PROSPECTS ON HIGGS COUPLINGS AT THE HL-LHC

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on behalf of the
ATLAS and CMS Collaborations

Projected Performance at the HL-LHC

ECFA (2016)
Projections from Run2
(13 TeV data)

TDR's
+ new analyses
+ new/improved techniques

Yellow report (2018)
Projections from Run2 (13 TeV data)
Full simulation of some benchmark channels

SNOWMASS (2013)
Projections from Run1
(8 TeV data)

Outlines

- Introduction
  - Why HL-LHC ?
  - Pileup
  - Production modes
  - A Higgs factory
  - Coupling scale factors
- Coupling to bosons
  - $H\rightarrow ZZ$, $H\rightarrow \gamma\gamma$, $H\rightarrow WW$
- Yukawa couplings
  - $H\rightarrow \tau\tau$, $H\rightarrow \mu\mu$
  - *[Top and bottom Yukawa couplings - see A. Calandri's talk]*
- Summary

Introduction: a gate to Precision and New Physics

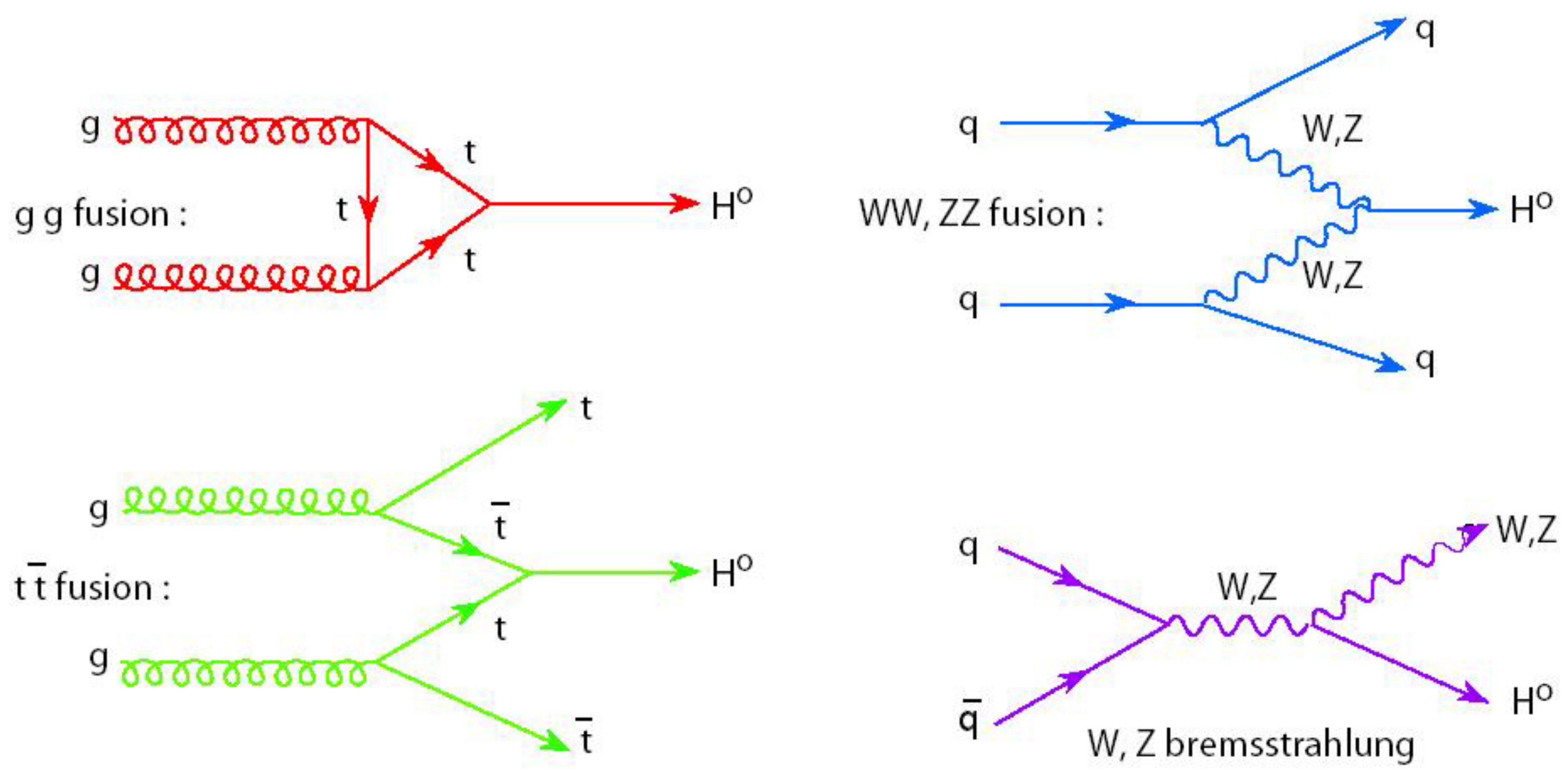
- Higgs boson studies are a major component of HL-LHC physics program
- High statistics of HL-LHC: unique opportunity to thoroughly test the Higgs boson properties
- HL-LHC needed
  - to achieve high precision measurements (down to the level of a few percents)
    - With this precision → any deviations from SM would reveal New Physics (additional particles in loop processes (gluon fusion, di-photon decay)
  - to reach sensitivity to coupling to 2nd generation ($H \to \mu\mu$)
  - to reach sensitivity to rare decays involving new physics

Introduction: Detector upgrades

- AT HL-LHC, the high expected instantaneous luminosity of 5 (7.5)$\cdot 10^{34}$ $cm^{-2}s^{-1}$ will lead to an average number of proton-proton collisions per bunch crossing [pileup] of $\langle\mu\rangle$ of 140 (200)
- In addition: detectors will be significantly affected by radiation damage especially in the endcaps) by the time of HL-LHC
- → series of upgrades of the detectors to recover the detector performance compromised by caused by radiation damage and increased pileup
- ATLAS and CMS detectors will be upgraded to achieve the same or better performance as in Run1
  - Maintain a good object reconstruction (leptons, photons, b-tagging, jets and missing E_T) in this harsh environment is crucial to maximise physics potential
  - Pileup mitigation is a critical element of detector designs
- ATLAS and CMS performed projections with upgraded detectors to provide a picture of the experimental reach on Higgs boson coupling measurements with 3000 fb^{-1}

Introduction: Production modes and σ

- SM Higgs production cross sections at $\sqrt{s}$ = 14 TeV (update in CERN Report4 2016)
- From $\sqrt{s}$ = 8 TeV to $\sqrt{s}$ = 14 TeV: the cross-section increases by a factor of 2 or more



Cross sections in pb for $m_H = 125$ GeV

$\sqrt{s}$ (TeV)	ggF	VBF	VH	$t\bar{t}H$	
14	54.8	4.28	2.50	0.614	→ *Yellow Report 4*
14	49.9	4.18	2.38	0.611	→ *Yellow Report 3*

Higgs Working Group Report
arXiv:1610.07922v2 Yellow Report 4

arXiv:1310.8361v2 Yellow Report 3

Introduction: HL-LHC … a Higgs factory

- Over 170 million Higgs bosons in 3000 fb^{-1}
- Over 1 million for each of the main production mechanisms, spread over many decay modes:
  - ~400k $H \to \gamma\gamma$
  - ~20k $H \to ZZ \to \ell\ell\ell\ell$
  - ~38k $H \to \mu\mu$
  - ~800 VBF $H \to \tau\tau$
  - ~17k $H \to Z\gamma$ (not covered here)

$pp \to H + X$ at $\sqrt{s} = 14$ TeV for $m_H = 125$ GeV

	ggF	VBF	VH	$t\bar{t}H$	Total
Cross section (pb)	49.9	4.18	2.38	0.611	57.1

→ *σ from Yellow Report 3*

Numbers of events in 3000 fb^{-1}

	ggF	VBF	VH	$t\bar{t}H$	Total
$H \to \gamma\gamma$	344,310	28,842	16,422	4,216	393,790
$H \to ZZ^* \to 4\ell$	17,847	1,495	851	219	20,412
$H \to WW^* \to \ell\nu\ell\nu$	1,501,647	125,789	71,622	18,387	1,717,445
$H \to \tau\tau$	9,461,040	792,528	451,248	115,846	10,820,662
$H \to b\bar{b}$	86,376,900	7,235,580	4,119,780	1,057,641	98,789,901
$H \to \mu\mu$	32,934	2,759	1,570	403	37,667
$H \to Z\gamma \to \ell\ell\gamma$	15,090	1,264	720	185	17,258
$H \to$ all	149,700,000	12,540,000	7,140,000	1,833,000	171,213,000

Higgs Working Group Report arXiv: 1310.8361v2 [hep-ex] 8 Jan 2014

Introduction: coupling scale factors

- The deviations from the SM are implemented as scale factors (κ's) of Higgs couplings relative to their SM values
- "Reduced" coupling scale factors y_i are respectively defined for weak bosons *V,i=W,Z* and for fermions *F,i* = μ, τ, *b*, *t:*

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

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

where

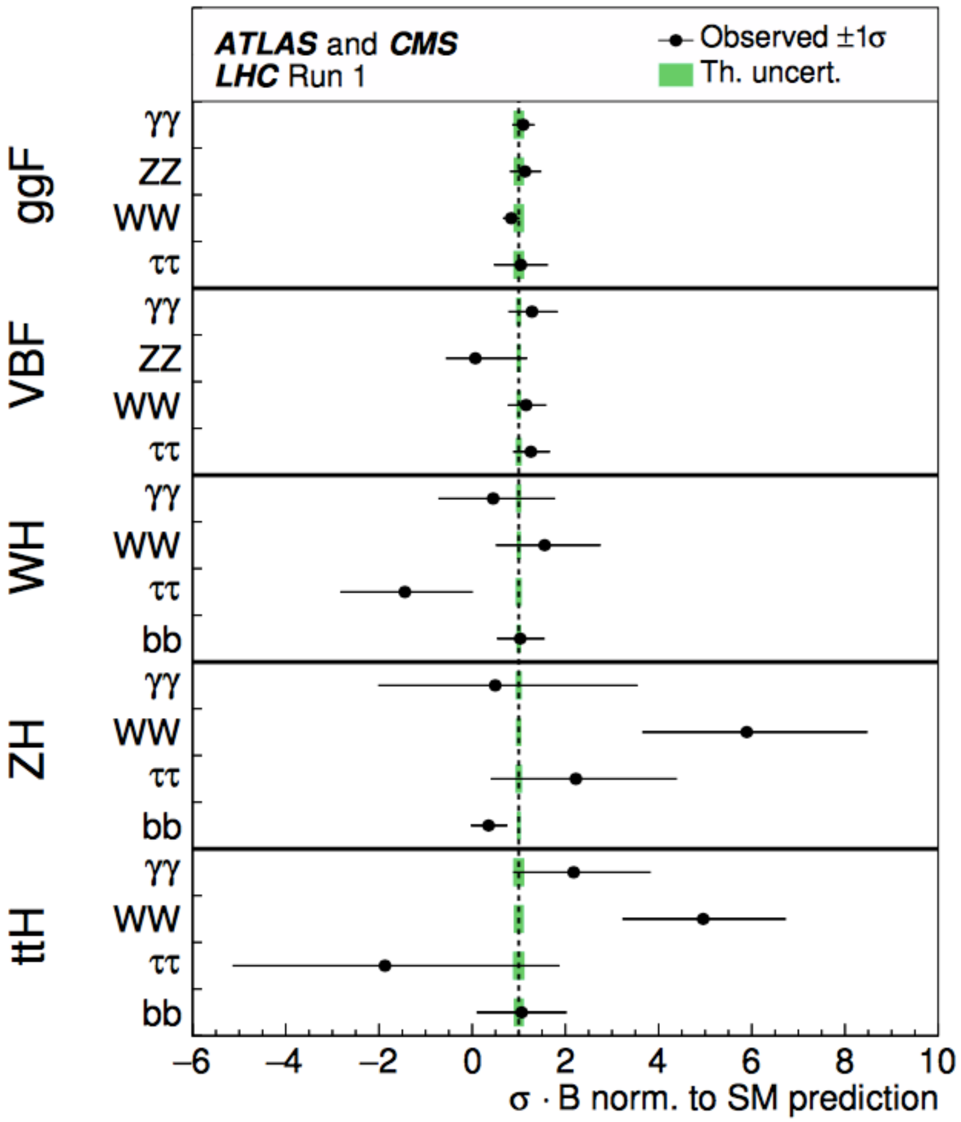
- $g_{V,i}$ are the gauge couplings to the various bosons and
- $g_{F,i}$ are the Yukawa couplings to the various fermions
- κ_i are scale factors ("coupling modifiers") defined in such a way that the cross-sections σ_i and the partial decay widths Γ_j associated with the SM particle *i* scale with κ_i^2 compared to the SM prediction

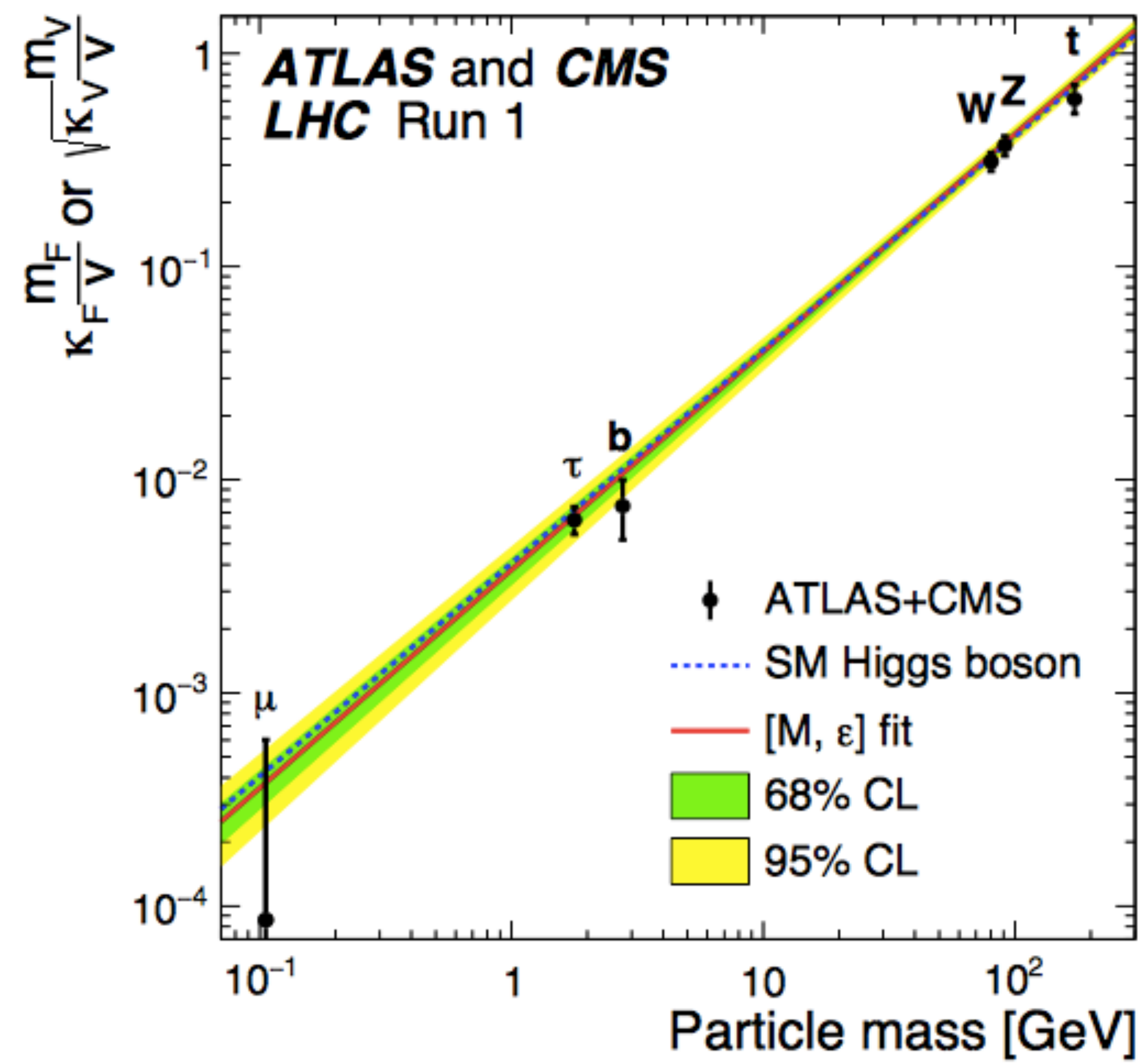
$$\kappa_i^2 = \sigma_i / \sigma_i^{SM}$$

$$\kappa_i^2 = \Gamma_i / \Gamma_i^{SM}$$

Introduction: Coupling scale factors from Run1

- Good agreement with SM expectation → SM-like Higgs boson
- No deviation with respect to SM expectation



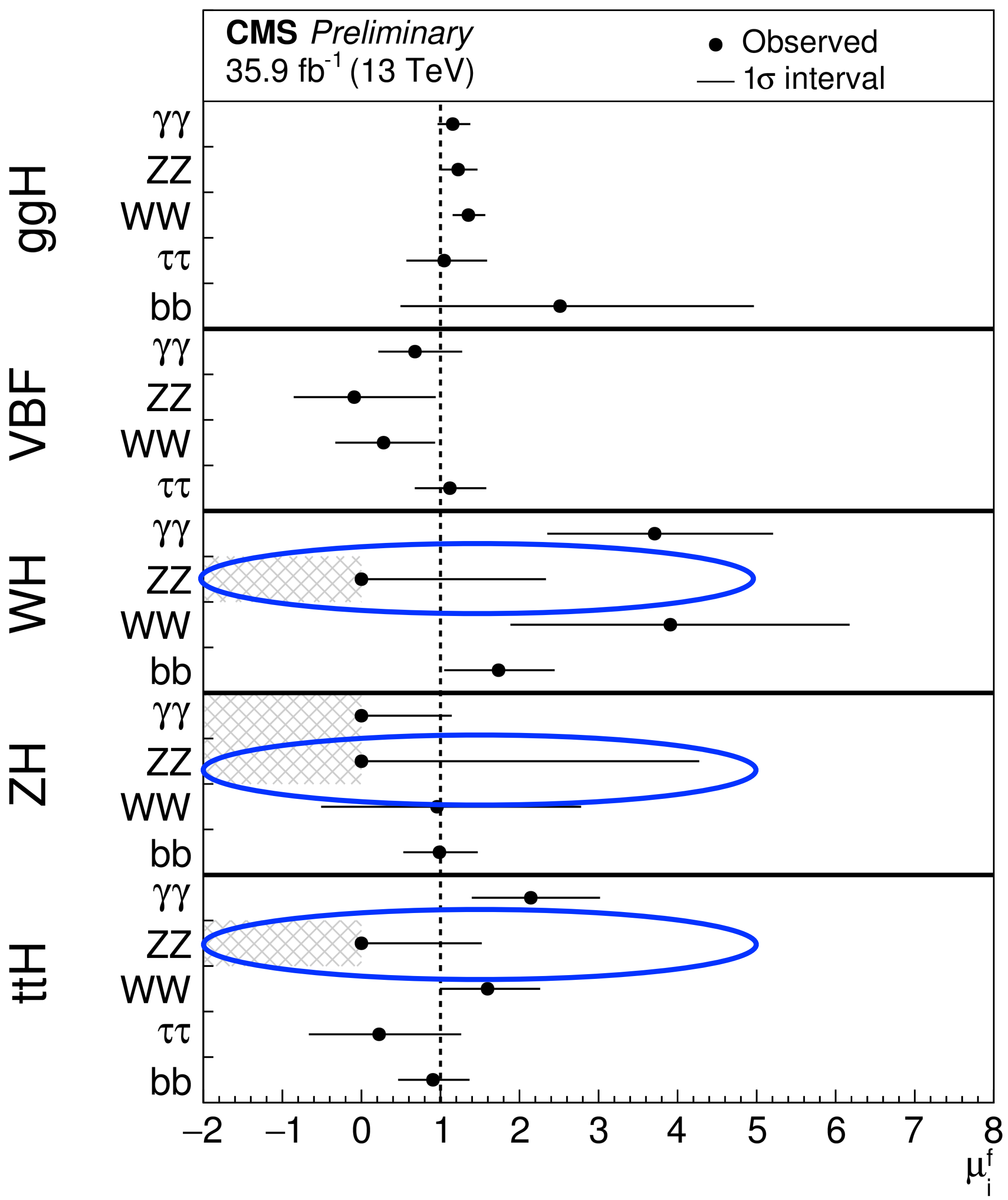


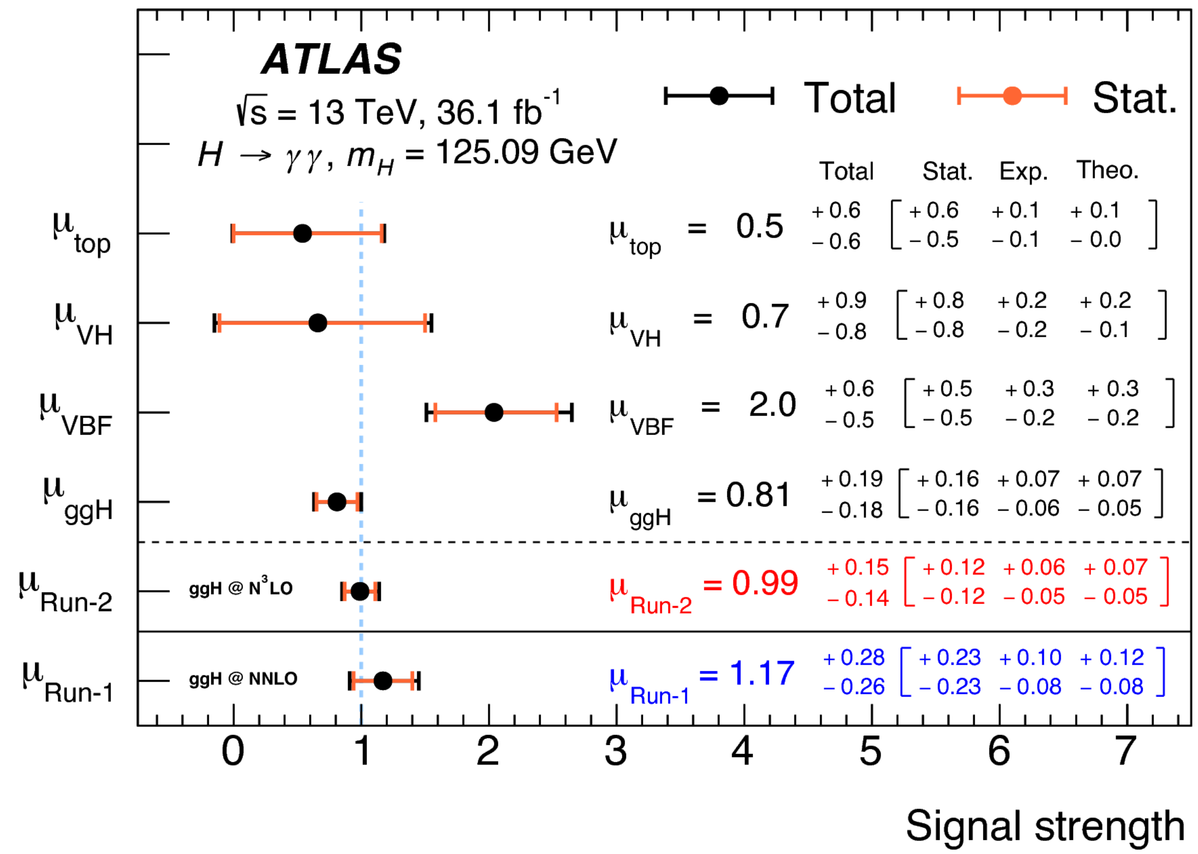
arXiv:1606.02266v2
JHEP 08 (2016) 045

- → need to probe small deviations to narrow down New Physics
- → need higher precision measurements on signal strengths and couplings

Introduction: Signal strengths from Run2

- With Run2 data, start to exploit new production-decay models e.g. VH and ttH with H → ZZ decay channels not considered in the ATLAS+CMS Run1 combination





CMS PAS HIG-17-031

arXiv:1802.0414

Strategy for projections: extrapolation scenarios

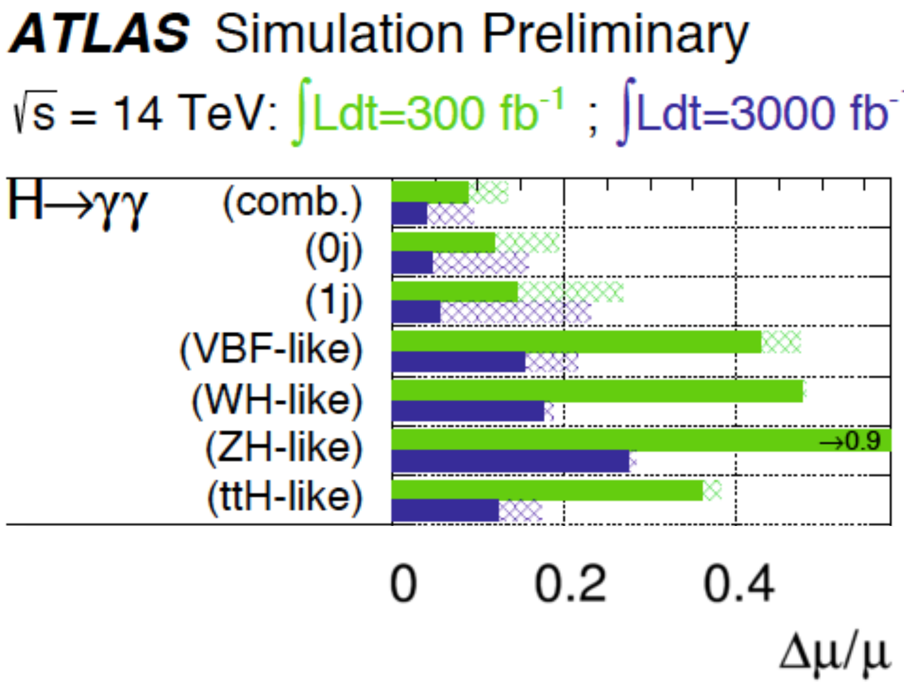
- Several scenarios assumptions made on how systematic and theoretical uncertainties will evolve and how detector upgrades will perform to compensate degradations due to high pileup

- **CMS:**
- **S1**: systematic uncertainties constant, unchanged detector performances (no upgrade considered)
- **S1+**: includes higher PU and detector upgrades effects
- **S2**: theoretical uncertainties scaled by 0.5, experimental uncertainties scaled by luminosity (until a lower limit based on estimates of achievable accuracy with upgraded detector)
- **S2+**: S2 +includes higher PU and detector upgrades effects

- **ATLAS:**
- Includes programmed detector upgrades, with extended η coverage of the tracker up to $|\eta|<4.0$ ("reference" scenario)
- Theoretical uncertainties scaled by 1 (unchanged), 0.5 or 0
- PU and upgrades taken into account
  - 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

Run1-based couplings: H → γ γ

- ATLAS
  - Run1 analysis strategy with expected performance at <μ>=140
  - Impact of theoretical uncertainty (shadow band) not negligible → reduced theoretical uncertainties needed
- CMS:
  - Extrapolations based on 12.9 fb^{-1} of data at 13 TeV
  - Effect of high pileup and upgraded detector
- Similar expected sensitivities between the two experiments: about 4% with 3000 fb^{-1} for the signal strength measurements (no theory uncertainty included)
- $\Delta\kappa_\gamma/\kappa_\gamma$ = [no theory uncert., full theory uncert] = [4.1-4.9%]



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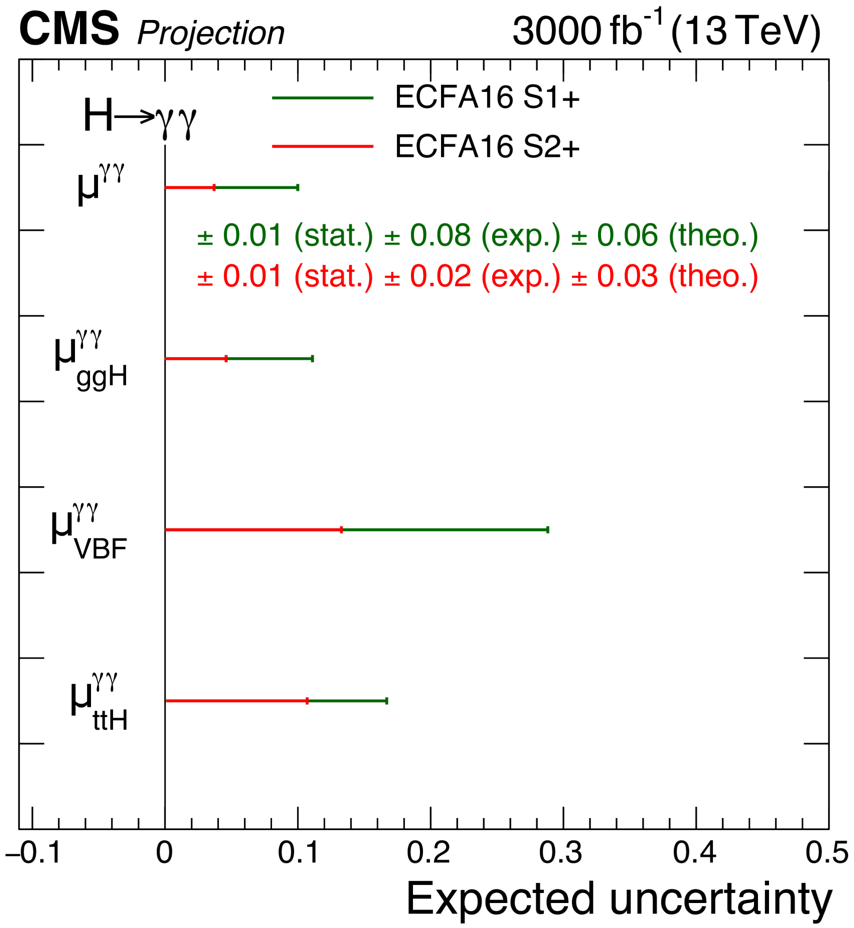
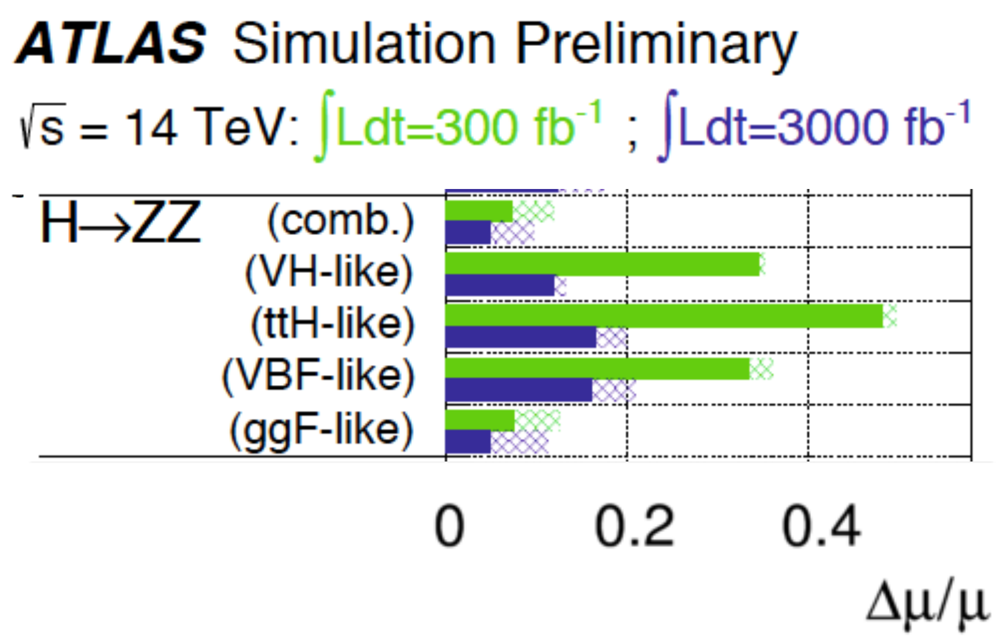


CMS-FTR-16-002

Run1-based couplings: H → ZZ*

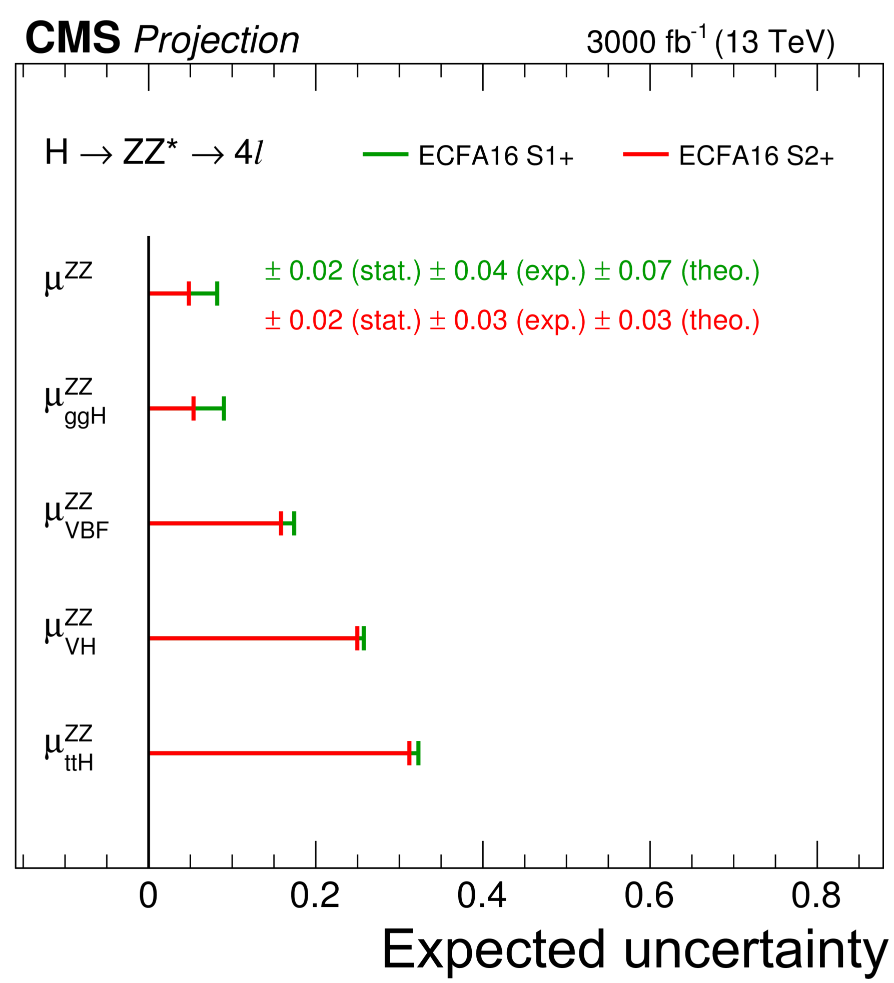
- Similar expected sensitivities between the two experiments: about 4% with 3000 fb^{-1} for the signal strength measurements (no theory uncertainty included)



- $\Delta\kappa_Z/\kappa_Z$

  = [no theory uncert., full theory uncert]

  = [3.8-4.4%]



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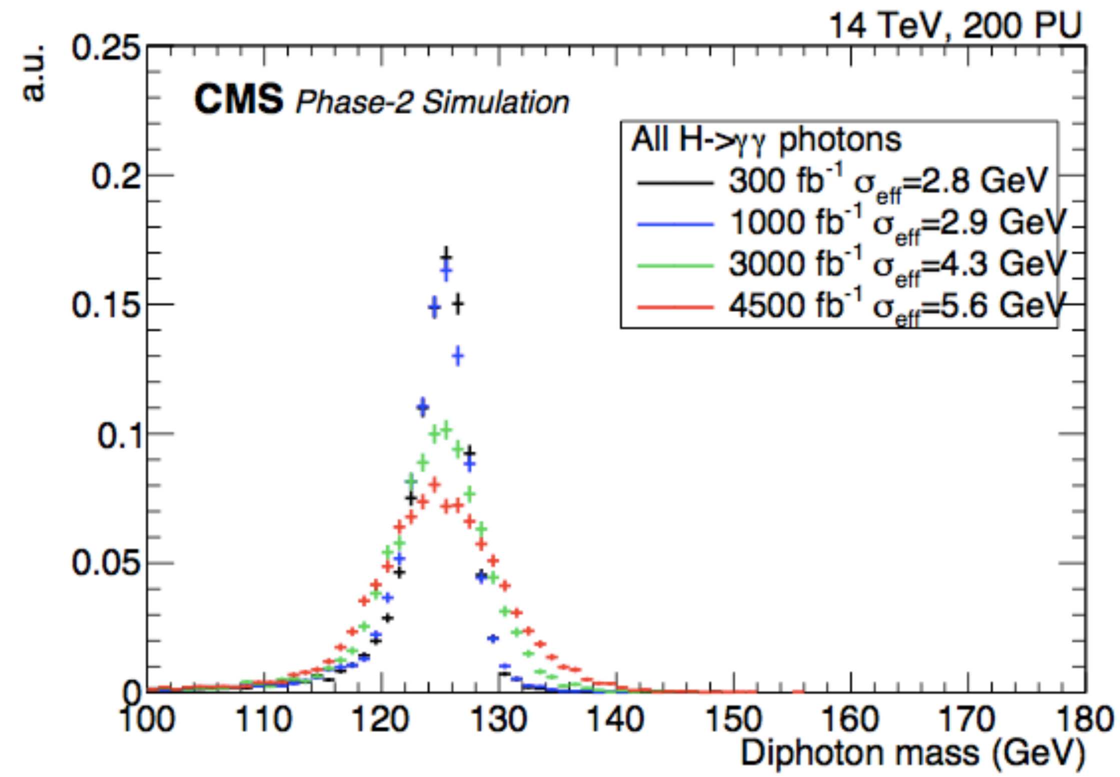
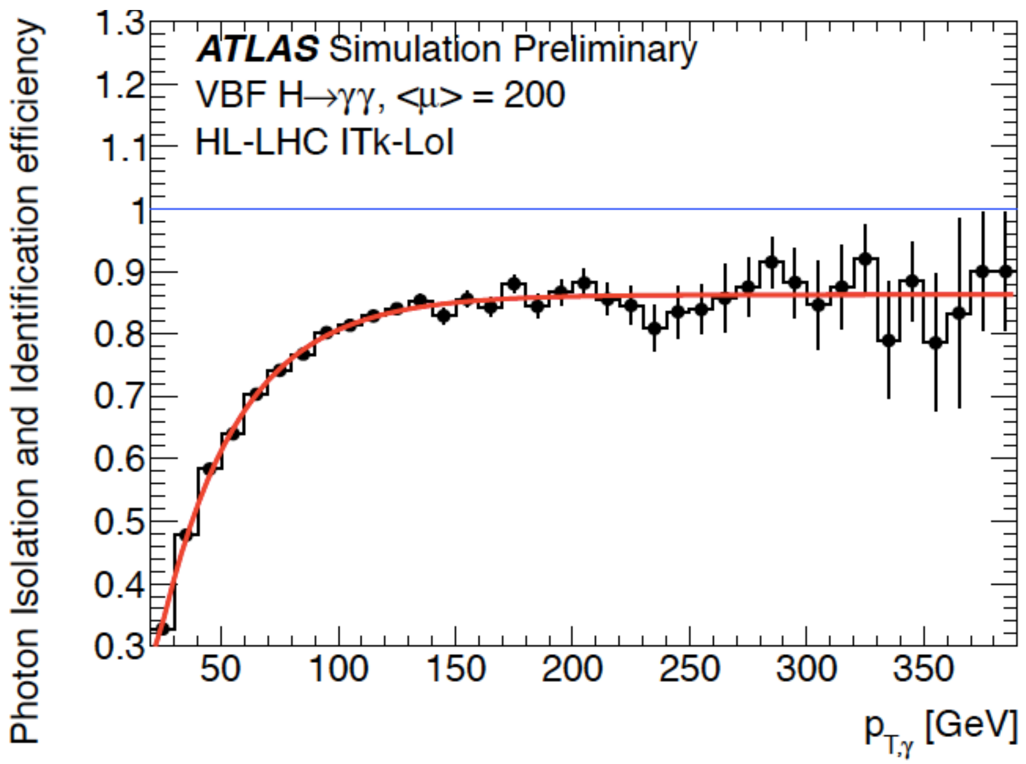
CMS-FTR-16-002
LHCC-P-008

H → γγ

- With an increasing number of pileup events, the di-photon mass resolution is mostly driven by photon energy and vertexing resolutions
- CMS: The di-Photon mass is shown for a pileup of 200 and for different radiation ageing scenarios of the barrel calorimeter
- ATLAS: Efficiency for a reconstructed photon to pass both the tight identification and isolation criteria
  - @ 60 GeV: ε = ~70%,
  - For higher E_T photons: ε = ~87%.
  - Note that for 2015 data: @ 60 GeV: ε = ~95%



CMS TDR-017-002



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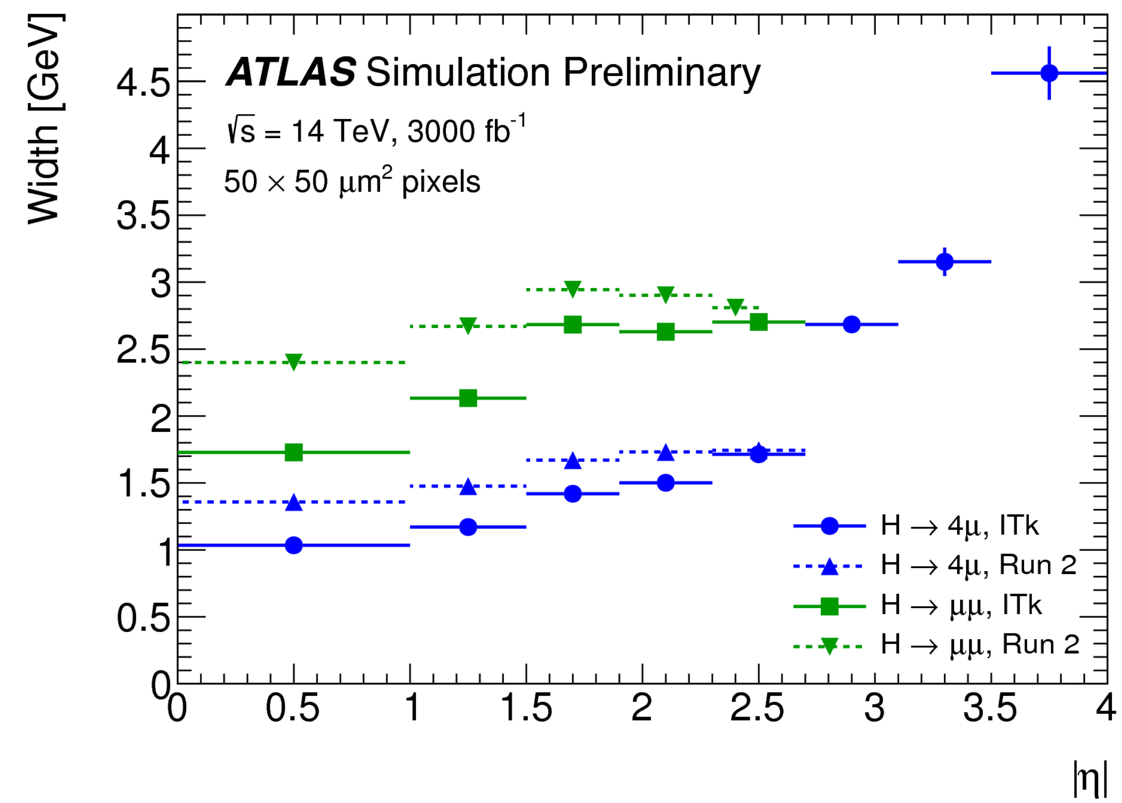
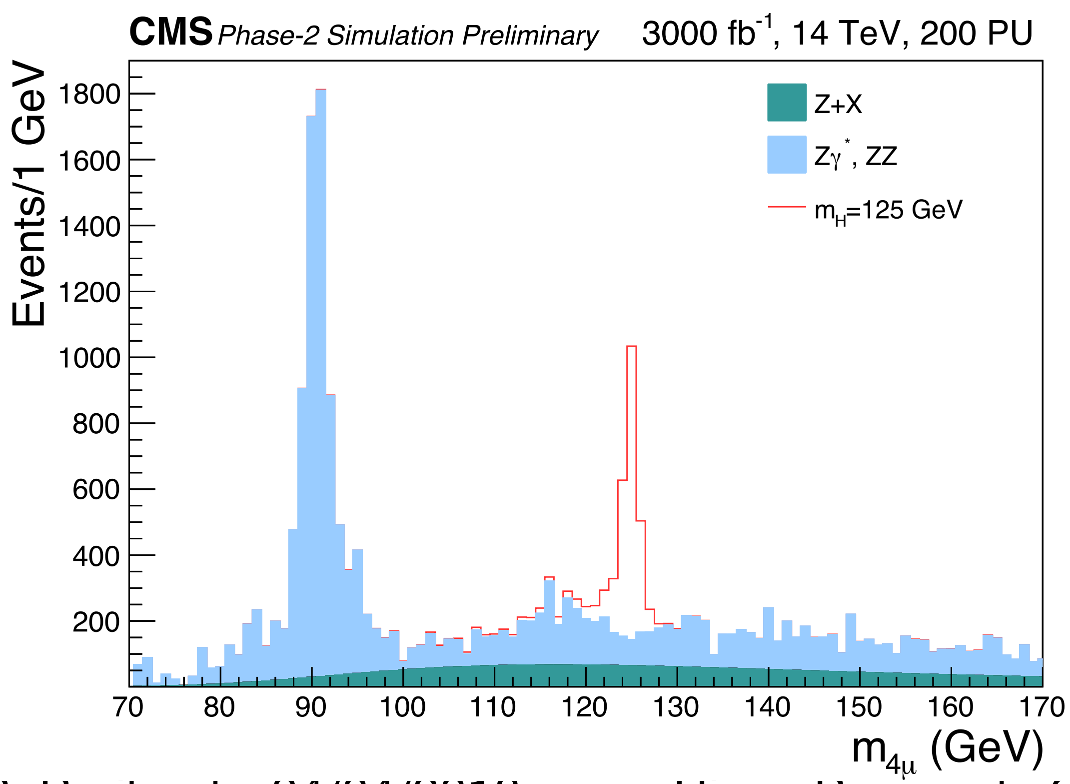
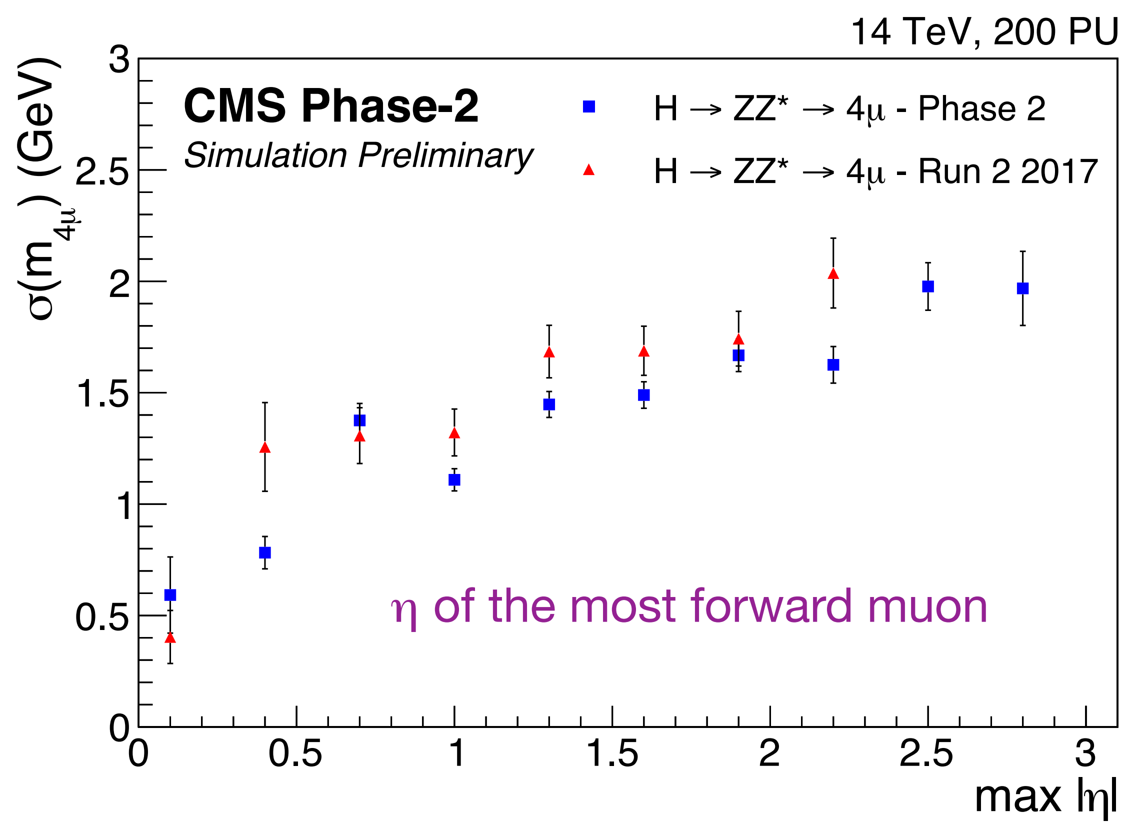
H → ZZ*

- Upgraded detectors bring significant improvements:
  - Increased CMS/ATLAS tracker acceptances up to $|\eta|<4$, new EM trigger, improved μ triggers, higher reconstruction efficiency and momentum resolution in Phase2
- Resolution of the four-muon invariant mass
- ATLAS: mass resolution improvement is ~30 %
- CMS → no worsening of the mass resolution due to the pileup increase is observed



ATLAS pixel TDR

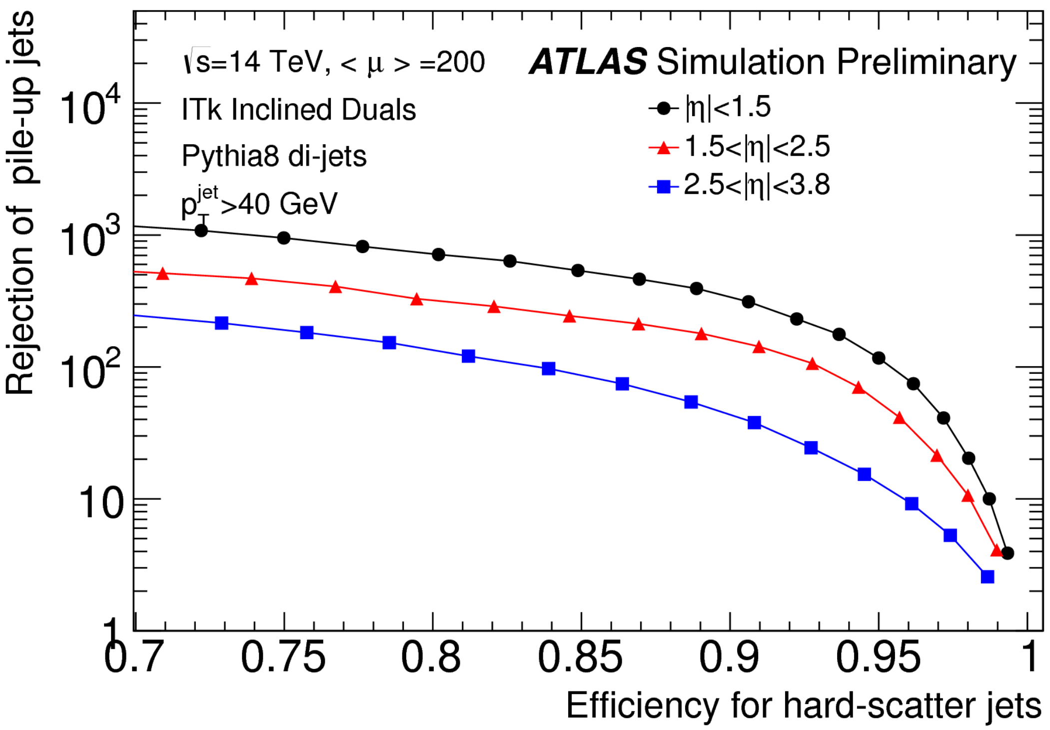




CMS TDR-017-001
CMS TDR-017-003

VBF H → WW, ZZ, γγ , ττ channels

- VBF production mode with subsequent Higgs decay in the WW, ττ, γγ, ZZ channels recently used as benchmark in ATLAS and CMS upgrade TDRs → showcase of the detector performance optimisation for pileup mitigation
- ATLAS:
- η acceptance important for signal selection efficiency in the VBF topology
- VBF topology selection:
  - leading two jets with |η| > 2 in opposite hemispheres
  - invariant mass of the two leading jets (m_{jj}) > 1250 GeV
  - suppression of additional jet activity within the event
- → pileup jet mitigation in the forward region
- → b-jets veto against tt in the forward region
- → central jet veto (CJV): remove events with additional jets with p_T > 30 GeV within the rapidity range spanned by the two leading jets

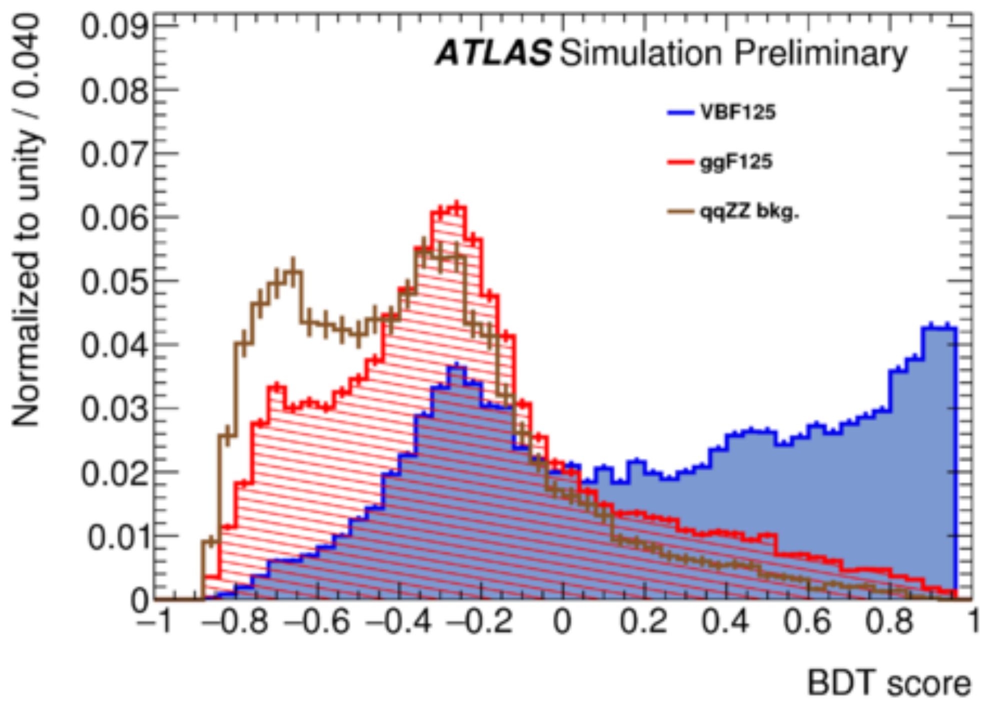


ATLAS TDR-025

- Efficiency of the CJV requirement:
  - 82% in | η |<4.0
  - 59% in | η |<3.2
  - 26% in | η |<2.7

VBF H → ZZ → ℓℓ ℓℓ

- Use parametrization of expected performances at <μ> = 200
- The acceptance of the new Inner Tracker up to |η|<4.0 enables better separation between ggF and VBF kinematic distributions
  - Use of track information to reject forward pileup jets



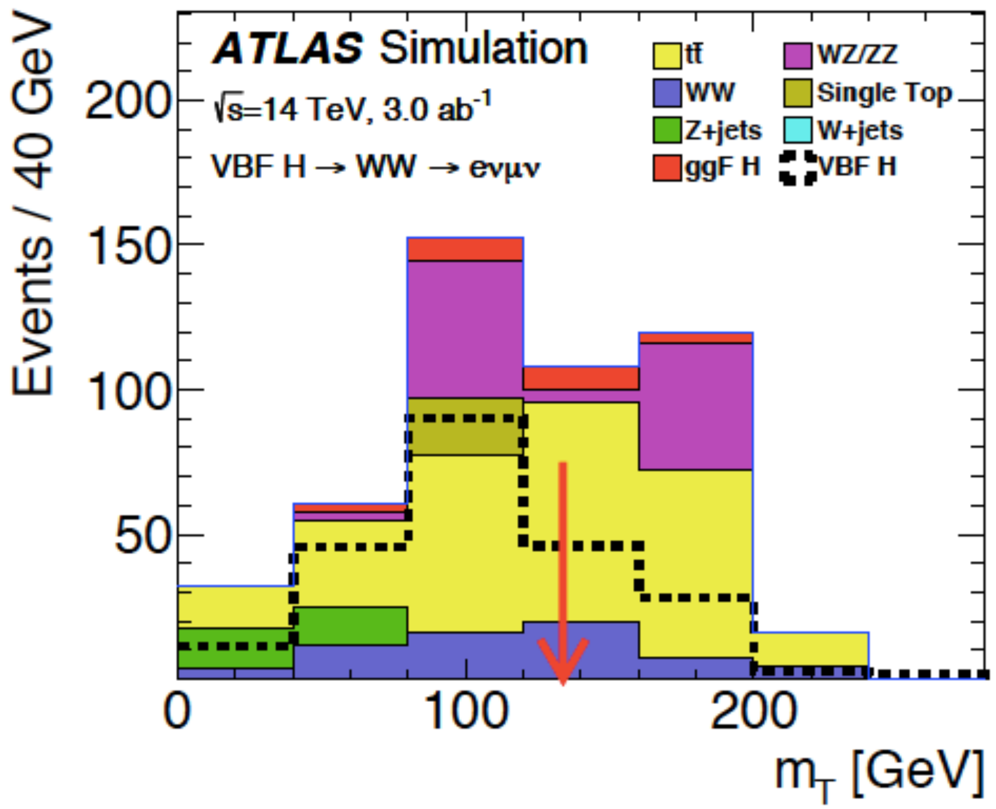
ATL-PHYS-PUB-2016-008

- Expected signal and background event yields, VBF signal significance and signal strength precision for 3000 fb^{-1} [$120 < m_{4\ell} < 130$ GeV] → Significant improvement with tracker acceptance

Statistical uncertainty only					
Scoping scenario	VBF + 2j events	ggF + 2j events	$qqZZ$ + 2j events	Z_0	$\Delta\mu/\mu$
Reference	192 (168)	287 (140)	39 (16)	10.2	0.152
Middle	218 (167)	454 (155)	69 (15)	9.5	0.157
Low	259 (159)	803 (182)	124 (21)	8.6	0.165

VBF H → WW → eν μν

- Use parametrization of expected performances at < μ > = 200
- Jet b-tagging from expected performances at <μ>=200
- e/μ efficiency from Run1 detector
- Even in worst case scenario: possibility to observe VBF H→WW production



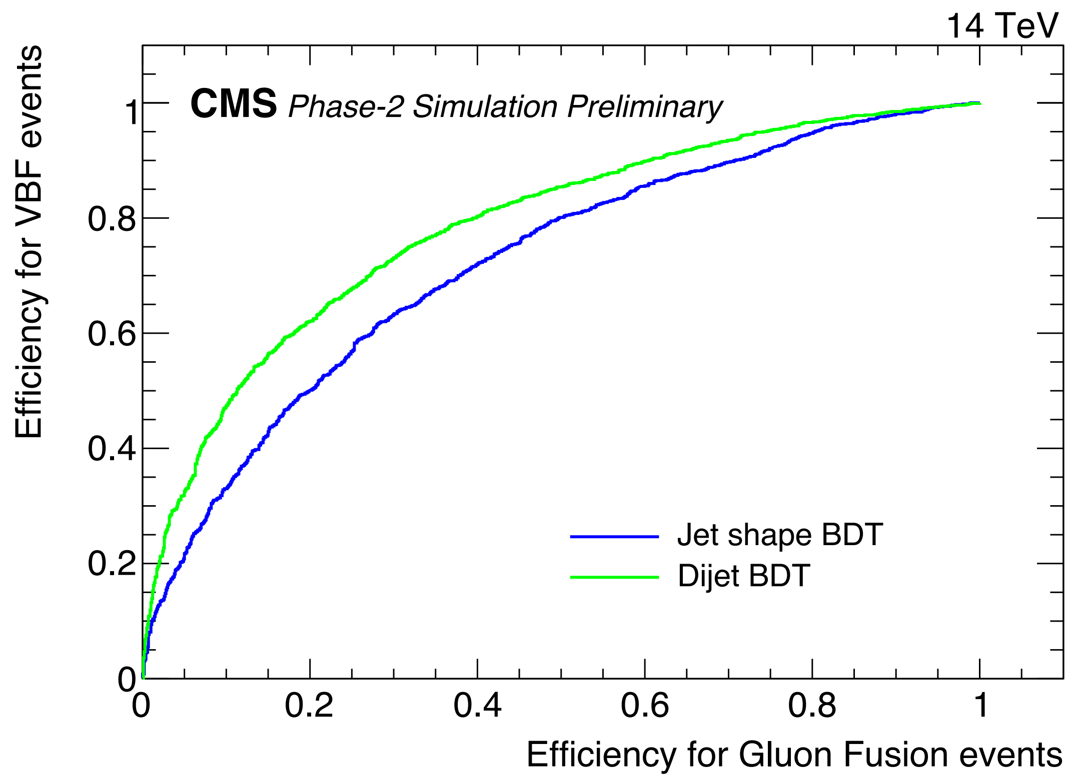
ATLAS TDR-025

- Expected precision of the VBF H → WW cross-section measurement for different tracking coverage scenarios (no theoretical uncertainties)

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

VBF $H \to \gamma\gamma$

- CMS High-Granularity Calorimeter (HGCAL) in the forward region allows inclusion of photons up to $|\eta| = 3.0$, compared with $|\eta| = 2.5$ in the Run2 → increase in efficiency of the analysis by 12%
- High granularity and precision timing capabilities of the HGCAL
  → improvement in pileup suppression in primary vertex reconstruction, isolation, jet shape observables and missing energy
  → improved reconstruction and identification of the characteristic forward jets in VBF production
- ROC curves for two trained BDTs. The classifier using the three jet shape and additional kinematic variables (green line) has an area of 0.79
- For comparison, in the Run2 analysis has an area of 0.75
- → discriminating power between ggH and VBF is comparable to Run2 despite the increase in amount of pileup

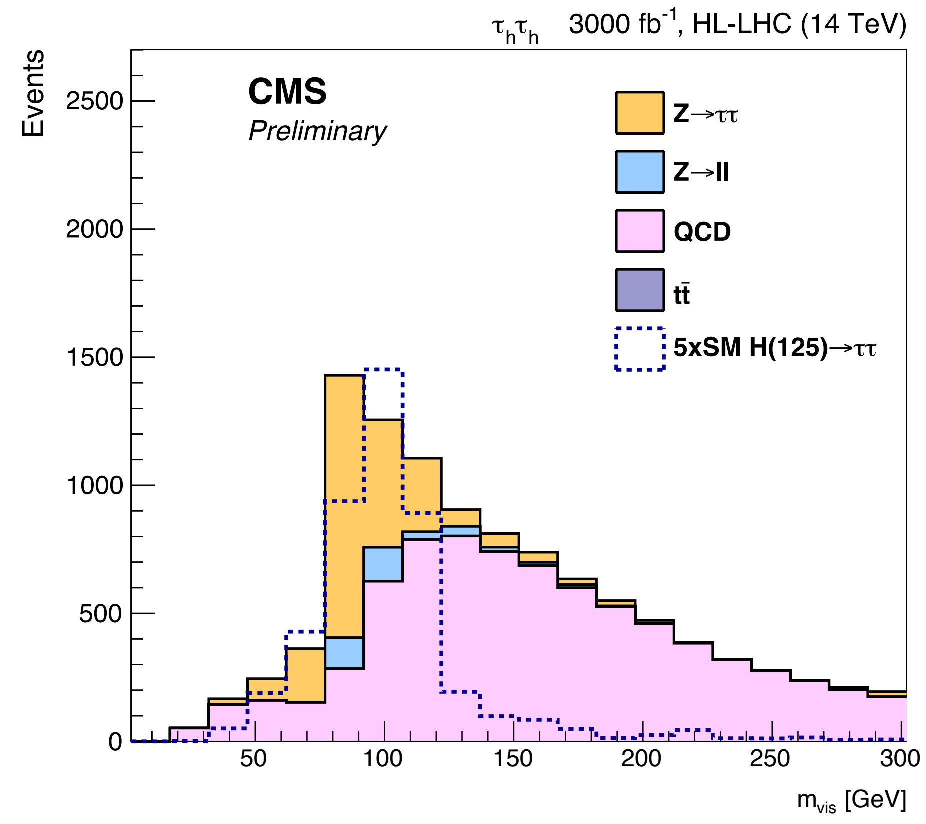


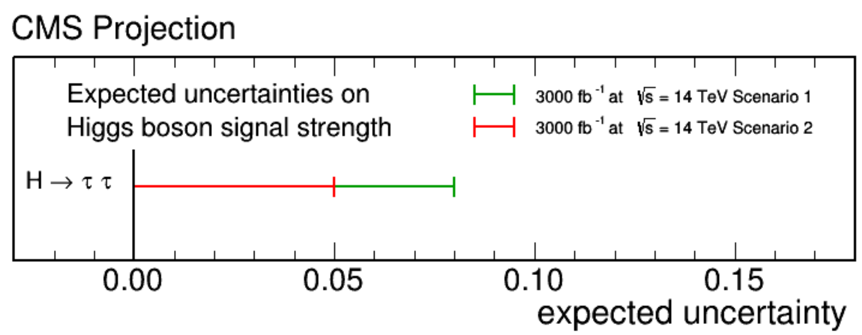
- VBF $H \to \gamma\gamma$ channel is a good benchmark to compare precisions extrapolated from Run1/Run2 with the ones obtained from full simulation samples at $\sqrt{s} = 14$ TeV at the HL-LHC

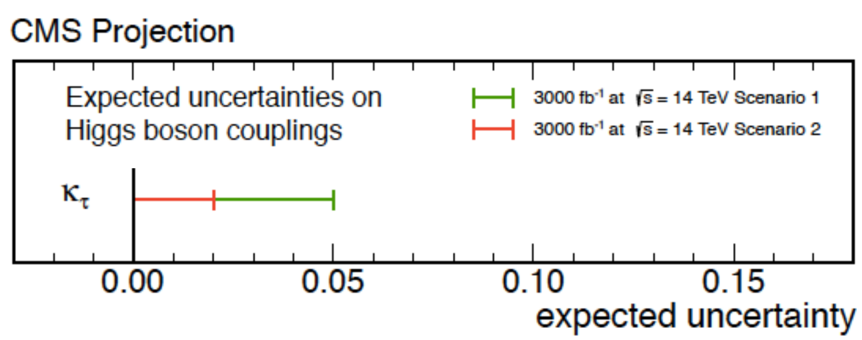
CMS TDR-017-007

VBF H → τ τ

- During the HL-LHC operation $\mathcal{O}$(1M) H → ττ events will be produced:
  - → important benchmark
  - → sensitivity to the Yukawa couplings between the Higgs boson and the tau leptons
- The measurement will require excellent performance discrimination of the Higgs signal from the dominant Z → ττ background
  - → An excellent mass resolution is required to obtain a reasonable separation of the H and Z peaks
    - Mass resolution at HL-LHC almost the same as in Run2
  - → A good measurement of the MET is crucial for pileup mitigation
- CMS projected precision at the [5-8]% level (3000 fb^{-1}) on the signal strength for [S1-S2] scenarios respectively
- CMS projected precision at the [2-5]% level (3000 fb^{-1}) on the coupling modifiers κ_τ for[S1-S2] scenarios respectively



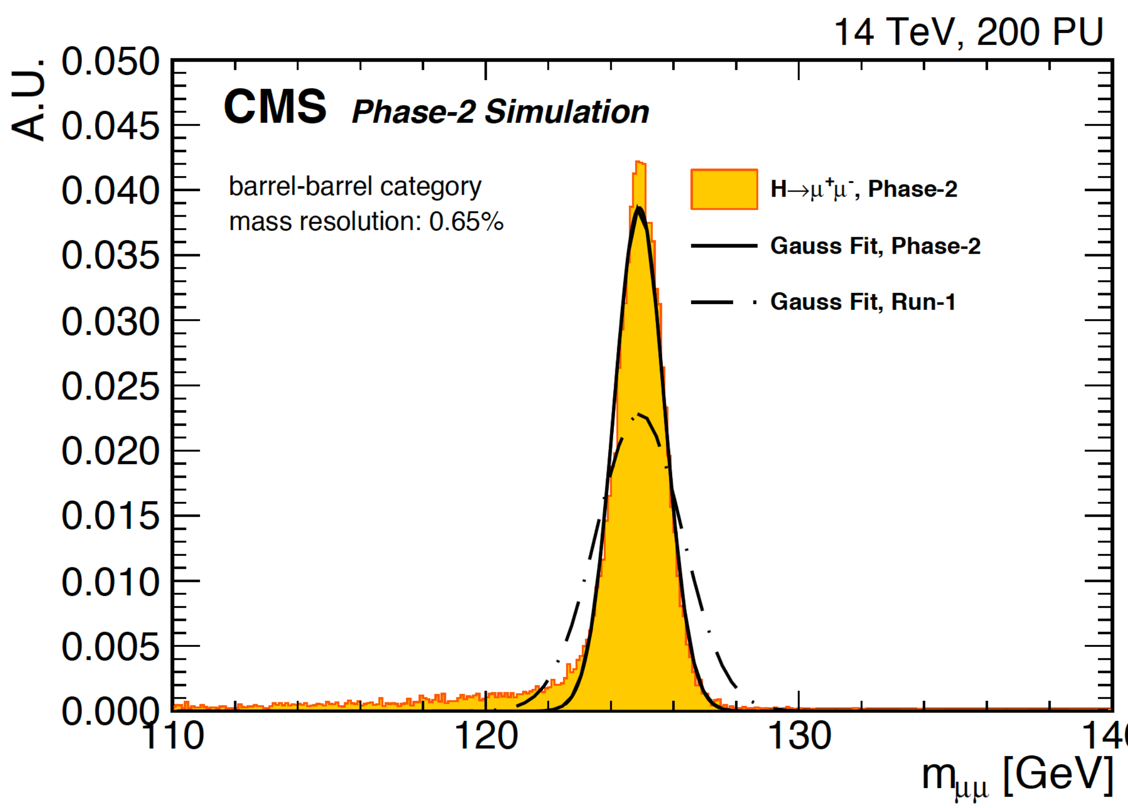




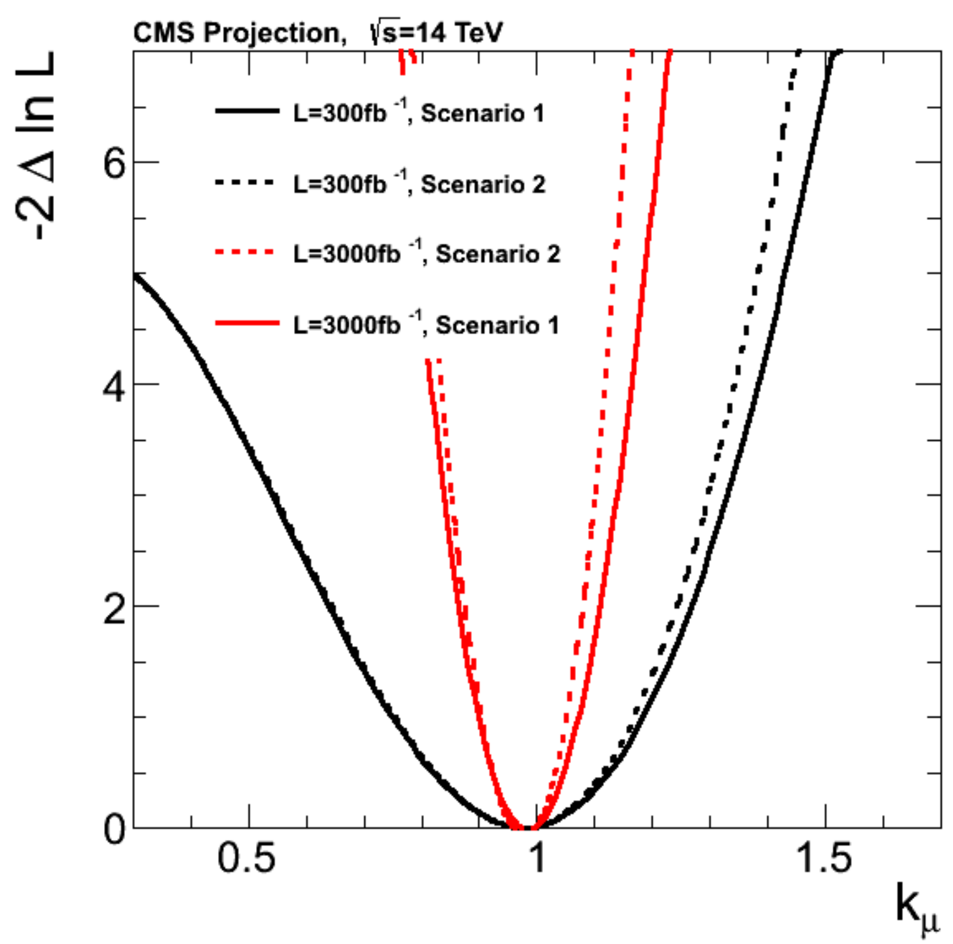
CMS TDR-017-007

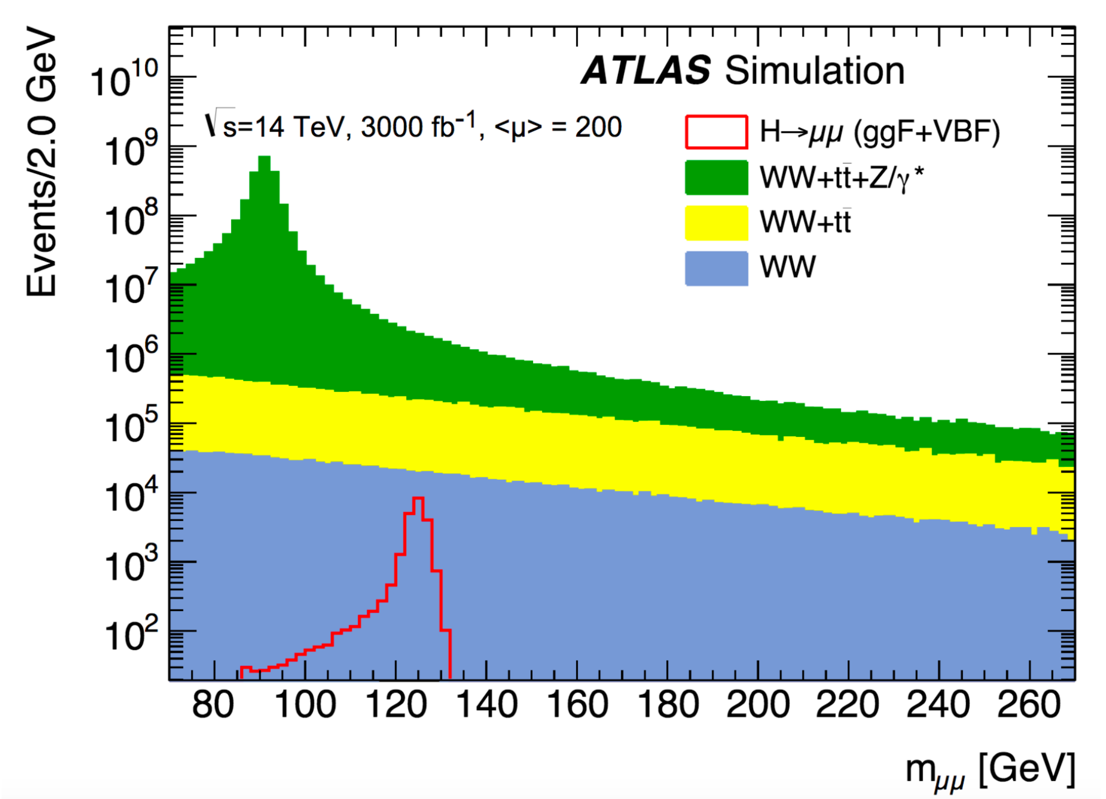
H → μμ

- High statistics: rare decays become accessible
- BR(H→μμ)=0.022
  - → Only visible at HL-LHC
  - → Probe coupling to 2nd generation
- With Phase2 detector: mass resolution <1%
- Prospects for coupling measurement
  → 5% uncertainty@3000fb^{-1}



CMS TDR-017-007

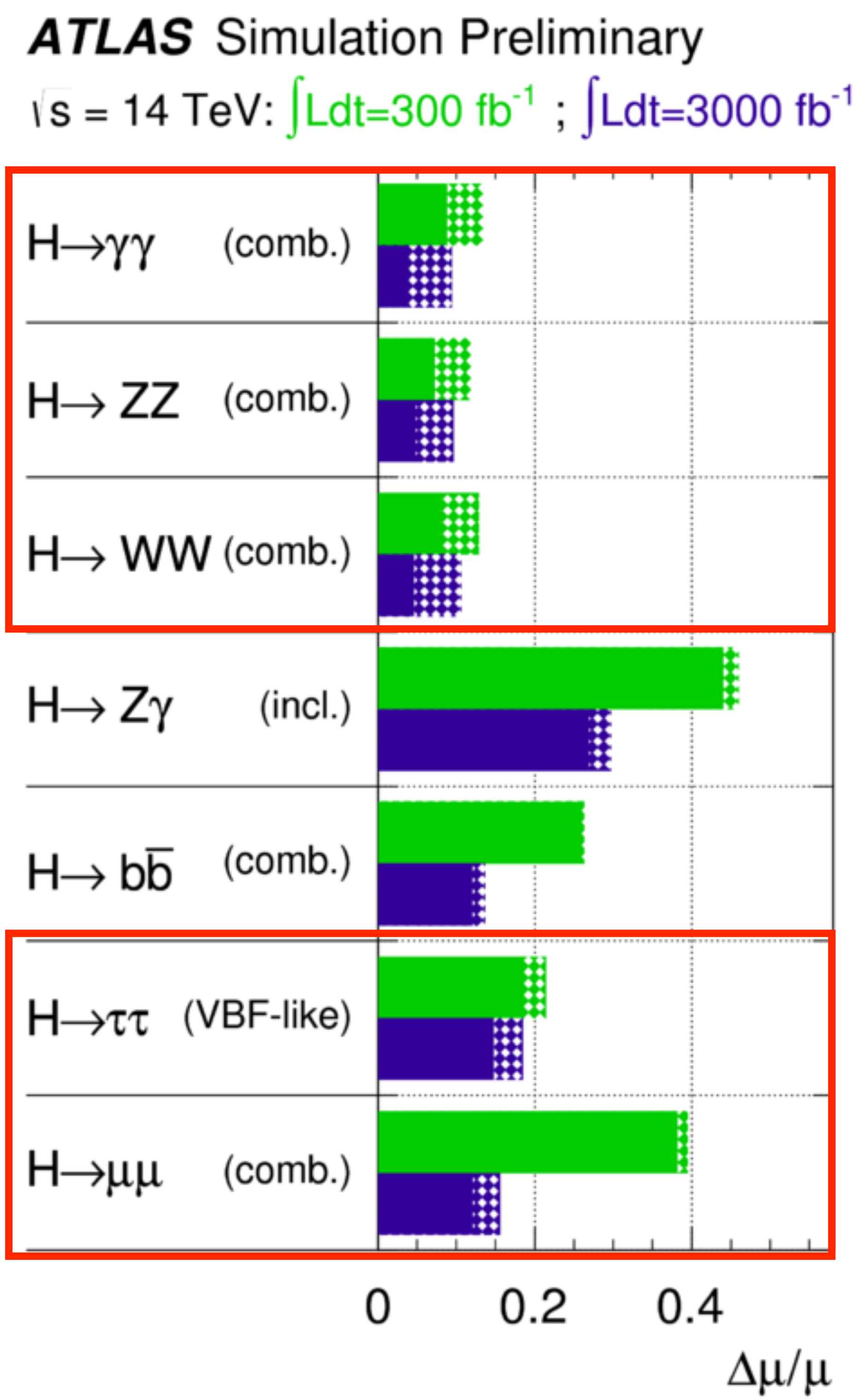


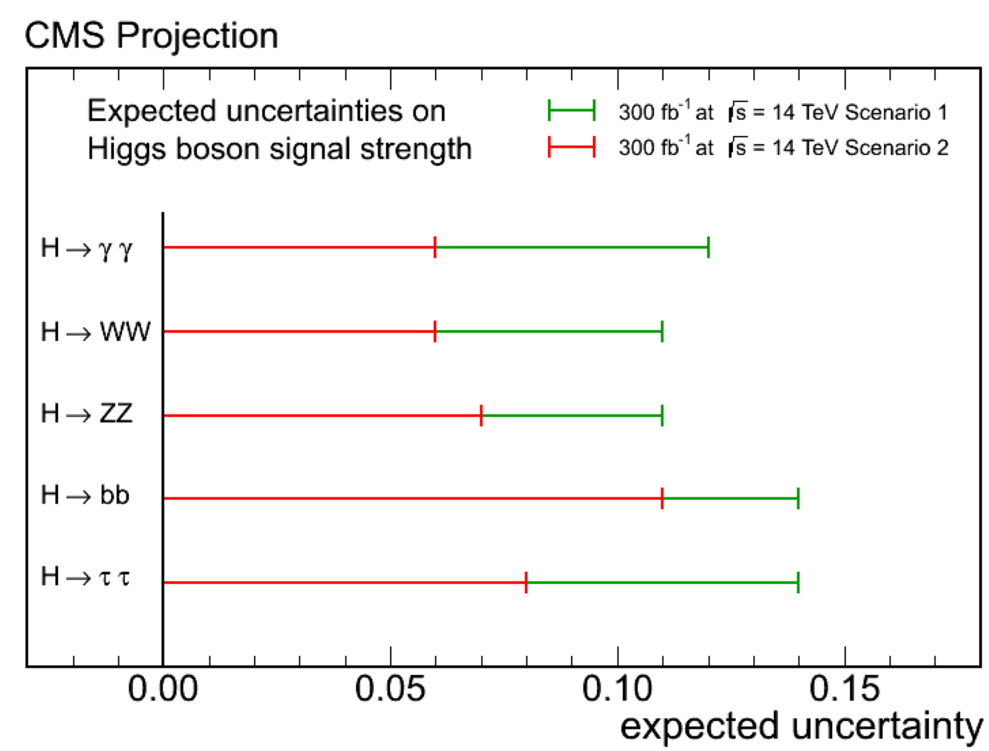


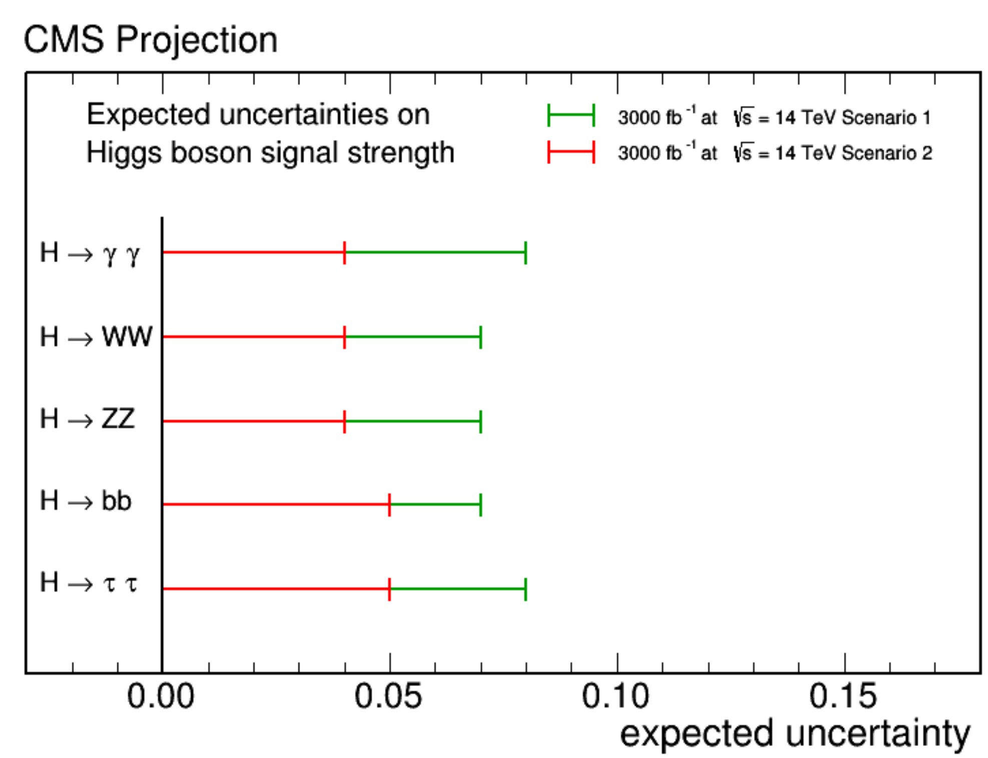
ATLAS TDR-025
ATLAS Pixel TDR

Summary: Expected sensitivity on signal strength

- Precision on the signal strength: -5% for main channels, 10~20% on rare modes







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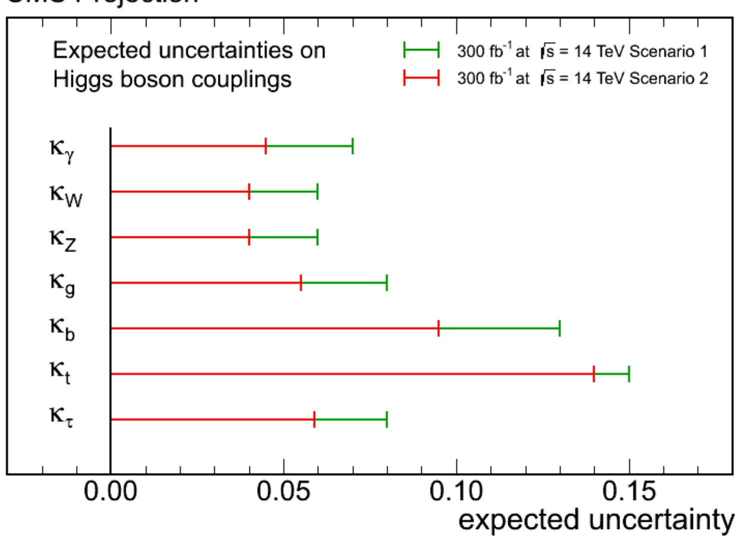
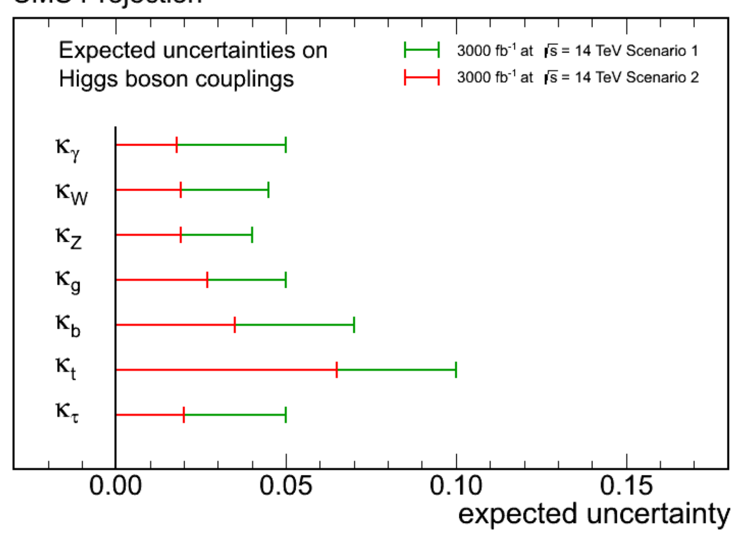
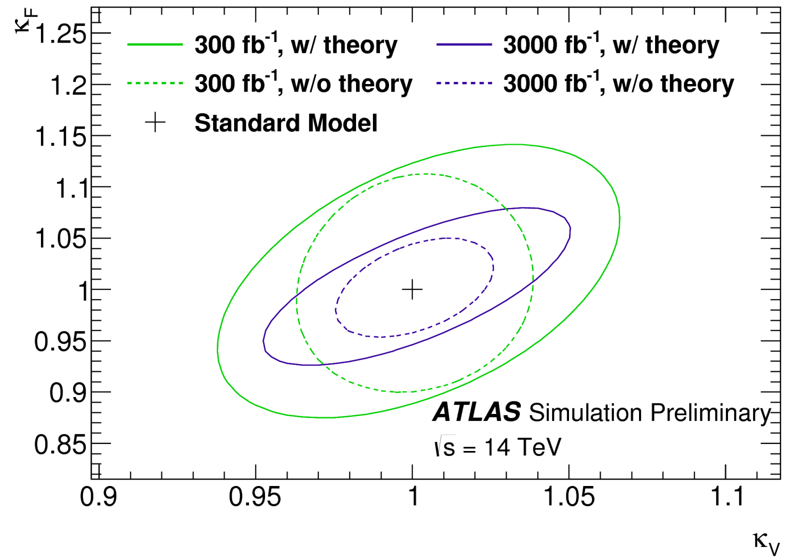
arXiv:1307.7135v2

Summary: Expected sensitivity on coupling

- Precision on couplings:-5% for main channels and smaller than 10% on rare modes







Coupling ATLAS	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
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%

arXiv:1307.7135v2

ATL-PHYS-PUB-2014-016

Conclusions and Plans

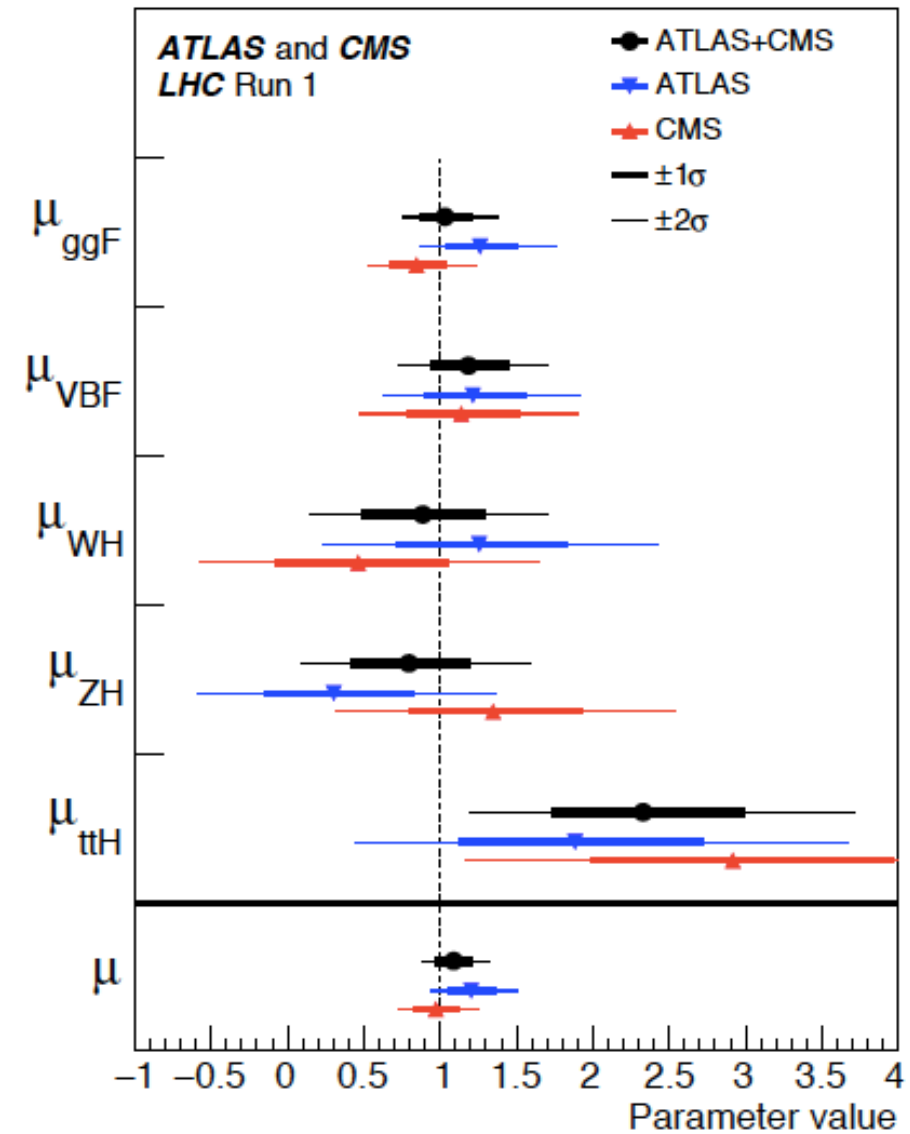
- Higgs studies are central to the HL(HE)-LHC program
- Impact of performances of reconstruction under HL-LHC pileup condition → new upgraded detectors
- Potential to reach the percentage level in precision on the Higgs coupling modifiers and signal strengths
- Thanks to the high statistics: rare processes become accessible

- **Plans for YR2018:**
  - Coherent extrapolation of couplings from Run2 results (36 fb^{-1}) is expected to be done by both experiments
  - → combination of ATLAS/CMS results
  - Some benchmark channels will be simulated @HL-LHC to validate the Run2 extrapolation

BACKUP

Introduction: Signal strengths from Run1

Production process	ATLAS+CMS
μ_{ggF}	$1.03\ ^{+0.16}_{-0.14}$ $\left(^{+0.16}_{-0.14}\right)$
μ_{VBF}	$1.18\ ^{+0.25}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$
μ_{WH}	$0.89\ ^{+0.40}_{-0.38}$ $\left(^{+0.41}_{-0.39}\right)$
μ_{ZH}	$0.79\ ^{+0.38}_{-0.36}$ $\left(^{+0.39}_{-0.36}\right)$
μ_{ttH}	$2.3\ ^{+0.7}_{-0.6}$ $\left(^{+0.5}_{-0.5}\right)$



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- → need to probe small deviations to narrow down New Physics
- → need higher precision measurements on signal strengths and couplings