Linear collider physics at 380 GeV

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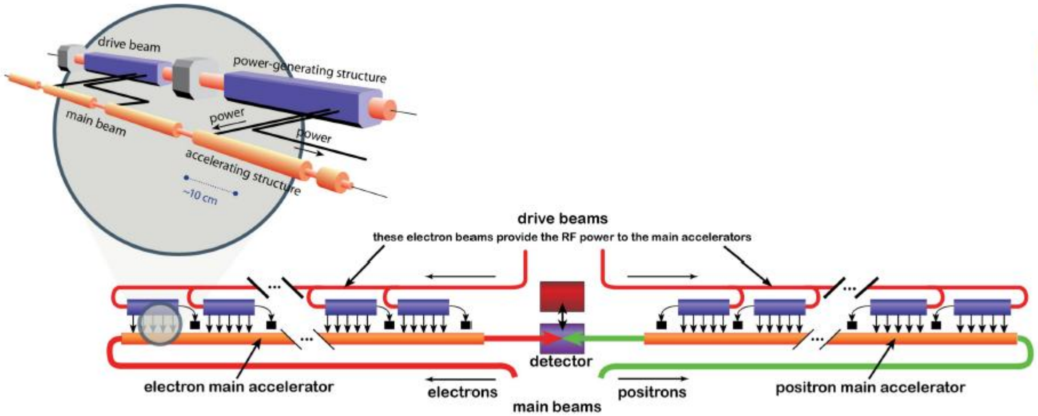
(CLICdp/Dubna)

Projects of future e+e- colliders

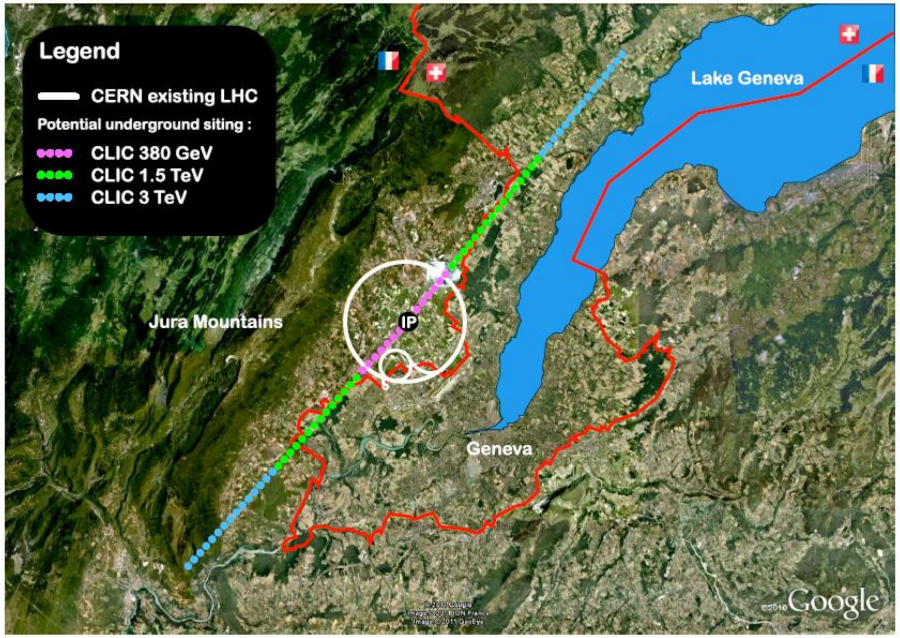
- Future Circular Collider (FCC-ee)
  - $\sqrt{s}$ = 91-350 GeV
- Circular Electron-Positron Collider (CEPC)
  - $\sqrt{s}$ = 90-240 GeV
- International Linear Collider (ILC)
  - $\sqrt{s}$ = 250-500 GeV (1 TeV)
- Compact Linear Collider (CLIC)
  - $\sqrt{s}$ = 380 GeV / 1.5 TeV / 3 TeV

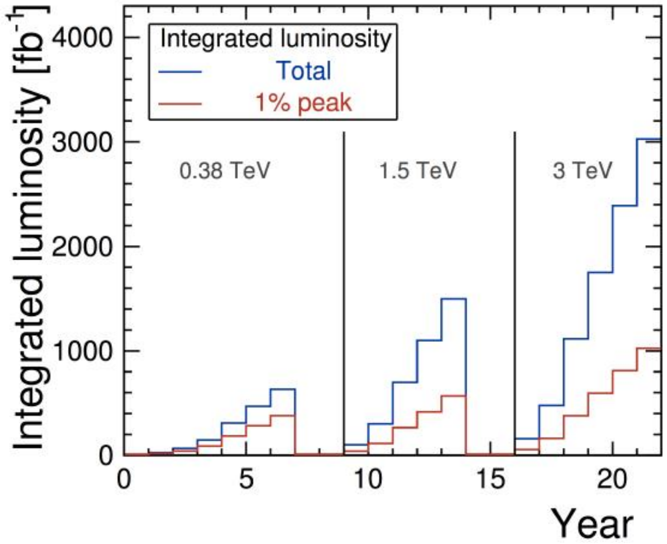
CLIC (Compact Linear Collider)



- 2-beam acceleration scheme
  - Low energy: 2.4 GeV → 240 MeV, 100 A
  - High energy: 9 GeV → 1500 GeV, 1.2 A
- Gradient 100 MV/m, operated at room temperature
- Energy: 380-3000 GeV (staged)
- Length: 50 km (for 3 TeV)

CLIC staging scenario

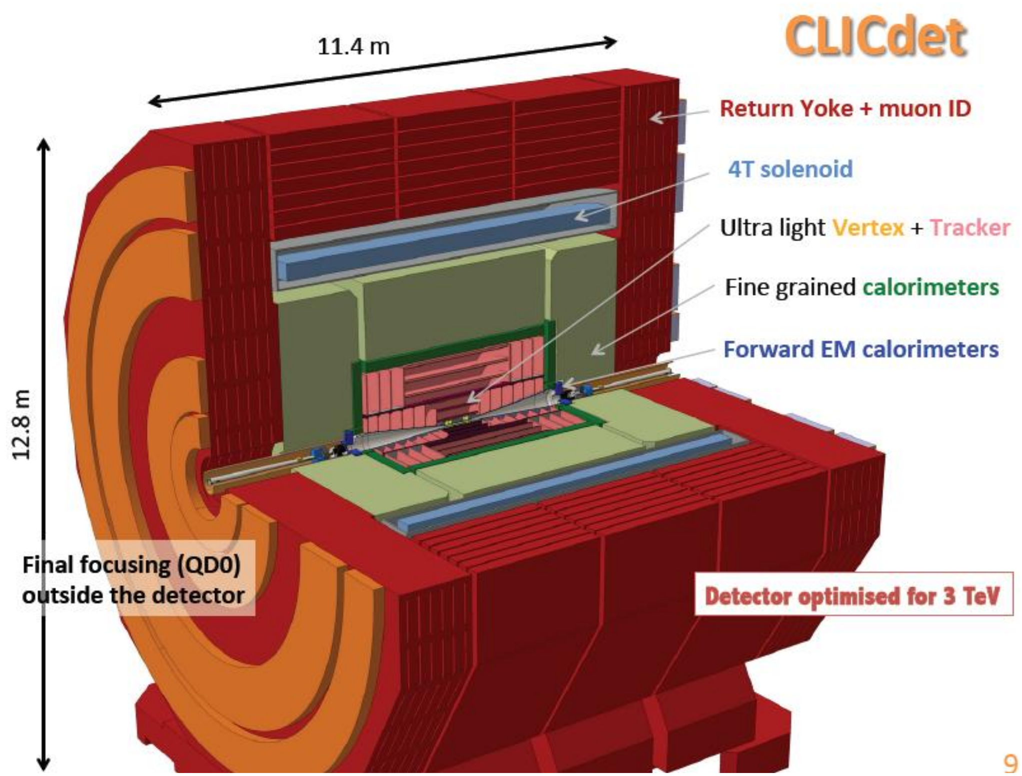




- Why 380 GeV?
  - Cost consideration (staging)
  - Unique and wonderful physics at 380 GeV!
  - Some benchmark results were obtained with “old” staging scenario, 350/1400/3000 GeV

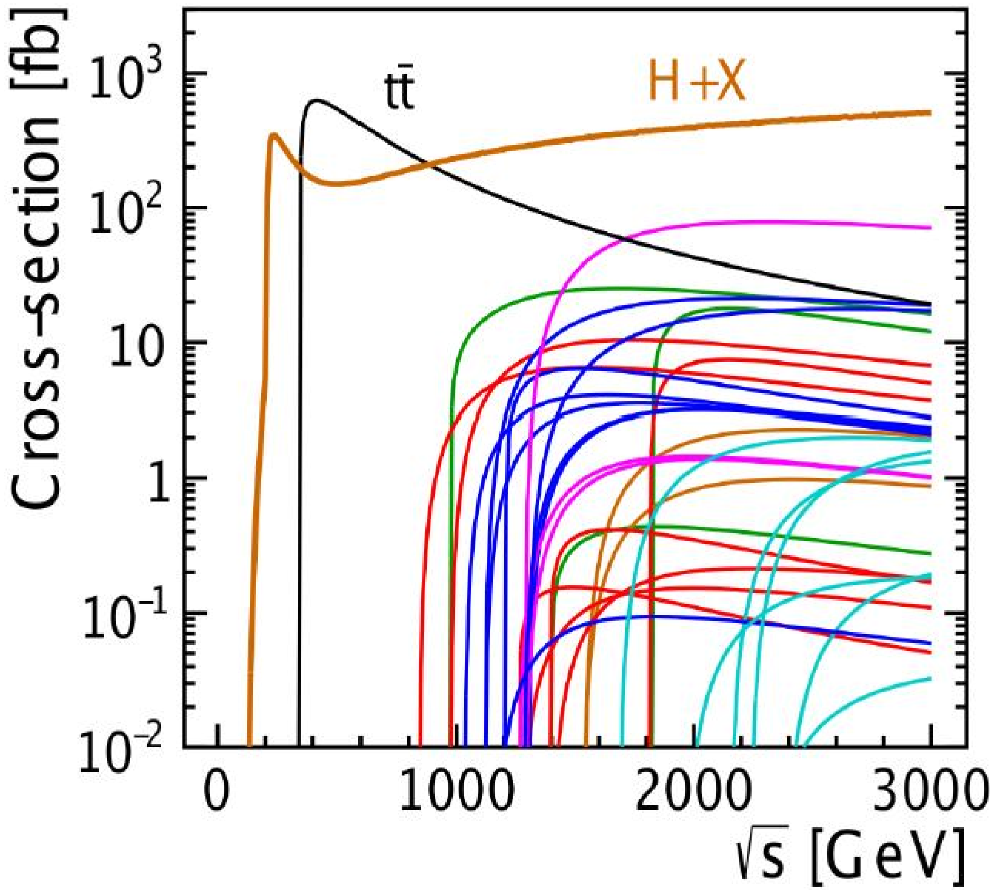
Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380 350	500 100
2	1500	1500
3	3000	3000

CLIC detector

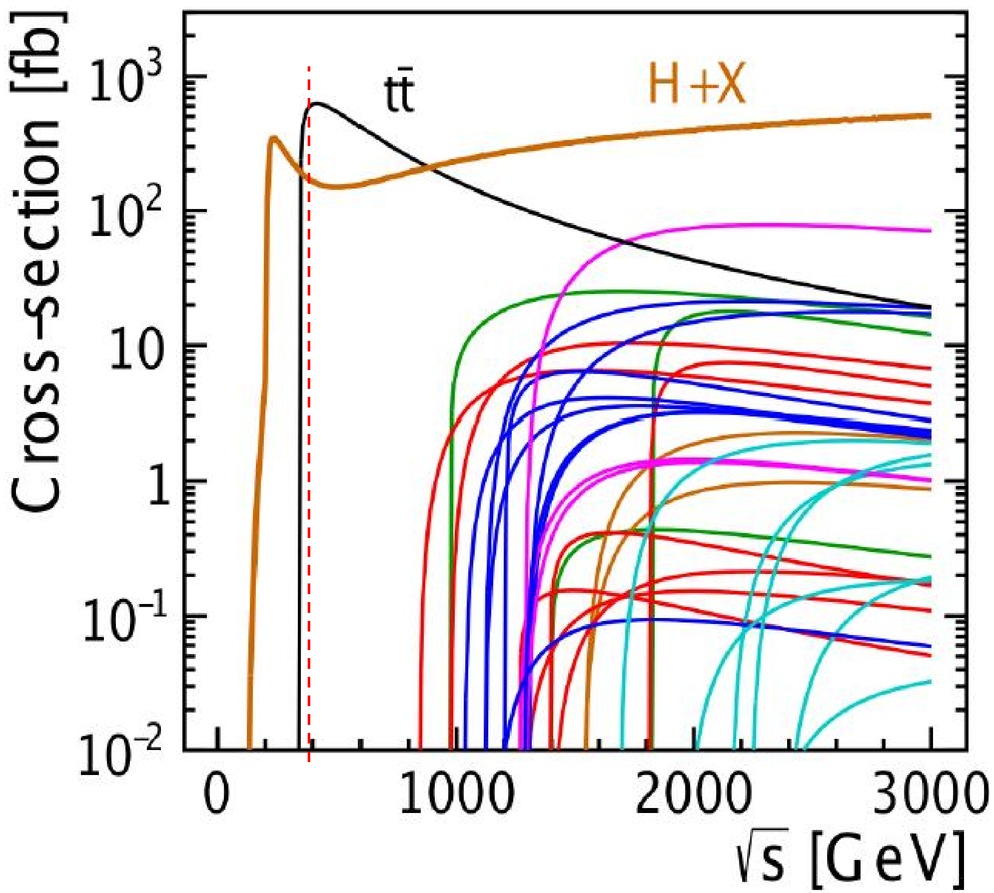


- New detector model CLICdet
- Replaces old options CLIC_ILD and CLIC_SiD
- Many benchmark results are still based on the old options
- See the detailed talk this afternoon!

CLIC physics versus energy

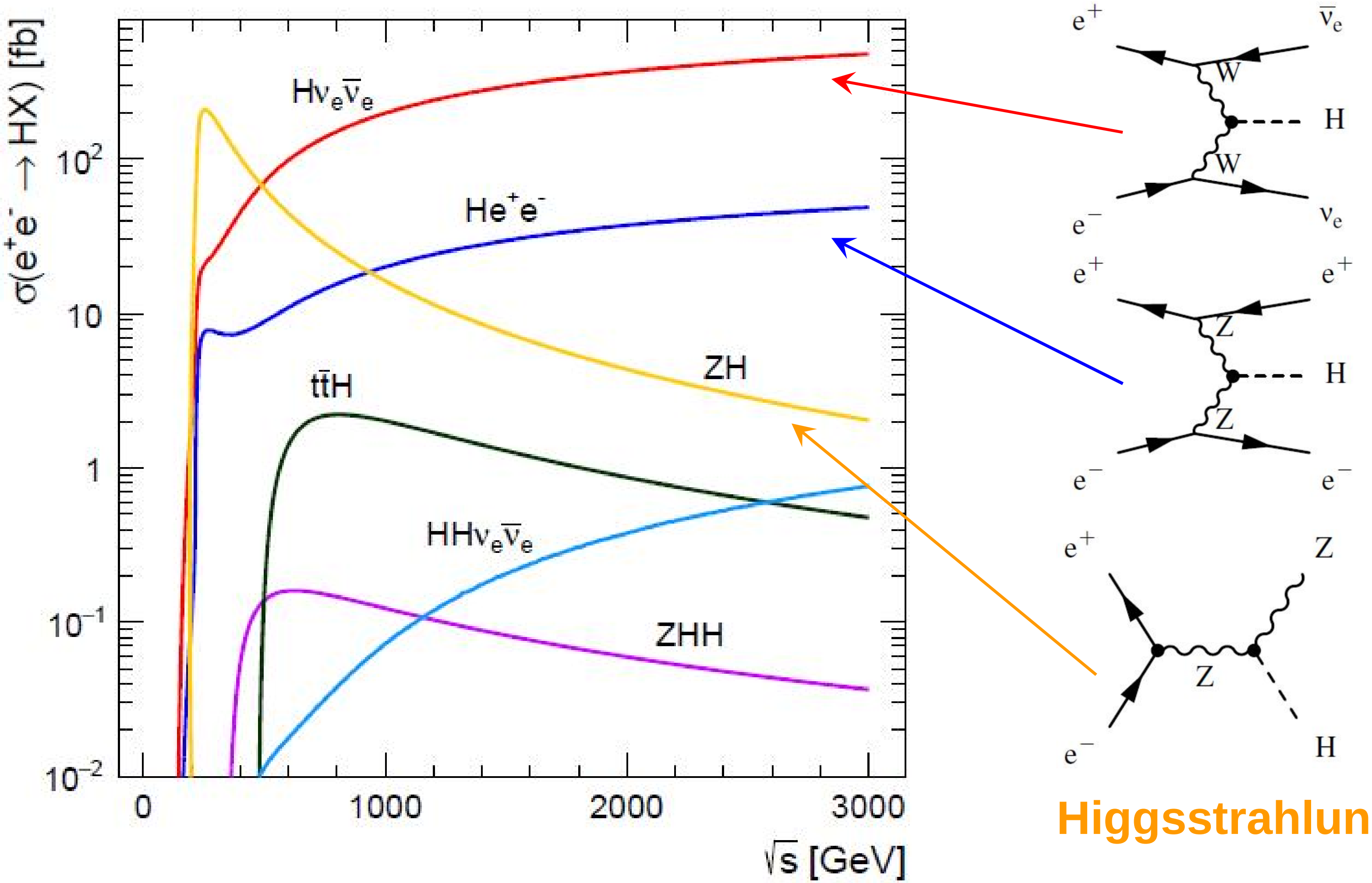


CLIC physics versus energy



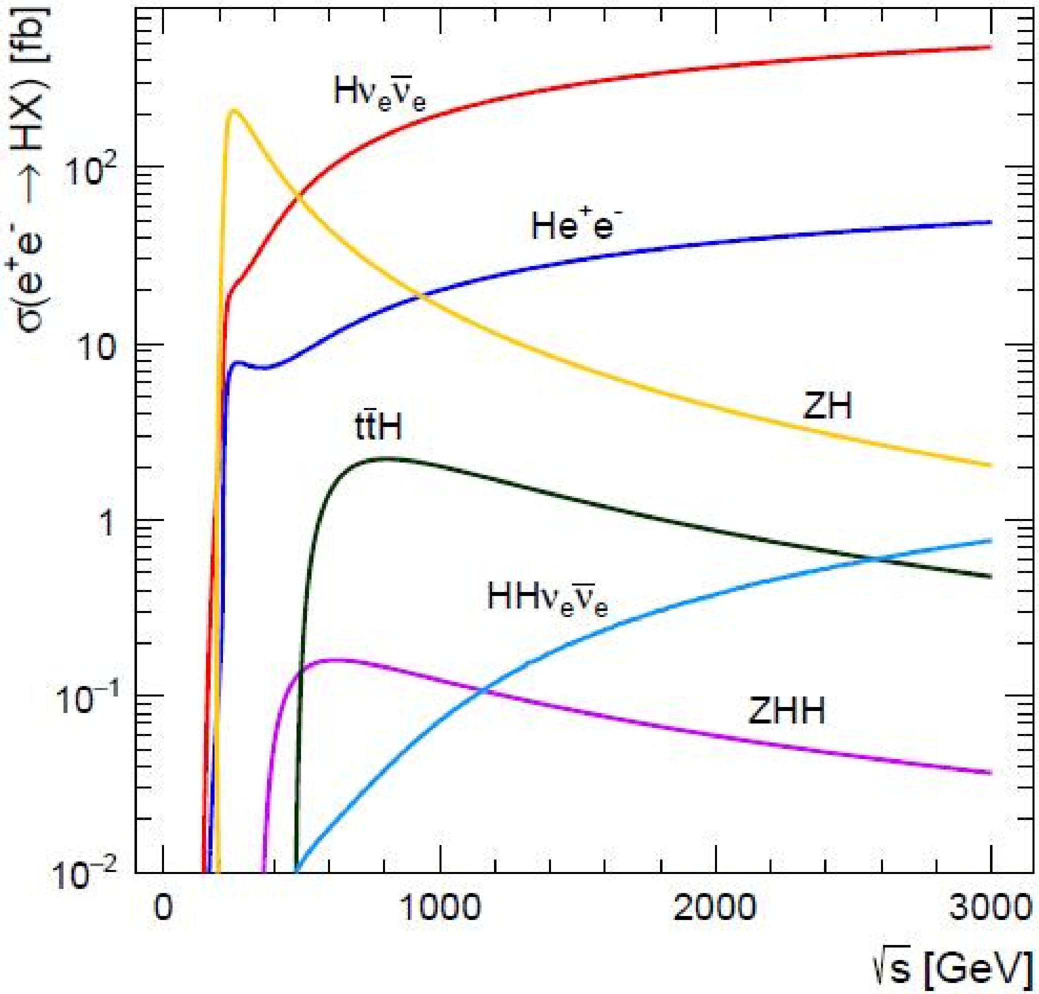
- BSM physics: direct searches require the highest possible energies
  - Note: deviations from the Standard Model can be observed in lower energy precision measurements
- Initial stage at 380 GeV is optimized for Higgs and Top physics (including tt-threshold scan at 350 GeV)

Higgs production at CLIC energies



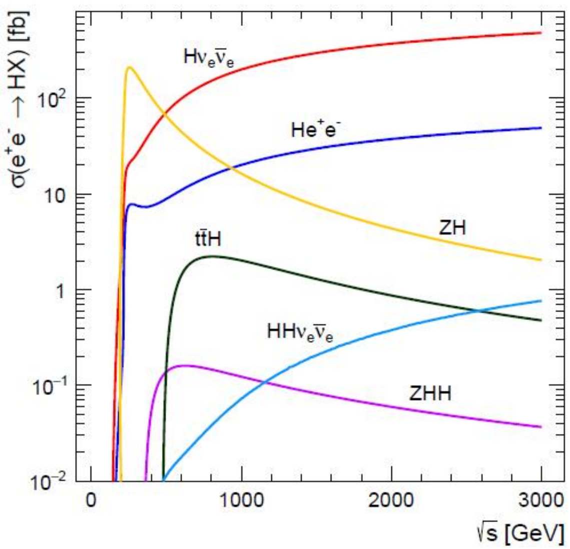
Higgsstrahlung!

Higgs production at CLIC energies



- For CLIC energies, the maximum Higgs cross-section is at 3 TeV, dominated by ee → Hνν mode
- At 250-500 GeV Higgs production is dominated by Higgsstrahlung ee → ZH
- It offers the unique opportunity of model-independent measurement, where Higgs is predicted as a system recoiling against the Z^0
- Although ZH cross-section peaks at ~250 GeV, the optimal precision is reached around 350 GeV

Expected Higgs statistics



$\sqrt{s}$	350 GeV	1.4 TeV	3 TeV
$\mathcal{L}_{\text{int}}$	500 fb^{-1}	1.5 ab^{-1}	2 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
# HZ events	68,000	20,000	11,000
# $H\nu_e\bar{\nu}_e$ events	17,000	370,000	830,000
# He^+e^- events	3,700	37,000	84,000

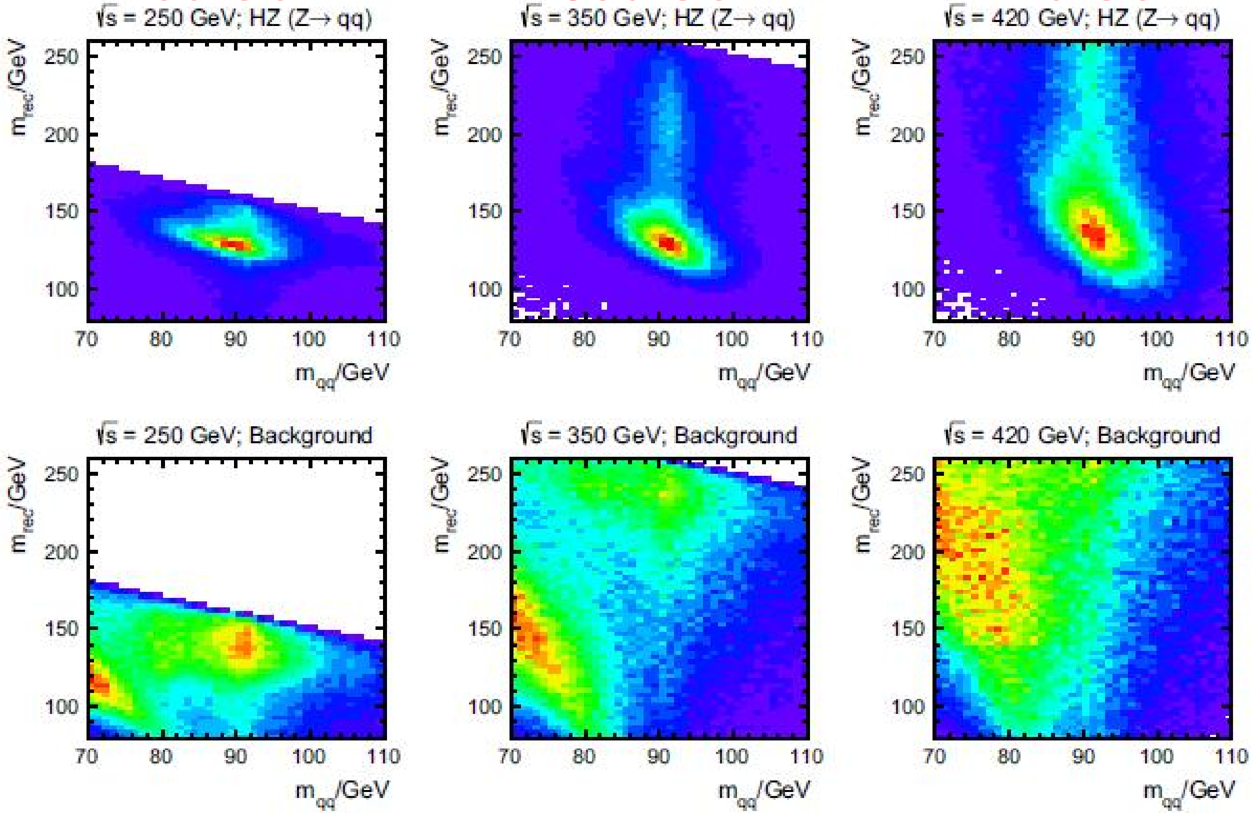
$P(e^-/e^+) = -80/+30\%$: (HZ)x1.4, (Hνν)x2.34

- The really big statistics will be provided by ee → Hνν at high energy running
- However, the ZH events at 350/380 GeV will provide a unique sample of "tagged" Higgses
  - Possibility of model-independent measurements

ee → HZ: energy optimization

Thomson, EPJ C76:72

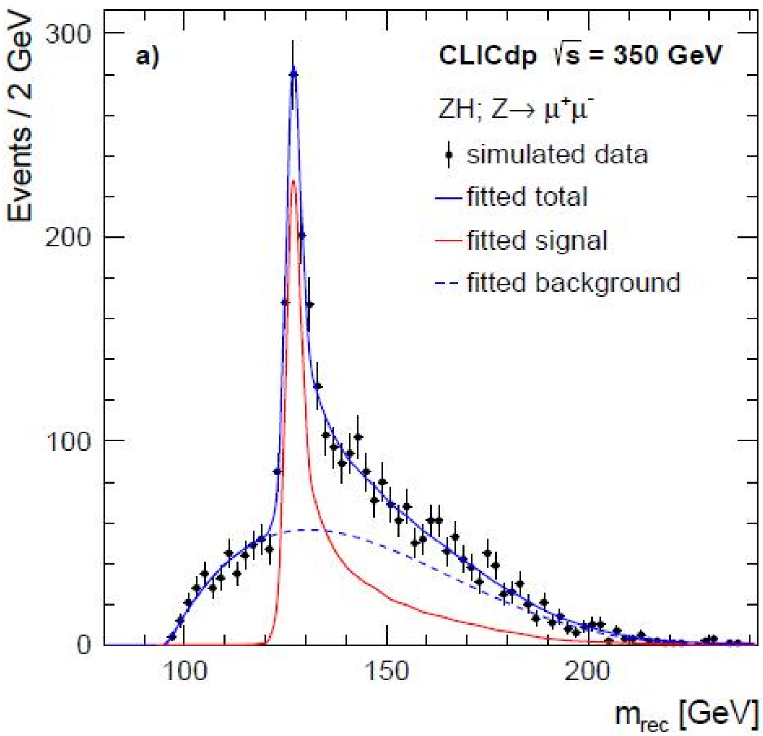
250 GeV **350 GeV** **420 GeV**



250 GeV	350 GeV	420 GeV
σ = 136fb,	σ = 93fb,	σ = 68fb,
Δσ/σ=3.65%	Δσ/σ=1.80%	Δσ/σ=2.63%

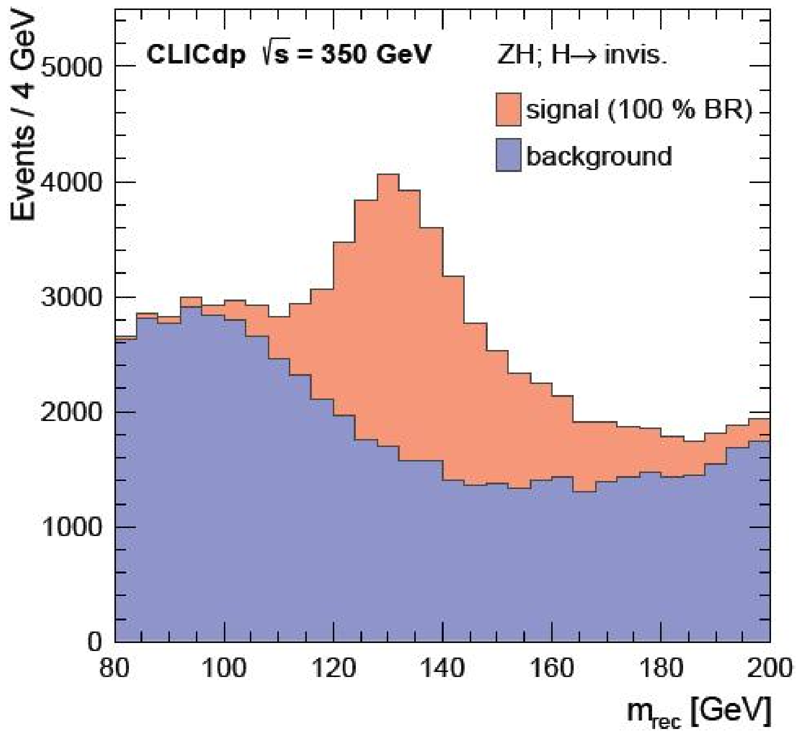
ZH with Z^0 reconstruction

M_H from recoil mass



$\sigma(M_H)$=110 MeV

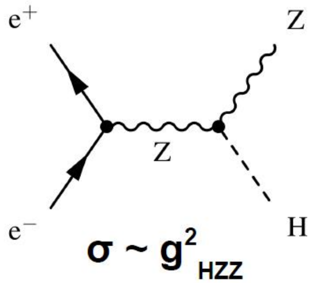
Invisible Higgs decays

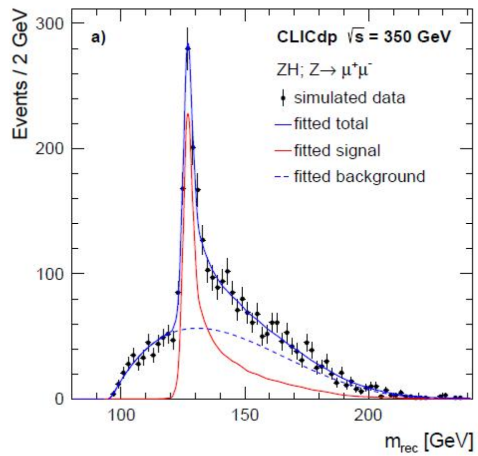


BR(H→invis)<0.97% (90%CL)

[SM: 0.1%]

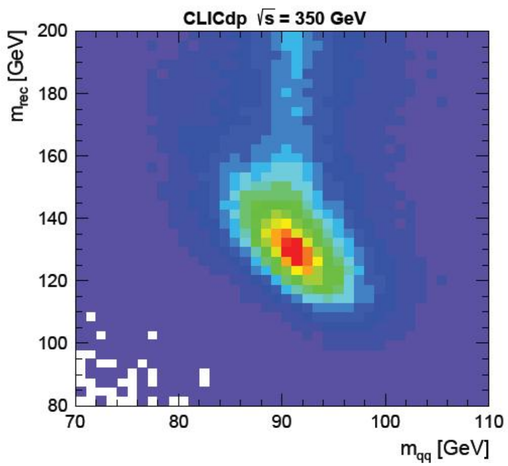
Model-independent measurement of HZZ coupling



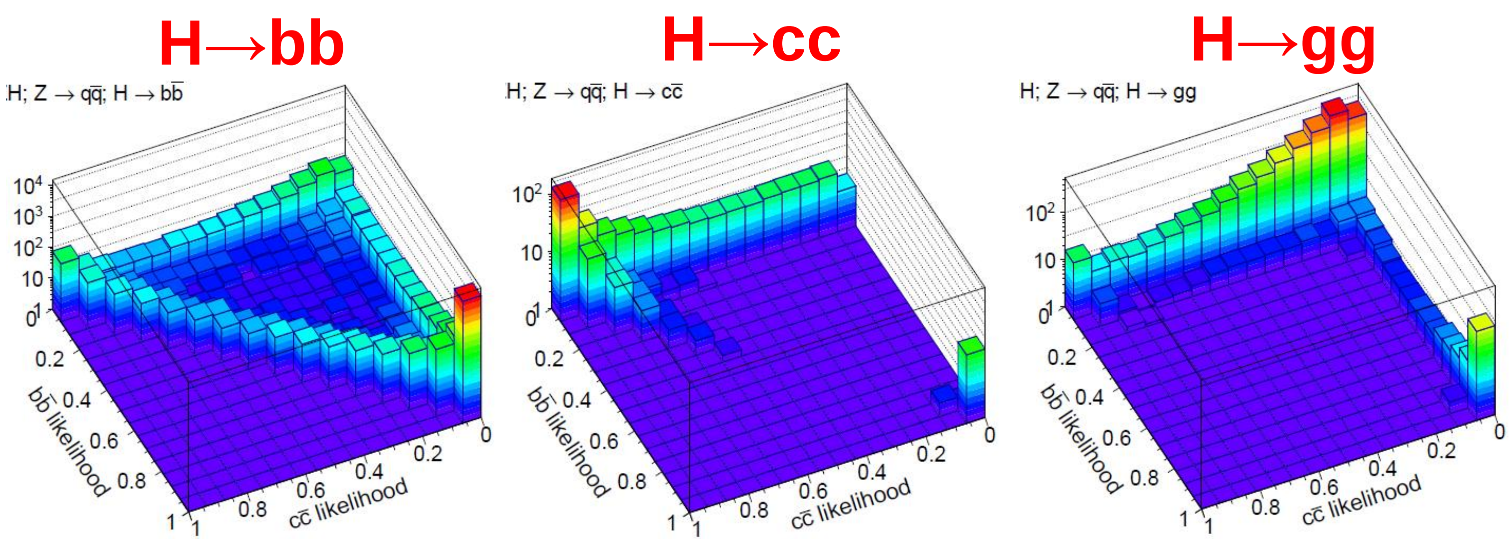


- Higgs is "tagged" rather than reconstructed
- Selection efficiency nearly independent from the Higgs decay mode
- Combining Z→ℓℓ and Z→qq:

$$\frac{\Delta\sigma(\mathrm{ZH})}{\sigma(\mathrm{ZH})} = 1.65\,\% \qquad \frac{\Delta g_{\mathrm{HZZ}}}{g_{\mathrm{HZZ}}} = 0.8\,\%$$



Higgs hadronic branchings



- Hadronic decay preselection
  - ZH → 4jets
  - (ZH, Hνν) → 2jets + missing p_T
- bb/cc/gg jets are separated using the MVA technique based on flavour tagging

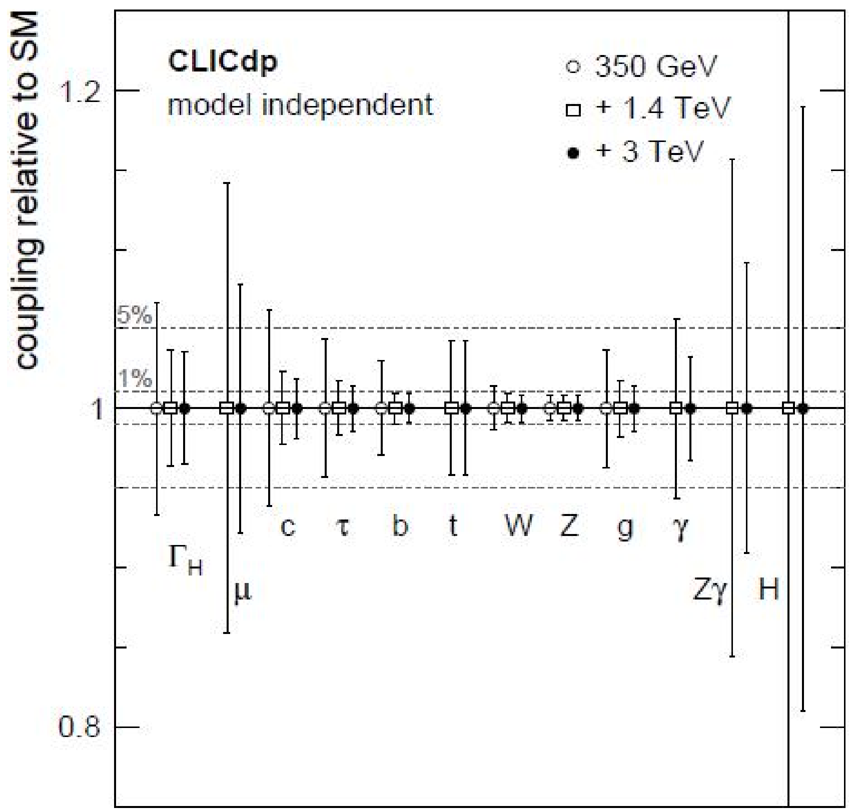
Decay	Statistical uncertainty	
	Higgsstrahlung	WW-fusion
$H \to b\bar{b}$	0.86 %	1.9 %
$H \to c\bar{c}$	14 %	26 %
$H \to gg$	6.1 %	10 %

Model-independent fit to Higgs couplings

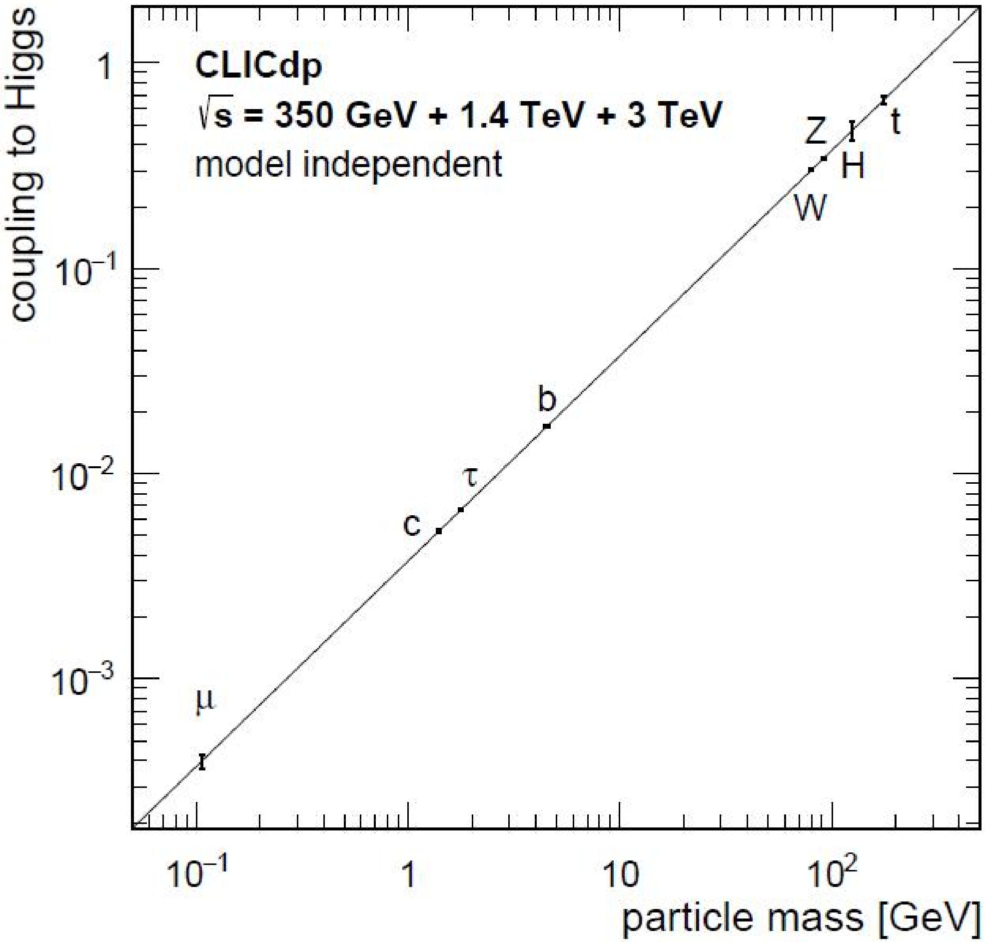
$$\frac{\sigma(e^+e^- \to ZH) \times BR(H \to b\bar{b})}{\sigma(e^+e^- \to \nu_e\bar{\nu}_e H) \times BR(H \to b\bar{b})} \propto \left(\frac{g_{HZZ}}{g_{HWW}}\right)^2$$

$$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*) \propto \frac{g^4_{HWW}}{\Gamma_H}$$

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 %



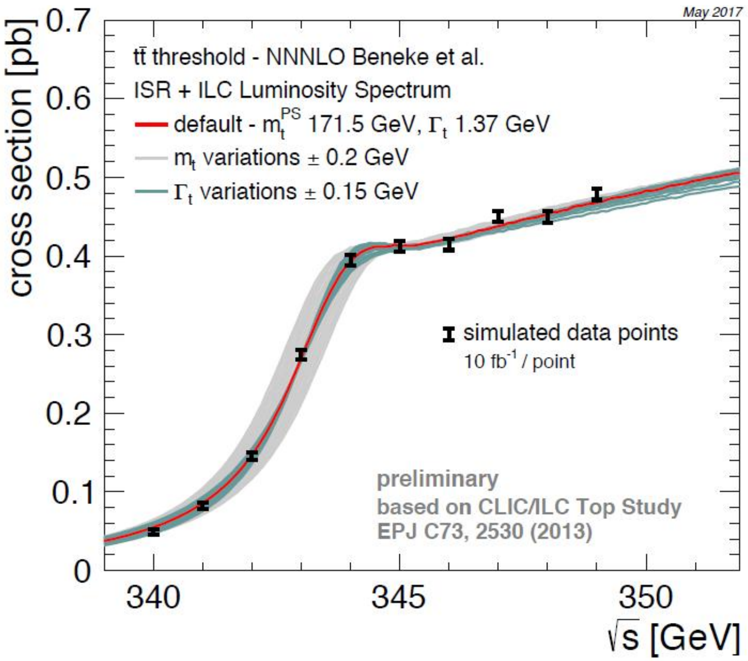
Higgs coupling precision



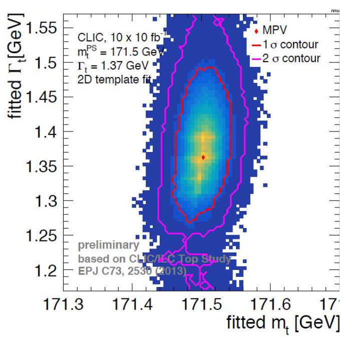
Top physics at 350-380 GeV

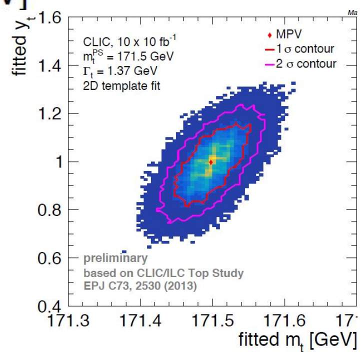
- Top mass (and width) from threshold scan
- Top mass from jet reconstruction
- Rare Top decays
- Precision electroweak couplings

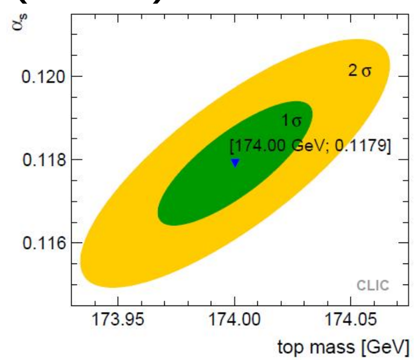
Top threshold scan



- 10 points, 10fb^{-1} each (1 year running at 350 GeV)
- Cross-section curve directly sensitive to the top mass, width, Yukawa coupling, strong coupling constant
- $\delta(m_t)$=±20MeV(stat) ±40MeV(syst) ±40 MeV(scale)
- $\delta(\Gamma_t)$=±45MeV(stat) ±60MeV(scale)

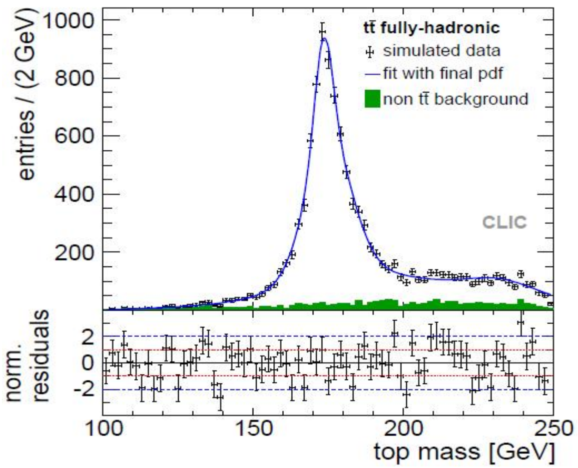






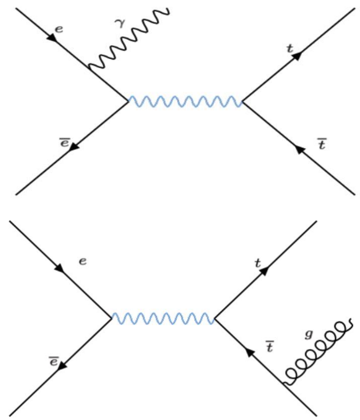
Top mass above threshold

Invariant mass reconstruction



- Systematics-dominated measurement
- Experimental systematic error on m_t about ±80 MeV, dominated by Jet Energy Scale
- Similar statistical error reached already with 100 fb^{-1}
- Additional theoretical errors from scale and colour reconnection uncertainties

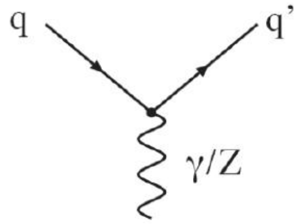
Radiative events

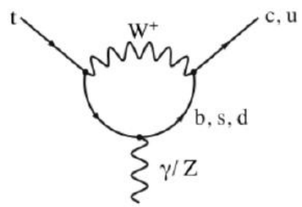


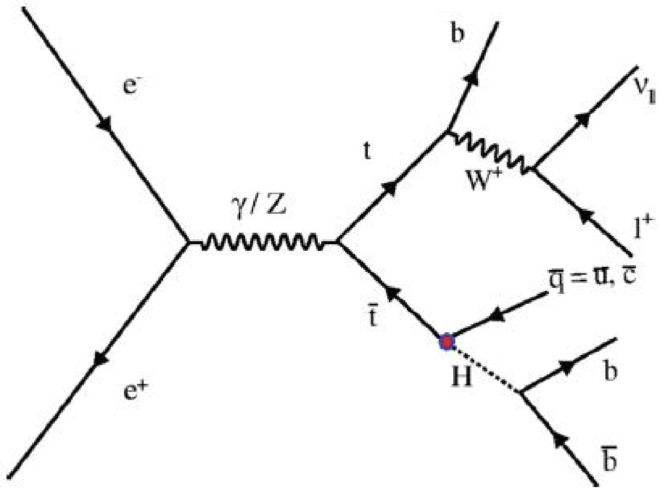
- Idea: measure differential cross-section of ISR (extra photon) or FSR (extra jet)
- Work in progress
- Very preliminary estimate: expect m_t precision of the order of ±100 MeV

Rare top decays

- The FCNC decays $t \to c\gamma/cZ/cg/cH$ have negligible branchings in the Standard Model (10^{-12}-10^{-14})
- Currently 2 channels are under study: $t \to c\gamma$ and $t \to cH$
- Signal: for $ee \to tt$ one top decays anomalously, another decay is standard, $t \to Wb$

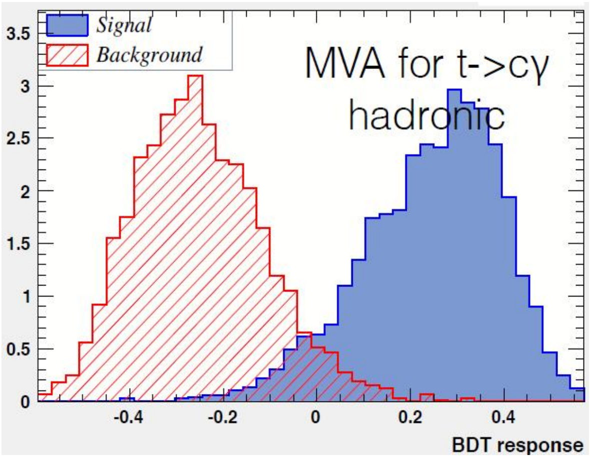




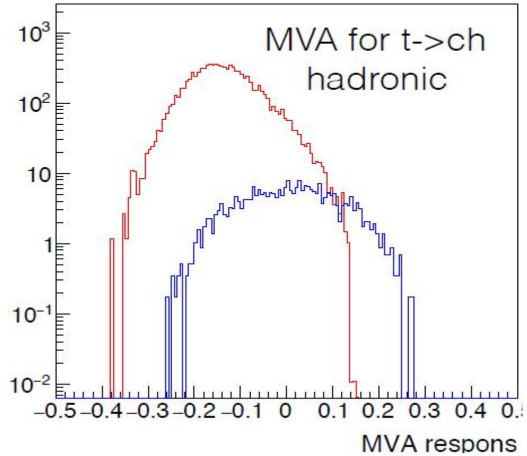


Rare top decays very preliminary results

- $t \to c\gamma$
  - CLIC sensitivity: $BR(t \to c\gamma) < 0.5 \cdot 10^{-4}$ (95%CL)
  - Expected HL-LHC: $2 \cdot 10^{-4}$



- $t \to cH$
  - CLIC sensitivity: $BR(t \to cH) < 1.6 \cdot 10^{-4}$ (95%CL)
  - Expected HL-LHC: $2 \cdot 10^{-4}$

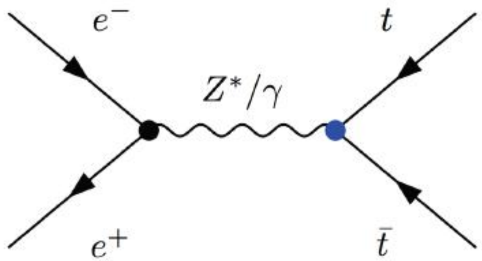


Top electroweak couplings

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

vector — axial — tensor — CPV

- Observables to distinguish Z and γ couplings:
  - Energy dependence of the cross-section
  - Forward-backward charge asymmetry
  - Beam polarization asymmetry (P_{e^-} = ±80%)
  - Top quark polarization
  - Spin correlation
- Deviations from SM can be parameterized in terms of New Physics, e.g. in the EFT language

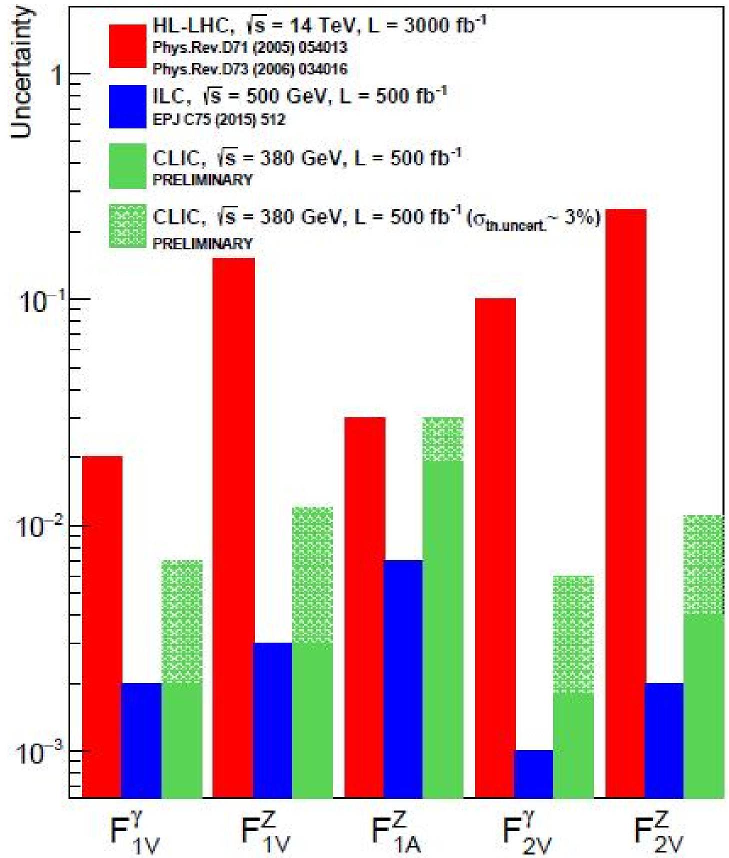


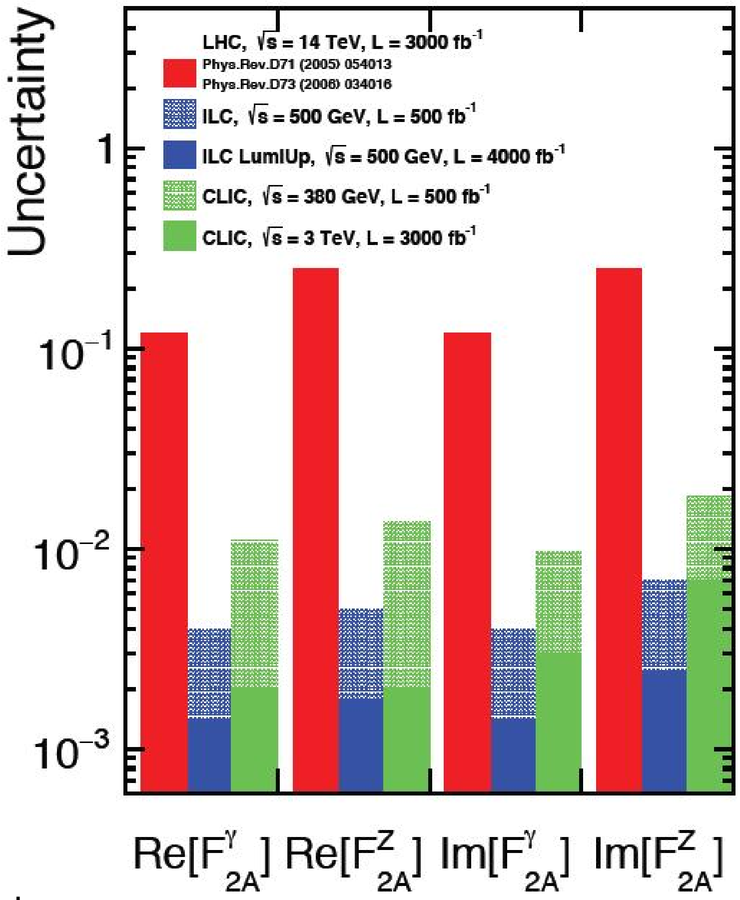
$$\begin{aligned}
F_{1,V}^Z - F_{1,V}^{Z,SM} &= \frac{1}{2}\left(C_{\varphi Q}^{(3)} - C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^V \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_{1,A}^Z - F_{1,A}^{Z,SM} &= \frac{1}{2}\left(-C_{\varphi Q}^{(3)} + C_{\varphi Q}^{(1)} - C_{\varphi t}\right)\frac{m_t^2}{\Lambda^2 s_W c_W} = -\frac{1}{2}C_{\varphi q}^A \frac{m_t^2}{\Lambda^2 s_W c_W} \\
F_{2,V}^Z &= \left(\mathrm{Re}\{C_{tW}\}c_W^2 - \mathrm{Re}\{C_{tB}\}s_W^2\right)\frac{4m_t^2}{\Lambda^2 s_W c_W} = \mathrm{Re}\{C_{uZ}\}\frac{4m_t^2}{\Lambda^2} \\
F_{2,V}^\gamma &= \left(\mathrm{Re}\{C_{tW}\} + \mathrm{Re}\{C_{tB}\}\right)\frac{4m_t^2}{\Lambda^2} = \mathrm{Re}\{C_{uA}\}\frac{4m_t^2}{\Lambda^2} \\
[F_{2,A}^Z, F_{2,A}^\gamma] &\propto [\mathrm{Im}\{C_{tW}\}, \mathrm{Im}\{C_{tB}\}]
\end{aligned}$$

Top coupling sensitivity

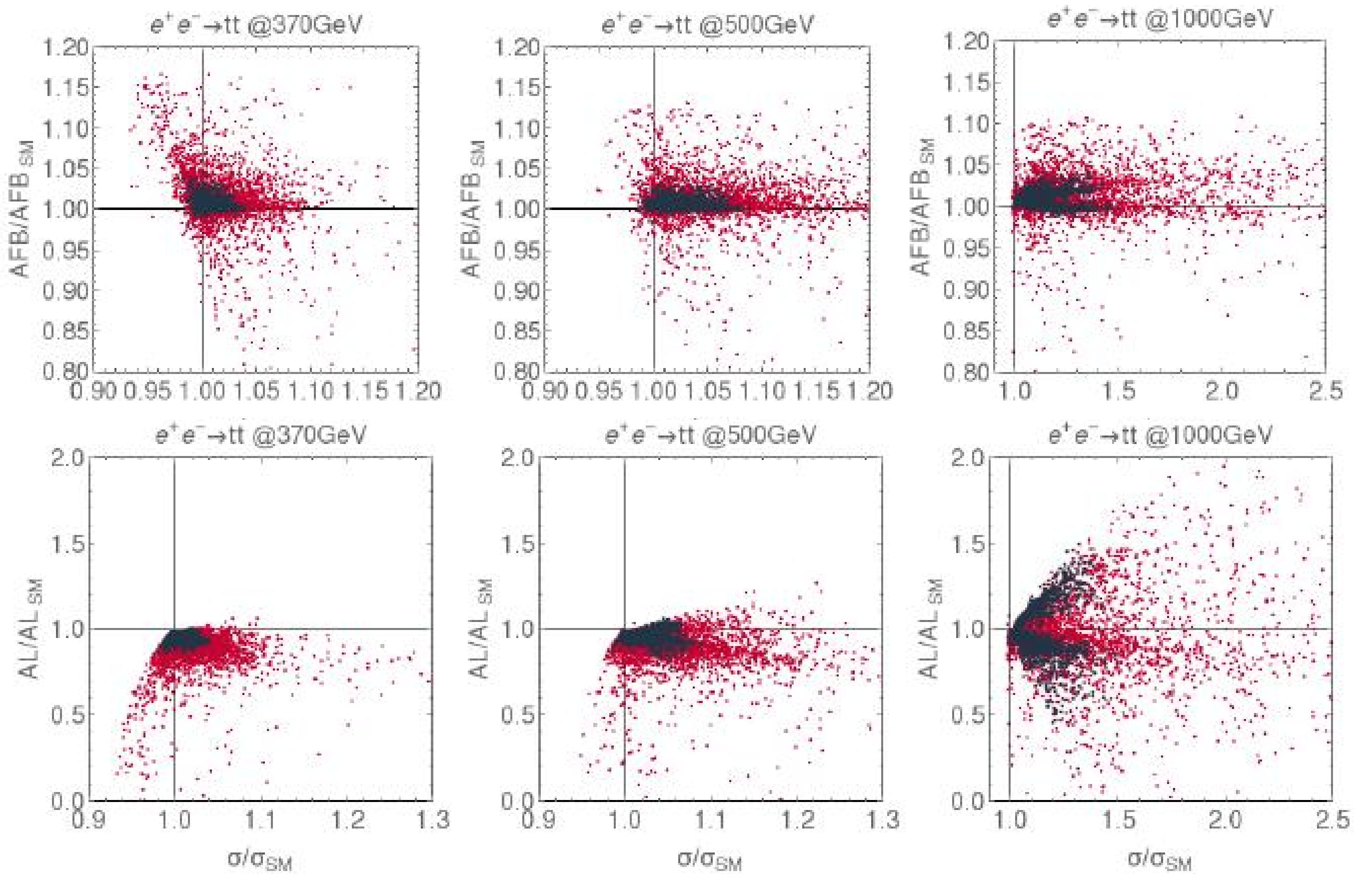
$$\Gamma^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2)+\gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2)+\gamma_5F_{2A}^X(k^2)\right)\right\}$$

vector axial tensor CPV





Top couplings: composite Higgs scenario



Barducci et al, 1504.05407

Points: 4DCHM scan with f=0.75-1.5 TeV, g_ρ=1.5-3

Summary

- CLIC-380 will be the first step on the way to the ultimate energy frontier at 3 TeV
- However, this stage on its own will provide invaluable data for precision measurements
  - Model-independent, low-systematics measurements with ZH sample
  - Top mass with unprecedented precision from the threshold scan
  - Precision top-quark measurements with the huge sample of tt pairs
  - Although direct BSM discoveries require higher energy, the hints of New Physics may be observed as small deviations in precision measurements