Higgs boson measurements at LHC after upgrade

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Outline

- **Introduction**
- **SM Higgs projections/studies**
- **Double Higgs projections/studies**
- **BSM Higgs projections**
- **Summary**

Introduction

Todo list at the LHC:

- Discover the Higgs boson ✓
- Open champagne bottle ✓
- Celebrate ✓

Is this the end of the story?

Many questions to be answered about the Higgs sector

- Is Higgs fundamental or composite?
- If fundamental, is it “minimal”?
- Are Yukawa couplings responsible for masses of all generations?
- How is the potencial?
- Is it a portal to new physics?

As for today, the Higgs sector looks standard-model like

What does HL-LHC brings us?

- proof of expected coupling to 2nd generation **(H$\rightarrow \mu\mu$)**
- first exploration of Higgs potential (**HH** production)
- $\times$300 sensitivity to rare decays involving new physics
- map out couplings to W/Z/3rd gen. with **precision** and across broad kinematics, which could reveal signs of:
  - new particles in loops (too heavy to produce, or hard to observe)
  - non-fundamental nature of Higgs
  - or simply confirm, in detail, a highly non-trivial part of the standard model

Introduction

inspired by G. Salam (ECFA16)

Precision is one of the goals of the HL-LHC:

- Ultimate goal might be $\mathcal{O}(1\%)$
- Theory is already making big steps towards the HL-LHC precision goals

LHC HXSWG Yellow Report 3 (2013, NNLO)

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0

CMS scenario 2 (reduction by 50%) already achieved!

$$48.58\,\mathrm{pb} \pm 1.89\,\mathrm{pb}(3.9\%)\ (\mathrm{theory}) \pm 1.56\,\mathrm{pb}(3.20\%)\ (\mathrm{PDF}+\alpha_s)$$

Anastasiou et al., (1602.00695, N3LO) + HXSWG YR4

Introduction

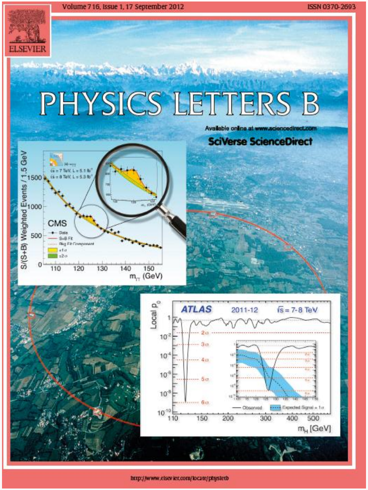
From the discovery machine to the Higgs factory

High Luminosity-LHC:

- Precision measurements
- Rare decays and couplings
- HH production - Higgs self-coupling

Performance studies at 3000 fb^{-1}:

- Projections from current analyses
- Studies using upgraded detector simulations



Analysis techniques

ATLAS HL-LHC analysis techniques:

- 14 TeV collision energy and 140 or 200 PU
- Smear p_T and energy of reconstructed physics objects to simulate the response of the detector
- Trigger efficiency functions to emulate triggers
- Validated with full simulation

CMS fast simulation for HL-LHC:

- Parameterised Delphes simulation
- 14 TeV collision energy and 200 PU
- Validated with full simulation

Extrapolation strategy - CMS

Public results are extrapolated to larger data sets 300 and 3000 fb^{-1}. In order to summarize the future physics potential of the CMS detector at the HL-LHC, extrapolations are presented under different uncertainty scenarios:

- **S1** All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be the unchanged with respect to the reference analysis
- **S1+** All systematic uncertainties are kept constant with integrated luminosity. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account
- **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 a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are not taken into account
- **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 a defined lower limit based on estimates of the achievable accuracy with the upgraded detector. The effects of higher pileup conditions and detector upgrades on the future performance of CMS are taken into account

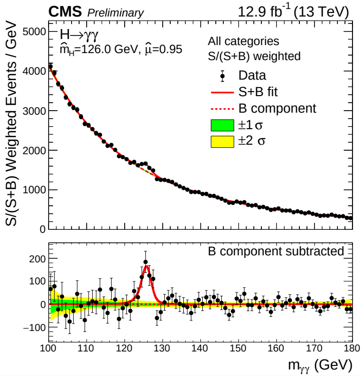
Extrapolation strategy - CMS

Public results are extrapolated to larger data sets 300 and 3000 fb^{-1}. In order to summarize the future physics potential of the CMS detector at the HL-LHC, extrapolations are presented under different uncertainty scenarios:

	systematics unchanged	exp. sys. scaled* $1/\sqrt{L}$	theo. sys. scaled 1/2	high PU effects
ECFA16 S1	✓	✗	✗	✗
ECFA16 S1+	✓	✗	✗	✓
ECFA16 S2	✗	✓	✓	✗
ECFA16 S2+	✗	✓	✓	✓

(*) until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector.

Higgs properties in the H$\rightarrow \gamma\gamma$ channel extrapolated from **12.9 fb^{-1}** of data at 13 TeV

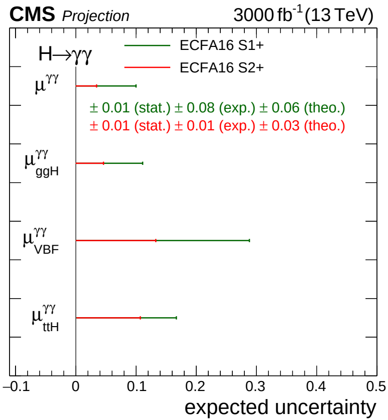


Selected measurements have been projected to 300 (3000) fb^{-1}:

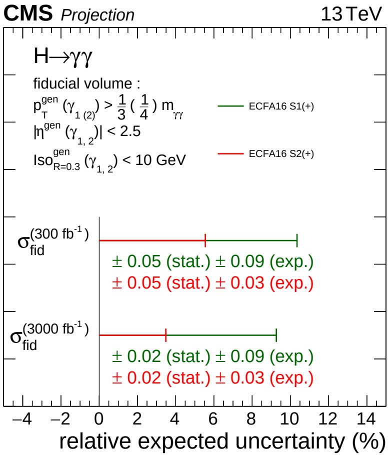
- Signal strength per production mode
- Fiducial cross section measurement

For 3000 fb^{-1}, the effect of high pileup and detector performance are considered (based on LHCC-P-008):

- The beamspot is simulated to have $\sigma_z \sim 5$ cm
- Vertex identification reduced from 80% to 40%
- Photon ID efficiency decreased by 2.3% (10%) in EB (EE)

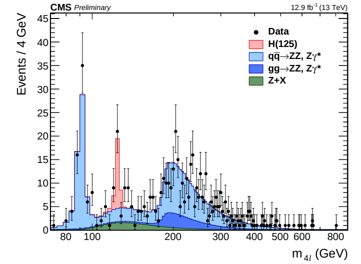


Extrapolation to 3000 fb^{-1}



Fiducial cross section

Higgs properties in the H$\rightarrow$ ZZ channel extrapolated from **12.9 fb^{-1}** of data at 13 TeV

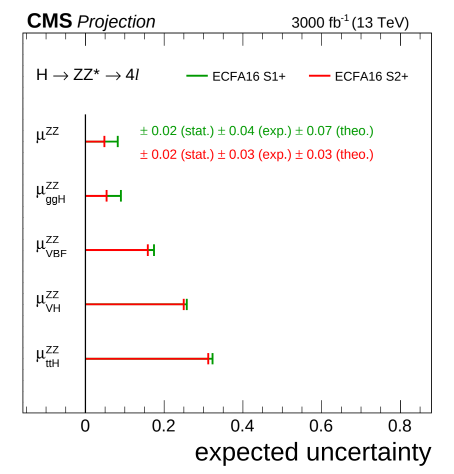


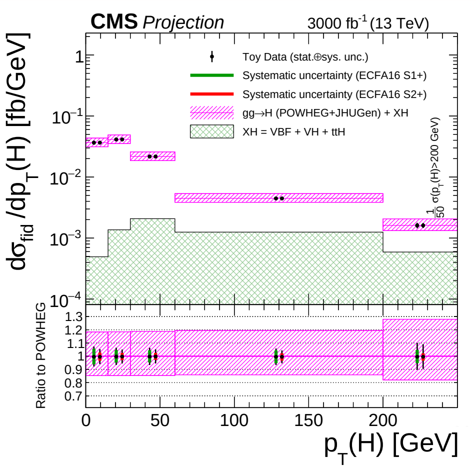
Selected measurements have been projected to 300 (3000) fb^{-1}:

- Signal strength per production mode
- Differential cross section for $p_T(H)$
- Constraints on anomalous couplings

For 3000 fb^{-1}, the effect of high pileup is considered (based on LHCC-P-008):

- Lepton efficiency
- Misidentification rates





Signal Strength

Differential $p_T(H)$ Cross Section

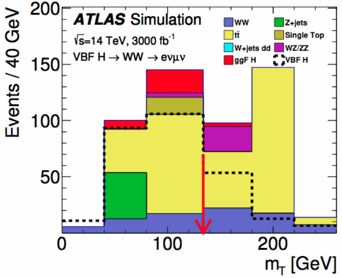
VBF H $\rightarrow$ WW* $\rightarrow e\nu\mu\nu$

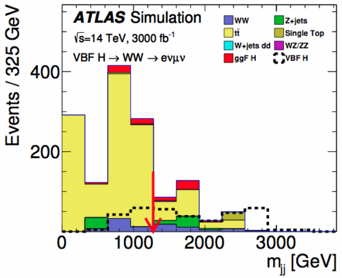
Cut based analysis:

- 2 forward jets with $|\eta| > 2$
- No additional jets with $p_T > 30$ GeV
- e and μ between fordwards jets
- $m_{jj} > 1250$ GeV

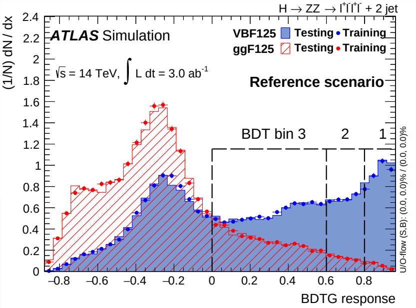
Expected precision of the cross-section, neglecting theoretical uncertainties:

Tracking coverage	Expected precision
$\|\eta\| < 4.0$	12%
$\|\eta\| < 3.2$	18%
$\|\eta\| < 2.7$	22%





- **Initial selection:**
  - 2 jets with $m_{jj} > 130$ GeV
  - 4 leptons consistent with $H \to ZZ^* \to 4\ell$
- BDT to separate **ggF** and **VBF** production
- Results presented for statistical uncertainty only and stat+signal QCD scale



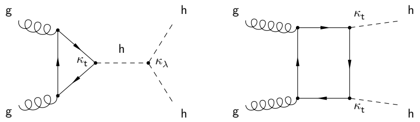
Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	Z_0 (VBF vs. ggF)	$\Delta\mu/\mu$
Statistical uncertainty only				
Reference	237 (206)	324 (159)	11.4	±0.134
Middle	270 (205)	520 (177)	10.9	±0.137
Low	325 (198)	917 (211)	9.8	±0.142
Statistical uncertainty + QCD scale var. uncertainty (S-T method)				
Scoping scenario	VBF + $2j$ events	ggF + $2j$ events	Z_0 (VBF vs. ggF)	$\Delta\mu/\mu$
Reference	237	324	7.6	±0.167
Middle	270	520	7.5	±0.174
Low	325	917	6.8	±0.186

Higgs boson Pair Production

Next milestone in Higgs physics

Access to the H **self-coupling** λ

- Scalar potential structure



- Very low production cross section
  - Destructive interference
  - $\sigma(\mathbf{pp} \rightarrow \mathbf{HH})^{\mathbf{SM}}_{\mathbf{NNLO+NNLL}} = \mathbf{33.45\ fb}$ (@ 13TeV)

Four CMS results at 13 TeV extrapolated to 3000 fb^{-1}:

- $HH \rightarrow bb\gamma\gamma$ **CMS-PAS-HIG-16-032**
- $HH \rightarrow bbbb$ **CMS-PAS-HIG-16-026**
- $HH \rightarrow bb\tau\tau$ **CMS-PAS-HIG-16-012**
- $HH \rightarrow bbWW \rightarrow bb\ell\nu\ell\nu$ **CMS-PAS-HIG-16-024**

Projections from public analyses extrapolated from 2015 data at 13 TeV

	Median expected limits in μ_r		Z-value		Uncertainty as fraction of $\mu_r = 1$	
Channel	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only	ECFA16 S2	Stat. Only
$gg \to HH \to \gamma\gamma bb$ (S2+)	1.3	1.3	1.6	1.6	0.64	0.64
$gg \to HH \to \tau\tau bb$	5.2	3.9	0.39	0.53	2.6	1.9
$gg \to HH \to VVbb$	4.8	4.6	0.45	0.47	2.4	2.3
$gg \to HH \to bbbb$	7.0	2.9	0.39	0.67	2.5	1.5

Results compatible with previous studies assuming the HL-LHC conditions **CMS-PAS-FTR-15-002**

HH → bbWW → bbjj$\ell\nu$ in Phase II

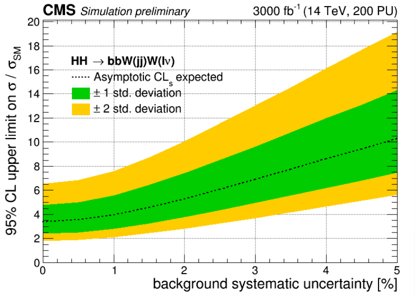
Study based on **Delphes** simulation of the **upgraded CMS detector**

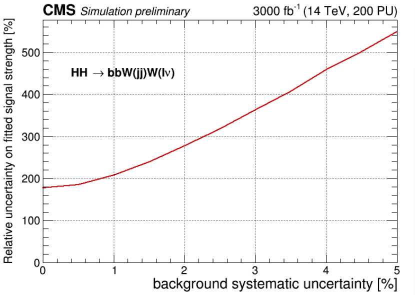
- Energy: 14 TeV
- Pile up 200
- Integrated luminosity: 3000 fb^{-1}

Analysis features:

- Only background considered: $t\bar{t}$
- Signal optimisation via BDT

Similar performance compared to previous studies on HH → bbWW → $bbl\nu l\nu$ (CMS-PAS-FTR-15-002)





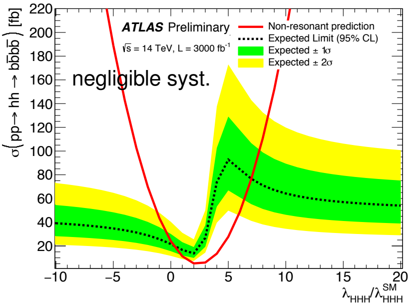
HH→bbbb

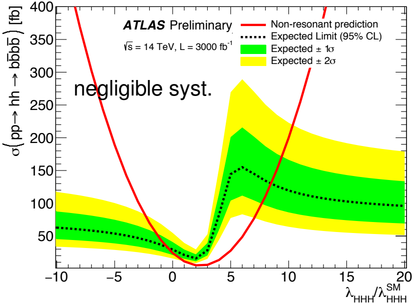
- Multijet QCD production is the main background
- Hard to model ⇒ Extrapolated from Run2 result

Trigger thresholds (4jet trigger):

- Run 2: $p_T^{jet} > 30$ GeV
- HL-LHC: $p_T^{jet} > 75$ GeV

Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14





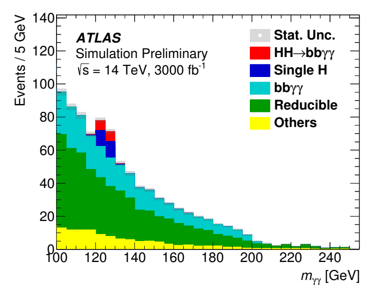
Higgs boson Pair Production

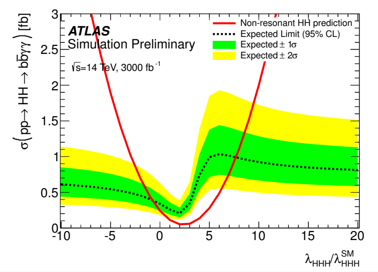
ATL-PHYS-PUB-2017-001

HH→bb$\gamma\gamma$

Event Selection Criteria
≥ 2 isolated photons, with $p_T > 30$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$
≥ 2 jets identified as b-jets with leading/subleading $p_T > 40/30$ GeV, $\|\eta\|$¡2.4
< 6 jets with $p_T > 30$ GeV, $\|\eta\| < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\|\eta\| < 2.5$
$0.4 < \Delta R_{b\bar{b}} < 2.0, 0.4 < \Delta R_{\gamma\gamma} < 2.0, 0.4 < \Delta R_{\gamma jet}$
$122 < m_{\gamma\gamma} < 128$ GeV, $100 < m_{b\bar{b}} < 150$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}} > 80$ GeV

- Average pileup, PU = 200
- No systematics applied
- Expected significance of **1.05** σ
- Self-coupling is expected to be constrained to $-0.8 < \lambda/\lambda_{SM} < 7.7$





$t\bar{t}$HH producton

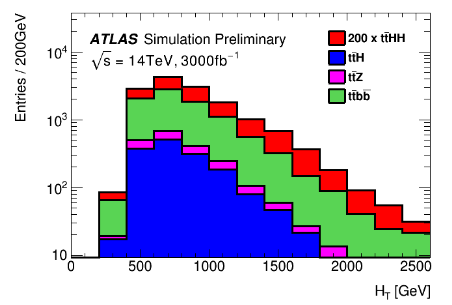
ATL-PHYS-PUB-2016-023

Small cross section $\sim \sigma(t\bar{t}HH)$1 fb

Analysis details:

- HH$\rightarrow$bbbb and $t\bar{t}$ semi-leptonic
- 6 b-jets, 2 light jets, e/μ and $\not{E}_T$
- Cut based analysis

Overall **significance of 0.35** σ, combining exactly 5 jets selection and $\geq$ 6 b-tag selection.



$\geq$ 5 b-tag selection:

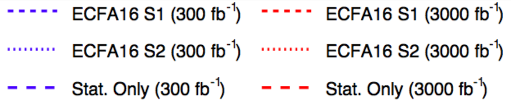
Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{\rm SM}$
0	6.8
5%	20
10%	32

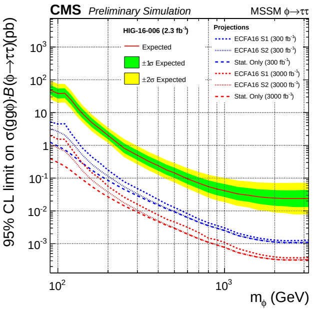
$\geq$ 6 b-tag selection:

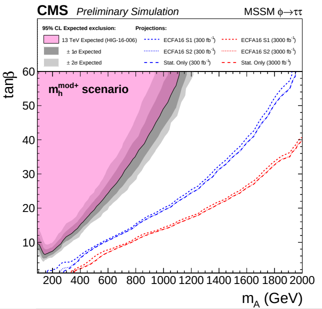
Background uncertainty	95% CL limit on $\sigma(t\bar{t}HH)/\sigma_{\rm SM}$
0	8.0
5%	10
10%	16

Results extrapolated from **2.3 fb^{-1}** of data at 13 TeV

- One of the most sensitive channels for constraining extended Higgs sectors
- Cross sections limits:
  - $gg(\phi \rightarrow \tau\tau)$
  - $bb(\phi \rightarrow \tau\tau)$
- Model dependent limits:
  - $\mathbf{m^{mod+}}$ benchmark
- Sensitivity at high m_A still dominated by statistics







Results extrapolated from **2.3 fb^{-1}** of data at 13 TeV

Main backgrounds:

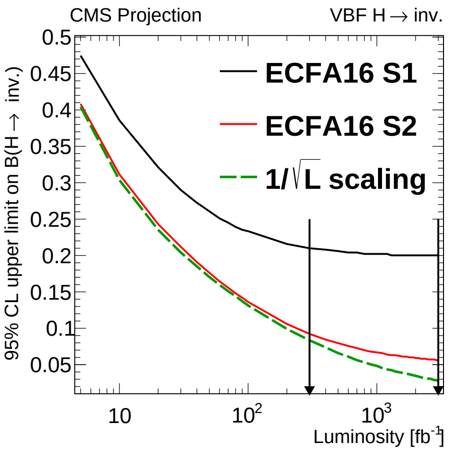
- $Z(\nu\nu)$+ jets
- $W(l\nu)$ + jets
- QCD multijet

Current expected limits (VBF @ 13 TeV):

- BR(H $\rightarrow$ inv.) < 0.63

Expected 95% CL upper limits on BR(H $\rightarrow$ inv.) as a function of luminosity

	ECFA16 S1	ECFA16 S2	$1/\sqrt{L}$ scaling
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

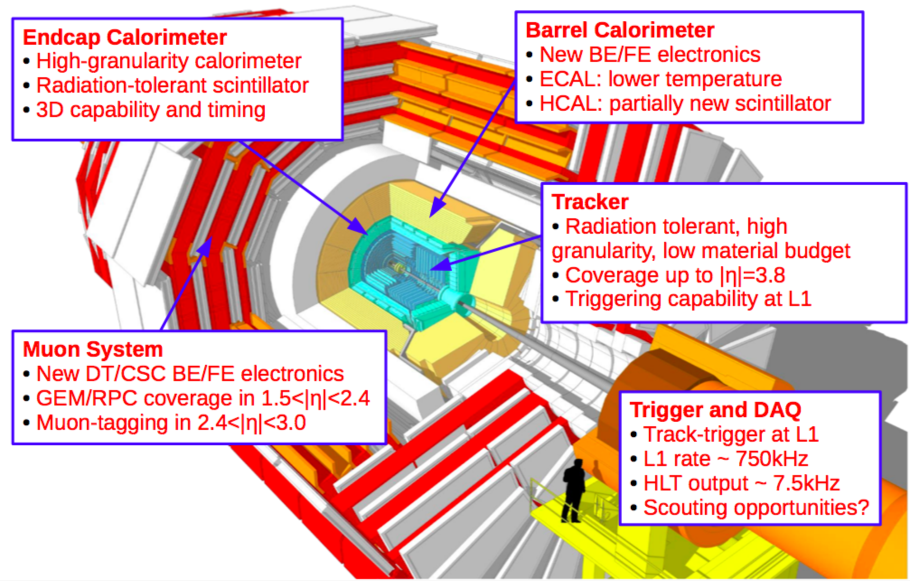


Summary

- Projections for 3000 fb^{-1} using 13 TeV analyses and studies based on simulation of the upgraded CMS and ATLAS detectors have been shown
  - Properties measured with uncertainties at percent level
  - Access to HH and ttHH production
  - BSM scenarios
- Additional studies with more detailed description of the upgraded detector will be performed in the coming months by both CMS and ATLAS as part of the TDRs for the HL-LHC
  - **ATLAS-TDR-025** - Inner Tracker Strip Detector

Backup Slides

CMS Phase II Upgrades



ATLAS Phase II Upgrades

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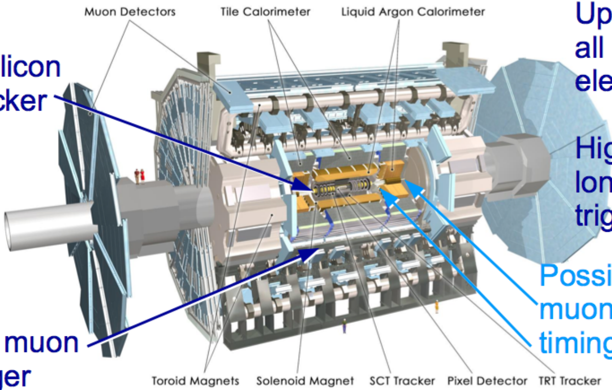
Overview of Phase-II Upgrades

Overall scope of Phase-II upgrades is mostly settled

New all-silicon Inner Tracker

New inner muon barrel trigger chambers



Upgrade all front-end electronics

Higher rate, longer latency trigger system

Possibly forward muon tagger and timing detector

Now evaluating different design/implementation options

$H \rightarrow ZZ$ - Anomalous couplings

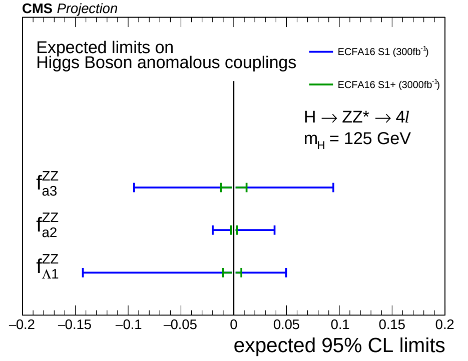
Generic decay amplitude of $H \rightarrow ZZ$ for spin-0 particle:

$$A(H \rightarrow VV) \sim \left[a_1 - e^{i\phi_{\Lambda Q}} \frac{(q_{V1}+q_{V2})^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}} \frac{(q_{V1}^2+q_{V2}^2)}{\Lambda_1^2}\right] m_V^2 \epsilon_1^* \epsilon_2^* + a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

- Test for anomalous HZZ couplings a_i:

  $$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j},\ \phi_{ai} = \tan^{-1}(a_i/a_1)$$

- Interference contribution becomes more dominant at smaller values of $f_{ai} \times \cos(\phi_{ai})$



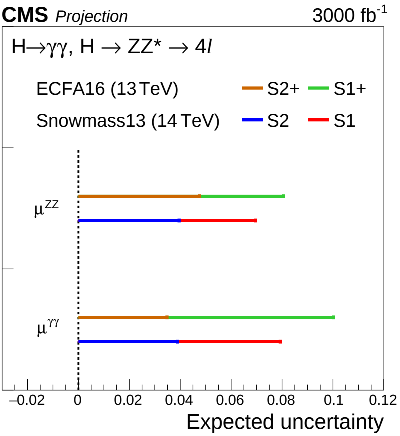
Comparison with previous results (Snowmass13) - CMS

ECFA16 vs Snowmass13

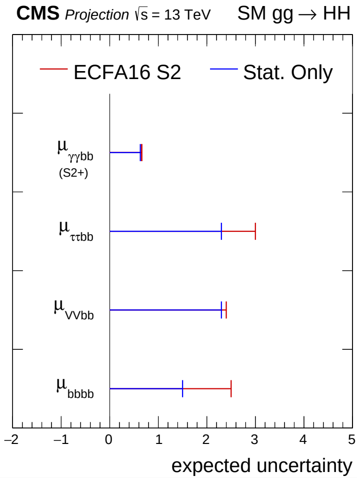
Snowmass assumptions:

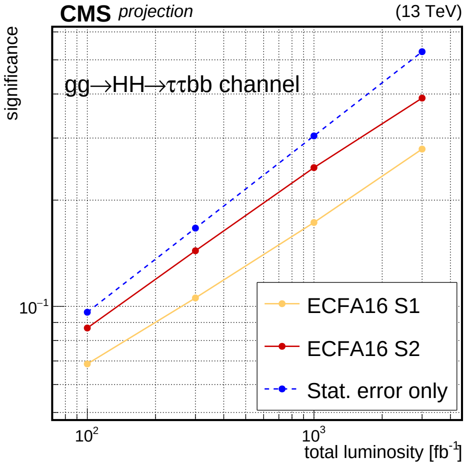
- Energy from 8 TeV to 14 TeV
- Theory uncertainties from YR3
- S2 scenario does not include any lower bound when scaling down the experimental uncertainties

ECFA16 theory uncertainties from YR4 (ducument in preparation)



Higgs boson Pair Production





Resonant HH $\rightarrow$ bbbb production - CMS

Table 5: Projection of the sensitivity to the resonant HH production at 3 ab^{-1} expected to be collected during the HL-LHC program. The projections are based on 13 TeV analysis performed with data collected in 2015. The 95% CL expected limits are provided for different spin-0 resonances masses assuming: preliminary analysis from 2015; Scenario 2 - reduced systematic uncertainties taking advantage of a larger data sample and upgraded detector; no systematic uncertainties. For each resonant mass the value of the mass scale $\Lambda_R = \sqrt{6}\exp[-kl]\overline{M}_{Pl}$ excluded at 95% CL is also provided.

m_X (TeV)	Median expected limits on σ (fb)			$\sigma_R(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded
	2.3 fb^{-1}	ECFA16 S2+	Stat. Only		
0.3	2990	46	41	7130	13
0.7	129.4	7.3	3.4	584	8.9
1.0	81.5	4.4	2.4	190	6.6