Measurement of the trilinear Higgs self-coupling at 1.4 TeV and 3 TeV CLIC

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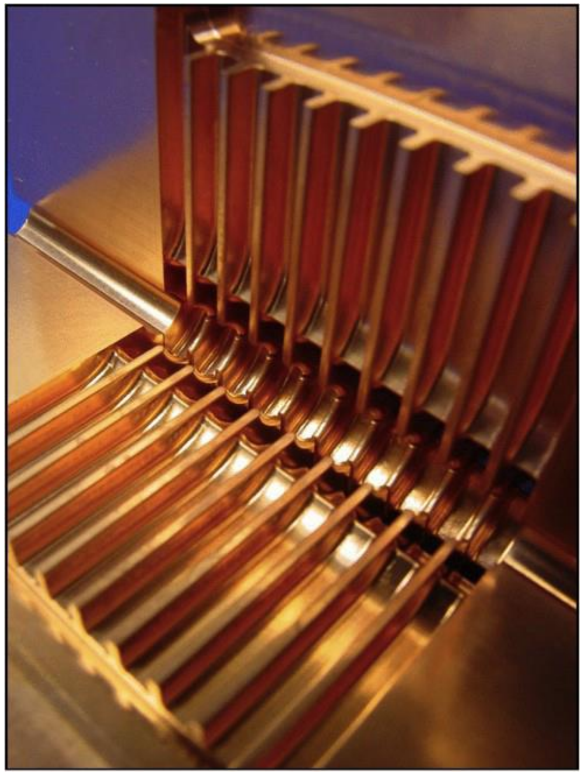
CLIC ENVIRONMENT

CLIC Environment

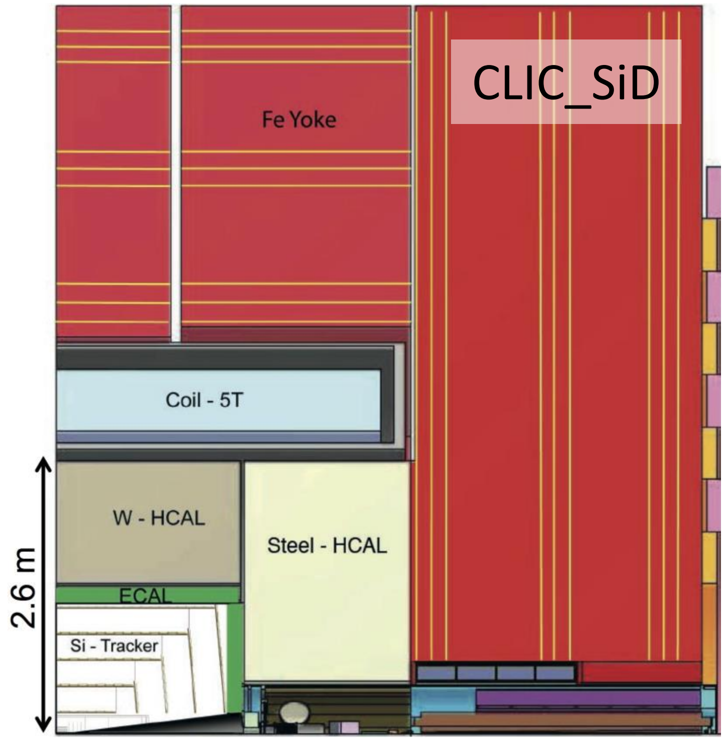
Center of mass energy	350 GeV	1.4 TeV	3 TeV
Bunch spacing		0.5 ns	
Bunches per train	354	312	312
$\gamma\gamma \rightarrow$ hadrons per BX	0.3	1.3	3.2

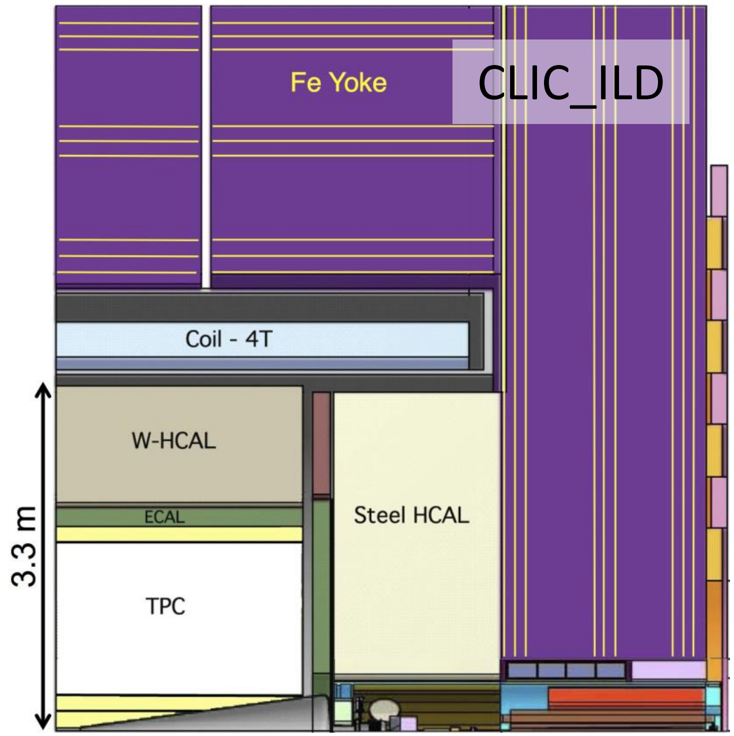
- Multi-staged approach
  - 350 GeV stage motivated by better luminosity and sizeable WW fusion cross section.
- CLIC will be operated at room temperature
- 100 MV/m gradient enabling multi-TeV CME
- Effective methods for beam-induced background suppression established
  - 10ns readout window (100ns for HCAL)
  - LHC-style jet reconstruction with FastJet



CLIC Detectors

- Two detector concepts: CLIC_SiD and CLIC_ILD
  - Based on SiD and ILD detector concepts for ILC, adapted to CLIC environment
  - Full simulation and reconstruction of events, beam induced background overlaid
  - Particle Flow Algorithm calorimetry





CLIC Higgs studies

- Event generation, both signal and background: Whizard 1.95
  - realistic beam spectrum, ISR
  - unpolarized beams; estimates for beam polarization scenarios
- Hadronization: Pythia 6.4
- Full event simulation
  - Geant4 via SLIC (CLIC_SiD)
  - 60 BX $\gamma\gamma \rightarrow$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

Updates Since LCWS2012

- Analysis was re-done assuming 126 GeV SM Higgs
- Jet reconstruction optimized
- Broken SiD reconstruction fixed (asymmetric cut on $\gamma\gamma \rightarrow$hadrons overlay)
- Beam induced background samples added ($e^-\gamma$, $e^+\gamma$, $\gamma\gamma$)
- Template fitting technique used to evaluate λ directly
  - i.e. we are avoiding “uncertainty relating factor” R whenever possible
  - R is not well understood and depends on event selection
    - while R is evaluated for the whole sample the actual measurement takes place in a corner of the phase-space (~10% of signal events).

- Focused on the 3 TeV stage for now, 1.4 TeV will follow

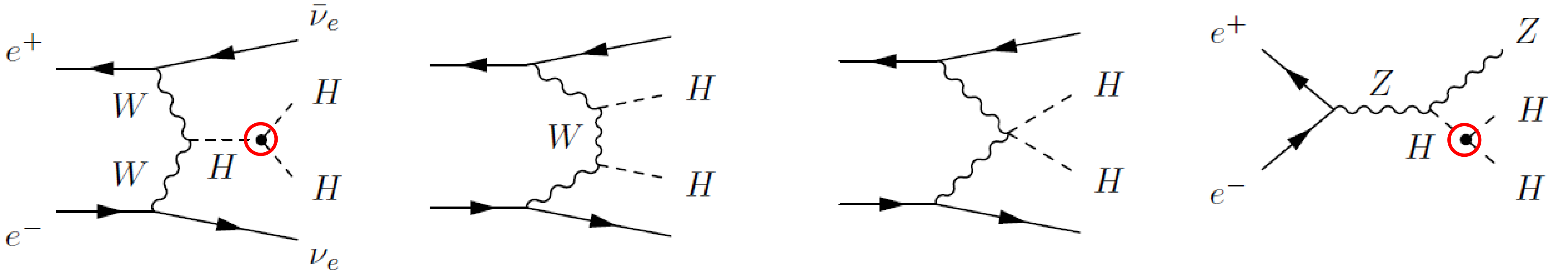
DATA SAMPLES

- Signal Samples
  - Generator final state is HHνν;
  - Pythia consequently decays Higgs to b, c, s, μ, τ, g, γ, Z, W

- Standard Model Backgrounds
  - Standard Model 4Q and 2Q backgrounds
    - qqqqνν, qqqqlν, qqqqll, qqqq
    - $e^-\gamma$, $e^+\gamma$, γγ (both EPA, BS and combinations) – important backgrounds
    - Hνν, qqνν, qqeν, qqll, qq – 2q, smaller effect

Trilinear Higgs self-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 (even much more 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 was added to Whizard to change the Higgs self-coupling parameter.
- 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.

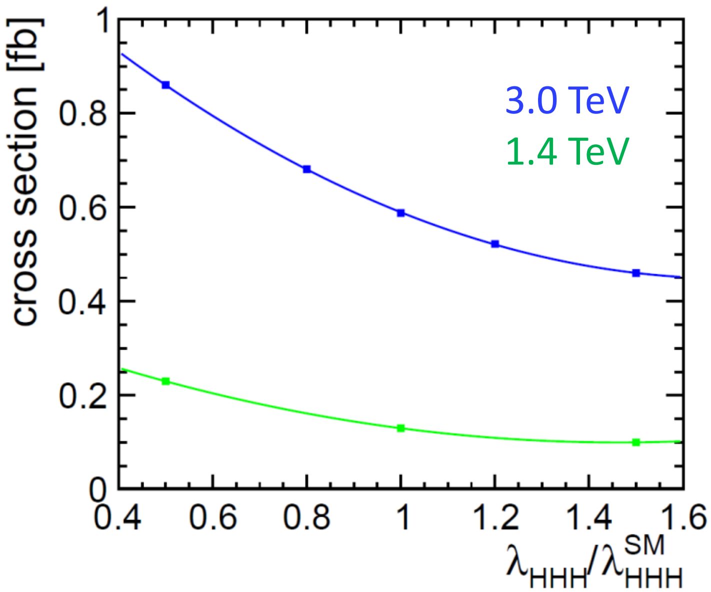
$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = R\,\frac{\Delta\sigma_{HH\nu\bar{\nu}}}{\sigma_{HH\nu\bar{\nu}}}$$

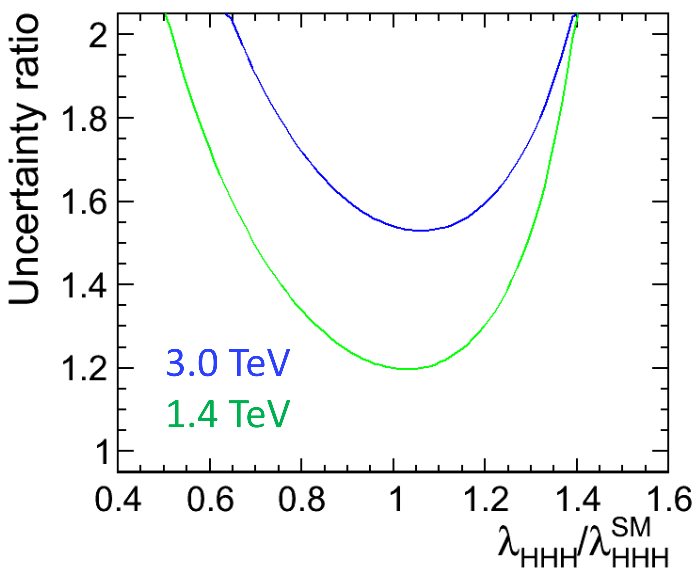
- Values of "uncertainty relating factor R" at $\lambda_{HHH}/\lambda^{SM}_{HHH} = 1$:

3.0 TeV: -1.47

1.4 TeV: -1.17

Smaller values than for previously assumed 120 GeV Higgs.





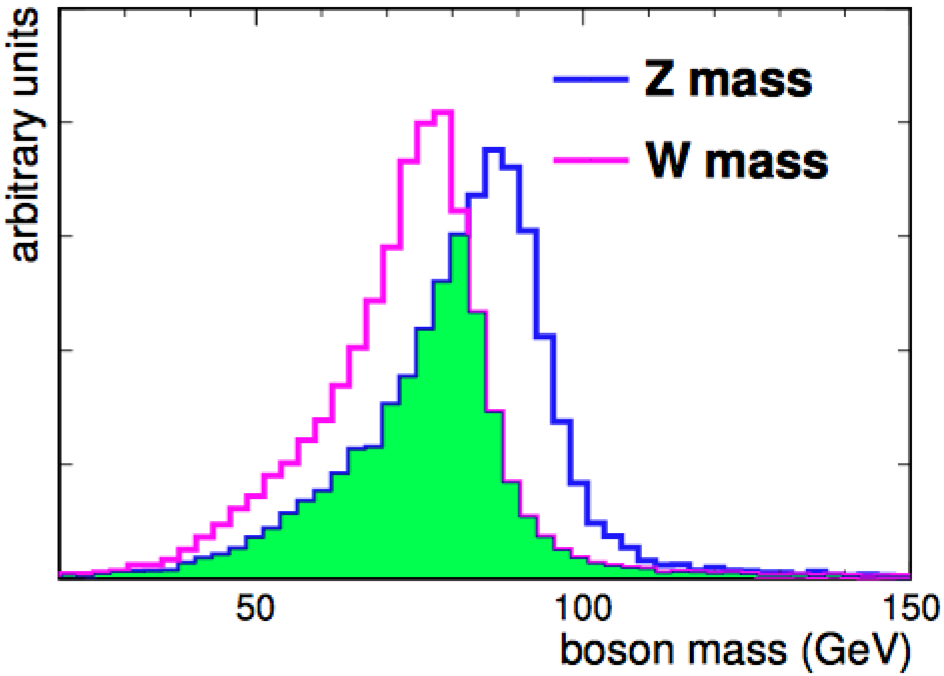
EXTRACTION OF λ FROM TEMPLATE FITS TO NN POLL OUTPUT

- Since factor R may depend on particular event selection a template fitting method to extract λ directly is investigated.
- Generate $O(10^5)$ toy experiments, based on randomized NN poll output.
  - Uncertainty may be evaluated both from
    - Mean value of signal normalization;
    - Per experiment uncertainty (via X^2+1).
  - Templates are binned so that a minimal number N of signal AND minimal number N of background events is required per bin, typically N = {2, 5, 10}
    - Sensitivity to N value – not yet fully understood
    - We give an uncertainty range

EVENT RECONSTRUCTION AND SELECTION

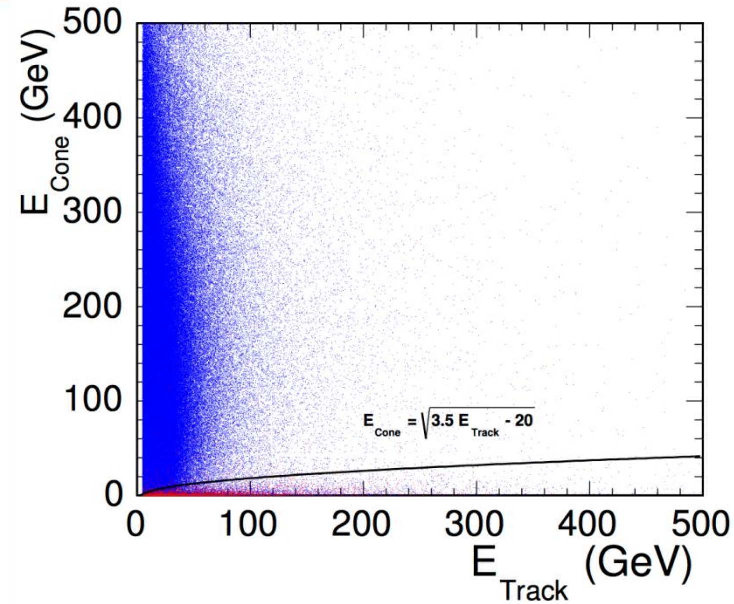
JET RECONSTRUCTION OPTIMIZATION

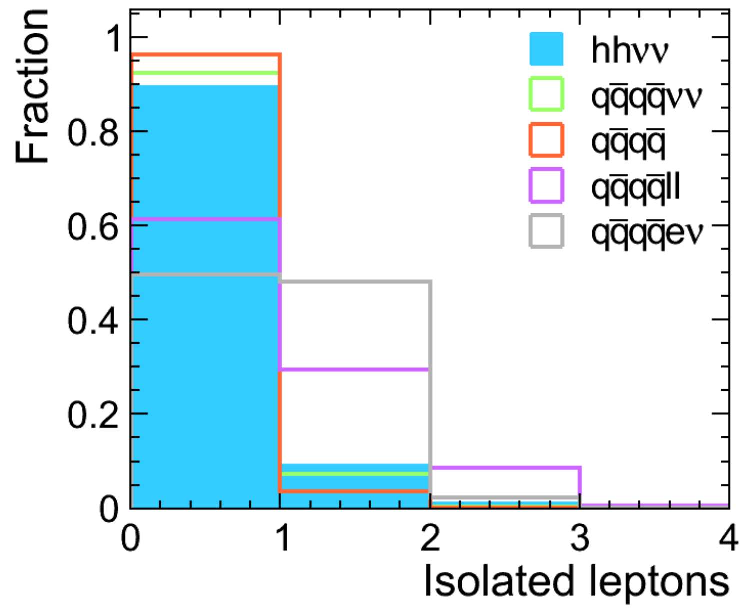
- Timing cuts and the jet size are optimized to minimize the green overlap area
  - Average mass of the two reconstructed bosons plotted
    - qqqqνν̄ sample
  - Area normalized to unity.
  - Best parameters @ 3TeV:
    - R = 0.7
    - Tight timing cuts
    - P = 0.5 (slightly better than P = 1.0)



Isolated Leptons

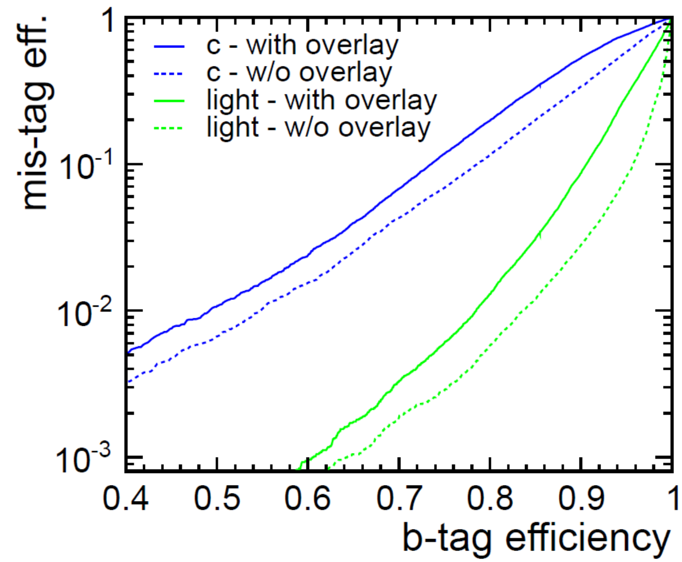
- IsolatedLeptonFinder in MarlinReco allows to use parabolic relationship between cone energy ECone and track energy Etrack.
- Performance has been studied in a sample containing one leptonic W decay.
- Parameters optimized for the best significance of correctly identified leptonic W decays vs. incorrectly finding leptons in jets.

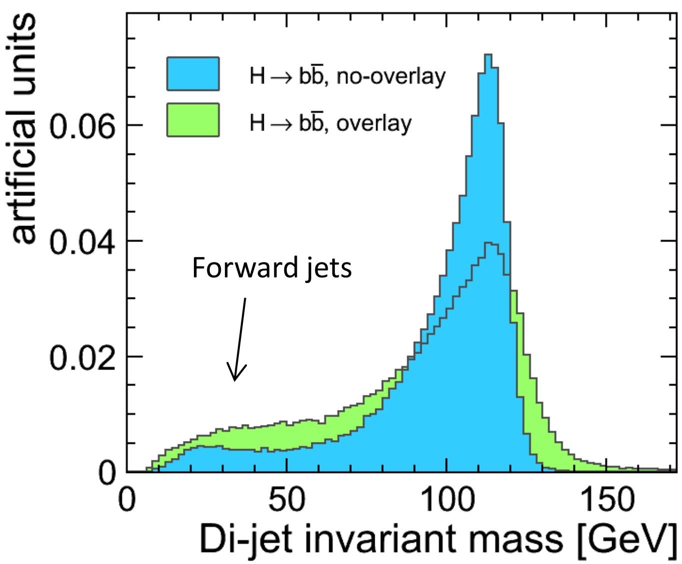


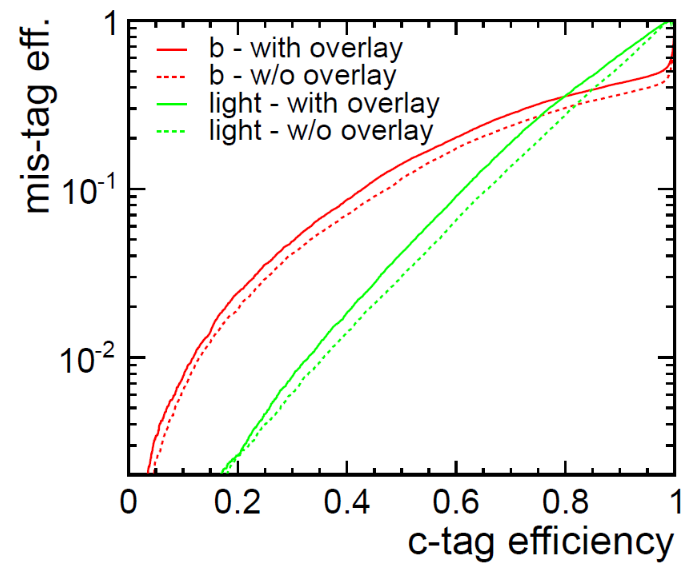


Jet flavour tagging at 3TeV with γγ overlay

- 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).

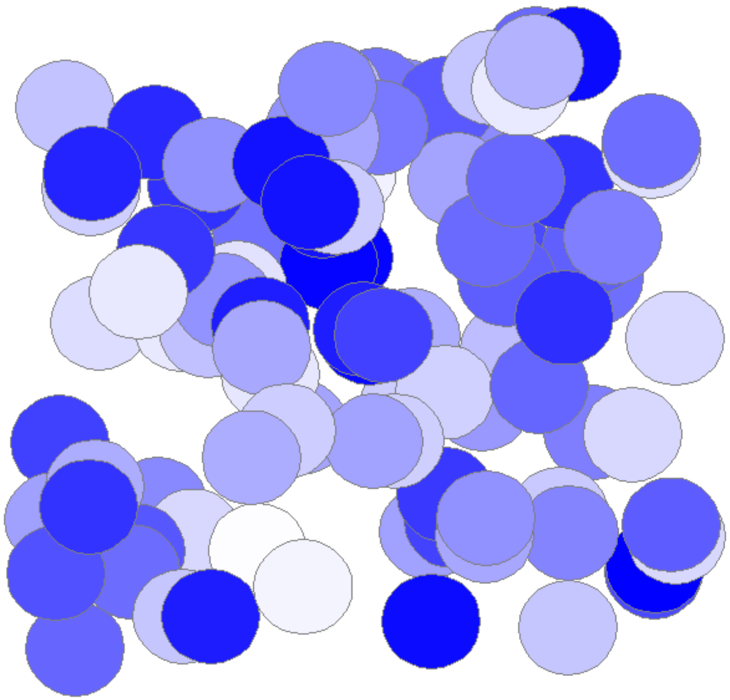






Neural Net Poll

- A poll of 100 FANN neural nets is used instead of a single neural net
  - Median of the poll votes is regarded as the NN output classifier;
  - Delivers stable and reproducible results;
  - Performance is not an average performance of all nets, it is actually matching the best performing ones.
- Nets checked against overtraining.
- Number of NN inputs: 23



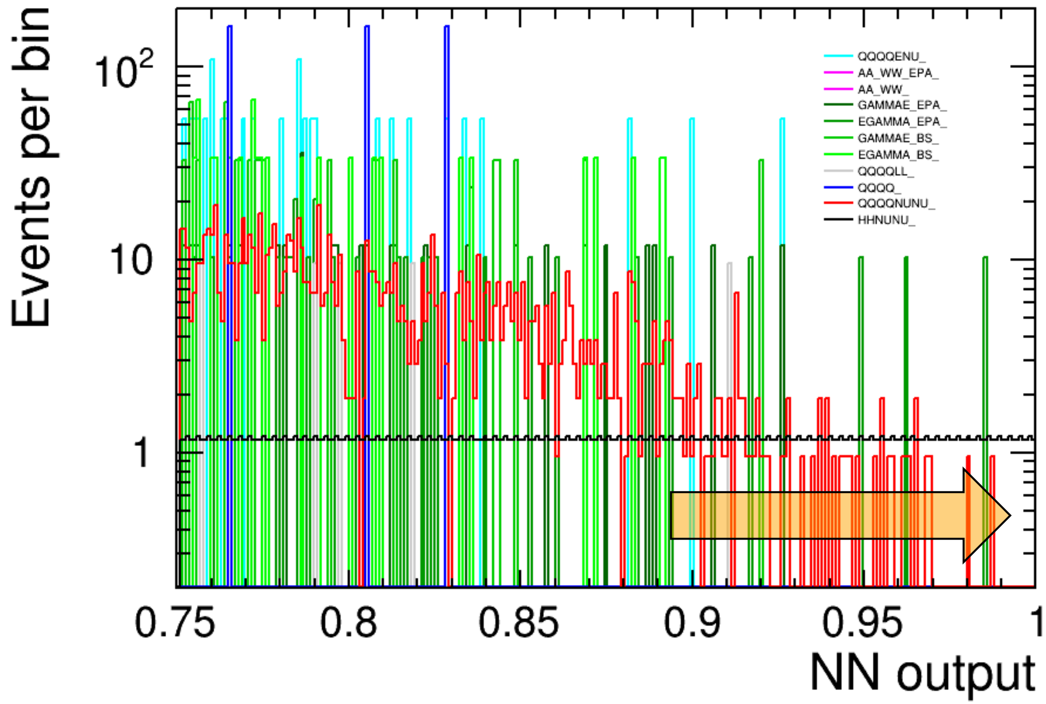
NB: BDTs have deterministic nature but they are not immune, instability (if present) reflects in a sensitivity to BDT parameters.

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, #isolated 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

ANALYSIS RESULTS @ 3TEV

- Cut-and-count Method
  - 14% on $\sigma_{HH\nu\bar{\nu}}$
- Super-fine binning shown:
  - re-binned for template fitting purposes based on a minimal number of signal and background events per bin.
- Flat signal distribution is by construction.



- Template fitting gives 10-12% on $\sigma_{HH\nu\bar{\nu}}$
  - which reflects (x 1.47) in 15-17.5% on λ_{HHH}
- **Template fitting λ_{HHH} directly: 15-18%** depending on the minimal number of events required per bin

Scaling Results to Polarized Beams @ 3 TeV

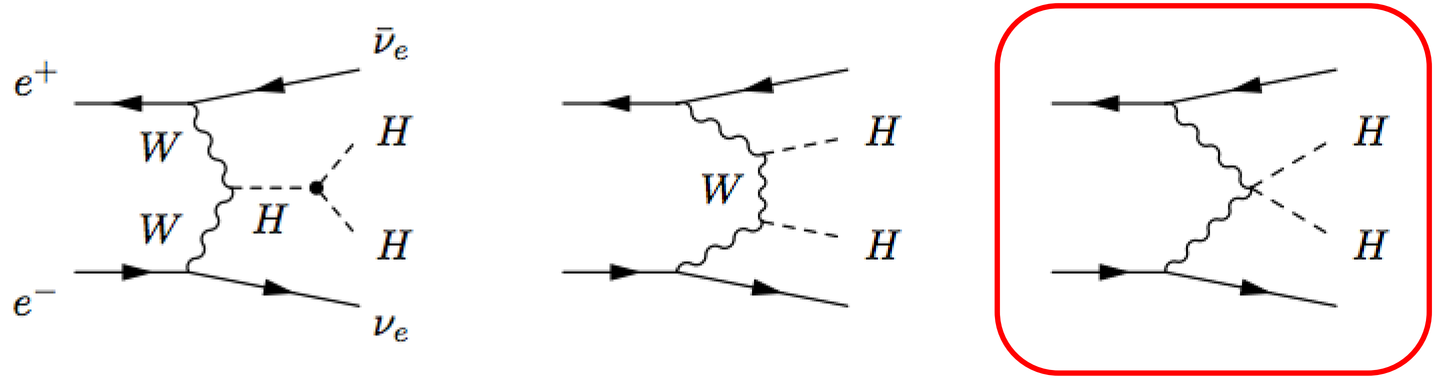
- Assuming polarized beams the cross section increases significantly:

Polarization	Enhancement factor	
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$
unpolarized	1.00	1.00
$-80\% : 0\%$	1.13	1.80
$-80\% : +30\%$	1.41	2.34

- This would reflect in estimated **12%** and **10%** uncertainty on λ_{HHH} for (-80,0) and (-80,30) polarization, respectively, assuming the same $2ab^{-1}$ integrated lumi.

- Further improvements possible by adding other channels (HHe^+e^-, ZHH)
  - and results from lower energy stages (350 GeV, 1.4 TeV).

QUARTIC COUPLING g_{HHWW}



- In an analogy to λ_{HHH}, the quartic coupling g_{HHWW} was modified in a private version of a Whizard1 and corresponding *uncertainty ratio factor* evaluated.
  - R' = –0.26
  - No template fitting done.

- This would translate in 3% uncertainty on the g_{HHWW} coupling at 3 TeV, assuming λ_{HHH} fixed at its SM value.

SUMMARY

- Results were presented of the Higgs self-coupling measurement with 3 TeV CLIC machine and m_H = 126 GeV
  - Full simulation and reconstruction in CLIC_SiD; realistic beam spectrum, ISR, …
  - Unpolarised beams – beam polarization impact discussed
  - Accounted for realistic $\gamma\gamma \rightarrow$hadrons event pile-up/overlay and for $\gamma\gamma$, $e^+\gamma$, $e^-\gamma$ backgrounds
  - Event selection based on a poll of neural networks, overtraining checked
  - Two methods: cut-and-count, template fitting
- We observe **15-18 % λ_{HHH}** uncertainty @ 3 TeV
  - Estimated **10%** and **12%** for (-80,30) and (-80,0) beam polarization, resp.
  - Updated numbers for 1.4 TeV are not available yet
    - EPS HEP 2013: 28% unpolarized beams
- Similar approach applied to quartic coupling **g_{HHWW}** leading to **3%** uncertainty @ 3 TeV.

SPARES

ADDRESSING HZνν BACKGROUND

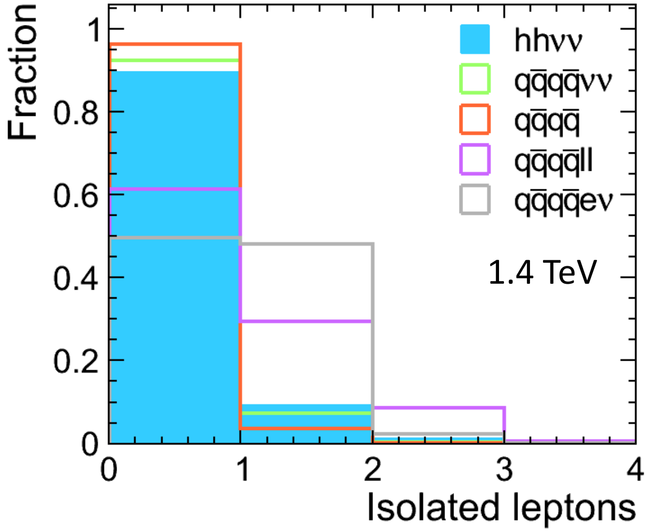
- HZν$\bar{\nu}$ contributes to qqqqν$\bar{\nu}$ background
  - We set m_H = 12 TeV to avoid signal double-counting;
  - Therefore, HZν$\bar{\nu}$ contribution is suppressed.
- Impact of HZν$\bar{\nu}$ estimated based on qqqqν$\bar{\nu}$ samples with m_H = 126 GeV
  - Double-counted signal subtracted *statistically;*
  - Unfortunately, this can not be done for neural net training and it still trains on signal assigned to both signal and background;
  - Good performance nevertheless, no significant degradation observed.
  - Degradation would be caused by both HZν$\bar{\nu}$ and signal considered as background in NN training.
- We conclude that the effect is negligible in our case, however, this exercise might have to be repeated with latest updates.

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.



EVENT SELECTION

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