Prospects for measurement of the Higgs couplings at TLEP

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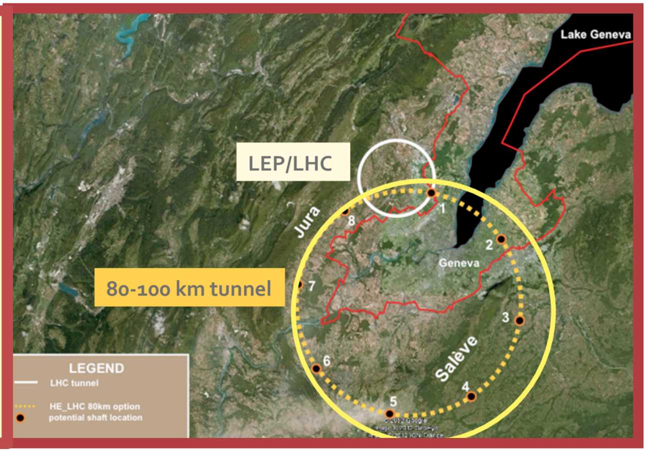
(presented by André David)

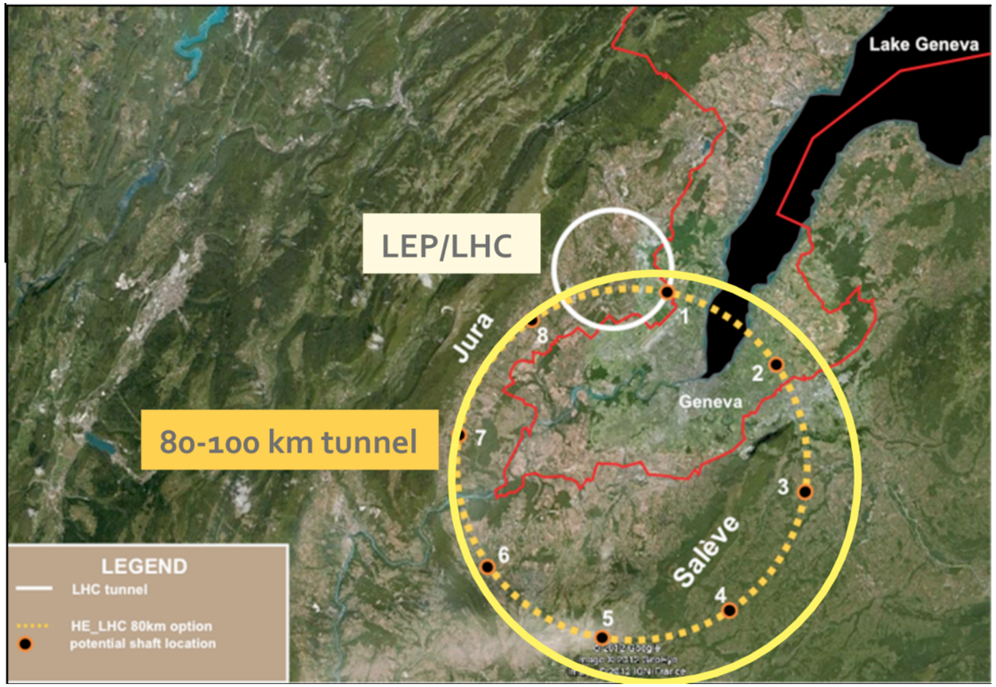
On behalf of the **FCC design study group**



Higgs Coupling 2013 - 14-16 October - Freiburg - Germany

The FCC project: CERN long term vision for HEP

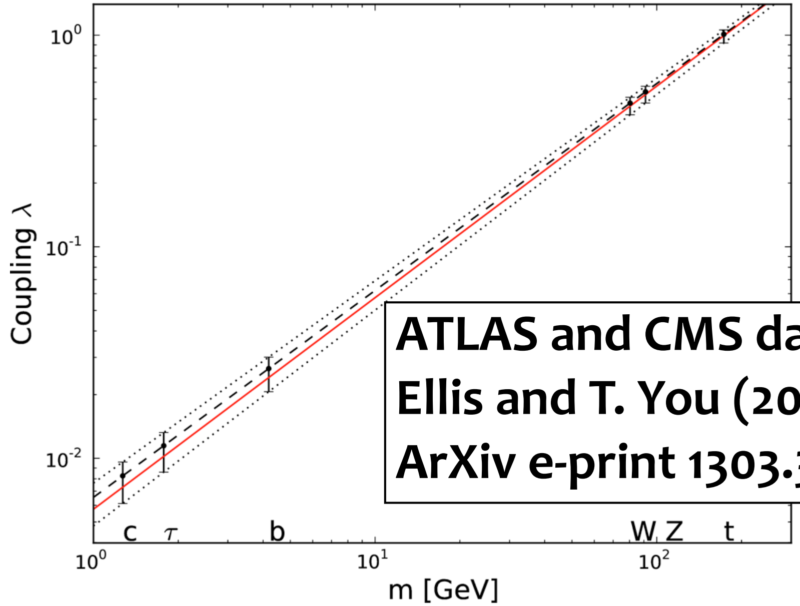
- The FCC (Future Circular Colliders) is now an **official project at CERN** with the highest priority after LHC



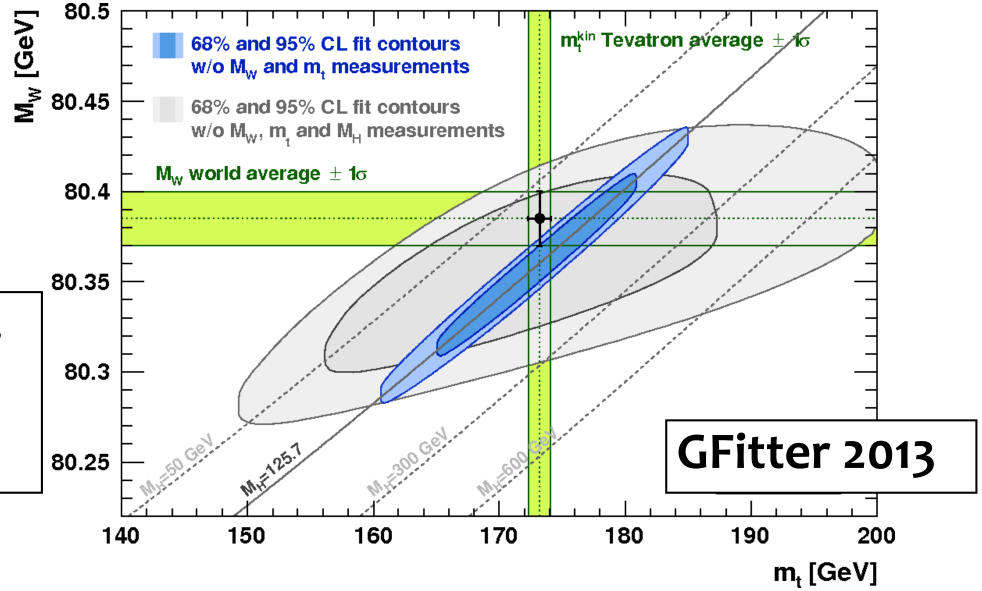
- TLEP: An **e^+e^- collider** in a new **80/100 km** tunnel with center of mass energy from **90 to 350 GeV** and beyond and several interaction points
- VHE-LHC: **an hadron collider** in the same tunnel, at a center of mass energy up to **100 TeV**

- "First look at the physics case of TLEP" just out [**arXiv:1308.6176**]
  - numbers and plots in this talk taken from this paper

Scientific motivation



ATLAS and CMS data, J. Ellis and T. You (2013) ArXiv e-print 1303.3879



GFitter 2013

- Driven by today's experimental situation
  - a **very Standard Model** Higgs boson
  - **no indication of new physics** BSM up to several hundred GeV
- With the results of the high-energy run of LHC (sensitivity for new physics extended up to 1 TeV or more) we might want to
  - Focus on probing the scale of new physics via **indirect measurements:**
    - **Measure with precision all the SM parameters including Higgs boson properties**

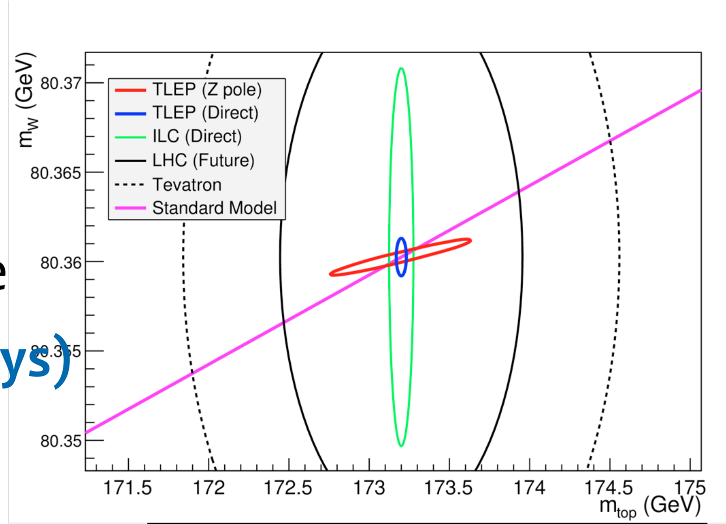
Precision needed

- **Higgs couplings: directly sensitive to New Physics**
  - Expected deviations from SM in the couplings depend on the NP scale

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \mathrm{TeV}}{\Lambda_{NP}}\right)^2$$

with $\delta < 5\%$ (exact value depend on model and coupling)

  - **Need at least a per-cent accuracy for a 5σ observation if $\Lambda_{NP} = 1$ TeV**
    - and a sub-per-cent accuracy for multi-TeV NP scale
  - **Need millions of Higgs bosons**
- **EWSB parameters: Stringent SM closure test**
  - Z pole measurements
    - improve by at least two orders of magnitude
      - **Need > 10^4 times LEP1 statistic (10^{11} Z decays)**
  - Direct m_W and m_{top} measurements
    - improve by at least one order of magnitude
      - **$\delta m_W < 1$ MeV and $\delta m_{top} < 50$ Mev**



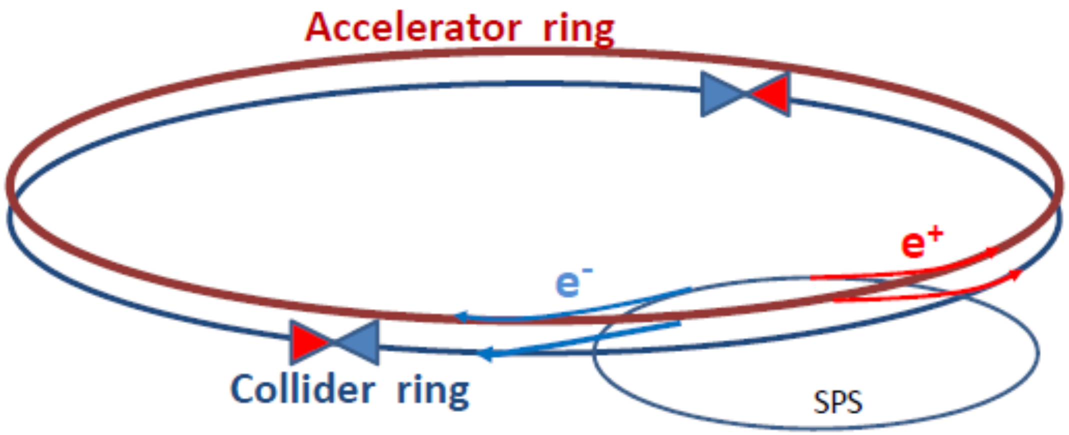
From GFitter, under the assumption that theory uncertainties can be reduced to match the experimental ones

The TLEP+VHE-LHC solution

- **TLEP e^+e^- collider with four interaction points**
  - Baseline preliminary physics program
    - **Tera-Z**: $\sqrt{s} \sim m_Z$ (1-2 years - 5.6 ab^{-1} per year and IP)
    - **Oku-W**: $\sqrt{s} \sim 2m_W$ (1-2 years - 1.6 ab^{-1} per year and IP)
    - **Mega-Higgs**: $\sqrt{s} \sim m_{240}$ GeV (5 years - 500 fb^{-1} per year and IP)
    - **Mega-top**: $\sqrt{s} \sim 2m_{top}$ (5 years - 130 fb^{-1} per year and IP)
- **VHE-LHC pp collisions at $\sqrt{s} \sim$ 100 TeV with 16T magnets**
- To follow the successful historical path for high-energy physics
  - **TLEP physics case**
    - precision measurements sensitive to multi-TeV NP
  - **VHE-LHC physics case**:
    - direct search for NP in the 10-100 TeV range

Luminosity and Energy

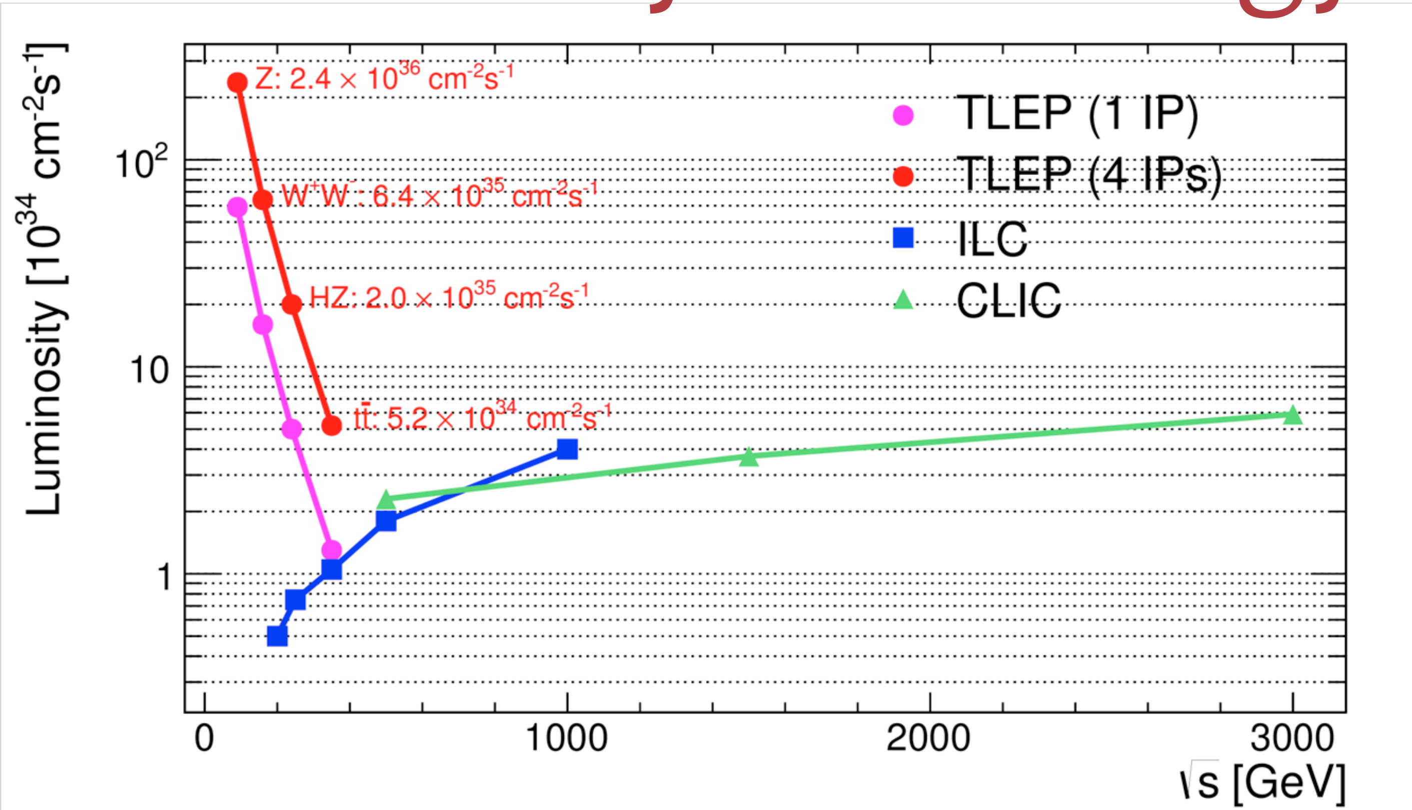
- TLEP collider complex: **accelerator and storage rings**, the former delivering continuous top-up injection (once per min @ 240 GeV)
  - beam lifetime due to **bhabha scattering** ~15 min
  - lifetime further reduced by **beamstrahlung** (harmless effect for physics, because of the rather large beam size)
- 12 GV RF system is designed to compensate for the energy loss by synchrotron radiation @ 350 GeV
  - the RF power is used at low √s to collide **more bunches**



Preliminary Parameters for 4 IP configuration

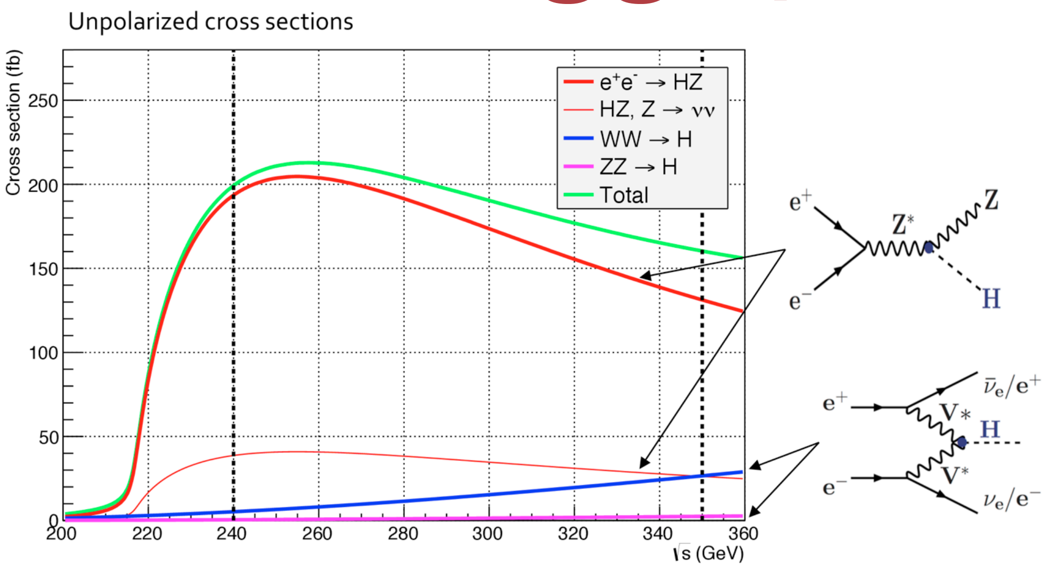
	TLEP-Z	TLEP-W	TLEP-H	TLEP-t
$\sqrt{s}$ (GeV)	90	160	240	350
L (10^{34} cm^{-2}s^{-1})	56	16	5	1.3
# bunches	4400	600	80	12
RF Gradient (MV/m)	3	3	10	20
Vertical beam size (nm)	270	140	140	100
Total AC Power (MW)	250	250	260	284
L_{int} (ab^{-1}/year/IP)	5.6	1.6	0.5	0.13

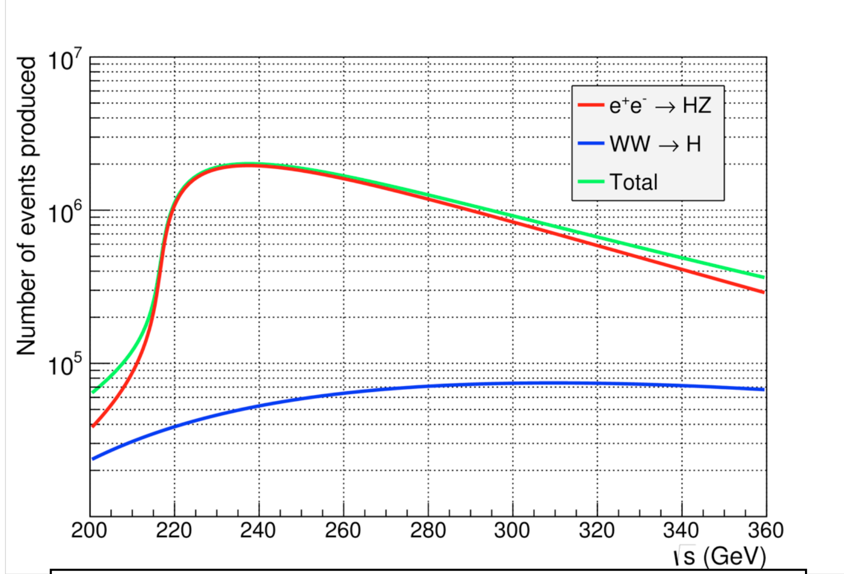
Luminosity and Energy



- Much higher **repetition rate** + multiple **interaction points**
  - **significantly larger luminosity up to the ttbar threshold with respect to ILC**
- TLEP luminosity values obtained in a configuration with 4 IP
  - parameters of **beam-beam effect** taken from LEP measurements
    - two detectors instead of 4 would only reduce the total lumi by 35%
- Note: **luminosity upgrade scenarios envisioned for ILC, energy upgrade for TLEP**

Higgs production





Higgs production cross section in un-polarized e+e- collisions (from the HZHA generator)

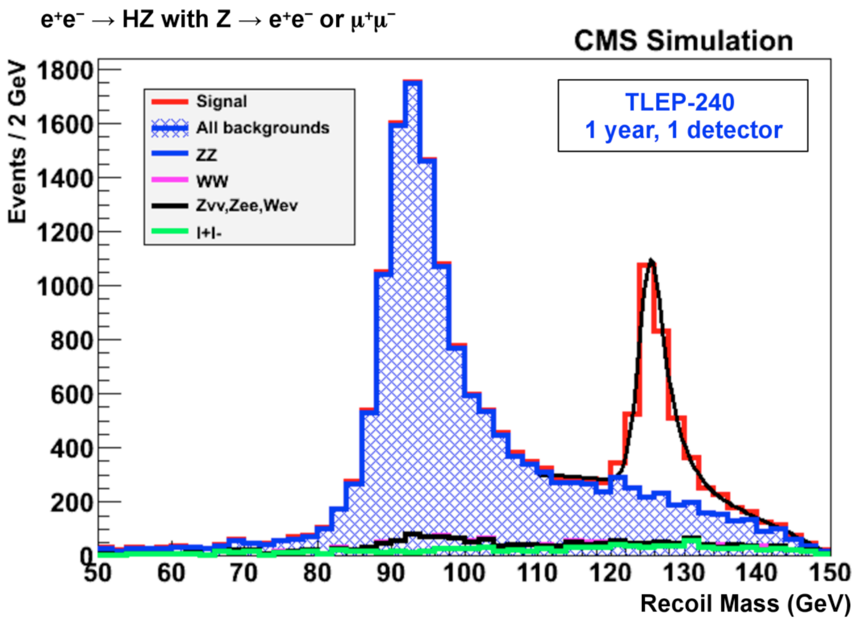
N Higgs boson produced in 5-year running program

- **Higgs-strahlung** process: for the choice of √s interplay between the luminosity profile and the cross section: **240 GeV** (max N_{higgs})
- **WW/ZZ fusion** process: broad maximum between √s 280 and 360 GeV: **350 GeV** (coupled with the tt threshold program)

	TLEP 240	ILC 250	TLEP 350	ILC 350
Total Integrated Luminosity (ab^{-1})	**10**	0.25	**2.6**	0.35
Number of Higgs bosons from $e^+e^- \to HZ$	**2,000,000**	70,000	**340,000**	65,000
Number of Higgs bosons from boson fusion	**50,000**	3,000	**70,000**	22,000

Higgs measurements @ 240 GeV

- Detailed simulation and simple analyses have been carried out
  - to prove the **sub-per-cent precision** for Higgs boson coupling measurement
  - full simulation with the **CMS detector**
  - 1 year of data taking at 240 GeV (500 fb^{-1})



ArXiv e-prints 1208.1662

- **One example:** distribution of the mass recoiling against the lepton pair in the e^+e^-H, $\mu^+\mu^-H$ final states
  - from the fit to this distribution the total **e^+e^- -> HZ cross section** with 0.4% precision (4 IP, 5 years running)

Higgs measurements @ 240 GeV (2)

	TLEP 240	ILC 250
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

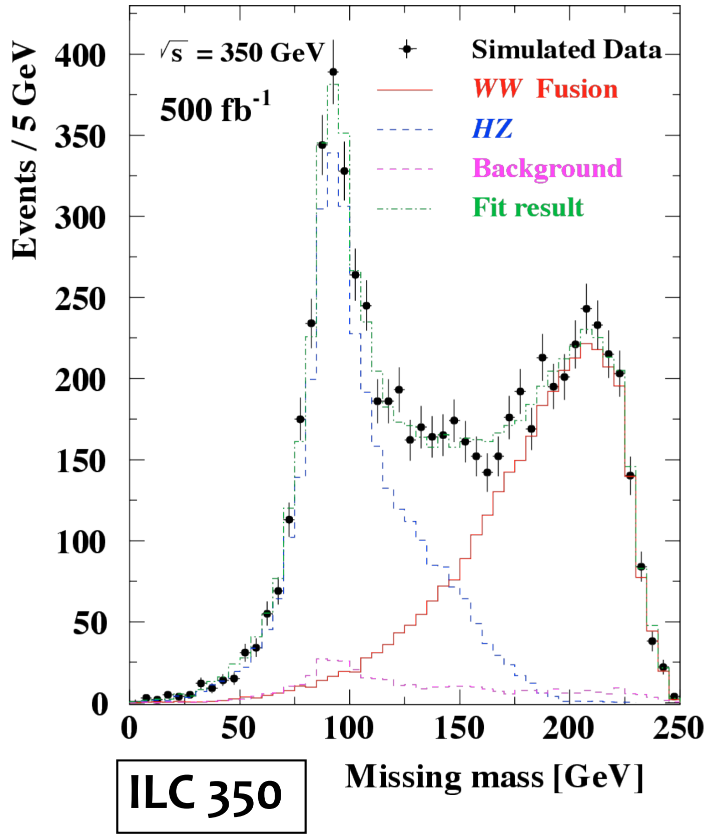
- Summary of **statistical precision** of all the measurements
  - for the **cc** and **gg** decays the precision is extrapolated **from ILC prediction** (need better vertex capability wrt the CMS detector)

- Total width determination:
  - **Γ_{tot}=Γ(H->ZZ)/BR(H->ZZ)**
  - **Γ(H->ZZ)** proportional to σ_{HZ} measured from the recoil mass distribution
  - **BR(H->ZZ)** proportional to the σ_{HZ} x BR(H->ZZ) measurement obtained from ZZZ final state events with 4 leptons (bkg-free)
    - **~3% precision on Γ_{tot} from this channel only**

Higgs measurements @ 350 GeV

- Additional events from the Higgs-strahlung process allow **5% improvement in the statistical precision** of previous measurements
- Large number of Higgs bosons produced in WW fusion allows a **measurement of the total width from the bbυυ final state**.
  - HZ with Z->vv and WW fusion (with H->bb) contribute with similar cross section
  - A **fit of the HZ and WW** contributions to the **mass recoiling against the bb system** allows $\sigma_{WW\text{->}H}$ x BR(H->bb) measurement with **0.6% precision**

$\sqrt{s}$ (GeV)	TLEP	ILC
240 - 250	**2.2%**	10.5%
350	**0.6%**	1.0%



  - assuming for TLEP same performances in separation as those expected for ILC (quick test with CMS detector simulation shows similar performances)

Higgs measurements @ 350 GeV (2)

- Total width determination:
  - Γ_{tot}=Γ(H->WW)/BR(H->WW)
  - Γ(H->WW) proportional to $\sigma_{WW\text{->}H}$
  - BR(H->WW) and BR(H->bb) obtained from the measurements @ √s=240 GeV

Process and final state	TLEP	ILC
$e^+e^- \to$ HZ with H $\to$ ZZ	**3.1%**	20%
WW $\to$ H with H $\to b\bar{b}$ at 240 GeV	**2.4%**	12%
WW $\to$ H with H $\to b\bar{b}$ at 350 GeV	**1.2%**	7%
Combined	**1.0%**	6.0%

240+350 programs

Global fit for Higgs boson couplings

- Accuracies on Higgs couplings are obtained from a fit to all observables
  - @ 240 and 350 GeV
- Following baseline fit procedure by M. Peskin [arXiv:1207.2516v3]
  - for each coupling **H->XX** assume a deviation $\mathbf{d_x}$ on the value $\mathbf{g_x/g_x(SM)}$
    - each inclusive cross section measurement **(XH)** will be scaled wrt to SM one by a factor equal to: $\mathbf{(1+d_x)^2}$
    - each $\mathbf{\sigma_{XZ}}$ **x BR (H->YY)** will be scaled by a factor: $\mathbf{[(1+d_x)^2 (1+d_y)^2]/D\Gamma}$
      - where $\mathbf{D\Gamma = [\, \sum_x BR_{SM}(H\to XX)\, (1+d_x)^2 \,] / (1-d^2_{exo})}$
        - $\mathbf{d_{exo}}$ is the deviation of the coupling to exotic particles

Global fit for Higgs boson couplings (2)

- The fit is performed in two ways:
  - **Constrained fit** (as in Peskin's paper. Fit validated: it gives consistent results with the same imputs)
    - **bounding from above the coupling to the Z and the W to the standard model couplings**
    - **saturating the exotic decay width by the sole invisible Higgs boson decays**
      - with the **l^+l^-H final state** and the **distribution of the recoiling mass** the invisible decay width of the Higgs boson can be measured with **0.25% precision (TLEP 240)**
  - **Model-Independent fit**
    - allow for the generic case of **additional exotic decays not just invisible**
      - **the measurement of BR to invisible is not used** in the fit to allow for model independent measurement of the exotic BR and hence the total width

Results @ 240+350 GeV

	Model-independent fit				Constrained fit		
Coupling	TLEP-240	TLEP		ILC	TLEP		ILC
g_{HZZ}	0.16%	**0.15%**	(0.18%)	0.9%	0.05%	(0.06%)	0.31%
g_{HWW}	0.85%	**0.19%**	(0.23%)	0.5%	0.09%	(0.11%)	0.25%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	2.4%	0.19%	(0.23%)	0.85%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	3.8%	0.68%	(0.84%)	3.5%
g_{Hgg}	1.1%	**0.80%**	(0.98%)	4.4%	0.79%	(0.97%)	4.4%
$g_{H\tau\tau}$	0.94%	**0.54%**	(0.66%)	2.9%	0.49%	(0.60%)	2.6%
$g_{H\mu\mu}$	6.4%	**6.2%**	(7.6%)	45%	6.2%	(7.6%)	45%
$g_{H\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	14.5%	1.4%	(1.7%)	14.5%
BR_{exo}	0.48%	**0.45%**	(0.55%)	2.9%	0.16%	(0.20%)	0.9%

Relative statistical uncertainty on the Higgs couplings from the physics program at 240+350 GeV at TLEP

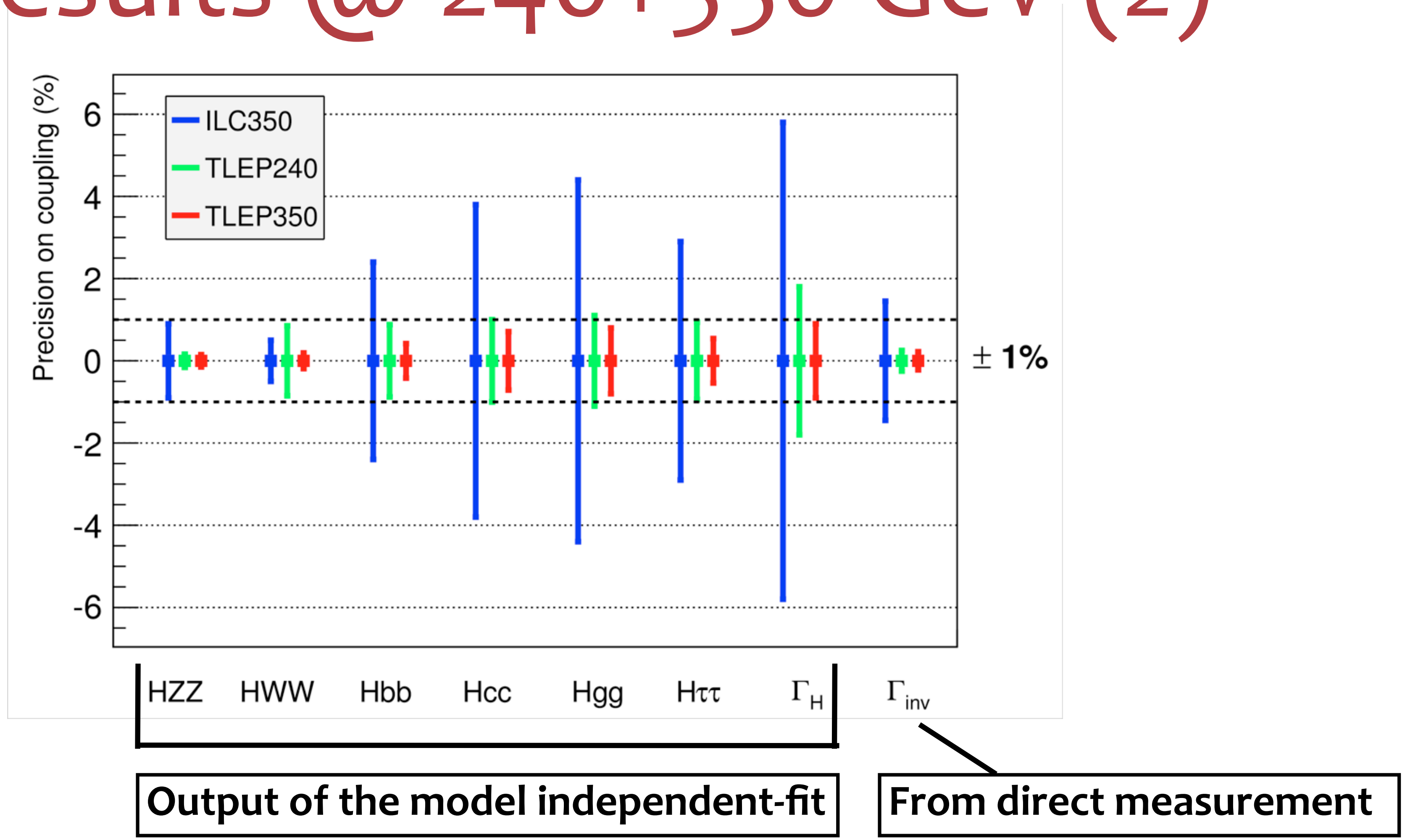
ILC baseline program at 250+350 GeV (inputs from TDR)

Same results for the sole 240 GeV program

If running with only two detectors

Absolute uncertainty on the Higgs BR to exotic (invisible or not)

Results @ 240+350 GeV (2)

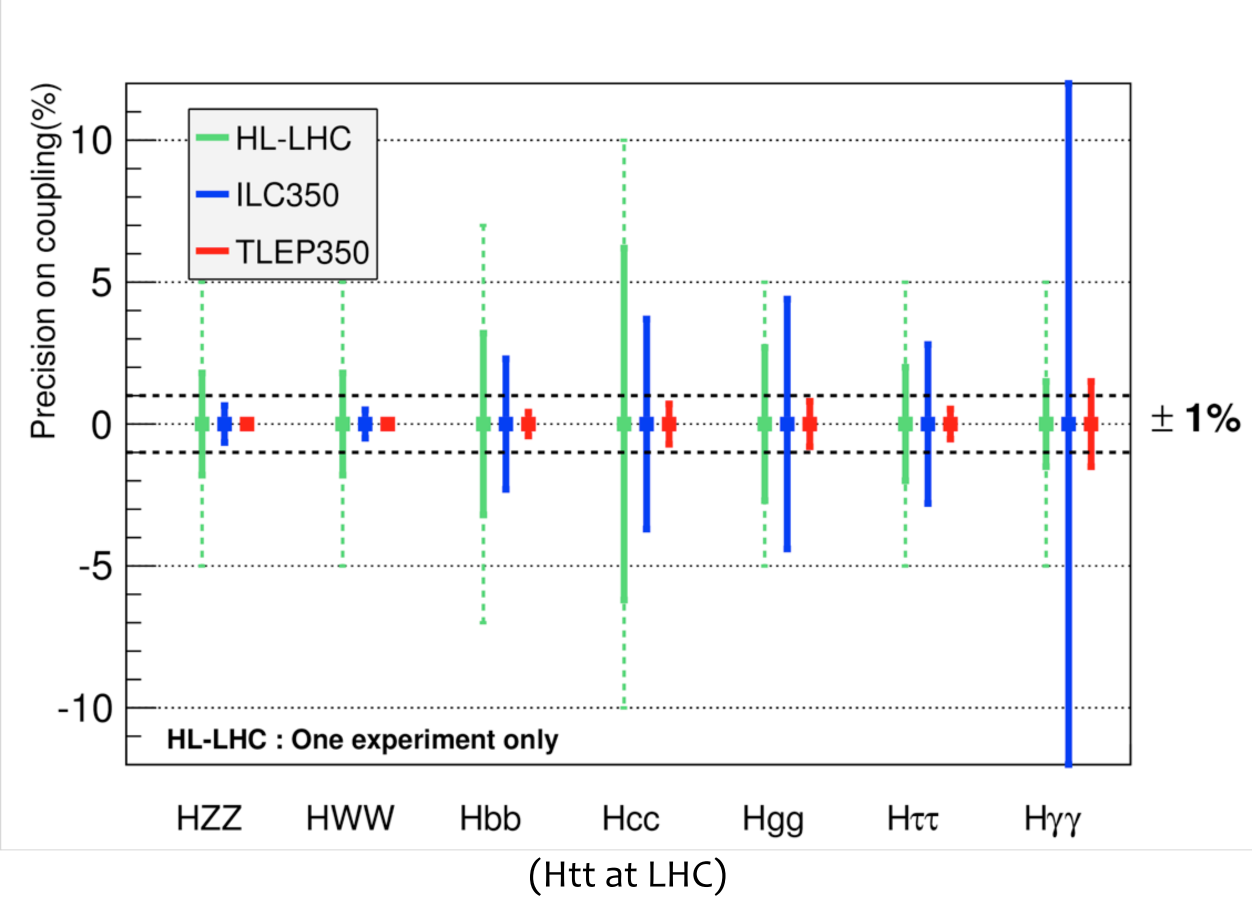


- **Only TLEP can reach the required sub-percent accuracy** on fermion and boson couplings with the 240+350 GeV program
- **Theoretical work** is required to achieve comparable systematic errors

Comparison with HL-LHC

- Important to compare the **TLEP** projection with those from **HL-HLC**
  - to evaluate the added value of e+e- Higgs factory **after 3 ab^{-1} pp collisions**
- A model-indepdendent fit cannot be performed from pp collision data:
  - make **assumptions similar to those currently made at LHC**
    - **no Higgs boson exotic decays**
    - **deviation of the charm and top couplings are correlated**
- For HL-HLC projections results come from CMS projections of current analyses for 3 ab^{-1} in two scenarios
    - **CMS scenario I** : all systematic uncertainties unchanged
    - **CMS scenario II** : with experimental systematic uncertainties scaling like $1/\sqrt{L}$ and theoretical ones halved

Comparison with HL-LHC



CMS Scenario I

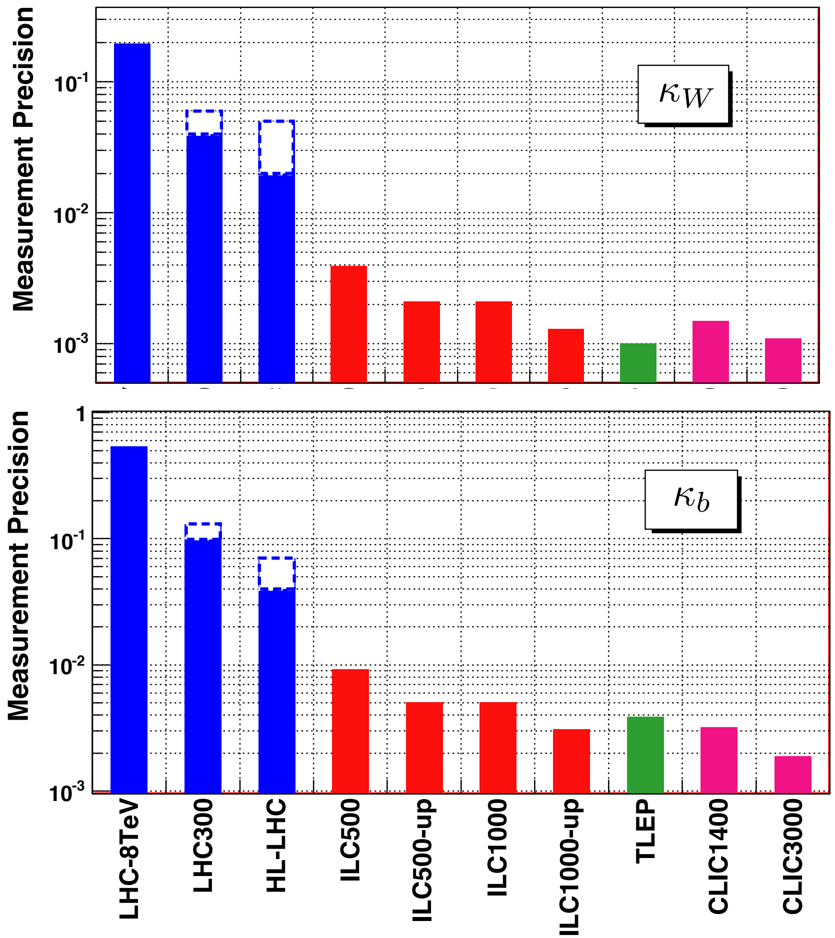
CMS Scenario II

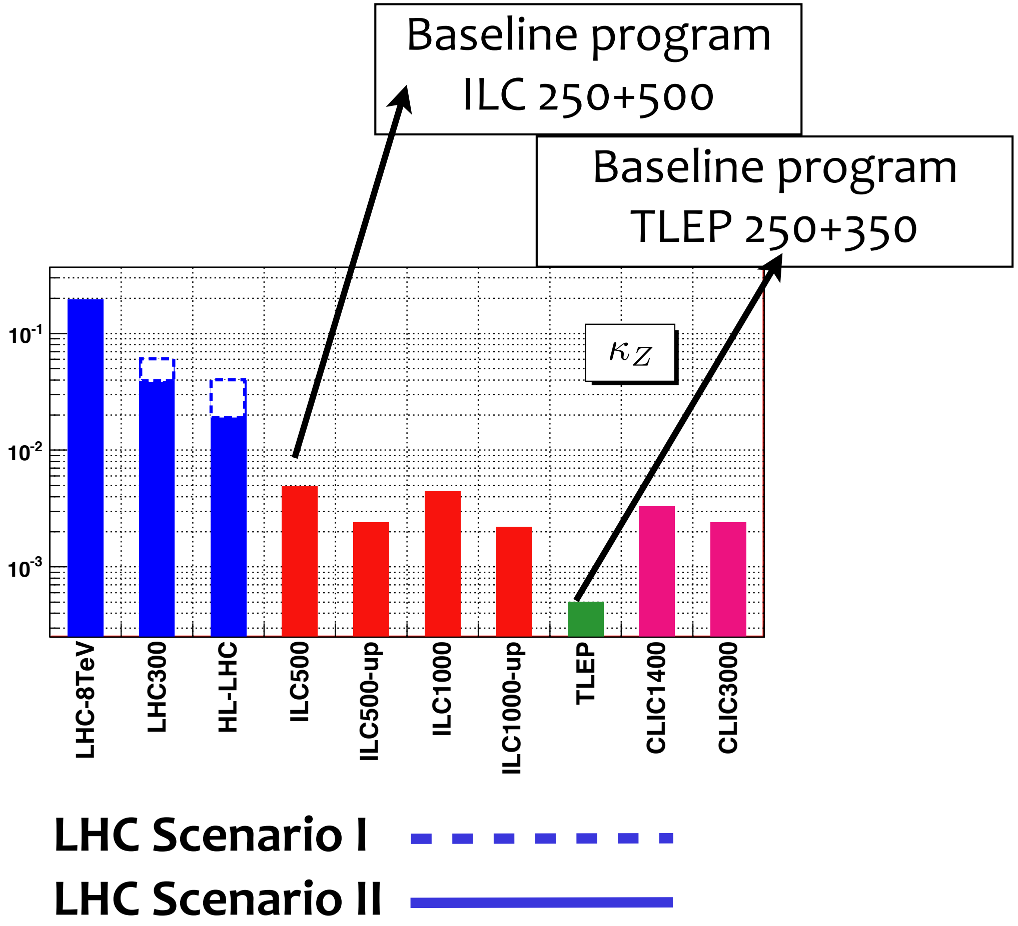
For Higgs factories data up to √s=350 GeV are combined

- **Only TLEP improves significantly LHC measurements in all couplings**
- The projections for HL-LHC in scenario 2 are truly impressive, and will further improve by including ATLAS and additional dedicated analyses
  - new channels to measure directly the λ_t coupling just been explored at CMS

Comparison with HL-LHC (2)

- Additional comparisons including Energy and Luminosity upgrades
  - from last **Higgs Snowmass report**





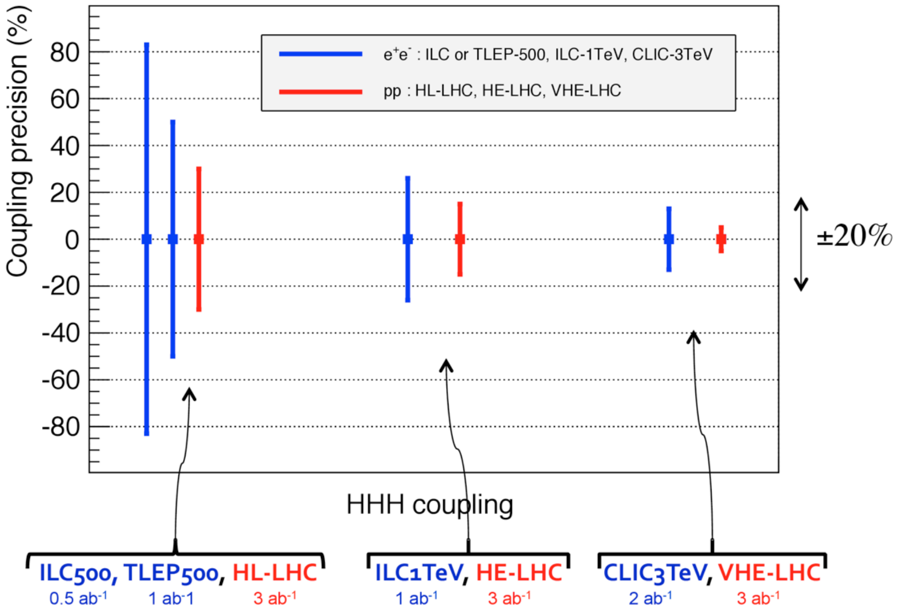
Relative statistical uncertainty on the Higgs couplings from different facilities

Higgs physics at higher energy

- TLEP has an energy upgrade option at **√s = 500 GeV** under study (ILC 500 program is in TDR)
  - at this energy the luminosity of TLEP and ILC will be comparable
  - from ILC TDR: additional 500 fb^{-1} at √s = 500 GeV would improve the precision on Higgs couplings obtained with (240+350 GeV) program of only a factor √2.
  - but the **opening of e^+e^-->ttH** process allows the **ttH coupling** to be measured directly with a precision of **10%** at TLEP (with 1 ab^{-1})
    - marginal improvement wrt what can be done at the tt threshold: **13%**
    - precision not competitive with HL-LHC projections
      - ex. CMS projection including all channels - ttH,H->γγ, ttH,H->$\tau_h\tau_h$, ttH,H->bb, ttH,H->WW/ZZ/$\tau_\ell\tau_{h(\ell)}$ - give for scenario II **4% precision**

Higgs physics at higher energy

- TLEP has an energy upgrade option at **√s = 500 GeV** under study (ILC 500 program is in TDR)
  - opening of the **double-Higgs-boson production**, which allows the measurement of the trilinear **Higgs self-coupling λ_H**
  - but - from available studies - a measurement of λ_H with a significance of at least 5σ can only be done at HE-LHC (33 TeV), CLIC (3 TeV) or the VHE-LHC (100 TeV)
  - deviations in λ_H from NP expected to be smaller than ±20% **[ArXiv e-prints 1305.6397]** wrt SM prediction
    - **therefore only VHE-LHC could probe these NP effects**



Expected relative statistical accuracy in % on the Higgs self coupling for e+e- and pp colliders at the high-energy frontier

Conclusions

- Sufficiently precise measurements of the Higgs properties and the EWSB parameters are **ideal probes for the new physics scale**
- In this respect **TLEP is the best complementary machine to LHC**
  - a large e^+e^- circular collider in a new 80-100 Km tunnel at CERN
  - per-mil precision on Higgs couplings, unequalled precision on EWSB parameters
  - first step towards a 100 TeV pp collider and a long-term vision for HEP
    - together with VHE-LHC it offers the best precision and search reach on the market