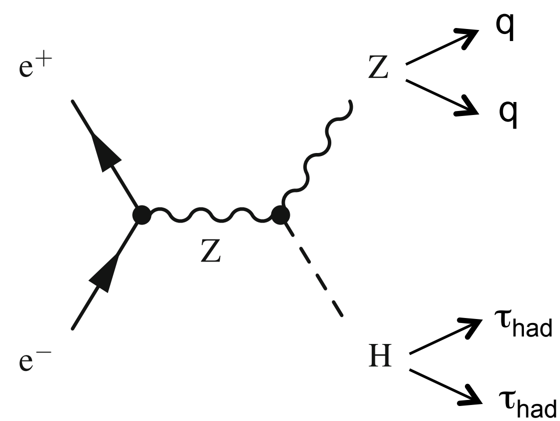
Precision on	Hbb	Hcc	Hgg
σ(ZH)×BR	0.86%	14%	6%
σ(Hνν)×BR	1.9%	26%	10%



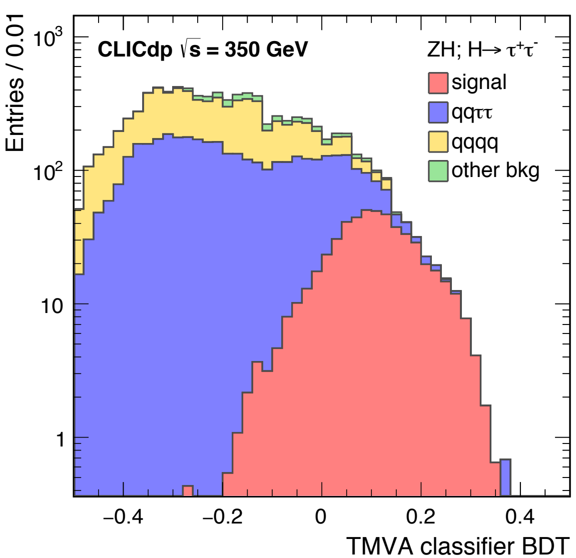
Excellent flavour tagging performance!

Exclusive σ×BR measurements





- H to WW*:
  - Only ZH process considered
  - Hadronic W decay to have complete m_H reconstruction
  - Precision on σ×BR: 5.1% (g_{HWW} couplings accessible also in Higgs production)
- H to ττ:
  - Only ZH process with hadronic τ decays considered
  - Template fit on BDT output
  - Precision on σ×BR: 6.2% (Hττ)



Results at 350 GeV

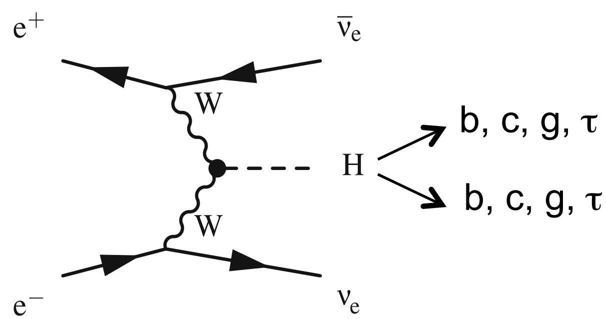
- Only statistical precision considered

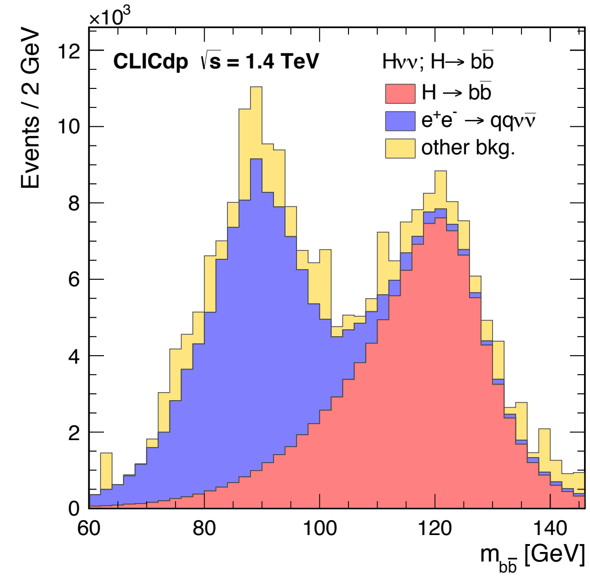
Channel	Measurement	Observable	Statistical precision 350 GeV 500 fb^{-1}
ZH	Recoil mass distribution	m_{H}	110 MeV
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{H} \to \mathrm{invisible})$	Γ_{inv}	0.6%
ZH	$\sigma(\mathrm{ZH}) \times BR(\mathrm{Z} \to \mathrm{l^+l^-})$	g^2_{HZZ}	3.8%
ZH	$\sigma(\mathrm{ZH})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

- Compelling results already at 350 (380) GeV !

1.4 TeV and 3 TeV

Couplings refinement

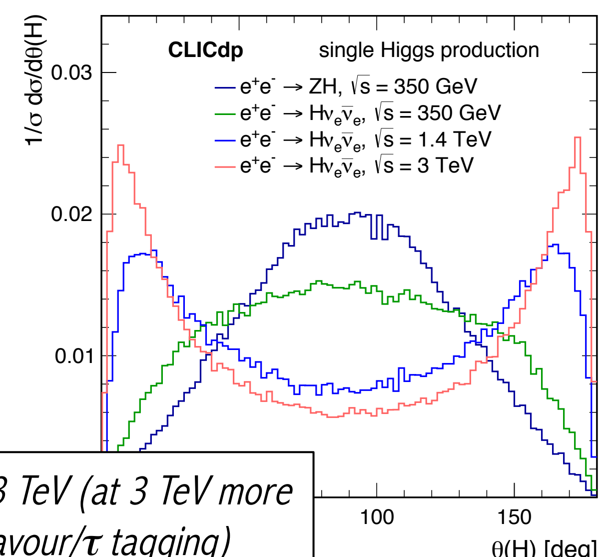




- At 1.4 and 3 TeV increase precision on Higgs couplings and mass measurement
- WW fusion production (p_T^{miss} from νs)
- H to bb, cc, gg
  - For couplings: flavour tagging used only in template fit

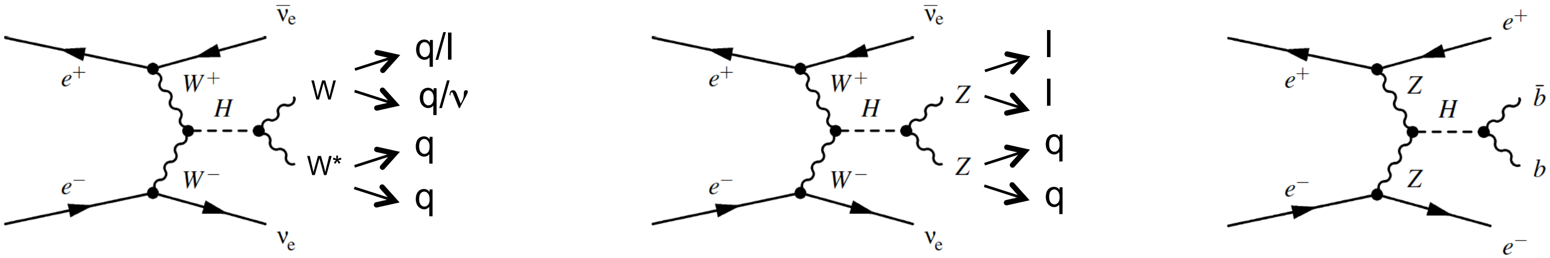
√s	Hbb	Hcc	Hgg
1.4 TeV	0.4%	6.1%	5.0%
3 TeV	0.3%	6.9%	4.3%

  - For mass measurement: tagging information used in BDT to target H to bb channel (higher BR) $\Delta(m_H)$ = 32 MeV (1.4+3 TeV)
- H to ττ
  - σ×BR: 4.2%(1.4TeV), 4.3%(3TeV)

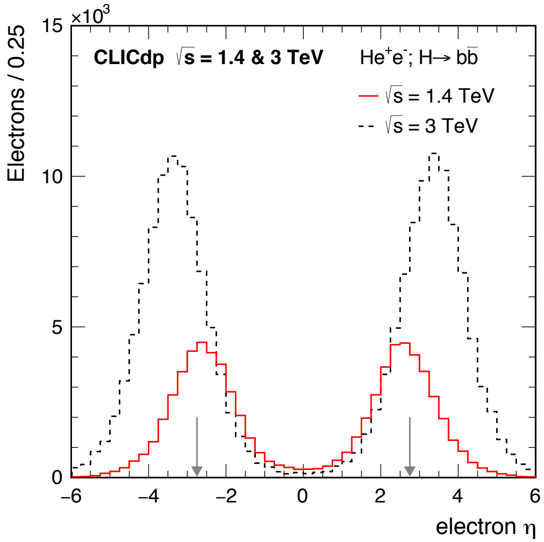


Similar precision at 1.4–3 TeV (at 3 TeV more forward events, harder flavour/τ tagging)

Couplings refinement



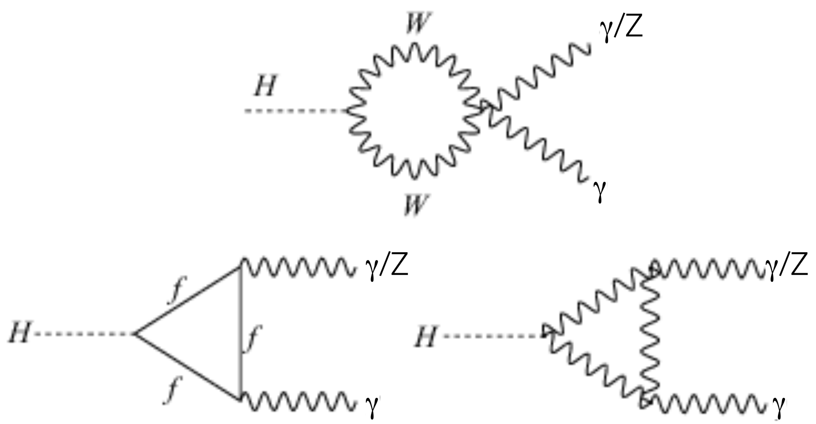
- WW fusion with H to WW*:
  - Fully hadronic (dominant) and semileptonic WW decays considered
  - Contamination from other Higgs decays → simultaneous fit
  - Precision on σ×BR: 1% at 1.4 TeV
- WW fusion with H to ZZ:
  - Semileptonic decays considered
  - Provide complementary access to g_{HZZ}
  - Precision on σ×BR: 5.6% at 1.4 TeV
- ZZ fusion with H to bb:
  - Low σ but very characteristic forward electrons
  - Provide complementary access to g_{HZZ}
  - Precision on σ×BR: 1.8% at 1.4 TeV



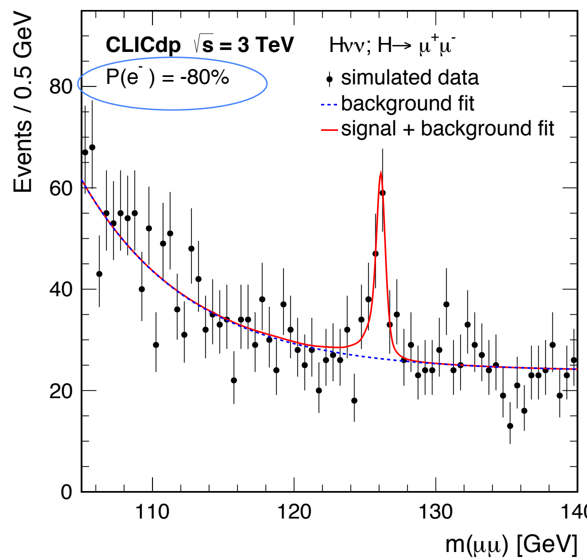
Results then extrapolated to 3 TeV

Rare Higgs decays

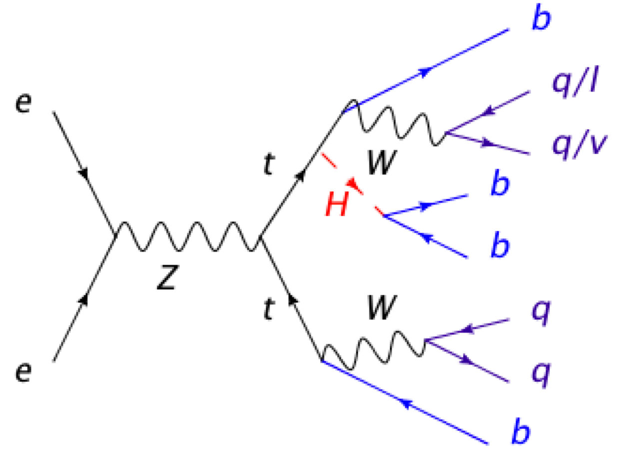
- H to γγ and H to Zγ
  - Studied in WW fusion production at 1.4 TeV
  - Decays via loop → low BR: BR(Hγγ)=0.23%, BR(HZγ)=0.16%
  - Photon final state challenging due to ISR and FSR
  - Precision on σ×BR: 15% (Hγγ), 42% (HZγ)

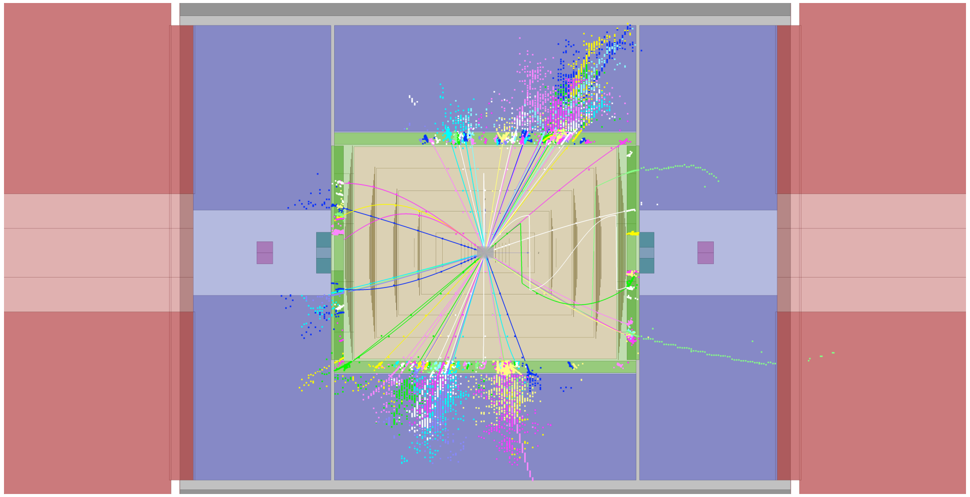


- H to μμ
  - Studied in WW fusion production at 1.4 and 3TeV
  - Very low BR: BR(Hμμ)=0.022%
  - High precision tracking required for mass reconstruction
  - Precision on σ×BR: 38% (1.4 TeV), 25% (3 TeV)
    - 80% polarisation assumed for the electron beam



Top Yukawa coupling

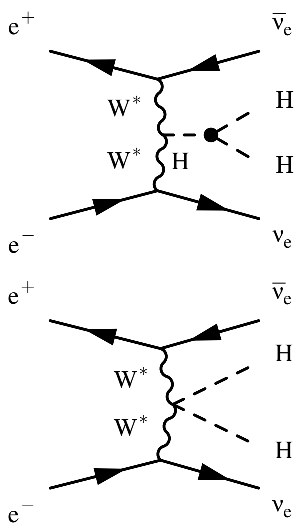


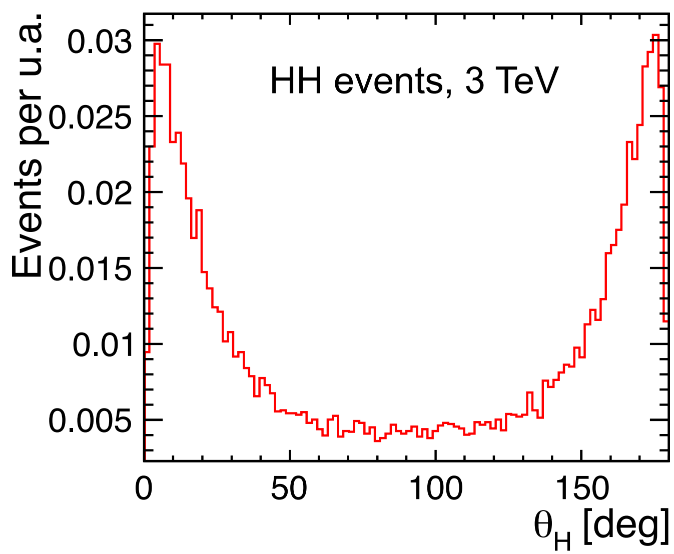


- Higgs radiated from top → ttH cross section related to top Yukawa coupling: $\Delta y_t/y_t = 0.503\ \Delta\sigma/\sigma$
- Studied at 1.4 TeV (not the peak of the production σ but the reduction of signal is compensated by the reduction of background → similar results)
- H in bb + both fully hadronic and semileptonic decays considered (6−8 jets)
- Main background from top processes (ttbb, ttZ, tt)
- Precision on Yukawa coupling $\Delta y_t/y_t$ = 4.2%
  - Down to 4% with 80% polarisation for the electron beam
  - No improvement expected at 3 TeV due to the reduction in the cross section
  - New: with refined analysis, $\Delta y_t/y_t$ = 3.8% (3.4%) without (with) polarisation

more in the next talk!

Double Higgs





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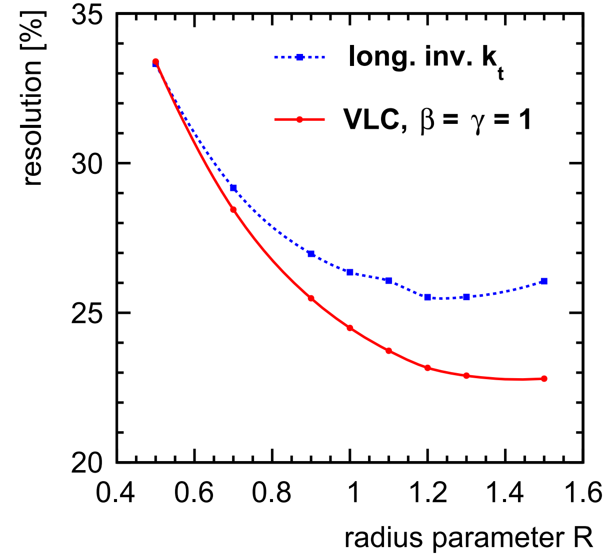
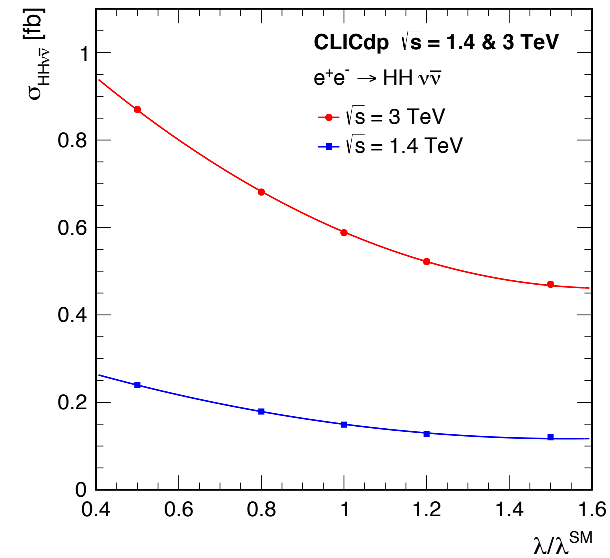


- Double Higgs production gives access to the Higgs potential
- Studied in WW fusion production at 1.4 and 3 TeV
  - Challenge: small cross section, very forward event topology
- Both HH→bbbb (dominant) and hadronic HH→bbWW* studied (4-6 jets)
  - Main background: ZHνν
- Jet reconstruction and flavour tagging very challenging
  - Use of VLC jet algorithms optimised for lepton colliders

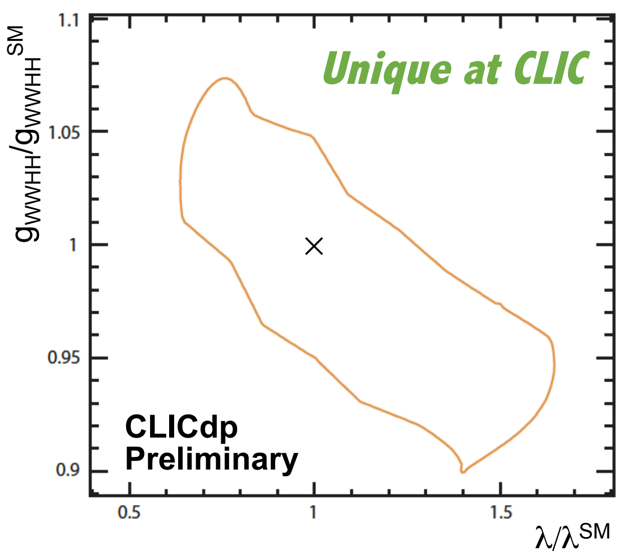
Double Higgs

- Fixing quartic coupling: $\Delta\lambda/\lambda \approx \kappa\ \Delta\sigma/\sigma$, κ=1.22 (1.47) at 1.4 (3) TeV
- Precision on the Higgs self coupling (g_{WWHH} fixed)
  - After MVA: S/B~1 (~60 signal events for $2ab^{-1}$ at 3 TeV)

$\Delta\lambda/\lambda$	conditions
19%	$1.5ab^{-1}$ at 1.4. TeV + $2ab^{-1}$ at 3 TeV + $P(e^-)$ = -80%
16%	$1.5ab^{-1}$ at 1.4. TeV + $3ab^{-1}$ at 3 TeV + $P(e^-)$ = -80%



- Possible simultaneous extraction of Higgs self and quartic coupling
  - Template fit using invariant mass
- 1D extraction of λ with template fit on BDT output (on-going): precision of $\approx$10%
  - Result to be finalised (not shown here)



Results at 1.4 and 3 TeV

- Only statistical precision considered

Channel	Measurement	Observable	Statistical precision	
			1.4 TeV 1.5 ab^{-1}	3 TeV 2.0 ab^{-1}
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	47 MeV	44 MeV
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW} g^2_{Hbb} / \Gamma_H$	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%	6.9%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		5.0%	4.3%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW} g^2_{H\tau\tau} / \Gamma_H$	4.2%	4.4%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW} g^2_{H\mu\mu} / \Gamma_H$	38%	25%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		15%	10%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		42%	30%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW} / Γ_H	1.0%	0.7%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW} g^2_{HZZ} / \Gamma_H$	5.6%	3.9%*
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ} g^2_{Hbb} / \Gamma_H$	1.8%	2.3%*
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt} g^2_{Hbb} / \Gamma_H$	8%	–
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	54%	29%
$HH\nu_e\bar{\nu}_e$	with −80% e^- polarisation	λ	40%	22%

*numbers marked with * are extrapolated from 1.4 TeV to 3 TeV*

Systematic uncertainties

- For detailed study, knowledge of the detector technology is required
- Systematics studied in the context of the H to bb analysis at 3 TeV
  - Channel with smallest statistical uncertainties
    precision on $\sigma\times$BR: 0.3%, precision on m_H: 44 MeV
- Luminosity spectrum
  - Measured from Bhabbha scattering
  - Uncertainties on the parameter propagated to on $\sigma\times$BR: 0.15%
- Total luminosity
  - Measured using the CLIC "luminometer", effect on $\sigma\times$BR: few per mille
- Beam polarisation
  - It can be controller to level of 0.2% → effect on $\sigma\times$BR: 0.1%
- Jet energy scale
  - Systematic on m_H similar as statistical error for JES precision of $3.5\cdot10^{-4}$
  - Processes useful for calibration: ee→Z$\nu\nu$;Z→bb and eγ→Ze;Z→bb
- Flavour tagging
  - To study effect of mis-tag rate: ad hoc variation of b-tag weight in background events (they contain very few b-jets) → effect on event rate for $\sigma\times$BR: 0.25%
  - Better understanding of the b-jet energy scale would be beneficial

Combined fit

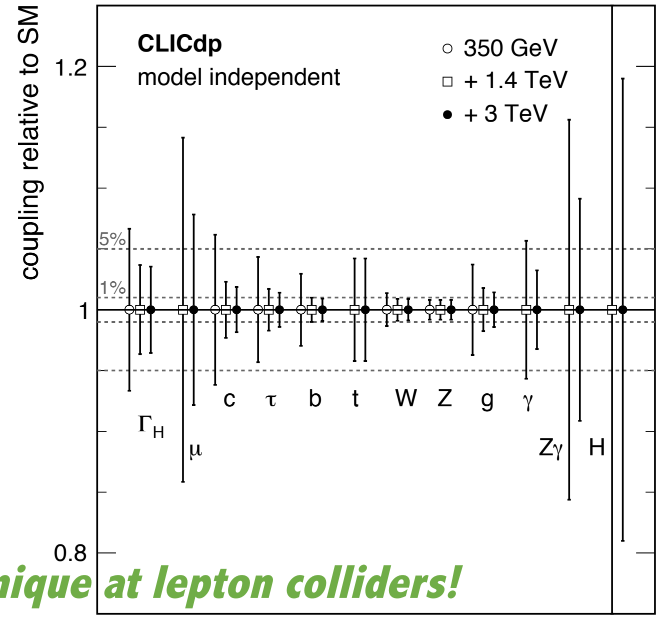
- Global fit uses statistical precision of all measurements to estimate Higgs couplings and total Higgs width Γ_H minimizing:

$$\chi_i^2 = \frac{(C_i / C_i^{SM} - 1)^2}{\Delta F_i^2}$$

C_i: observables (coupling combination, Γ_H)
ΔF_i: statistical uncertainties

- At each energy stage, data from all previous stages are included

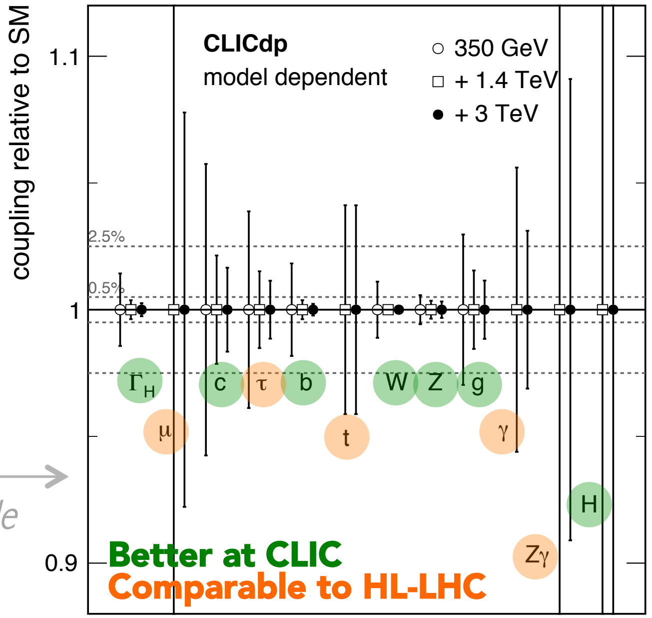
Model independent fit:
total width as free parameter



Unique at lepton colliders!

different y scale

Model dependent fit: LHC-like constraints (no invisible decays)



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C_i: observables (coupling combination, Γ_H)
ΔF_i: statistical uncertainties

- At each energy stage, data from all previous stages are included

Model independent fit:
total width as free parameter

Parameter	Relative precision		
	350 GeV 500 fb^{-1} (%)	+ 1.4 TeV + 1.5 ab^{-1} (%)	+ 3 TeV + 2 ab^{-1} (%)
g_{HZZ}	0.8	0.8	0.8
g_{HWW}	1.4	0.9	0.9
g_{Hbb}	3.0	1.0	0.9
g_{Hcc}	6.2	2.3	1.9
$g_{H\tau\tau}$	4.3	1.7	1.4
$g_{H\mu\mu}$	–	14.1	7.8
g_{Htt}	–	4.2	4.2
$g^{\dagger}_{Hgg}$	3.7	1.8	1.4
$g^{\dagger}_{H\gamma\gamma}$	–	5.7	3.2
$g^{\dagger}_{HZ\gamma}$	–	15.6	9.1
Γ_H	6.7	3.7	3.5

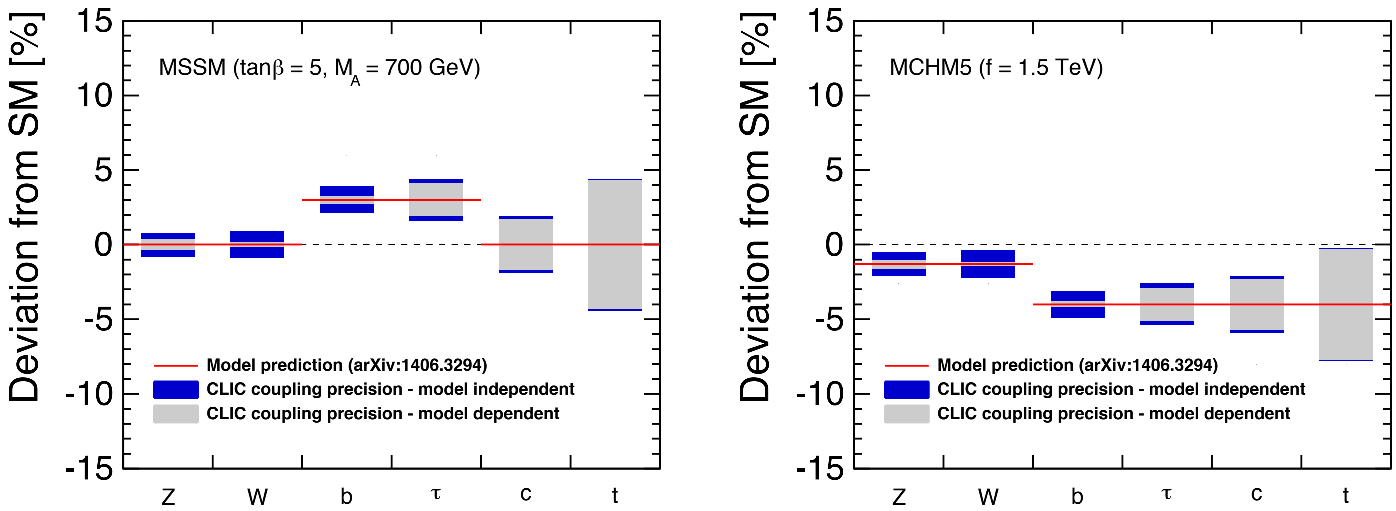
Model dependent fit: LHC-like constraints (no invisible decays)

Parameter	Relative precision		
	350 GeV 500 fb^{-1} (%)	+ 1.4 TeV + 1.5 ab^{-1} (%)	+ 3 TeV + 2 ab^{-1} (%)
κ_{HZZ}	0.6	0.4	0.3
κ_{HWW}	1.1	0.2	0.1
κ_{Hbb}	1.8	0.4	0.2
κ_{Hcc}	5.8	2.1	1.7
$\kappa_{H\tau\tau}$	3.9	1.5	1.1
$\kappa_{H\mu\mu}$	–	14.1	7.8
κ_{Htt}	–	4.1	4.1
κ_{Hgg}	3.0	1.5	1.1
$\kappa_{H\gamma\gamma}$	–	5.6	3.1
$\kappa_{HZ\gamma}$	–	15.6	9.1
$\Gamma_{H,md,derived}$	1.4	0.4	0.3

Conclusion

- Competitive Higgs physics program already at the initial energy stage
  - Precise model independent estimation of many Higgs couplings
- At higher energies and luminosities
  - Increase precision on Higgs couplings and mass
  - Access to rare Higgs processes (including Higgs self coupling)

Precision measurement of Higgs coupling can probe new physics !! (see next talks)

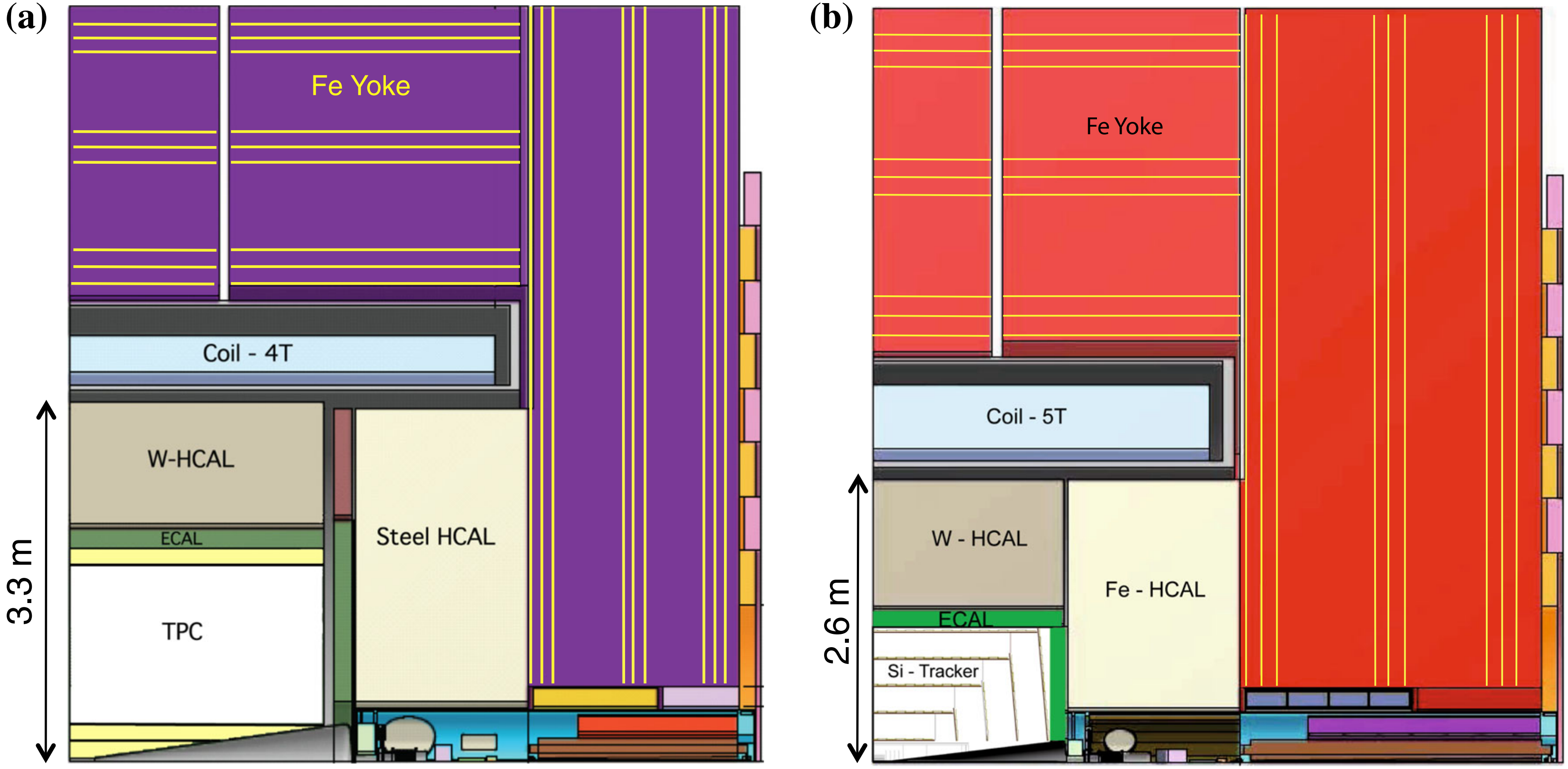


Back-up

BR for m_H = 126 GeV

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

Detector models



Longitudinal cross section of the top right quadrant of the CLIC_ILD (**a**) and CLIC_SiD (**b**) detector concepts