Prospects of measuring the Higgs self-coupling at the ILC.

DPG Spring Meeting

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HELMHOLTZ

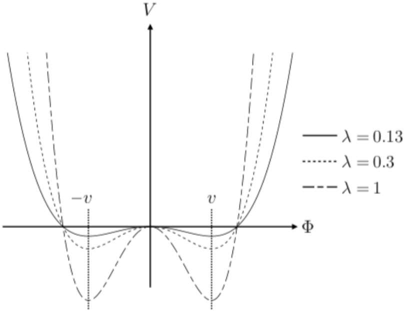
Understanding the Higgs Field

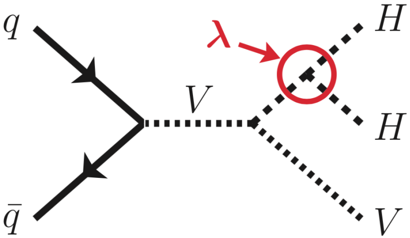
$$\mathcal{L}_{\text{Higgs}} = -g_{Hf\bar{f}} + \frac{g_{HHH}}{6} H^3 + \frac{g_{HHHH}}{24} H^4 + \delta_V V_\mu V^\mu (g_{HVV} H + \frac{g_{HHVV}}{2} H^2)$$

> The Lagrangian describes the the Higgs couplings to fermions, gauge bosons, and to itself

$$g_{HHH} = 6\boldsymbol{\lambda}\nu \text{ and } g_{HHHH} = 6\boldsymbol{\lambda}$$

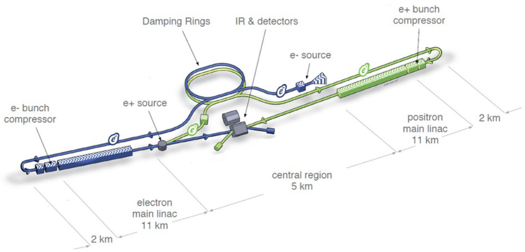
> Measuring $\boldsymbol{\lambda} \rightarrow$ Higgs potential





The International Linear Collider

High-luminosity linear electron-positron collider



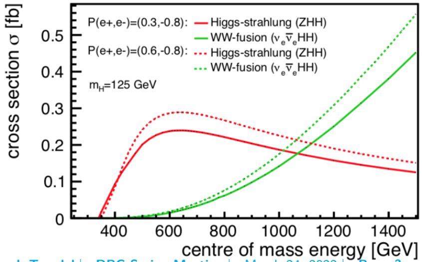
Polarised beams: $P(e^+, e^-) = (\pm 30, \mp 80)\%$
$\sqrt{s}$-range: 250–500GeV (extendable to 1TeV)

Clean experimental environment:

- No substructure of electrons
- No underlying event
- No PDFs i.e. initial state is known in all directions
- Particle physics $\rightarrow$precision frontier

Double Higgs Production @ ILC

Planned phase: $\sqrt{s} = 500 GeV$ with $\mathcal{L} = 4ab^{-1}$



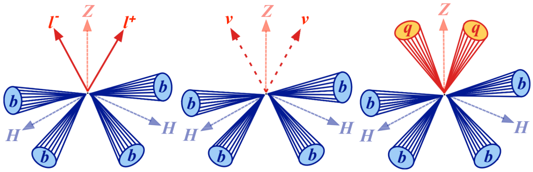
Measuring the Higgs Self-Coupling

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
$\rightarrow 395$ events in total



Previous results [DESY-THESIS-2016-027]

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

$\rightarrow \Delta\sigma_{\mathrm{ZHH}}/\sigma_{\mathrm{ZHH}} = 16.8\%$
$\rightarrow \Delta\lambda_{\mathrm{SM}}/\lambda_{\mathrm{SM}} = 26.6\%$

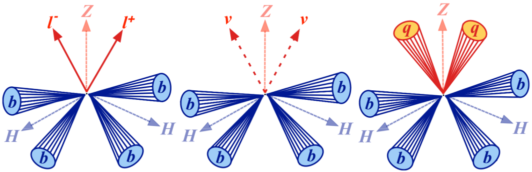
$\rightarrow \Delta\lambda_{\mathrm{SM}}/\lambda_{\mathrm{SM}} = 10\%$ when combined with additional running scenario at 1 TeV

Discovery potential clearly demonstrated

Strategy for further improvements

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

Event reconstruction



- Isolated lepton tagging — selection or rejection
- Overlay removal
- Jet reconstruction from remaining event
- Flavour tagging

- ErrorFlow
- Kinematic fit

Isolated lepton tagging

- identify signature leptons

Overlay removal

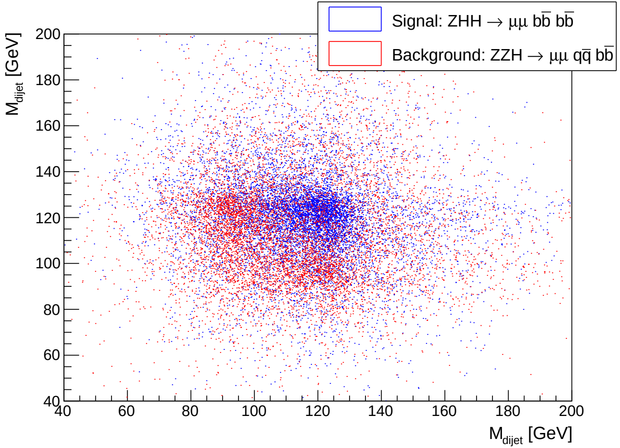
- $\gamma\gamma \to$ low-p_T hadrons
- Expect $\langle N_{overlay} \rangle = 1.2$ particles/event
- Not included previously ✗

***b*-tagging tools**

- Better *b*-tagging efficiency ✓ [arXiv:2003.01116]
  5% relative improvement in $\varepsilon_{b\text{-tag}}$
  $\to 11\%$ relative improvement in $\Delta\sigma_{\mathrm{ZHH}}/\sigma_{\mathrm{ZHH}}$
  [DESY-THESIS-2016-027]

ZZH Background

Main irreducible background with a similar signature to ZHH



Large overlap between signal and background
→ Z/H separation is crucial!

Solution: Kinematic fit

Kinematic Fitting

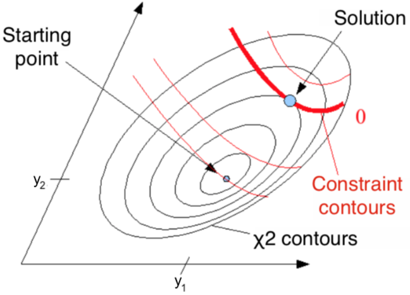
Event Reconstruction

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

- Jet-pairing
- Measurement corrections

χ^2-function to minimise:

$$L(y) = S(y) + 2\sum_{k=1}^{m} \lambda_k f_k(a, y)$$



- y: set of measured parameters
- a: set of unmeasured parameters
- Δy: corrections to y
- $\mathbf{V}(y)$: covariance matrix for y

- **Least Squares Principle:** $S(y) = \Delta y^T \mathbf{V}(y)^{-1} \Delta y = \min$
- **Lagrange multipliers:** $2\sum_{k=1}^{m} \lambda_k f_k(a, y)$
- **Model expressed as m constraints:** $f_k(\bar{a}, \bar{y}) = 0 \quad , \quad k = 1, \dots, m$

ErrorFlow
Jet energy resolution parametrisation

Correct error parametrisation is crucial for kinematic fitting

Parametrize sources of uncertainties for jets:

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

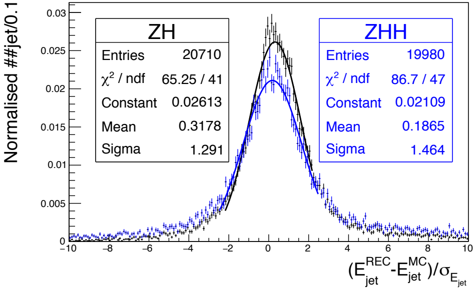
- σ_{Det}: Detector resolution
- σ_{Conf}: Particle confusion in Particle Flow Algorithm
- σ_{ν}: Semi-leptonic decays: neutrino correction currently done with **cheating**
  Coming soon: netrino correction done from **reconstruction**
- σ_{Clus}: Misassignment of particles in the jet clustering
- σ_{Had}: Mismodeling of QCD effects

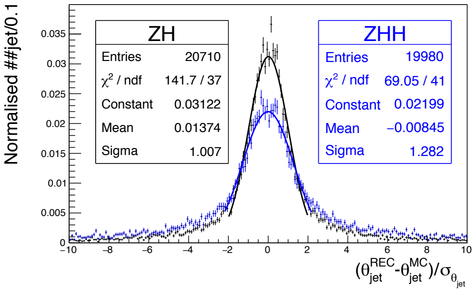
not included yet

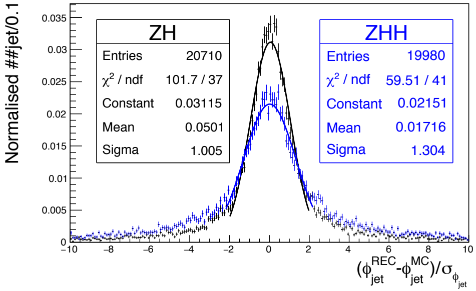
Residuals

- No semileptonic decays
- No overlay events ($\gamma\gamma \rightarrow$ hadrons)

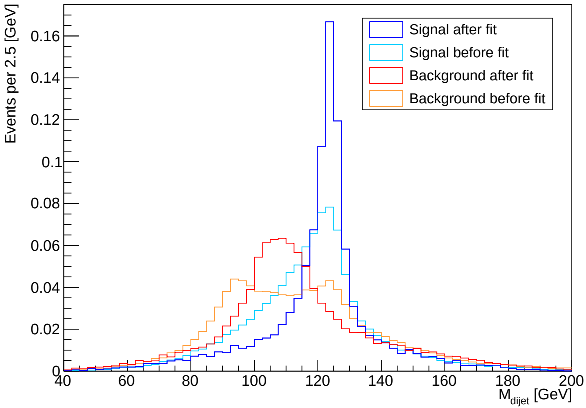
- Residuals show correctly estimated errors for ZH but underestimated errors for ZHH
- Expect larger multiplicity for ZHH than for ZH i.e. more mis-clustering $\longrightarrow$ σ_{Clus}







Z/H Separation



Four-momentum conservation constraints:

$$\sum p_x = \sqrt{s} \cdot \sin(0.007) \approx 3.5 \text{ GeV}$$

$$\sum p_y = 0$$

$$\sum p_z = 0$$

$$\sum E = 500 \text{ GeV}$$

Equal mass constraint:

$$m_{j_1 j_2} - m_{j_3 j_4} = 0$$

Including ISR in fit

Summary

- **Past results:** ILC can discover HH production and measure λ
- **Last 5+ years:** Achieved even better high level reconstruction tools
- **Now:** Expect even better sensitivity to HH production and λ at ILC

- **Next step:** **How much better?** — important for shaping the landscape of future colliders