The ILC physics program at energies above 250 GeV

16 May 2024

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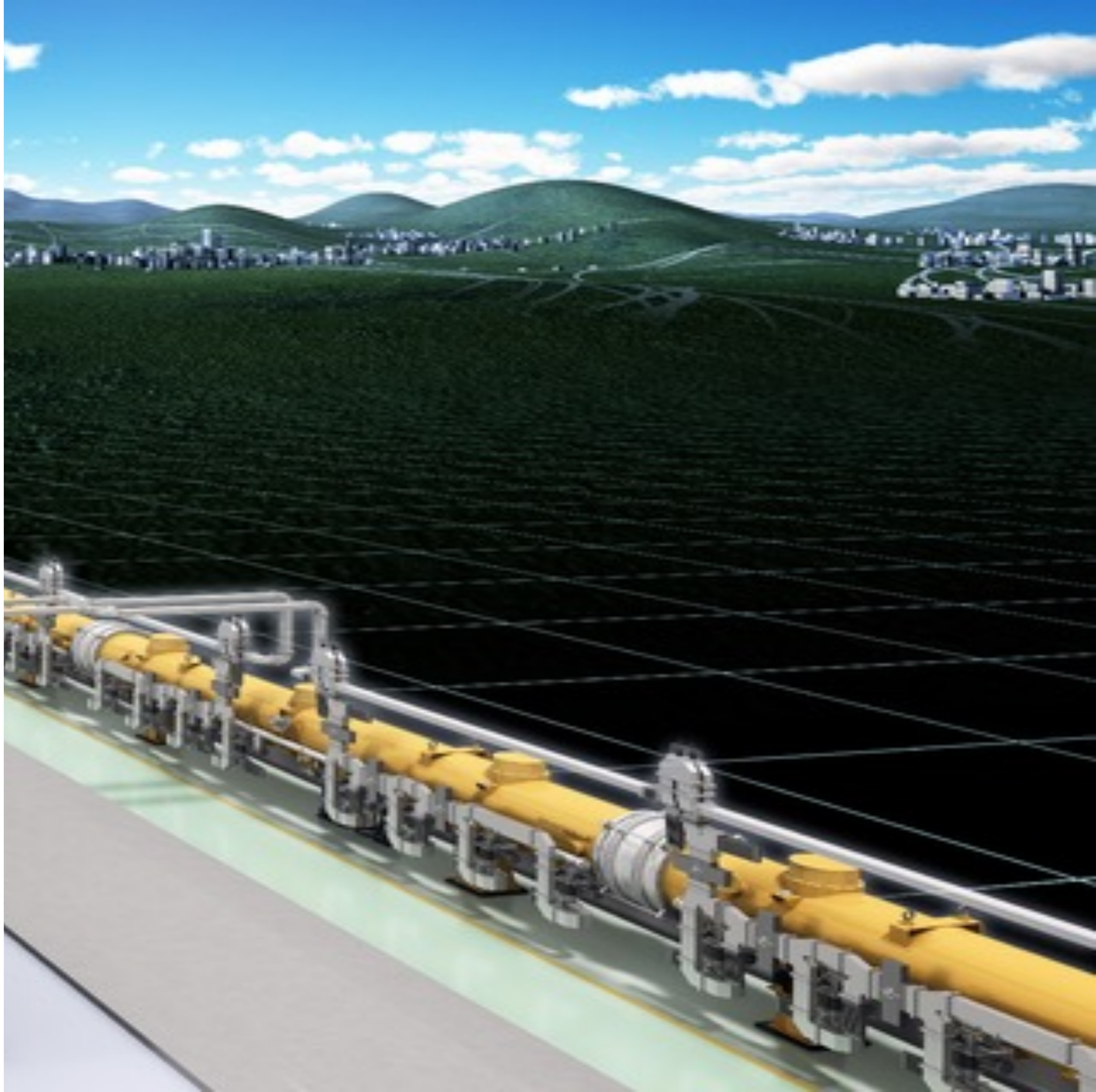

PNNL is operated by Battelle for the U.S. Department of Energy

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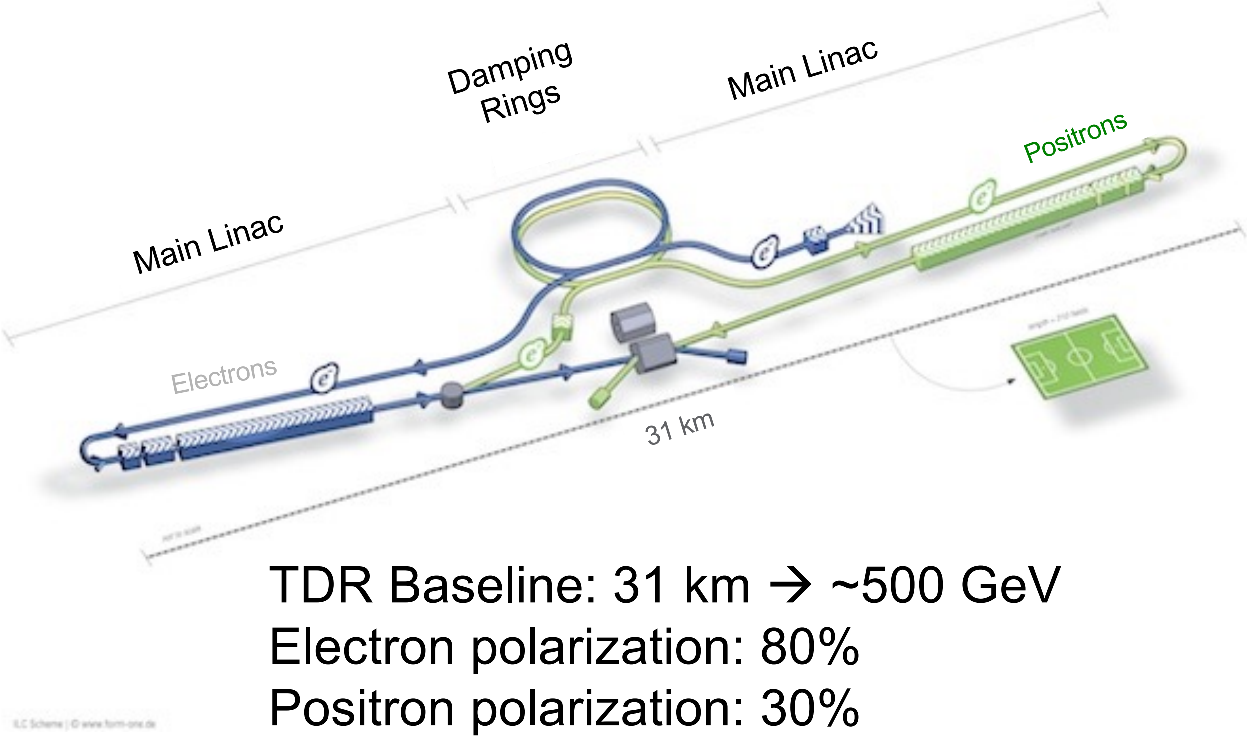
The ILC Accelerator

- Candidate site in Japan has been studied
- Layout being targeted towards site



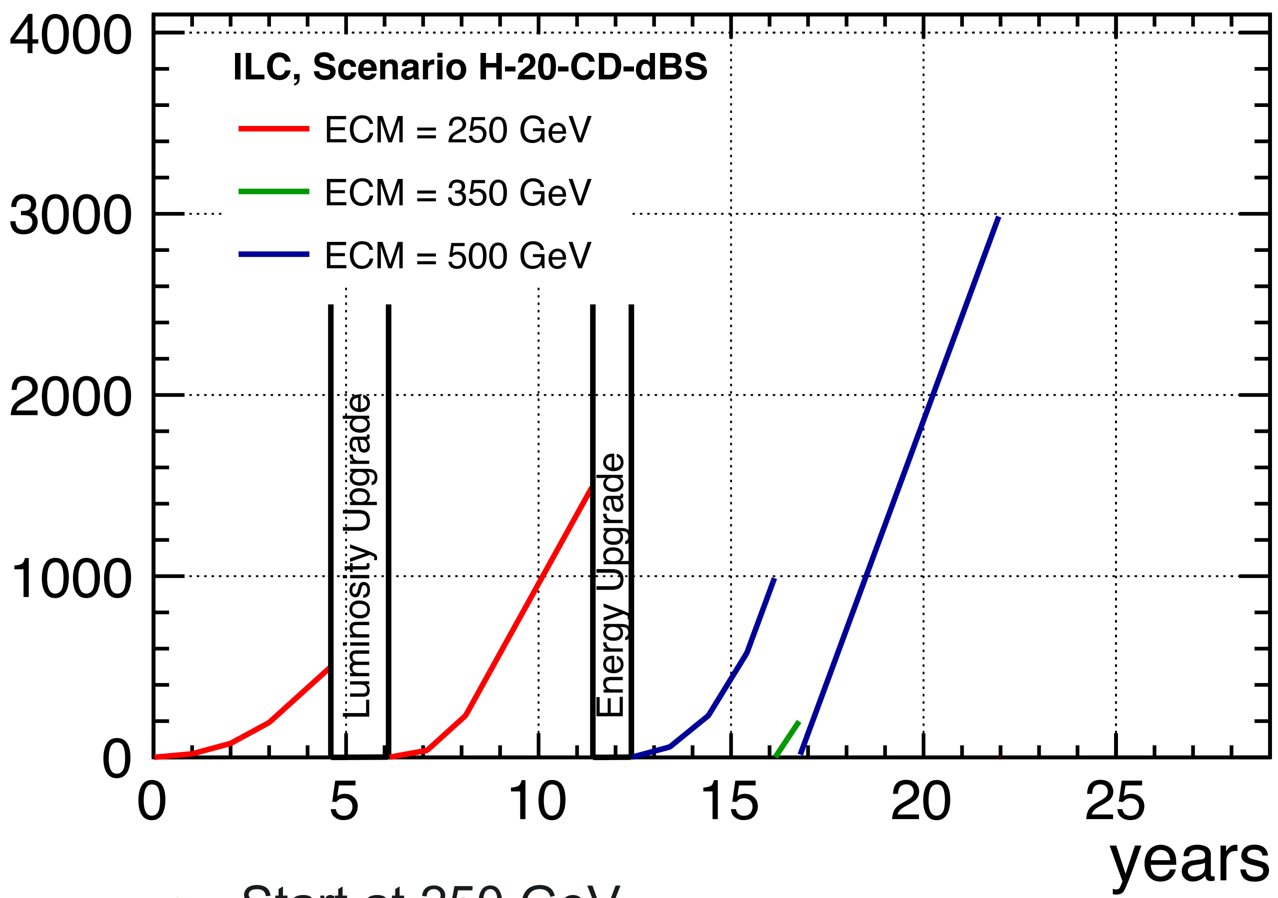
TDR Baseline: 31 km → ~500 GeV
Electron polarization: 80%
Positron polarization: 30%
Upgrade option to ~1 TeV

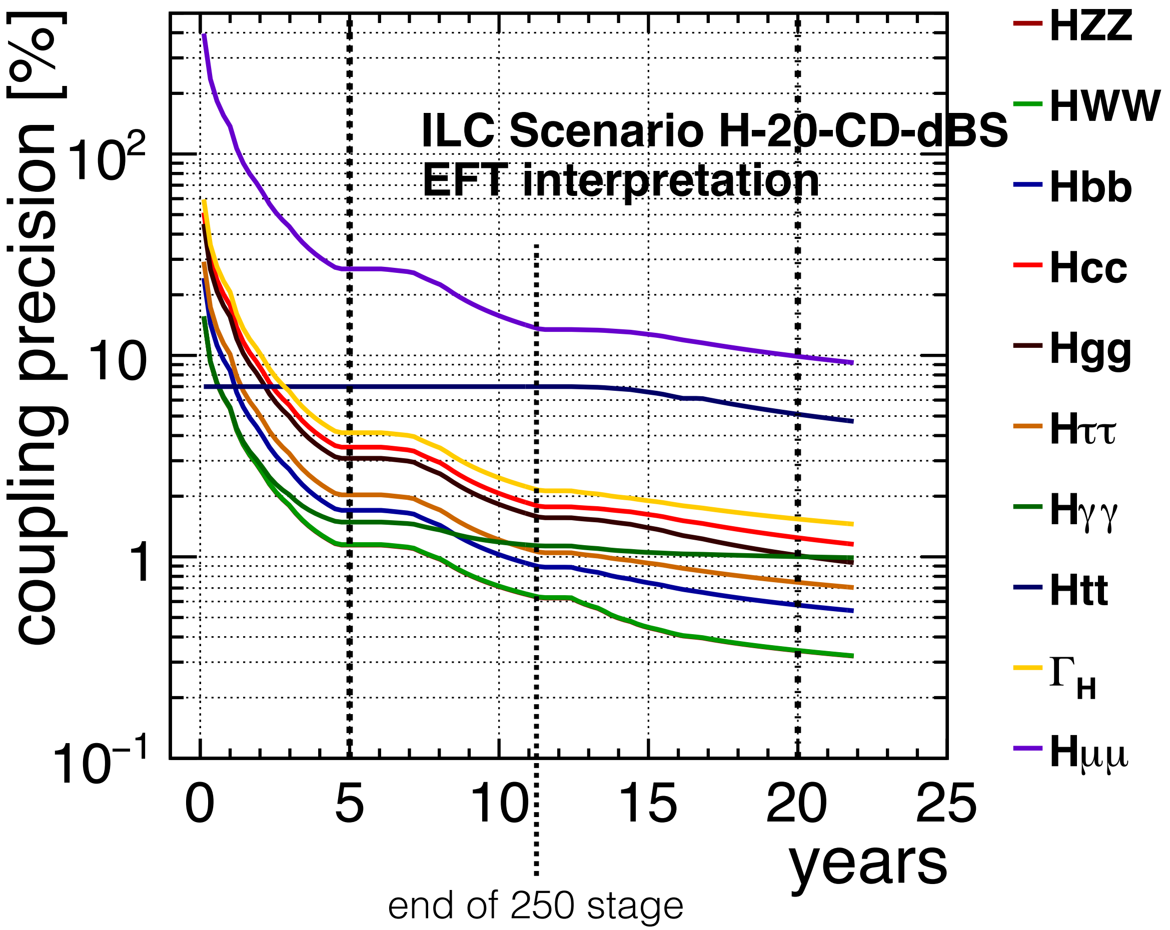
- TDR has been delivered in 2012
- Technology installed in XFEL at DESY and LCLS-II at SLAC

From the P5 report: *An offshore Higgs factory, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of FCC-ee and ILC meet our scientific requirements.*

ILC Staging scenarios

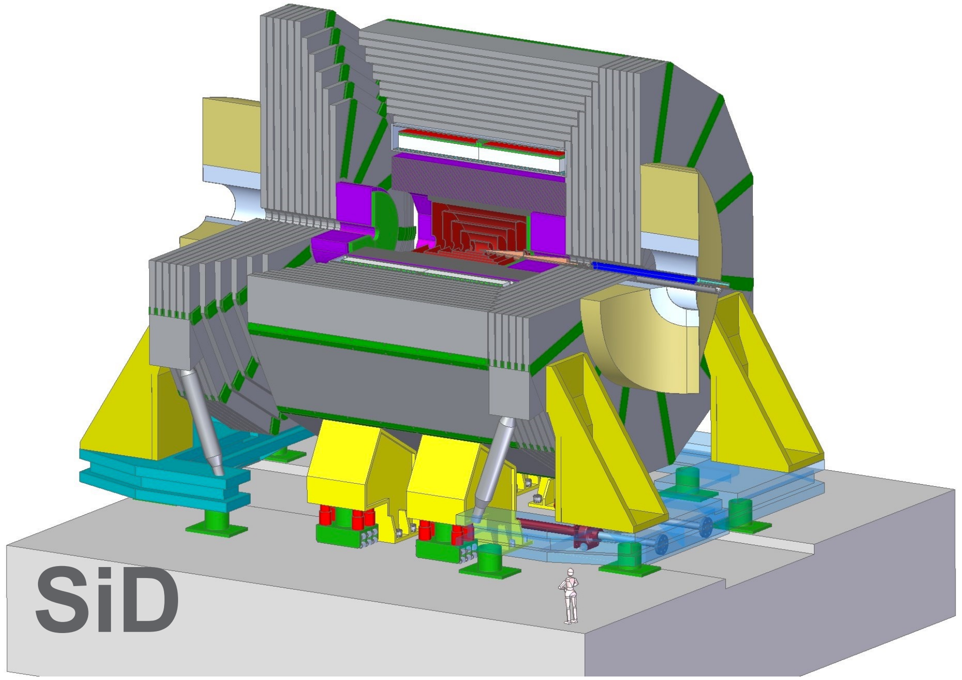
Includes machine ramp-up





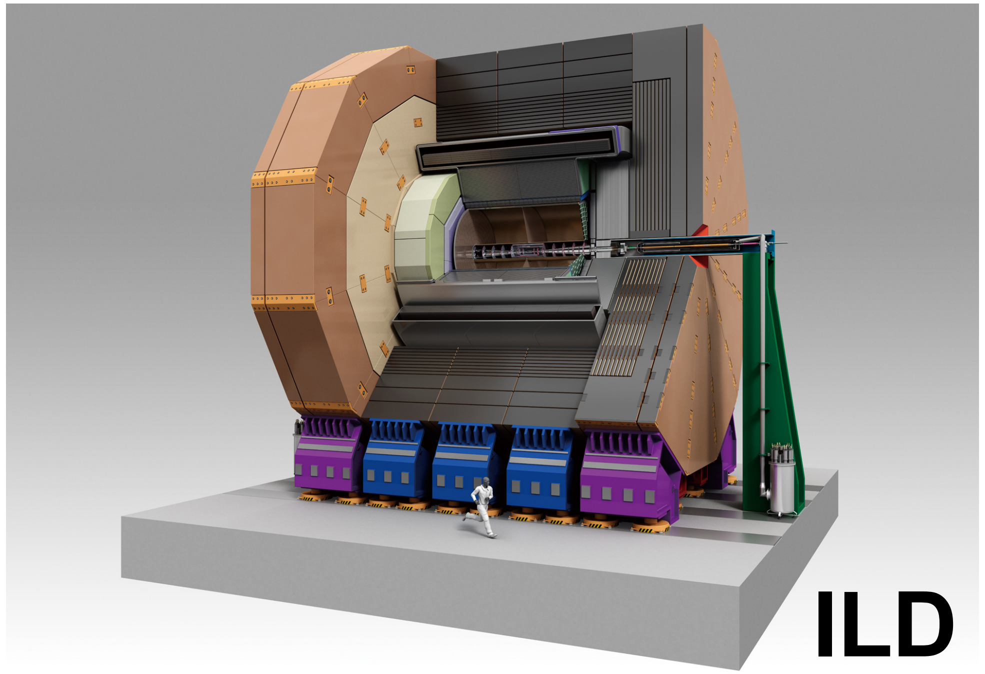
- Start at 250 GeV
- Runs at 500 GeV for full program, 350 GeV for higher precision of top properties
- Other thresholds possible, informed by LHC or early ILC Data
- **Goal**: per cent-level precision on (most) Higgs couplings
- Possible upgrade to 1 TeV, ~10 years for 8 ab^{-1}
  - improve ttH, self-coupling measurements, searches for new particles

ILC Detectors



5 T field
Silicon Tracking

Detectors not at same scale



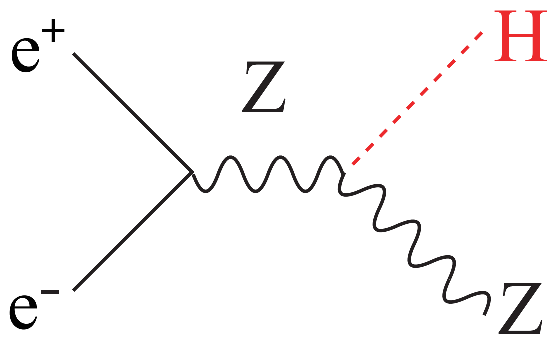
3.5 T field
Gaseous Tracking

Pixelated Si-W ECAL
Highly Granular HCAL
Optimized for Particle Flow (calorimeter inside coil)
No Trigger
Shared Beam Time in Push-Pull setup

Both can deliver the physics

Higgs Production at the ILC

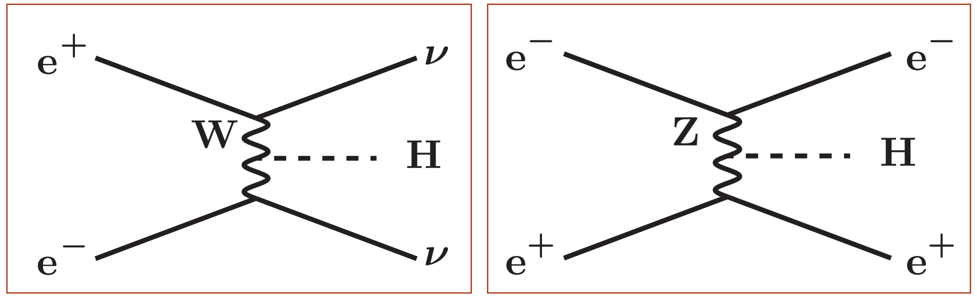
Baseline of 500 GeV



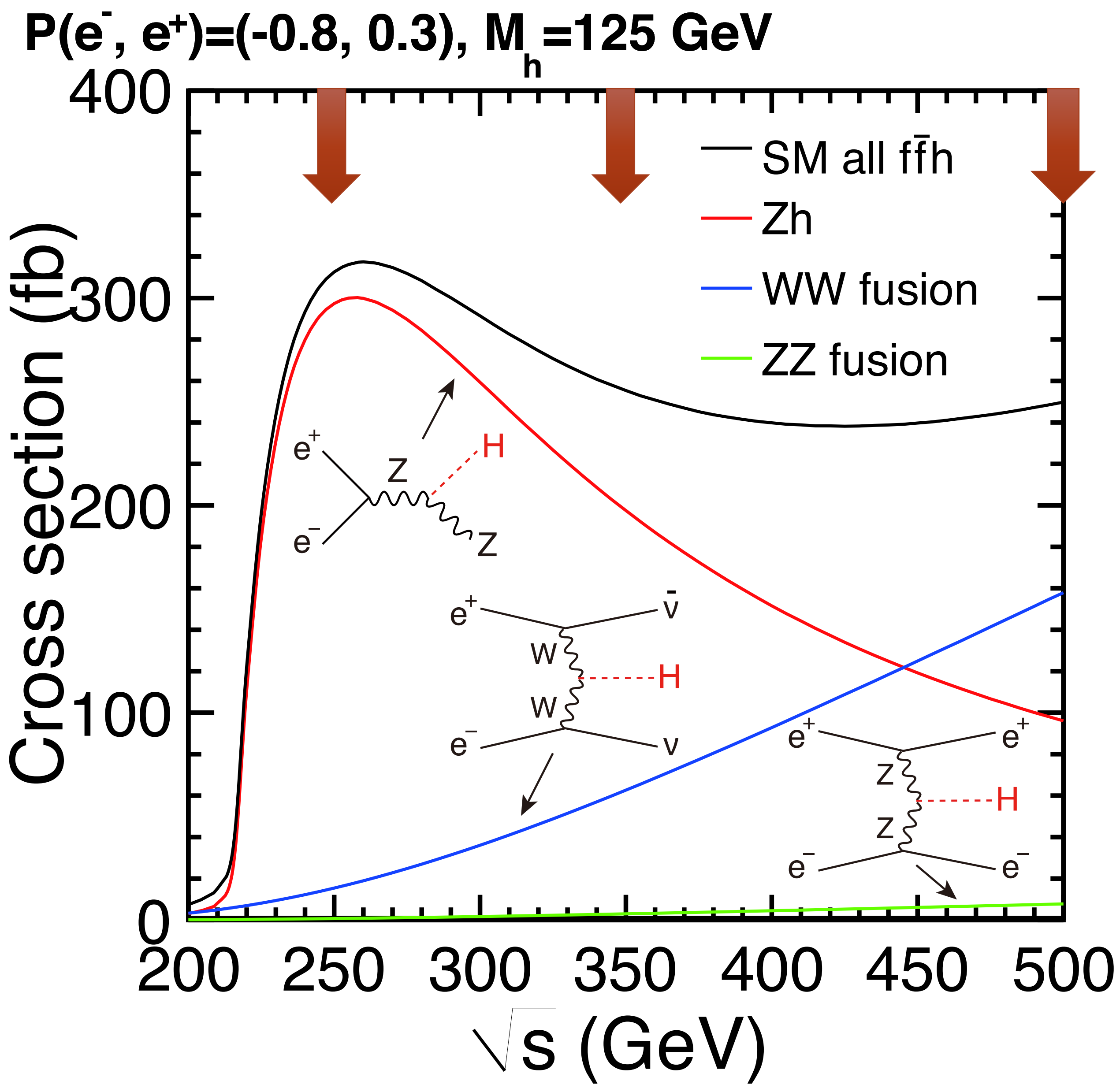
Recoil method: ILC staple at all stages

Z ➞ ll for precision

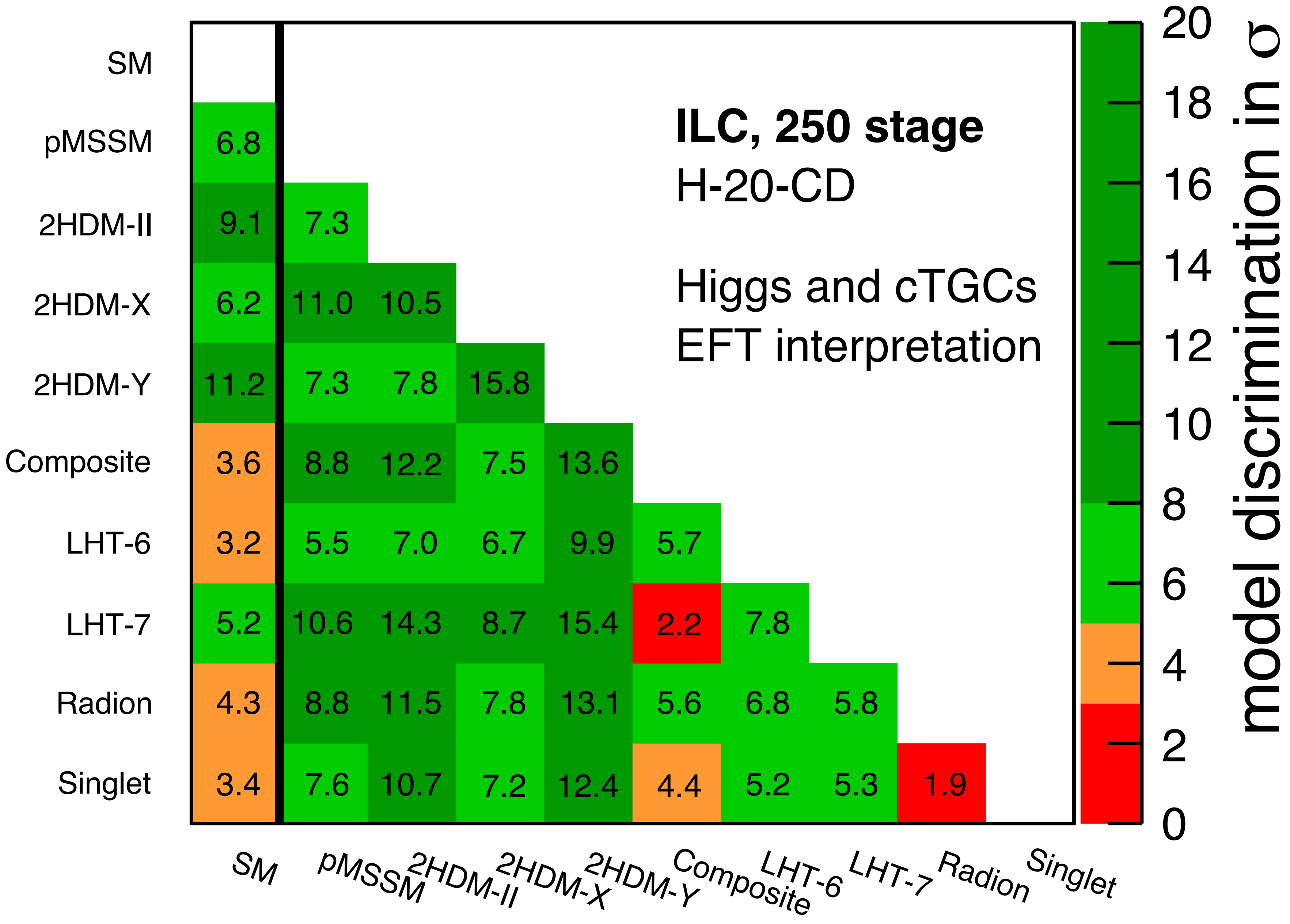
Z ➞ qq for higher cross section



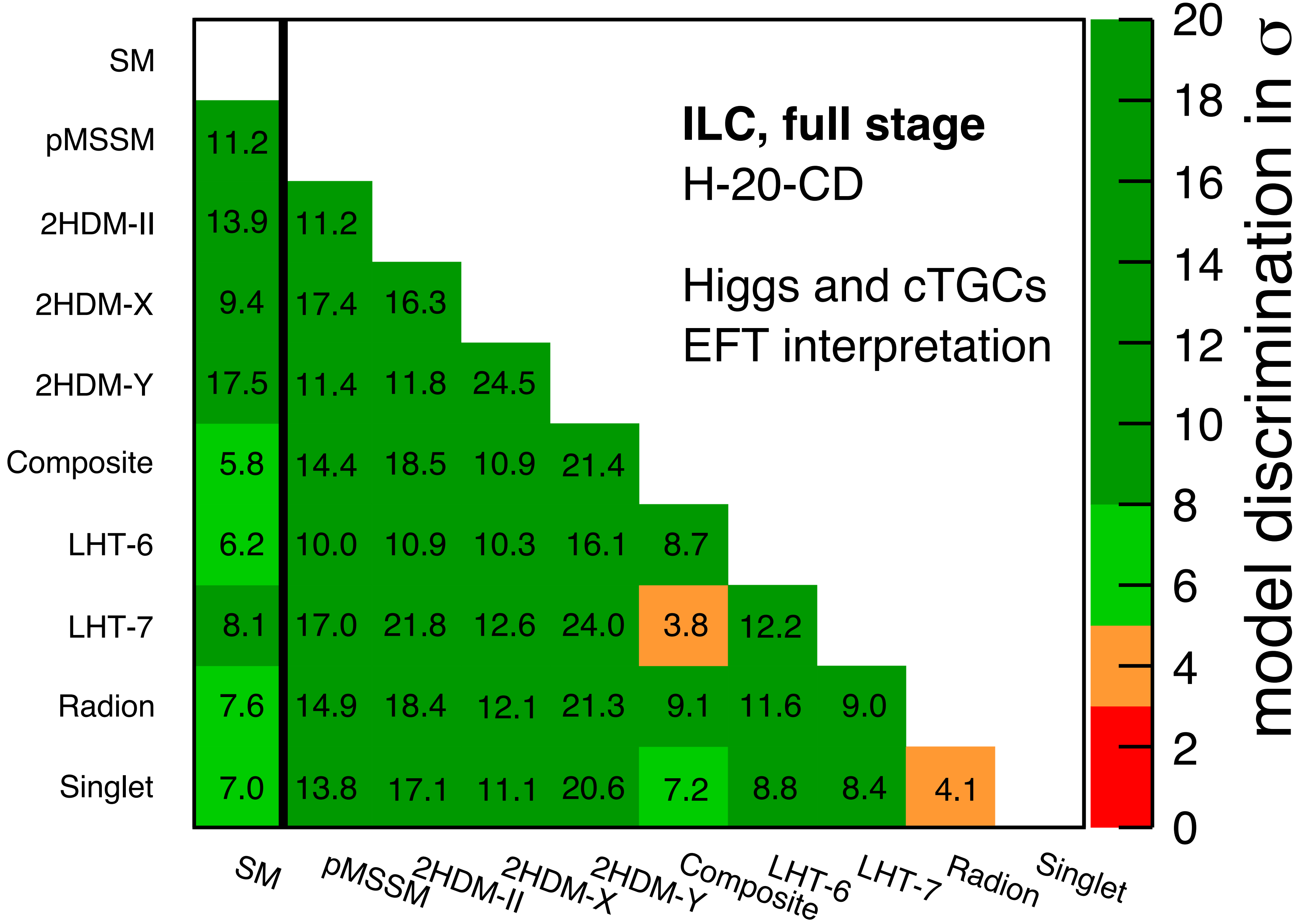
Vector boson fusion cross section increases at higher energies



Discriminating power between new physics models – 250 GeV

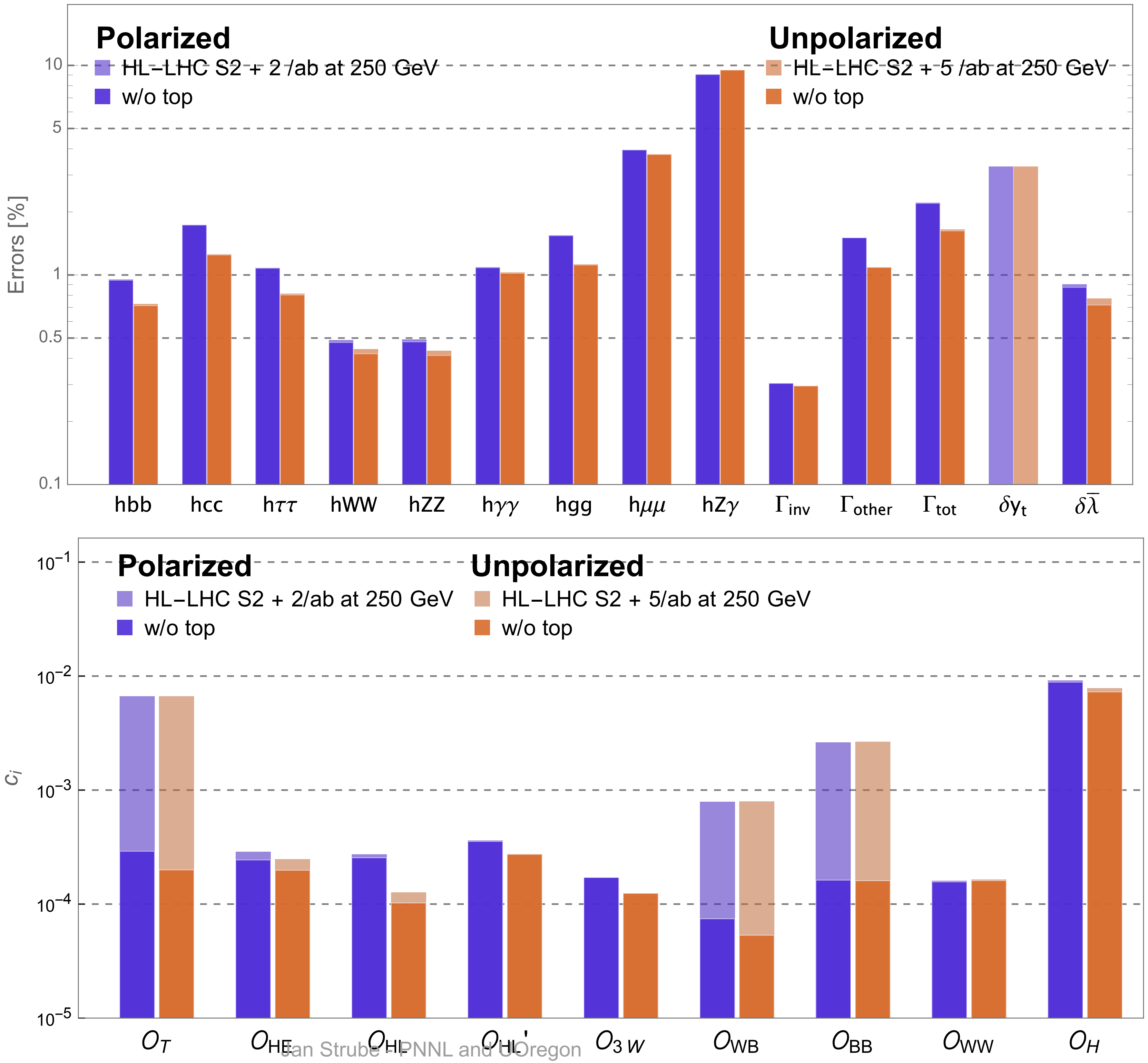


Discriminating power between new physics models – full ILC program

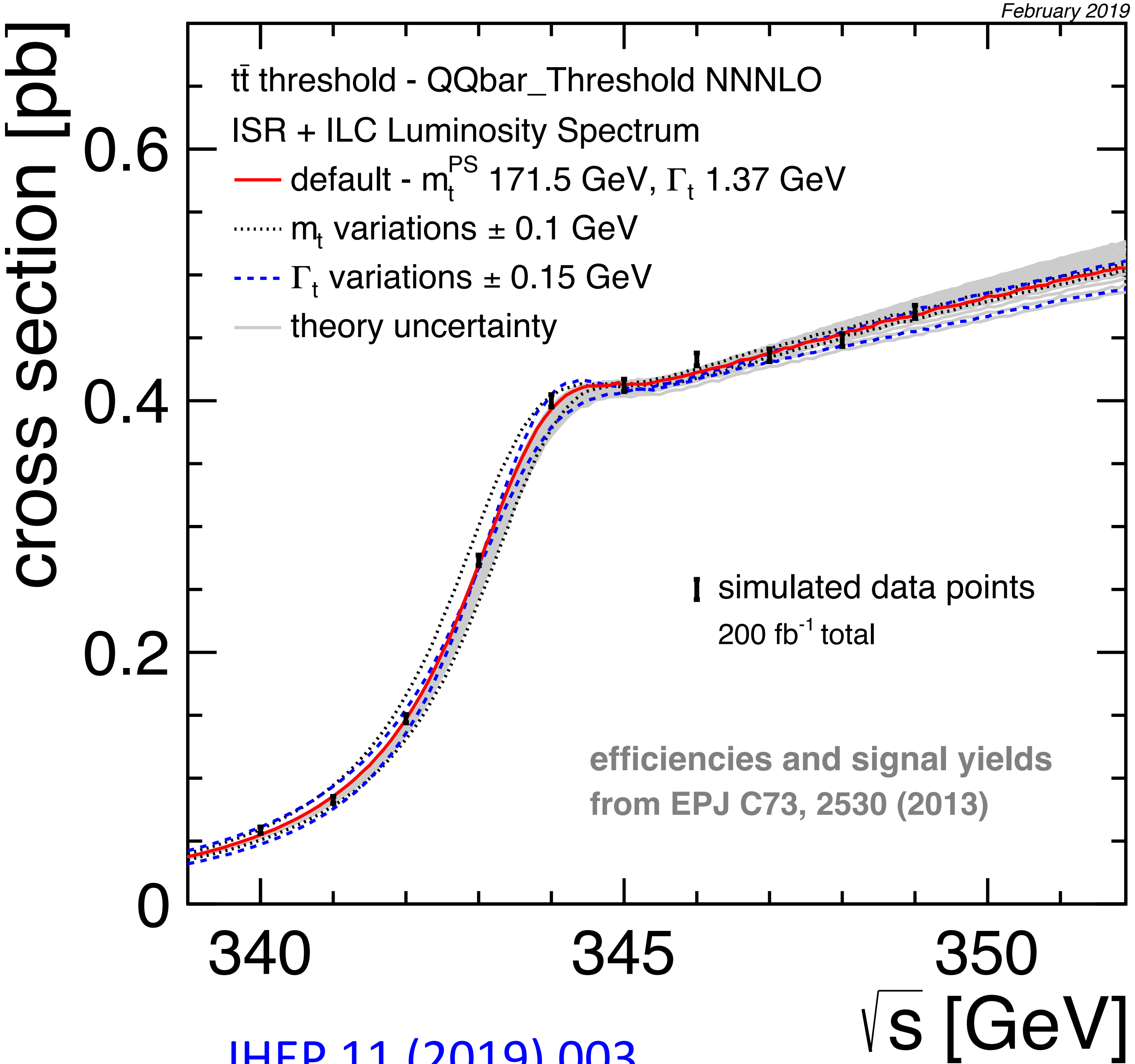


The role of polarization

arXiv:2006.14631



The top quark mass



JHEP 11 (2019) 003

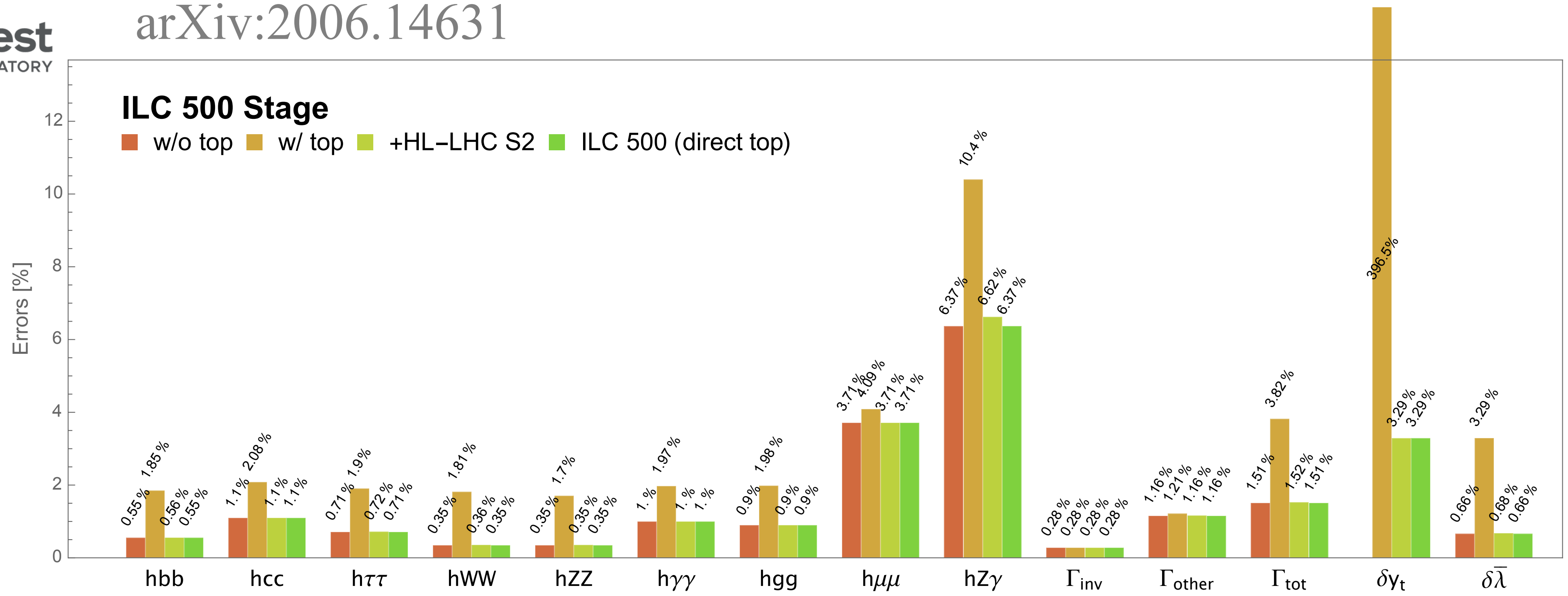
The top mass can be measured in decays at any mass above threshold.

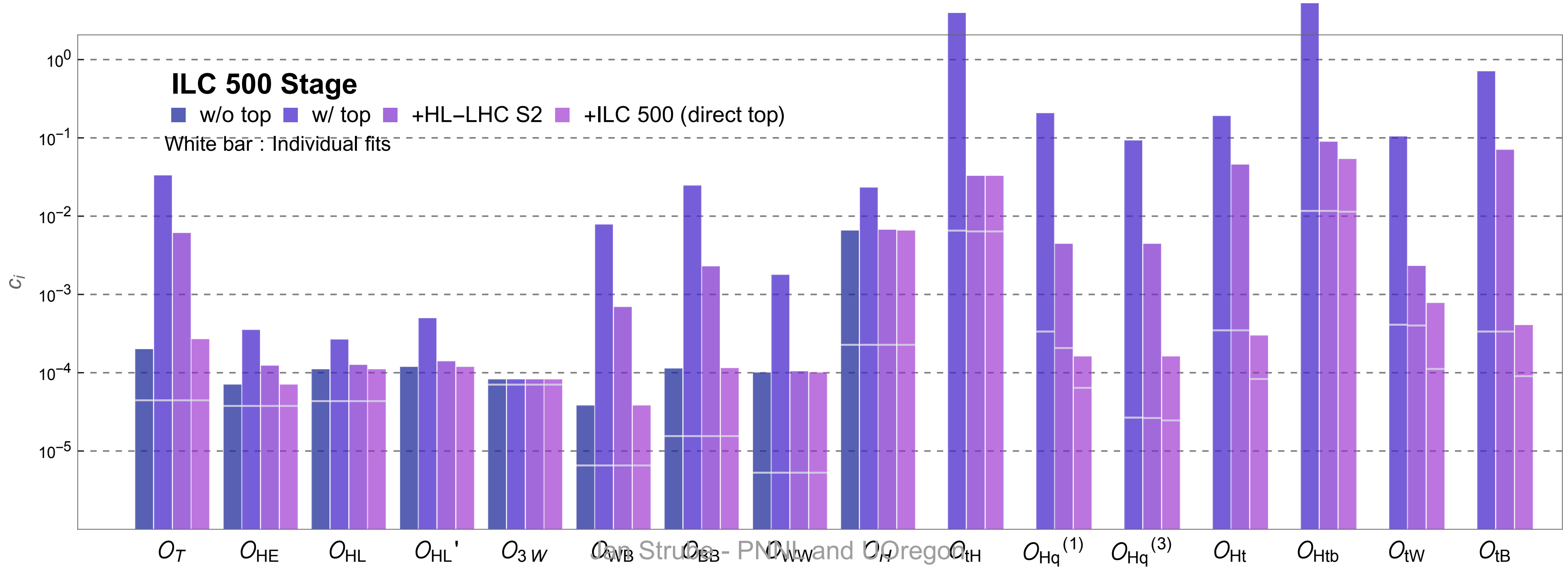
However, this is usually happens via template fits using a generator.

The mass at threshold can be converted to different regularization schemes directly, so comparison between direct measurement and the threshold scan will help understand these MC generator effects.

The benefits of higher energy

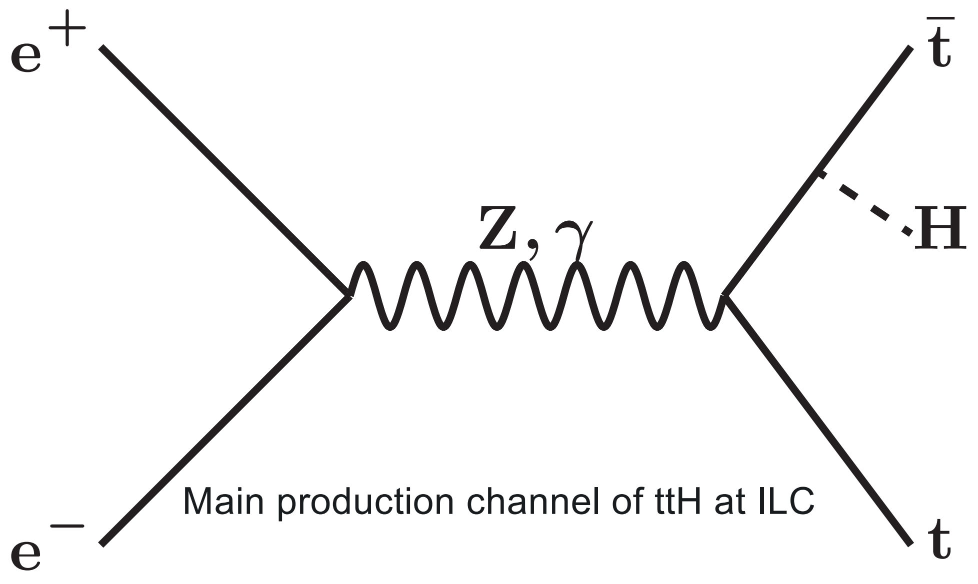
arXiv:2006.14631



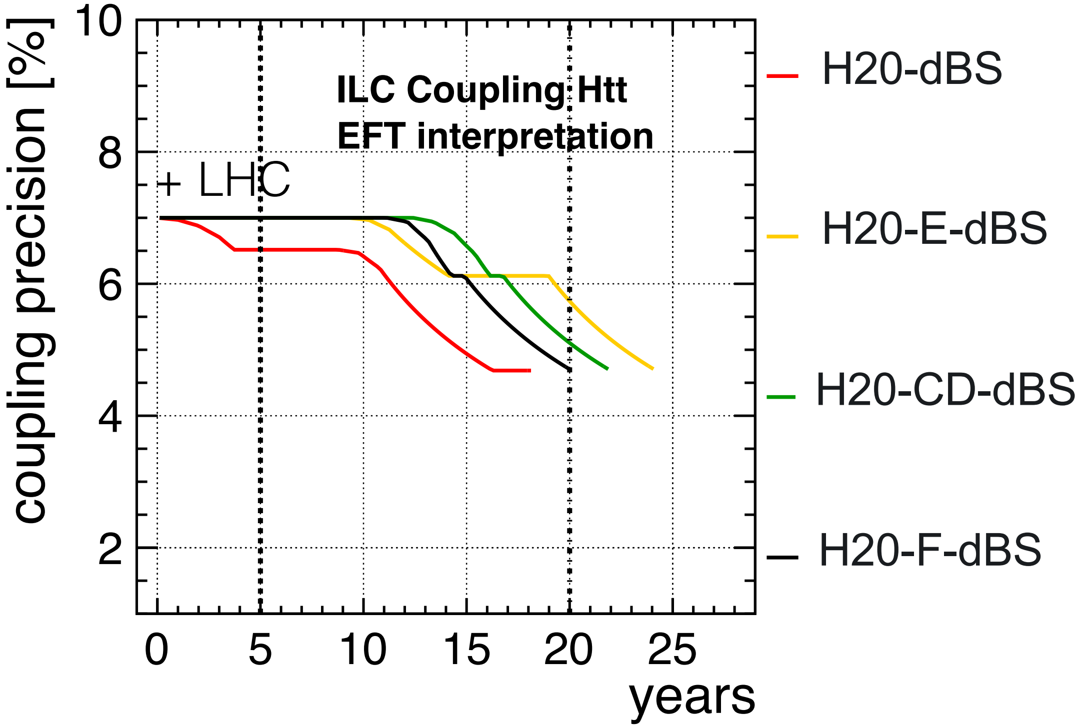


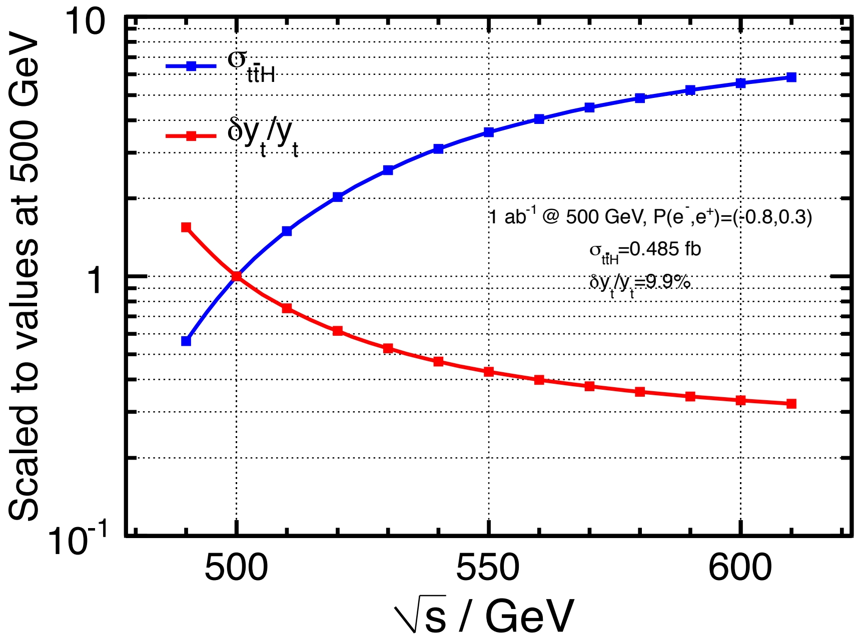
Precision measurements of top quark electroweak form factors are an important probe of Higgs compositeness.

Top Yukawa coupling at the ILC



Main production channel of ttH at ILC



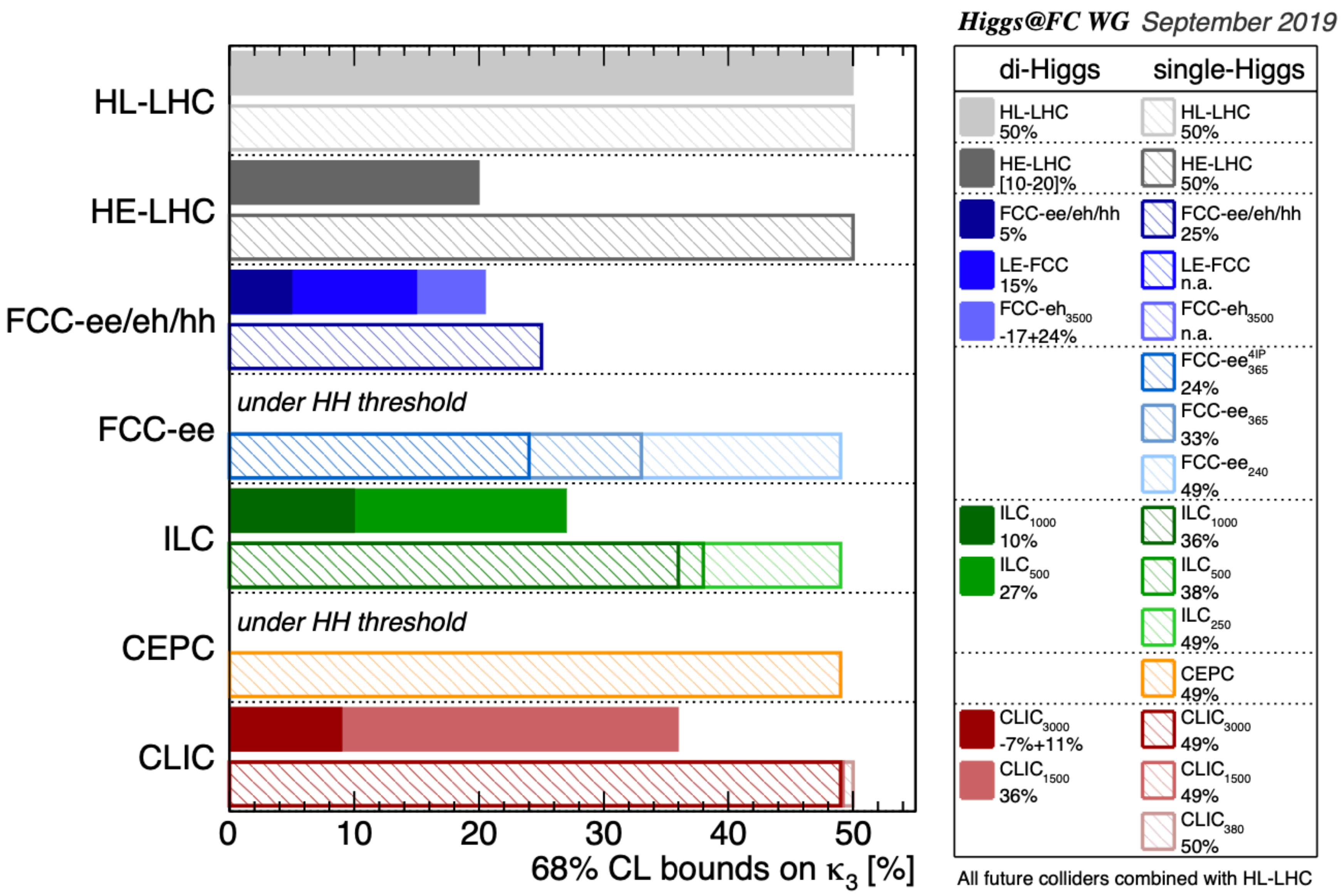


Coupling measurement at ILC500: 18%,
In full program w/ luminosity upgrade: 6.3%

Important to reach at least 500 GeV.
Potential at higher energy:
Measurement error with 4 ab^{-1} at 550 GeV: ~3%

Higgs self-coupling at future colliders

[Physics Briefing Book, arXiv:1910.11775]



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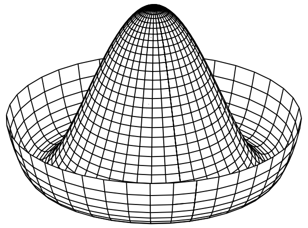
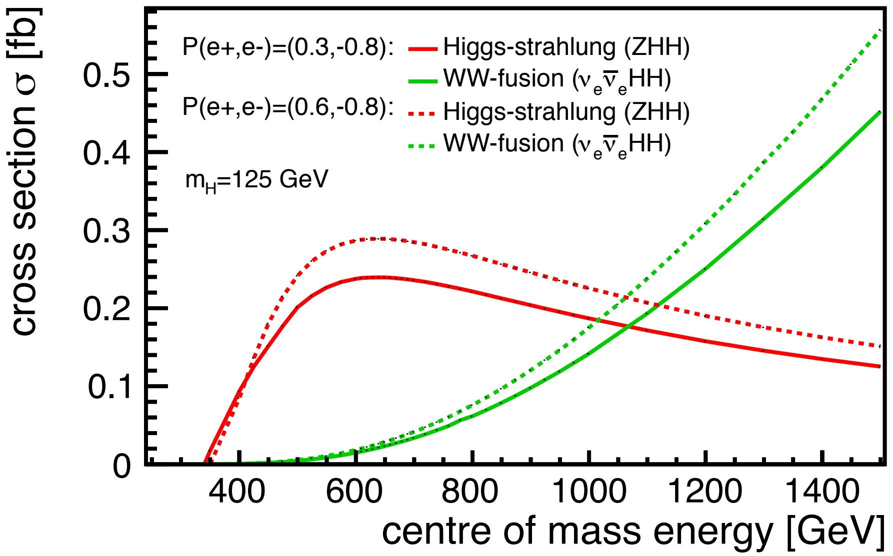
Tri-Linear Higgs Self-Coupling

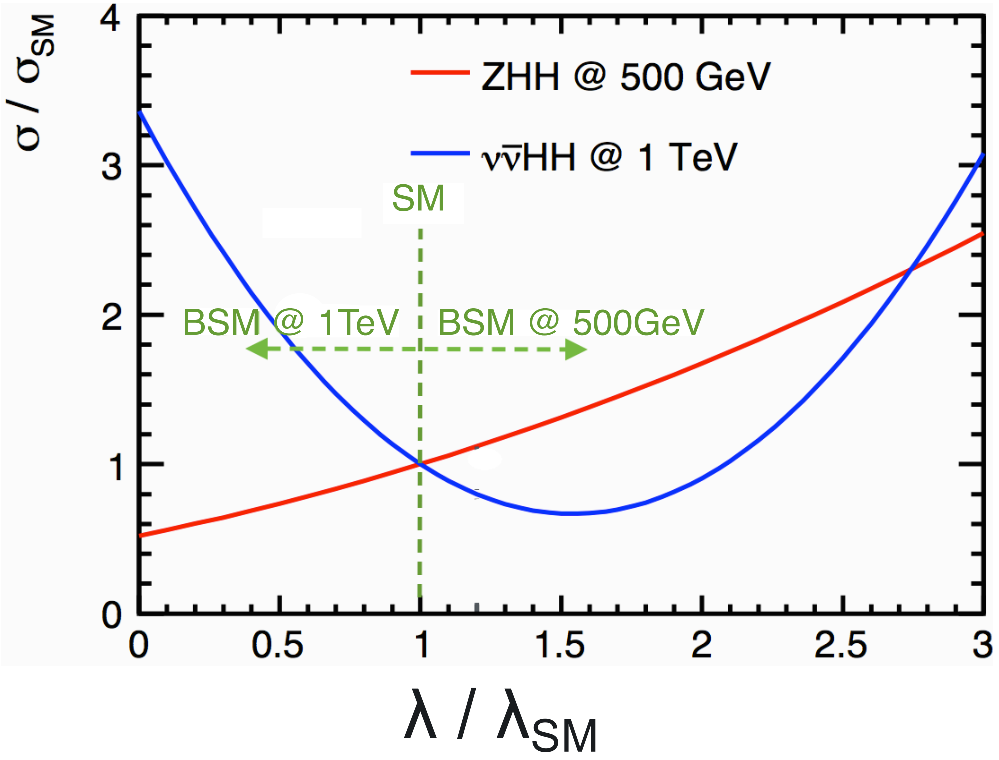


$$\mathbf{V} = \frac{1}{2}\mathbf{m_H^2}\boldsymbol{\Phi}_\mathbf{H}^\mathbf{2} + \lambda \mathbf{v}\boldsymbol{\Phi}_\mathbf{H}^\mathbf{3} + \frac{1}{4}\kappa\boldsymbol{\Phi}_\mathbf{H}^\mathbf{4}$$

In the SM, self-coupling terms fixed by mass. Other models can lead to potentially large deviations. Important to measure independently.

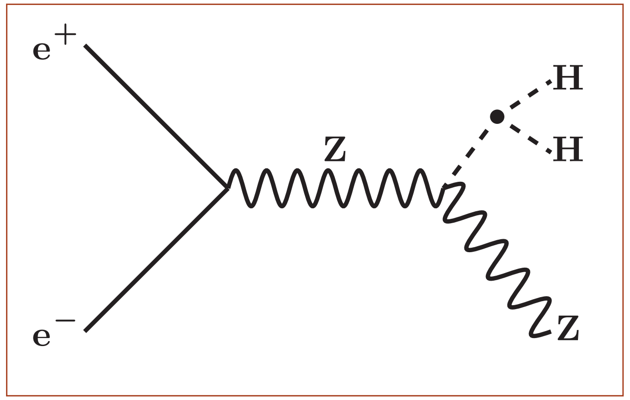
At the ILC: Measure the rate of double Higgs production
ZHH (500 GeV) or HHvv (1 TeV)

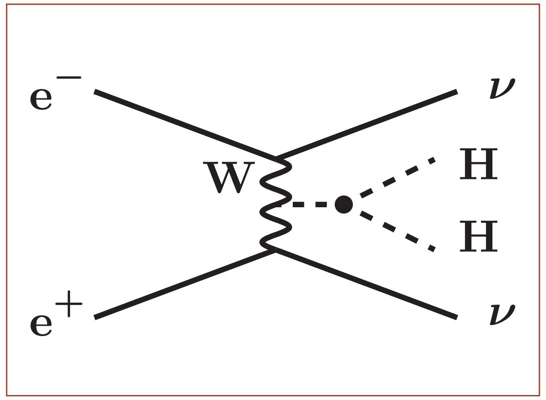


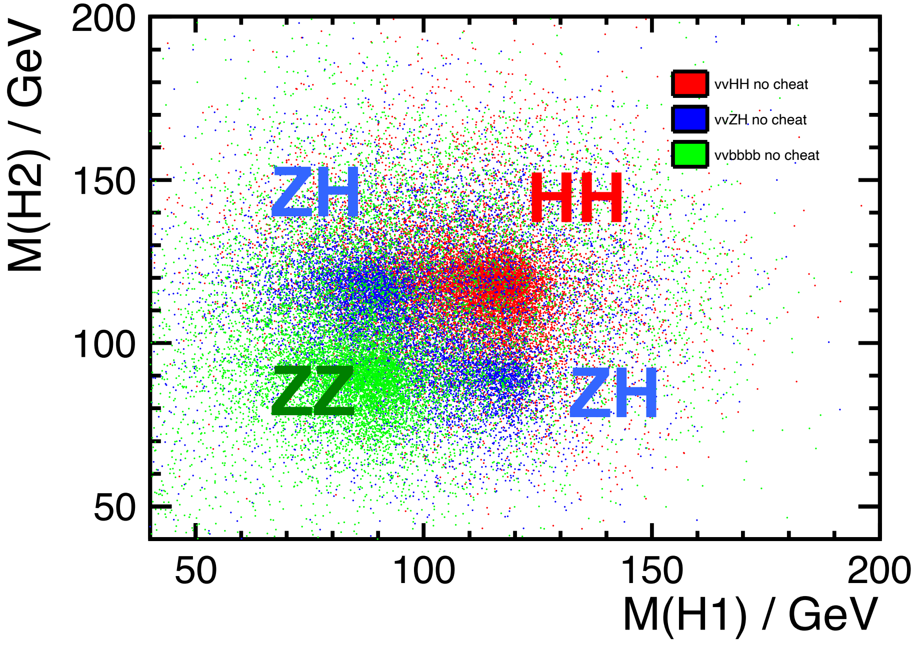


Deviations in λ lead to a change in cross section

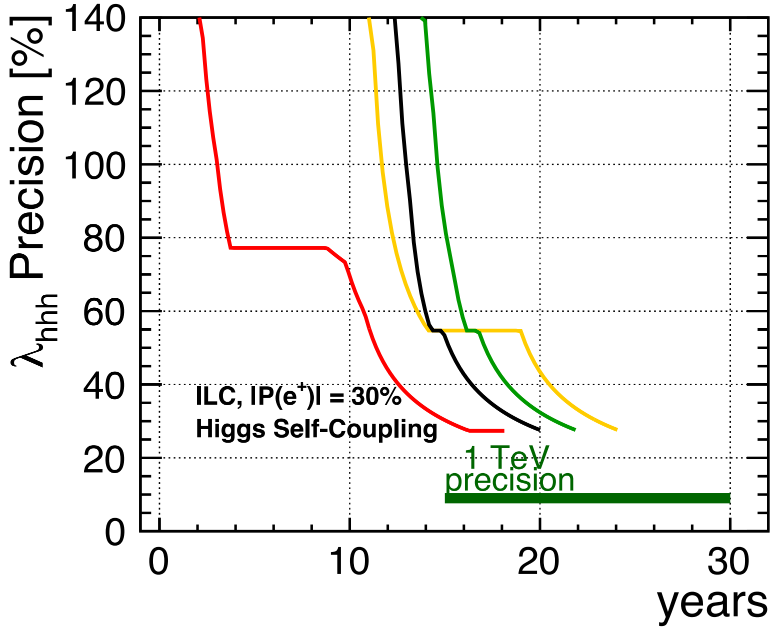
Measurement of double Higgs Production at the ILC







Very challenging experimentally: Low signal rates, high multiplicity.
b – tagging, jet clustering…



Mass resolution in double Higgs production and dominant background at 500 GeV

Experimental precision limited by jet clustering.

Estimate with ILC500 : 27%
Estimate with ILC1000: ~10%

Summary

- The LHC experiments have discovered a Higgs boson that is still consistent with various models (including SM). Higher precision is needed to discover the influence of BSM, which would give a path to new physics.
- This goal is strongly endorsed in the P5 report.
- Higgs – and top quark – precision measurements at $\sqrt{s} > 250$ GeV are an essential part of this program which will allow us to identify which BSM is a candidate for SM2.0.

Disclaimer

- The numbers presented here are based on realistic simulation studies including beam background, with today's reconstruction methods.
- The LHC experiments are demonstrating how much clever approaches in analysis and reconstruction can improve error bars.

Acknowledgments

- Material and suggestions from
  - Jim Brau
  - Benno List
  - Maxim Perelstein
  - Michael Peskin
  - Junping Tian

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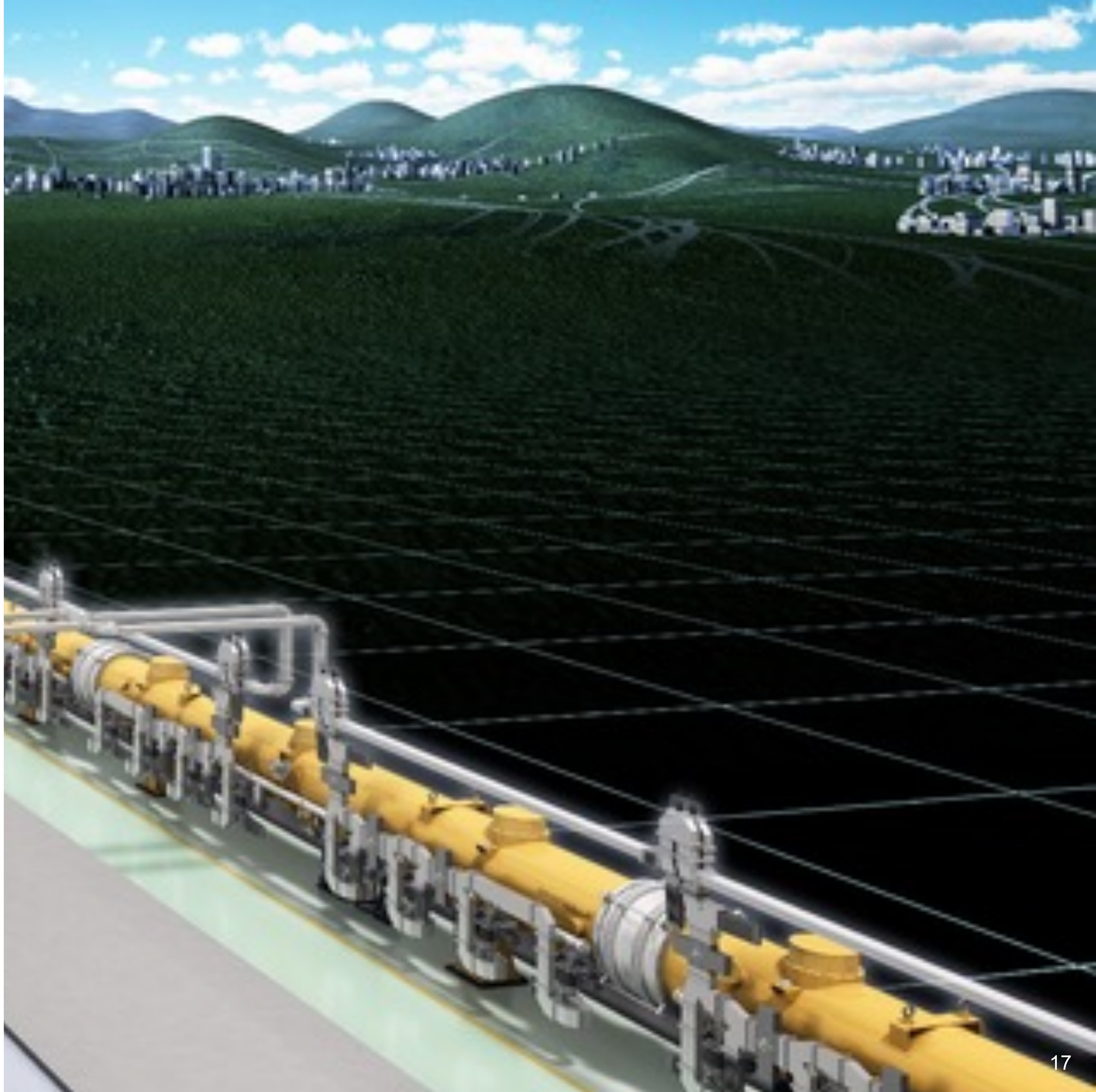
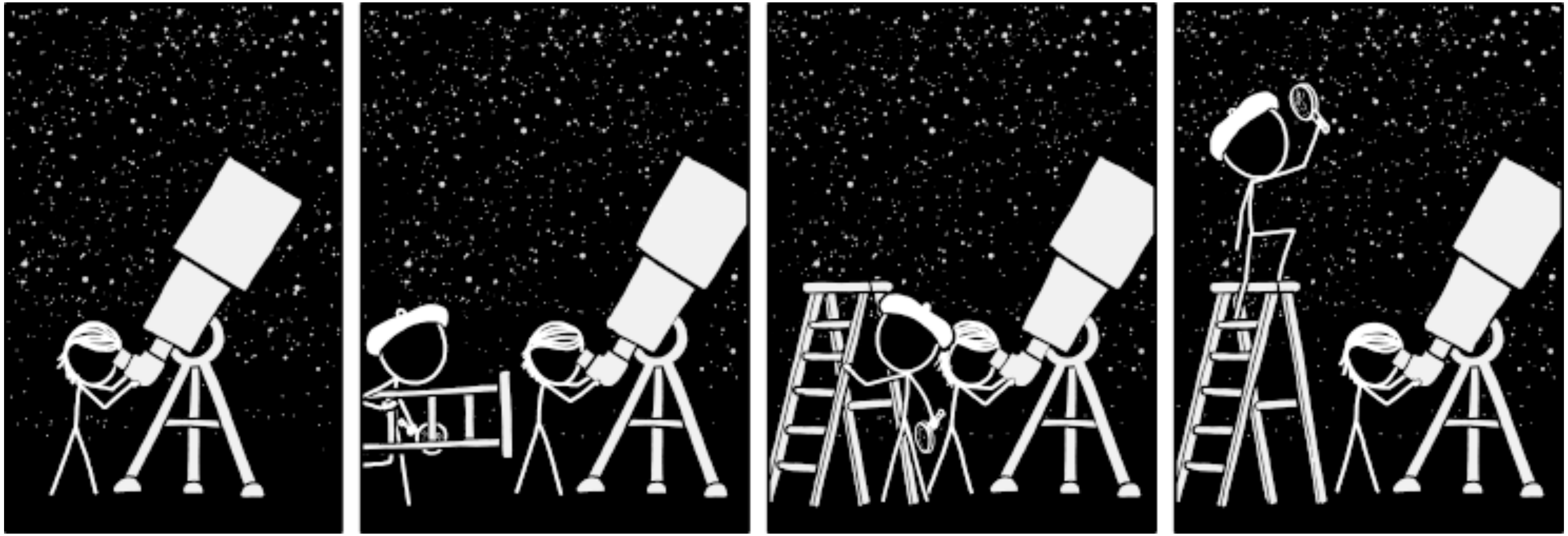
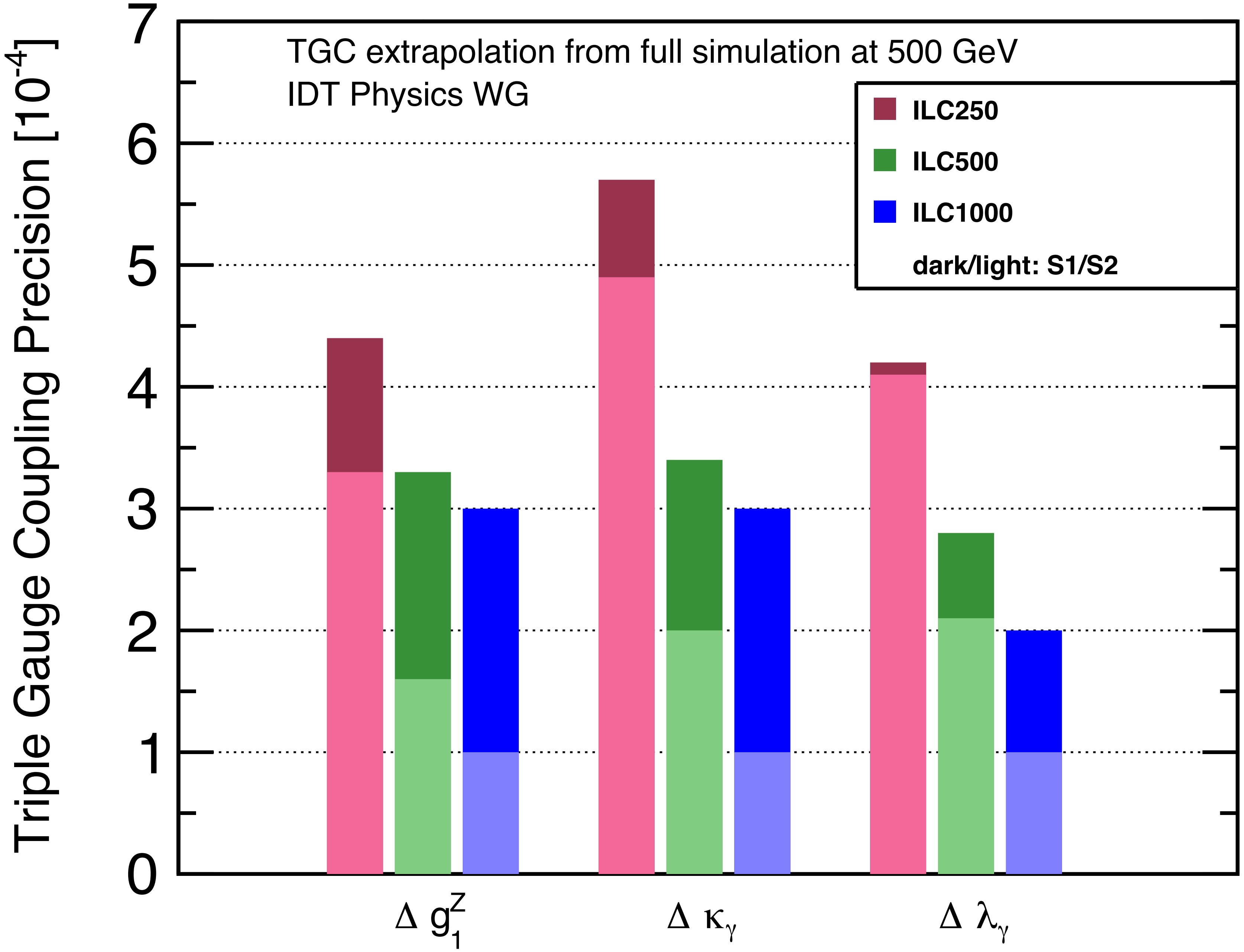
Thank you



Backup



Triple Gauge Couplings



Motivation for an effective field theory

- The most common formalism to interpret the measurements of Higgs branching ratios (times cross section) is the ϰ – formalism
- seven parameters: $\delta\kappa_Z, \delta\kappa_W, \delta\kappa_b, \delta\kappa_c, \delta\kappa_g, \delta\kappa_\tau, \delta\kappa_\mu$
  - multiply the SM Higgs couplings $g_{hA\overline{A}} = g_{hA\overline{A}}(1 + \delta\kappa_A)$
  - use HL-LHC projection for H ➞ γγ / H ➞ ZZ
  - for the ILC: add two parameters for invisible and other couplings

$$\delta\mathcal{L} = \kappa_{\mathrm{Z}} \frac{2m_{\mathrm{Z}}^2}{v} h Z_\mu Z^\mu + \kappa_{\mathrm{W}} \frac{2m_{\mathrm{W}}^2}{v} h W_\mu W^\mu$$

This approach is appropriate for the fermion couplings.

However, it is not the most general for WW and ZZ couplings

→ Effective Field Theory to account for effects of new physics (dim-6)

- 10 new parameters c_i related to Higgs couplings (84 new parameters total)
- allows to connect measurements to model

Effective field theory approach

With an effective field theory, the deviation from the SM Lagrangian can be written as

$$\delta\mathcal{L} = (1+\eta_Z)\frac{2m_Z^2}{v}hZ_\mu Z^\mu + \zeta_Z\frac{h}{2v}Z_{\mu\nu}Z^{\mu\nu}$$
$$+ (1+\eta_W)\frac{2m_W^2}{v}hW_\mu W^\mu + \zeta_W\frac{h}{2v}W_{\mu\nu}W^{\mu\nu}$$

sensitive to spin structure, can not be probed by ϰ - formalism

$$\sigma(e^+e^- \to Zh) = (SM)\cdot(1+\eta_Z+5.5\zeta_Z)$$
$$\Gamma(h\to WW^*) = (SM)\cdot(1+2\eta_W-0.78\zeta_W)$$
$$\Gamma(h\to ZZ^*) = (SM)\cdot(1+2\eta_Z-0.50\zeta_Z)$$

additionally, we have: $\delta\mathcal{L} = \zeta_{AZ}\frac{h}{v}A_{\mu\nu}Z^{\mu\nu}$

➞ This leads to a formalism that lets us probe new physics models with polarized beams and precision measurements at different energies

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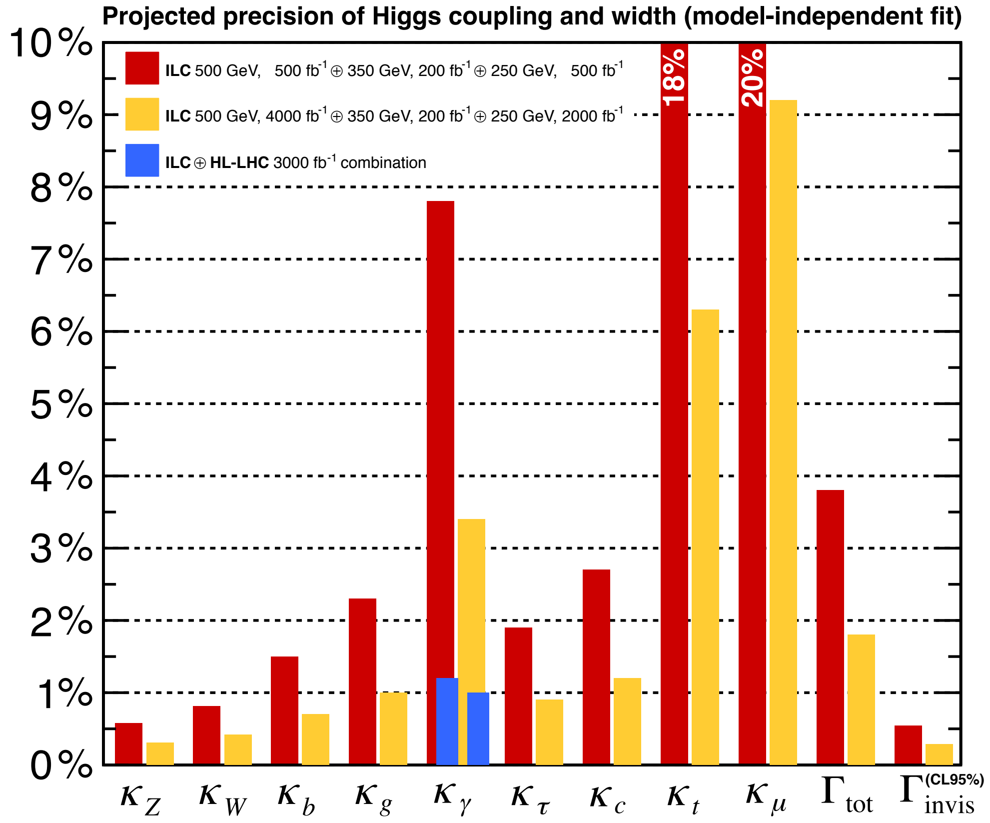
Global Fit of Higgs couplings

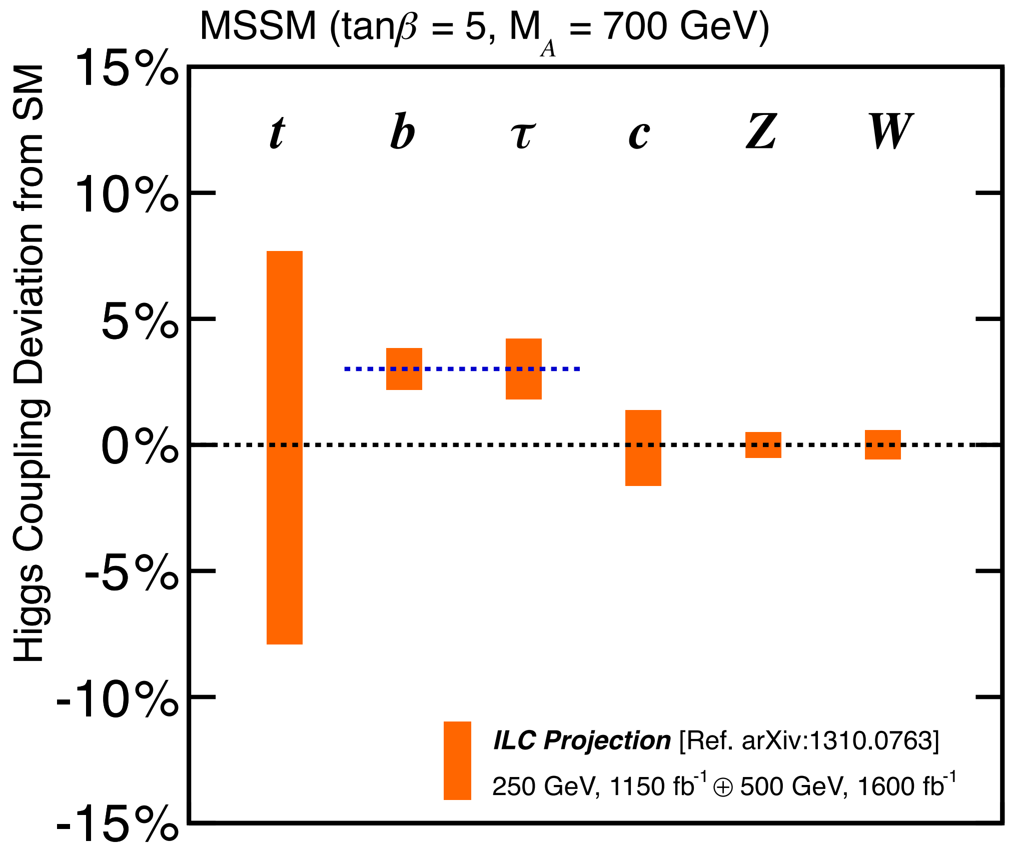


Best measurement of cross section: σ_{ZH} from recoil method. Error < 2.5%

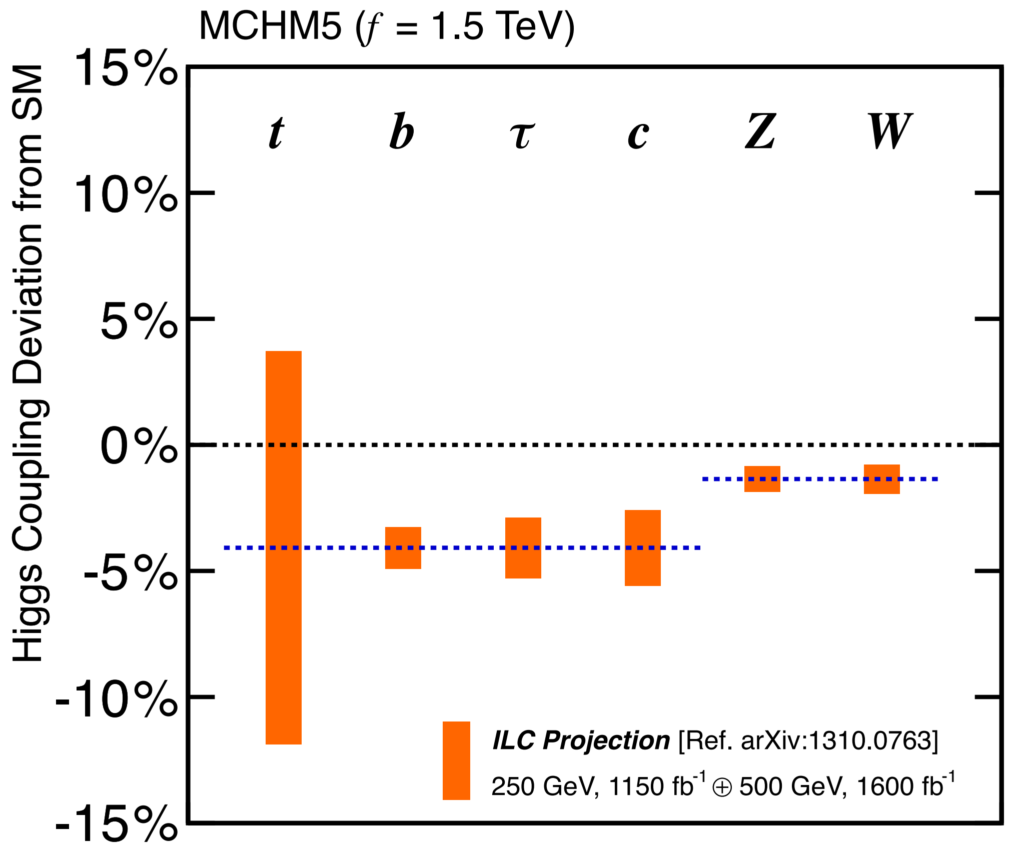
parameter	ILC500	ILC500 LumiUp
Γ_H	3.8%	1.8%
g(HZZ)	0.58%	0.31%
g(HWW)	0.81%	0.42%
g(Hbb)	1.5%	0.7%
g(Hcc)	2.7%	1.2%
g(Hgg)	2.3%	1.0%
g(ττ)	1.9%	0.9%
g(Hγγ)	7.8%	3.4%
g(Hγγ)+LHC	1.2%	1.0%
g(Hμμ)	20%	9.2%
g(Htt)	18%	6.3%

Precision Measurements are not optional

Supersymmetry (MSSM)



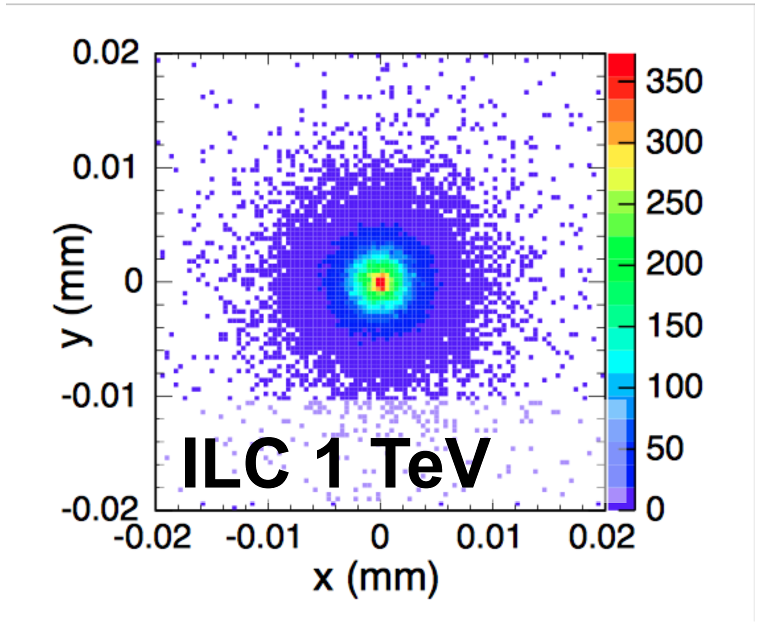
Composite Higgs (MCHM5)



ILC 250+500 LumiUp

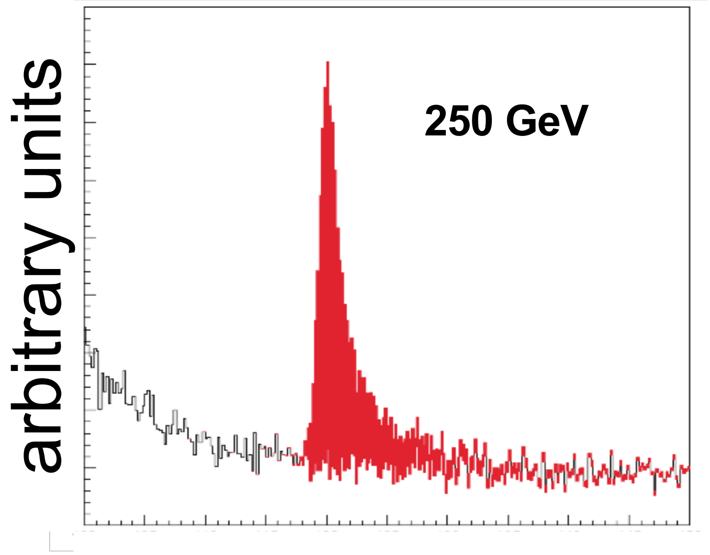
Detector Requirements are driven by Higgs physics

primary vertices in tth events



Exceptionally good impact parameter resolution, time stamping, material budget in the vertex detector

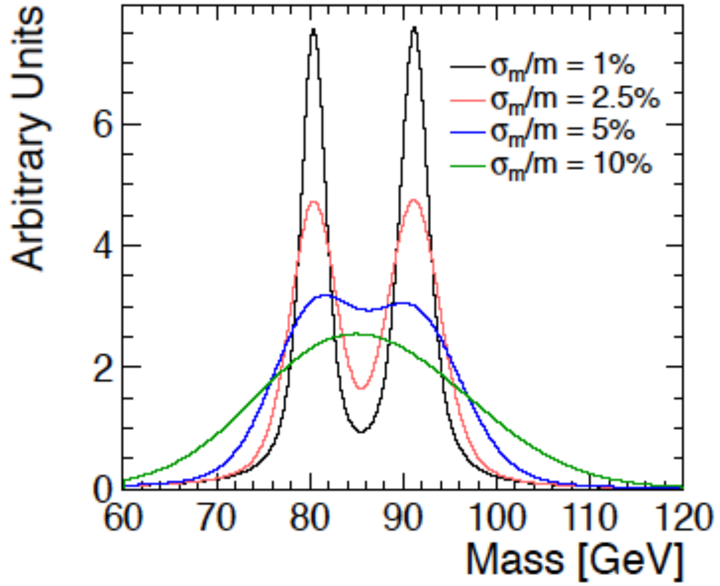
ZH → μ+μ- + anything



Extremely low material budget in the main tracker, with high tracking efficiency

$\sigma(1/p) \sim 2.5 \times 10^{-5}$

W-Z separation



Not only good calorimeter resolution, but excellent track-shower matching and shower separation

The ILC TDR

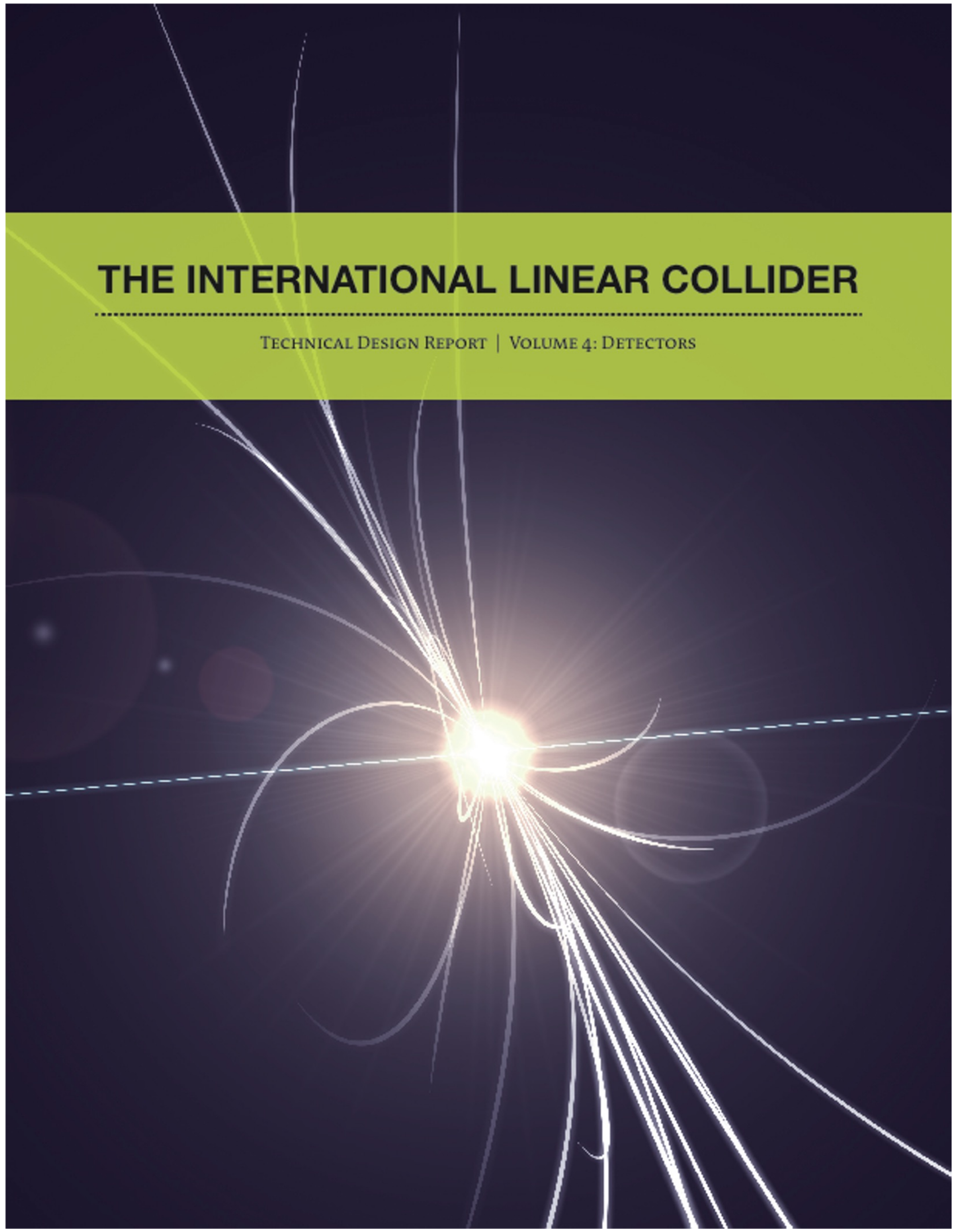
Volume 1 – Executive Summary:
http://arxiv.org/abs/1306.6327

Volume 2 – Physics:
http://arxiv.org/abs/1306.6352

Volume 3.I – Accelerator R&D in the Technical Design Phase:
http://arxiv.org/abs/1306.6353

Volume 3.II – Accelerator Baseline Design
http://arxiv.org/abs/1306.6328

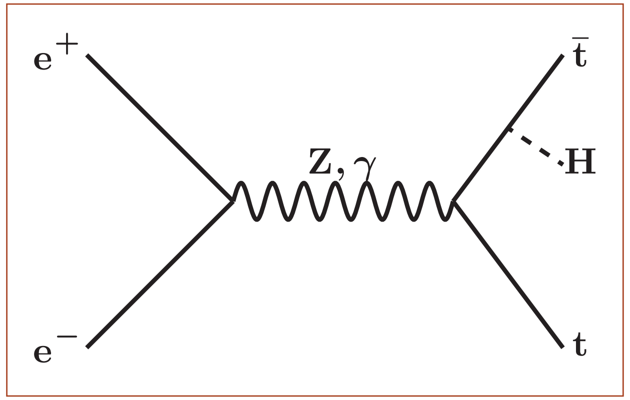
Volume 4 – Detectors:
http://arxiv.org/abs/1306.6329



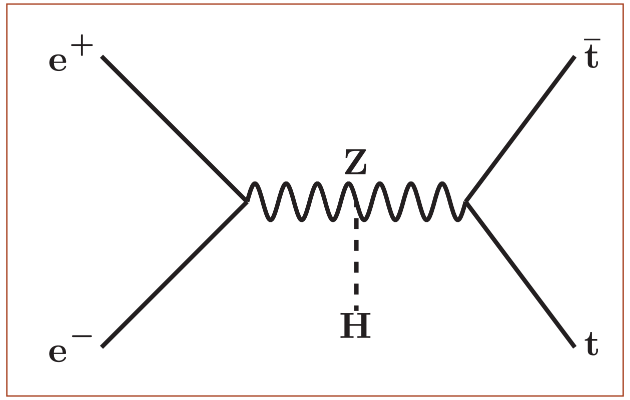
Top Yukawa coupling at a 1 TeV ILC

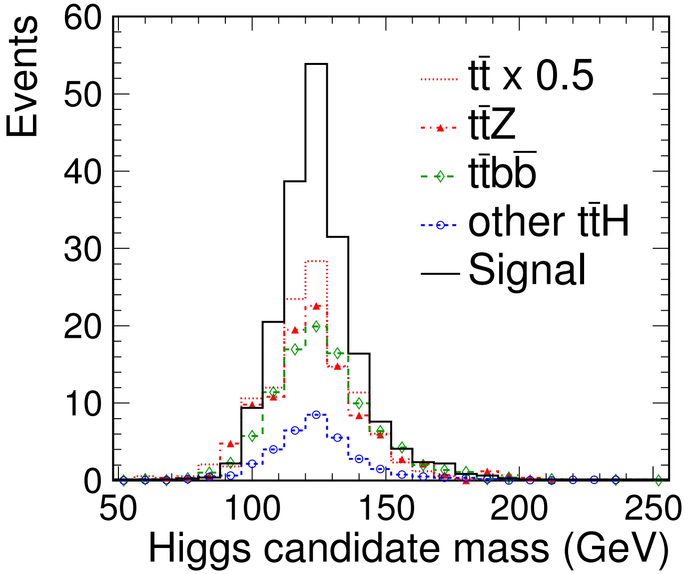
doi:10.1140/epjc/s10052-015-3532-4

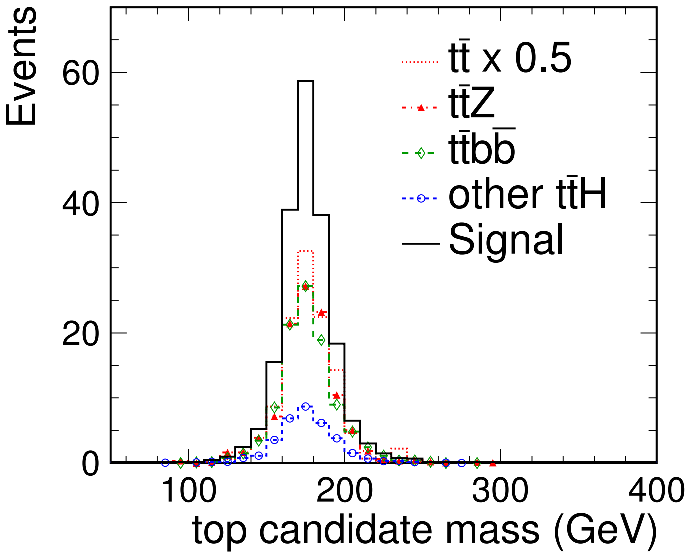
Main production channel of ttH at ILC



ttH channel not sensitive to
top Yukawa coupling,~4% effect







Analysis in 6-jet+lepton and in 8-jet mode
Main background processes:
Other Higgs decays, ttZ, ttbb, tt

4% with 1 ab^{-1} at 1 TeV with only left-handed polarization.

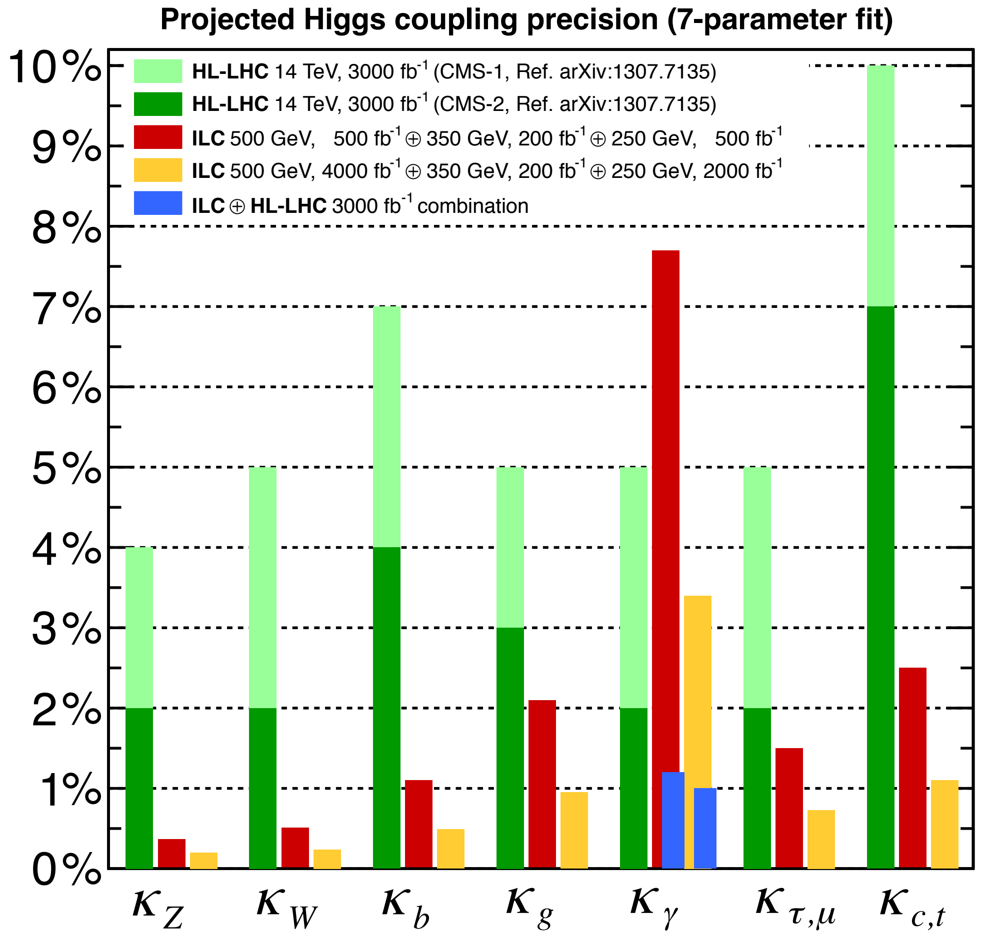
Expected precision with full ILC program + Energy upgrade: 2%

Comparison with the LHC

The expected deviation of Higgs couplings from the SM are ~5%, depending on the model.

The HL-LHC program will measure several Higgs couplings to <10%.

The ILC program will improve upon this precision by ~ one order of magnitude.



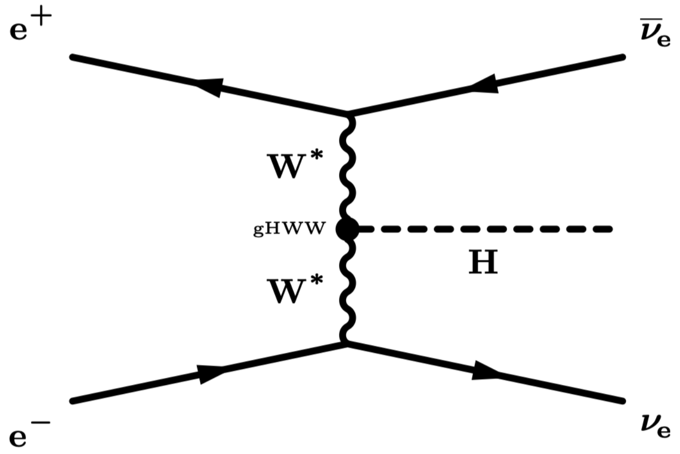
The combination of HL-LHC and ILC improves the $\varkappa_\gamma$ measurement by nearly one order of magnitude.

The Higgs width at the ILC

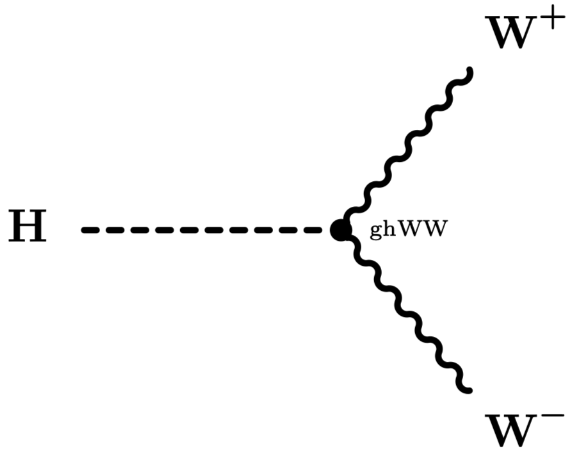
For precision measurements, at some point $\Delta\Gamma_H$ becomes a limiting factor Standard Model: $\Delta\Gamma_H \cong 4$ MeV

At the LHC: Use rate of off-shell $H \rightarrow ZZ$: $\sigma(\Gamma_H) = 22$ MeV,

At the ILC: Use the fact that the same tree-level coupling enters production and decay and that ZH cross section can be measured inclusively



g_{HWW} in both, production and decay



$$\Gamma_H = \frac{\Gamma(H \rightarrow WW)}{\mathcal{BR}(H \rightarrow WW)} \propto \frac{g^2_{HWW}}{\mathcal{BR}(H \rightarrow WW)}$$

$$\frac{g^2_{HWW}}{g^2_{HZZ}} \propto \frac{\sigma_{\nu\nu H} \times \mathcal{BR}(H \rightarrow \bar{b}b)}{\sigma_{ZH} \times \mathcal{BR}(H \rightarrow \bar{b}b)}$$

Expected Precision at full ILC: $\Delta\Gamma_H / \Gamma_H = 1.4\%$

$\Delta g_{HWW} / g_{HWW} = 0.28\%$