Study of the Higgsstrahlung process ($e^+e^- \rightarrow Z(qq)H$) in the hadronic decay mode for the context of the ILC with the SDHCAL

Héctor García Cabrera

1 February, 2023

ILD Analysis meeting

Universidad Autónoma de Madrid

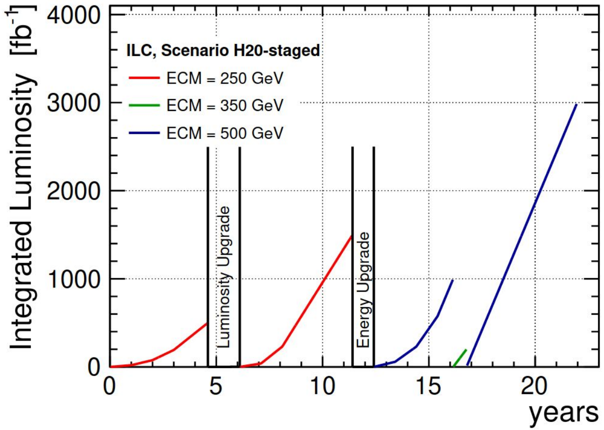
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

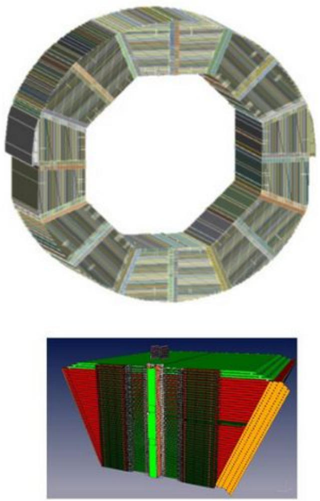
CIEMAT física de partículas

Setup

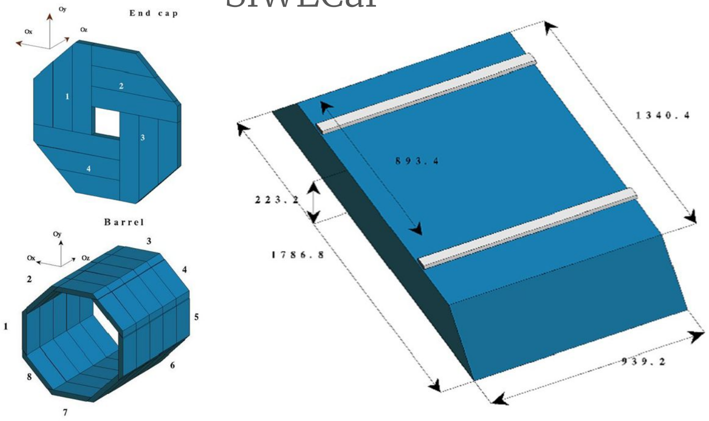
- Analysis of the Higgsstrahlung process (e+e- → h(qq)Z) in the hadronic channel for the ILC simulations.
- The detector model used is the ILD l5_o2_v02. Large model with a calorimeter system composed of the SDHCAL in the Tesla geometry and the SiWECal.
- Current baseline scenario taken from the ILC report to Snowmass 2021: ILC report to Snowmass 2021
- Results will be shown for the integrated luminosities at the end of each segment of the 250 GeV stage: L = 500 fb-1 and L = 2000 fb-1



SDHCal

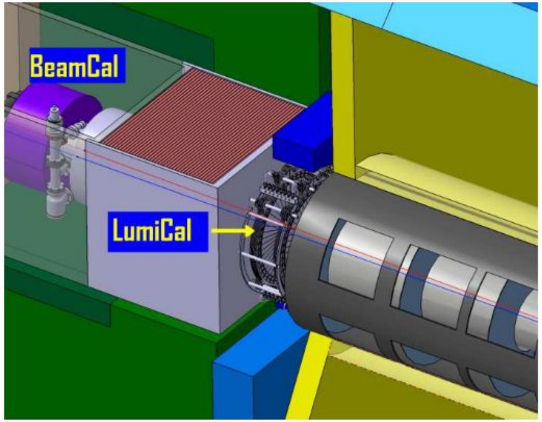


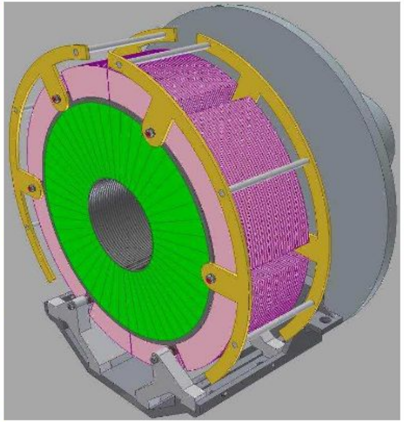
SiWECal



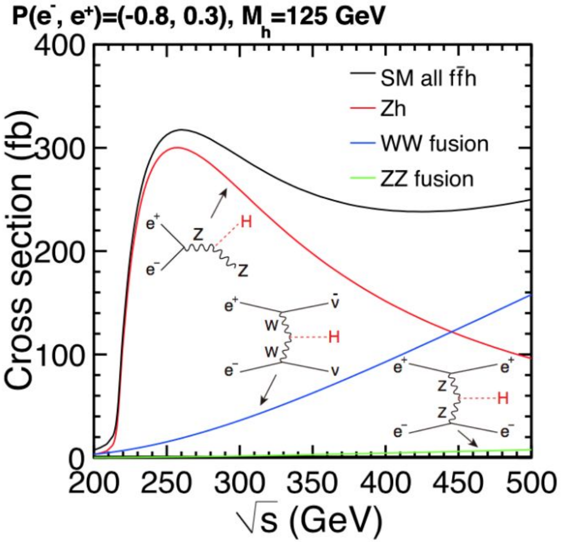
Physics environment

- The integrated luminosity has a precision of ~0.05% for 250 and 500 GeV.
- Beam energy measurements reach relative precisions of 10-4%
- Beam crossing angle: 14 mrad





	250 GeV	350 GeV	500 GeV
$\int \mathcal{L}$ [fb^{-}1]	2000	200	4000
duration [years]	11	0.75	9
beam polarization (e^-/e^+) [%]	80/30	80/30	80/30
(LL,LR,RL,RR) [%]	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)
δ_{ISR} [%]	11.7	12.0	12.4
δ_{BS} [%]	2.6	1.9	4.5



Signal

Process and recoil mass technique

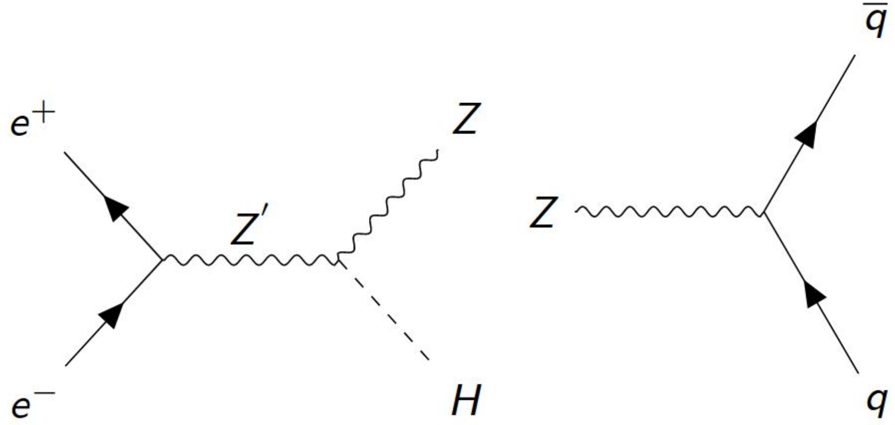
Taking into account the incident angle of the two beams and √s = 250GeV, the computations of the recoil mass are the following:

$$E_{q\bar{q}} = E_q + E_{\bar{q}} \;;\; \overrightarrow{p_{q\bar{q}}} = \overrightarrow{p_q} + \overrightarrow{p_{\bar{q}}} \;;\; M_Z = \sqrt{E_{q\bar{q}}^2 - \overrightarrow{p_{q\bar{q}}}^2}$$

$$M_{Recoil}^2 = (2E + E_{q\bar{q}})^2 - ((2p_x + p_{q\bar{q}_x})^2 + p_{q\bar{q}_y}^2 + p_{q\bar{q}_z}^2)$$

$$2E = 250.0061252\,GeV \;;\; 2p_x = 1.7500286\,GeV$$

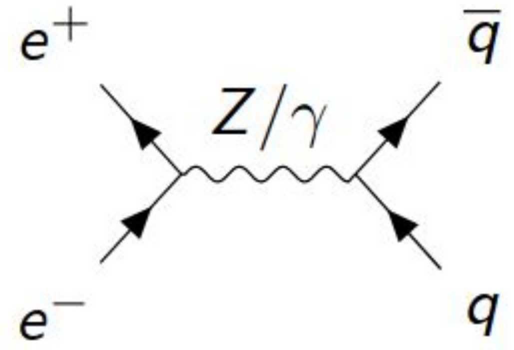
where E and p are the energy and momentum of each of the quarks produced by the Z hadronic decay.



Also the MC request includes all the Higgs decay modes to make per channel tests: H → bb, H → cc, H → gg, H → WW ∗, H → ZZ ∗,H → μμ, H → τ τ , H → γγ and H → Zγ

Background
2 jets background

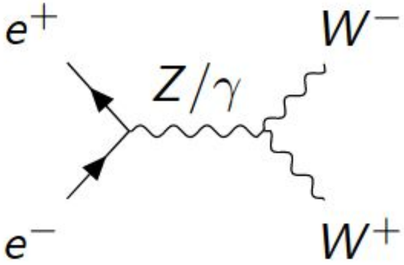
The strongest contribution to the background comes from the decay of the Z mediator into two quarks.

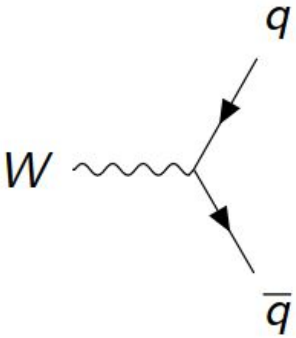


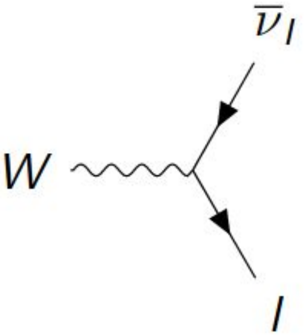
Background

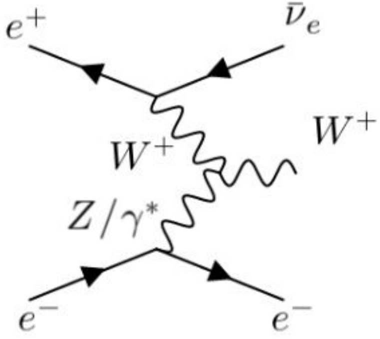
WW and single W production

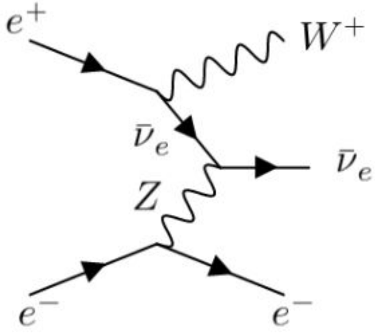
The hadronic decays of the W boson produce a final state that has a great contribution to the background.

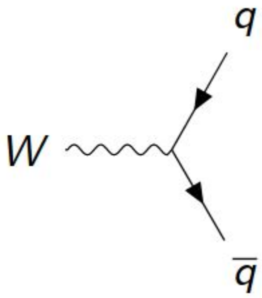








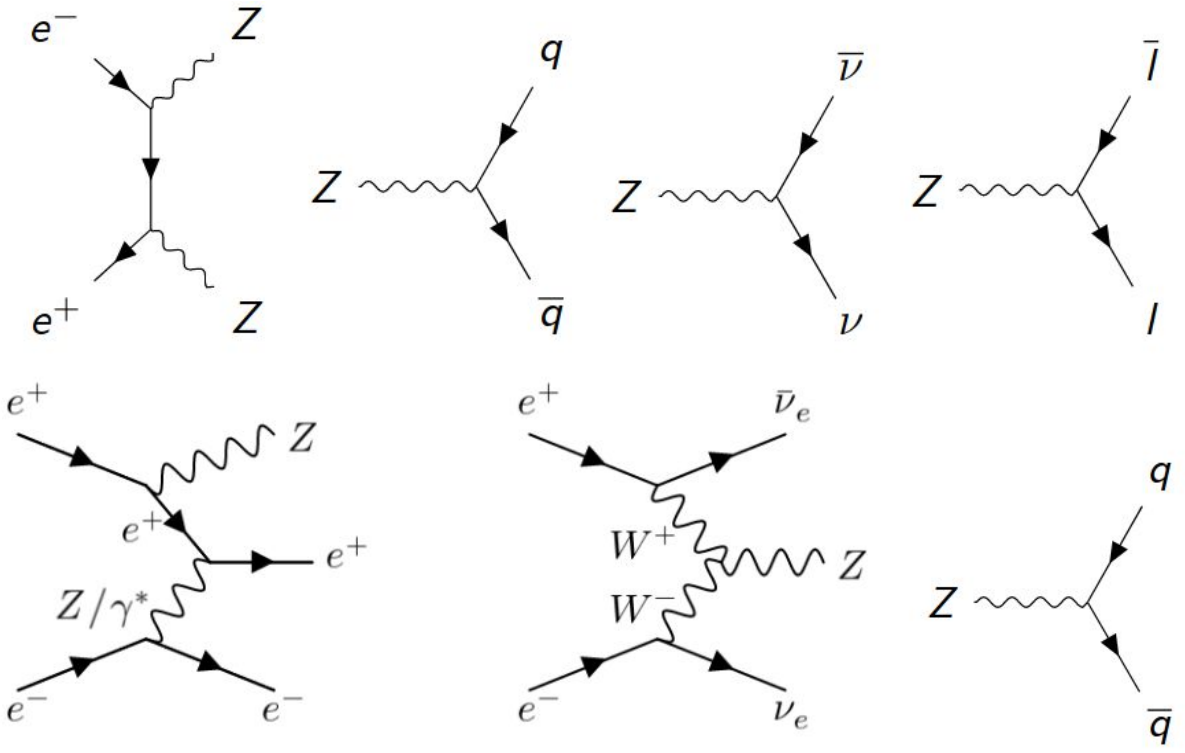




Background

ZZ and single Z production

Also the hadronic decays of the Z boson produce a final state that contribute to the background.



Background

Beam interactions

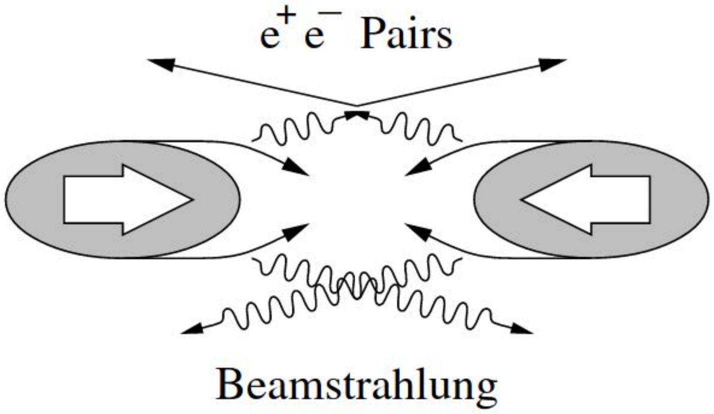
The deflection of the beam particles through the interaction with the electric field of the incoming beam cause the electrons to emit photons, Beamstrahlung.

The main sources of electron-positron pairs are:

- Breit-Heitler process: a real Beamstrahlung photon interacts with a virtual photon emitted by a beam electron or positron.
- Landau-Lifshitz process: two virtual photons from the beams interact producing the pair.

A small energy quark pair production by a Beamstrahlung photon creates a mini-jet in the detectors. This contribution is rather small compared with the other two backgrounds.

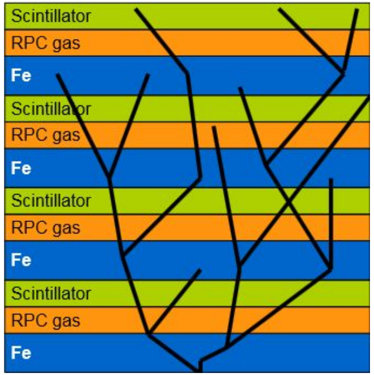
The beam interaction background is included as Overlay to the produced simulations.



Simulations

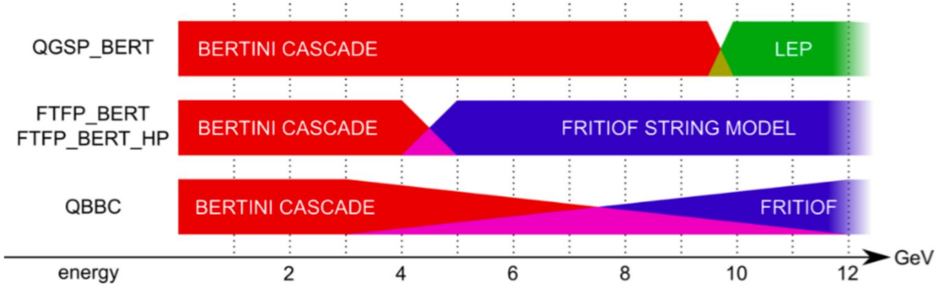
Software:

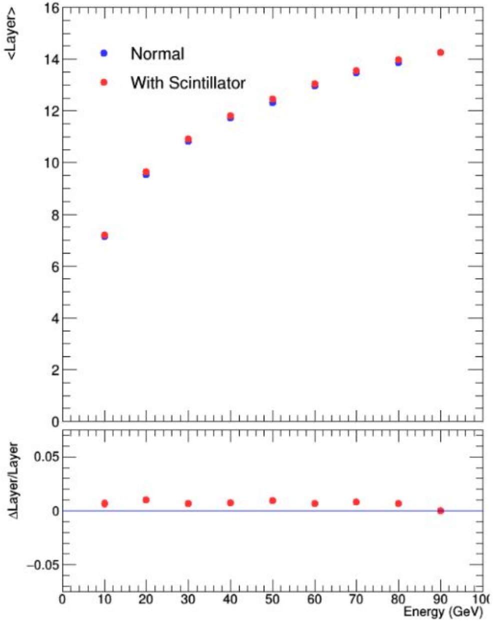
- Generator = WHIZARD
- Beam spectra = GUINEA-PIG
- Particle interactions = GEANT4, using the *QGSP_BERT* physics list.
- Digitization and high-level reconstruction = ILCSoft



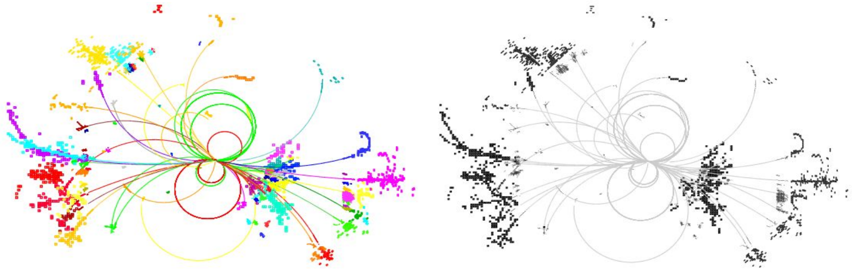
Hybrid simulation technique:

- Two read-out calorimeter technologies are simulated together in the GEANT4 step.
- An agreement to the standalone simulations better than 1%.





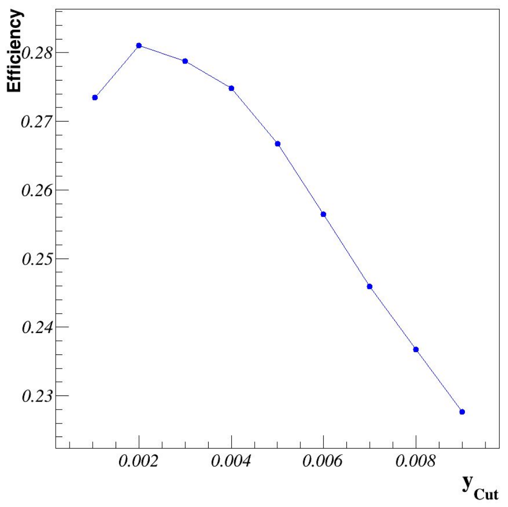
Reconstruction

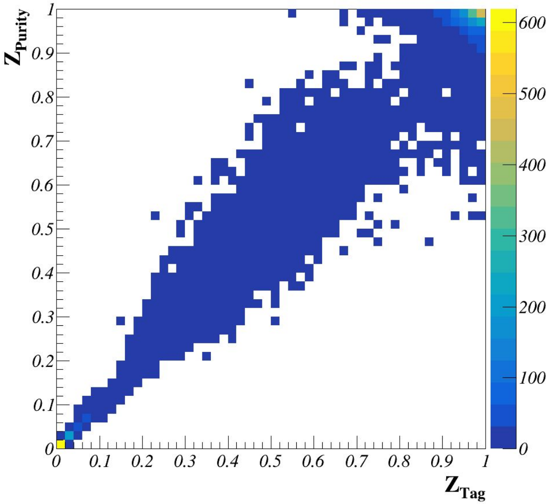


The energy deposits must be converted into realistic signals:

- Digitization
- Tracks of charged particles
- Particle Flow: Pandora
- High level analysis

The parameters of the Jet-Clustering algorithm must be optimized to properly reconstruct the Z boson and discard Overlay.The parameters from FastJet are optimized by maximizing the percentage of well reconstructed jets. (ZTag > 0.9 and ZPurity > 0.9).





$$\{j_1, j_2\} = argmin|m_{j1,j2} - m_Z| \;\; ; \;\; j_1, j_2 \in N_{Jets} \; ; j_1 \neq j_2$$

$$Z_{Tag} = \frac{E_Z^{j1,j2}}{E_Z^{Total}} \;\; ; \;\; Z_{Purity} = \frac{E_Z^{j1,j2}}{E^{j1,j2}}$$

Background rejection

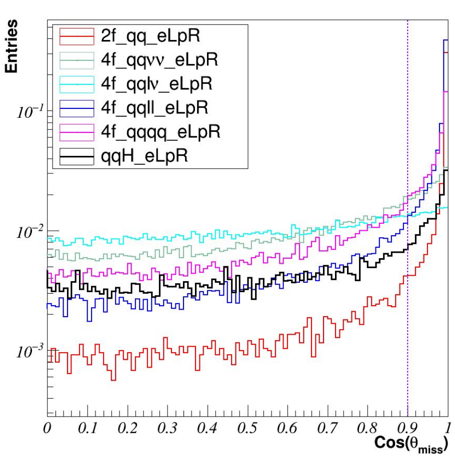
Global cuts

$$e^+ \, e^- \to X_1 \, X_2$$

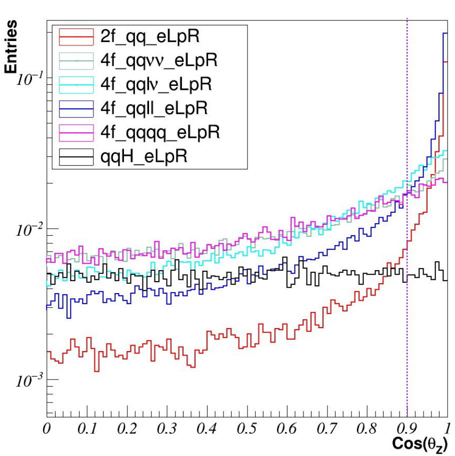
$$\vec{p}_{miss} = \vec{p}_{e^-} + \vec{p}_{e^+} - \sum_{i}^{N} \vec{p}_i$$

$$\frac{m_{X1}}{E_{X1}} = \frac{2\sqrt{s} \cdot m_{X1}}{s + m_{X1}^2 - m_{X2}^2}$$

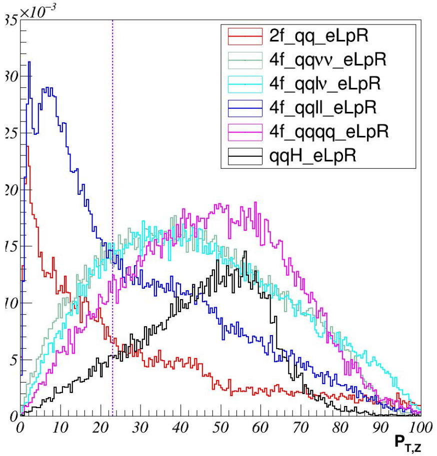
$|cos(\theta_{miss})| > 0.9$



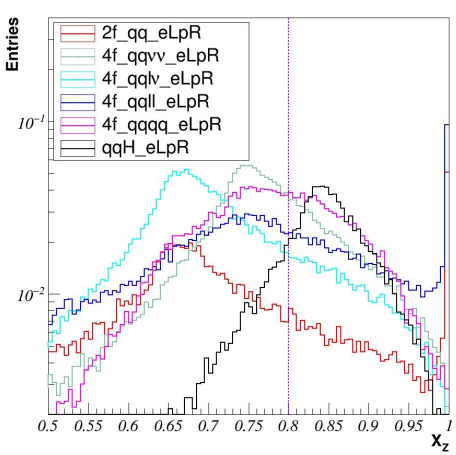
$|cos(\theta_Z)| > 0.9$



$p_{T,Z} < 25$ GeV



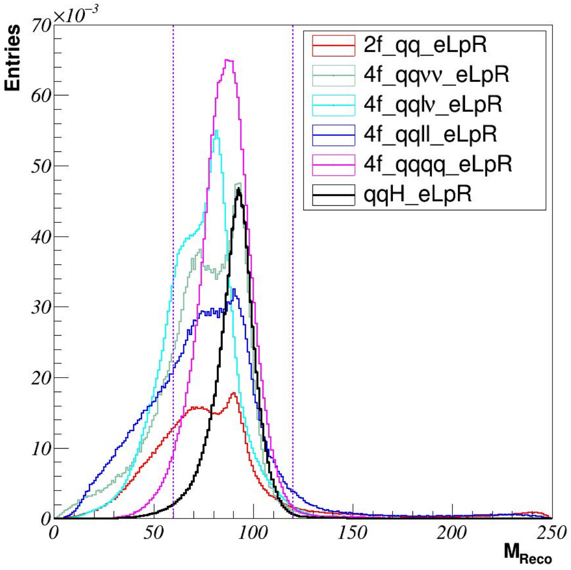
$m_Z/E_Z < 0.8$

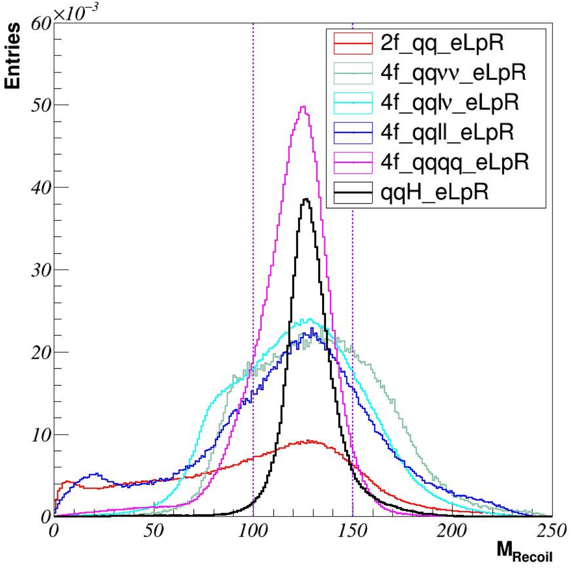


Background rejection

Global cuts

$$M_{Rec} < 60 \quad or \quad M_{Rec} > 120\ GeV$$
$$M_{Recoil} < 100 \quad or \quad M_{Recoil} > 170\ GeV$$





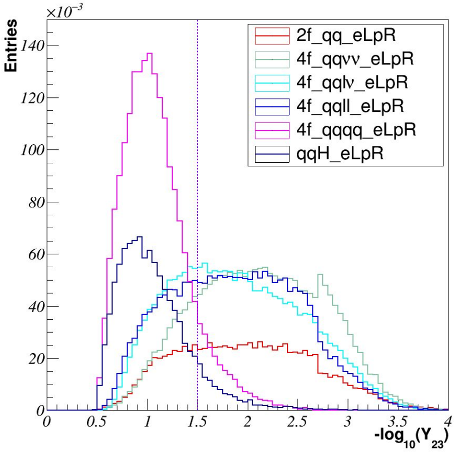
Background rejection

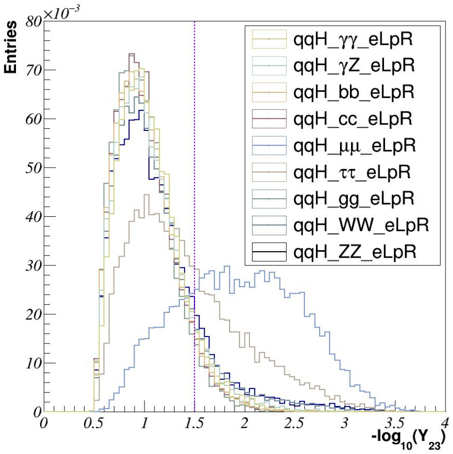
2 jets categorization

If an event is above the threshold -log(y23) > 1.5 it is treated as a two jet case. The cuts are selected finding the compromise between the background rejection and the

-log(y23)

Signal + Backgr. **Higgs decays**





Background rejection

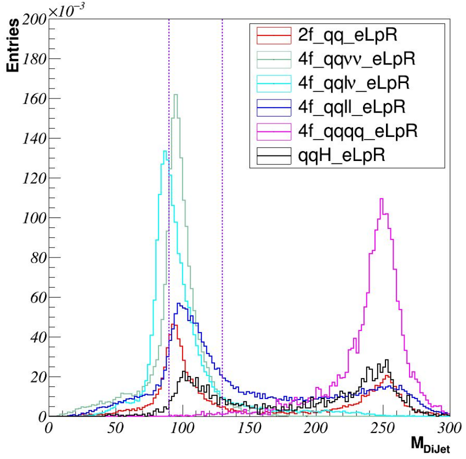
2 jets categorization

If an event is above the threshold -log(y23) > 1.5 it is treated as a two jet case. If $M_{DiJet} > 130$ then the event is considered mis-identified and return to other criteria.

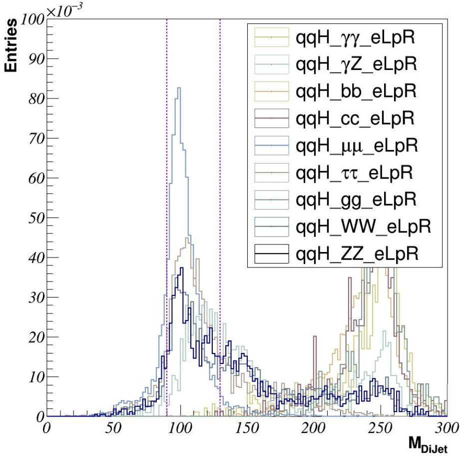
$$M_{DiJet} < 90\ GeV \quad or \quad Recoil_{DiJet} < 110 \quad or \quad Recoil_{DiJet} > 130\ GeV$$

Di-jet Z mass

Signal + Backgr.

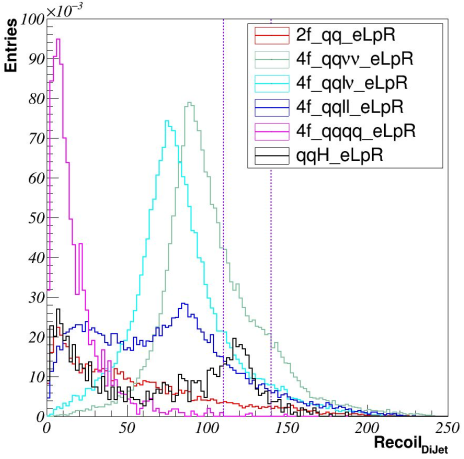


Higgs decays

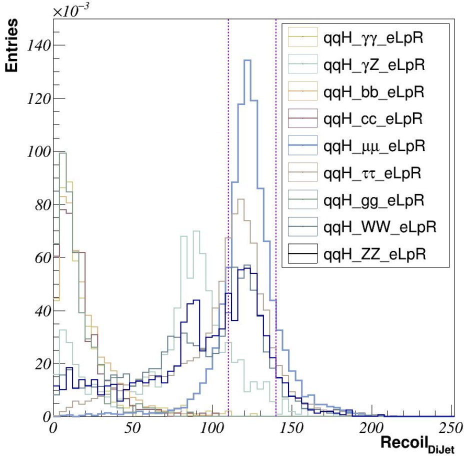


Di-jet recoil mass

Signal + Backgr.



Higgs decays



Background rejection

Thrust

$$T_M = max_{\hat{n_M}} \left(\frac{\sum_i |\overrightarrow{p}_i \cdot \hat{n_M}|}{\sum_i \overrightarrow{p}_i} \right) \quad with \quad \hat{n_M} \perp \hat{n_T}$$

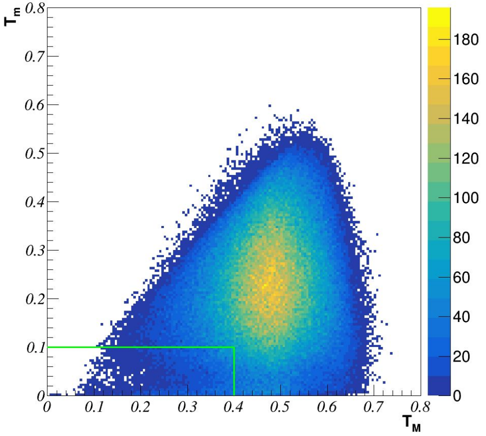
$$T = max_{\hat{n_T}} \left(\frac{\sum_i |\overrightarrow{p}_i \cdot \hat{n_T}|}{\sum_i \overrightarrow{p}_i} \right)$$

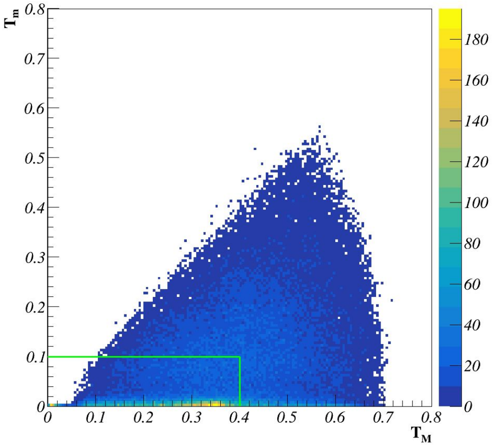
$$T_m = max_{\hat{n_m}} \left(\frac{\sum_i |\overrightarrow{p}_i \cdot \hat{n_m}|}{\sum_i \overrightarrow{p}_i} \right) \quad with \quad \hat{n_m} \times \hat{n_T}$$

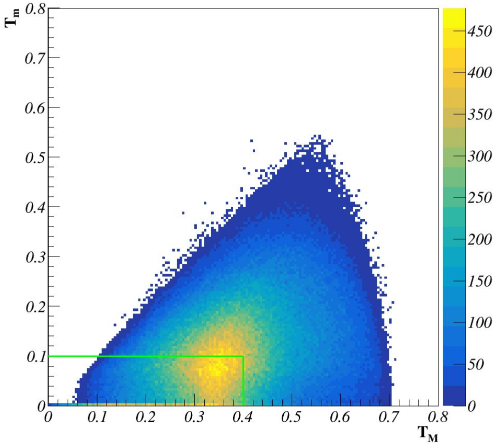
$$T_M < 0.4 \qquad T_m < 0.1$$

Thrust selection

Signal | WW Semi-leptonic | ZZ Semi-leptonic







Background rejection

4 jet backgrounds

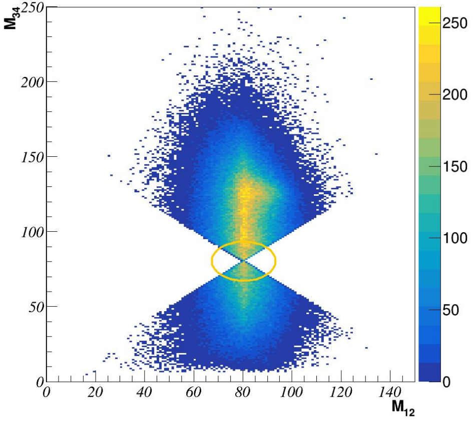
To identify the WW and ZZ hadronic channel backgrounds (4 jets) the mass of the two di-jets of the 4 jets categorizations are computed (M12 and M34).

$$\sqrt{(m_{12} - m_W)^2 + (m_{23} - m_W)^2} \; < \; 13GeV$$

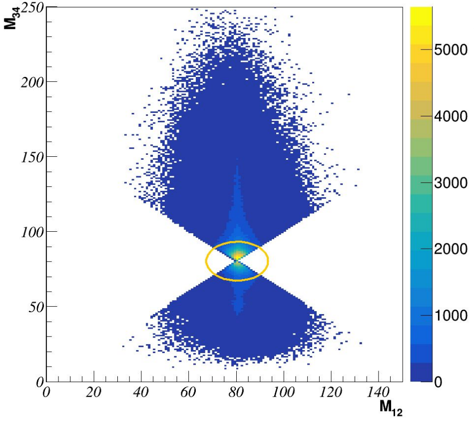
$$\sqrt{(m_{12} - m_Z)^2 + (m_{23} - m_Z)^2} \; < \; 13GeV$$

4 jets, WW

Signal

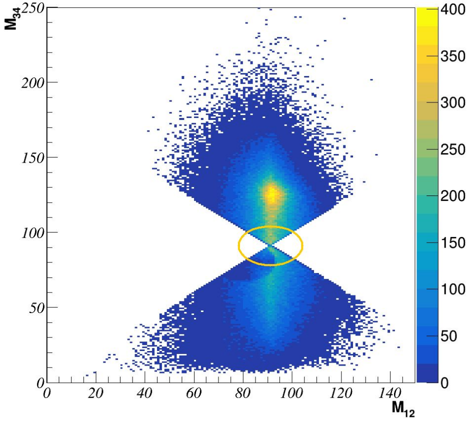


Background

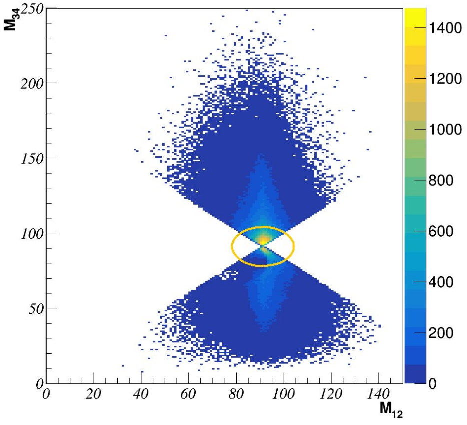


4 jets, ZZ

Signal



Background



Background rejection

Summary

Final State	ε	$P(eLpR)$ Events	ε	$P(eRpL)$ Events	ε	$P(eLpL)$ Events	ε	$P(eRpR)$ Events
$Z(q\bar{(q)})H$	41.81 %	71K	41.9 %	44K				
$q\bar{q}$	1.46 %	936K	0.54 %	190K				
$q\bar{q}\nu\nu$	6.84 %	36K	5.91 %	11K				
$q\bar{q}l\nu$	6.50 %	944K	6.99 %	9K	10.74 %	10K	11.13 %	10K
$q\bar{q}ll$	4.32 %	49K	3.10 %	44K	1.02 %	6K	1.05 %	6K
$q\bar{q}q\bar{q}$	9.37 %	760K	11.90 %	44K				

Summary of the selected events per final state in each of the four possible polarizations with $\mathcal{L} = 500\text{fb}^{-1}$.

Estimations of the measurement resolution

Cross section and coupling to ZZ

$$\sigma_{ZH} = \frac{N_S}{BR(Z \to q\bar{q})\,\varepsilon\,\mathcal{L}} = \frac{N_T - N_B}{BR(Z \to q)\bar{q}\,\varepsilon\,\mathcal{L}} \qquad \frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} = \frac{1}{2}\frac{\Delta g_{HZZ}}{g_{HZZ}}$$

$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} = \left(\frac{\Delta N_T}{N_S}\right)_{Stat} \oplus \left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta\mathcal{L}}{\mathcal{L}} \oplus \frac{\Delta Br(Z \to q\bar{q})}{Br(Z \to q\bar{q})}\right)_{Syst}$$

- The statistical resolution is directly related to the significance S of the signal: $\left(\frac{\Delta N_T}{N_S}\right)_{Stat} = \frac{\sqrt{N_S + N_B}}{N_S} = S^{-1}$
- From studies of the ILC environment: $\frac{\Delta\mathcal{L}}{\mathcal{L}} \sim 0.05\%$
- From other Higgs studies: $\frac{\Delta Br(Z\to q\bar{q})}{Br(Z\to q\bar{q})} \sim 0.08\%$

$\Delta N_T/N_S$	$P(eLpR)$	$P(eRpL)$	All
$\mathcal{L} = 500$ fb^{-1}	2.33 %	1.38 %	2.82 %
$\mathcal{L} = 2000$ fb^{-1}	1.17 %	0.69 %	1.41 %

Estimations of the measurement resolution

Cross section and coupling to ZZ

The term $\Delta\varepsilon/\varepsilon$ is a systematic uncertainty arising from the selection cuts, since each decay mode of the Higgs has a different selection efficiency within the same analysis. To study it a dedicated production of each decay mode has been produced. Taking into account the theoretical branching ratios of the Higgs $\omega(H \to X)$ then $\varepsilon_{expected} = \sum_i \varepsilon_i \cdot \omega_i$

	$P(eLpR)$	$P(eRpL)$	All
Final State	ε	ε	ε
$Z(q\bar{q}) + H$	41.81 ± 0.24 %	41.94 ± 0.37 %	41.85 ± 0.36 %
$H \to \gamma\gamma$	39.75 ± 0.73 %	38.74 ± 0.72 %	39.24 ± 0.95 %
$H \to \gamma Z$	40.97 ± 0.74 %	42.05 ± 0.76 %	42.01 ± 0.98 %
$H \to b\bar{b}$	42.03 ± 0.24 %	41.71 ± 0.44 %	41.95 ± 0.39 %
$H \to c\bar{c}$	41.11 ± 0.75 %	41.46 ± 0.75 %	41.28 ± 0.97 %
$H \to \mu\bar{\mu}$	27.20 ± 0.56 %	26.51 ± 0.57 %	26.85 ± 0.73 %
$H \to \tau\bar{\tau}$	42.95 ± 0.75 %	41.92 ± 0.74 %	42.44 ± 0.97 %
$H \to gg$	41.21 ± 0.75 %	40.96 ± 0.74 %	41.08 ± 0.96 %
$H \to WW^*$	42.23 ± 0.44 %	42.30 ± 0.76 %	42.25 ± 0.70 %
$H \to ZZ^*$	40.97 ± 0.74 %	40.53 ± 0.74 %	40.91 ± 0.96 %
$\varepsilon_{expected}$	41.98 %	41.72 %	41.94 %
$\|\Delta\varepsilon/\varepsilon\|$	0.41 %	0.52 %	0.12 %

Decay mode	$\mathrm{BR}(H \to X)$
$H \to \gamma\gamma$	0.23 %
$H \to \gamma Z$	0.15 %
$H \to b\bar{b}$	58.1 %
$H \to c\bar{c}$	2.88 %
$H \to \mu\bar{\mu}$	0.02 %
$H \to \tau\bar{\tau}$	6.26 %
$H \to gg$	8.18 %
$H \to WW^*$	21.5 %
$H \to ZZ^*$	2.64 %

Table 7.6: Higgs branching ratios.

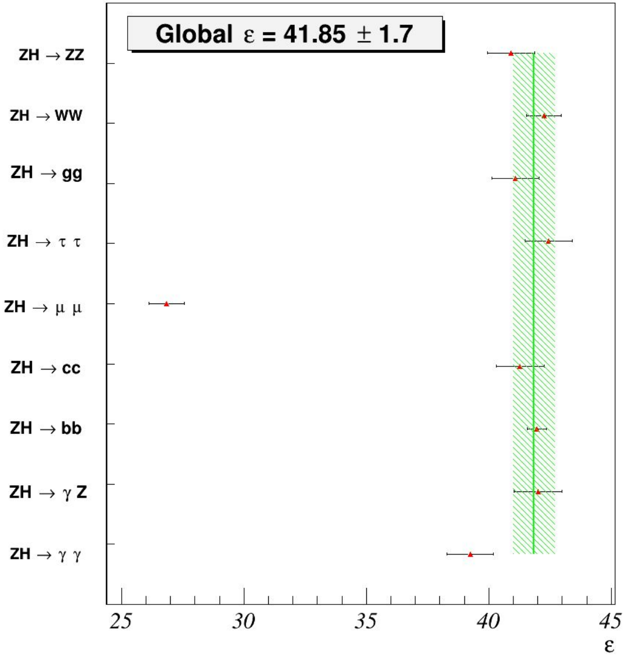
Estimations of the measurement resolution

Cross section and coupling to ZZ

Comparing the different selection efficiencies with the one obtained with the signal that includes all the decay modes shows that the analysis is indeed model independent. Due to the small branching ratios of these decay modes, the bias introduced by H → μμ and H → γγ is negligible compared to the statistical and systematic uncertainties.

$\mathcal{L} = 500\text{fb}^{-1}$	$\Delta\sigma_{ZH}/\sigma_{ZH}$	$\Delta g_{HZZ}/g_{HZZ}$
$P(eLpR)$	$2.33 \oplus 0.41$ %	$1.16 \oplus 0.20$ %
$P(eRpL)$	$1.38 \oplus 0.52$ %	$0.69 \oplus 0.26$ %
All polarizations	$2.92 \oplus 0.12$ %	$1.46 \oplus 0.06$ %

$\mathcal{L} = 2000\text{fb}^{-1}$	$\Delta\sigma_{ZH}/\sigma_{ZH}$	$\Delta g_{HZZ}/g_{HZZ}$
$P(eLpR)$	$1.17 \oplus 0.41$ %	$0.58 \oplus 0.20$ %
$P(eRpL)$	$0.69 \oplus 0.52$ %	$0.34 \oplus 0.26$ %
All polarizations	$1.46 \oplus 0.12$ %	$0.73 \oplus 0.06$ %



Summary and prospects

- This chapter study has reviewed the Higgstrahlung process in a model independent method for the hadronic Z channel.
- It includes the beam-beam backgrounds which have never been included in the ILD simulations that made use of the Semi-Digital Hadronic Calorimeter. Nevertheless, by re-optimizing the jet clustering algorithm and by applying clever modifications to the selection rules, the impact of the Overlay has been found to be small, obtaining similar results to the previous studies.
- Also the analysis of two realistic scenarios have been performed: L = 500fb-1 and L = 2000fb-1, which correspond to two clear milestones in the H-20 running scenario: the luminosity upgrade and the end of the $\sqrt{s}$ = 250 GeV stage, respectively.
- The next steps for this analysis would be to delve into the fit method of the signal and background for the selected recoil mass. The difficulty arises from the shapes being very similar in the range of study MRecoil $\in$ [100, 170] GeV. Another approach would be to fit the recoil mass in each of the different jet topologies, in which the difference becomes more clear, and combine the results. This would be possible thanks to this analysis introducing very small bias from each Higgs decay mode.

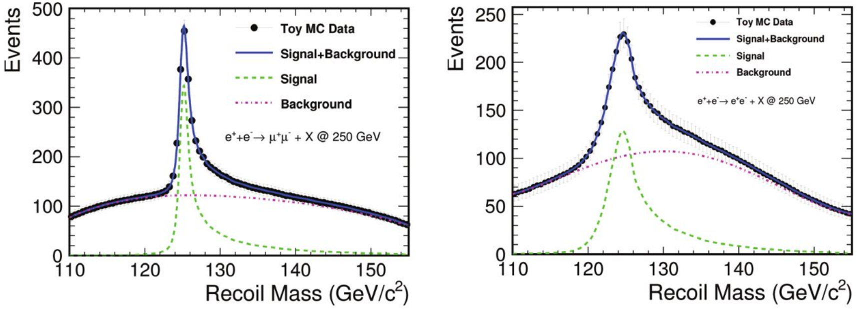
Backup

ILC
Physics

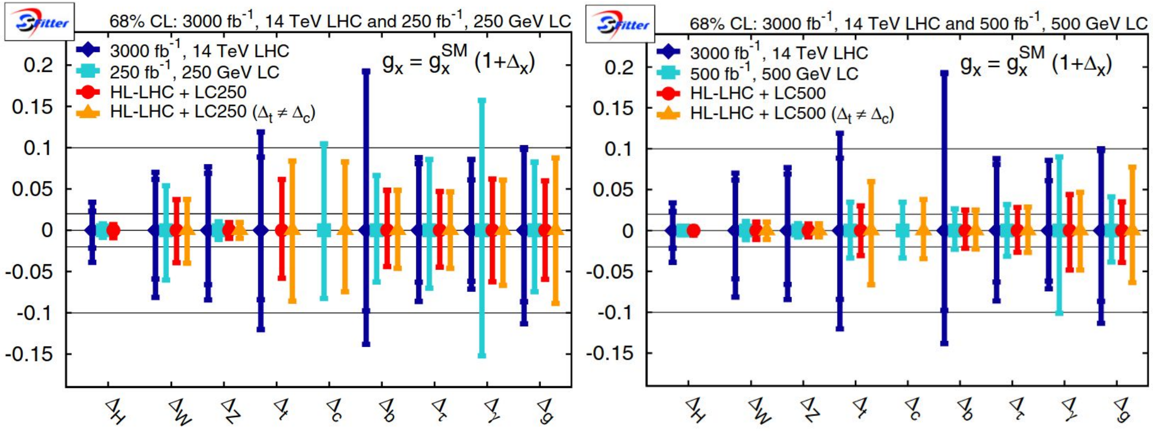
The main efforts of the physics studies will be focused on the Higgs sector through model independent analyses.

The initial stage of the ILC program starts at the maximum cross section of the *Higgstrahlung* ($e^+e^- \rightarrow ZH$) production process.

Leptonic channel



Expected precision for the Higgs couplings:

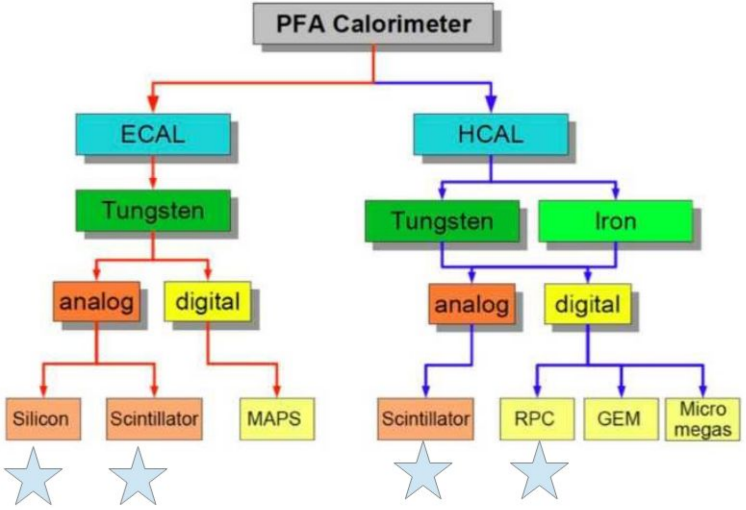


CALICE

What is CALICE?

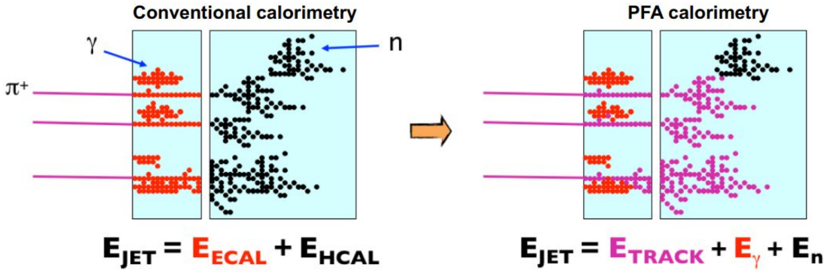
"The CALICE Collaboration (Calorimetry for Linear Collider Experiments) is an R&D group of around 280 physicists and engineers from around the world, working together to develop new, high granularity detectors for high energy e^+e^- experiments."

- Future experiments: **ILC** → ILD and SiD, CLIC, FCCee, CEPC, LUXE, ...
- Precision physics and Higgs model independent analysis.
- **REQUIRED:** calorimetry compatible with jet energy resolutions ~3-4% above 100 GeV.
- **APPROACH**: Particle Flow Algorithms. New high granularity calorimetry is needed.



Particle Flow Algorithm

The Particle Flow Algorithm (PFA) allows the reconstruction of individual particles, following it through all subsystems and measuring its four momentum in the system which provides the best resolution.



Requires: high granularity in all systems

$$\sigma_{jet} = f_{\pm} \cdot \sigma_{\pm} \oplus f_{\gamma} \cdot \sigma_{\gamma} \oplus f_{h^0} \cdot \sigma_{h^0} \oplus \sigma_{conf} \oplus \sigma_{loss}$$