Higgs self-coupling measurement at future e+e- colliders.

EPS-HEP2023 Rehearsal

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Higgs self-coupling

Higgs potential in SM after SSB

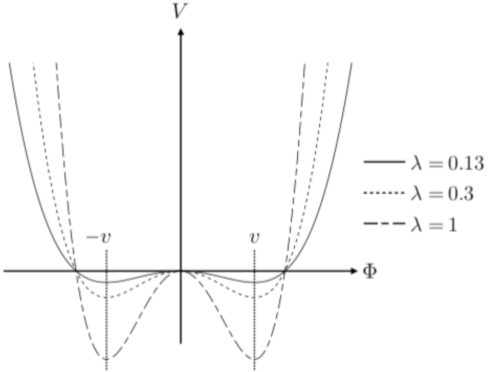
$$V(h) = \frac{1}{2}m_H^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

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

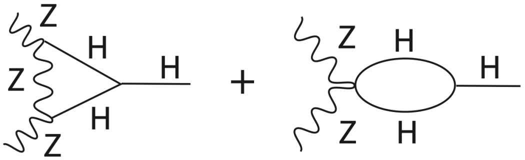
BSM: deviations in λ $\rightarrow$ new physics in Higgs sector



Higgs self-coupling

Indirect access:

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

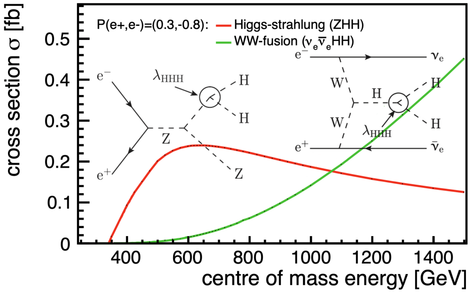


Direct access:

- through double-Higgs production

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

→ cross section measurement

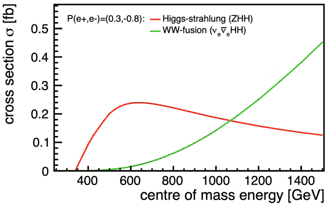


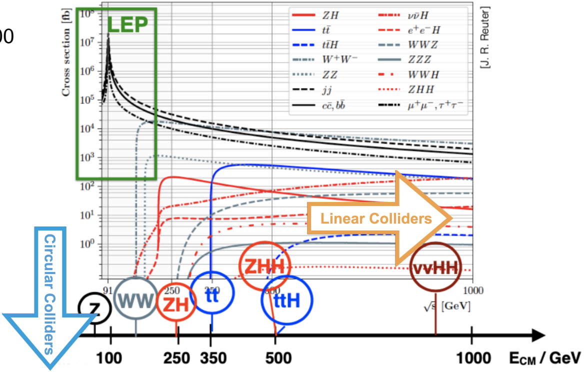
Landscape of future e^+e^- colliders

Centre-of-mass energies:

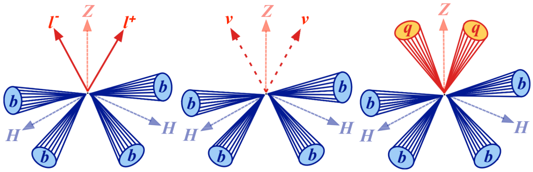
$\sqrt{s}$ /GeV	Z	WW	ZH	$t\bar{t}$	ZHH $+ttH$	$\nu\nu HH$
ILC	-	-	250	350	500	1000
C^3	-	-	250	-	550	-
CLIC	-	-	380(350)		1500	3000
FCC-ee	91	160	240	365 (350)	-	-
CEPC	91	160	240	360	-	-

- ILC/C^3 proposes to run at 500/550 GeV which targets the direct ZHH measurement





The ZHH analysis



- State-of-the-art projections at ILC performed 7-10 years ago DESY-THESIS-2016-027
- Performed at proposed E_{CM} of 500 GeV
- Precision reach after full ILC running scenario ($HH \rightarrow bbbb$ + $HH \rightarrow bbWW$)
  $\rightarrow \Delta\sigma_{\text{ZHH}}/\sigma_{\text{ZHH}} = 16.8\%$
  $\rightarrow \Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 26.6\%$
  $\rightarrow \Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 10\%$ when combined with additional running scenario at 1 TeV
- Improvements in reconstruction tools has the potential to bring the sensitivity to **better than 20%**

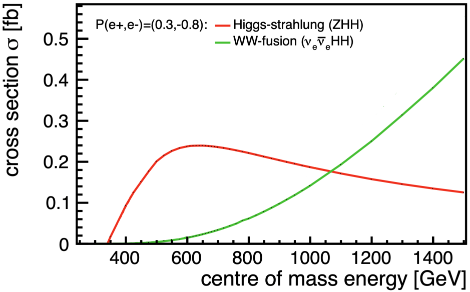
Discovery potential clearly demonstrated

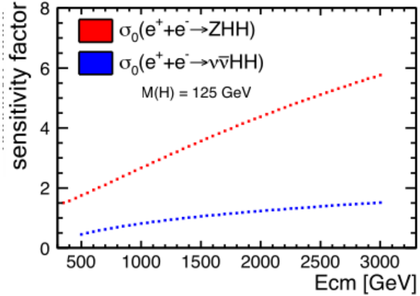
Open questions:

- How does the improvements in reconstruction tools improve the sensitivity to the Higgs self-coupling?
- How does increasing the ECM improve or impair the sensitivity to the Higgs self-coupling?

Choice of centre-of-mass energy

- More ZHH events **but** larger σ_{ZHH} contributions from diagrams NOT containing the Higgs self-coupling





Advantages of going to higher energies:

- More boosted jets

→ Less misclustering, better jet-pairing?

→ Better kinematic separation of signal and background?

→ Improved b-tagging efficiencies?

Disadvantages of going to higher energies:

- Sensitivity factor increases with the E_{CM}

→ Less sensitivity to Higgs self-coupling?

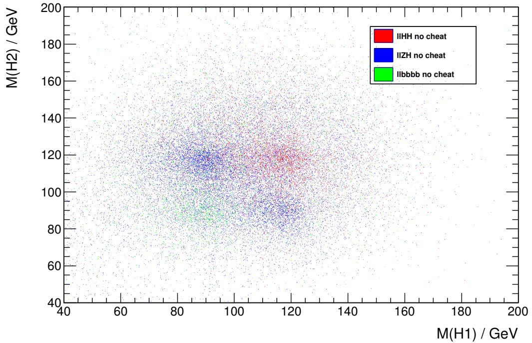
$$\frac{\Delta\lambda}{\lambda} = F \cdot \frac{\Delta\sigma}{\sigma}$$

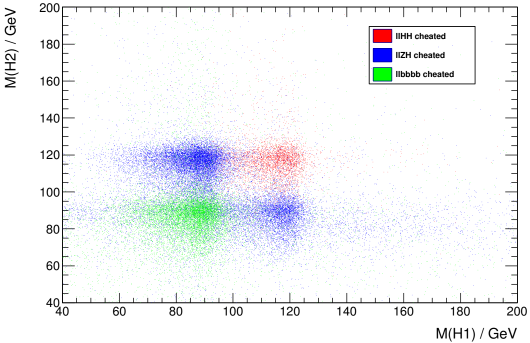
Jet clustering

Junping Tian, Claude Dürig, 2012

☑ Durham algorithm:

☐ Perfect jet clustering:



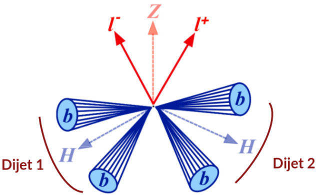


- jet-finding ambiguities from high multiplicities in ZHH, ZZH and ZZZ events

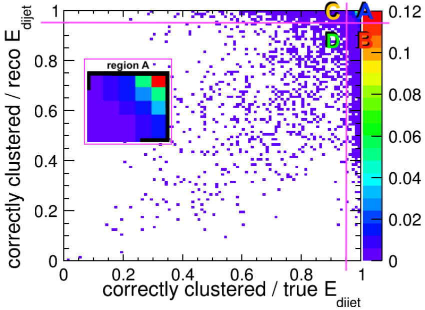
$\rightarrow$ degrades mass resolutions $\rightarrow$ reduces separation $\rightarrow$ reduces $\delta\lambda$ by factor ~ 2

Misclustering

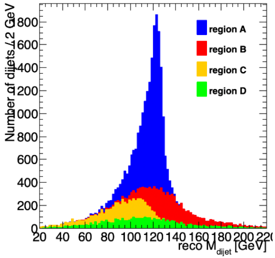
Jet clustering



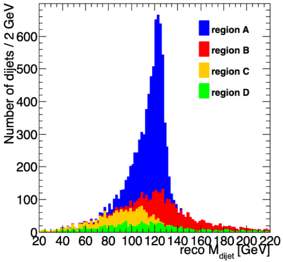
Dijets are classified in misclustering categories, based on the overlap fraction between the true and reco dijet energy.



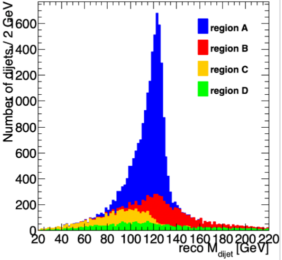
500



550



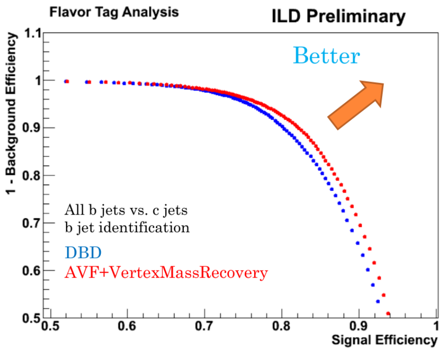
600



Fraction of dijets in category A:

$\sqrt{s}$ [GeV]	A [%]
500	45.5
550	50.5
600	53.7

Flavor tagging



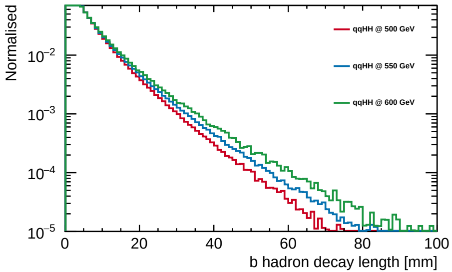
Example @ 80% signal efficiency:

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

Improved *b*-tagging efficiency since state-of-the-art projections from 2016 [DESY-THESIS-2016-027]

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

→ 11% expected relative improvement in $\Delta\sigma_{\mathrm{ZHH}}/\sigma_{\mathrm{ZHH}}$



- *b*- (and *c*-) hadron decay lengths increases with E_{CM}

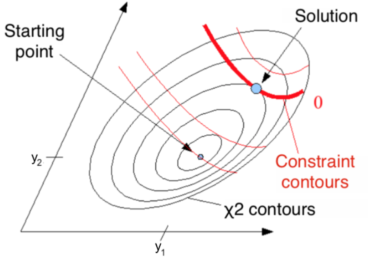
Kinematic fitting

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:

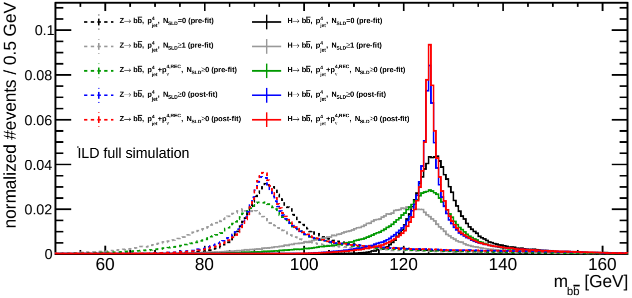
$$L(y) = \Delta y^T \mathbf{V}(y)^{-1} \Delta y + 2 \sum_{k=1}^{m} \lambda_k f_k(a, y)$$



Errorflow

Parametrize sources of uncertainties for *individual* jets [Yasser Radkhorrami, 2023]:

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

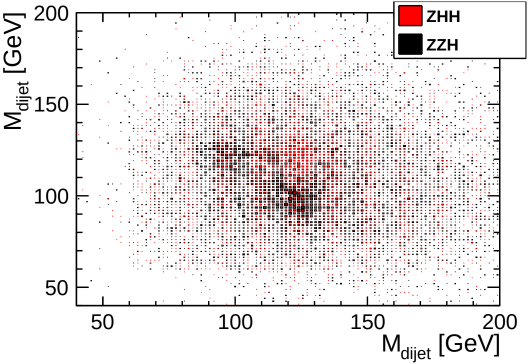


- σ_{Det}: Detector resolution
- σ_{Conf}: Particle confusion in Particle Flow Algorithm
- σ_{ν}: Neutrino correction

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

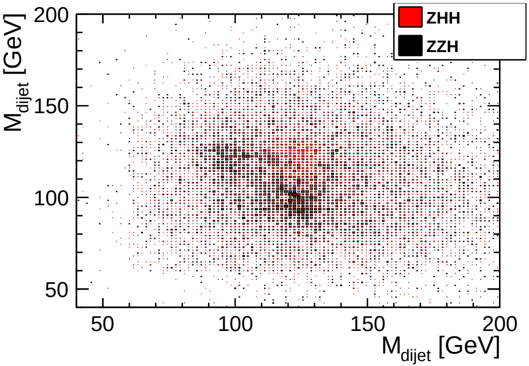
ZZH hypothesis:

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

Hypothesis testing

Kinematic fitting

PRELIMINARY



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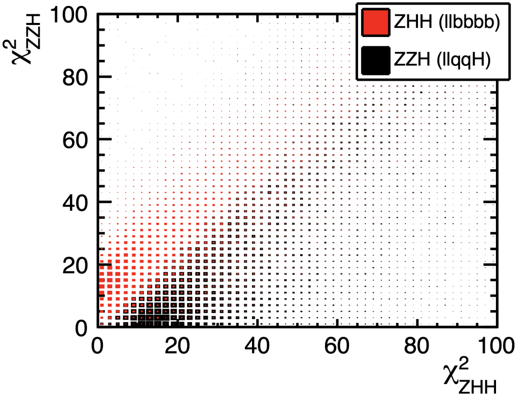


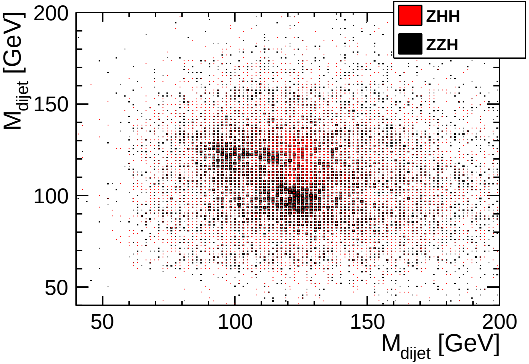
- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)

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

Hypothesis testing

Kinematic fitting

PRELIMINARY



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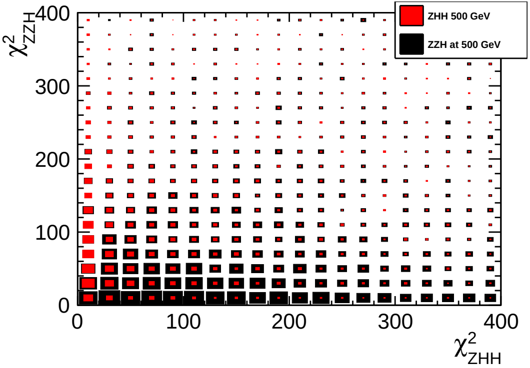
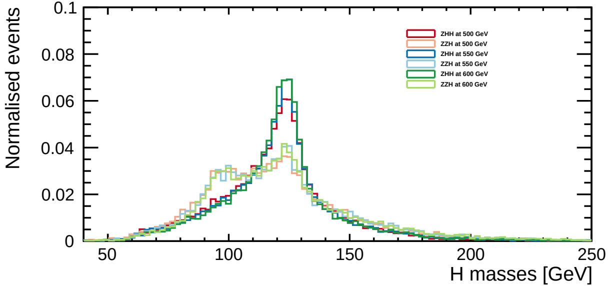


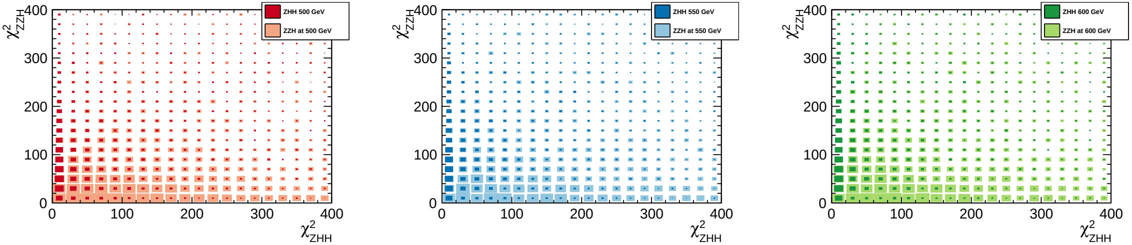
- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)
- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

Kinematic fitting at higher E_{CM}

PRELIMINARY



- Sharper dijet mass distributions for ZHH at 550 GeV and 600 GeV compared to at 500 GeV – but also for ZZH
- Comparable kinematic fit performance thus far



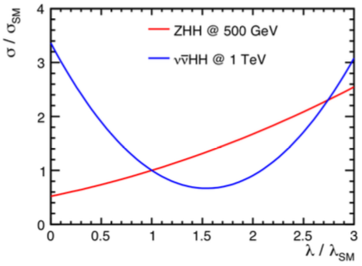
Precision on Higgs self-coupling

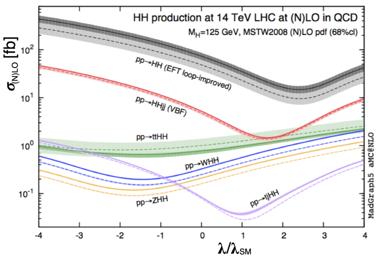
collider	indirect-h	direct-hh
HL-LHC	100-200%	50%
ILC250	–	—
ILC500	58%	20%*
ILC1000	52%	10%*
CLIC380	–	—
CLIC1500	–	36%
CLIC3000	–	9%
FCC-ee 240	–	—
FCC-ee 240/365	44%	–
FCC-ee (4 IPs)	27%	—
FCC-hh	–	3.4-7.8%

[arXiv:1910.00012, arXiv:2211.11084]

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

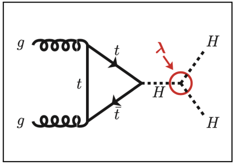
- Higgs self-coupling precision dependent on value of λ itself

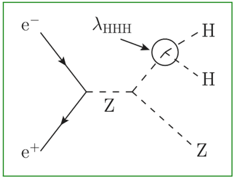


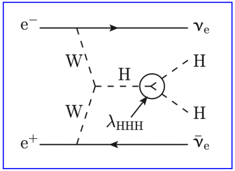


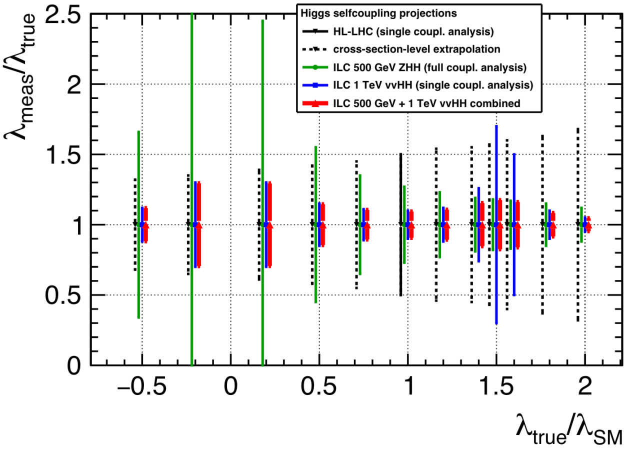
DESY.

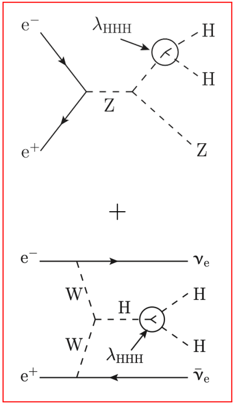
Precision on Higgs self-coupling with new physics





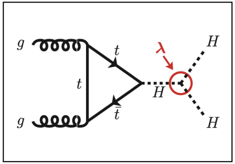


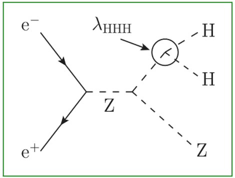


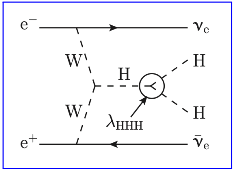


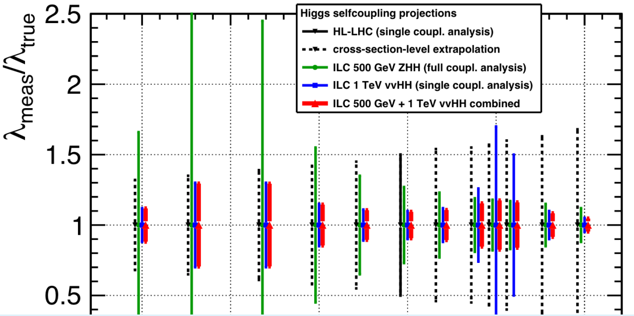
- complementarity compensates for λ precision

Precision on Higgs self-coupling with new physics

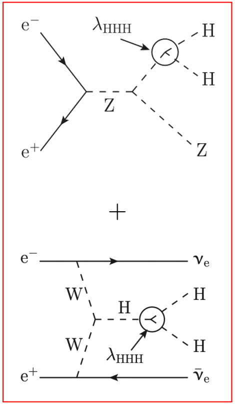








Combining *ZHH* and $\nu\nu HH$ ensures at least 10-15% precision for *any* value of λ



- complementarity compensates for λ precision

DESY.

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 ILC is underway at 500, 550 or 600 GeV depending on the decision on E_{CM}

- Complementarity of ZHH and $\nu\nu HH$ measurements to ensure at least 10-15% precision for *any* value of $\boldsymbol{\lambda}$

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

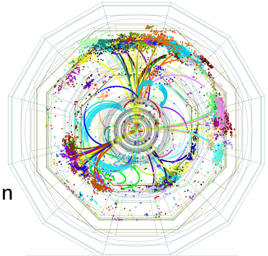
→ Update to the state-of-the-art projections for ILC is underway at 500, 550 or 600 GeV depending on the decision on E_{CM}

- Complementarity of ZHH and $\nu\nu HH$ measurements to ensure at least 10-15% precision for *any* value of $\boldsymbol{\lambda}$

Thank you.

Backup

Strategy for improving the Higgs self-coupling measurement at ILC



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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 $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Flavor tagging

- ☑ Improve b-tagging efficiency

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

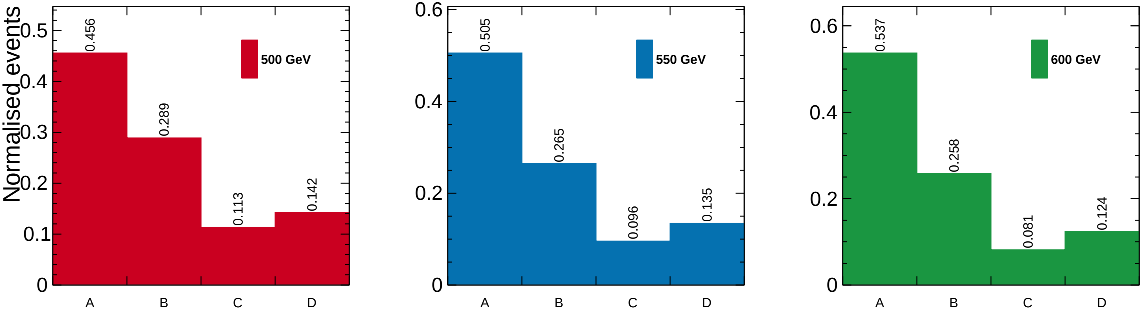
$\to 11\%$ relative improvement in $\Delta\sigma_{ZHH}/\sigma_{ZHH}$

Error parametrisation in kinematic fitting

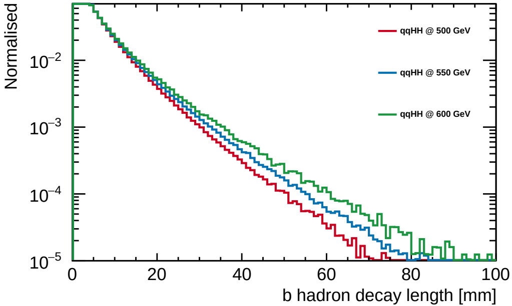
Mass resolution $\propto$ jet energy resolution

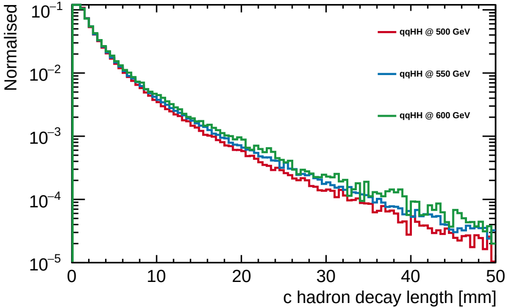
- ☑ Errorflow: Energy resolution parametrisation for individual jets

Dijets in misclustering categories



b and *c* hadron decay length





- only weak decay b and c hadrons
- simple distance calculation between vertex and endpoint of the hadron
- does not account for magnetic field