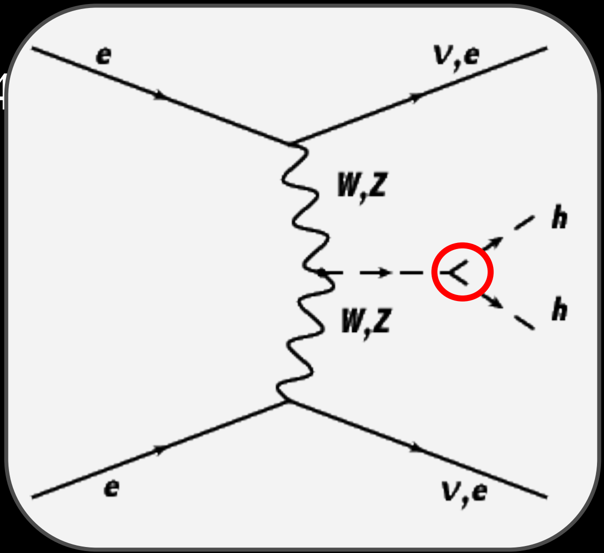
Measurement of the trilinear Higgs self-coupling at CLIC

Tomáš Laštovička (Prague)
Jan Strube (CERN)

Introduction

$$V(\eta_H) = \tfrac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \tfrac{1}{4} \lambda' \eta_H^4$$



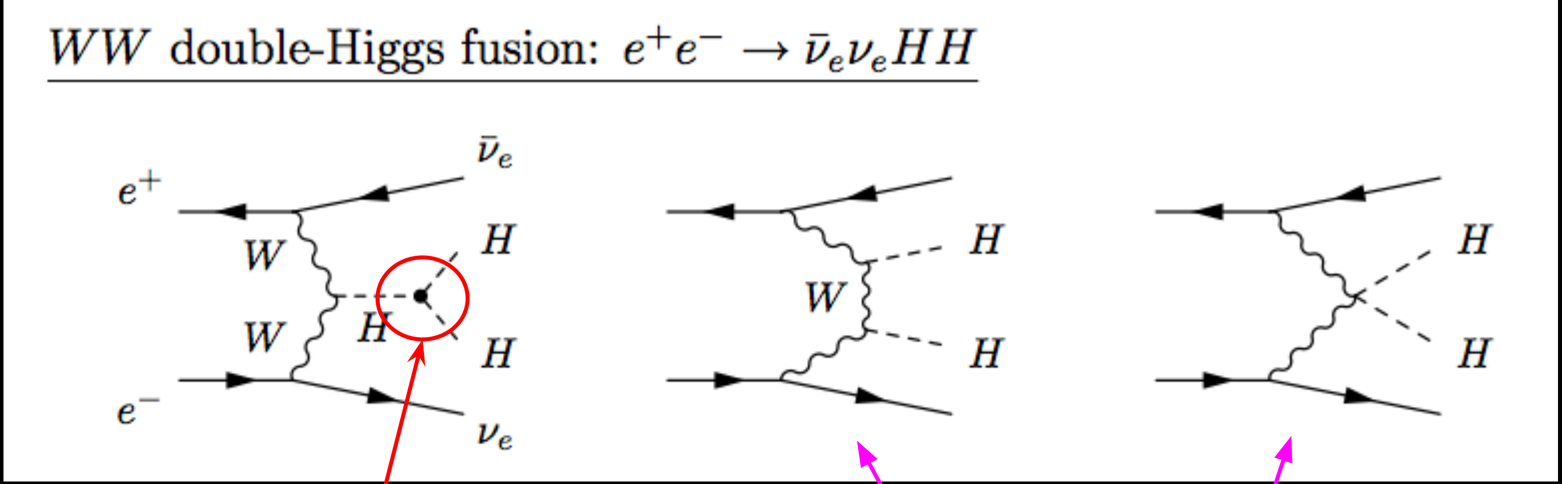
In the Standard Model:

$$\lambda = \lambda' = \lambda_{SM} = m_H^2/2v^2$$

Radiative corrections decrease this by ~10%
Can be increased by 100% in 2HDM

We want to measure the rate of double Higgs production and relate it to λ_{hhh}

Double Higgs Production channels


WW double-Higgs fusion: $e^+e^- \to \bar{\nu}_e\nu_e HH$

That's the one we are interested in

Signal modes that don't contribute to the measurement

There is destructive interference between the diagrams.
The greater the value of λ_{hhh} the smaller the rate of producing two Higgs bosons.

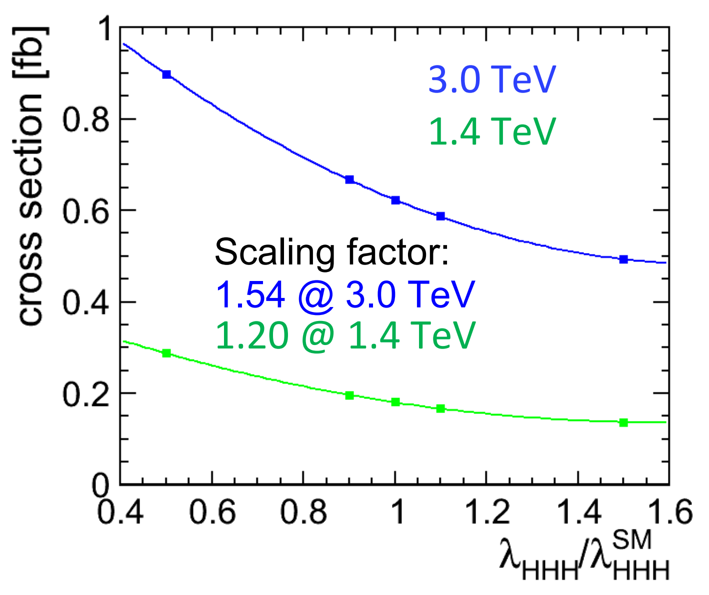
Analysis Overview

- m_H = 120 GeV (m_H = 126 GeV iteration started)
  - analysis results for m_H = 120 GeV unless stated otherwise
- Analysis at the 1.4 TeV and 3.0 TeV stages at CLIC
- Small signal cross section:
  - 0.16 fb at 1.4 TeV
  - 0.64 fb at 3.0 TeV
- Baseline: unpolarized beams
  - 1.5 ab^{-1} at 1.4 TeV
  - 2 ab^{-1} at 3 TeV

Measuring the tri-linear self-coupling by measuring the cross section

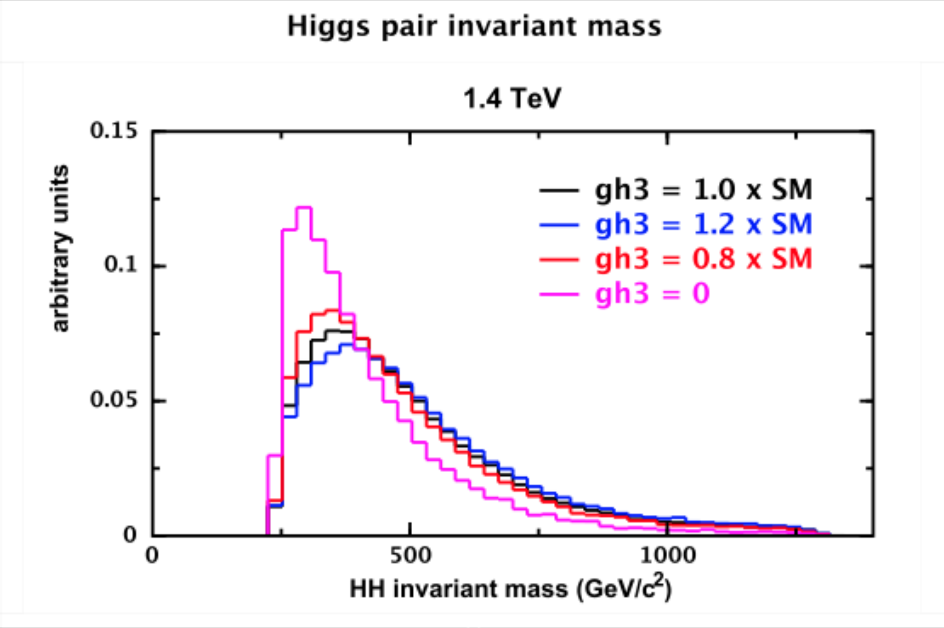
Relating the measured uncertainty on the cross section to lambda

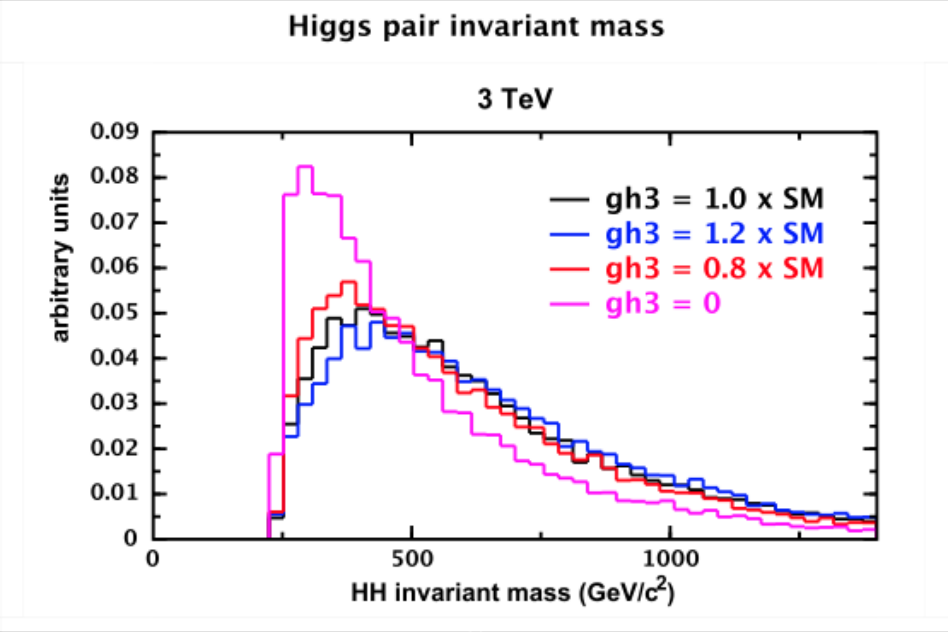
1. Change the value of λ in the event generator (whizard1)
2. Compute cross section taking into account the full CLIC beam spectrum and ISR
3. Fit with parabola. Derivative at $\lambda=\lambda_{SM}$ is the scaling factor R in the relationship $\Delta\lambda = R\,\Delta\sigma$



⇒ R=1.20 @ 1.4 TeV
⇒ R=1.54 @ 3.0 TeV

Signal Properties with different values of the tri-linear self-coupling

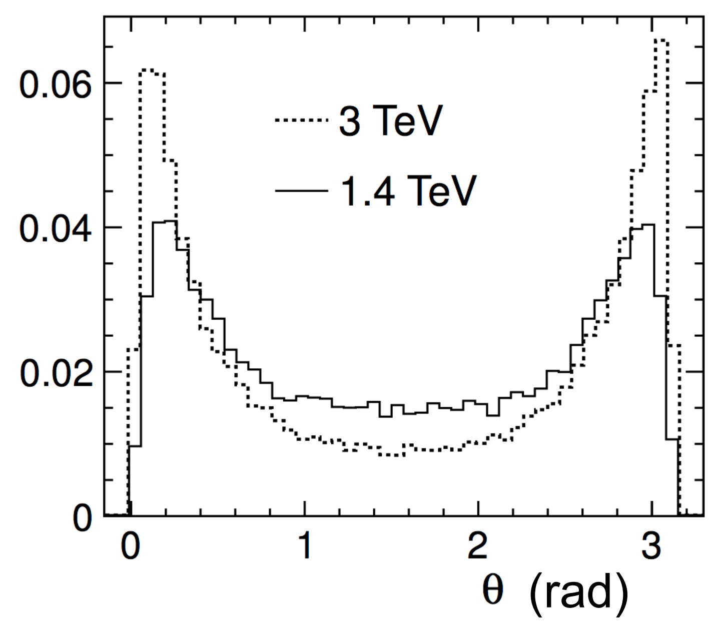




The shape of the invariant mass of the Higgs pair changes with the value of the self-coupling. A neural network selection is sensitive to this change.

Signal event properties

Higgs Boson polar angle



SM Higgs Boson Branching Ratios

Higgs Decay	m_H = 120 GeV	m_H = 126 GeV
H → bb	65%	56%
H → WW	14%	23%
H → τ τ	7.0%	6.1%
H → cc	3.3%	2.8%
H → ZZ	1.6%	2.9%

Analysis
baseline

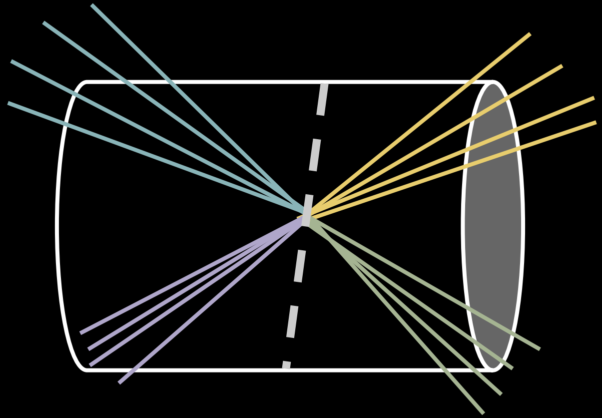
Available Event Samples (m_H = 120 GeV)

Target 1.5 ab^{-1}

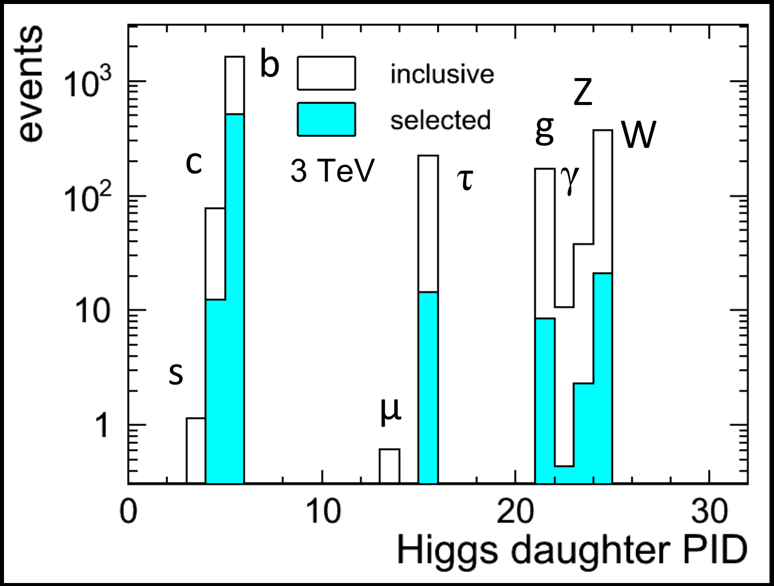
Target 2.0 ab^{-1}

Channel	$\sqrt{s}$ = 1.4 TeV cross section (fb)	$\sqrt{s}$ = 3.0 TeV cross section (fb)
2 Higgs + missing energy	0.16	0.63
4 jets + missing energy	24.7	74.1
4 jets + 2 leptons	71.7	182
4 jets + 1 lepton	115	
4 jets	1325	593
2 jets		3076
2 jets + missing energy	646	1305
2 jets + 2 leptons		3341
2 jets + 1 lepton		5255

Analysis Strategy



- Isolated Lepton Finding
  - Reduces 4 jets + 1-2 leptons background
- Force events into four jets (FastJet kt R=1.0)
- Divide event into hemispheres based on thrust
  - Pair jets by hemisphere, if possible
  - Using kinematic criteria otherwise
- Neural Network (FANN) to distinguish between signal / background
  - Train 50 networks independently to improve stability
  - Using inclusive Higgs sample as signal
  - Works reasonably well for 120 GeV Higgs
  - Somewhat different BR for 126 GeV Higgs call for more differentiated approach
- Cut-and-count as cross-check.
  Neural network template fit for improved performance



The CLIC_SID detector

<u>Features:</u>

All-silicon tracker:

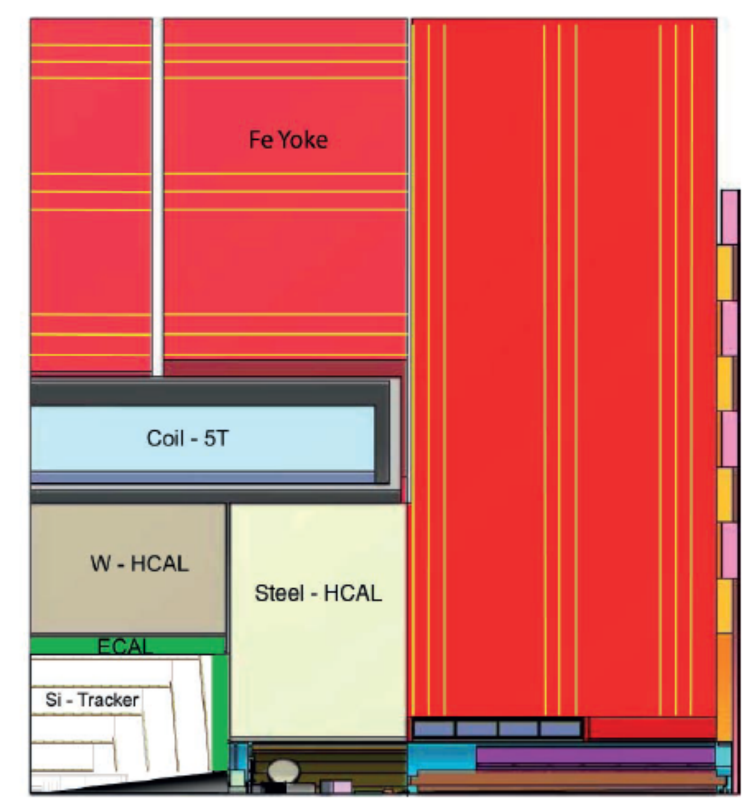
- 5 layers VTX
  (inner layer 27 mm from IP)
- 5 layers strip tracker

(20+10) layers Si-W ECAL

7.5 λ W-HCAL barrel

5 T field

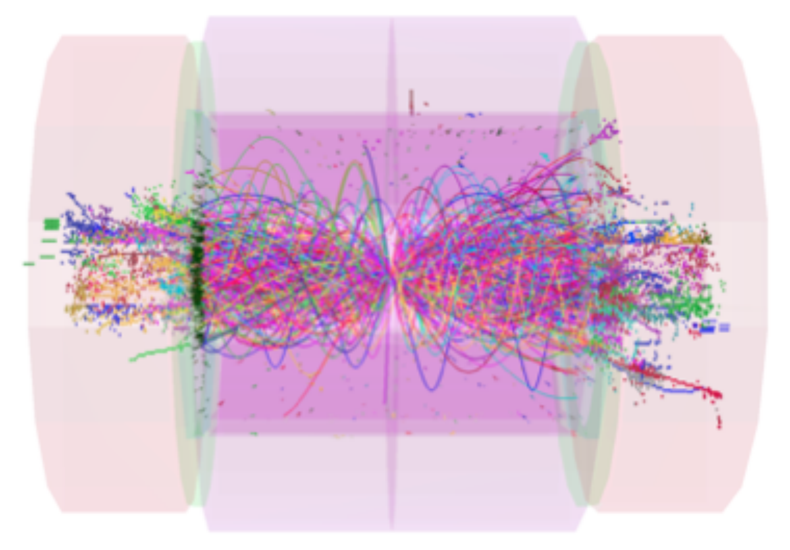
Tracking down to 7°



The CLIC environment

Collision energy	1.4 TeV	3.0 TeV
Bunch spacing	0.5 ns	0.5 ns
Bunches / Train	312	312
Bunch repetition rate	50 Hz	50 Hz
$\gamma\gamma \rightarrow$ hadrons per BX	1.3	3.2

Events pile up in the detectors
19 TeV / train deposited in the calorimeters at $\sqrt{s} = 3.0$ TeV



Treatment of Background

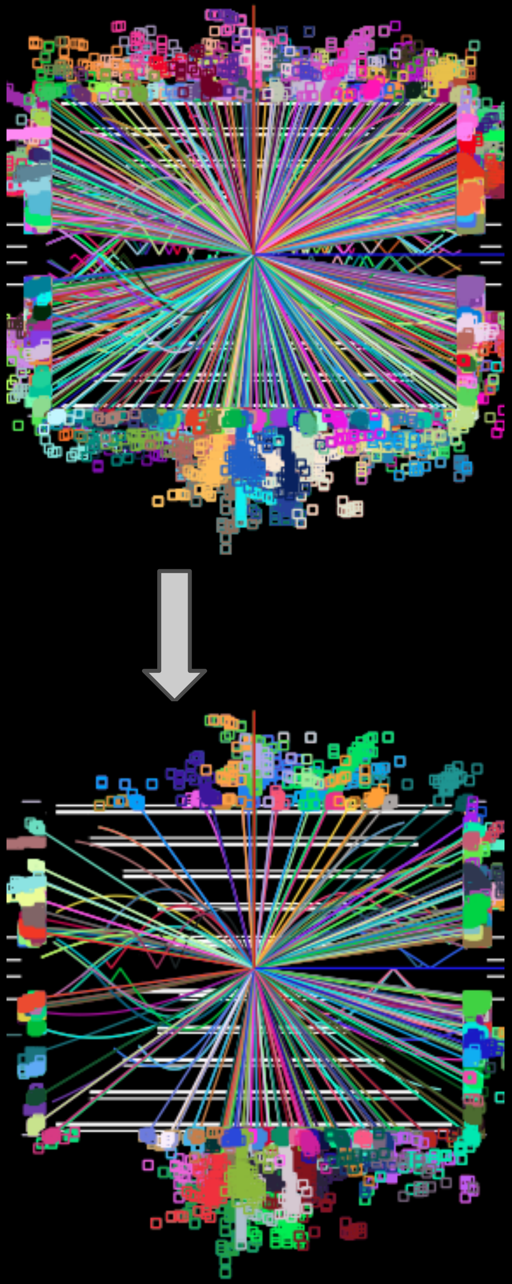
Gained experience with background during CDR analyses

Three ingredients:

1. Identify physics event in the bunch train offline, discard hits outside of 10ns window (100 ns in the HCAL barrel)
2. Precise time stamping in the subdetectors (~ few ns) allows to apply cuts on PFO time
3. Jet reconstruction used in hadron colliders to collect remaining background in beam jets

All studies done with full simulation of signal + 60BX of $\gamma\gamma \rightarrow$ hadrons

HH$\nu\nu$ at 3.0 TeV



The second technique reduce this

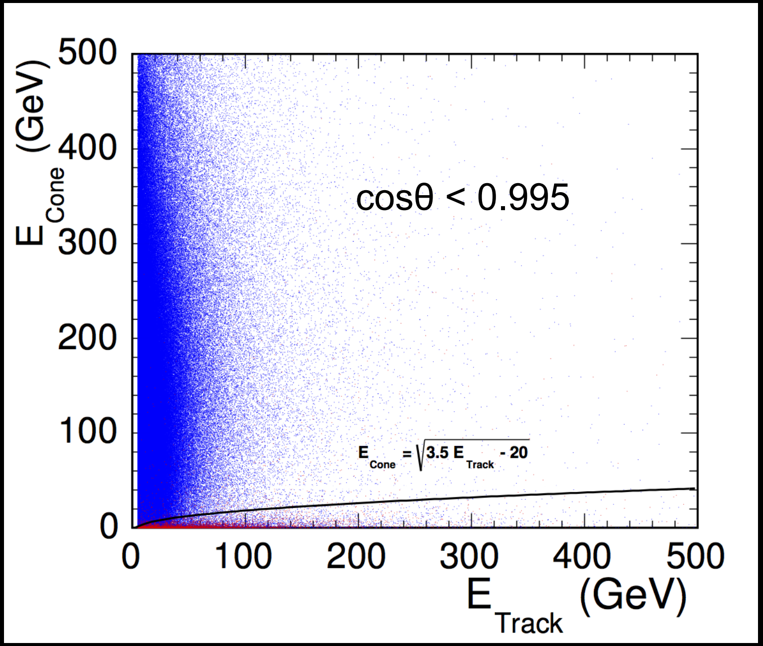
to this

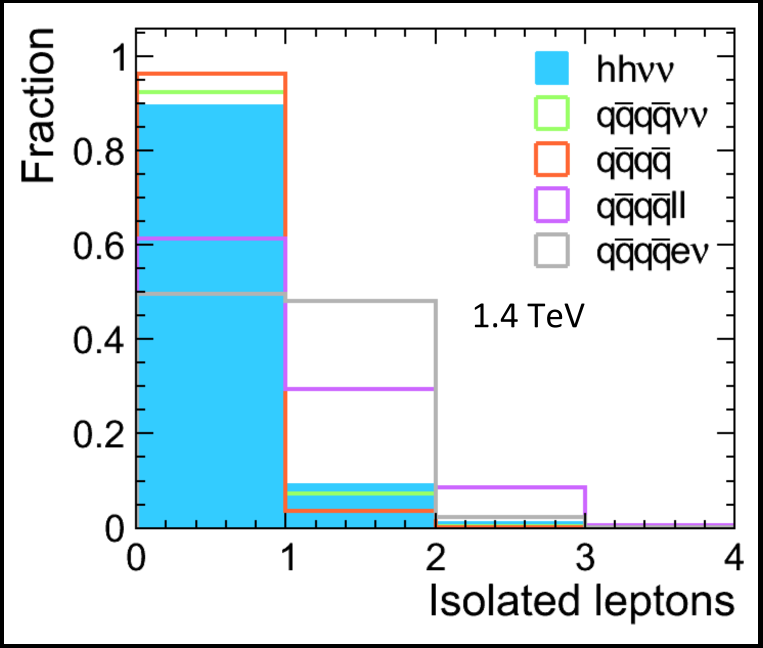
Isolated Leptons

IsolatedLeptonFinder in MarlinReco allows to use parabolic relationship between cone energy and track energy

Performance has been studied in a sample containing one leptonic W decay

Optimization studies ongoing



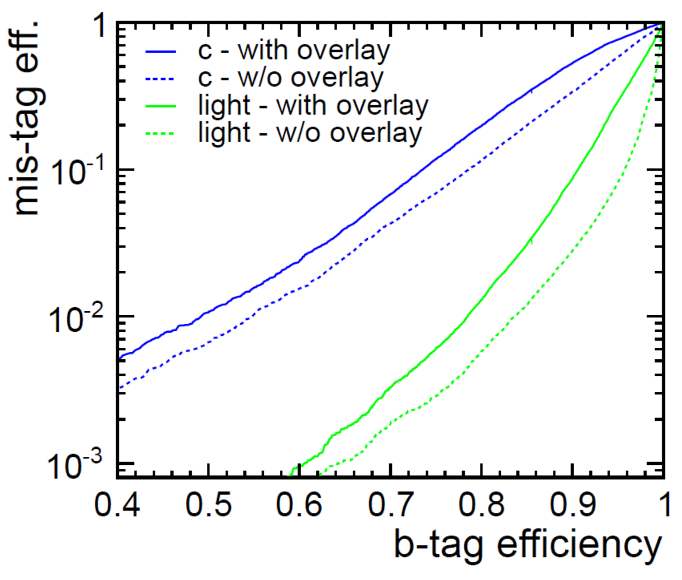


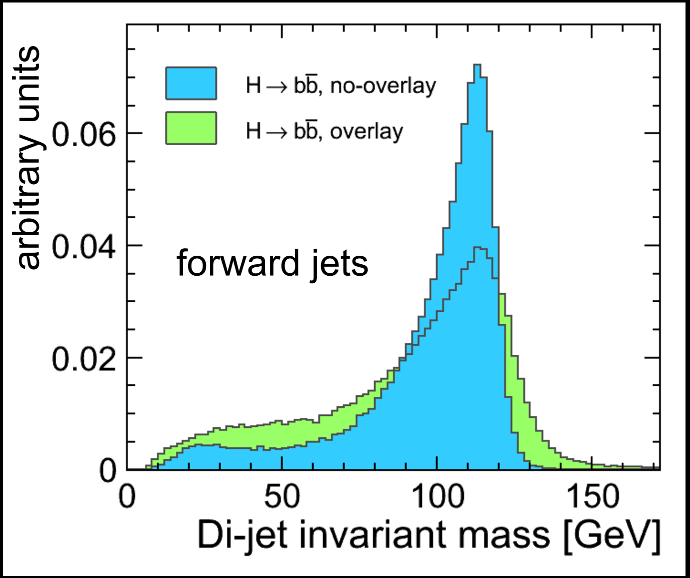
b-jet reconstruction

LCFIVertex package:

- ZVTop vertex reconstruction
- Flavor tagging using FANN

Impact of machine-related background on both invariant mass and b-tagging performance has been documented in more detail in CLIC CDR





Neural net event selection

Inputs (22 in total):

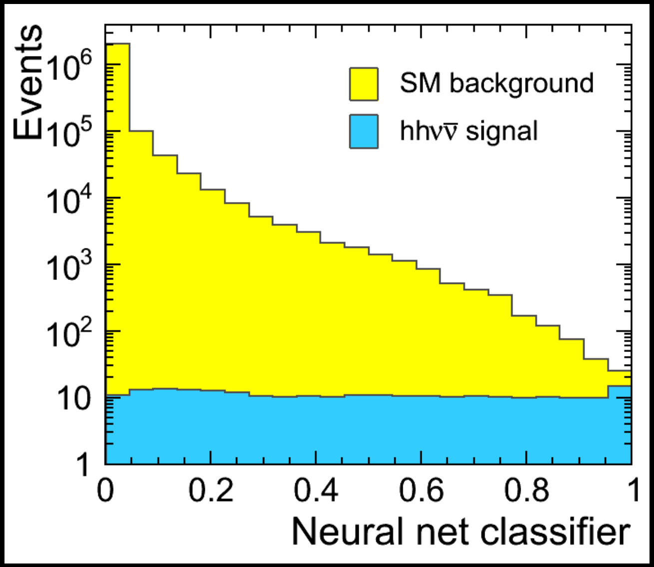
- Invariant masses of jet pairs
- Sum of jet flavour tags for each pair separately
- Angle between jet pairs
- Event invariant mass and total energy
- number of leptons and photons
- max(|eta_i|) of jets
- p_T^{max} and p_T^{min} of jets
- y_{min} from FastJet

depends on the jet pairing, depends only on the jet reconstruction

does not depend on the jet pairing nor on the jet reconstruction (except the beam jet)

Neural Network Results

1.4 TeV (1.5 ab^{-1})

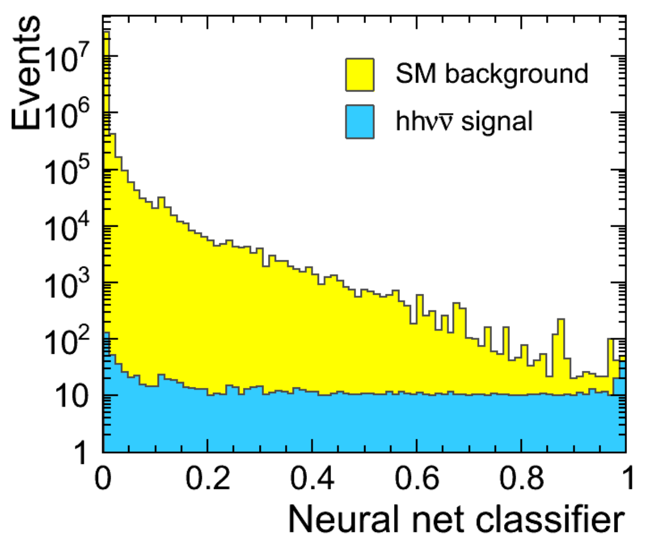


$\sigma_{HH\nu\nu}$ uncertainty: 22%

λ_{HHH} uncertainty: 28%

background dominated by generic 4-jet background (+ $l\nu$ or $\nu\nu$)

3.0 TeV (2 ab^{-1})



$\sigma_{HH\nu\nu}$ uncertainty: 10%

λ_{HHH} uncertainty: 16%

complete set of backgrounds, except 4 jets + 1 lepton (in progress)

Quoted Results from template fitting of the modified coupling samples. Cross-section analysis using scaling factors gives consistent values.

Ways to increase the number of signal events

Polarization significantly increases the signal cross section
e.g. from 0.63 fb (unpolarized) to 1.37 fb (-80%, +30%)

collision energy Polarization e^-/e^+	√s = 1.4 TeV unpolarized	√s = 1.4 TeV -80% / +30%	√s = 3.0 TeV unpolarized	√s = 3.0 TeV -80% / +30%
Δ σ(HHνν)	≈ 22%	≈ 18%	≈ 10%	≈ 7%
Δ λ_{HHH}	≈ 28%	≈ 22%	≈ 16%	≈ 11%

Numbers with polarized beams obtained by scaling signal and background cross sections, ignoring polarization-dependent changes to kinematic properties.

all cross section values:
mH = 120 GeV

Other Channels contributing
at 1.4 TeV: ZHH cross section ~50% of HHνν
at 3.0 TeV: ZHH cross section < 10% of HHνν

Z boson fusion diagrams (electrons in final state)
< 15% of W boson fusion cross section

Note:
m_H = 126 GeV results in slightly smaller signal cross sections
σ(HHνν) = 0.15 fb at 1.4 TeV
σ(HHνν) = 0.59 fb at 3.0 TeV
both with unpolarized beams

Further development

Limiting factors are

- Forward Jet reconstruction
- Flavor tagging
- Forward lepton tagging

Each can be addressed by optimizing detector performance and improvements to reconstruction

Needs careful study -- a lot of work

Further opportunities for improvement in analysis strategy and reconstruction software remain.

Summary and Conclusions

- The measurement of the Higgs tri-linear self-coupling requires large luminosity (and probably a high-energy linear collider)
  - The measurement at 1.4 TeV with unpolarized beams is very difficult
  - The higher cross section (esp. with polarized beams) at 3.0 TeV makes this measurement feasible
- The study is currently being updated with m_H = 126 GeV and will be cross-checked with performance in CLIC_ILD
  - e - gamma background being added
- Further Improvements to the analysis and possibility of detector optimization can still be explored