Stony Brook University

Measuring the Higgs Trilinear Coupling at an HE-LHC

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Brookhaven Forum, October 11, 2017

Introduction

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Directly probes nature of Electroweak Phase Transition.

However, a precision measurement is nearly impossible at 14 TeV.

Expect to constrain $\lambda_3 \in [-0.8, 7.7]$ with 3 ab^{-1}.

The trilinear coupling is a primary benchmark for future hadron colliders (~ 100 TeV)

Future Colliders and HE-LHC

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Alternative scenario: Upgrade magnets at LHC to get to ~ 27 TeV – "HE-LHC"
Several advantages:

- Requires 16 T magnets – already being developed for FCC, using current technology

  Further advances hope to get to 20 T, ~ 33 TeV
- Continue to use the ATLAS and CMS detectors

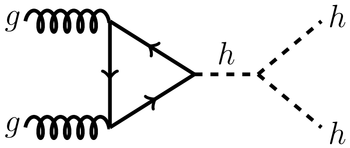
Important to build the physics case: is it worth pursuing a shorter-term measurement?

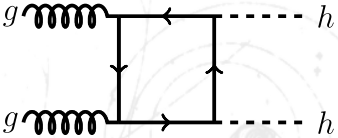
The Higgs Potential and Di-Higgs Production

After spontaneous symmetry breaking,

$$\mathcal{L}_{SM} \supset -\frac{1}{2}m_h^2 h^2 - \lambda_3 \frac{m_h^2}{2v} h^3 - \lambda_4 \frac{m_h^2}{8v^2} h^4$$

$\lambda_3 = \lambda_4 = 1$ in the Standard Model.
The trilinear interaction contributes to di-higgs production:





Prospects in the $bb\gamma\gamma$ Channel

A number of decay channels are possible:

$hh \to b\bar{b}\tau^+\tau^-, b\bar{b}b\bar{b}, b\bar{b}\gamma\gamma, b\bar{b}ZZ^*$

We focus on the $b\bar{b}\gamma\gamma$ channel – optimal mix of higher BR and lower backgrounds.

A number of previous studies project attainable precision on λ_3:

	14 TeV	33 TeV	100 TeV
Snowmass 1308.6302	50%	20%	10%
ATLAS ATL-PHYS-PUB-2017-001	$\sim 200 - 800\%$	–	–
FCC Whitepaper 1606.09408	–	–	5%

All shown at 3 ab^{-1}.

Simulation Setup

The hh signal was generated directly at LO (one-loop) with `MadGraph5_aMC@NLO`

- Scaled to fit NNLO rate
- SM code, modified to float λ_3
- Higgs decayed using `MadSpin`, Showering & hadronization in `Pythia8`.

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All backgrounds generated at LO:

- Zh, $t\bar{t}h$, $b\bar{b}h$ generated direclty in `Pythia8`

  k-factors used to account for NLO effects.

- Other backgrounds (mostly QCD) generated in `MadGraph5` interfaced to `Pythia8`

All hadronized events passed to `Delphes3` for reconstruction.

Detector Simulation with Delphes3

A custom `Delphes3` card based off the current ATLAS projections (see ATL-PHYS-PUB-2016-006) was used to model reconstruction efficiencies.

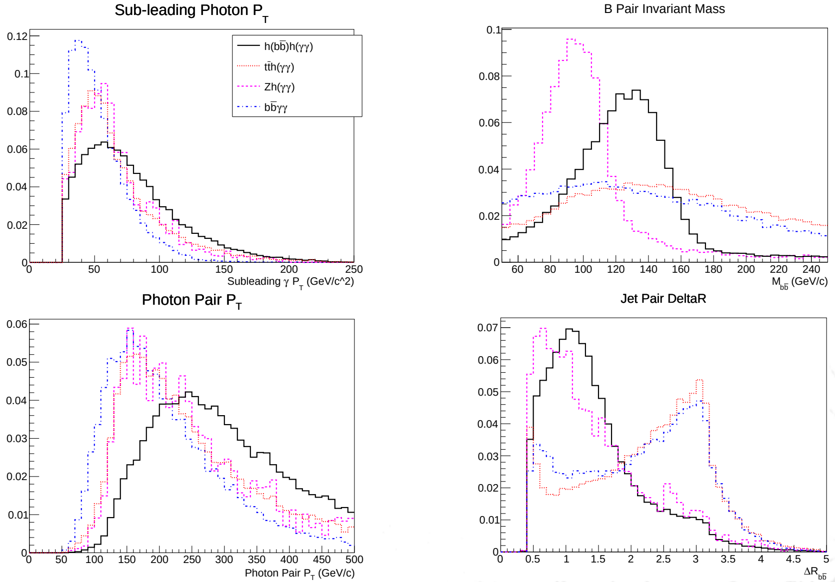
Flavor-tagging and jet-faking-photon probabilities added at analysis level, using a reweighting scheme.

$$p_{b\to b} \sim 0.7, \quad p_{c\to b} \sim 0.15, \quad p_{j\to b} \sim 0.01$$

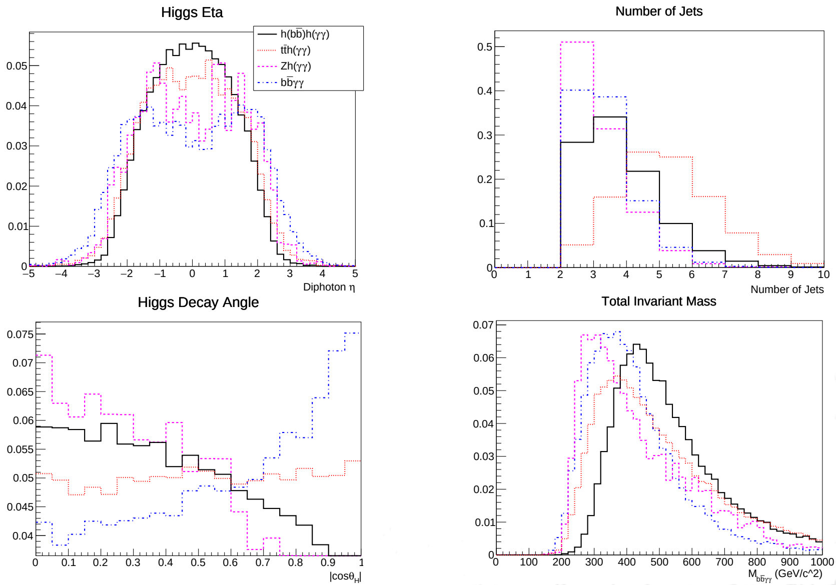
$$p_{j\to\gamma} = 6 \cdot 10^{-4} \cdot \exp\left(-p_{T,j}/300 \text{ GeV}\right)$$

Performance validated against HL-LHC di-Higgs study (ATL-PHYS-PUB-2017-001)

Signal & Background Kinematics



Signal & Background Kinematics (cont.)



Choice of Final Cuts

Our final selection cuts were similar to those in 1606.09408:

- $|\eta_{b,\gamma}| < 2.5$
- $p_T(b_1), p_T(\gamma_1) > 60$ GeV
- $p_T(b_2), p_T(\gamma_2) > 35$ GeV
- $m_{b\bar{b}} \in [100, 150]$ GeV
- $|m_{\gamma\gamma} - m_h| < 2.5$ GeV
- $p_T(b\bar{b}), p_T(\gamma\gamma) > 100$ GeV
- $\Delta R(b\bar{b}), \Delta R(\gamma\gamma) < 3.5$
- $N_{\text{leps}} = 0$
- $N_{\text{jets}} < 6$
- $|\cos\theta_{hh}| < 0.8$

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To improve:

- Stricter p_T cuts on j, γ?
- ΔR cut can be tighter at higher $p_{T,h}$.
- Optimal number of jets allowed?
- Looser $\cos\theta_{hh}$ cut?

Expected Events (3 ab^{-1})

(In Progress)

Process	HL-LHC (14 TeV)	HE-LHC (27 TeV)
$h(b\bar{b})h(\gamma\gamma)$	9.2 ± 0.1	38.6 ± 0.3
$t\bar{t}h(\gamma\gamma)$	11.9 ± 0.1	47.4 ± 0.5
$Zh(\gamma\gamma)$	5.8 ± 0.2	14.8 ± 0.3
$b\bar{b}h(\gamma\gamma)$	0.1 ± 0.01	0.6 ± 0.1
$bb\gamma\gamma$	14.4 ± 1.1	26.8 ± 3.0
$cc\gamma\gamma$	5.02 ± 0.4	16.1 ± 2.4
$bbj\gamma$	12.5 ± 1.5	66.3 ± 4.2
Others*	17.7 ± 1.1	~ 80
Total Bkg.	67.4 ± 2.2	$\sim 300 \pm 10$
$S/\sqrt{B}$	1.12 ± 0.02	2.23 ± 0.07

*includes $jj\gamma\gamma$, $ccj\gamma$, $bbjj$, $Z\gamma\gamma$, $t\bar{t}$ and $t\bar{t}\gamma$.

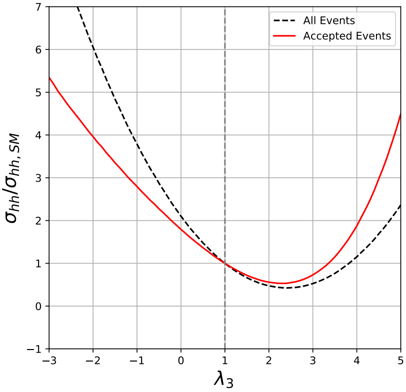
Sensitivity to λ_3

Assuming $\lambda_3 = \lambda_{3,\text{SM}}$, we can estimate the precision using the slope of the σ_{hh} vs. λ_3 curve.

Must correct for the acceptance!
(Computed at $\lambda_3 = -1, 0, 1, 2$)

$$|d(\sigma/\sigma_{SM})/d\lambda_3| \approx 0.65$$

Without any improvements, estimated precision is $\sim 70\%$ on $\lambda_{3,SM}$



Conclusions and Next Steps

With 3 ab^{-1}, HE-LHC could see evidence of hh production at 2.2σ, with 70% precision on the SM coupling.

Some benchmarks:

- Need only 250 fb^{-1} to overtake a 1 ab^{-1} measurement at HL-LHC
- .. or 750 fb^{-1} to beat the full 3 ab^{-1} measurement at 14 TeV.

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Next steps:

- Optimize cuts – new ideas?
- Can we change analysis to maximize precision instead of significance?
- What can we gain with detector upgrades?

Thanks for your attention!

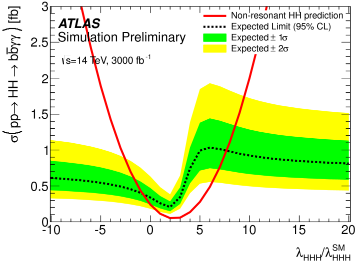
Backup: ATLAS HL-LHC Study

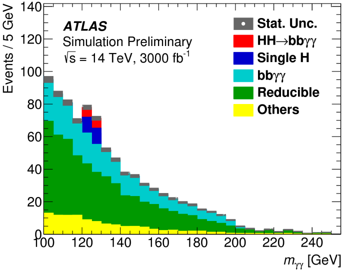
ATLAS has studied the $b\bar{b}\gamma\gamma$ channel in the context of the HL-LHC (14 TeV), assuming 3 ab^{-1} of data.

Expected significance of 1.05σ for the standard model signal.

Trilinear coupling constrainted to the range $-0.8 < \lambda_3 < 7.7$ at 95% confidence level.

$hh \to b\bar{b}b\bar{b}$ at HL-LHC estimates $0.2 < \lambda_3 < 7.0$.





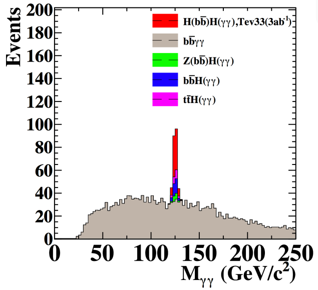
Backup: Validation with ATLAS HL-LHC Study

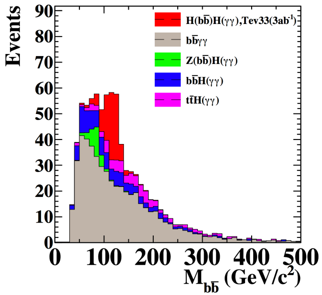
Process	**ATLAS Study**	**Our Results**
$h(b\bar{b})h(\gamma\gamma)$	9.54 ± 0.03	9.29 ± 0.06
$t\bar{t}h(\gamma\gamma)$	7.9 ± 0.2	11.9 ± 0.1
$Zh(\gamma\gamma)$	5.0 ± 0.1	5.6 ± 0.15
$b\bar{b}h(\gamma\gamma)$	0.15 ± 0.01	0.11 ± 0.01
$bb\gamma\gamma$	21.8 ± 0.6	17.1 ± 1.2
$cc\gamma\gamma$	8.5 ± 0.5	8.8 ± 0.59
$bbj\gamma$	22.6 ± 1.1	19.2 ± 2.9
$jj\gamma\gamma$	4.0 ± 0.6	4.3 ± 0.2
$ccj\gamma$	3.2 ± 0.8	4.3 ± 0.7
$bbjj$	5.4 ± 0.8	7.1 ± 0.9
$Z\gamma\gamma$	2.1 ± 0.1	2.6 ± 0.2
$t\bar{t}$	5.2 ± 0.4	3.1 ± 0.3
$t\bar{t}\gamma$	2.4 ± 0.5	1.6 ± 0.3
Total Bkg.	90.1 ± 2.0	85.7 ± 3.4

Backup: Snowmass 2013 Study (1308.6302)

Preliminary study at 14, 33, and 100 TeV, estimated precision of $50\%, 20\%, 8\%$ resp.

- Only included single-h and $bb\gamma\gamma$ backgrounds
- Slope $d(\sigma/\sigma_{\text{SM}})/d(\lambda/\lambda_{\text{SM}}) = -0.8$ didn't account for the acceptance. (overestimates precision by a factor of ~ 2.)
- Lots of room for improvement on analysis!





Backup: FCC Projections (1606.09408)

FCC Studies claim 3% precision attainable with 30 ab^{-1}

Requires improvements on photon reconstruction, energy resolution

B-Tagging performance roughly unchanged.

At 30 ab^{-1} get 12k signal events, 27k background ($\sim 50\%$ from $bbj\gamma$, the rest from $t\bar{t}h, jj\gamma\gamma, bb\gamma\gamma$)