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

DPG Spring Meeting

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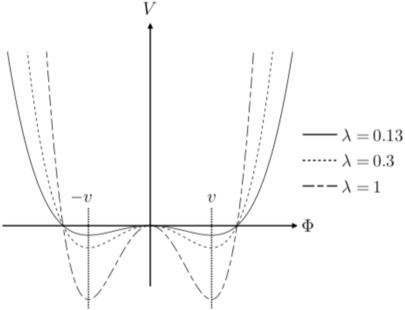
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

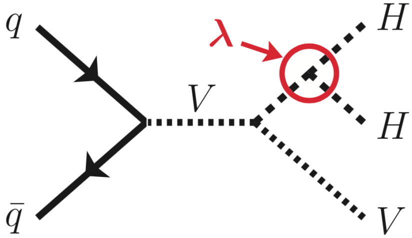
DESY.

Understanding the Higgs Field

$$\mathcal{L}_{\text{Higgs}} = -g_{Hf\bar{f}} + \frac{g_{HHH}}{6}H^3 + \frac{g_{HHHH}}{24}H^4 + \delta_V V_\mu V^\mu (g_{HVV}H + \frac{g_{HHVV}}{2}H^2) \quad (1)$$

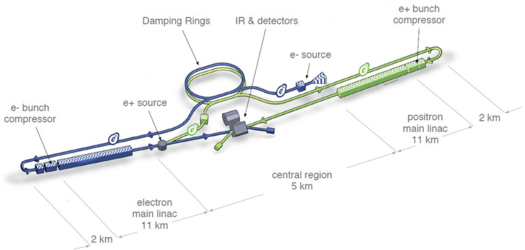
- The Lagrangian describes the the Higgs couplings to fermions, gauge bosons, and to itself where the self-coupling parameters are defined as $g_{HHH} = 6\boldsymbol{\lambda}\nu$ and $g_{HHH} = 6\boldsymbol{\lambda}$
- Measuring the Higgs self-coupling can lead to better understanding the Higgs potential
- Double Higgs production gives access to Higgs self-coupling





The International Linear Collider

High-luminosity linear electron-positron collider



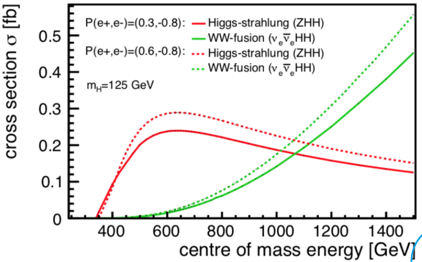
Polarised beams: $P(e^+, e^-) = (\pm 30, \pm 80)\%$
$\sqrt{s}$-range: 250–500GeV (extendable to 1TeV)
Length: $\sim 31km$

Particle physics at the precision frontier:

- No substructure of electrons
- No underlying event
- No PDFs i.e. initial state is known is all directions

Double Higgs Production @ ILC

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



Measuring the Higgs Self-Coupling

Signature: 6-particle final state

$ZHH \to \ell\ell b\bar{b}b\bar{b}$	$ZHH \to \nu\nu b\bar{b}b\bar{b}$	$ZHH \to q\bar{q}b\bar{b}b\bar{b}$
2 leptons + 4 jets	Missing energy + 4 jets	6 jets

Expected precision on the measurement:

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

Latest full detector simulation study at ILC [DESY-THESIS-2016-027] clearly demonstrated the ILC's ability to discover double Higgs production and to measure λ ... and gave a *strategy for further improvements*.
After full ILC running scenario a precision

$\to$ on σ_{ZHH} of 16.8 %

$\to$ on λ_{SM} of 26.6 %

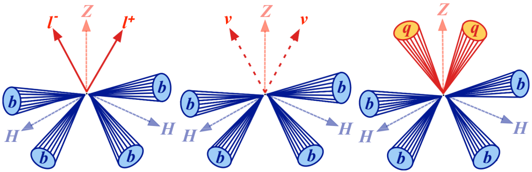
$\to$ on λ_{SM} combined with additional running scenario at 1 TeV of 10 %

> assumed combining the most dominant channels $HH \to bbbb$ and $HH \to bbWW$

Challenges:

- Small cross section: only 395 events are expected in total
- Overlapping jets: Jet-finding ambiguities

Event reconstruction



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

- ErrorFlow
- Kinematic fit

Isolated lepton tagging

- neural-based approach
- separate signature leptons from leptons in semi leptonic decays and mis-identified leptons

Overlay removal

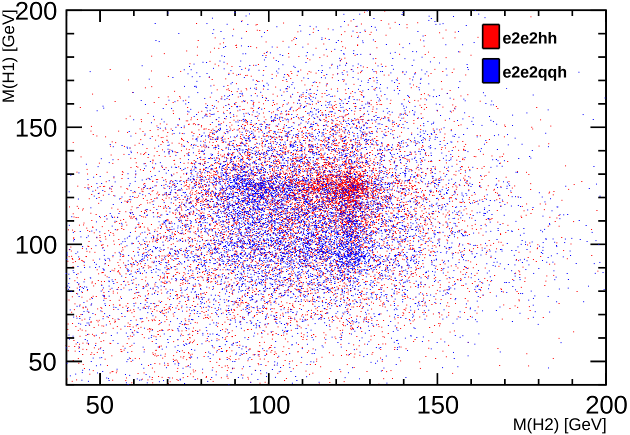
- $\gamma\gamma \rightarrow$ low-p_T hadrons
- Expect $\langle N_{overlay} \rangle = 1.2$ particles/event
- Not included in the results of the latest analysis

***b*-tagging tools**

- Latest analysis showed that a 5% relative improvement in the *b*-tagging efficiency for the same purity would lead to a relative improvement of 11% in the precision on σ_{ZHH} [DESY-THESIS-2016-027]
- This improvement in b-tagging tools has already been achieved [arXiv:2003.01116]

ZZH Background

Main irreducible background with a similar signature to ZHH



Large overlap between signal and background → Z/H separation crucial for identifying Higgs production!

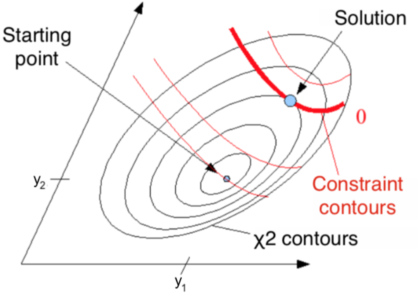
Event reconstruction can be improved with a kinematic fit

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:** $f_k(\bar{a}, \bar{y}) = 0 \quad , \quad k = 1, \ldots, m$

ErrorFlow
Jet energy resolution parametrisation

Correct error parametrisation is crucial for kinematic fitting

Parametrize sources of uncertainties (assumed uncorrelated) in jet energy measurements (ErrorFlow):

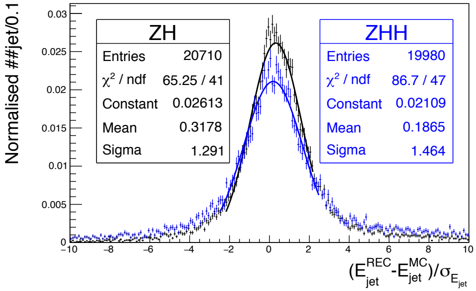
$$\sigma_{E_{jet}} = \sigma_{Det} \oplus \sigma_{Conf} \oplus \sigma_{\nu} \oplus \sigma_{Clus} \oplus \sigma_{Had}$$

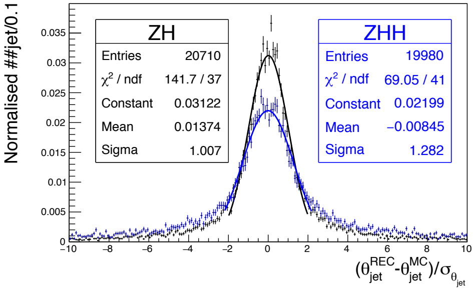
- σ_{Det}: Detector resolution using track and cluster parameters
- σ_{Conf}: Particle confusion in Particle Flow Algorithm
  Estimated based on jet energy and neutral hadron / photon energy fractions
- σ_{ν}: Semi-leptonic decays: error propagation from neutrino correction currently done with cheating
  Recent advancements for future iterations where netrino correction is done from reconstruction
- σ_{Clus}: Misassignment of particles in the jet clustering, has not been included yet
- σ_{Had}: Mismodeling of QCD effects in parton shower and hadronization, has not been included yet

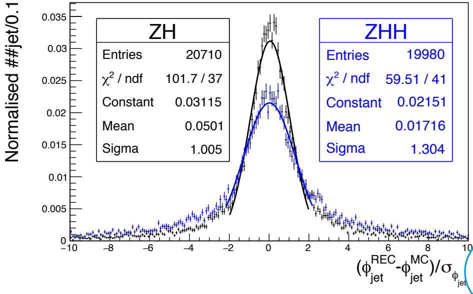
Residuals

- No semileptonic decays
- No overlay

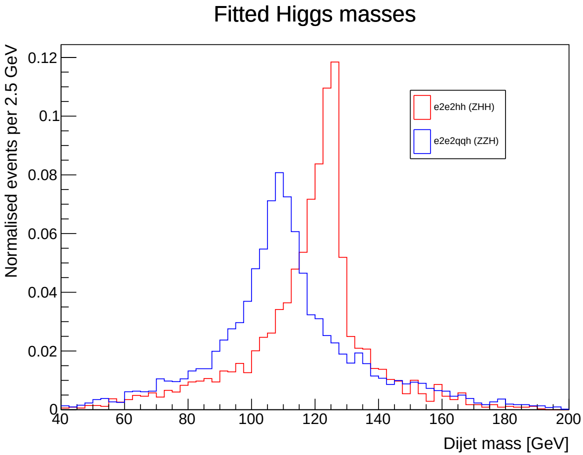
- Residuals show correctly estimated errors for ZH but underestimated errors for ZHH
- Expect larger multiplicity for ZHH than for ZH i.e. more mis-clustering $\longrightarrow$ σ_{Clus}







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

- ILC's ability to discover double Higgs production and measure λ has been clearly demonstrated in the past
- Tremendous improvements in high level reconstruction tools have been achieved in the last 5+ years
- The sensitivity to the Higgs self-coupling is expected to improve when propagating the newest tools to the analysis

- With this new analysis, the question of how well the Higgs self-coupling can be measured at the ILC *now* will be answered — important for shaping the landscape of future colliders