Highlights of the Higgs precision program at ILC

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- On behalf of the ILC International Development Team -

ICHEP 2022 Bologna, Italy

Overview

- ILC as a Higgs factory
- Higgs physics at ILC
  - Higgs couplings as a probe to BSM
  - Higgs self-coupling
  - CPV in the Higgs sector
  - Ongoing studies
- Outlook

ILC as a Higgs factory

- $\sim 10^6$ Higgs bosons
- Known initial state
- No PDFs, dominant statistical uncertainty
- **Higgsstrahlung offers model-independence**
- **Absolute normalization of the Higgs couplings**

(Γ_H measurement in a model independent way)

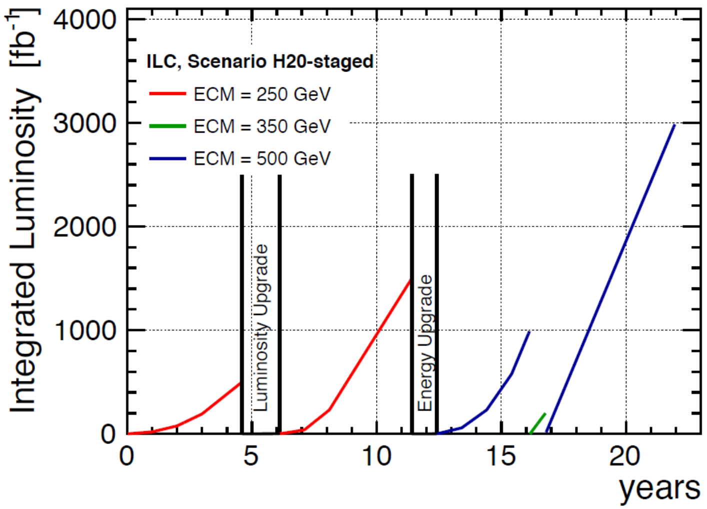
Clean experimental environment:
- No pile-up
- (practically) QCD free
- Trigger-less readout

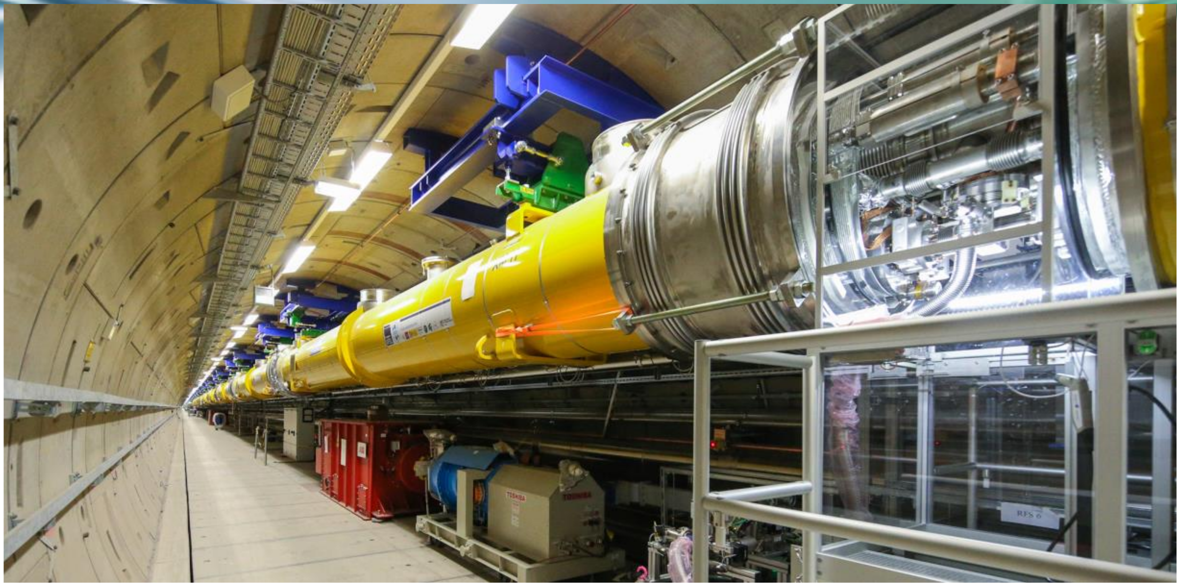
PRECISION MEASUREMENTS

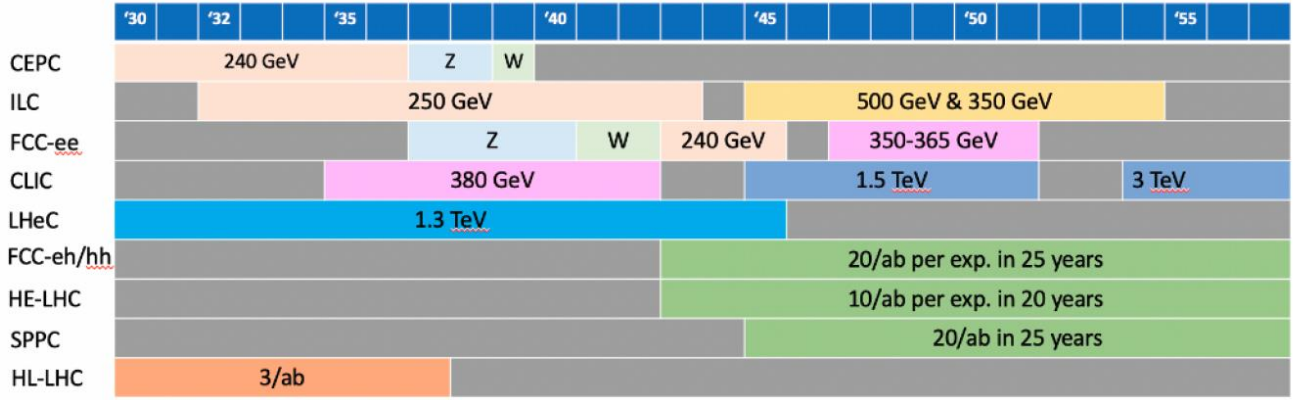
- Added values of:
  - polarization/ model discrimination, better precision with smaller statistics
  - high-energy reach – linear machine (improved BSM sensitivity, λ determination)

What to expect (in the Higgs sector)?
- Higgs couplings improvement O (10) w.r.t. HL-LHC (in particular for H to EW bosons)
- NP scale O(10 TeV) to be probed indirectly (EFT)
- Higgs BSM model discrimination $\geq 5\sigma$
- λ precision < 10% (ILC 1000)

A word on ILC



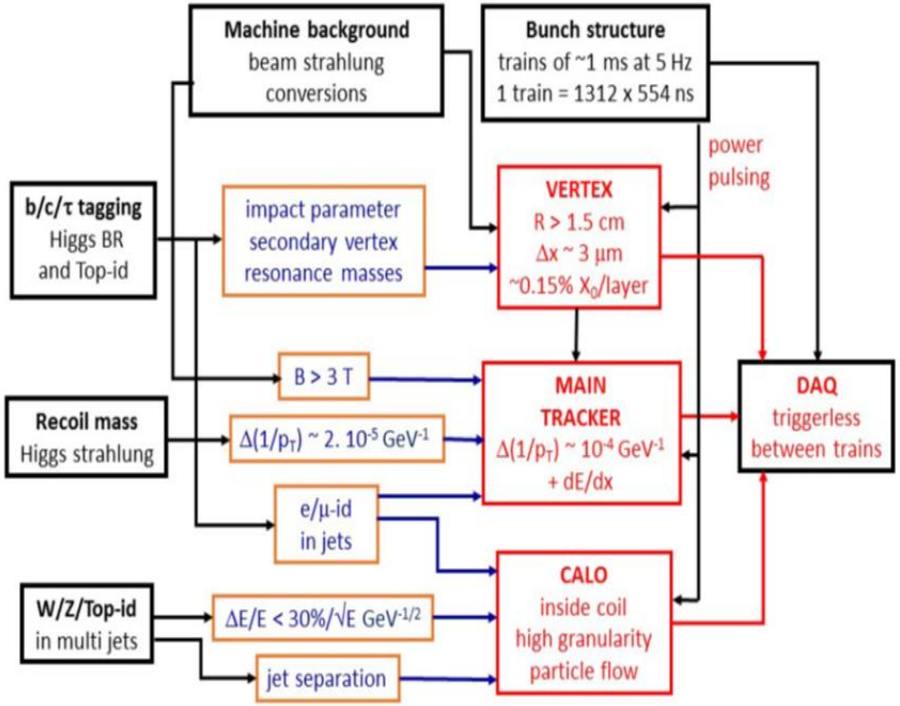


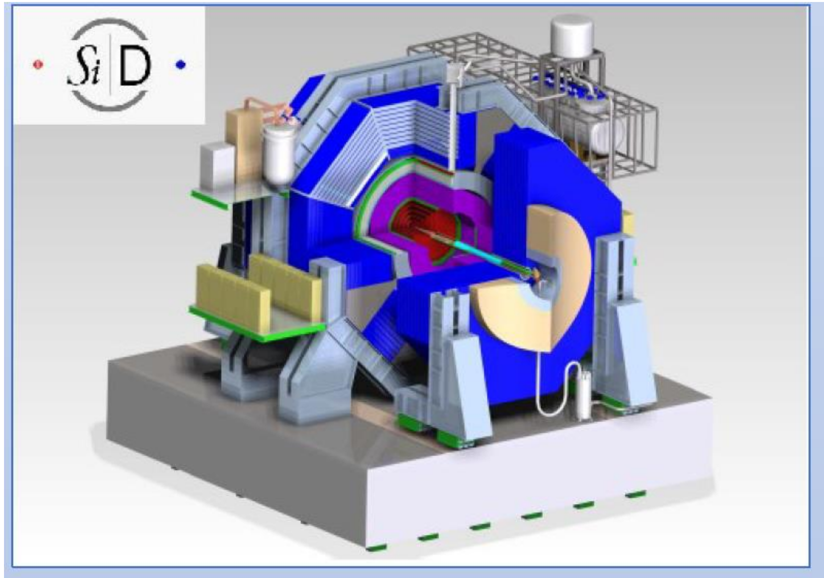


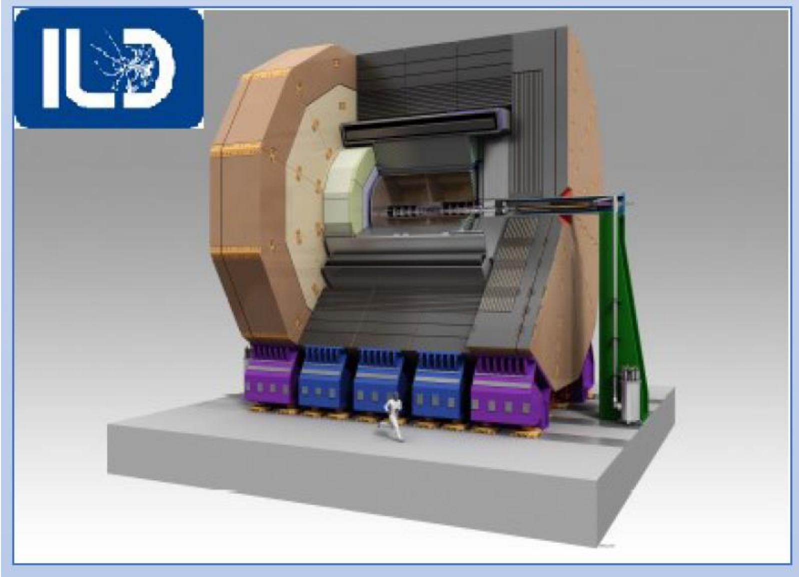
- Comes as a ‘ready to take’ project (mature design, proven technologies)
- Largest ever accelerator prototype (operating now as E-XFEL), full industrialization of ILC-type SCRF cavity production
- Tunable, upgradeable (detector optimized from Z-pole to 1 TeV run)
- Comes with a rich program of auxiliary experiments – ILCX (dark sector, fixed-target and beam dump experiments)

A word on detector

- Two validated detector concepts: ILD and SiD
- Physics driven requirements
- Decades of extensive detector R&D $\Rightarrow$ mature design (& available technologies)
- Multiple R&D collaborations involved (CALICE, FCAL, LCTPC,..)







Higgs physics at ILC

Higgs couplings (from model - independent measurements in ZH, κ-framework to EFT)

- Clear improvement w.r.t. HL-LHC precision
- Should not over interpret differences between the projects
- See what does it mean for BSM model interpretation in the Higgs sector

	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	$FCCee_{240}$	$FCCee_{365}$	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC

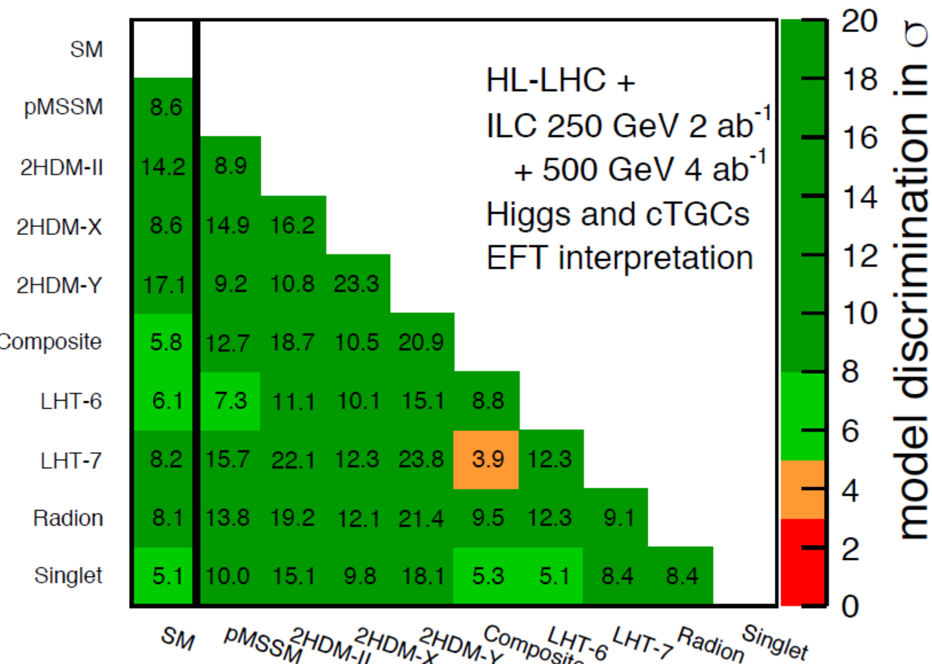
Factor of improvement w.r.t. the HL-LHC

Higgs@Future Colliders WG EPPSU

Higgs physics at ILC –probing BSM in the Higgs sector

g_H relative deviations in %

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [37]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [38]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [39]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [40]	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [41]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5



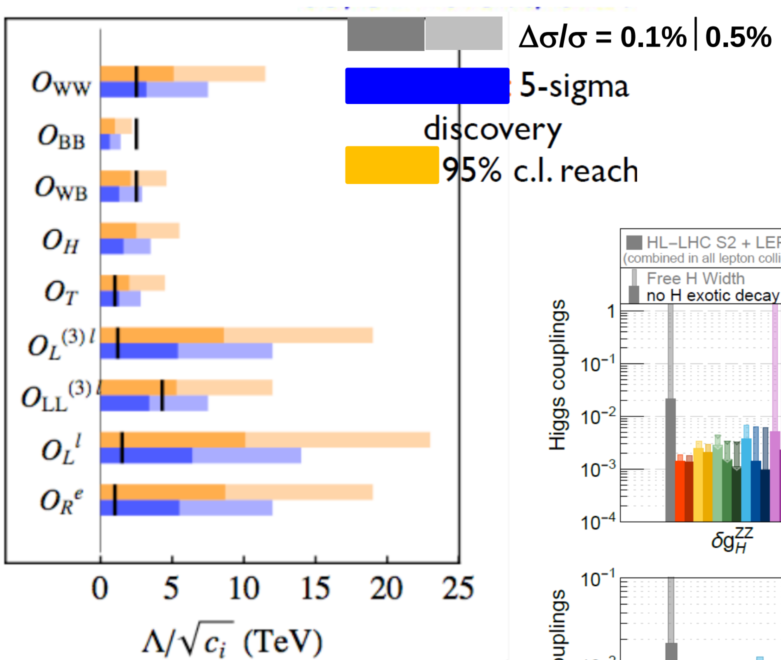
- Boosted sensitivity in combination with HL-LHC
- <u>Higher energies (500 GeV) pin down, above the discovery limit, BSM models of the Higgs sector difficult to be probed at HL-LHC</u>

Higgs physics at ILC - EFT

- All couplings (except Hμμ and Htt)<1% in combination with HL-LHC ⇒ evident synergy
- EFT: Smaller the uncertainty – larger the NP scale to be probed (~$1/\Lambda^2$) independently of a particular model
- Polarization helps to reduce the run-time and to constrain the most general set of triple gauge coupling deviations allowed by Lorentz invariance - only if both beams are polarized

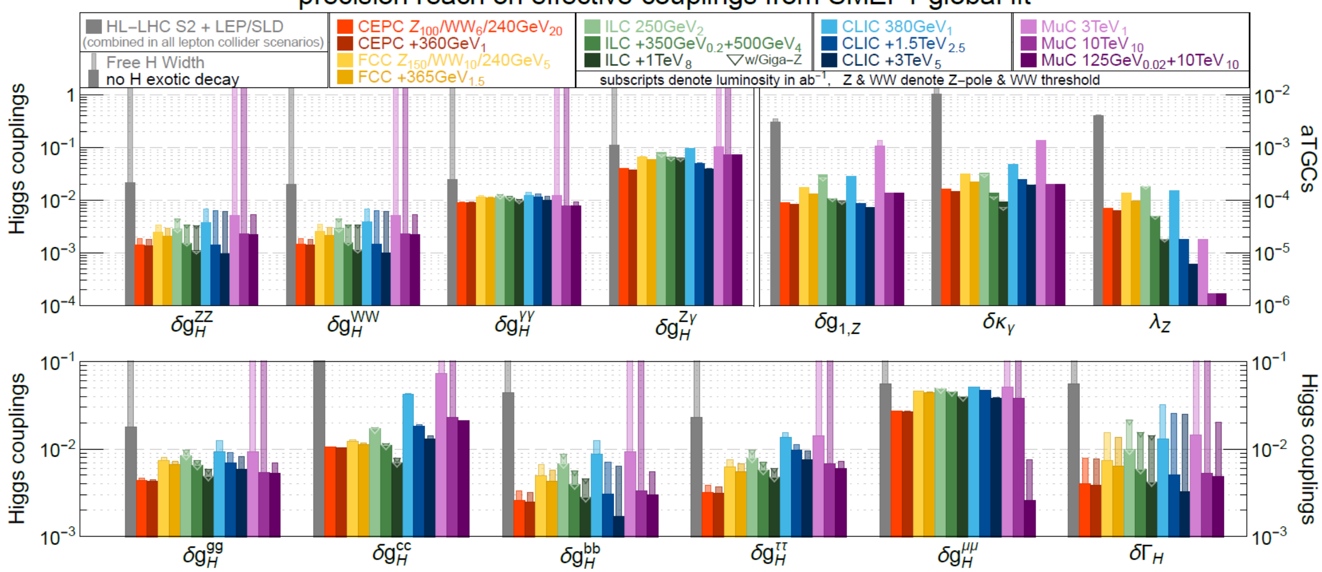
Projected relative errors in%

	no pol.	80%/0%	80%/30%
$g(hbb)$	1.33	1.13	1.09
$g(hcc)$	2.09	1.97	1.88
$g(hgg)$	1.90	1.77	1.68
$g(hWW)$	0.978	0.683	0.672
$g(h\tau\tau)$	1.45	1.27	1.22
$g(hZZ)$	0.971	0.693	0.682
$g(h\gamma\gamma)$	1.38	1.23	1.22
$g(h\mu\mu)$	5.67	5.64	5.59
$g(h\gamma Z)$	14.0	6.71	6.63
$g(hbb)/g(hWW)$	0.911	0.909	0.861
$g(h\tau\tau)/g(hWW)$	1.08	1.08	1.02
$g(hWW)/g(hZZ)$	0.070	0.067	0.067
Γ_h	2.93	2.60	2.49
$BR(h \to inv)$	0.365	0.327	0.315
$BR(h \to other)$	1.68	1.67	1.58



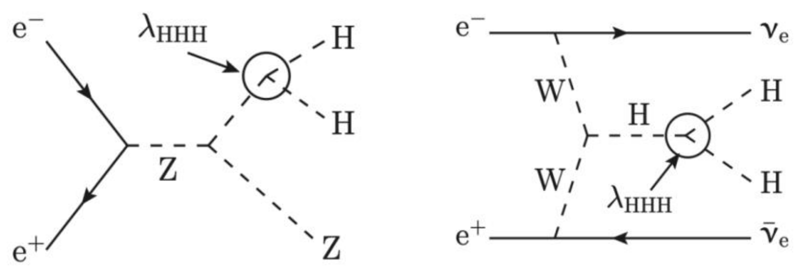
arXiv:2206:08326

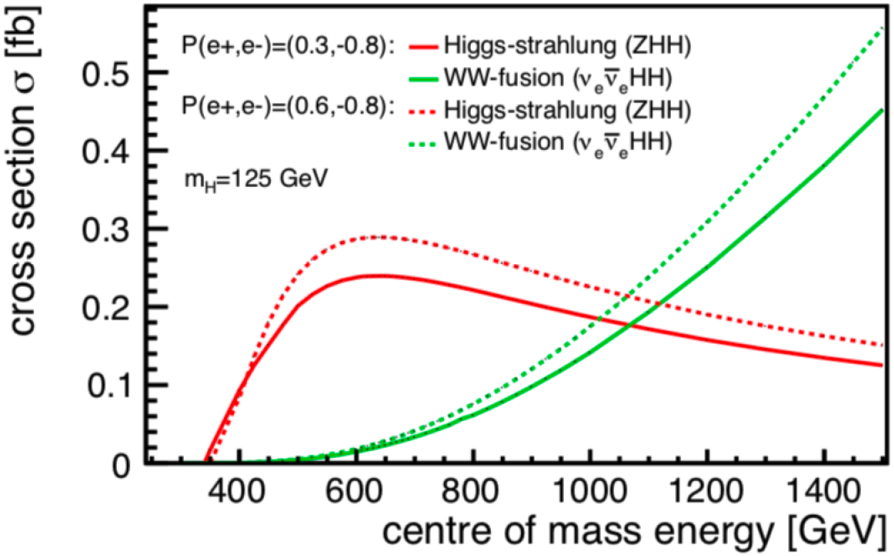
precision reach on effective couplings from SMEFT global fit



I. Bozovic

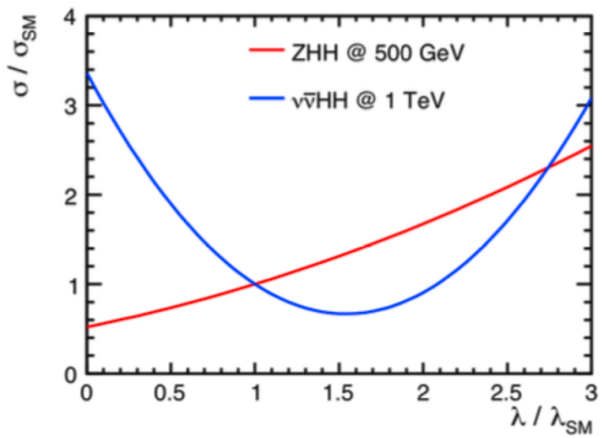
Higgs physics at ILC - λ





Higgs self-coupling parameter λ

- Two complementary processes available
- WW-fusion (HHνν) statistically preferred at high energies
- Polarization significantly influences the HHνν rate
- Different behavior of ZHH and HHνν x-section resolves ambiguity for non-SM values of λ



- High energy (≥ 500 GeV) e+e- collider is superior in determination of the Higgs self-coupling
  - HHνν is the most sensitive to deviations of the Higgs self-coupling

Higgs physics at ILC - λ

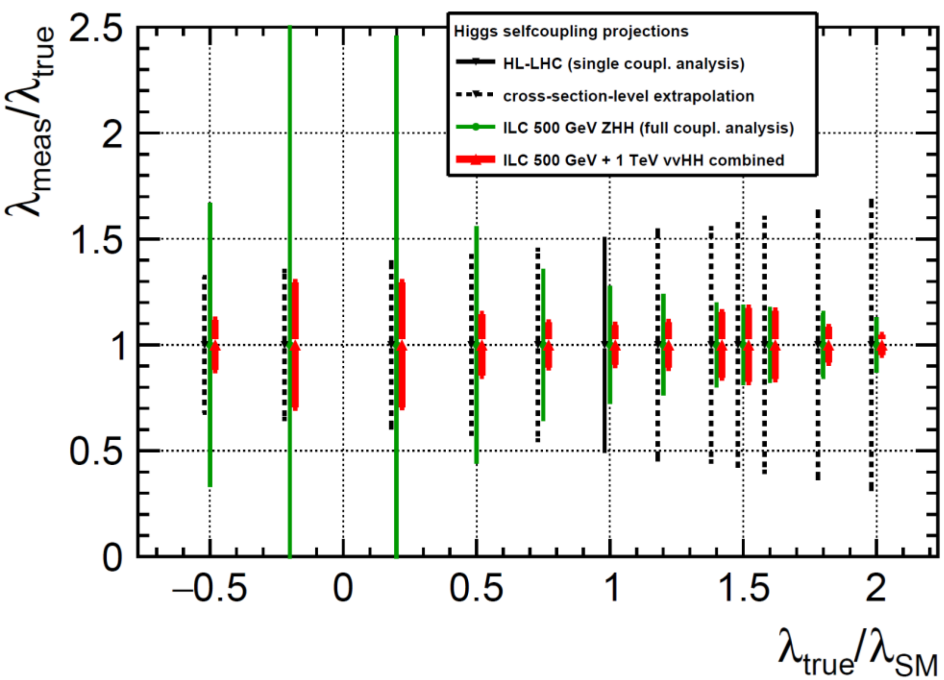
Higgs self-coupling parameter λ

- Clear advantage of high-energy e+e- colliders
- Unlimited by theoretical uncertainties (PDFs, non-perturbative calculations, etc.) unlike hh colliders

68% CL for $\lambda=\lambda_{SM}$

collider	excl. from HH
HL-LHC	50%
ILC 500	27%
ILC 1000	10%
CLIC 1500	36 %
CLIC 3000	[-7%, 11%]

FCCee (4IP) 27%
FCChh < 8%



- High energy e+e- collider is particularly sensitive to non-SM values of λ

Higgs physics at ILC - CPV in the Higgs sector

CP violation in the Higgs sector

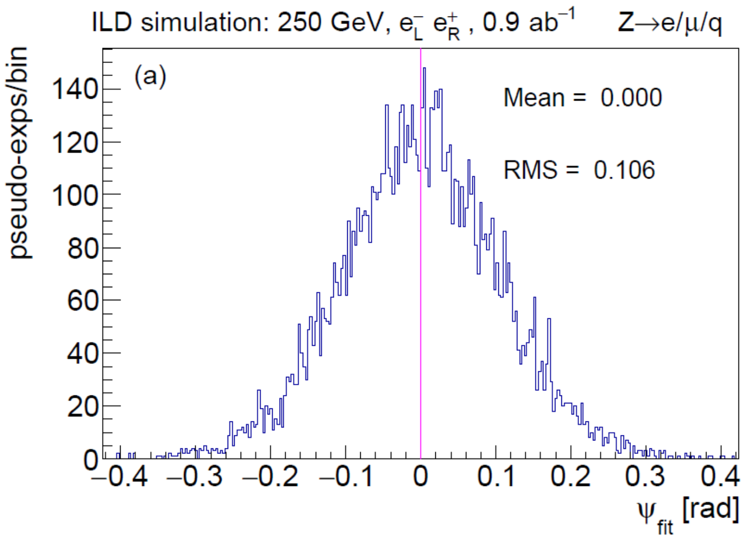
- Higgs can be a CPV mixture of scalar and pseudoscalar states – mixing angle to be determined
- Several vertices to be probed (Hττ, HZZ, HWW) in Higgs production and decays
- The most precise result in H→ττ decays comes from ILC

fermion couplings	
$H \to \tau^-\tau^+$	250+ GeV
$e^-e^+ \to Ht\bar{t}$	500+ GeV
boson couplings	
$e^-e^+ \to HZ$	250+ GeV
$H \to ZZ$	250+ GeV
$H \to WW$	250+ GeV
$e^-e^+ \to He^-e^+$ (ZZ-fusion)	1000+ GeV

[J. de Blas et al, JHEP 01 (2020) 139]

Name	α_τ
HL-LHC	8°
HE-LHC	–
CEPC	–
$FCC\text{-}ee_{240}$	10°
ILC_{250}	4°

[arXiv:1804.01241]



Higgs physics at ILC - CPV in the Higgs sector

CP violation in the Higgs sector

- Why ILC measurement is this precise?

- CPV mixing angle measurement in $H \rightarrow \tau\tau$ is a nice illustration of ILC advantages:
  - Clean environment
  - Different beam polarizations
  - Reduction of statistical uncertainty in combination
- Background free assumption with 100% signal reconstruction will give $\Delta\psi_{CP} < 1.5°$

$\mathcal{L}$(ab^{-1})	H20-staged: 250 GeV, 2 ab^{-1}			$\Delta\psi_{CP}$ (mrad)
0.9	-0.8	$+0.3$	only $e^-_L e^+_R$	102
0.9	$+0.8$	-0.3	only $e^-_R e^+_L$	120
0.1	-0.8	-0.3	only $e^-_L e^+_L$	359
0.1	$+0.8$	$+0.3$	only $e^-_R e^+_R$	396
2.0	mixed		full analysis	75

[arXiv:1804.01241]

Higgs physics at ILC – exotic decays and ongoing searches

Flavorful Higgs (ongoing)

- 2HDMs with a non-standard Yukawa sector
- One Higgs doublet responsible for the masses of the weak gauge bosons and the 3rd generation fermions, while the second Higgs doublet provides mass for the lighter fermion generations
- Including flavor violating decays H→cs or cb

- Room for improvement of existing algorithms

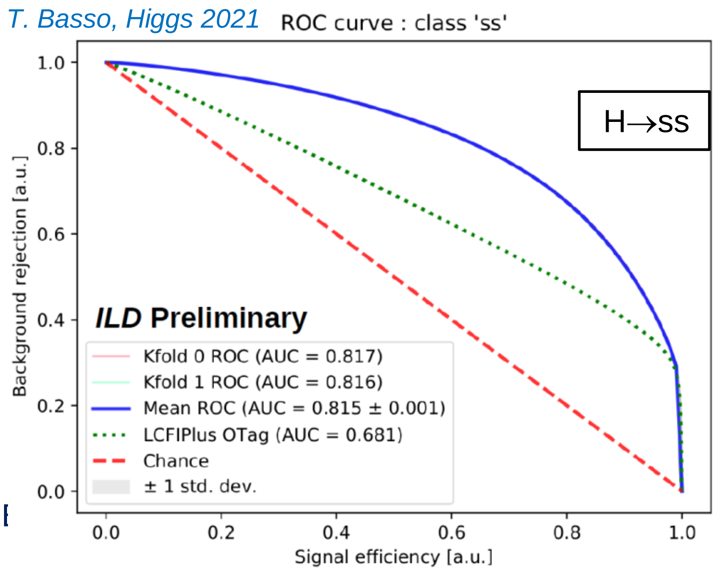
Higgs exotic decays

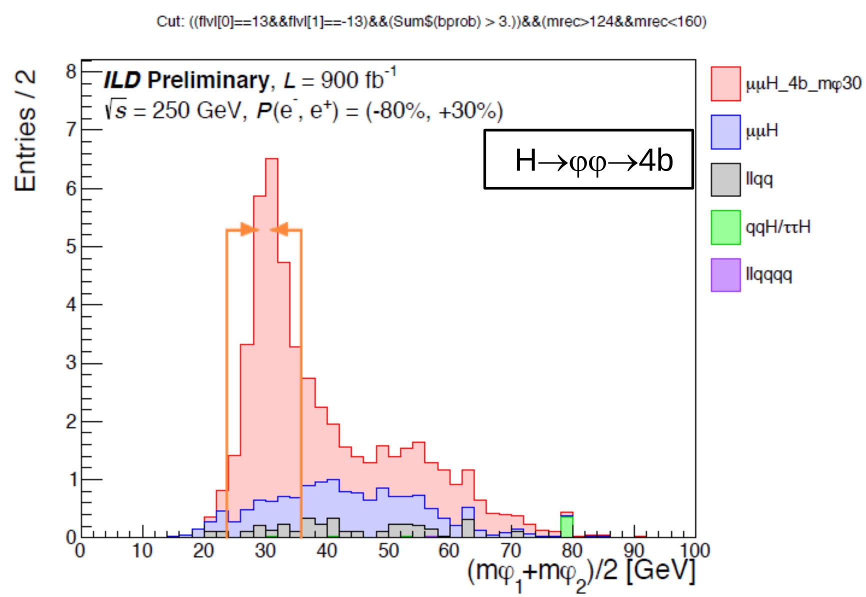
- H→φφ(→4b)
- Full simulation analysis at 250 GeV ILD
- Scalar mediator mass range: 15 - 60 GeV
- 95% CL upper limit on BR(H→φφ→4b) < 0.1%

mφ	UL on BR(H→4b)
15 GeV	0.07%
30 GeV	0.09%
45 GeV	0.10%
60 GeV	0.09%

Yu Kato, Higgs 2021

T. Basso, Higgs 2021





Outlook – can we do better?

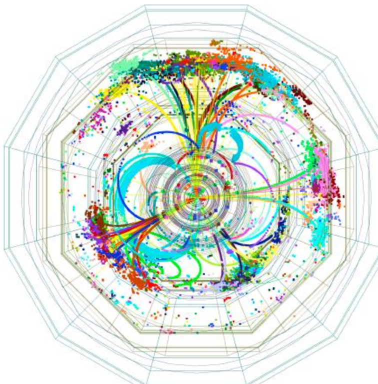
Is there a room for improvement?

- We tried to highlight results were ILC is leading (or next to the leading) in precision
- Some measurements (like λ) are clearly preferred at high energy lepton collider
- Benefits from different polarizations and combinations are evident

Jet Clustering

Perfect jet clustering
$\rightarrow \sim 40\%$ relative
improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Flavour Tagging



☑ Better b-tagging efficiency

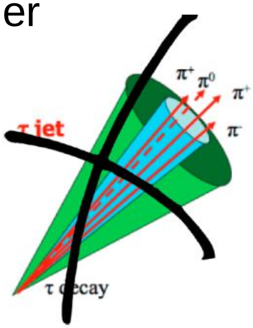
5% relative improvement in $\varepsilon_{b\text{-tag}}$
$\rightarrow 11\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Isolated lepton tagging

Optimised for $\ell = \{e, \mu\}$

For $\varepsilon_\tau \sim \varepsilon_{e,\mu}$
$\rightarrow 8\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Tau Reconstruction



- Improved reconstruction
- Better tau decay mode identification
- Use of additional tau decay modes
- CPV in $H\rightarrow\tau\tau$ decays ~ 1-2%

Jet Reconstruction and Pairing

- Important for λ precision (among others)
- Observables: σ_{ZHH},$\sigma_{HH\nu\nu}$, m(HH)
- Processes: HH$\rightarrow$ bbbb and HH $\rightarrow$ bbWW
- Possibility to reach $\Delta\lambda/\lambda$<10%

DESY-THESIS-2016-027 & Julie Munch Torndal, SWANA Meeting, May 2022

Summary

- ILC is viable, mature and technologically available option for a future Higgs factory

- It offers: clean environment, flexible polarization and upgradeable energy

- Combination of the above enables utmost precision in Higgs sector measurements

- What makes it competitive when it comes to:
  - **Higgs coupling measurements to probe BSM physics**
  - **Higgs self-coupling measurement**
  - **CP violation probes in the Higgs sector**
  - **…and many more**

- There is still a room for reconstruction and identification algorithms improvements leading to additional enhancements:
  - Higgs self-coupling precision <10%
  - Higgs to EW bosons couplings precision enhancement $\mathcal{O}$(10s)%
  - Higgs CPV mixing angle statistical precision ~ 1-2°
  - Explore new possibilities like flavor violating or invisible Higgs decays

But, possibly one of ILC greatest advantages is its (almost) imminent availability

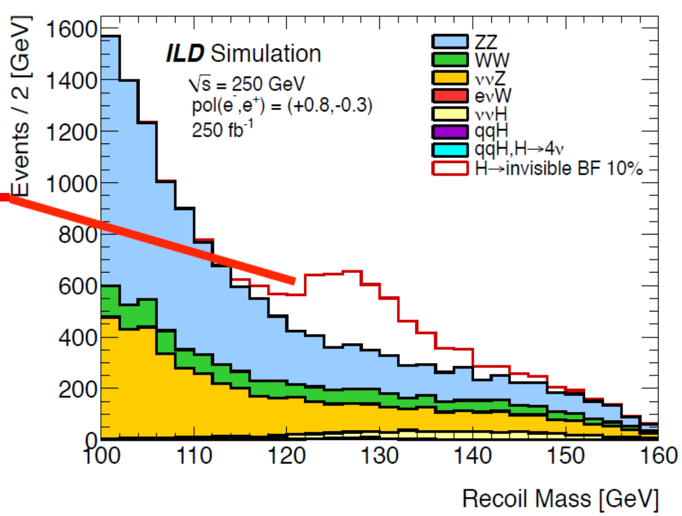
BACKUP

Higgs to invisible

- Looking at the recoil mass in HZ under the condition that nothing observable is recoiling against the *Z* boson
- Access to DM connected to SM particles through a specific set of operators (portals)

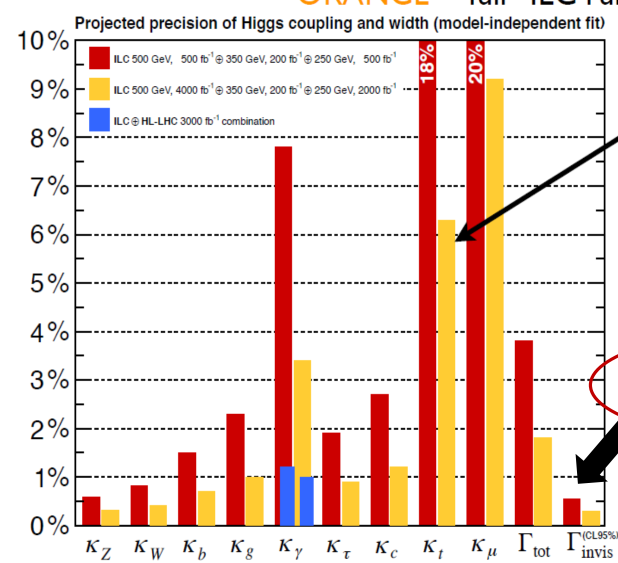
$$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu} \qquad \epsilon_H |H|^2 |\Phi|^2 \qquad \epsilon_a \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

H→inv.



RED - "initial" ILC running, 8 years

ORANGE - "full" ILC running, 20 years



$\kappa_t \rightarrow 3\%$ if run @550 GeV

<0.5% , 95% CL