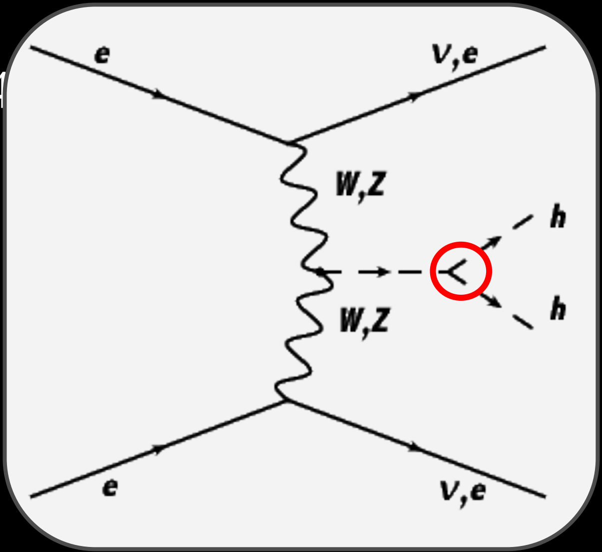
Measurement of the trilinear Higgs self-coupling at CLIC

Tomáš Laštovička (Prague)
Jan Strube (CERN)

Introduction

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



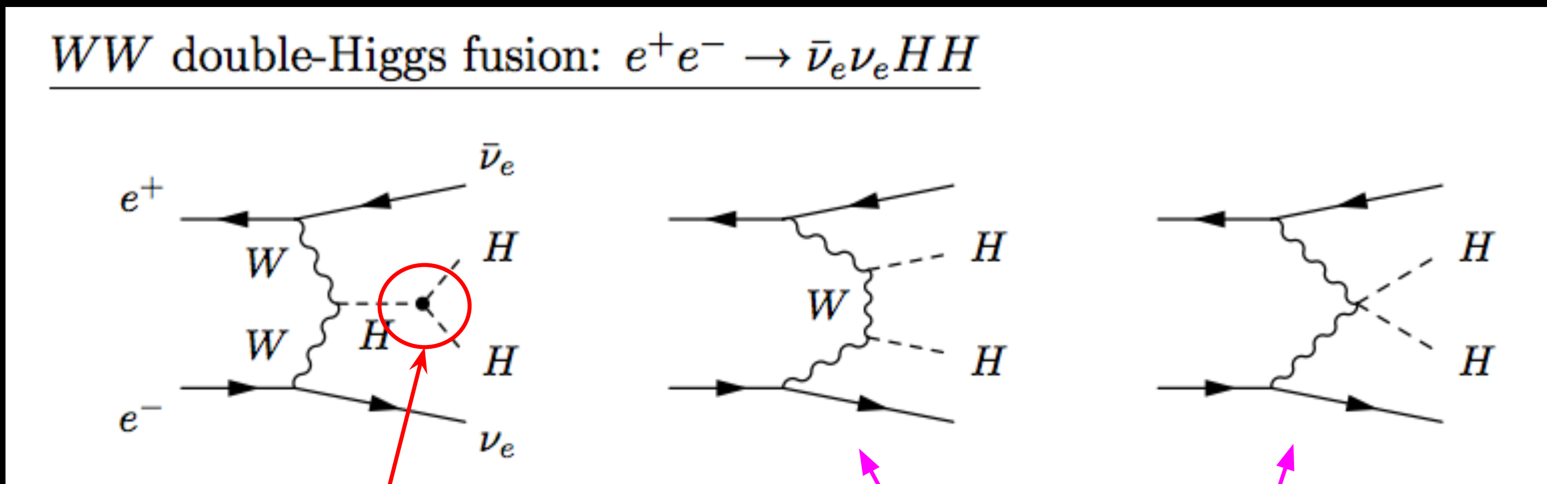
In the Standard Model:

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

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

Double Higgs Production channels



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.

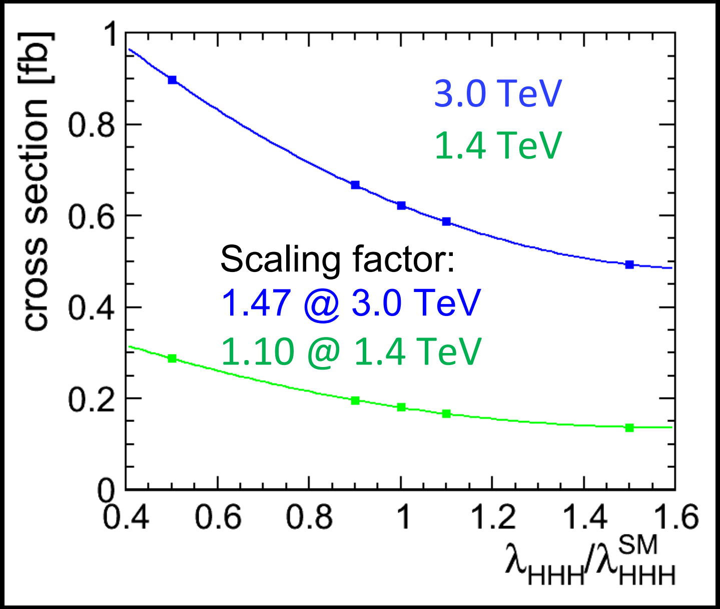
Analysis Overview

- m_H = 126 GeV
  - major update from m_H = 120 GeV since ECFA/LC2013
- Analysis at the 1.4 TeV and 3.0 TeV stages at CLIC
- Small signal cross section:
  - 0.15 fb at 1.4 TeV
  - 0.59 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 to determine factor K according to:



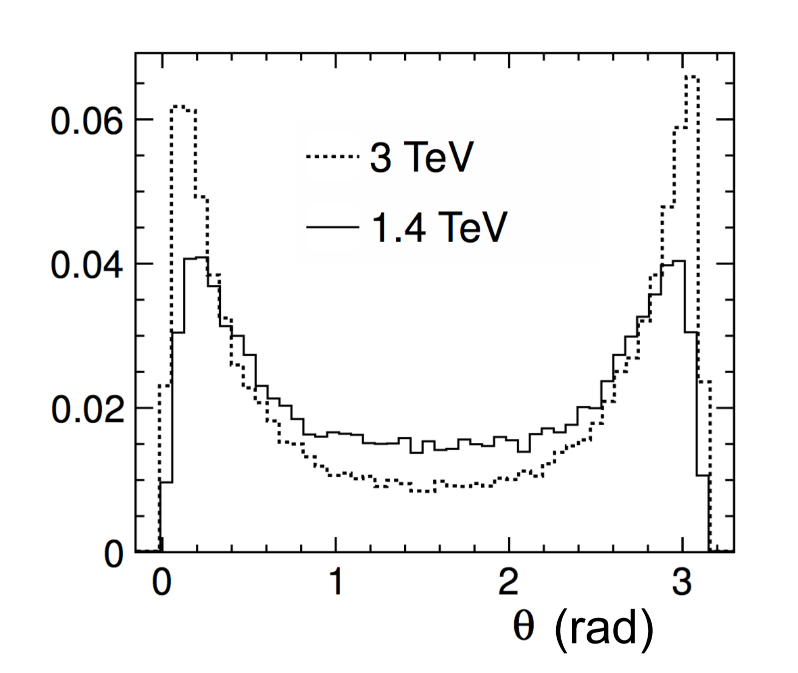
$$\frac{\partial\lambda_{\mathrm{HHH}}}{\lambda_{\mathrm{HHH}}} = K\frac{\partial\sigma_{hh\nu\nu}}{\sigma_{hh\nu\nu}}$$

⇒ K=1.10 @ 1.4 TeV

⇒ K=1.47 @ 3.0 TeV

Signal event properties

Higgs Boson polar angle

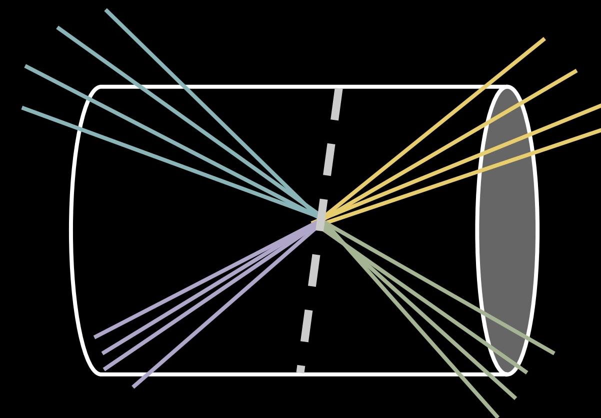


SM Higgs Boson Branching Ratios

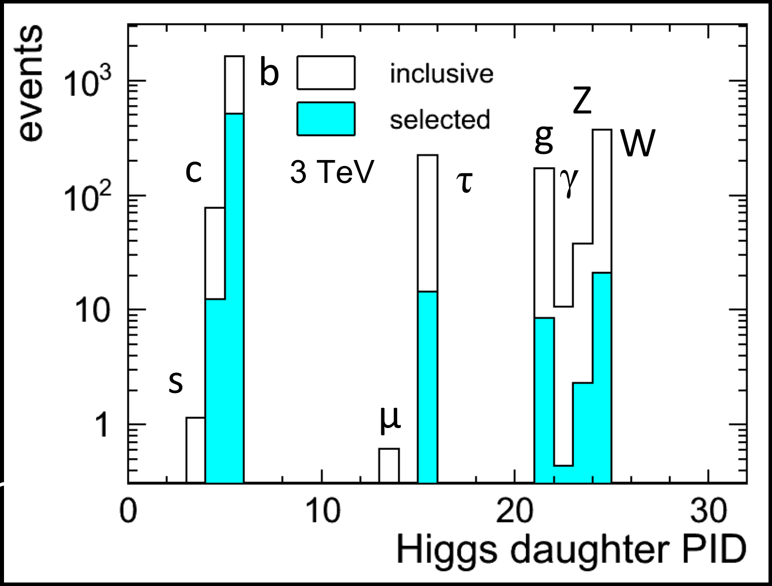
Higgs Decay	m_H = 126 GeV
H → bb	56%
H → WW	23%
H → τ τ	6.1%
H → cc	2.8%
H → ZZ	2.9%

Challenges: forward jet reconstruction,
forward b tagging

Analysis Strategy



- Isolated Lepton Finding
  - Reduces 4 jets + 1-2 leptons background
- Force events into four jets (FastJet kt tight R=0.7)
- Divide event into hemispheres
  - 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
- Cut-and-count as cross-check.
  Neural network template fit for improved perfor



Analysis Steps

1. Samples produced either privately or in production
2. Fix for broken SiD reco as DIRAC user jobs
3. Jet clustering, vertexing, flavor tagging in Oxford queues
4. Analysis event properties put into ~/public on afs as text files

Available Samples I

Sample	$\sqrt{s} = 3\,\text{TeV}$ ProdID	cross section (fb)	events	$\sqrt{s} = 1.4\,\text{TeV}$ ProdID	cross section (fb)
signal (HH$\nu\nu$)	1539	0.59	1180	1535	0.15
from electron-positron interactions					
4 quarks + 2 ν	1460	74.1	150k	1081	24.7
4 quarks + 2 l	1458	182	360k	1089	71.68
4 quarks	1112	593	1.2M	1097	1325
2 quarks + 2 ν_e	636	1305	2.6M	864	646
4 quarks + 1 electron + 1 ν	?	77	154k	1085	115
2 quarks + 1 electron + 1 ν	598	5255	11M	-	-
2 quarks + 2 electrons	600	3341	6.7M	-	-
2 quarks	599	3076	6.2M	-	-
2 quarks + 1 H + 1 e + 1 ν	?	11.42	22k	-	-
2 quarks + 1 H + 2 ν	?	4.94	10k	-	-
2 quarks + 1 H	?	3.72	7.4k		

New samples

Major developments since CLIC workshop:

4q lnu sample now being processed on dedicated VM in CERN cloud.

- Not done, yet, but looks promising…
- Previous attempts on lxbatch, private machine all failed

Large number of samples from photon-photon, photon-electron, photon positron added.

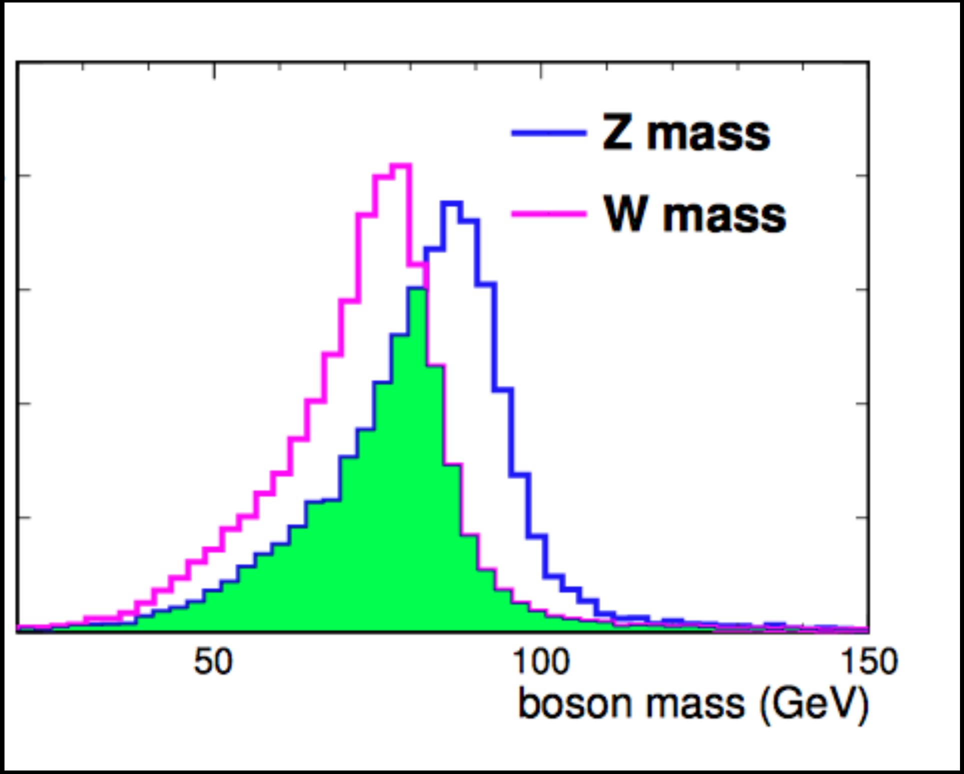
Available Samples II

Sample	$\sqrt{s} = 3\,\mathrm{TeV}$ ProdID	cross section (fb)	events	$\sqrt{s} = 1.4\,\mathrm{TeV}$ ProdID	cross section (fb)
signal ($HH\nu\nu$)	1539	0.59	1180	1535	0.15
from photo-production					
$e^-\gamma \rightarrow e^- + 4$ quarks (BS)	2370	2.6×10^3	4.1M	2358	1.16×10^3
$e^+\gamma \rightarrow e^+ + 4$ quarks (BS)	2376	2.6×10^3	4.1M	2364	1.16×10^3
$e^-\gamma \rightarrow e^- + 4$ quarks (EPA)	2367	662	1.3M	2355	287
$e^+\gamma \rightarrow e^+ + 4$ quarks (EPA)	2373	662	1.3M	2361	287
$e^-\gamma \rightarrow \nu_e + 4$ quarks (BS)	2588	360	570k	2576	-
$e^+\gamma \rightarrow \bar{\nu}_e + 4$ quarks (BS)	2594	360	570k	2582	-
$e^-\gamma \rightarrow \nu_e + 4$ quarks (EPA)	2585	84.3	170k	2573	-
$e^+\gamma \rightarrow \bar{\nu}_e + 4$ quarks (EPA)	2591	84.3	170k	2579	-
$\gamma(BS)\gamma(BS) \rightarrow 4$ quarks	2657	$11740^{\diamond}$	16.20M	2643	$4^{\diamond} \times 10^3$
$\gamma(BS)\gamma(EPA) \rightarrow 4$ quarks	2654	$2070^{\diamond}$	3.271M	2640	$7^{\diamond} \times 10^2$
$\gamma(EPA)\gamma(BS) \rightarrow 4$ quarks	2651	$2070^{\diamond}$	3.271M	2637	$7^{\diamond} \times 10^2$
$\gamma(EPA)\gamma(EPA) \rightarrow 4$ quarks	2648	$325^{\diamond}$	650k	2634	$128^{\diamond}$
$\gamma\gamma \rightarrow 2\nu + 4$ quarks (BS)	?	$17^{\dagger}$	$23.5^{\dagger}$		
$\gamma\gamma \rightarrow 2\nu + 4$ quarks (EPA)	?	$0.42^{\dagger}$	840		

Jet size optimization

Jet size and timing cuts are optimized to minimize the green area of overlap.

Note: Histogram filled with “average” boson mass $0.5*(m_1+m_2)$ for each event.
Samples are normalized to unity.

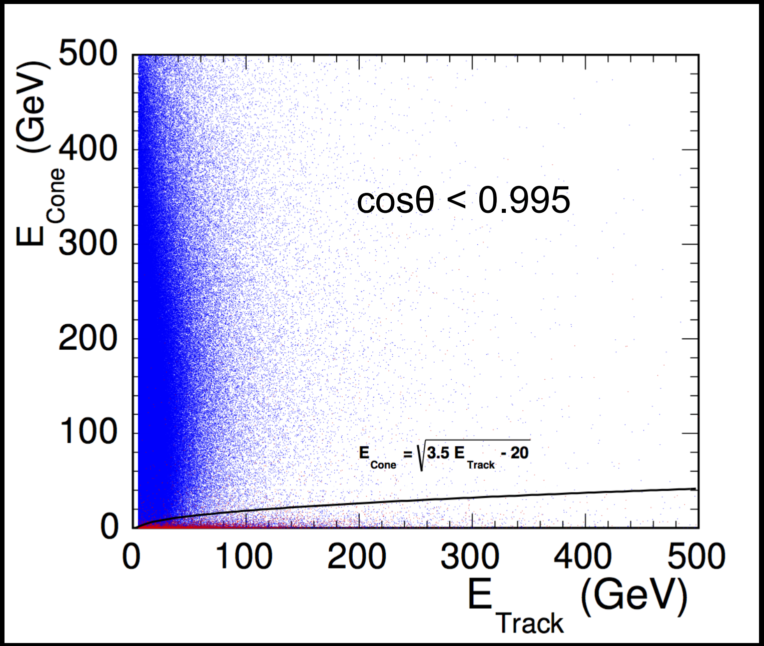


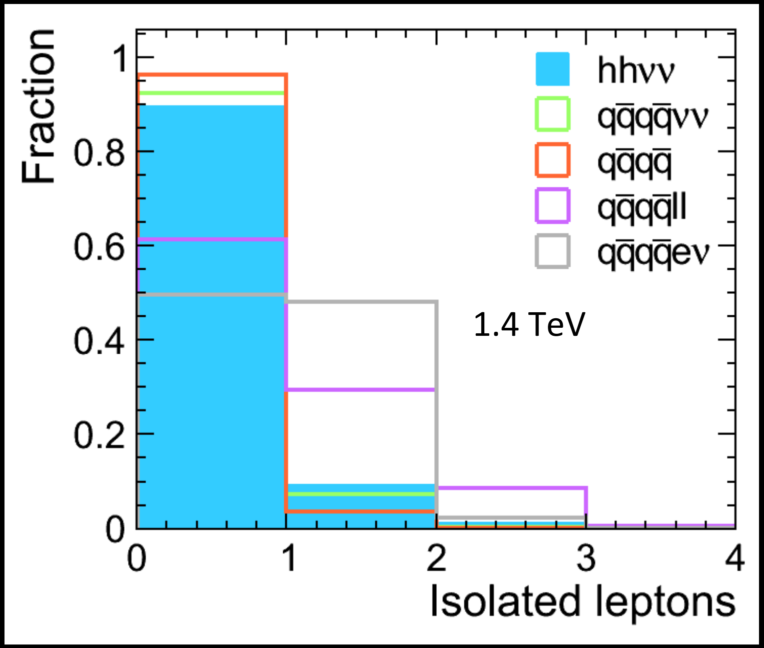
Best value at tight cuts, R=0.7, exponent 1.0

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



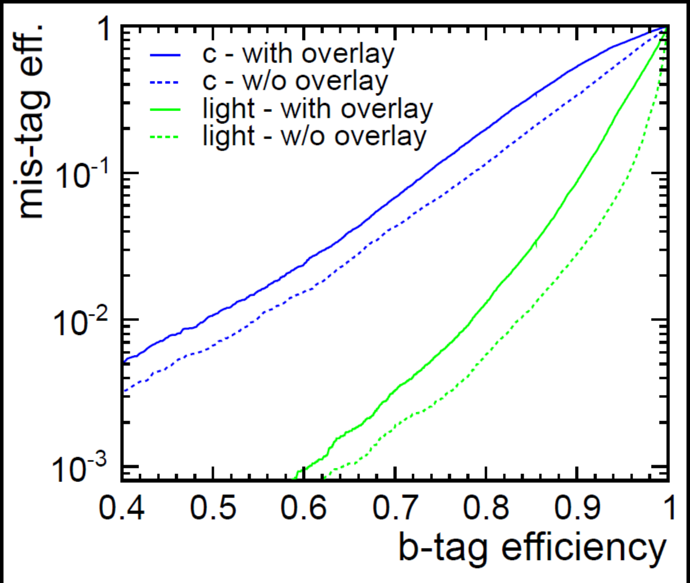


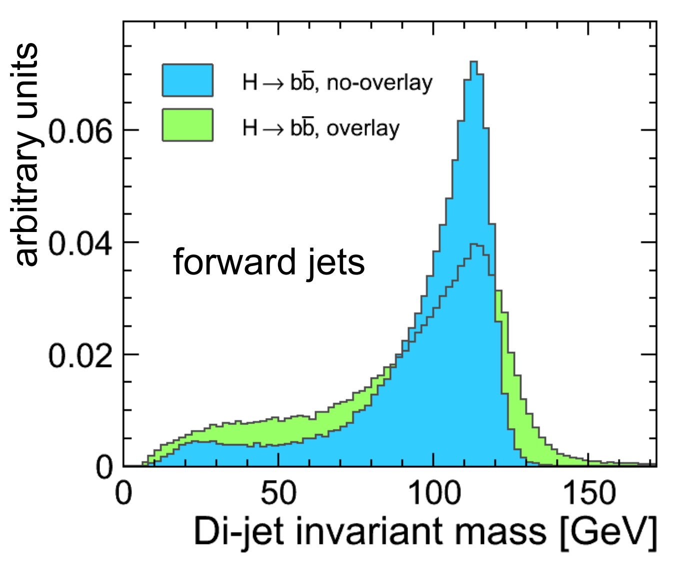
b-jet reconstruction

<u>LCFIVertex package:</u>

- 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)

Samples used (3 TeV)

Most samples are now available as production samples.
Some Samples in current iteration still from private production, focus on biggest backgrounds

Some more samples available.
1.4 TeV still needs to be done

ProdID	Sample name	# Events
100000	AA_WW	17500
2370	EGAMMA_BS_	164569
1460	QQQQNUNU_	205734
2376	GAMMAE_BS_	163846
2367	EGAMMA_EPA_	135012
1644	HHNUNU_1.2	55149
2373	GAMMAE_EPA_	117634
1539	HHNUNU_	26982
1112	QQQQ_	9726
1640	HHNUNU_0.8	59171
100001	AA_WW_EPA	17600
1458	QQQQLL_	50734
100002	QQQQENU_	4284
100003	QQQQMUNU_	5449

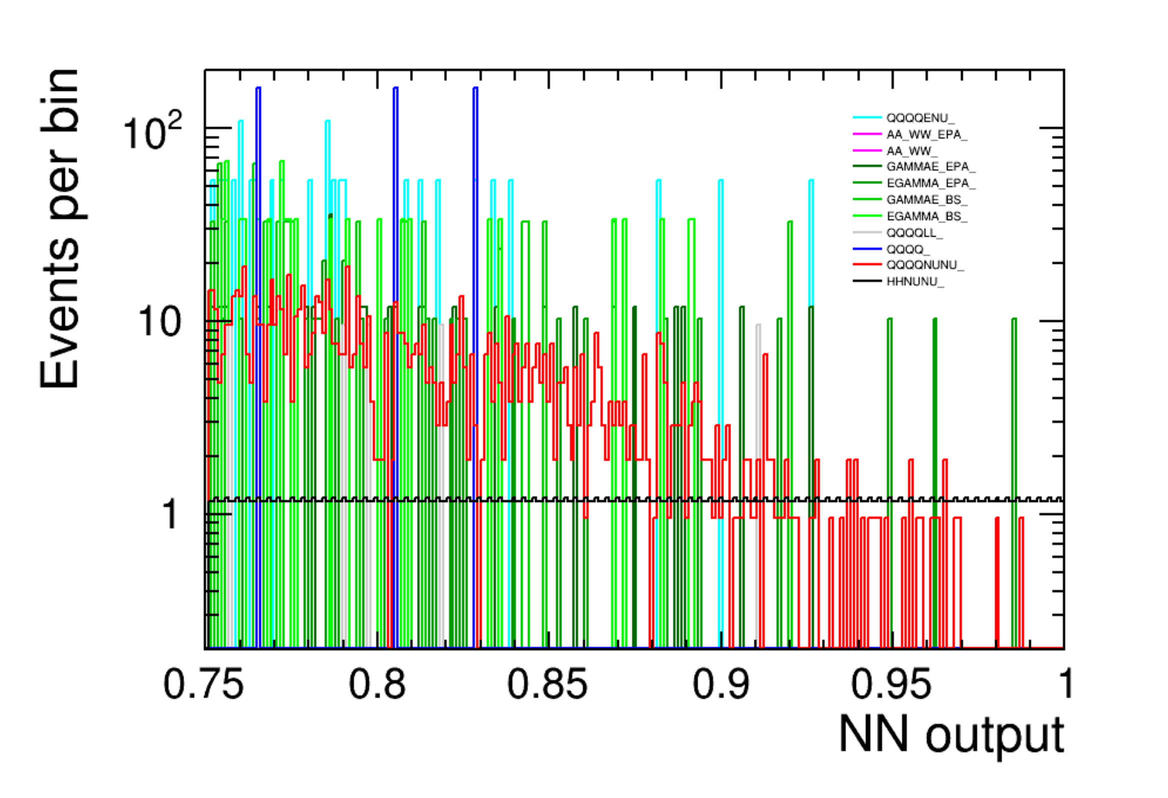
Analysis results

<u>3 TeV:</u>

Cut and count:

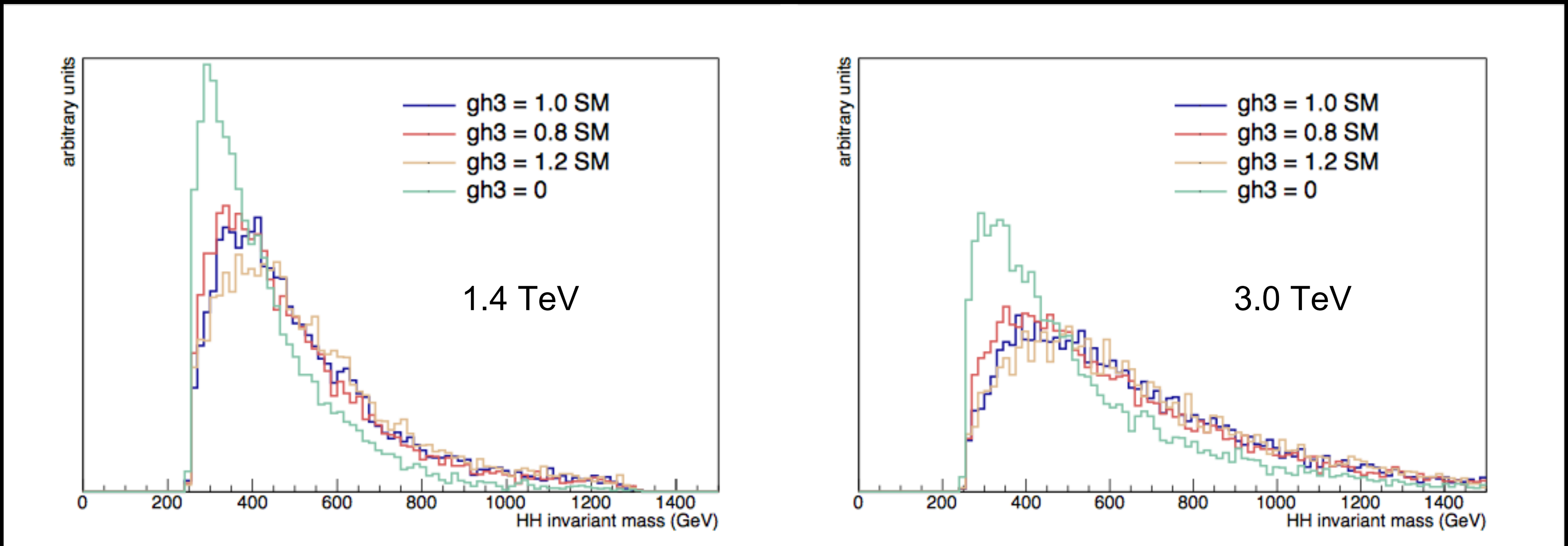
14% on $\sigma_{HH\nu\nu}$

template fitting the neural net output:



10%-12%,depending on the minimal number of events required in each bin of the templates

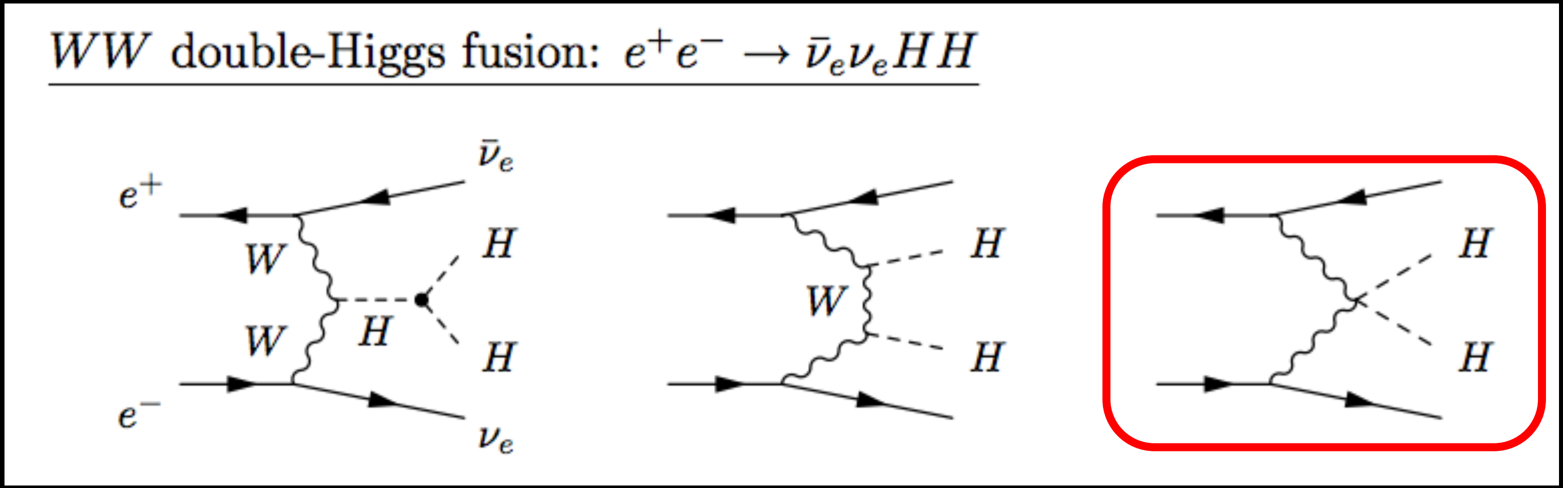
Signal Properties with different values of the tri-linear self-coupling



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.

Samples created with different values for gh3 (λ). Template fitting directly to the different NN outputs somewhat less stable against minimal number of events / bin than cross section extrapolation.

Quartic coupling



Similarly to λ_{HHH}, the quartic coupling λ_{HHWW} was modified in a private version of Whizard1.

Factor translating cross section uncertainty to coupling uncertainty K’ = -0.26

Summary and Conclusions

- The biggest ingredients for the analysis of the tri-linear Higgs self-coupling are in place
  - Most of the samples are now there
    - There’s hope for the remainder
  - The reconstruction of jets, isolated leptons and vertices is more or less optimized
- Work on smaller items still needed before analysis is publication-ready.
  - Need to process again with all samples
  - Efficiencies should be understood better - do we have the right backgrounds for the inclusive analysis?
  - Extraction of both HHWW and HHH coupling needs some thought. Would need fully reconstructed samples with different HHWW couplings.
- Hope to finish this over the course of the next two months