Prospects of LHC Higgs Physics at the end of Run III

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On behalf of the ATLAS and CMS Collaborations

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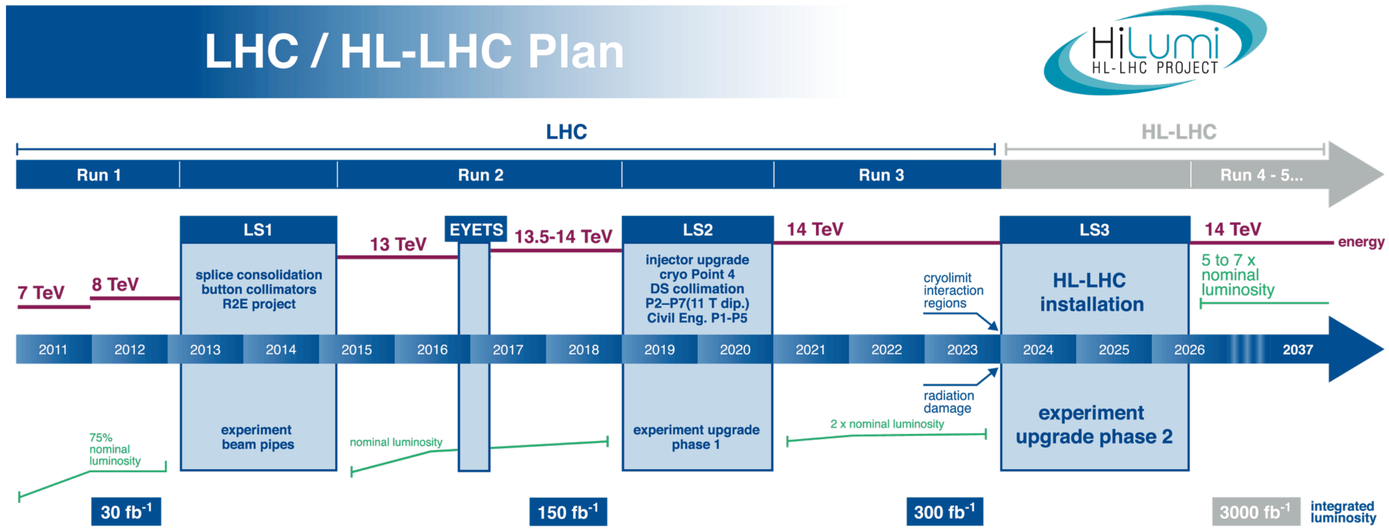
LHC plan and CMS/ATLAS upgrades



- Phase-I Upgrade for $L=2\text{-}3\times10^{34}\ cm^{-2}s^{-1}$. In the advanced stages – production started
- Phase-II Upgrade for $L=5\text{-}7.5\times10^{34}\ cm^{-2}s^{-1}$. Have to cope with the high pileup rate of $\langle\mu_{PU}\rangle$= 140-200. In the design and prototyping stage

Major upgrades to the CMS/ATLAS:

	CMS	ATLAS
Tracking	Extend to $\|\eta\|<3.8$	Extend to $\|\eta\|<4.0$. All silicon
Calorimeter	Update all readout electronics. Timing in EM endcap (to reject pileup)	
Trigger	Tracking added at L1, larger bandwith, finer granularity	
Muon	New chamber to complete $1.6<\|\eta\|<2.4$, muon tagger up to $\|\eta\|<3.0$	New endcap wheel to reject fake L1 muons (Phase-I)

Higgs highlights from Run-2

[ATLAS-CONF-2016-067]
[CMS-PAS-HIG-16-020]

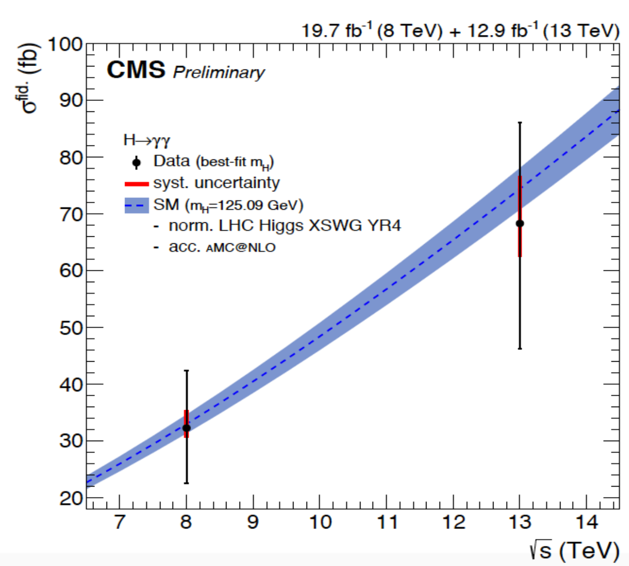
$H\to\gamma\gamma$:

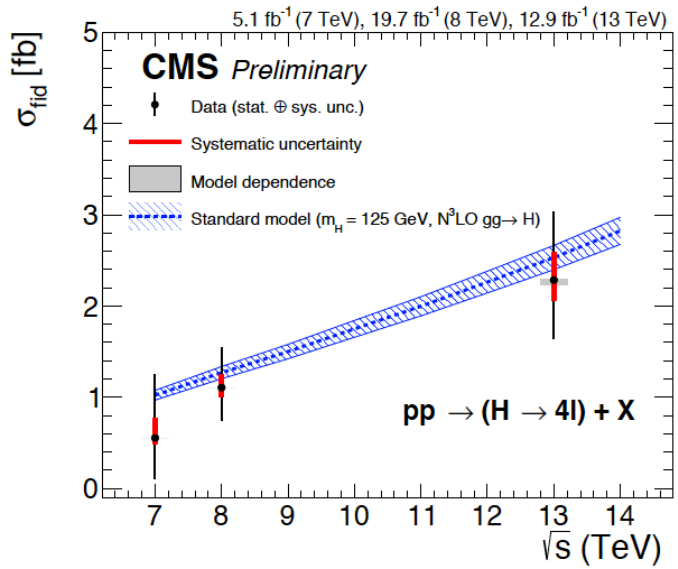
	σ(fiducial) (fb)	SM pred. (fb)
ATLAS(13.3 fb^{-1})	43.2±14.9(stat) ±4.9(sys)	$62.8^{+3.4}_{-4.4}$(N3LO)
CMS(12.9 fb^{-1})	69^{+16}_{-22}(stat)$^{+8}_{-6}$(sys)	73.8±3.8

[ATLAS-CONF-2016-079]
[CMS-PAS-HIG-16-033]

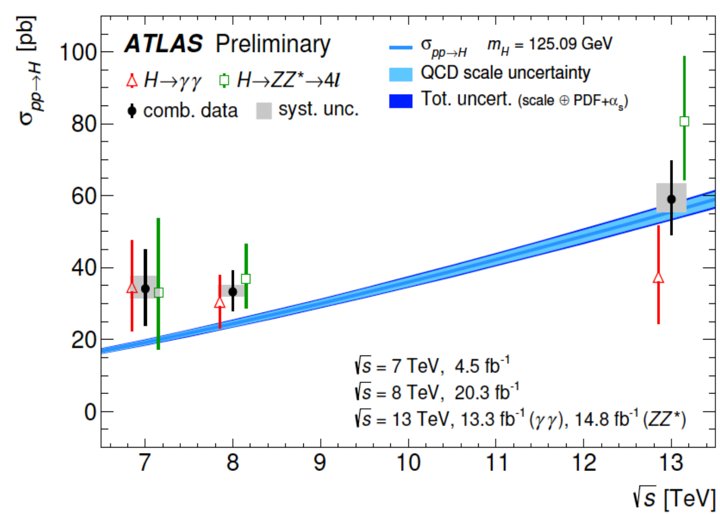
$H\to ZZ^*\to 4l$:

	σ(fiducial) (fb)	SM pred. (fb)
ATLAS(14.8 fb^{-1})	$4.54^{+1.02}_{-0.90}$	$3.07^{+0.21}_{-0.25}$
CMS(12.9 fb^{-1})	$2.29^{+0.74}_{-0.64}$(stat)$^{+0.30}_{-0.23}$(sys)	2.53±0.13





[ATLAS-CONF-2016-081]



Measured fiducial cross sections roughly scale with the CM energy

Higgs physics with 300 fb^{-1} and beyond

With ~10× existing data set, and larger Higgs cross sections compared to Run-1, we are able to:

- Precisely measure Higgs production and decay rates and couplings
- Test of the SM in the Higgs sector and probe for new physics such as MSSM, double Higgs (order of few percent effects on Higgs couplings in most models)
- Search for rare/new/invisible decay modes
- Use EFT for Higgs tensor structure study

Current theory limit on Higgs cross section and BRs: [arXiv:1610.07922]

- Theory error of Higgs ggF (VBF) production cross sections at about 3-4% (0.5%) for scale and 3% (2%) for PDF+α_s
- Branching ratios typically at 3-5%

Caution 1: many projection results have simple systematics estimations, or have particular assumptions made. The systematics can change and the analysis method can also improve
Caution 2: a bit beyond the talk title, projections to 300 fb^{-1} and/or to 3000 fb^{-1} are given for some channels

Projection Methods

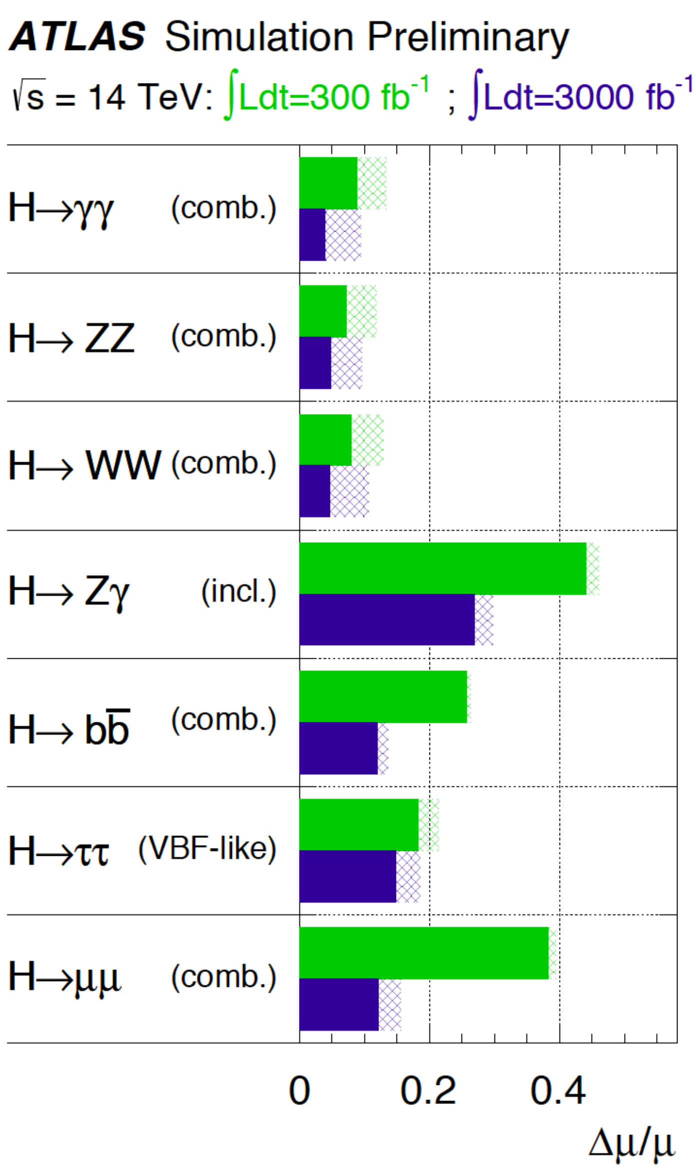
Physics Projections HL-LHC Higgs prospects done in two ways:

- Parameterized detector performance
  - Event-generator level particles smeared with detector performance parameterized from full simulation and reconstruction of upgraded HL-LHC detectors
  - Effects of pile-up included for either $5\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ (140 pile-up events, old default) or $7\times10^{34}\text{cm}^{-2}\text{s}^{-1}$ (200 pile-up events, current)
  - Analysis mostly based on existing 8 TeV analyses with simple re-optimization for higher luminosity

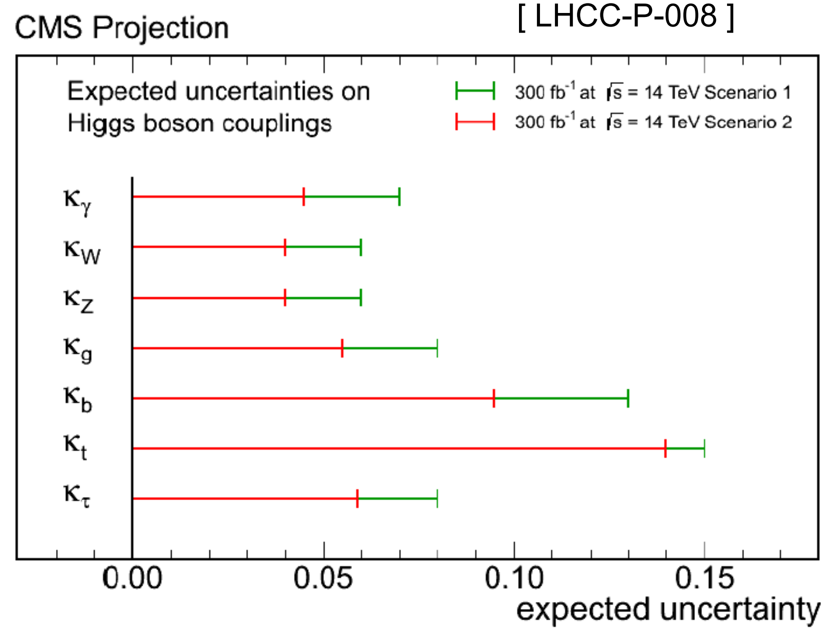
- Extrapolation of Run-1 or Run-2 results
  - Scale signal and background to higher luminosities
  - Correct for different center-of-mass energy
  - Assume unchanged analysis (not re-optimized for higher luminosity)
  - Assume same detector performance as in Run-1/2 (some use corrections based on studies in first approach)

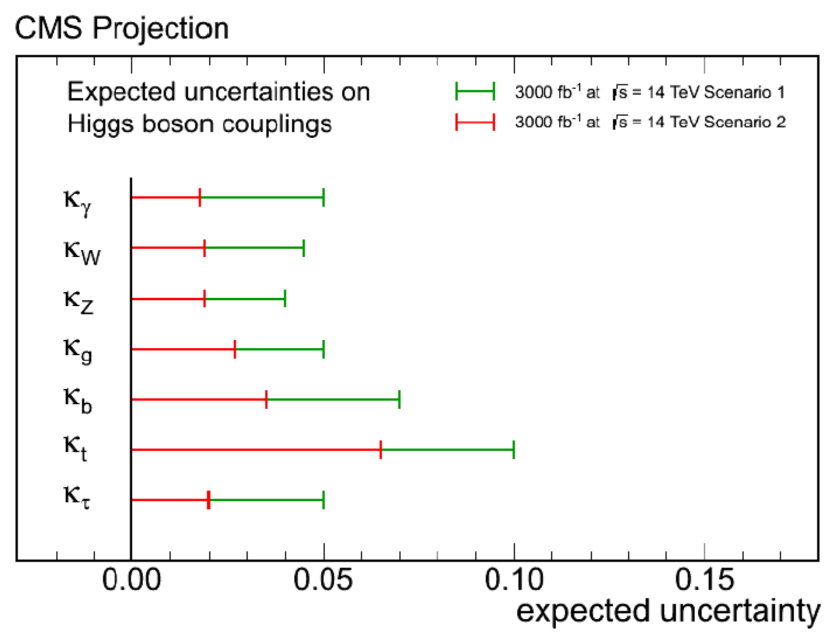
Projections for signal strength and coupling factors

[ATL-PHYS-PUB-2014-016]



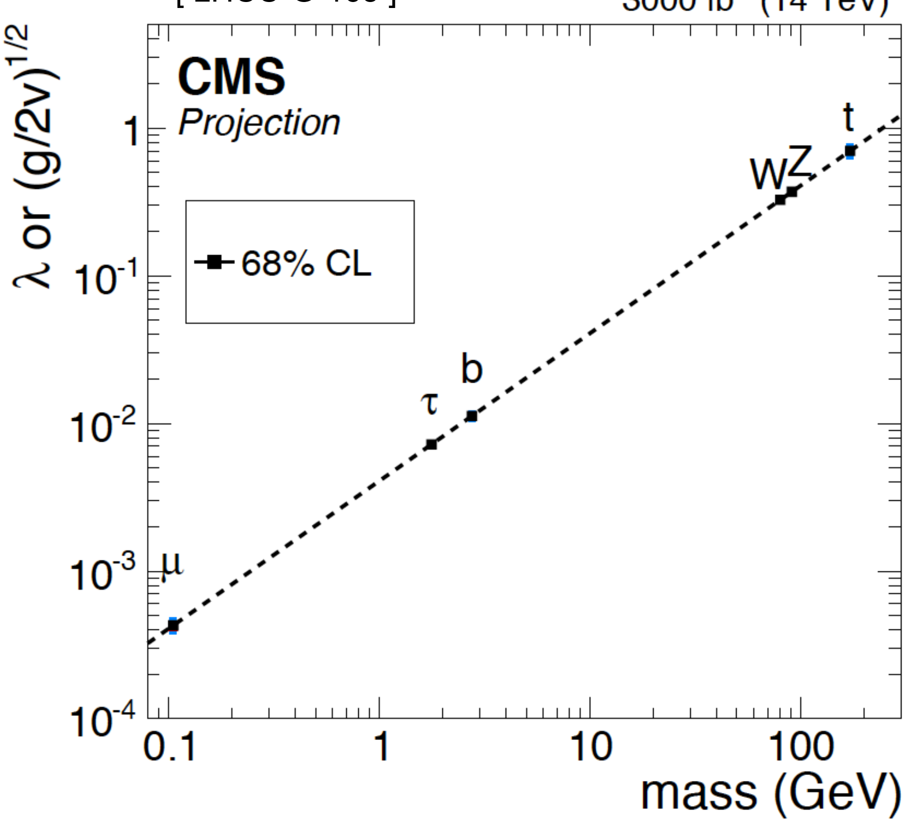
[LHCC-P-008]



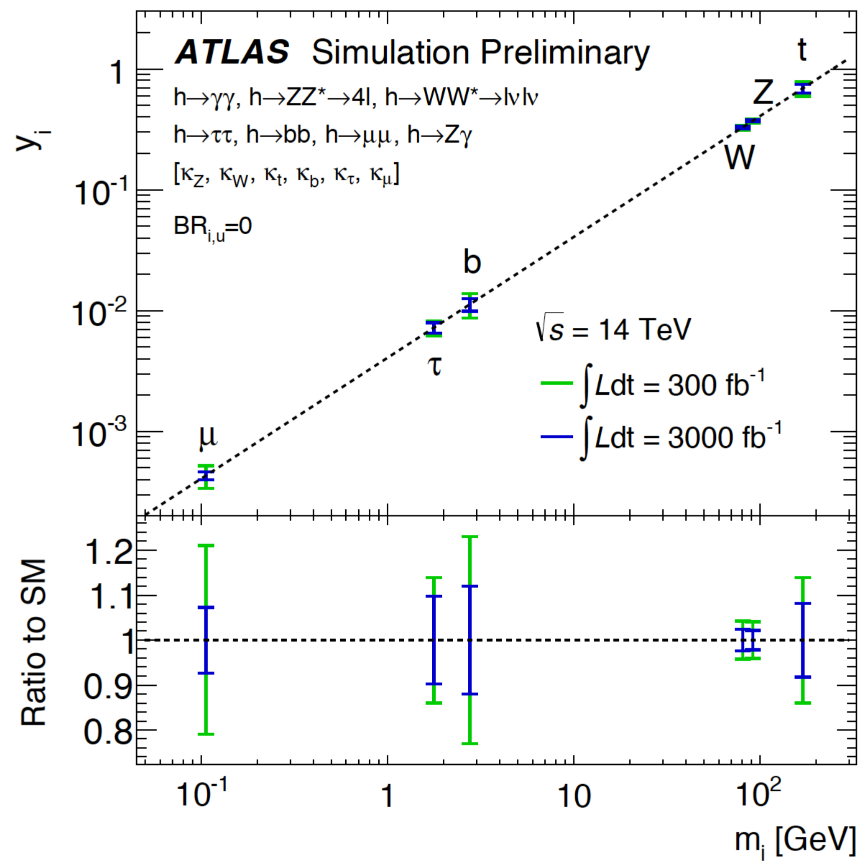


Reduced coupling scale factors vs. mass

[LHCC-G-165]



[ATL-PHYS-PUB-2014-016]



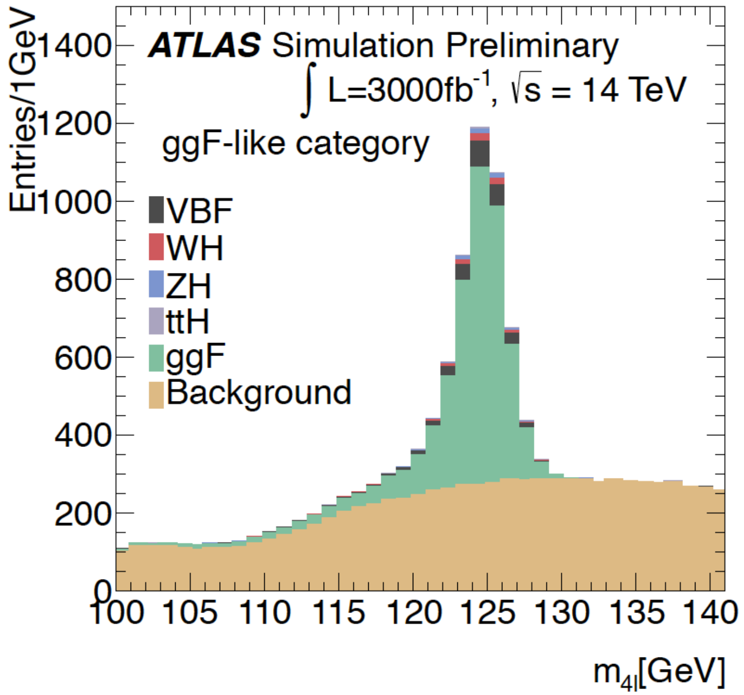
- With larger statistics, can plot reduced coupling scale factors to test the Higgs coupling dependence on the mass

- Uncertainty from ATLAS at 3 ab^{-1}:
  - W, Z couplings to 3%
  - μ coupling to 7%
  - t/b/τ couplings to 8-12%

Projections for H→ZZ*→4l

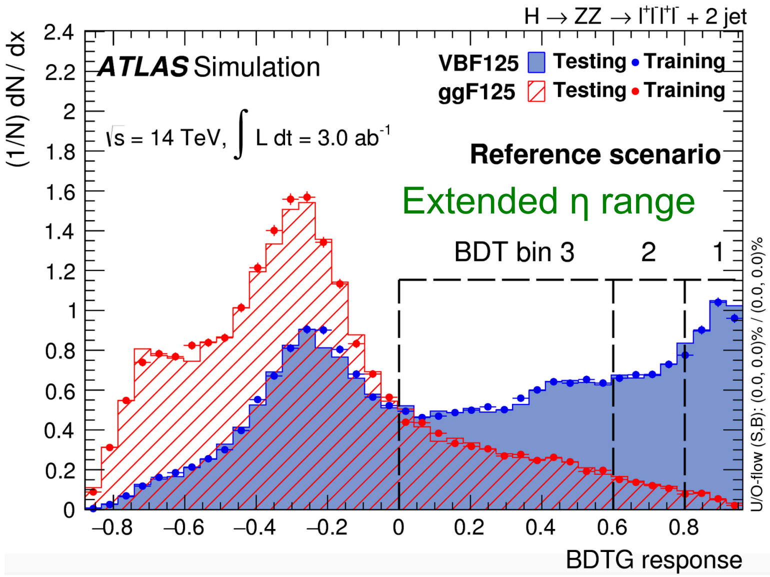
[ATL-PHYS-PUB-2013-014]
[ATL-PHYS-PUB-2016-008]

Signal events are very clean. Further divide the signals into VBF, VH, ttH and ggH categories



$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode		300 fb^{-1}		
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}$H	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108

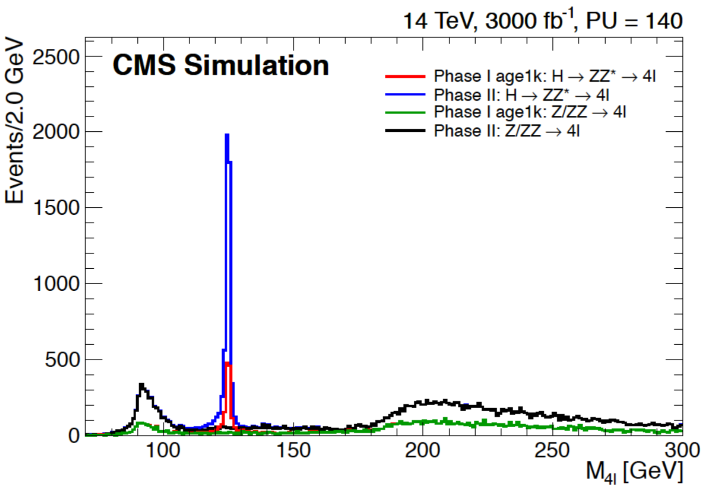
VBF region is almost bkg. free, but can use BDT to further separate ggF and VBF productions:

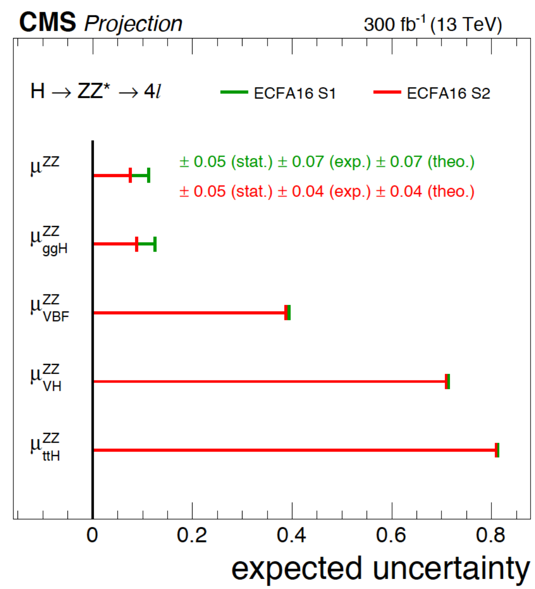


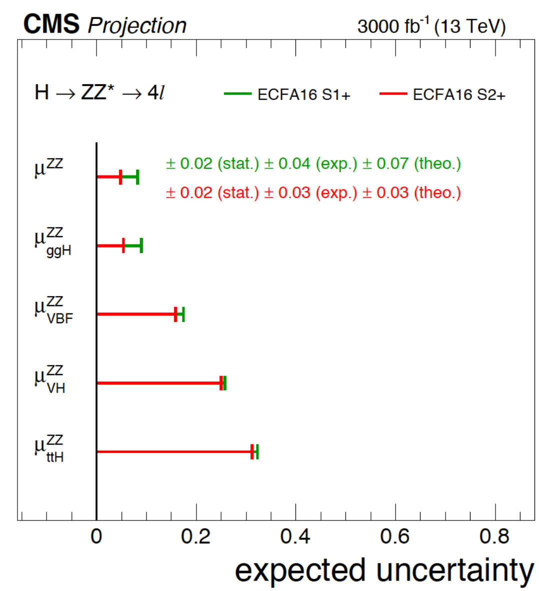
	$<\mu_{PU}>=200$	$<\mu_{PU}>=140$
$\Delta\mu/\mu$	0.18	0.17
significance	7.2σ	7.7σ

Projections for H→ZZ*→4l

[LHCC-P-008]
[CMS DP-2016/064]





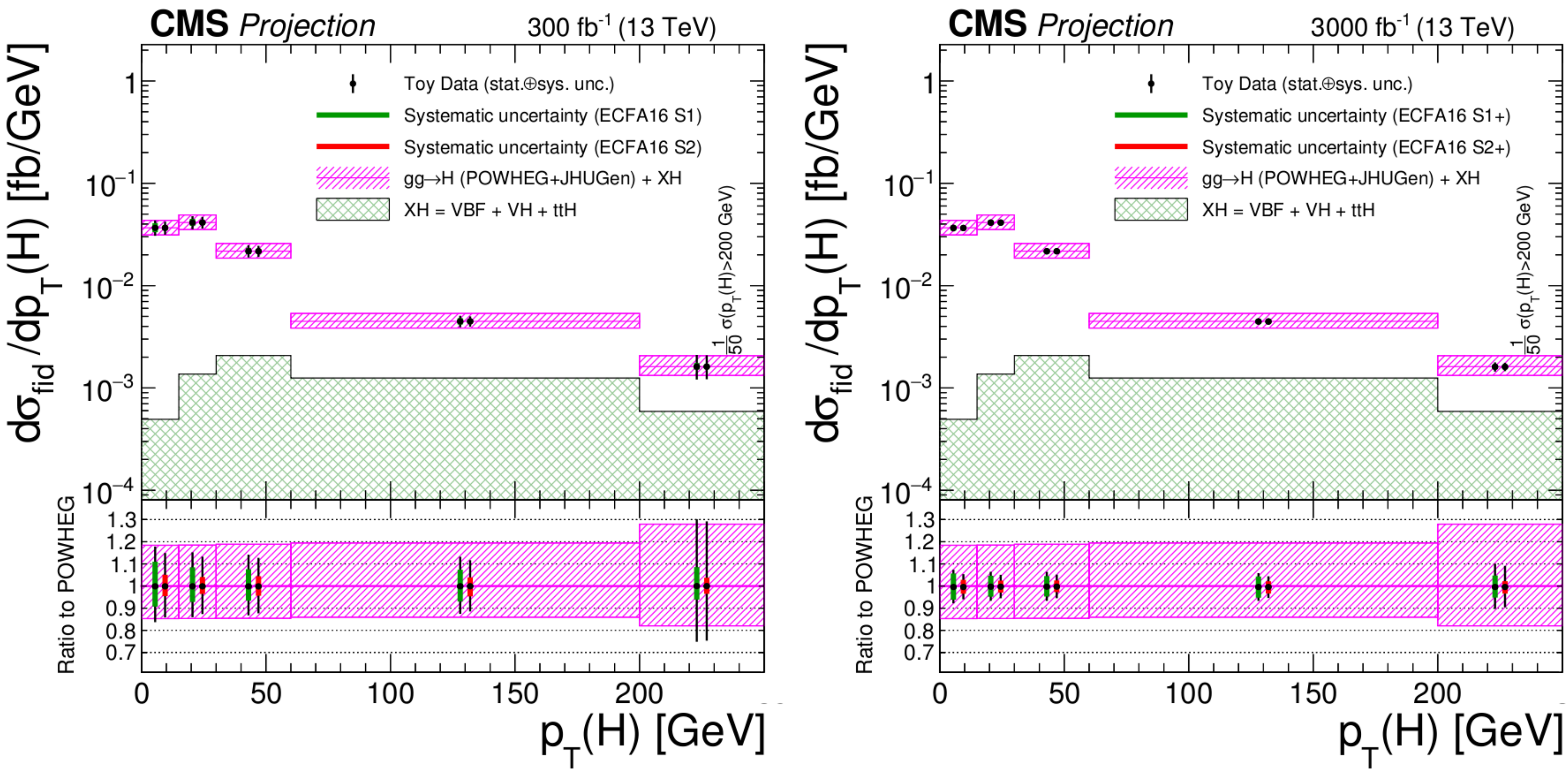


Δμ of 5-10% can be achieved on the combined production of H→ZZ*→4l (dominated by ggH) at 3 ab^{-1}. Some nomenclature

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

Projections for H→ZZ*→4l

[CMS-PAS-HIG-16-033]
[CMS DP-2016/064]



- Look at differential distributions after fiducial cuts – relatively pure H→ZZ*→4l signal events
- Going from 300 fb^{-1} to 3 ab^{-1}, the statistical and some systematical errors are greatly reduced (less than the theory errors at NLO). Will also look at normalized differential cross section to reduce systematic error

H→ZZ anomalous tensor coupling [CMS DP-2016/064]

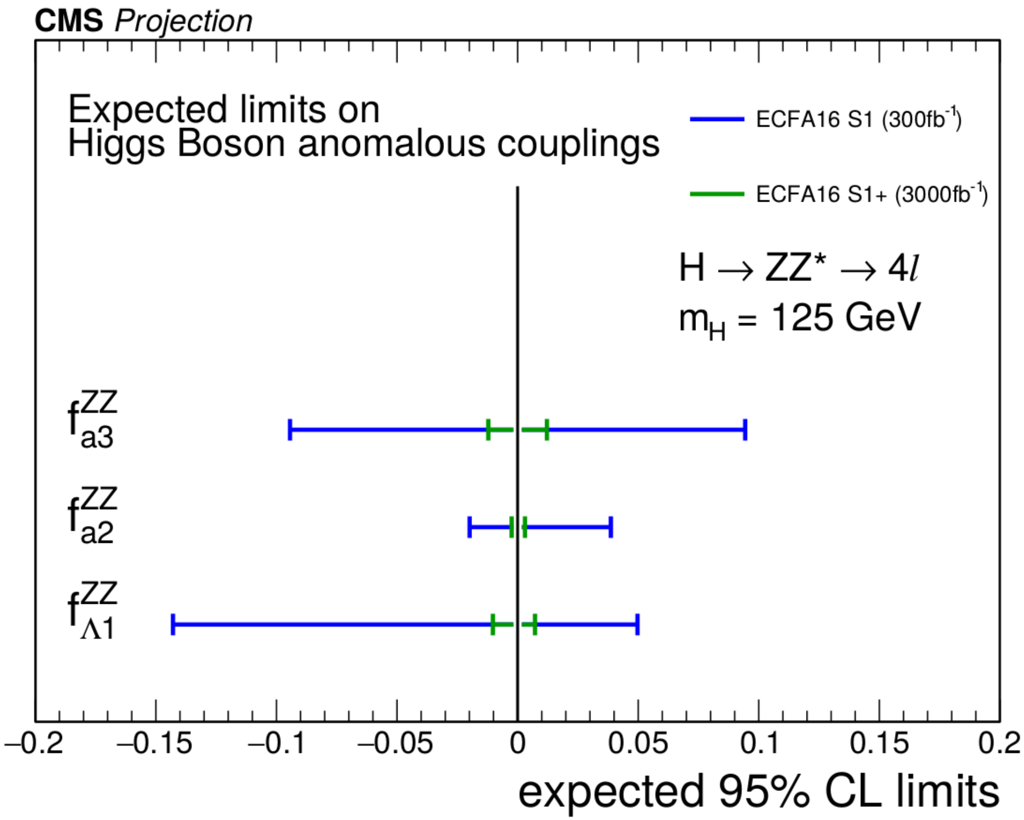
Assuming the following EFT for the generic HZZ coupling with spin-0 Higgs

$$L(\mathrm{HVV}) \sim a_1 \frac{m_Z^2}{2} \mathrm{H}Z^{\mu} Z_{\mu} - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_{\mu} \Box Z^{\mu} - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$

- The terms other than a_1 are all from BSM (dim-6)
- The definition of f_{ai}:

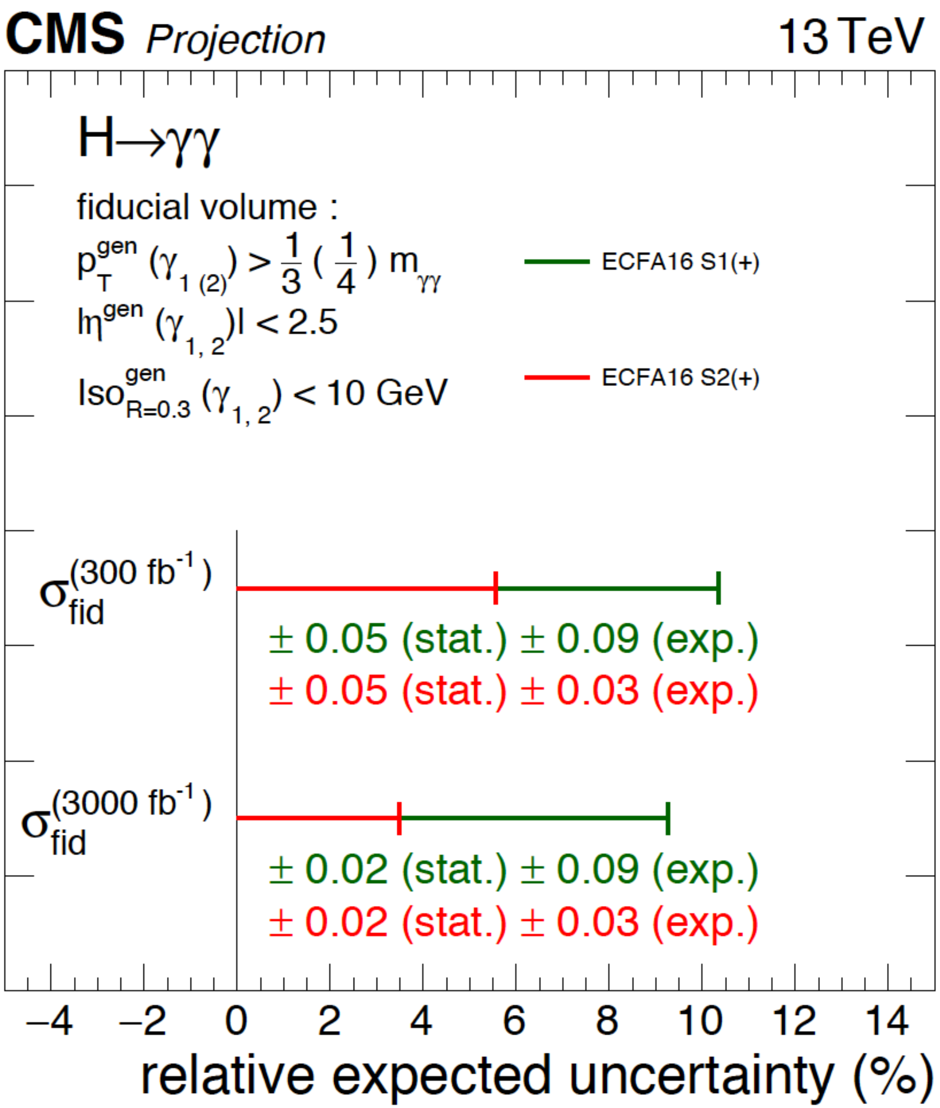
$$f_{ai} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j}$$

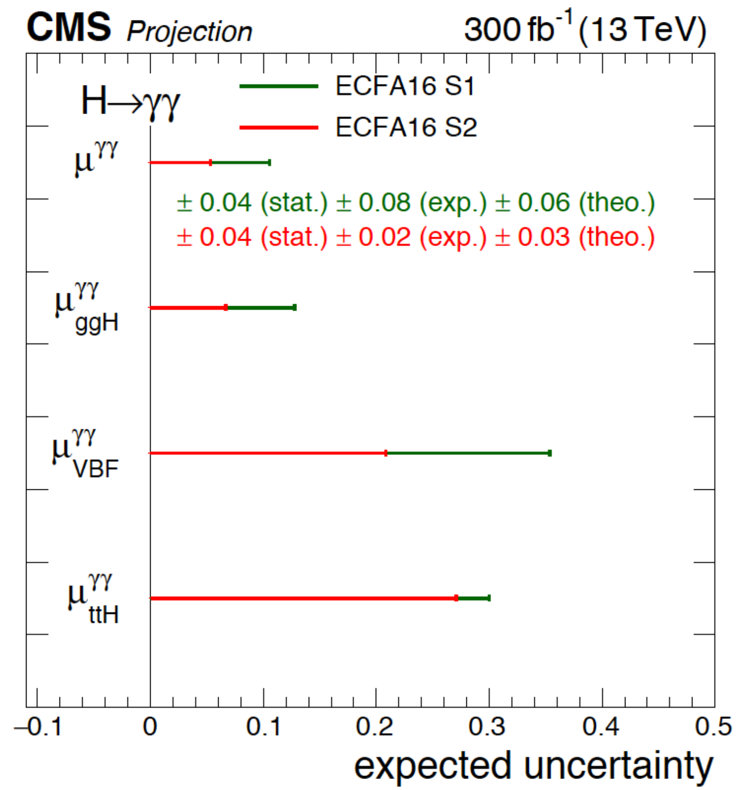
- As the measurement is statistically limited, expect a huge improvement in the sensitivity to the anomalous couplings with 3 ab^{-1}



Projections for H→γγ

[CMS DP-2016/064]

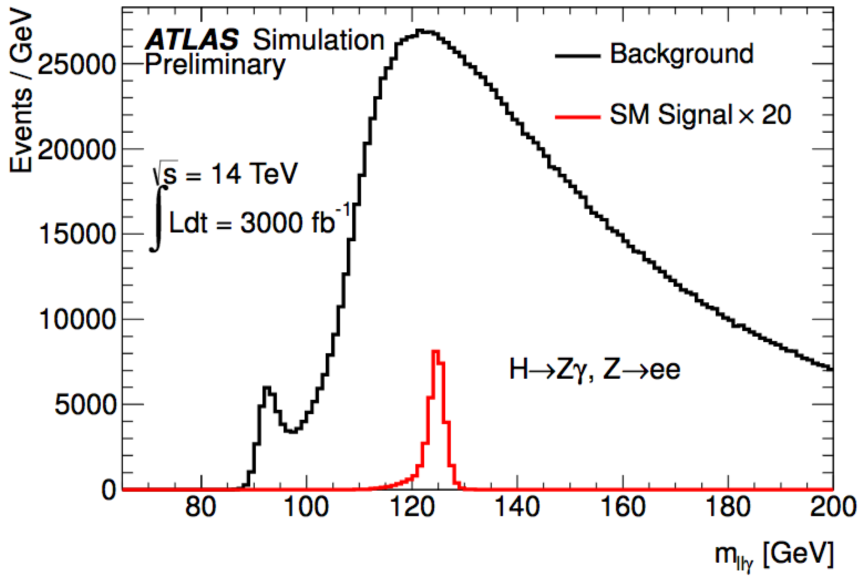


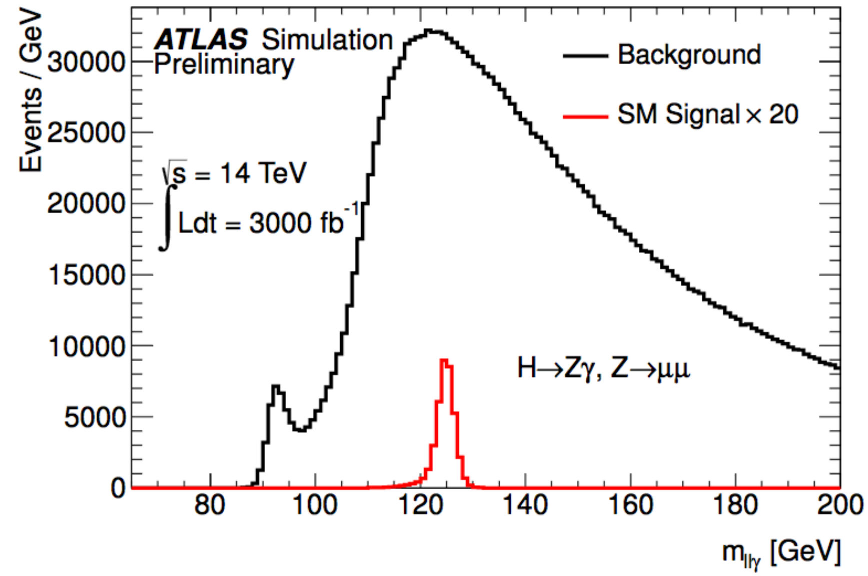


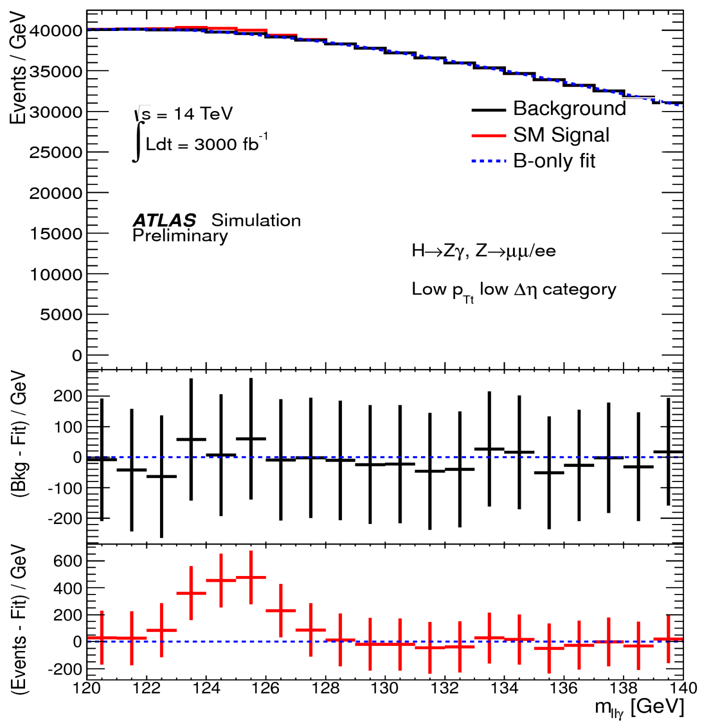
- Fiducial cuts defined at the generator level
- Beam spot simulated to be ~5 cm
- Degraded vertex efficiency
- Photon ID efficiency is degraded by 2.3% (10%) for EB (EE)

Projections for H→Zγ

[ATL-PHYS-PUB-2014-006]







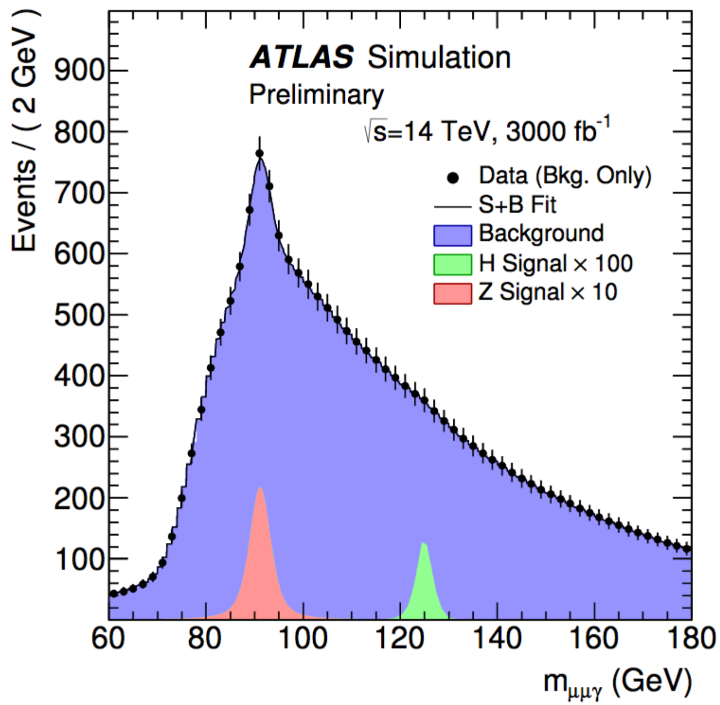
Still a very tough channel, S/B ratio much worse than $\gamma\gamma$

	significance
300 fb^{-1}	2.3σ
3000 fb^{-1}	3.9σ

However, may be sensitive to New Physics through the loop

Projections for $H \to J/\psi\gamma$

[ATL-PHYS-PUB-2015-043]



- Sensitive to Higgs coupling to charm quarks

SM exp.	$BR(H \to J/\psi\gamma) = (2.9 \pm 0.2) \times 10^{-6}$
Run-1 limit	$BR(H \to J/\psi\gamma) < 1.5 \times 10^{-3}$

- Use the $J/\psi \to \mu^+\mu^-$ decay only
- Use the $Z \to \mu\mu$ decay to validate

With 3 ab^{-1}, about 3 signal events are expected out of 1700 background events. Expected limits with Multi-Variate-Analysis (no background sys):

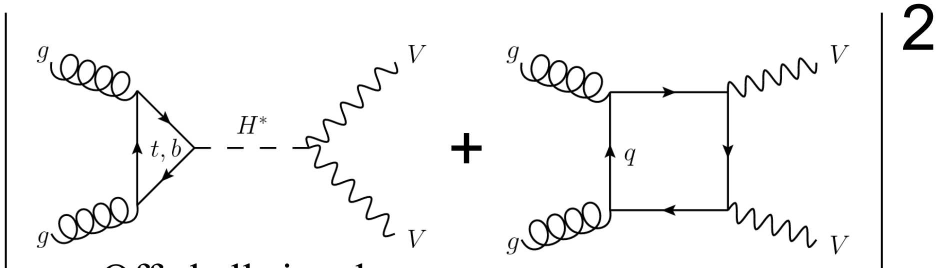
$BR(H \to J/\psi\gamma)$	$\left(44^{+19}_{-12}\right) \times 10^{-6}$
$\sigma(gg \to H) \times BR(H \to J/\psi\gamma)$	$3.1^{+0.9}_{-1.3}$ fb

Although sensitivity is not great, BSM physics can potentially enhance the rate

Probing the off-shell Higgs

[ATL-PHYS-PUB-2015-024]

Measure VV differencial process to probe off-shell Higgs:



Off-shell signal
gg→H*→VV

ggVV background
(interfere with signal)

For ZZ→4l final state, can use m(4l) shape and the Matrix Element for each event to discriminate between signal and background. Then combined with the on-shell measurements to estimate Higgs width

Run-1 limit (combining 3 channels of ZZ→4l, ZZ→2l2ν, WW→eνμν):

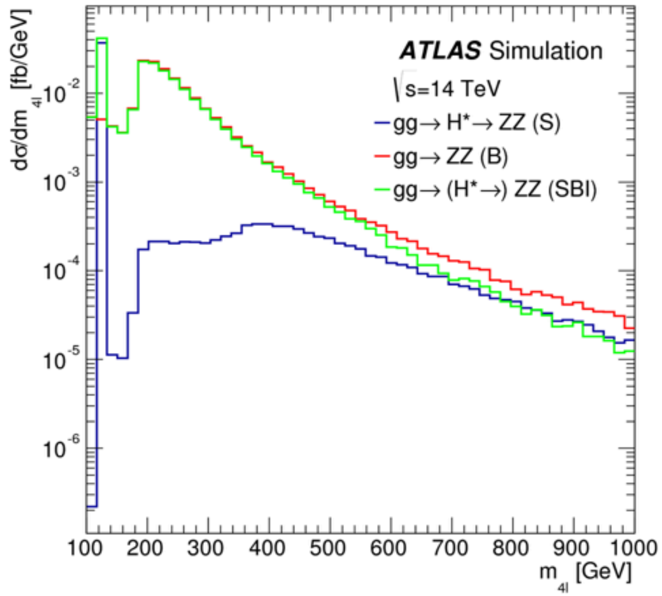
$\mu_{\text{off-shell}} < 6.2(8.1)$ for obs. (exp.)

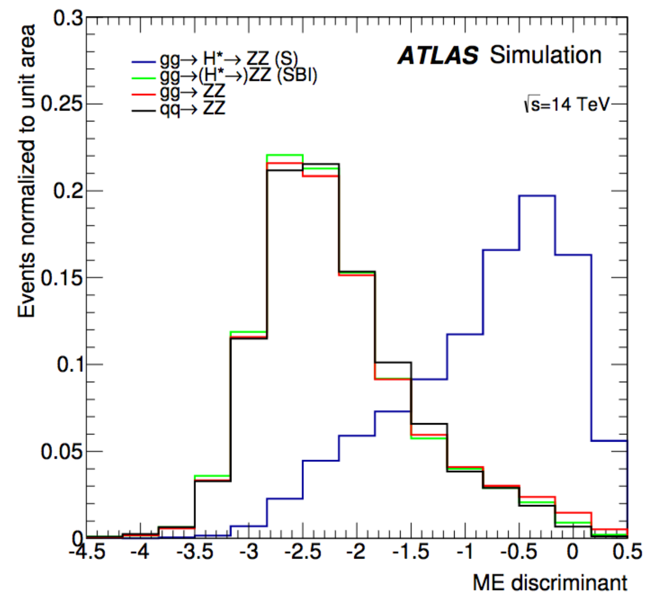
$\Gamma_H / \Gamma_H^{SM} < 5.5(8.0)$ for obs. (exp.)

With 3 ab^{-1}, the precision can be much improved:

$\mu_{\text{off-shell}} = 1.00^{+0.43}_{-0.50}$ (stat+sys)

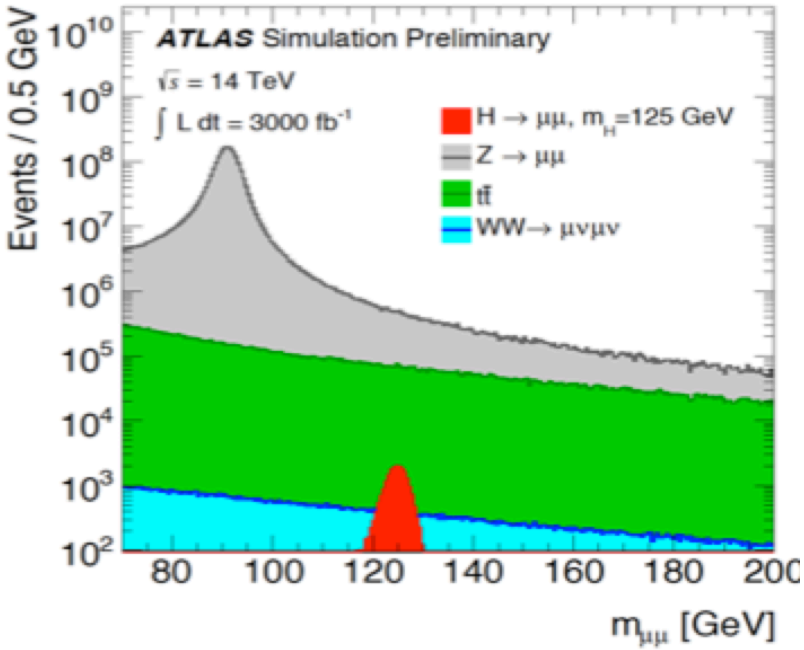
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)

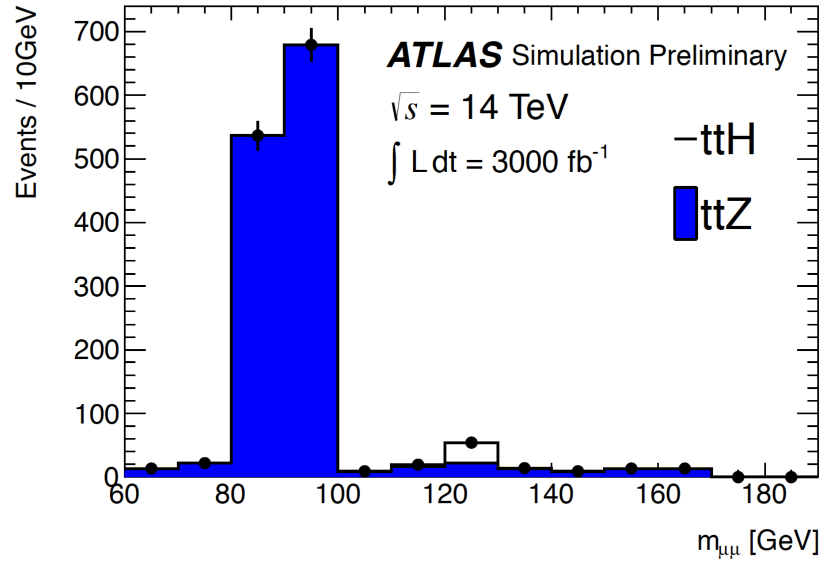


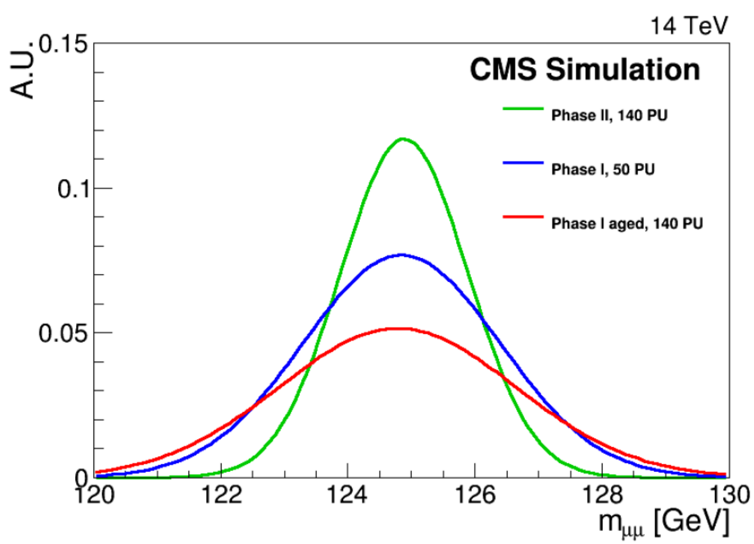


Projections for H→μμ

[ATL-PHYS-PUB-2013-014]
[LHCC-P-008]







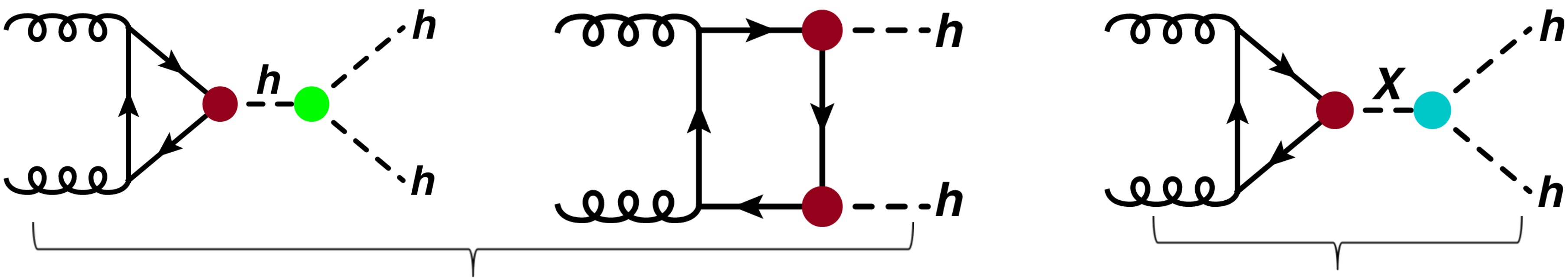
Still very tough even at 3000 fb^{-1}, but ATLAS can have about 33 signal events (with 22 background events) in the ttH→μμ channel

$\mathcal{L}$ [fb^{-1}]	300
Signal significance	2.3σ
$\Delta\mu/\mu$	46%

Sharpness of dimuon mass is crucial for both ATLAS/CMS. The H→μμ coupling can be measured to 8-20% with 3 ab^{-1}

Projections for HH

[CMS DP-2016/064]



SM

BSM

- Higgs self-coupling can be measured through the double Higgs production
- For SM non-resonant double Higgs production, the triangle and box diagrams have negative interference. NNLO+NNLL prediction σ=33.45 fb (at 13 TeV)

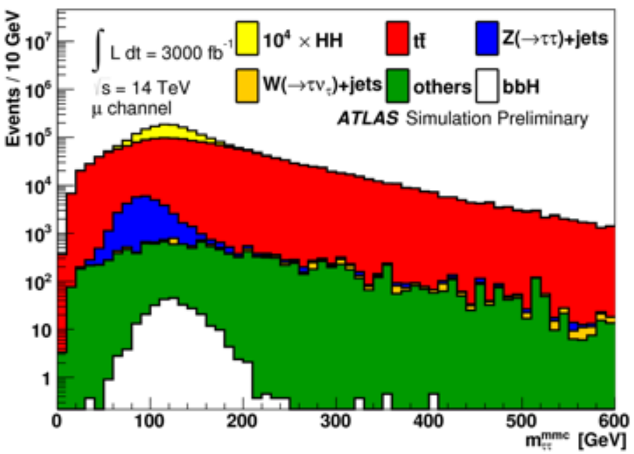
CMS projections to 3 ab^{-1}:

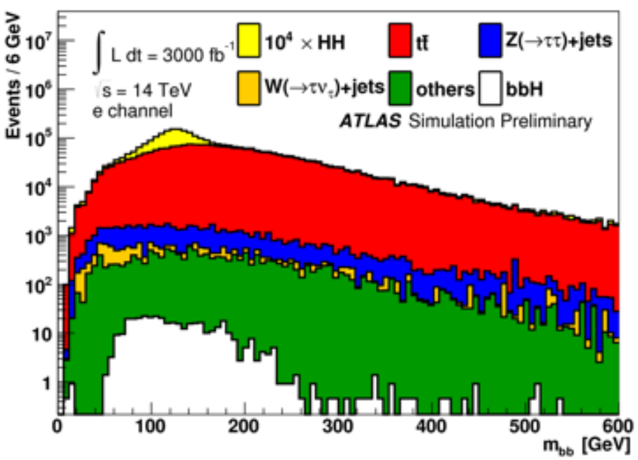
Channel	Median expected limits in μ_r			Z-value			Uncertainty as fraction of $\mu_r = 1$		
	ECFA16		Stat.	ECFA16		Stat.	ECFA16		Stat.
	S1	S2	Only	S1	S2	Only	S1	S2	Only
$gg \to HH \to \gamma\gamma bb$ (S1+/S2+)	1.3	1.3	1.3	1.6	1.6	1.6	0.64	0.64	0.64
$gg \to HH \to \tau\tau bb$	7.4	5.2	3.9	0.28	0.39	0.53	3.7	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

[ATL-PHYS-PUB-2014-019]
[ATL-PHYS-PUB-2015-046]
[ATL-PHYS-PUB-2016-023]
[ATL-PHYS-PUB-2016-024]
[CMS DP-2016/064]

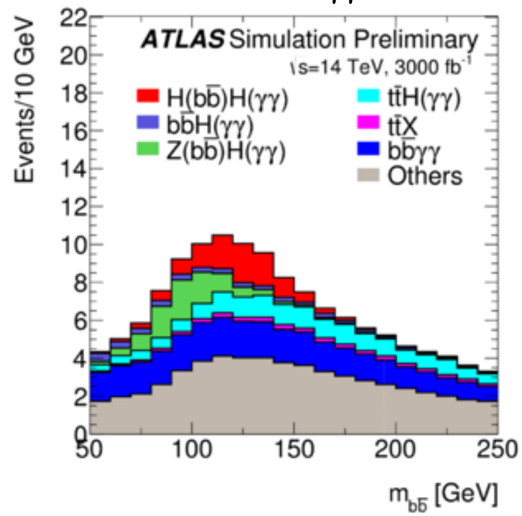
Projections for HH

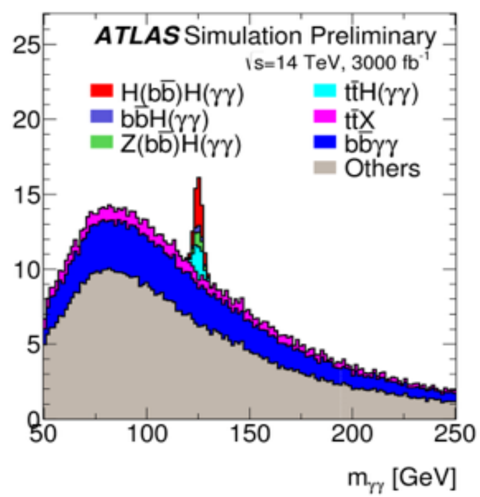
$HH \to bb\tau\tau$:

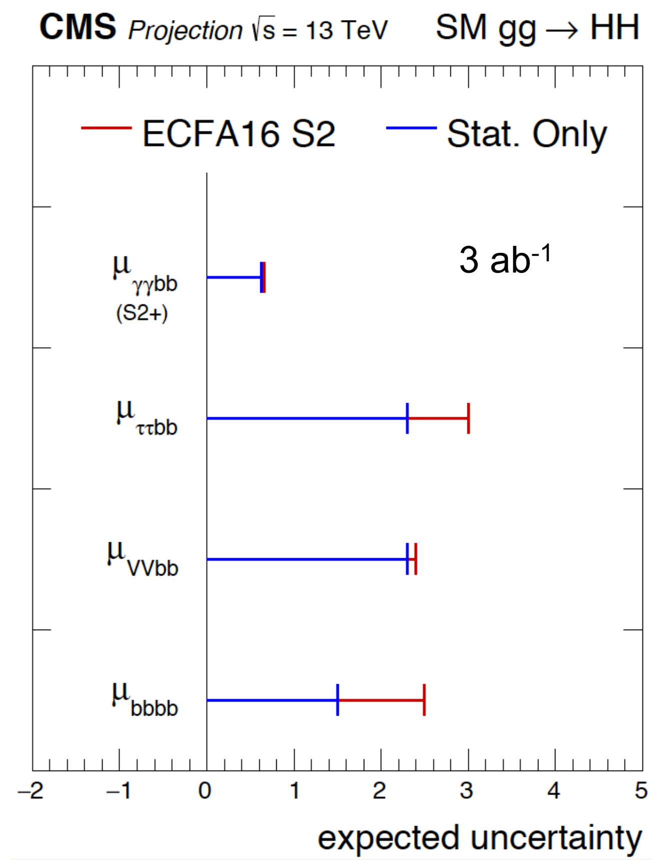




$HH \to bb\gamma\gamma$:







$\tau\tau bb$ event yields at 3 ab^{-1}

	Signal	Bkg.
$\tau_{lep}\tau_{had}$	20	880
$\tau_{had}\tau_{had}$	19	830

ATLAS 95% CL interval at 3 ab^{-1}

$\gamma\gamma bb$	$1.3<\lambda/\lambda_{SM}<8.7$
bbbb	$-7.4<\lambda/\lambda_{SM}<14$

ATLAS significance at 3 ab^{-1}

$\gamma\gamma bb$	1.3σ
$\tau\tau bb$	0.6σ
$ttHH \to tt4b$	0.35σ

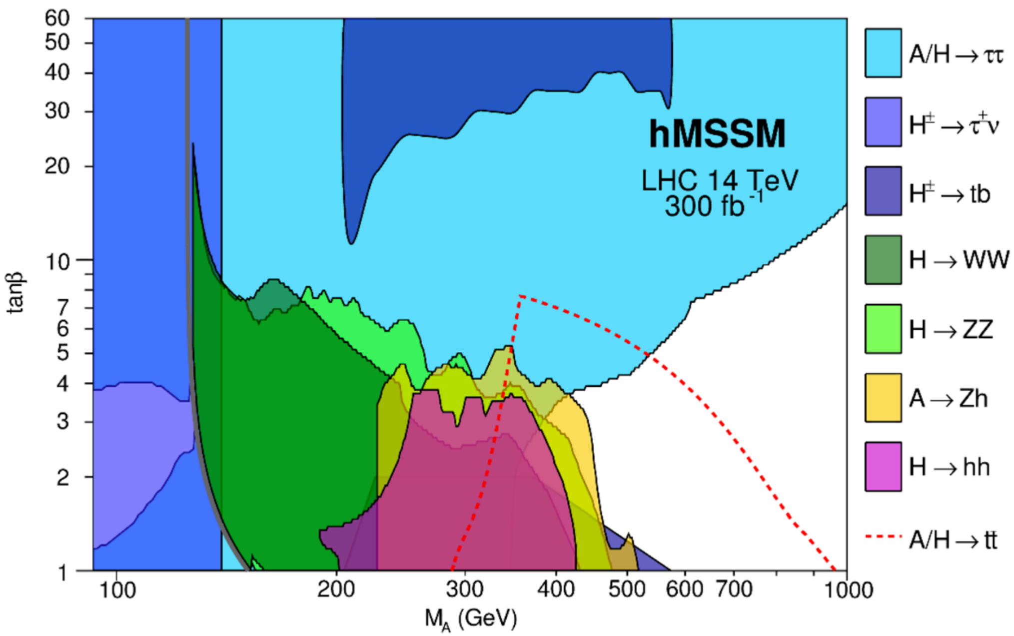
Projections for MSSM H→ττ

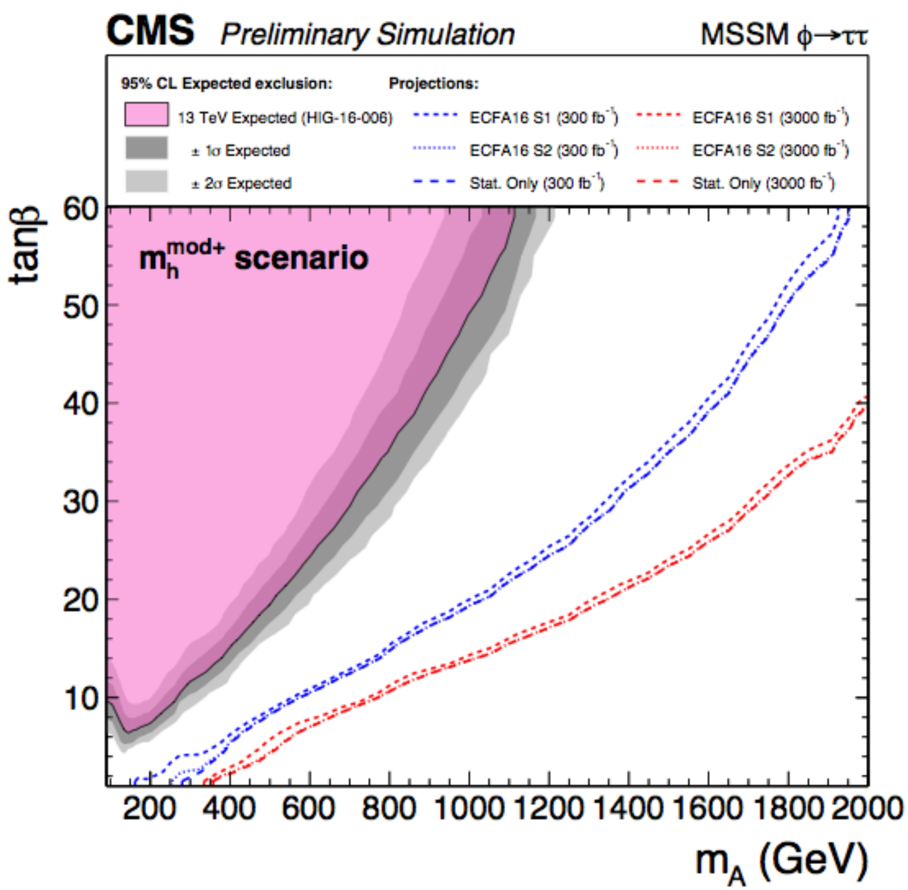
[CMS DP-2016/064]

The MSSM (h, A, H, H±) should be compatible with a 125 GeV Higgs. Two scenarios:

- hMSSM scenario: the measured value of 125 GeV can be used to predict masses and decay branching ratios of the other Higgs bosons
- m_h^{mod+} scenario: the lightest CP-even Higgs is assigned to be the 125 GeV boson

[Djouadi, A. et al. JHEP 06 (2015) 168]





CMS A/H→ττ with Run-2: [CMS-PAS-HIG-16-006]

ATLAS A/H→ττ with Run-2: [ATLAS-CONF-2016-085]

ATLAS A/H→ttbar with Run-1: [ATLAS-CONF-2016-073]

VBF H→invisible

[JHEP 01 (2016) 172]
[CMS DP-2016/064]

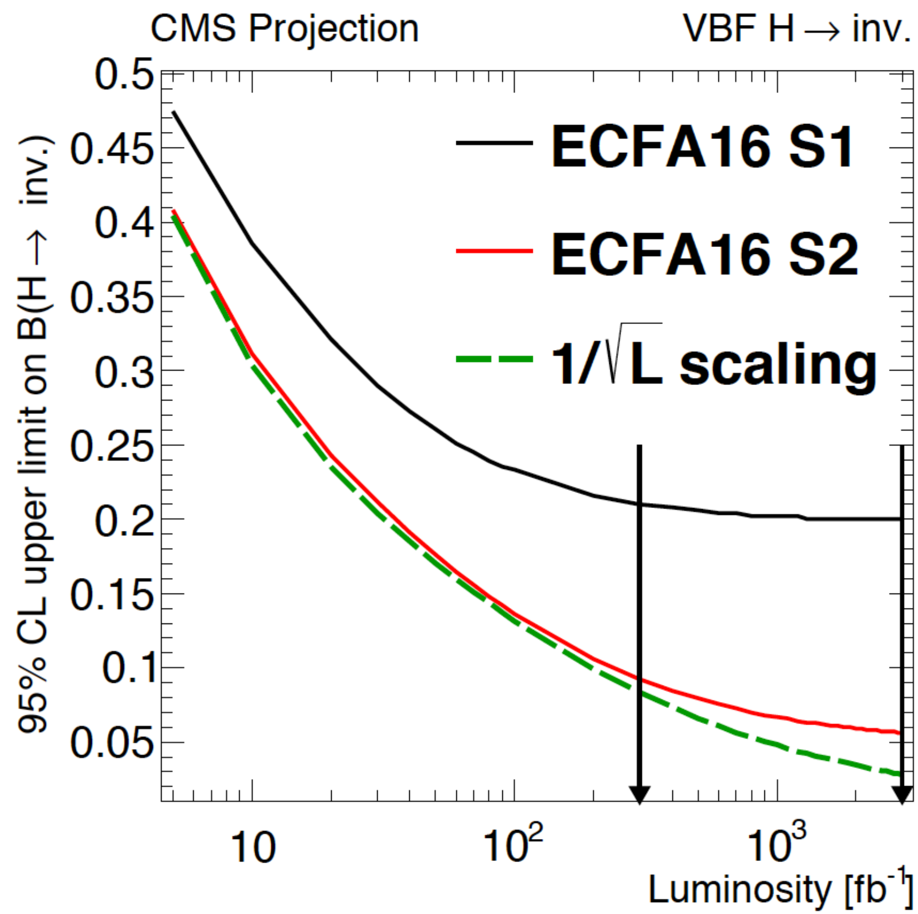
Higgs can decay to dark matter particles leading to large MET events

- Require MET trigger
- Look at VBF region: large m_{JJ} and $\Delta\eta_{JJ}$. It is found to be more powerful than the VH(H→invisible) channel
- Dedicated Zll and Wlv control regions

ATLAS Run-1 95% CL limit:

$$\mathrm{BR}(\mathrm{H} \rightarrow \mathrm{invisible}) < 0.28$$

(<0.31 is expected)



CMS projections for VBF H→invisible:

	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 and Outlook

We had a successful startup of LHC Run 2. Both CMS and ATLAS are fully engaged in the early 13 TeV analysis. For the best Higgs results of Run 3 and HL-LHC, we have to cope with the challenges of increased pileup rates with dedicated upgrades to the detectors

At the end of Run 3 or HL-LHC, both ATLAS and CMS are able to do precision Higgs measurements, and look for BSM signatures

- Can measure the Higgs couplings to 10-20% (5-10%) level with 300 (3000) fb^{-1} of data
- Can look at differential Higgs distributions, and test for dim-6 Higgs operators
- With 3 ab^{-1}, can probe $H\to\mu\mu$ at <20% precision, and have sensitivity for the anomalous decay $H\to J/\psi\gamma$ at 10×SM level
- Can probe the Higgs self-coupling via double Higgs search, although still quite challenging
- Indirect search for BSM through Higgs width, and direct search for new signatures such as H→invisible, MSSM Higgs

Higgs precision physics is one of the main motivations and design considerations for the upgrade programs. Many studies are still on-going, and not all are covered in this talk. Stay tuned!

Backup Slides

Coupling scale factors

[ATL-PHYS-PUB-2014-016]

- Results are derived in the coupling fit framework:

$$\sigma \cdot \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{\mathrm{SM}} \cdot \Gamma_f^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

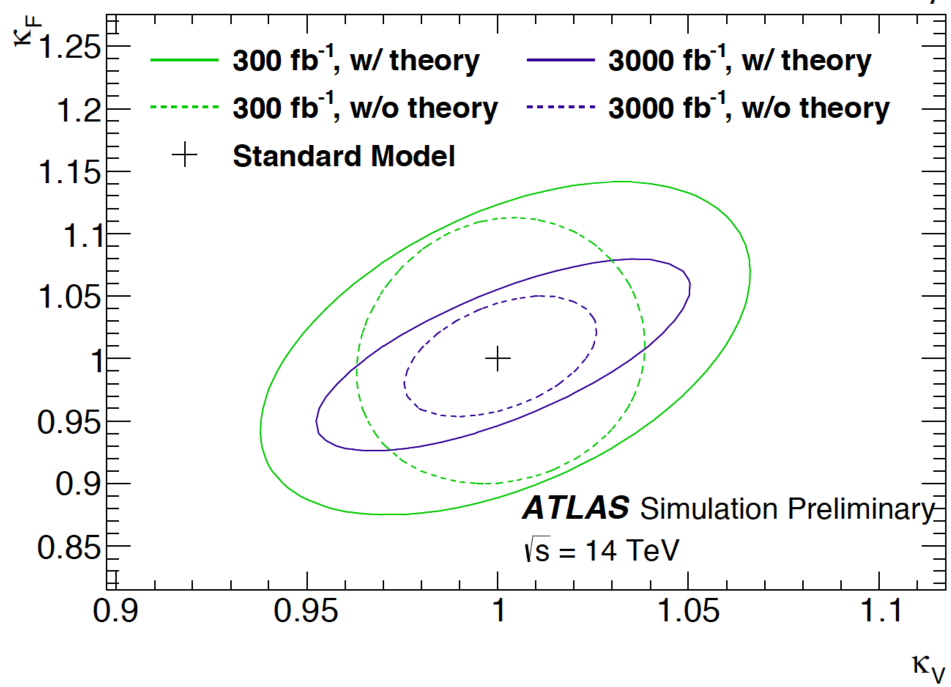
$$\kappa_h^2 = \sum_i \frac{\kappa_i^2 \Gamma_i^{\mathrm{SM}}}{\Gamma_h^{\mathrm{SM}}}, (i = WW, ZZ, b\bar{b} \ldots)$$

Errors on individual factors:

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
8	κ_Z	8.1%	7.9%	7.9%
	κ_W	9.0%	8.7%	8.6%
	κ_t	22%	21%	20%
	κ_b	23%	22%	22%
	κ_τ	14%	14%	13%
	κ_μ	21%	21%	21%
	κ_g	14%	12%	11%
	κ_γ	9.3%	9.0%	8.9%
	$\kappa_{Z\gamma}$	24%	24%	24%

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$



Minimal Composite Higgs Model [ATL-PHYS-PUB-2014-017]

- Mininal Composite Higgs Models (MCHM) represent a possible explanation for the scalar naturalness problem.
- Higgs in MCHM is a composite, pseudo-Nambu-Goldstone boson rather than an elementary particle
- Higgs couplings to SM particles are modified as a function of the Higgs boson compositeness scale f
- In MCHM4:

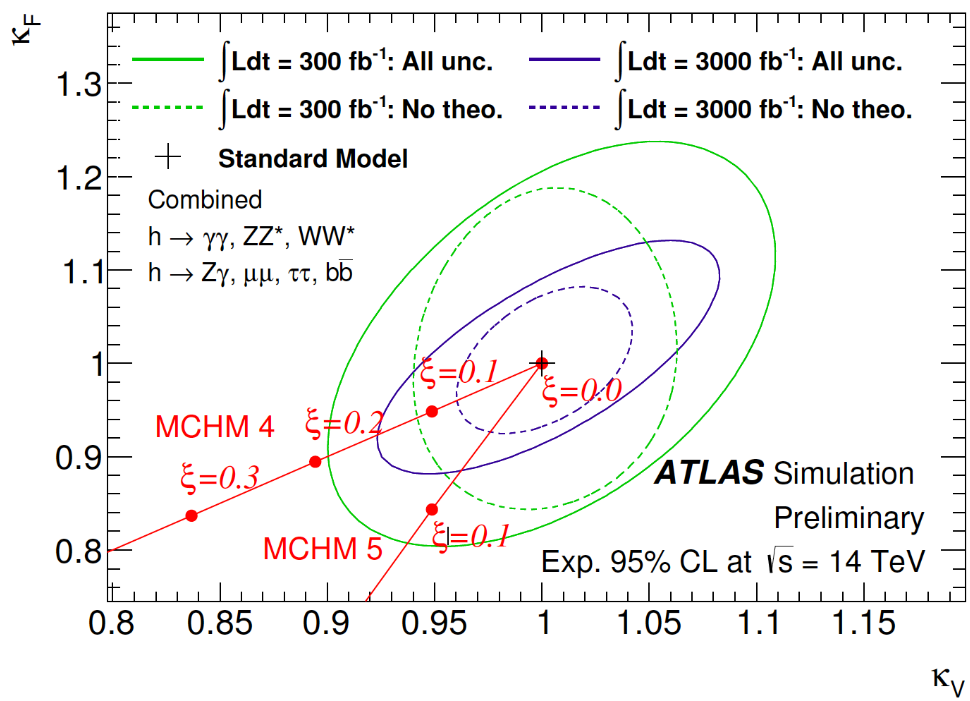
$$\kappa_f = \kappa_V = \sqrt{1-\xi}, \xi = \upsilon^2 / f^2$$

- In MCHM5:

$$\kappa_V = \sqrt{1-\xi}, \kappa_f = \frac{1-2\xi}{\sqrt{1-\xi}}$$

- f=∞ is SM. Lower limits of f:

Model	300 fb^{-1}	
	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV
MCHM5	780 GeV	950 GeV



Two Higgs Doublet Model

- In Two Higgs Doublet Model (2HDM), both acquire a VEV and five Higgs bosons are resulted:

$$m_h, m_H, m_A, m_{H^\pm}$$

- Two additional parameters are need to describe the model: the ratios of VEV's ($\tan\beta = \upsilon_2 / \upsilon_1$) and the mixing angle α of the two neutral CP-even Higgs
- Assume h is the 125 GeV Higgs, its coupling to vector bosons is complementary with H:

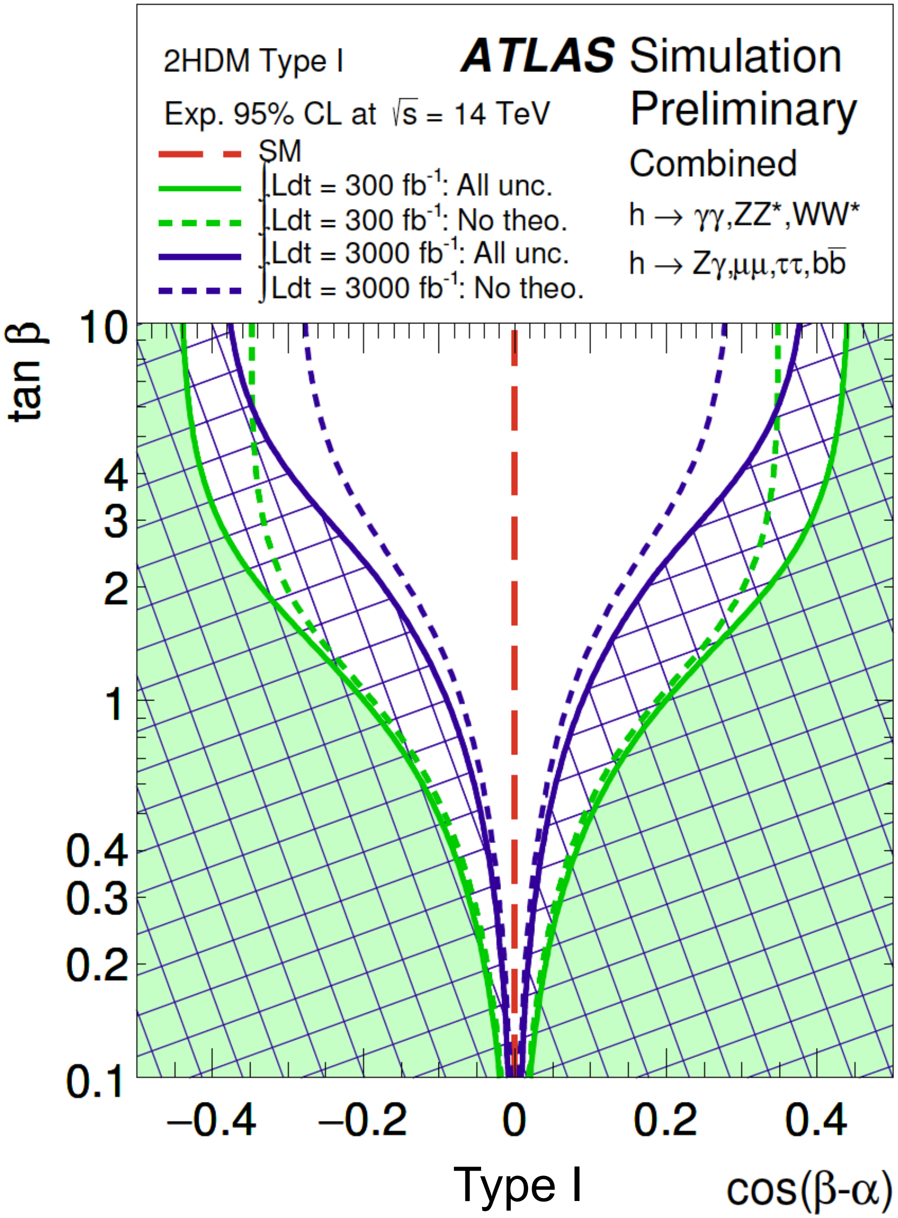
$$g_{hVV}^{2HDM} / g_{hVV}^{SM} = \sin(\beta - \alpha), \quad g_{HVV}^{2HDM} / g_{HVV}^{SM} = \cos(\beta - \alpha)$$

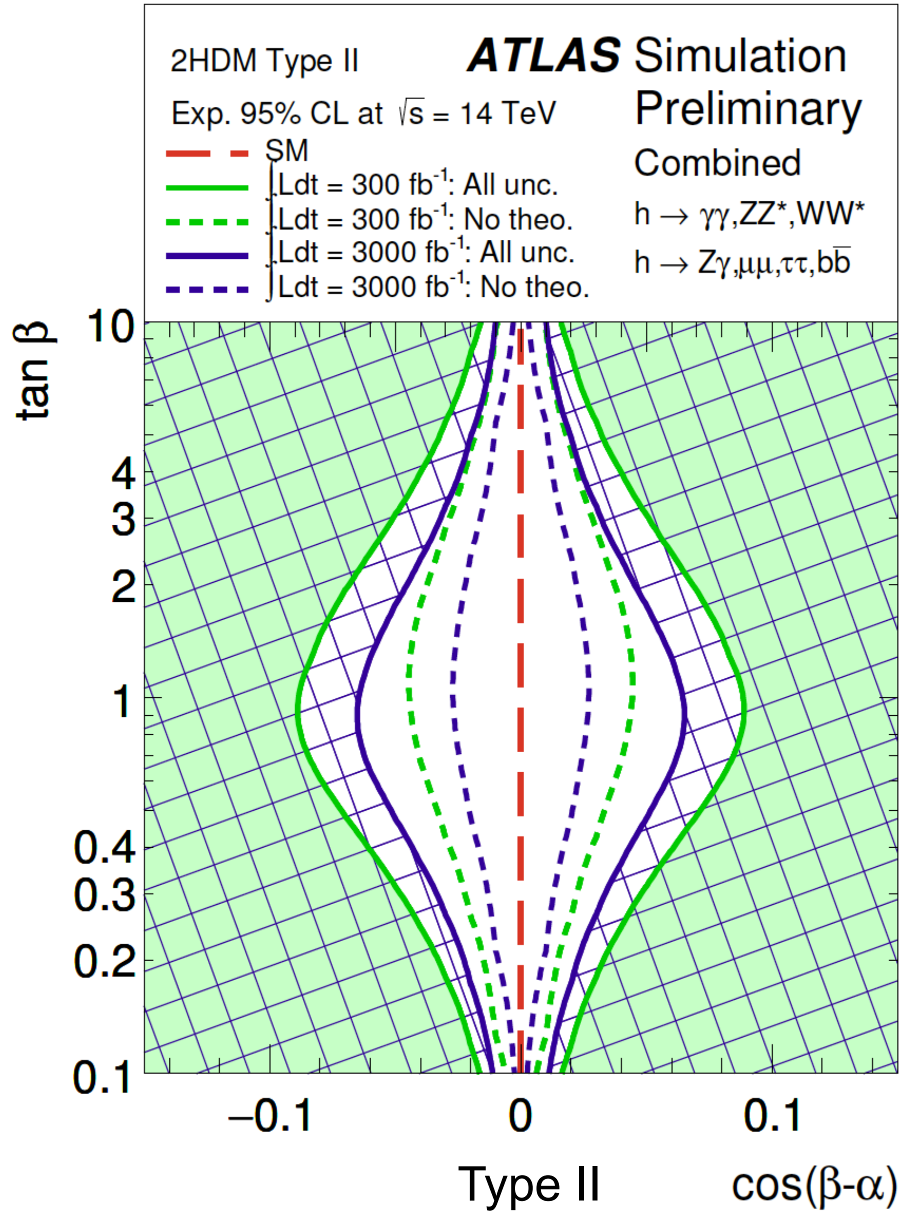
- 4 types of models if CP is conserved and no FCNC:

• Type I 2HDM: All fermions couple to just one of the Higgs doublets
• Type II 2HDM: All up-type fermions couple to one Higgs doublet and all down-type fermions couple to the other
• Lepton-specific 2HDM: All quark couplings are like in the Type 1, lepton couplings are like in Type II
• Flipped 2HDM: All lepton couplings are like in the Type 1, quark couplings are like in Type II

Two Higgs Doublet Model

[ATL-PHYS-PUB-2014-017]





CMS CORE costs for Phase II Upgrade

[LHCC-G-165]

CORE cost estimate	MCHF (2014)
Pixel Detector	23
Outer tracker	89
Tracking System	**112**
EB electronics	10
HB scintillators	1
Endcap HGC+BHE	64
Calorimeters	**75**
DT and CSC electronics	10
Muon stations: GE11, GE21, RE31 and RE41	10
Muon extension ME0	5
Muon Systems	**25**
Beam Monitors and Luminosity	**4**
Hardware trigger	7
HLT	11
DAQ	6
Trigger and DAQ	**24**
Infrastructure, Systems and Support, Installation	**25**
Total	**265**

CMS cost reduction impacts on physics

[LHCC-G-165]

Cost reduction Scenario 1. Impact given as a factor of additional luminosity to achieve the same result:

Process	Descoped items	Effects considered	Impact
VBF $H \to \tau\tau$	trigger	trigger acceptance	1.25
$H \to \mu\mu$	RPC	muon ID	1.02
$H \to 4e$	HGCAL (24/11)	electron resolution and ID	1.3

Cost reduction Scenario 2. Impact given as a factor of additional luminosity to achieve the same result:

Process	Descoped items	Effects considered	Impact
VBF $H \to \tau\tau$	trigger, tracker ext.	trigger acc., $E_{\mathrm{T}}^{\mathrm{miss}}$ res., jet counting	4.2
$H \to \mu\mu$	muon system	muon ID	1.25
$H \to 4\mu$	tracker ext.	muon acceptance	1.25
$H \to 4e$	HGCAL (18/9), tracker ext.	electron res., ID, and acc.	2.0
$W^{\pm}HE_{\mathrm{T}}^{\mathrm{miss}}$	tracker ext.	$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	6.7

CMS systematics

[CMS DP-2016/064]

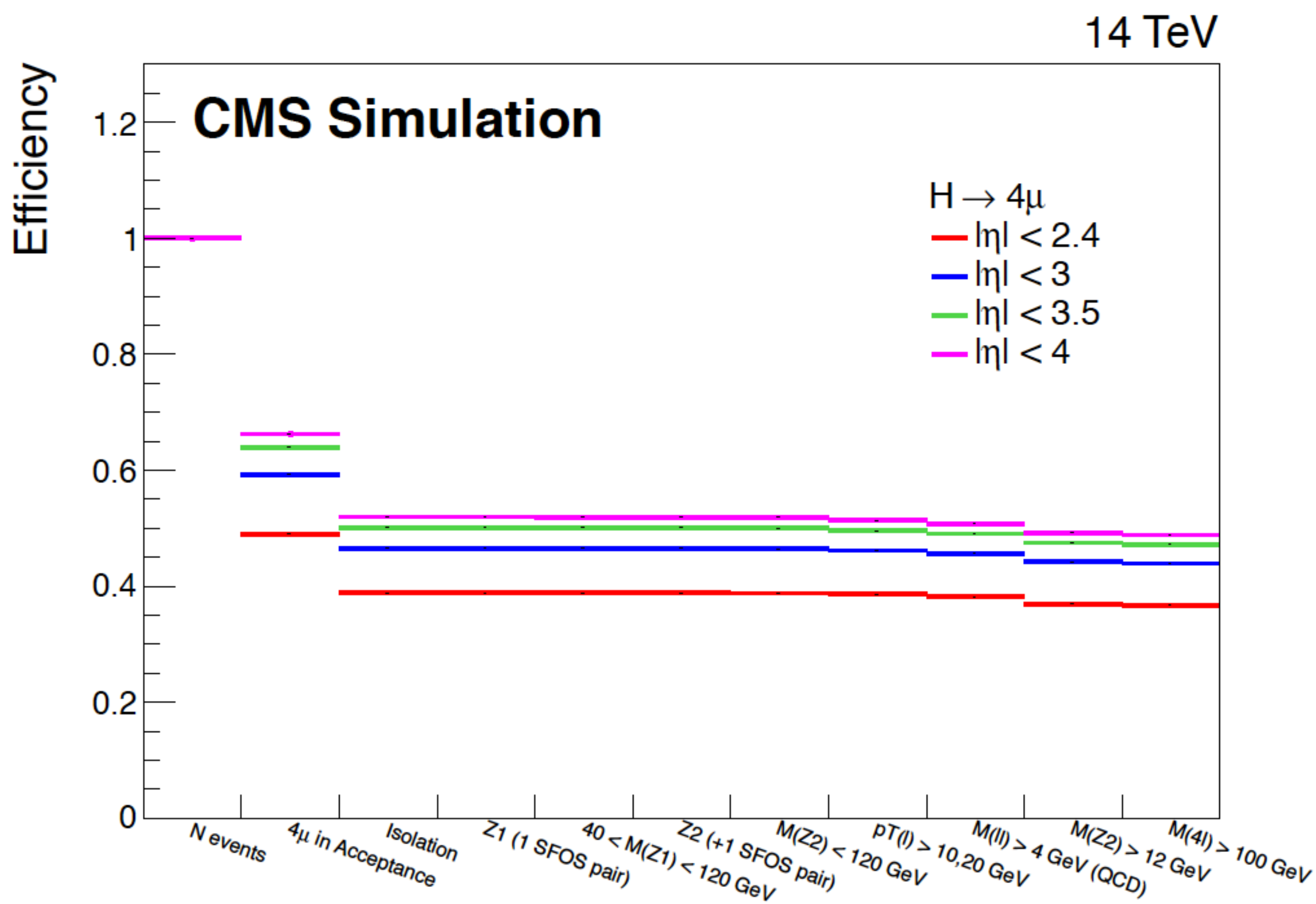
S1 All systematic uncertainties are kept constant with integrated luminosity. The performance of the CMS detector is assumed to be unchanged with respect to the reference analysis.

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 performance of the CMS detector is assumed to be unchanged with respect to the reference analysis.

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.

Extended tracking for H→ZZ*→4μ [LHCC-P-008]



A significant increase in signal efficiency extending the muon detector coverage: a coverage of |η|<3.0 shows a 20% larger acceptance with respect to a coverage of |η|<2.4

ATLAS Scoping layouts

[CERN-LHCC-2015-020]

Detector System	Scoping Scenarios		
	Reference (275 MCHF)	**Middle** (235 MCHF)	**Low** (200 MCHF)
Inner Tracker			
Pixel Detector	$\|\eta\| \leq 4.0$	$\|\eta\| \leq 3.2$	$\|\eta\| \leq 2.7$
Barrel Strip Detector	✓	✓ [No stub layer]	✓ [No stereo in layers #2,#4] [Remove layer #3] [No stub layer]
Endcap Strip Detector	✓	✓ [Remove 1 disk/side]	✓ [Remove 1 disk/side]
Calorimeters			
LAr Calorimeter Electronics	✓	✓	✓
Tile Calorimeter Electronics	✓	✓	✓
Forward Calorimeter	✓	✗	✗
High Granularity Precision Timing Detector	✓	✗	✗