

The scalar sector of the standard model

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for the ATLAS and CMS collaborations

LHCSki16, 2016/04/11



The Higgs game started >50 years ago

...though for a long time only theorists were allowed to play it:

Ellis et al, twelve years after the BEH papers:

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John Ellis, Mary K. Gaillard ^{*}) and D.V. Nanopoulos ⁺)

CERN -- Geneva

Nucl. Phys. B 106, 292 (1976)

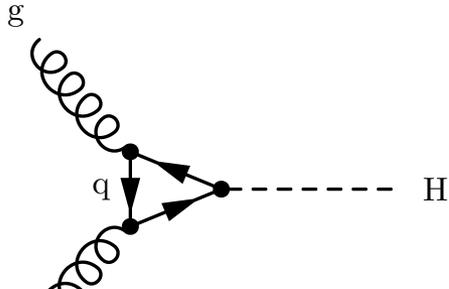
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm ^{3),4)} and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs boson production



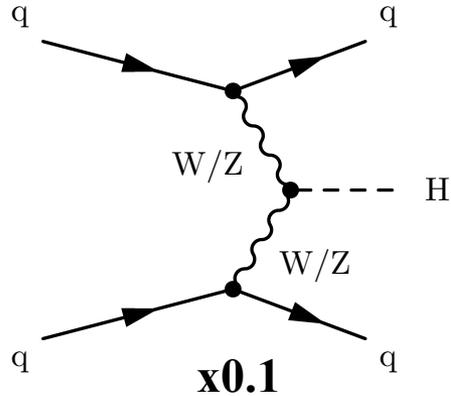
OAW

gg fusion

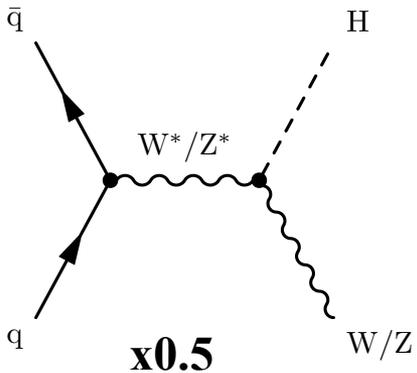


LHC: 1M Higgs bosons in Run1

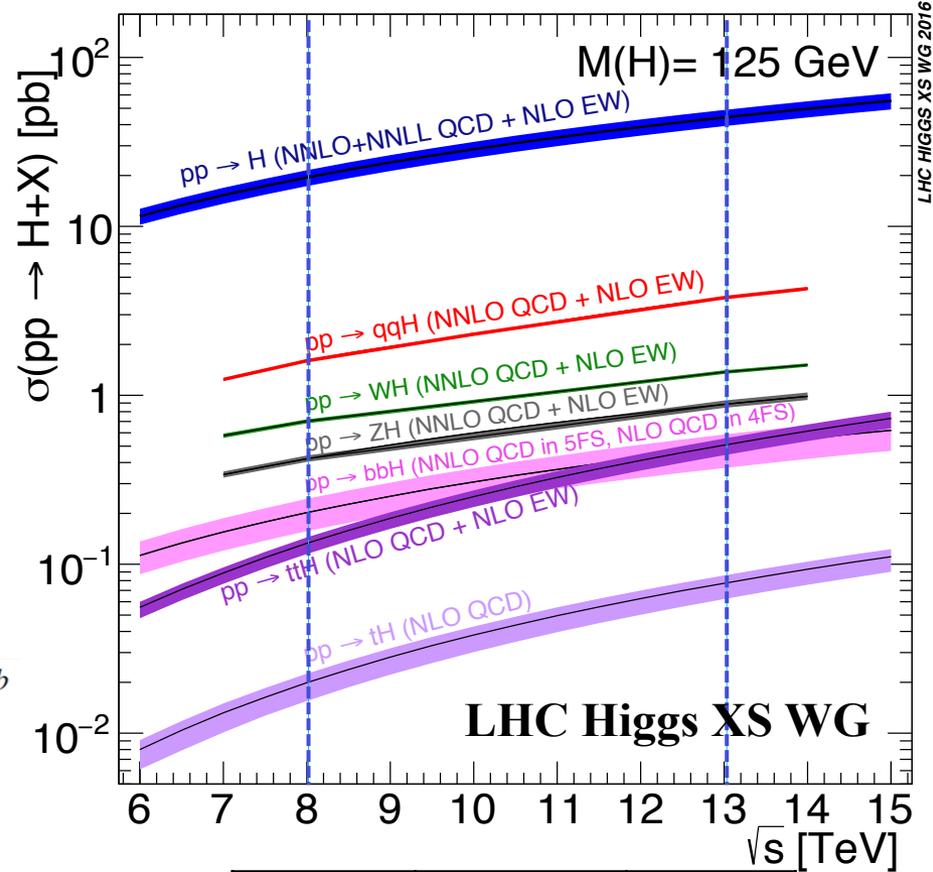
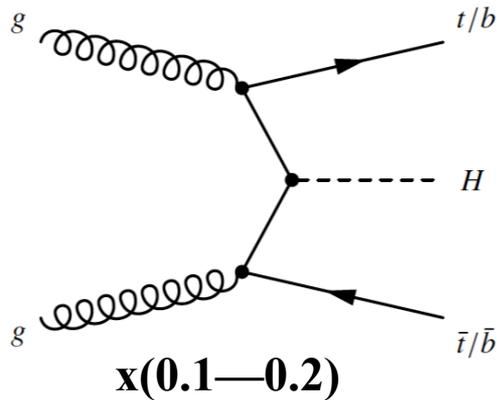
VBF



VH



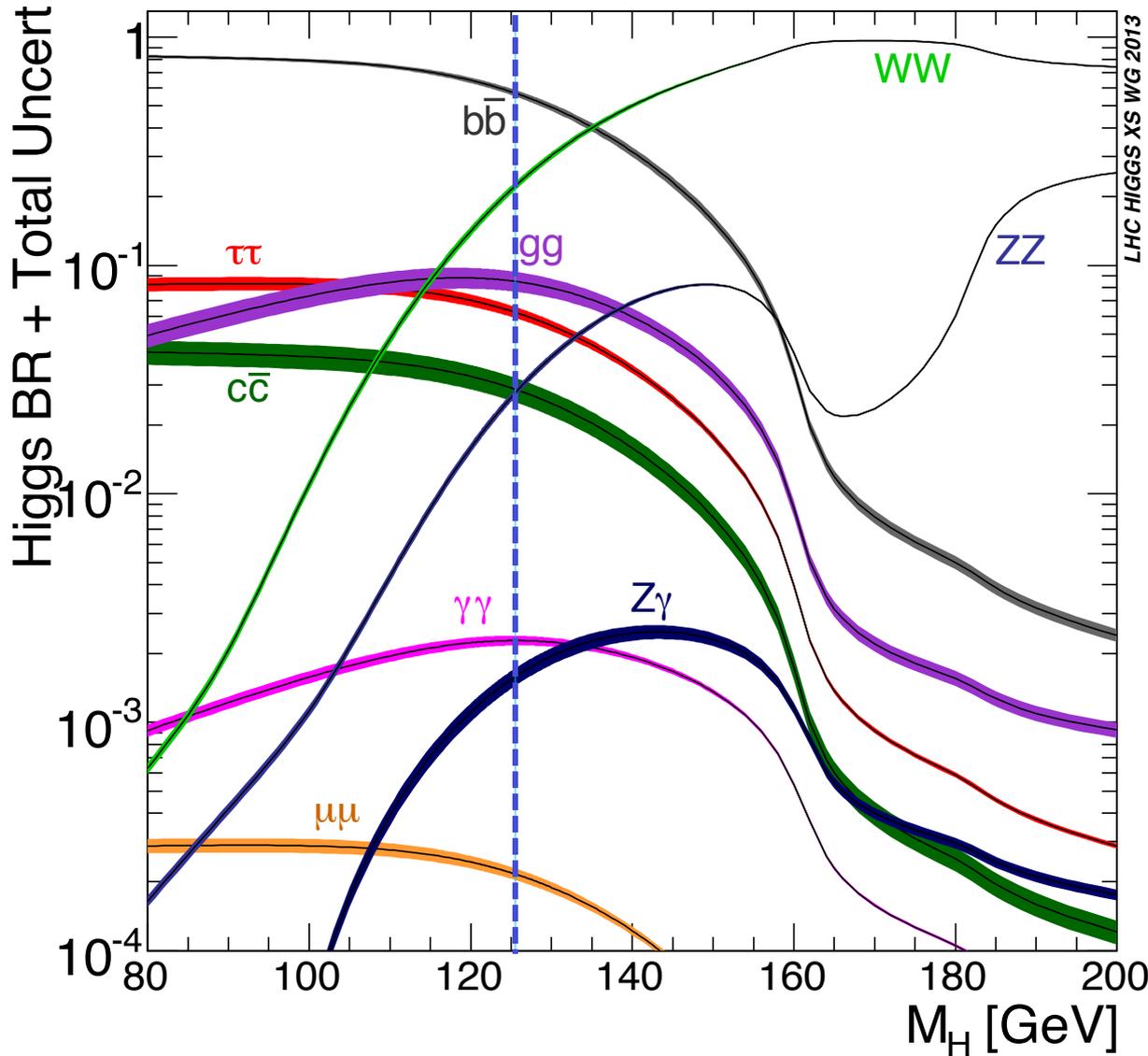
ttH



Mode	8 TeV	13 TeV
ggF	19	44
VBF	1.6	3.8
WH	0.70	1.4
ZH	0.42	0.88
ttH	0.13	0.51
bbH	0.20	0.49

σ [pb],
 $m_H=125$ GeV

Higgs boson decay



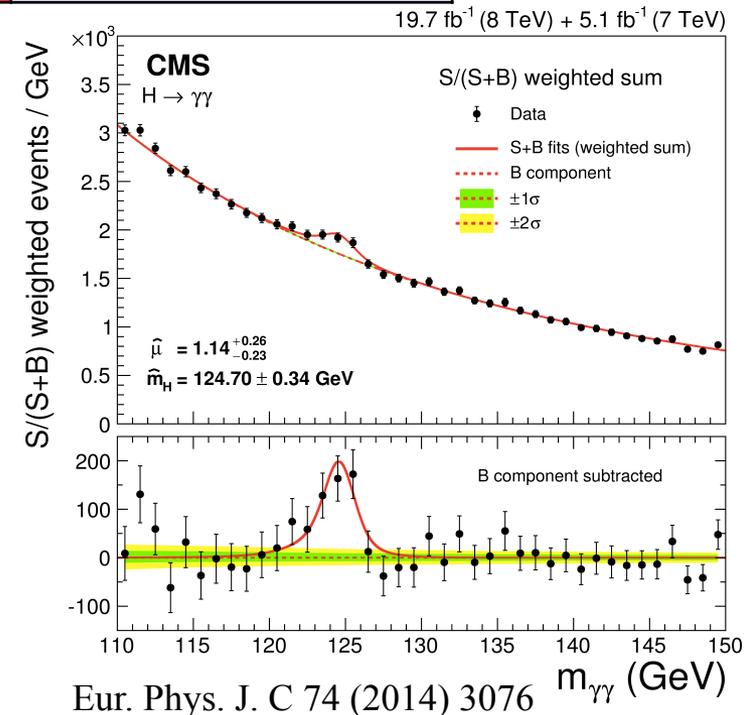
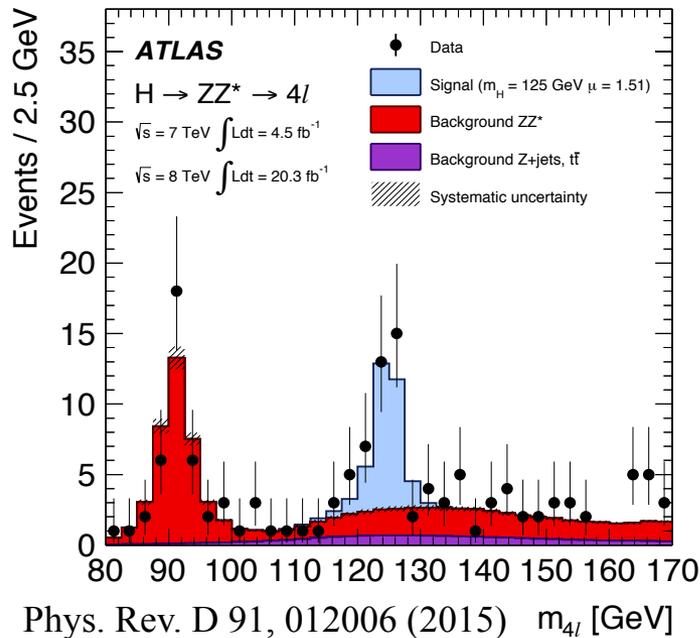
$m_H=125$ GeV

Mode	BR
bb	57.7%
WW	21.5%
gg	8.6%
$\tau\tau$	6.3%
cc	2.9%
ZZ	2.6%
$\gamma\gamma$	0.23%
$Z\gamma$	0.15%
$\mu\mu$	0.022%

Overview of Higgs boson channels

Mode	Sensitivity	Mass res.	S/B (incl)	rate	comments
$ZZ^* \rightarrow 4l$	Green	Green	Green	Red	very pure; m_H ; SpinCP
$\gamma\gamma$	Green	Green	Yellow	Green	m_H ; via loop
$WW \rightarrow l\nu l\nu$	Green	Red	Yellow	Green	high rate
$\tau\tau$	Yellow	Red	Red	Green	mainly VBF (sensitivity)
bb	Yellow	Red	Red	Green	mainly VH (trigger, QCD)
$ZZ^* \rightarrow llqq/ll\nu\nu$	Yellow	Green	Yellow	Yellow	high-mass (mainly)
$WW \rightarrow lvqq$	Yellow	Green	Yellow	Green	high-mass (mainly)
$\mu\mu$	Red	Green	Red	Red	rare
$Z\gamma$	Red	Green	Red	Red	

Searches for SM-like Higgs bosons, assuming SM



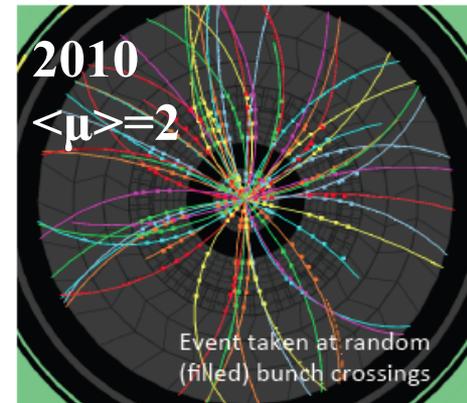
Run 1: Higgs summary

**Only some highlights;
there are about 150—200
LHC publication on the Higgs sector;
plus a few hundred CONF/PAS**

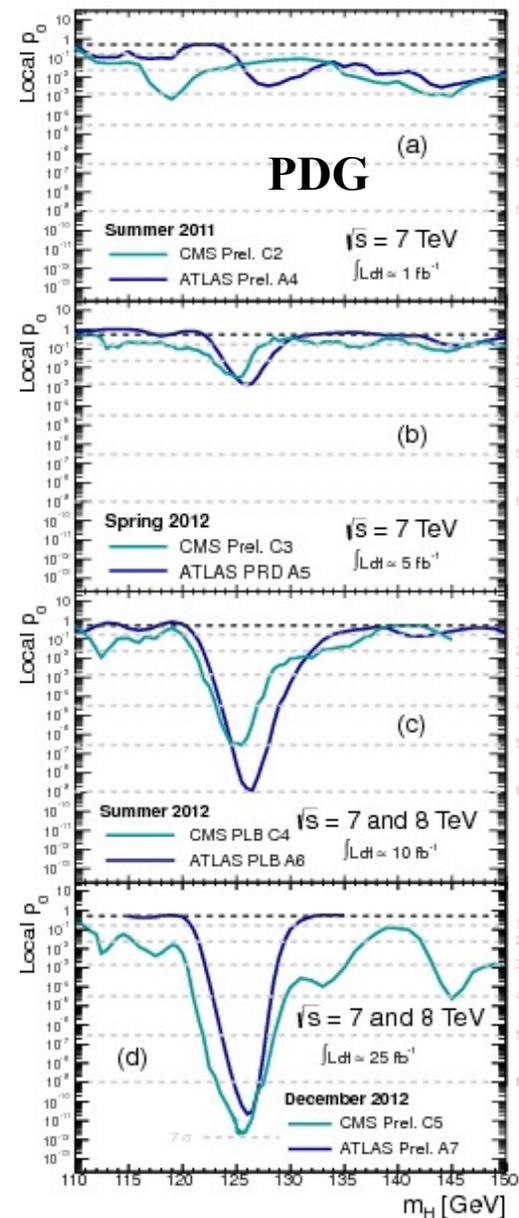
2015 : $\langle\mu\rangle=14$ (25 ns)

$\langle\mu\rangle=20$ (50 ns)

2030s: $\langle\mu\rangle=200$



Higgs boson discovery



Higgs boson properties

- A typical Higgs boson property measurement is the result of combining dozens of analysis
 - Not all analyses used everywhere: e.g. m_H – only $\gamma\gamma$, 4l
 - Combined with the property as parameter-of-interest

Decay/Production tag	GGF	VBF	VH	ttH
$H \rightarrow \gamma\gamma$	X	X	X	X
$H \rightarrow ZZ$	X	X	X	X
$H \rightarrow WW$	X	X	X	X
$H \rightarrow \tau\tau$	X	X	X	X
$H \rightarrow bb$		X	X	X
$H \rightarrow \text{inv}$		X	X	
$H \rightarrow \mu\mu$	X	X		
$H \rightarrow Z\gamma$	X	X		

(maximum) input used for property measurements

Bold **X**: used in

ATLAS+CMS combination

Signal significance

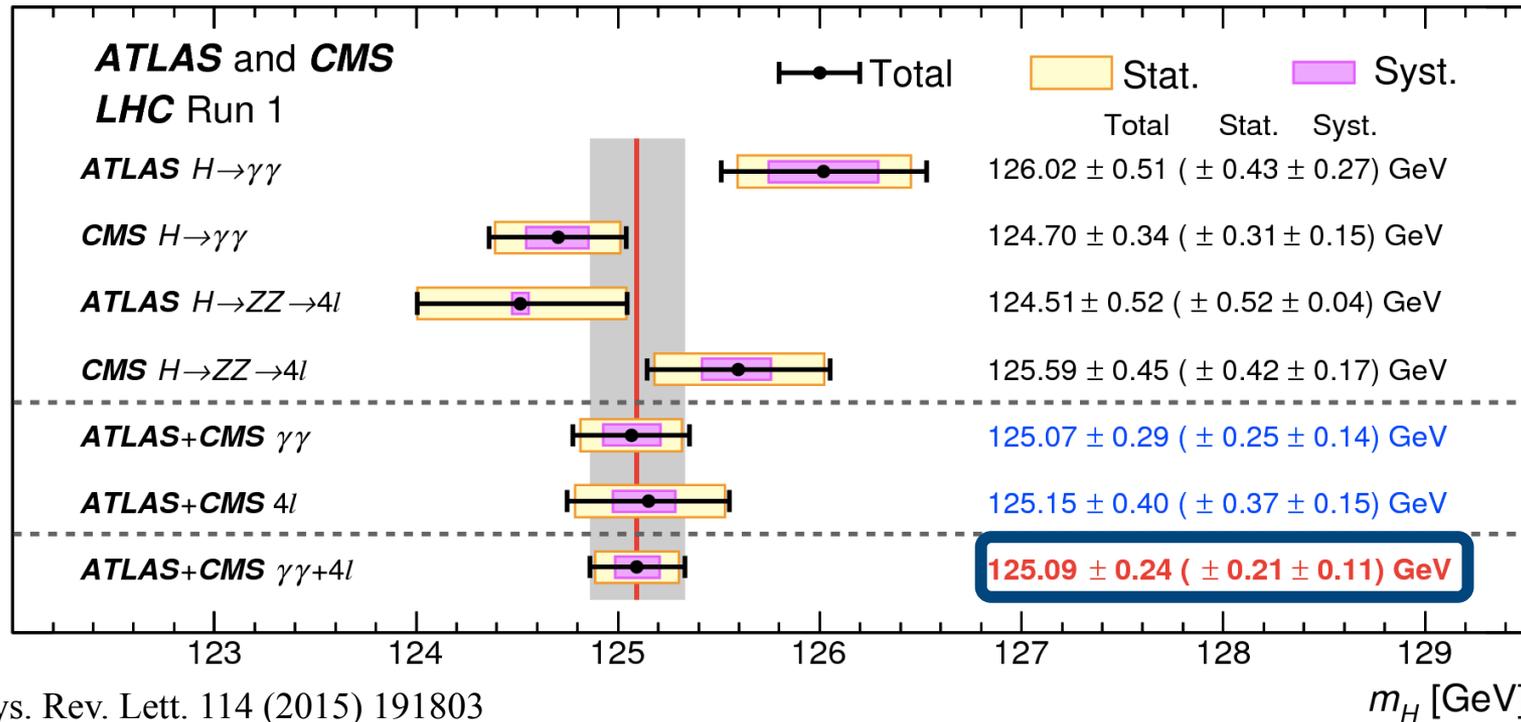
- Already measured well beyond 5σ :
 - ggF
 - $\gamma\gamma$, ZZ, WW

Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

- NB: We always measure production times decay
 - Need assumptions to separate both (e.g. SM production/decay)

Mass measurement



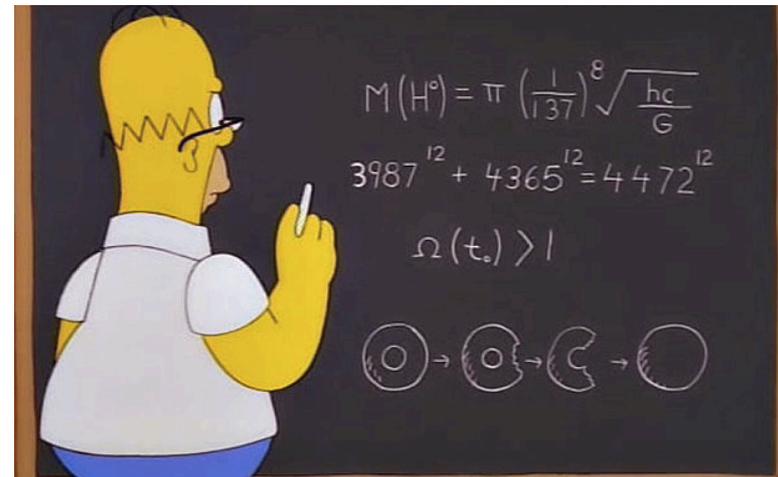
Phys. Rev. Lett. 114 (2015) 191803

Precision: per mille-level (0.2%)

Compatible with SM & MSSM

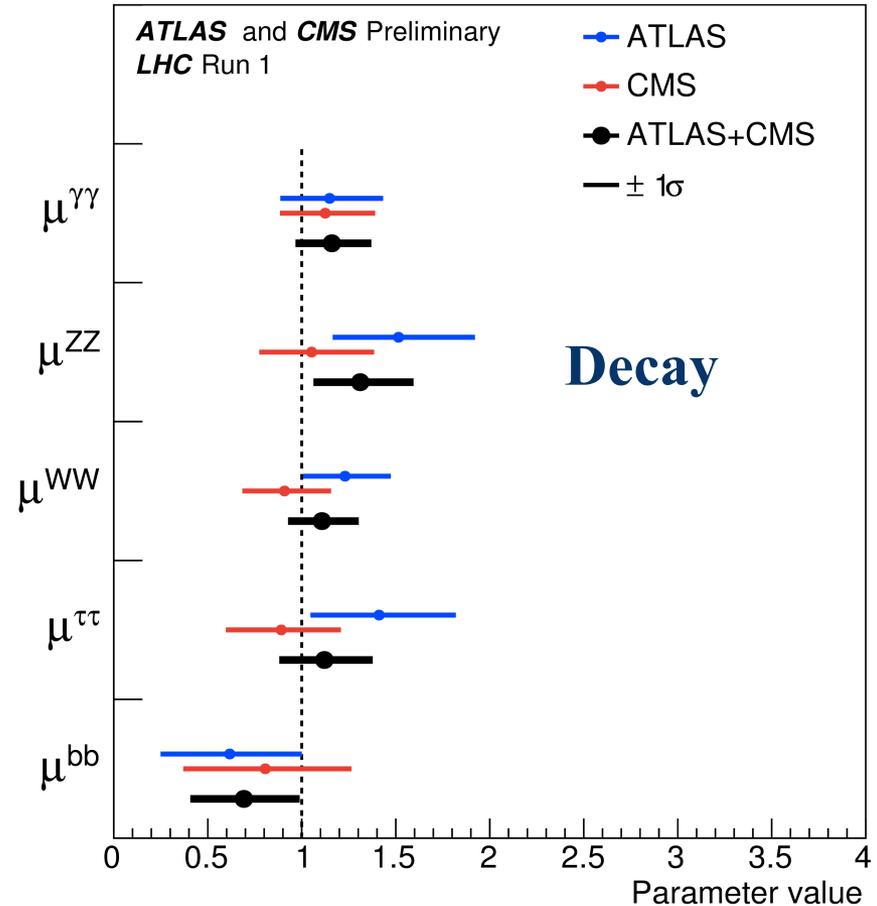
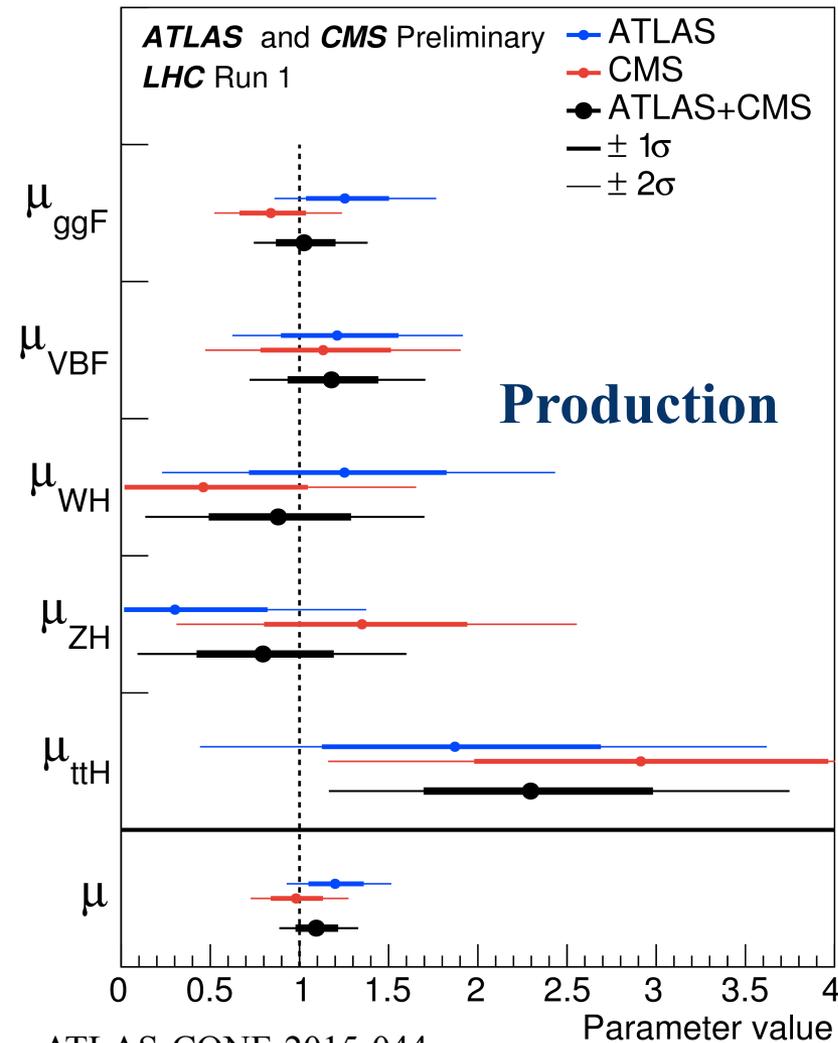
Took almost 20 years to falsify Prof. Homer

$m_H = 775$ GeV, published 1998 in FOX Rev. Lett.



Signal strength

$$\mu_{ij} = (\sigma_i \text{BR}_j)_{\text{obs}} / (\sigma_i \text{BR}_j)_{\text{SM}}$$



ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

$$\mu = 1.09 \pm 0.11$$

Global

Mostly $\sigma(gg \rightarrow H)$

$$= 1.09 \pm 0.07(\text{stat}) \pm 0.04(\text{expt}) \pm 0.03(\text{thbgd}) \pm 0.07(\text{thsig})$$

Coupling strength

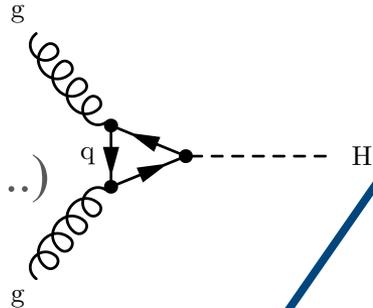
- Coupling strength modifier κ :

Ratio to SM expectation

- $\kappa_i^2 = \sigma_i / \sigma_i^{SM}$
- $\kappa_f^2 = \Gamma_f / \Gamma_f^{SM}$

- Loops

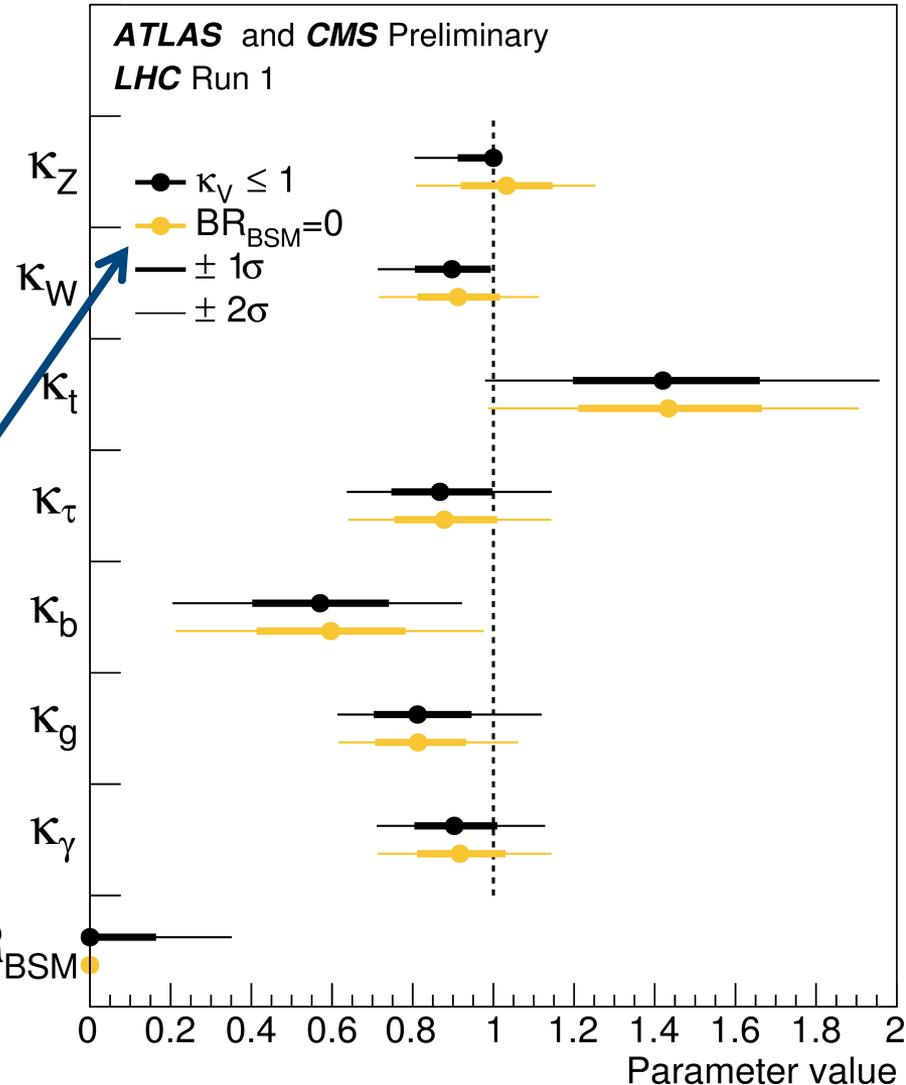
- Resolved ($\kappa_t, \kappa_b, \dots$)
- Effective** (κ_g, \dots)



- Total width

- Assume: **No BSM contribution**
- Allow **BSM decays**

→ BR_{BSM}



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CMS-PAS-HIG-15-002

Coupling strength

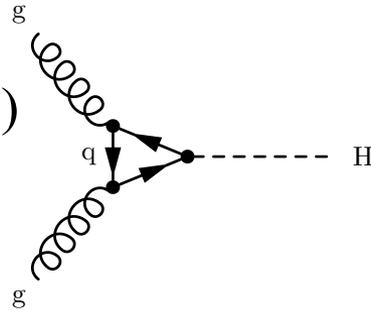
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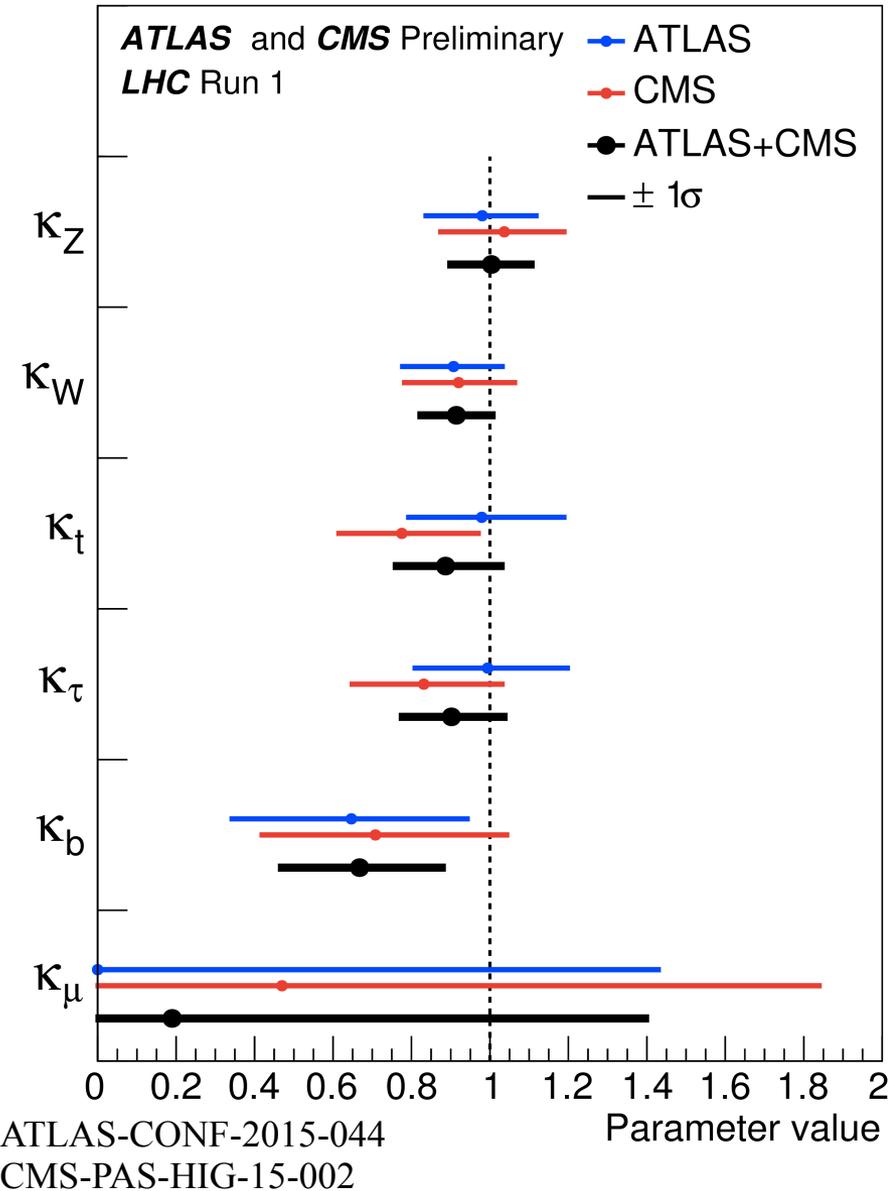
- Loops

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Coupling strength

- Coupling strength modifier κ :

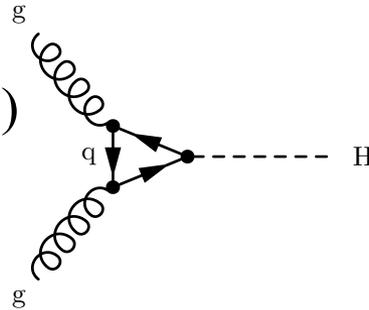
Ratio to SM expectation

- $\kappa_i^2 = \sigma_i / \sigma_i^{SM}$
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CMS-PAS-HIG-15-002

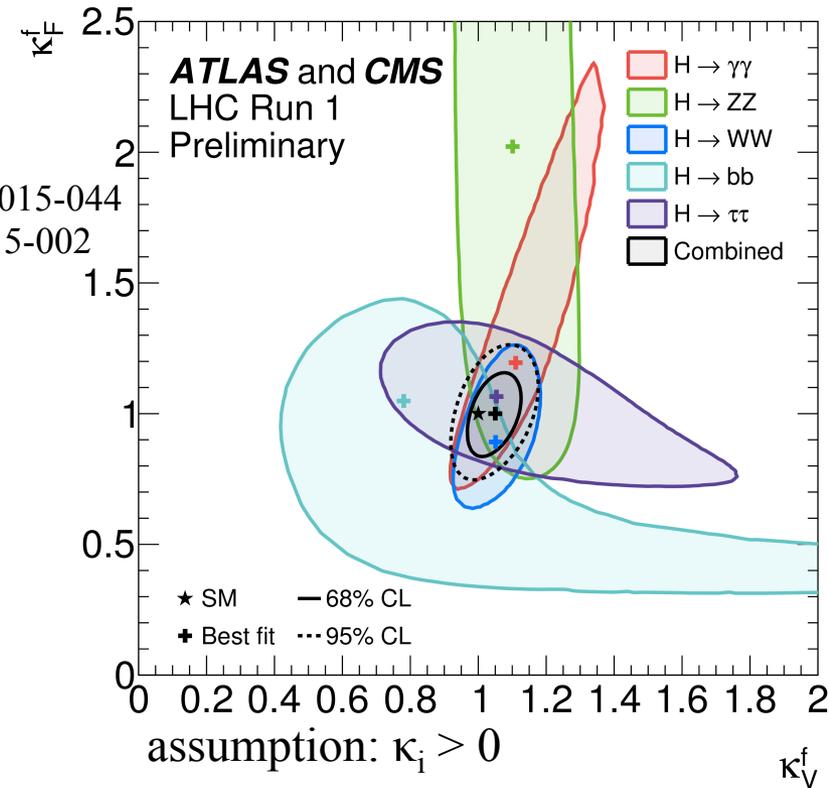
- Loops

- Resolved** ($\kappa_t, \kappa_b, \dots$)
- Effective (κ_g, \dots)



- Total width

- Assume: **No BSM contribution**
- Allow BSM decays



$$\lambda_{du} = 0.91 \pm 0.12$$

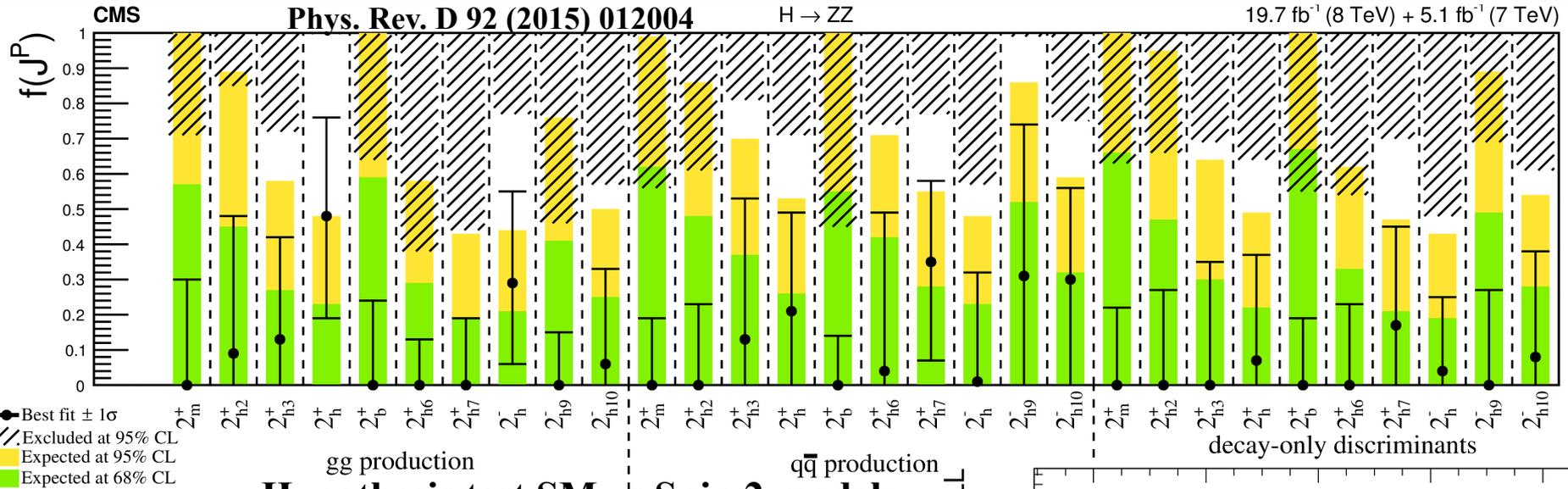
test e.g.

MSSM

$$|\lambda_{|q|} = 1.06 \pm 0.15$$

2HDM

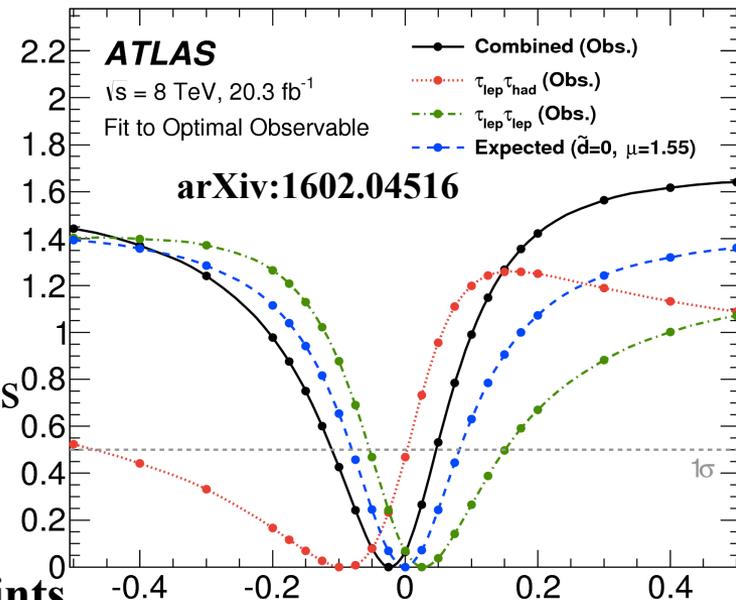
Tensor coupling structure



Hypothesis test SM vs Spin 2 models

- Hypotheses to explain the 125-GeV boson:
 - Spin 0: SM 0⁺; 0⁻; (anom.) 0⁺; mixtures
 - Spin 2: Multidimensional space of models
 - Rest: Strongly disfavored (from th and/or exp)
- Data agree with SM. Most tested Spin-2 hypotheses excluded, but Spin 2 and CP-odd admixtures still allowed

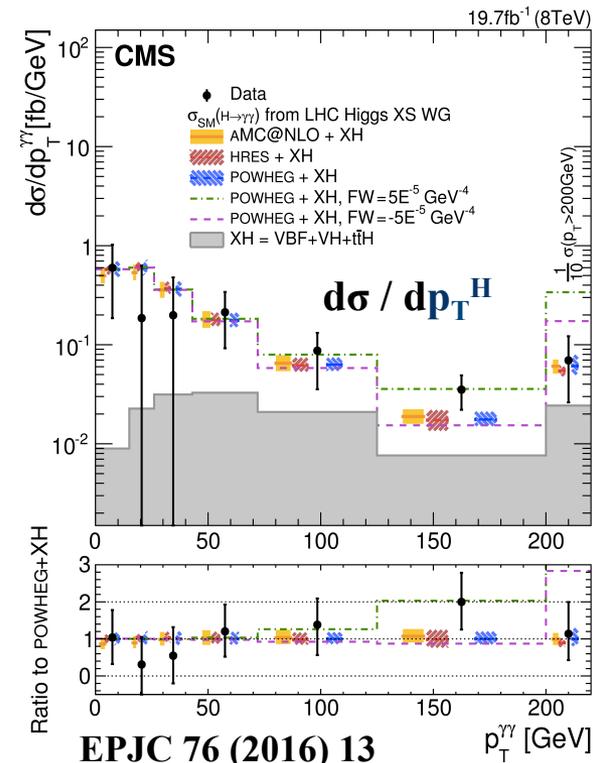
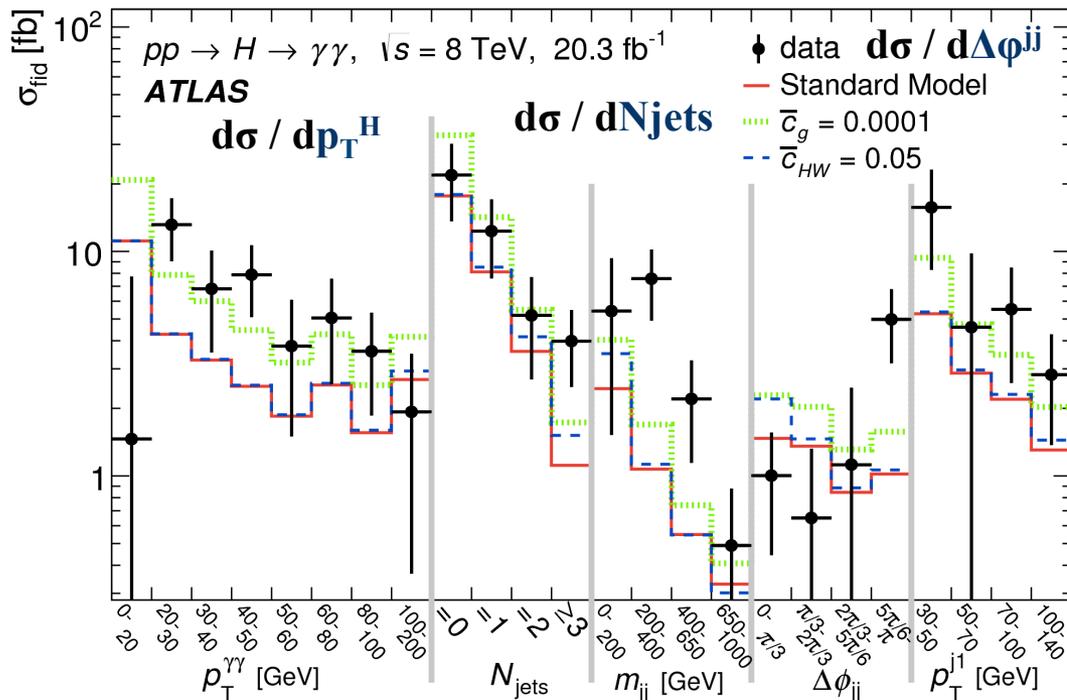
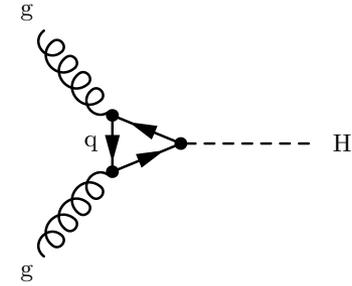
Optimal Observables, H → ττ –
10x better than previous constraints



\bar{d} is constrained to the interval $[-0.11, 0.05]$

Differential cross sections

- Differential distributions in H events: test for BSM interactions.
 - $d\sigma / dp_T^H$: BSM in (ggF production) loops
 - $d\sigma / dN_{\text{jets}}$: QCD calculations
 - $d\sigma / d\Delta\phi_{jj}$: CP properties
- No significant deviation from SM expectation

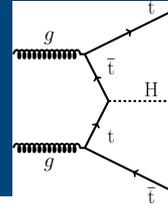


Run 1: (Barely) significant anomalies

NB: With hundreds of measurements in the Higgs sector, a few 2σ or even 3σ “effects” are expected. Nonetheless they deserve special attention during Run 2.

Selection criteria:

$>2\sigma$, plus consistency of ATLAS/CMS results

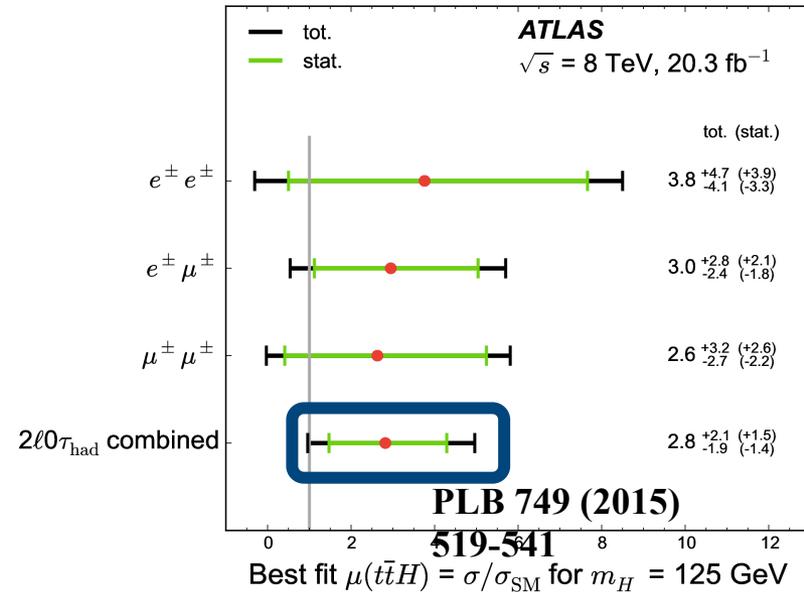
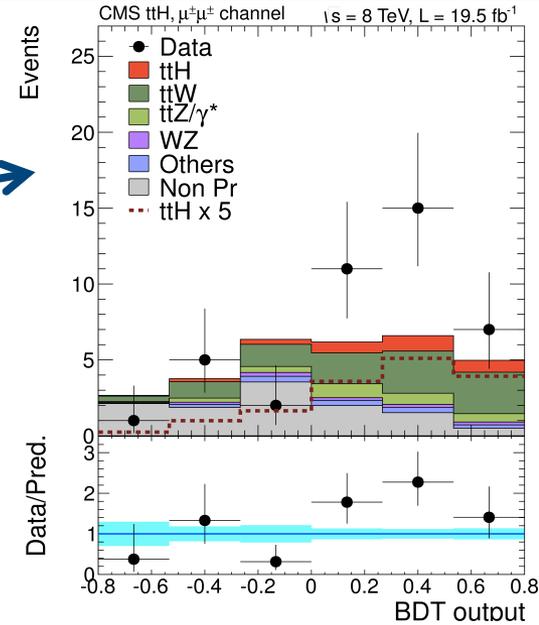
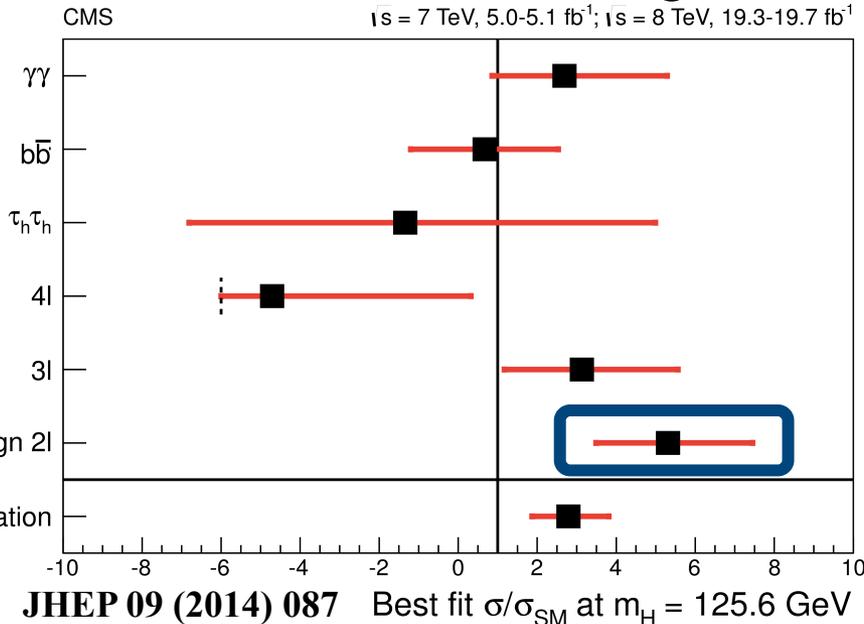


- Signal strength in ttH about 2σ from the SM

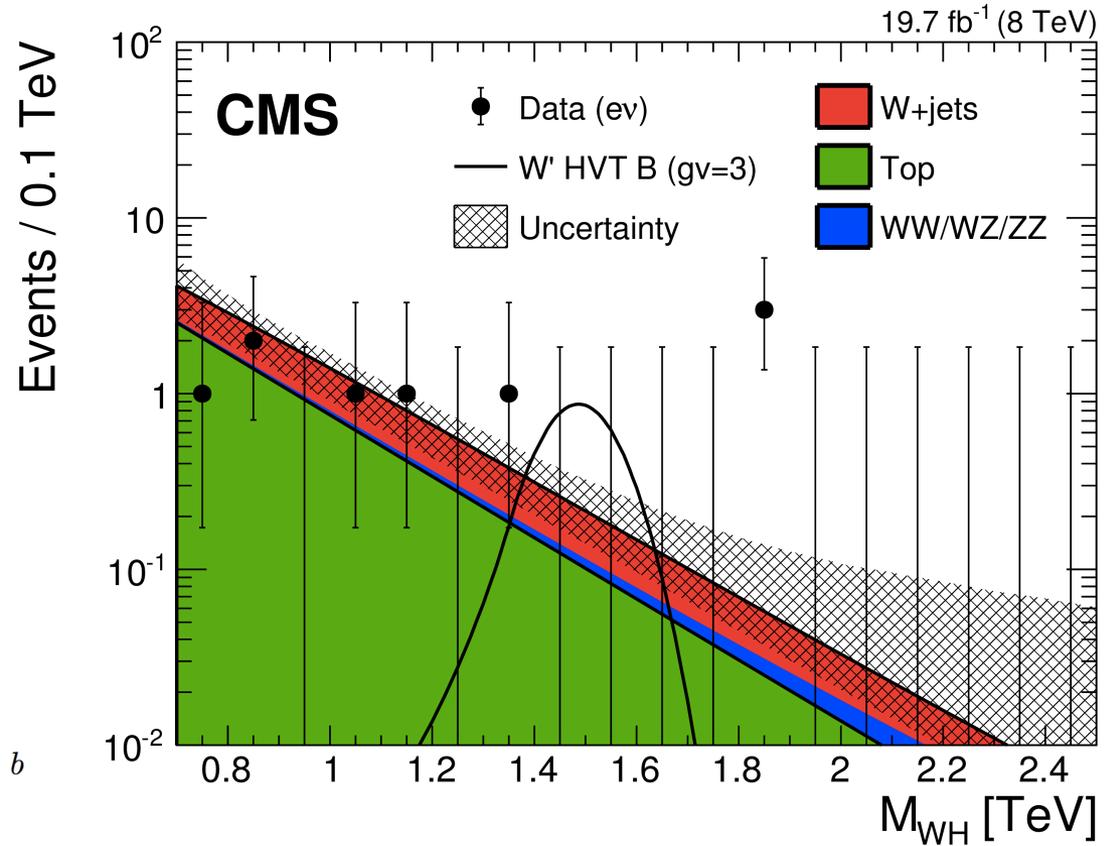
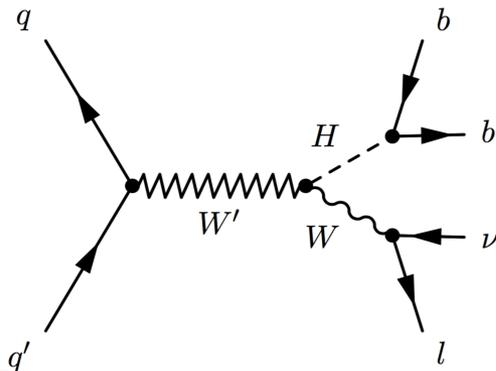
ATLAS+CMS	ATLAS	CMS
$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

- Mostly driven by CMS same-sign $\mu\mu$
- ATLAS: insignificant excess (1σ)
- Run 2 will tell if it is a fluctuation...

- ttH rate at 13 TeV: 4x higher



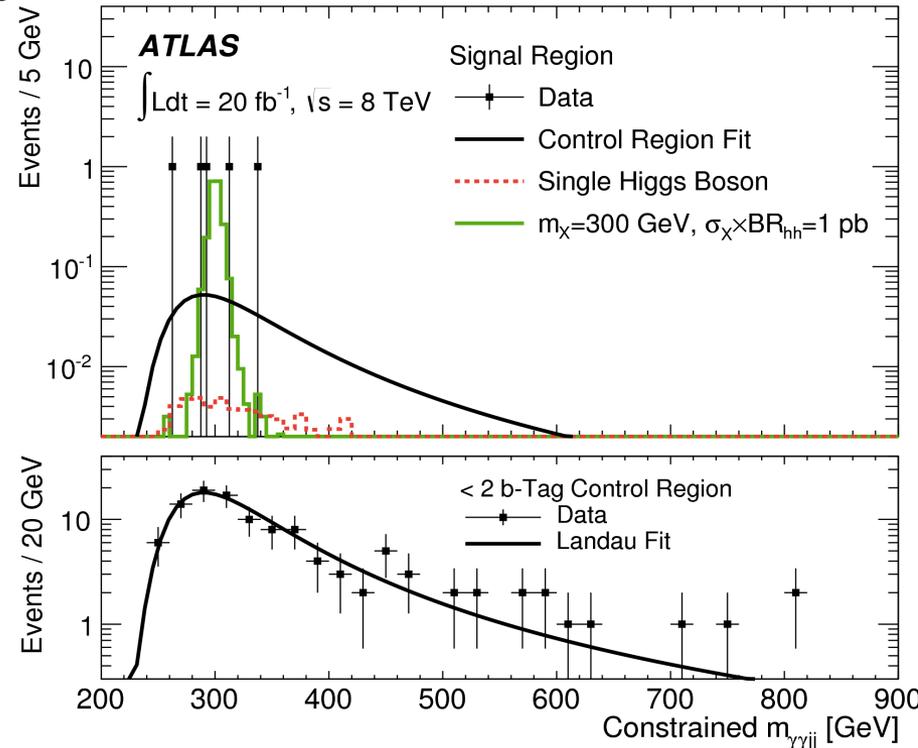
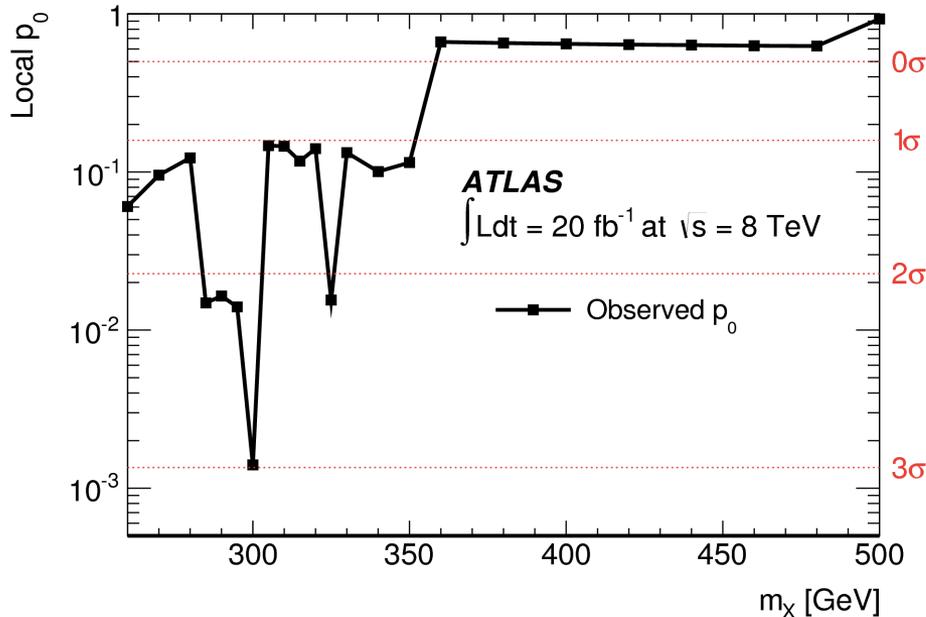
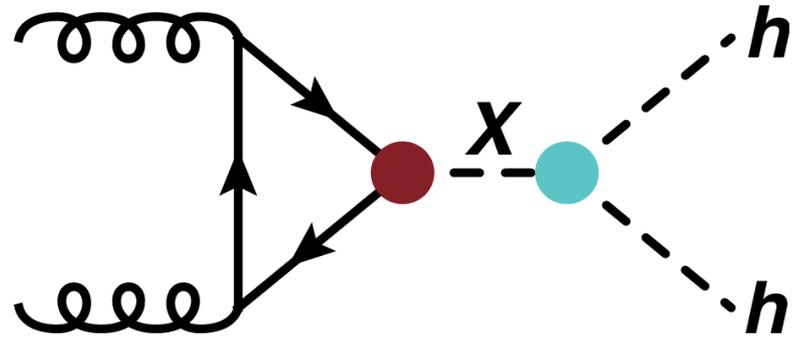
- WH resonance search
 - $e\nu$ $b\bar{b}$ channel
 - Three excess events at $m_{WH}=1.8-1.9\text{TeV}$, 2.9σ (global: 1.9σ)
 - No excess observed in the μ channel.
 - No excess observed by ATLAS
 - early access at 13 TeV



arXiv:1601.06431

HH → bbyγ

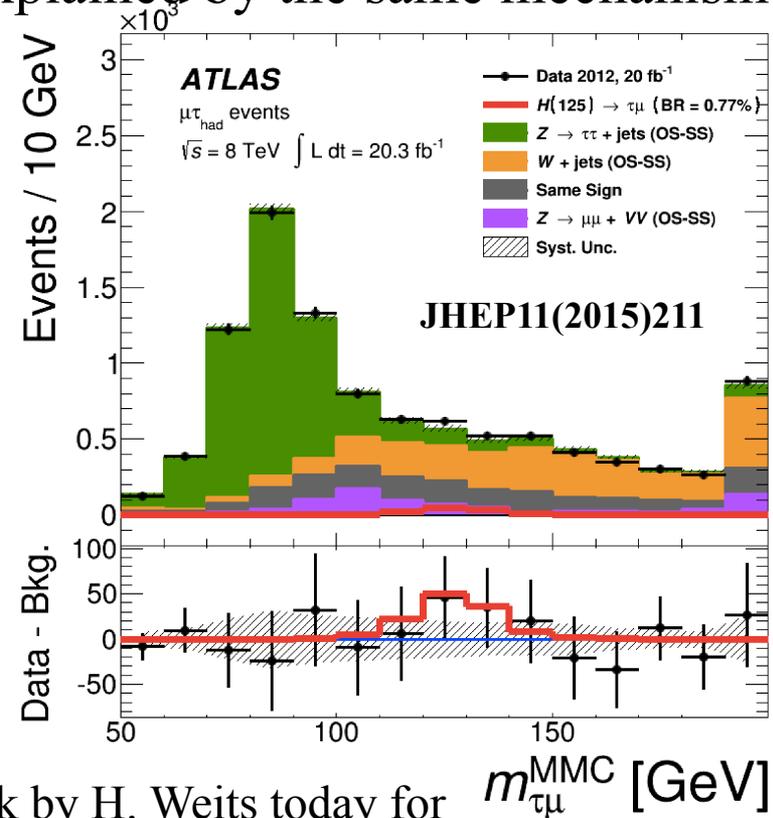
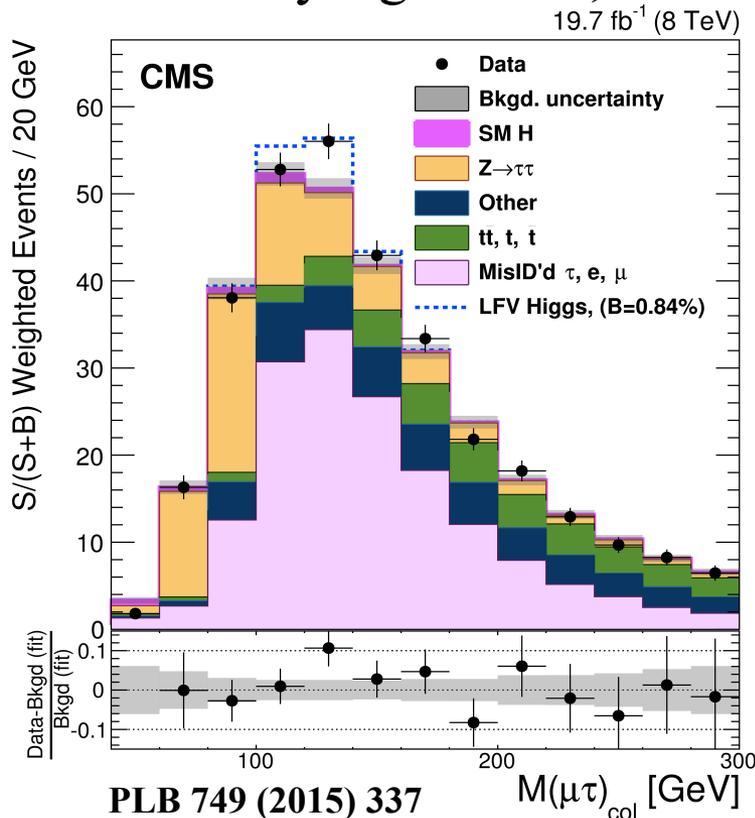
- Resonant search
 - 3σ tension with SM (global: 2.1σ):
 - 5 events around 300 GeV with <1 expected
 - No corresponding CMS run 1 result
 - Not observed in other HH searches



LFV $H \rightarrow \tau\mu$

- CMS: 2.4σ excess, best-fit: $\mathcal{B}(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ [$\mu\tau_e, \mu\tau_h$]
- ATLAS: 1σ , $\mathcal{B}(H \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$ [$\mu\tau_h$]
- LHCb sees hints of LFV in B decays ($B \rightarrow K l l$)

So far not very significant, but could be explained by the same mechanism



see talk by H. Weits today for details on the ATLAS result

LFV $H \rightarrow \tau\mu$: update

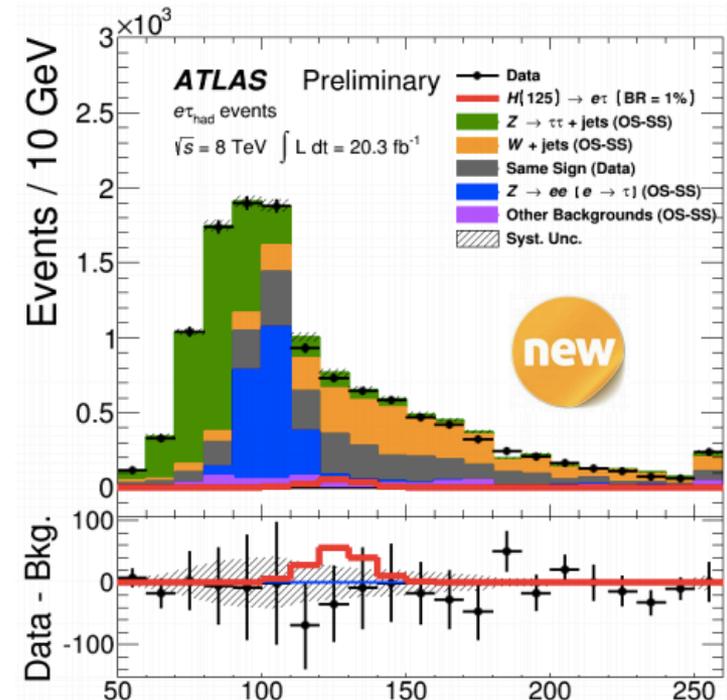
- CMS: 2.4σ excess, best-fit: $\mathcal{B}(H \rightarrow \mu\tau) = (0.84^{+0.39}_{-0.37})\%$ $[\mu\tau_e, \mu\tau_h]$
- ATLAS: 1σ , $\mathcal{B}(H \rightarrow \mu\tau) = (0.77 \pm 0.62)\%$ $[\mu\tau_h]$
- LHCb sees hints of LFV in B decays ($B \rightarrow Kll$)

So far not very significant, but could be explained by the same mechanism

- BR(1%) would suggest BSM physics at ≈ 1 TeV
 - But difficult to reconcile with absence of $H \rightarrow e\mu$ observation

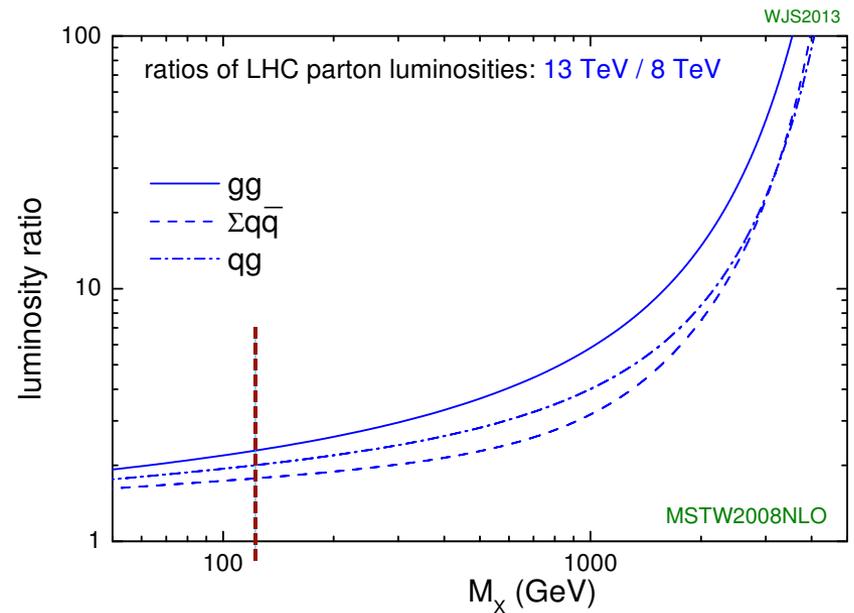
- ATLAS update:
 - $e\tau, \mu\tau_1$ spot-on with SM expectation
 - $e\tau$: $\mathcal{B}(H \rightarrow e\tau) < 0.69\%$ (95% CL)
 - $\mu\tau_1$: $\mathcal{B}(H \rightarrow \mu\tau) < 1.9\%$ (95% CL)

see talk by H. Weits today for details on the ATLAS result



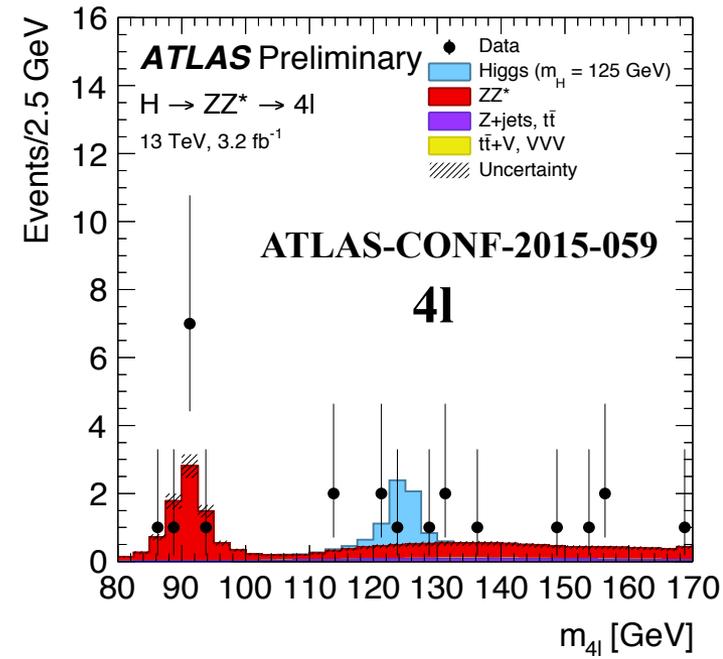
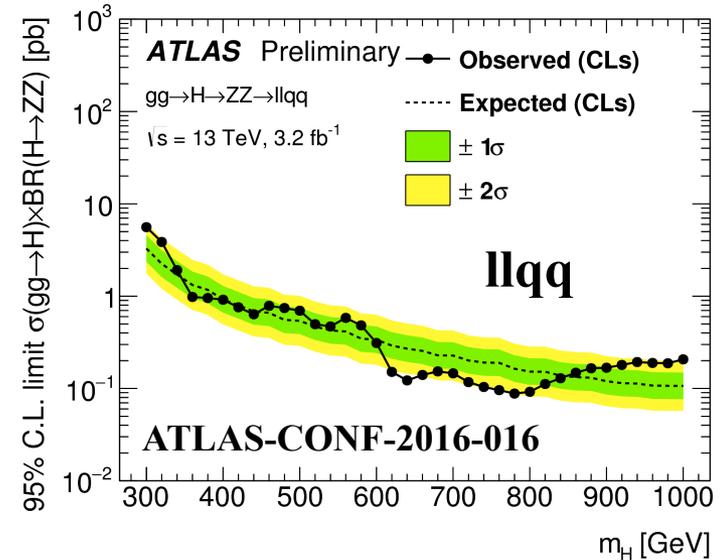
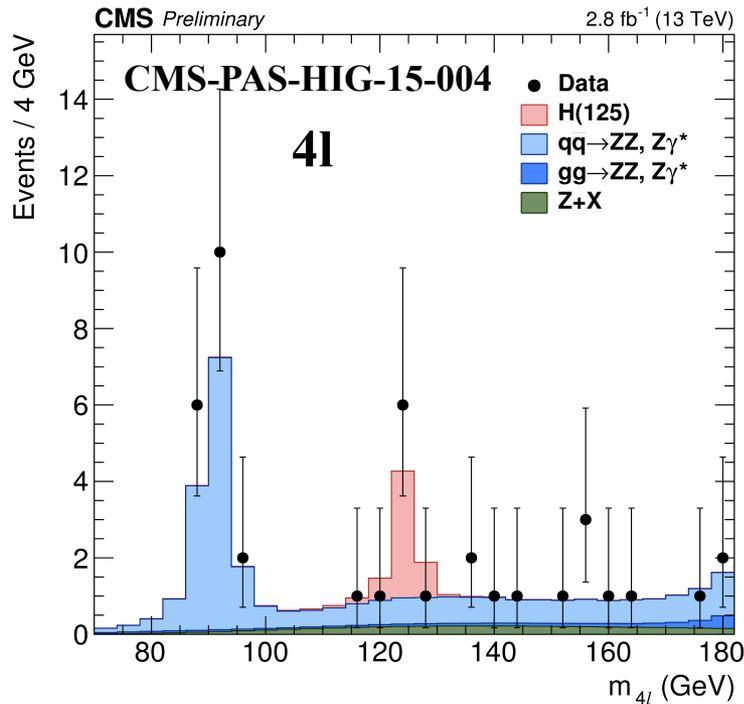
Run 2: 13 TeV results

- $H \rightarrow 4l$
- $H \rightarrow \gamma\gamma$ (+MET)
- VH
- ttH
- HH



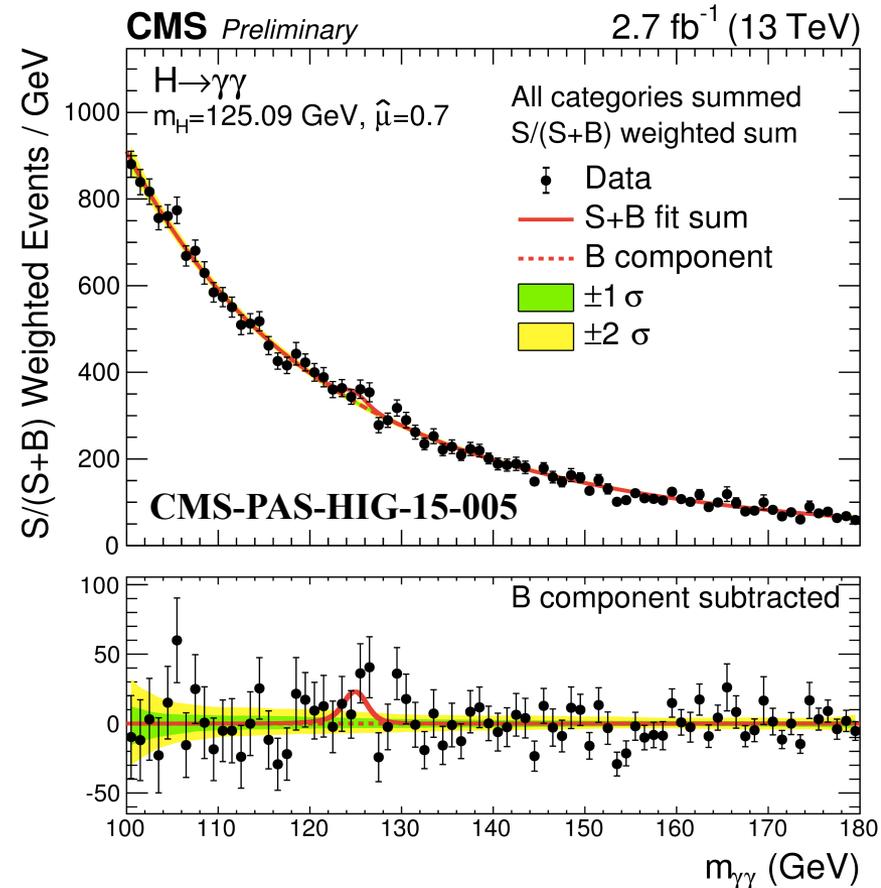
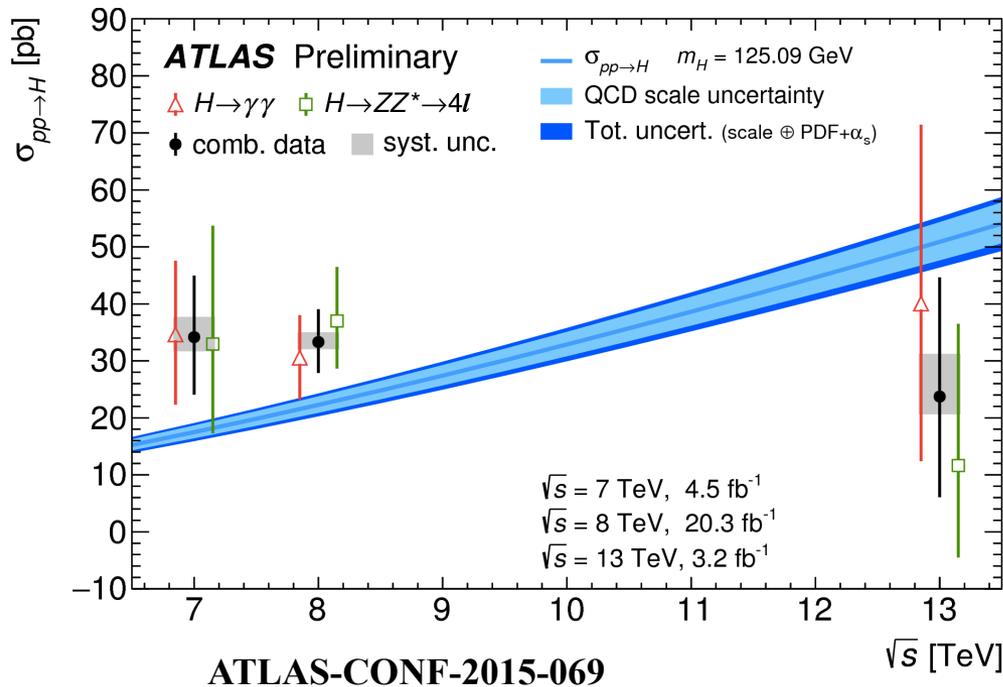
H → 4l

- Statistics-limited
 - CMS significance: 2.5σ (exp: 3.4σ)
- Searches for $X \rightarrow ZZ$:
 - $llll$, $llqq$, $ll\nu\nu$: agree with SM



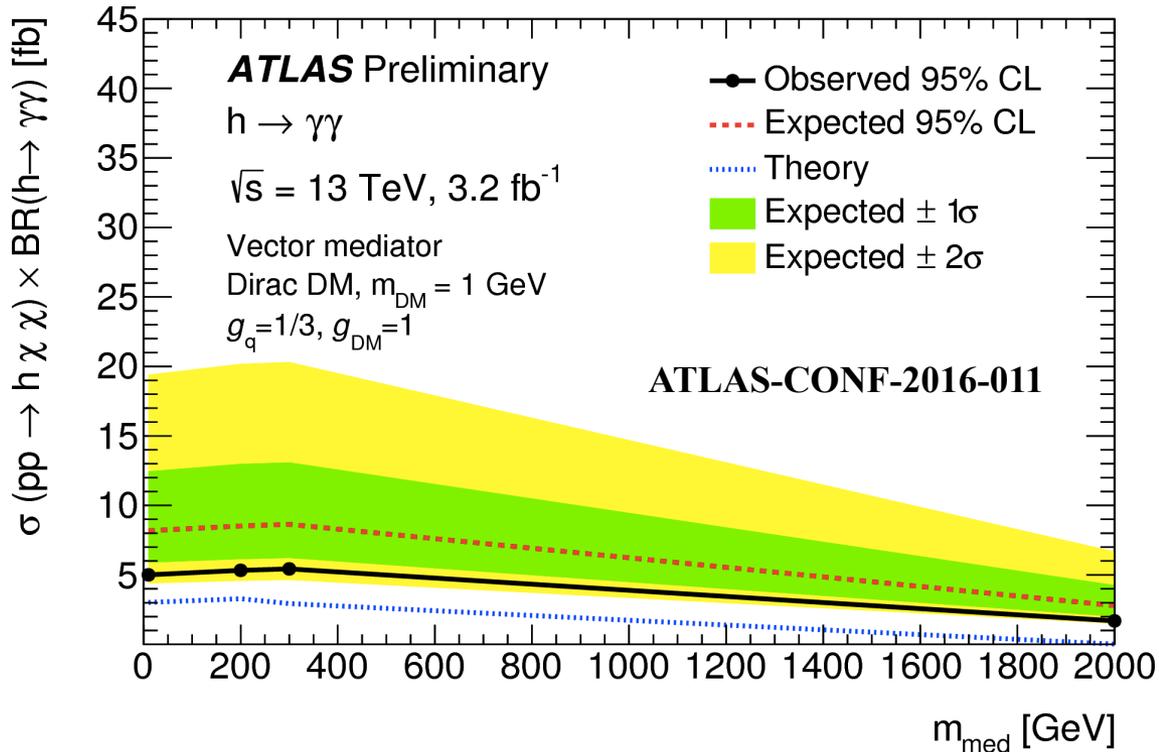
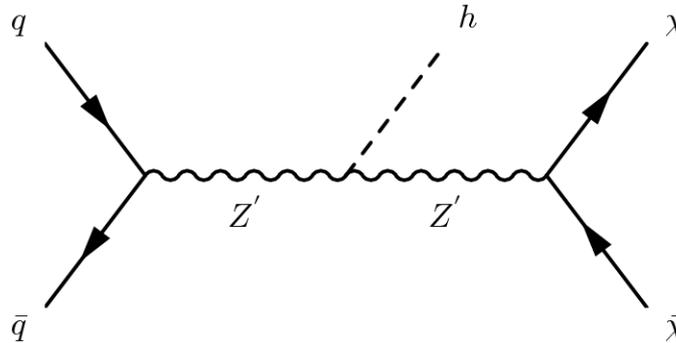
H \rightarrow $\gamma\gamma$ and combination with 4l

- CMS significance: 1.7σ (exp: 2.7σ)
- ATLAS: Combined total cross section measurement
 - Agrees with SM expectation



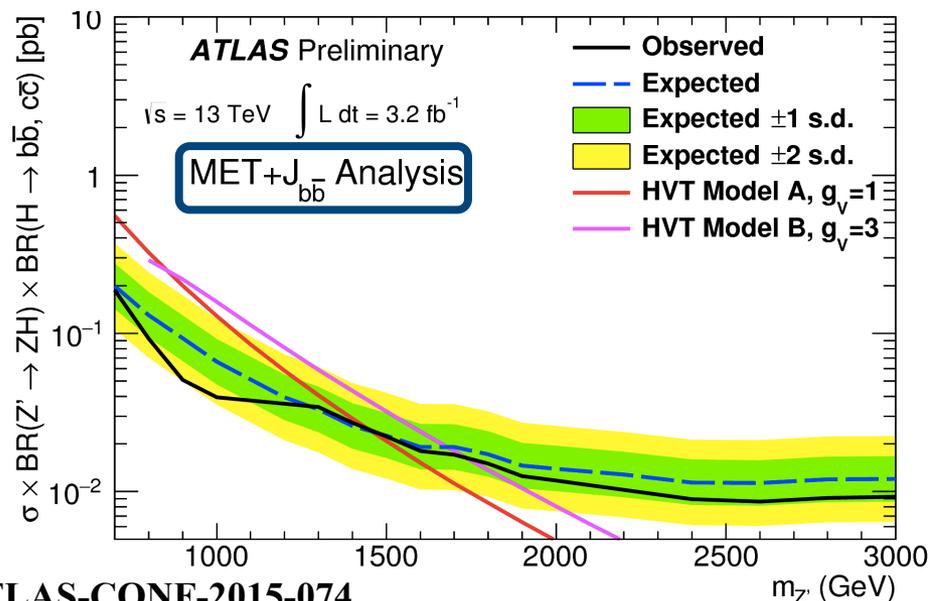
H($\rightarrow\gamma\gamma$) + MET search

- H + MET: DM search
 - results agree with SM

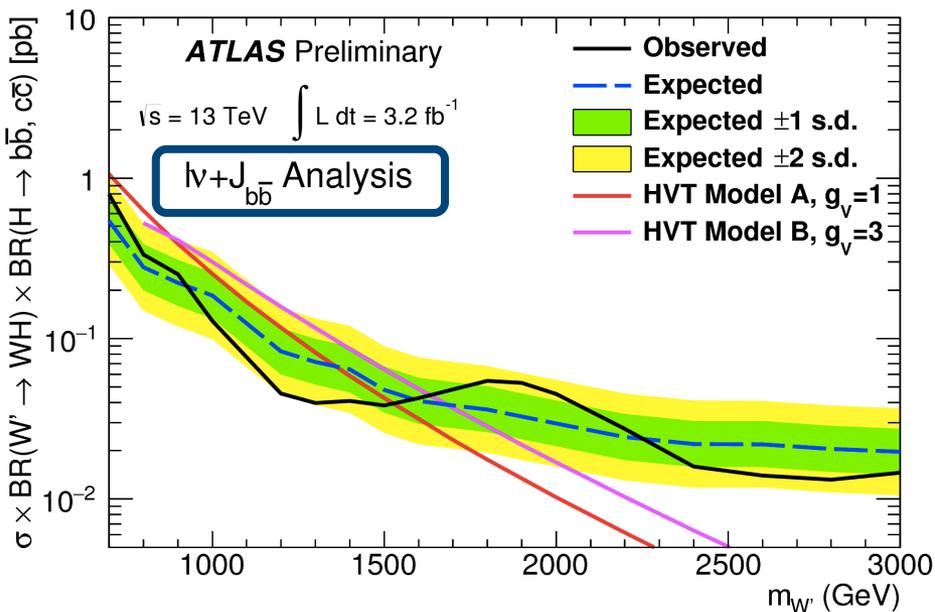
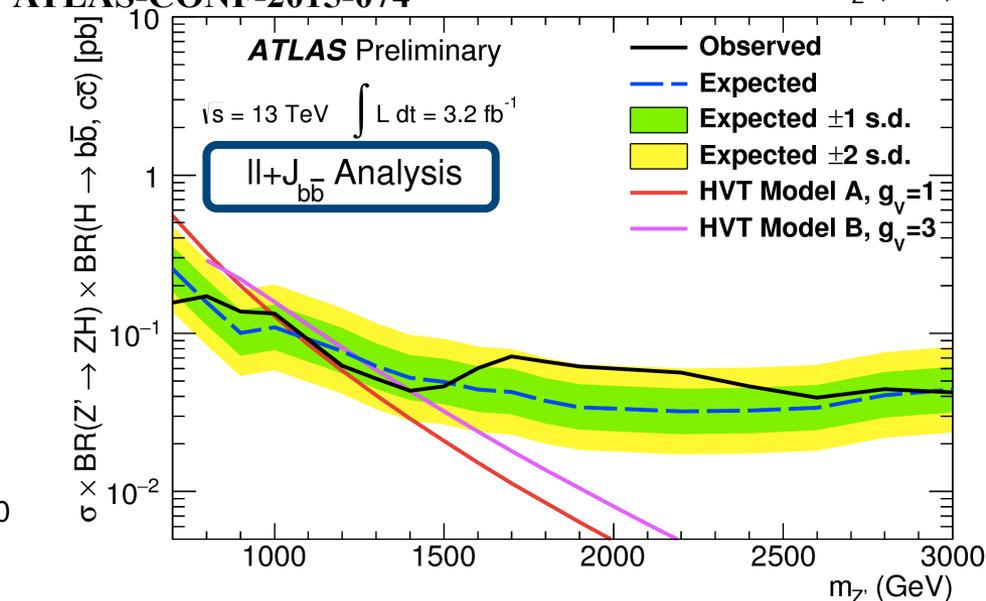


VH resonances

- Remember: CMS: a few excess events in run-1 (evbb), 1.85 TeV
 - 2015 sensitivity similar or better than for run 1
 - Run 2 result
 - consistent with SM: no significant excess



ATLAS-CONF-2015-074



- 2015 data equivalent to 50% of run 1 [factor 4 increase in cross section]
- Run 1 combination: 2σ tension with SM
- Run 2: CMS results for $\gamma\gamma$, bb, leptons
 - Good agreement with SM, deficit in bb

ttH($\gamma\gamma$)

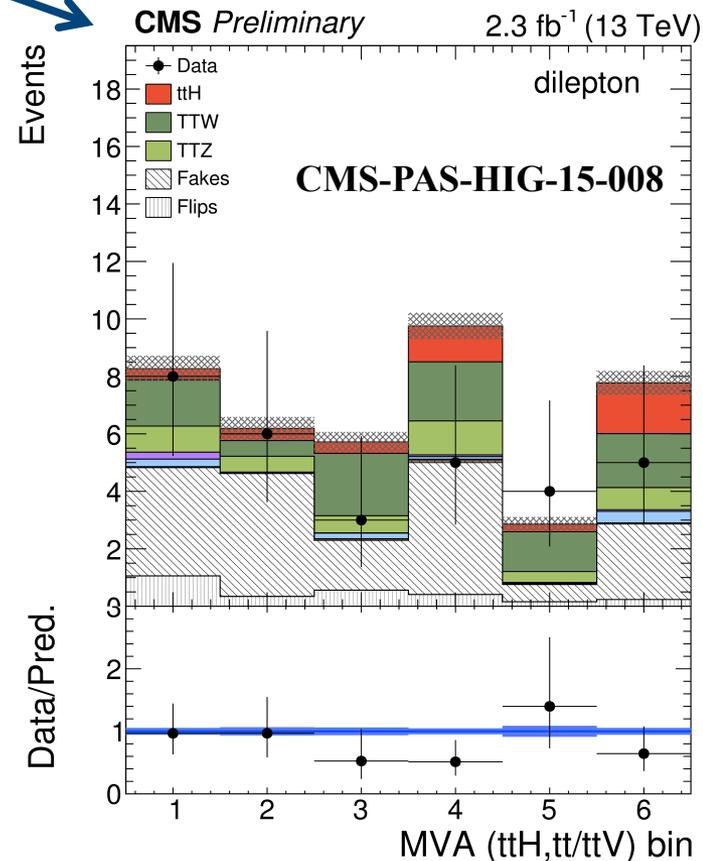
$$\hat{\mu}_{\text{obs}} = 3.8^{+4.5}_{-3.6}$$

ttH(multilepton)

$$\hat{\mu}_{\text{obs}} = 0.6^{+1.4}_{-1.1}$$

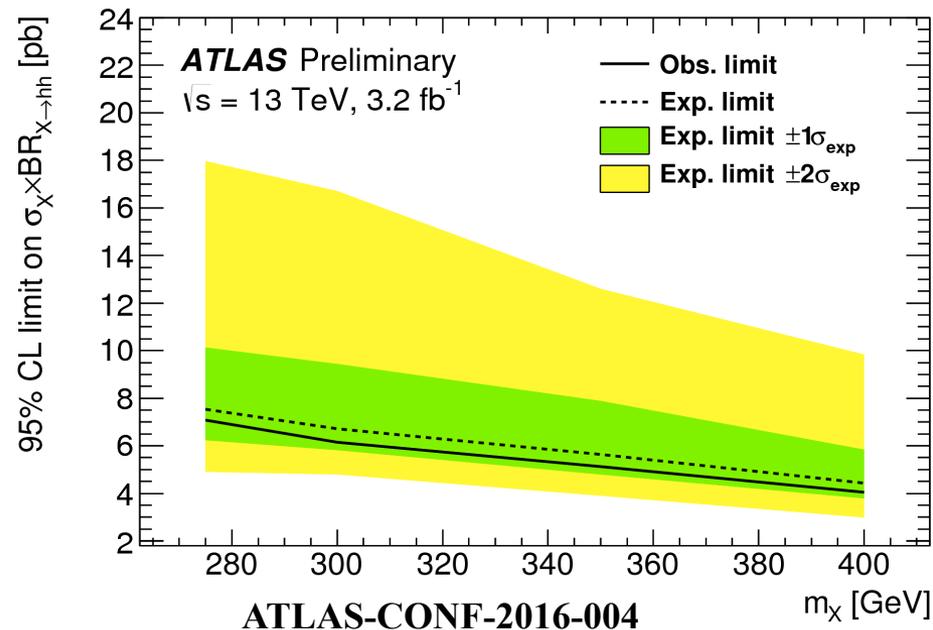
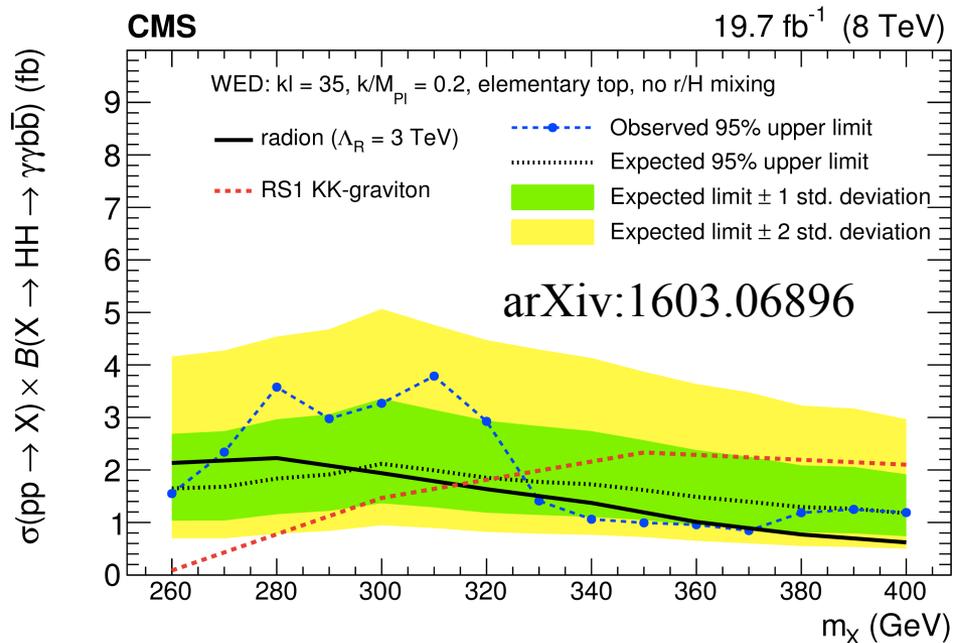
ttH(bb)

$$\hat{\mu}_{\text{obs}} = -2.0^{+1.8}_{-1.8}$$



HH → bbyγ

- 3σ effect in run 1: ATLAS bbyγ (300 GeV)
- 2015: Neither CMS nor ATLAS observe any excess
- ATLAS run 1 result: would translate to two expected events at ≈300 GeV for the 2015 dataset [under certain assumptions]
 - The current result excludes more than 3 events at 95% C.L.



Prospects: LHC & beyond

"Data! Data! Data!"

he cried impatiently.

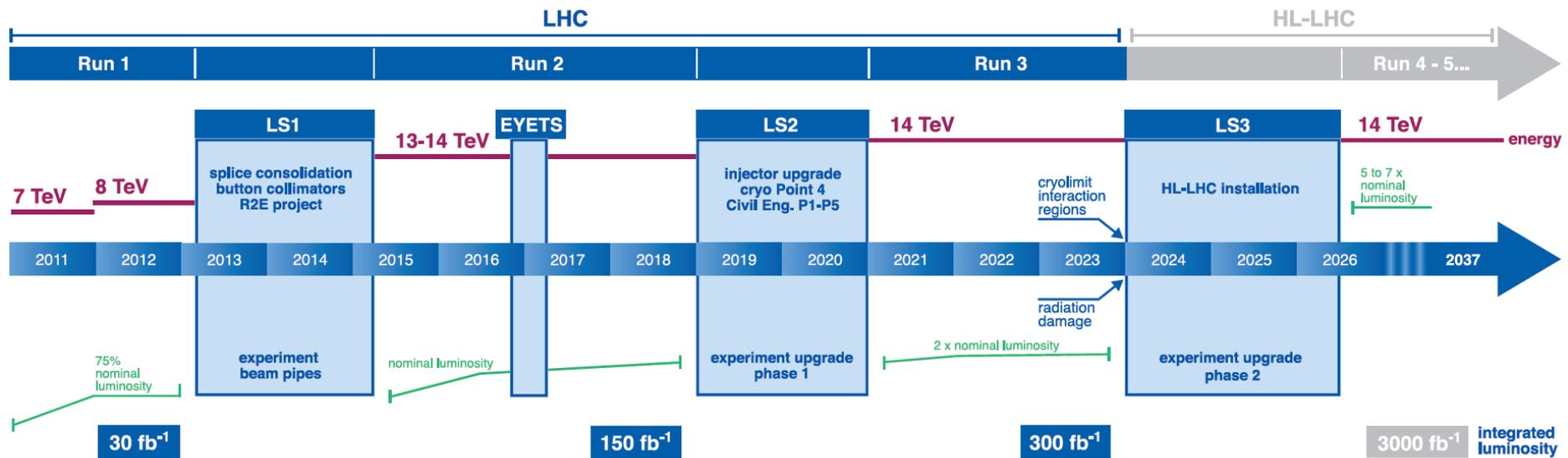
"I can't make bricks without clay."

*Sherlock Holmes, in: Arthur Conan Doyle,
The Adventure of the Copper Beeches*



LHC schedule

LHC / HL-LHC Plan

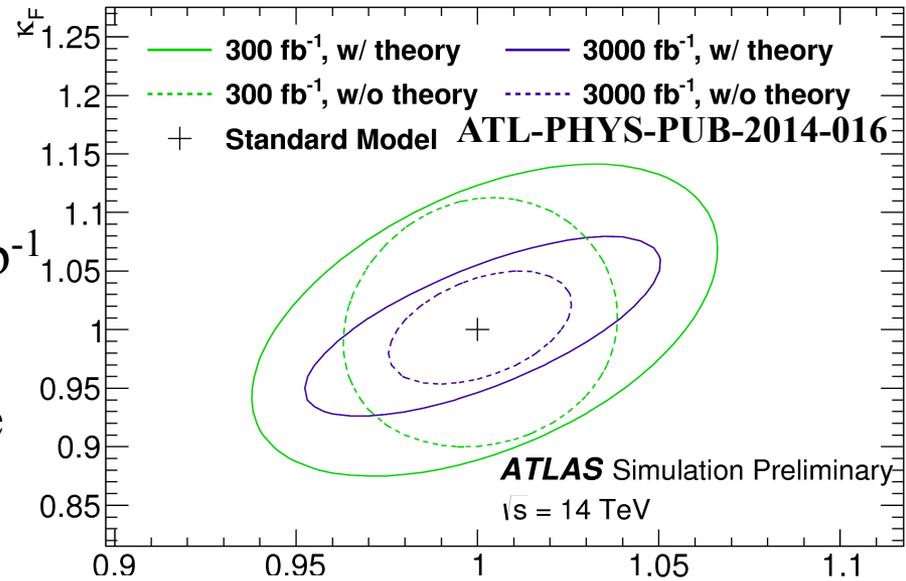


- 150 fb⁻¹: by 2018 Run 2
- 300 fb⁻¹: by 2023 Run 3
- 3000 fb⁻¹: by 2037 High-lumi LHC (HL-LHC)

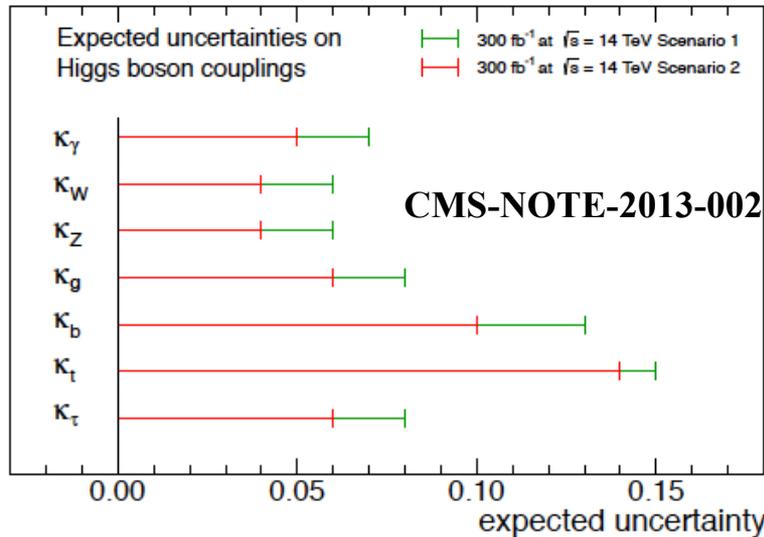
- More than 10x the parton luminosity of Run 1 [150 fb^{-1} at 13 TeV]
 - Until end of 2018 at latest,
 - All 3σ -ish excesses will either disappear, be revealed as systematic effects or have led to new discoveries
 - precision in Higgs coupling measurements will enter the really interesting regime: hints or constraints of SUSY, composite Higgs, singlet Higgs, twin Higgs
 - Projections exist only for 300 fb^{-1}
 - In addition to current flagships, these will start getting more attention:
 - ttH production
 - HH production
 - $\mu\mu$ decays
 - $Z\gamma^*$ decays
- cross section increase: factor 4
- } not measured yet, limits getting closer to SM cross section

LHC by 2023 and 2037: couplings

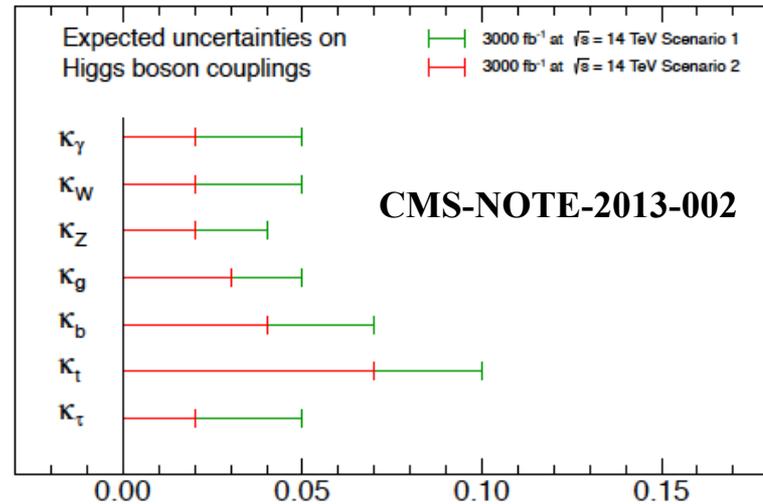
- Precision per experiment, 300 fb⁻¹:
 - ≈5% : bosons (today: 20-30%)
 - ≈10%: fermions (τ,b,t; today 30%)
- Substantial improvement with 3000 fb⁻¹
 - Uncertainties will be almost halved
- 5-20% are needed to probe composite Higgs, MSSM, additional H singlet



CMS Projection



CMS Projection

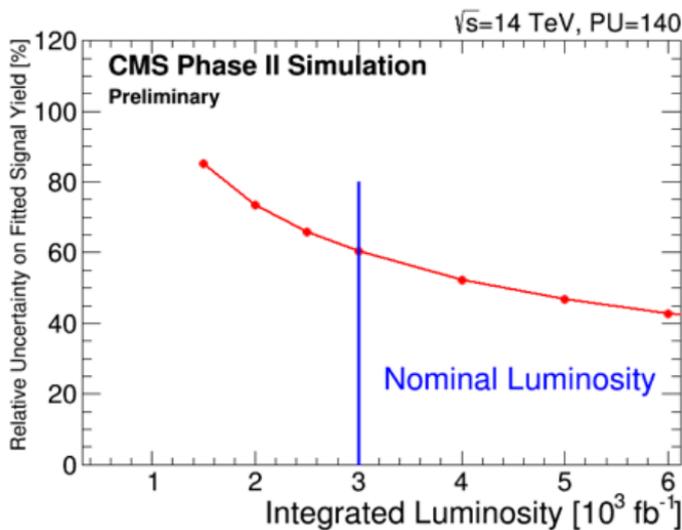
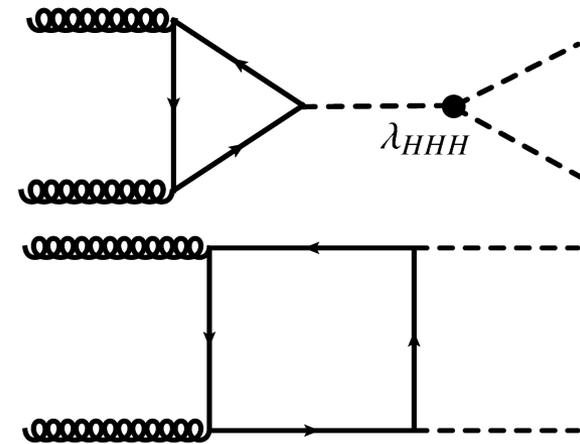
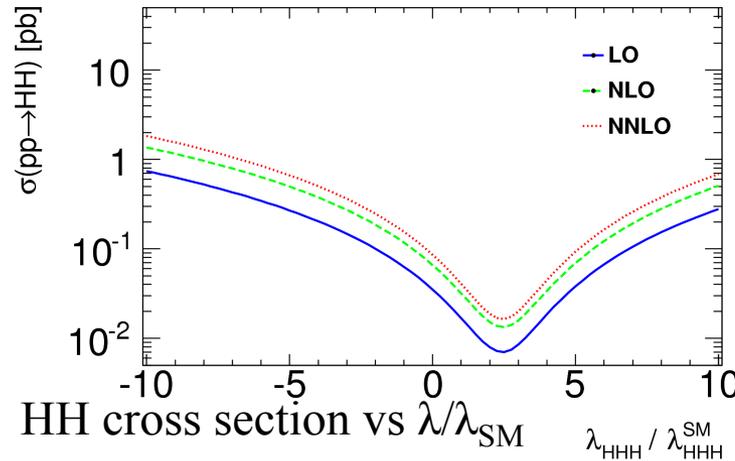


Scenario 1: Systematics as in Run 1

Scenario 2: TH uncertainties halved; other systematics ~√lumi

LHC by 2037: self-coupling

SM: Negative interference between HH production with and without HHH vertex

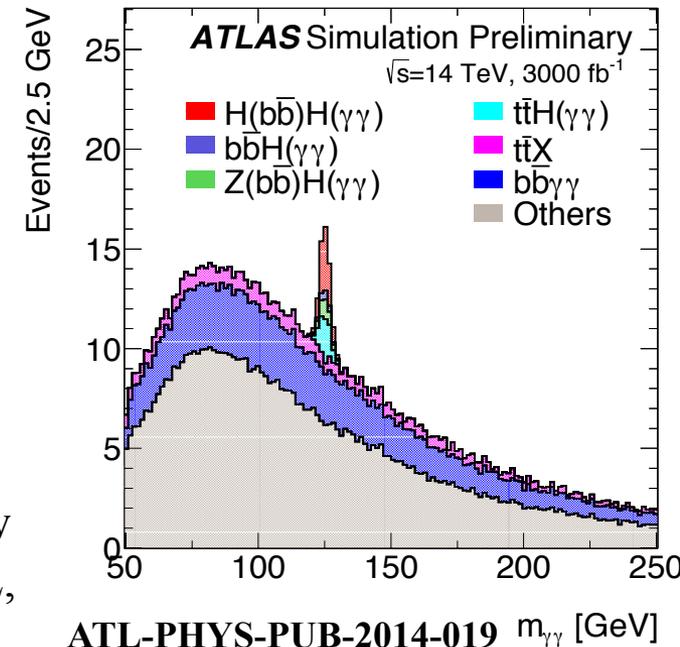


ECFA CMS Results

HH \rightarrow bb $\gamma\gamma$

3000 fb^{-1} :
 CMS: relative unc. on HH cross section: 60%
 ATLAS: exp. significance for HH production: 1.3σ

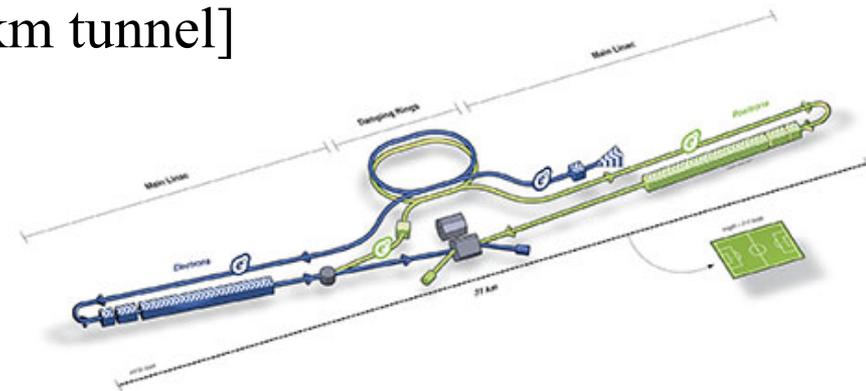
8-10 signal events
 \Rightarrow potential for self-coupling measurement low (λ/λ_{SM} in $[-1;9]$ at 95% CL, SM expectation)



ATL-PHYS-PUB-2014-019 $m_{\gamma\gamma}$ [GeV]

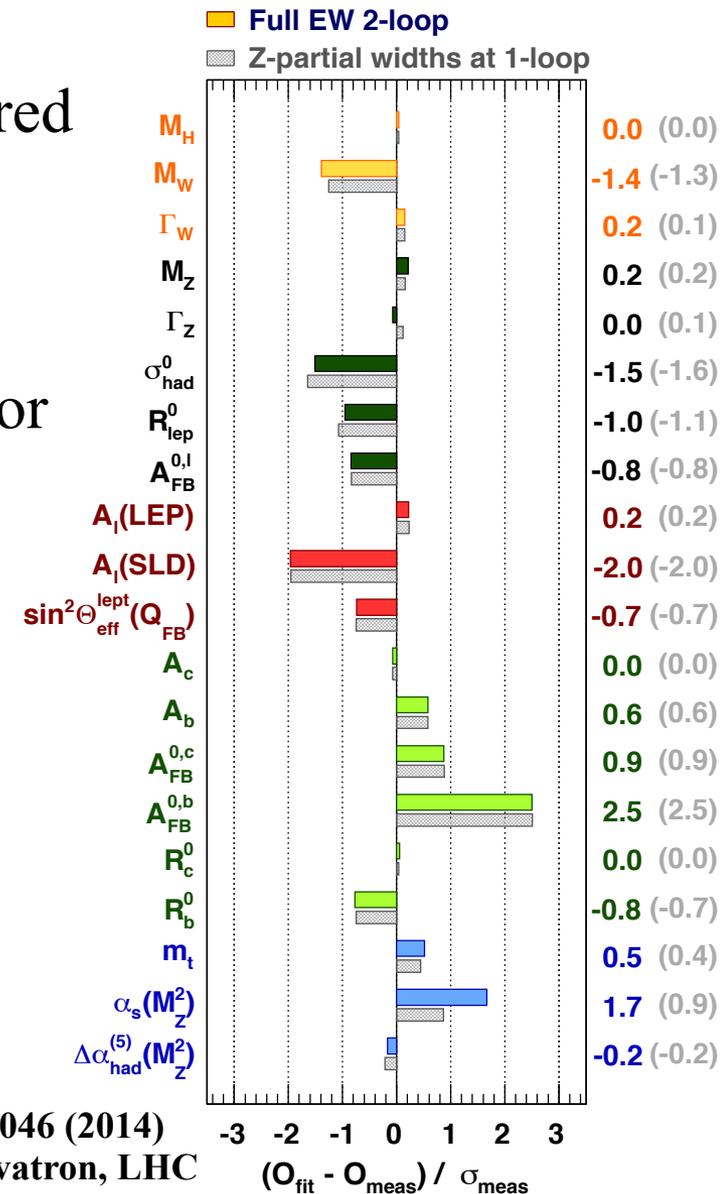
Higgs searches beyond the LHC

- couplings in atomic physics [novel idea] arXiv:1601.05087
 - LHC cannot probe coupling to 1st-generation fermions
 - Higgs boson: attractive force between nuclei and electrons
 - Potential proportional to $y_q y_e$ ($q=u,d$)
 - Leads to a shift in transition energies
 - Can be measured with high precision $O(10^{-15})$
 - theoretical uncertainties are larger, but partially cancel when comparing isotopes
- Precision measurement of the Higgs sector, in particular: total width; self-coupling; other couplings
 - ILC (Japan) [$\sqrt{s}=0.5-1$ TeV, 50-70km tunnel]
 - CEPC (China): Higgs factory [$\sqrt{s}=240-250$ GeV, 30km length]
 - CLIC, FCC, muon collider, ... ?



Consistency of the EW theory

- Global EW fit (Gfitter collaboration) after Higgs boson discovery & m_H measured
 - $\chi^2 / \text{dof} = 17.8 / 14$ (p value: 0.21)
[for $m_H=300$ GeV, would be $p=3 \times 10^{-5}$]
- For the first time: self-consistent EW sector
 - **No direct observation of BSM physics**
 - **No (indirect) indication of BSM physics in measurements**
- Time to forget about the Higgs boson and move on to something more interesting?



Eur. Phys. J. C 74, 3046 (2014)
Data: LEP, SLC, Tevatron, LHC

Why the Higgs sector is still awesome

- Open questions related to the Higgs sector

- **Naturalness:** $m_H^2 \sim \mu^2 + c\Lambda^2$.

- If it is real: low fine-tuning requires TeV-scale BSM physics (for 1%: $\Lambda < 10$ TeV)

- **Vacuum stability**

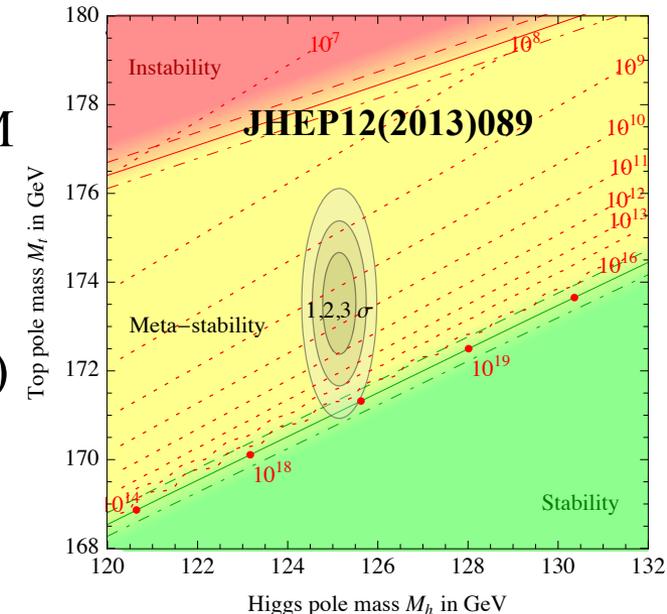
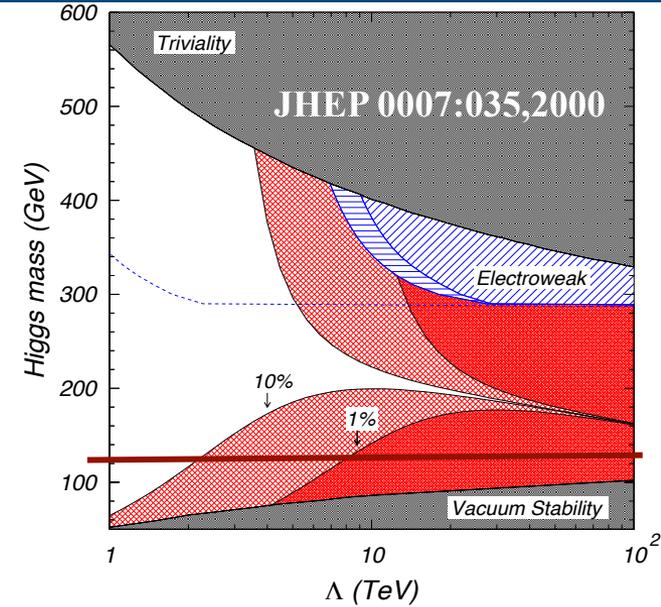
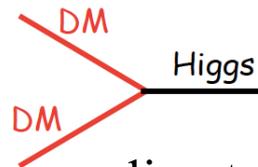
- Nature of EW vacuum tied to m_{top} and m_H

- **Dark matter, dark sector**

- H could be the only SM particle coupling to DM

- Indirect **probe for BSM physics**

- BSM models: typical effect on couplings $O(5\%)$
 - MSSM, composite Higgs, twin-Higgs, add. singlet
 - Just about to enter this region of precision!





Backup slides

Kappa framework

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{ see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_c^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_s^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\mu^2$$

arXiv:1307.1347

Modified couplings, parameterized in terms of scale factors κ

- single-resonance assumption
- narrow width assumption
- no change of tensor structure in fields and couplings

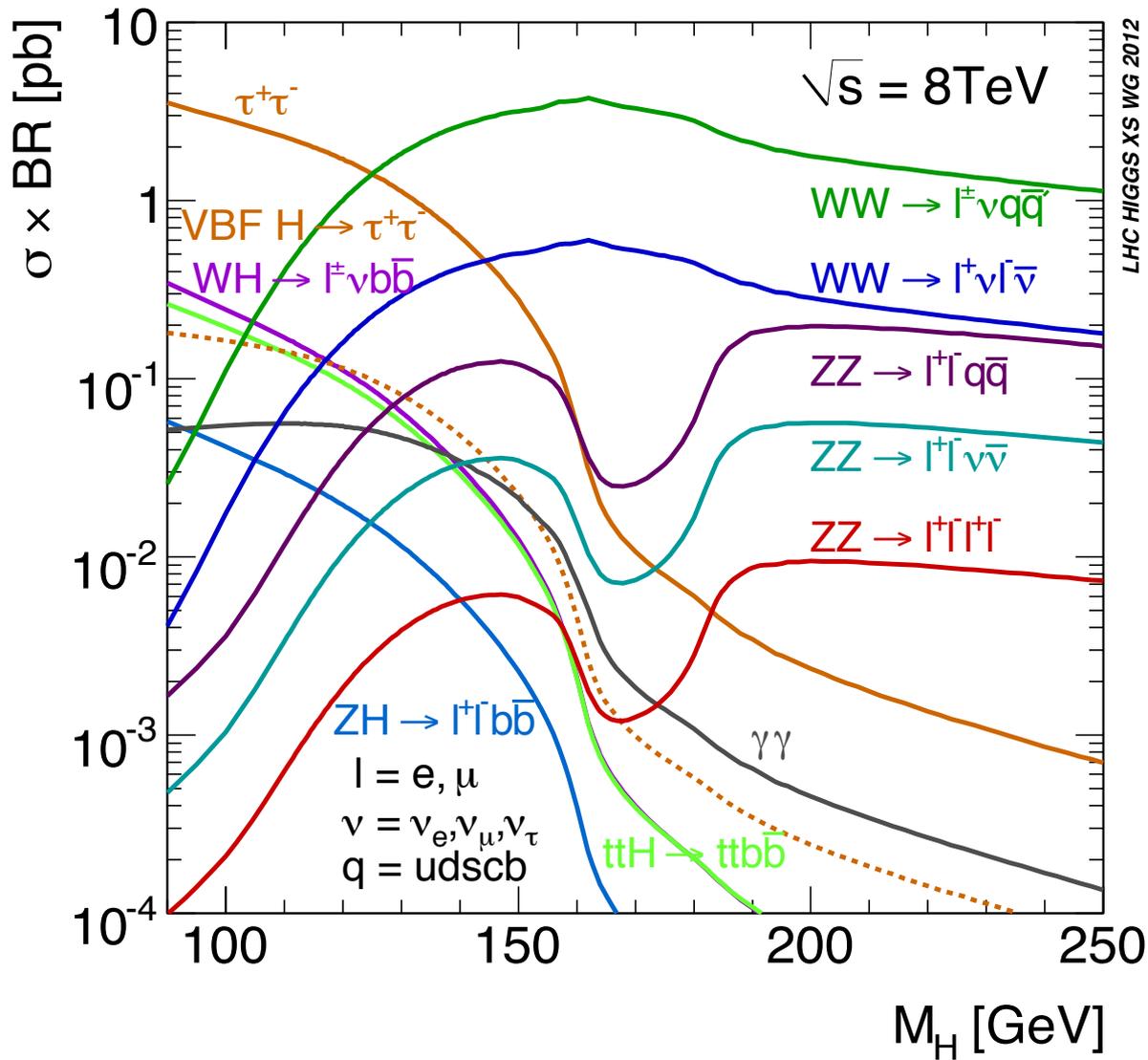
Example : diphoton
from gluon fusion

$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \sigma_{SM}(gg \rightarrow H) \cdot BR_{SM}(H \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$\sigma \times \text{BR}$ (SM)



OAW



Width measurement

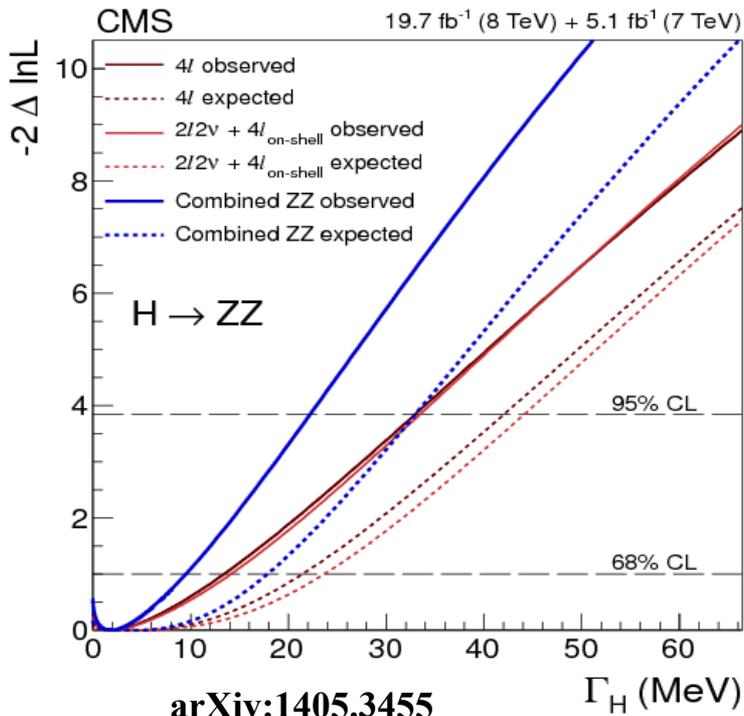
- Direct: ATLAS: $H \rightarrow \gamma\gamma$: Width limit: 5.0 GeV; $H \rightarrow ZZ$: 2.6 GeV
- CMS: $H \rightarrow \gamma\gamma$: Width limit: 2.4 GeV; $H \rightarrow ZZ$: 3.4 GeV
- Indirect: Coupling fits and Higgs-to-invisible searches
- Indirect: From comparison of on- and off-shell $H \rightarrow 4l$ signal strength

Phys. Rev. D. 90, 052004

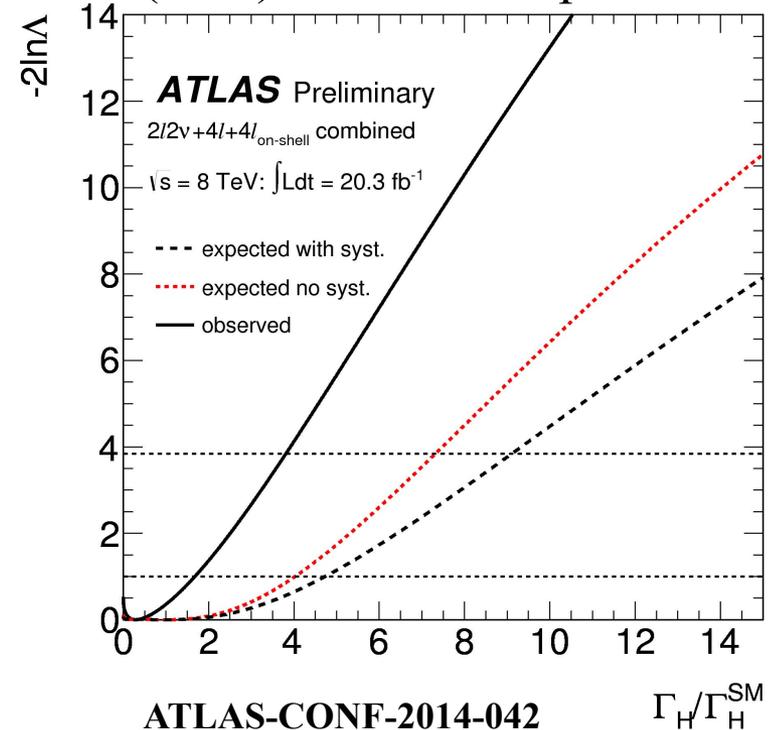
arXiv:1312.5353

arXiv:1407.0558

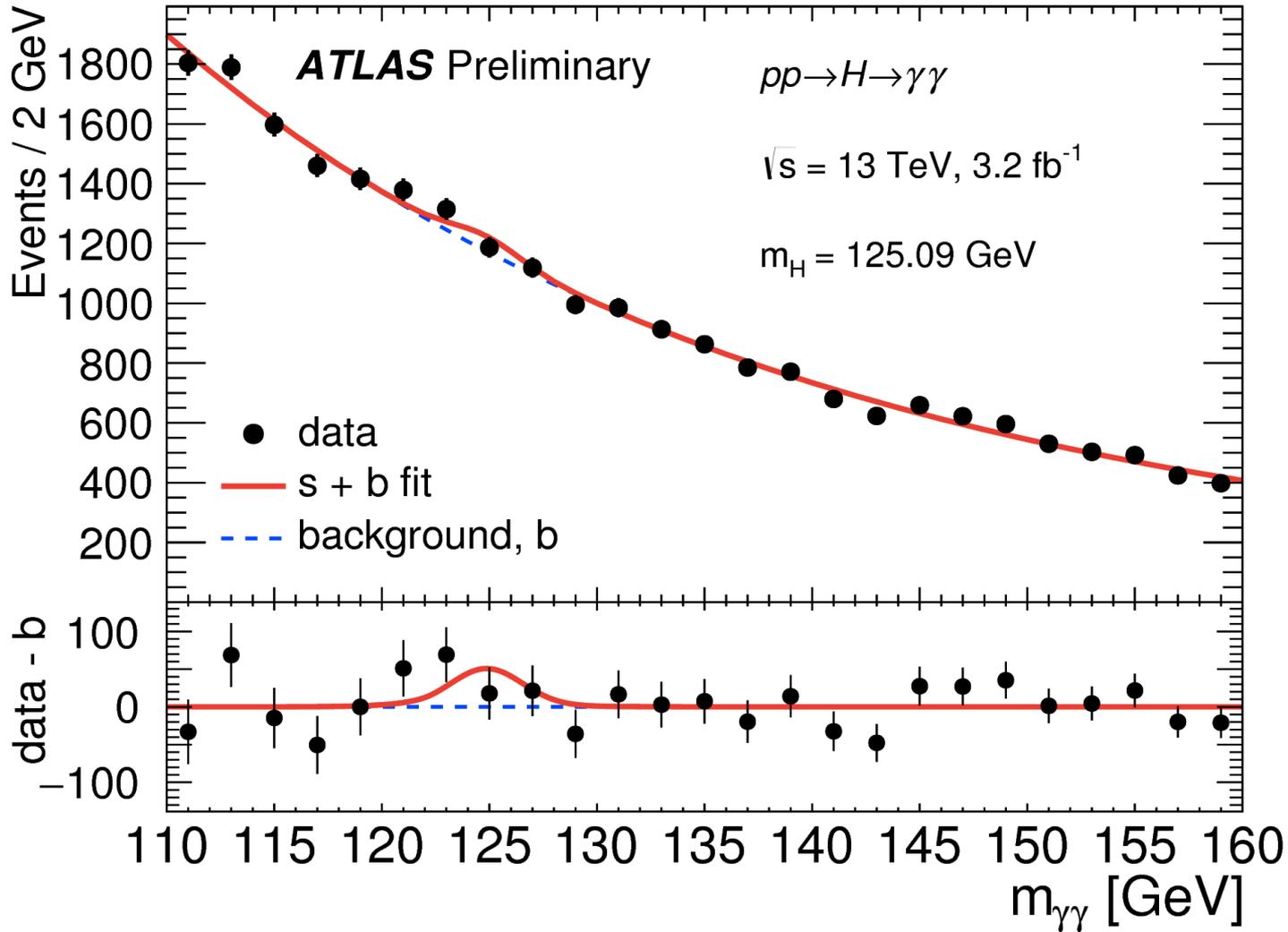
CMS: $\Gamma(H) < 22$ (33) MeV
5.4 (8.0) times SM expectation



ATLAS:
5-8 (7-12) times SM expectation



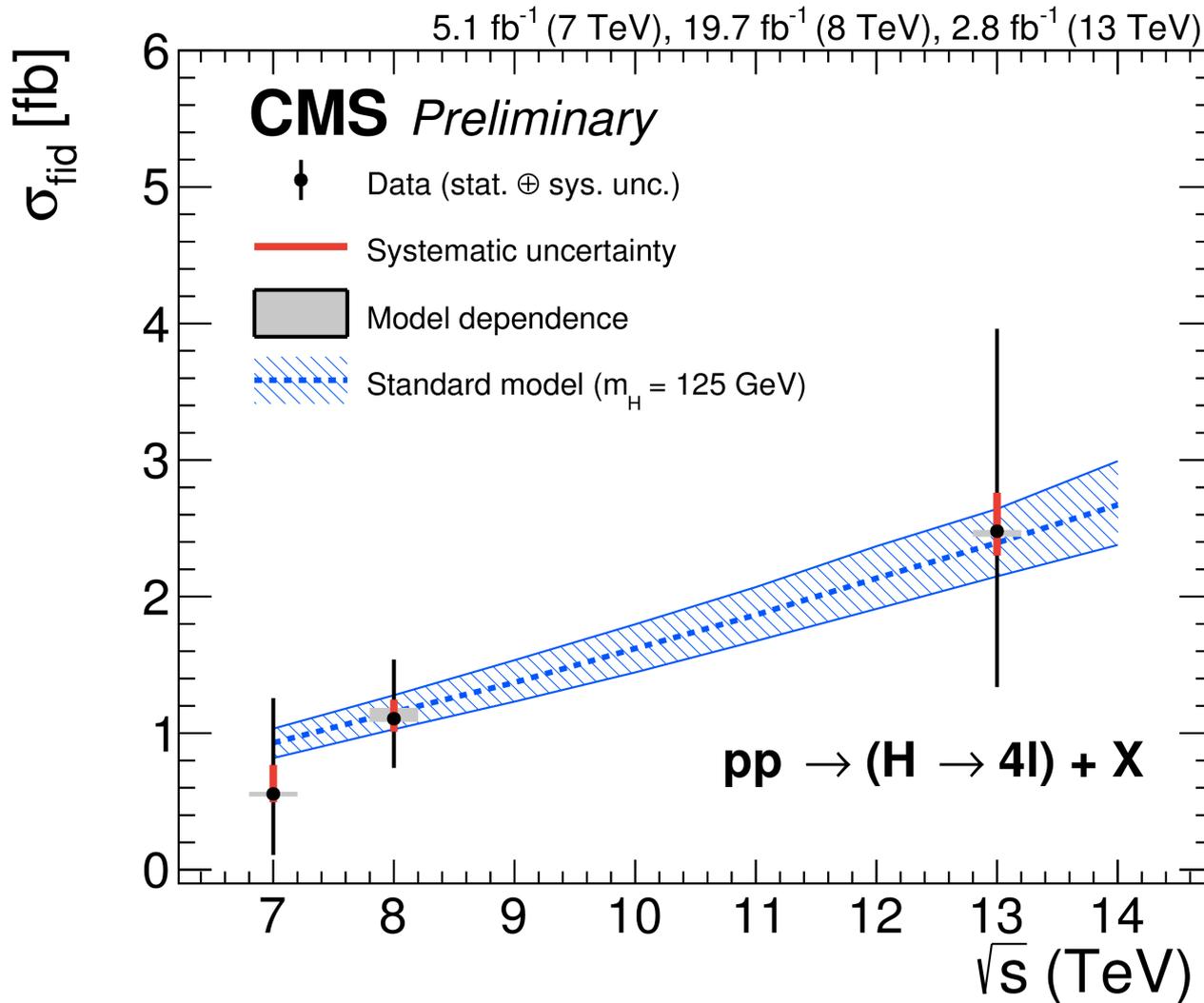
$H \rightarrow \gamma\gamma$



Cross section



OAW



$$\sigma^{\text{tot}} = \frac{N_s}{\mathcal{A} \cdot C \cdot \mathcal{B} \cdot \mathcal{L}_{\text{int}}}$$

$$\sigma_{4\ell}^{\text{fid}} = \frac{N_s}{C \cdot \mathcal{L}_{\text{int}}}$$

Couplings projection: assumptions

ATLAS:

Parametrisation of the detector response derived from

- full run 1 detector simulation with pile-up up to $\langle\mu\rangle = 69$ and
- full Phase I detector simulation for $\langle\mu\rangle$ up to 80 and 14 TeV cms energy.
- Also simulation of Phase II detector options for $\langle\mu\rangle = 80, 140, 200$ for HL-LHC.

CMS:

Rescaling of run 1 signal and background yields for 14 TeV cms energy with the assumption that current detector performance kept after upgrades. Complemented by parametrized detector simulation (e.g. for 2HDM studies).

CMS Scenario 1: Systematic uncertainties as in Run 1

CMS Scenario 2: Theory uncertainties halved;
other systematics scale with \sqrt{lumi}