Higgs physics at ILC

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- On behalf of the ILC International Development Team -

OUTLINE

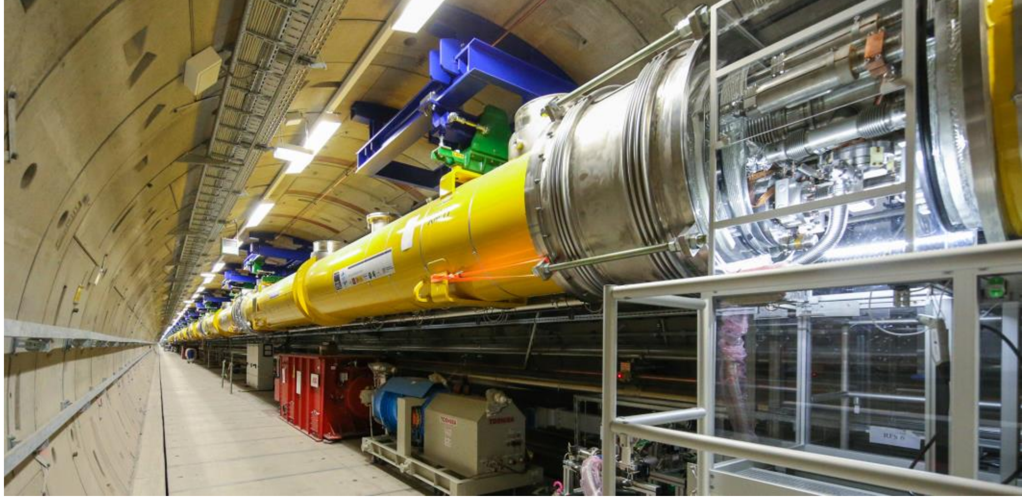
- ILC as a Higgs factory

- Key measurements at 250 (350, 500) GeV
  - Higgs mass
  - Higgs width
  - Higgs couplings

- High energy operation (≥ 500 GeV)
  - Higgs couplings as a probe to BSM
  - Higgs self-coupling
  - CPV in the Higgs sector
  - ttH production

- Summary

A WORD ON ILC



	√s	beam polarisation	∫Ldt (baseline)
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV

- 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 (from Z-pole, via Higgs factory mode, 500 GeV up to 1 TeV, or by replacing accelerating structures with advanced technologies)
- Numerous benefits from the high energy phase (≥500 GeV) and beam polarization

ILC AS A HIGGS FACTORY

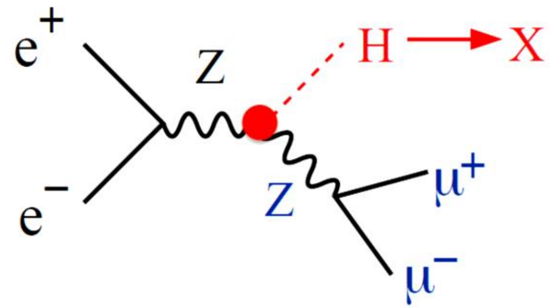
- Known initial state
- No PDFs, dominant statistical uncertainty
- Higgsstrahlung offers model-independence
- Absolute normalization of the Higgs couplings: σ_{ZH} measurement in a model independent way

PRECISION MEASUREMENTS

Clean experimental environment:
- No pile-up
- QCD background free
- Trigger-less readout

Added values of polarization:
- model discrimination
- background suppression
- effectively increasing $\mathcal{L}_{\text{int}}$

KEY MEASUREMENTS AT ILC



ZH: recoil mass measurements

- Independent of Higgs decay mode
- σ_{ZH} measurement instead of σ_{ZH} x BR
- m_H measurement

$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

e_L^-, e_R^+, $Z\to ee$, $Z\to\mu\mu$:

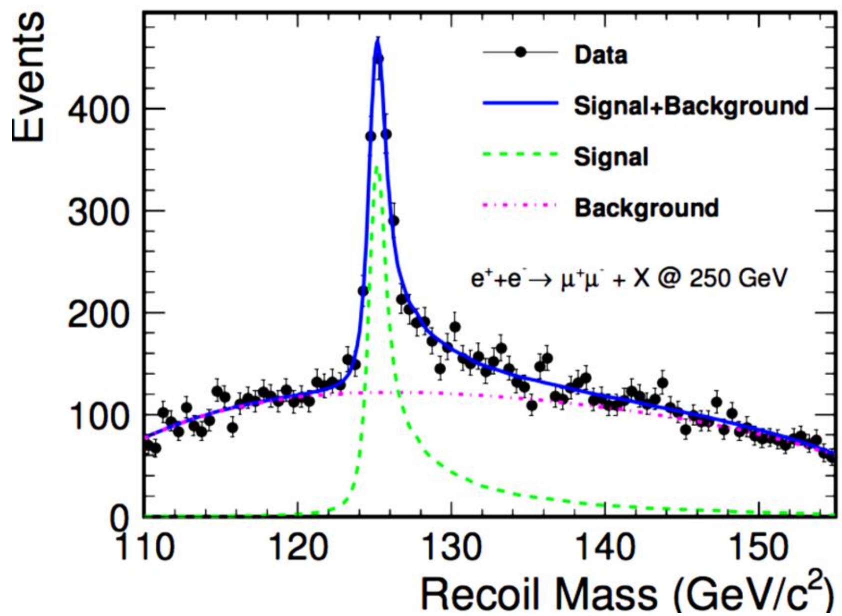
250 GeV (250 fb^{-1} – first 3 years)

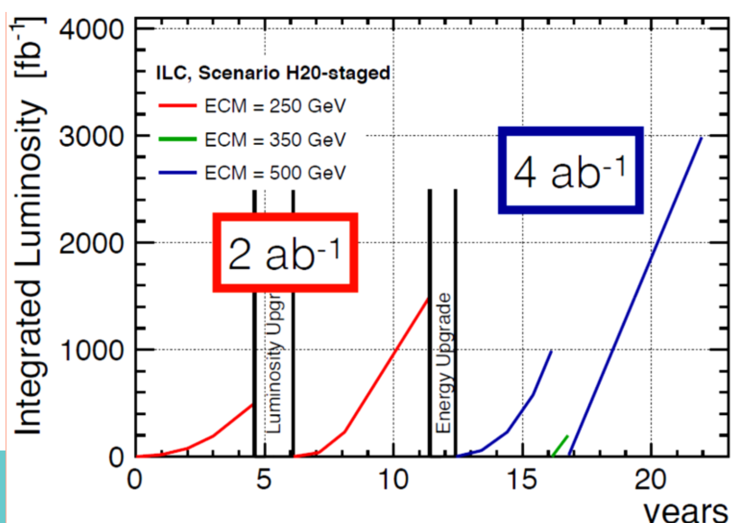
- Δm_H=37 MeV, $\delta\sigma_{ZH}$=2.5%

H-20, 250 GeV, 350 GeV, 500 GeV

- Δm_H=14 MeV, $\delta\sigma_{ZH}$=0.4%

[Physical Review D 94,113002 (2016)]





KEY MEASUREMENTS AT ILC

Γ_H: at least one partial width and corresponding BR needed

SMEFT:

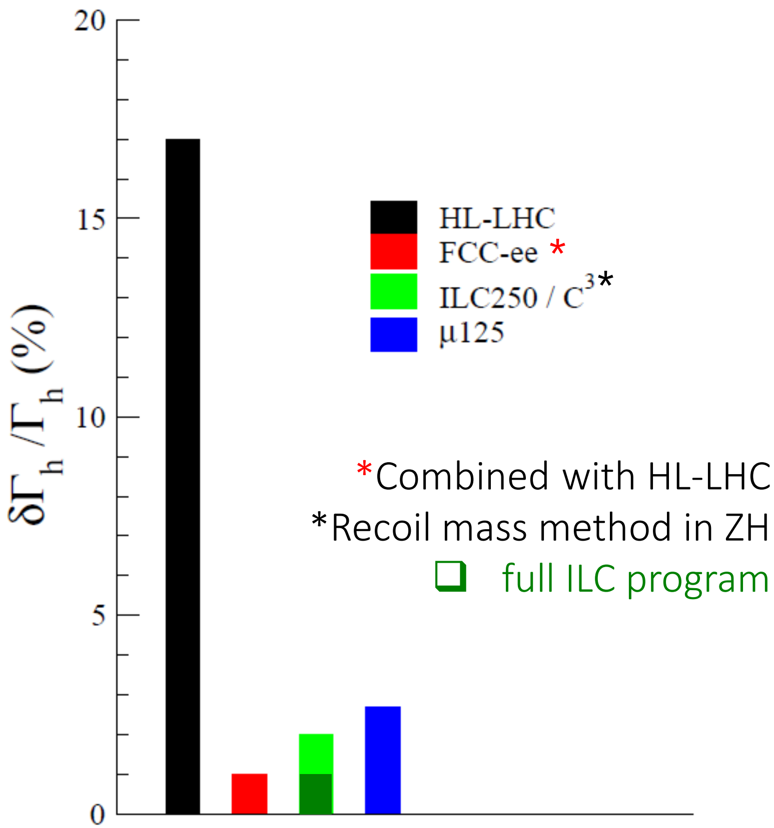
250 GeV, (250 fb^{-1} – first 3 years)

- $\delta\Gamma_H$=2%

H-20, 250 GeV, 350 GeV, 500 GeV

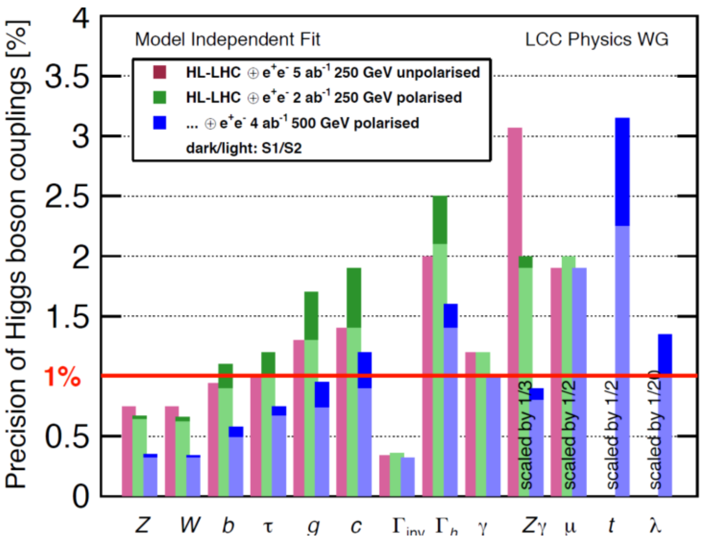
- $\delta\Gamma_H$=1%

[arXiv:2203.07622v3 [physics.acc-ph]]



[arXiv:2209.07510v2 [hep-ph]]

HIGGS COUPLINGS AT 250 GeV



[arXiv:1903.01629 [hep-ex]]

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κ/EFT fit

Collider	HL-LHC	μColl$_{125}$	ILC$_{250}$	CLIC$_{380}$	CEPC$_{240}$	FCC-ee$_{240\to365}$
Lumi (ab^{-1})	3	0.005	2	1	5.6	5 + 0.2 + 1.5
Years	10	6 to 10	11.5	8	7	3 + 1 + 4
g_{HZZ} (%)	1.5/3.6	SM	0.29/0.39	0.44/0.50	0.18/0.45	0.17/0.26
g_{HWW} (%)	1.7/3.2	3.9	1.0/0.41	0.73/0.50	0.88/0.43	0.41/0.27
g_{Hbb} (%)	3.7/5.3	3.8	1.1/0.78	1.2/0.99	0.92/0.63	0.64/0.56
g_{Hcc} (%)	SM/SM	SM	2.0/1.8	4.1/4.0	2.0/1.8	1.3/1.2
g_{Hgg} (%)	2.5/2.3	SM	1.4/1.1	1.5/1.3	1.0/0.76	0.89/0.82
$g_{H\tau\tau}$ (%)	1.9/3.4	6.2	1.1/0.81	1.4/1.3	0.91/0.66	0.66/0.57
$g_{H\mu\mu}$ (%)	4.3/5.5	3.6	4.2/4.1	4.4/4.4	3.9/3.8	3.9/3.8
$g_{H\gamma\gamma}$ (%)	1.8/3.6	SM	1.4/1.3	1.4/1.4	1.3/1.3	1.3/1.2
$g_{HZ\gamma}$ (%)	10./11.	SM	10./9.6	10./9.7	6.3/6.3	10./9.3
g_{Htt} (%)	3.4/3.5	SM	3.1/3.2	3.2/3.2	3.1/3.1	3.1/3.1
g_{HHH} (%)	50.	SM	49.	50.	49.	33./24.
Γ_H (%)	SM	6.1	2.2	2.5	1.7	1.1
$\mathscr{B}_{\text{inv}}$ (%)	1.9	SM	0.26	0.63	0.27	0.19
$\mathscr{B}_{\text{EXO}}$ (%)	SM (0.0)	SM (0.0)	1.8	2.7	1.1	1.0

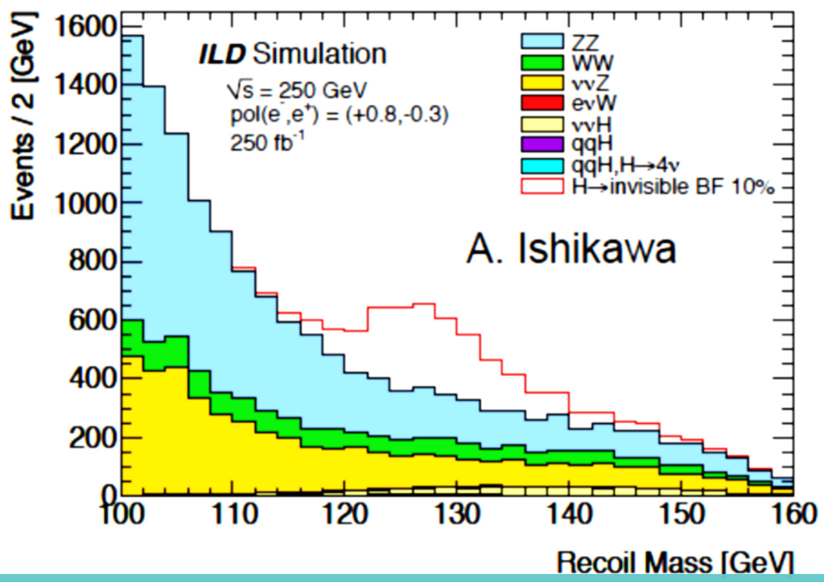
- Per mille precision already at 250 GeV
- Polarization effectively doubles the integrated luminosity

HIGGS INVISIBLE DECAYS

- 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)
- In example, moderately coupled Higgs to a light scalar H→SS→ SM particles

ΔBR(H—>Invisible)=0.26%



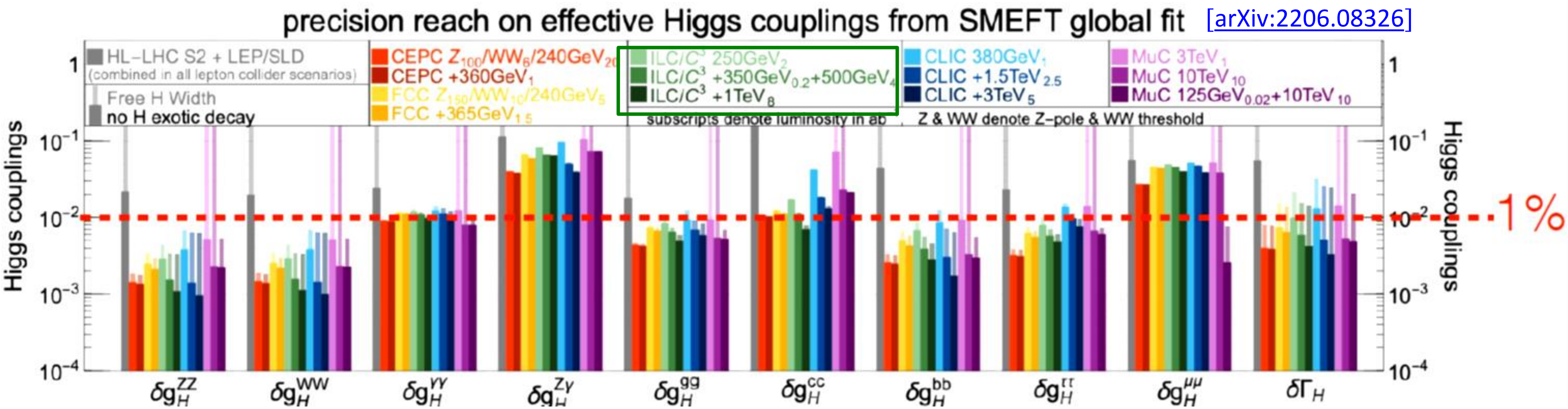
95% CL limits

Channel	HL-LHC	ILC	FCC-ee
E_T^{miss}	0.056	.0025	.005
$b\bar{b}b\bar{b}$	0.2	9×10^{-4}	3×10^{-4}
$b\bar{b}E_T^{miss}$	0.2	2×10^{-4}	5×10^{-5}
$jj\gamma\gamma$	0.01	2×10^{-4}	3×10^{-5}

[arXiv:2209.07510v2 [hep-ph]]

Lepton colliders can play a key role in the exotic Higgs decay program

HIGGS COUPLINGS (2)



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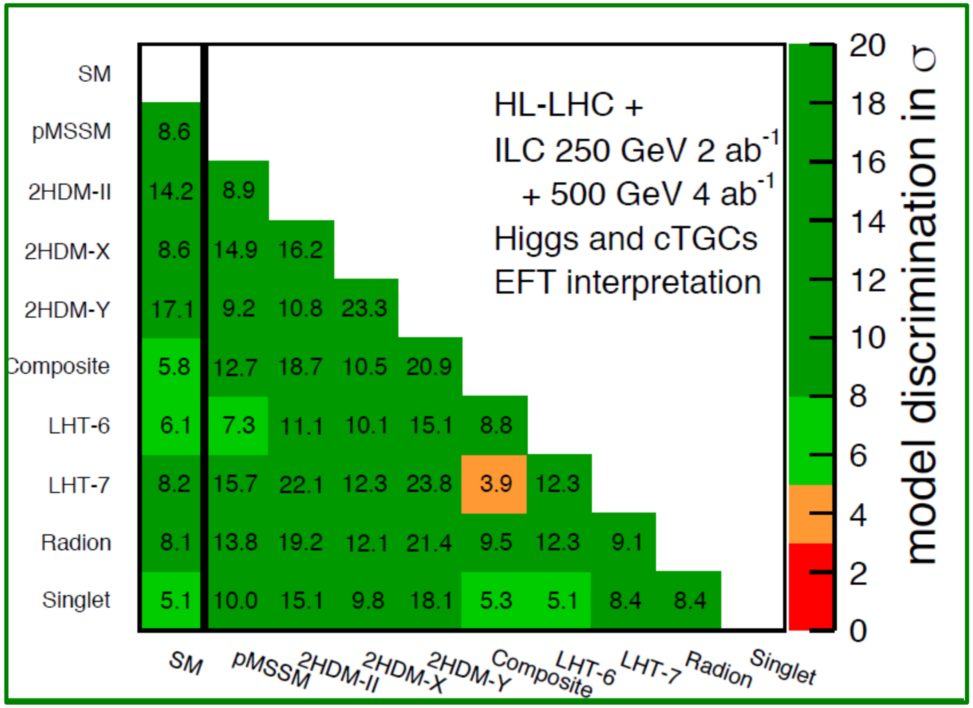
Collider	ILC$_{500}$	ILC$_{1000}$	CLIC	FCC$_{full}$
g_{HZZ} (%)	0.23/0.22	0.23/0.16	0.39/0.16	0.16/0.13
g_{HWW} (%)	0.29/0.22	0.24/0.17	0.38/0.15	0.19/0.13
g_{Hbb} (%)	0.56/0.52	0.47/0.43	0.53/0.38	0.48/0.44
g_{Hcc} (%)	1.2/1.2	0.90/0.88	1.4/1.4	0.96/0.95
g_{Hgg} (%)	0.85/0.79	0.63/0.55	0.86/0.75	0.50/0.49
$g_{H\tau\tau}$ (%)	0.64/0.58	0.54/0.49	0.82/0.73	0.46/0.46
$g_{H\mu\mu}$ (%)	3.9/3.9	3.6/3.5	3.5/3.5	0.43/0.42
$g_{H\gamma\gamma}$ (%)	1.2/1.2	1.1/1.1	1.2/1.1	0.31/0.34
$g_{HZ\gamma}$ (%)	10./6.8	10./6.7	5.7/3.7	0.70/0.70

- High energies improves precision (also for rare Higgs decays), **O**(10) w.r.t. HL-LHC
- Added value (w.r.t. the HL-LHC) Higgs exotic decays
- Performance is comparable (between Higgs factories)

BSM INTERPRETATIONS OF THE HIGGS COUPLINGS

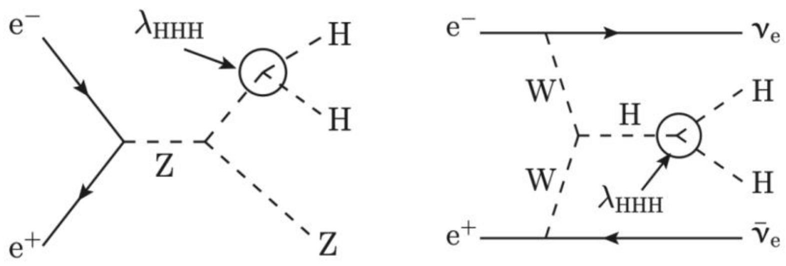


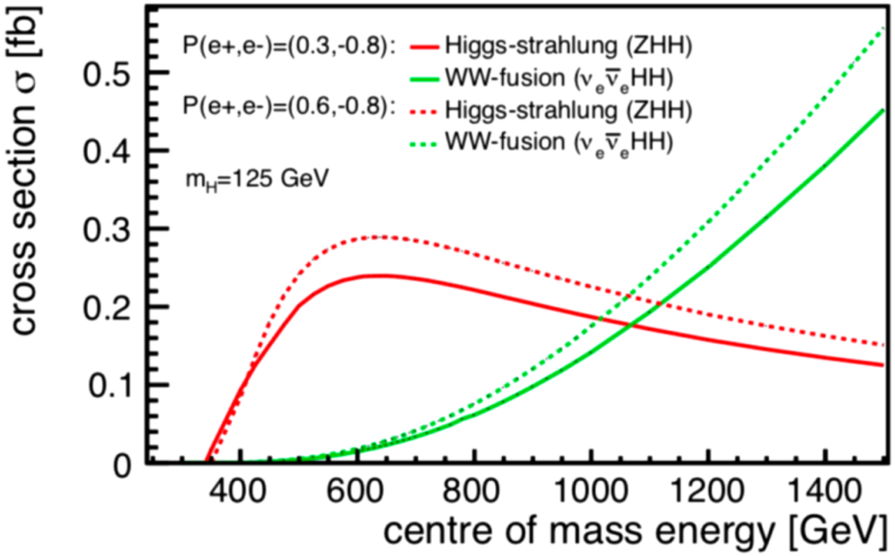
- Clear gain from high-energy operation
- Illustrates ILC as a power tool to probe and discriminate between BSM models

Model parameters (chosen as escaping direct search at HL-LHC)

- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600$ GeV, $\tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450$ GeV, $\tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600$ GeV, $\tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2$ TeV, $m_T = 1.7$ TeV
- a Little Higgs model with T-parity with $f = 785$ GeV, $m_T = 2$ TeV
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2$ TeV, $m_T = 1.7$ TeV
- A Higgs-radion mixing model with $m_r = 500$ GeV
- a model with a Higgs singlet at 2.8 TeV creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

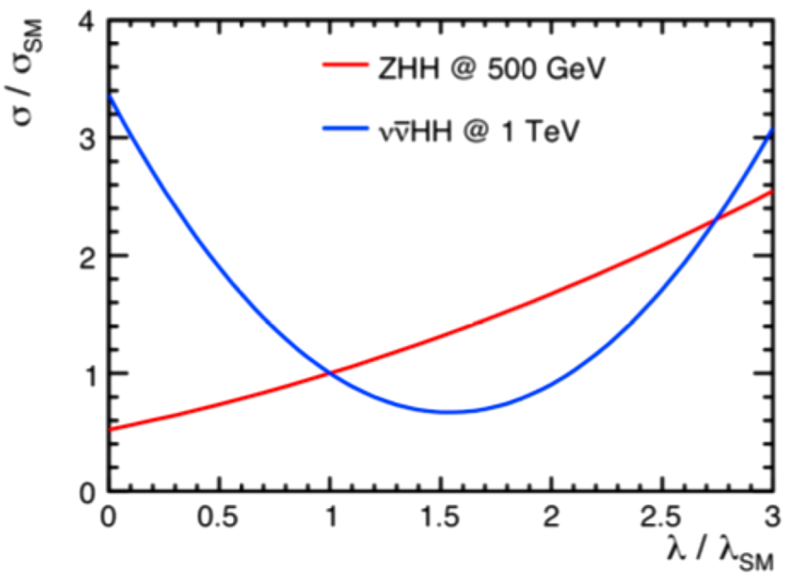
HIGGS SELF COUPLING





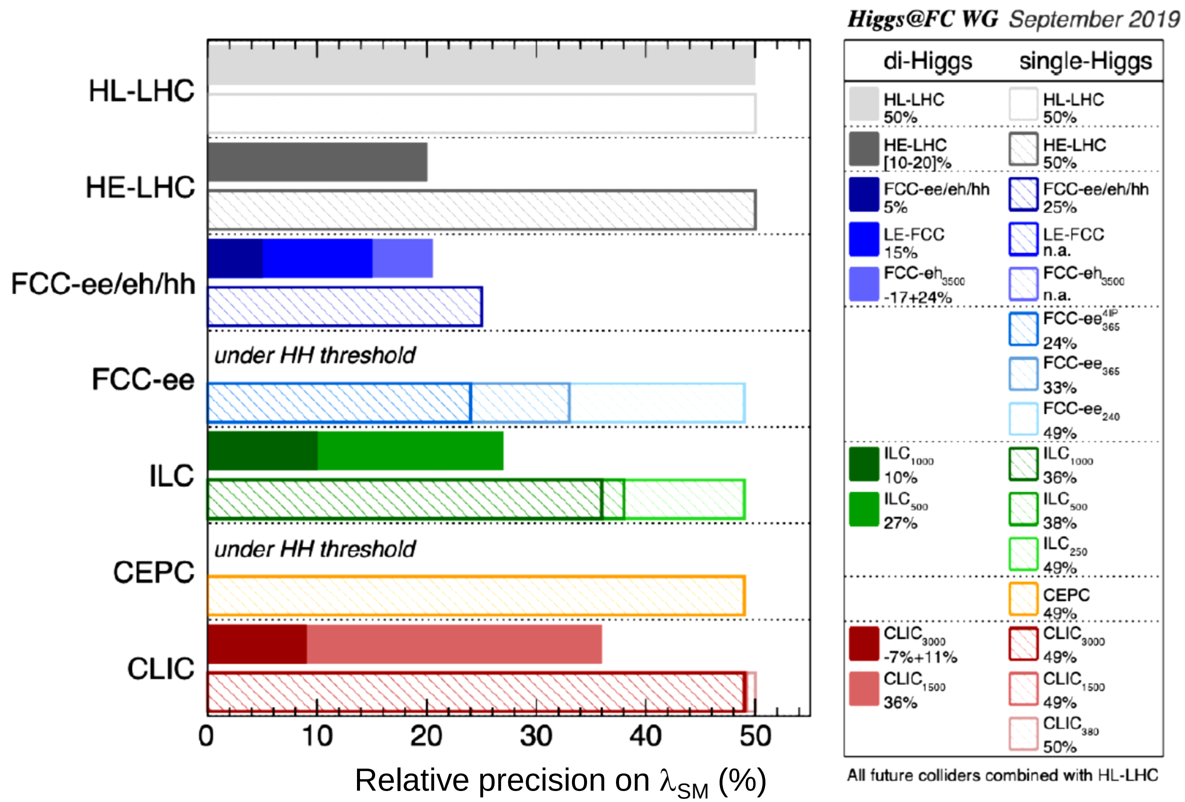
Higgs self-coupling parameter λ

- Two complementary processes available
- WW-fusion (HHνν) statistically preferred at (above) 1 TeV
- Polarization significantly influences the HHνν rate
- Different behavior of ZHH and HHνν x-section resolves ambiguity for non-SM values of λ



HIGGS SELF COUPLING

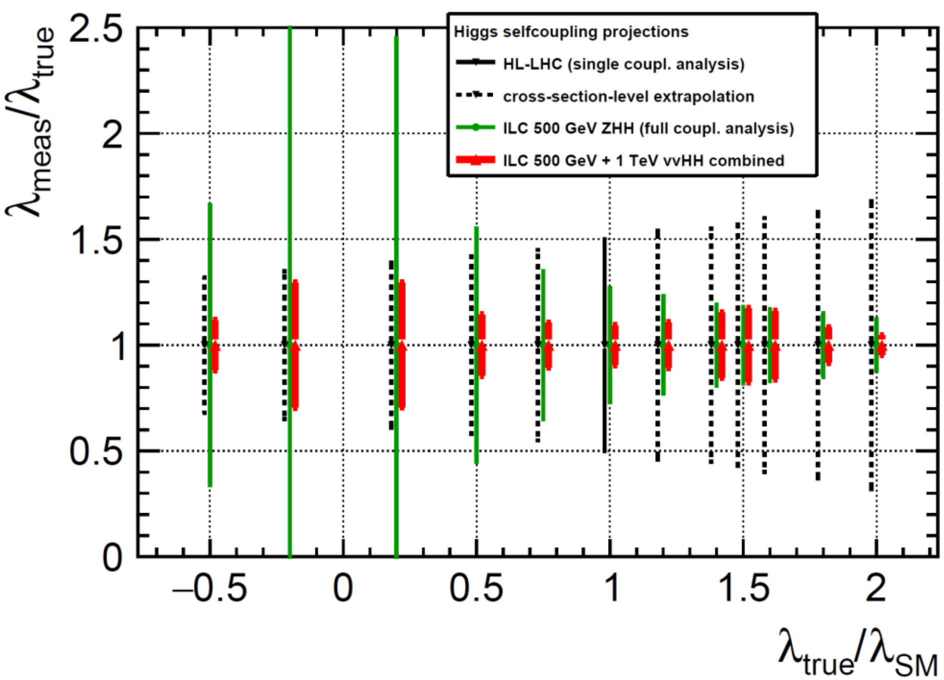
- Clear advantage of high-energy e+e- colliders
- Unlimited by theoretical uncertainties (PDFs, non-perturbative calculations, etc.) unlike hh colliders

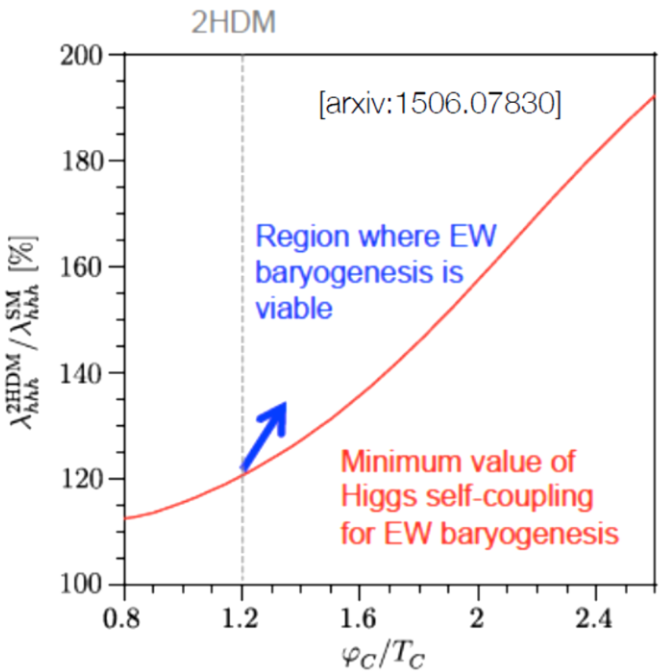


HIGGS SELF COUPLING

High energy e+e- collider is particularly sensitive to non-SM values of λ preferred by EW bariogenesis

- Bariogenesis requires Universe out of thermal equilibrium
- 1st order phase transition provided by EWSB? $\Rightarrow \lambda > \lambda_{SM}$





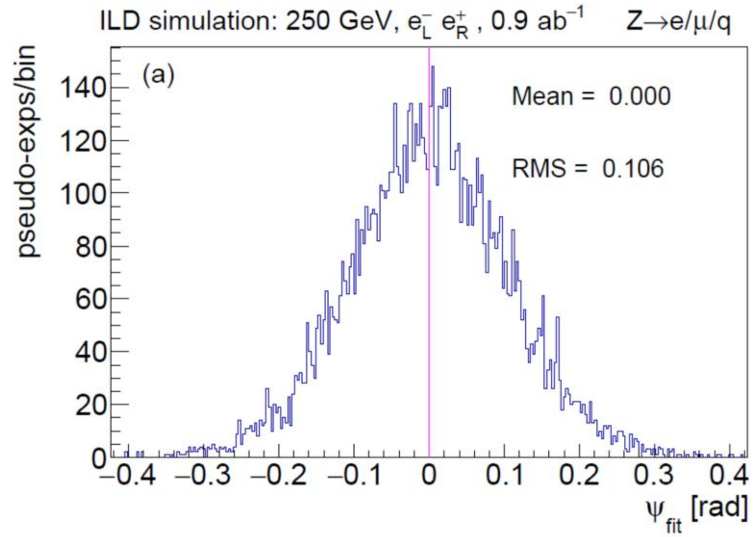
CPV IN THE HIGGS SECTOR

$$h_{125} = H \cdot \cos\ \Psi_{CP} + A \cdot \sin \Psi_{CP}$$

- CPV mixing angle measurement in $H \rightarrow \tau\tau$ at 250 GeV is a nice illustration of ILC advantages:
  - Clean environment
  - Different beam polarizations
  - Reduction of statistical uncertainty in combination

$\mathcal{L}$(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]



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

- Plethora of Higgs production and decay mechanisms available at ILC

CPV IN THE HIGGS SECTOR

ILC analyses at the theoretical target (realistic running scenario, full simulation signal and/or background)

$$f_{CP}^{hX} \equiv \frac{\Gamma_{h\to X}^{CP\,\text{odd}}}{\Gamma_{h\to X}^{CP\,\text{odd}} + \Gamma_{h\to X}^{CP\,\text{even}}}$$

68% CL scalar

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	**1 TeV VBF**	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	**8 ab^{-1}**	1,000	250	20	1,000	
HZZ/HWW	$4.0\cdot10^{-5}$	$2.5\cdot10^{-6}$	✓	$3.9\cdot10^{-5}$	$2.9\cdot10^{-5}$	$1.3\cdot10^{-5}$	**$1.6\cdot10^{-5}$**	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	~ 1	✓	–	–	–	~ 1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	$\boxed{0.01}$	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

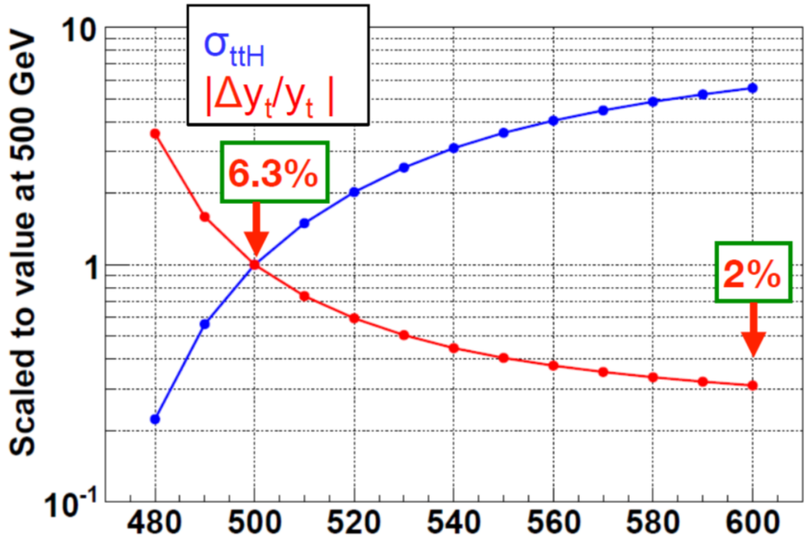
[arXiv:2205.07715v3]

See the last talk in this session

ttH production

[arXiv:1506.07830]

- ttH production is particularly important:
  - To measure the largest Higgs coupling (Also requires high energies to surpass HL-LHC projections: δg_{ttH}~3.2%/3.4% in κ/EFT)
  - To probe CPV: beam polarization is essential (to increase cross-section and t-quark polarization asymmetry)



$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%

[arXiv:2205.07715v3]

f_{CP}	500 GeV e^+e^- ($\mathcal{L}_{int}$/8)	1 TeV e^+e^- ($\mathcal{L}_{int}$/8)
	0.29	0.08

SUMMARY

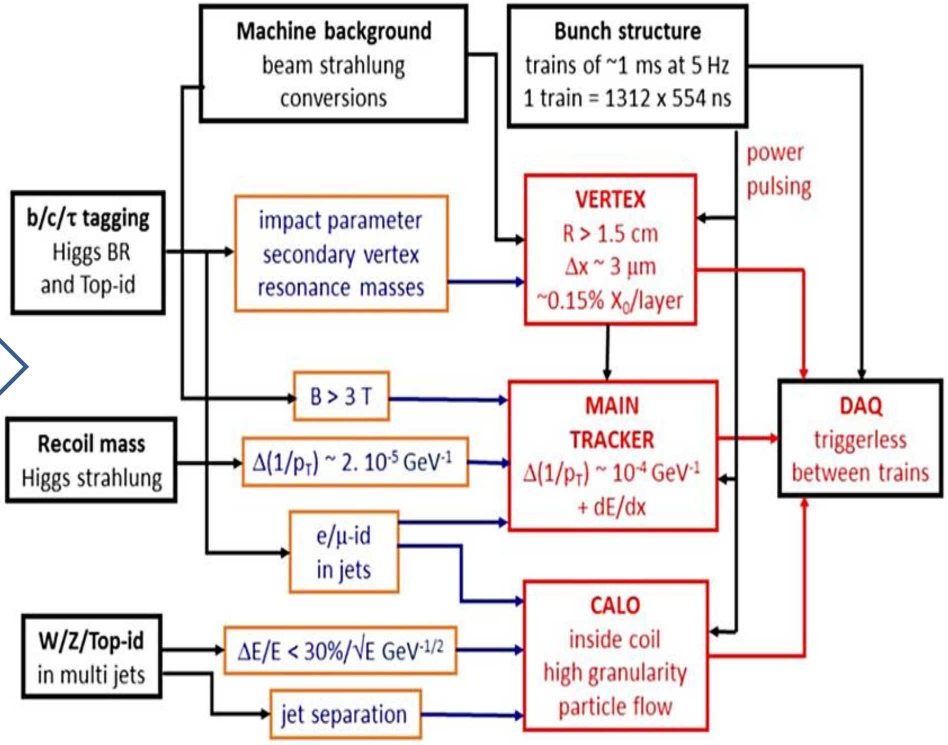
- ILC is ‘ready-to-take’, mature and technologically available option for a future Higgs factory
- It offers: clean environment, flexible polarization and upgradeable energy
- In the Higgs factory mode, it offers similar precision to other Higgs factories
- At higher center-of-mass energies and with benefits from both beams being polarized, ILC offers:
  - Higgs couplings improvement in precision $\mathcal{O}$ (10) w.r.t. HL-LHC
  - Higgs BSM model discrimination $\geq 5\sigma$
  - λ precision ~10% (ILC 1000), also in the region relevant for EW bariogenesis
  - And many more…

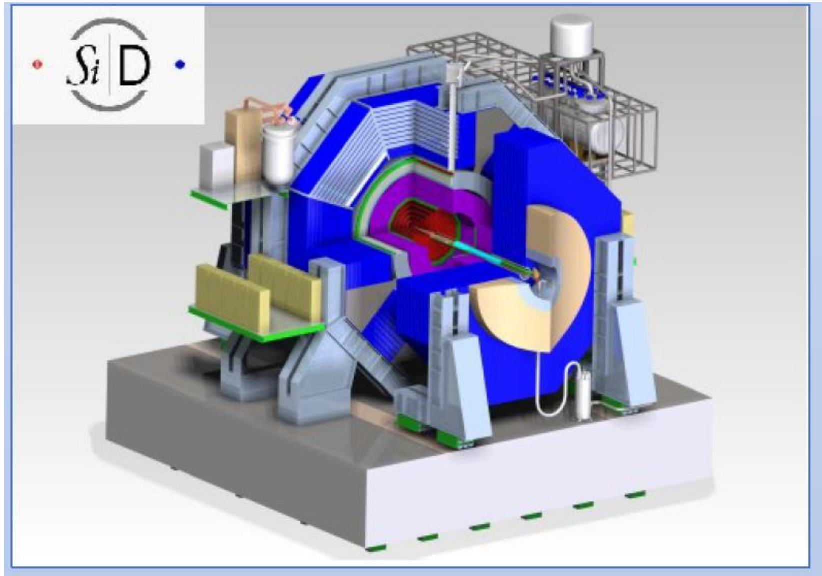
You can join us – WG3 Physics Potential and Opportunities

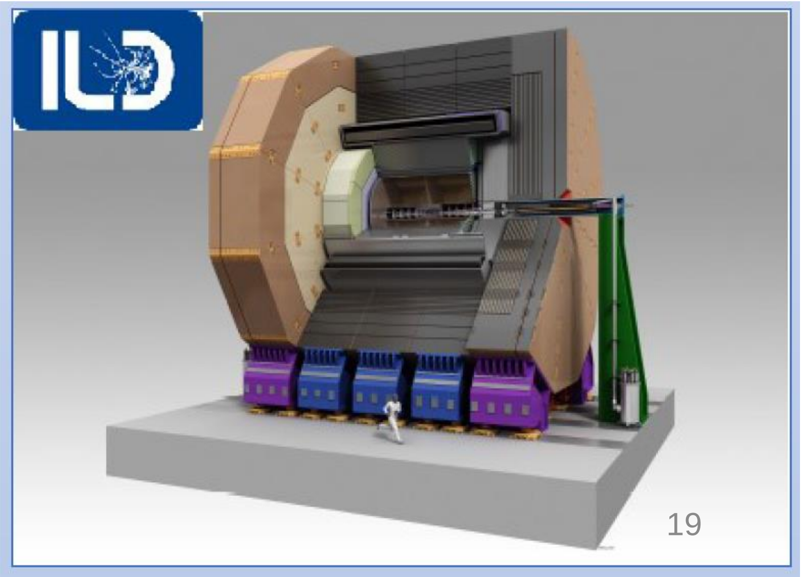
https://linearcollider.org/team/wg3/physics/

BACKUP

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







2nd Stage ILC TN develops TC-WP

Community cultivates environment for international discussion (both @ scientist community and government level)

Japan takes role / initiative in ILCTN (we are asking to JG)

Condition

- FCC-ee FS final report
- recognize ILC as the most realistic, cost-friendly, carbon-friendly project
- Understand of Governments/Communities ILC is global project
- Better International situation(Pandemic, global economy, tension

3rd Stage Governments discuss cost sharing/responsibility of ILC (as Global project)

Condition

- Fix final cost including civil engineering
- Cost sharing / responsibilities are agreed @ Governments

Start construction.

Taken from J. Tian, HPNP23

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

Polarization impact:

- Constrain the most general set of triple gauge coupling deviations allowed by Lorentz invariance - only if both beams are polarized
- Not so large impact on Higgs couplings