Higgs self coupling & HH at the HL/HE-LHC

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on behalf of the CMS+ATLAS collaborations

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HH contributions to YR

- Section 3b: "Double Higgs measurements and trilinear coupling"

One of highest priority reseach subjects for future LHC operations

- For sensitivity projections important to incorporate:
  - Detector upgrades
  - Theory developments
  - Analysis improvements

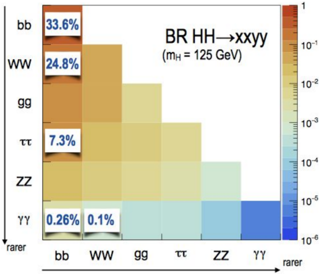
- Section 3c: "Indirect probes of trilinear coupling through differential distributions measurements"

Novel approach to investigating λ_3

- Projected constraints of trilinear coupling from $H \rightarrow \gamma\gamma$ differential measurements

HH analyses: run II status

- several final states explored @13TeV by ATLAS+CMS
- resonant + non-resonant production
- no signs of HH @ run-II
  - sensitivity @ HL-LHC?



Observed $\sigma/\sigma_{\rm SM}$ (exp)		
Channel	**ATLAS**	**CMS**
bbbb	<13 (20.7) ($36.1 fb^{-1}$) [submitted to JHEP]	<342 (308) ($2.32 fb^{-1}$) [HIG-PAS-16-026]
$bb\gamma\gamma$	<22 ($36.1 fb^{-1}$) NEW paper coming soon	<23.6 (19) ($35.9 fb^{-1}$) [submitted to Phys.Lett.B]
$bb\tau\tau$		<31.4 (25) ($35.9 fb^{-1}$) [Phys.Lett.B 778(18)101]
bbVV		<79 (89) ($35.9 fb^{-1}$) [JHEP 01 (2018) 054]
$WW\gamma\gamma$	<230 ($36.1 fb^{-1}$) NEW paper coming soon	

Non-resonant di-Higgs @95% C.L. **13TeV**

HH analyses: HL-LHC

Two alternative approaches to sensitivity prediction of HH @ HL-LHC:

CMS

- Full analysis based on Delphes:
  - Phase-II CMS @HL-LHC
  - Better account for experimental effects + 14 TeV + detector upgrades
- *bbbb*, *bbγγ*, *bbττ*, *bbVV*, *bbZZ*

ATLAS

- Based on extrapolation from run-II:
  - Studying systematics and triggers in HL-LHC environment
- *bbbb*, *bbττ*, *bbγγ*

+ → **Combination** ← +

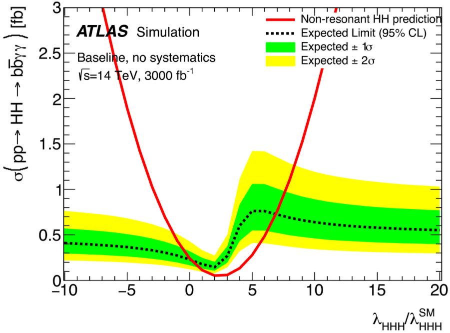
Channel	CMS	ATLAS
HH→ bbbb	$Z(\sigma_{HH}(SM))=0.39\ \sigma$	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L.
HH→ bbττ	1.6 xSM	$0.6\ \sigma$ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L.
HH→ bbγγ	$1.43\ \sigma$	$1.5\ \sigma$ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only)
HH→ WWbb	$0.45\ \sigma$	

current projections: more info see Back-up

HH physics results

How to present results for HH@HL-LHC: **input from theory community**

- goals: SM-HH cross-section + λ_3
- non-resonant:
  - ggH in 5 channels + combination
  - VBF in higher BR (CMS only) $\Longrightarrow$ VVHH constraint, parametric modelling of VBF
- discussion on results to deliver:
  - agreement: SM HH limit, κ_λ, benchmarks
  - possibilities: BSM couplings, 2D scans (e.g. κ_λ-vs-κ_t)
- Paradigm shift: exclusion $\longrightarrow$ likelihood contours

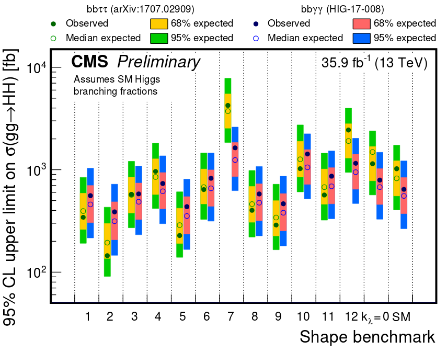


Master formula: $\lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}}$

HH physics results

How to present results for HH@HL-LHC: **input from theory community**

- 5D EFT parameter space:
  $\Longrightarrow$ [arXiv:1608.06578]
  - BSM effective lagrangian:
    $\Longrightarrow \kappa_\lambda, \kappa_t, c_2, c_g, c_{2g}$
  - partition space: regions w/ similar pheno
  - sensitivity in different regions
  - correlations between anomalous couplings in ggH and VBF



ATLAS+CMS Combination

For successful combination need to work under common hypothesis

- combine at results level?
- most likely SM HH + κ_λ scans

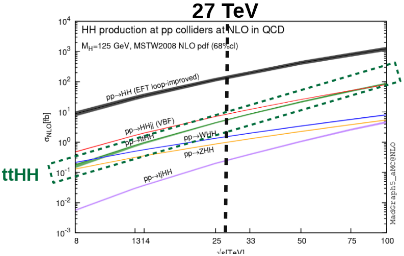
Implementation: combining CMS full sim studies w/ ATLAS projections

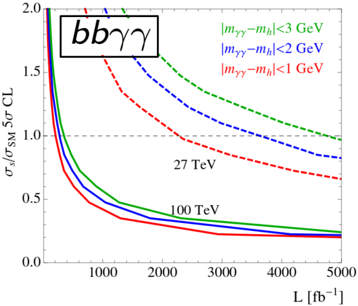
- experiments have technical know-how from experience
- need to understand **correlations in systematics**
  - **experimental**: experience from run I
  - **theoretical**: known correlations

Results: again important to discuss optimal way for presenting

HH at HE-LHC

No central results planned (ATLAS+CMS), encouraging individual contributions





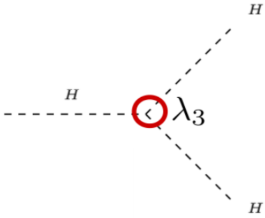
- Significant motivation: $\sigma^{SM}_{HH}(27\text{TeV}) = 127.88$ fb [G.Heinrich]
  - ~4 × @13TeV
- Recent pheno studies on prospects at HE collider: $bb\gamma\gamma$
  - Quote 30% accuracy on λ_3 achievable @27TeV
- Potential methods:
  1. full 27 TeV Delphes analysis using upgraded detector config [M.Selvaggi+G.Ortona]
  2. simply scale cross-section from 14 TeV analysis ⟹ projections

Indirectly probing λ_3 via single-Higgs differential measurements

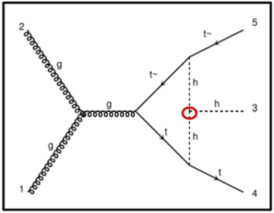
Disclaimer: studies are standalone, not yet official

Single Higgs vs Di-Higgs

- Di-Higgs standard process for studying λ_3 at LHC
  - SM cross-section $\sim$0.001 $\times$ single-Higgs: not yet demonstrated @HL-LHC
    $\Longrightarrow \kappa_\lambda >\sim$7.7 & $\kappa_\lambda <$-0.8 [ATLAS (2b2γ)]
- investigate complementary avenues for determining λ_3
- Access λ_3 via NLO EWK corrections:
  precision differential measurements of single-Higgs events
  - motivated by
    F.Maltoni, D.Pagani, A.Shivaki and X.Zhao
    $\Longrightarrow$ [Eur. Phys. J. C (2017) 77: 887]
  - competitive with di-Higgs limits:
    $\Longrightarrow \kappa_\lambda >\sim$7.0 & $\kappa_\lambda <$-2.0
  - use $H \to \gamma\gamma$



Master formula: $\lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}}$



Single-Higgs differential measurements

- LO cross-section in bins of some observable (e.g. $p_T(H)$) scales with κ_λ as:

$$\mu(\kappa_\lambda, C_1) = \frac{\sigma_{\text{NLO}}(\kappa_\lambda)}{\sigma_{\text{LO}}(\kappa_\lambda = 0)}\bigg|_{C_1} = \frac{1 + \kappa_\lambda C_1}{1 - \kappa_\lambda^2 \delta Z_H}$$

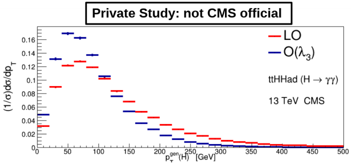
  - C_1: interference between LO amplitude and λ_3-dependent virtual corrections at one-loop.

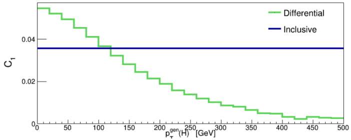
$$C_1(\{p_n\}) = \frac{2\Re(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\text{SM}}})}{|\mathcal{M}^0|^2}$$

- **Key**: C_1 process + kinematic dependence
  - $C_1 \equiv C_{1i}$: function of bin i of the observable
    $\implies$ **differential** $\mu_i(\kappa_\lambda, C_{1i})$
    $\implies$ Non-flat dependence on κ_λ
- Focus on associated modes: ttH and VH
- Use public code to calculate $\mathcal{O}(\lambda_3)$ effects: extract C_1 at gen-level

Range of validity

- neglect higher order terms $\implies |\kappa_\lambda| \lesssim 20$
- indicate validity region in results
- th. unc framework



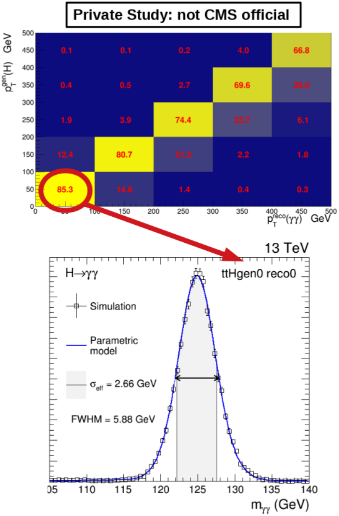


$p_T(H)$ for ttH $\to$ bjj bjj $\gamma\gamma$

Analysis Overview

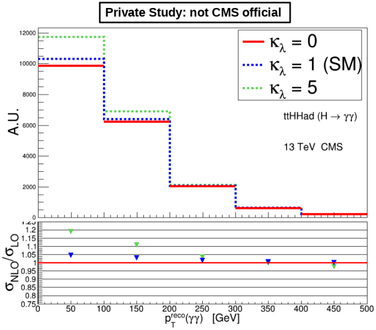
- **Differential cross-section measurements using Delphes CMS-PhaseII @HL samples**
  - Event selection for particular final state
    - mimic tags as in $H \to \gamma\gamma$ 13 TeV analysis
    - calculate observable at gen and reco-level
  - Coarser binning: statistically limited
    - still to be optimised
  - Gen $\to$ reco-bin migration: governed by detector resolution
    - characterised by response matrices
  - Fit sig+bkg model to $m_{\gamma\gamma}$ distribution in each bin (e.g. ttHgen0 $\times$ reco0)
  - Incorporate κ_λ dependence: $\mu_i(\kappa_\lambda, C_{1i})$
    - Using C_{1i} values extracted at gen-level $\Longrightarrow$ sensitvity to κ_λ at 3 ab^{-1}

$p_T(H)$ for ttH $\to$ bjj bjj $\gamma\gamma$



Signal extraction and interpretation

Signal yield varies w/ κ_λ



$p_T(H)$ for ttH → bjj bjj $\gamma\gamma$

1. **Uncertainties for differential cross-sections**: ttH and VH @HL-LHC
2. **Sensitivity to κ_λ**
   - 1D likelihood scan with κ_λ as POI
   - 2D scan of κ_λ vs κ_t?

Important towards final sensitivity

- Systematics
  - experimental: YR2018
  - theoretical
- Theoretical assumptions
  - only λ_3 variations
  - impact of EW unc close to SM
  - role of QCD higher order effects

3. **Combination with HH**
   - 1D κ_λ scan, increased sensitivity
   - global fit: constraints from standard single-Higgs measurements

Summary

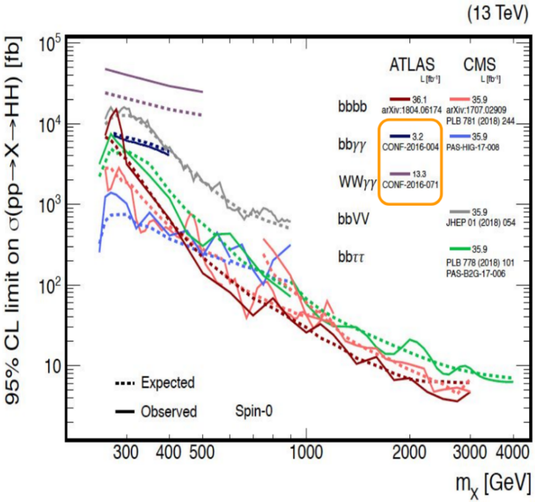
- several HH final states explored @13TeV by both ATLAS + CMS
- YR2018 guidelines HH prospective studies @HL-LHC
  - simple (conservative) projections show some sensitivity to HH
  - improvement by incorporating experimental + detector + analysis developments
  - CMS + ATLAS putting significant effort and time using different techniques
- Require input from theory community on most useful way to present results
  - SM-HH + λ_3 are HL-LHC primary goals
- Single-Higgs differential measurements complimentary probe of λ_3
- Combinations ATLAS + CMS/H+HH offer best sensitivity

Back-Up Slides

HH analyses: run II status

Search for new physics via resonant production:

- interpreted in terms of exclusion limits on m_X



HH analyses: HL-LHC (more info)

CMS

- Full analysis based on Delphes: five channels + combine results
  - Fast simulation of CMS HL-LHC conditions
  - Better account for experimental effects + 14 TeV + detector upgrades

- *bbbb*: impact of trigger thresholds
- $bb\gamma\gamma$: full analysis + cross-check w/ projections
- $bb\tau\tau$: HGCAL TDR
- *bbVV* ($2\ell 2\nu$): importance of MVA
- *bbZZ* (4ℓ): new channel

ATLAS

- Analysis mainly based on extrapolation from run-II:
  - Considering 3 channels for YR + combination
  - Studying systematics and triggers in HL-LHC environment

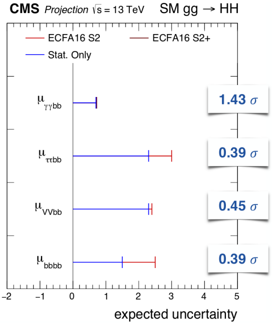
- *bbbb*: extrapolation of 2015+2016, improved IT *b*-tagging efficiency
- $bb\tau\tau$: extrapolation from run II
- $bb\gamma\gamma$: dedicated HL-LHC prospects analysis $\Longrightarrow$ upgraded detector + pile-up conditions

Combination of final states + ATLAS/CMS crucial to observe HH production
$\Longrightarrow$ orthogonal analyses with common structure

HH analyses: current HL-LHC projection results

(N.B. significances assuming SM signal + background)

CMS: extrapolation of early run II results. (2.3/2.7 fb^{-1} to 3000 fb^{-1})



Channel	Median expected limits on $\mu = \sigma_{HH}/\sigma_{HH}^{SM}$		Significance (Z-value)		Uncertainty as a fraction of μ	
	ECFA16 S2	Stat. only	ECFA16 S2	Stat. only	ECFA16 S2	Stat. only
$HH \to bb\gamma\gamma$(S2+)	1.44	1.37	1.43	1.47	0.72	0.71
$HH \to bb\tau\tau$	5.2	3.9	0.39	0.53	2.6	1.9
$HH \to bbVV$	4.8	4.6	0.45	0.47	2.4	2.3
$HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5

ECFA16 S2 Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach the ultimate level expected to be achievable by CMS with a sufficiently large accumulated dataset. The performance of the CMS detector is assumed to be the unchanged with respect to the reference analysis.

UNCERTAINTIES SCALE DOWN WITH LUMI

ECFA16 S2+ Theoretical uncertainties scaled down by a factor 1/2, while experimental systematic uncertainties are scaled down by the square root of the integrated luminosity until they reach the ultimate level expected to be achievable by CMS with a sufficiently large accumulated dataset. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account.

HH analyses: current HL-LHC projection results

(N.B. significances assuming SM signal + background)

CMS: updates in projection studies

$bb\gamma\gamma$: Barrel TDR

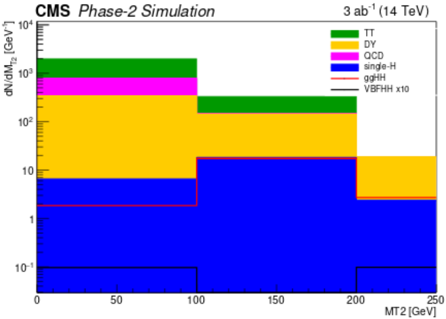
- knowledge of expected CMS detector w/ ageing ECAL + 200 PU
- upgraded detector: photon iso eff, energy resolution + vertex-finding eff
- improved CMS-II tracker

	Median expected limits in μ_r		Significance	
Process	Stat. + Sys.	Stat. Only	Stat. + Sys.	Stat. Only
$HH \to \gamma\gamma bb$	1.1	1.00	1.9	2.0

$bb\tau\tau$: HGCAL TDR

- Phase-II CMS upgrades, in particular HGCAL
- profits from HGCAL both in acceptance + better reco of jets + τs
- use dedicated sim to incorporate collision conditions of HL-LHC + performance of CMS-II
- reduced systematics to current values

Category	σ_{HH}/σ_{SM}	$\sigma_{ggHH}/\sigma_{SM}$	σ_{VBF}/σ_{SM}
2b0j	1.8	3.0	72.6
VBF	3.9	5.4	86.6
Combined	1.6	2.8	52.2



HH analyses: current HL-LHC projection results

(N.B. significances assuming SM signal + background)

ATLAS: from TDRs

- $HH \to bb\gamma\gamma$: based on truth level particles convoluted w/ detector resolution + efficiencies + fake rates computed for PU 200
  - Re-evaluation of photon energy resolution $\Longrightarrow$ narrower $H \to \gamma\gamma$ peak
  - Improved b-tagging performance: more powerful MV2 alg. + dedicated tune for ITk
  - Improved inner tracking performance

- $HH \to bbbb$: extrapolation of run II results (24.3 fb^{-1})
  - improved b-tagging performance (as in $bb\gamma\gamma$)
  - improved trigger described in TDAQ TDR
  - two projections: none & current systematics

- $HH \to bb\tau\tau$:
  - truth-level studies
  - ATLAS at HL-LHC: representative samples to extract detector performance

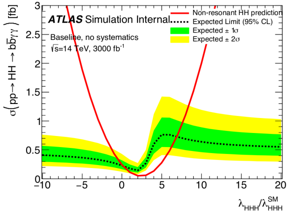
Channel	ATLAS
$HH \to bbbb$	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L.
$HH \to bb\tau\tau$	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L.
$HH \to bb\gamma\gamma$	1.5 σ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only)

HH analyses: current HL-LHC projection results

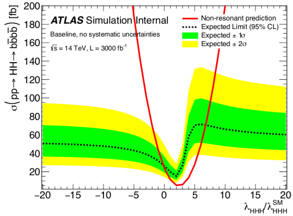
(N.B. significances assuming SM signal + background)

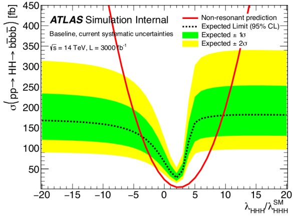
ATLAS: from TDRs

- *HH → bbγγ*

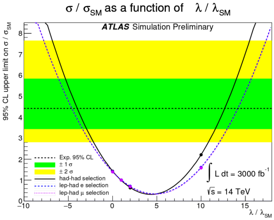


- *HH → bbbb*





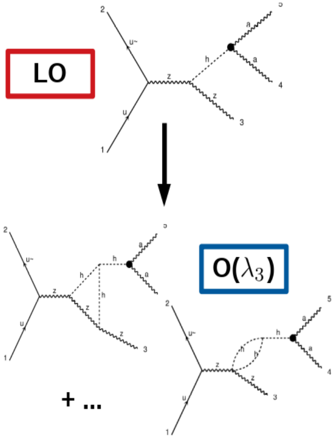
- *HH → bbττ*



HH cross section measurement: theory uncertainties

√s	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma_{NNLO\ FTapprox}$ [fb]	6.572 -6.5%+3.0%	9.441 -6.1% + 2.8%	31.05 -5.0% + 2.2%	36.69 -4.9% +2.1%	139.9 -3.9% +1.3%	1224 -3.2% +0.9%
mt unc.	±2.2%	±2.3%	±2.6%	±2.7%	±3.4%	±4.6%
PDF unc.	±3.5%	±3.1%	±2.1%	±2.1%	±1.7%	±1.7%
αS unc.	±2.6%	±2.4%	±2.1%	±2.1%	±1.8%	±1.7%
PDF+αS unc.	±4.3%	±3.9%	±3.0%	±3.0%	±2.5%	±2.4%

Analysis Overview: extracting C_1



- **Derive C_1 values appropriate for CMS analyses** (using $H \to \gamma\gamma$ 13 TeV analysis strategy)
  - Generate LO signal samples with MADGRAPH (v2.5.5)
    - LO in terms of both QCD and EWK
  - Use public code to calc $\mathcal{O}(\lambda_3)$ effects by re-weighting LO on event-by-event basis.
  - Extract C_{1i} in bins of observable (at gen-level) as ratio of LO to $\mathcal{O}(\lambda_3)$ contribution.
    - Currently using at $p_T(H)$, but investigating others