Measuring the Higgs Trilinear Coupling at an HE-LHC

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Introduction

The Higgs self-coupling is one of the most important parameters yet to be measured in the Standard Model.

Elementary scalar interactions have never been observed.

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}.

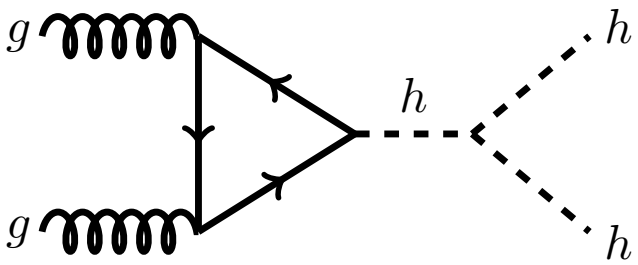
The trilinear coupling is a primary benchmark for future hadron colliders (~ 100 TeV)

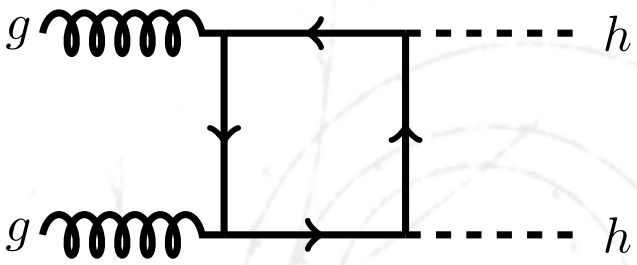
The Higgs Potential and Di-Higgs Production

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:



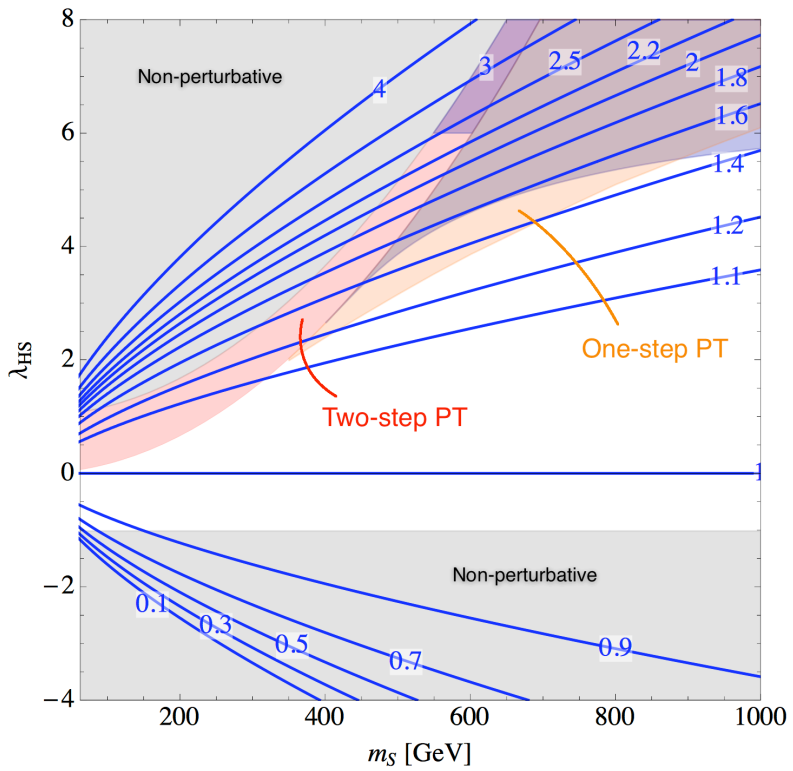


How Well Do We Need to Measure λ_3?

If BSM states are inaccessible at LHC, maximal deviations from λ_3 are $\mathcal{O}(10\%)$

Process	$\Delta\lambda_3$
Mixed-in Singlet	-18%
Composite Higgs	$\mathcal{O}(10\%)$
MSSM	-2% to -15%
NMSSM	-25%

(1305.6397)



"Nightmare scenario": SM + singlet S (1409.0005)

For regions where direct production of S is unfeasible, strong first order EWPT requires deviations of $\lambda_3 \sim 10\%$.

Prospects in the $b\bar{b}\gamma\gamma$ 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`.

$ggF(\gamma\gamma)$ background generated with `POWHEG-BOX`, showered with `Pythia8`.

Important to accurately model extra jet production

All other backgrounds generated at LO:

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

  k-factors used to account for NLO effects.

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

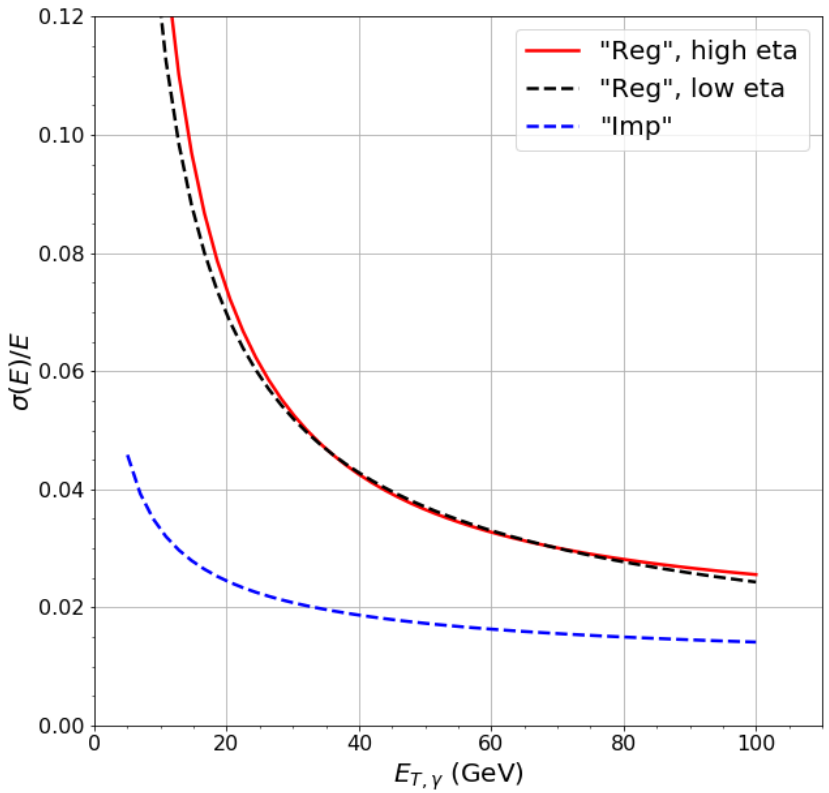
All hadronized events passed to `Delphes3` for reconstruction.

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.

Two different assumptions for E-Cal resolution:

- Regular: $\frac{\sigma_E}{E} \sim 4\%$ (similar to current ATLAS performance)
- Improved: $\frac{\sigma_E}{E} \sim 2\%$ (similar to FCC "Med." benchmark)



Detector Parameterization (cont.)

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

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

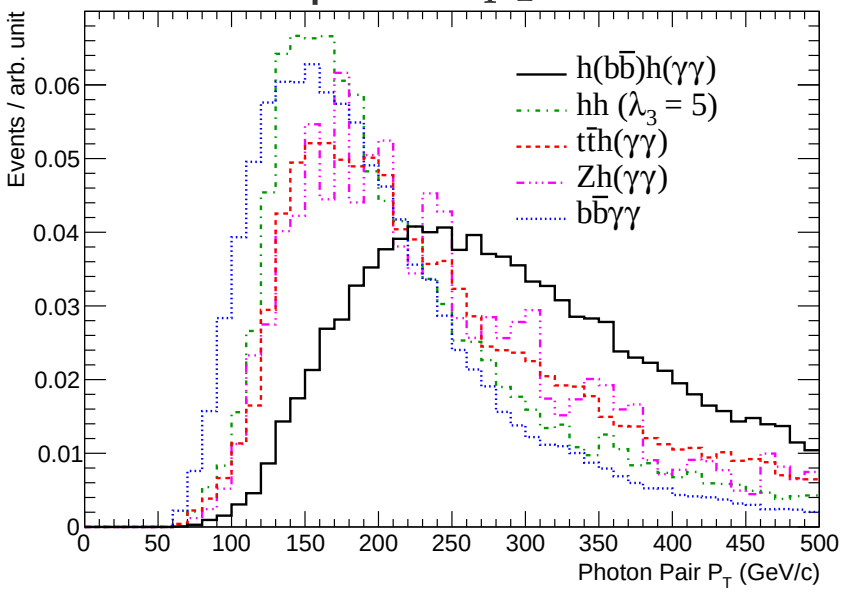
$$p_{j\to\gamma} \sim 7 \cdot 10^{-4} \cdot \exp\left(-p_{T,j}/100 \text{ GeV}\right)$$

Also include electron misidentification probability of 2% (5%) for $|\eta| < 1.7$ (≥ 1.7) in Delphes card.

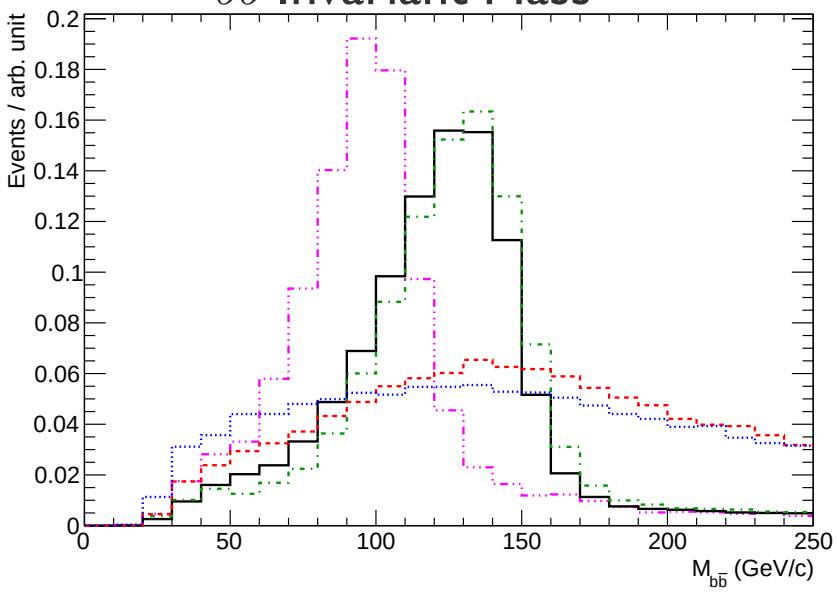
Performance validated against HL-LHC di-Higgs study (ATL-PHYS-PUB-2017-001)

Signal & Background Kinematics

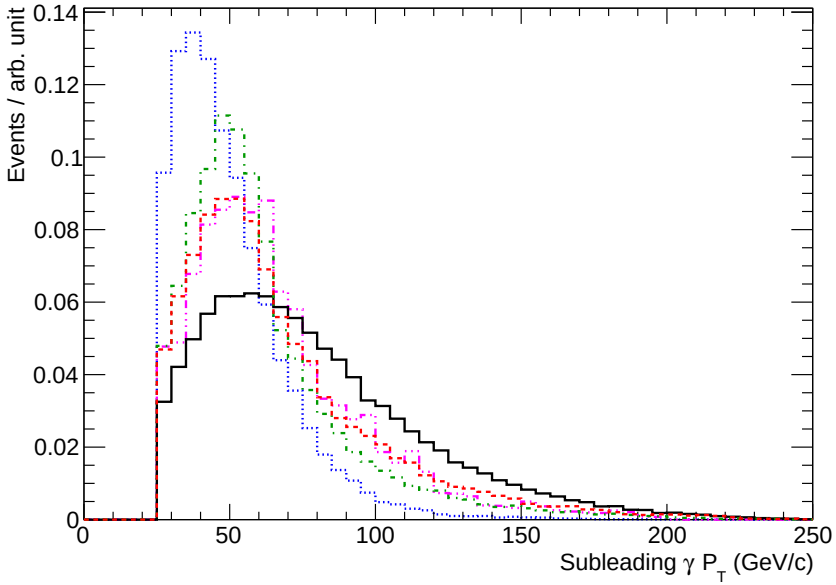
Diphoton p_T



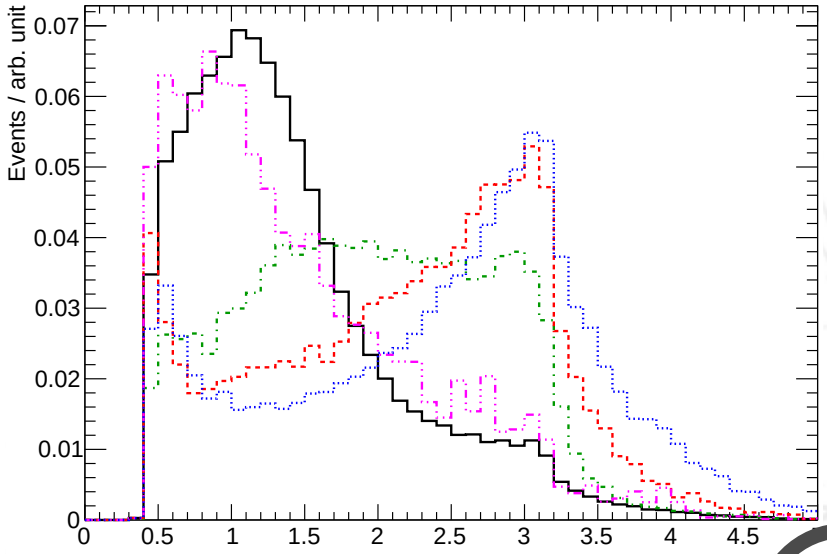
$b\bar{b}$ Invariant Mass



Sub-leading photon p_T

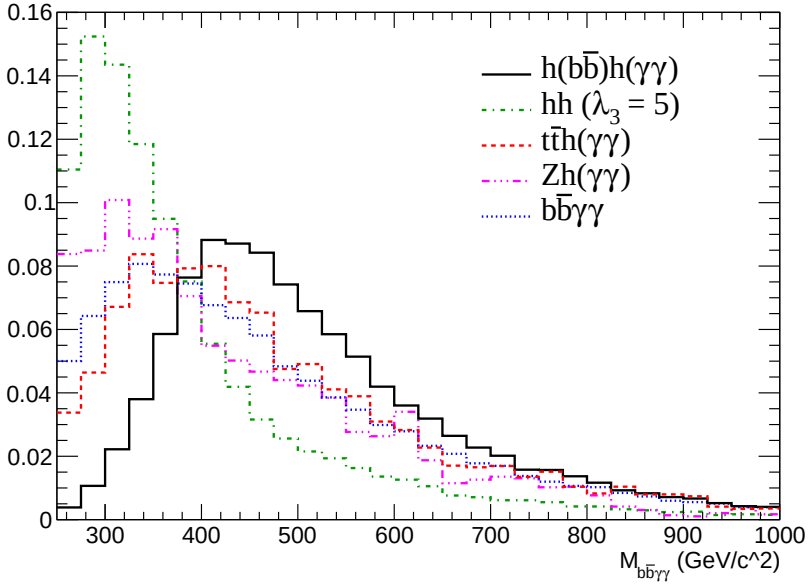


b-pair ΔR

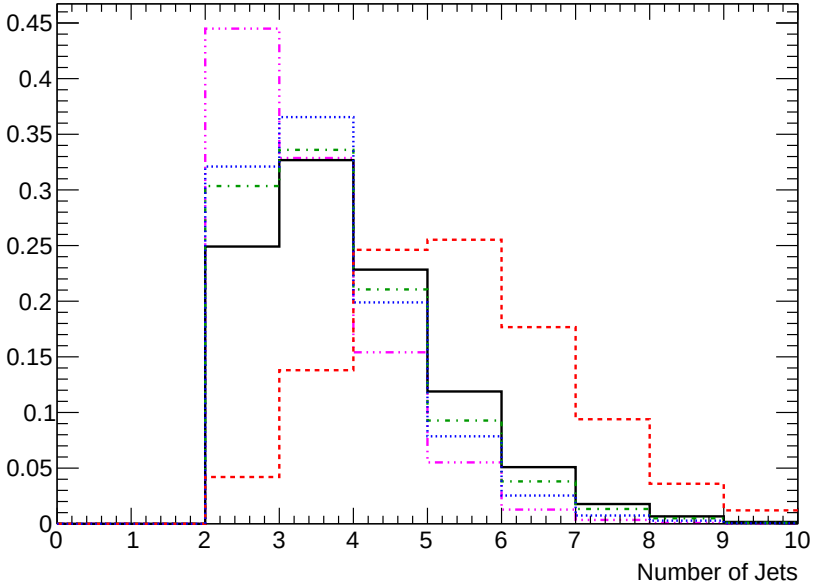


Signal & Background Kinematics (cont.)

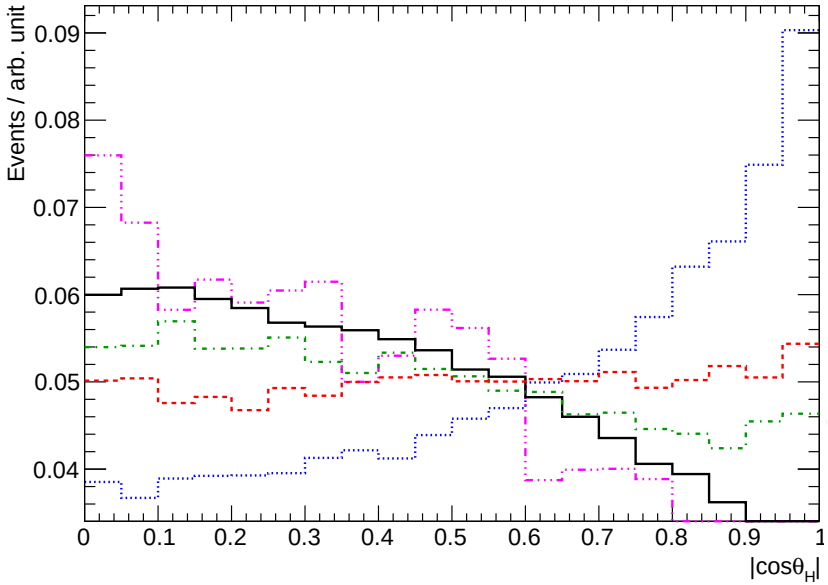
Di-Higgs Invariant Mass



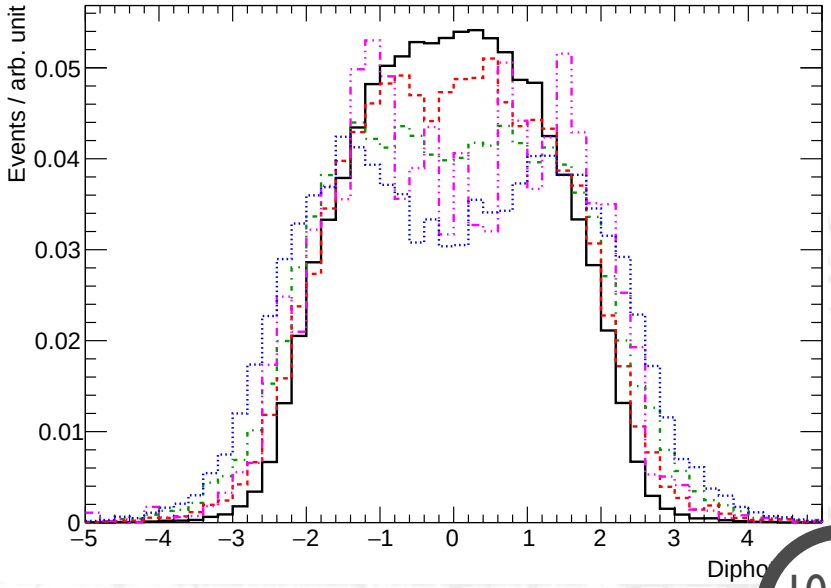
Number of Jets



Higgs Decay Angle



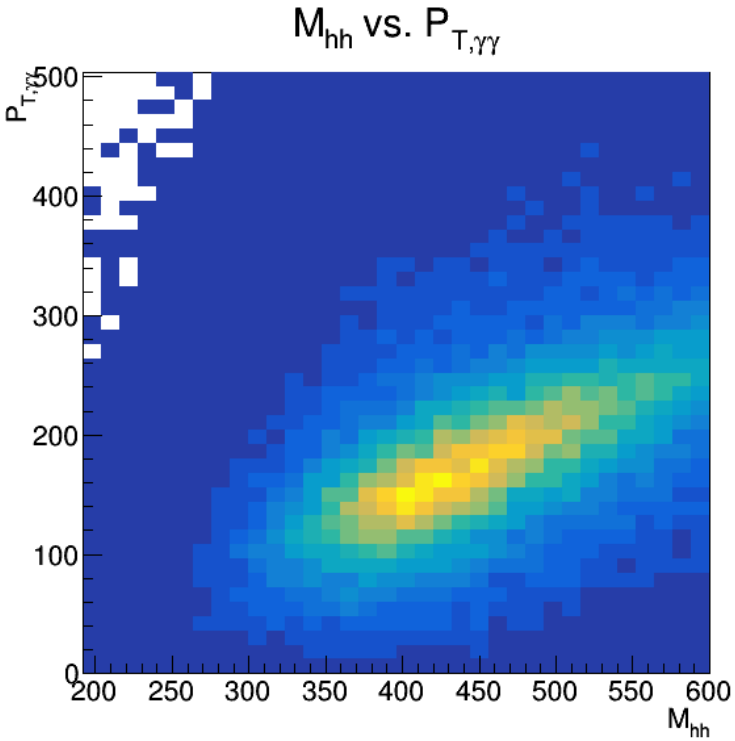
Diphoton η



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
- $|m_{\gamma\gamma} - m_h| <$ 3.0 GeV(Reg.) / 2.2 GeV(Imp.)
- $p_T(b\bar{b}), p_T(\gamma\gamma) > 125$ GeV
- $\Delta R(b\bar{b}), \Delta R(\gamma\gamma) < 3.0$
- $N_{\text{leps}} = 0$
- $N_{\text{jets}} < 6$
- $|\cos\theta_{hh}| < 0.8$



$p_{T,h}$, $\Delta R_{\gamma\gamma,b\bar{b}}$ cuts similar to cut on m_{hh}

Expected Events ($15\ \mathrm{ab}^{-1}$)

Process	Regular			Improved		
$h(b\bar{b})h(\gamma\gamma)$	157.1	$\pm$	0.2	157.1	$\pm$	0.4
$t\bar{t}h(\gamma\gamma)$	161.4	$\pm$	1.3	156.9	$\pm$	0.6
$Zh(\gamma\gamma)$	53.8	$\pm$	0.9	63.3	$\pm$	0.6
$ggF(\gamma\gamma)$	24.1	$\pm$	1.1	32.2	$\pm$	3.2
$bb\gamma\gamma$	155.1	$\pm$	2.3	129.5	$\pm$	11.9
$jj\gamma\gamma$	154.3	$\pm$	6.4	112.3	$\pm$	1.5
$bbj\gamma$	166.5	$\pm$	9.1	179.1	$\pm$	9.5
$bbjj$	168.0	$\pm$	8.4	153.2	$\pm$	6.8
$t\bar{t}$, $t\bar{t}\gamma$	114.1	$\pm$	8.2	106.7	$\pm$	8.0
Others*	40.9	$\pm$	2.2	56.3	$\pm$	6.7
Total Bkg.	1038.2	$\pm$	16.7	963.4	$\pm$	19.8
$S/\sqrt{B}$	4.88	$\pm$	0.17	5.06	$\pm$	0.22

*includes $b\bar{b}h(\gamma\gamma)$, $ccj\gamma$ and $Z\gamma\gamma$.

With Yellow Report Delphes Card (15 ab^{-1})

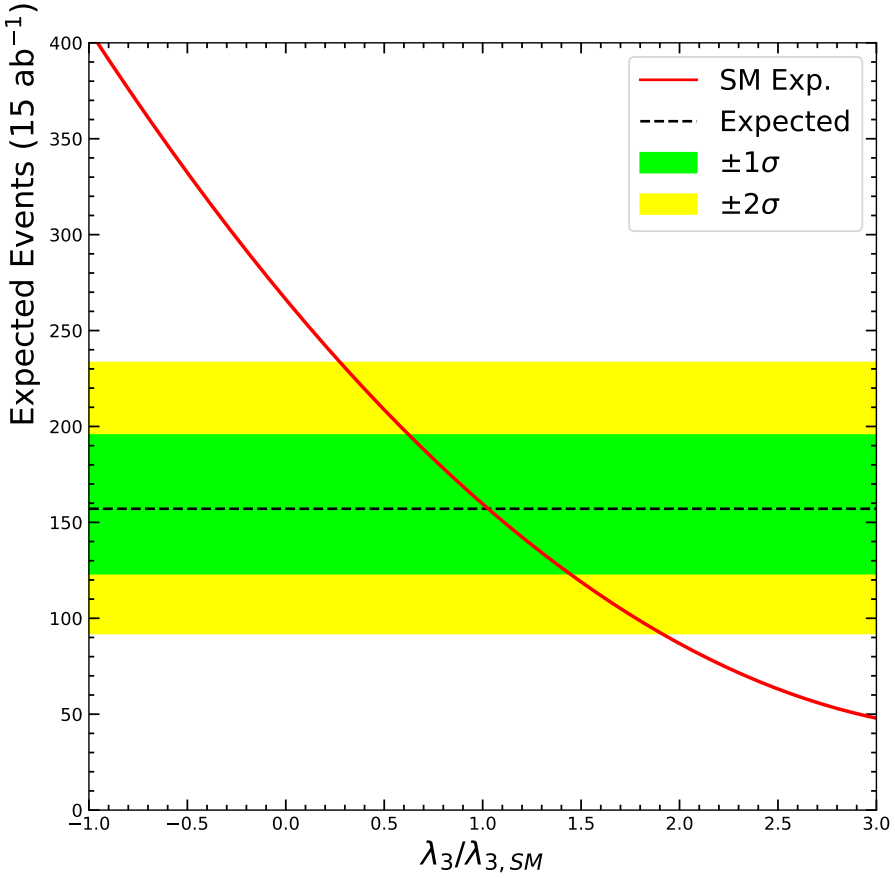
(Preliminary)

Process	
$h(b\bar{b})h(\gamma\gamma)$	141.1 ± 0.3
$t\bar{t}h(\gamma\gamma)$	227.0 ± 1.8
$Zh(\gamma\gamma)$	18.4 ± 0.3
$ggF(\gamma\gamma)$	50.1 ± 3.3
$bb\gamma\gamma$	248.9 ± 6.3
$jj\gamma\gamma$	212.7 ± 5.3
$bbj\gamma$	122.0 ± 1.9
$bbjj$	91.3 ± 5.6
$t\bar{t}$, $t\bar{t}\gamma$	113.8 ± 7.4
Others*	28.2 ± 2.8
Total Bkg.	1113.6 ± 13.5
$S/\sqrt{B}$	4.23 ± 0.11

Sensitivity to λ_3

Estimate the precision on the self-coupling in a hypothetical experiment assuming $\lambda_3 = \lambda_{3,SM}$

Expected events in SM depends on acceptance as a function of λ_3



$$|d(\sigma/\sigma_{SM})/d\lambda_3| \approx 0.55$$

Estimated precision of $\sim 40\%$ on $\lambda_{3,SM}$

Conclusions and Next Steps

With 15 ab^{-1}, HE-LHC could see evidence of hh production at $\sim 5.0\sigma$, with $\sim 40\%$ precision on the SM coupling.

Some benchmarks:

- Need only 250 fb^{-1} to overtake a 1 ab^{-1} measurement at HL-LHC
- significance $= 1.3 \times \sqrt{L/\text{ab}^{-1}}$.

Further improvements:

- Use the m_{hh} distribution? (1802.04319)
- Combination with other decay channels?
- Potential gains from machine learning?

Thanks for your attention!

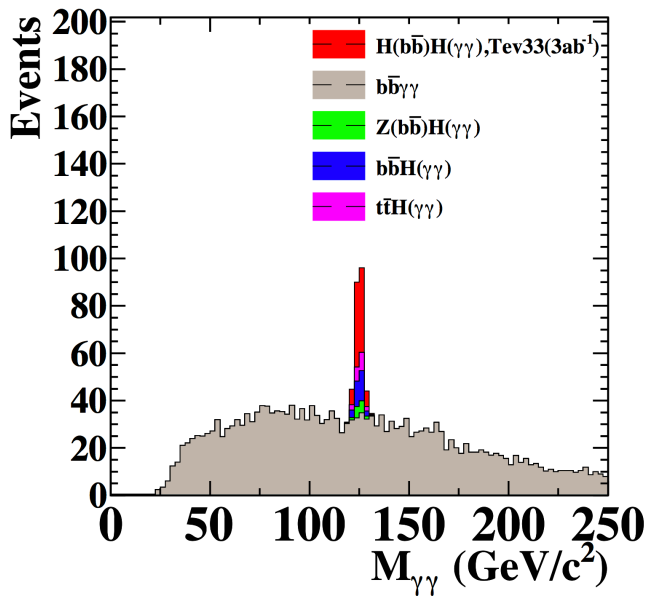
Backup: Validation with ATLAS HL-LHC Study

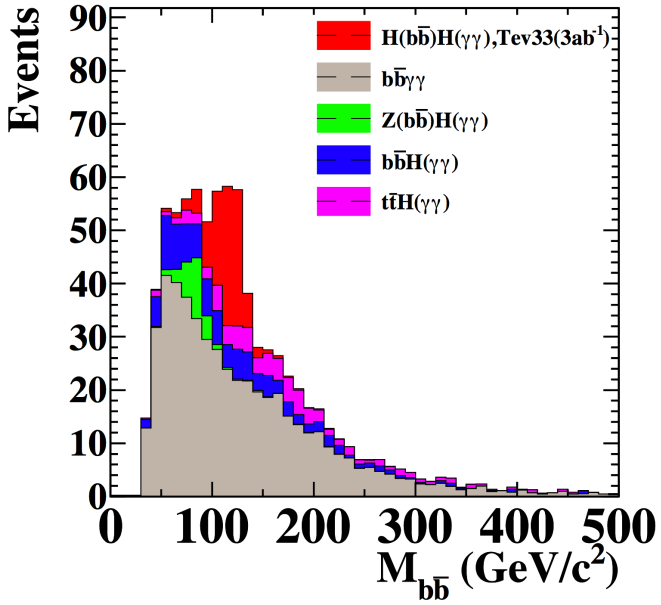
Process	ATLAS Study			Our Results		
$hh \to bb\gamma\gamma$	9.54	$\pm$	0.03	9.89	$\pm$	0.04
$t\bar{t}h(\gamma\gamma)$	7.87	$\pm$	0.2	10.26	$\pm$	0.05
$Zh(\gamma\gamma)$	4.98	$\pm$	0.1	4.68	$\pm$	0.05
$b\bar{b}h(\gamma\gamma)$	0.15	$\pm$	0.01	0.12	$\pm$	0.01
$ggF(\gamma\gamma)$	2.74	$\pm$	0.35	4.6	$\pm$	0.5
$b\bar{b}\gamma\gamma$	21.80	$\pm$	0.6	33.1	$\pm$	1.7
$c\bar{c}\gamma\gamma$	8.47	$\pm$	0.5	9.5	$\pm$	0.3
$jj\gamma\gamma$	4.04	$\pm$	0.6	7.1	$\pm$	0.3
$b\bar{b}j\gamma$	22.60	$\pm$	1.1	17.1	$\pm$	1.9
$c\bar{c}j\gamma$	3.20	$\pm$	0.8	3.5	$\pm$	0.4
$b\bar{b}jj$	5.35	$\pm$	0.8	11.6	$\pm$	0.5
$Z(b\bar{b})\gamma\gamma$	2.06	$\pm$	0.1	1.7	$\pm$	0.1
$t\bar{t}^*$	2.40	$\pm$	0.4	2.5	$\pm$	0.5
$t\bar{t}\gamma$	5.16	$\pm$	0.5	7.4	$\pm$	1.2
Total Background	90.82	$\pm$	2.0	113.3	$\pm$	3.0

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!

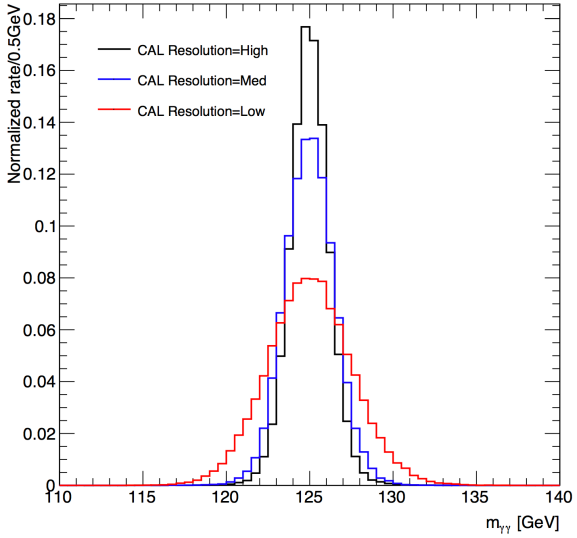
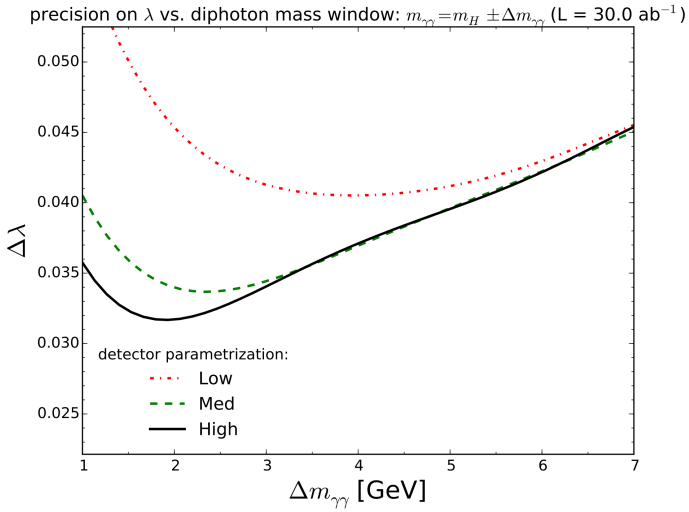




Backup: FCC Projections (1606.09408)

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 $t\bar{t}h, jj\gamma\gamma, bb\gamma\gamma$)