Proposed updated CLIC staging baseline and physics implications

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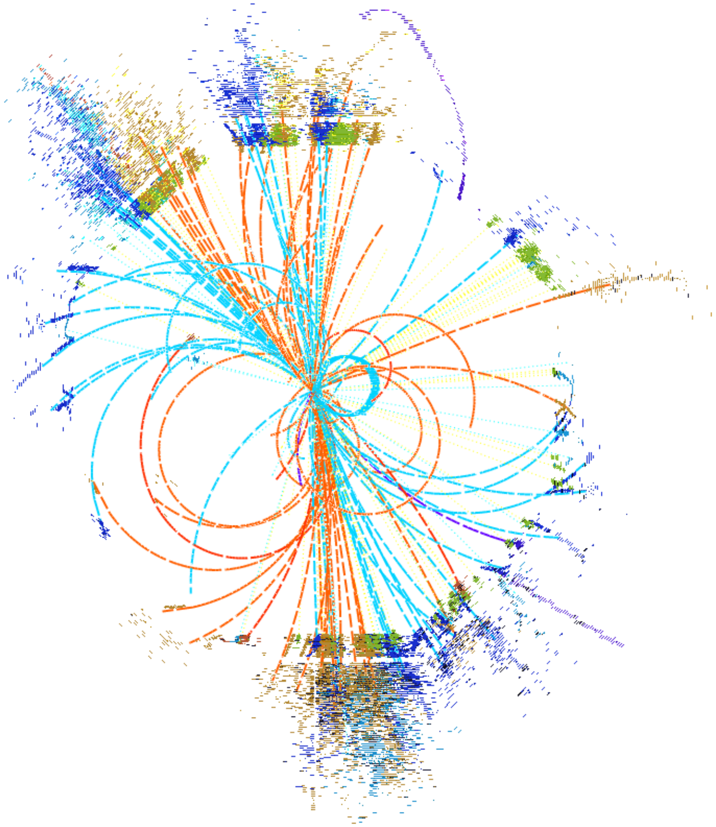
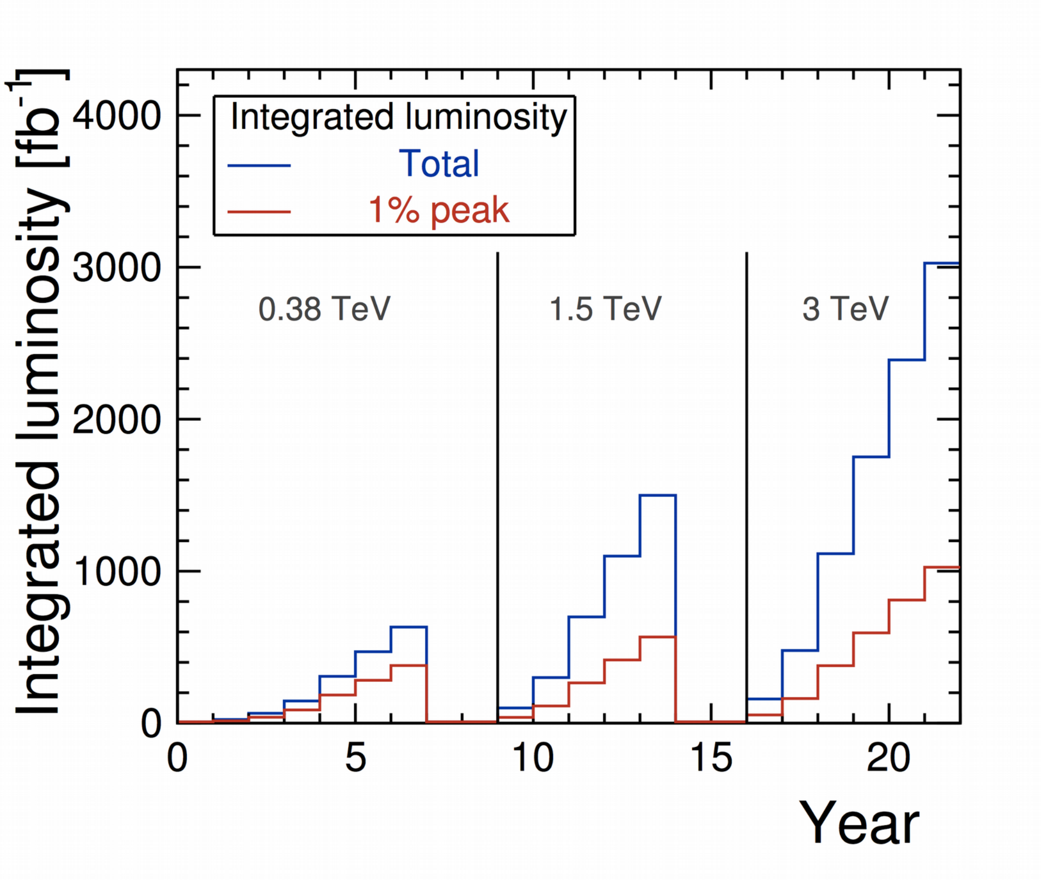
CLICdp general meeting



26/07/2018
CERN, Geneva

Reminder: published baseline scenario



- Initial stage at 380 GeV optimised for Higgs and top measurements (including $t\bar{t}$ threshold scan)

- Baseline scenario of 22 years with three energy stages presented in CERN-2016-004

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

Motivations for an update

1.) Physics:

- σ(ZH) using recoil method only possible at the first stage
→ limited by relatively short first stage
(only 3 years with nominal luminosity)

- Several flagship measurements at high energy, e.g. double Higgs, limited by statistics

2.) More consistency with other options:

- Run time per year:
1.08×10^7 s (CLIC), 1.2×10^7 s (FCC-ee), 1.6×10^7 s (ILC)

- Very different ramp-up scenarios (CLIC most conservative)

Other considerations

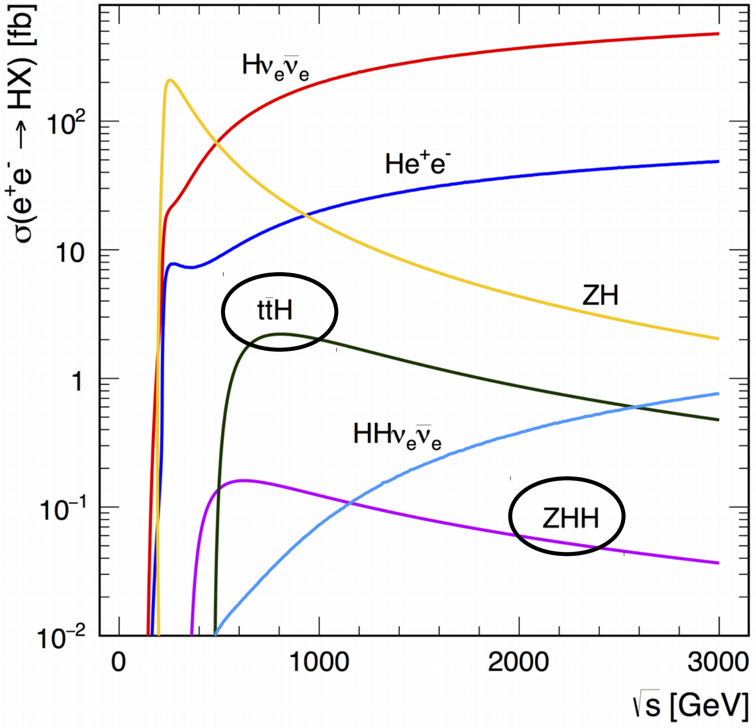
1.) CLIC Stage at 550 GeV for $t\bar{t}H$ and ZHH?

- $\Delta g_{ttH}/g_{ttH} \approx$ 3% using $L = 4\ \mathrm{ab}^{-1}$ (ILC study)
- $\Delta\lambda/\lambda \approx$ 25% using $L = 4\ \mathrm{ab}^{-1}$ (ILC study scaled)

HL-LHC: $\Delta g_{ttH}/g_{ttH} = 8.5\%$, $\Delta\lambda/\lambda \approx 50\%$

→ Only attractive if we can get to O(5) ab^{-1}

arXiv:1506.05992, ATLAS-PHYS-PUB-2014-016

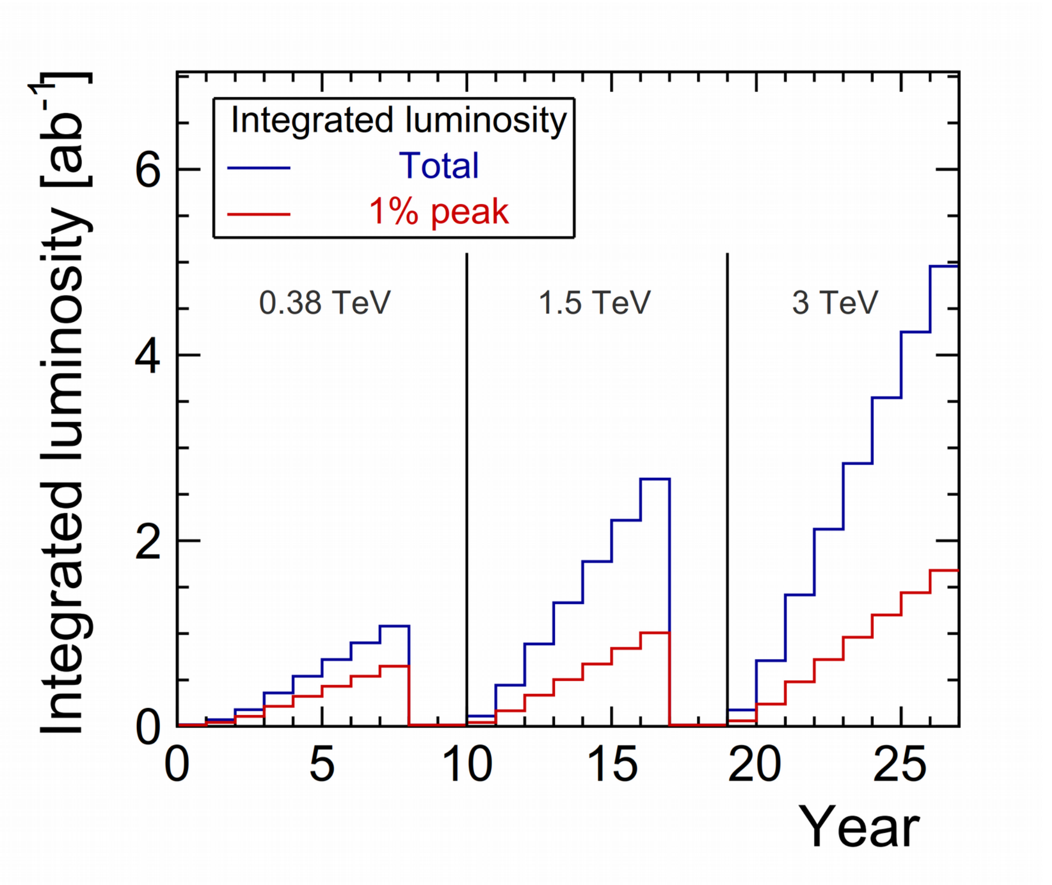


2.) Two instead of three stages?

- Very interesting to study impact, e.g. in in global EFT fits

- However, each stage provides unique physics opportunities
→ important not to limit new ideas too much by the baseline strategy

Proposed updated staging baseline



- The energies of the three stages are unchanged
- Ramp up first stage: 10% / 30% / 60% ramp up 2nd and 3rd stage: 25% / 75% (identical to ILC)
- Following presentation by Frédérick Bordry in the SPC:
  1 year = 1.2×10^7 seconds
  (75% of 185 days)
- Full program of 27 years provides:

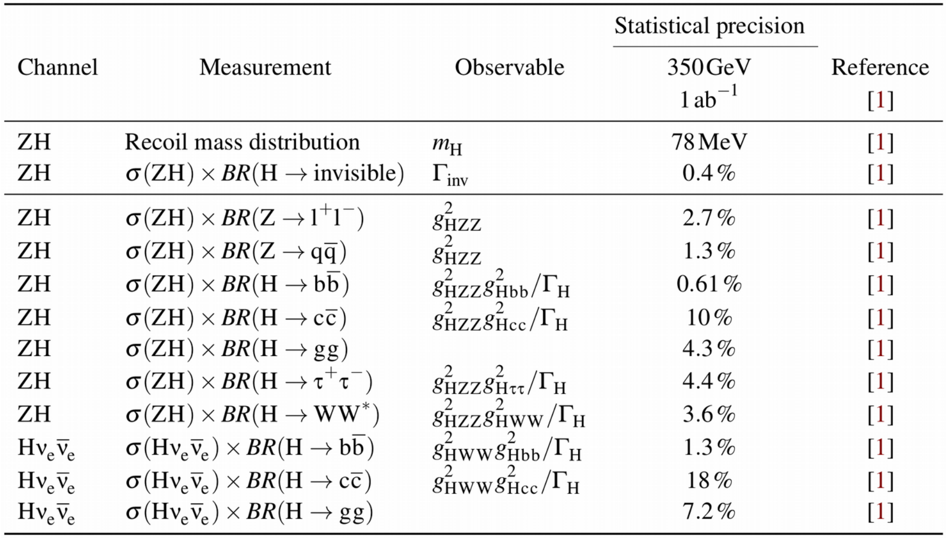
1 ab^{-1} at 380 GeV
(incl. $t\bar{t}$ threshold scan)
+ 2.5 ab^{-1} at 1.5 TeV
+ 5 ab^{-1} at 3 TeV

Based on discussions with Lucie Linssen, Aidan Robson, Frank Simon, Daniel Schulte and Steinar Stapnes.

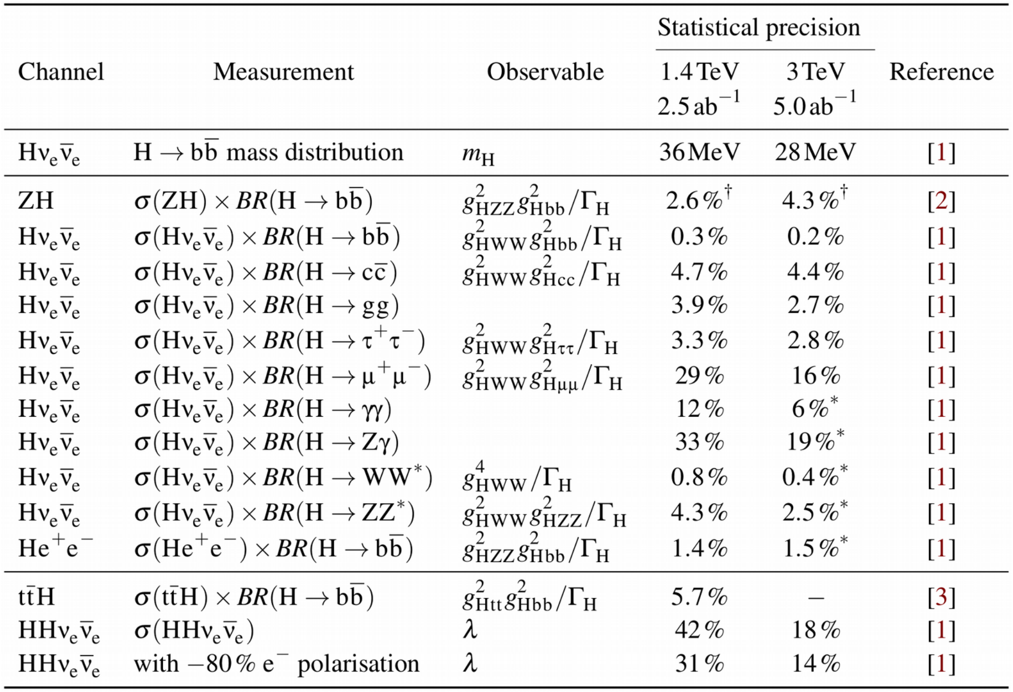
Impact on the physics potential

(mostly Higgs)

CLIC Higgs coupling sensitivity



Channel	Measurement	Observable	Statistical precision 350 GeV 1 ab^{-1}	Reference [1]
ZH	Recoil mass distribution	m_H	78 MeV	[1]
ZH	$\sigma(ZH) \times BR(H \to \text{invisible})$	Γ_{inv}	0.4 %	[1]
ZH	$\sigma(ZH) \times BR(Z \to l^+l^-)$	g^2_{HZZ}	2.7 %	[1]
ZH	$\sigma(ZH) \times BR(Z \to q\bar{q})$	g^2_{HZZ}	1.3 %	[1]
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	0.61 %	[1]
ZH	$\sigma(ZH) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	10 %	[1]
ZH	$\sigma(ZH) \times BR(H \to gg)$		4.3 %	[1]
ZH	$\sigma(ZH) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	4.4 %	[1]
ZH	$\sigma(ZH) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	3.6 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	1.3 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	18 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		7.2 %	[1]



Channel	Measurement	Observable	Statistical precision 1.4 TeV 2.5 ab^{-1}	 3 TeV 5.0 ab^{-1}	Reference
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	36 MeV	28 MeV	[1]
ZH	$\sigma(ZH) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	2.6 %†	4.3 %†	[2]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	0.3 %	0.2 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	4.7 %	4.4 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		3.9 %	2.7 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	3.3 %	2.8 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	29 %	16 %	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		12 %	6 %*	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		33 %	19 %*	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	0.8 %	0.4 %*	[1]
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	4.3 %	2.5 %*	[1]
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1.4 %	1.5 %*	[1]
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	5.7 %	–	[3]
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	42 %	18 %	[1]
$HH\nu_e\bar{\nu}_e$	with −80 % e^- polarisation	λ	31 %	14 %	[1]

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

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

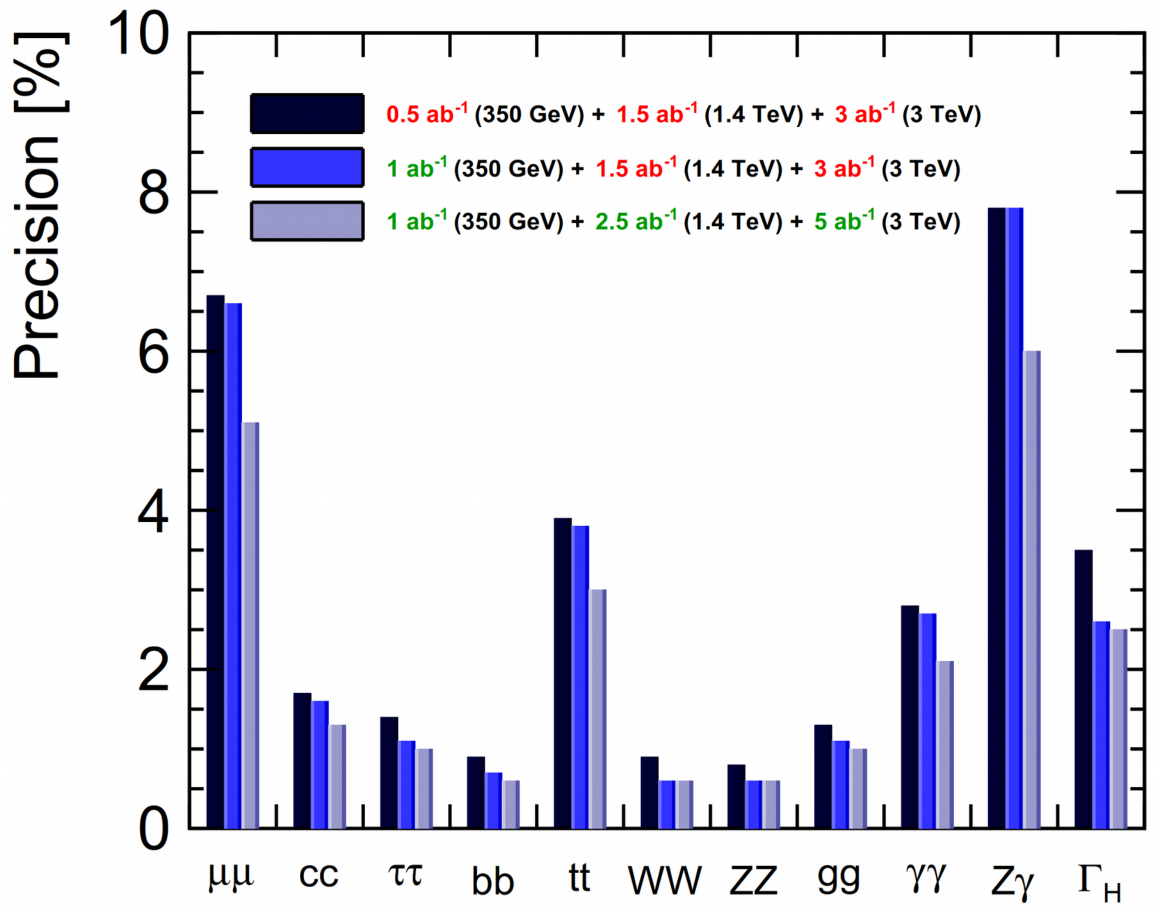
$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to VV/ff) \sim g^2_{HWW}g^2_{HVV/Hff} / \Gamma_H$

- No assumptions on additional Higgs decays (requires lepton collider)
- Correlations of the measurements included where relevant
- All results limited by σ(HZ) measurement

*: extrapolated from 1.4 to 3 TeV
†: fast simulation

[1] Eur. Phys. J. C 77, 475 (2017)
[2] JHEP 05, 096 (2017)
[3] arXiv:1807.02441 (2018)

Impact of the updated luminosities



- More luminosity at the first stage also increases the sensitivity of the full program (g_{HZZ}, g_{HWW}, g_{Hbb}, Γ_H, ...)
- Couplings from rare decays and g_{ttH} benefit from more luminosity at high energies

Comparison to HL-LHC

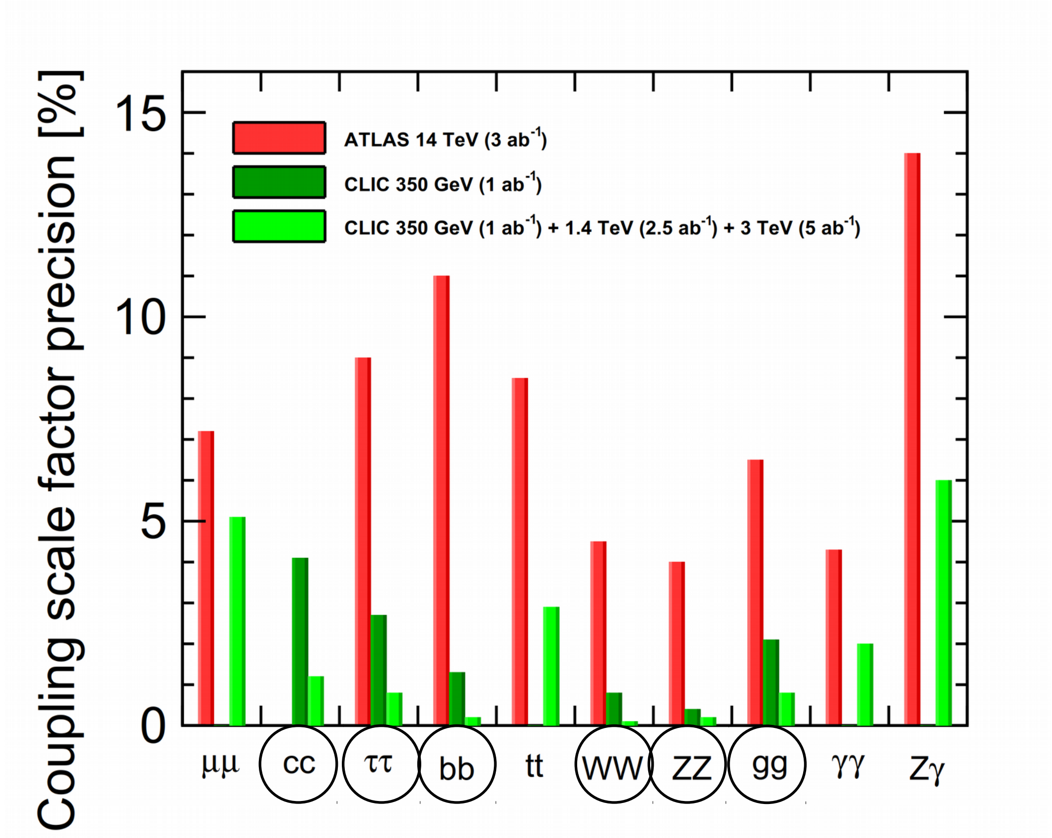
Model dependent fit:

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

Only SM Higgs decays:

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

BR$_i$: SM branching fractions (prediction)



- Already the first CLIC stage significantly better than HL-LHC for several couplings
- The full program enhances the precision further
- μμ, γγ and Zγ would benefit from HL-LHC + CLIC combination

ATLAS-PHYS-PUB-2014-016

Impact of beam polarisation

Assumptions on beam polarisation in physics studies have been inconsistent in the past!

- **Higgsstrahlung at first stage:** precision almost independent of electron beam polarisation

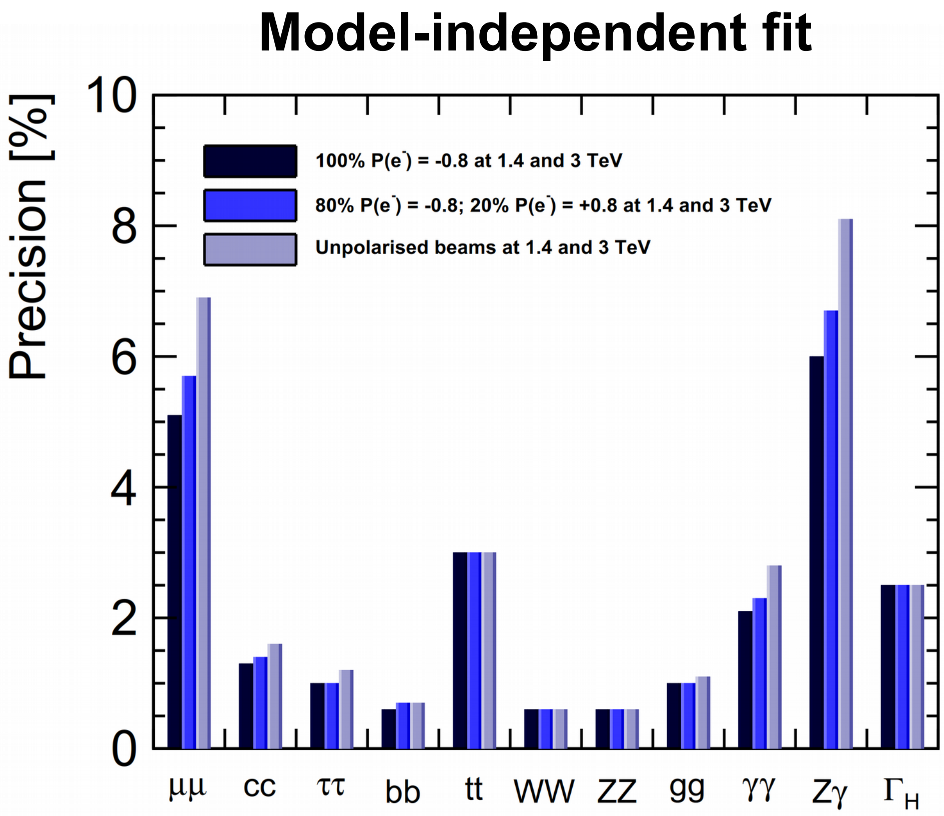
- **$e^+e^- \to H\nu_e\bar{\nu}_e$ and $e^+e^- \to HH\nu_e\bar{\nu}_e$:** cross section scales by 1.8 (0.2) for -80% (+80%) electron beam polarisation
→ The Higgs program prefers the -80% configuration at high energy
(equivalent to reduction of run time due)

- **The BSM sensitivity of two fermion production:** benefits from some fraction with +80%, examples:
1.) **$e^+e^- \to t\bar{t}$** (less than 50% with +80% acceptable)
2.) **Z' from $e^+e^- \to \mu^+\mu^-$** (systematics limited already with 1 ab^{-1})
→ Also at high energy some faction of data with +80% is desired

- **If new physics is discovered:** polarisation might be useful to constrain the underlying theory

Eur. Phys. J. C 77, 475 (2017)
arXiv:1807.02441 (2018)
arXiv:1208.1148 (2012)

Impact of polarisation at the 2nd and 3rd stage



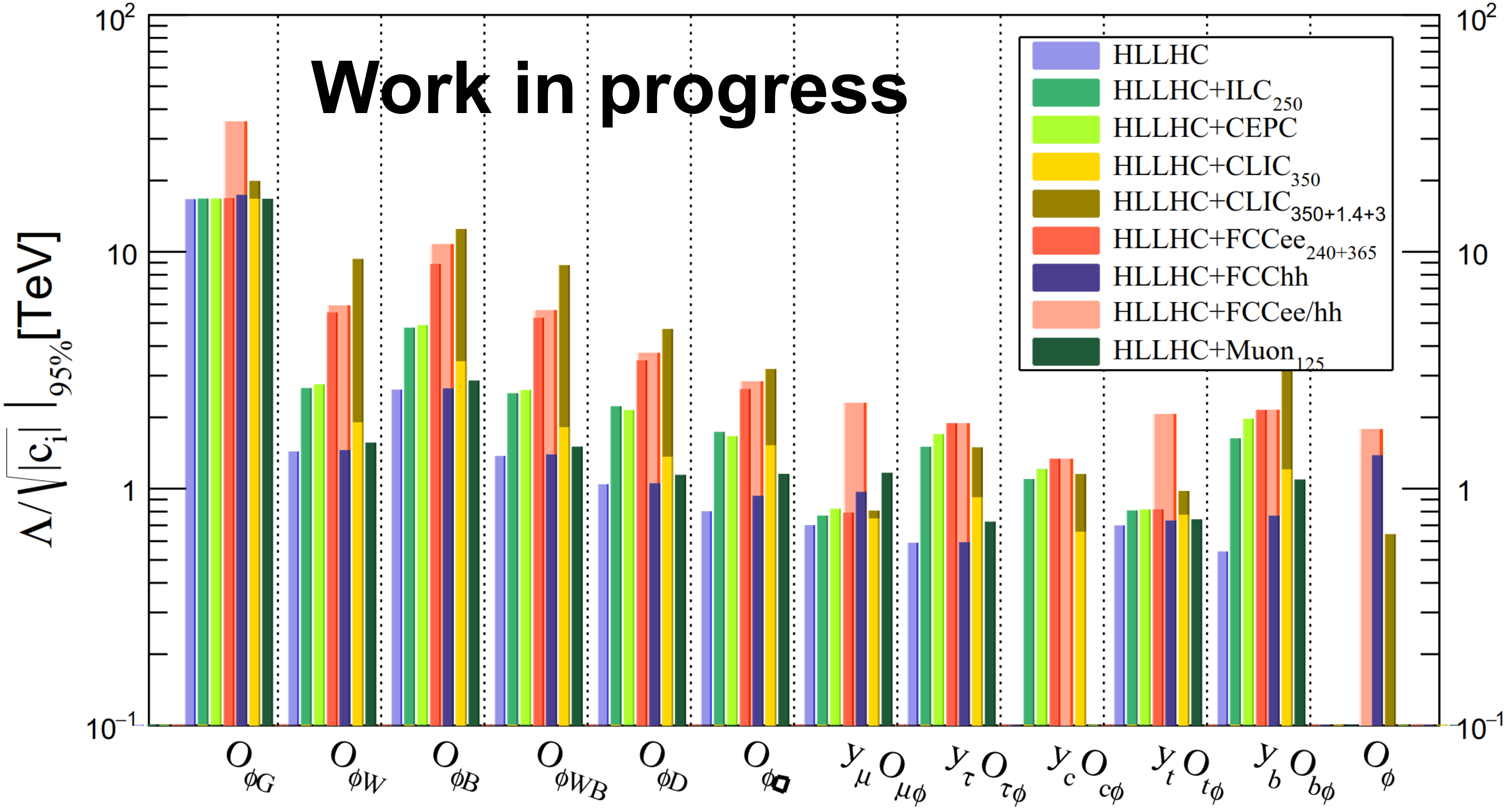
Fraction $P(e^-) = -0.8$	$\Delta\lambda/\lambda$
unpolarised	16.5%
70%	14.4%
80%	13.7%
100%	12.3%

2.5 ab^{-1} at 1.5 TeV + 5 ab^{-1} at 3 TeV

Collecting 80% (70%) of the luminosity with -80% electron beam polarisation at high energy corresponds to 48% (32%) more run time for double Higgs production and rare decays

NB: <10% precision on λ expected from differential distributions (same dependence on the polarisation)

EFT analysis of Higgs projections



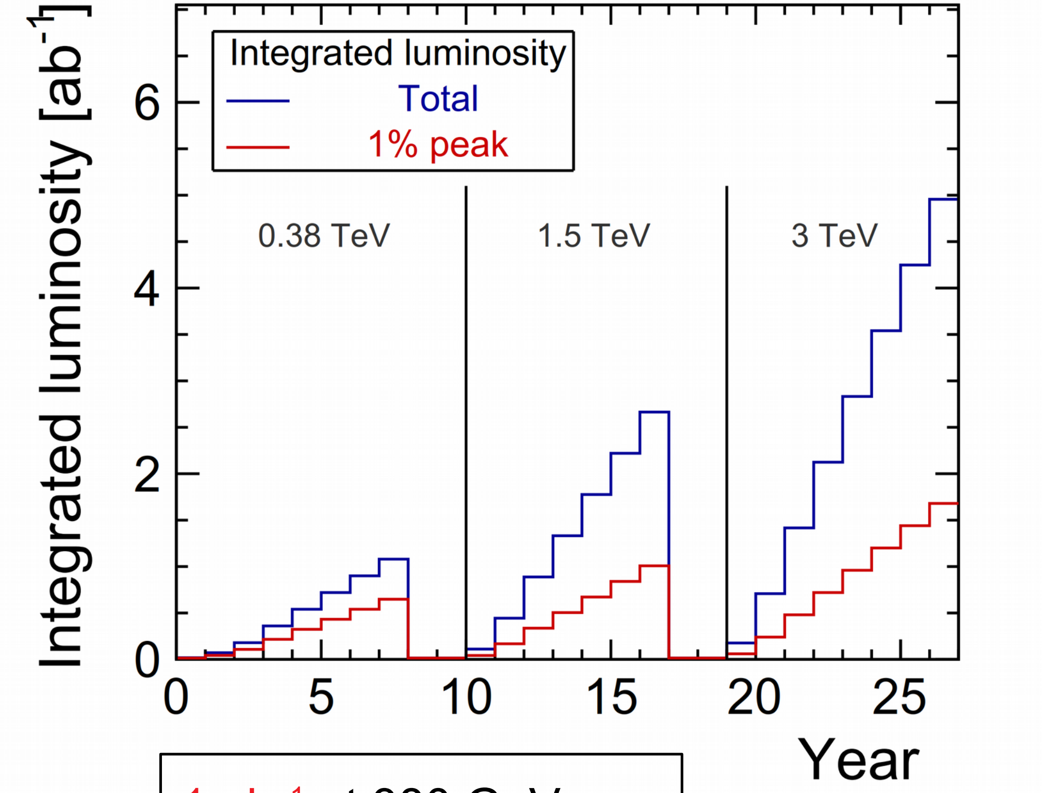
Jorge de Blas

10 - 40% improvement due to proposed updates to the staging scenario

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

For discussion (instead of a summary)

Proposed updated CLIC staging baseline:



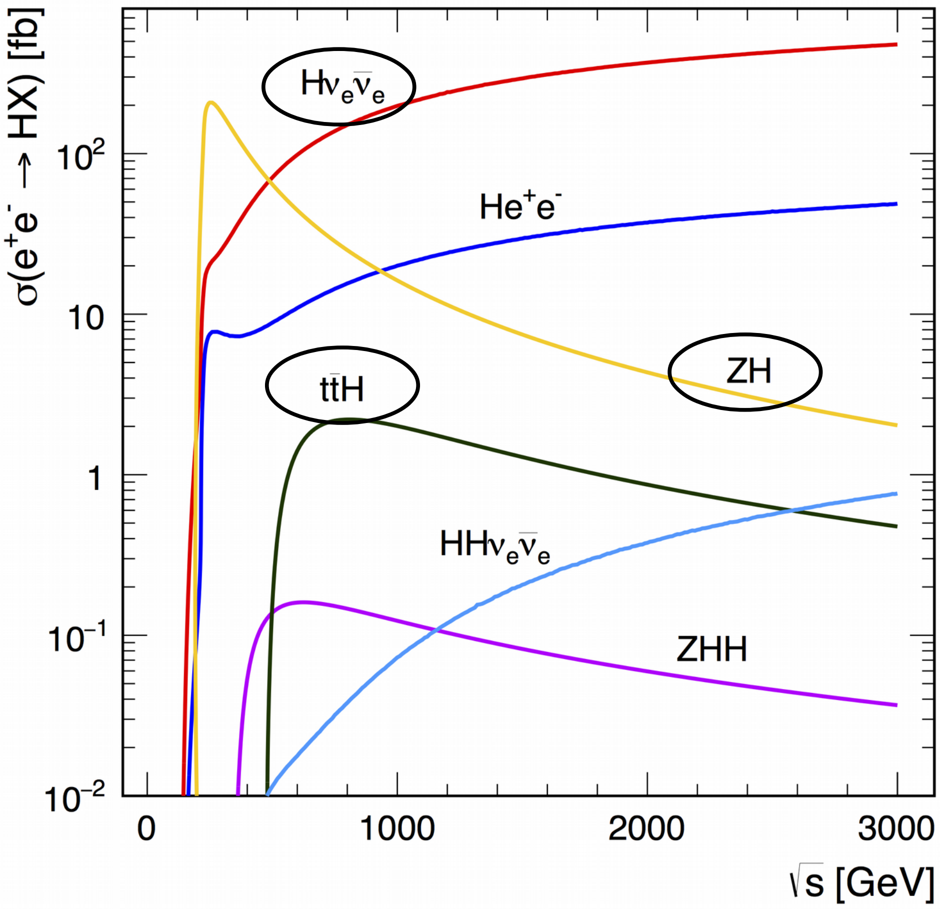
1 ab^{-1} at 380 GeV
(incl. $t\bar{t}$ threshold scan)
\+ 2.5 ab^{-1} at 1.5 TeV
\+ 5 ab^{-1} at 3 TeV

Splitting of beam polarisation configurations to maximise the overall physics potential:

- **380 GeV:** equal luminosity with +80% and -80%
- **1.5 and 3 TeV:** 80% (70%?) of the luminosity with -80% polarisation

Backup slides

Reminder: single Higgs production



Higgsstrahlung: $e^+e^- \to ZH$

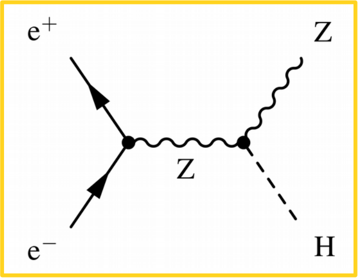
- $\sigma \sim 1/s$, dominant up to ≈ 500 GeV

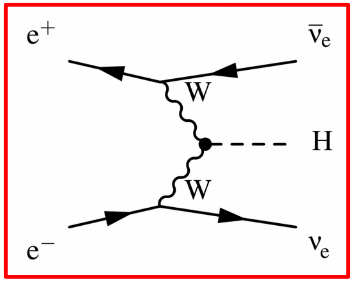
WW fusion: $e^+e^- \to H\nu_e\bar{\nu}_e$

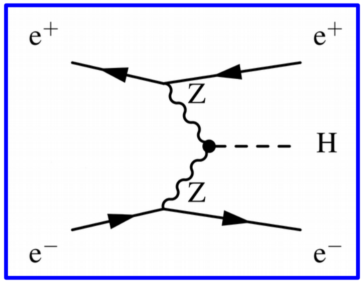
- $\sigma \sim \log(s)$, dominant above 500 GeV
- Large statistics at high energy

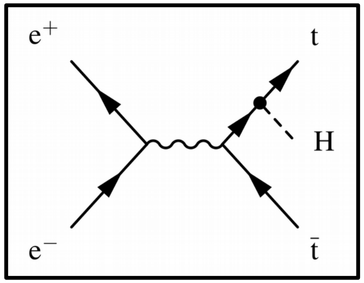
$t\bar{t}H$ production: $e^+e^- \to t\bar{t}H$

- Accessible ≥ 500 GeV, maximum ≈ 800 GeV
- Direct extraction of the top-Yukawa coupling

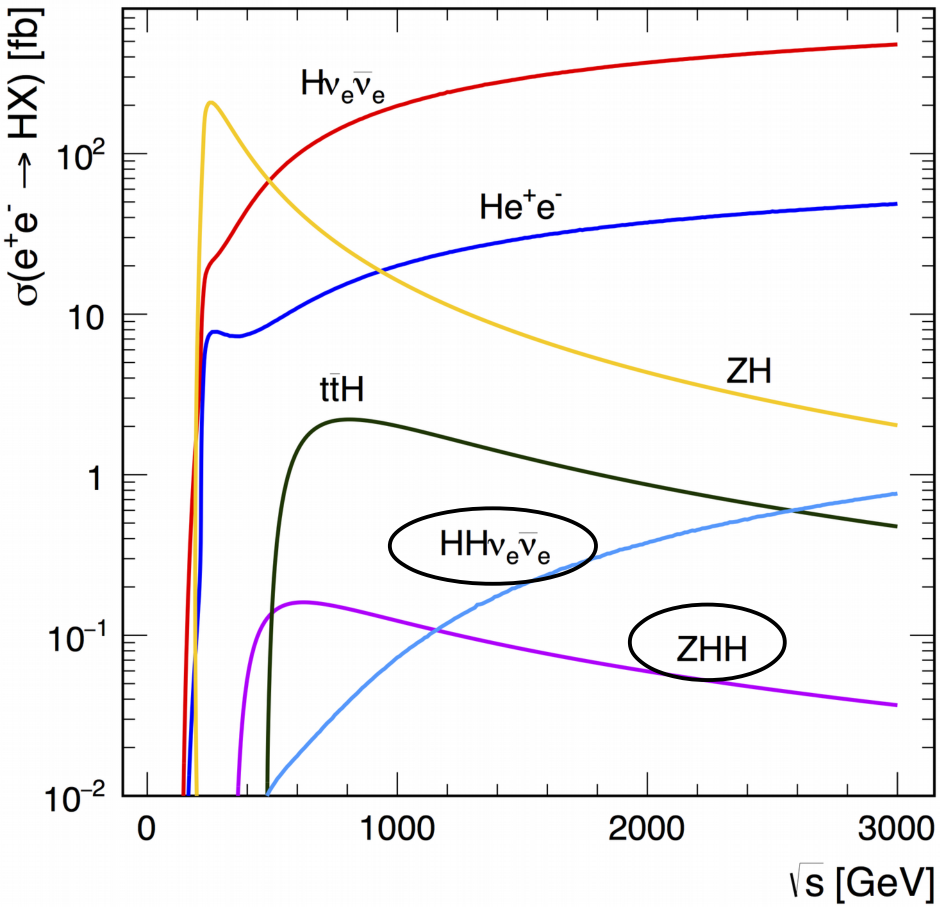








Reminder: double Higgs production



$e^+e^- \to$ ZHH:

- Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \leq 0.2$ fb)

$e^+e^- \to HH\nu_e\bar{\nu}_e$:

- Benefits from high-energy operation
- Also allows to extract the quartic WWHH coupling

The deviations of the Higgs self-coupling from its SM expectation might be sizeable:

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

Phys. Rev. D 88, 055024 (2013)