Higgs self-coupling in double Higgs production at 3 TeV

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Introduction

Goal Full simulation study of double Higgs production at CLIC

- determine prospects for the measurement of the triple Higgs self-coupling and quartic HHWW coupling
- provide input for more global EFT study

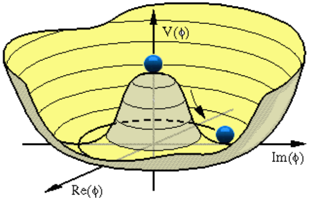
Basis Building on previous work in the collaboration (Rosa Simoniello, Boruo Xu)

- 2017 Higgs paper: Precision of double Higgs production cross-section measurement and resulting expected limits on trilinear Higgs self-coupling
- Analysis selection for bbbb and bbWW final state
- Defined limit setting procedure

NEW

- Updated background estimates
- New BDT trained (Rosa)
- Refined template fit procedure
- Pseudo-experiments for g_{HHH}-only limits
- $\Delta\chi^2$ from template fit for g_{HHH} vs. g_{HHWW} limits extraction
- Update to $\mathcal{L} = 5000\,\text{fb}^{-1}$ and 80 % e^- polarisation

Higgs self-coupling



Self-couplings $\rightsquigarrow$ shape of the Higgs potential

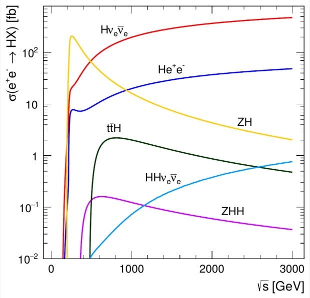
SM Higgs mechanism:

- $V = -\mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$
- μ, λ related to the Higgs mass

Beyond SM:

- $\lambda \neq \lambda_{SM}$ measured as effective coupling

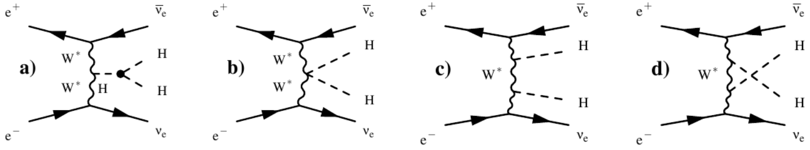
Higgs self-coupling at CLIC



- Measure HH production at 3 TeV in VBF
- Small contribution from ZHH, $\nu\bar{\nu}HH$ at 1.5 TeV
- Higher-order effects in single H production and decay

Higgs self-coupling in VBF at CLIC

- Effectively measure the value of the Higgs trilinear self-coupling by modifying the HHH vertex
- Simultaneously vary the quartic Higgs-W coupling g_{HHWW} as this vertex contributes as well:



- Modified $HH \to bbbb$ production could be due to:
  - non-SM Hbb coupling
  - non-SM single H production
  - ⇒ global analysis taking into account other Higgs measurements; use EFT
- Using differential distributions enhances the discrimination power between modification of the Higgs self-coupling and other non-SM contributions

Analysis

HH production on the bbbb final state: dominant channel by far

Vetoes

- Exclude events containing isolated leptons or hadronic taus
- Require events to pass exclusive jet clustering with N=4

Preselection

- bbbb/bbWW orthogonality cuts:
  - bbbb candidates: $\sum$b-tag ≥ 2.3 and $-\log(y_{34}) \geq 3.7(3.6)$ at 1.4 TeV (3 TeV) where log is the natural logarithm $\log_e$
  - bbWW candidates: all else

BDT in bbbb

- Optimal cut on BDT score for the signal extraction: BDT > 0.1276 (0.1184) used in the Higgs paper (with new BDT)
- BDT > 0.05 for the template fit

Event yields for HH→bbbb cross-section measurement

- Use $\mathcal{L} = 2000\,\text{fb}^{-1}$ (as in the Higgs paper), using the respective optimal BDT score cuts
- Newly trained BDT ("BDT2018") with corrected background normalization

Process	N_{BDT} paper	N_{BDT} 2018
HH→all	61+1	67.520
ee→qqqq	3	3.577
ee→qqqqvv	17	24.293
ee→qqqqlv	6	6.155
ee→qqHvv	50	47.085
egam→vqqqq	11	13.924
egam→qqHv	9	5.695
$s/\sqrt{b}$	6.3	6.7
$s/\sqrt{s+b}$	4.9	5.2

CLIC Higgs paper: Eur. Phys. J. C 77, 475 (2017)

Comparison to results in Higgs paper

- Significance is slightly higher than in the paper
- Compare cross section precisions to the Higgs paper (for $\mathcal{L}$=2000 fb^{-1}):
  - Higgs paper $\frac{\sqrt{S+B}}{S} = 20.3\,\%$
  - BDT2018 $\frac{\sqrt{S+B}}{S} = 19.2.\,\%$

Limits on trilinear Higgs self-coupling from cross-section

Precision of cross-section measurement for different scenarios:

$\mathcal{L}_{\mathrm{tot}}$	$2\,\mathrm{ab}^{-1}$	$5\,\mathrm{ab}^{-1}$
no polarization	19.2. %	12.2 %
$p(e^-) = -80\,\%$	14.3 %	9.1 %
mixed		10.0 %

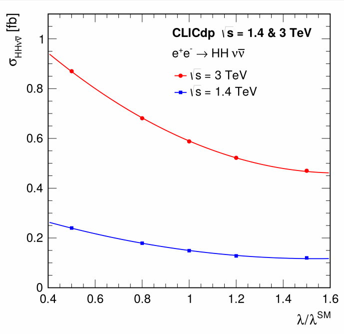
- Mixed: $1\,\mathrm{ab}^{-1} : +80\,\% \oplus 4\,\mathrm{ab}^{-1} : -80\,\%$
- For polarised e^- beams, assume same enhancement factor for background as signal (slightly overestimating)

with $\kappa = 1.47$ at 3 TeV:

$\Rightarrow$ for $5\,\mathrm{ab}^{-1}$, mixed polarisation scenario:

$$\Delta g_{HHH}/g_{HHH} = 14.7\,\%$$

Limits derived from cross-section precision

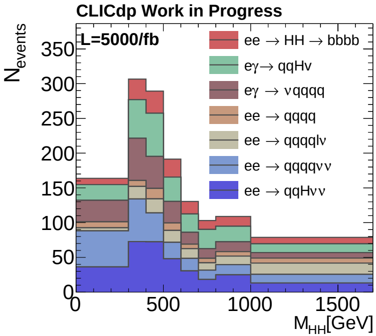


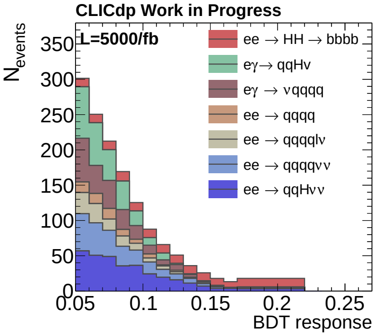
$$\frac{\Delta g_{\mathrm{HHH}}}{g_{\mathrm{HHH}}} = \kappa \cdot \frac{\Delta[\sigma(HH\nu_e\bar{\nu}_e)]}{\sigma(HH\nu_e\bar{\nu}_e)}$$

Kinematics of double Higgs production

BDT input variables

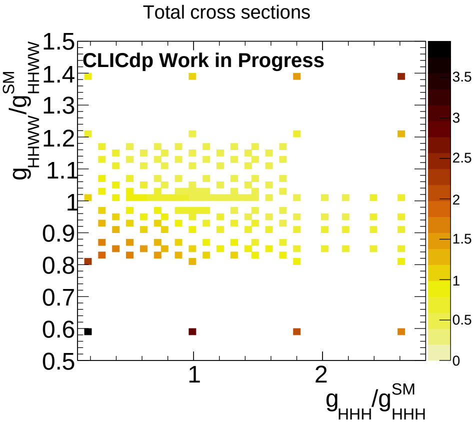
- Flavor tagging information (b, c)
- Jet pair invariant masses and angles
- Invariant mass of the system
- etc.

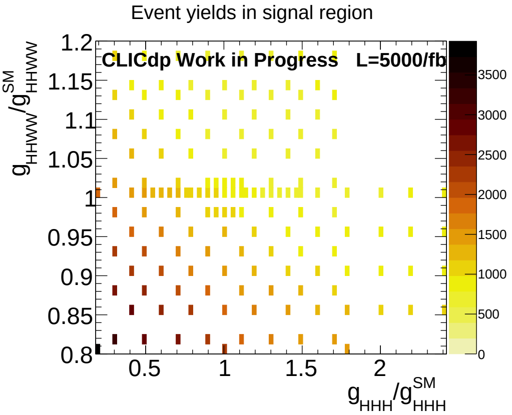




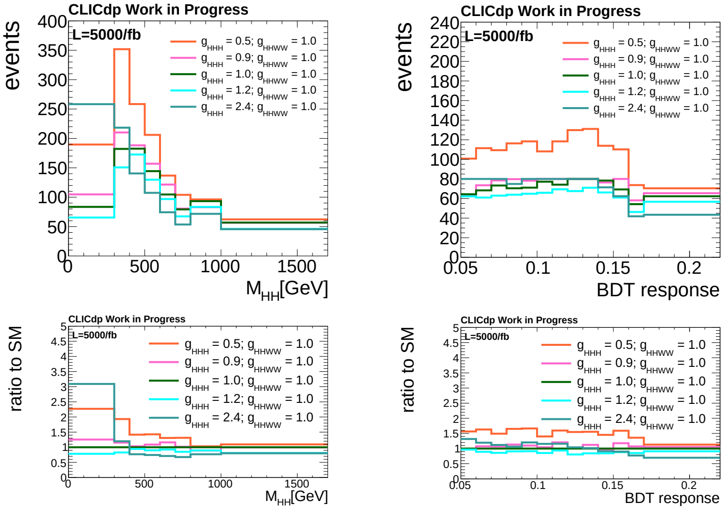
Couplings dependent behaviour: total cross section

- For the measurement, make use of change in production according to the values of the couplings
- Dependence on the couplings:





Kinematic properties of non-SM Higgs self-coupling



- g_{HHWW}=0 for all samples
- Shapes sensitive to coupling

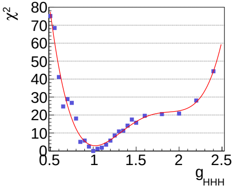
  `http://arxiv.org/abs/1309.7038`
- M_{HH} shows stronger shape-dependence than BDT
- Distinction between points with similar cross-section, but $g_{\mathrm{HHH}} > 1$ vs. $g_{\mathrm{HHH}} < 1$ (example: $g_{\mathrm{HHH}} = 0.9$ vs. $g_{\mathrm{HHH}} = 1.2$)

Template fit method and estimation of limits

For the 1D fit, $g_{HHWW} = g_{HHWW}^{SM}$ is assumed and a measurement of g_{HHH} is performed: 1 d.o.f.
For the 2D fit, both g_{HHWW} and g_{HHH} are varied: 2 d.o.f.

1. Procedure to measure gHHH from the "data": template fit with χ^2 minimization
   - Calculate χ^2 from the binned distributions for each coupling

$$\chi^2 = \sum_i \frac{(N_i^{(exp)} - N_i^{(obs)})^2}{N_i^{(exp)}}$$



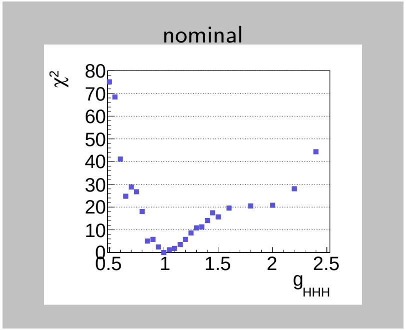
   - Minimum is estimate for gHHH
   - 1σ limits determined from $\Delta\chi^2 = 1(2.3)$ for 1 (2) d.o.f.
   - However, this is sensitive to fluctuations in the samples as the SM point is artificially fixed at $\chi^2 = 0$ (→ outlier from parabola)

⇒ In the g_{HHH}-only (1D) fit, the confidence interval is estimated from pseudo-experiments

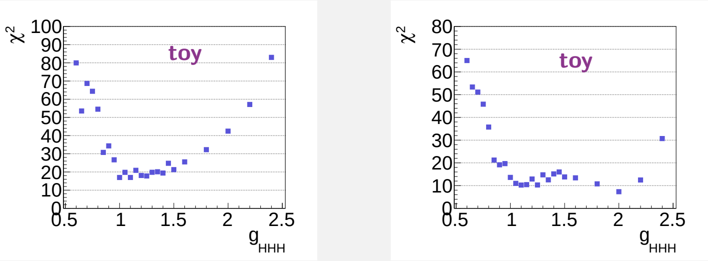
⇒ In the g_{HHWW} vs. g_{HHH} (2D) fit, limits are obtained from $\Delta\chi^2$

Template fit method and estimation of limits, continued

2. Confidence interval corresponding to the Gaussian standard deviation of the measured g_{HHH} values from pseudo-experiments
   - Generate pseudo-experiments randomly from the sensitive distribution
   - Calculate χ^2 with the "observed" number of events from the pseudo-experiment
   - If the distribution of g_{HHH} from pseudo-experiments is Gaussian, its standard deviation σ corresponds to the confidence interval at 68 % C.L.



Pseudo-experiments can lead to large variations, for example:

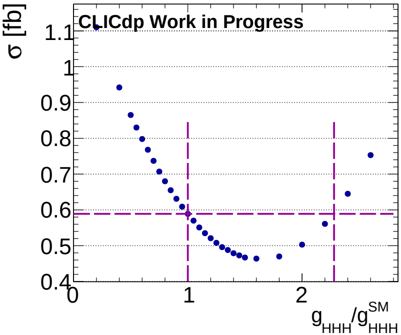


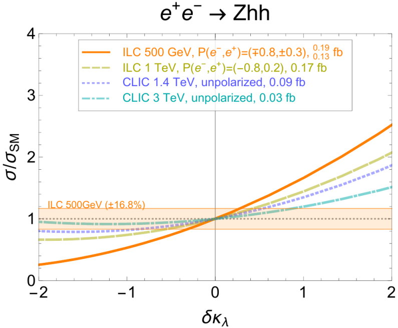
→ even these rare cases have to be covered by the fit procedure

⇒ use polynomial of fourth order to fit the χ^2 points

Second minimum in χ^2

- Behavior explained by cross-section dependence on g_{HHH}
- Kinematic properties help distinguish $g_{\mathrm{HHH}} > 1$ vs. $g_{\mathrm{HHH}} < 1$
- Additionally include double Higgs-Strahlung at 1.5 TeV
  → to be included in the current fit





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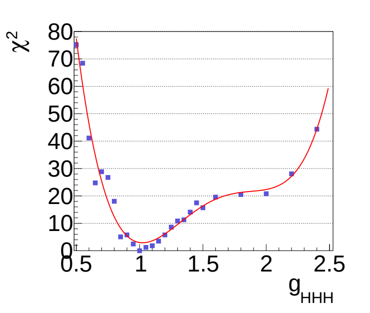
Comparing direct $\Delta\chi^2$ limits and those from toys

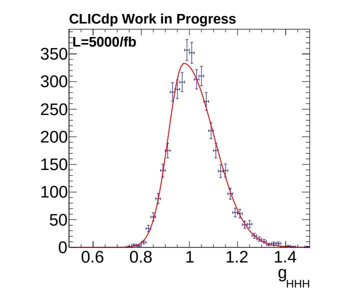
Limits from $\Delta\chi^2$



Best fit: $g_{\mathrm{HHH}} = 1.023$

Limits from $\Delta\chi^2 = 1$: [0.943, 1.115] (68 % C.L.)

Limits from pseudo-experiments



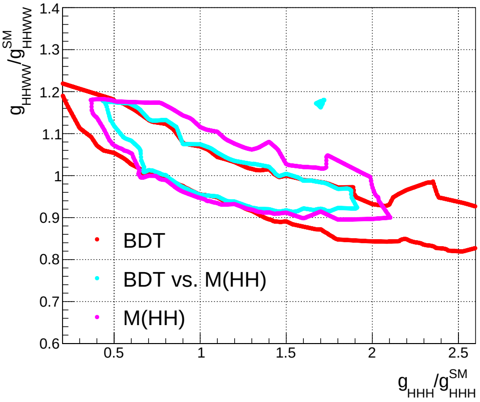
2-sided Gaussian with $\mu = 0.977$;

$\sigma_{\mathrm{left}} = 0.065$, $\sigma_{\mathrm{right}} = 0.125$

Limits from toys: [0.935, 1.125] (68 % C.L.)

Both methods yield asymmetric limits; agreement between methods

Optimization



(not the full statistics)

BDT score → tighter constraints on g_{HHWW}

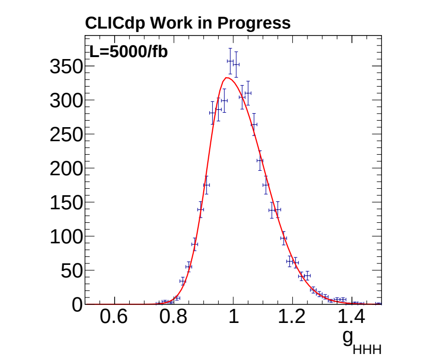
M(HH) → tighter constraints on g_{HHH}

NB BDT was optimized for SM-Signal measurement → not necessarily optimal for couplings extraction

Best observable based on BDT vs. M(HH)

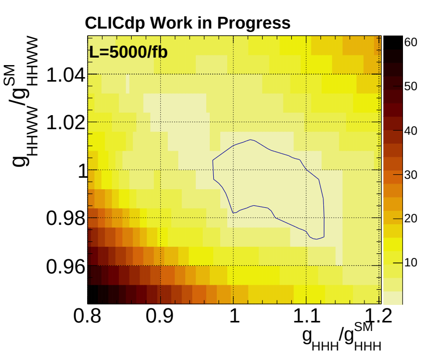
Preliminary results

g_{HHH} only



Expected 68 % C.L. limits [0.935, 1.125]

g_{HHH} vs. g_{HHWW}



$\Delta\chi^2 = 2.3$ contour corresponds to 68 % C.L. limits

Dependence on Luminosity and polarization

- Electron beam polarization enhances the signal cross section: for $p(e^-) = -80\,\%$ the cross section is enhanced by a factor of 1.8

luminosity [fb^{-1}]	e^- polarisation	$g_{HHH}/g_{HHH}^{\mathrm{SM}}$ limits
3000	0	[0.915, 1.252]
3000	-80 %	[0.922, 1.168]
5000	0	[0.915, 1.196]
5000	-80 %	[0.935, 1.125]

- Lower limit below 10 % for all cases
- Upper limit reaches 12 % only for full statistics and polarization
- Illustrates impact of polarization

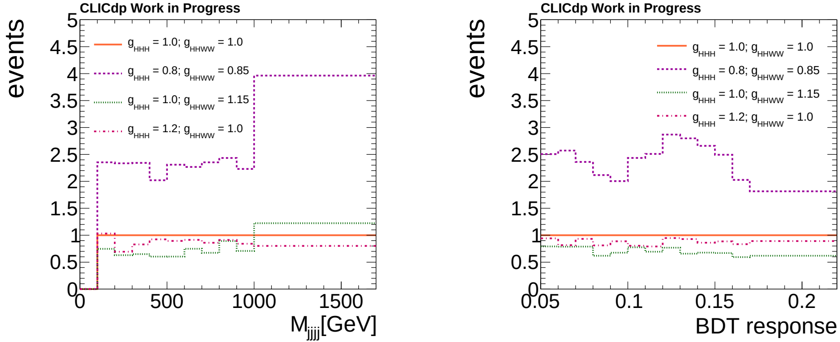
Conclusions and Outlook

- Limit setting procedure for g_{HHH} only as well as g_{HHH} vs. g_{WWHH} defined and optimized
- Preliminary 68 % C.L. limits for g_{HHH}-only: [0.935, 1.125] with full statistics and polarization
- Next steps:
    - Estimate of other contributions ($HH \to bbWW$ at 3 TeV; HH at 1.5 TeV; higher-order contributions in single H production at 1.5 TeV stage)
    - Provide statistical uncertainties for differential cross-section measurement in M(HH)
    - Description within global EFT fit

Additional Material

BDT vs M(HH)

Better limits for M(HH) than for the BDT distribution can be explained by comparing the bin-wise ratios to the SM of some exemplary samples:

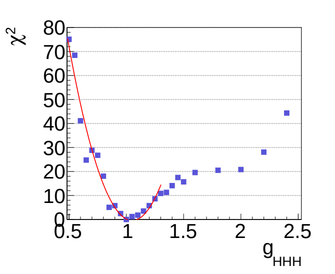


(y-axis should be "ratio to SM")

- In the M(HH) distribution the differences are larger, mainly thanks to the last bin
- Without the last bin the values of the ratio are similar to the BDT
- Ratios of $g_{HHH} = 1, g_{HHWW} = 1.15$ and $g_{HHH} = 1.2, g_{HHWW} = 1$ are closer to SM and flatter for the BDT → BDT less sensitive in this direction

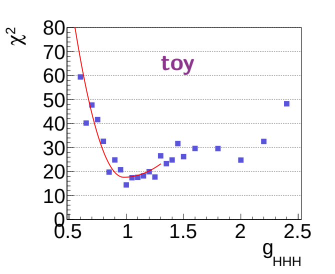
Finding a good fit function a.k.a. estimator for gHHH

Parabola



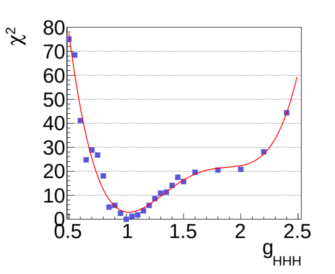
- – Behavior not truly symmetric
- – Does not describe full fit range
- – Highly fit-range dependent
- – Second minimum found sometimes

2-sided Parabola



- – Does not describe the full range → sensitive to fluctuations
- – Pushes minimum lower
- – Second minimum found sometimes

4th order Polynomial



- ✓ Describes full range
- ✓ Finds correct minimum

Best solution: → fit with a 4th order polynomial and estimate g_{HHH} from the left minimum