Higgs physics at ILC

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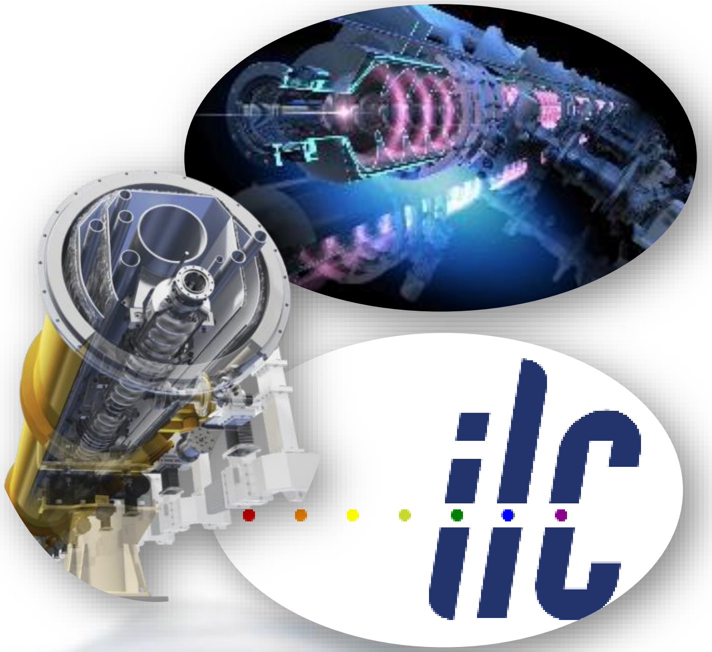
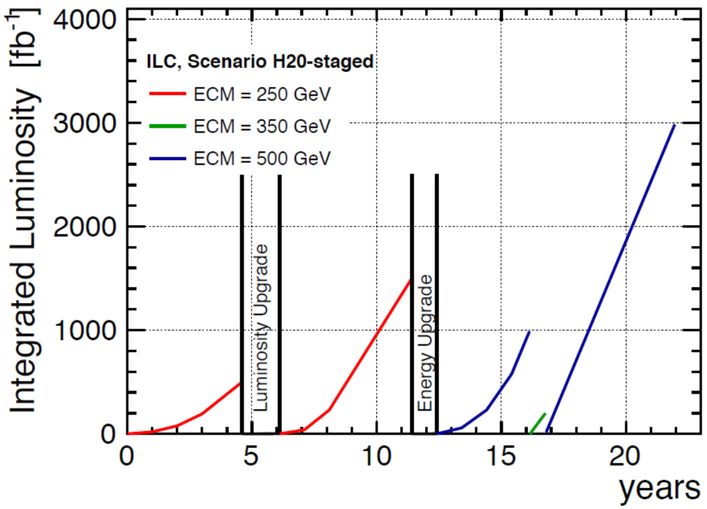


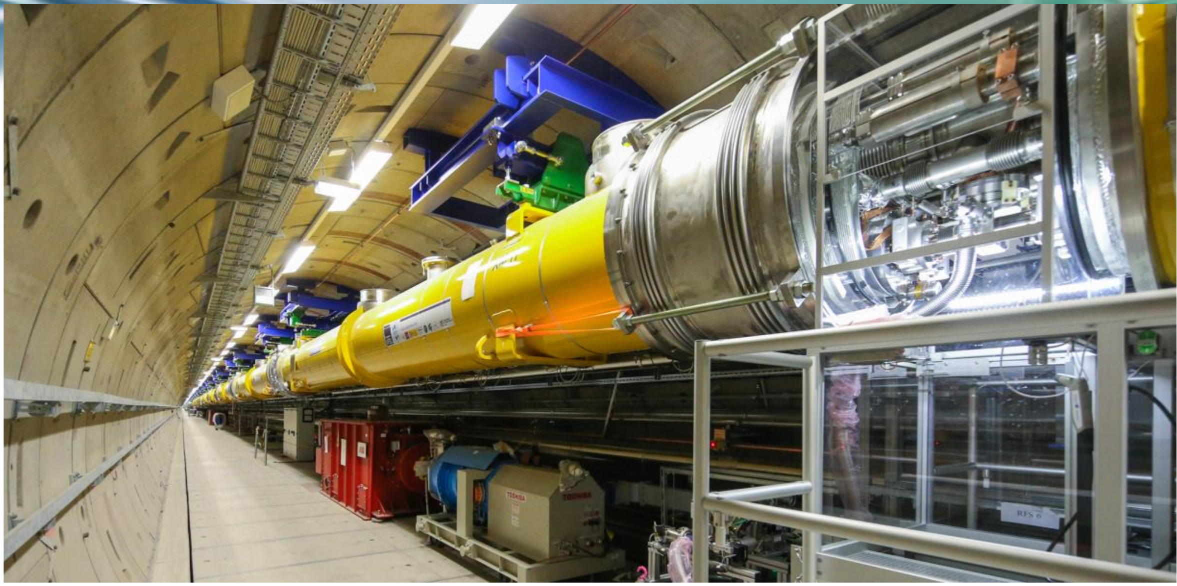
ICNFP 2022 Crete, Greece

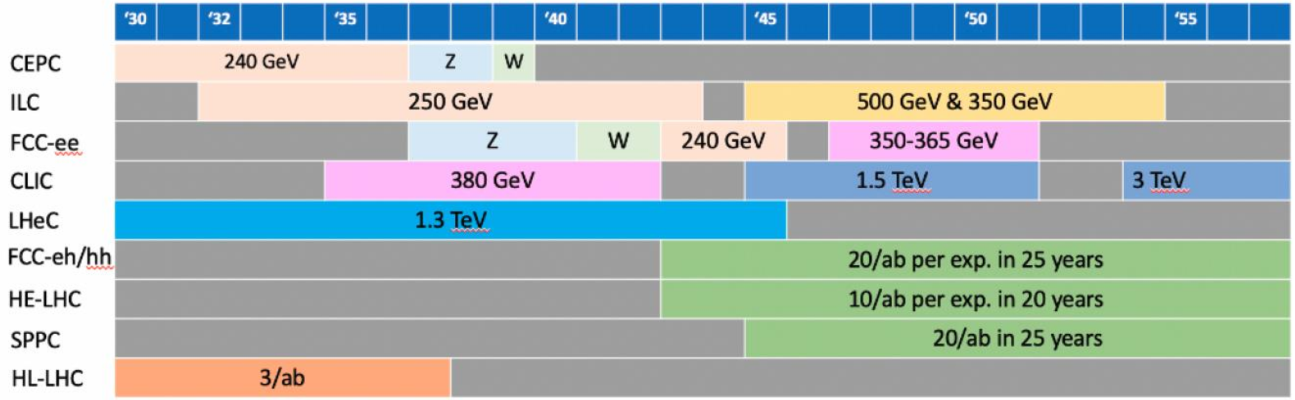
Overview

- ILC as a Higgs factory
- Higgs physics at ILC
  - Higgs couplings
  - Higgs self-coupling
  - CPV in the Higgs sector
  - Exotic and rare decays
- Outlook

A word on ILC



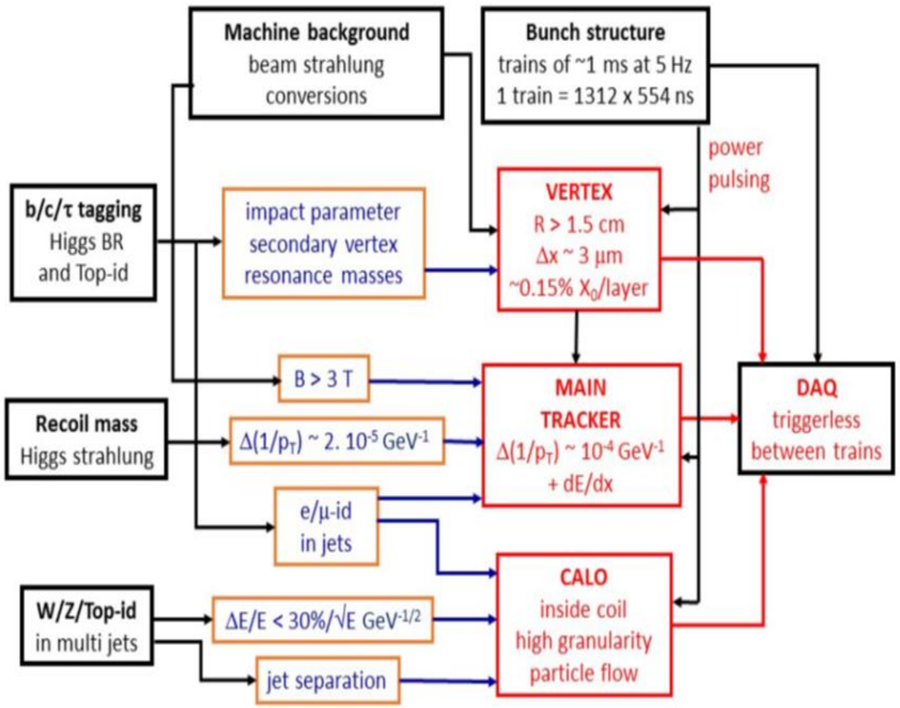


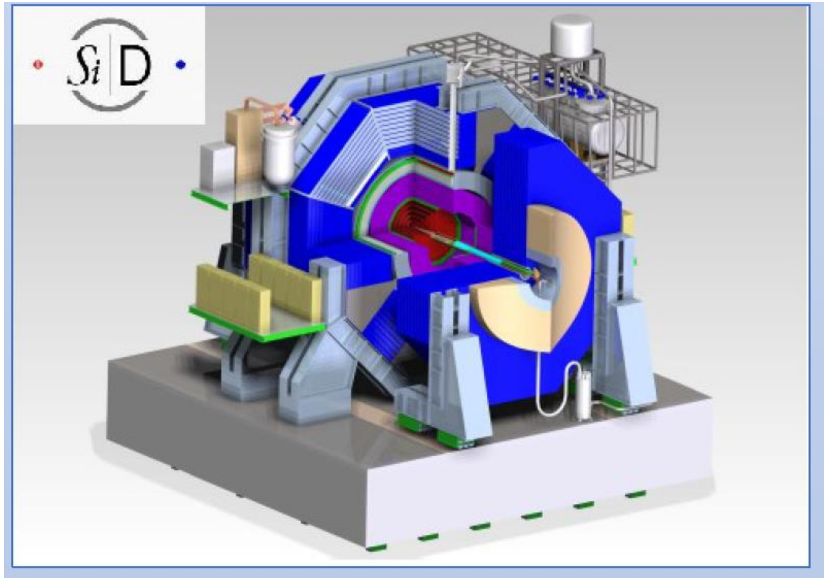


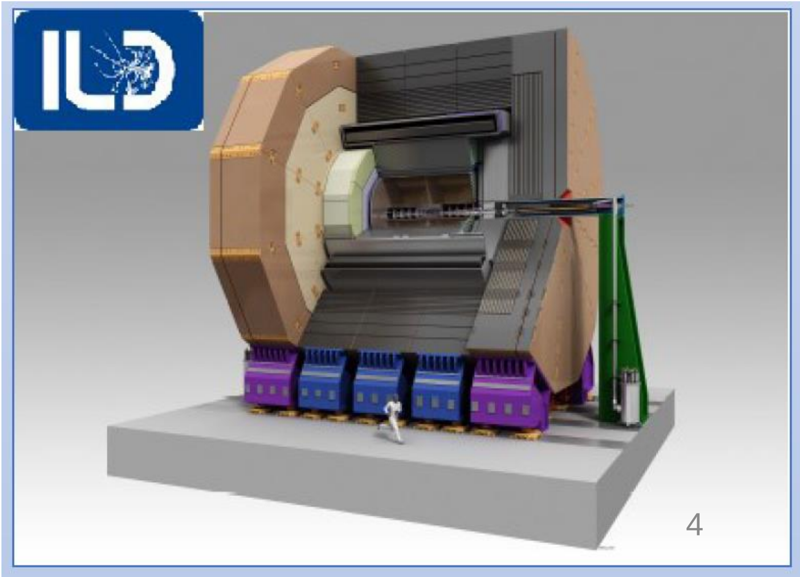
- Comes as a <u>'ready to take' project</u> (mature design, proven technologies)
- <u>Largest ever accelerator prototype</u> (operating now as E-XFEL), full industrialization of ILC-type SCRF cavity production
- <u>Tunable, upgradeable</u> (detector optimized from Z-pole to 1 TeV run)
- Comes with a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

A word on detector

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







Higgs physics - motivation

Fact I & II:

We have discoved an SM-like Higgs!

The SM cannot be the ultimate theory!

Conclusion: The discovered Higgs cannot be "the SM Higgs"!

Q: Does the BSM physics have any (relevant) impact on the Higgs?
$\Rightarrow$ any hints from LHC results (as guideline/toy example)?
Q': Which model?

A1: check changed properties of the h_{125} ← couplings, self-coupling, spin/parity

A2: check for additional Higgs bosons
check for additional Higgs bosons above and below 125 GeV ← extended Higgs sector

Sven Heinemeyer, ICHEP 2022, Bologna, 12.07.2022 5

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PROGRAM OF THE HIGGS FCTORIES

- Couplings
- self-coupling
- spin/parity – CPV in the Higgs sector

- extended Higgs sector

Higgs production at ILC

- **Plethora of Higgs production processes**
- As staged machine benefits from additional statistics from WW-fusion
- Double Higgs production at higher energies enables precise self-coupling determination

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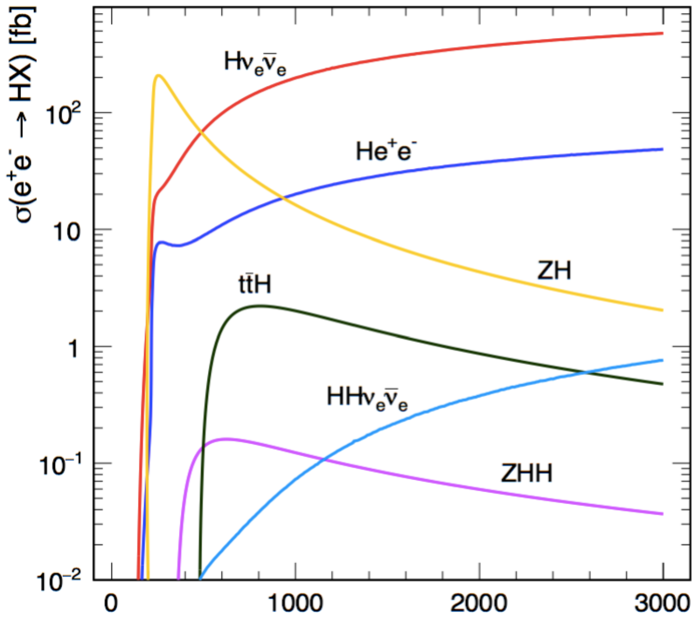
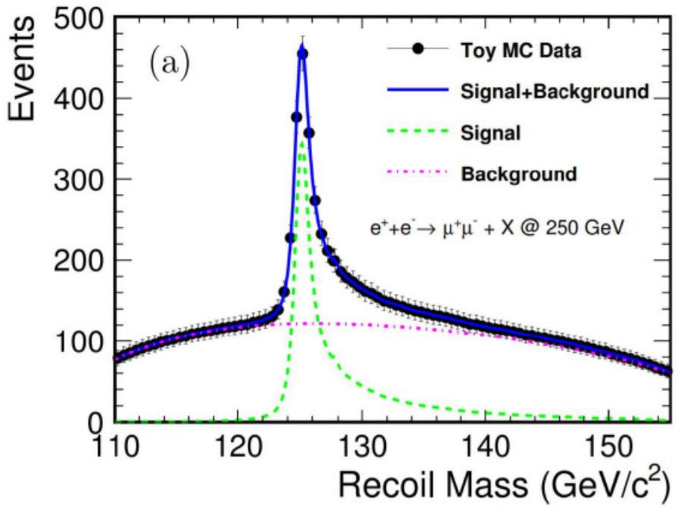
- Higgsstrahlung (ZH) facilitates recoil mass technique
- Absolute Γ_H measurement
- Access to invisible Higgs decays
- Most of the Higgs couplings can be determined with a better precision than at HL-LHC only from ZH

- 20 years running (250 GeV + 500 GeV) + beam polarization:
  - Δm_H=14 MeV (impact on $H \rightarrow ZZ^*$ width - a few tens of MeV required),
  - $\Delta\sigma_{ZH}/\sigma_{ZH}$ = 0.7%,
  - $\delta(g_{HZZ})$=0.4%





Higgs to invisible

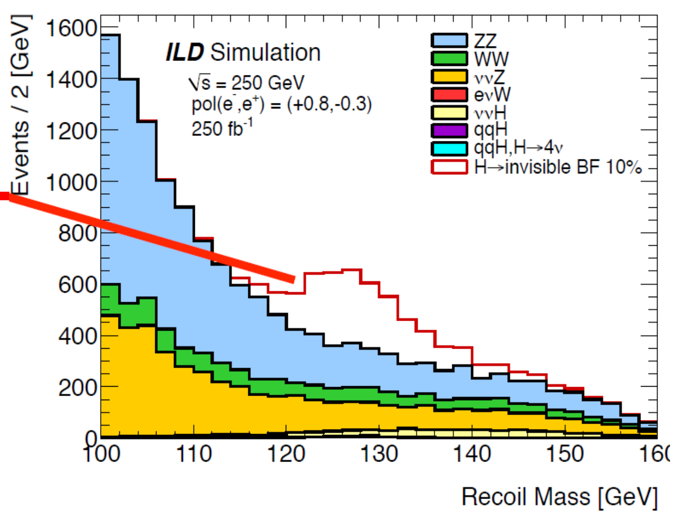
- Looking at the recoil mass in HZ under the condition that nothing observable is recoiling against the *Z* boson
- Access to DM connected to SM particles through a specific set of operators (portals)

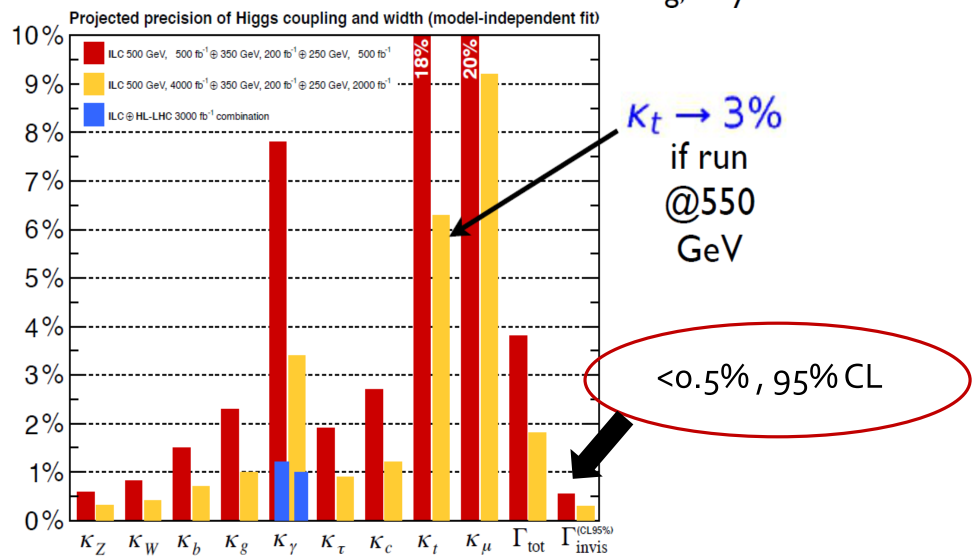
$$\frac{1}{2}\epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu} \qquad \epsilon_H |H|^2 |\Phi|^2 \qquad \epsilon_a \frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

RED - "initial" ILC running, 8 years

ORANGE - "full" ILC running, 20 years

H→inv.

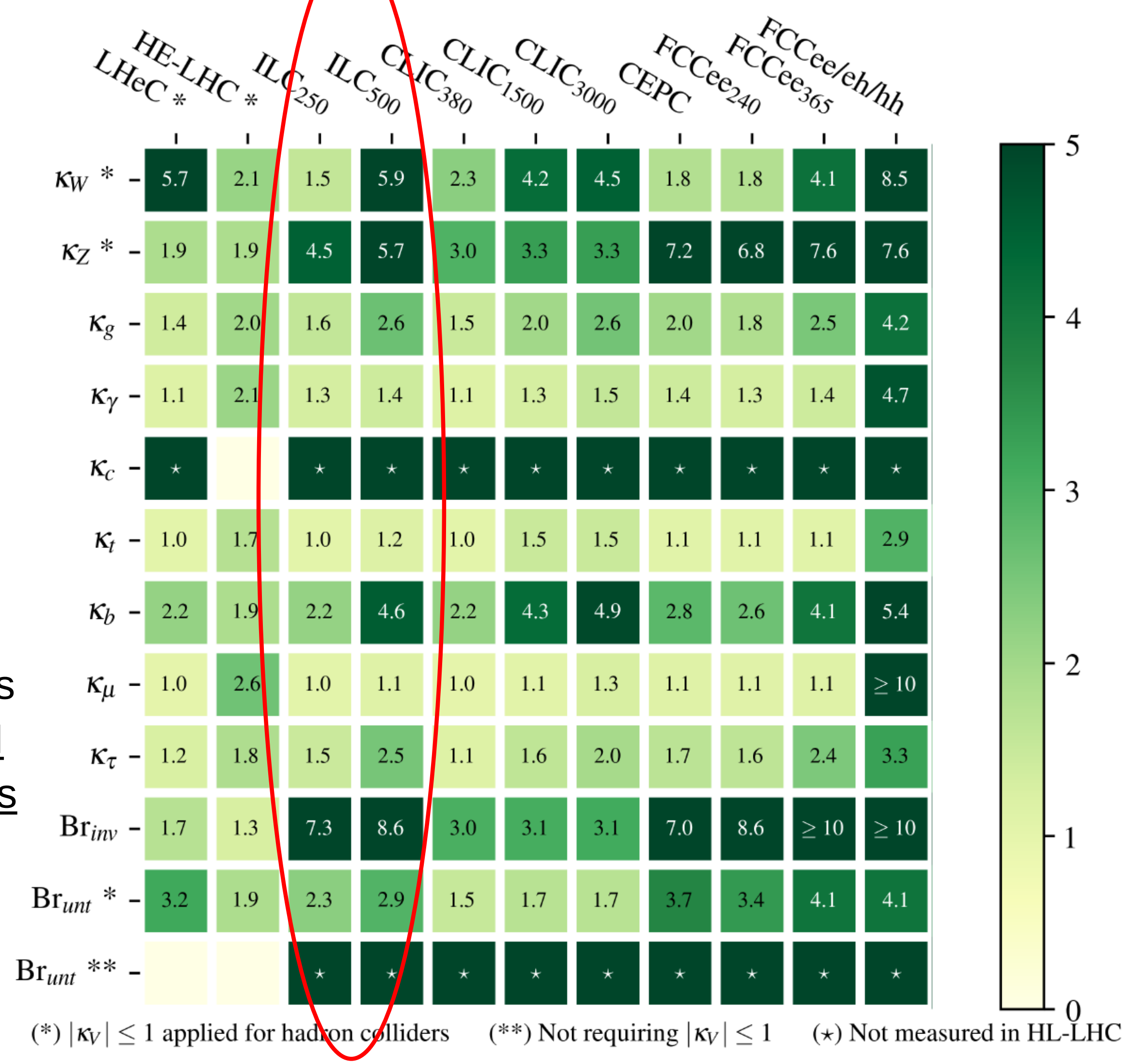




Higgs couplings - κ framework

Higgs couplings – global fit
(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

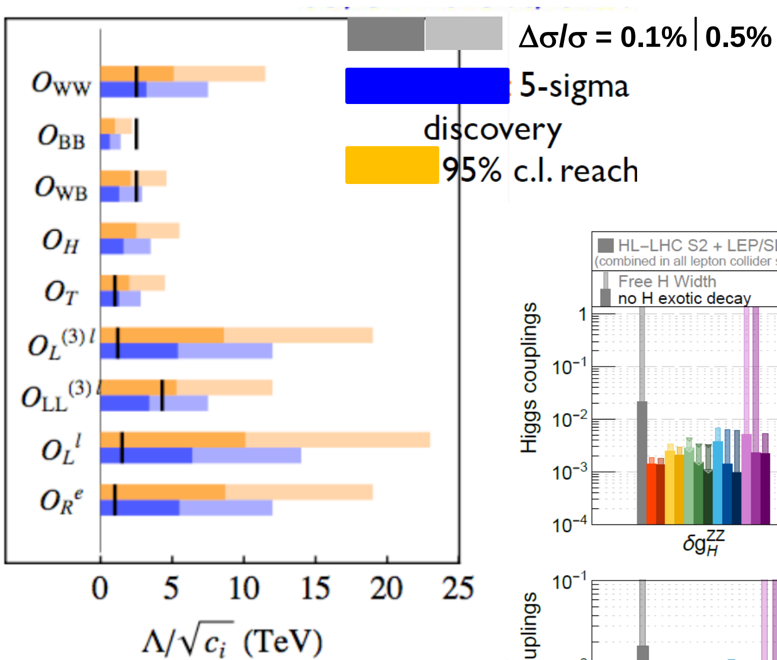


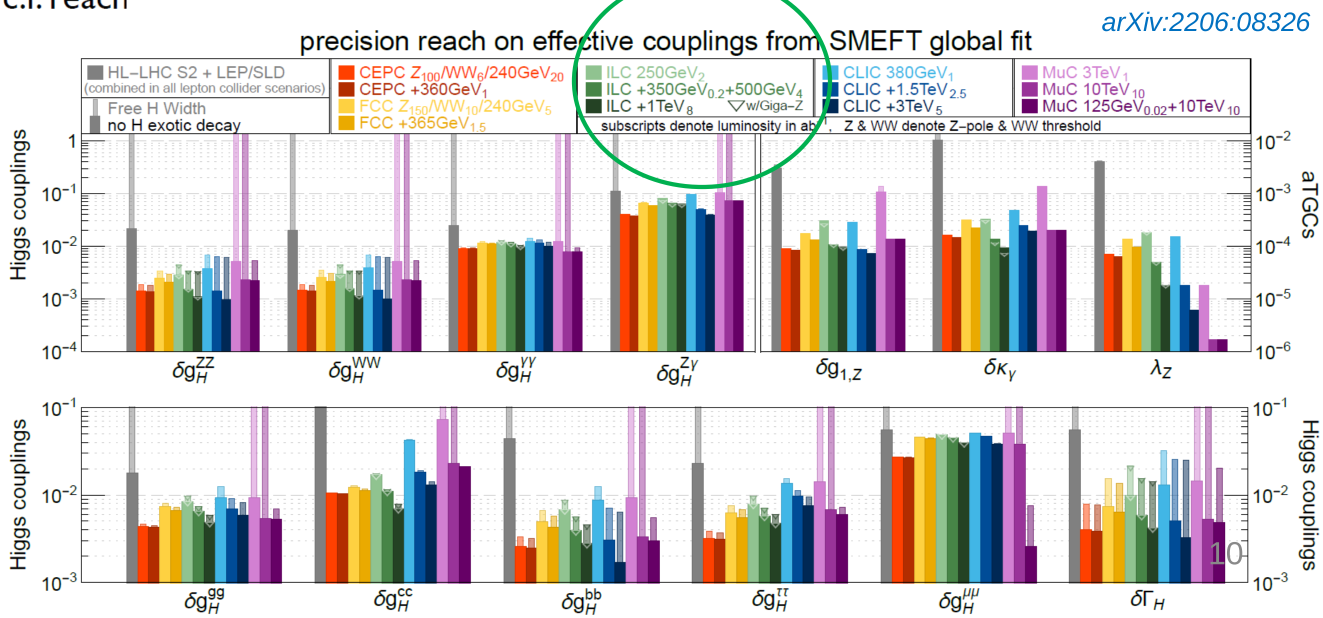
Factor of improvement w.r.t. the HL-LHC

Higgs@Future Colliders WG EPPSU

Higgs couplings - EFT

- Most couplings (except Hμμ and Htt)<1%
- EFT: Smaller the uncertainty – larger the NP scale to be probed (~1/Λ^2) independently of a particular model
- Polarization improves a bit the run-time
- … helping primarily to constrain the most general set of triple gauge coupling deviations allowed by Lorentz invariance - only if both beams are polarized



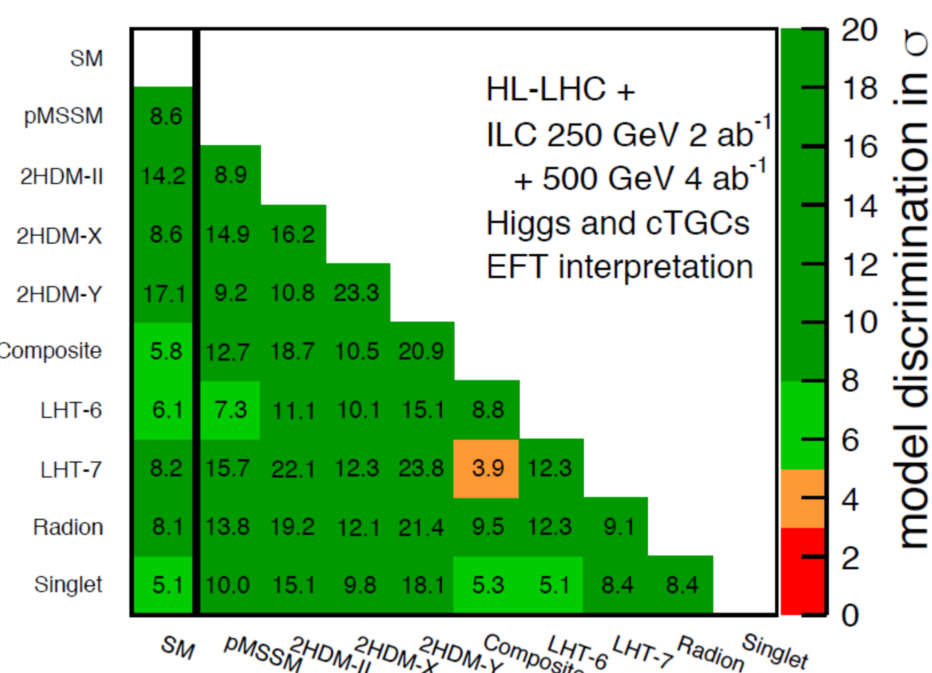


I. Bozovic

Higgs as a probe to BSM

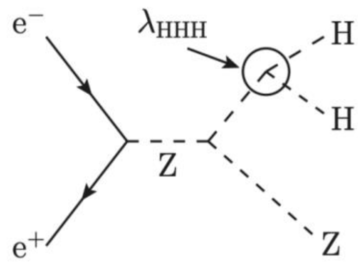
g_H relative deviations in %

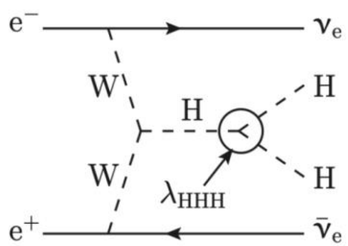
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [36]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [35]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [35]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [35]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite 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

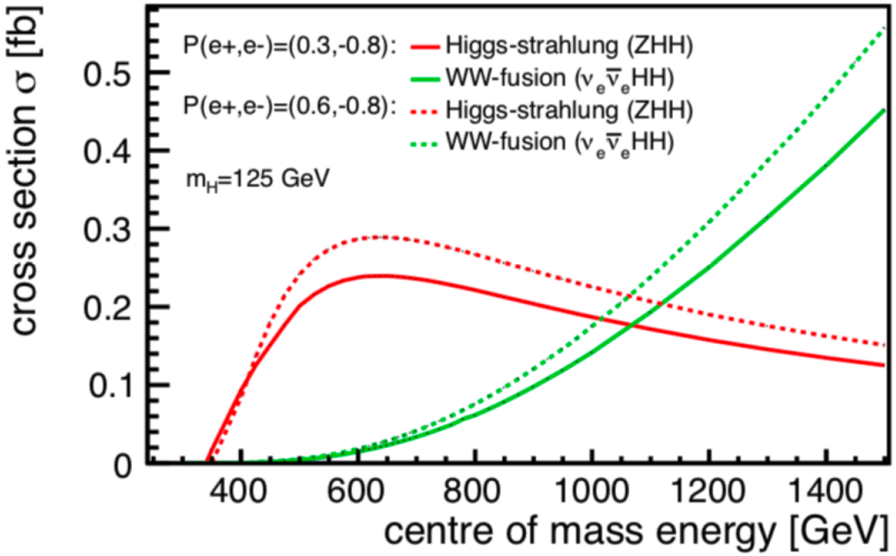


- Boosted sensitivity in combination with HL-LHC, evident synergy
- Higher energies (500 GeV) pin down above the discovery limit, BSM models of the Higgs sector difficult to be probed at HL-LHC

Higgs self-coupling λ

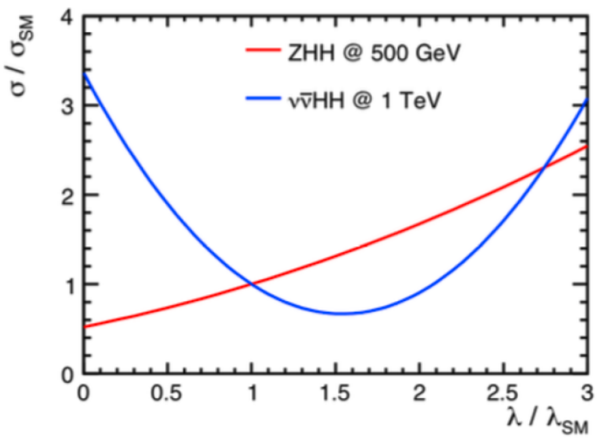






Higgs self-coupling parameter λ

- 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
- HHνν is the most sensitive to deviations of the Higgs self-coupling



High energy (≥ 500 GeV) e^+e^- collider is superior in determination of the Higgs self-coupling

Higgs self-coupling λ

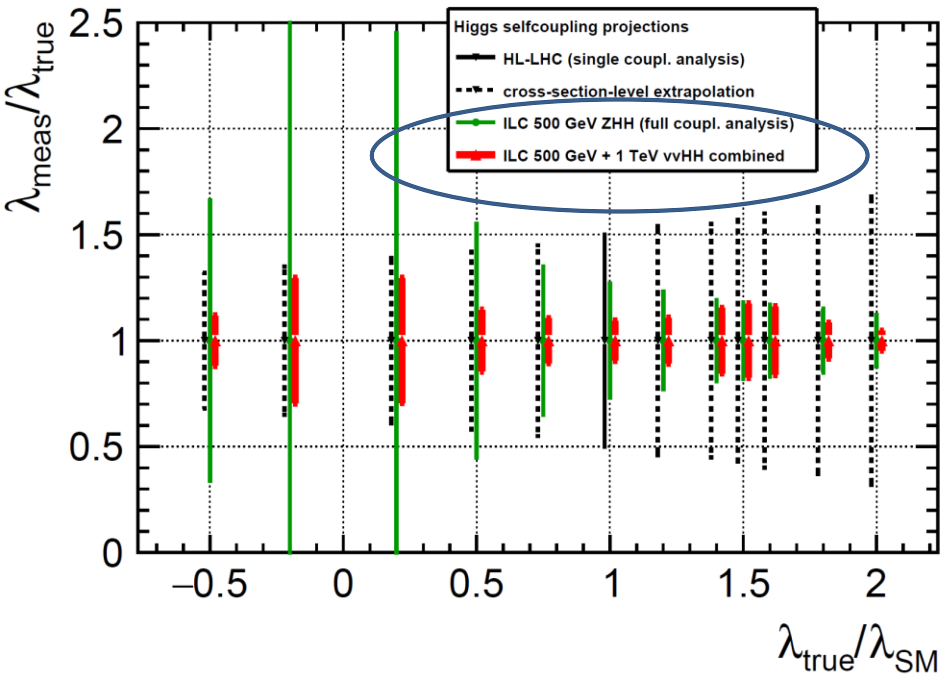
Higgs self-coupling parameter λ

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

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

CPV in the Higgs sector

CP violation in the Higgs sector

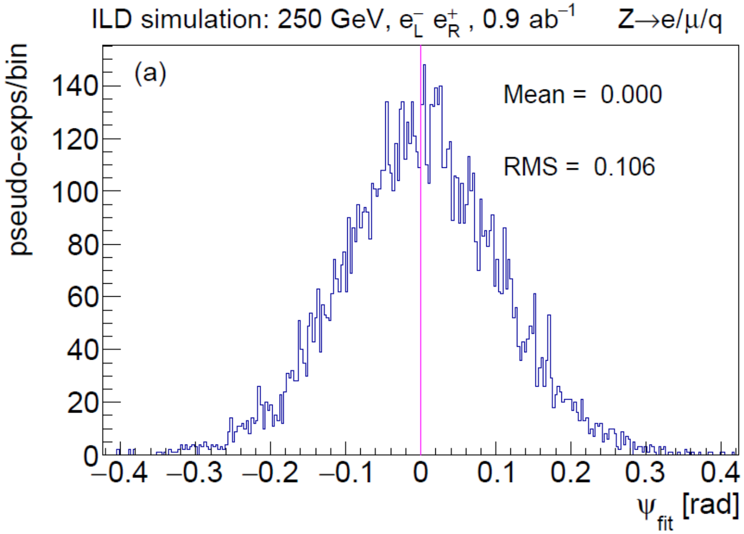
- Higgs can be a CPV mixture of scalar and pseudoscalar states $h = H \cdot cos\Psi_{CP} + A \cdot sin\Psi_{CP}$ mixing angle to be determined
- Several vertices to be probed (Hττ, HZZ, HWW) in Higgs production and decays
- The most precise result in H→ττ decays comes from ILC

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]



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

Probably too conservative

Name	α_τ
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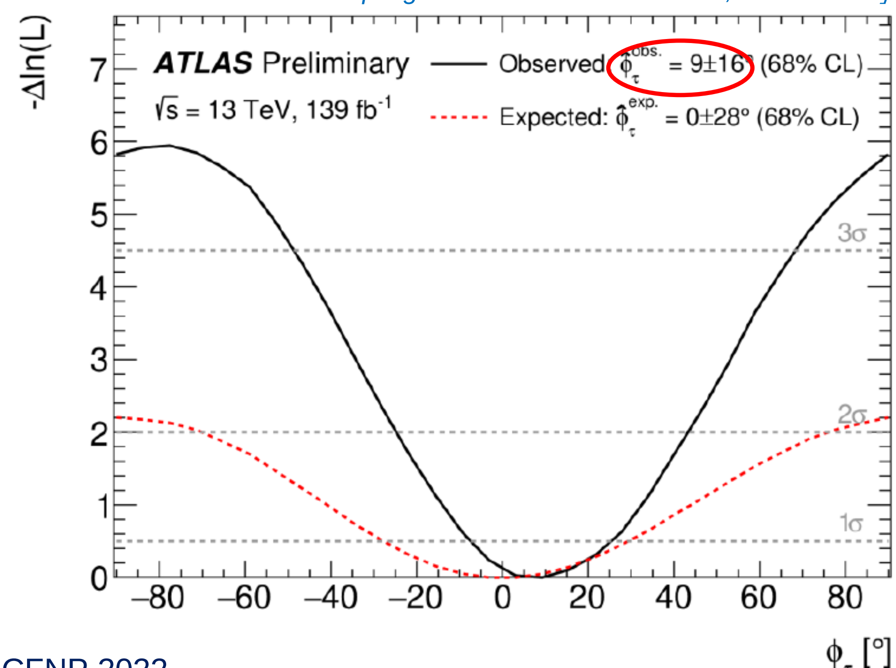
CEPC	–
FCC-ee$_{240}$	10°
ILC$_{250}$	4°

[Max Goblirsch, Measurements of the CP structure of Higgs boson couplings with the ATLAS detector, ICHEP2022]



Key to precision

CP violation in the Higgs sector – understanding the precision

- 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 $\Delta\psi_{CP} < 1.5°$

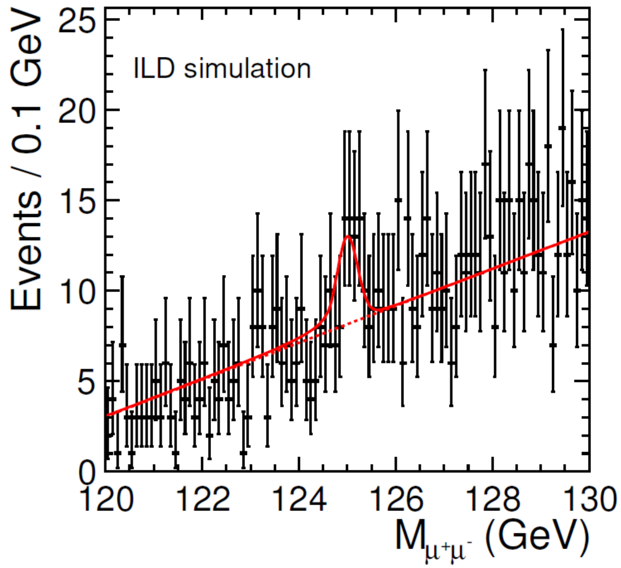
$\mathcal{L}$(ab^{-1})	H20-staged: 250 GeV, 2 ab^{-1}			$\Delta\psi_{CP}$ (mrad)
0.9	-0.8	$+0.3$	only $e^-_L e^+_R$	102
0.9	$+0.8$	-0.3	only $e^-_R e^+_L$	120
0.1	-0.8	-0.3	only $e^-_L e^+_L$	359
0.1	$+0.8$	$+0.3$	only $e^-_R e^+_R$	396
2.0	mixed		full analysis	75

[arXiv:1804.01241]

Higgs rare decays

Power of combination: polarization, energy staging

The same mechanisms in place for rare decays H $\rightarrow \mu\mu$ (BR = 0.021%)



S. Kawada, Prospects of measuring Higgs boson decays into muon pairs at the ILC, arXiv:1902.05021

$\sqrt{s} = 250$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC250	ILC250+500
L	34%	113%	23%	17%
R	36%	111%		
$\sqrt{s} = 500$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC500	
L	43%	37%	24%	
R	48%	106%		

Higgs exotic decays

Flavorful Higgs

- 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

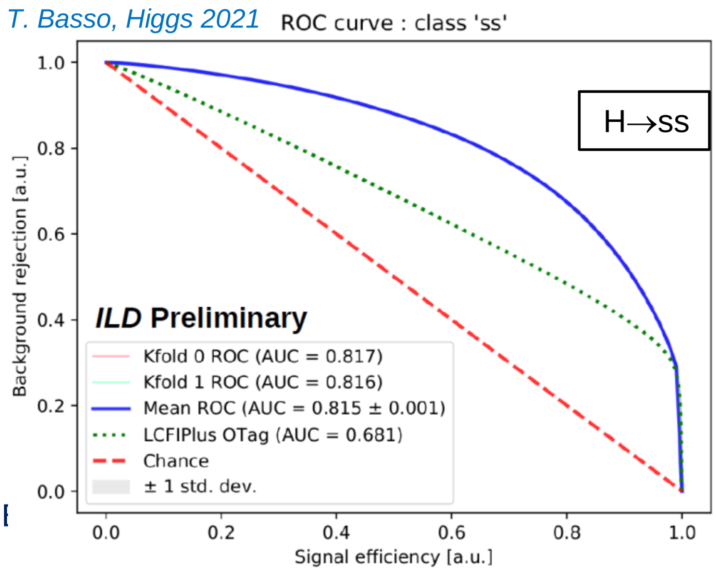
Higgs exotic decays

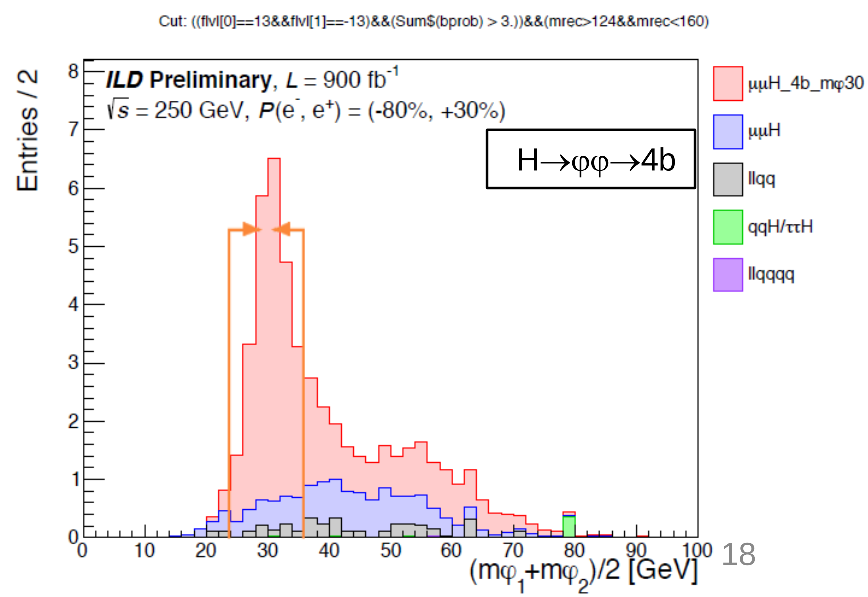
- H→φφ(→4b)
- Full simulation analysis at 250 GeV ILD
- Scalar mediator mass range: 15 - 60 GeV
- 95% CL upper limit on BR(H→φφ→4b) < 0.1%

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?

- Some measurements (like λ) are clearly preferred at high energy lepton collider
- Benefits from different polarizations and combinations are evident

- Room for improvement, beneficial also to other precision measurements

Jet Clustering

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

Flavour Tagging

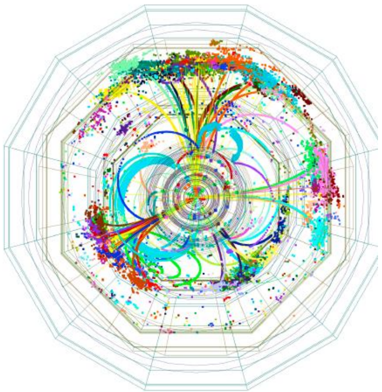
☑ Better *b*-tagging efficiency

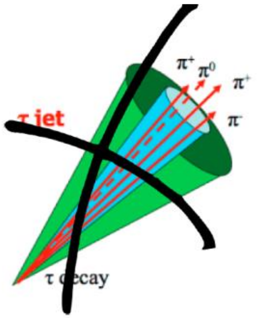
5% relative improvement in $\varepsilon_{b\text{-tag}}$
$\rightarrow 11\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

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 ~ 2°

Jet Reconstruction and Pairing

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

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

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)

Summary

- ILC is viable, mature and imminently 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

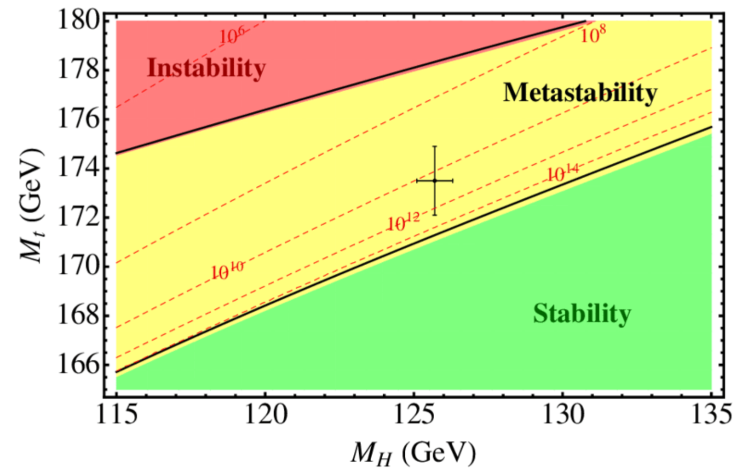
- Higgs couplings improvement $\mathcal{O}$ (10) w.r.t. HL-LHC (in particular for H to EW bosons)
- NP scale $\mathcal{O}$(10 TeV) to be probed indirectly (EFT)
- Higgs BSM model discrimination $\geq 5\sigma$
- λ precision < 10% (ILC 1000)

- Ongoing effort on improvement of reconstruction/identification algorithms will be leading to further precision enhancements

BACKUP

Higgs mass

- Which precision of the Higgs mass is needed?
  - Vacuum stability (at least several GeV)
  - Impact on H→ZZ* width (a few tens of MeV)



ATLAS+CMS Run1 125.09 ± 0.24 (± **0.21 stat** ± 0.11 syst) GeV

CMS Run1 + 2016 125.38 ± 0.14 (± **0.11 stat** ± 0.08 syst) GeV

ATLAS Run1 + 4*l* Run2 124.94 ± 0.17 (± **0.17 stat** ± 0.03 syst) GeV

[C. Mariotti, Higgs results: From the discovery to precision physics, ICHEP2022]

Collider Scenario	Strategy	δm_H (MeV)	$\delta(\Gamma_{ZZ^*})$ (%)
LHC Run-2	$m(ZZ), m(\gamma\gamma)$	160	1.9
HL-LHC	$m(ZZ)$	10-20	0.12-0.24
ILC_{250}	ZH recoil	14	0.17
$CLIC_{380}$	ZH recoil	78	1.3
$CLIC_{1500}$	$m(bb)$ in $H\nu\nu$	30[15]	0.56
$CLIC_{3000}$	$m(bb)$ in $H\nu\nu$	23	0.53
FCC-ee	ZH recoil	11	0.13
CEPC	ZH recoil	5.9	0.07

[M. Cepeda, Higgs precision measurements at future colliders, IFT UAM-CSIC, Madrid, 2019]

Higgs width

- Being less than 5 MeV, Higgs decay width can not be *directly* measured at any proposed e+e- collider
- Can be determined from individual decays like H→ZZ in HZ (or H→WW decays in WW-fusion)

$$\sigma(\mathrm{ee} \to \mathrm{ZH}) \cdot \mathrm{BR}(\mathrm{H} \to \mathrm{ZZ}) \propto \frac{g_{\mathrm{HZ}}^4}{\Gamma}$$

- In a combination of measurements:

$$\frac{\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{WW})\cdot\sigma(\mathrm{ee}\to\mathrm{ZH})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}{\sigma(\mathrm{ee}\to\nu\nu\mathrm{H})\cdot\mathrm{BR}(\mathrm{H}\to\mathrm{bb})}$$

$$\propto \frac{g_{\mathrm{HZ}}^2\cdot \cancel{g_{\mathrm{HW}}^2}}{\Gamma}\cdot\frac{g_{\mathrm{HZ}}^2\cdot \cancel{g_{\mathrm{Hb}}^2}}{\cancel{\Gamma}}\cdot\frac{\cancel{\Gamma}}{\cancel{g_{\mathrm{HW}}^2}\cdot\cancel{g_{\mathrm{Hb}}^2}} = \frac{g_{\mathrm{HZ}}^4}{\Gamma}$$

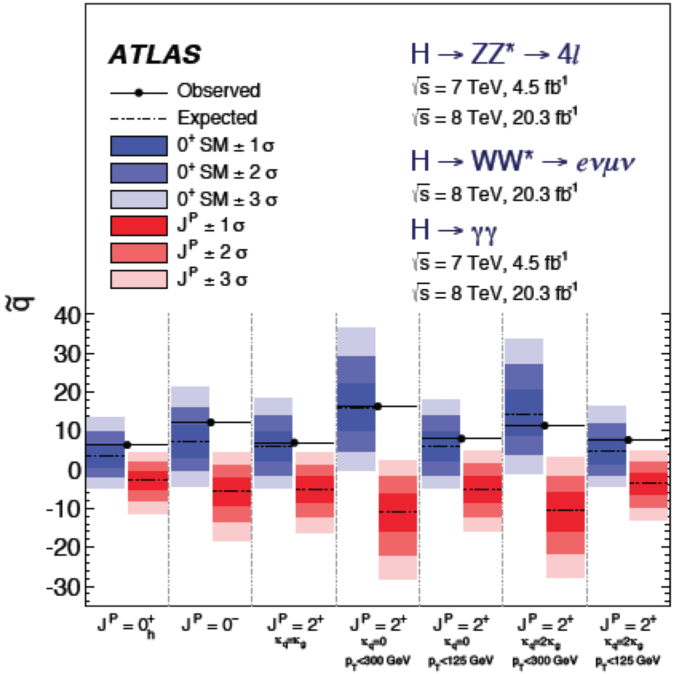
- The ultimate precision is reached in a global fit i.e. κ-framework (model-independent, EFT):

$$\Gamma_H = \frac{\Gamma_H^{SM}\cdot\kappa_H^2}{1-(BR_{inv}+BR_{unt})}$$

Collider	Extraction technique standalone result	$\delta\Gamma_H$ [%] kappa-3 fit
ILC_{250}	EFT fit [3,4]	2.2
ILC_{500}	EFT fit [3,4,14]	1.1
ILC_{1000}	EFT fit [4]	1.0
CLIC_{380}	κ-framework [98]	2.5
CLIC_{1500}	κ-framework [98]	1.7
CLIC_{3000}	κ-framework [98]	1.6
CEPC	κ-framework [103,104]	1.7
$\mathrm{FCC\text{-}ee}_{240}$	κ-framework [1]	1.8
$\mathrm{FCC\text{-}ee}_{365}$	κ-framework [1]	1.1

[J. de Blas et al, arXiv:1905:03764]

ATLAS and CMS many analyses, lots of results → **Spin 0 Positive parity at > 99.9% CL**



CP structure of various Higgs couplings probed for fermions (top, τ), gluons, EW vector bosons, with a variety of production and decay modes

- Measurement globally in accord with SM CP-even hypothesis
- Pure CP-odd ttH coupling excluded 3.9 σ
- Pure CP-odd Hττ coupling excluded 3.4 σ

[C. Mariotti, Higgs results: From the discovery to precision physics, ICHEP2022]