ATLAS and CMS prospects for Higgs measurements and searches at the high luminosity LHC

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on behalf of the ATLAS
and CMS collaborations

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on New Frontiers in Physics
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Outline

- HL-LHC and detector upgrades
- H(125) precision measurements in di-boson channels
- Pair-production of Higgs bosons
- Direct searches for physics beyond the SM

Related talks

- Marcello Bindi: *"Future Prospects (ATLAS)"*
  Thursday 24-August

- Kerstin Hoepfner: *"Overview talk on upgrades, future plans and prospects of the CMS experiment at the future HL-LHC"*
  Thursday 24-August

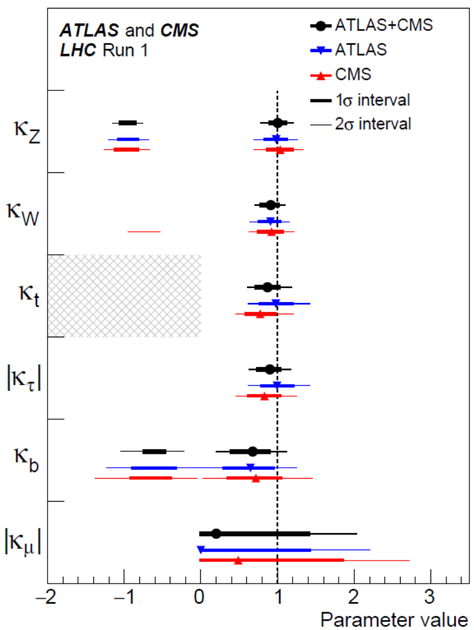
- Stewart Patrick Swift: *"Tracking and Vertexing with the ATLAS Inner Detector in the LHC Run2 and Beyond"*
  Monday 28-August

The Higgs boson – as of Summer 2017

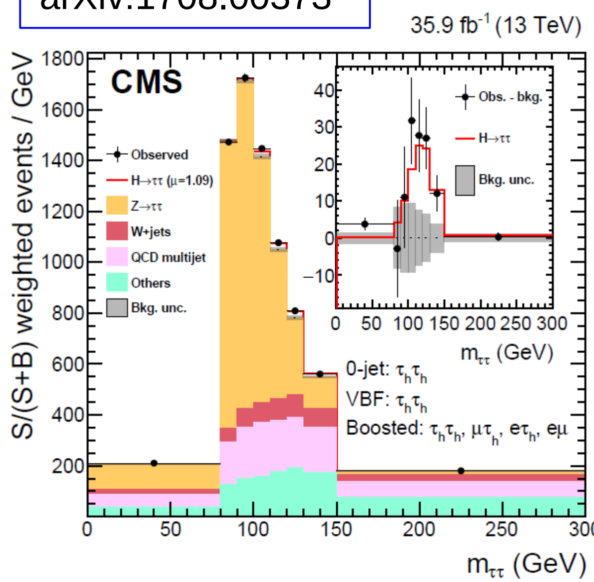
What we know (spotlight)

- Higgs boson: prime research object to understand the origin of masses in particle physics; potential portal to New Physics
- Mass known to ~0.2%, prominent couplings measured down to the ~10-20% level
- Recent highlight:
  - decays to fermions directly established (observation of H→$\tau\tau$, evidence for H→bb)

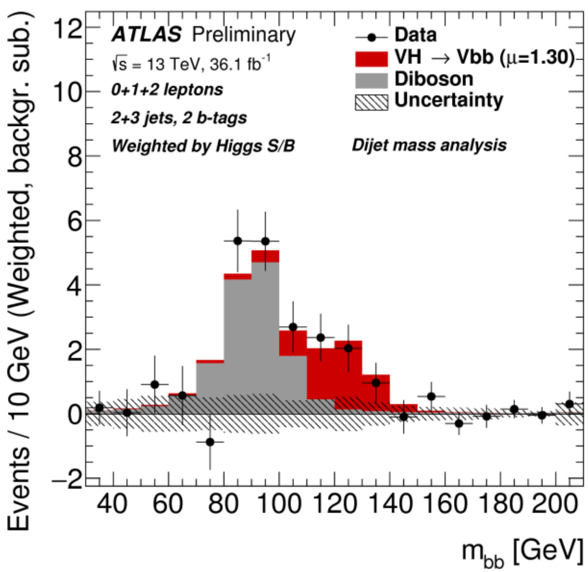
JHEP 08 (2016) 045



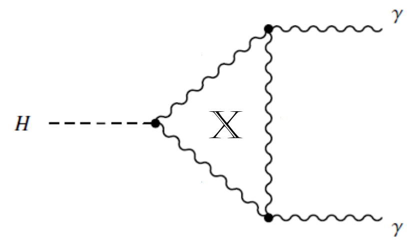
arXiv:1708.00373



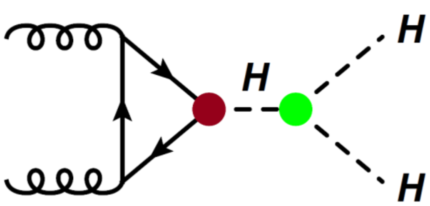
ATLAS-CONF-2017-041



What we need to know



- Accurate measurement of Higgs couplings, down to the level of few percents
  - ➔ deviations from SM would reveal New Physics
  - ➔ example: additional particles in loop processes (gluon fusion, di-photon decay)



- Does the Higgs boson couple to itself, as predicted by SM?
  - ➔ measure trilinear Higgs coupling → Higgs pair production
  - ➔ shape of Higgs potential (fingerprint of Higgs boson)

- Is the Higgs boson just one member of an extended Higgs sector?
  - ➔ search for additional Higgs bosons

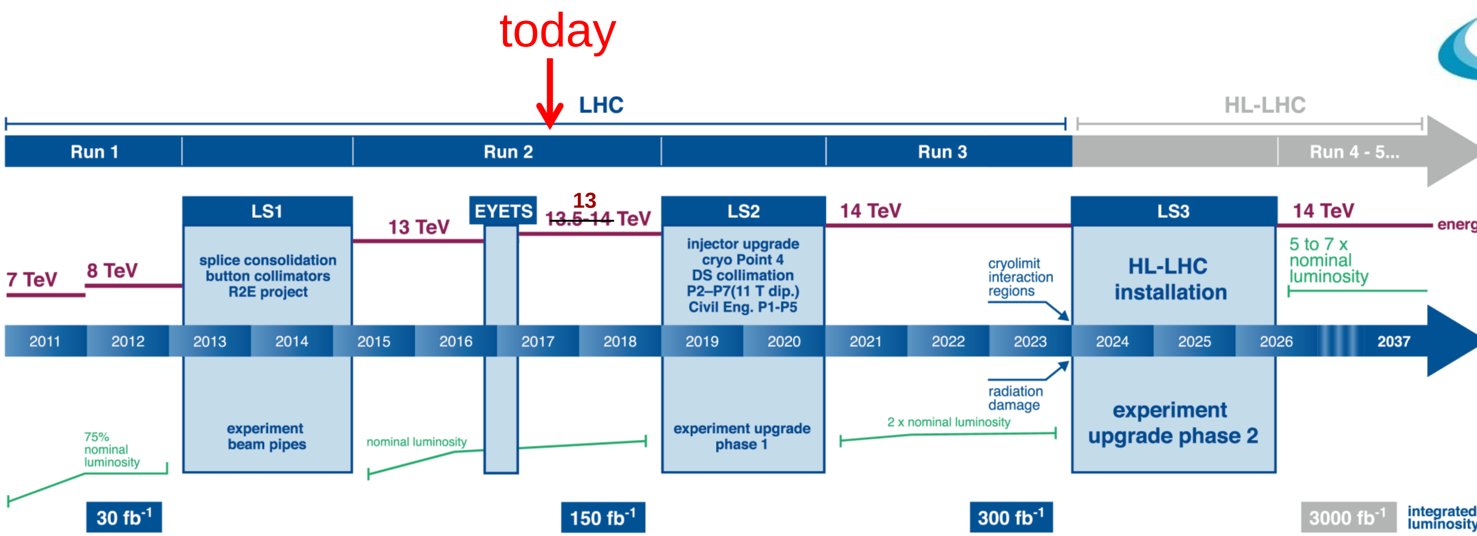
- Are there heavy resonances decaying to Higgs bosons?

➔ Need much better access to these rare processes and decays

➔ High luminosity LHC (HL-LHC)

The HL-LHC and the detector upgrades

The HL-LHC

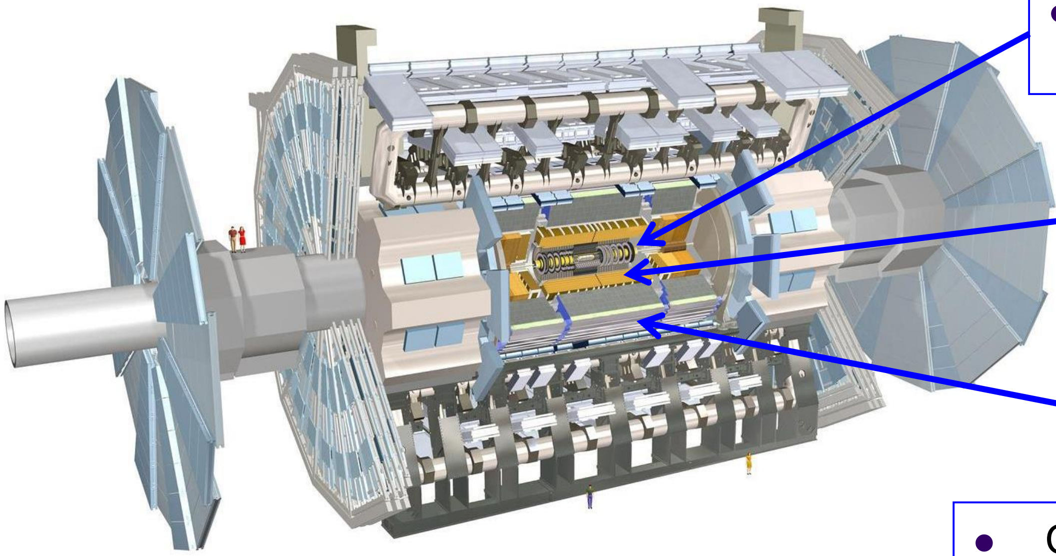


- HL-LHC could be completed in second half of 2026
- Luminosity: $5{\times}10^{34}cm^{-2}s^{-1}$ (baseline), $7.5{\times}10^{34}cm^{-2}s^{-1}$ (ultimate)
- Mean pileup: 140 (baseline), 200 (ultimate)
  - ➔ big challenge for experiments
  - ➔ comprehensive detector upgrades planned
- Total target integrated luminosity: 3000 fb^{-1} per experiment (ATLAS, CMS)

ATLAS Phase 2 upgrade

in a nutshell

- Upgrade trigger & data acquisition system
  - based on FPGA technology
  - high rate capability
  - L1 track trigger



- All-silicon inner tracker (strip & pixel), extended coverage to $|\eta| < 4$

- Upgrade electronics for tile and LAr calorimeters

- New inner muon barrel trigger chambers (MDT)

- Optional:
  - forward muon tagger
  - timing detectors

CMS Phase 2 upgrade

in a nutshell

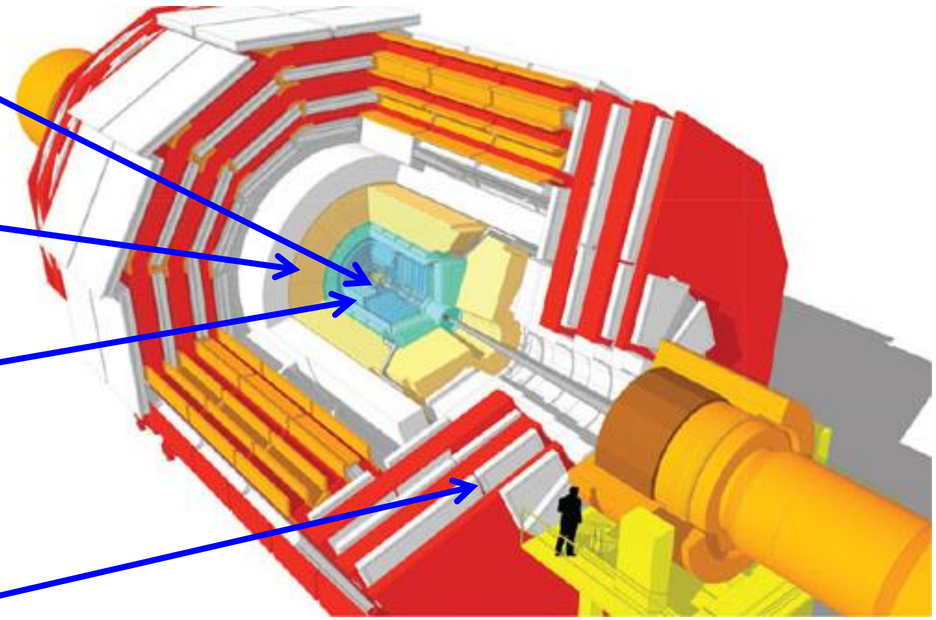
- Upgrade trigger
  - L1 track trigger
  - extended L1 latency
  - improved rate capability

- New all-silicon inner tracker (strip & pixel), extended coverage to $|\eta| < 4$

- New High Granularity Calorimeter endcaps using silicon sensors; 3D shower imaging

- Upgrade in barrel calorimeters
  - electronics
  - cooling of photodetectors

- Improve muon system coverage in $1.5 \le |\eta| \le 2.4$, extension to $|\eta| \le 3.0$ (GEM,RPC)



Strategy for projections (ATLAS)

- In general, use generator-level 14 TeV MC samples
  - overlay with pile-up interactions, according to mean pileup of 140 or 200
  - in some cases, extrapolations of Run 1 / Run 2 analyses are performed
- Detector response simulation
  - smearing functions for p_T and energy of physics objects
  - reconstruction efficiencies for electrons, muons and jets
  - all determined from fully-simulated samples, using ATLAS HL-LHC detector and high pile-up
- Theoretical uncertainties: three assumptions
  - unchanged (as current)
  - reduced $\times$½
  - zero
- Three tracker scenarios:
  - **Low** : $|\eta| < 2.7$, **Middle** : $|\eta| < 3.2$, **Reference**: $|\eta| < 4$

Chosen scenario

Strategy for projections (CMS)

- Extrapolation of analyses performed at 13 TeV on 2015 (2.3-2.7 fb^{-1}) or 2016 datasets (12.9 fb^{-1})
- Evolvement of systematic + theoretical uncertainties: several scenarios
  - assumptions made on how systematic & theoretical uncertainties will develop
  - detector upgrades designed to (at least) compensate degradations due to high pileup

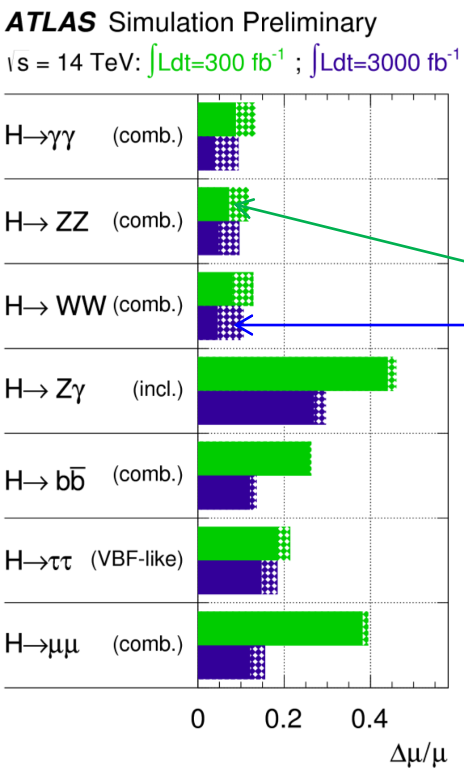
	Systematic & theoretical uncertainties	High-PU + detector improvements	Description
S1	constant	no	All systematic uncertainties are kept constant.
S1+	constant	yes	
S2	scaled	no	Theoretical uncertainty ×½, experimental systematic uncertainty $\propto 1/\sqrt{L}$ until detector-driven lower limit is reached.
S2+	scaled	yes	
Stat. only	--	no	

H(125) properties in bosonic decay channels

Higgs couplings

ATL-PHYS-PUB-2014-016

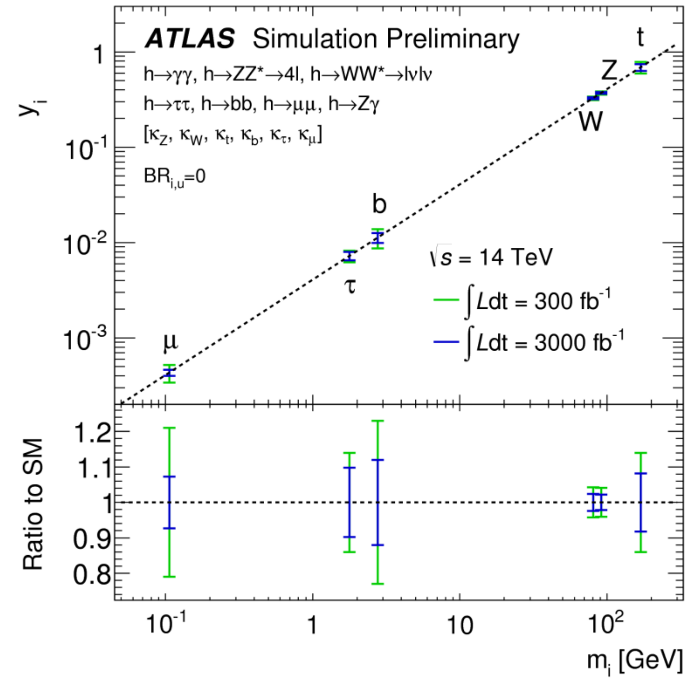
- Extrapolations from Run 1 analyses at pileup of 140 (first shown at ECFA 2014)



$$\mu = \frac{\sigma}{\sigma_{SM}}$$

hashed areas: increase of estimated error due to theory systematic uncertainties

Reduced couplings

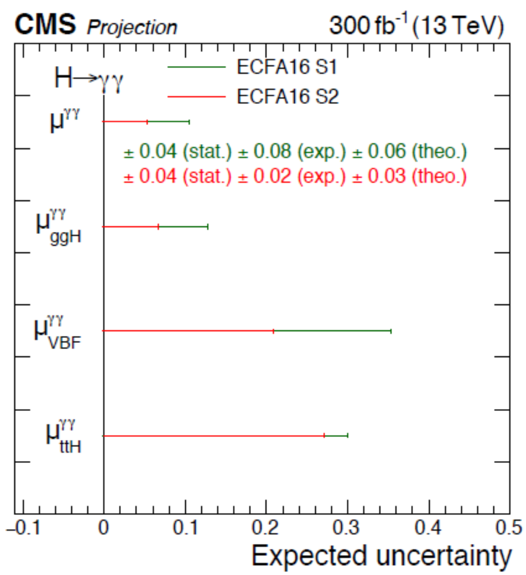


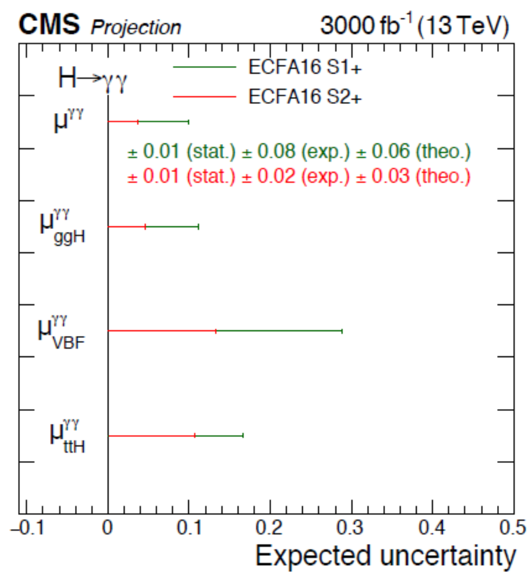
- W/Z couplings to ~4%, μ coupling to ~7%, τ/b/t couplings to 8-12%

H→γγ

CMS PAS FTR-16-002

- Projections performed from analysis performed on 2016 dataset (12.9 fb^{-1})
  - production modes: gluon fusion, VBF, ttH
  - the 3000 fb^{-1} scenarios take degradations of photon+vertex identification due to pileup conditions into account



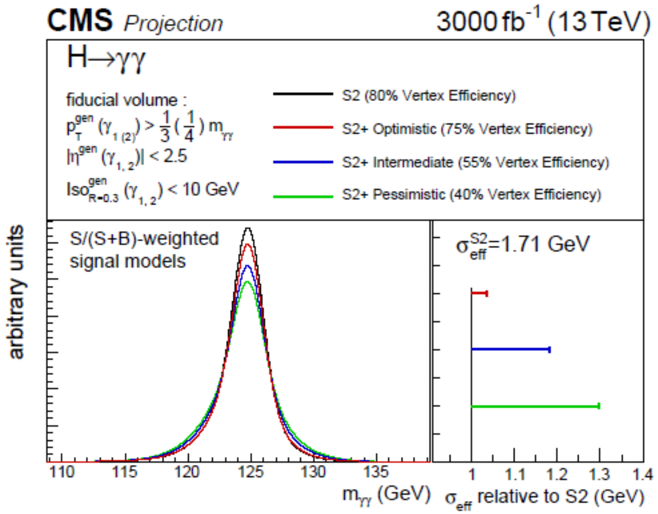


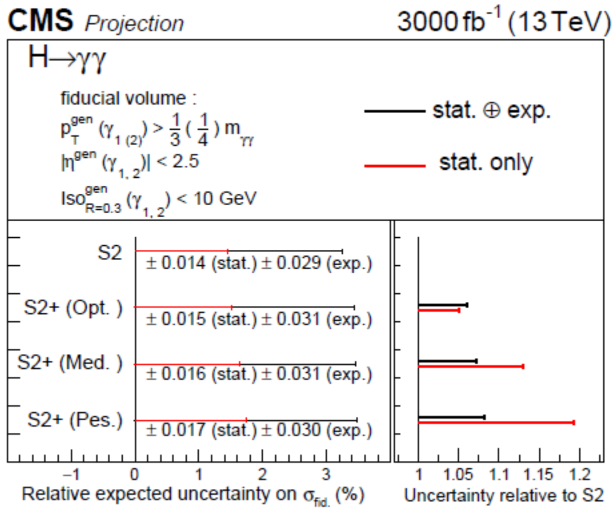
➔ In S2 and S2+ scenarios, experimental uncertainty ultimately dominated by luminosity measurement

H→γγ: precision timing

CMS PAS FTR-16-002

- Precision timing for calorimeter clusters and/or tracks can improve the vertex association for photons from Higgs decay
  - effective if photons are well separated in rapidity (~50% of events)
  - ➔ corresponds to a 5x pileup suppression for such candidates
- Three variants of the S2+ scenario have been studied
  - ➔ significant impact on Higgs signal shape (mass resolution)
  - ➔ significant impact on (fiducial) cross section uncertainty

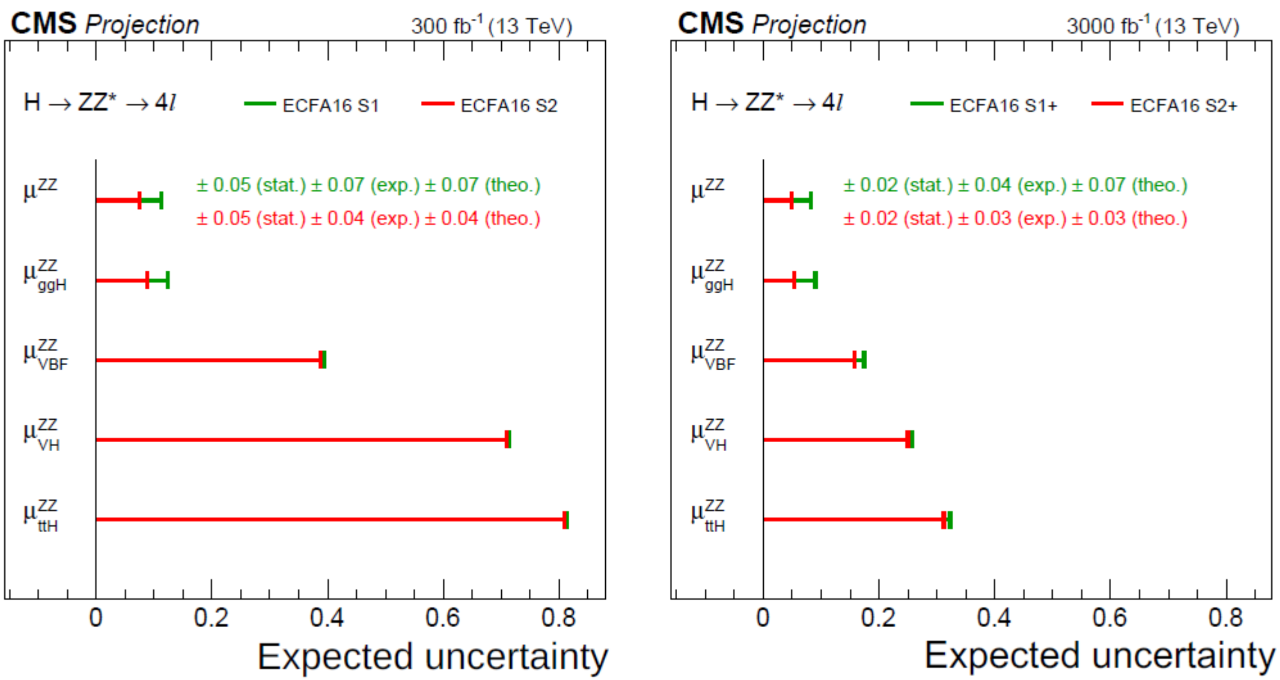




H→ZZ*→4 ℓ (inclusive)

CMS PAS FTR-16-002

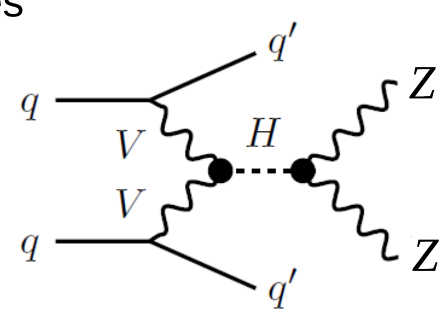
- Very clean, low backgrounds → expect huge benefit from high luminosity
- Projection of 2016 data analysis (12.9 fb^{-1}) to 300 and 3000 fb^{-1}.
  - ➔ sub-leading production modes are dominated by statistical component
  - ➔ theory uncertainties are crucial

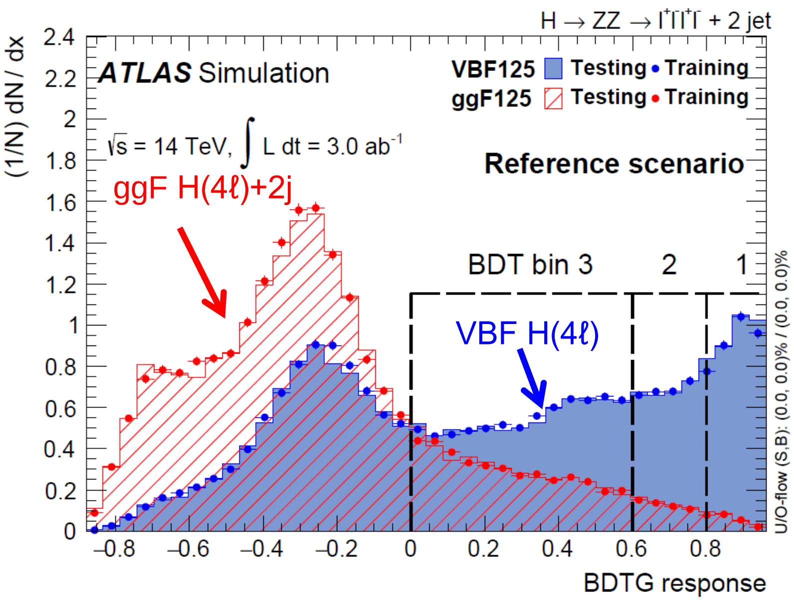


H→ZZ*→4 ℓ (VBF)

ATL-PHYS-PUB-2016-008

- Vector boson fusion of Higgs bosons provides very clean signatures
- Initial selection:
  - 2 jets with m(jj) > 130 GeV
  - 4 leptons consistent with H→ZZ*
- Test benefit from extension of tracker acceptance → use of track information to reject forward pileup jets





- Results for pileup 200 presented for:
  - statistical uncertainty only
  - stat + systematic uncertainty from QCD scale

→ Significant improvement with tracker acceptance

Tracker Scenario	Δμ / μ		Significance	
Signal unc.	w/syst.	stat only	w/syst.	stat only
Reference: $\|\eta\| < 4$	0.182	0.152	7.2	10.2
Middle : $\|\eta\| < 3.2$	0.192	0.157	6.9	9.5
Low : $\|\eta\| < 2.7$	0.208	0.165	6.2	8.6

H→WW*→eνμν (VBF)

ATLAS-TDR-025 | ATL-PHYS-PUB-2016-018

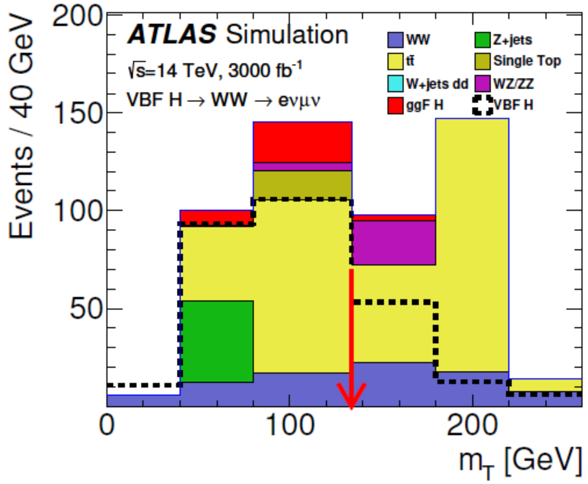
- Cut based analysis
- Main selection:
  - 2 forward jets with |η| > 2 in opposite hemispheres
  - b-jet veto (to suppress top-backgrounds)
  - no additional jets between forward jets
  - $E_T^{miss} > 20\ GeV$

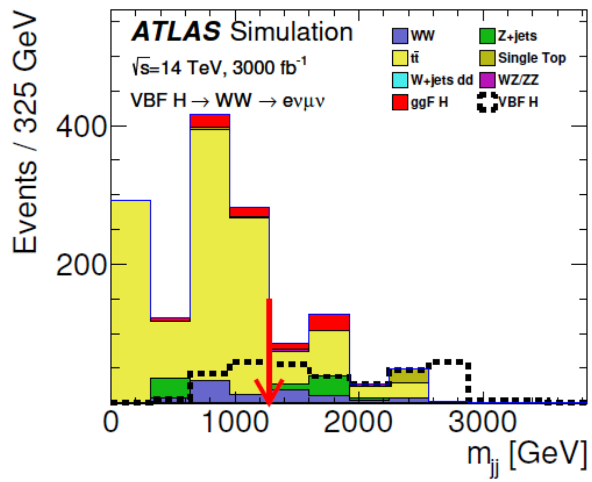
Tracking coverage		Expected precision
$\|\eta\| < 4.0$	Reference	12%
$\|\eta\| < 3.2$	Middle	18%
$\|\eta\| < 2.7$	Low	22%

excluding VBF + ggF prod. theor. uncertainties

➔ Large impact of tracker extension to $|\eta| < 4$

- Two main effects:
  - without extended track confirmation → 60% worse
  - without extended b-tagging → 55% worse

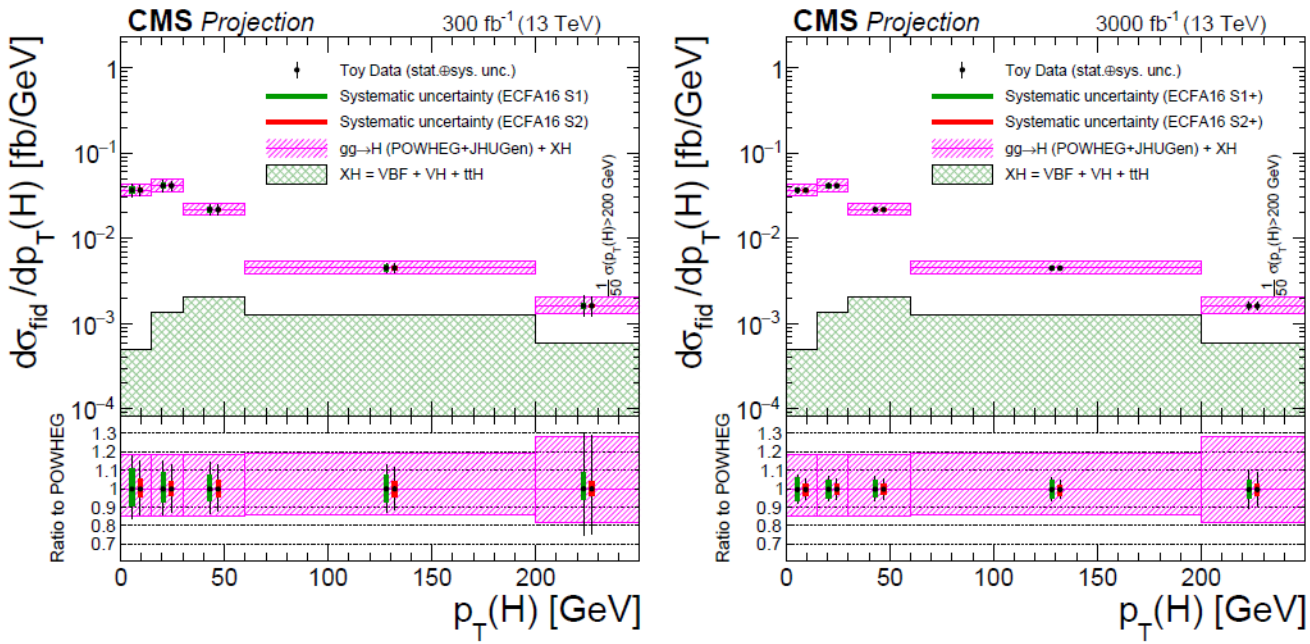




H→ZZ*→4 ℓ (differential)

CMS PAS FTR-16-002

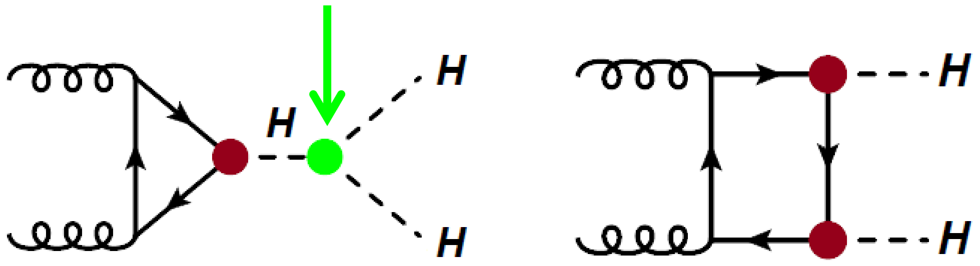
- Differential cross section measurement as function of p_T^H
  - measured in a fiducial phase space, closely matching experimental acceptance
    - ➔ measurement independent of theoretical uncertainty



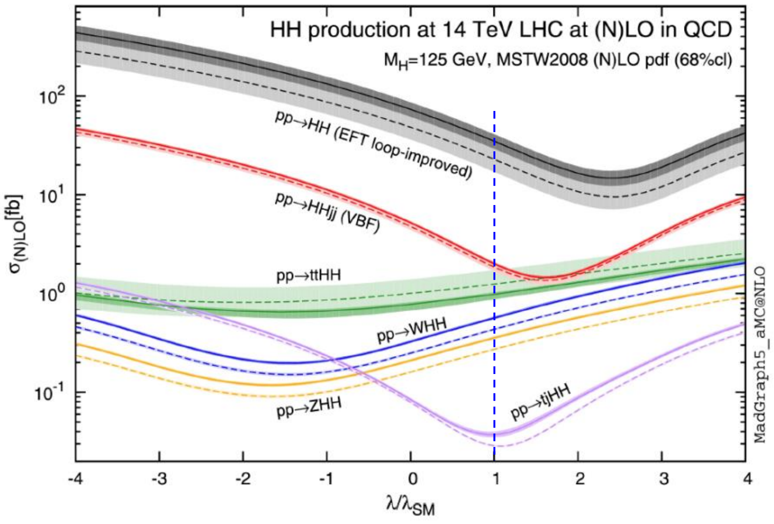
➔ High p_T region still dominated by statistical uncertainty, even at 3000 fb^{-1}

Higgs pair production & trilinear coupling

HH production



- Measurement of Higgs self coupling is a prime goal of the experimental program
  - ➔ shape of Higgs potential
- Study pair production of Higgs bosons
- HHH vertex contribution interferes destructively with other important diagrams
- Dominant production mode: gluon fusion
  - $\sigma_{NNLO}(HH) \sim 40\ fb^{-1}$
  - ➔ need to combine many decay channels
  - ➔ choose at least one H→bb decay (large BR)

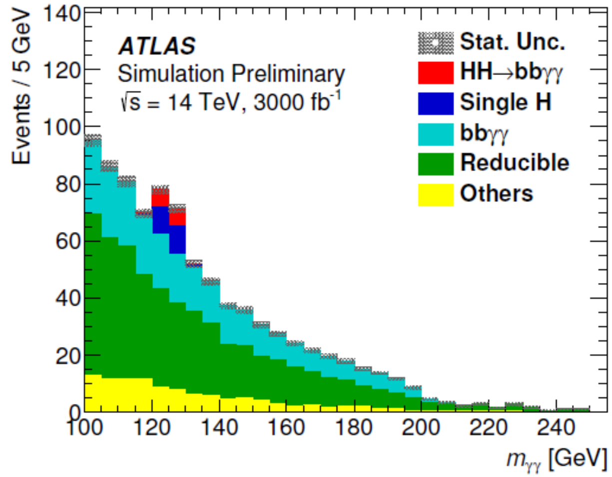


R. Frederix et al., PL B732 (2014) 142.

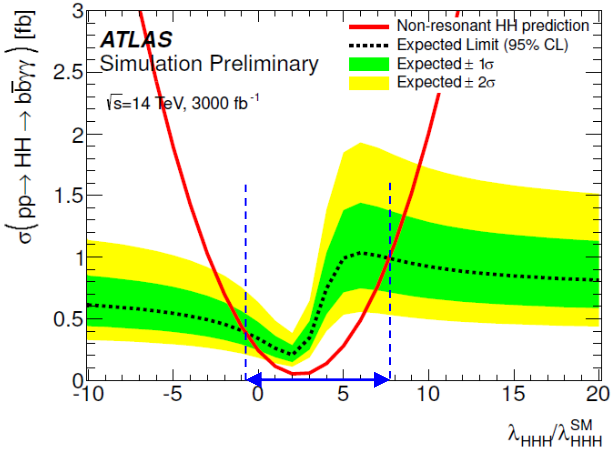
H(γγ)H(bb)

ATL-PHYS-PUB-2017-001

- Clean signature
  - narrow mass peak in H→γγ
  - large BR in H→bb
- Generator-level analysis
- Dominant backgrounds: bbγγ and bbjγ
  - also single-Higgs background has significant impact
- At 3000 fb^{-1}, expect
  - 9.5 signal and 90.9 background events
  - significance S / √B = 1.052



- Measured cross section can be used to constrain the triple-Higgs coupling
- If systematic uncertainties are neglected:
  - → $-0.8 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 7.7$ (at 95% CL)

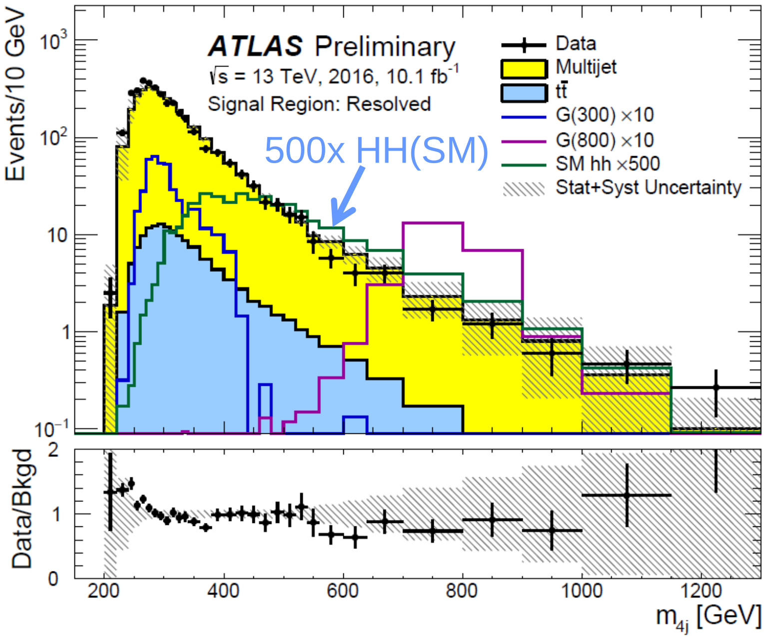


H(bb)H(bb)

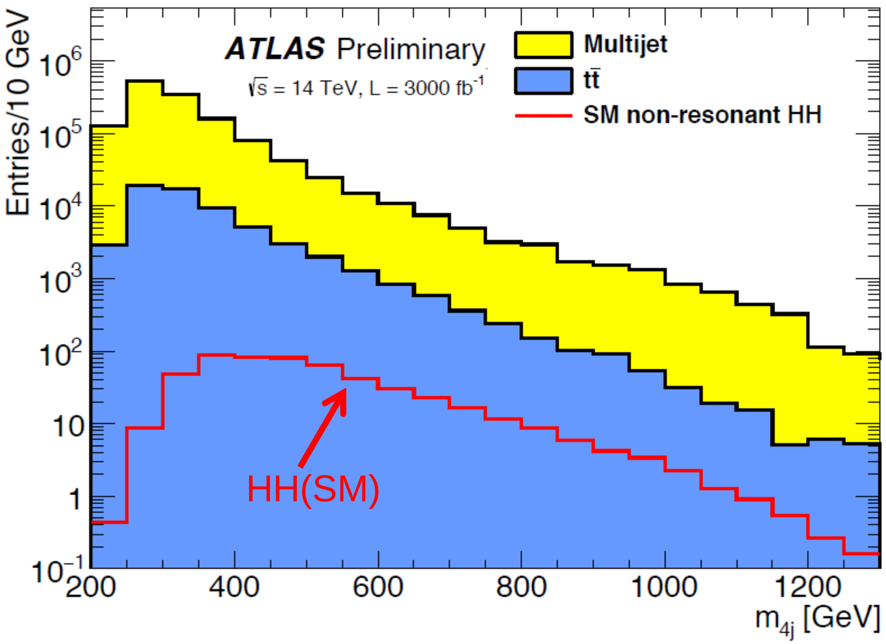
ATL-PHYS-PUB-2016-024

- Study based on full simulation. Run 2 detector performance, no additional pileup accounted for
- Resolved analysis, m_{4j} as final discriminant
- Main background QCD multijet → modeled with data-driven method

2016 analysis (10.1 fb^{-1})



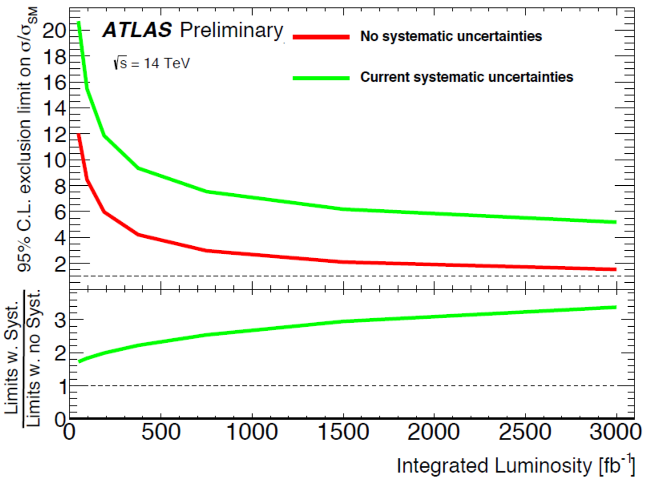
HL-LHC projection (3000 fb^{-1})

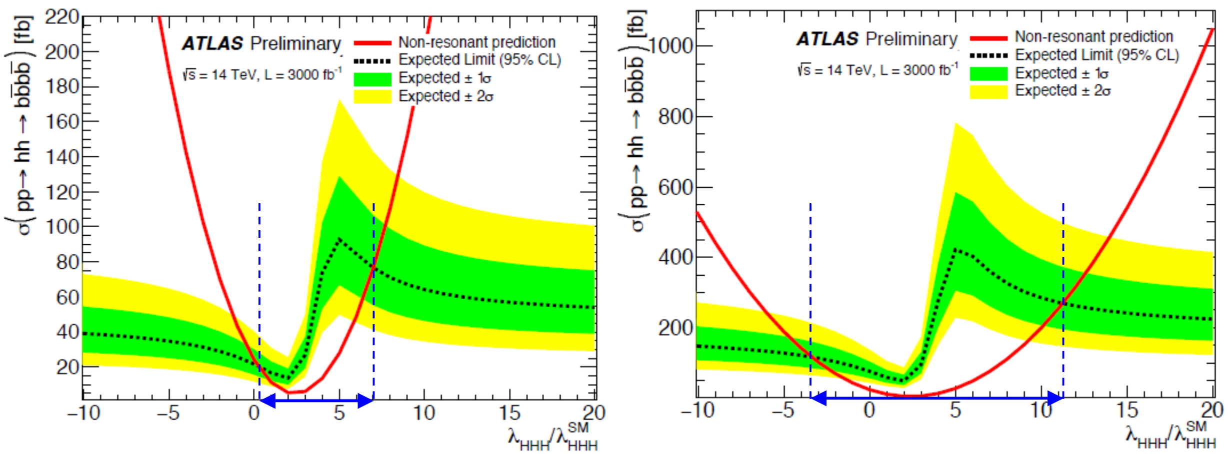


H(bb)H(bb) [cont'd]

ATL-PHYS-PUB-2016-024

- Multi-jet background drives the limiting systematics
  - ➔ background estimation likely to improve with more data





(a) No systematics

(b) Current systematics

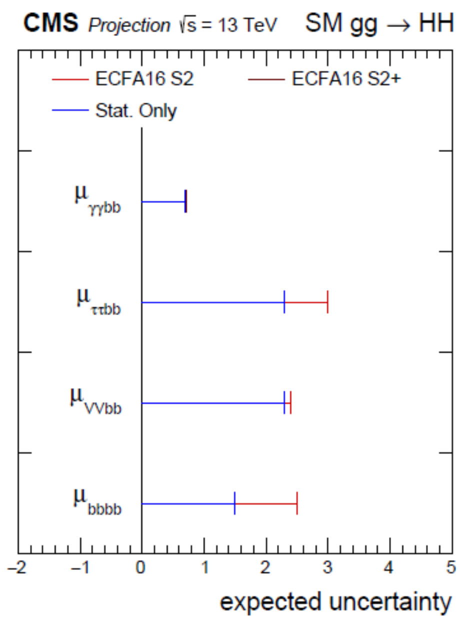
- Constraints on Higgs self-coupling (keeping $p_T^{jet} > 30\ GeV$):
  - $0.2 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 7.0$ (at 95% CL), without systematic uncertainties
  - $-3.5 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 11$ (at 95% CL), with systematic uncertainties as of 2016
- If p_T thresholds need to be raised for trigger reasons ($p_T^{jet} > 75\ GeV$):
  - $-7.4 < \lambda_{HHH}/\lambda_{HHH}^{SM} < 14$, with systematic uncertainties as of 2016

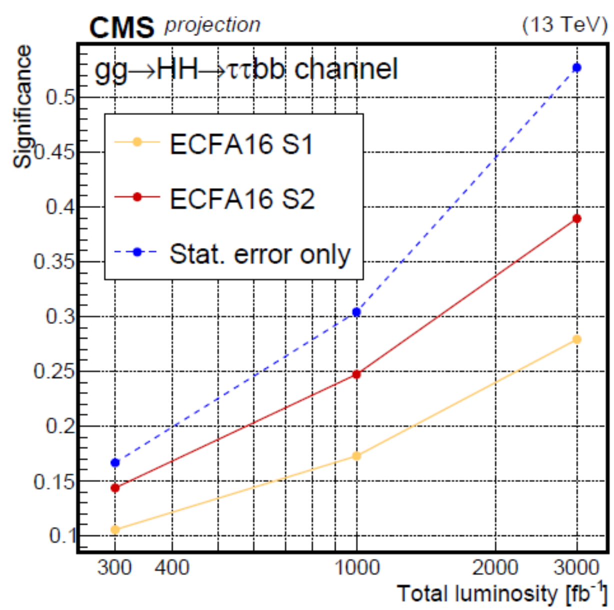
HH sensitivity (CMS)

CMS PAS FTR-16-002

- Extrapolate searches made with 2.3-2.7 fb^{-1} to 3000 fb^{-1}
- Channels studied: HH→ (γγ)(bb), (ττ)(bb), (bb)(bb), (VV)(bb)
- Based on S2 scenario*: experimental uncertainty ∝1/√L until detector-driven lower limit is reached, theoretical uncertainty ×½

*for (γγ)(bb): S2+





➔ Impact of systematics differs across the channels. (γγ)(bb) most sensitive.

Search for Physics beyond the SM

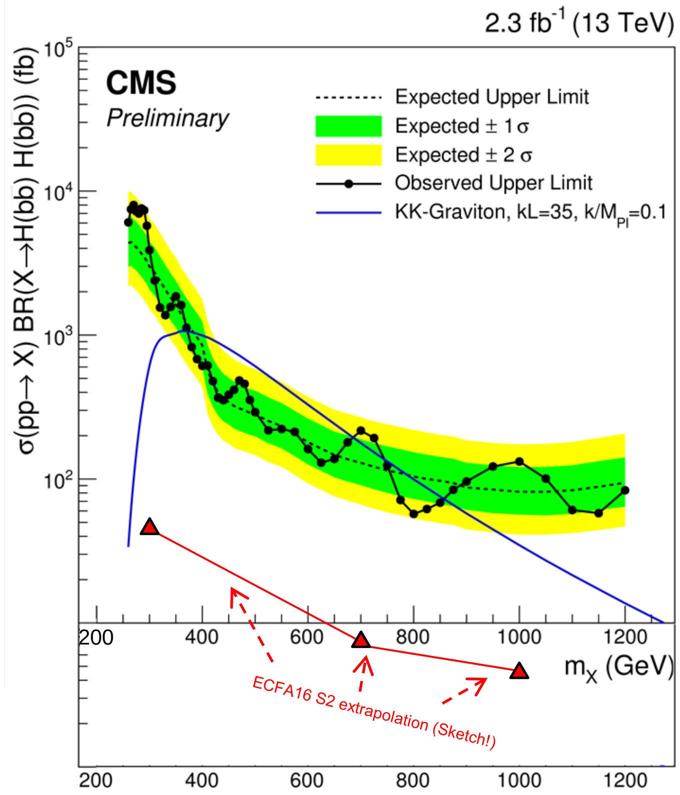
Di-Higgs resonances

CMS PAS HIG-16-002, FTR-16-002

- New physics could reflect in a heavy resonance decaying to HH final state: X→ HH
  - motivation: warped extra dimension theory
  - here: massive spin 0 particle (Radion)
- Projection of search from 2.3 fb^{-1} to 3000 fb^{-1}
  - experimental uncertainty $\propto 1/\sqrt{L}$, theoretical uncertainty ×½
  - three mass points: m_X=300, 700, 1000 GeV

➔ Huge improvement compared to current sensitivity

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



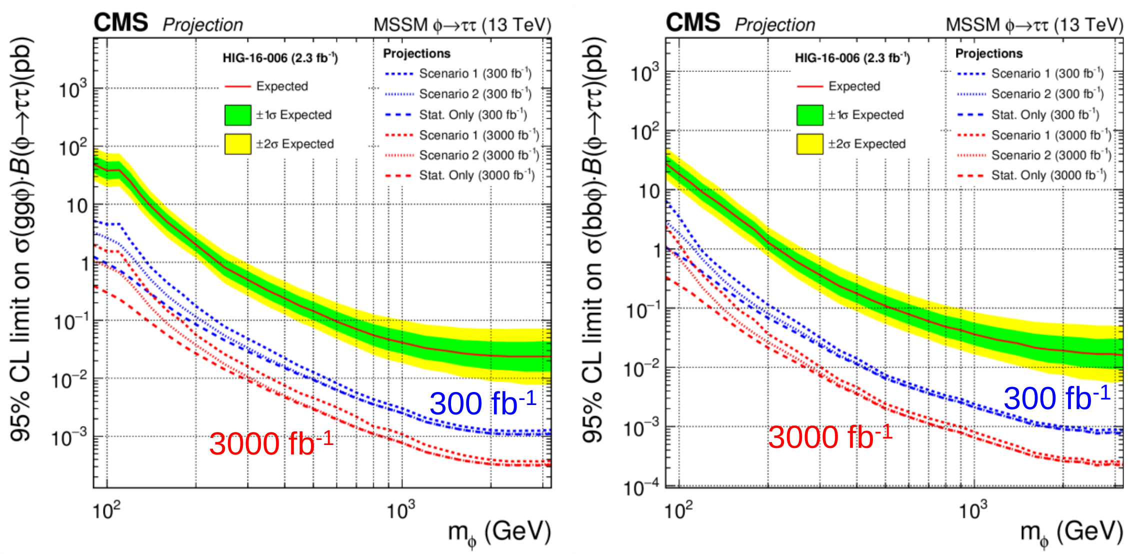
MSSM H→ττ

CMS PAS FTR-16-002

- Search for neutral Higgs bosons of Minimal Supersymmetric SM (MSSM): h, H, A
  - production enhanced ~tan β
- Projection of search from 2.3 fb^{-1} to 300 and 3000 fb^{-1}
  - production modes: gluon fusion, b-associated production
- Three cases considered:
  - Scenario 1: systematic uncertainties unchanged
  - Scenario 2: experimental uncertainty $\propto 1/\sqrt{L}$, theoretical uncertainty ×½
  - Statistical uncertainties only
- Differences between scenarios shrink towards higher masses
  - background expectation is smaller

gluon fusion

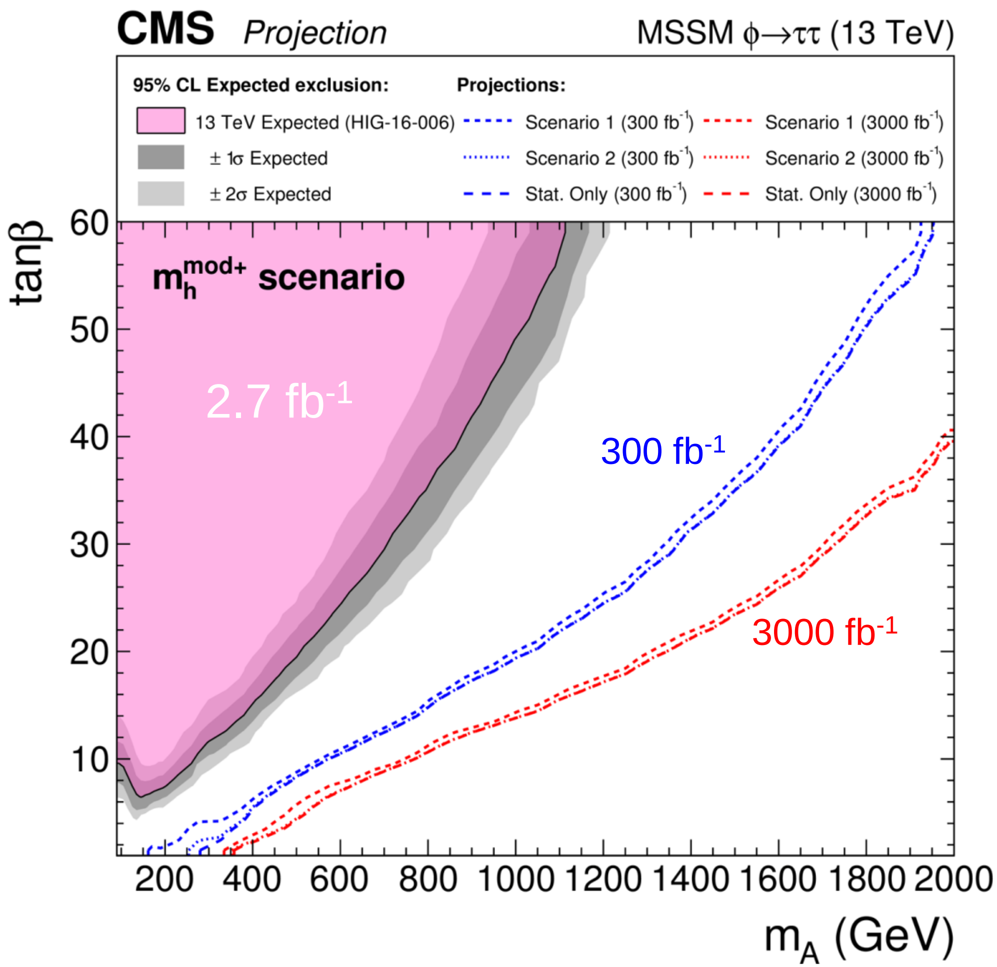
b-associated



(a) (b)

MSSM H→ττ (cont'd)

- Interpretation in MSSM parameter space, m_h^{mod+} scenario
- → Huge impact of HL-LHC luminosity
  - large parts of MSSM parameter space can be excluded, even up to 2 TeV of mass
- → At high masses, the analysis still remains statistics-limited



Summary

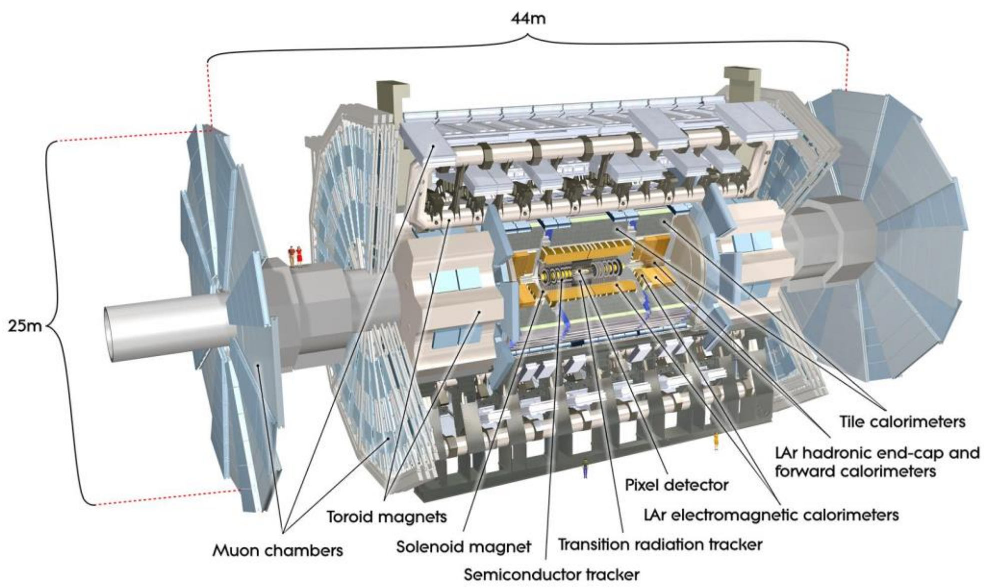
- Exploration of the Higgs boson is a prime motivation for the HL-LHC programme
- High luminosity is key to access rare processes and decays, but also very challenging experimentally → comprehensive detector upgrades for ATLAS and CMS
- Detailed studies demonstrate
  - impact of detector improvements
  - substantial boost of accuracy for Higgs boson couplings and other properties
  - access to Higgs pair production (→self coupling)
  - greatly enhanced sensitivity to New Physics involving Higgs bosons

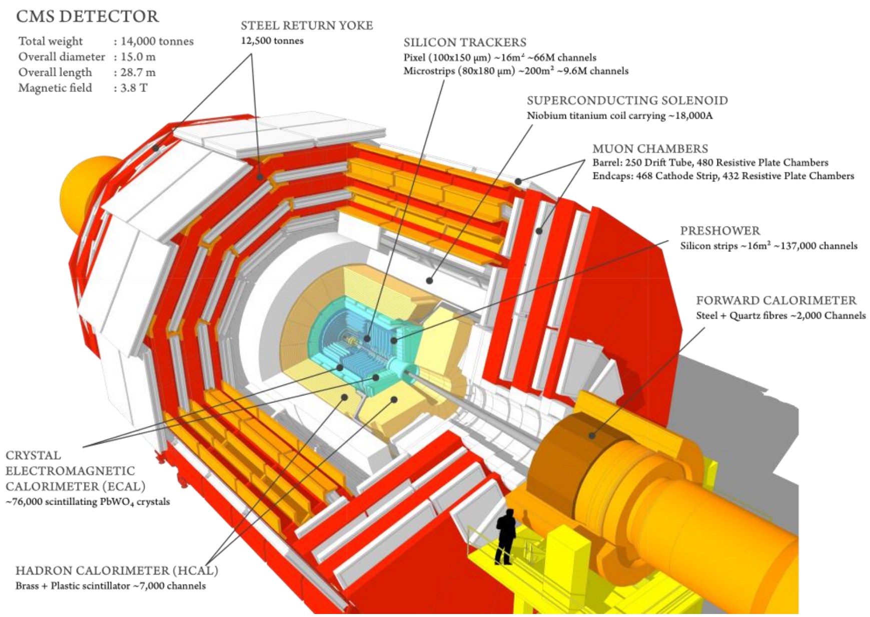
➔ A new era of Higgs boson research at the LHC!

Backup

ATLAS & CMS experiments

- The two multi-purpose detectors at the LHC



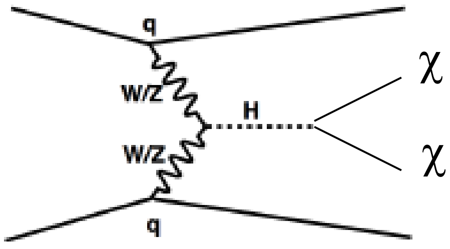


44 m x 25 m, 7,000 tons

29 m x 15 m, 14,000 tons

Invisible Higgs decays

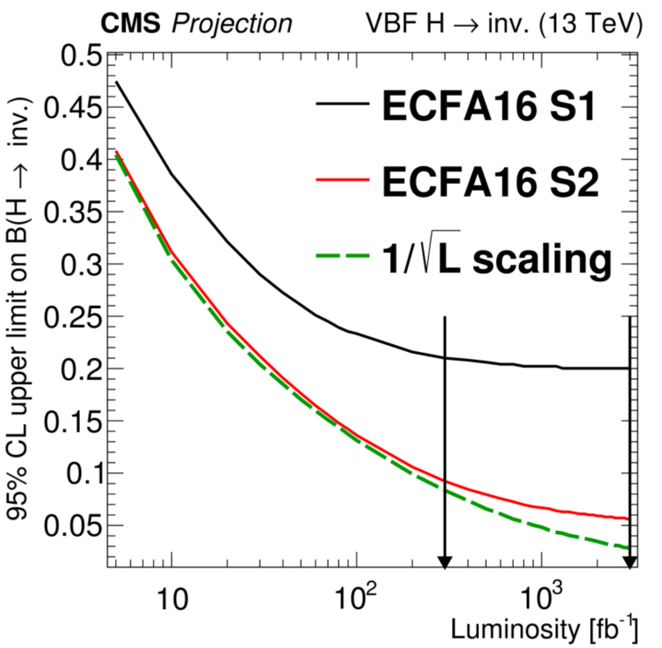
CMS PAS FTR-16-002



- Invisible Higgs decay modes may be possible through
  - decays to neutralinos (in supersymmetric models)
  - via graviscalars (in models with extra dimensions)
- Invisible Higgs decays can be assessed in signatures where Higgs boson is accompanied by something visible
  - here: VBF production
- Projection of search from 2.3 → 3000 fb^{-1}
  - ECFA16 Scenarios S1+S2(+)
  - pure $\propto 1/\sqrt{L}$ scaling also shown

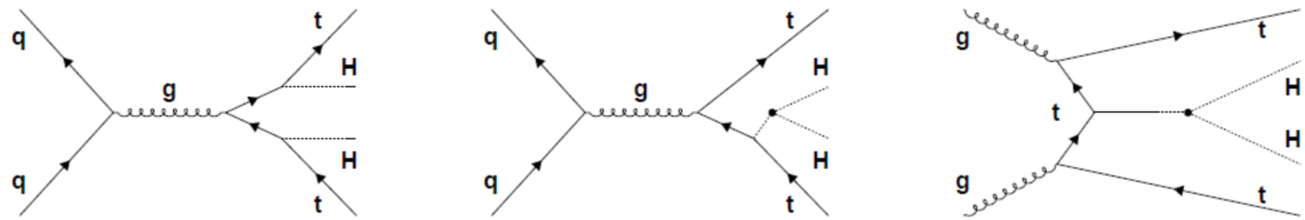
➔ Direct search limit for invisible decays may be pushed below 10%, based on this channel alone

	ECFA2016 (S1)	ECFA2016 (S2+)	ECFA2016 (S2)
300 fb^{-1}	0.210	0.092	0.084
3000 fb^{-1}	0.200	0.056	0.028

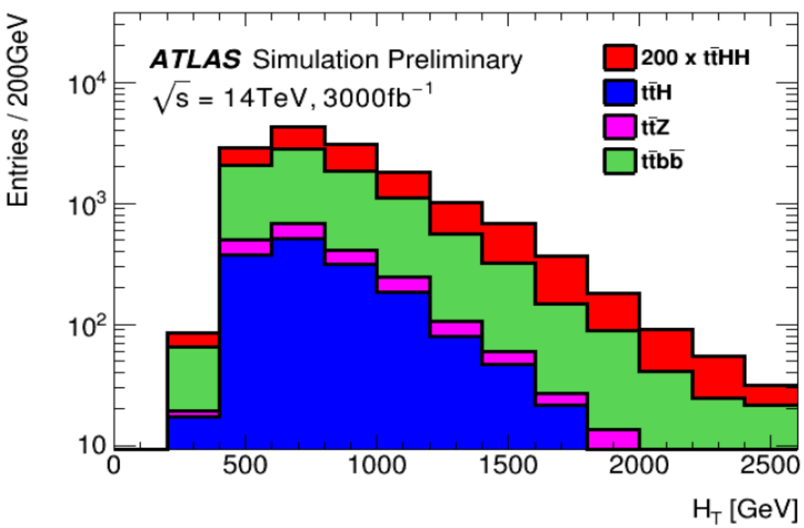


ttHH

ATL-PHYS-PUB-2016-023



- Compared to gluon-fusion, much lower cross section, but potentially also less background
- $t\bar{t}$ system reconstruction in lepton+jet mode, H→bb decay modes
- Generator level study
- Crucial backgrounds: ttH, ttbb

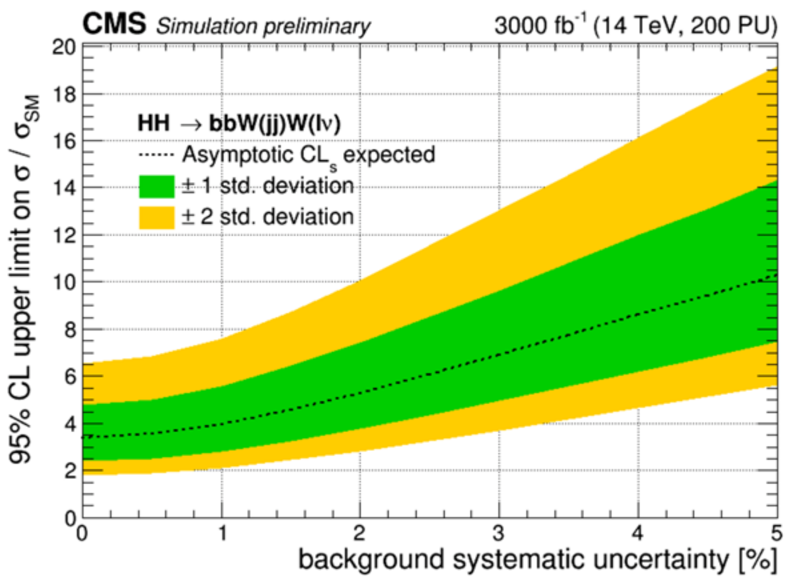


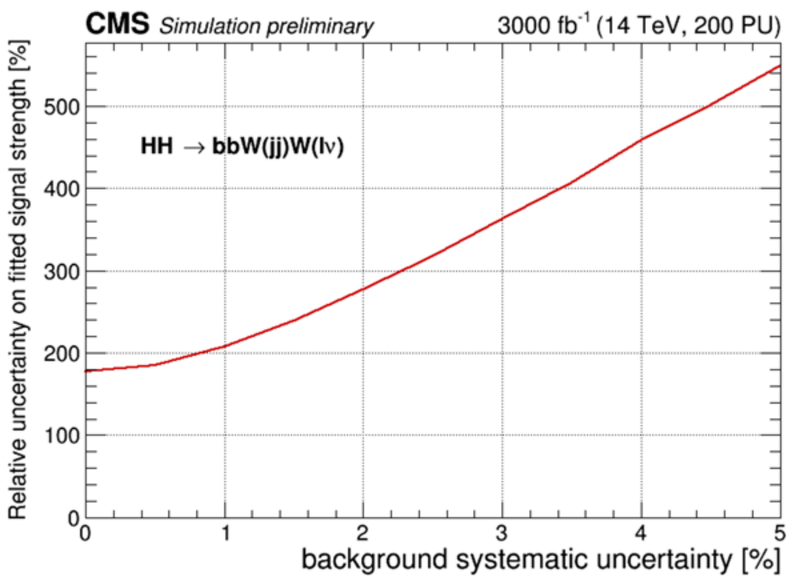
- Overall significance at 3000 fb^{-1}:
  - 0.35 σ
  - → only small contribution to evidence for HH production compared to bbγγ or bbττ channels

HH→(bb)(WW)→(bb)(qq)(ℓ ν)

CMS PAS FTR-16-002

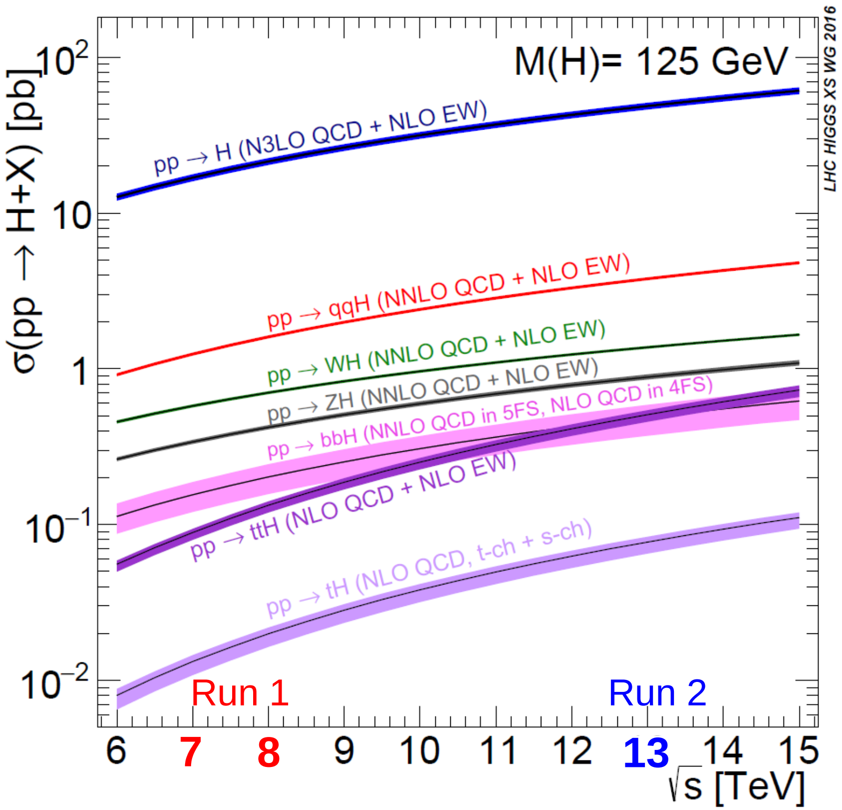
- Based on Phase-II detector simulation (DELPHES)
  - performance parameterization based on GEANT-simulation
- Dominant background tt + jets (SL)

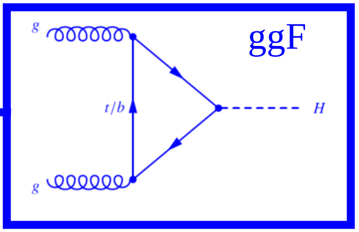


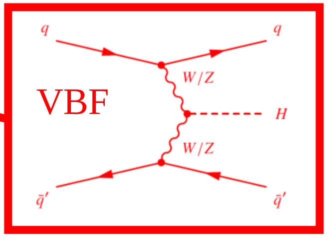


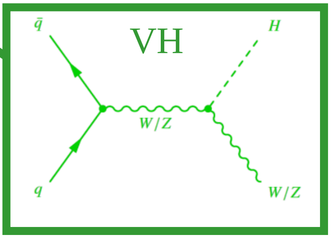
Channel	Median expected limits in μ_r ECFA16 S2	Median expected limits in μ_r Stat. Only	Z-value ECFA16 S2	Z-value Stat. Only	Uncertainty as fraction of $\mu_r = 1$ ECFA16 S2	Uncertainty as fraction of $\mu_r = 1$ Stat. Only
gg $\rightarrow$ HH $\rightarrow$ $\gamma\gamma$bb (S2+)	1.44	1.37	1.43	1.47	0.72	0.71
gg $\rightarrow$ HH $\rightarrow$ $\tau\tau$bb	5.2	3.9	0.39	0.53	2.6	1.9
gg $\rightarrow$ HH $\rightarrow$ VVbb	4.8	4.6	0.45	0.47	2.4	2.3
gg $\rightarrow$ HH $\rightarrow$ bbbb	7.0	2.9	0.39	0.67	2.5	1.5

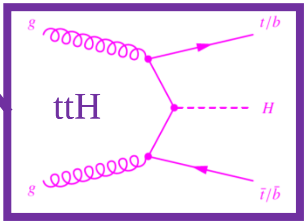
Higgs boson production mechanisms











- ➔ Sizable increase in cross sections in transition 8 → 13 TeV
  - factors of ~2.3 (ggF), ~4 (ttH)
- ➔ Significant improvements in theory
  - e.g. uncertainty of ggF cross sections reduced to ~½ (N^3LO)

Higgs boson decay modes

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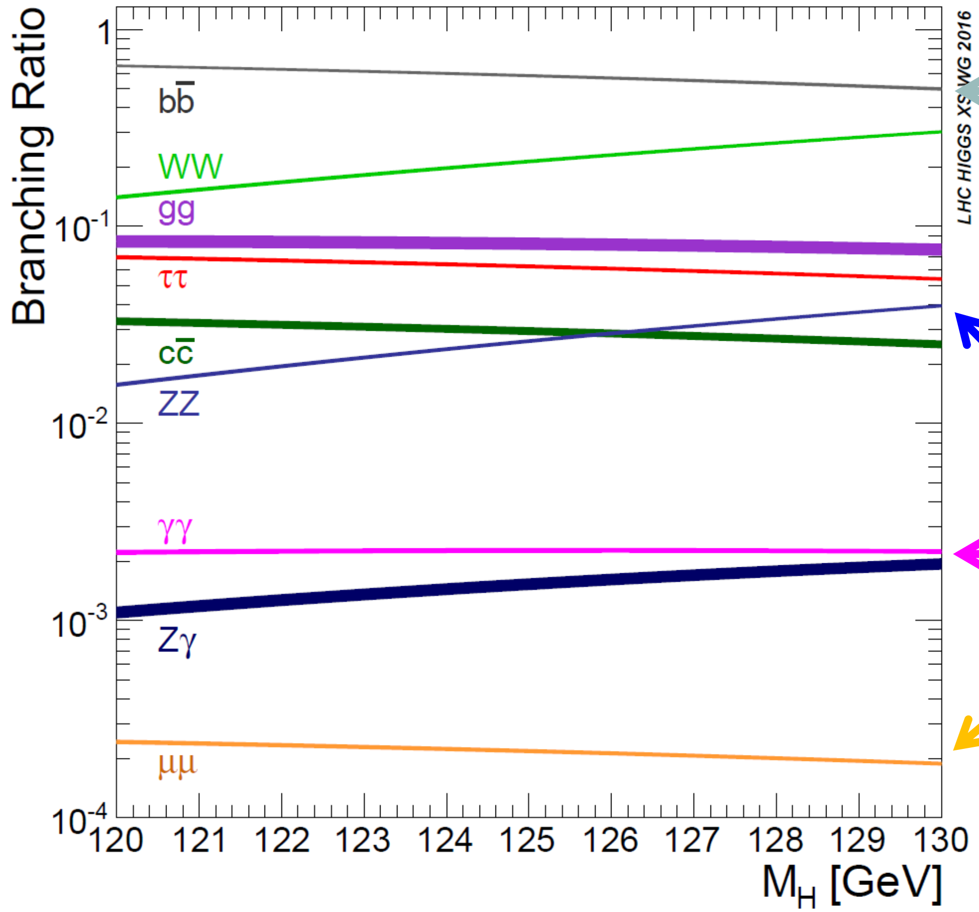


largest BR, but huge backgrounds

cleanest in terms of mass resolution & backgrounds

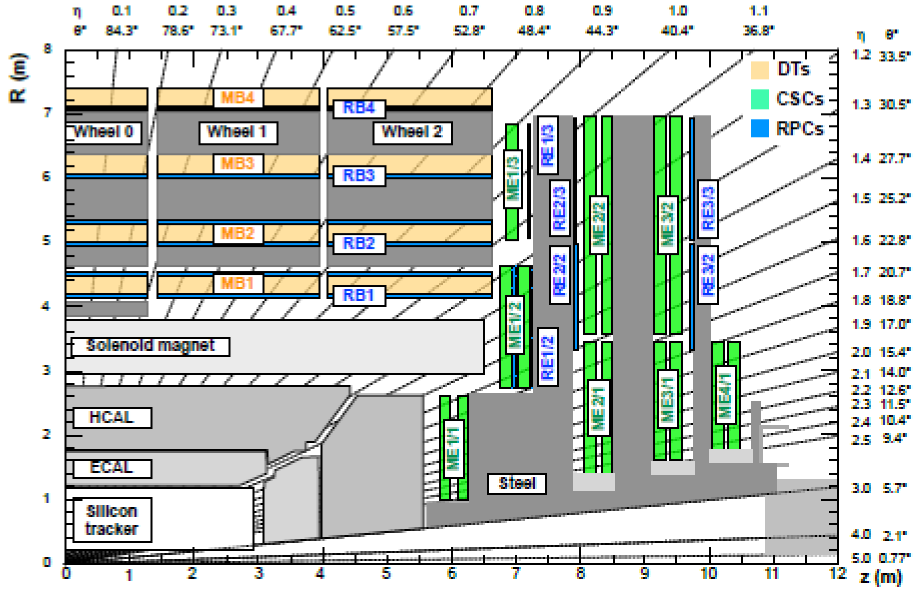


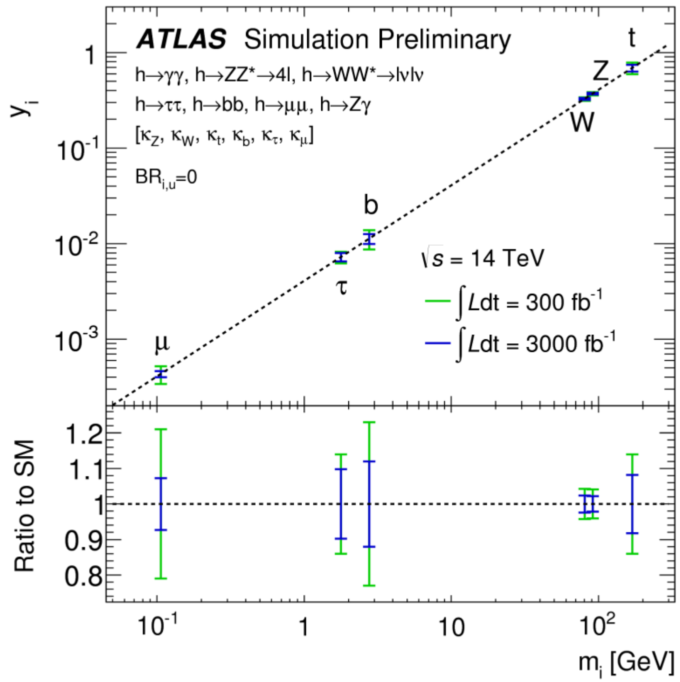
Figure 1: An R–z cross section of a quadrant of the CMS detector with the axis parallel to the beam (z) running horizontally and radius (R) increasing upward. The interaction point is at the lower left corner. Shown are the locations of the various muon stations and the steel disks (dark grey areas). The 4 drift tube (DT, in light orange) stations are labeled MB ("muon barrel") and the cathode strip chambers (CSC, in green) are labeled ME ("muon endcap"). Resistive plate chambers (RPC, in blue) are in both the barrel and the endcaps of CMS, where they are labeled RB and RE, respectively.

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
1	κ	4.2%	3.0%	2.4%	3.2%	2.2%	1.7%
2	$\kappa_V = \kappa_Z = \kappa_W$	4.3%	3.0%	2.5%	3.3%	2.2%	1.7%
	$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$	8.8%	7.5%	7.1%	5.1%	3.8%	3.2%
3	κ_Z	4.7%	3.7%	3.3%	3.3%	2.3%	1.9%
	κ_W	4.9%	3.6%	3.1%	3.6%	2.4%	1.8%
	κ_F	9.3%	7.9%	7.3%	5.4%	4.0%	3.4%
4	κ_V	5.9%	5.4%	5.3%	3.7%	3.2%	3.0%
	κ_u	8.9%	7.7%	7.2%	5.4%	4.0%	3.4%
	κ_d	12%	12%	12%	6.7%	6.2%	6.1%
5	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	8.7%	7.8%	6.6%	4.5%	3.6%
	κ_l	10%	9.6%	9.3%	6.0%	5.3%	5.1%
6	κ_V	4.3%	3.1%	2.5%	3.3%	2.2%	1.7%
	κ_q	11%	9.0%	8.1%	6.7%	4.7%	3.8%
	κ_τ	12%	11%	11%	9.2%	8.4%	8.1%
	κ_μ	20%	20%	19%	6.9%	6.3%	6.1%
7	κ_Z	8.1%	7.9%	7.8%	4.3%	3.9%	3.8%
	κ_W	8.5%	8.2%	8.1%	4.8%	4.1%	3.9%
	κ_t	14%	12%	11%	8.2%	6.1%	5.3%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	13%	13%	9.8%	9.0%	8.7%
	κ_μ	21%	21%	21%	7.3%	7.1%	7.0%
8	κ_Z	8.1%	7.9%	7.9%	4.4%	4.0%	3.8%
	κ_W	9.0%	8.7%	8.6%	5.1%	4.5%	4.2%
	κ_t	22%	21%	20%	11%	8.5%	7.6%
	κ_b	23%	22%	22%	12%	11%	10%
	κ_τ	14%	14%	13%	9.7%	9.0%	8.8%
	κ_μ	21%	21%	21%	7.5%	7.2%	7.1%
	κ_g	14%	12%	11%	9.1%	6.5%	5.3%
	κ_γ	9.3%	9.0%	8.9%	4.9%	4.3%	4.1%
	$\kappa_{Z\gamma}$	24%	24%	24%	14%	14%	14%

Table 3: Expected precision on Higgs coupling scale factors with 300 or 3000 fb^{-1} of $\sqrt{s} = 14$ TeV data for selected parametrizations, assuming no decay modes beyond those in the SM. With SM decay modes only, the Higgs total width can still differ from the SM value if any of its couplings to SM particles differ from the expected values. The coupling scale factor κ represents all SM particles, κ_V represents the gauge bosons W and Z, κ_F represents all fermions, κ_u represents all up-type fermions, κ_d represents all down-type fermions, κ_q represents all quarks, and κ_l represents all leptons. The results are reported for 3 different assumptions on the theory uncertainties: the current size, half of the current size, and no theory uncertainties.

Couplings vs mass

-



$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v} \qquad y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$

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Source	$\Delta\mu$
Luminosity	0.05
Jet Energy	0.09
b-tagging	0.34
Theoretical	0.10
Multijet	1.85
$t\bar{t}$	2.83

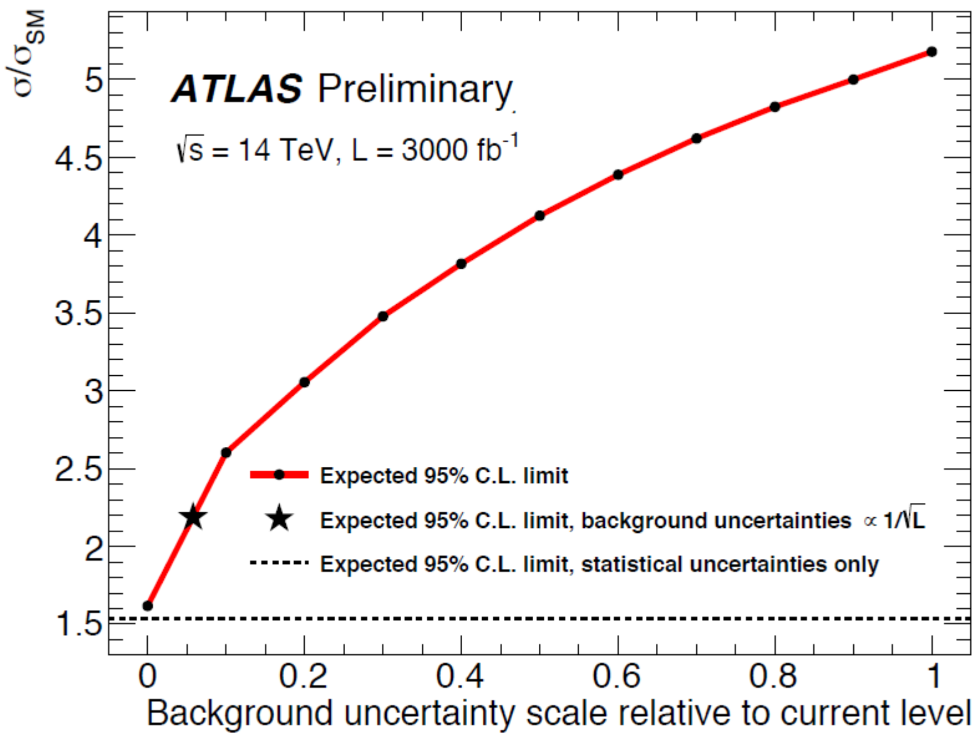

Figure 5: Expected 95% C.L. upper limit on the cross-section $\sigma\left(HH \to b\bar{b}b\bar{b}\right)/\sigma_{SM}$, as a function of the background modelling uncertainties. The background modelling uncertainties are each scaled by a common, constant factor relative to the 2016 uncertainties (i.e. the current uncertainties correspond to 1 here). The limit achievable if the uncertainties scaled proportionally to integrated luminosity is shown as the star. The statistical-only limit is shown as the dashed line. The extrapolated sensitivities are shown using a jet p_T threshold of 30 GeV.

H→WW*→eνμν (VBF)

ATL-PHYS-PUB-2016-018

- Cut based analysis
- Main selection:
  - 2 forward with jets with $|\eta| > 2$ in opposite hemispheres
  - no additional jets between e+μ and forward jets
  - $E_T^{miss} > 20\ GeV$
- Results for pileup 200 presented for:
  - "Full": full theoretical uncertainties
  - "None": no theoretical uncertainties

➔ Factor ~2 improvement in precision with $|\eta| < 4$

Tracker Scenario	Δ_μ		Significance	
Theor. unc.	Full	None	Full	None
Reference: $\|\eta\| < 4$	0.20	0.14	5.7	8.0
Middle : $\|\eta\| < 3.2$	0.25	0.20	4.4	5.4
Low : $\|\eta\| < 2.7$	0.39	0.30	2.7	3.5