Higgs self-coupling measurement at ILC500.

LCWS2023

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Higgs self-coupling

Higgs potential in SM after SSB

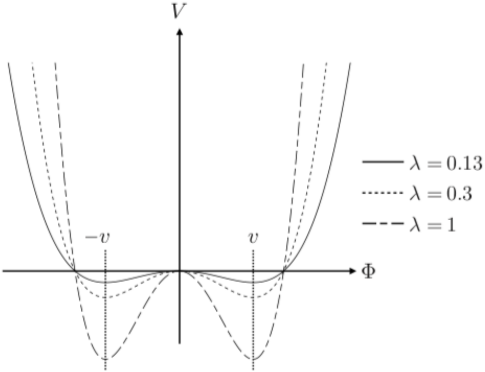
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

with $\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2\nu^2}$

Measure $\boldsymbol{\lambda}$

- $\rightarrow$ determine shape of **Higgs potential**
- $\rightarrow$ establish **Higgs mechanism** experimentally
- $\rightarrow$ determine how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, and the Higgs itself

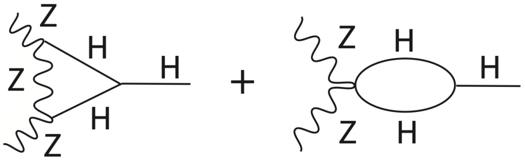
BSM: deviations in $\lambda \rightarrow$ new physics in Higgs sector



Higgs self-coupling

Indirect access:

- through loop-order-corrections found from EFT fits using single Higgs measurements and running at two different E_{cm}

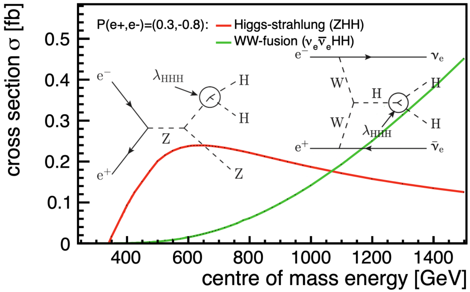


Direct access:

- through double-Higgs production

$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = c \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHx}}$$

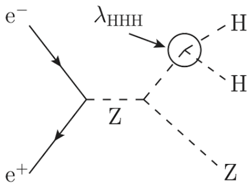
→ cross section measurement

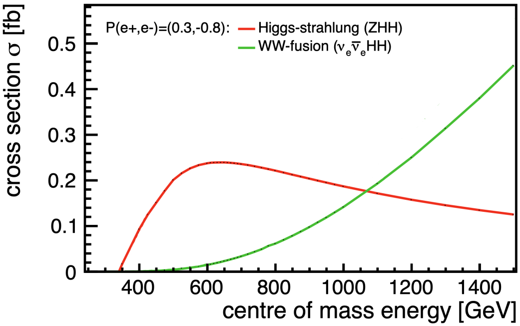


DESY.

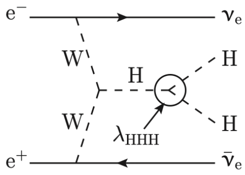
Direct measurement of the Higgs self-coupling from e^+e^-

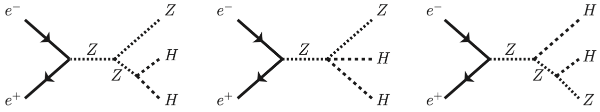
Di-Higgs strahlung:
dominant below 1 TeV

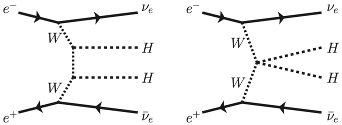




WW fusion:
dominant above 1 TeV







→ constructive interference

→ destructive interference

Direct measurement of the Higgs self-coupling from e^+e^-

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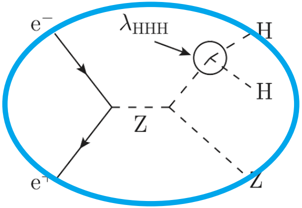
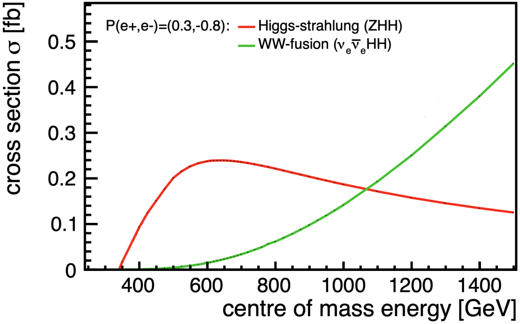


→ **only ∼400 events**



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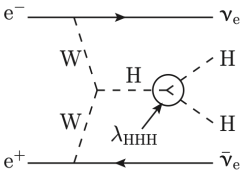

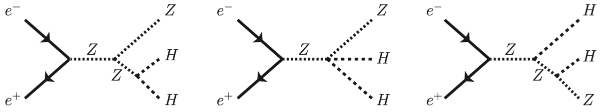

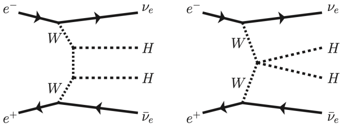

→ constructive interference

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The analysis from nearly a decade ago

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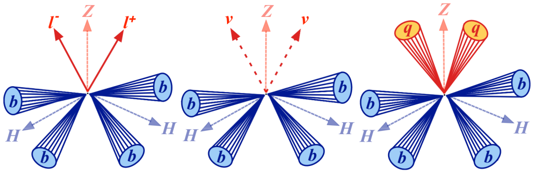
State-of-the-art projections at ILC performed 7-10 years ago



Precision reach

After full ILC running scenario ($HH \rightarrow bbbb + HH \rightarrow bbWW$)

$\rightarrow \Delta\sigma_{ZHH}/\sigma_{ZHH} = 16.8\%$

$\rightarrow \Delta\lambda_{SM}/\lambda_{SM} = 26.6\%$

$\rightarrow \Delta\lambda_{SM}/\lambda_{SM} = 10\%$ when combined with additional running scenario at 1 TeV

Discovery potential clearly demonstrated

Strategy for further improvements

Better reconstruction tools now $\rightarrow$ improve precision on σ_{ZHH} and λ_{SM} !

Strategy for improving the Higgs self-coupling measurement at ILC

Overlay removal

$\gamma\gamma \to$ low-p_T hadrons

Expect $\langle N_{overlay} \rangle = 1.05$ event @ 500 GeV

- ✔ Better modelling of the $\gamma\gamma$ overlay
- ••• Advanced overlay removal strategy

Isolated lepton tagging

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

- ••• Dedicated search for τs

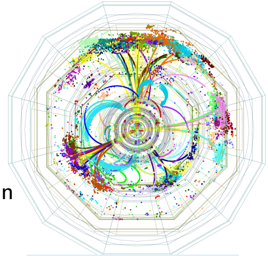
For $\varepsilon_\tau \sim \varepsilon_{e,\mu}$

$\to 8\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Jet clustering

- ☐ Perfect jet clustering

$\to \sim 40\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$



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Flavor tagging

- ✔ Improve b-tagging efficiency

For 5% relative improvement in $\varepsilon_{b\text{-tag}}$

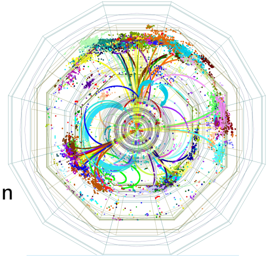
$\to 11\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Error parametrisation in kinematic fitting

Mass resolution $\propto$ jet energy resolution

- ✔ Errorflow: Energy resolution parametrisation for individual jets

Strategy for improving the Higgs self-coupling measurement at ILC



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Improvements in reconstruction tools has the potential to bring the sensitivity to **better than 20%**

Error parametrisation in kinematic fitting

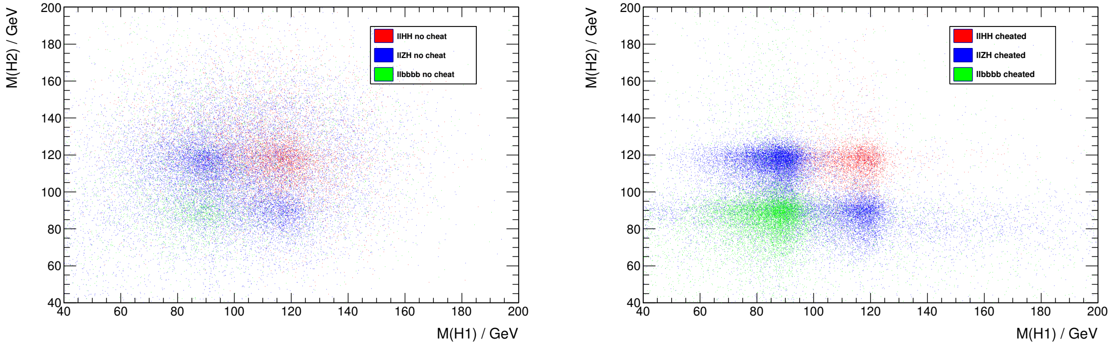
Mass resolution $\propto$ jet energy resolution

- ✔ Errorflow: Energy resolution parametrisation for individual jets

Jet clustering

Junping Tian, Claude Dürig, 2012

☑ Durham algorithm: ☐ Perfect jet clustering:



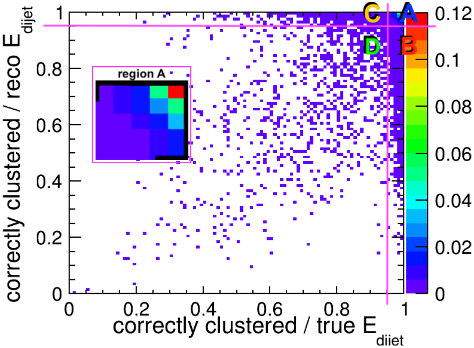
- jet-finding ambiguities from high multiplicities in ZHH, ZZH and ZZZ events

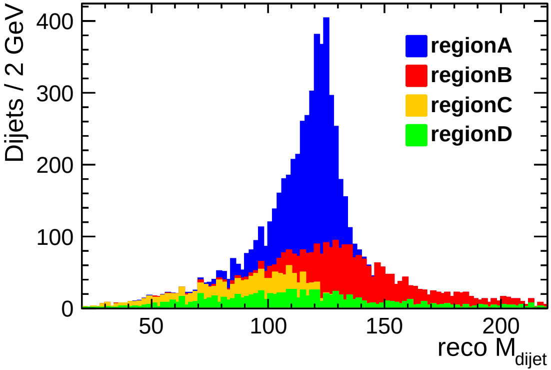
→ degrades mass resolutions → reduces separation → reduces $\delta\lambda$ by factor ~ 2

DESY.

Misclustering

Jet clustering





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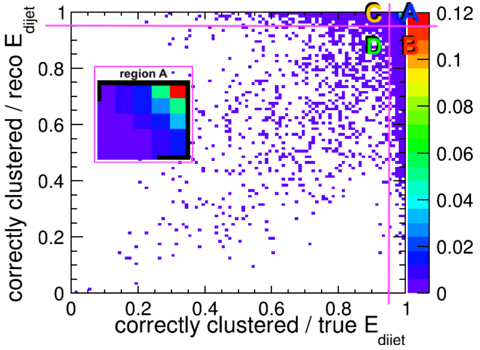
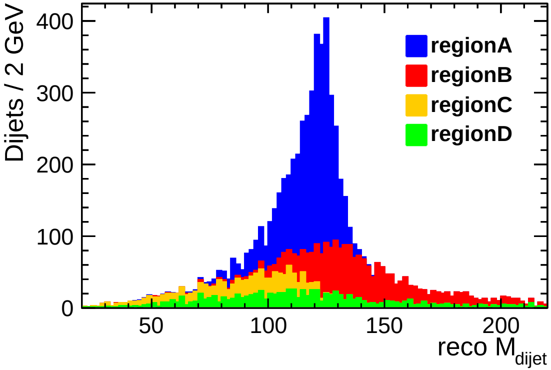
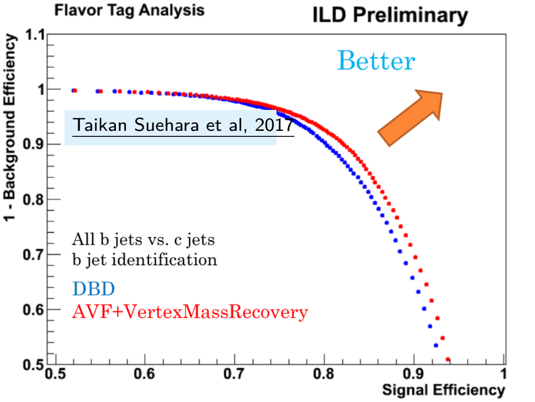




Advanced jet clustering methods needed to address regions B, C, and D!

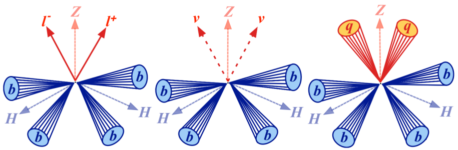
Flavor tagging

☑ Improve *b*-tagging efficiency



Example @ 80% signal efficiency:

	DBD	new	ATLAS
1-eff(c)	90%	95%	75%
Rejection factor	10	20	4



Better signal efficiencies observed in preselections

Preselection in neutrino channel

PRELIMINARY

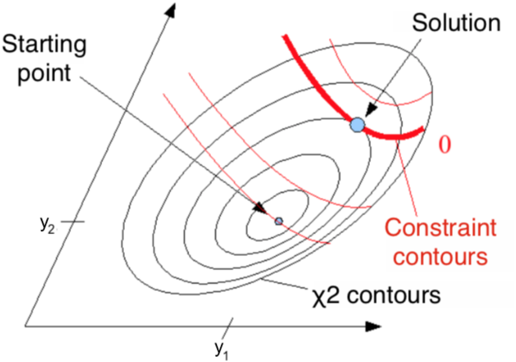
Selection	$\nu\nu HH$ (new)	$\nu\nu HH$ (old)	ϵ_{sig} (new)	ϵ_{bkg} (old)
Initial	89.8 ± 0.6	80.14	1.0	1.0
$\#\ell_{ISO} = 0$	70.9 ± 0.6	62.4 ± 0.1	0.79	0.78
$\lvert M_{jj} - M_H \rvert > 80$ GeV	69.0 ± 0.5	61.0 ± 0.1	0.77	0.76
bmax3 > 0.2	55.1 ± 0.5	28.2 ± 0.1	0.61	0.35
60 GeV$< M_{jj} <$180 GeV	53.2 ± 0.5	27.3 ± 0.1	0.59	0.34
10 GeV $< \not{p}_T <$ 180 GeV	52.5 ± 0.5	27.0 ± 0.1	0.59	0.34
thrust < 0.9	52.2 ± 0.5	26.8 ± 0.1	0.58	0.33
$E_{\text{vis}} < 400$ GeV	51.8 ± 0.5	26.6 ± 0.1	0.58	0.33
$M(HH) > 220$ GeV	49.0 ± 0.5	25.7 ± 0.1	0.55	0.32

- $\nu\nu HH$: 74 % relative improvement after b-tag cut

Kinematic fitting

Exploit well-known initial state in e^+e^- colliders for:

- Improve kinematics, e.g. mass resolution
- Hypothesis testing
- Jet-pairing



χ^2-function to minimise:

$$L(y) = \Delta y^T \mathbf{V}(y)^{-1} \Delta y + 2 \sum_{k=1}^{m} \lambda_k f_k(a, y)$$

- y: set of measured parameters
- a: set of unmeasured parameters
- Δy: corrections to y
- $\mathbf{V}(y)$: covariance matrix for y
- f_k: set of constraints expressing the fit model
- λ_k: lagrange multipliers

ErrorFlow

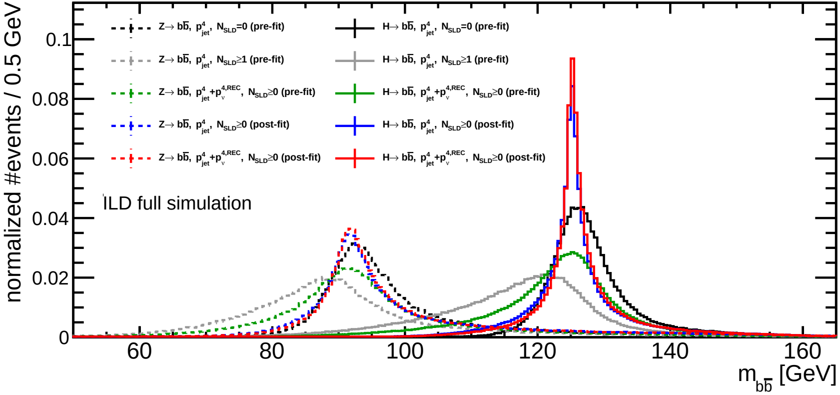
Kinematic fitting

Yasser Radkhorrami, 2023

- ☑ Parametrize sources of uncertainties for *individual* jets:

$$\sigma_{E_{jet}} = \sigma_{Det} \oplus \sigma_{Conf} \oplus \sigma_{\nu} \oplus \sigma_{Clus} \oplus \sigma_{Had} \oplus \sigma_{\gamma\gamma}$$

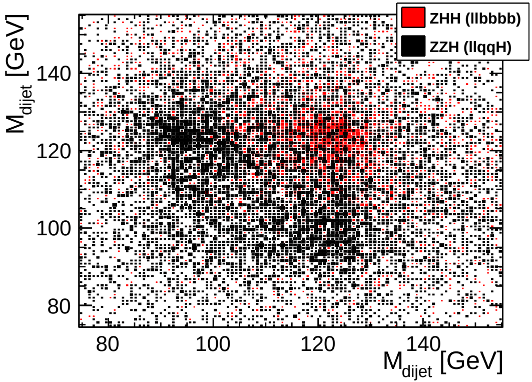
- σ_{Det}: Detector resolution
- σ_{Conf}: Particle confusion in Particle Flow Algorithm
- σ_{ν}: Neutrino correction



Hypothesis testing

Kinematic fitting

PRELIMINARY



- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

→

Calculate χ^2 for ZHH and ZZH hypotheses for both ZHH and ZZH events

ZHH hypothesis:

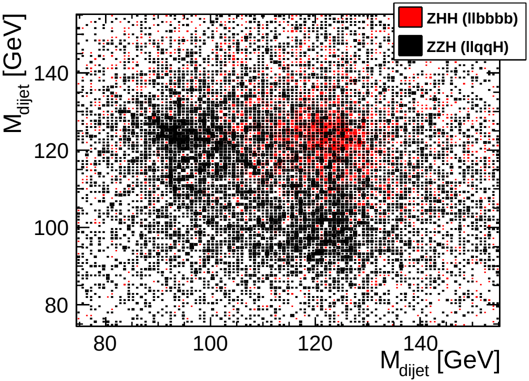
- 4-momentum conservation
- 2 $\times$ Higgs mass constraints

ZZH hypothesis:

- 4-momentum conservation
- Higgs mass constraint + Z mass constraint

Hypothesis testing
Kinematic fitting

PRELIMINARY



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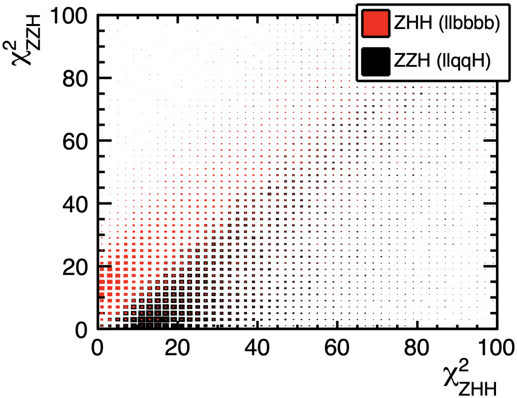


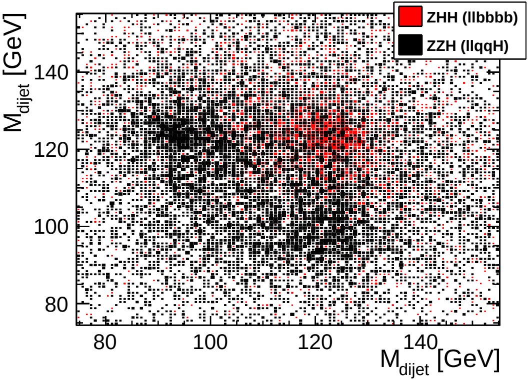
- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

- Hypothesis testing showed good separation for low χ^2-values of signal (*ZHH*) and background (*ZZH*) in previous analysis DESY-THESIS-2016-027

DESY.

Hypothesis testing
Kinematic fitting

PRELIMINARY



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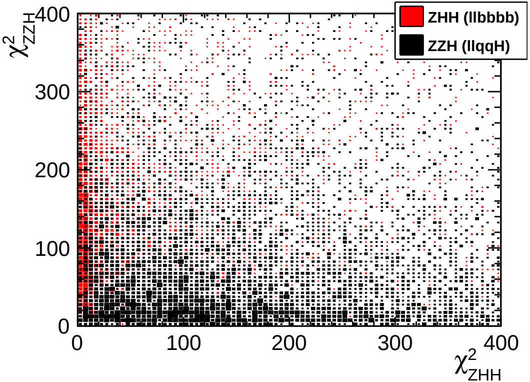
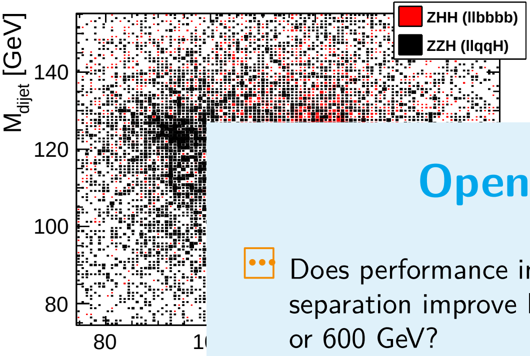


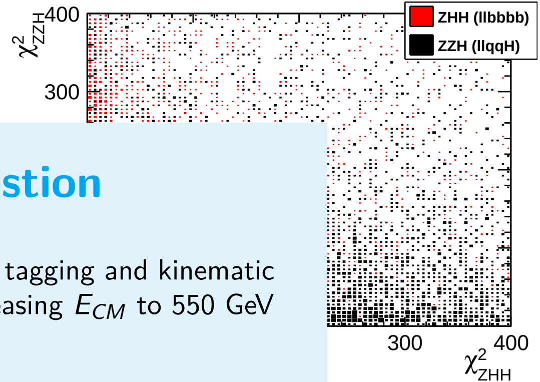
- Pre-fitted dijet-masses show large overlap between signal (ZHH) and background (ZZH)
- With ErrorFlow → larger separation of signal (ZHH) and background (ZZH)

DESY.

Hypothesis testing
Kinematic fitting

PRELIMINARY





Open question

- Does performance in flavor tagging and kinematic separation improve by increasing E_{CM} to 550 GeV or 600 GeV?

- Pre-fitted dijet-m… between signal (ZHH) and background (ZZH)
- …paration of signal (ZHH) and background (ZZH)

Precision on Higgs self-coupling

collider	indirect-h	direct-hh
HL-LHC	100-200%	50%
ILC250	–	–
ILC500	58%	20%*
ILC1000	52%	10%
CLIC380	–	–
CLIC1500	–	36%
CLIC3000	–	9%
FCC-ee 240	–	–
FCC-ee 240/365	44%	–
FCC-ee (4 IPs)	27%	–
FCC-hh	–	3.4-7.8%

[arXiv:1910.00012, arXiv:2211.11084]

50% sensitivity: establish that $\lambda_{HHH} \neq 0$ at 95% CL
20% sensitivity: 5σ discovery of the SM λ_{HHH} coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

Precision on Higgs self-coupling

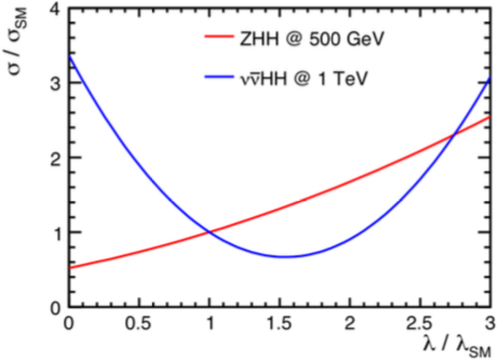
collider	indirect-h	direct-hh
HL-LHC	100-200%	50%
ILC250	–	–
ILC500	58%	20%*
ILC1000	52%	10%
CLIC380	–	–
CLIC1500	–	36%
CLIC3000	–	9%
FCC-ee 240	–	–
FCC-ee 240/365	44%	–
FCC-ee (4 IPs)	27%	–
FCC-hh	–	3.4-7.8%

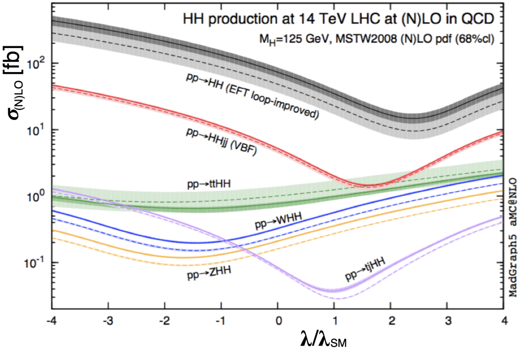
[arXiv:1910.00012, arXiv:2211.11084]

ONLY VALID FOR $\lambda = \lambda_{SM}$

Higgs self-coupling precision dependent on value of λ itself

Precision as a function of new physics



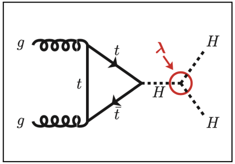


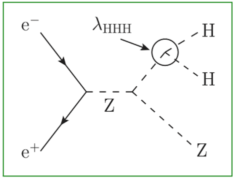
The two channels provide complementary information

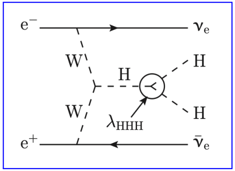
- *ZHH* gives stronger constraints on $\lambda/\lambda_{SM} > 1$
- $\nu\bar{\nu}HH$ gives stronger constraints on $\lambda/\lambda_{SM} < 1$

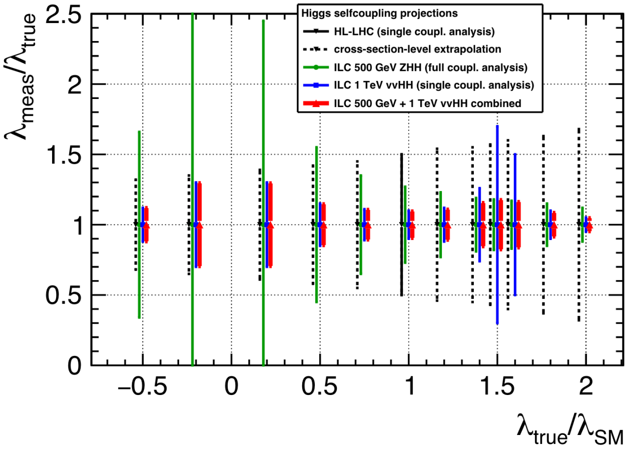
- LHC gives stronger constraints on $\lambda/\lambda_{SM} < 1$

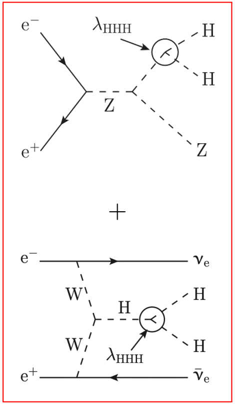
Precision on Higgs self-coupling with new physics





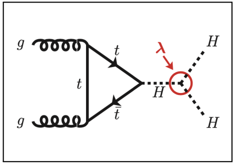


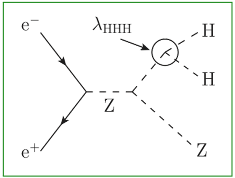


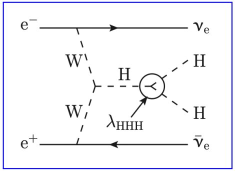


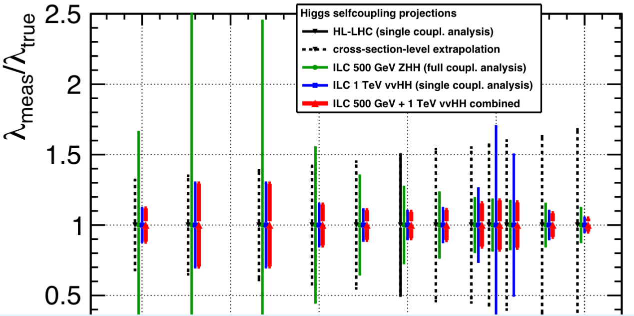
- complementarity compensates for λ precision

Precision on Higgs self-coupling with new physics

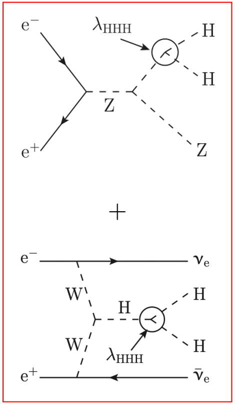








Combining *ZHH* and $\nu\nu HH$ ensures at least 10-15% precision for *any* value of λ



- complementarity compensates for λ precision

Conclusion

- Discovery potential of Higgs self-coupling at ILC clearly demonstrated in the past
- Improvements in reconstruction tools are expected to improve the sensitivity to **better than 20%** at ILC500

→ Update to the state-of-the-art projections for ILC500 is underway!

- Complementarity of ILC500 and ILC1000 to ensure at least 10-15% precision for *any* value of $\boldsymbol{\lambda}$

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Thank you.