ILC capabilities for the measurement of double Higgs production at 500 GeV.

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January 12, 2023

Higgs self-coupling

- Establish **Higgs mechanism** experimentally $\rightarrow$ reconstruct **Higgs potential**

Higgs potential in SM after SSB

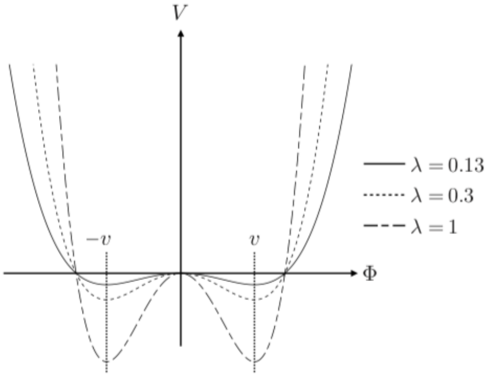
$$V(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4} \lambda_4 h^4$$

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

Measure $\boldsymbol{\lambda}$

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

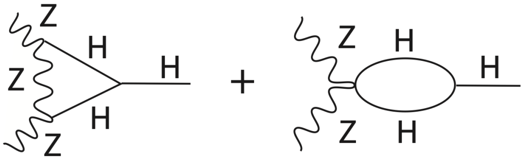
BSM: deviations in $\lambda \rightarrow$ new physics in Higgs sector



Higgs self-coupling

Indirect access:

- through loop-order-corrections found from EFT fits
- single Higgs measurements reaching or exceeding the 1% level in e^+e^-
- large number of independent observables
- running at two different E_{cm} to lift degeneracies between λ and other Higgs couplings



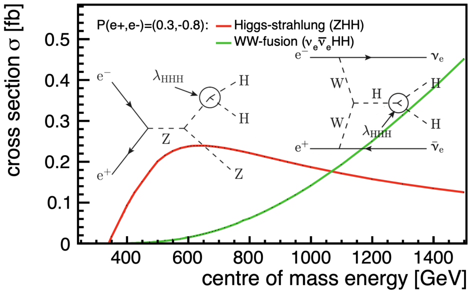
See M.Peskin's talk

Direct access:

- through double-Higgs production

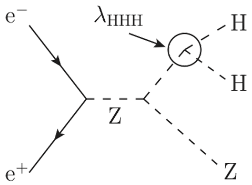
$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = c \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHx}}$$

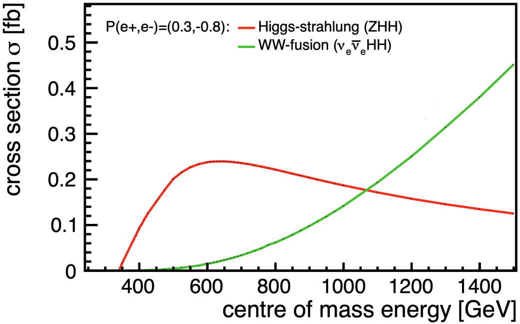
→ cross section measurement



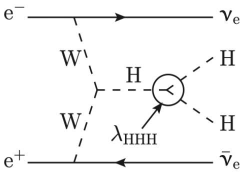
Direct measuement of the Higgs self-coupling

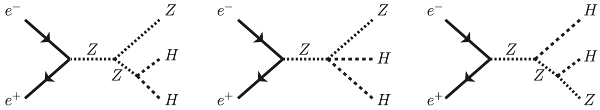
Di-Higgs strahlung:
dominant below 1 TeV

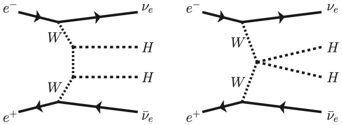




WW fusion:
dominant above 1 TeV







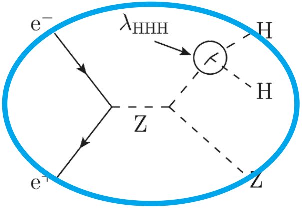
→ constructive interference

→ destructive interference

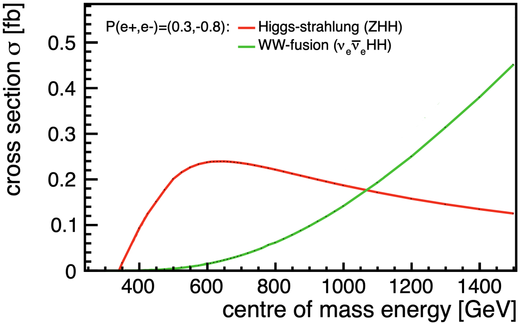
DESY.

Direct measuement of the Higgs self-coupling

Di-Higgs strahlung:
dominant below 1 TeV



→ **only ∼400 events**



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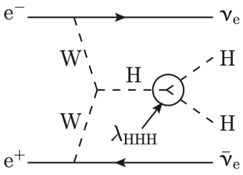
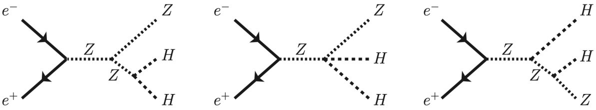
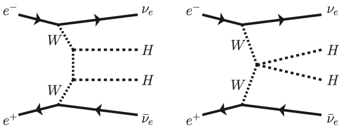






→ constructive interference

→ destructive interference

The analysis from nearly a decade ago

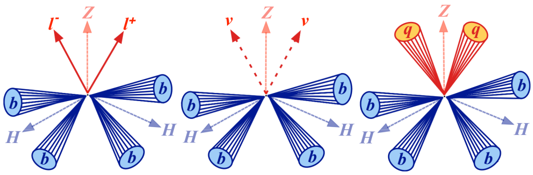
DESY-THESIS-2016-027

Signature: 6-particle final state

Expected precision on the measurement:

$$\frac{\Delta\lambda}{\lambda} \propto \frac{\Delta\sigma}{\sigma}$$

Challenging because of small cross section



Precision reach

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

$\to \Delta\sigma_{\mathrm{ZHH}}/\sigma_{\mathrm{ZHH}} = 16.8\%$

$\to \Delta\lambda_{\mathrm{SM}}/\lambda_{\mathrm{SM}} = 26.6\%$

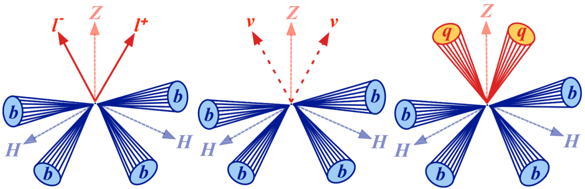
$\to \Delta\lambda_{\mathrm{SM}}/\lambda_{\mathrm{SM}} = 10\%$ when combined with additional running scenario at 1 TeV

Discovery potential clearly demonstrated

Strategy for further improvements

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

Analysis strategy



Event reconstruction

Overlay removal

- $\gamma\gamma \rightarrow$ low-p_T hadrons
- Expect $\langle N_{overlay} \rangle = 1.05$ particles/event

Isolated lepton tagging

- identify leptons for selection or rejection

Jet reconstruction

- cluster together remaining event

Flavor tagging

- look for b-jets

Event selection

Cut-based preselection

- $ZHH \rightarrow \ell\ell bbbb$
- $ZHH \rightarrow \nu\nu bbbb$
- $ZHH \rightarrow qqbbbb$

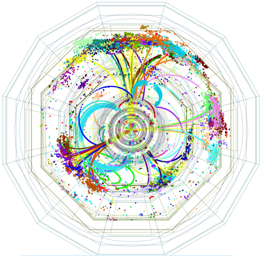
Kinematic fitting

- hypotheses testing to separate ZHH from ZZH background

Event selection

- based on MVAs

Strategy for improving the Higgs self-coupling measurement at ILC



DESY-THESIS-2016-027

State-of-the-art projections at ILC performed 6-9 years ago
Meanwhile $\rightarrow$ significant improvements in our analysis tools

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

Flavor tagging

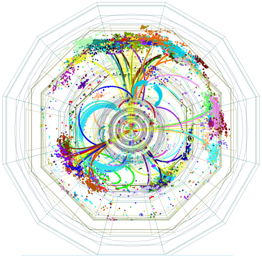
- ✔ Improve b-tagging efficiency

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

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



DESY-THESIS-2016-027

State-of-the-art projections at ILC performed 6-9 years ago
Meanwhile $\rightarrow$ significant improvements in our analysis tools

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

Overlay removal
$\gamma\gamma \rightarrow$ low-p_T hadrons
Expect $\langle N_{overlay} \rangle = 1.05$ even

- ✔ Better modelling of the γ
- ••• Advanced overlay removal

Isolated lepton tagging
Optimised for $\ell = \{e, \mu\}$

- ••• Dedicated search for τs

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

cy

nt in $\varepsilon_{b\text{-tag}}$

nt in $\Delta\sigma_{\text{ZHH}}/\sigma_{\text{ZHH}}$

Error parametrisation in kinematic fitting
Mass resolution $\propto$ jet energy resolution

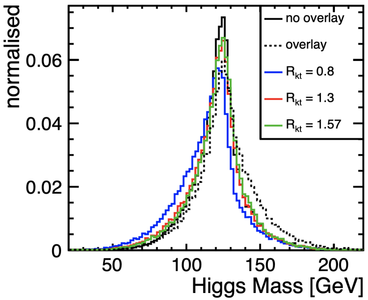
- ✔ Errorflow: Energy resolution parametrisation for individual jets

Overlay removal

Event reconstruction

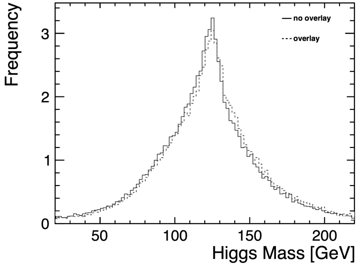
- $\gamma\gamma \rightarrow$ low-p_T hadrons
- cluster into very forward beam jets and remove $\rightarrow$ uncover original event

Problem: Overlapping jets $\rightarrow$ mis-clustering of jets complicating overlay removal



✔ Better modelling of the $\gamma\gamma$ overlay

- Previous: $\langle N_{overlay} \rangle = 1.7$ particles/event $\rightarrow$ pessimistic results
- Now: $\langle N_{overlay} \rangle = 1.05$ particles/event $\rightarrow$ more realistic results



••• Advanced overlay removal strategy

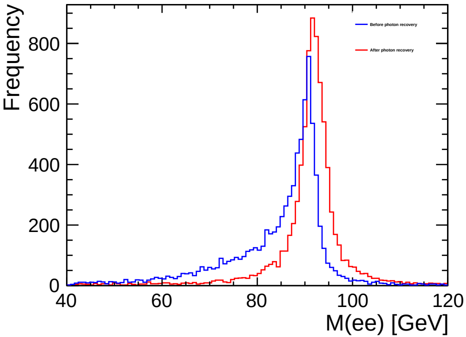
- More detailed study needed to determine whether more advanced removal strategy is needed

Isolated lepton tagging

Event reconstruction

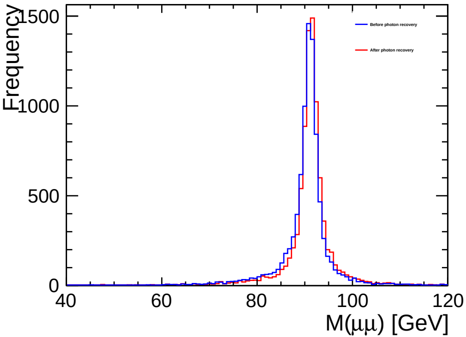
Step 1: identify all isolated leptons

- based on a MVA approach
- optimised for $\ell = e, \mu$



Step 2: pair selection

- closest to Z-mass + opposite charge requirement
- followed by BS/FSR recovery



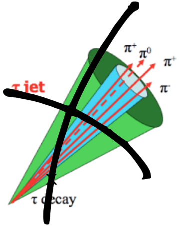
Dedicated search for τs

- Separate method for tau lepton reconstruction

Tau lepton reconstruction

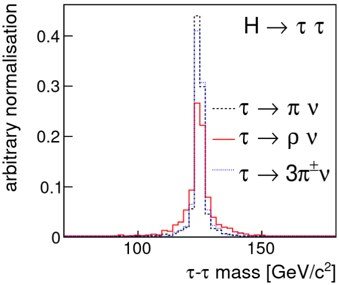
Event reconstruction

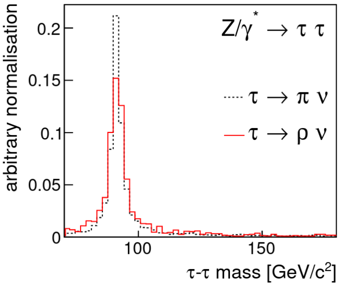
[arXiv:1507.01700]



Reconstruction using impact parameters

- requires accurate τ vertex + precise measurement of decay products
- parametrisation only for single neutrino production
- $e^+e^- \to \mu^+\mu^-\tau^+\tau^-$ simulated in ILD





Jet reconstruction

Event reconstruction

Jet clustering

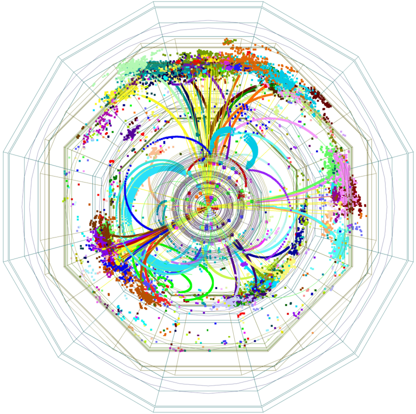
- jet-finding ambiguities from high multiplicities in ZHH
- degrades mass resolutions

☐ Perfect jet clustering

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

- For now, Durham algorithm used

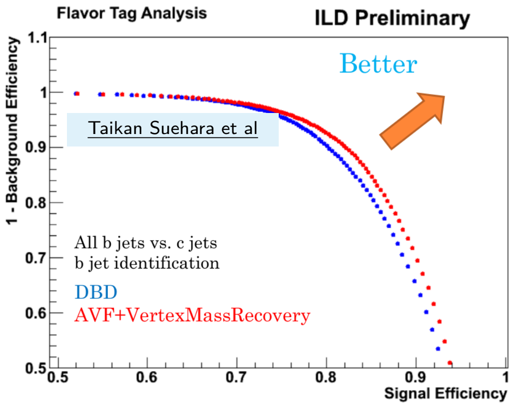
$$d_{ij} = \min(E_i^2, E_j^2)(1 - \cos\theta_{ij})$$



Flavor tagging

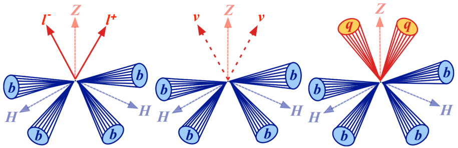
Event reconstruction

- ☑ 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 lepton channel

PRELIMINARY

Selection	$\ell\ell HH$ (new)	$\ell\ell HH$ (old)	ϵ_{sig} (new)	ϵ_{sig} (old)
Initial	41.17 ± 0.23	40.51	1.0	1.0
$\#\ell_{ISO} >= 2$	26.99 ± 0.19	25.20 ± 0.07	0.66	0.62
$\|M_{\ell\ell} - M_Z\| < 40$ GeV	24.98 ± 0.18	24.00 ± 0.07	0.61	0.59
$\|M_{jj} - M_H\| < 80$ GeV	24.12 ± 0.18	22.50 ± 0.06	0.59	0.56
60 GeV $< M_{jj} <$ 180 GeV	22.71 ± 0.17	22.40 ± 0.06	0.55	0.55
$\not{p}_T < 70$ GeV	21.67 ± 0.17	21.40 ± 0.06	0.53	0.53
thrust < 0.9	21.65 ± 0.17	21.40 ± 0.06	0.53	0.53

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
$\|M_{jj} - M_H\| > 80$ 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

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
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$\|M_{jj} - M_H\| > 80$ 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
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$M(HH) > 220$ GeV	49.0 ± 0.5	25.7 ± 0.1	0.55	0.32

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

Preselection in hadron channel

PRELIMINARY

Selection	$qqHH$ (new)	$qqHH$ (old)	ϵ_{sig} (new)	ϵ_{sig} (old)
Initial	274.1 $\pm$ 2.7	273.1	1.0	1.0
$\#\ell_{ISO} = 0$	216.4 $\pm$ 2.4	214.0 $\pm$ 0.3	0.79	0.78
btag > 0.16	138.7 $\pm$ 1.9	81.7 $\pm$ 0.2	0.51	0.30
60 GeV $< M_{jj} <$ 180 GeV	132.2 $\pm$ 1.8	78.9 $\pm$ 0.2	0.48	0.29
$\not{p}_T <$ 70 GeV	129.4 $\pm$ 1.8	77.4 $\pm$ 0.2	0.47	0.28
thrust $<$ 0.9	129.4 $\pm$ 1.8	77.3 $\pm$ 0.2	0.47	0.28

Preselection in hadron channel

PRELIMINARY

Selection	$qqHH$ (new)	$qqHH$ (old)	ϵ_{sig} (new)	ϵ_{sig} (old)
Initial	274.1 $\pm$ 2.7	273.1	1.0	1.0
$\#\ell_{ISO} = 0$	216.4 $\pm$ 2.4	214.0 $\pm$ 0.3	0.79	0.78
btag > 0.16	138.7 $\pm$ 1.9	81.7 $\pm$ 0.2	0.51	0.30
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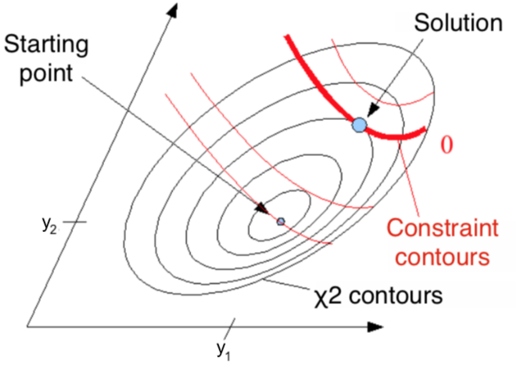
$\not{p}_T <$ 70 GeV	129.4 $\pm$ 1.8	77.4 $\pm$ 0.2	0.47	0.28
thrust < 0.9	129.4 $\pm$ 1.8	77.3 $\pm$ 0.2	0.47	0.28

- *qqHH*: 70 % 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

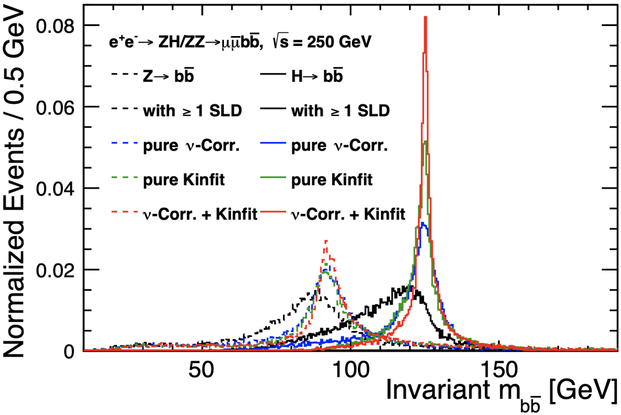
ErrorFlow
Kinematic fitting

arXiv:2110.13731

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



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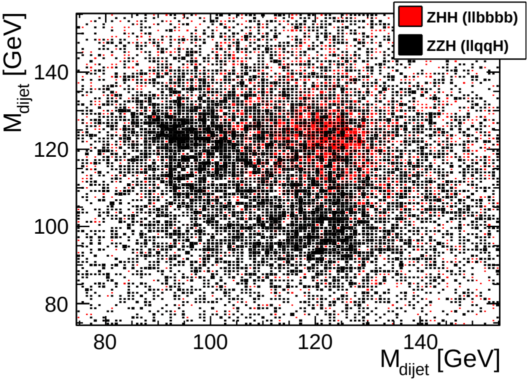
Hypothesis testing
Kinematic fitting



- 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:

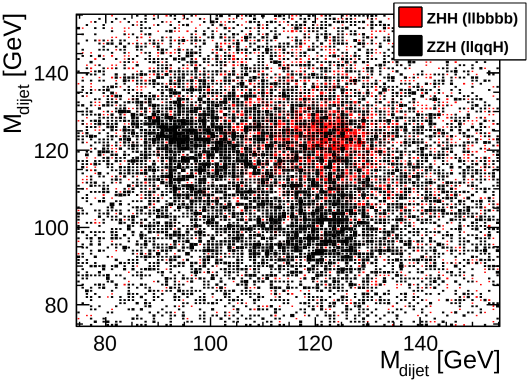
- 4-momentum conservation
- 2 × Higgs mass constraints

ZZH hypothesis:

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

Hypothesis testing

Kinematic fitting



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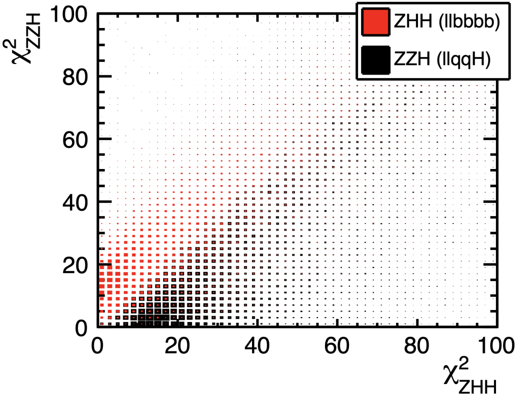
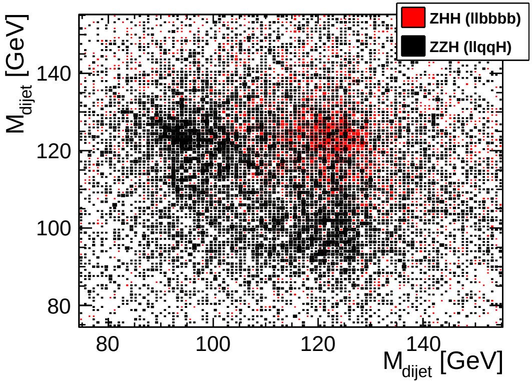


- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)
- Hypothesis testing showed good separation for low χ^2-values of signal (*ZHH*) and background (*ZZH*) in previous analysis DESY-THESIS-2016-027

Hypothesis testing

Kinematic fitting



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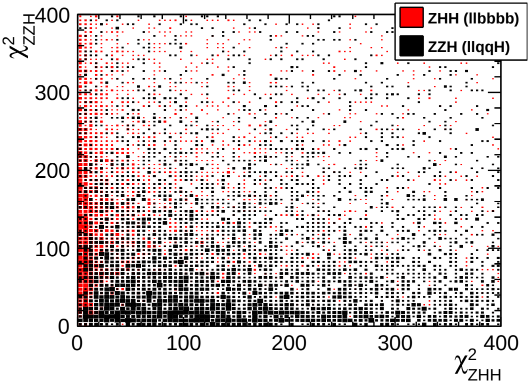


- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)
- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

DESY.

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

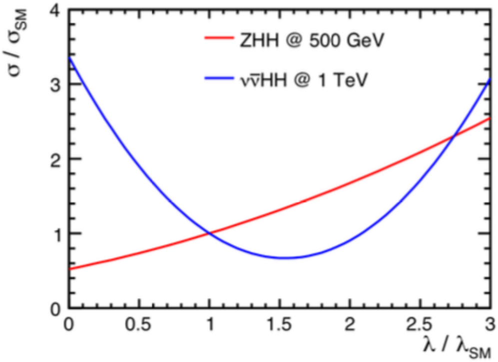
collider	indirect-h	direct-hh
HL-LHC	100-200%	50%
ILC250	–	–
ILC500	58%	20%*
ILC1000	52%	10%
CLIC380	–	–
CLIC1500	–	36%
CLIC3000	–	9%
FCC-ee 240	–	–
FCC-ee 240/365	44%	–
FCC-ee (4 IPs)	27%	–
FCC-hh	–	3.4-7.8%

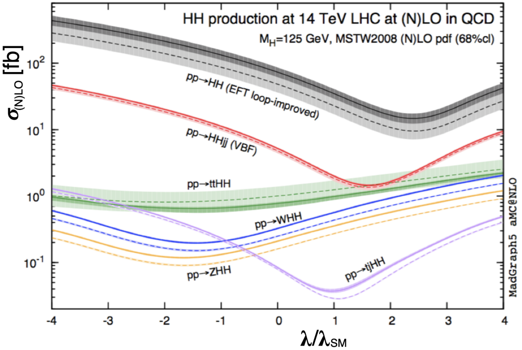
[arXiv:1910.00012, arXiv:2211.11084]

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

Higgs self-coupling precision dependent on value of λ itself

Precision as a function of new physics



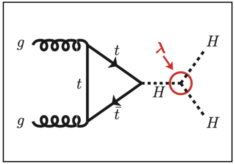


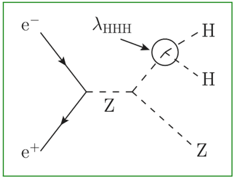
The two channels provide complementary information

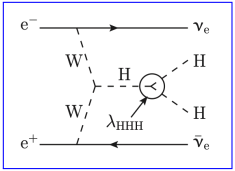
- *ZHH* gives stronger constraints on $\lambda/\lambda_{SM} > 1$
- $\nu\bar{\nu}HH$ gives stronger constraints on $\lambda/\lambda_{SM} < 1$

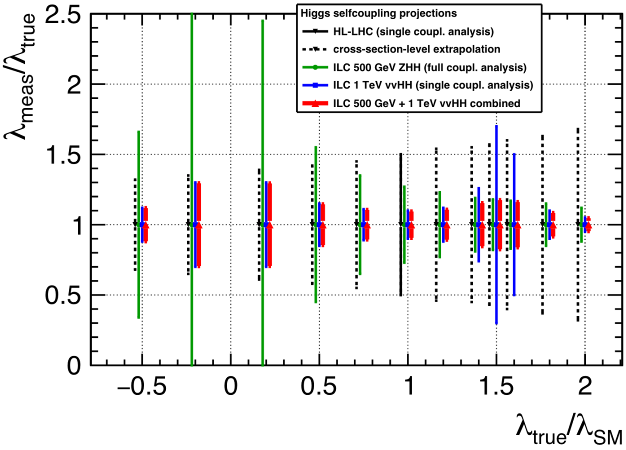
- LHC gives stronger constraints on $\lambda/\lambda_{SM} < 1$

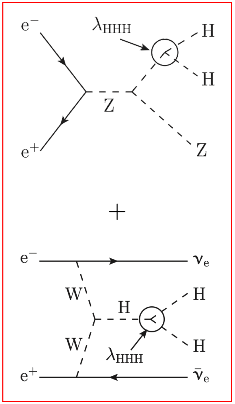
Precision on Higgs self-coupling with new physics





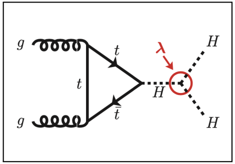


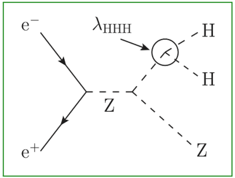


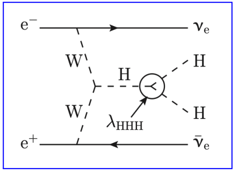


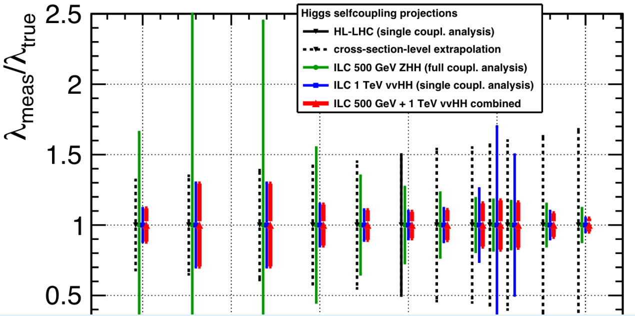
- complementarity compensates for λ precision

Precision on Higgs self-coupling with new physics

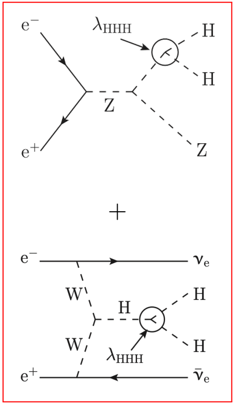








Combining *ZHH* and $\nu\nu HH$ ensures at least 10-15% precision for *any* value of λ



- complementarity compensates for λ precision

Conclusion

- Discovery potential of ILC500 clearly demonstrated in the past
- Improvements in reconstruction tools are expected to improve the sensitivity to **better than 20%**
- 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.