Update on double Higgs analysis, and extraction of g_{HHH} and g_{WWHH} at CLIC

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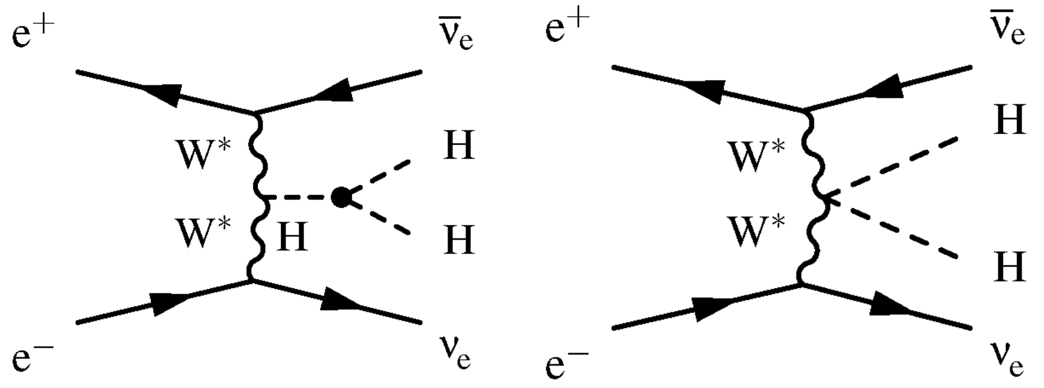
Motivations

- To measure triple higgs self coupling, g_{HHH}, and quartic coupling, g_{HHWW} via double higgs production
- Divide analysis into sub-channels to increase significance
- Sub-channels: (Branching Ratio for mH=126GeV)
  - HHνν→bbWW*νν→bbqqqqνν BR = 0.119 / bbqqlνννν BR = 0.114 / bblνlννν BR = 0.0274
  - HHνν→bbbbνν BR = 0.315
- Independent analysis at $\sqrt{s}$ = 1.4 TeV and 3 TeV



Strategy

- Veto events with isolated light lepton/tau
  - Light lepton and tau finders in MarlinReco
  - Boruo light lepton and tau finders
  - Simulate forward electron & photon veto for LumiCal and BeamCal
- X^2 constraint for jet pairing; b-jet tagging
- Pre selection cuts
- MVA i.e.
  - HHνν->bbWW*νν->bbqqqqνν / HHνν→bbbbνν is signal
  - HHνν->other does not participate in MVA training

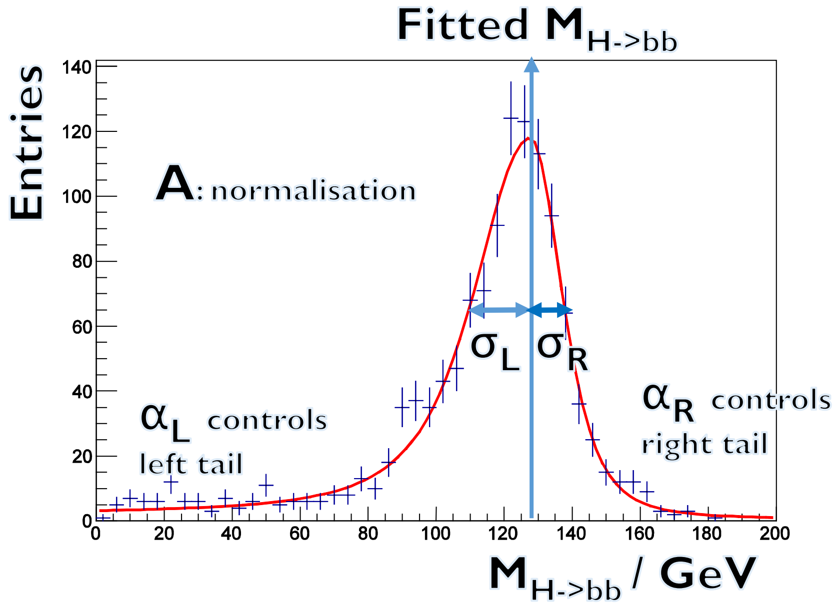
MC samples

- Many background channels, include ee→qqHν and eγ→qqHν
  - γγ→qqHν checked, negligible cross section
  - * and + represents generator cut m(qq)>50 and 120 GeV
  - BS represents a real photon from beamstrahlung. EPA represents a "quasi-real" photon, simulated with Equivalent Photon Approximation

Channel	$\sigma(\sqrt{s}=1.4\,\text{TeV})$ / fb	$\sigma(\sqrt{s}=3\,\text{TeV})$ / fb
$e^-e^+ \to HH\nu\bar{\nu}$	0.149	0.588
$e^-e^+ \to q_l q_l H\nu\bar{\nu}$	0.86	1.78
$e^-e^+ \to c\bar{c}H\nu\bar{\nu}$	0.36	1.12
$e^-e^+ \to b\bar{b}H\nu\bar{\nu}$	0.31	1.91
$e^-e^+ \to qqqq$	1245.1	546.5*
$e^-e^+ \to qqqq\ell\ell$	62.1*	169.3*
$e^-e^+ \to qqqq\ell\nu$	110.4*	106.6*
$e^-e^+ \to qqqq\nu\bar{\nu}$	23.2*	71.5*
$e^-e^+ \to qq$	4009.5	2948.9
$e^-e^+ \to qq\ell\nu$	4309.7	5561.1
$e^-e^+ \to qq\ell\ell$	2725.8	3319.6
$e^-e^+ \to qq\nu\nu$	787.7	1317.5
$e^-\gamma(BS) \to e^-qqqq$	1160.7	1268.7*
$e^+\gamma(BS) \to e^+qqqq$	1156.3	1267.6*
$e^-\gamma(EPA) \to e^-qqqq$	287.1	287.9*
$e^+\gamma(EPA) \to e^+qqqq$	286.9	287.8*
$e^-\gamma(BS) \to \nu qqqq$	136.9†	262.5*
$e^+\gamma(BS) \to \bar{\nu}qqqq$	136.4†	262.3*
$e^-\gamma(EPA) \to \nu qqqq$	32.6†	54.2*
$e^+\gamma(EPA) \to \bar{\nu}qqqq$	32.6†	54.2*
$e^-\gamma(BS) \to qqH\nu$	15.8*	58.6*
$e^+\gamma(BS) \to qqH\nu$	15.7*	58.5*
$e^-\gamma(EPA) \to qqH\nu$	3.39*	11.7*
$e^+\gamma(EPA) \to qqH\nu$	3.39*	11.7*
$\gamma(BS)\gamma(BS) \to qqqq$	21406.2*	13050.3*
$\gamma(BS)\gamma(EPA) \to qqqq$	4018.7*	2420.6*
$\gamma(EPA)\gamma(BS) \to qqqq$	4034.8*	2423.1*
$\gamma(EPA)\gamma(EPA) \to qqqq$	753.0*	402.7*

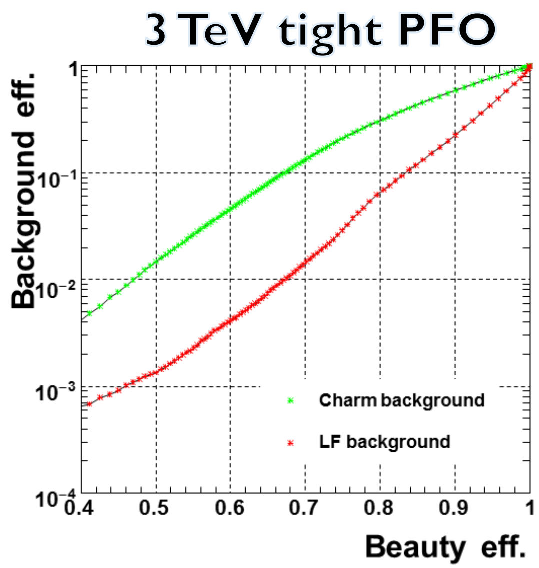
Mass reconstruction

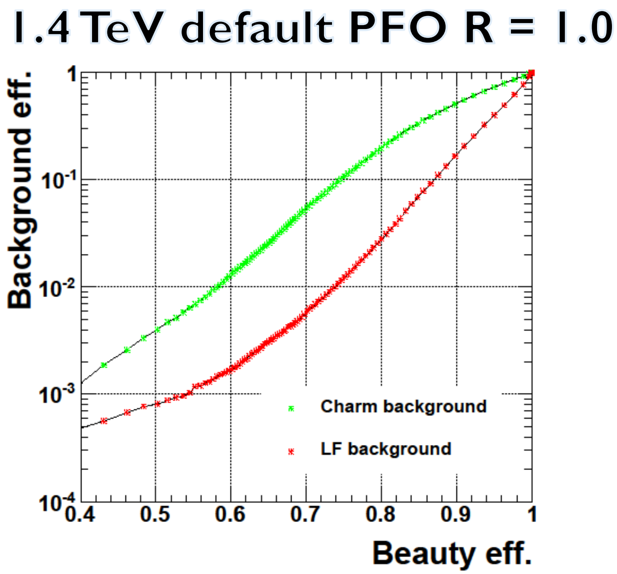
- HHνν->bbbbνν, 4 jets in the final state
  - Minimise $\chi_4^2 = |M_{12} - M_{34}|$
- HHνν->bbWWνν->bbqqqqνν, 6 jets in the final state
  - Minimise $\chi_6^2 = \frac{(M_{12}-M_{H_{bb}})^2}{\sigma_{H_{bb}}^2} + \frac{(M_{3456}-M_{H_{WW}})^2}{\sigma_{H_{WW}}^2} + \frac{(M_{34}-M_{W^\pm})^2}{\sigma_{W^\pm}^2}$
- $M_{H_{bb}}$, $M_{H_{WW}}$, $M_{W^\pm}$, $\sigma_{H_{bb}}$, $\sigma_{H_{WW}}$, $\sigma_{W^\pm}$ are obtained from fitting of signal events, use HHνν->bbWWνν ->bbqqqqνν channel, cheated jet pairing
  - $f = \mathrm{A}\exp(\frac{-(x-\mu)^2}{g}) \begin{cases} g = 2\sigma_L^2 + \alpha_L(x-\mu)^2, x < \mu \\ g = 2\sigma_R^2 + \alpha_R(x-\mu)^2, x > \mu \end{cases}$



B,C jets tagging

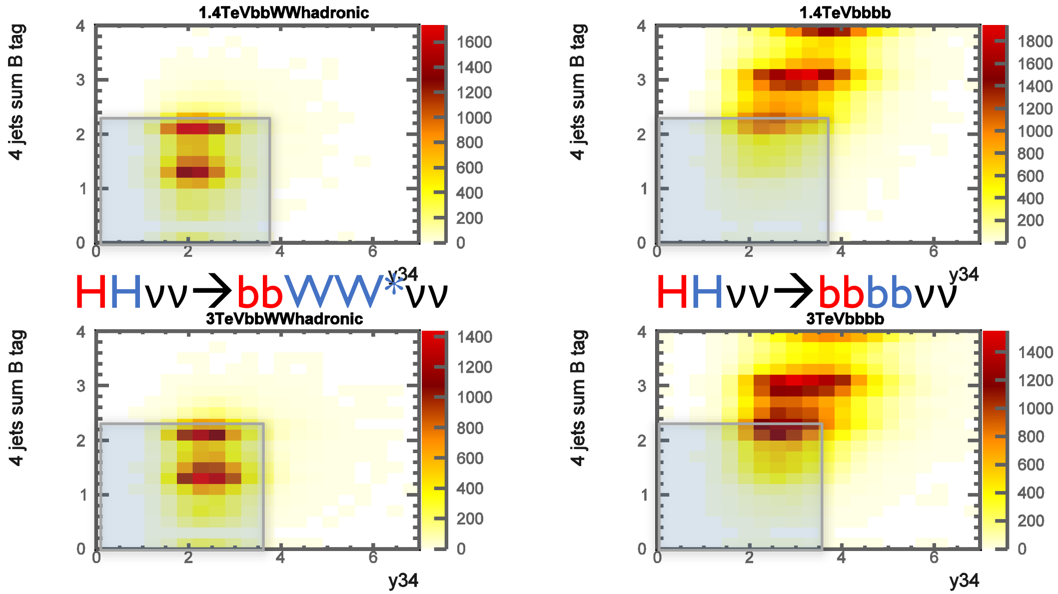
- Want to find B jets as signal events contain H->bb
- Based on LCFIPlus with root 5.28. Jet reconstruction, Vertexing and Durham algorithm in LCFIPlus
  - Samples ee->Zvv, Z->cc/bb/uu/dd/ss
- Primary and corresponding secondary vertices are forced into the same jet.





Mutually exclusive pre-selection cuts

- Mutually exclusive pre-selection cuts for HHνν→bbbbνν and HHνν→bbWW*νν, to avoid double counting
- y-parameters and b-tag scanned for the best separation
- 1.4 TeV: Y34 < 3.7, sum b tag < 2.3;
  - bbWW 86%, bbbb 78%; Overall 67.06%
- 3TeV: Y34 < 3.6, sum b tag < 2.3
  - bbWW 89%, bbbb 82%; Overall 72.4%



MVA

- Optimised to avoid pairwise correlation whilst preserving significance
- HHνν→bbbbνν, 10 variables
- HHνν→bbWW*νν, 32 variables
  - Smaller cross section. Harder to select signal

1.4TeV 1.5ab^{-1}

Process	σ/fb	ε_{presel}	ε_{BDT}	N_{BDT}
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}b\bar{b}$	0.047	94 %	24 %	16
$HH\nu_e\bar{\nu}_e$; $HH \to$ other	0.102	29 %	0.77 %	0.3
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	23	6.2 %	0.38 %	8
$e^+e^- \to q\bar{q}q\bar{q}l\nu$	110	16 %	0.03 %	7
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	1.5	39 %	2.0 %	18
$e^{\pm}\gamma \to \nu q\bar{q}q\bar{q}$	154	13 %	0.01 %	3
$e^{\pm}\gamma \to qqH\nu$	30	28 %	0.01 %	1
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}WW^*$; $W^+W^- \to q\bar{q}q\bar{q}$	0.018	60 %	8.2 %	1.3
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}b\bar{b}$	0.047	15 %	0.5 %	0.1
$HH\nu_e\bar{\nu}_e$; $HH \to$ other	0.085	20 %	1.7 %	0.5
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	23	17 %	0.002 %	0.1
$e^+e^- \to q\bar{q}q\bar{q}l\nu$	110	10 %	0.01 %	2
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	1.5	35 %	0.1 %	0.8
$e^{\pm}\gamma \to \nu q\bar{q}q\bar{q}$	154	22 %	0.0045 %	2
$e^{\pm}\gamma \to qqH\nu$	30	27 %	0.02 %	3

3TeV 2ab^{-1}

Process	σ/fb	ε_{presel}	ε_{BDT}	N_{BDT}
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}b\bar{b}$	0.19	66 %	24 %	61
$HH\nu_e\bar{\nu}_e$; $HH \to$ other	0.40	5.4 %	3.2 %	1
$e^+e^- \to q\bar{q}q\bar{q}$	547	0.16 %	0.16 %	3
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	72	1.8 %	0.68 %	17
$e^+e^- \to q\bar{q}q\bar{q}l\nu$	107	1.8 %	0.15 %	6
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	4.7	18 %	3.0 %	50
$e^{\pm}\gamma \to \nu q\bar{q}q\bar{q}$	523	1.2 %	0.09 %	11
$e^{\pm}\gamma \to qqH\nu$	116	2.7 %	0.14 %	9
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}WW^*$; $W^+W^- \to q\bar{q}q\bar{q}$	0.07	62 %	12 %	10
$HH\nu_e\bar{\nu}_e$; $HH \to b\bar{b}b\bar{b}$	0.19	19 %	1.5 %	1
$HH\nu_e\bar{\nu}_e$; $HH \to$ other	0.34	20 %	3.6 %	5
$e^+e^- \to q\bar{q}q\bar{q}$	547	1.4 %	0.01 %	1
$e^+e^- \to q\bar{q}q\bar{q}\nu\bar{\nu}$	72	9.0 %	0.05 %	6
$e^+e^- \to q\bar{q}q\bar{q}l\nu$	107	7.3 %	0.05 %	8
$e^+e^- \to q\bar{q}H\nu\bar{\nu}$	4.8	32 %	0.6 %	19
$e^{\pm}\gamma \to \nu q\bar{q}q\bar{q}$	523	15 %	0.04 %	67
$e^{\pm}\gamma \to qqH\nu$	116	27 %	0.2 %	140

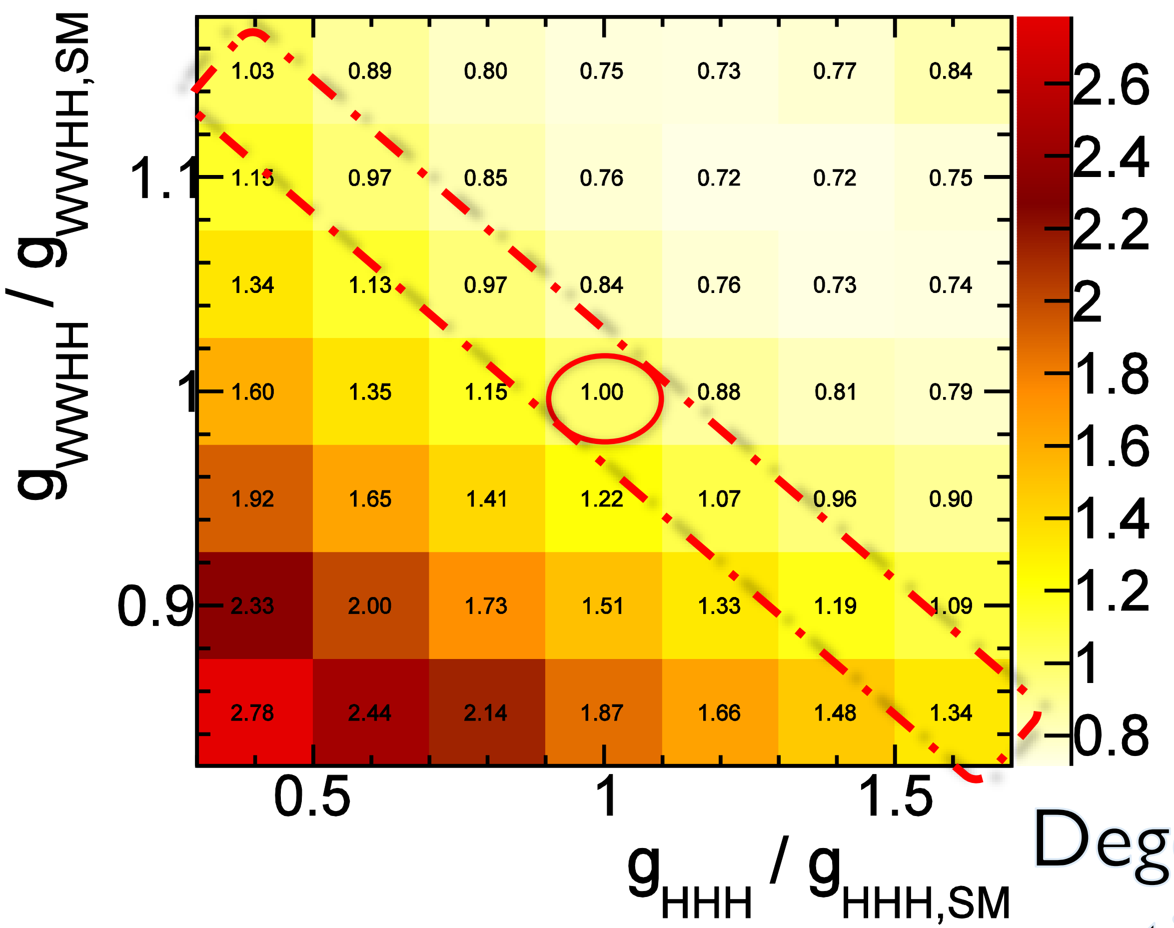
- Corrected higgs decay branching ratio with LHC results

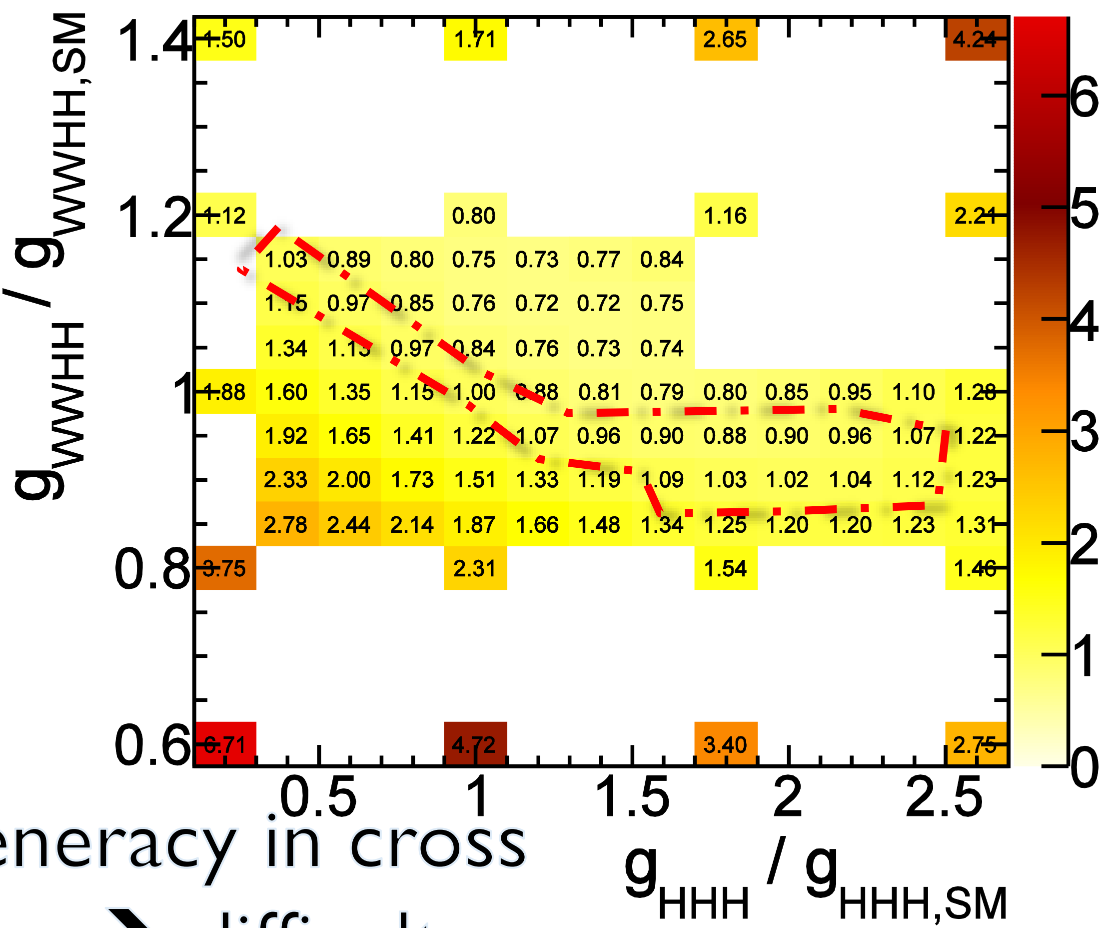
Extraction of g_{HHH} and g_{WWHH}

- Full analysis for $HH\nu\nu \rightarrow bbWW^{*}\nu\nu \rightarrow bbqqqq\nu\nu$ and $HH\nu\nu \rightarrow bbbb\nu\nu$ at $\sqrt{s}$ = 1.4 and 3 TeV completed. Simple scaling for g_{HHH} sensitivity presented in higgs paper

- Simultaneous extraction of g_{HHH} and g_{WWHH} using template fitting method is work in progress

Cross section plots, normalised to nominal SM





Degeneracy in cross section → difficult

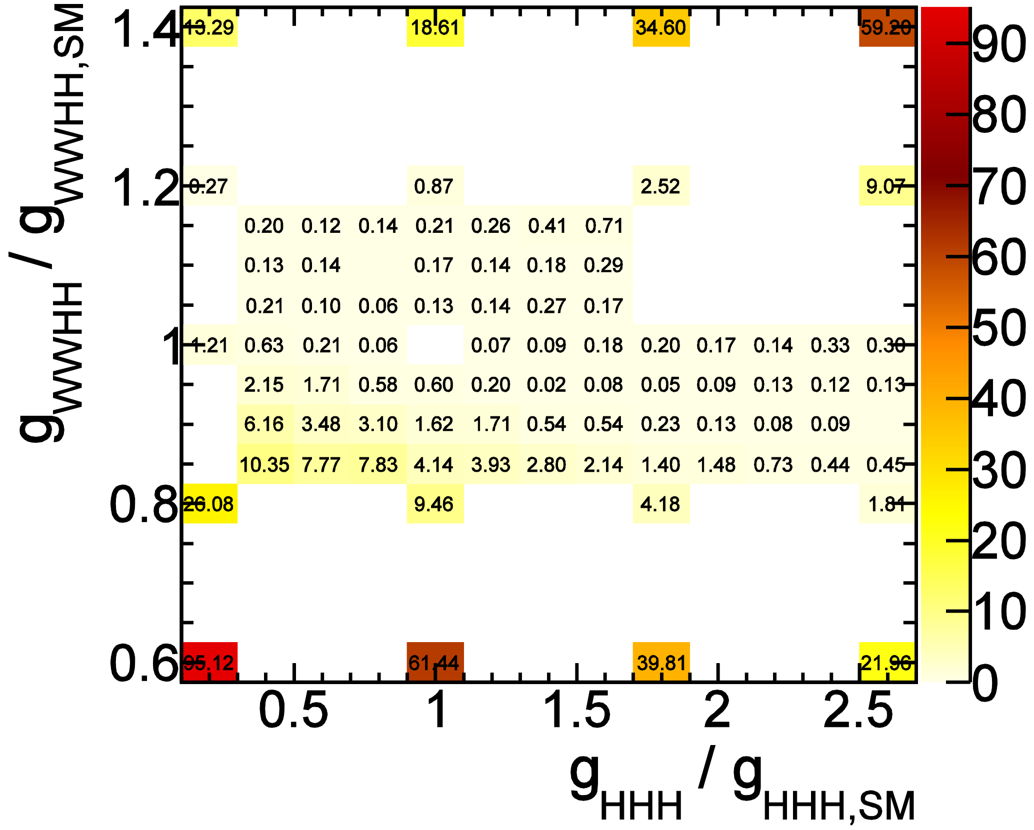
Work in progress

Simultaneous extraction of g_{HHH} and g_{WWHH}

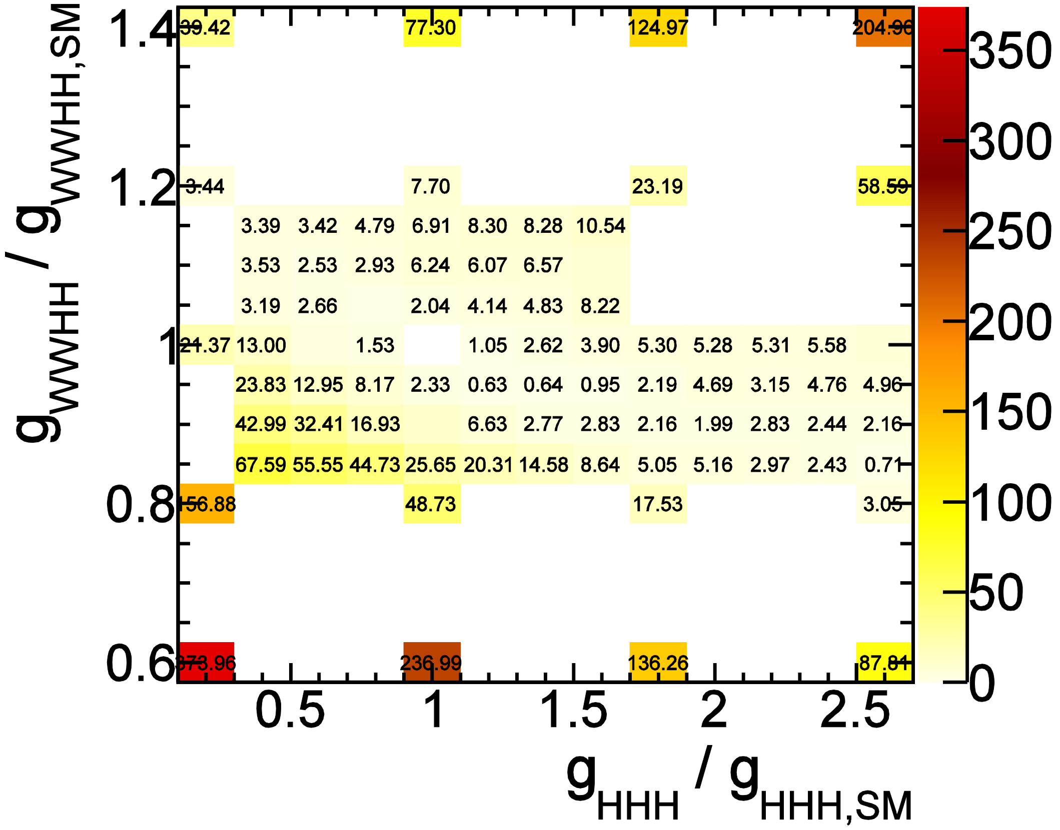
- Template fitting
- Samples with modified g_{HHH} and g_{WWHH}
- Apply MVA trained with nominal SM couplings
- Perform Chi-Square calculation on the template
- $\chi^2 = \sum_{i=1}^{4} \frac{(Expected - Observed)^2}{Expected}$, index i is for kinematic bins, expected is the template distribution, observed is the poisson fluctuated nominal coupling distribution
  - Event numbers normalised to $3ab^{-1}$ luminosity

Chi-Square template

HHνν->bbWW*νν



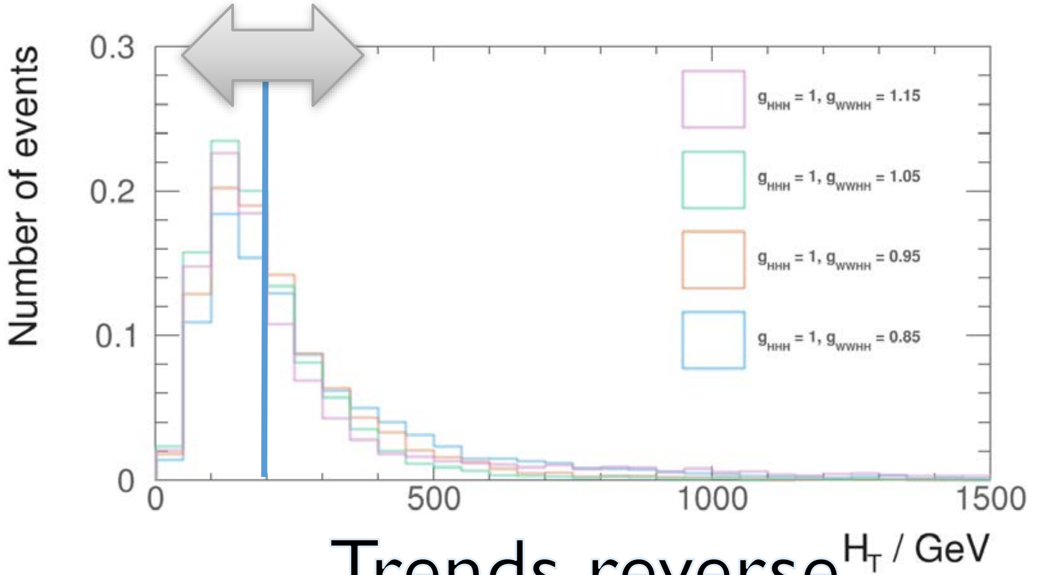
HHνν→bbbbνν



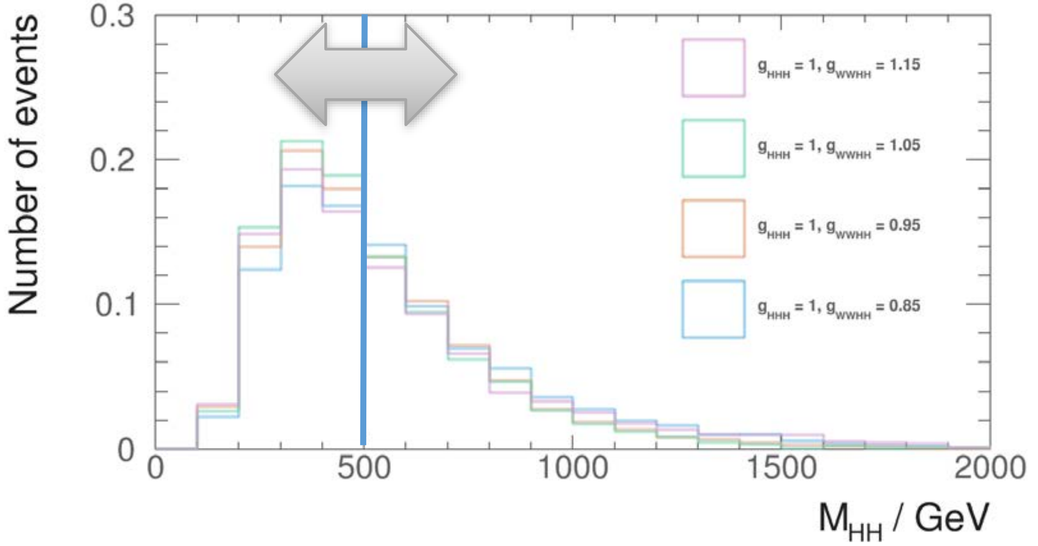
Work in progress

Kinematic bins: H_T and M_{HH}

- Kinematic bins: H_T, sum of P_T of two Higgs; M_{HH}, invariant mass of two Higgs system
  - Motivated by theory paper CERN-PH-TH-2013-161
- One example: H_T: cut at 200 GeV; m_{HH}: cut at 500 GeV
- Another example: H_T: cut at 150, 250, 350 GeV; m_{HH}: cut at 500 GeV
  - Modified couplings samples, plotted ee→HHνν→bbWWνν after pre-selection cuts. Normalised integrated area to 1



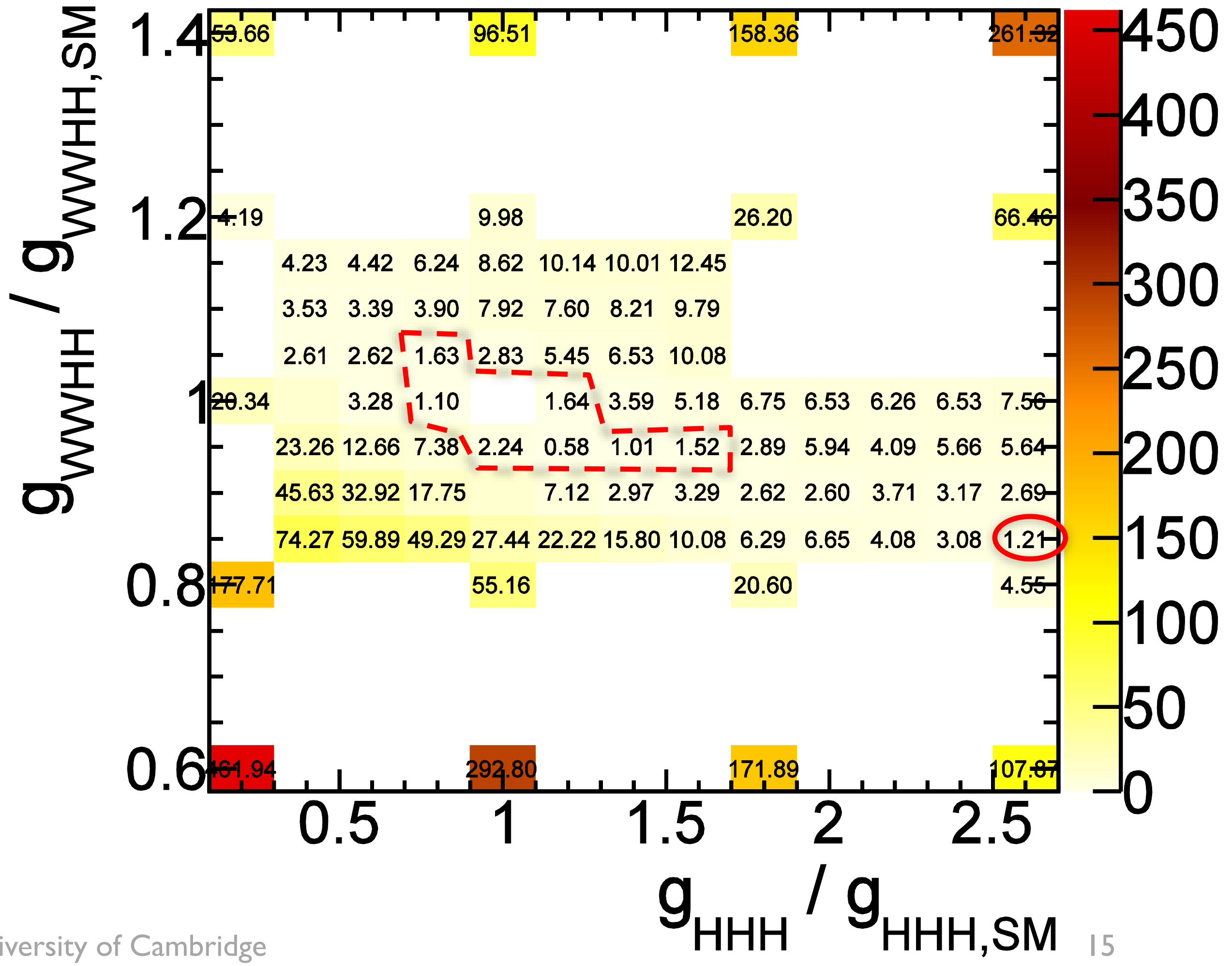
Trends reverse



Work in progress

Toy MC, Chi-square average

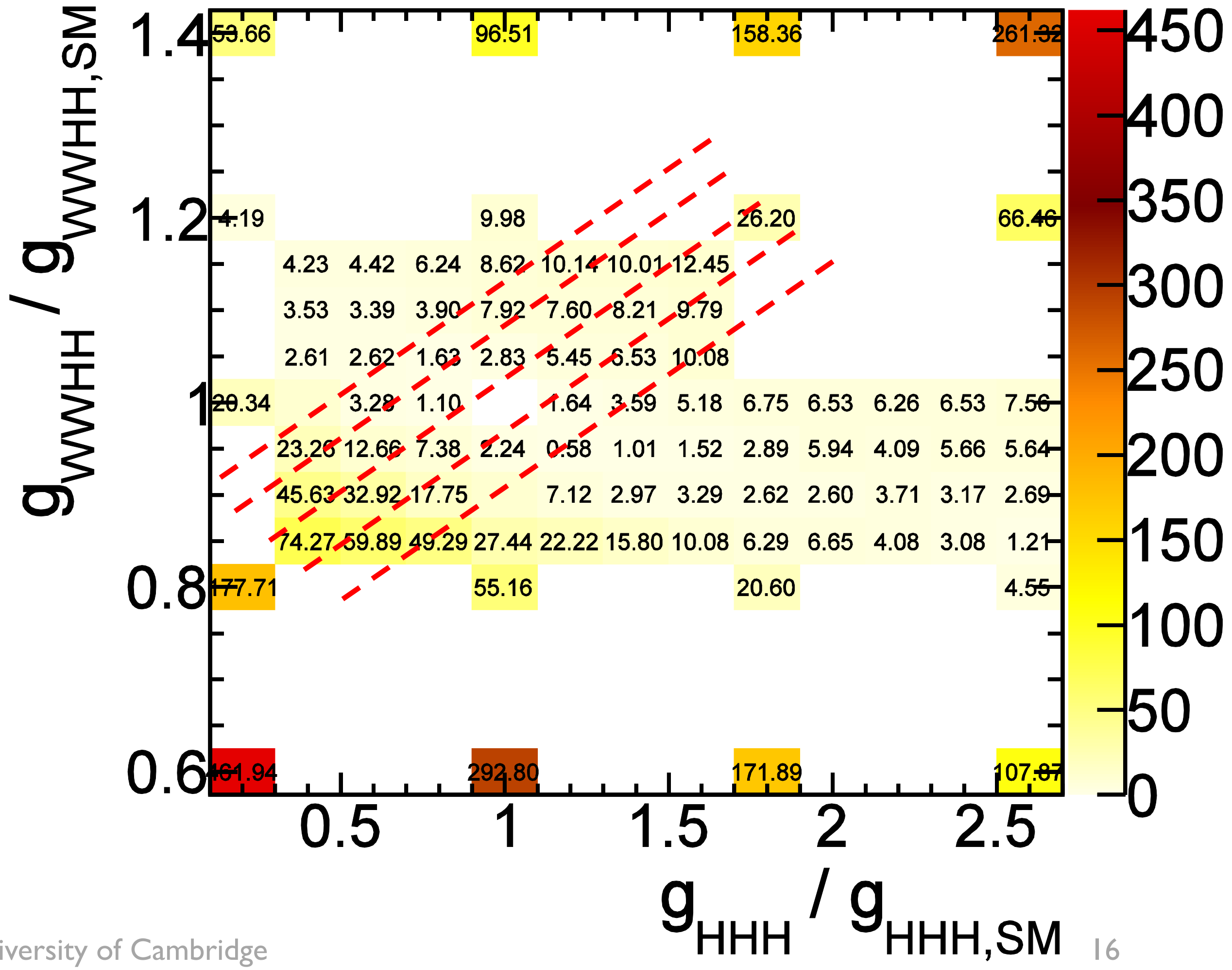
- 100,000 toy MC experiments, averaged χ^2 template for combined channel
- More stable template
- Extract contour with 2 degrees of freedom
- Dotted line shows 1σ (χ^2 =2.3)
- More samples generating



Work in progress

Toy MC, Chi-square average, interpolation

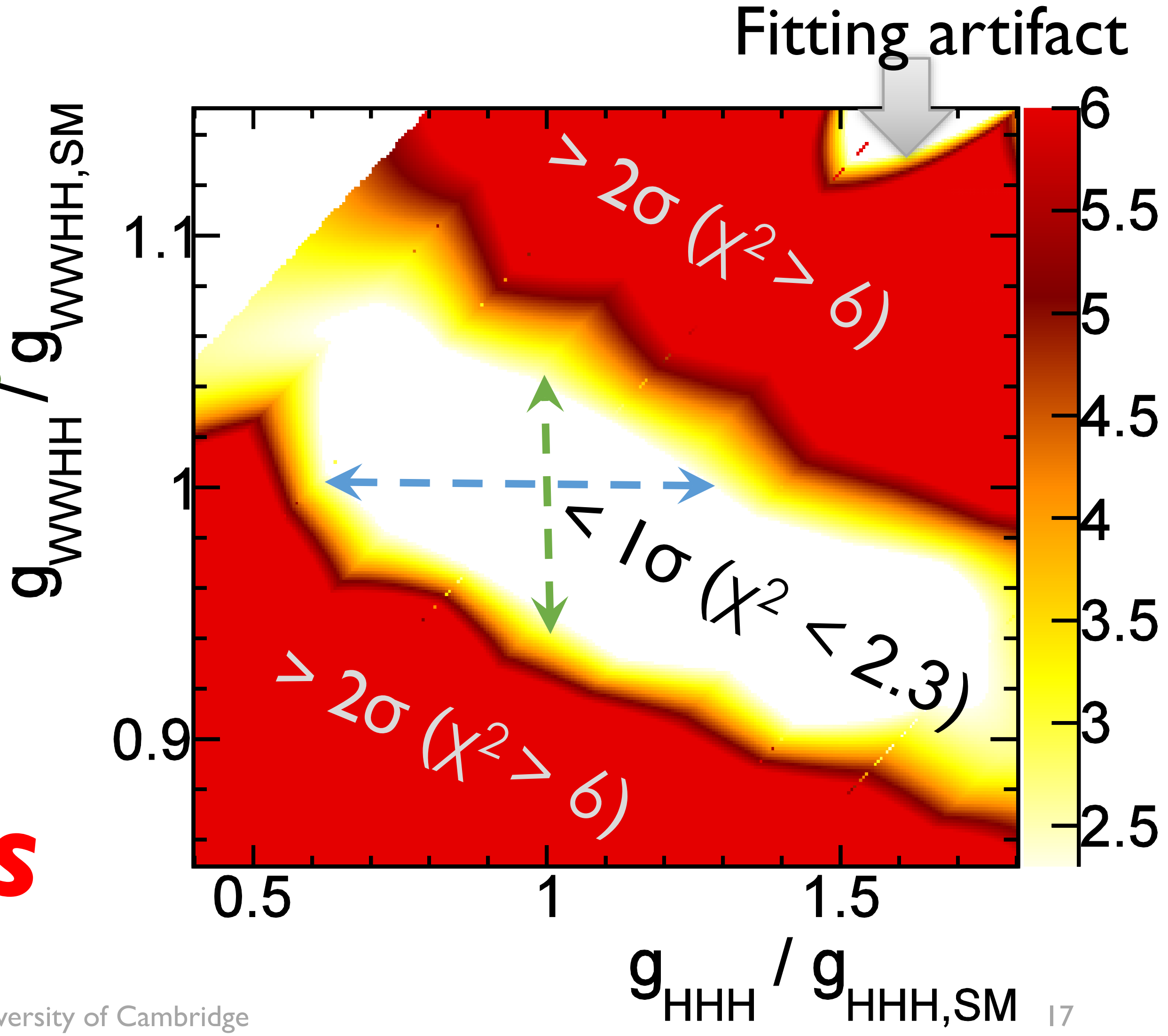
- Slice the template diagonally.
- Fit a cubic function, 4 degrees of freedom, for each slice
- Smooth transition between slices
- Fitting works well close to the minimum points



Toy MC, Chi-square average, interpolation

- Central white: $< 1\sigma (\chi^2 < 2.3)$
- Outer red: $> 2\sigma (\chi^2 > 6)$
- g_{HHH} = 1, %ΔgWWHH ~ 5%
- g_{WWHH} = 1, %ΔgHHH ~ 33%
  - Higgs paper, $2ab^{-1}$, only extract g_{HHH}, crude assumption, %ΔgHHH = 29%

Work in progress



Conclusion

- HHνν→bbbbνν and HHνν→bbWW*νν selection at $\sqrt{s}$ = 1.4 and 3 TeV finalised and presented in the higgs paper. A CLIC note in writing.

- For g_{HHH} and g_{WWHH} extraction, on-going work.
- Optimising kinematic bins cuts: Try to increase bins, different cuts.
- More template points being generated