Higgs self-coupling studies at CLIC

(preliminary)

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Overview

- CLIC environment
- Higgs trilinear coupling
- Event reconstruction and selection
- Results for 1.4 TeV and 3 TeV CLIC
  - Cut-and-count method
  - Template fitting
- 126 GeV Higgs
- Polarised CLIC beams
- Analysis prospects
- Summary

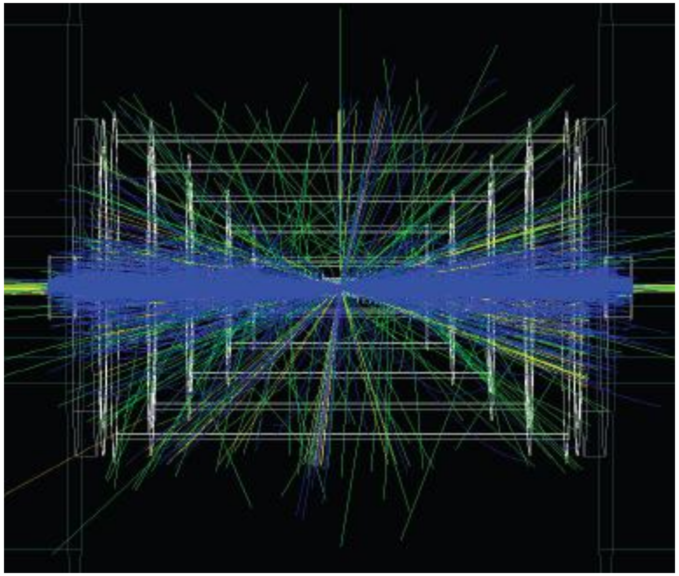
CLIC ENVIRONMENT

THE CLIC ACCELERATOR ENVIRONMENT

Center of mass energy	500 GeV	1.4 (1.5) TeV	3 TeV
Bunch spacing	0.5ns	0.5 ns	0.5 ns
Bunches per train	354 (312)	312	312
Train repetition rate	50 Hz	50 Hz	50 Hz
$\gamma\gamma \rightarrow$ hadrons per BX	0.3	1.3	3.2

Staging scenario A(B)

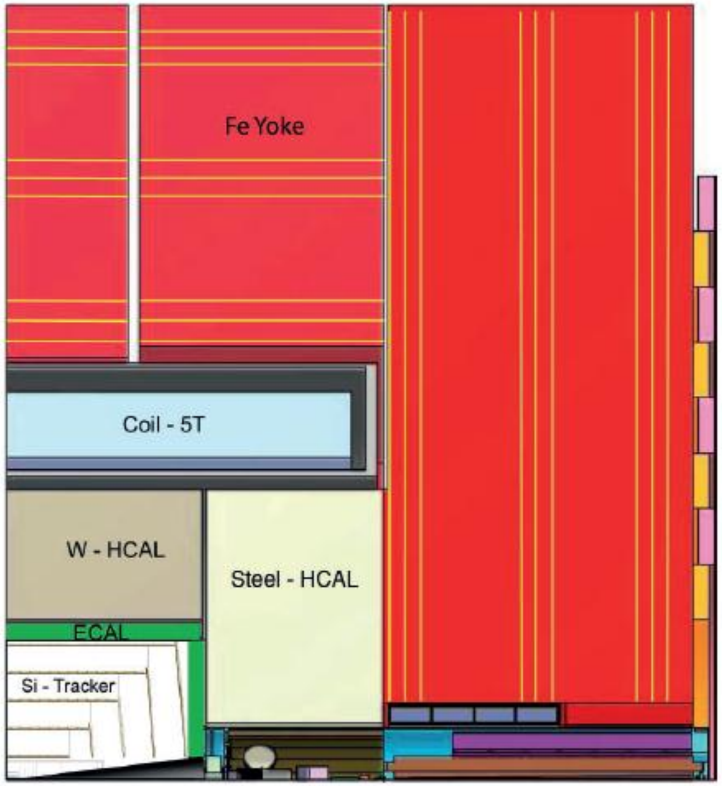
- Challenging environment
- $\gamma\gamma$ overlay → 19TeV visible energy @ 3 TeV
  - Reduced by a factor of 16 in 10ns readout window.
  - Requires to employ "LHC-style" jet reconstruction algorithms (typically FastJet k_T).
- For CLIC staging see D. Schulte's presentation.



THE CLIC DETECTORS

- CLIC_SiD and CLIC_ILD
  - based on SiD and ILD detector concepts for ILC Letters of Intent.

- CLIC_SiD concept
  - CDR Light Higgs analyses
    - H → bb, H → cc, H → μμ
    - H → HH
  - Inner vertex layer @ 27mm
    was 14mm for the SiD
  - 7.5 λ W-HCAL barrel
  - Tracking down to 10°
  - 5T magnetic field



CLIC_SiD

CLIC HIGGS STUDIES

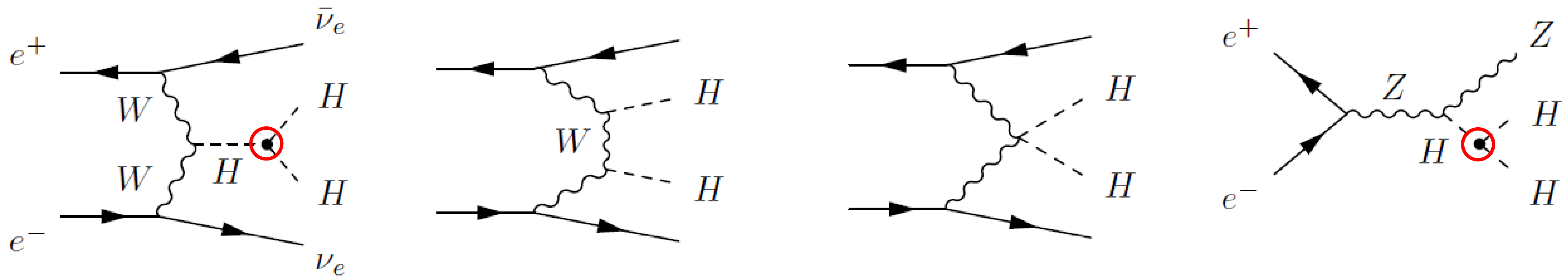
- Event generation, both signal and background: Whizard 1.95
  - realistic beam spectrum, ISR
  - unpolarised beams
- Hadronisation: Pythia 6.4
- Full event simulation
  - Geant4 via SLIC (CLIC_SiD)
  - 60 BX γγ→hadrons overlaid in each event @ both 3.0 and 1.4 TeV
- Full event reconstruction
  - PFA with PandoraPFA
  - 10 ns readout window; except HCAL: 100 ns
- Target integrated luminosity: 2 ab^{-1} (3 TeV) and 1.5 ab^{-1} (1.4 TeV)
- CLIC @ 3.0 (1.4) TeV: $\sigma_{hh\nu\nu}$ = 0.63 (0.164) fb; via WW fusion

Data samples

- Due to historical reasons most of the analysis is done for 120 GeV Higgs.
- Higgs decay modes
  - The final state is HHνν; Pythia consequently decays Higgs to: b, c, s, μ, τ, g, γ, Z, W
- 126 GeV samples generated and tested
  - small degradation of results w.r.t. 120 GeV Higgs is observed
- SM Background
  - Standard Model 4Q and 2Q backgrounds
    - qqqqνν, qqqqeν, qqqqll, qqqq
    - Hνν, qqνν, qqeν, qqll, qq – (3 TeV only)
  - Due to technical difficulties qqqqeν background is not included at 3 TeV
    - currently being simulated and reconstructed

HIGGS TRILINEAR COUPLING

HIGGS TRILINEAR COUPLING



$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4 \qquad \lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$$

- λ represents the trilinear coupling
  - and quartic coupling (difficult to measure)
  - direct determination of the Higgs potential
  - the force that makes Higgs condense in the vacuum
- WW fusion HHνν dominates over Higgs-strahlung ZHH for √s ≈ 1.2 TeV and above
  - In WW (ZHH) channel the cross section increases (decreases) with decreasing λ.

Extraction of λ from $\sigma_{HH\nu\nu}$ cross section

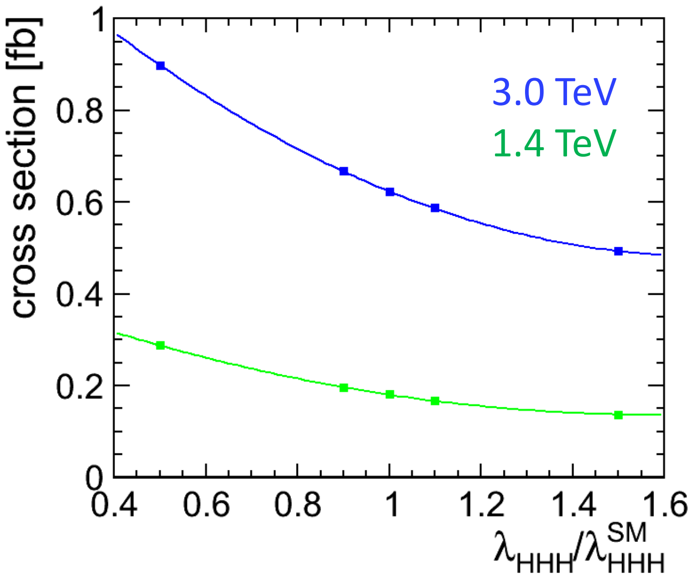
- An option to change the Higgs self-coupling parameter was added to Whizard.
- Cross section $\sigma_{hh\nu\nu}$ calculated with various $\lambda_{HHH}/\lambda^{SM}_{HHH}$
  - 3 TeV and 1.4 TeV CLIC beam spectrum, ISR
- Cross section dependence fitted by a 2nd order polynomial.

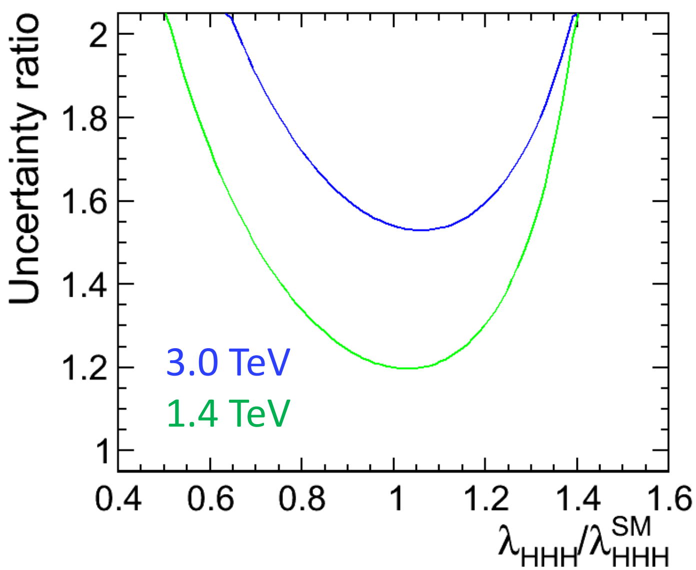
$$\frac{\Delta\lambda}{\lambda} = R\frac{\Delta\sigma}{\sigma}$$

- Values of "uncertainty relating factor R" at $\lambda_{HHH}/\lambda^{SM}_{HHH} = 1$ (Whizard 2):

3.0 TeV: 1.54

1.4 TeV: 1.20





EXPERIMENTAL CHALLENGES AT CLIC

- Multi-jet final state with missing energy

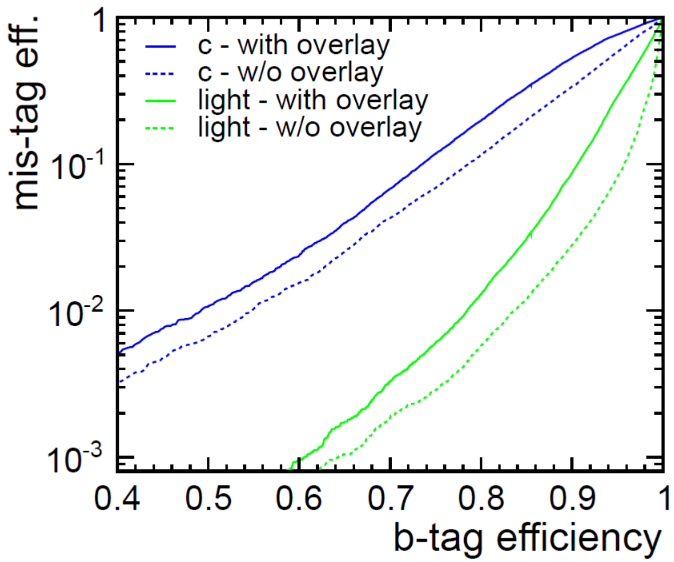
- Missing energy leads to low energy jets

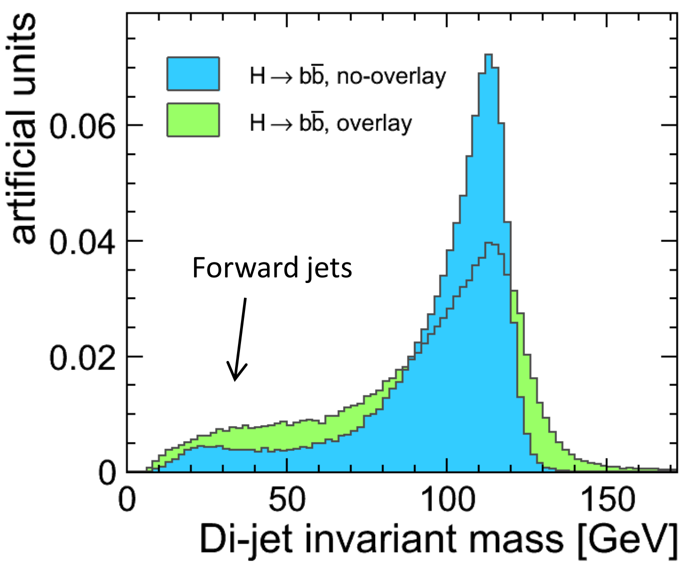
- Pile-up from $\gamma\gamma \rightarrow$hadrons beam background
  - Jet flavour tagging affected
  - Downgrades jet/event reconstruction

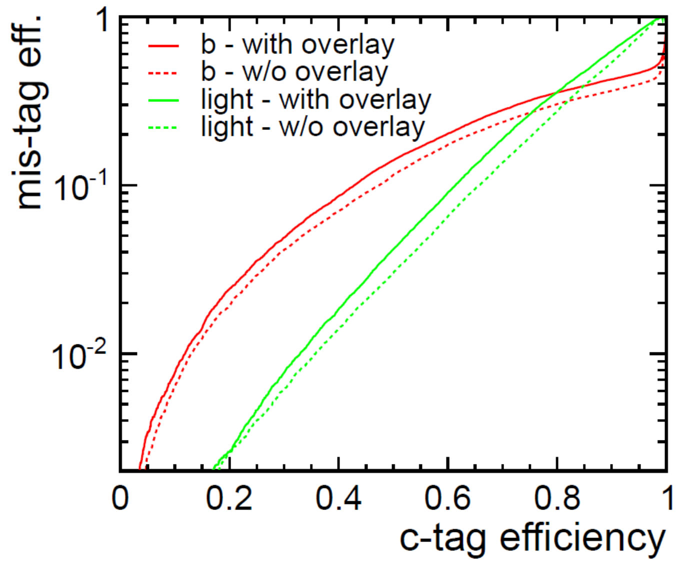
- Small separation between H and W/Z

JET FLAVOUR TAGGING AT 3TeV WITH γγ OVERLAY

- **LCFIVERTEX package**
  - FANN neural net package used throughout the Higgs analysis both for the flavour tag and the event selection.
  - Presence of γγ overlay (60BX considered) degrades both the jet-finding and the jet flavour tag quality (shown for di-jet events).





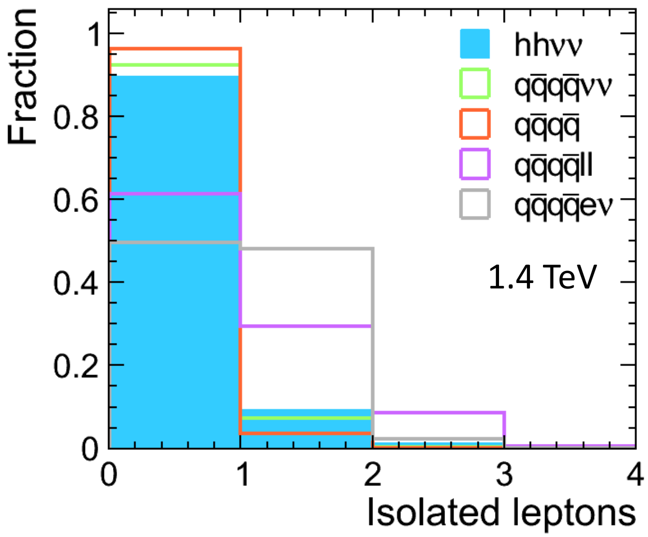


Event selection

- 4 jets reconstructed with FastJet
  - 3 possible combinations to make two Higgs bosons.
  - Jets paired in hemispheres.
  - A purely geometric criterion to pair jets is less biased than a kinematic one.
  - Forward jet reconstruction is difficult and at some point leads to losing particles and replacing them with background.

- No isolated leptons
  - Suppression of qqqqll and qqqqev.

- Neural network classifier
  - Combining 22 quantities into one.

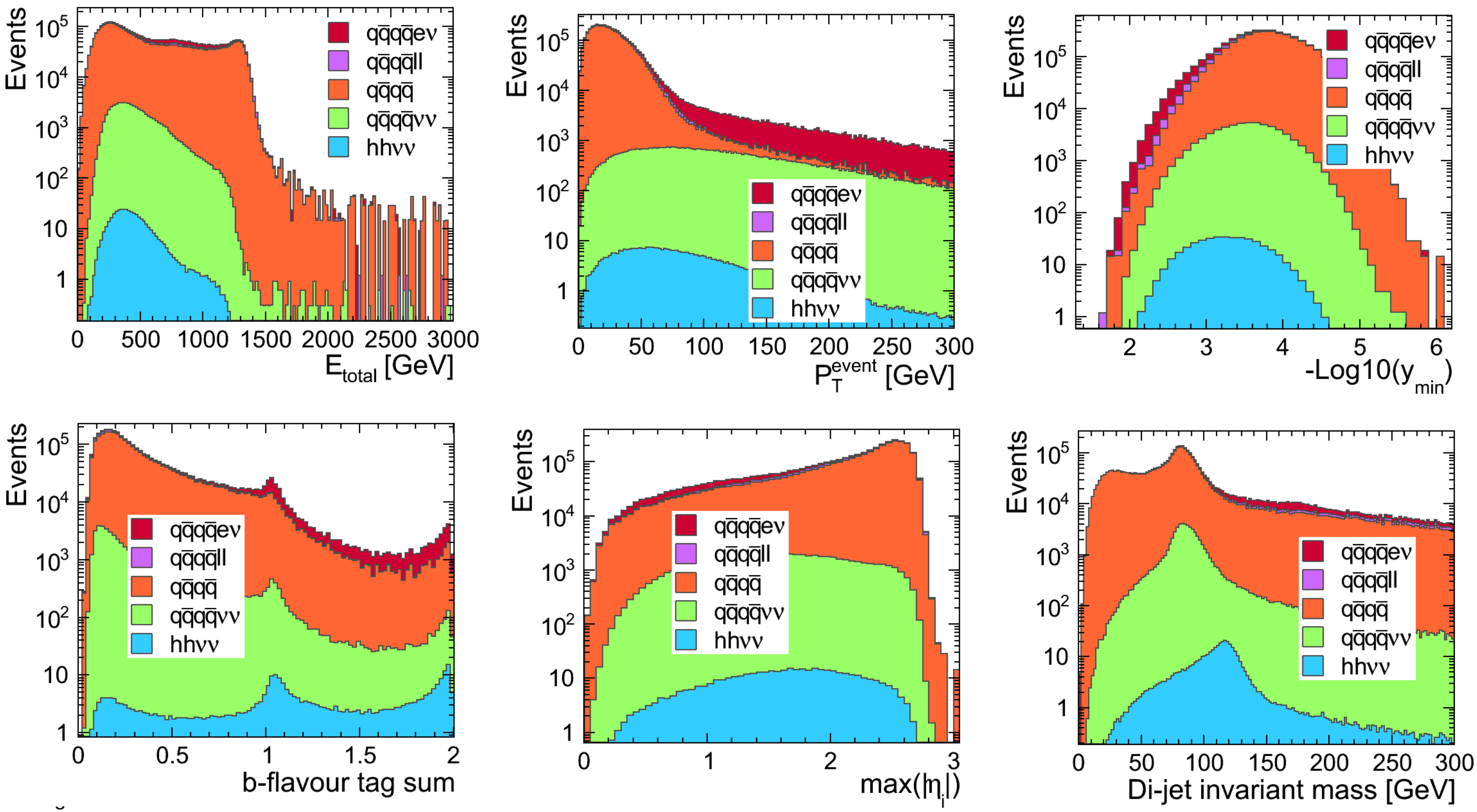


Neural net inputs

invariant masses of jet pairs
event invariant mass and visible energy
missing transverse energy E_t
y_{min} and y_{max} from FastJet
p_t^{min}, p_t^{max} of jets
#leptons and #photons in event
$\max(\lvert\eta_i\rvert)$ and $\mathrm{sum}(\lvert\eta_i\rvert)$ of jet pseudorapidities η_i
angle between jet pairs
sums of LCFI flavour tag outputs (per jet pair):
b-tag, c(b)-tag, c-tag and b(light)-tag

EVENT SELECTION

- Example variables/inputs for 1.4 TeV; signal and 4q backgrounds shown.



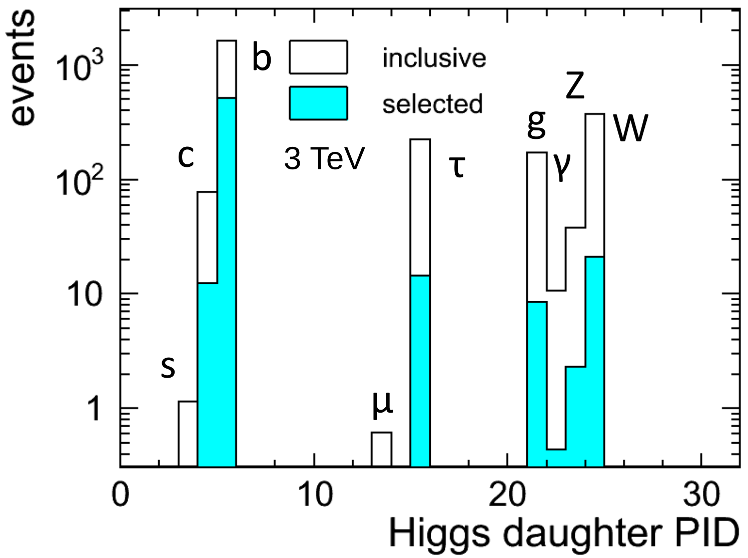
CUT-AND-COUNT METHOD

- Find a cut on the neural network output which minimises
  - Signal (HHνν) cross section uncertainty

    - or -

  - Directly the λ_{HHH} uncertainty
    - Uncertainty ratio R may depend on the event selection.
    - Signal samples with 0.8 λ_{SM} and 1.2 λ_{SM} added to evaluate λ_{HHH} uncertainty per cut.

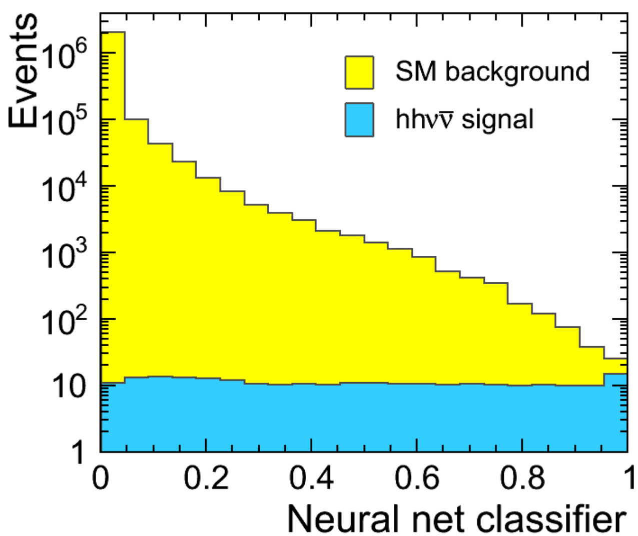
- No explicit channel selection enforced
  - H→bb channel naturally dominates after the neural net selection.
- Statistical uncertainty evaluation
  - Count signal (S) and background events (B): √(S+B)/S



1.4 TeV Results for 1.5 ab^{-1}

	$\sigma_{HH\nu\nu}$ minimisation	λ_{HHH} minimisation
$\sigma_{HH\nu\nu}$ uncertainty	**30%**	
λ_{HHH} uncertainty	36% (R = 1.2)	**35%**
Signal	$28^{+8.8}_{-8.1}$	$28^{+8.8}_{-8.1}$
Background	43	43
Signal total	246	246
Signal efficiency	11%	11%

- Both minimisations give about the same result.
- Background dominated by
  - qqqqνν, qqqqlν and qqqq (4xCS than at 3 TeV)

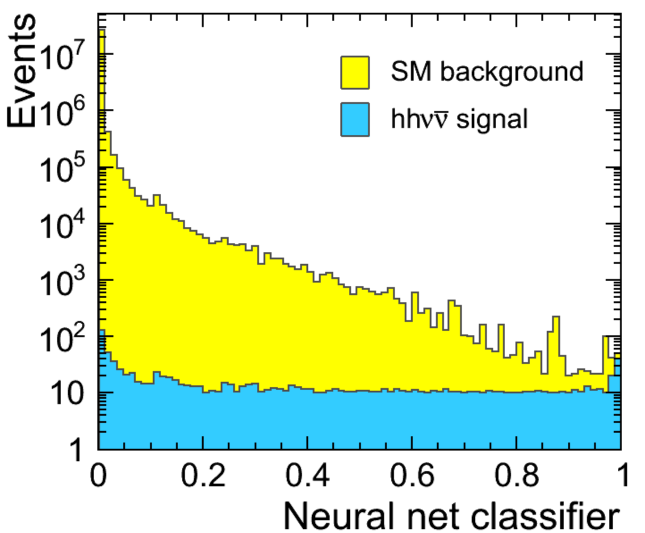


3.0 TeV Results for 2 ab^{-1}

	$\sigma_{HH\nu\nu}$ minimisation	λ_{HHH} minimisation
$\sigma_{HH\nu\nu}$ uncertainty	**13%**	
λ_{HHH} uncertainty	20% (R = 1.54)	**21.3%**
Signal	151	291
Background	229	1235
Signal total	1260	1260
Signal efficiency	12%	23%

- Direct λ_{HHH} minimisation prefers almost twice as many events compared to $\sigma_{HH\nu\nu}$ minimisation.

- Complete set of backgrounds except qqqqlν
  - Currently being generated and simulated.



TEMPLATE FITTING

- Neural network (BDT, …) should digest all available information from its inputs and concentrate it in its output.
- Cut-and-count method does not fully harvest the neural net output information, however, the template fitting should.
- Template fitting merely considered as an indicator of measurement limits.

  – BINNED TEMPLATE FITTING

    Neural net output binned into a fine-binned histogram

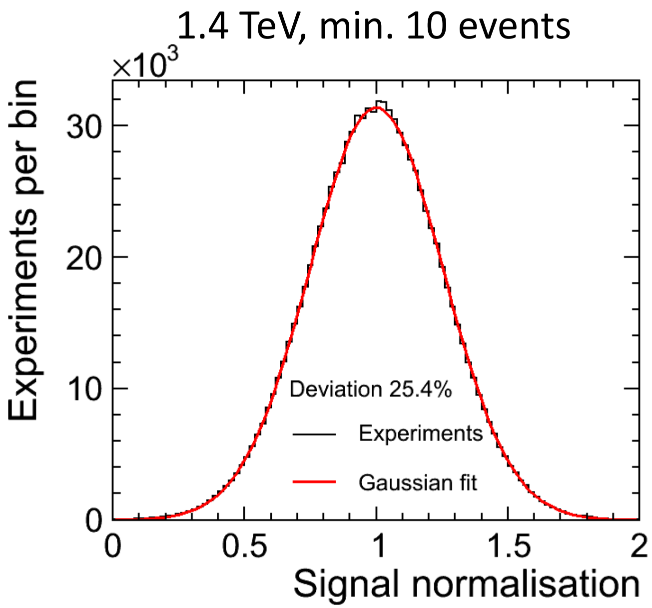
    re-binned: at least N signal and bkgr. events per bin

    10^6 "experiments" generated and fitted

  – UNBINNED TEMPLATE FITTING

    ROOFIT employed to obtain signal and bkgr. PDFs

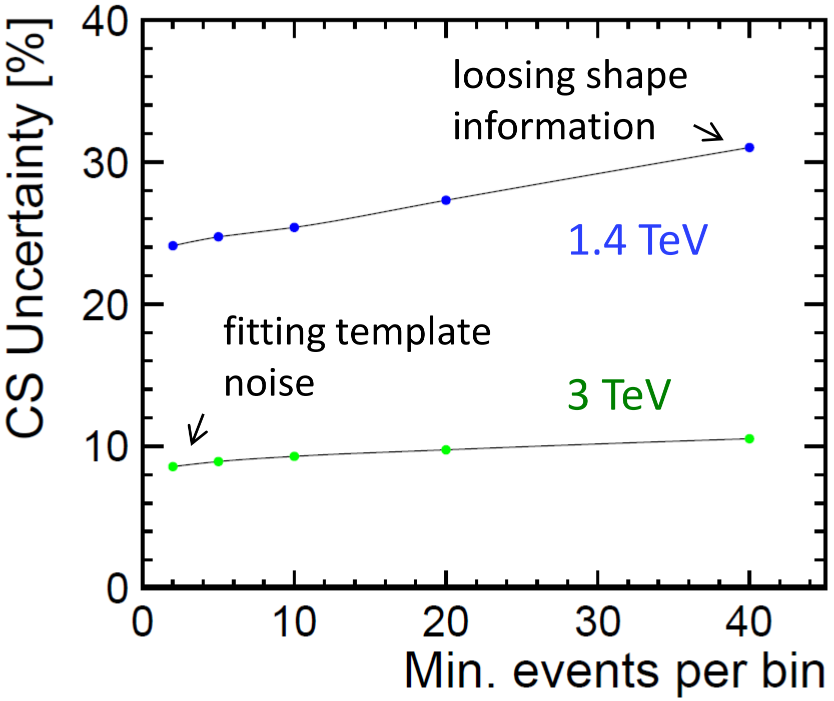
    work in progress…



RESULTS

1.4 TeV	$\sigma_{HH\nu\nu}$ uncertainty	Ratio R	λ_{HHH} uncertainty
	24 – 26%	x 1.20	29 – 31%
3.0 TeV			
	9 – 10%	x 1.54	13.5 – 15%

- There is a dependency of the $\sigma_{HH\nu\nu}$ uncertainty on the expected number of events per bin
  - When the number of entries per bin is large, the information in the “distribution shape” is lost.
  - On the other hand, when it is small, we fit the template/event noise.
- Unbinned template fitting.
  - under progress



126 GeV Higgs

- Analysis was repeated with 126 GeV Higgs samples.
- Default self-coupling value only
  - Modified coupling samples will be added.

1.4 TeV		$\sigma_{HH\nu\nu}$ unc. 126 GeV	$\sigma_{HH\nu\nu}$ unc. 120 GeV
	Cut-and-count:	35%	30.2%
	Template fit:	~30%	24-26%
3.0 TeV			
	Cut-and-count:	13.5%	13%
	Template fit:	10.5-11%	9-10%

- $\sigma_{HH\nu\nu}$ uncertainty degradation observed. Effect on λ_{HHH} yet to be evaluated.

CLIC WITH POLARISED BEAMS

- Polarisation considered: 80% – 0%
  - The signal cross sections are about 1.4-1.7x larger (qqqqvv, qqvv 2.2x larger)
  - The following results are merely indicative
    - only cross sections changed, no events simulated/reconstructed, no NN re-training

1.4 TeV		σ_{HHvv} unc. (80%-0%)	σ_{HHvv} unc. (0%-0%)
	σ_{HHvv}	0.233 fb	0.164 fb
	Cut-and-count:	~26%	30.2%
	Template fit:	~20-21%	24-26%
3.0 TeV			
	σ_{HHvv}	1.05 fb	0.63 fb
	Cut-and-count:	~10%	13%
	Template fit:	~7-8%	9-10%

Analysis prospects

- Background samples will be completed.
- There may be some potential in improving the jet reconstruction.
  - Few paths pursued: e.g. vertex assisted jet finding and jet reconstruction (small effect).
  - FastJet was not tuned for e^+e^- collissions.
- 126 GeV Higgs
  - Modified coupling samples
- Polarised beams
  - 80% – 0% considered, uncertainty improved by a factor of 1.2-1.3 when compared to unpolarised beams
  - @ 80% – 30% the signal cross section is even larger (1.364 fb @ 3 TeV)
    - This would, naively, lead to a factor of ~1.5, compared to unpolarised beams.
    - Eventually reaching 10% λ_{HHH} uncertainty (?)

SUMMARY

- Preliminary results were presented of the Higgs self-coupling measurement with 1.4 TeV and 3 TeV CLIC machine.
  - Full simulation and reconstruction in CLIC_SiD; realistic beam spectrum, ISR, …
  - Unpolarised beams
  - Accounted for realistic $\gamma\gamma \rightarrow$hadrons event pile-up/overlay.
  - Event selection based on neural networks.
  - Two methods: cut-and-count, template fitting.
  - We observe 30 – 35% λ_{HHH} uncertainty @ 1.4 TeV and 15 – 20% uncertainty @ 3 TeV
    - for 120 GeV Higgs
    - Note: qqqqlv background will be added at 3 TeV.
  - For 126 GeV Higgs a degradation of cross section uncertainty has been observed.
    - Effect on λ_{HHH} yet to be evaluated.
  - Beam polarisation will significantly improve $\sigma_{HH\nu\nu}$ and λ_{HHH} uncertainties due to higher signal cross sections.