A COMBINED FIT TO THE HIGGS BRANCHING RATIOS AT ILD

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THE INTERNATIONAL LINEAR COLLIDER (ILC)

- Linear $e^+e^-$ collider.
- Polarized beams.
- Initial stage $\sqrt{s} = 250$ GeV (considered here).
- Upgradable (350 GeV, 500 GeV, 1 TeV).

ILC Technical Design Report (2013)
The International Linear Collider : A Global Project : arXiv:1903.01629

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THE INTERNATIONAL LARGE DETECTOR (ILD)

Based on the Particle Flow approach.

Interim Design Report: arXiv:2003.01116
HIGGSSTRAHLUNG

\[ Z \rightarrow \mu^+ \mu^-, Z \rightarrow e^+ e^- : \]
- IsolatedLeptonTagger:
  Lepton pair with same type and opposite charge.
- Final state radiation:
  Add photons with \( \cos \theta_{l\gamma} > 0.99 \).

Golden channels due to recoil mass method, 
\[ M^2_{\text{recoil}} = s + M^2_Z - 2\sqrt{s} \cdot E_Z. \]

- Higgs:
  Event selection that keeps events with all Higgs decays.
EVENT SELECTION

Selection only on information from decay of the primary Z boson.

Step 0: Find a lepton pair.
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2. Construct categories to separate the decay modes (& background) as well as possible.
3. Fit the Higgs branching ratios to the observed category counts.
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Reconstructed events from $\sqrt{s} = 250$ GeV MC2020 ILD mass production.

- $\sqrt{s} = 250$ GeV ideal for the Higgsstrahlung process.
  - $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ as signal channels.
  - $\geq 400k$ simulated events/Standard Model decay mode.

- Considered backgrounds: Standard model processes with 2 or 4 fermions in the final state.

- Polarized initial beams:
  - 80% left polarized electron beam.
  - 30% right polarized positron beam.

- 2000 fb$^{-1}$ integrated luminosity.
OMITIZATION - SETUP

BRs from minimization through MINUIT/iminuit.

- **MC2**: Will be replaced by the detector data.
- \( \vec{S} = M \cdot \vec{B} = \vec{f}(\vec{B}) \), with
  - \( \vec{S} \): The signal counts per category \((S = \text{data} - \text{bkg})\). **MC2**.
  - \( M \): The matrix built from simulated events, as outlined above. **MC1**.
  - \( \vec{B} \): The target. Use e.g. the Standard Model BRs as fit starting values.
- The cost function : Multinomial log-likelihood.
  - \(-\ln L = -N_{\text{data}} \sum_i S_i \ln \left( \sum_j M_{ij} B_j \right)\).
  - \( B_{H \rightarrow ZZ^*} = 1 - \sum_{i \neq H \rightarrow ZZ^*} B_i \).
OPTIMIZATION - RESULTS

The fitted $\text{BR}_{\text{min}}$ reproduces $\text{BR}_{\text{true}}$ within its uncertainties. $\sigma_{B_{H \rightarrow ZZ^*}}$ through uncertainty propagation.

The plot shows the comparison of input branching ratios (BRs) and the fit result. The HESSE 67% CL interval is also displayed for each branching ratio.
OPTIMIZATION - VALIDITY CHECK

Toy study: Draw from multinomial ($N_{\text{data}}$ fixed).
Shown: 2 of the toy fit distributions for multinomial $\ln \mathcal{L}$ with $[0, 1]$ boundaries.

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FIT IN A NON-SM SCENARIO

Assume $57.7\% \rightarrow 42.7\% \ BR(H \rightarrow b\bar{b})$, $21.8\% \rightarrow 36.8\% \ BR(H \rightarrow W^+W^-)$.

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Beam polarization
Fit described in slides
eLpR
eRpL
unpolarized

ILD preliminary

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CONCLUSIONS

- More work needed:
  - Better categories.
  - Exotic Higgs decays.

+ Extraction of major branching ratios from single analysis.
  → Correlation matrix.

+ Independent of $\sigma_{ZH}$ and $\sigma_{VV}$-fusion.

+ Can automatically adapt to BR scenarios drastically different from SM.

|                | SM BR | $\sigma_{stat}$ |
|----------------|-------|-----------------|
| $H \rightarrow bb$ | 57.72 | 0.86            |
| $H \rightarrow WW$  | 21.76 | 1.34            |
| $H \rightarrow gg$  | 8.55  | 1.25            |
| $H \rightarrow \tau\tau$ | 6.20  | 1.30            |
| $H \rightarrow cc$  | 2.72  | 0.55            |
| $H \rightarrow ZZ$  | 2.62  | 1.93            |
| $H \rightarrow \gamma\gamma$ | 0.24  | 0.17            |
| $H \rightarrow Z\gamma$ | 0.17  | 0.35            |
| $H \rightarrow \mu\mu$ | 0.03  | 0.14            |
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BACK-UP
EXPECTED COUNTS PER (CATEGORY, BR) PAIR

Distribution of the 8_923 signal events in the channel as expected for SM BRs

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Higher correlations motivate improvements in the category definition. Needed to include the results in a global fit. Also needed for the last BR:

\[
B_{ZZ^*} = 1 - \sum_{i \neq ZZ^*} B_i \Rightarrow \sigma_{ZZ^*}^2 = \sum_{i \neq ZZ^*} \sum_{j \neq ZZ^*} \rho_{ij} \sigma_i \sigma_j
\]
COMPARISON WITH GLOBAL COUPLING FITS

• [1], [2] use existing analyses and combine them to extract a combined sensitivity for the Higgs boson couplings.
• [1] scaled to the H-20 ILC250 scenario.
• This fit is our approach.
  - A single analysis directly fitting the branching ratios to data.
  - So far only $Z \rightarrow e^+e^-$, $Z \rightarrow \mu^+\mu^-$. 
  - Only statistical uncertainty.

[1] J. Tian, K. Fujii *Measurement of Higgs boson couplings at the International Linear Collider*. 
[2] SFitter *Measuring Higgs Couplings at a Linear Collider*.
• $Z \rightarrow \mu^+\mu^-, Z \rightarrow e^+e^-$:
  Golden channels due to recoil mass method, 
  \[ M_{\text{recoil}}^2 = s + M_Z^2 - 2\sqrt{s} \cdot E_Z. \]

• $Z \rightarrow \tau^+\tau^-$:
  Event tagging on the $\tau$ is complicated.
  - Large $\tau$ decay opening angle (low $E_\tau$).
  - Diverse environment from the Higgs decay.

• $Z \rightarrow \nu\bar{\nu}$:
  - Significant WW-fusion contribution in $\nu\bar{\nu}H$.
  - Cannot tag event on $\nu$.
  + Only Higgs boson (and beam overlay) in event.
  + $6 \times$ higher cross section.

• $Z \rightarrow q\bar{q}$:
  + Higtest cross section.
  - Hard to identify the traces from the $Z$ decay without making assumptions on the Higgs decay.
EXAMPLE EVENTS

After removing the primary $Z$ boson, the *signal* events per channel are interchangeable.

$$e^+ e^- \rightarrow H \ Z, \ Z \rightarrow \mu^+ \mu^-$$

$$e^+ e^- \rightarrow H \ Z, \ Z \rightarrow e^+ e^-$$
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