Higgs Physics at the ILC

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Pacific Northwest National Laboratory and University of Oregon,
For the ILC Detector and Physics community

APS DPF Meeting, FNAL 2017

Overview

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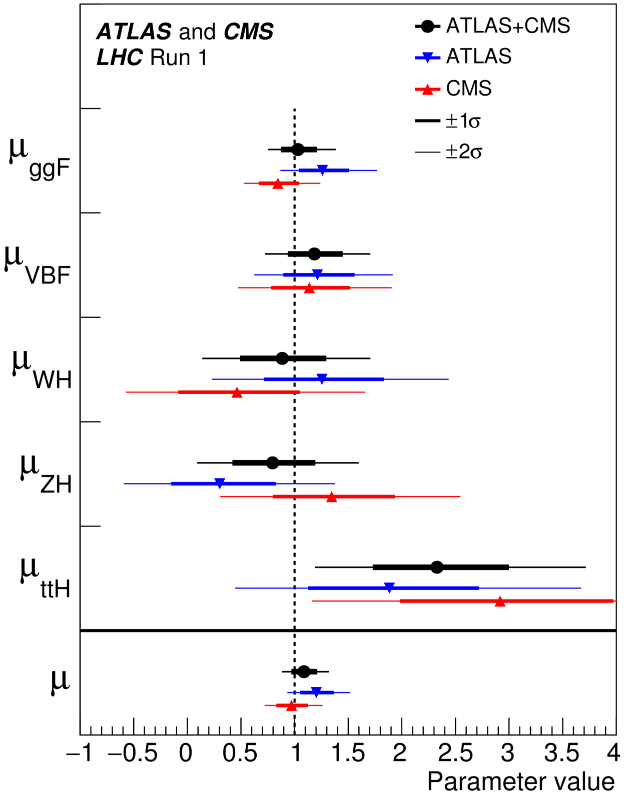
- The Higgs at the LHC
- The ILC accelerator and detectors
- Higgs physics at the ILC
  - Fermions
  - Self-coupling
  - Top Yukawa
  - Combined Fit
- Summary

RUN1: PRODUCTION & DECAY

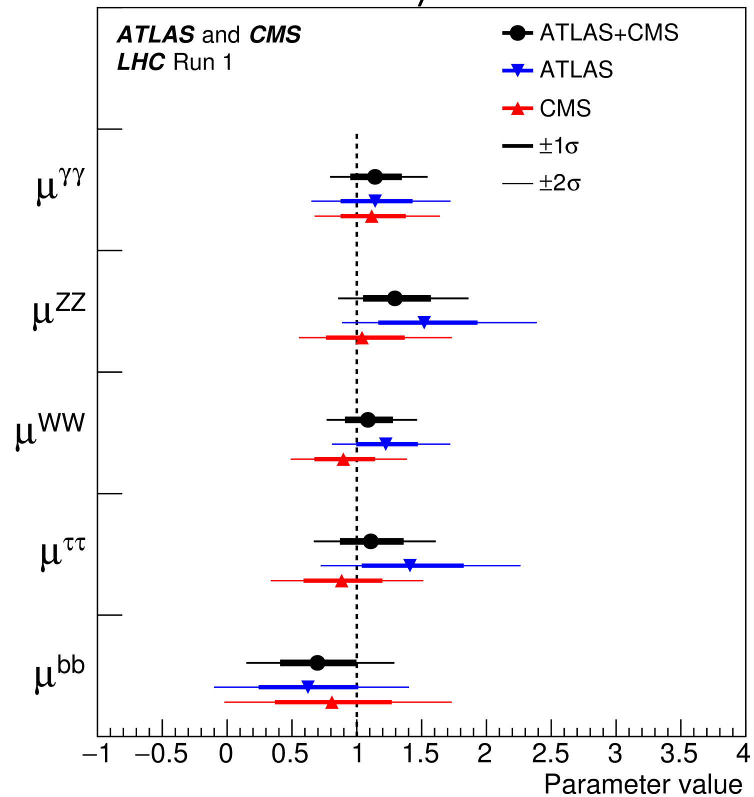
signal strength $\mu=\sigma/\sigma_{SM}$

ATLAS+CMS JHEP 08 (2016) 045

production



decay



Production & decay measured to be compatible with SM Higgs: precision [20-60]%

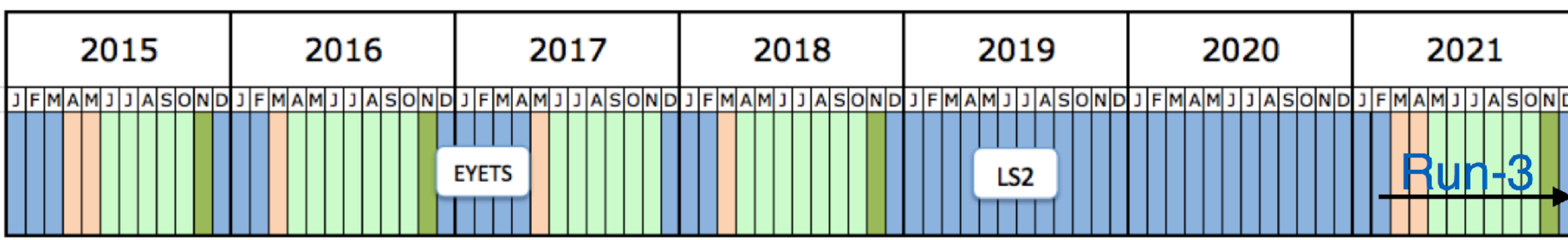
Observation of boson decay modes: γγ, WW, ZZ

Direct coupling to fermions not fully established: $H\to\tau\tau$ 5.5σ (exp 5σ), $H\to bb$ 2.6σ (exp 3.7σ)

IN OTHER WORDS

Looks like SM

More precision is needed



$3fb^{-1}$ $36fb^{-1}$ Target ~$45fb^{-1}$ x year

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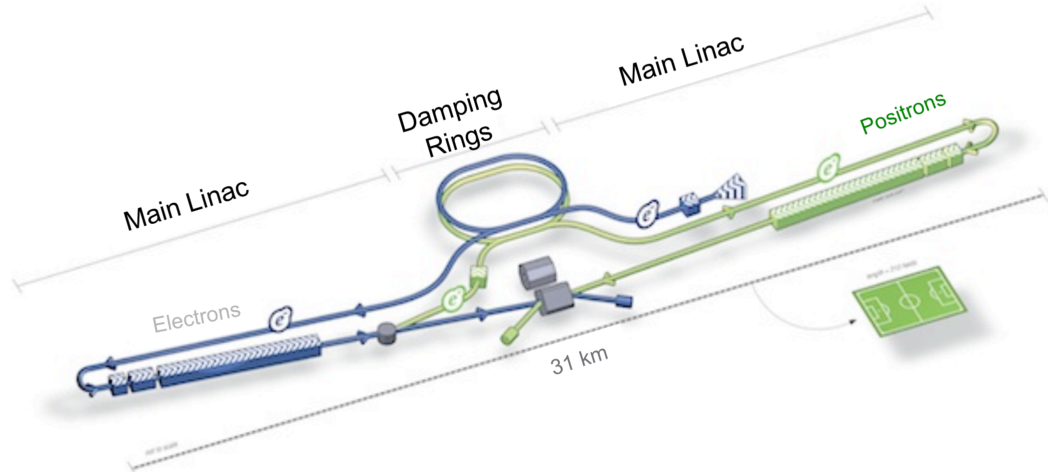
The ILC accelerator and detectors

U.S. DEPARTMENT OF ENERGY

The ILC Accelerator



TDR Baseline: 31 km → ~500 GeV
Upgrade option to ~1 TeV

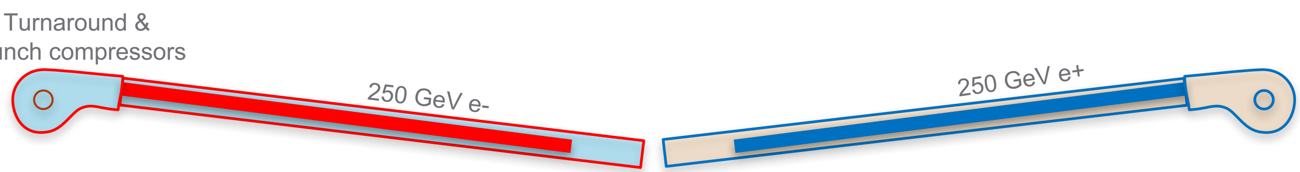
- Candidate site in Japan has been studied
- Layout being targeted towards site
- TDR has been delivered in 2012
- Technology being installed in XFEL at DESY

From the P5 report: *As the physics case is extremely strong, …*

Recommendation 11: *Motivated by the **strong scientific importance** of the ILC and the recent initiative in Japan to host it, the U.S. should engage in modest and appropriate levels of ILC accelerator and detector design in areas where the U.S. can contribute critical expertise. Consider higher levels of collaboration if ILC proceeds.*

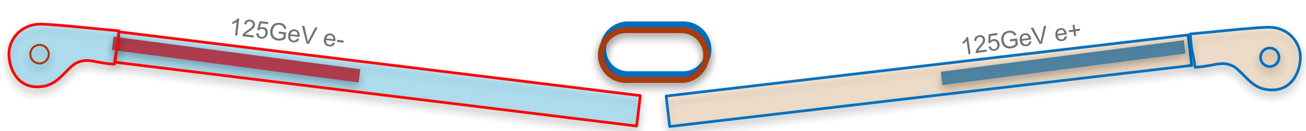
Recent developments: Staging options

500GeV **TDR:**

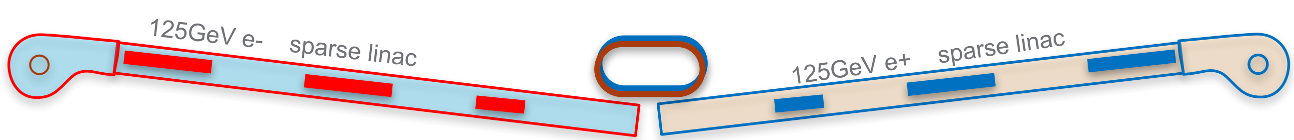


Staging options under discussion:
Example(s): Tunnel like in TDR, stage 1 with fewer cryo modules.

Option E:

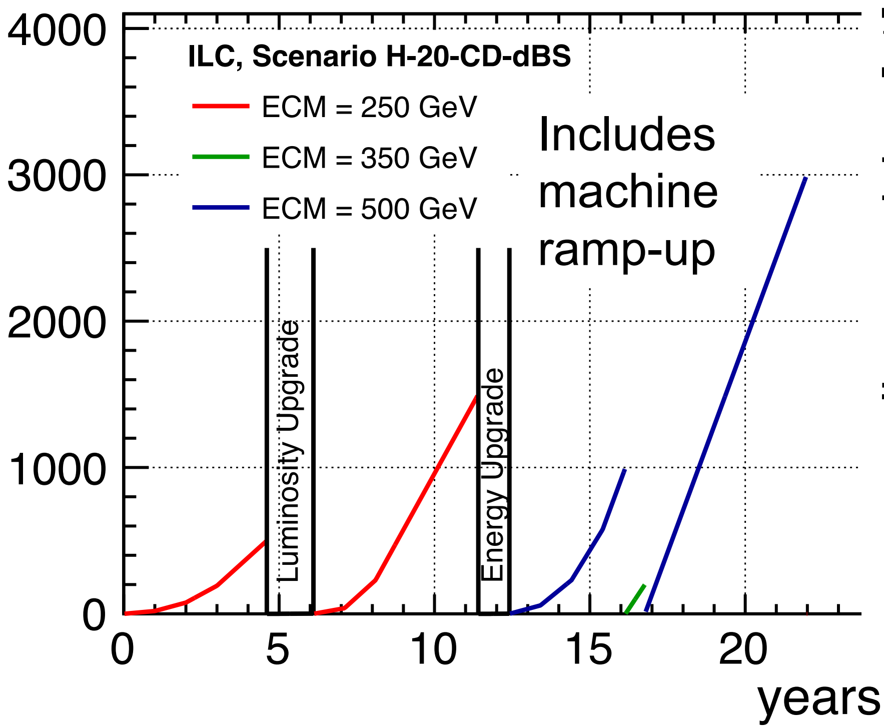


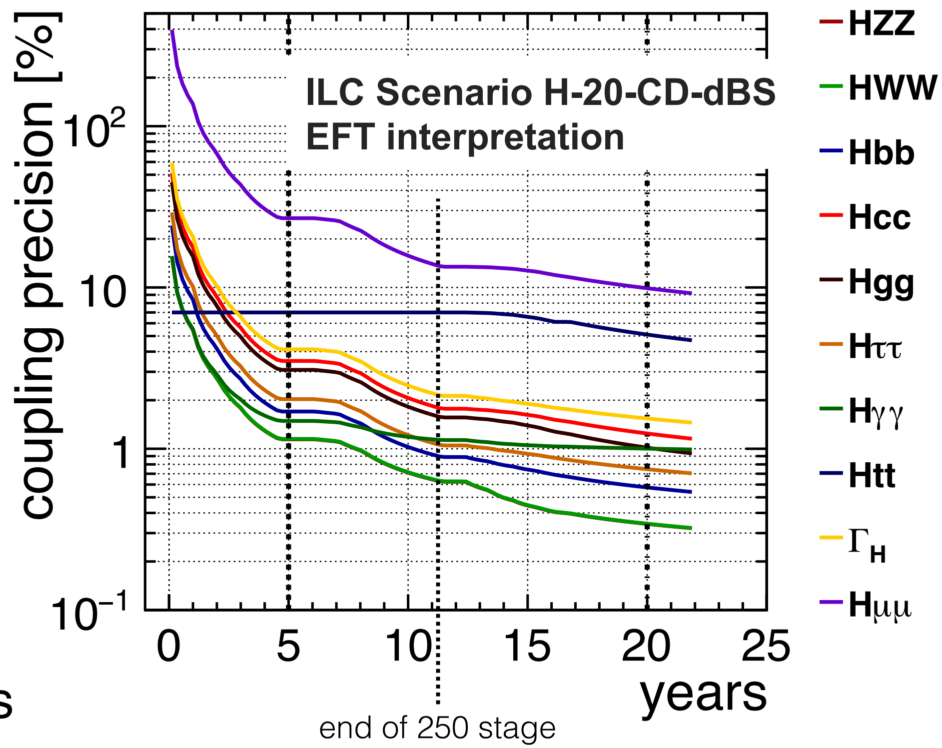
Option F:



For more details, see talks by B. List, S. Michizono @ AWLC17

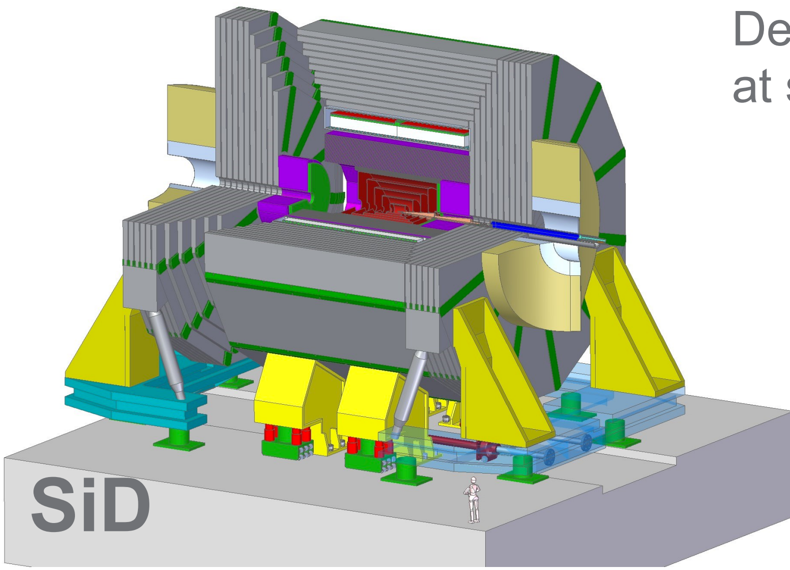
ILC Staging scenarios



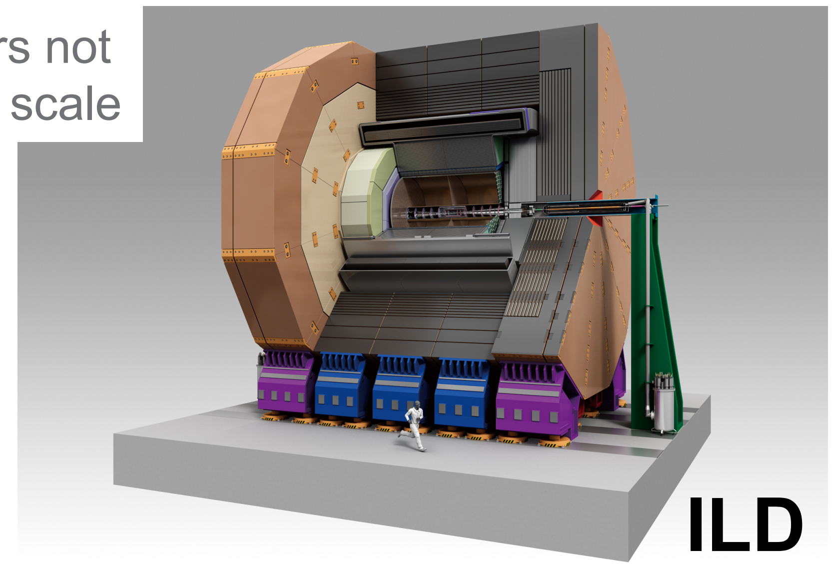


- Start at 250 GeV
- Runs at 500 GeV for full program, 350 GeV for higher precision of top properties
- Other thresholds possible, informed by LHC or early ILC Data
- **Goal**: per cent-level precision on (most) Higgs couplings
- Possible upgrade to 1 TeV
  - improve ttH, self-coupling measurements,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

ILC Detectors



Detectors not at same scale



5 T field
Silicon Tracking

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. Now working toward TDR

Detector Requirements are driven by Higgs physics

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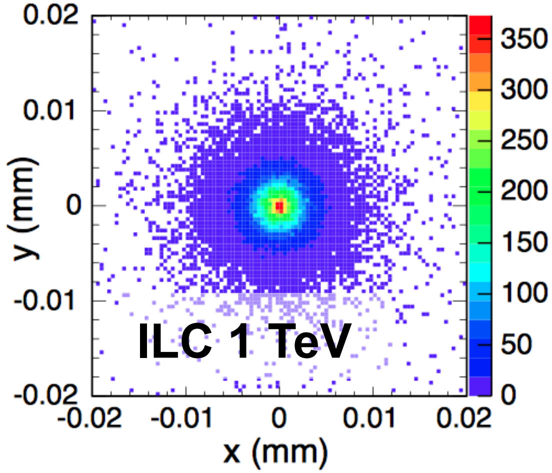
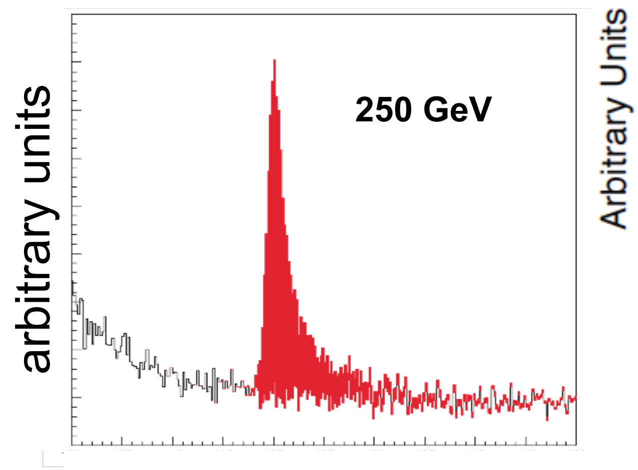
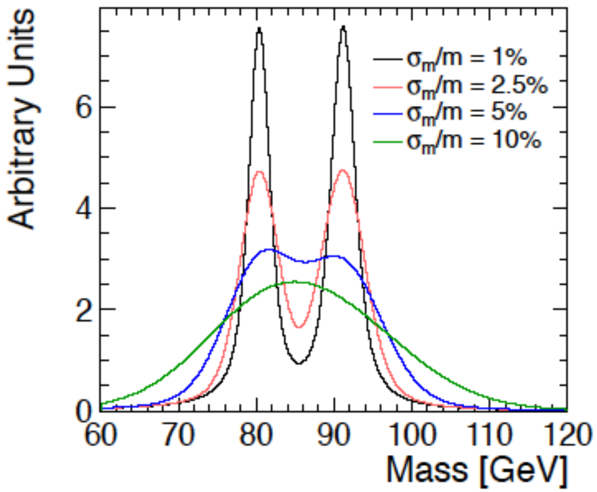
primary vertices in tth events



ZH → μ+μ- + anything



W-Z separation



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

→ R&D ongoing to meet all of these requirements

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

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

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

The ILC TDR

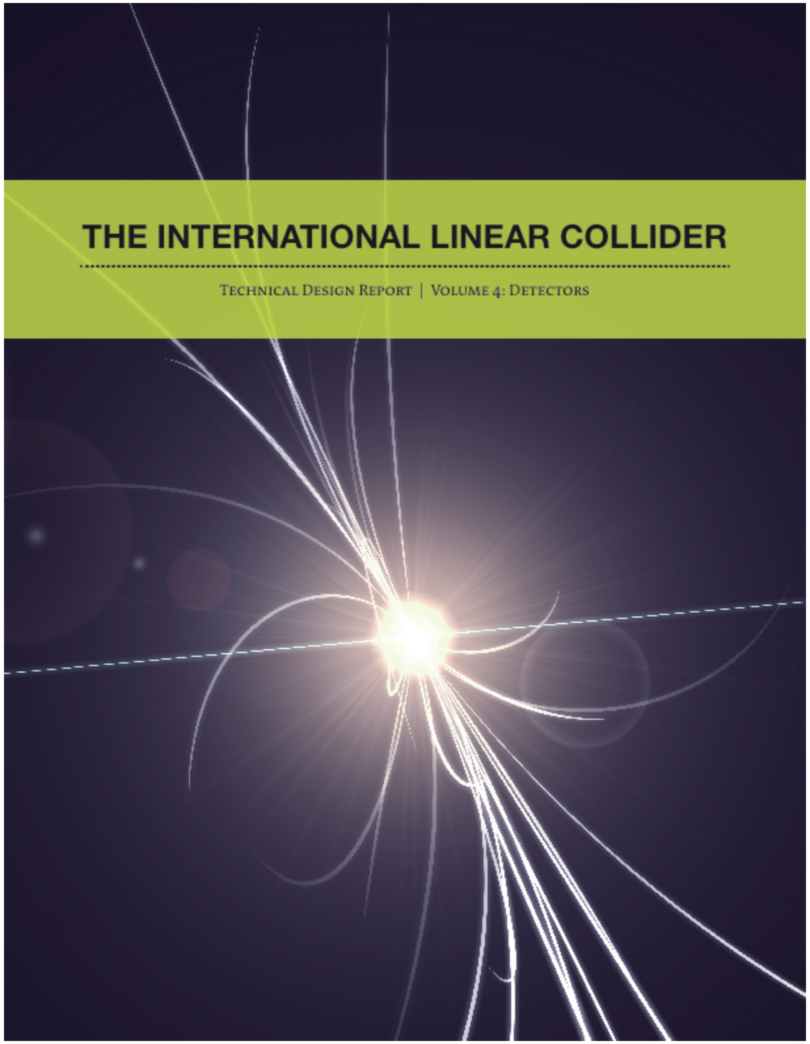
Volume 1 – Executive Summary:
    http://arxiv.org/abs/1306.6327

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



Physics with Higgs bosons at the ILC

Input to the studies in the following slides is largely based on detailed detector simulations

Higgs Production at the ILC

Baseline of 500 GeV

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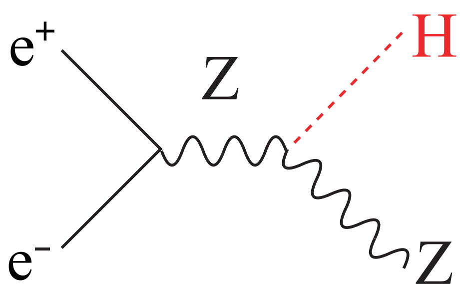
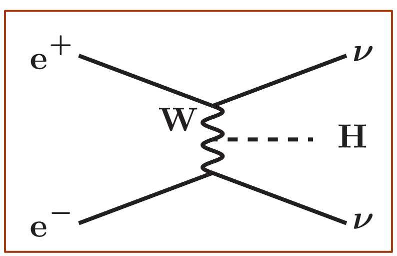
A Higgs program in 3 stages

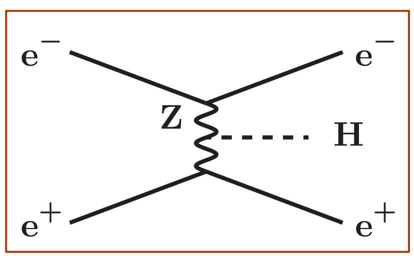


Recoil method: ILC staple at all stages

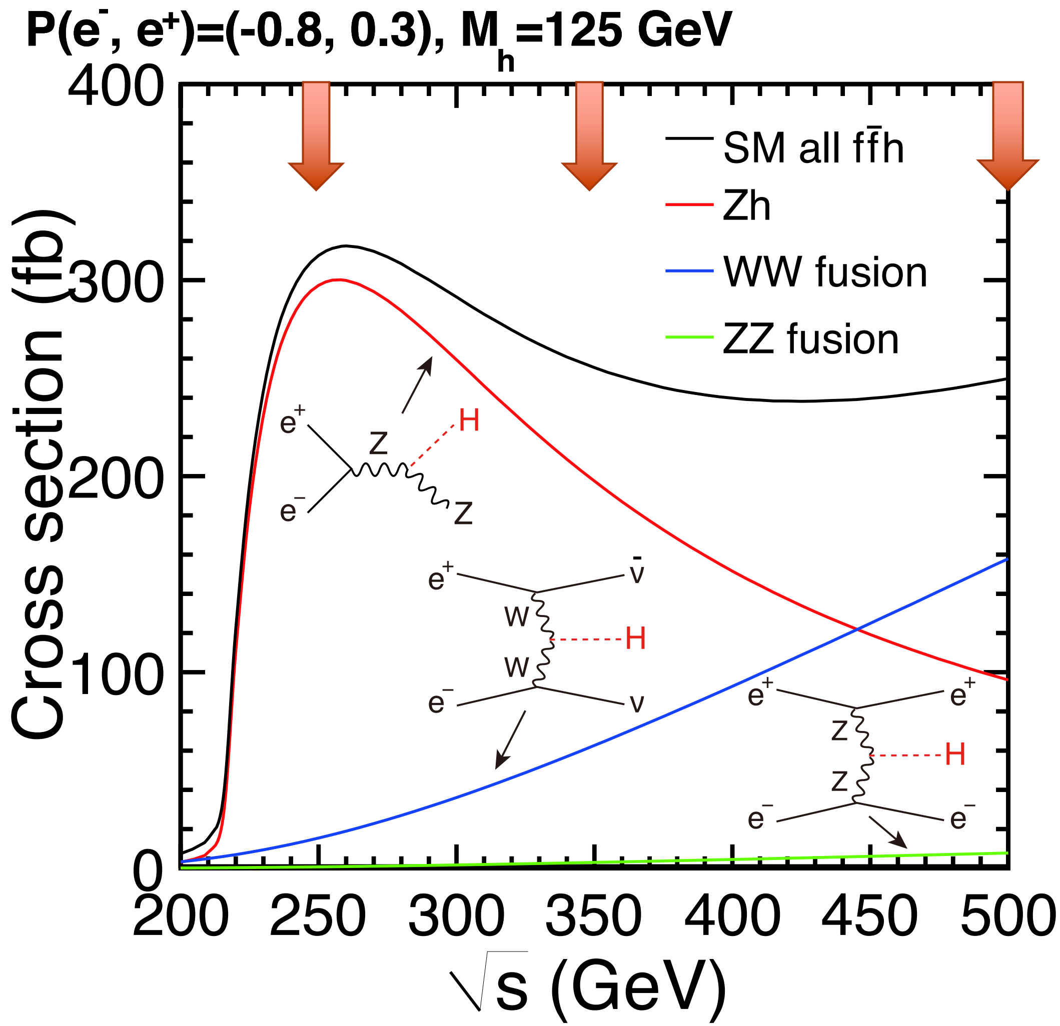
Z ➞ ll for precision

Z ➞ qq for higher cross section

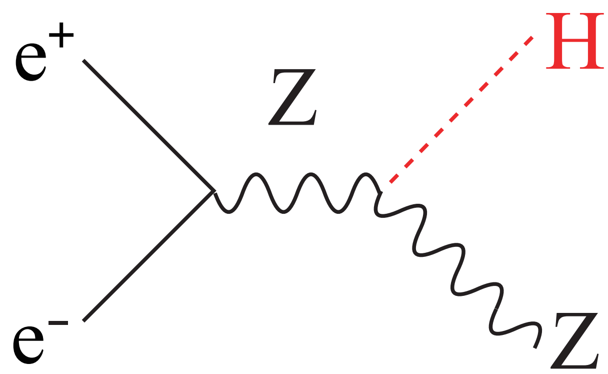




Vector boson fusion cross section increases at higher energies



Higgsstrahlung at the ILC

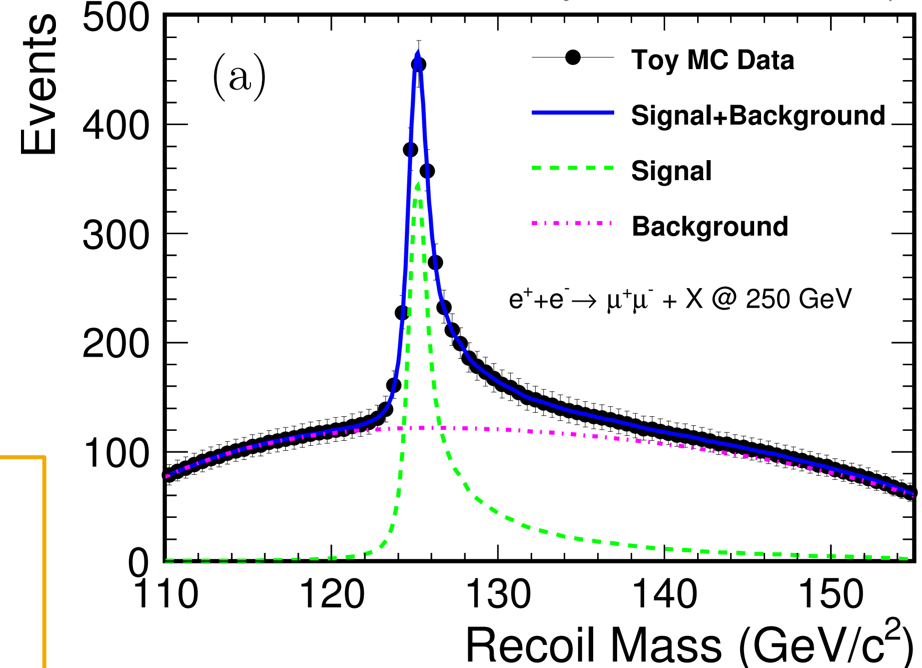


$$\mathbf{M}_{\text{recoil}} = \left((\sqrt{\mathbf{s}} - \mathbf{E}_{\mathrm{Z}})^{\mathbf{2}} - \mathbf{P}_{\mathrm{Z}}^{\mathbf{2}}\right)^{\mathbf{1/2}}$$

Well-known initial state at ILC allows to measure the Higgs in a model-independent way: Reconstruction efficiencies are independent of the final states to within < 1%

Sensitivity to invisible decays, certain CP violating scenarios

Phys. Rev. D 94, 113002 (2016)



This method has the smallest uncertainty near threshold.

Comparison with the LHC

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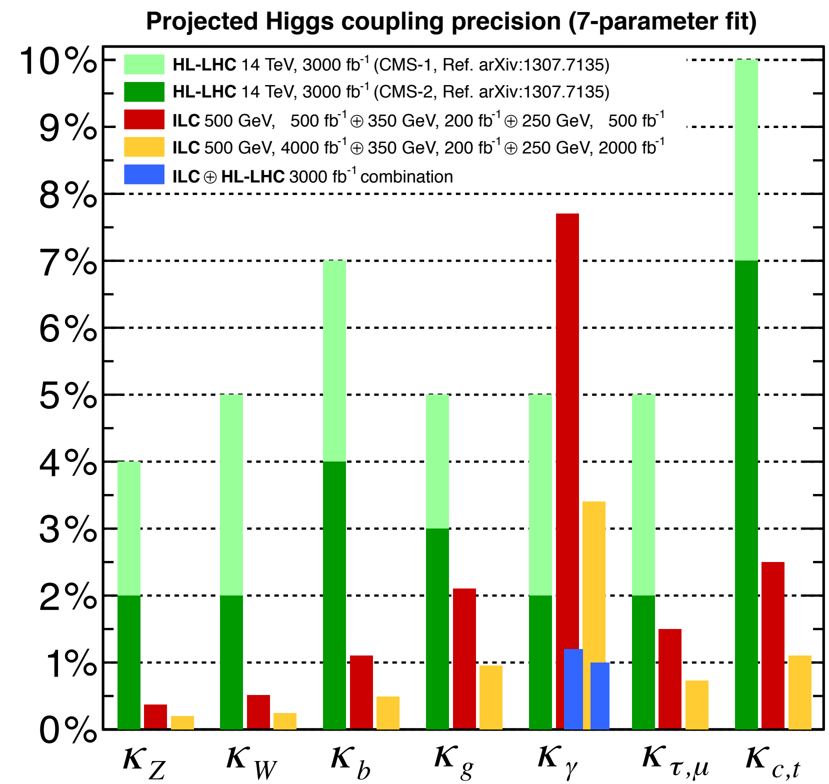
As we heard on Monday, the expected deviation of Higgs couplings from the SM are ~5%, depending on the model.

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 κ_γ measurement by nearly one order of magnitude.

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

$$\delta\mathcal{L} = \kappa_{\mathrm{Z}} \frac{2m_{\mathrm{Z}}^2}{v} hZ_\mu Z^\mu + \kappa_{\mathrm{W}} \frac{2m_{\mathrm{W}}^2}{v} hW_\mu W^\mu$$

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

$$\delta\mathcal{L} = (1+\eta_{\mathrm{Z}})\frac{2m_{\mathrm{Z}}^2}{v}hZ_\mu Z^\mu + \zeta_{\mathrm{Z}}\frac{h}{2v}Z_{\mu\nu}Z^{\mu\nu} + (1+\eta_{\mathrm{W}})\frac{2m_{\mathrm{W}}^2}{v}hW_\mu W^\mu + \zeta_{\mathrm{W}}\frac{h}{2v}W_{\mu\nu}W^{\mu\nu}$$

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

$$\sigma(\mathrm{e^+e^-} \to \mathrm{Zh}) = (\mathrm{SM}) \cdot (1 + \eta_{\mathrm{Z}} + 5.5\zeta_{\mathrm{Z}})$$

$$\Gamma(\mathrm{h} \to \mathrm{WW^*}) = (\mathrm{SM}) \cdot (1 + 2\eta_{\mathrm{W}} - 0.78\zeta_{\mathrm{W}})$$

$$\Gamma(\mathrm{h} \to \mathrm{ZZ^*}) = (\mathrm{SM}) \cdot (1 + 2\eta_{\mathrm{Z}} - 0.50\zeta_{\mathrm{Z}})$$

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

The Higgs width at the ILC

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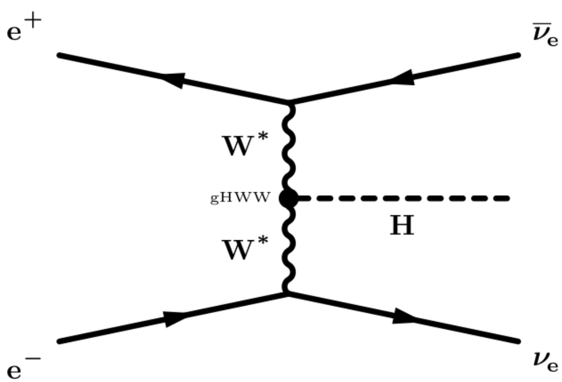
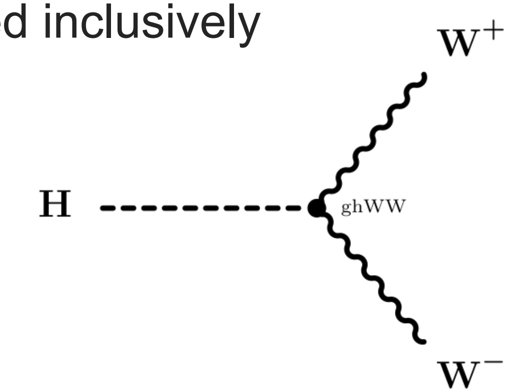
For precision measurements, at some point $\Delta\Gamma_H$ becomes a limiting factor
Standard Model: $\Delta\Gamma_H \cong 4$ MeV

At the LHC: Use rate of off-shell H → 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



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

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

Expected Precision at full ILC: $\Delta\Gamma_H / \Gamma_H$ = 1.4% $\Delta g_{HWW} / g_{HWW}$ = 0.28%

Coupling fit in EFT

- At ILC250, the t-channel diagram contribution is too small
  - Could use Higgs decays to Z, but SM branching ratio is only ~2.5% …
- With EFT, we can use the full expression for the ZH cross section

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

For a fully polarized $e^-_L e^+_R$ initial state

$$Q_{ZL} = (\frac{1}{2} - s_w^2)\ , \qquad a_L = -c_H/2$$

$$b_L = c_w^2(1+\frac{s_w^2}{1/2-s_w^2}\frac{s-m_Z^2}{s})(8c_{WW})$$

For a fully polarized $e^-_R e^+_L$ initial state

$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H/2$$

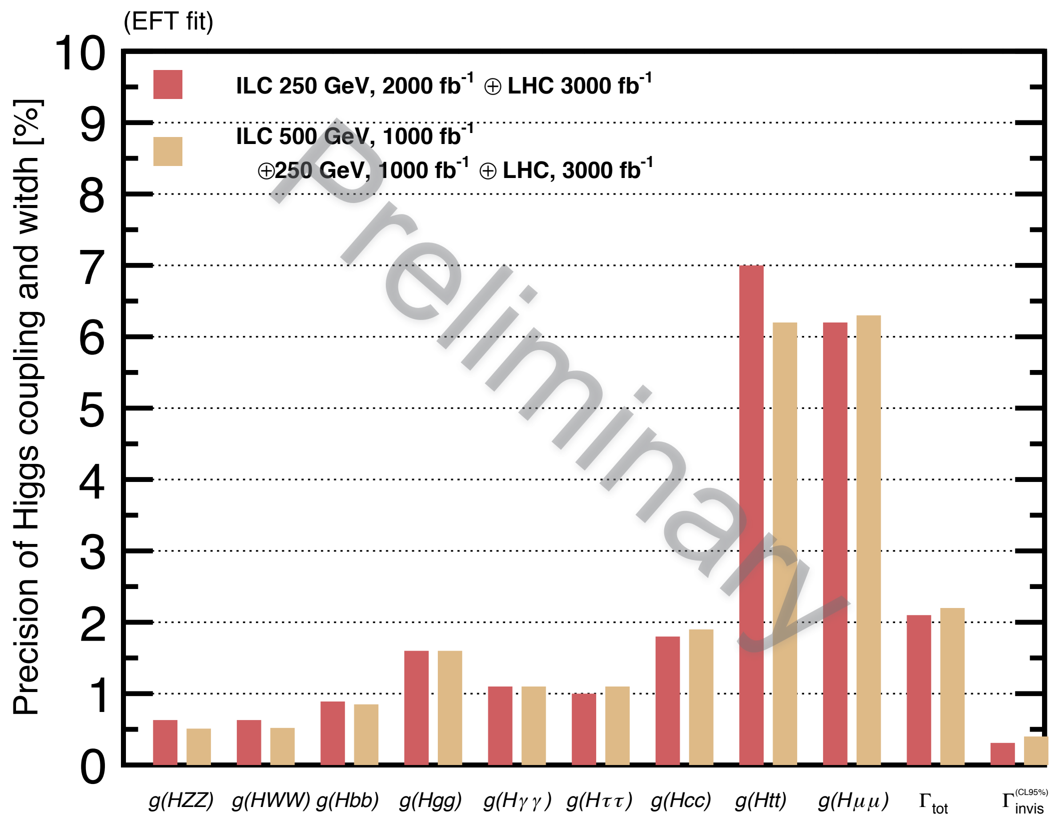
$$b_R = c_w^2(1-\frac{s-m_Z^2}{s})(8c_{---W})\ .$$

angular analysis of the ZH recoil could be used, but has less discriminating power

Model-independent measurements at the ILC

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

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



ILC will add measurements. Studies can be carried out in a self-contained and model-independent way

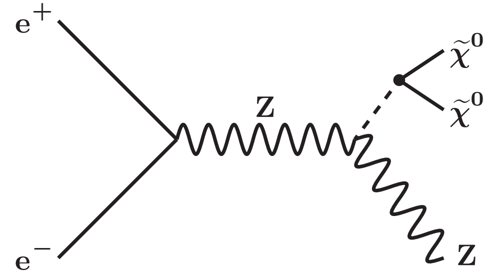
Comparison of coupling precision in different run scenarios

	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	10 ab^{-1} no pol.	full ILC 250+500 GeV
$g(hb\bar{b})$	1.46	1.09	1.03	0.81	0.58
$g(hc\bar{c})$	2.06	2.08	1.38	1.04	1.12
$g(hgg)$	1.91	1.66	1.29	0.98	0.92
$g(hWW)$	1.00	0.45	0.78	0.66	0.28
$g(h\tau\tau)$	1.56	1.33	1.09	0.85	0.76
$g(hZZ)$	0.98	0.44	0.76	0.65	0.27
$g(h\gamma\gamma)$	1.37	1.08	1.21	1.12	0.99
$g(h\mu\mu)$	12.8	7.56	8.11	5.75	8.63
$g(hbb)/g(hWW)$	1.08	0.97	0.68	0.48	0.49
$g(hWW)/g(hZZ)$	0.034	0.038	0.037	0.036	0.018
Γ_h	3.12	2.32	2.34	1.69	1.39
$\sigma(e^+e^- \to Zh)$	0.70	0.30	0.44	0. 31	0.47
$BR(h \to inv)$	0.34	0.50	0.24	0.19	0.32
$BR(h \to other)$	1.60	1.29	1.02	0.73	0.94

Preliminary

Discovery Potential for new physics of the ILC250

Invisible Higgs Decays



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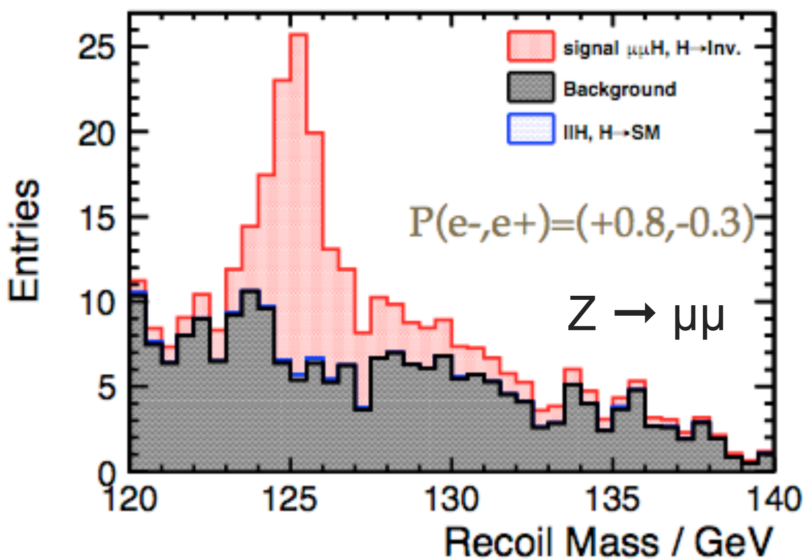
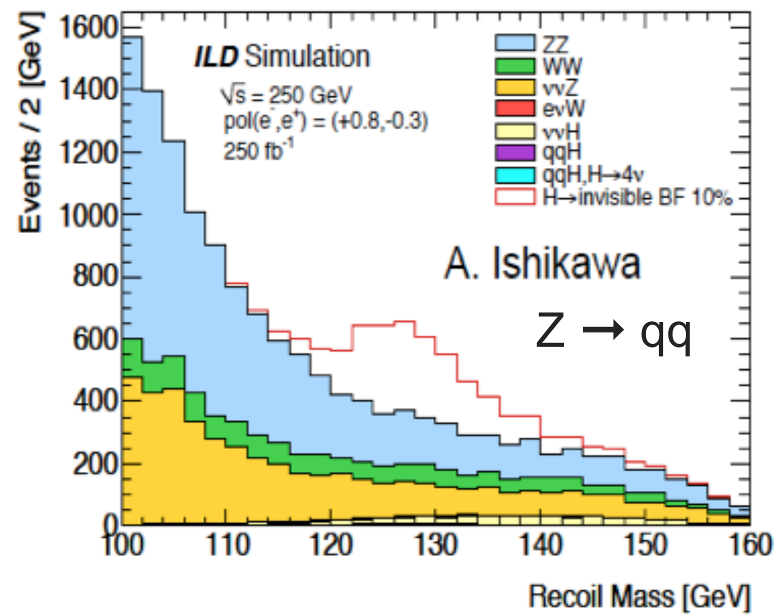
Invisible Higgs decays occur in the SM, e.g. BR (H → ZZ → 4ν) ~ 0.4%

Higgs decay to e.g. neutralinos is kinematically allowed, if $2m_X < m_H$





Dominant background channels + 25x SM signal

HL-LHC predictions: < 6-17%

ILC Sensitivity down to ~SM prediction in full ILC program: 95% CL: BF < 0.27%

Discovery potential for new physics

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With the full EFT fit, including constraints from LHC and $e^+e^- \to W^+W^-$, we can test the sensitivity to new models that escape the HL-LHC bounds.

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

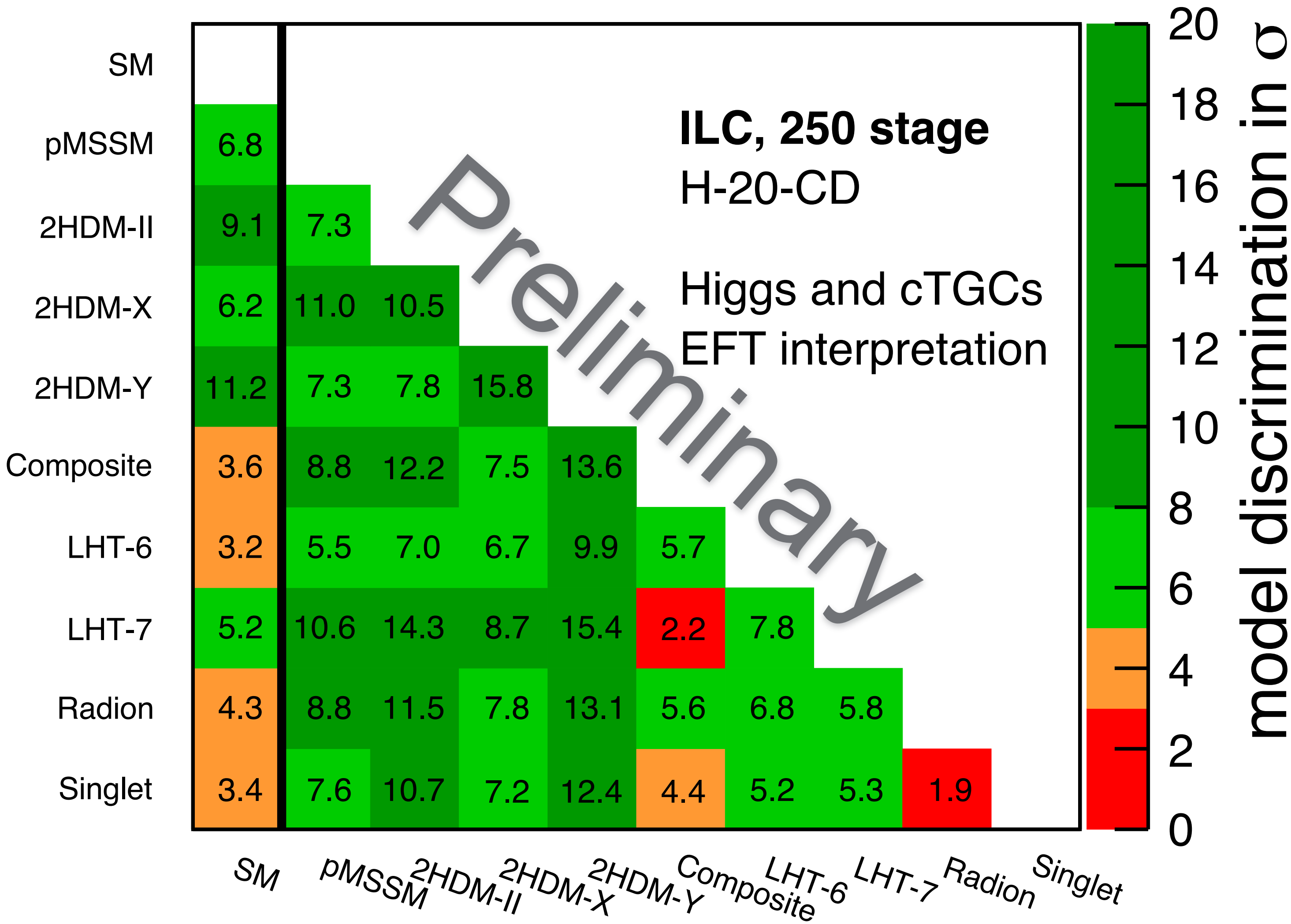
Deviation of Higgs couplings from the Standard Model, in %

We can now define a χ^2, for each pair of vectors of SM deviations:

$$(\chi^2)_{AB} = (g_A^T - g_B^T)\ [VCV^T]^{-1}\ (g_A - g_B)$$

The significance of separating two models is then $\sim\sqrt{\chi^2}$

Discriminating power between new physics models – 250 GeV



Discriminating power between new physics models – full ILC program

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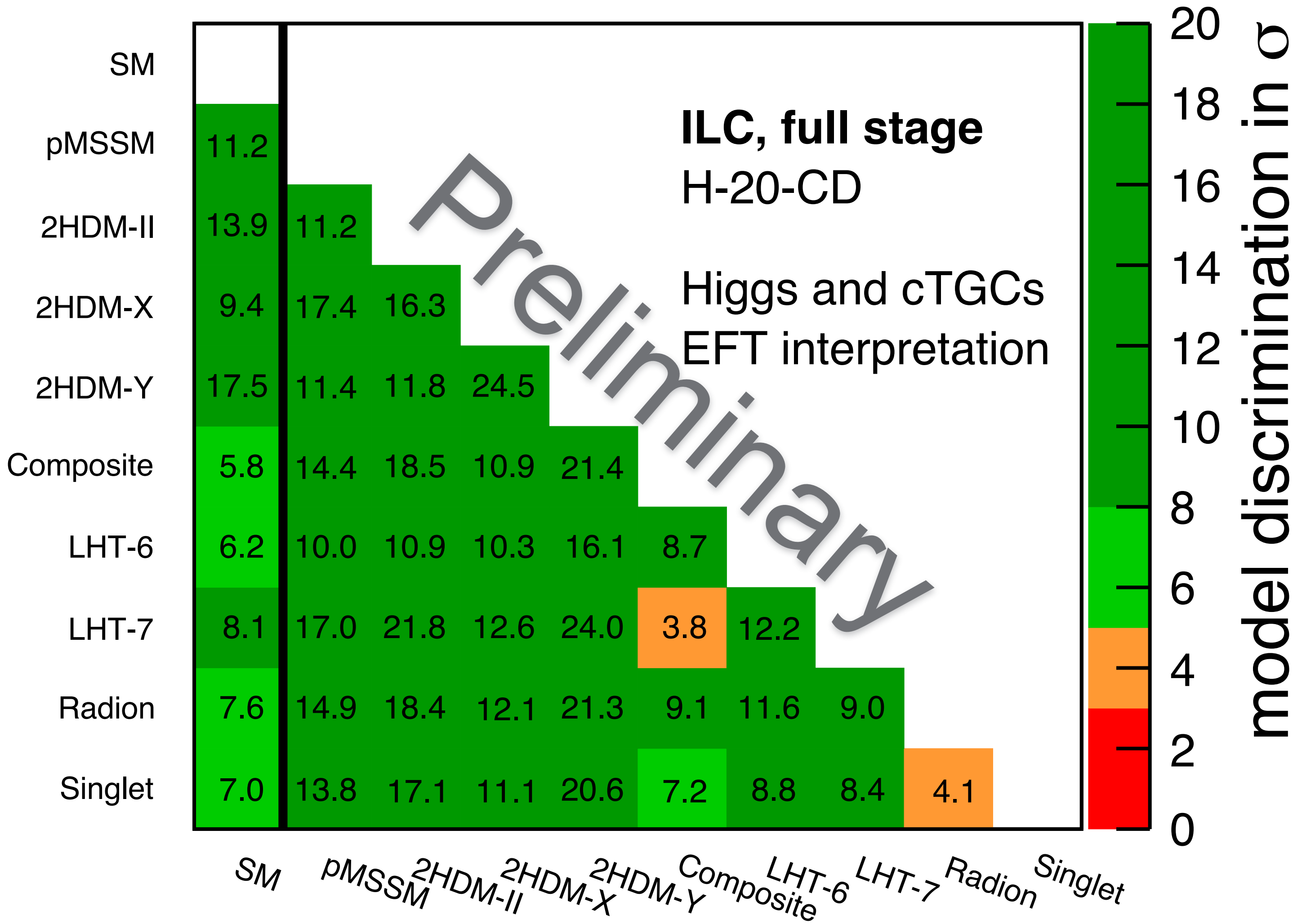
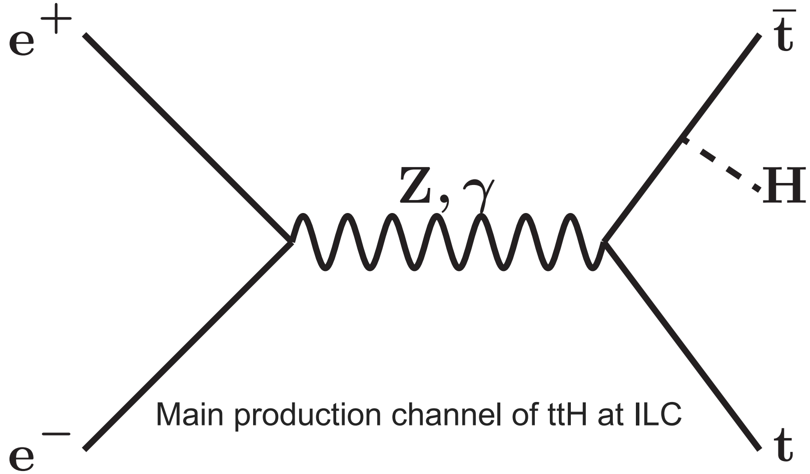
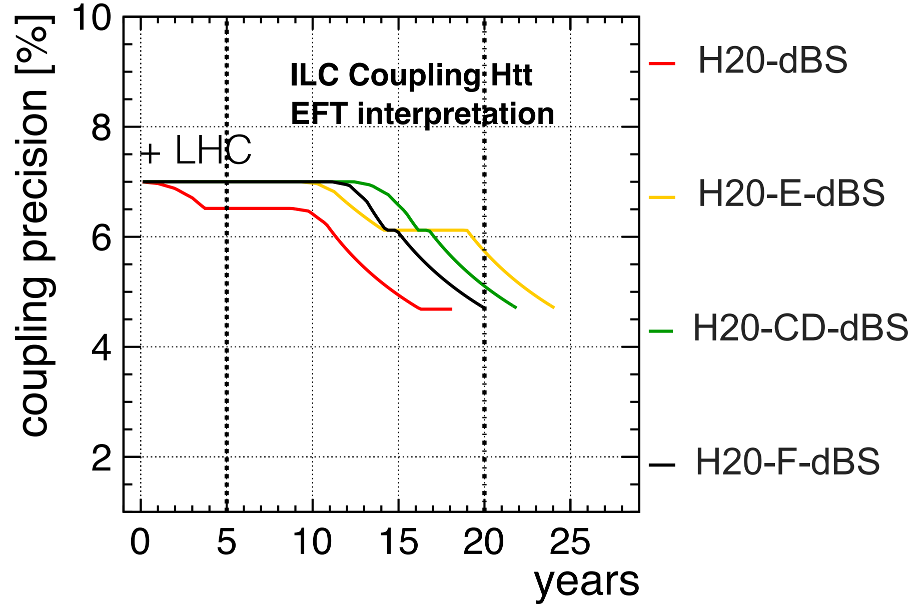
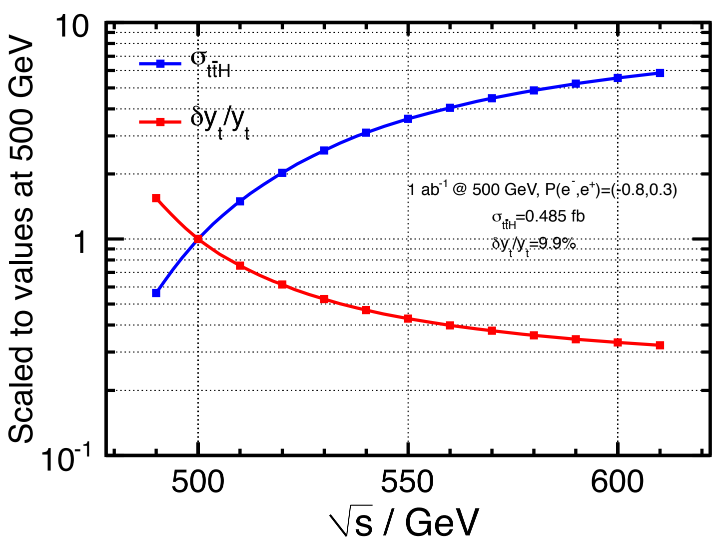


ILC500 and beyond

Top Yukawa coupling at the ILC







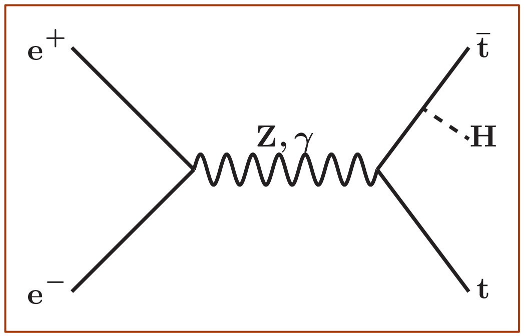
Coupling measurement at ILC500: 18%,
In full program w/ luminosity upgrade: 6.3%

Important to reach at least 500 GeV.
Potential at higher energy:
Coupling measurement in full program ~3%

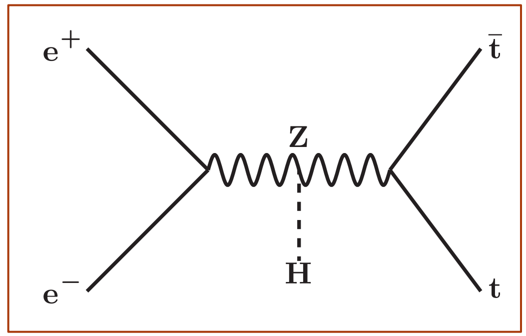
Top Yukawa coupling at a 1 TeV ILC

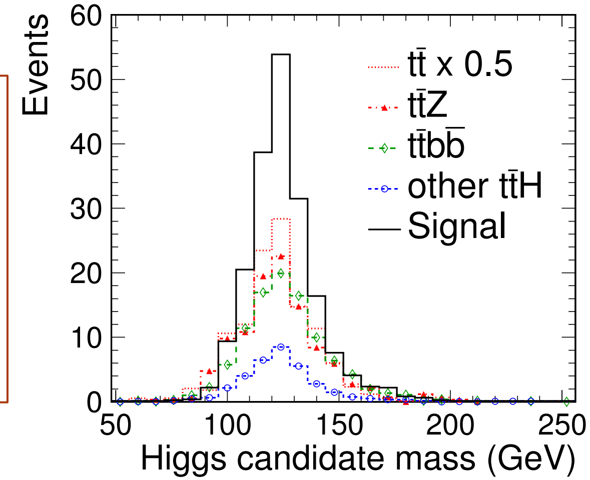
doi:10.1140/epjc/s10052-015-3532-4

Main production channel of ttH at ILC



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

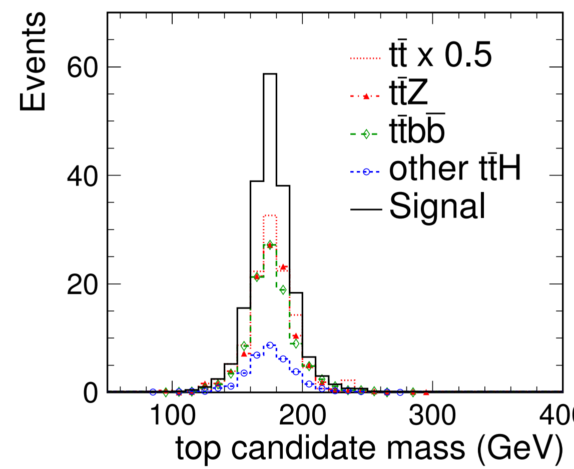




Analysis in 6-jet+lepton and in 8-jet mode
Main background processes:
Other Higgs decays, ttZ, ttbb, tt

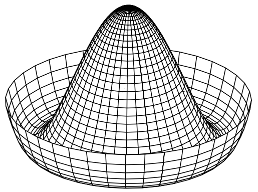
4% with 1 ab^{-1} at 1 TeV with only left-handed polarization.

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



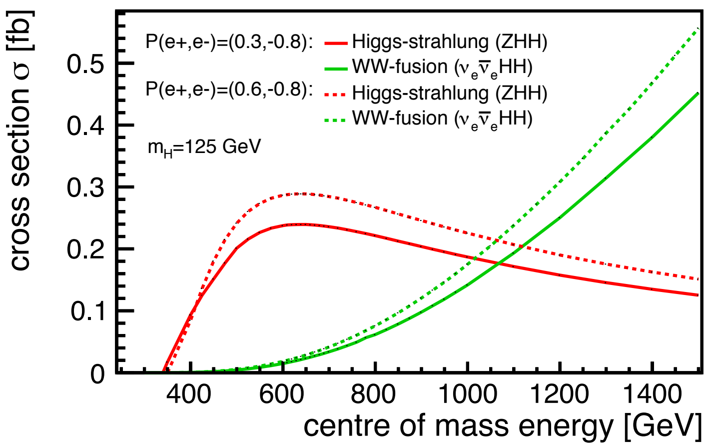
Tri-Linear Higgs Self-Coupling

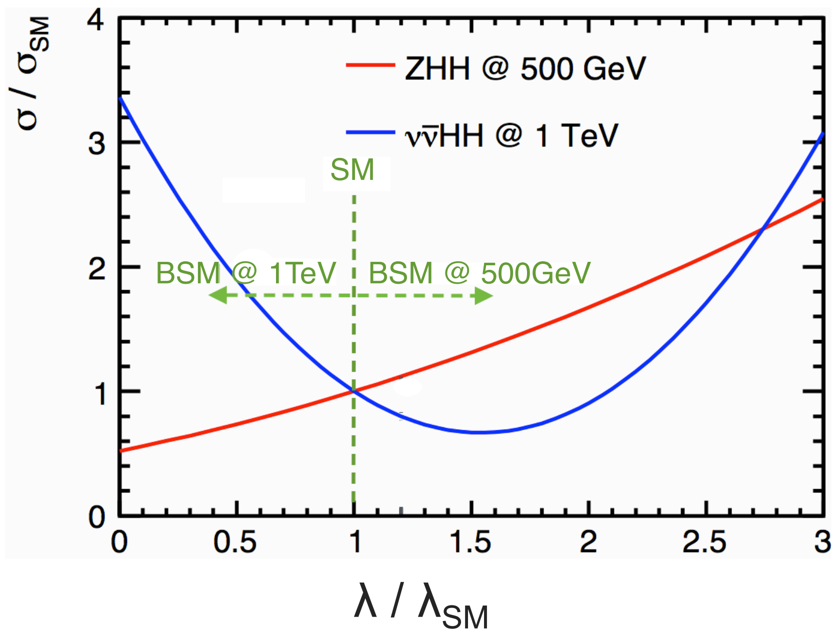
$$\mathbf{V} = \frac{1}{2}\mathbf{m}_{\mathbf{H}}^{2}\boldsymbol{\Phi}_{\mathbf{H}}^{2} + \lambda\mathbf{v}\boldsymbol{\Phi}_{\mathbf{H}}^{3} + \frac{1}{4}\kappa\boldsymbol{\Phi}_{\mathbf{H}}^{4}$$



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

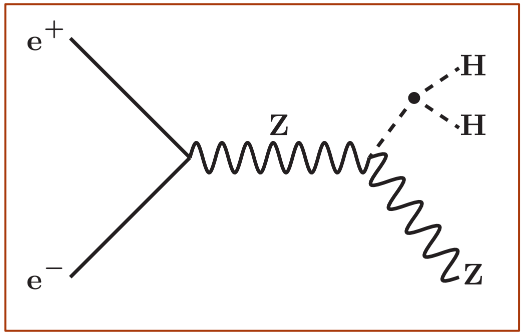
At the ILC: Measure the rate of double Higgs production ZHH (500 GeV) or HHvv (1 TeV)

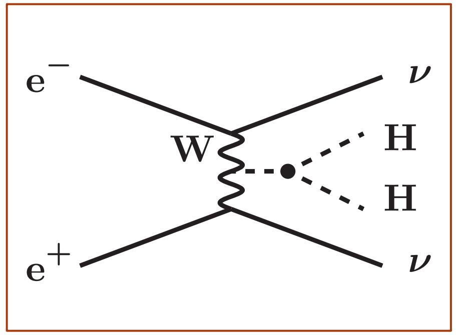


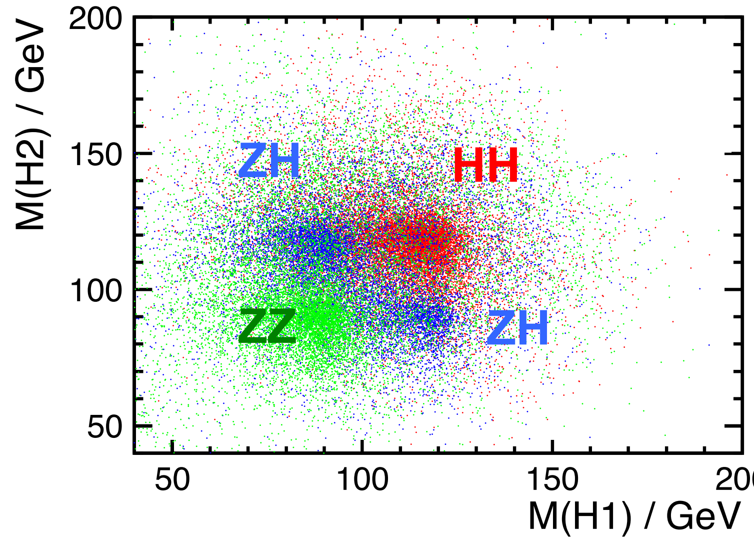


Deviations in λ lead to a change in cross section

Measurement of double Higgs Production at the ILC

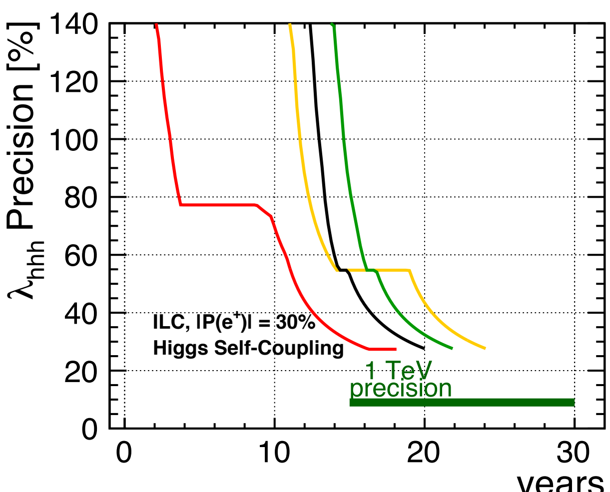






Mass resolution in double Higgs production and dominant background at 500 GeV

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



Experimental precision limited by jet clustering.

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

Summary

- The LHC experiments have discovered a Higgs boson consistent with various BSM models
- It will take ILC precision to really use the Higgs as a tool for new discovery, as recommended by P5
  - Precision measurements are an integral part of the ILC physics program. BSM searches, top properties and Higgs physics are tightly coupled thanks to this precision
- The staging options allow us to make a compelling case for this machine
  - Very high discovery potential for new physics at the first stage at 250 GeV
  - The extensibility of the machine allows us to unlock the full potential in additional stages that improve measurements of top properties, Higgs self-coupling and allow additional searches for new particles

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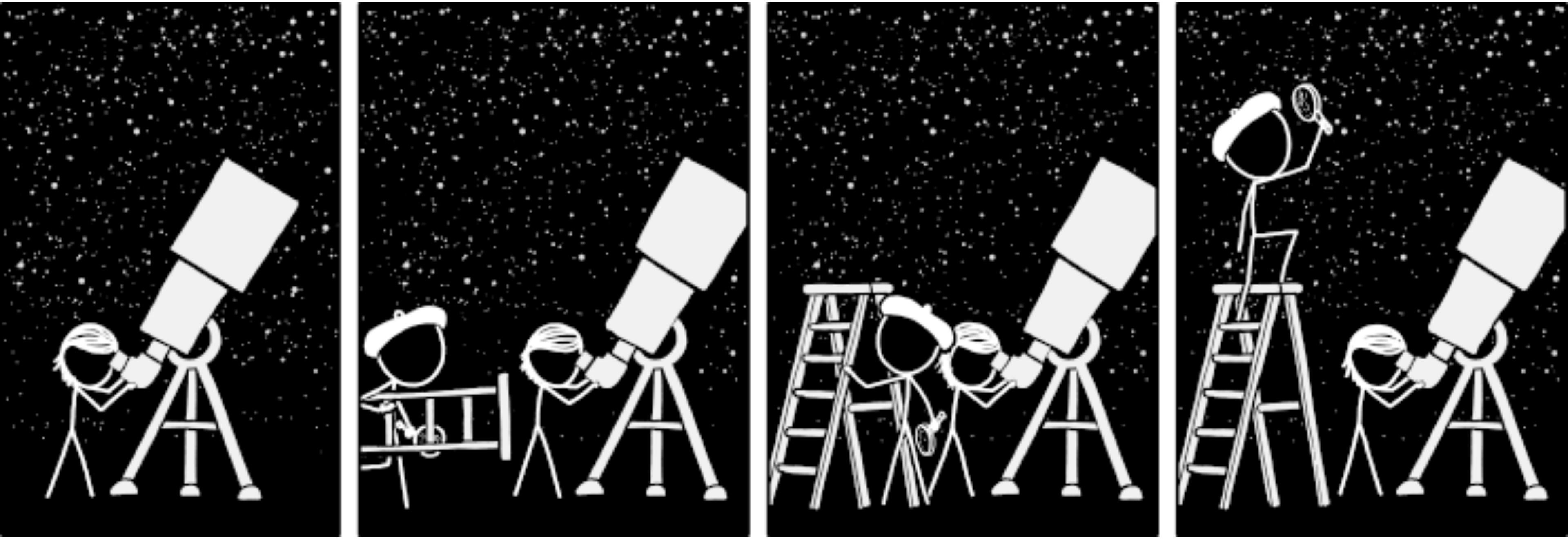
Disclaimer

- 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

Backup



Global Fit of Higgs couplings

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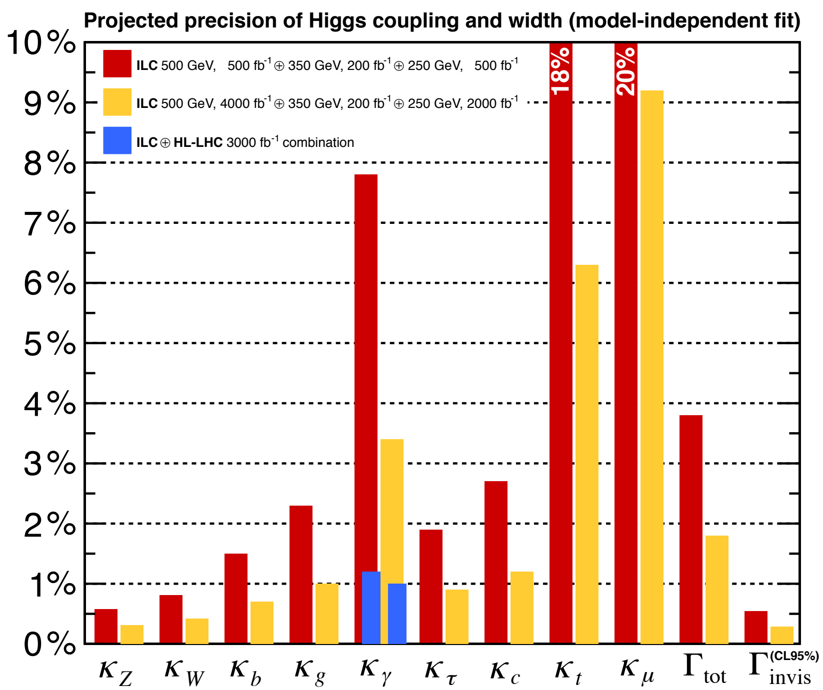

Best measurement of cross section:
σ_{ZH} from recoil method. Error < 2.5%

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

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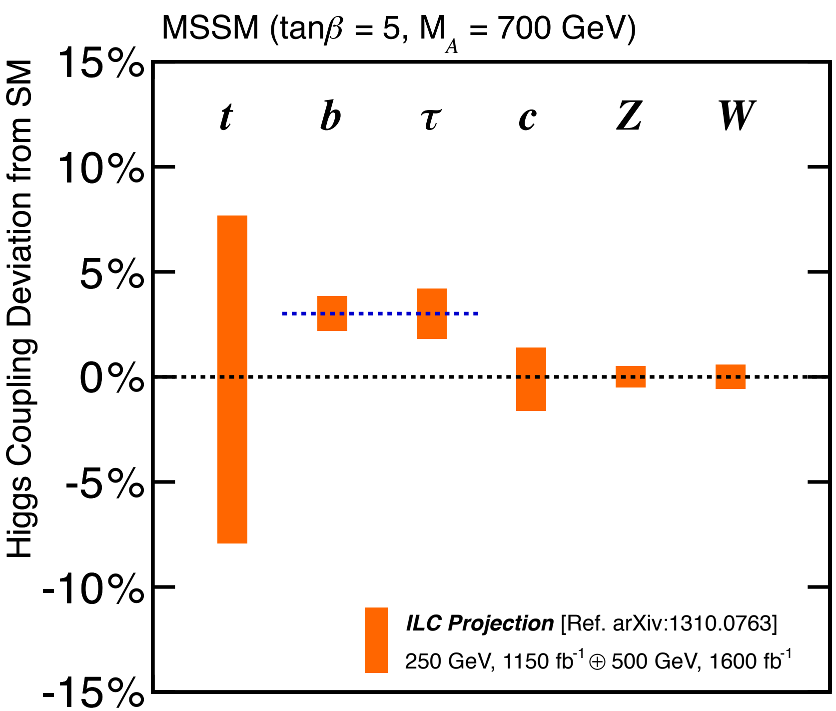
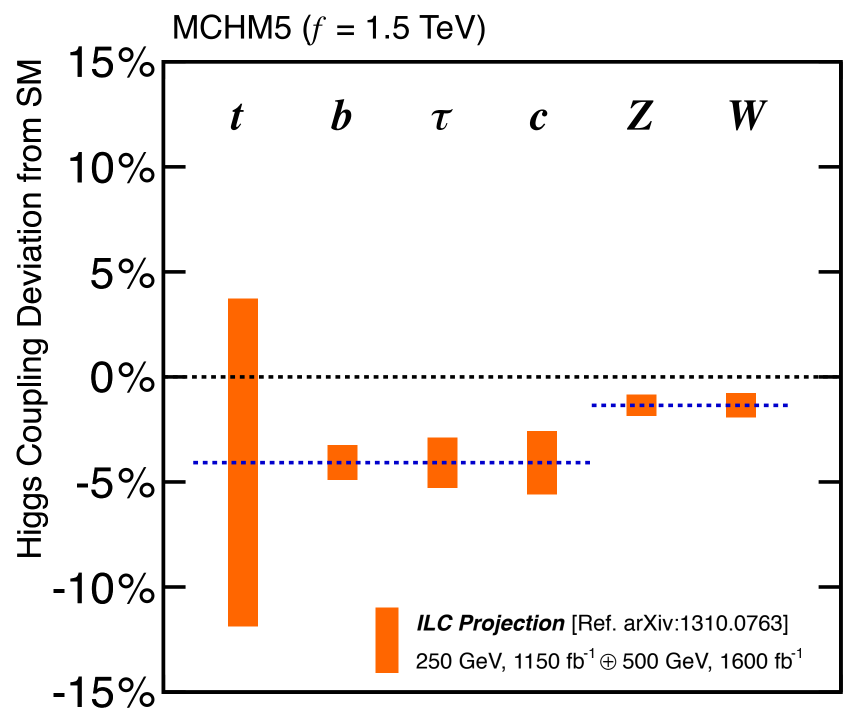
Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



ILC 250+500 LumiUp

Status of Machine and Detectors

- The ILC accelerator has completed its TDR
- A potential site has been identified
- In Japan, the prime minister is aware of this project, and the possibility to host is being investigated
- Staging gives us a credible option that can be proposed for funding

- Two Detector concepts have been designed to deliver high-precision physics
  - Measurements of Higgs properties drive the design on many fronts

- The concept groups are moving towards the start of a TDR process

Higgs to b and c quarks, gluons

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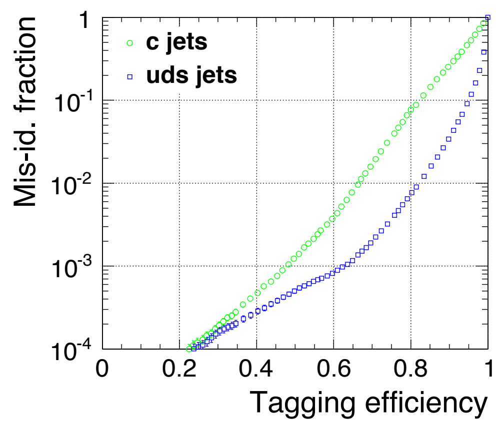
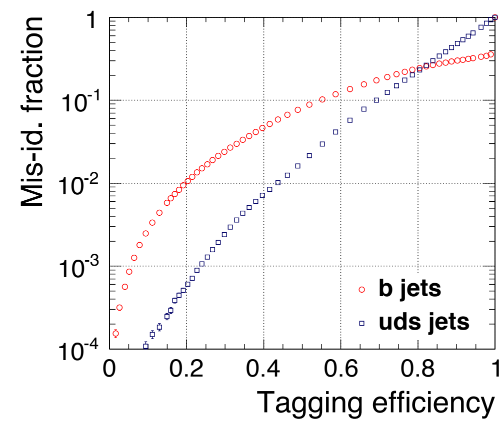
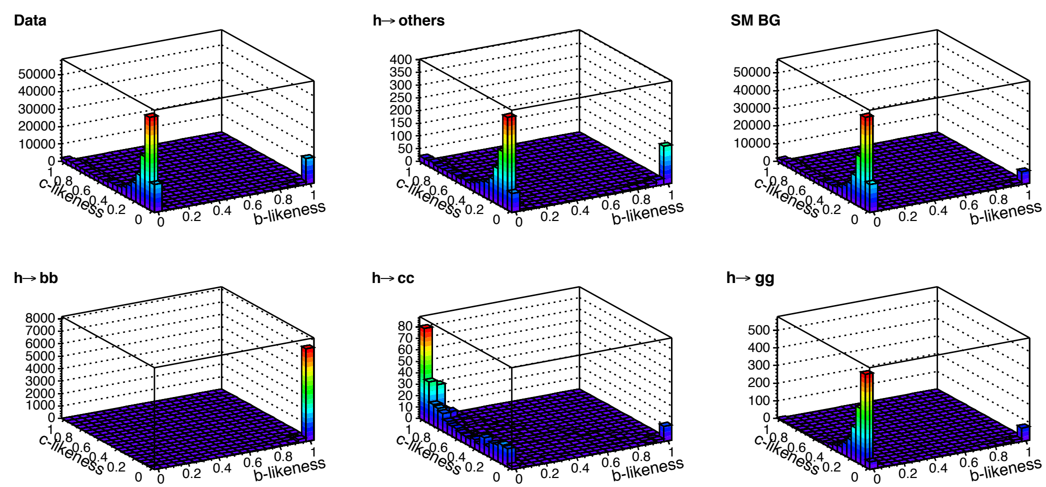
- Higgs decays to jets benefit from excellent vertex detector
    - b- and c-tagging
- Jet-clustering after vertex finding as to not break up the vertices
- Branching ratios extracted simultaneously with template method







Measurement precision goals:

g(Hbb) = 0.7%
g(Hcc) = 1.2%
g(Hgg) = 1.0%

Higgs Decay to τ Leptons

Nucl.Instrum.Meth. A810 (2016) 51-58

- Ideal probe for new physics: Sizeable BR, well-known τ mass, CP properties in angular analysis
- Reconstruction in hadronic recoil: qq τ τ
- Analysis steps: τ “jet” finder, jet charge
- Collinear Approximation:
  - Visible τ decay products and ν are collinear
  - No other source of missing momentum
  - Result: 1.9% baseline, 0.9% luminosity upgrade

Reconstruction efficiency in recoil – Independent of the final state

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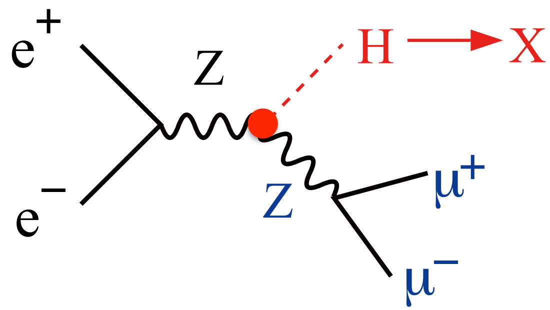

Phys. Rev. D 94, 113002 (2016)

Cuts are tuned to be independent of the final state. Decays to unknown particles are assumed to introduce a bias that is no larger than the largest measured bias to SM final states (γγ).

$H \to XX$	bb	cc	gg	$\tau\tau$	WW^*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
Lepton Finder	93.70%	93.69%	93.40%	94.02%	94.04%	94.36%	93.75%	94.08%
Lepton ID+Precut	93.68%	93.66%	93.37%	93.93%	93.94%	93.71%	93.63%	93.22%
$M_{l^+l^-} \in [73, 120]$ GeV	89.94%	91.74%	91.40%	91.90%	91.82%	91.81%	91.73%	91.47%
$p_T^{l^+l^-} \in [10, 70]$ GeV	89.94%	90.08%	89.68%	90.18%	90.04%	90.16%	89.99%	89.71%
$\lvert\cos\theta_{miss}\rvert < 0.98$	89.94%	90.08%	89.68%	90.16%	90.04%	90.16%	89.91%	89.41%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%