Higgs self-coupling projections for future e+e- colliders.

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HELMHOLTZ

The Higgs self-coupling

- Establish **Higgs mechanism** experimentally → reconstruct **Higgs potential**

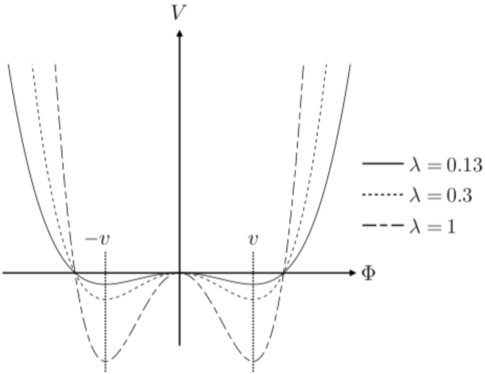
Higgs potential in SM after SSB

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

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

- Measure $\boldsymbol{\lambda}$ → determine shape of **Higgs potential**

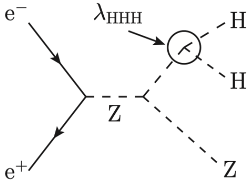
SM: self-couplings determined by m_H, ν
EXP: need measurements to confirm/refute this
BSM: deviations in λ → new physics in Higgs sector

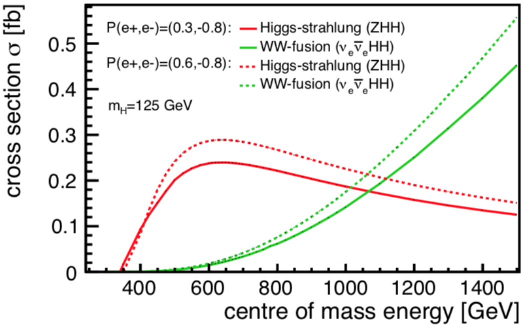


- Direct access to trilinear Higgs self-coupling through the measurement of double Higgs production

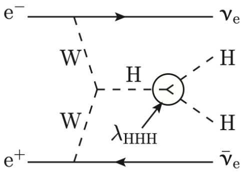
Accessing the Higgs self-coupling directly at e^+e^- colliders

Di-Higgs strahlung:
dominant below 1 TeV

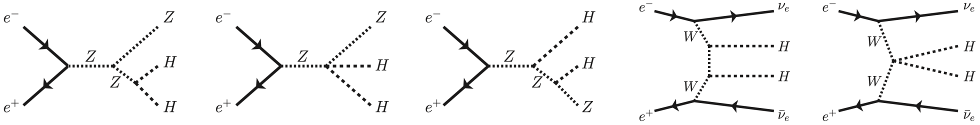




WW fusion:
dominant above 1 TeV



Interference diagrams:



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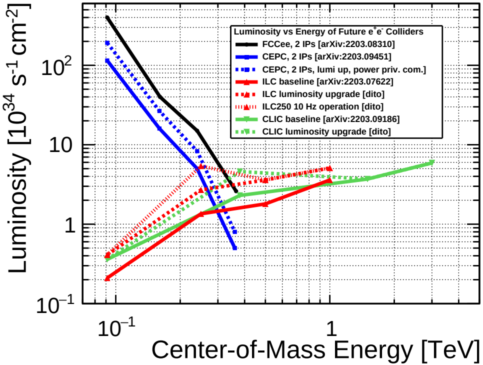
Linear vs circular colliders

Proposed future e^+e^- colliders	
circular	linear
FCC-ee	ILC
CEPC	CLIC

Precision requires luminosity



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Precision reach in direct measurements at future colliders

Expected precision from HH production channels (1σ bounds)

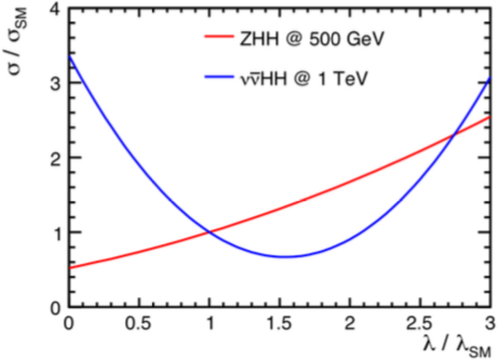
collider	excl. from HH	End of data taking
HL-LHC	50 %	primo 2040s
ILC 500	27 %	ultimo 2050s
ILC 500+1000	10 %	primo 2070s
CLIC 1500	36 %	medio 2060s
CLIC 1500+3000	[-7 %, 11 %]	medio 2070s
FCC-hh[1]	[3.4 %-7.8 %]	2090s

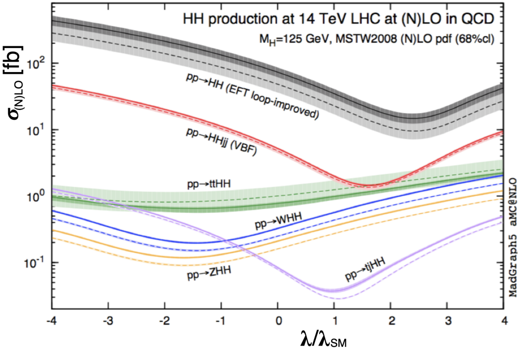
Assumes
$\lambda = \lambda_{SM}$

- high-energy colliders ($\text{ILC}_{500+1000}$, $\text{CLIC}_{1500+3000}$, FCC-hh) can reach the $<10\%$ precision level
- Higgs self-coupling can also be measured indirectly in EFT fit
  - e.g. projected precision at FCC-ee is 27 %

[1]DELPHES based analysis

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 $\lambda/\lambda_{SM} < 1$

Projections for Higgs self-coupling measurement at CLIC

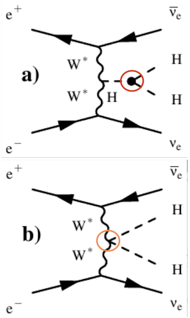
arXiv:1901.05897

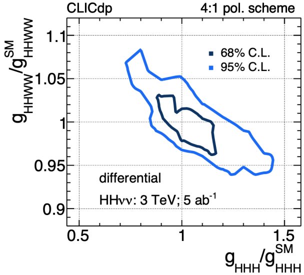
Double Higgs production at CLIC:
Access to both ZHH and $HH\nu\nu$ at $\sqrt{s} = 1500$ GeV and $\sqrt{s} = 3000$ GeV

Observables: σ_{ZHH}, $\sigma_{HH\nu\nu}$, and $M(HH)$ distribution with $HH \to bbbb + HH \to bbWW$

After full CLIC running scenario
$\to \Delta\lambda_{SM}/\lambda_{SM} = [-7\%, 11\%]$

***HHH* vs. *HHWW* vertex**





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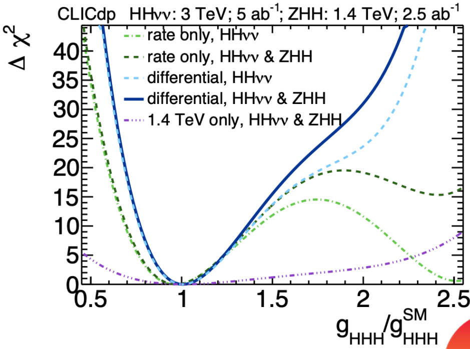
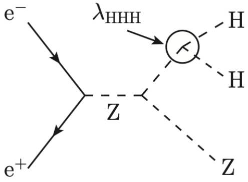


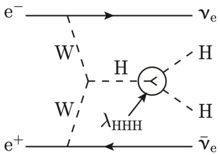
Projections for Higgs self-coupling measurement at ILC

DESY-THESIS-2016-027

Double Higgs production at ILC:
Access to both ZHH at $\sqrt{s} = 500$ GeV and $HH\nu\nu$ at $\sqrt{s} = 1000$ GeV

Observables: σ_{ZHH} and $\sigma_{HH\nu\nu}$ with $HH \to bbbb + HH \to bbWW$



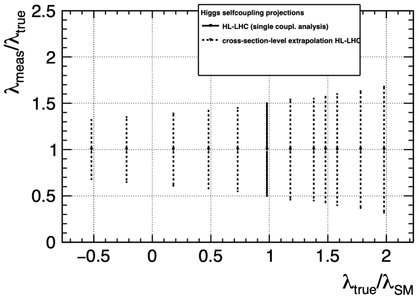


$$\frac{\Delta\lambda}{\lambda} = 1.62\,\frac{\Delta\sigma_{\rm ZHH}}{\sigma_{\rm ZHH}} \qquad \frac{\Delta\lambda}{\lambda} = 0.73\,\frac{\Delta\sigma_{\rm WW}}{\sigma_{\rm WW}}$$

Interference degrades the sensitivity to the Higgs self-coupling

After full ILC running scenario

→ $\Delta\sigma_{\rm ZHH}/\sigma_{\rm ZHH} = 16.8\%$ for ZHH only
→ $\Delta\lambda_{\rm SM}/\lambda_{\rm SM} = 26.6\%$ for ZHH only
→ $\Delta\lambda_{\rm SM}/\lambda_{\rm SM} = 10\%$ for ZHH & $HH\nu\nu$



Projections for Higgs self-coupling measurement at ILC

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Double Higgs production at ILC:
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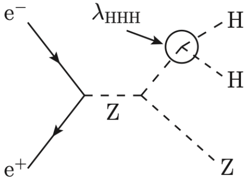
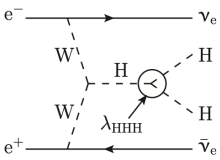
Observables: σ_{ZHH} and $\sigma_{HH\nu\nu}$ with $HH \rightarrow bbbb + HH \rightarrow bbWW$





$$\frac{\Delta\lambda}{\lambda} = 1.62\,\frac{\Delta\sigma_{\mathrm{ZHH}}}{\sigma_{\mathrm{ZHH}}} \qquad \frac{\Delta\lambda}{\lambda} = 0.73\,\frac{\Delta\sigma_{\mathrm{WW}}}{\sigma_{\mathrm{WW}}}$$

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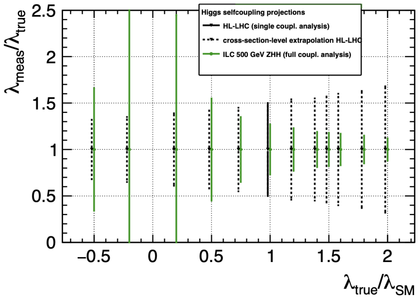

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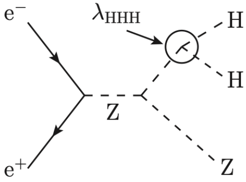
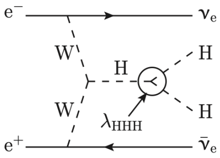


$$\frac{\Delta\lambda}{\lambda} = 1.62 \frac{\Delta\sigma_{ZHH}}{\sigma_{ZHH}}$$



$$\frac{\Delta\lambda}{\lambda} = 0.73 \frac{\Delta\sigma_{WW}}{\sigma_{WW}}$$

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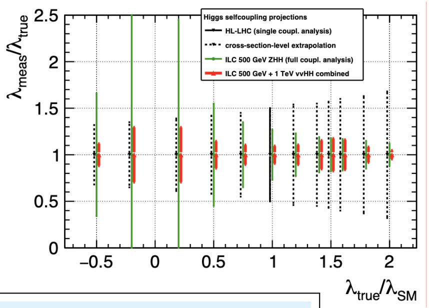

Combination of ZHH and $\nu\nu HH$ ensures at least $10 - 15\%$ precision for all λ

Strategy for improving the Higgs self-coupling measurement at ILC

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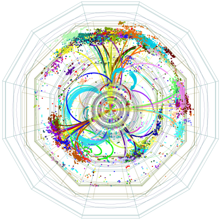
State-of-the-art projections at ILC performed 6-9 years ago
Meanwhile $\rightarrow$ significant improvements in our analysis tools



Jet clustering

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

Flavour tagging

- ✔ Better b-tagging efficiency

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

Isolated lepton tagging

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

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

Error parametrisation in kinematic fitting

Mass resolution $\propto$ jet energy resolution

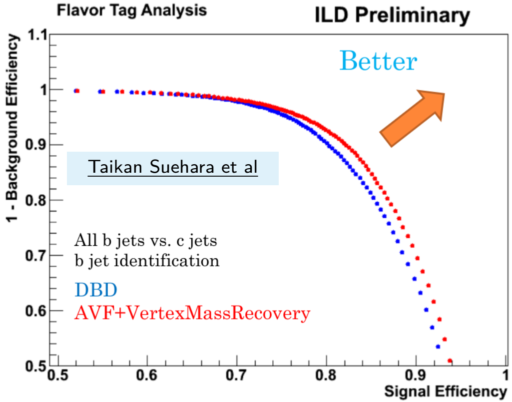
- ✔ Errorflow: Energy resolution parametrisation for individual jets

Overlay removal

$\gamma\gamma \rightarrow$ low-p_T hadrons
Expect $\langle N_{overlay} \rangle = 1.2$ event @ 500 GeV
Not included previously

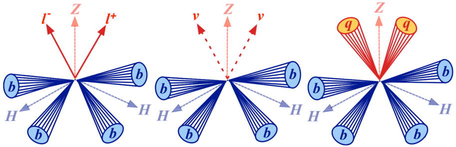
- ✔ Better modelling of the $\gamma\gamma$ overlay
- ••• Advanced overlay removal strategy

Flavour tagging



Example @ 80% signal efficiency:

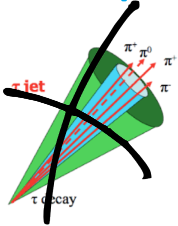
	DBD	new	ATLAS
1-eff(c)	90%	95%	75%
Rejection factor	10	20	4



Better signal efficiencies in preselections

- $\nu\nu HH$: 74 % relative improvement after b-tag cut
- $qqHH$: 70 % relative improvement after b-tag cut

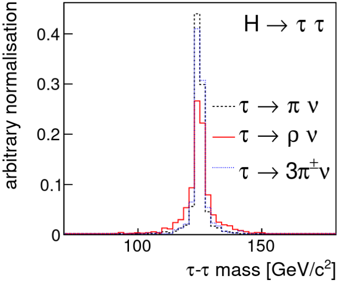
Tau lepton reconstruction

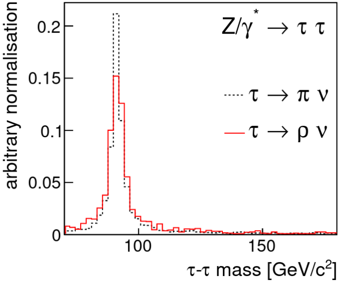


arXiv:1507.01700

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



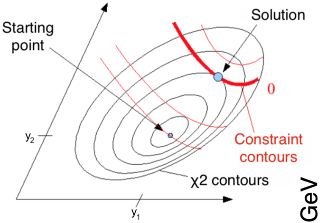


Kinematic fitting & ErrorFlow

arXiv:2110.13731

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:

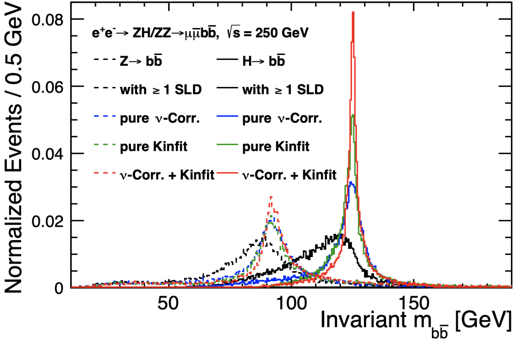
$$L(y) = \Delta y^T \mathbf{V}(y)^{-1} \Delta y + 2 \sum_{k=1}^{m} \lambda_k f_k(a, y)$$

Correct error parametrisation is crucial for kinematic fitting

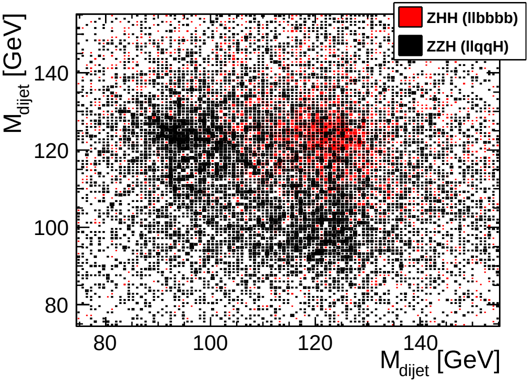
ErrorFlow: Parametrizes the sources of uncertainties for individual jets

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

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



Kinematic fitting for hypothesis testing



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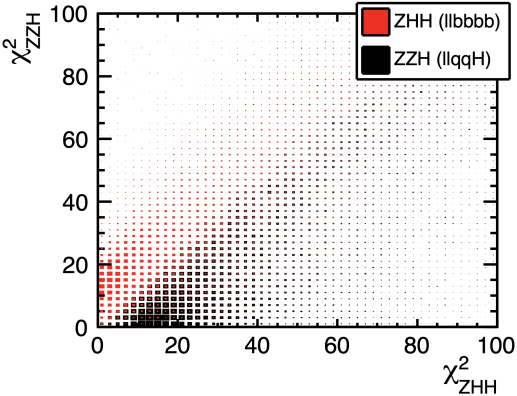
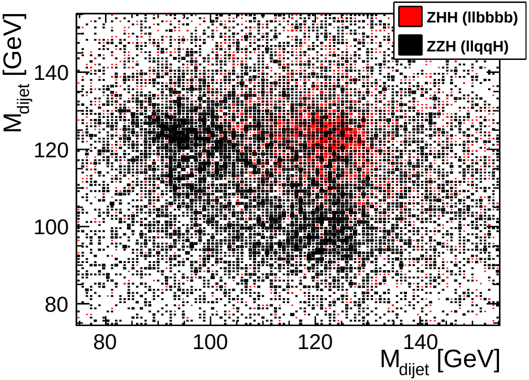


- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

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

Kinematic fitting for hypothesis testing



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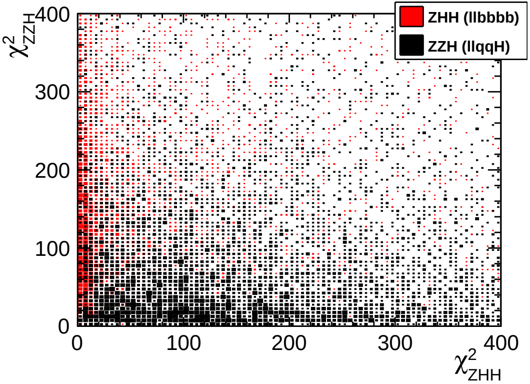

- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

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Summary and next steps

Future high-energy e^+e^- colliders can directly access the Higgs self-coupling through HH production.

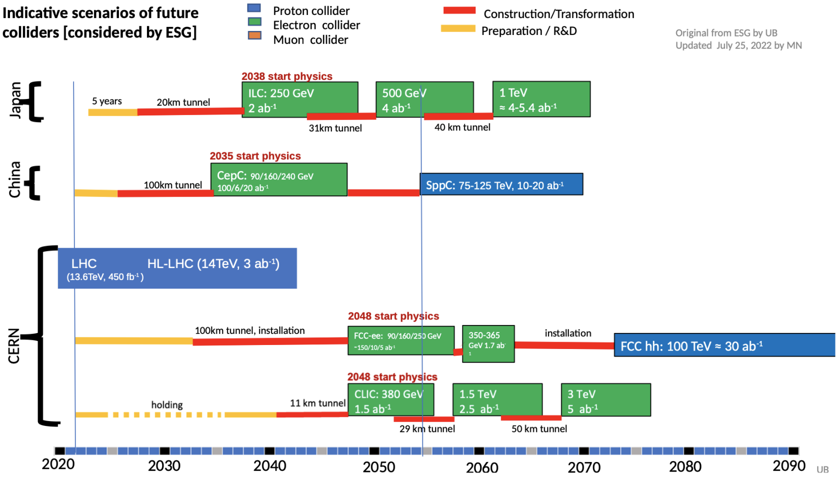
ILC and CLIC both hold the opportunity to reach the $< 10\%$ precision level.

Next steps: Continue work of propagating improvements in reconstruction tools to ZHH analysis @ ILC

- Update state-of-the-art projections — important for shaping the landscape of future colliders

Backup

"Updated" timelines



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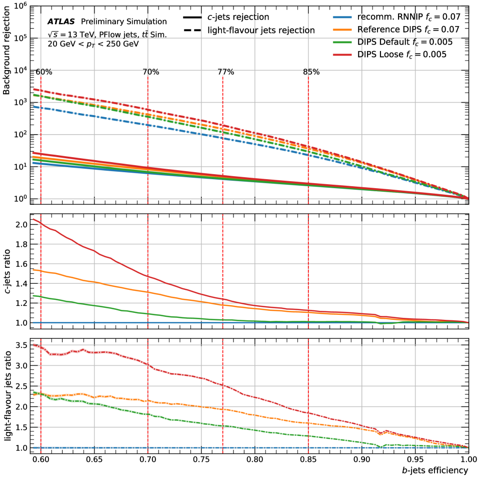
Flavor Tagging at ATLAS



FTAG-2021-004

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