Experimental Status of the Scalar Sector

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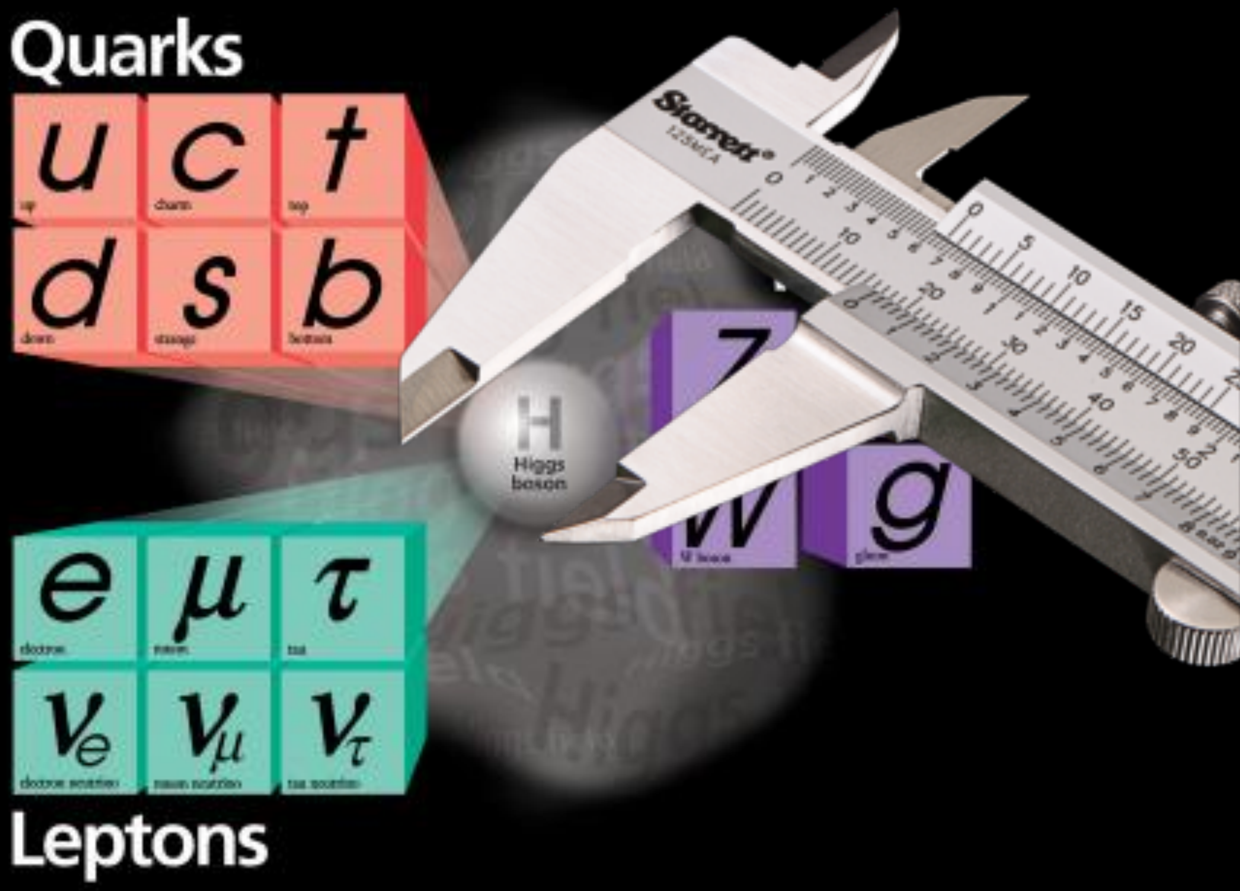
OUTLINE

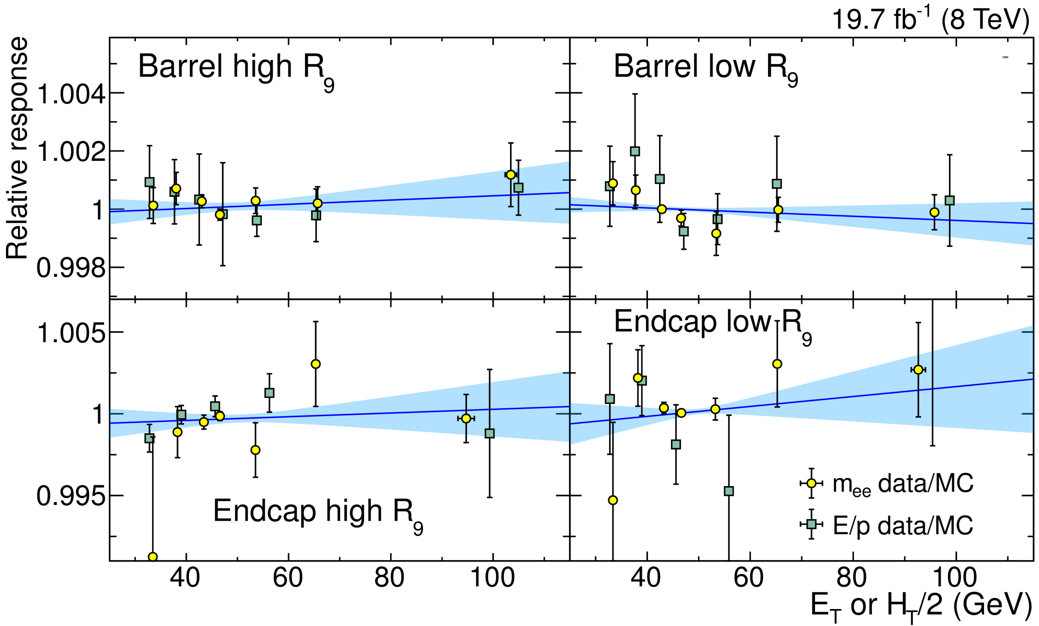
- Introduction
- 125 GeV Higgs Properties
  - Mass
  - Spin/CP
  - Width and lifetime
  - Differential cross sections
  - Higgs couplings
- Beyond the SM
  - High mass searches
  - Implications of BSM Higgs physics from couplings
  - Exotic decays
- Conclusions and Outlook



INTRODUCTION

- First Run 1 Higgs results with full dataset were first presented in March of 2013

- In the last two years, detectors were re-calibrated, reconstruction and analysis techniques were improved, and the data were re-analyzed



Error band scaled to get χ^2/dof =1

CMS Photon Performance: CERN-PH-EP-2015-006

- The final Run 1 results are in general significantly better than those presented in early 2013

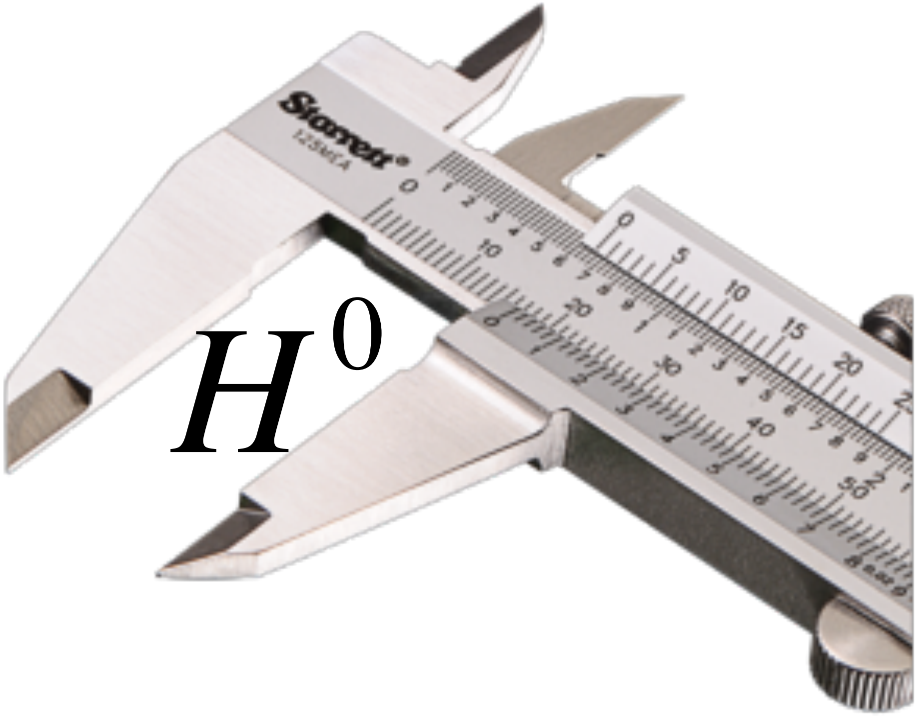
  - Legacy papers on couplings and spin CP by CMS were submitted a few months ago: Phys. Rev. D. 92.012004., Eur. Phys. J. C (2015) 75-212

  - Final results on Higgs spin CP and couplings from ATLAS recently submitted: arxiv:507.04548, arxiv:1506.05669

SM Higgs boson Physics

A comprehensive program to test the SM Higgs hypothesis:

- Precision mass measurements
- Measurement of couplings
    - Main production modes
        - ggH, WH, ZH, VBF, ttH
    - Main decay modes:
        - γγ, WW, ZZ, tt, bb
- Rare Decay modes:
    - μμ, Zγ, J/ψ γ
- Rare production modes:
    - tH, hh, bbH
- Spin and CP-mixing properties
- Width
    - Direct, off-shell couplings, interference, lifetime
- Fiducial and differential measurements



HIGGS MASS

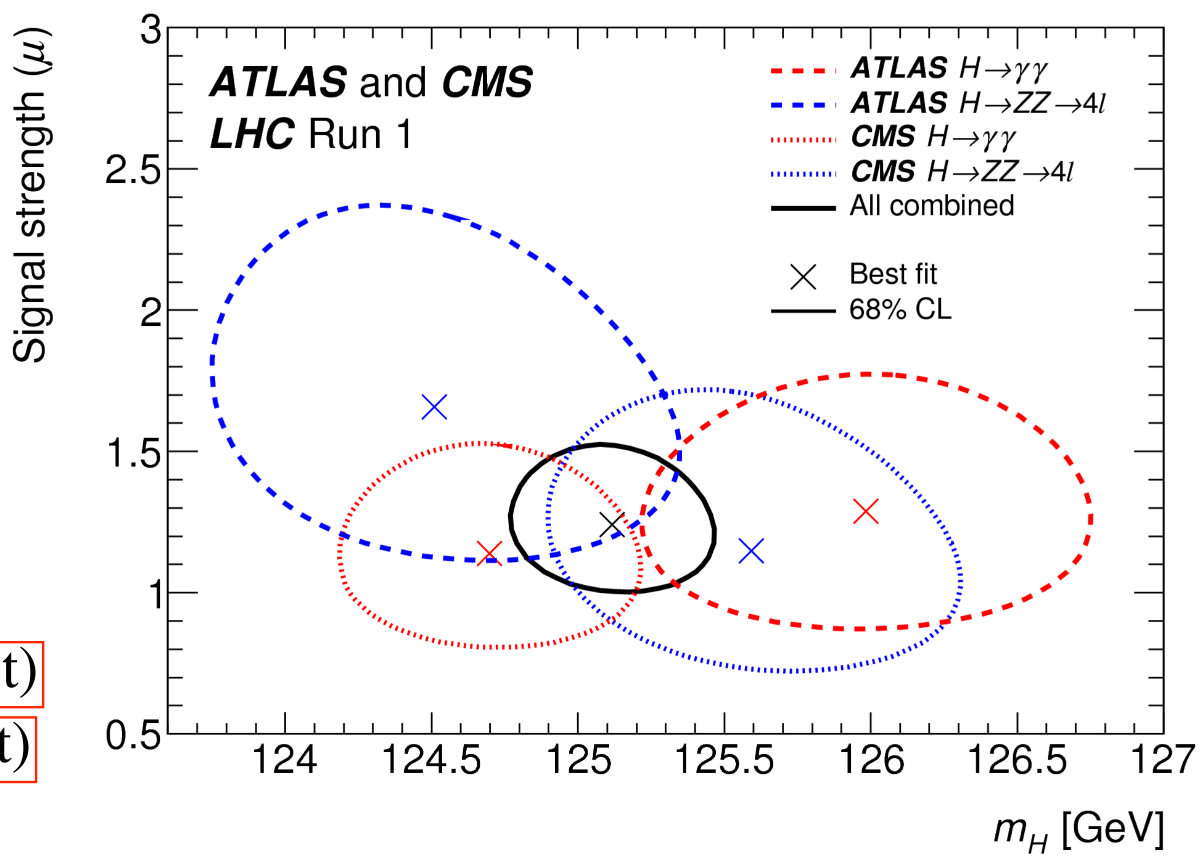
The SM does not predict the Higgs boson mass: we need to measure it

Given a mass, we can make predictions* for the production cross section and decay rates

Higgs mass measurements (GeV):

ATLAS: 125.36 ± 0.37 (stat) ± 0.18 (syst)
CMS: 125.02 ± 0.27 (stat) ± 0.15 (syst)

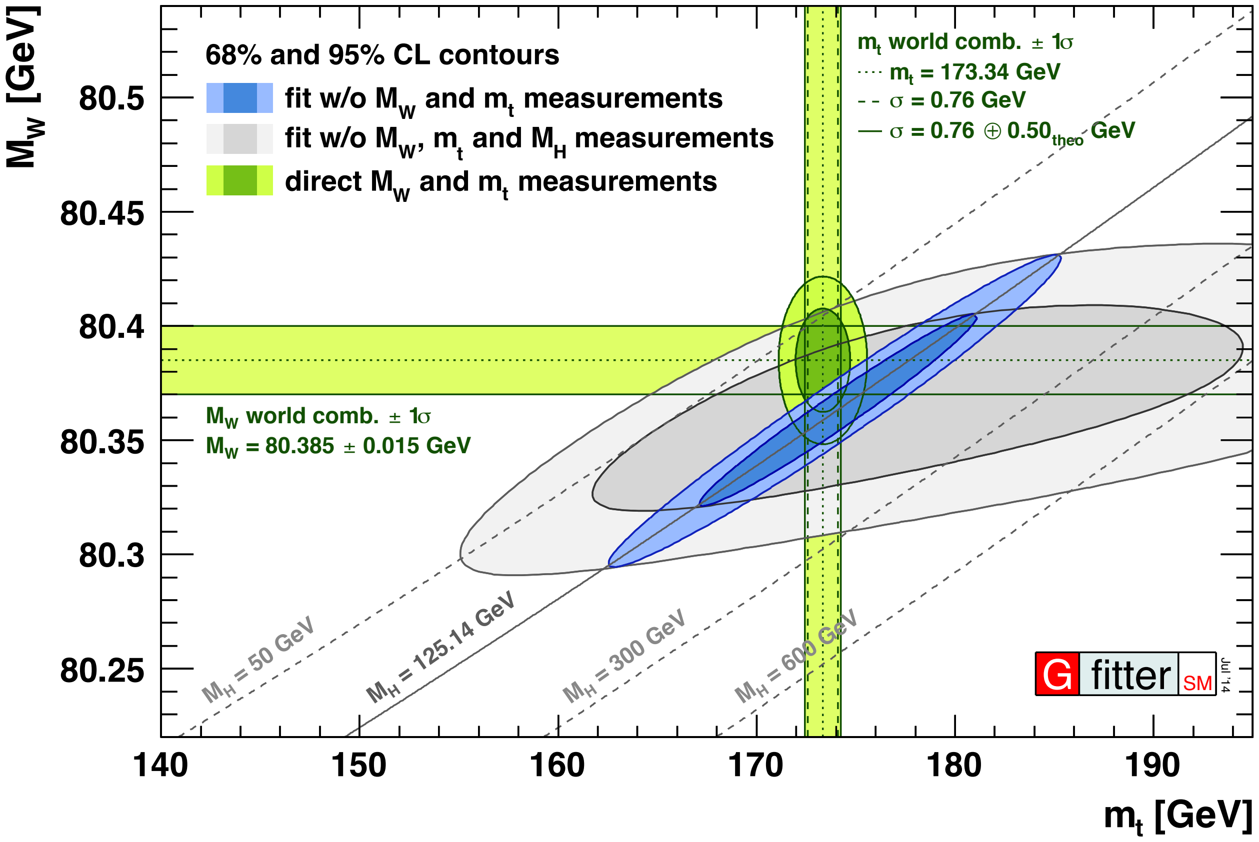
LHC combination:
125.09 ± 0.21 (stat) ± 0.11 (syst)

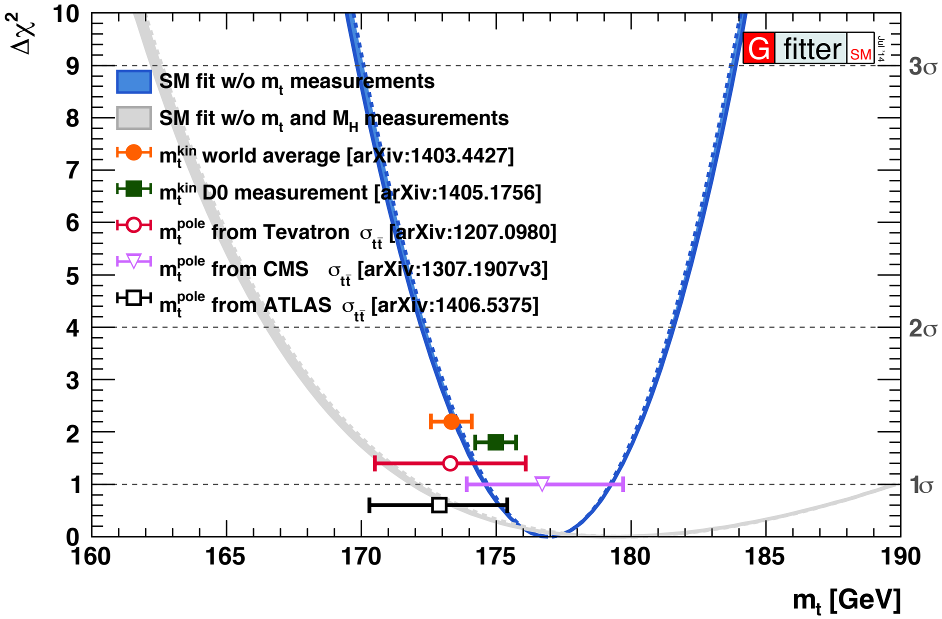


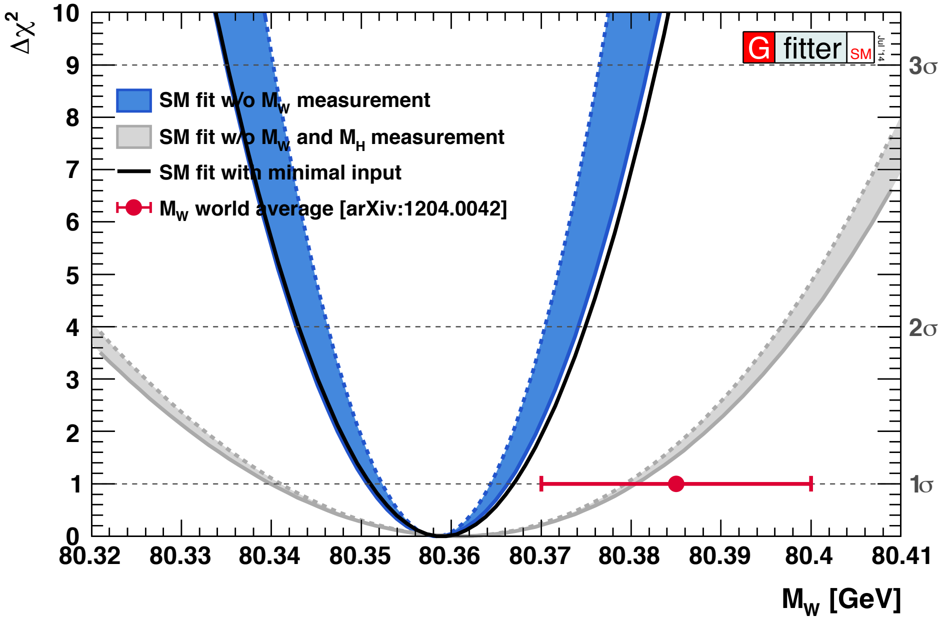
Precision measurement: <0.2%

*a lot of progress by theory community, LHCXSWG. Improvements continue…

Impact of Higgs Mass Measurement on Electroweak Fits

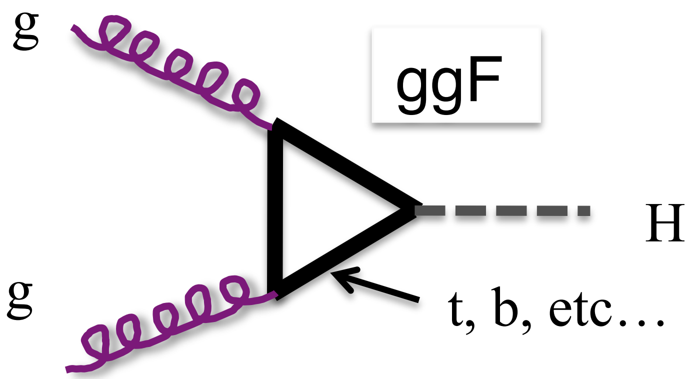


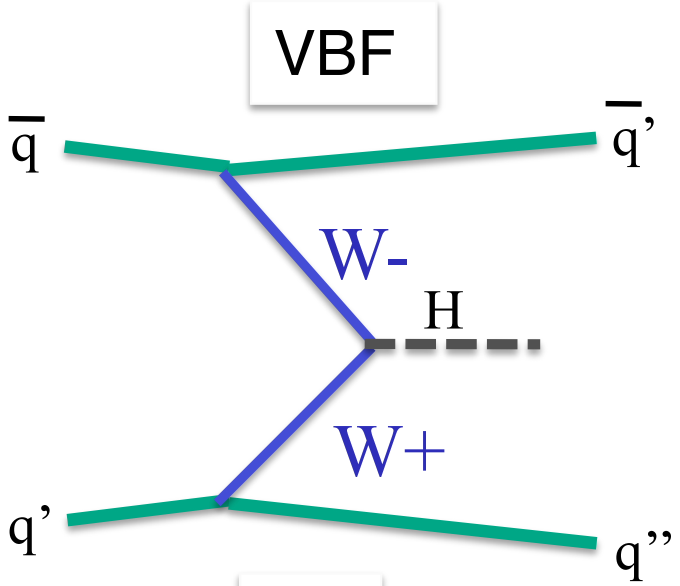


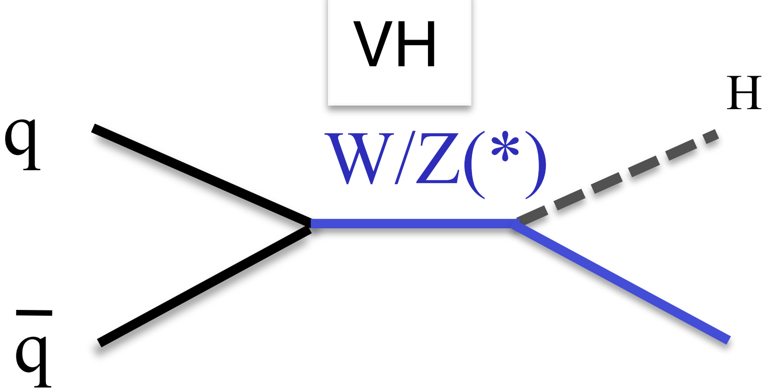


Eur. Phys. J. C 74, 3046 (2014)

Higgs Production at the LHC

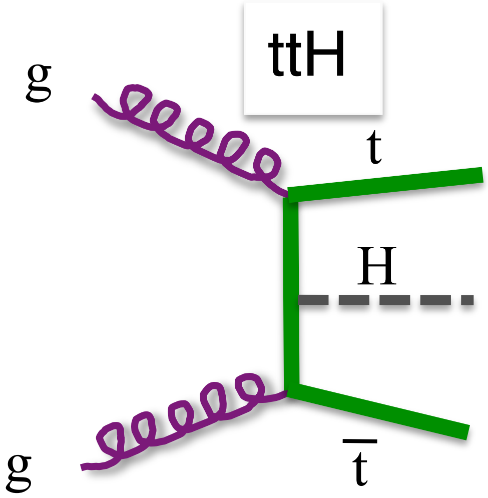


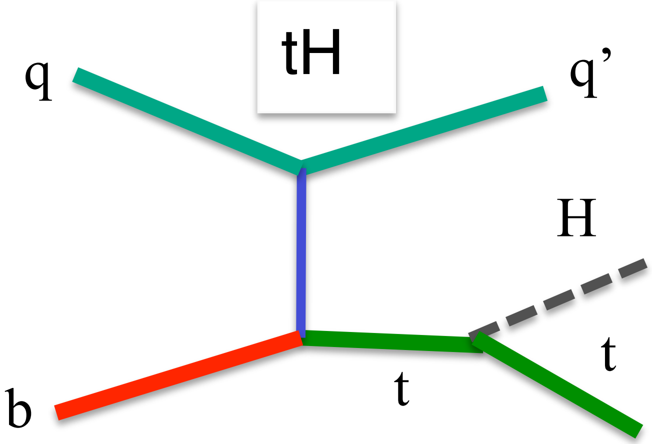




	process	8 TeV	13 TeV
ggF	gluon-gluon fusion	19 pb	44 pb
VBF	vector-boson fusion	1.6 pb	3.7 pb
VH	associated production	1.1 pb	2.2 pb
ttH	associated production	0.13 pb	0.51 pb
tH	Associated production	~20 fb	~90 fb

SM Production Modes
(M_H = 125 GeV)

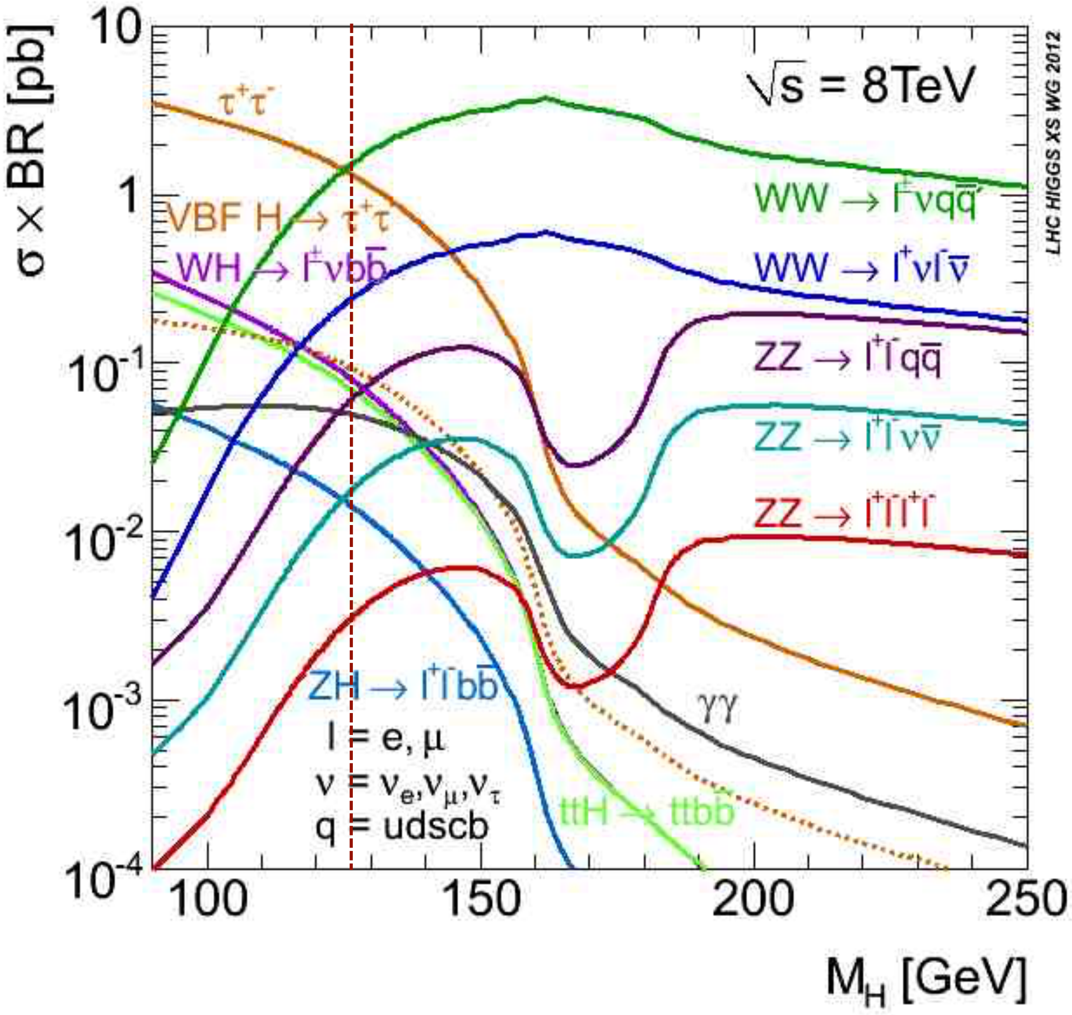




HIGGS DECAYS

- At m_H = 125 GeV, many decay channels can be studied

SM Decay Modes
(M_H = 125.1 GeV)



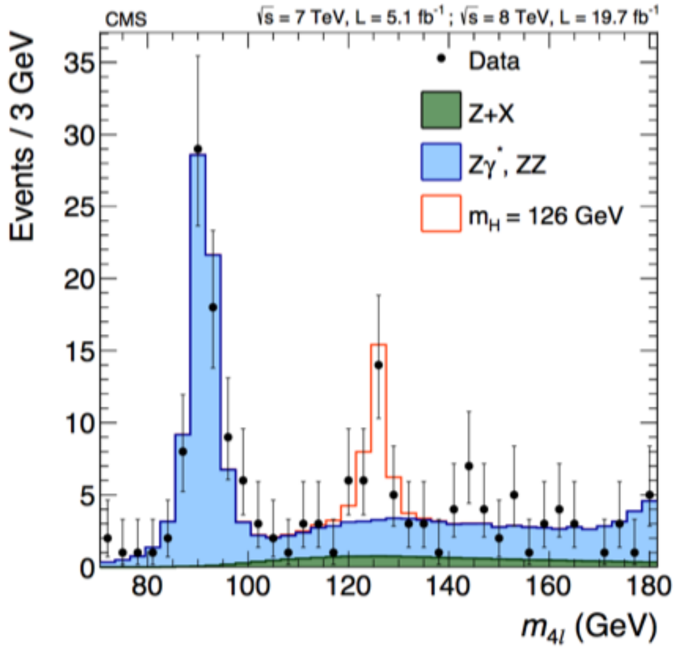
Process	Br
bb	0.58
WW	0.22
$\tau\tau$	0.06
ZZ	0.027
$\gamma\gamma$	0.0023
$Z\gamma$	0.0016
$\mu\mu$	0.0002

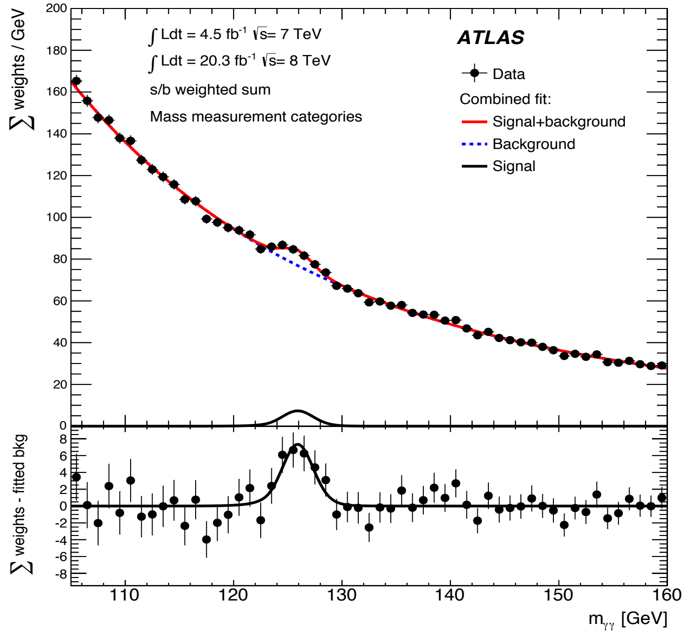
Main Production and Decays

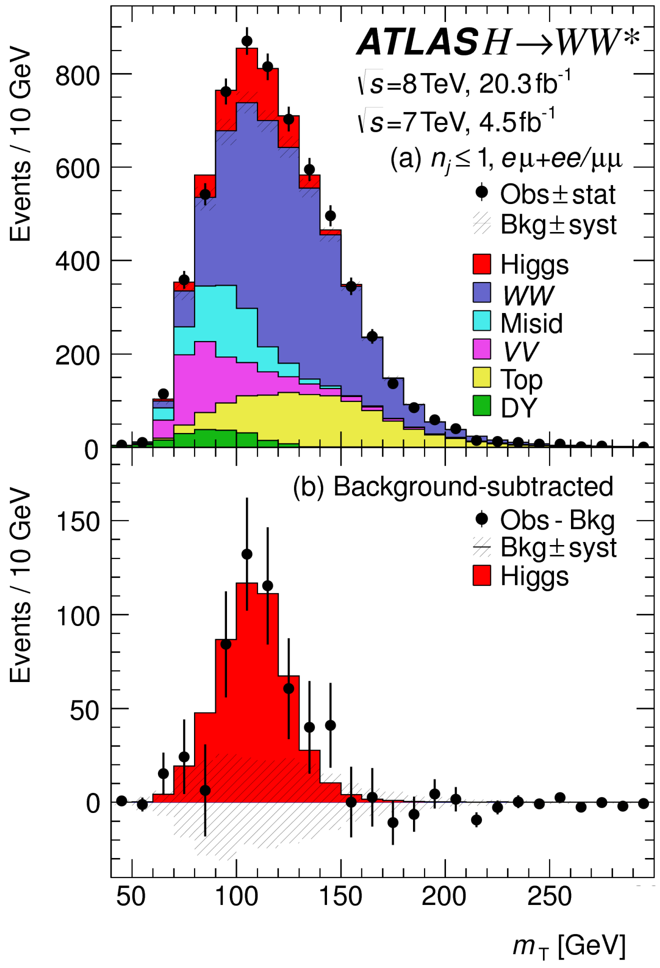
Analyses performed by either ATLAS or CMS targeting specific production and decay modes

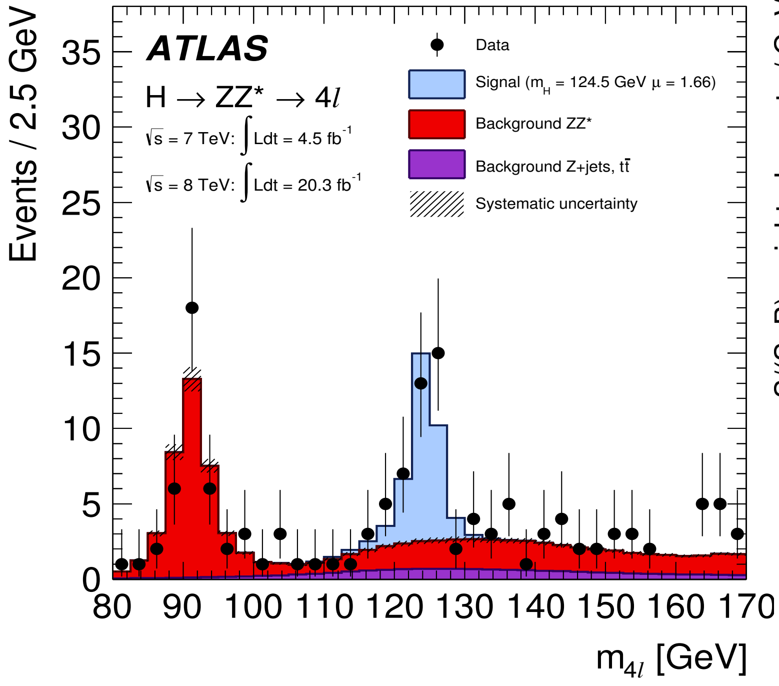
	WW	ZZ	$\gamma\gamma$	bb	$\tau\tau$
ggH	X	X	X		X
VBF	X	X	X	X	X
WH	X	X	X	X	X
ZH	X	X	X	X	X
ttH	X	X	X	X	X

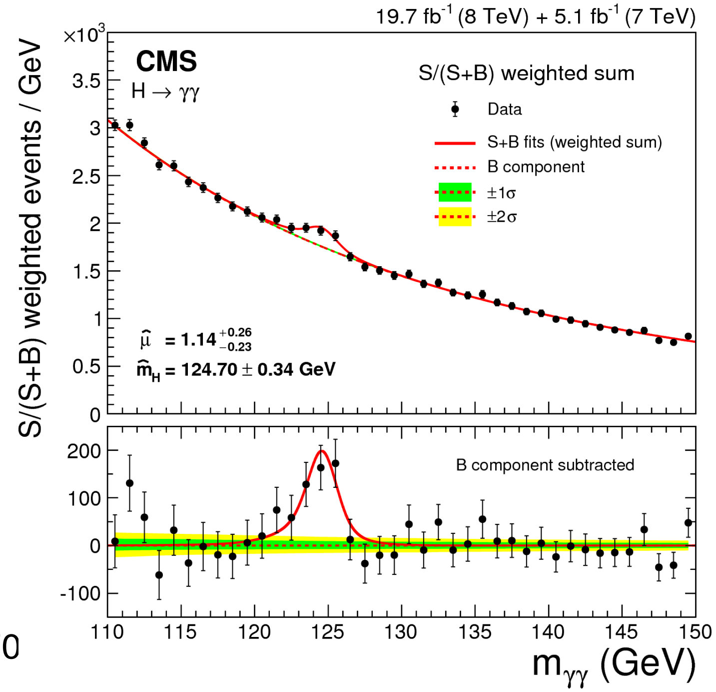
5σ Observation in all Decays to Bosons

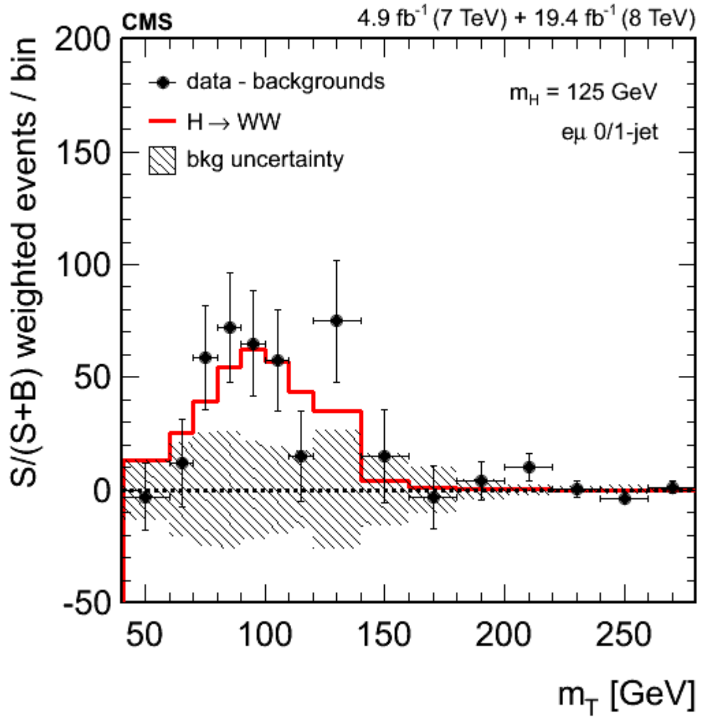










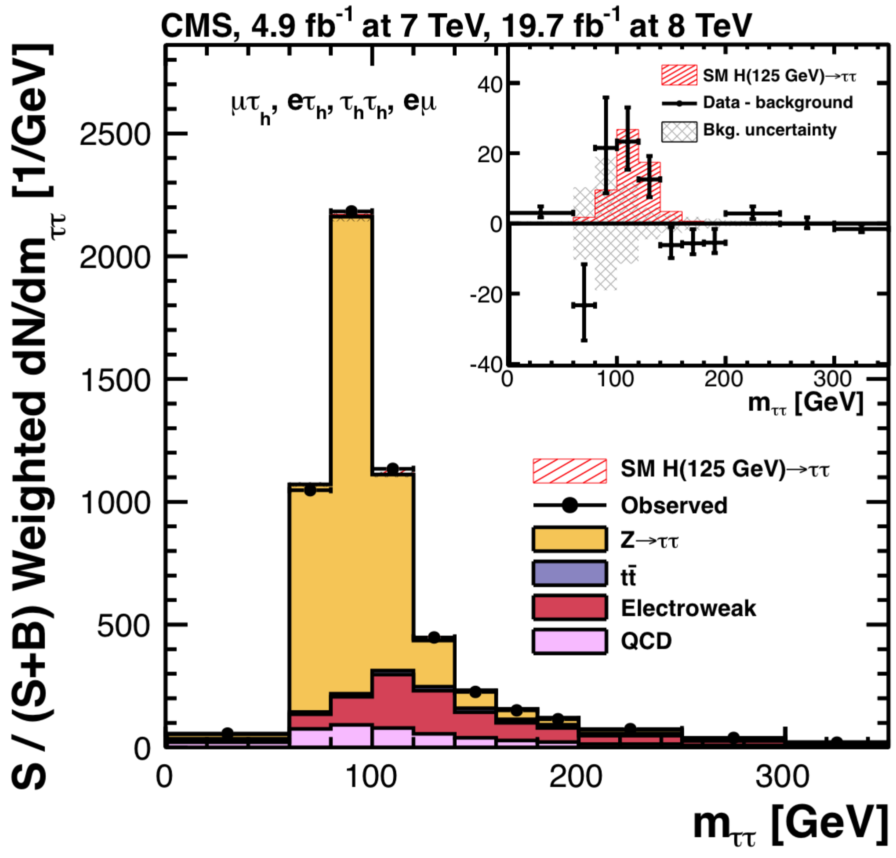


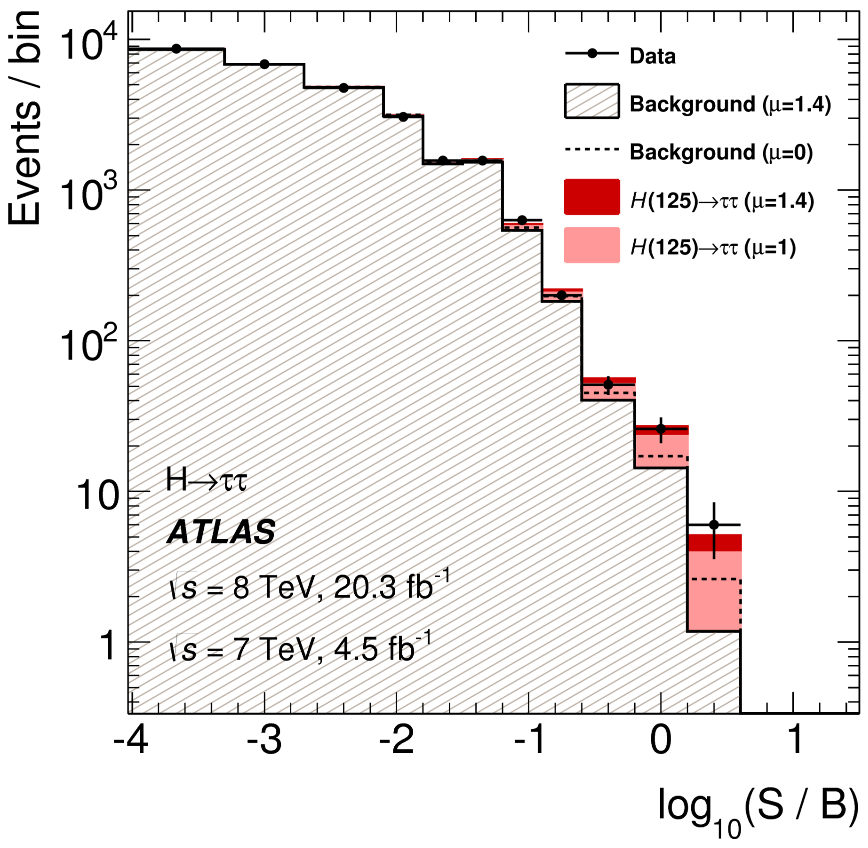
DECAYS TO FERMIONS (ττ)

Significance obs. (exp.)

CMS:
- **3.2 (3.7) σ**

ATLAS:
- **4.5 (3.4) σ**





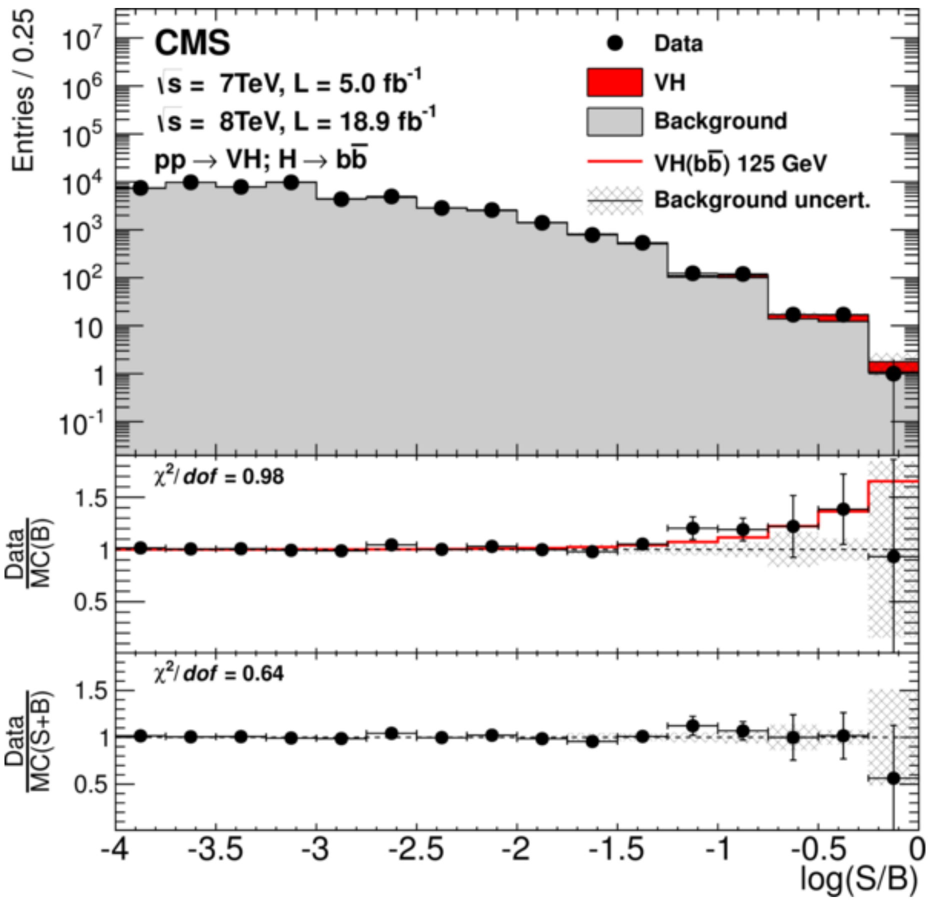
DECAYS TO FERMIONS (bb)

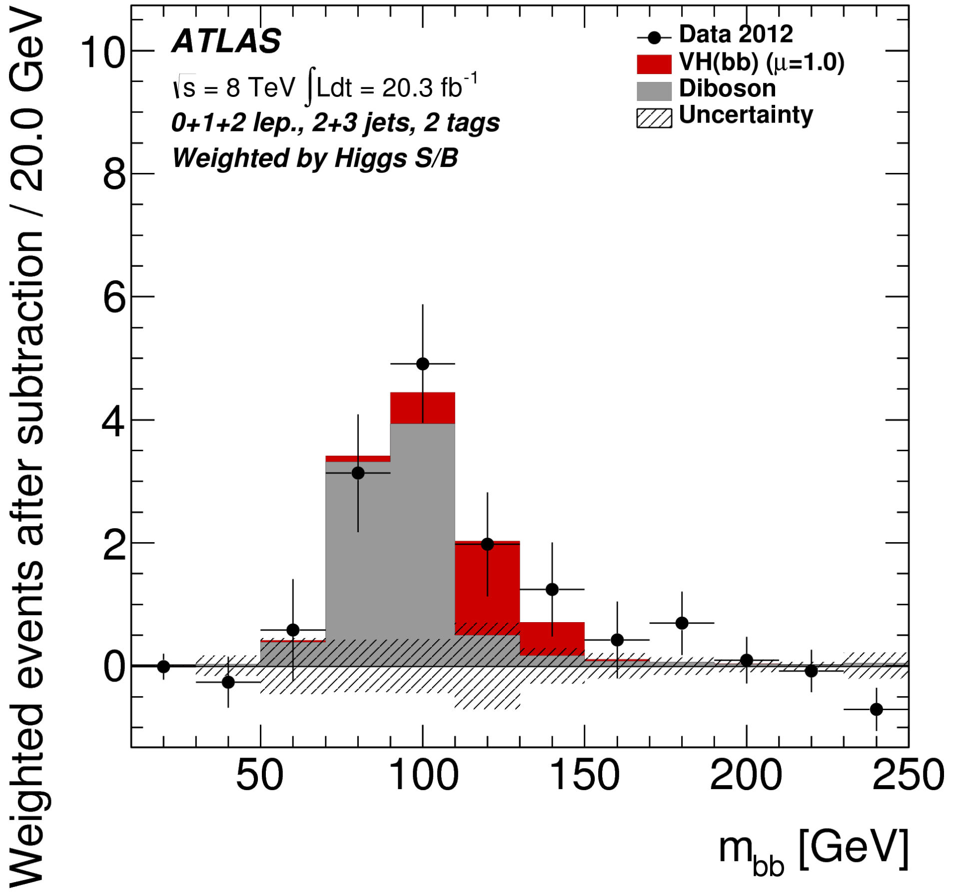
Significance obs. (exp.)

CMS(VH+VBF*+ttH):
- **2.6 (2.7) σ**

Tevatron(VH):**
- **2.2 (1.4) σ**

ATLAS(VH+ttH):
- **1.8 (2.8) σ**





*NEW! arXiv:1506.01010

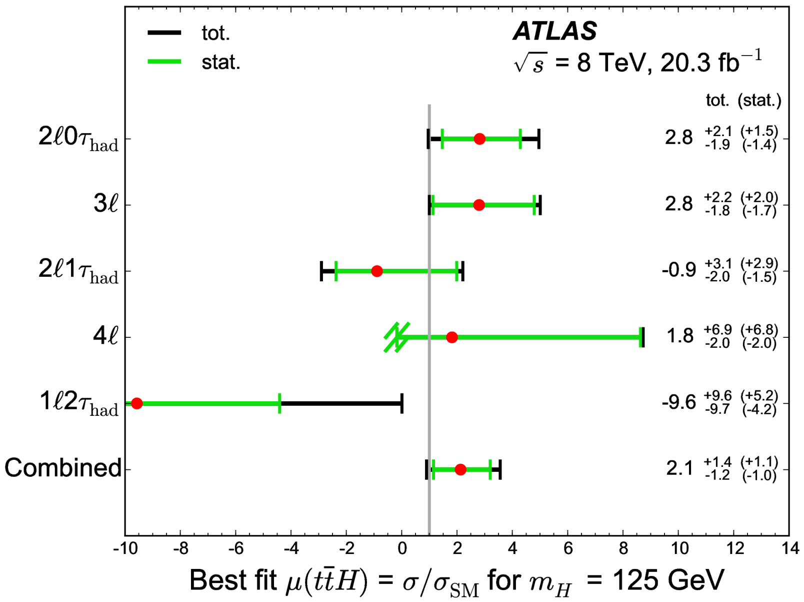
**my estimate from: Phys. Rev. D 88, 052014 (2013)

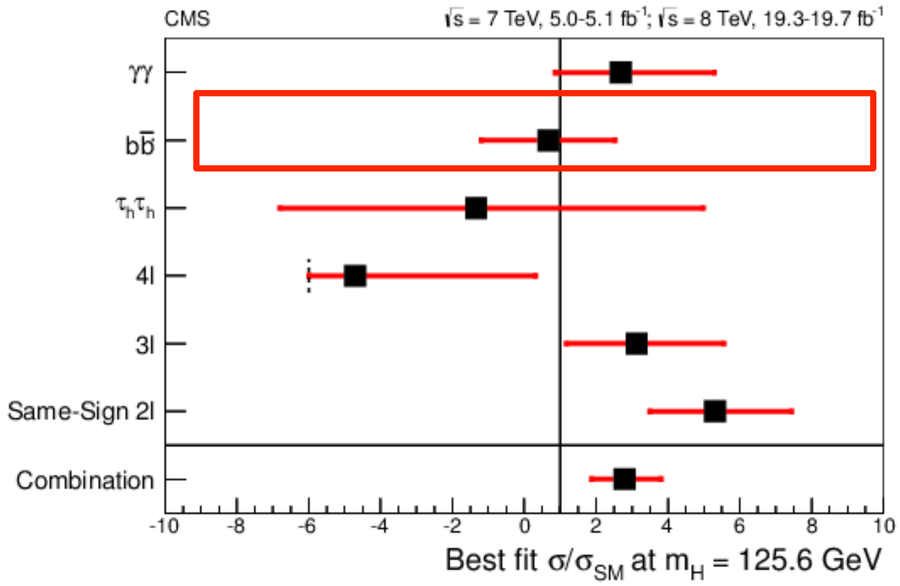
ttH Associated Production

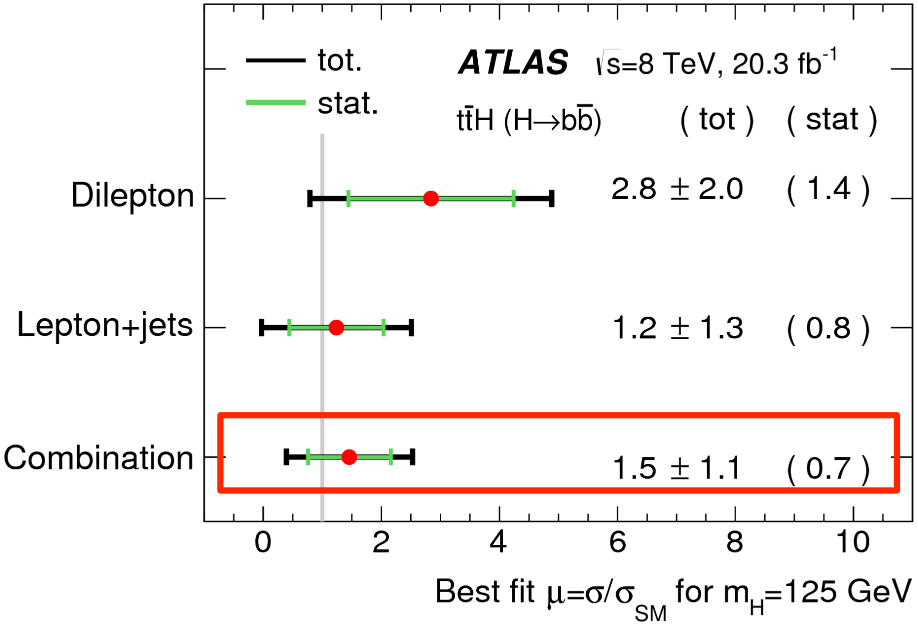
Test Yukawa coupling of the top quark (large! ~1.0 in the SM)

Production cross section is small (<1% of ggH) but spectacular final state

Very large top background…







Combination of signal strengths:
CMS: μ = 2.8 +/- 1.0
ATLAS: μ = 1.8 +/- 0.8

ttH Associated Production

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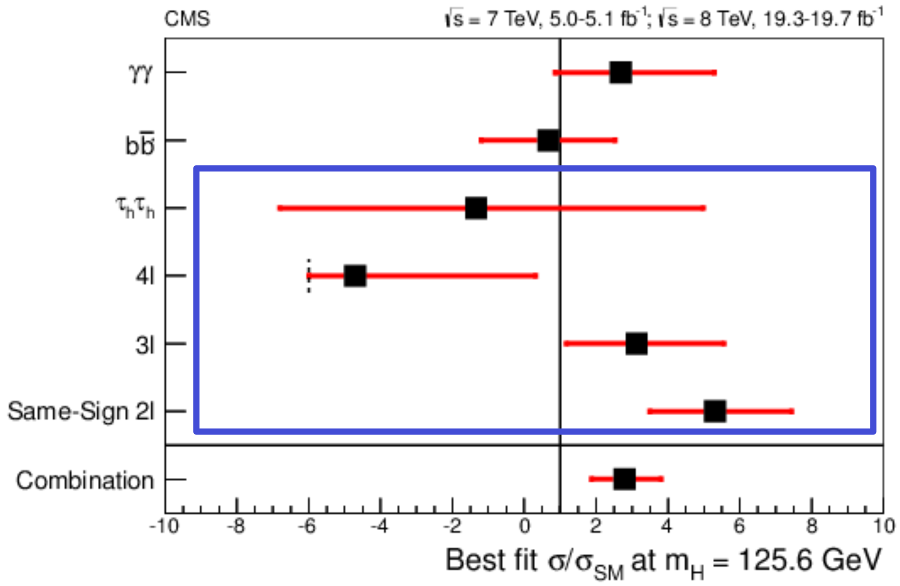

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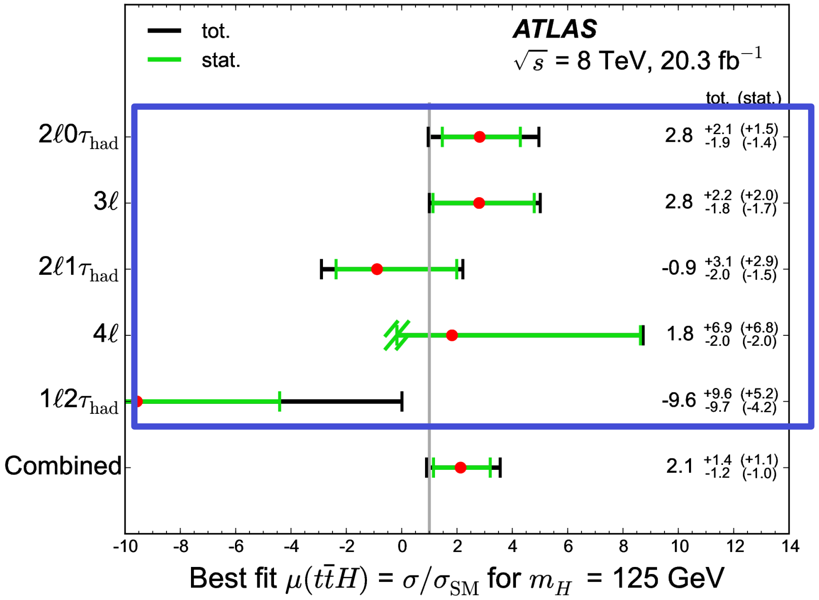
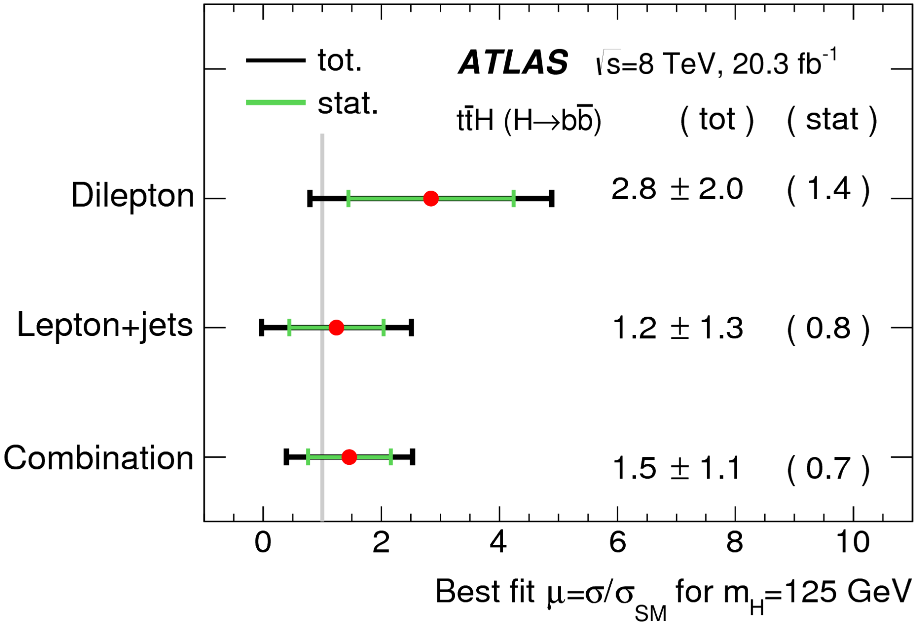




STATUS OF SM RARE DECAYS

Searches for rare decays performed in various channels

Observation of these decays in Run 1 would signal BSM physics

Non-universal coupling of Higgs to leptons:

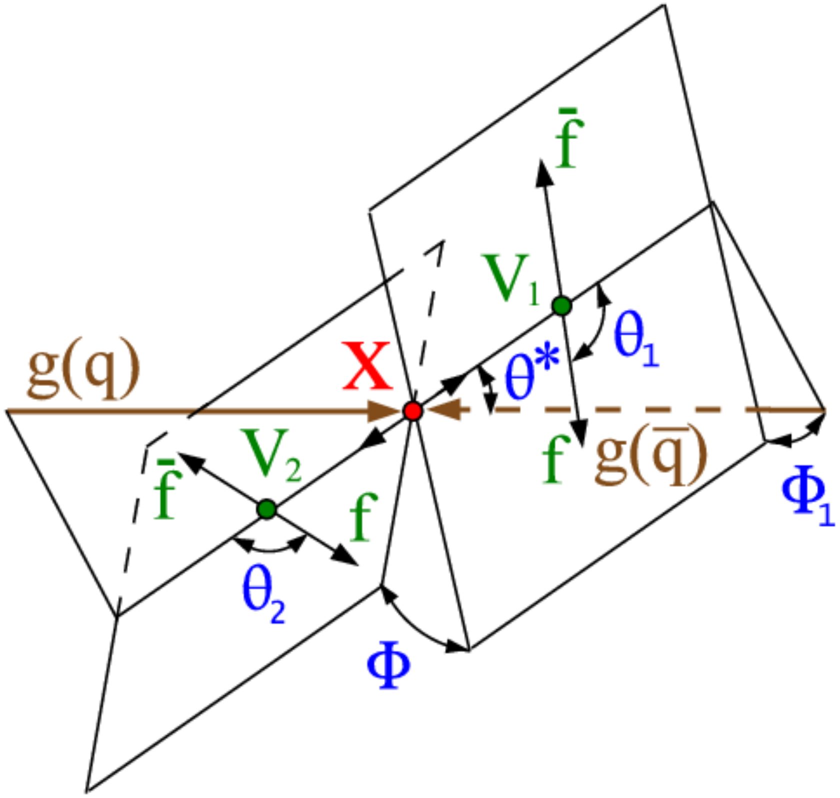
- $\mu\mu$ signal would be 280 times larger than SM if μ coupling was equal to that of τ

Process	**limit (times SM)**
$\mu\mu$ (ATLAS)	7.0
$\mu\mu$ (CMS)	7.4
$Z\gamma$ (ATLAS)	11
$Z\gamma$ (CMS)	9
$\gamma\gamma^*$ (CMS)	7.7
$J/\psi\gamma$ (ATLAS)	540
$J/\psi\gamma$ (CMS)	540
ee(CMS)	10^5

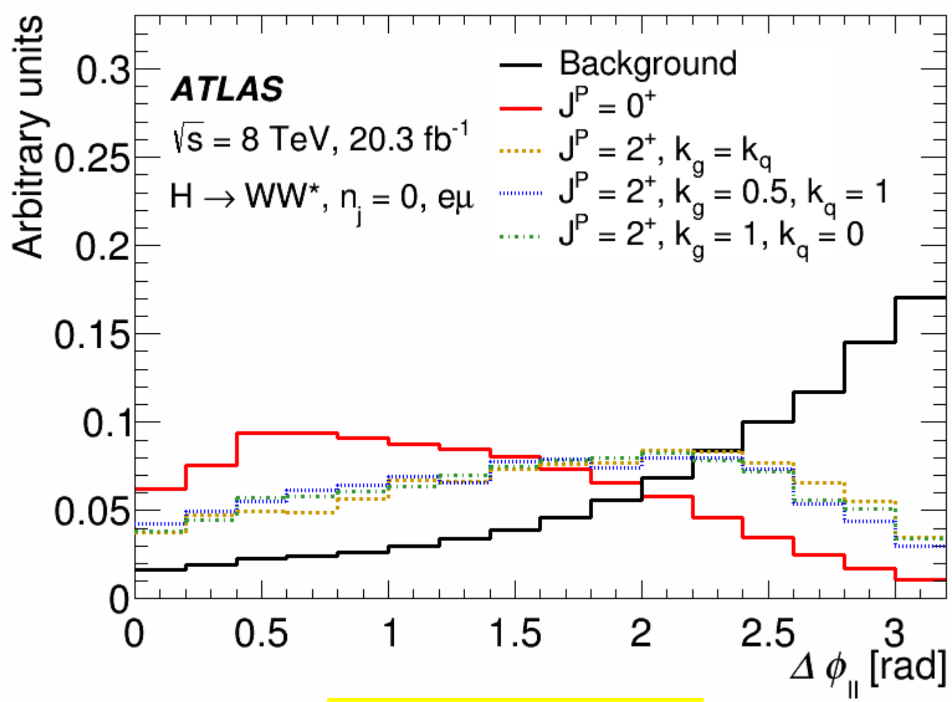
SPIN/CP HYPOTHESES TESTS

Tests of spin/CP properties performed in ZZ, γγ, WW channels

ZZ: full kinematic information available for spin/CP determination

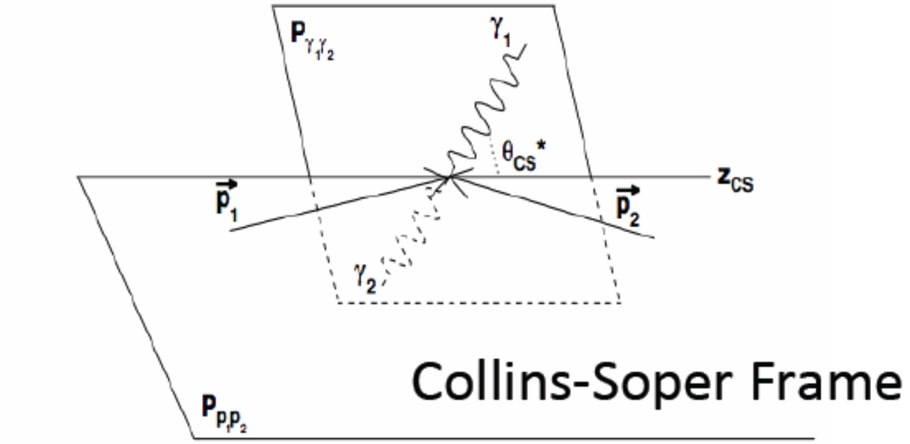


WW spin information from kinematic variables



γγ: use cos(θ*)

γγ



Collins-Soper Frame

Fixed Spin and Parity Tests

Test alternative fixed spin and parity hypotheses relative to the SM 0^+ hypothesis

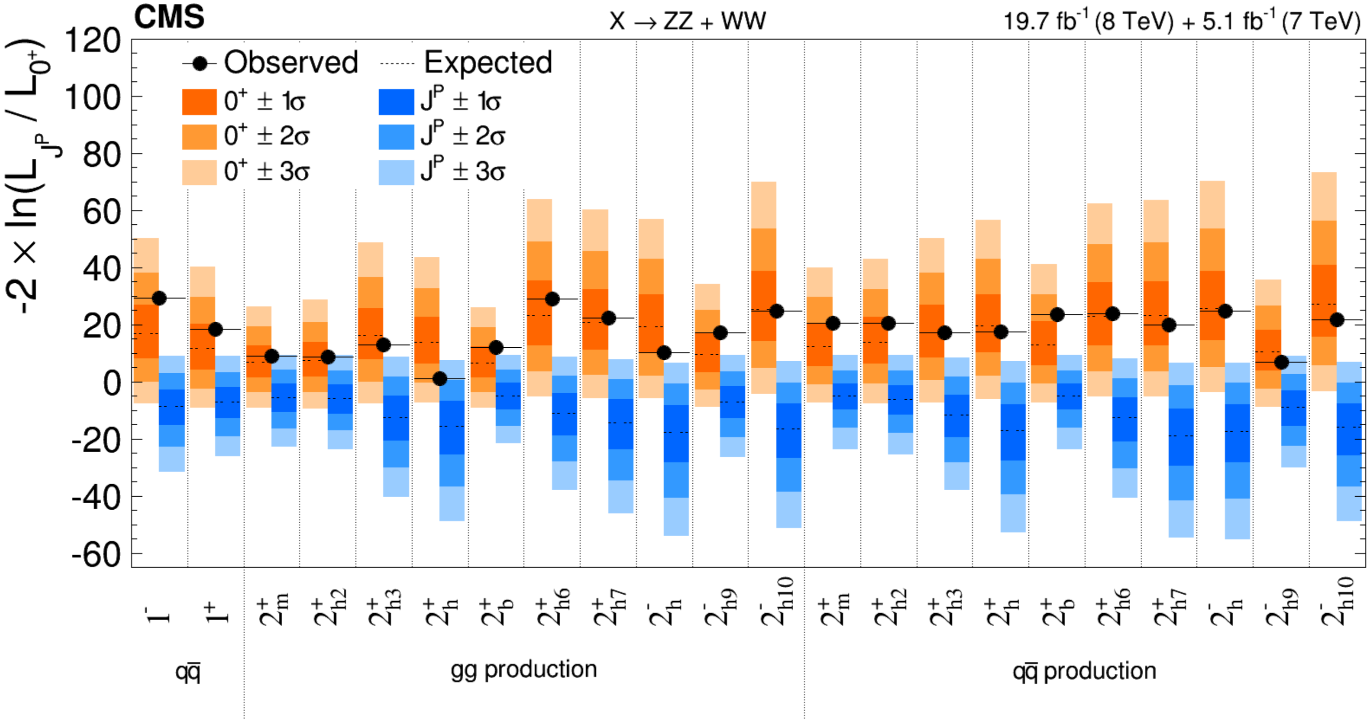
$$\tilde{q} = \log \frac{\mathcal{L}(J^P_{\rm SM}, \hat{\mu}_{J^P_{\rm SM}}, \hat{\hat{\theta}}_{J^P_{\rm SM}})}{\mathcal{L}(J^P_{\rm alt}, \hat{\mu}_{J^P_{\rm alt}}, \hat{\hat{\theta}}_{J^P_{\rm alt}})}$$

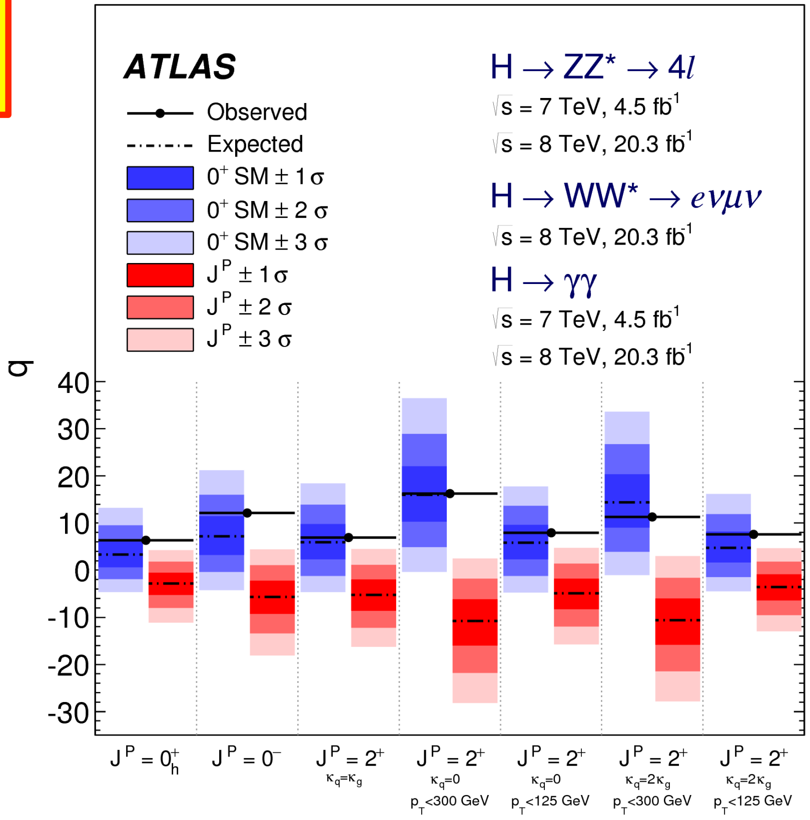
Results favour the spin 0^+ hypothesis

Alternatives: 0-, 1-, 1+, various spin 2 models are typically excluded at > 99.9% CL

Also Tevatron results: **PRL 114, 151802 (2015)**

Large anomalous couplings are excluded. Next step: look for presence of smaller contributions





CP MIXING RESULTS

Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

$$A(\mathrm{HVV}) \sim \left[\underbrace{a_1^{\mathrm{VV}}}_{\text{SM}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V}1}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V}2}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} \underbrace{f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}}_{\text{BSM CP-even}} + a_3^{\mathrm{VV}} \underbrace{f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}}_{\text{BSM CP-odd}}$$

ATLAS: different formulation (see backup), but results can be compared

No significant contributions from BSM terms are observed (yet…)

BSM CP-even (95% CL)

CMS $f_{a2}\cos(\phi_{a2}) \in [-0.11, 0.17]$

ATLAS $f_{a2} < 0.12$ for $\phi_{a2} = 0$

$f_{a2} < 0.16$ for $\phi_{a2} = \pi$

BSM CP-odd (95% CL)

CMS $f_{a3}\cos(\phi_{a3}) \in [-0.27, 0.28]$

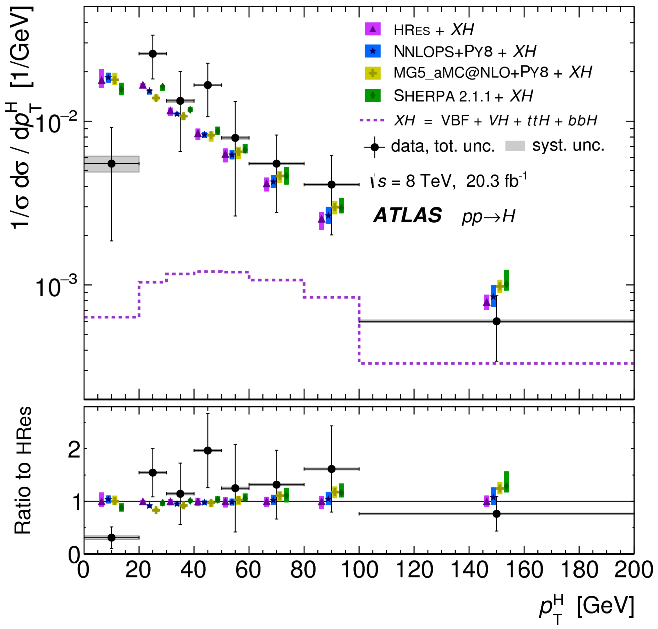
ATLAS $f_{a3} < 0.090$ for $\phi_{a3} = 0$

$f_{a3} < 0.41$ for $\phi_{a3} = \pi$

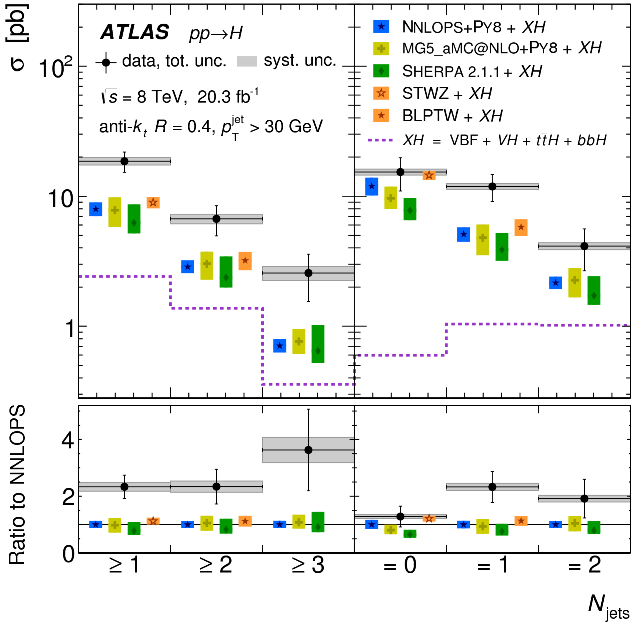
DIFFERENTIAL CROSS SECTIONS (ATLAS)

SM Higgs theory predictions for kinematics: combination of γγ and ZZ

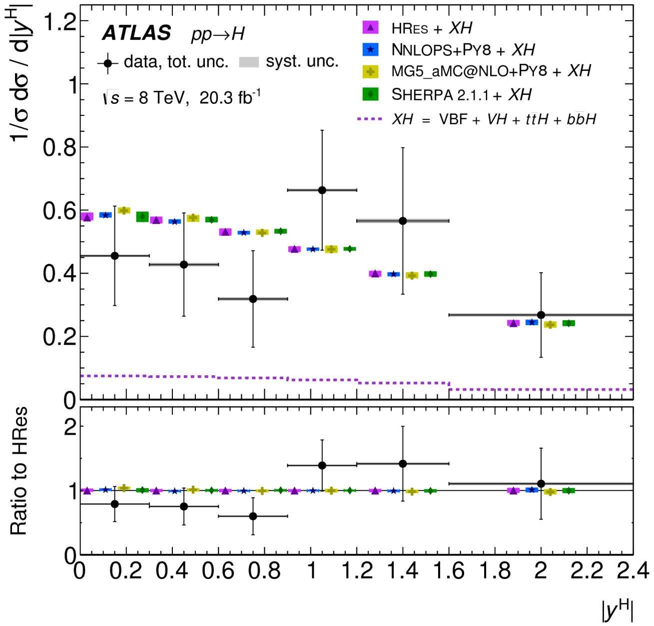
$p_T(H)$



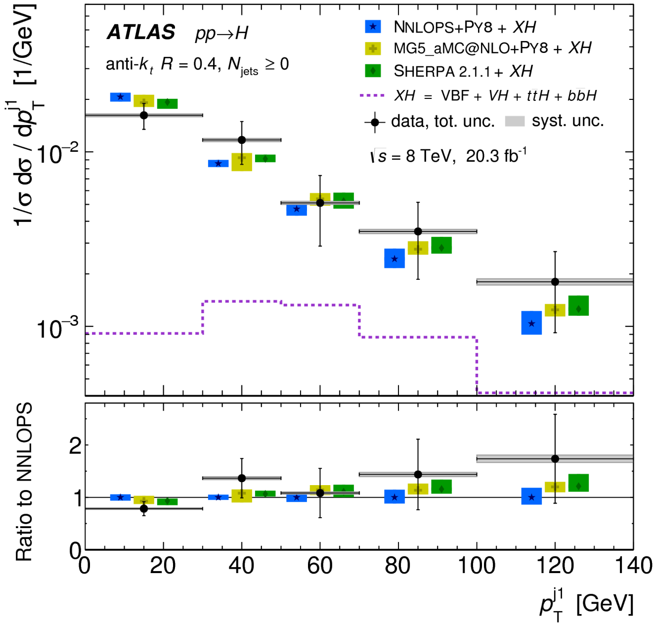
N_{jets}



$|y|(H)$



$p_T(j_1)$



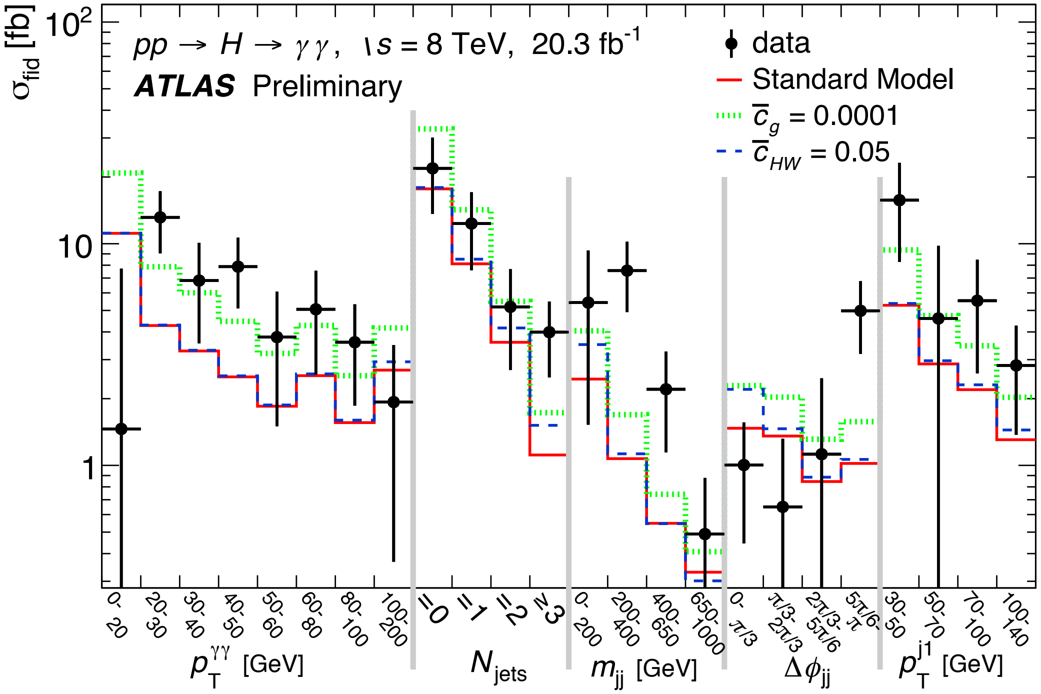
Differential Cross Sections and EFT

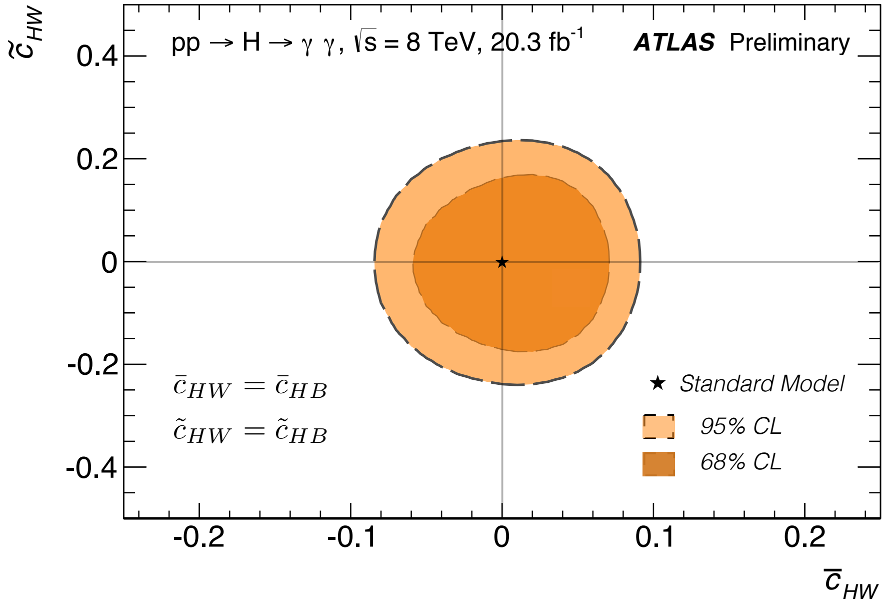
EFT papers:
JHEP 07(2015) 035
JHEP 06(2007) 045

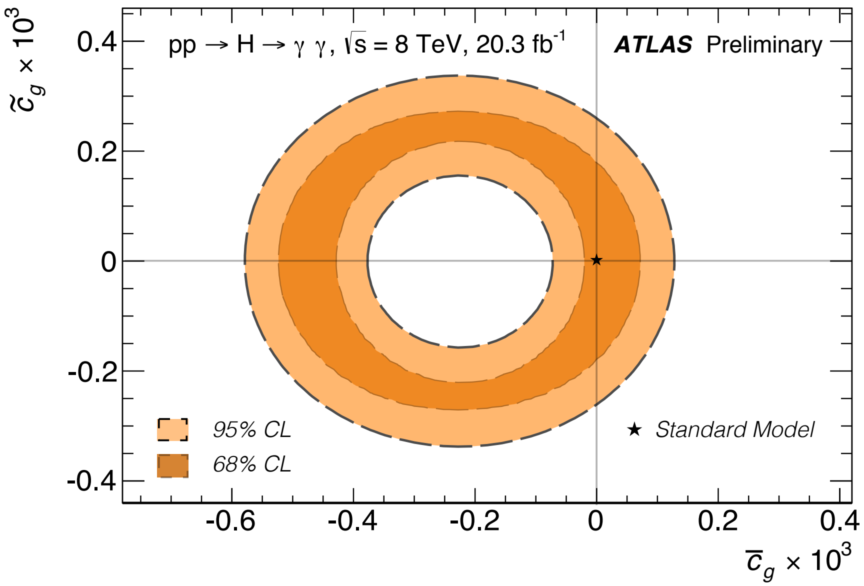
- Study tensor structure and strength of Higgs interactions in the context of an Effective Field Theory framework
- Use Strongly Interacting Light Higgs (SILH) formulation:

$$\mathcal{L} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB}$$

Statistical combination of 5 γγ input variables:



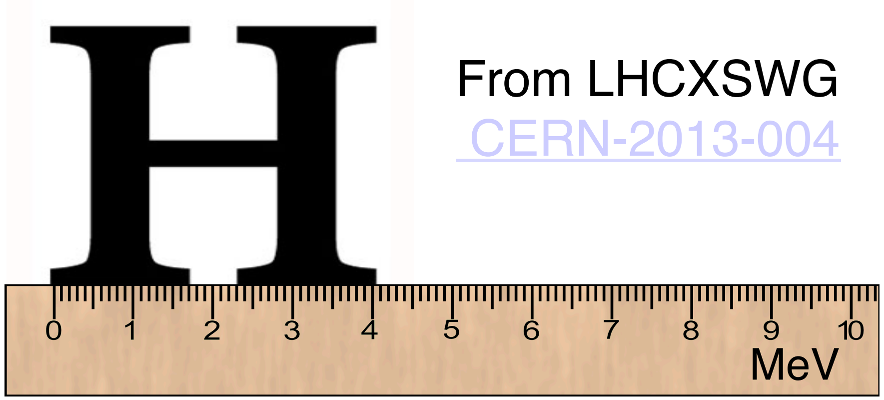




WIDTH AND LIFETIME

Higgs width measurements at LHC:

SM width (m_H=125.1 GeV): 4.1 MeV



From LHCXSWG
[CERN-2013-004]

- Direct (limit at 95% CL obs. (exp.))
  - CMS ($\gamma\gamma$ +ZZ): 1.7 (2.3) GeV
  - ATLAS:
    - ZZ: 2.6 (6.2) GeV
    - $\gamma\gamma$: 5.0 (6.2) GeV
- Via off-shell couplings:

Direct measurement of Off Shell couplings (independent of width)

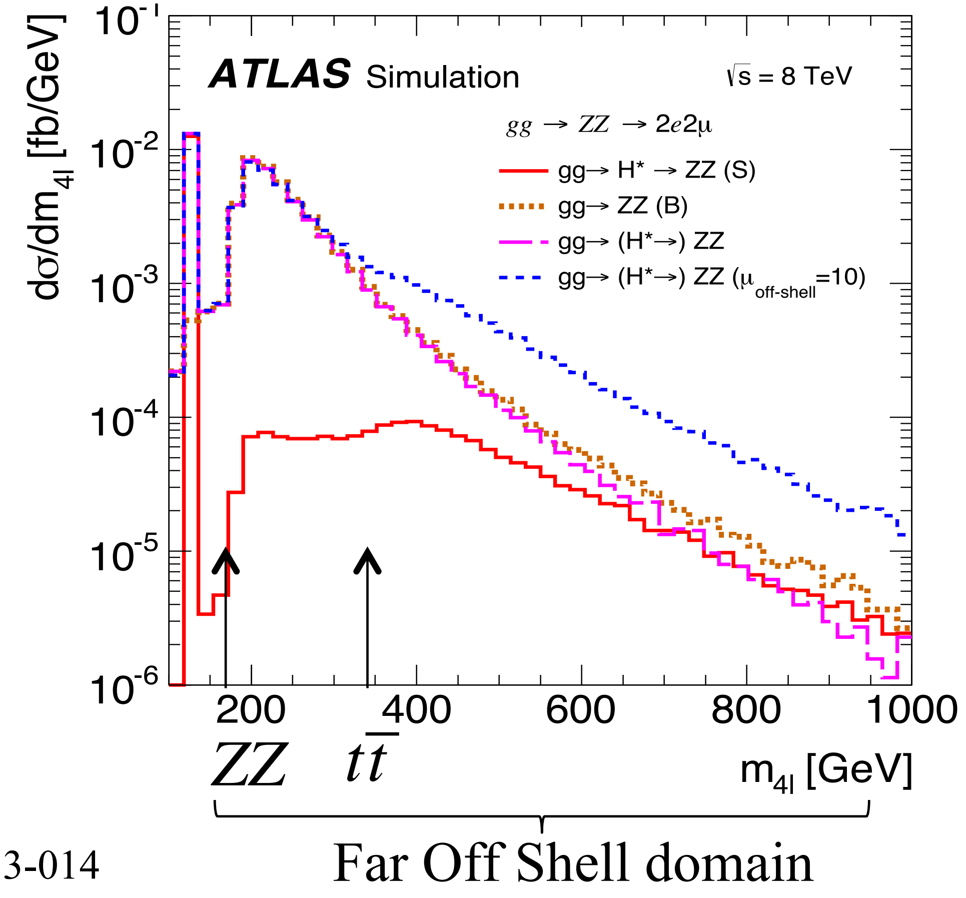
- Measure width assuming SM running (or measure running assuming width)

Assuming* $\mu_{\text{OffShell}} = \mu_{\text{OnShell}}$

- CMS: 22 (33) MeV (95%CL)
- ATLAS: 23 (33) MeV (95%CL)

at HL-LHC*:

$$\Gamma = 4.1^{+1.5}_{-2.1}\, Mev$$



- Interference in $\gamma\gamma$ (signal – continuum)
  - Expected mass shift ~50 MeV (ATL-PHYS-PUB-2013-014)
  - No assumptions but small effect
- Lifetime *(Next slide)*

*ATL-PHYS-PUB-2013-014

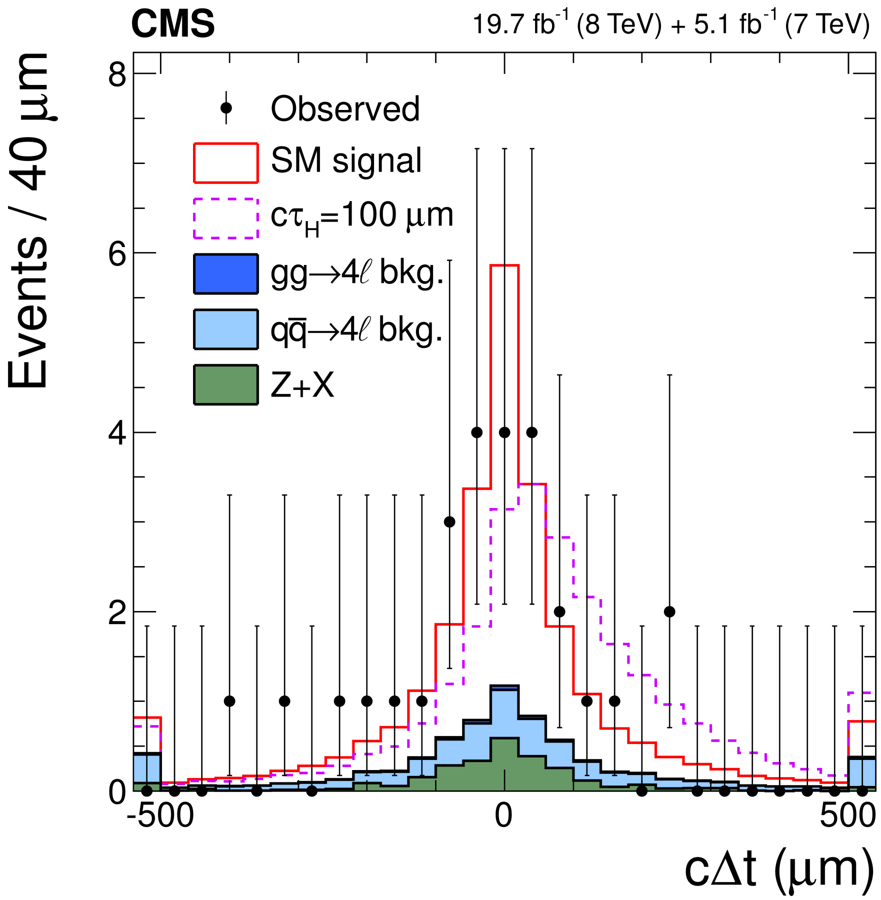
WIDTH: LIFETIME AND OFF-SHELL COUPLINGS (CMS)

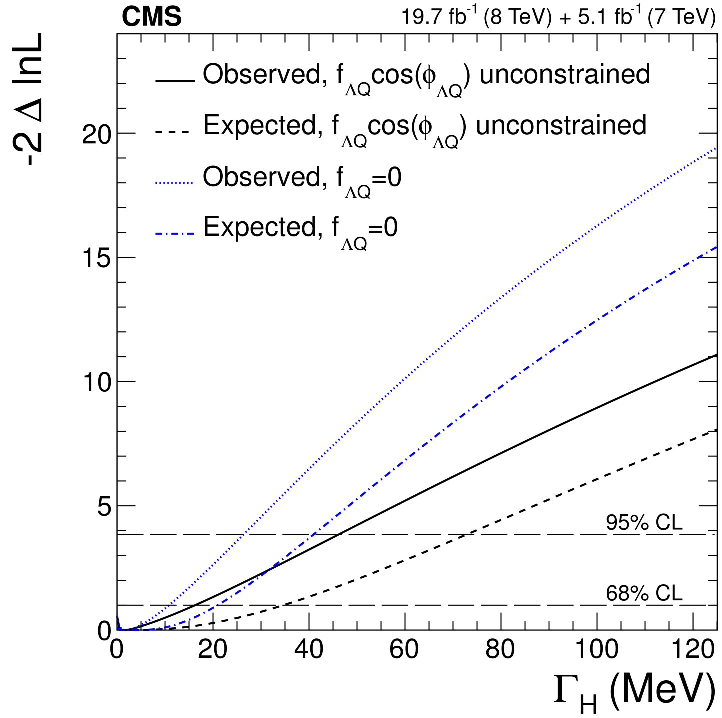
SM lifetime (m_H= 125 GeV): 1.6x10^{-7} fs

Measure flight distance in the detector using H->ZZ->4l channel

τ(H) < 190 fs at 95% CL

Γ(H) > 3.9 x10^{-9} MeV





Enhancement of off-shell production possible through anomalous HVV couplings:

$$A(\mathrm{HVV}) \propto \left[a_1 - e^{i\phi_{\Lambda Q}}\frac{(q_{V1}+q_{V2})^2}{(\Lambda_Q)^2} - e^{i\phi_{\Lambda 1}}\frac{(q_{V1}^2+q_{V2}^2)}{(\Lambda_1)^2}\right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$

$$+ a_2 f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3 f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

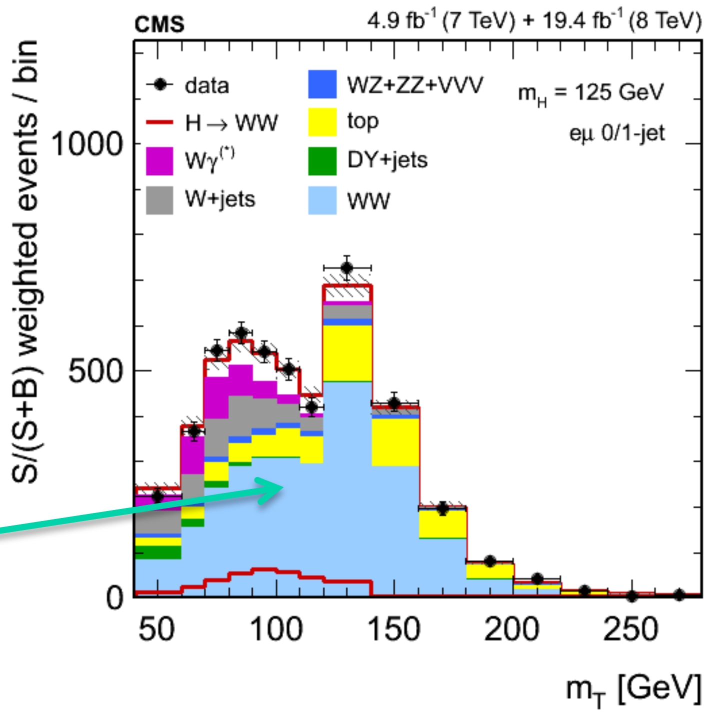
Width derived with/without profiling of cross section fraction:

$$f_{\Lambda Q} = \frac{m_H^4/\Lambda_Q^4}{|a_1|^2 + m_H^4/\Lambda_Q^4}$$

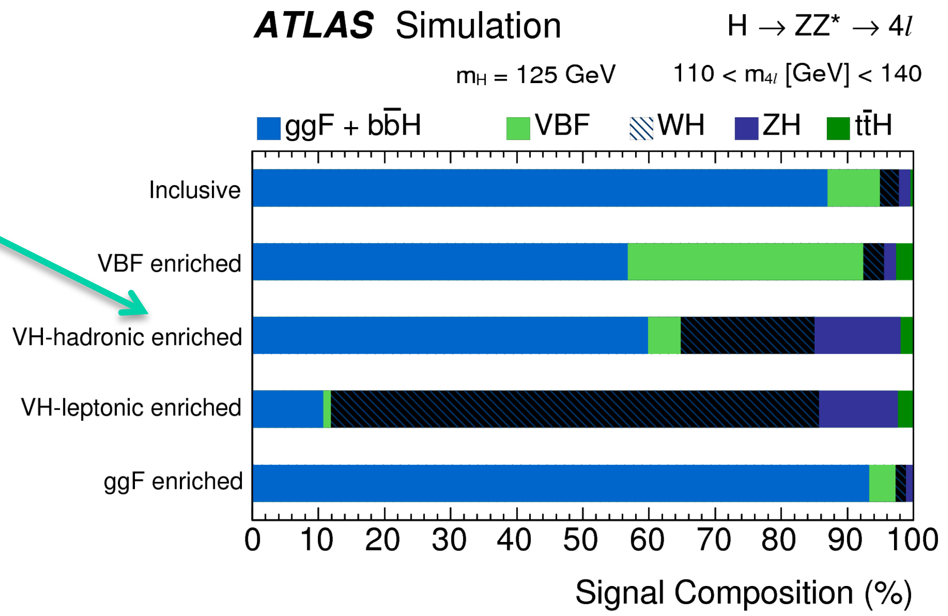
COMBINATION OF SIGNAL STRENGTHS

- We measure event yields n_{evt} and we need to extract signal yields n_s
  - Estimate and subtract backgrounds

$n_s = n_{evt} - n_{bkg}$



- Production mode categories c are contaminated by other signal processes
- Global fit to all categories can take into account all contributions and correlations



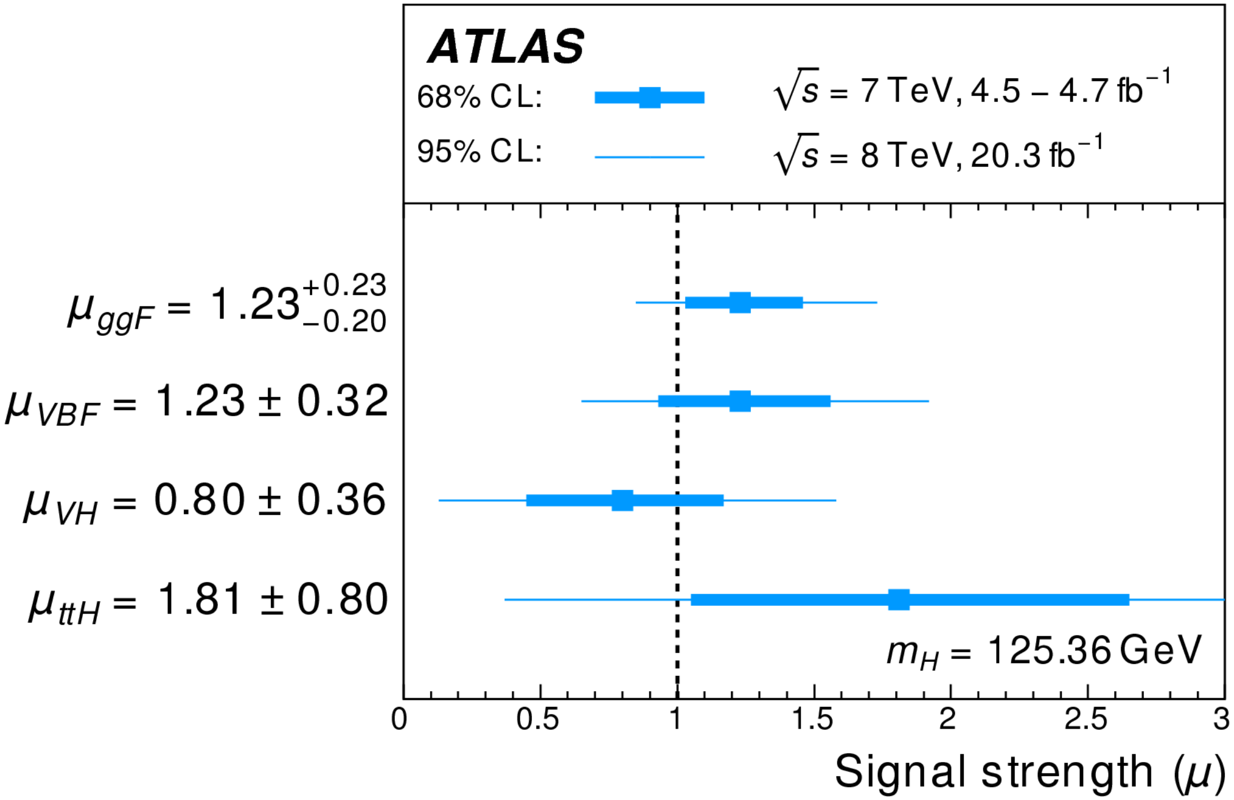
We extract the signal strength μ : ratio of the observed yield to the SM prediction

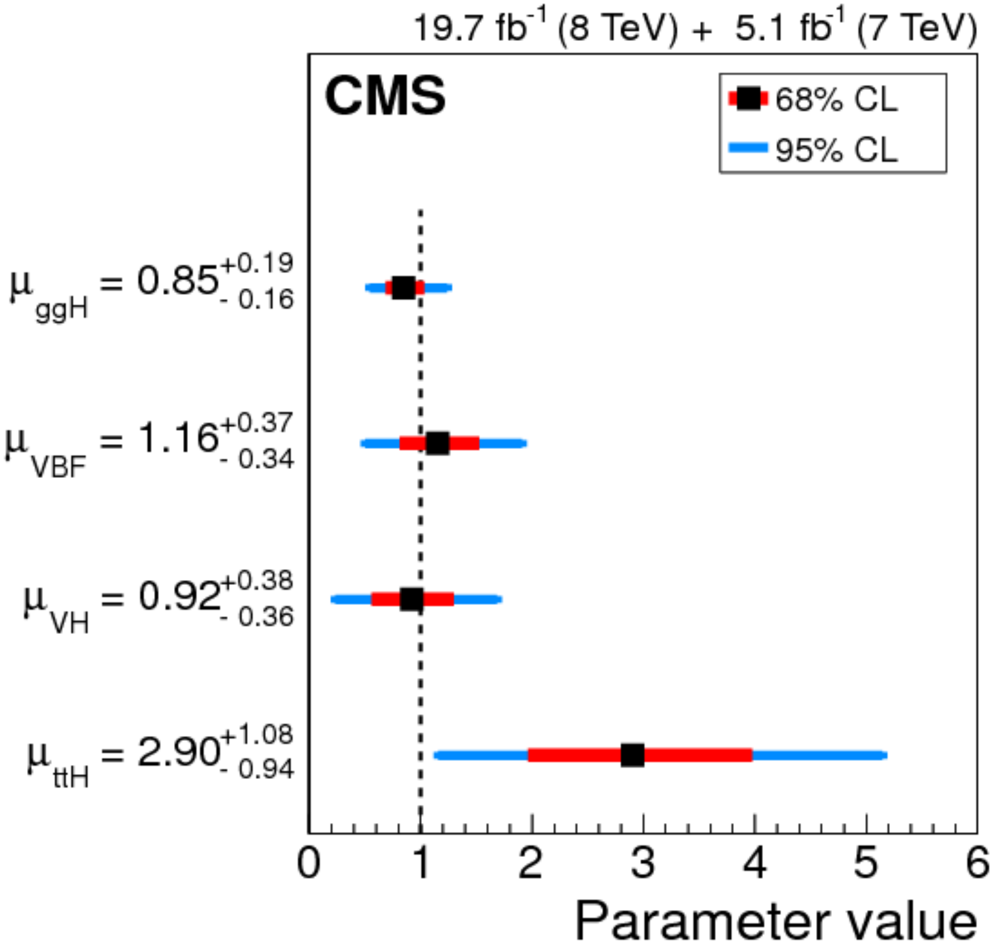
$$n_s^{c,i} = \sum_p \left[\mu^p \mu_{BR}^i\right] \times (\sigma^p \times Br^i)_{SM} \times A_p^{c,i} \times \varepsilon_p^{c,i} \times Lumi$$

$$p \in (ggF, VBF, VH, ttH) \quad i \in (\gamma\gamma, ZZ, WW, bb, \tau\tau)$$

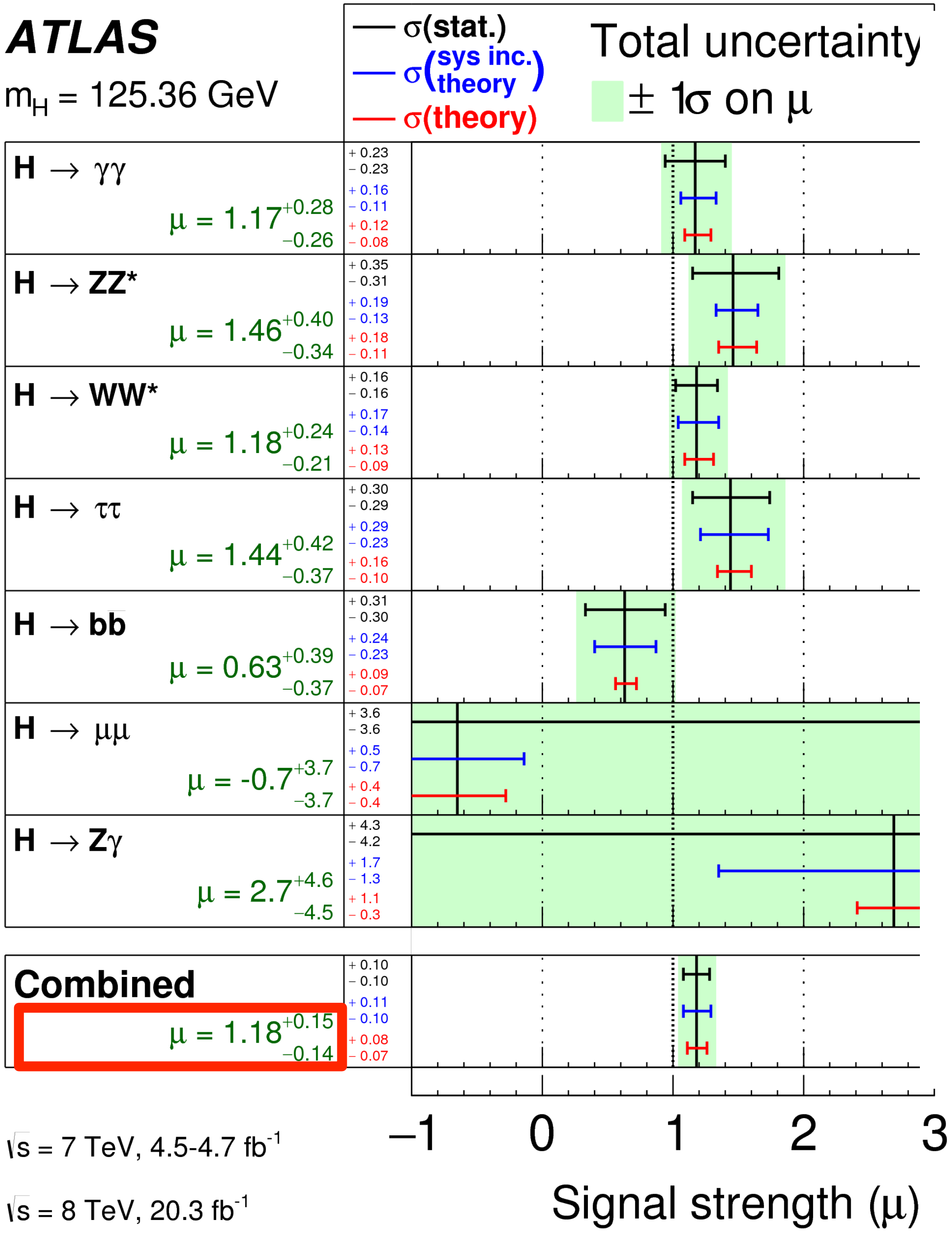
SIGNAL STRENGTH FOR PRODUCTION MODES

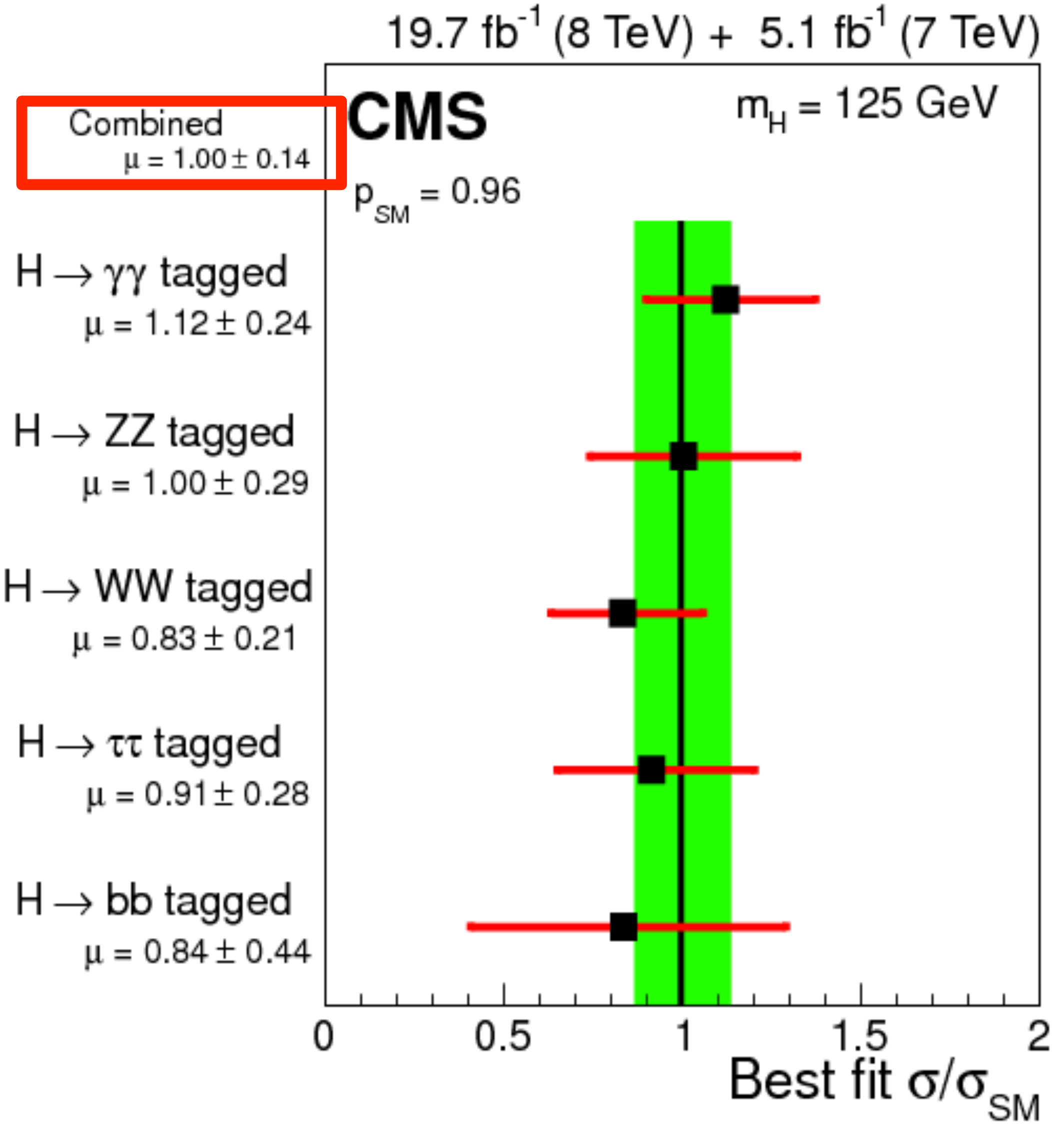
Obtain production signal strengths assuming SM ratios for branching ratios





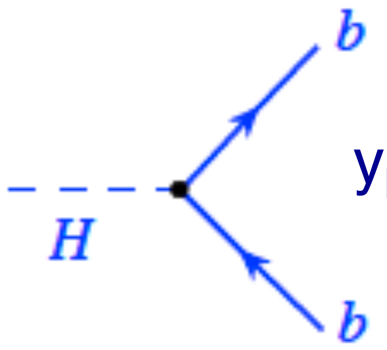
SIGNAL STRENGTH FOR DECAY MODES



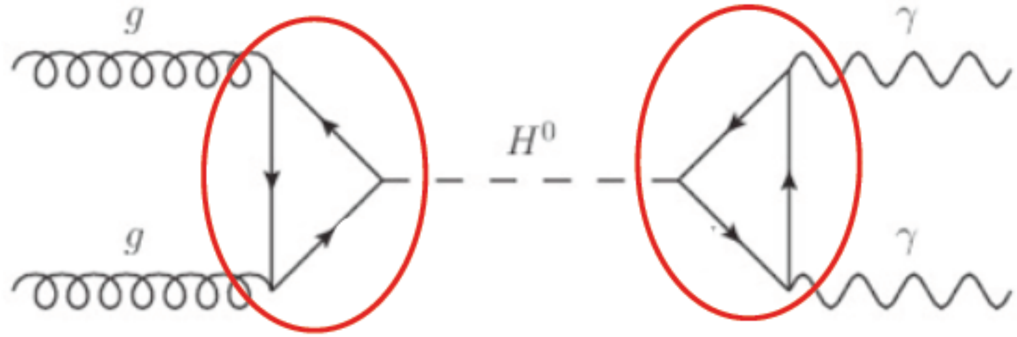


ATLAS: individual μ values from combination of channels
CMS: individual μ values from tagged analyses

COUPLINGS FRAMEWORK



y_b : b yukawa



assuming no BSM particles in the loops

$$\kappa_g^2 \propto 1.06 \times \kappa_t^2 - 0.07 \times \kappa_t \kappa_b + 0.01 \times \kappa_b^2$$

$$\kappa_\gamma^2 \propto 1.6 \times \kappa_W^2 - 0.7 \times \kappa_t \kappa_W + 0.1 \times \kappa_t^2$$

- $y_b := \kappa_b \; y_b^{SM}$

- "κ framework": interpret signal strength parameters (μ_p, μ^i_{BR}) in terms of modifiers to the SM couplings:

- Decay: $\Gamma_i = \kappa_i^2 \; \Gamma_i^{SM}$
- Production: $\sigma_i = \kappa_i^2 \; \sigma_i^{SM}$
- Width: $\Gamma_H = \Sigma_i \, \kappa_i^2 \; \Gamma_i^{SM}$

Assumptions (see LHCXSWG YR3):
- Only one Higgs
- SM production and decay kinematics
  - Tensor structure is that of SM
  - 0+ scalar
- Narrow resonance

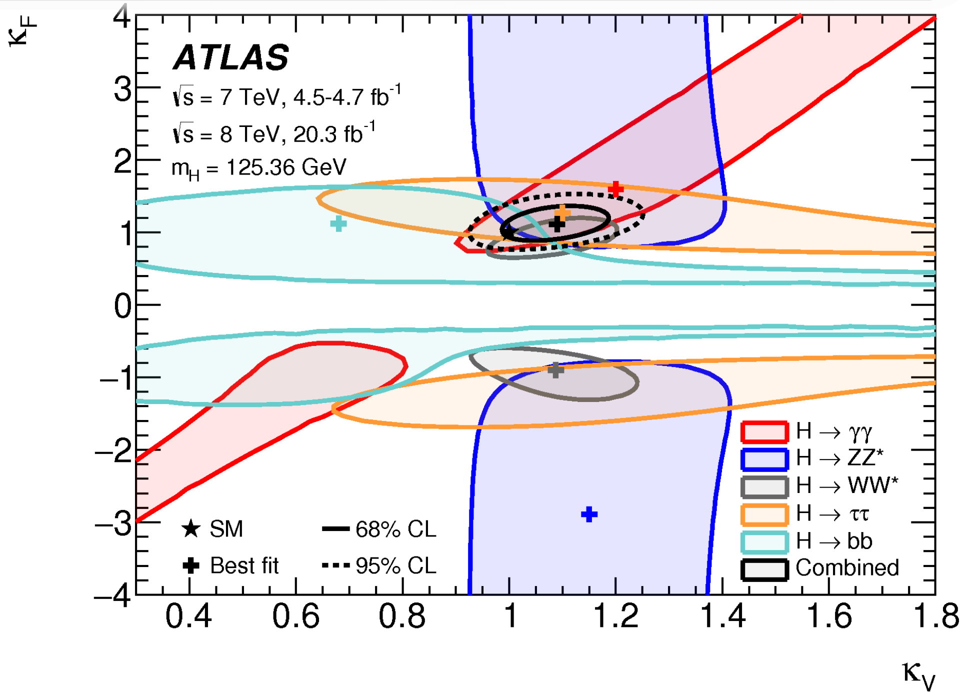
COUPLING TO FERMIONS AND BOSONS

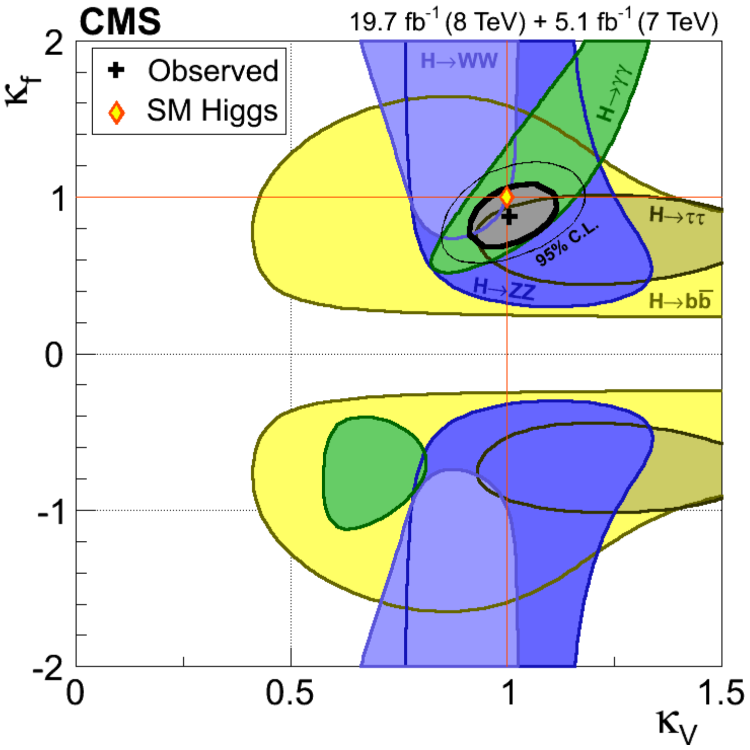
Test gauge vs Yukawa couplings

- Assumptions:
  - Common scaling factor for fermions and gauge bosons:
    - κ_F and κ_V
  - No BSM contributions to width
  - No BSM contributions to loops

- Interference in $\gamma\gamma$, tH, gg->ZH can resolve relative sign between κ_F and κ_V

- Results compatible with SM

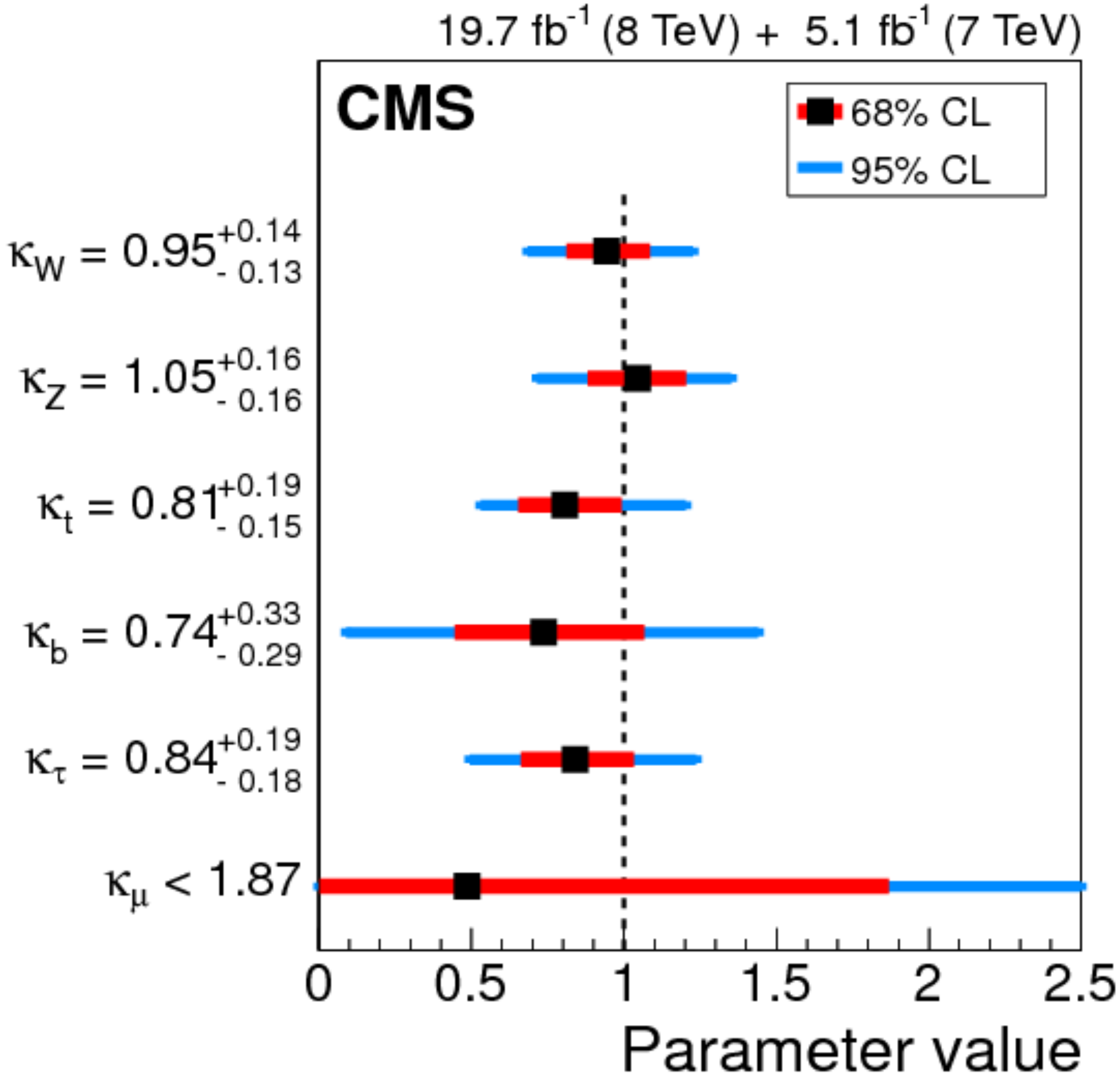


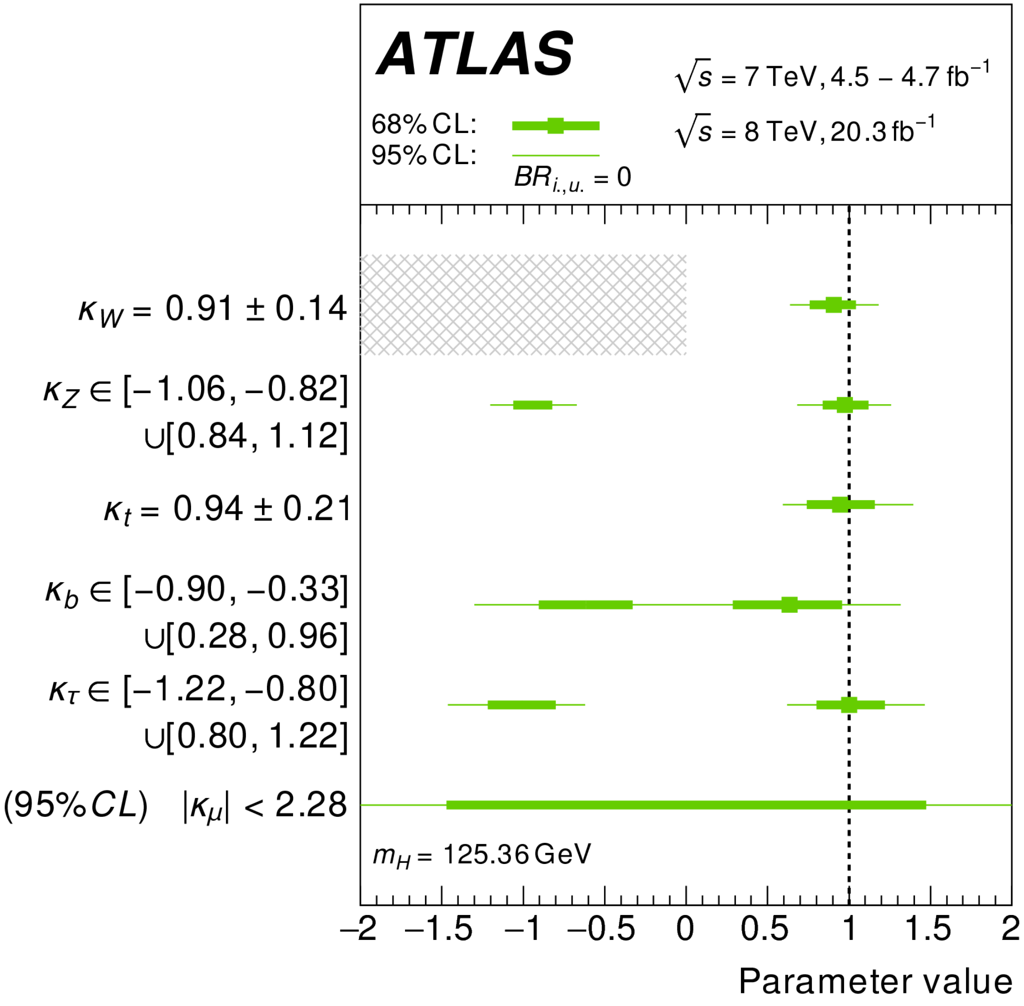


COUPLINGS WITH SM PARTICLE CONTENT

“Absolute couplings”. Assumptions:

- No contributions to width from BSM particles
- No contributions to loops from BSM particles

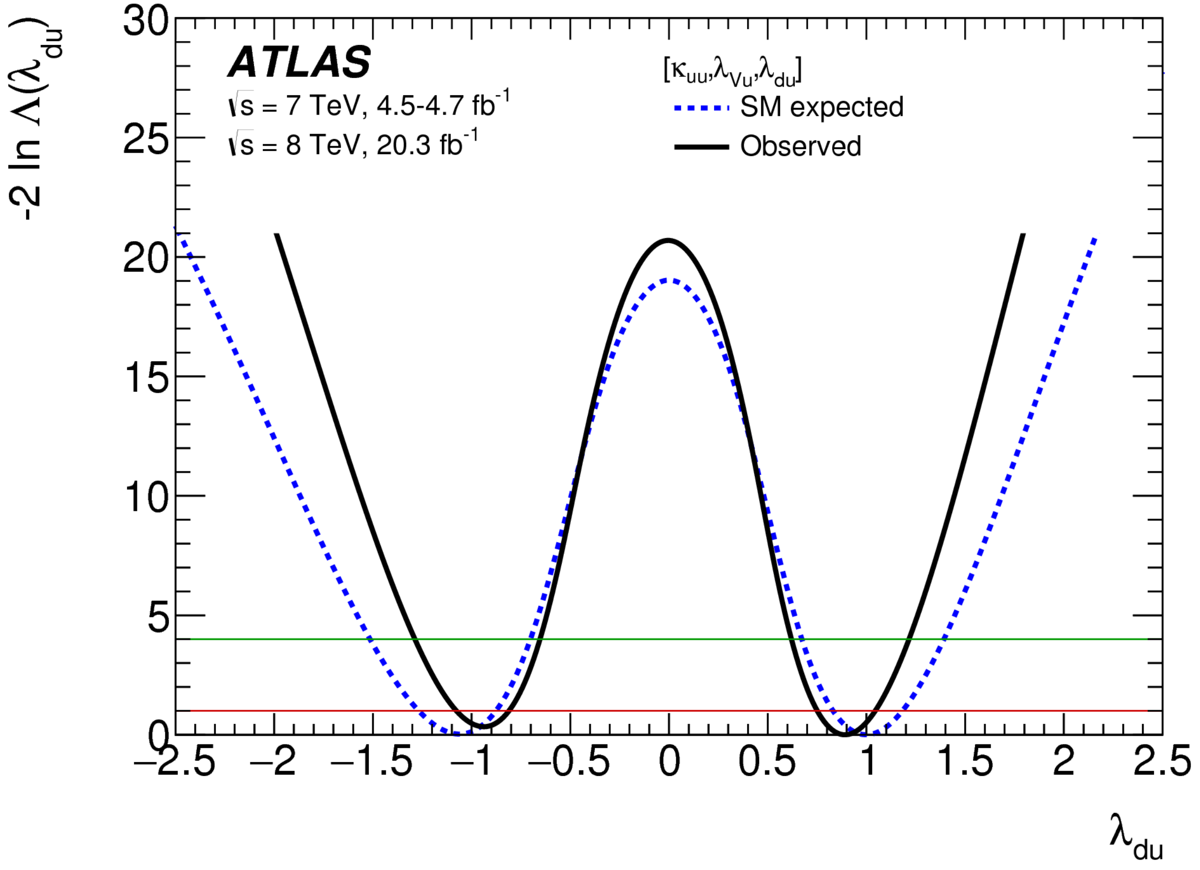


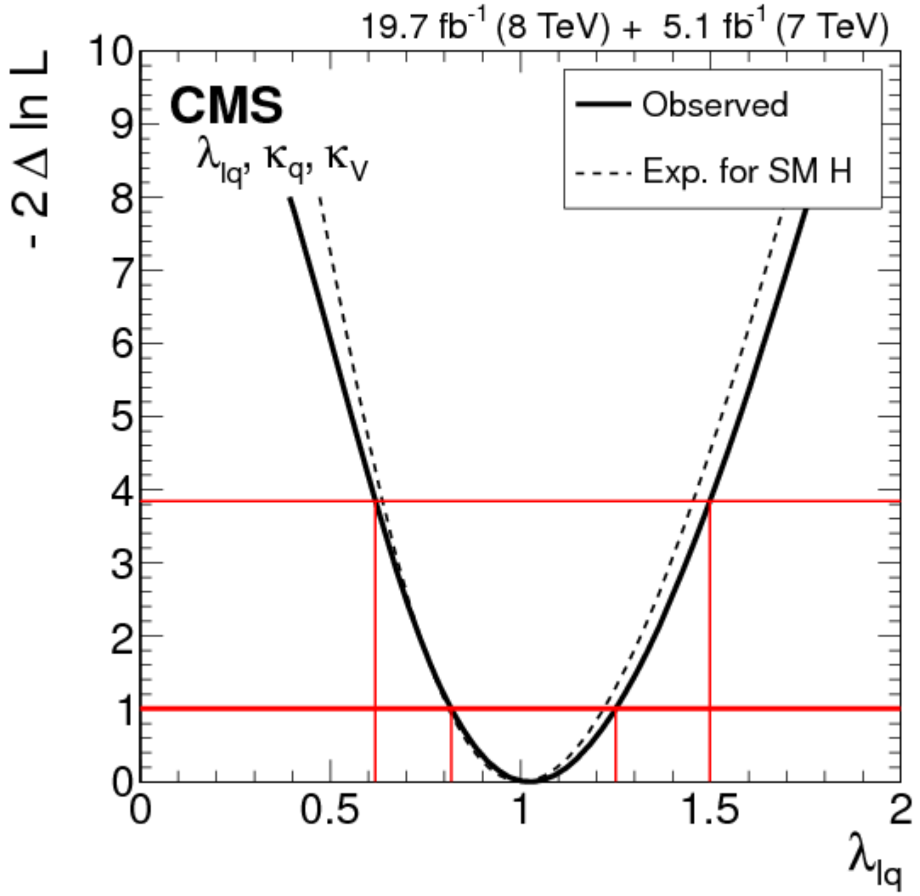


UP/DOWN AND LEPTON QUARK COUPLINGS

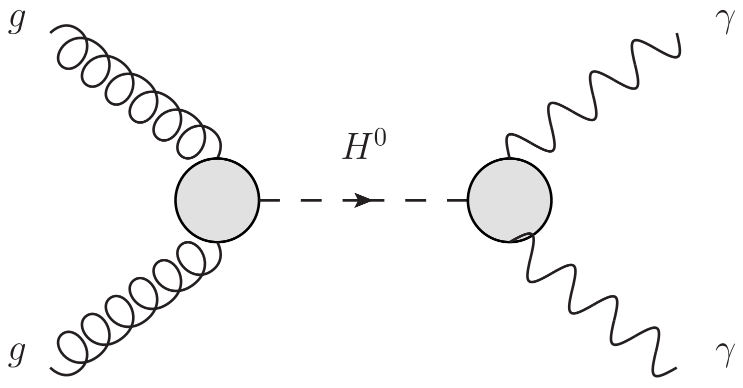
Check coupling ratios between up-type and down-type fermions (left) and quarks and leptons (right)

- motivated by e.g. two Higgs doublet scenarios





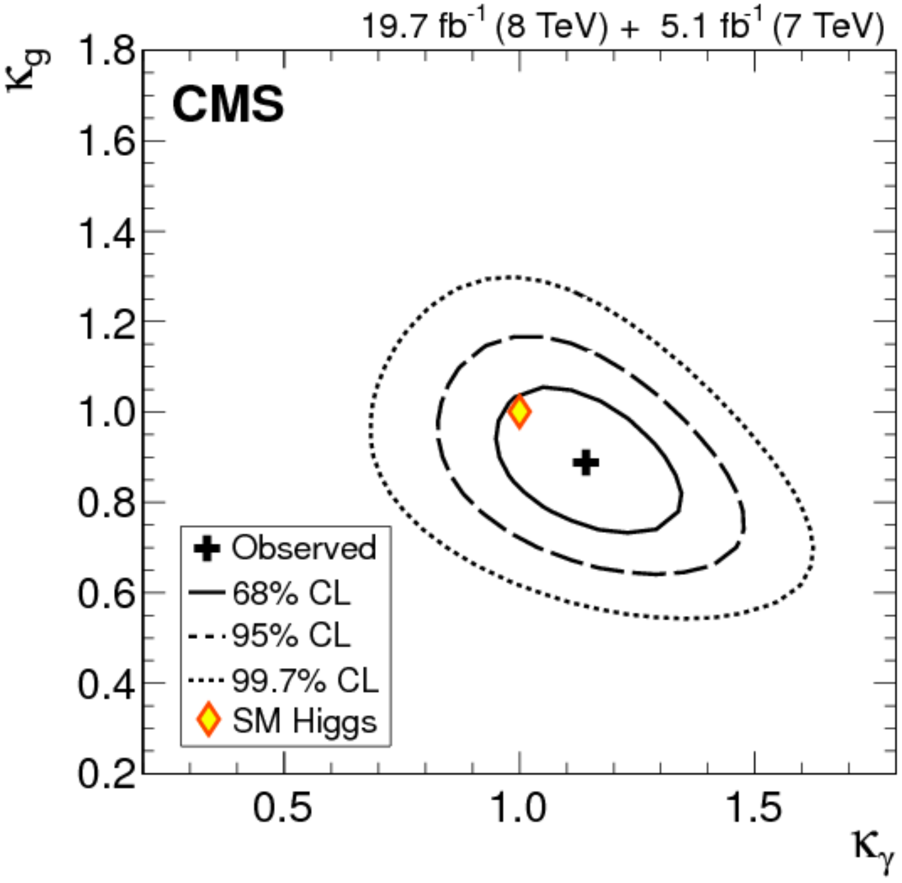
New Physics in Loops?

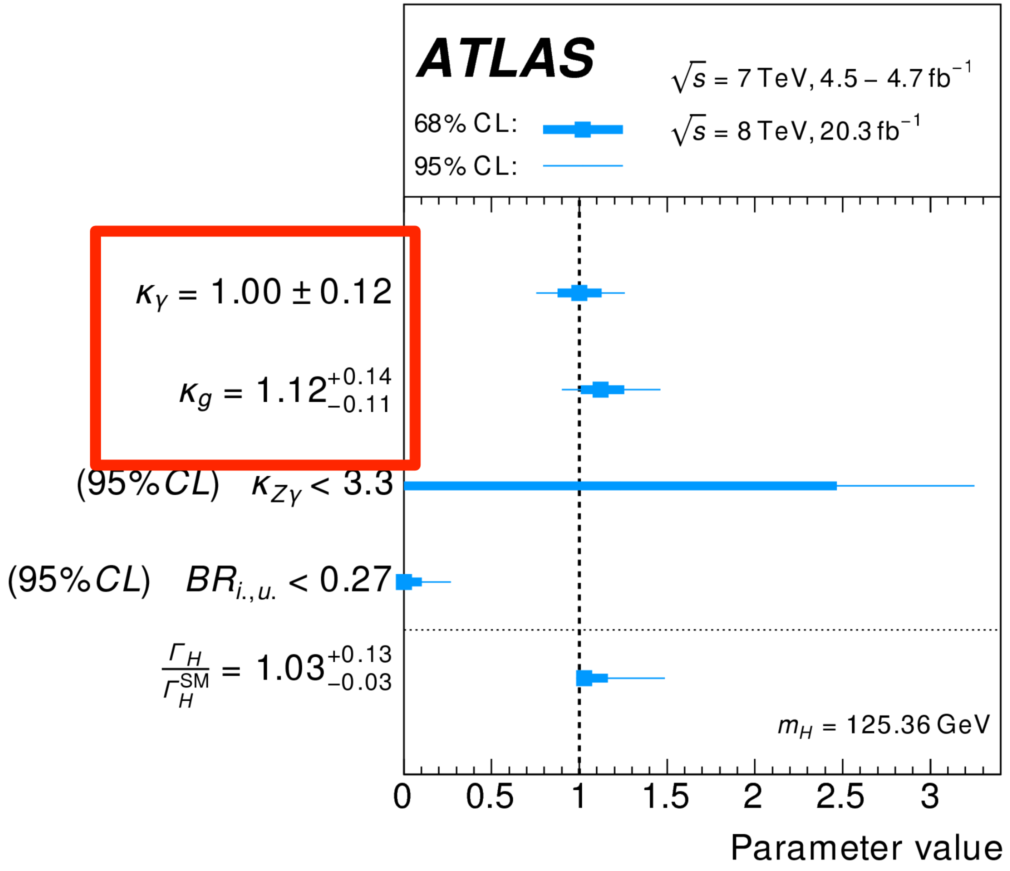


Test for “heavy” BSM physics (BSM particles > $m_H/2$) with possible contributions to ggH, H$\gamma\gamma$ (and HZγ) loops

$$\frac{(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)} = \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_\gamma^2}{\kappa_{\mathrm{H}}^2}$$

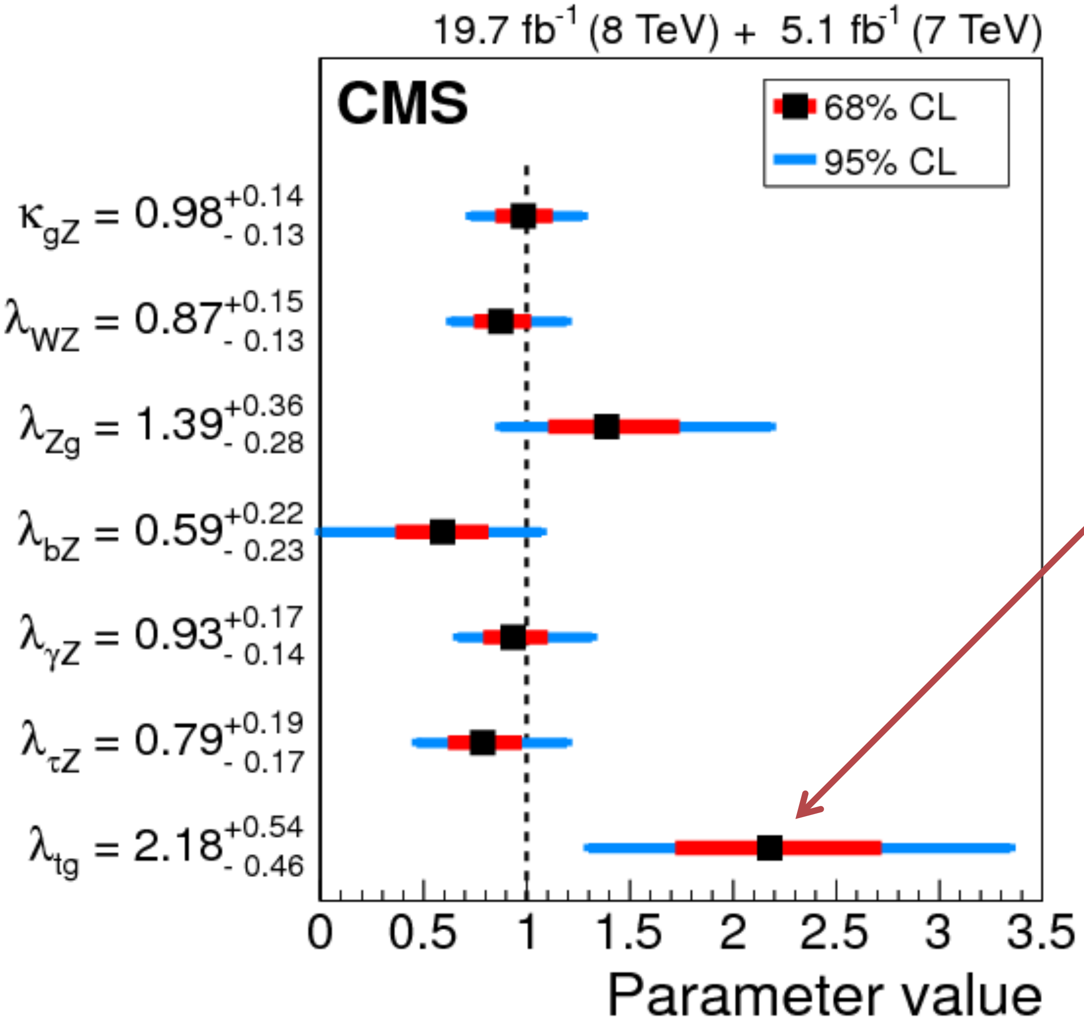
- Assume no contributions to width from BSM particles (discussed later)
- Assume SM couplings for known particles

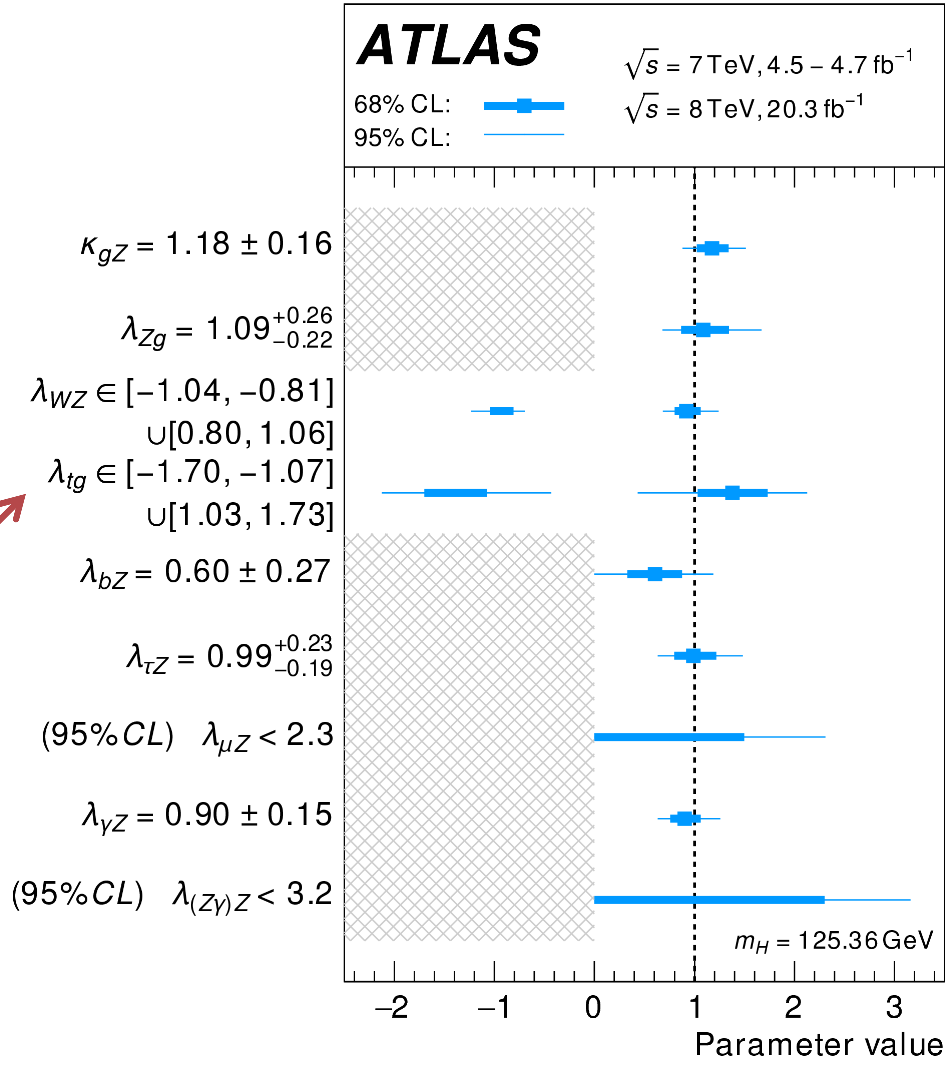




Most General Fit

- No assumptions on particle content in loops
- No assumptions on BSM decay or Higgs width
  - Drawback: can only fit ratios





BSM HIGGS PHYSICS

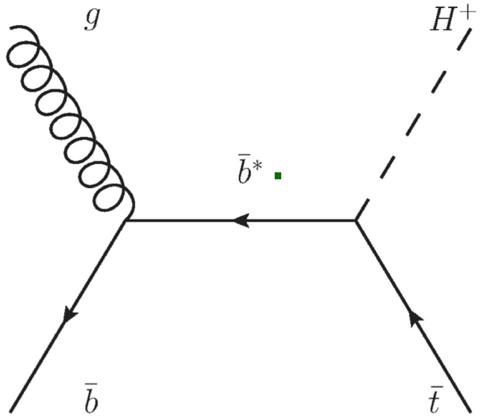
Does the Higgs sector extend beyond the single doublet of the SM?

Different strategies:

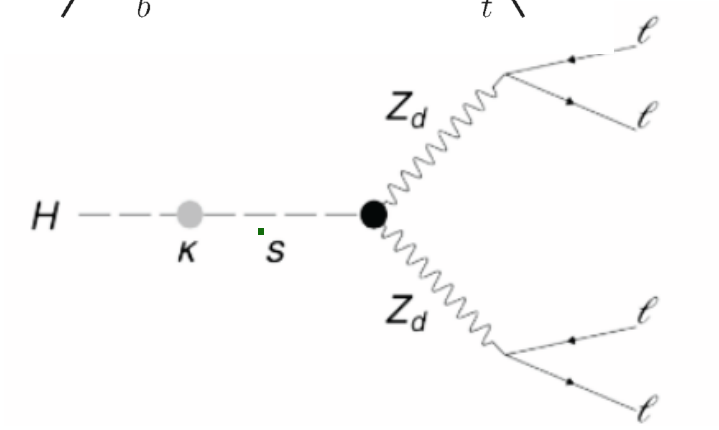
1. Search for another Higgs boson
2. Search for exotic decays of the 125 Higgs
3. Use the 125 GeV Higgs as a tool to find new physics

  - Tag a Higgs in decay chains
  - Use SM Higgs measurements to constrain BSM scenarios (observed Higgs constrains BSM parameter space)

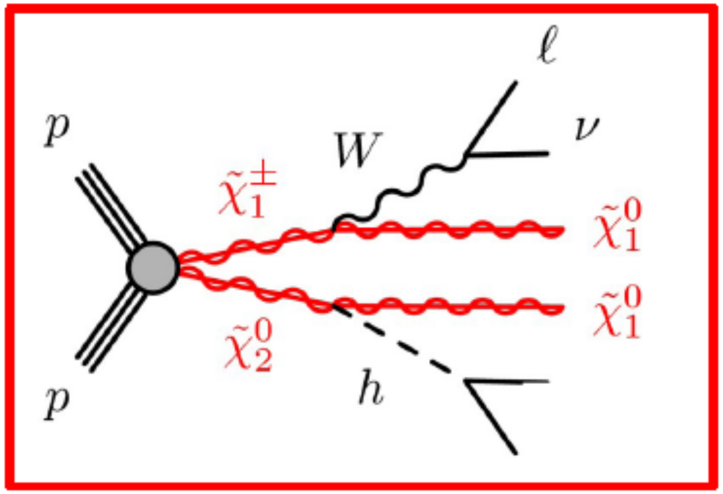
1.



2.

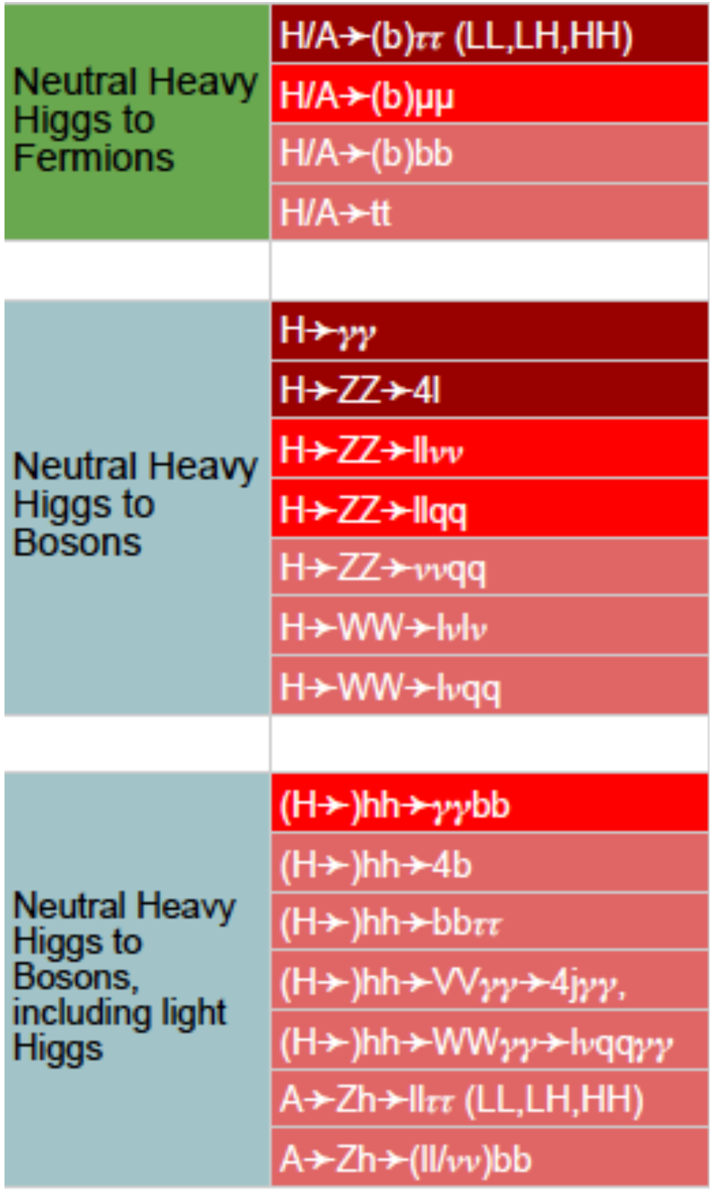


3.



BSM HIGGS SEARCHES

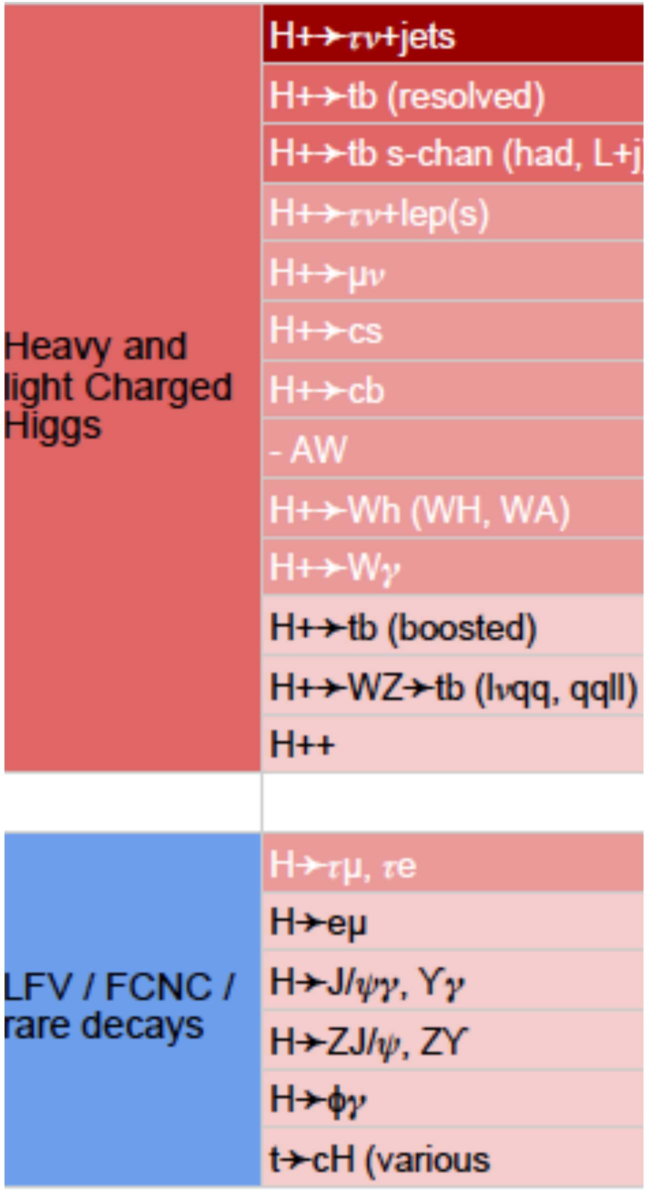
A non-exhaustive list… Many of the searches below were performed in Run 1



Neutral Heavy Higgs to Fermions	$H/A \to (b)\tau\tau$ (LL,LH,HH)
	$H/A \to (b)\mu\mu$
	$H/A \to (b)bb$
	$H/A \to tt$

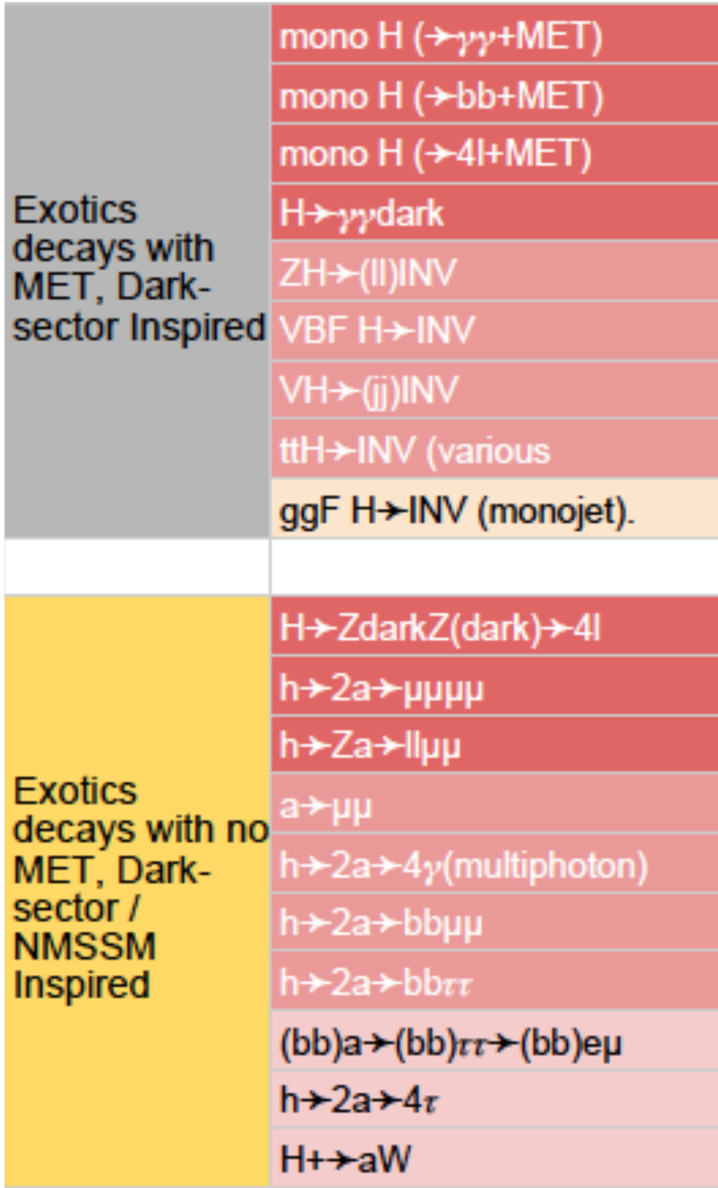
Neutral Heavy Higgs to Bosons	$H \to \gamma\gamma$
	$H \to ZZ \to 4l$
	$H \to ZZ \to ll\nu\nu$
	$H \to ZZ \to llqq$
	$H \to ZZ \to \nu\nu qq$
	$H \to WW \to l\nu l\nu$
	$H \to WW \to l\nu qq$

Neutral Heavy Higgs to Bosons, including light Higgs	$(H \to)hh \to \gamma\gamma bb$
	$(H \to)hh \to 4b$
	$(H \to)hh \to bb\tau\tau$
	$(H \to)hh \to VV\gamma\gamma \to 4j\gamma\gamma$,
	$(H \to)hh \to WW\gamma\gamma \to l\nu qq\gamma\gamma$
	$A \to Zh \to ll\tau\tau$ (LL,LH,HH)
	$A \to Zh \to (ll/\nu\nu)bb$



Heavy and light Charged Higgs	$H^+ \to \tau\nu$+jets
	$H^+ \to tb$ (resolved)
	$H^+ \to tb$ s-chan (had, L+j
	$H^+ \to \tau\nu$+lep(s)
	$H^+ \to \mu\nu$
	$H^+ \to cs$
	$H^+ \to cb$
	- AW
	$H^+ \to Wh$ (WH, WA)
	$H^+ \to W\gamma$
	$H^+ \to tb$ (boosted)
	$H^+ \to WZ \to tb$ ($l\nu qq$, qqll)
	H^{++}

LFV / FCNC / rare decays	$H \to \tau\mu$, τe
	$H \to e\mu$
	$H \to J/\psi\gamma$, $\Upsilon\gamma$
	$H \to ZJ/\psi$, ZY
	$H \to \phi\gamma$
	$t \to cH$ (various

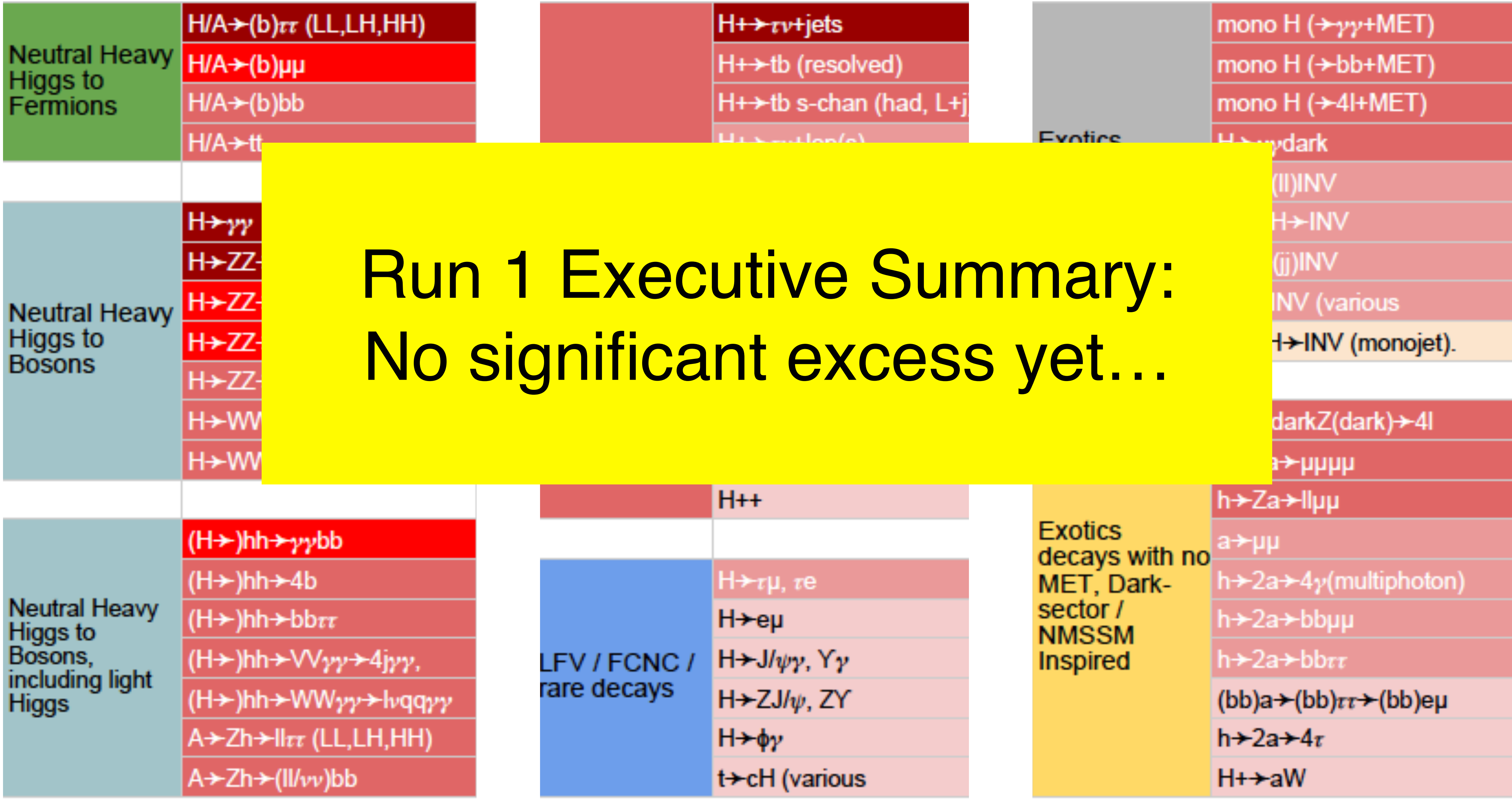


Exotics decays with MET, Dark-sector Inspired	mono H ($\to \gamma\gamma$+MET)
	mono H ($\to bb$+MET)
	mono H ($\to 4l$+MET)
	$H \to \gamma\gamma$dark
	$ZH \to (ll)$INV
	VBF $H \to$ INV
	$VH \to (jj)$INV
	$ttH \to$ INV (various
	ggF $H \to$ INV (monojet).

Exotics decays with no MET, Dark-sector / NMSSM Inspired	$H \to ZdarkZ(dark) \to 4l$
	$h \to 2a \to \mu\mu\mu\mu$
	$h \to Za \to ll\mu\mu$
	$a \to \mu\mu$
	$h \to 2a \to 4\gamma$(multiphoton)
	$h \to 2a \to bb\mu\mu$
	$h \to 2a \to bb\tau\tau$
	$(bb)a \to (bb)\tau\tau \to (bb)e\mu$
	$h \to 2a \to 4\tau$
	$H^+ \to aW$

BSM HIGGS SEARCHES

A non-exhaustive list… Many of the searches below were performed in Run 1



Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ-
	H→ZZ-
	H→ZZ-
	H→ZZ-
	H→WW
	H→WW
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

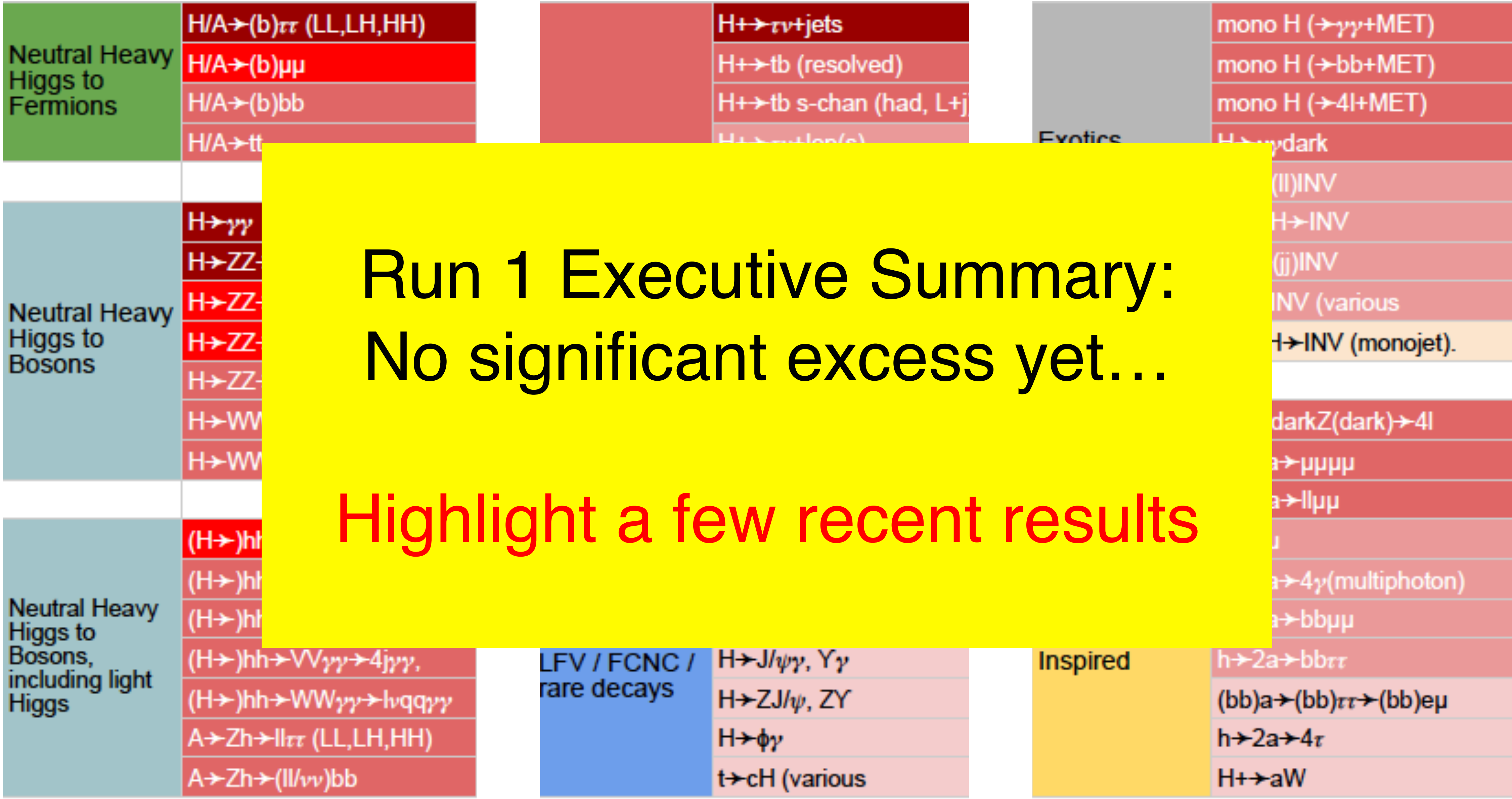
	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j
	H+→τν+lep(s)
	H++
LFV / FCNC / rare decays	H→τμ, τe
	H→eμ
	H→J/ψγ, Υγ
	H→ZJ/ψ, ZY
	H→ϕγ
	t→cH (various

Exotics	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γγdark
	(ll)INV
	H→INV
	(jj)INV
	INV (various
	H→INV (monojet).
Exotics decays with no MET, Dark-sector / NMSSM Inspired	darkZ(dark)→4l
	a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

Run 1 Executive Summary:
No significant excess yet…

BSM HIGGS SEARCHES

A non-exhaustive list… Many of the searches below were performed in Run 1



Neutral Heavy Higgs to Fermions
H/A→(b)$\tau\tau$ (LL,LH,HH)
H/A→(b)$\mu\mu$
H/A→(b)bb
H/A→tt

Neutral Heavy Higgs to Bosons
H→$\gamma\gamma$
H→ZZ-
H→ZZ-
H→ZZ-
H→ZZ-
H→WW
H→WW

Neutral Heavy Higgs to Bosons, including light Higgs
(H→)hh
(H→)hh
(H→)hh
(H→)hh→VV$\gamma\gamma$→4j$\gamma\gamma$,
(H→)hh→WW$\gamma\gamma$→lνqq$\gamma\gamma$
A→Zh→ll$\tau\tau$ (LL,LH,HH)
A→Zh→(ll/$\nu\nu$)bb

H+→$\tau\nu$+jets
H+→tb (resolved)
H+→tb s-chan (had, L+j

LFV / FCNC / rare decays
H→J/$\psi\gamma$, Yγ
H→ZJ/ψ, ZY
H→$\phi\gamma$
t→cH (various

Exotics
mono H (→$\gamma\gamma$+MET)
mono H (→bb+MET)
mono H (→4l+MET)
H→$\gamma\gamma$dark
(ll)INV
H→INV
(jj)INV
INV (various
H→INV (monojet).

darkZ(dark)→4l
a→$\mu\mu\mu\mu$
a→ll$\mu\mu$
a→4γ(multiphoton)
a→bb$\mu\mu$

Inspired
h→2a→bb$\tau\tau$
(bb)a→(bb)$\tau\tau$→(bb)eμ
h→2a→4τ
H+→aW

Run 1 Executive Summary:
No significant excess yet…

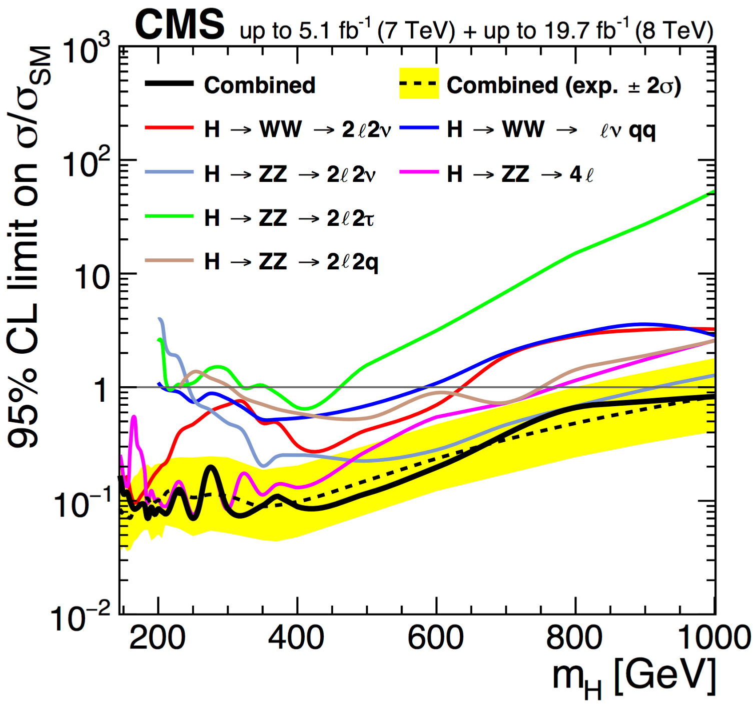
Highlight a few recent results

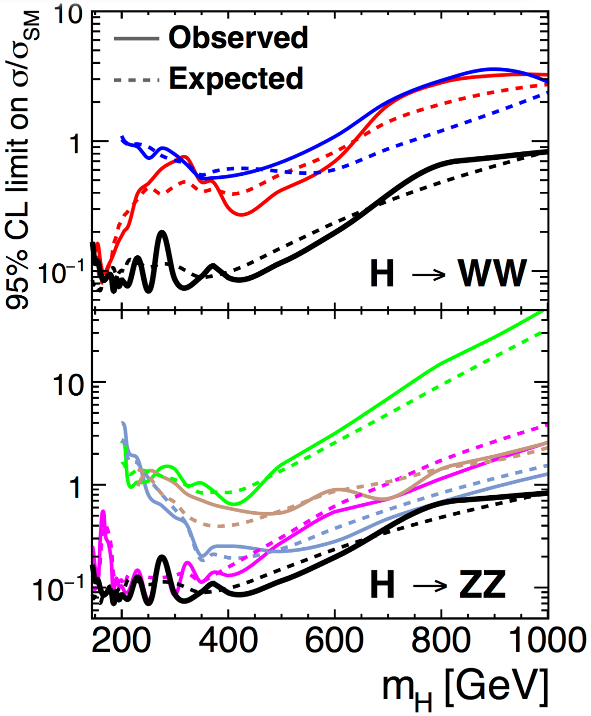
HIGH MASS SEARCHES: WW/ZZ (CMS)

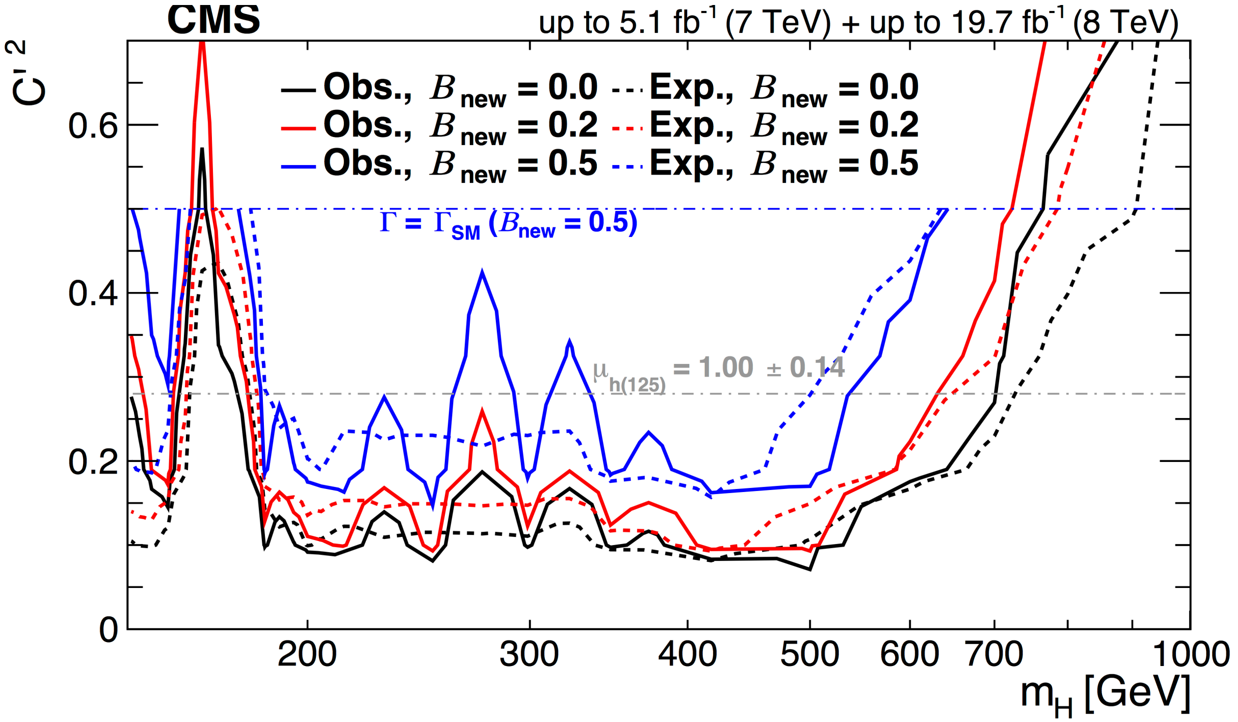
Search for a SM-like Higgs boson decaying to WW or ZZ final states:

- WW->lνlν
- WW->lνjj
- ZZ->llll
- ZZ->llττ
- ZZ->llνν
- ZZ->llqq

- Search for electroweak singlet
  - C'²+C²=1
    - C: SM coupling
  - *B*new: BR to non-SM



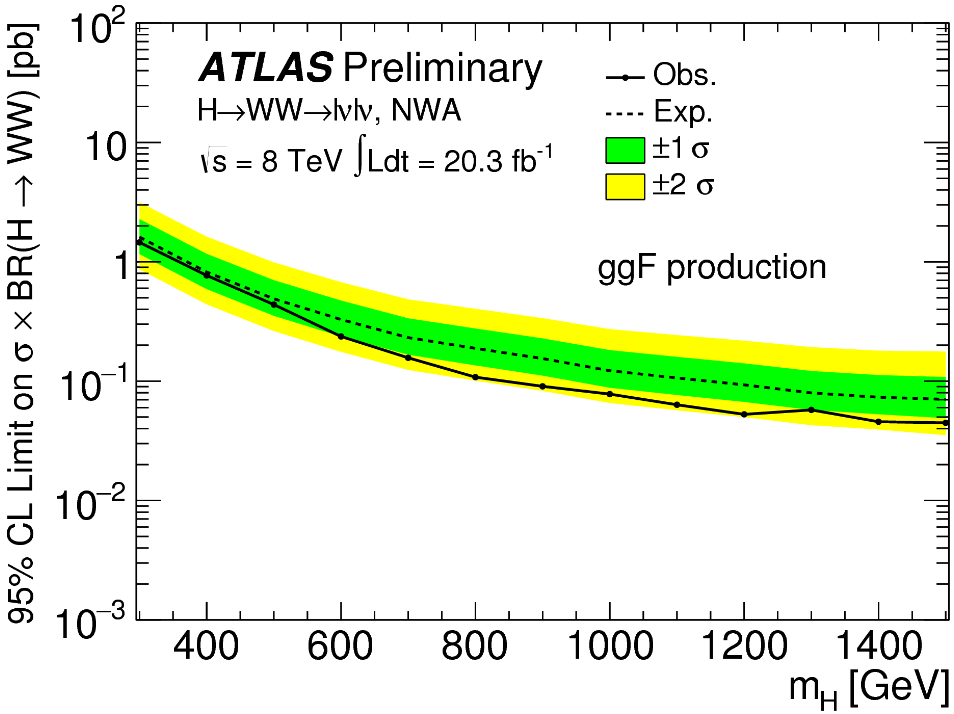




HIGH MASS SEARCHES: WW/ZZ (ATLAS)

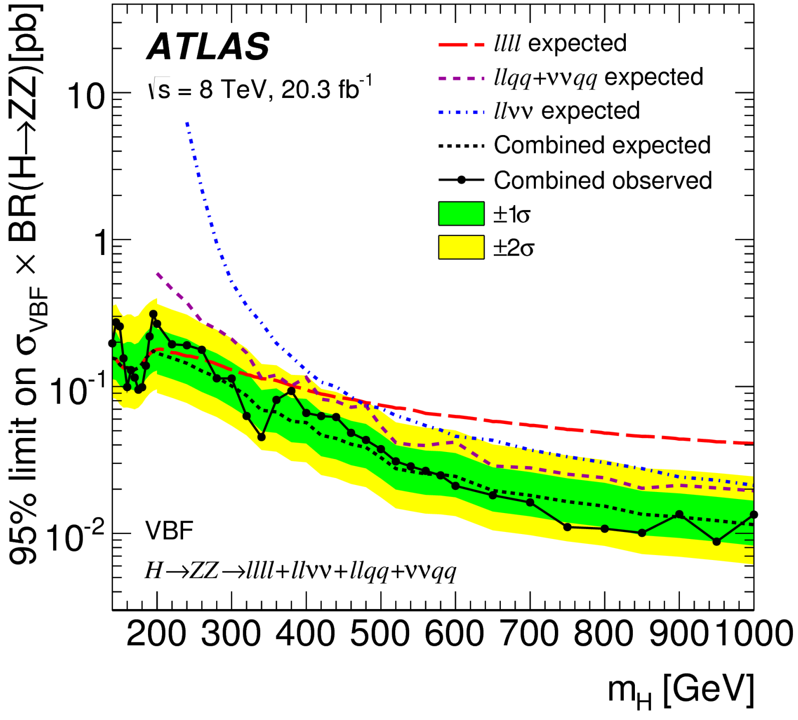
High mass searches in WW and ZZ final states

- WW->lνlν
- WW->lνjj
- ZZ->llll
- ZZ->llνν
- ZZ->llqq



- Limits given for narrow width signal

- No significant deviations observed



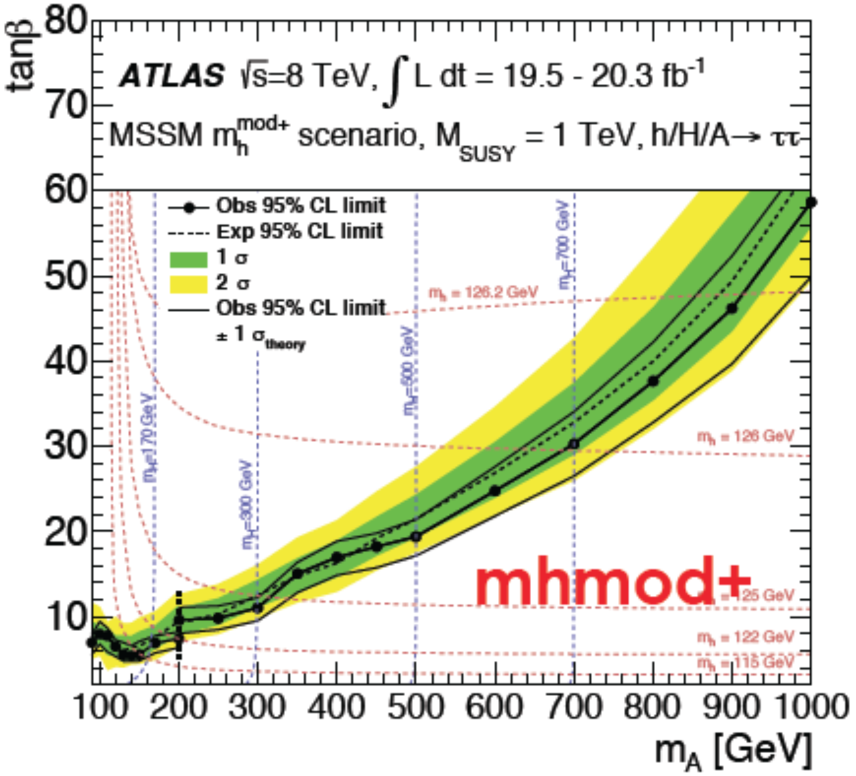
A->ττ (LOW/HIGH MASS)

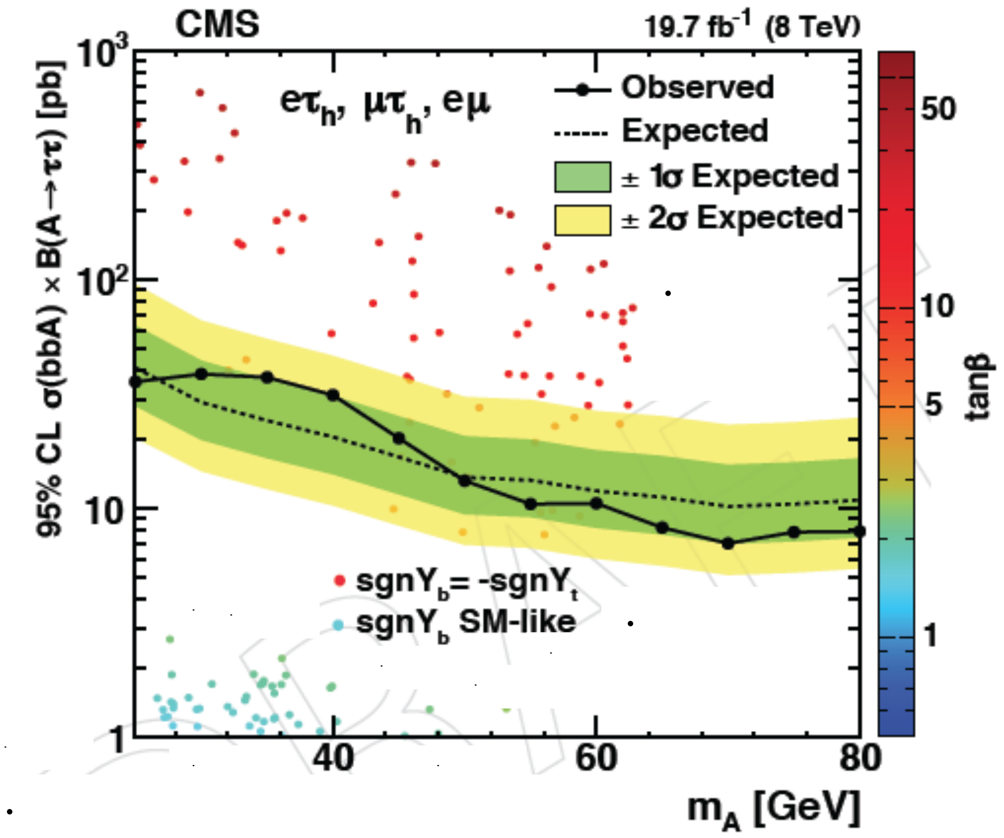
Search for pseudoscalar (A) boson decaying to τ leptons

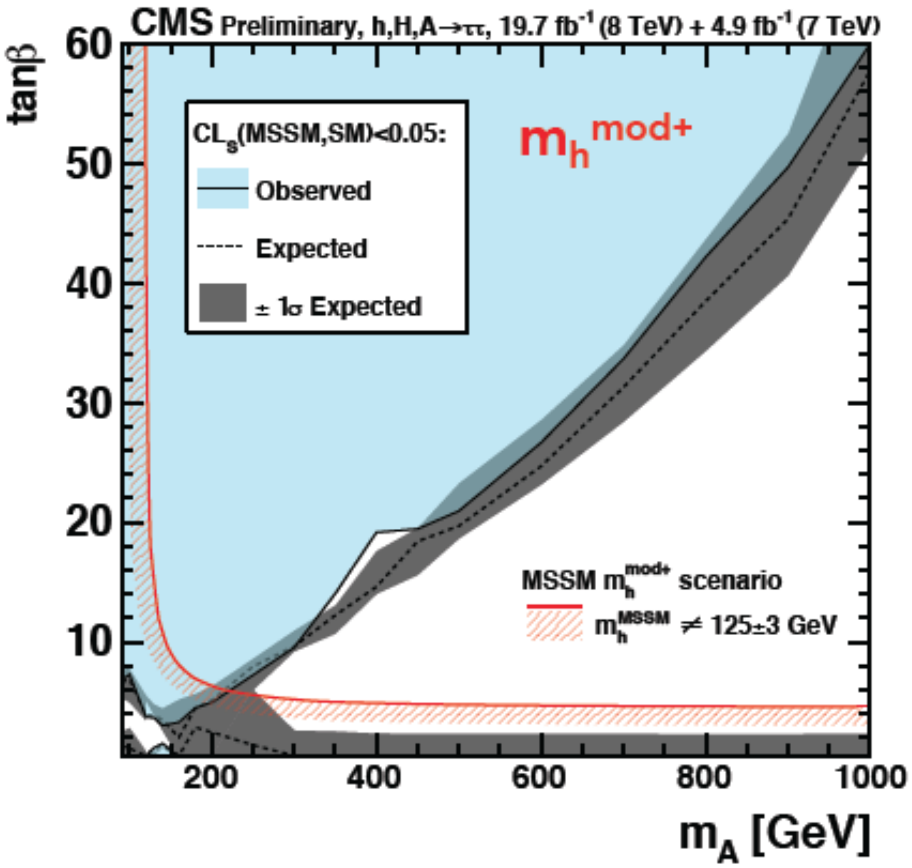
- Sensitive in high tan(β) regime

Searches performed at high and low mass

Results interpreted in the context of SUSY scenarios. Limits given on σ x BR

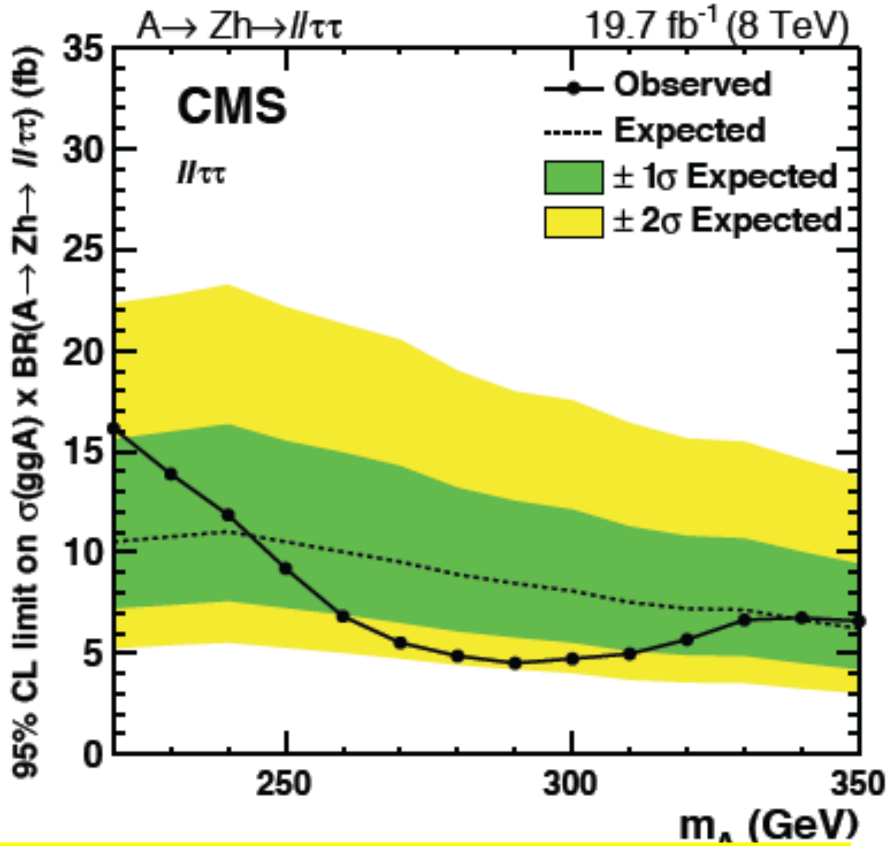




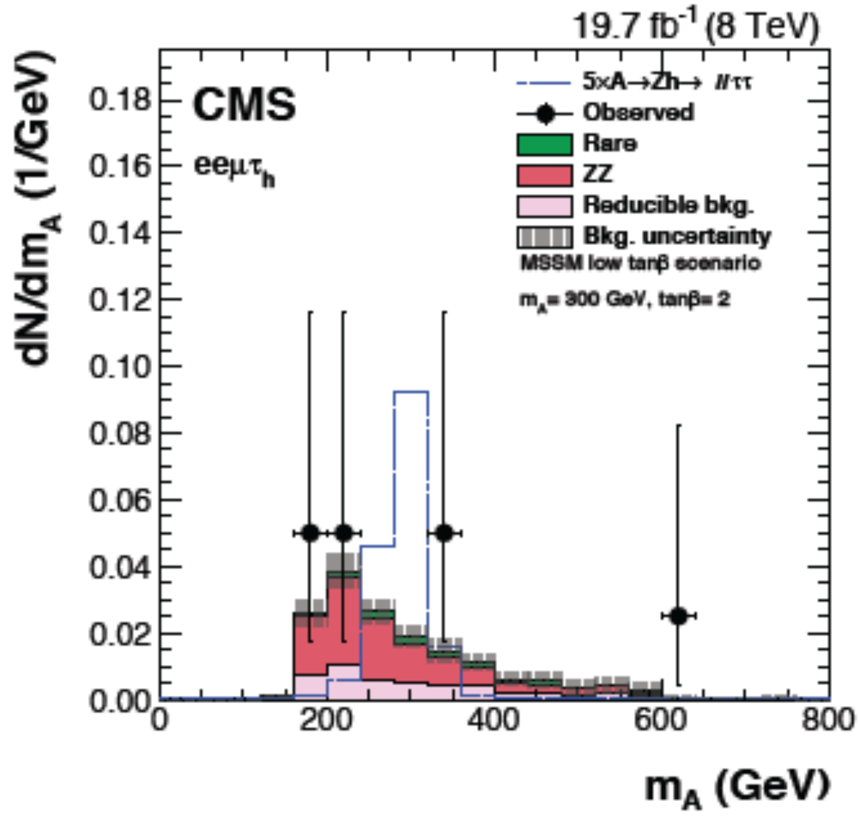


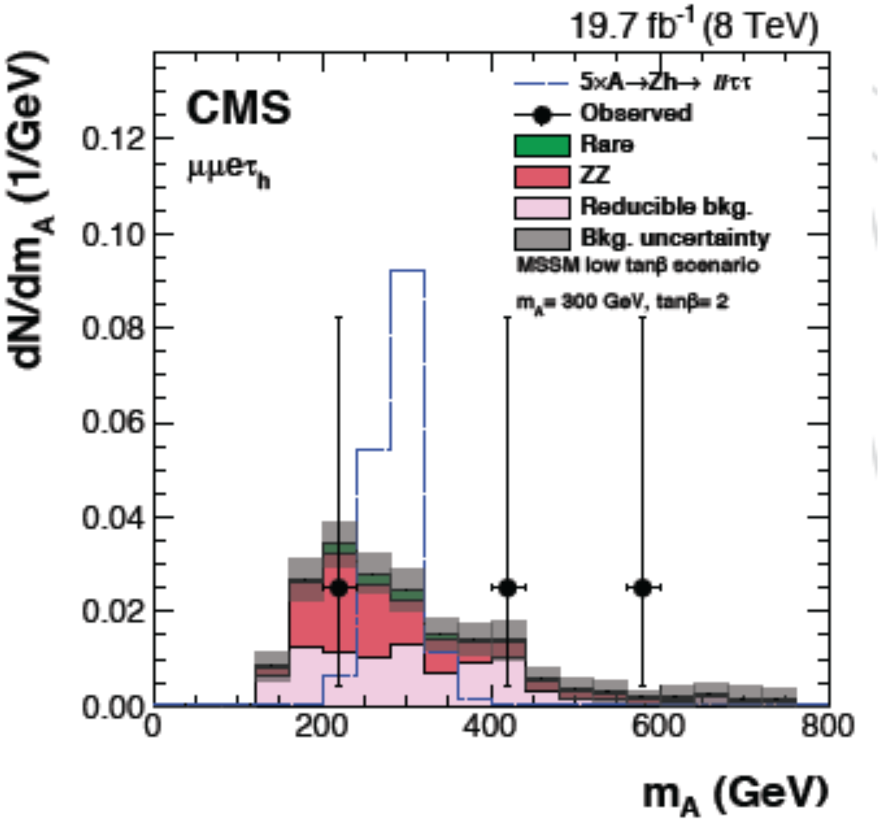
A->ZH (CMS)

- If $M_{SUSY} > 1$TeV, low values of tan(β) can accomodate mH = 125 GeV
- Decays A->ZH, H->hh can have sizable branching ratios if m_A, $m_H < 2m_{top}$
- Look at AZ->(ee,μμ)ττ final states



ATLAS results with H->bb and ττ and CMS with bb

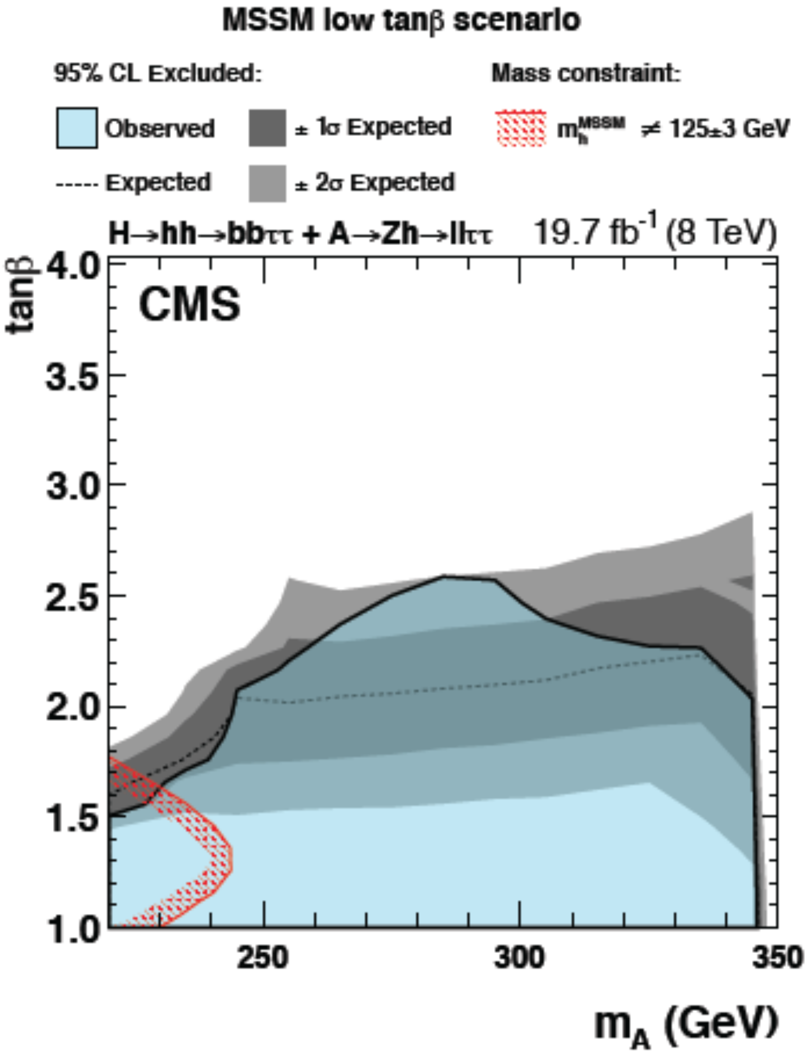


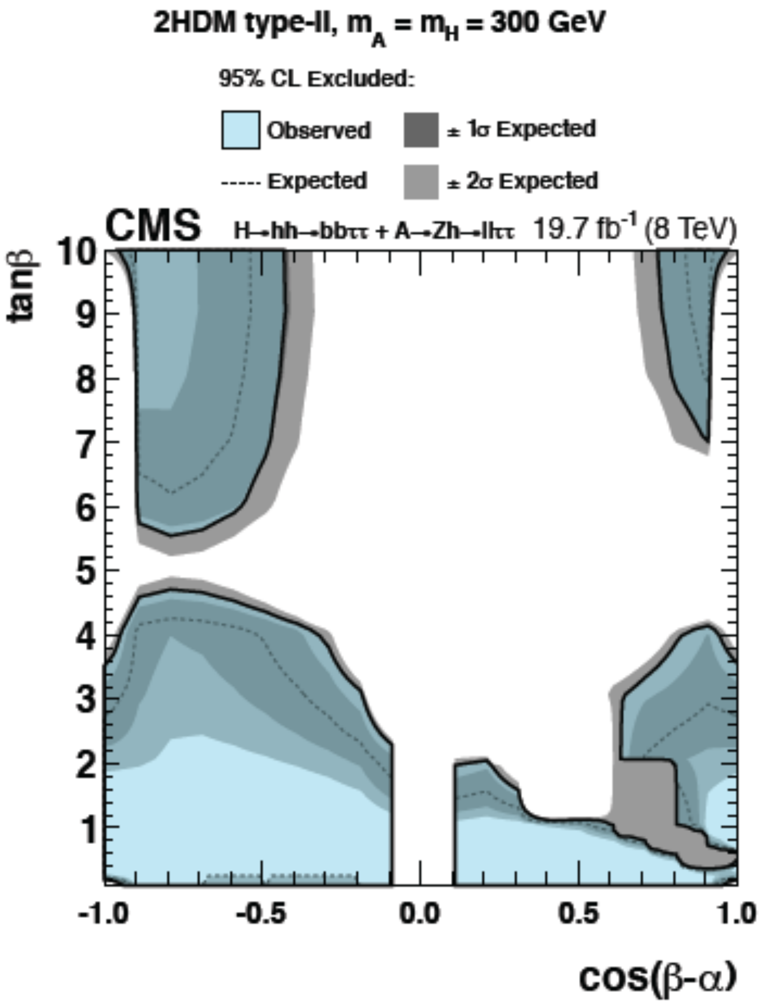


A->ZH, H->hh (CMS)

Combination of two analyses ($ll\tau\tau,\tau\tau bb$) performed in the context of two BSM scenarios:

- MSSM low tan(b)-> M_{SUSY} consistent with m_h=125 GeV
- 2HDM (Type II). Assume $m_H=m_A=m_{H+}$

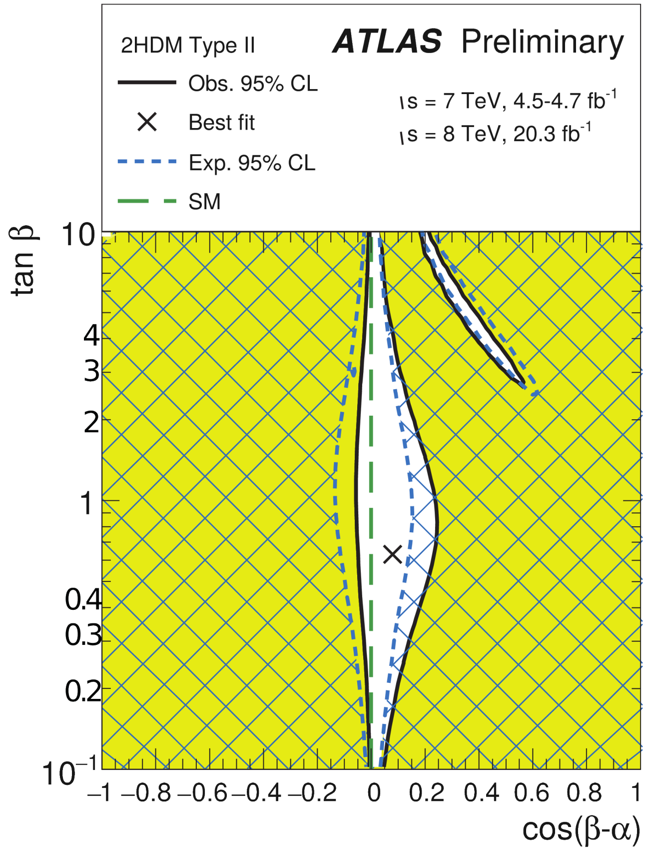


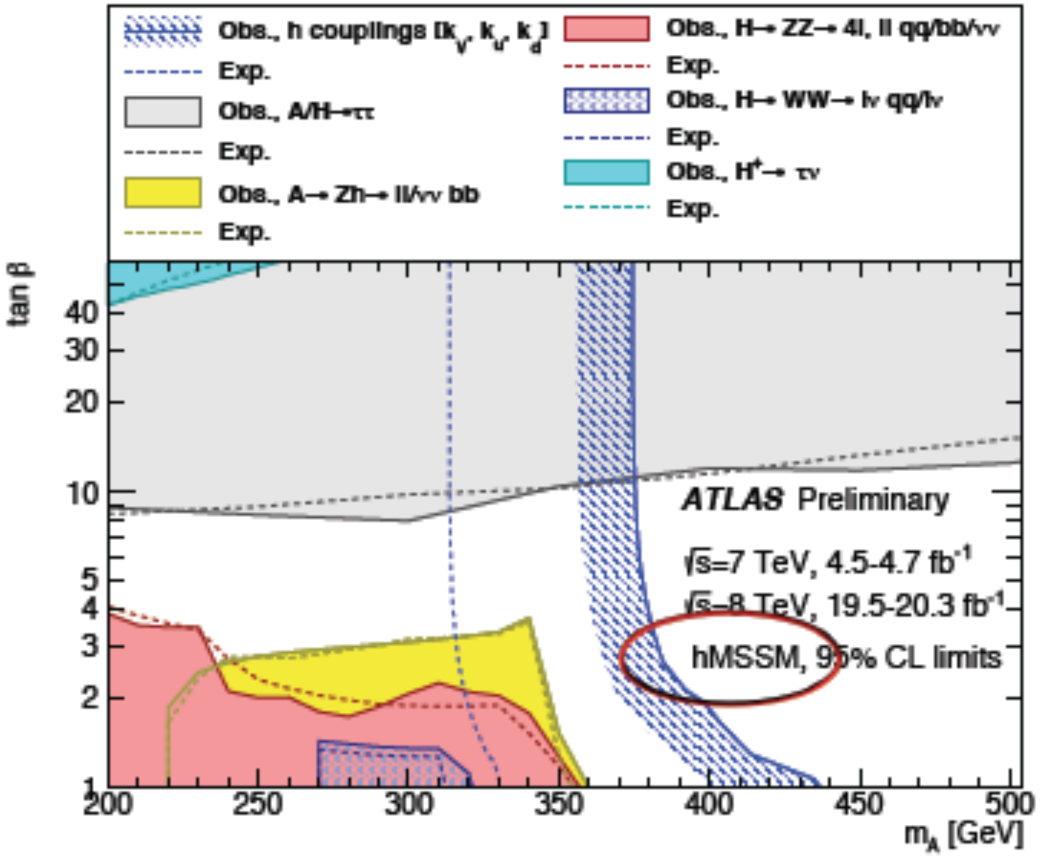


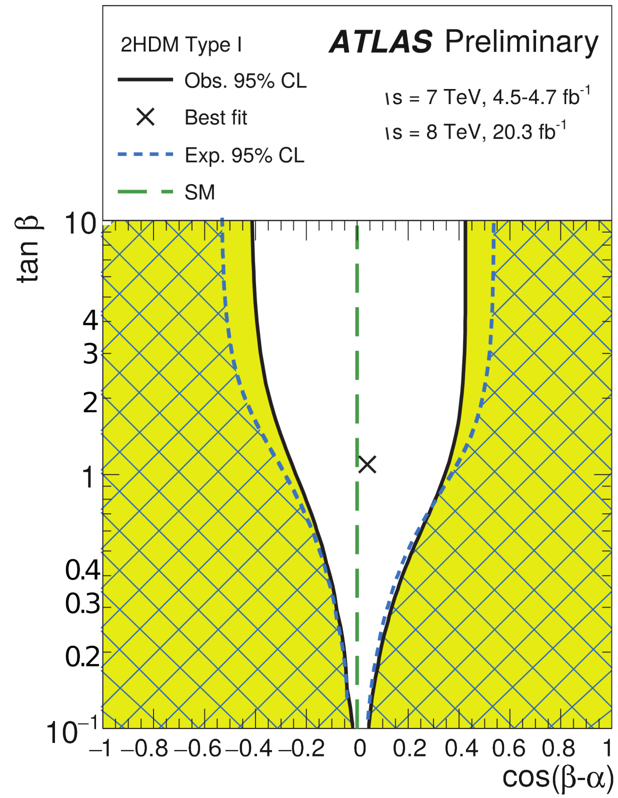
BSM CONSTRAINTS FROM COUPLINGS (ATLAS)

Measurements of the discovered Higgs boson can constrain parameters in various BSM scenarios (asymmetry)

- Right: 2HDM (type I and II)
- Below: simplified SUSY model hMSSM



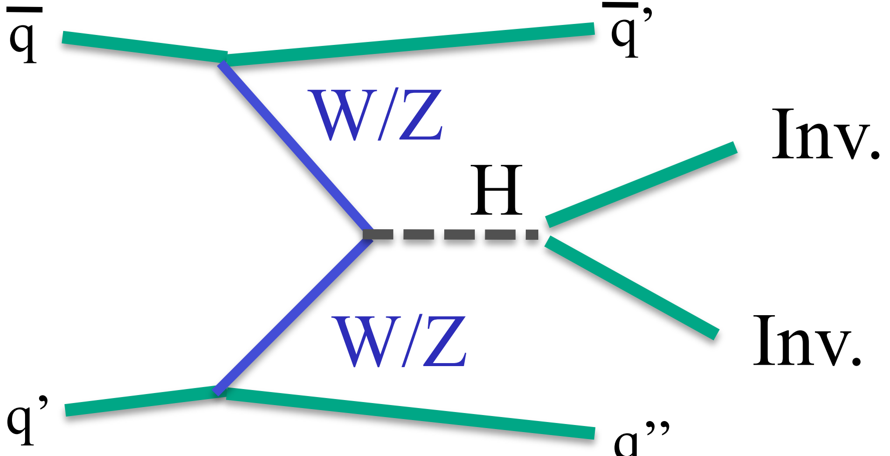




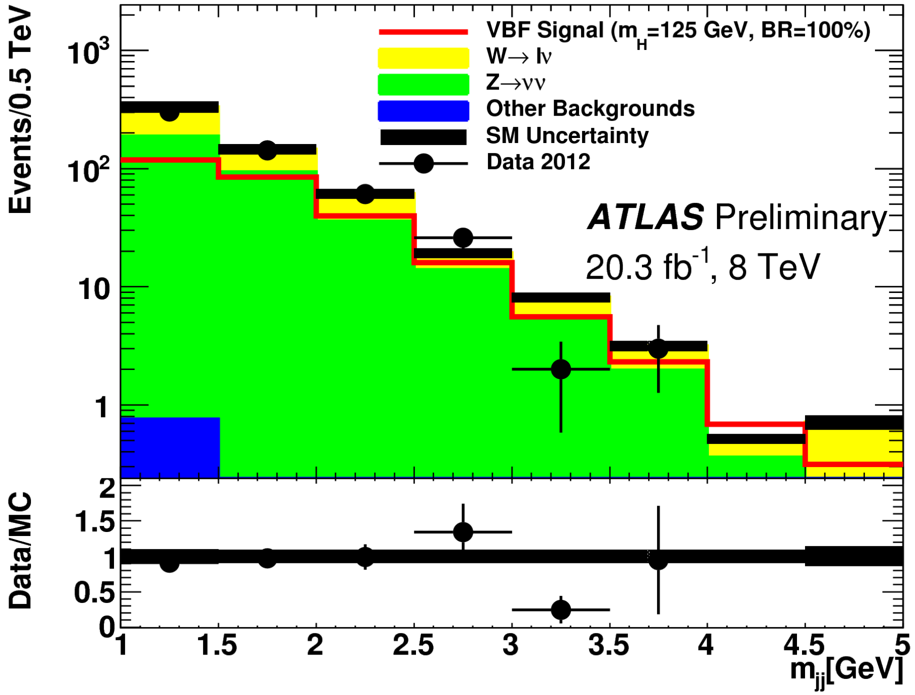
INVISIBLE DECAYS: DIRECT SEARCHES

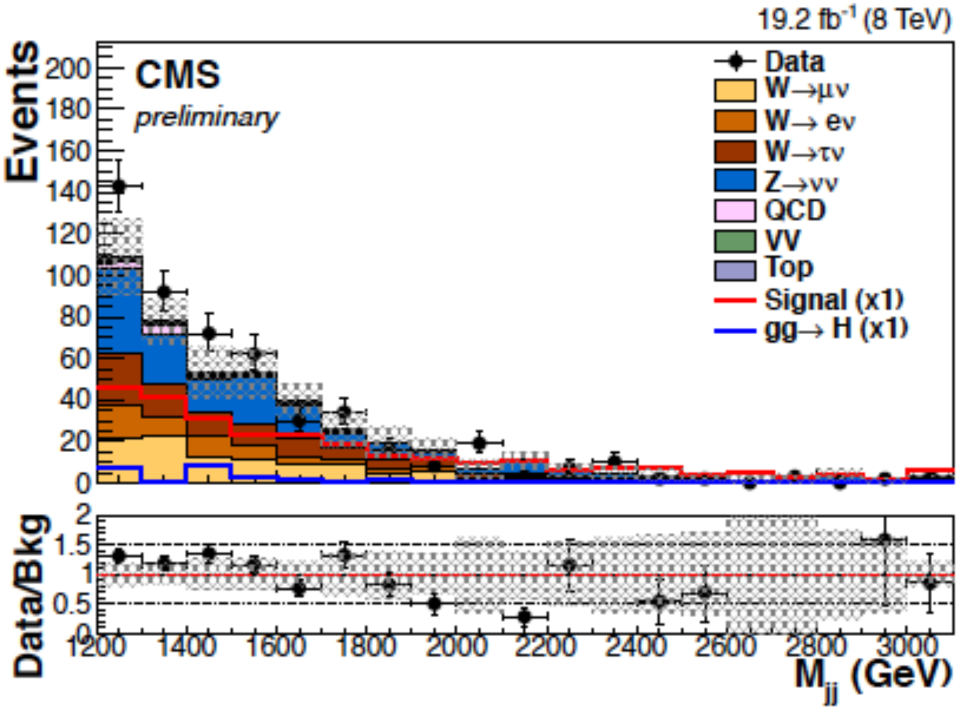
SM BR to invisible: 0.1% (ZZ->4ν)

Weak vector boson fusion is the most sensitive production mode



- Require E_TMiss and VBF signature:
    - Large separation between jets in η
    - Large mjj
- Main backgrounds:
    - Z(νν)+jets, W(lν)+jets
- Results (95% CL) on BR:
    - ATLAS: 28% (31% exp.)
    - CMS: 58 % (40% exp.)
- ATLAS combination with Z(ll)H and V(jj)H: BR(inv) < 25% (27% exp.) at 95% CL





LEPTON FLAVOUR VIOLATING DECAYS

Search for LFV violating Higgs decays to τμ in hadronic τ decays (CMS and ATLAS) and leptonic τ decays (CMS)

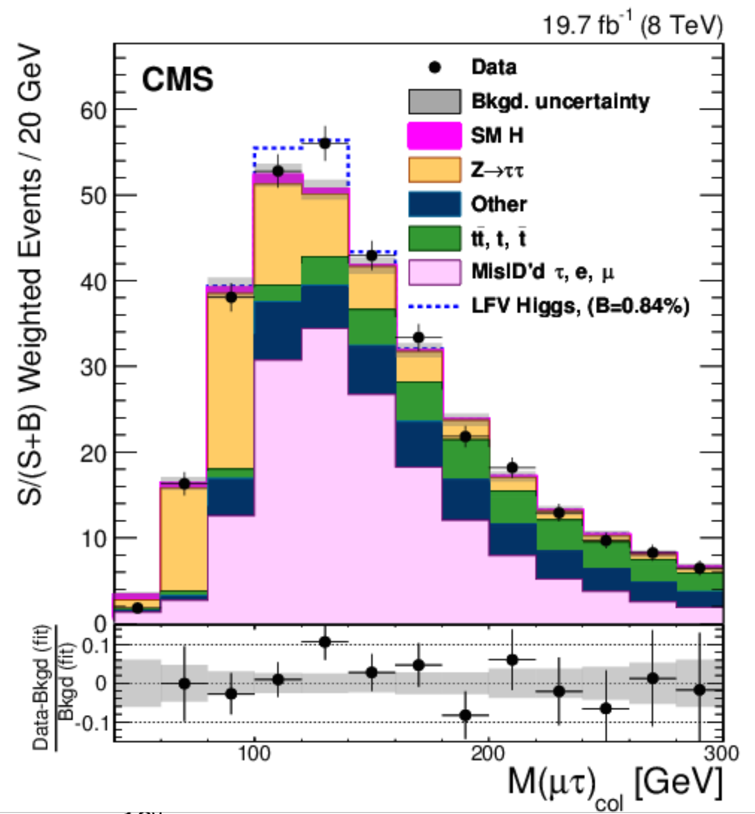
- Some excess is observed: to be followed-up in Run 2

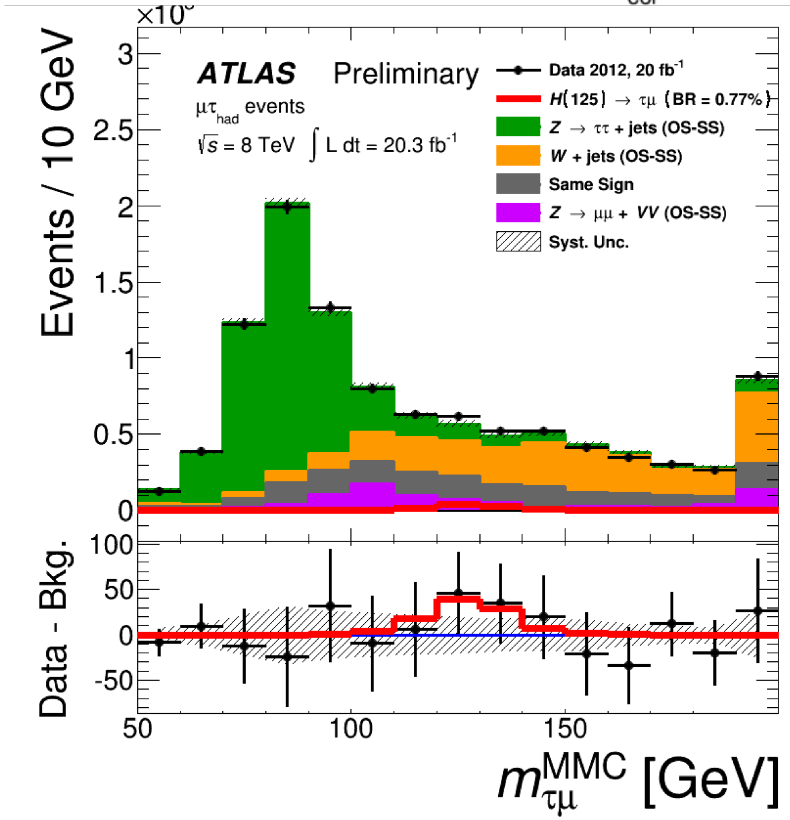
CMS

$\mu\tau_e$	$0.87^{+0.66}_{-0.62}$	$0.81^{+0.85}_{-0.78}$	$0.05^{+1.58}_{-0.97}$
$\mu\tau_h$	$0.41^{+1.20}_{-1.22}$	$0.21^{+1.03}_{-1.09}$	$1.48^{+1.16}_{-0.93}$
$\mu\tau$		$\boxed{0.84^{+0.39}_{-0.37}}$	

ATLAS

- Best fit BR: 0.77 +/- 0.62 %
- Limit: 1.85 % @ 95% CL (1.24% Exp.)



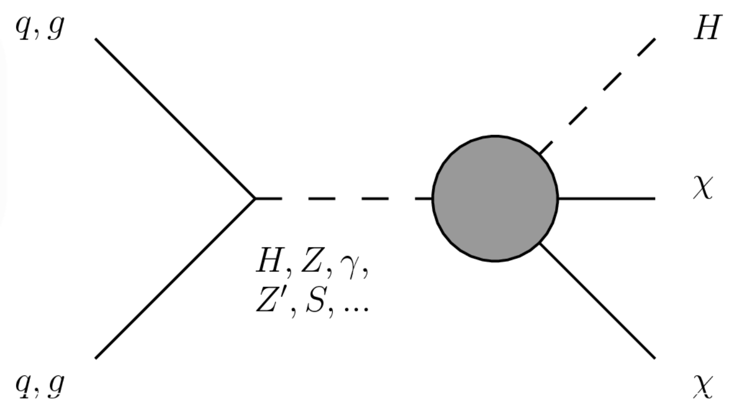


CONCLUSIONS

- A lot of progress made since the discovery 3 years ago
    - The measurements of the production and decay properties of the Higgs boson are consistent with SM predictions
        - The SM 0^+ hypothesis is preferred over all other tested spin/parity alternatives (almost all excluded at > 95% CL)
        - Coupling strengths consistent with SM
    - No evidence of BSM physics in the scalar sector (yet…)
- Realization of Run 1 Higgs physics program made possible thanks to outstanding performance of the LHC
- We have a very exciting and challenging Higgs physics program for Run II

Backup Slides

MONO-HIGGS (ATLAS)



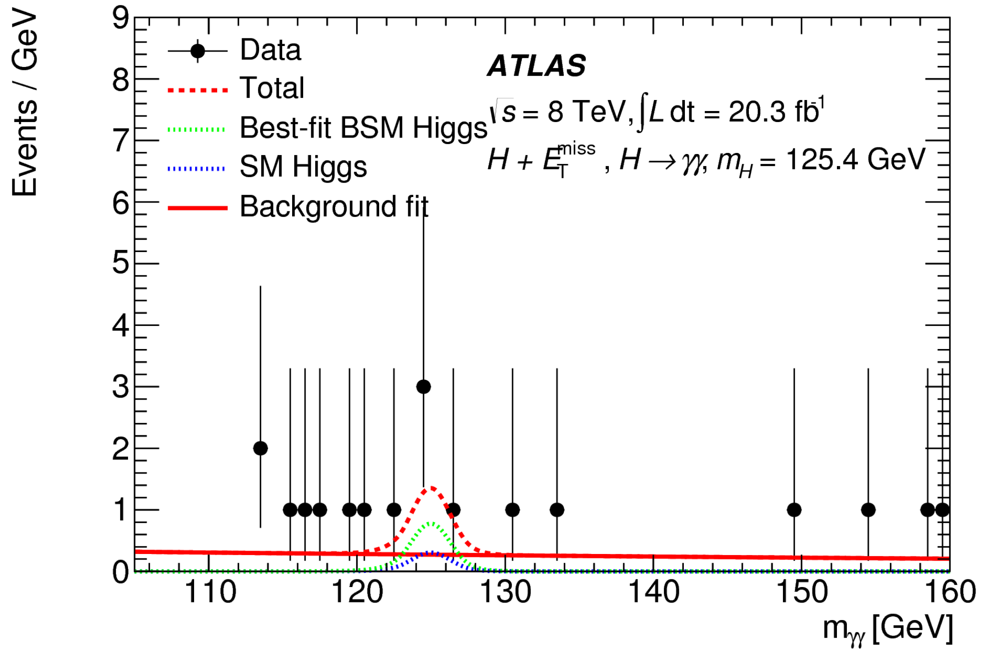
- Search for the production of invisible particles in association with a Higgs boson in H->γγ channel

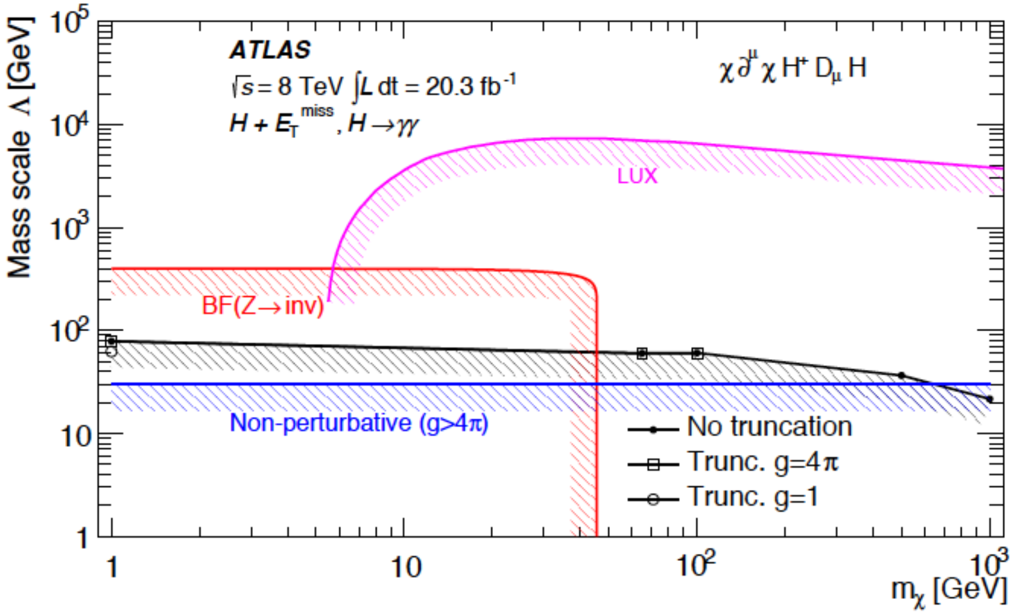
- Require:
  - $p_T(\gamma\gamma) > 70$ GeV
  - E_T(Miss) > 90 GeV

- Main SM background:
  - ZH -> ννγγ (irreducible)
  - WH ->lνγγ (lost lepton)

- Results interpreted in context of suppression scale Λ for given EFT operators.

Example:





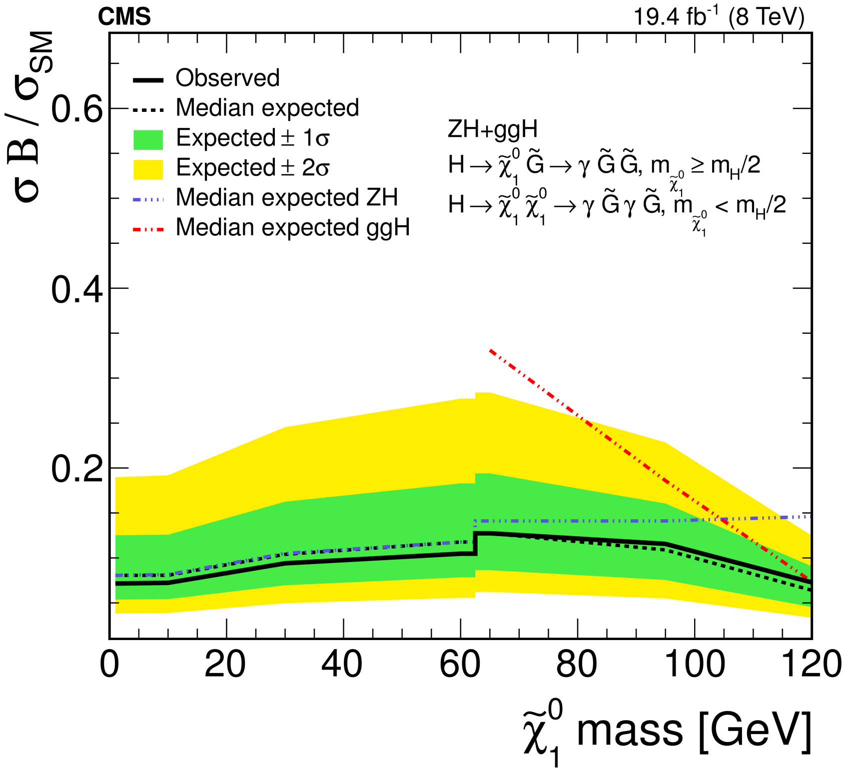
HIGGS DECAY TO $\gamma(\gamma)+E_T$(MISS) (CMS)

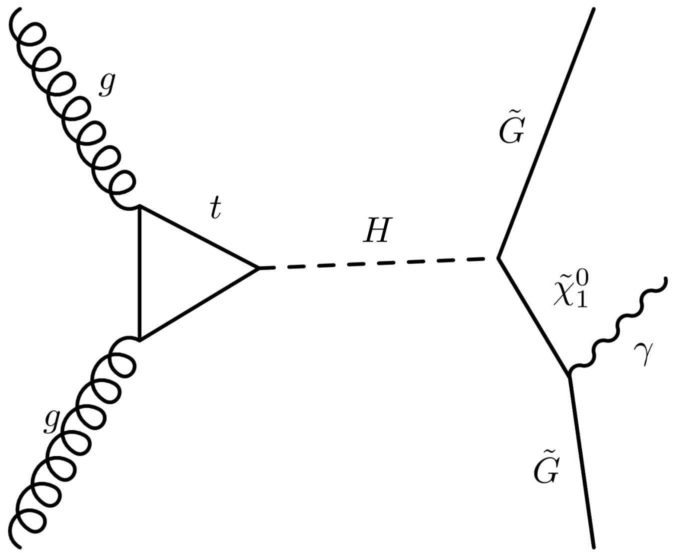
In some SUSY scenarios, the gravitino is the Dark Matter candidate, with final states with ETMiss + photon(s)

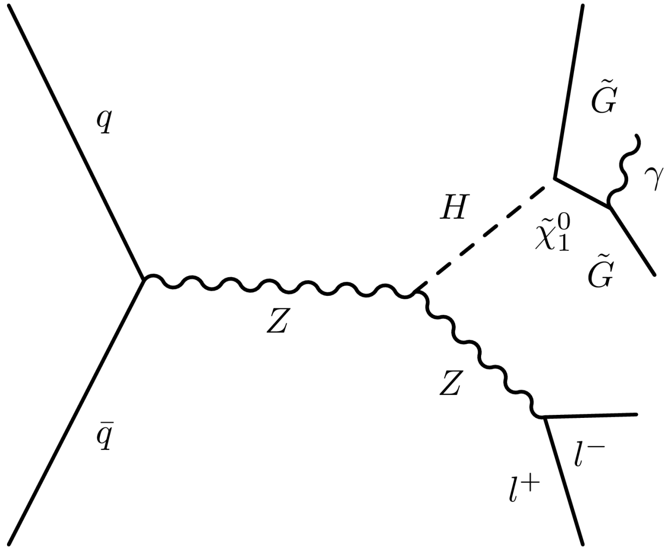
Selections target ggH and ZH channels

- Backgrounds ggH:
  - $Z(\nu\nu)+\gamma$
  - Mono-e
  - Mono jet
  - G+jet

- Backgrounds ZH:
  - $Z\gamma$
  - Z+jets
  - ZW, ZZ
  - Non-resonant dilepton

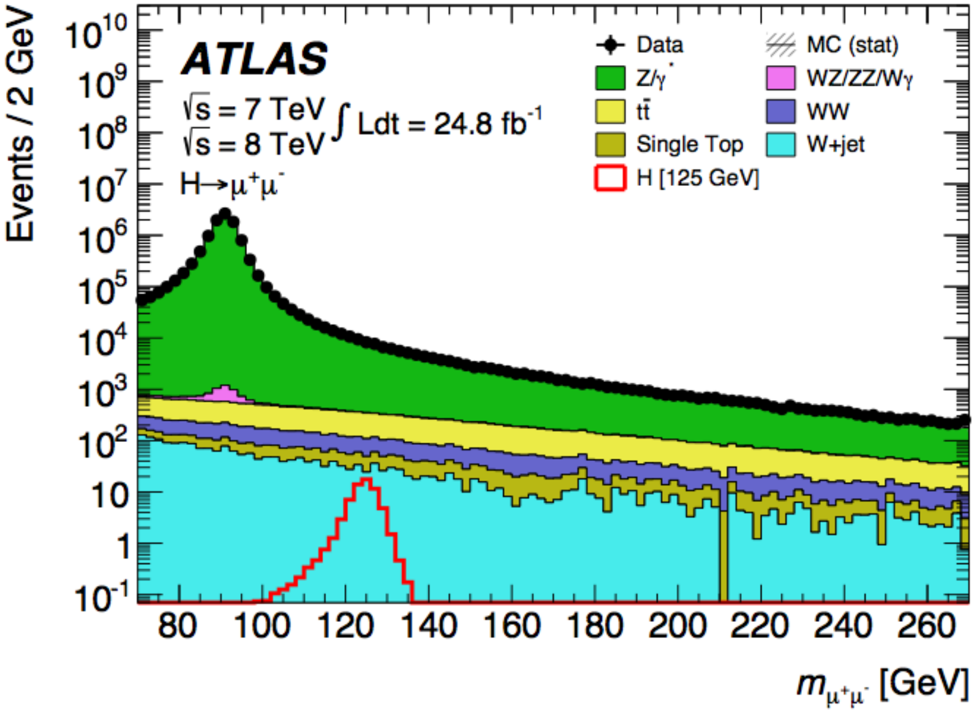






See also: ATLAS-CONF-2015-001

STATUS OF RARE SM DECAYS: μμ



$\mu^+\mu^-$ analysis:

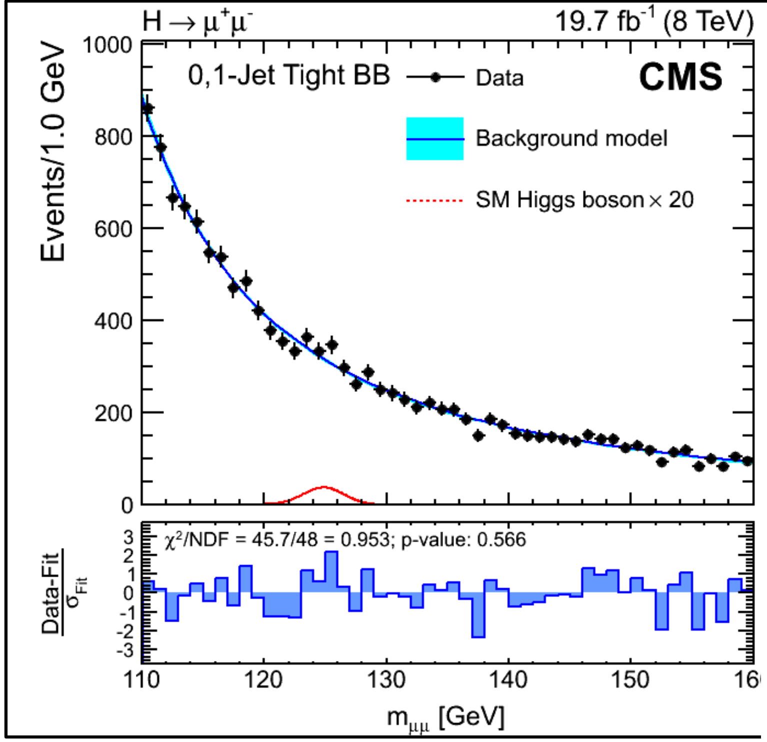
- 2 analysis channels (ggF and VBF)
- Analytic background model (similar to γγ)

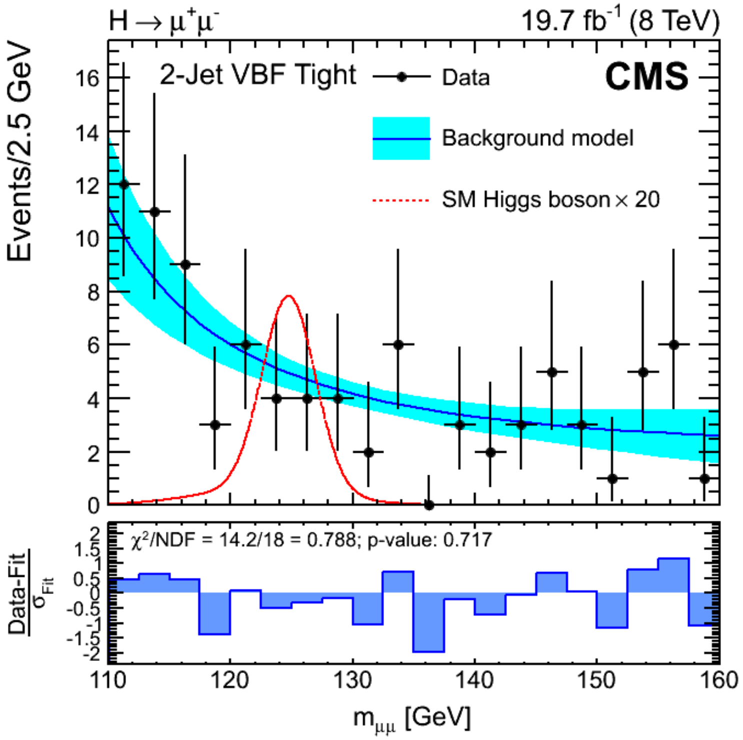
Results at 95% CL:

$\sigma.\mathrm{Br} < 7.0\ (7.2)(\sigma.\mathrm{Br})_{\mathrm{SM}}$

Universal couplings (same as τ lepton) would imply signal ~280 times SM

PLB



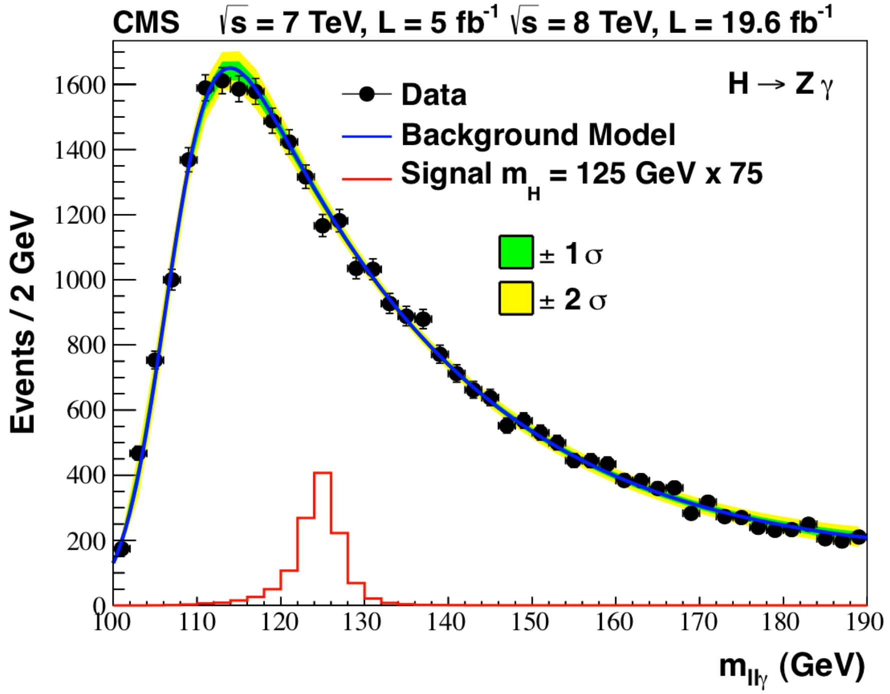


PLB 732 (2014)

Results at 95% CL :

$\sigma.\mathrm{Br} < 7.4\ (6.5)(\sigma.\mathrm{Br})_{\mathrm{SM}}$

STATUS OF RARE SM DECAYS: Zγ



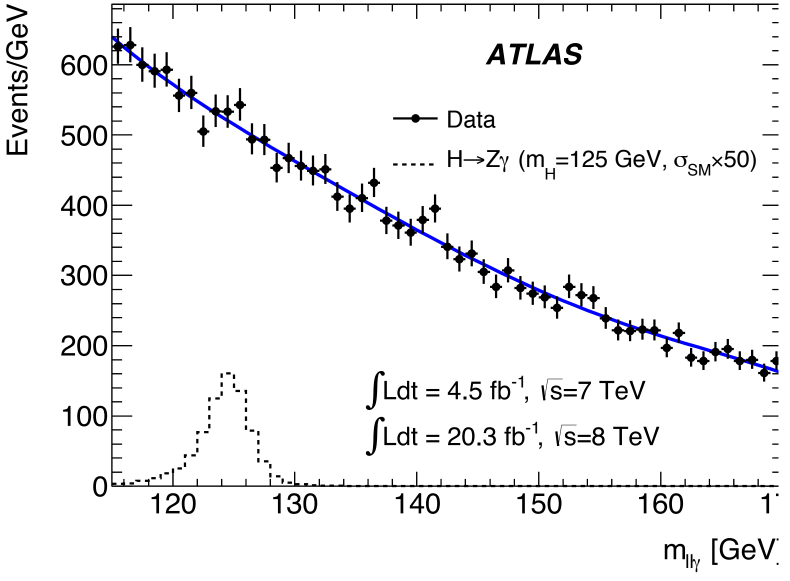
Zγ analysis strategy

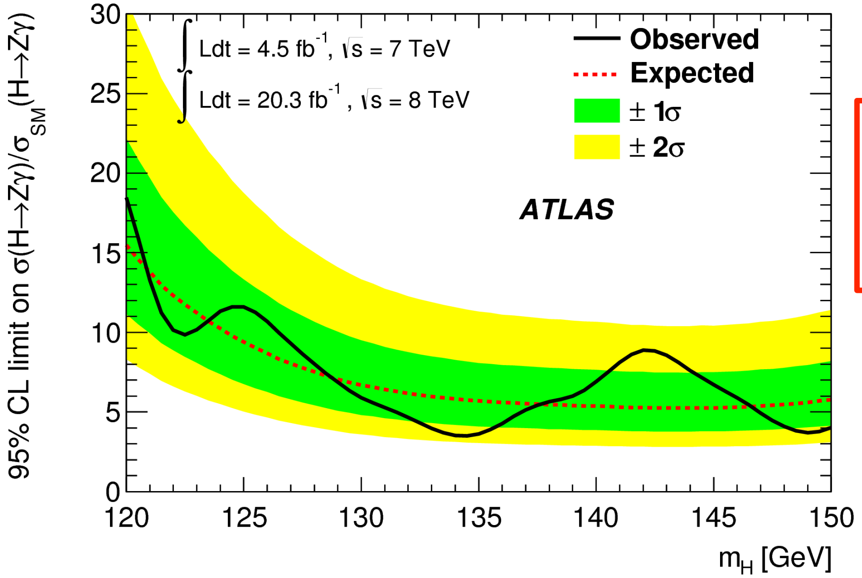
- Detector and p_T categories
- Analytic background model (similarly to γγ)

Results at 95% CL:

$\sigma.Br < 9\ (9)(\sigma.Br)_{SM}$

PLB 732 (2014)





Results, 95% CL:

$\sigma.Br < 11\ (9)(\sigma.Br)_{SM}$

CMS CP MIXING RESULTS

Probe potential CP-mixing and tensor structure of Higgs interactions

- Amplitude describing interaction between a spin 0 and two spin 1 particles:

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

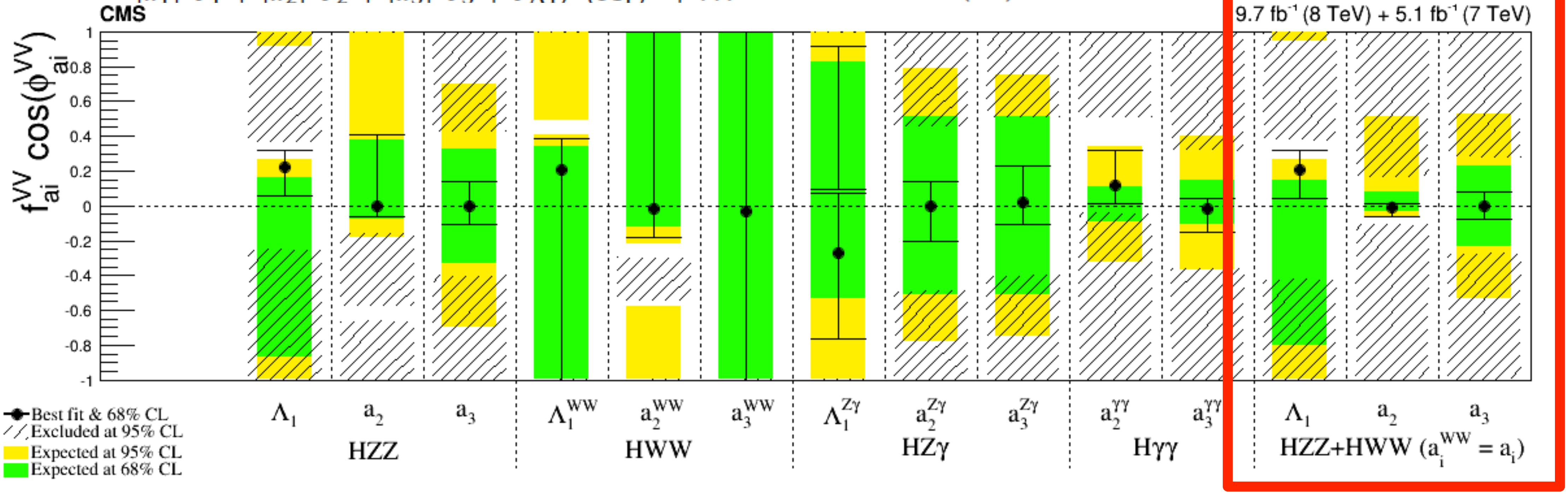
$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

σ_i : xs for $a_i = 1$

$\Lambda_1 = 1$ TeV

Phys Rev D. 89.035007



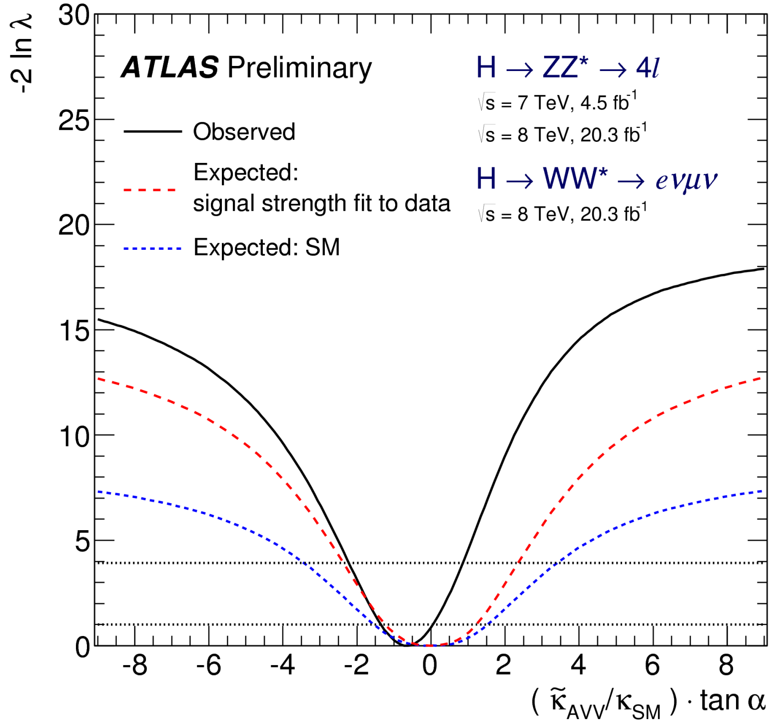
ATLAS CP MIXING RESULTS

Lagrangian describing interaction between a spin 0 and a pair of W or Z bosons (from JHEP 1311 (2013) 043):

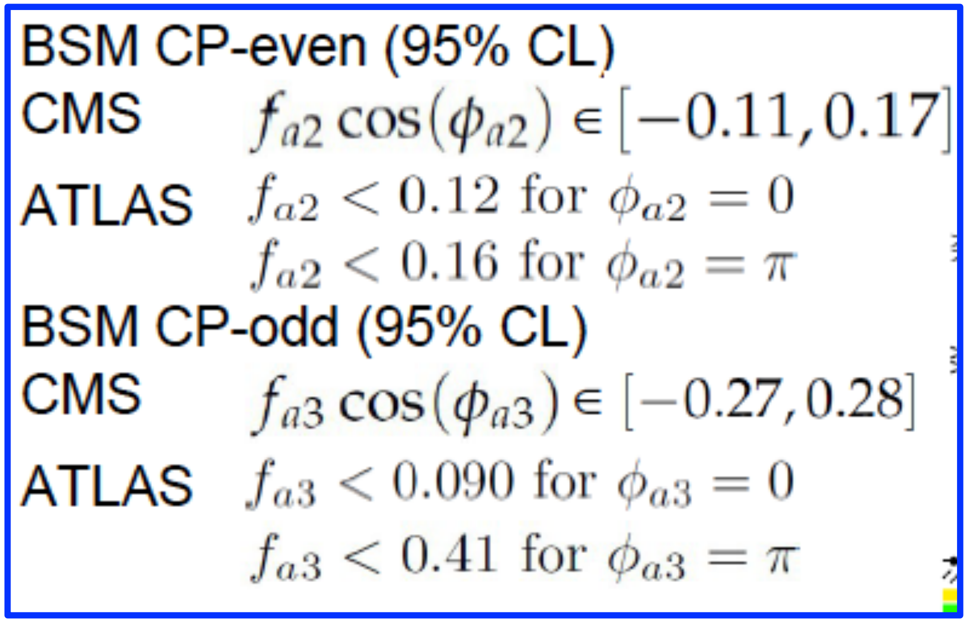
$$\mathcal{L}_0^V = \left\{c_\alpha \kappa_{\mathrm{SM}}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W_\mu^+W^{-\mu}\right] -\frac{1}{4}\frac{1}{\Lambda}\left[c_\alpha\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + s_\alpha\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] -\frac{1}{2}\frac{1}{\Lambda}\left[c_\alpha\kappa_{HWW}W_{\mu\nu}^+W^{-\mu\nu} + s_\alpha\kappa_{AWW}W_{\mu\nu}^+\tilde{W}^{-\mu\nu}\right]\right\}X_0.$$

J^P	Model	Choice of tensor couplings			
		κ_{SM}	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

ATLAS paper: JHEP 1311 (2013) 043



CMS/ATLAS comparison (Michael Duehrssen)



BSM CP-even (95% CL)

CMS $f_{a2}\cos(\phi_{a2}) \in [-0.11, 0.17]$

ATLAS $f_{a2} < 0.12$ for $\phi_{a2} = 0$

$f_{a2} < 0.16$ for $\phi_{a2} = \pi$

BSM CP-odd (95% CL)

CMS $f_{a3}\cos(\phi_{a3}) \in [-0.27, 0.28]$

ATLAS $f_{a3} < 0.090$ for $\phi_{a3} = 0$

$f_{a3} < 0.41$ for $\phi_{a3} = \pi$

No significant contributions from BSM terms are observed

GLUON FUSION VS VBF

Calculate production ratios for each final state:

- Branching ratios cancel:

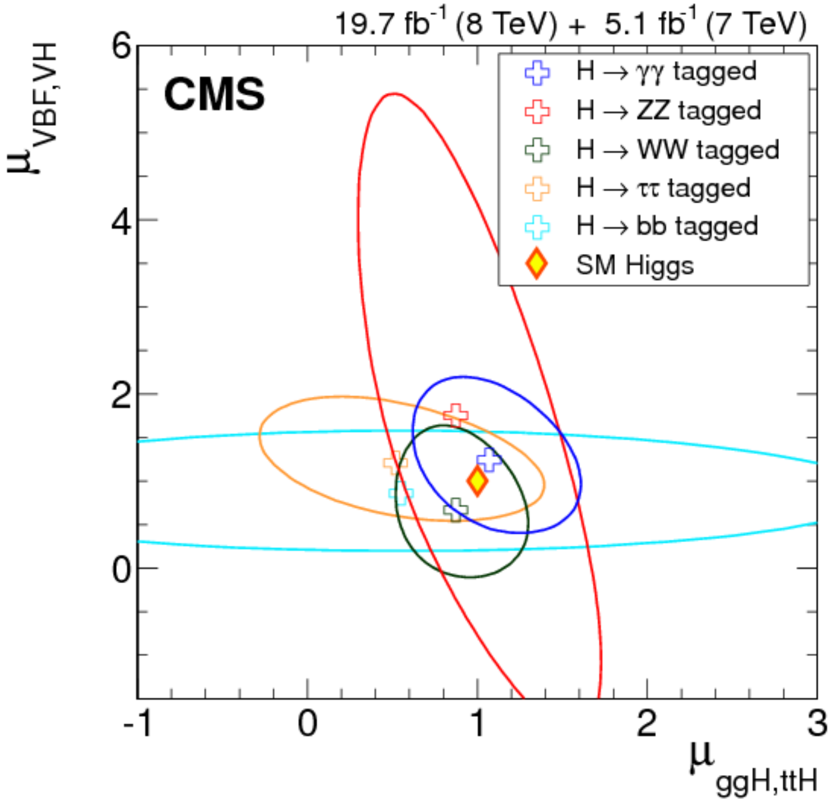
$$\frac{\mu^{i}_{VBF+VH}}{\mu^{i}_{ggF+ttH}} = \frac{\mu_{VBF+VH}}{\mu_{ggF+ttH}}$$

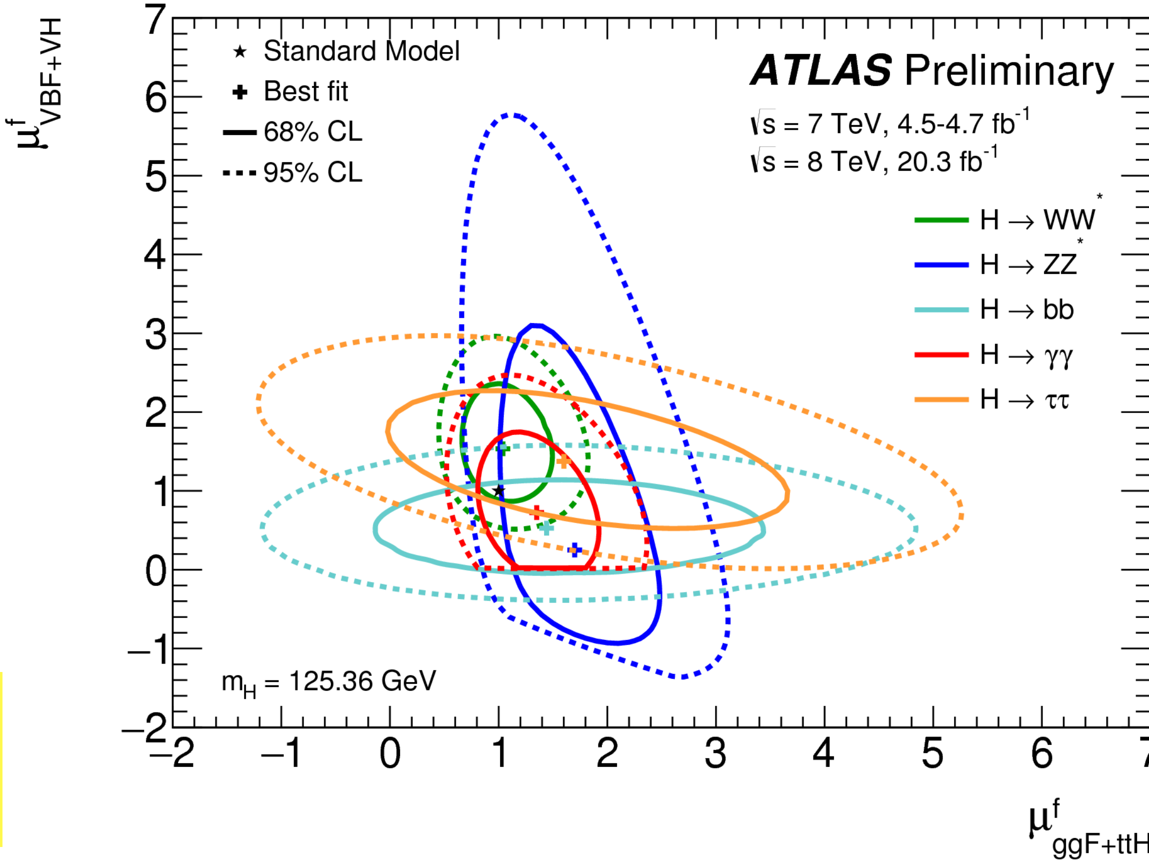
CMS Result: $1.25^{+0.62}_{-0.44}$

ATLAS Result: $0.96^{+0.43}_{-0.31}$

CMS VBF significance:
3.7σ (3.3σ expected)
(assuming SM BRs)

ATLAS VBF significance:
4.3σ (3.8σ expected)

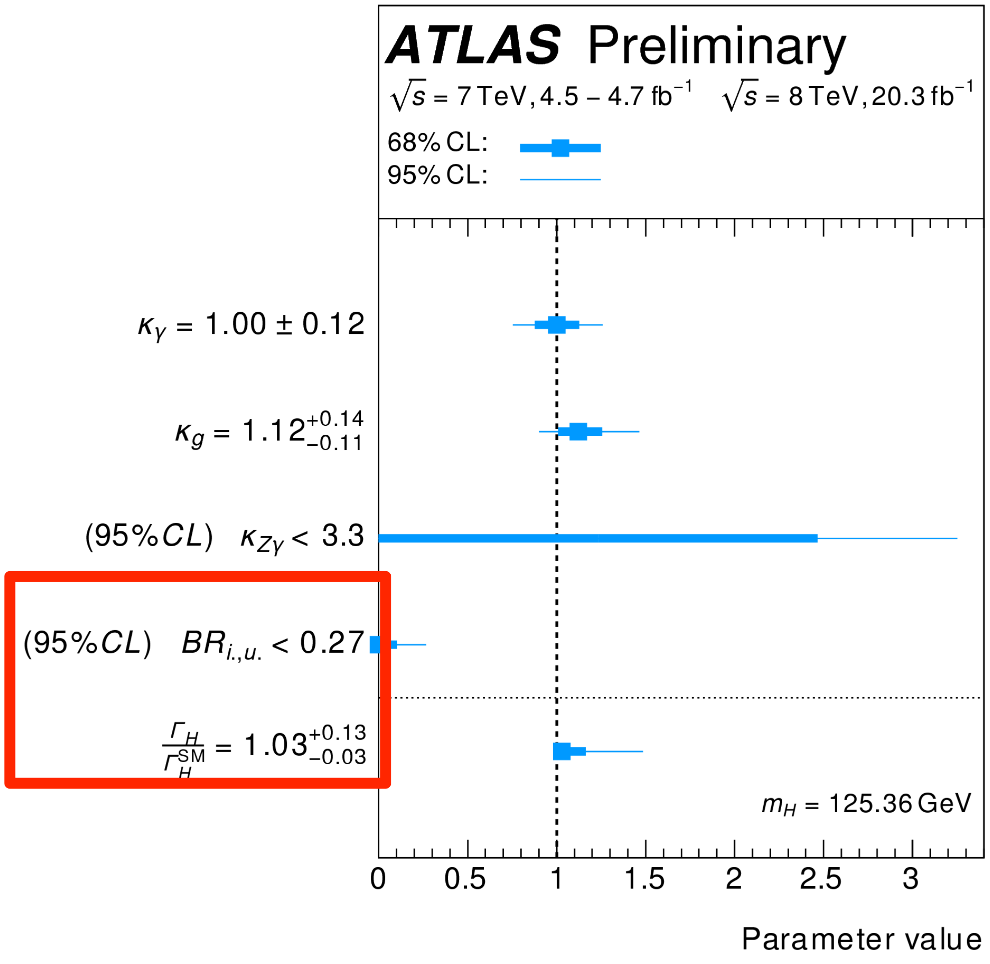


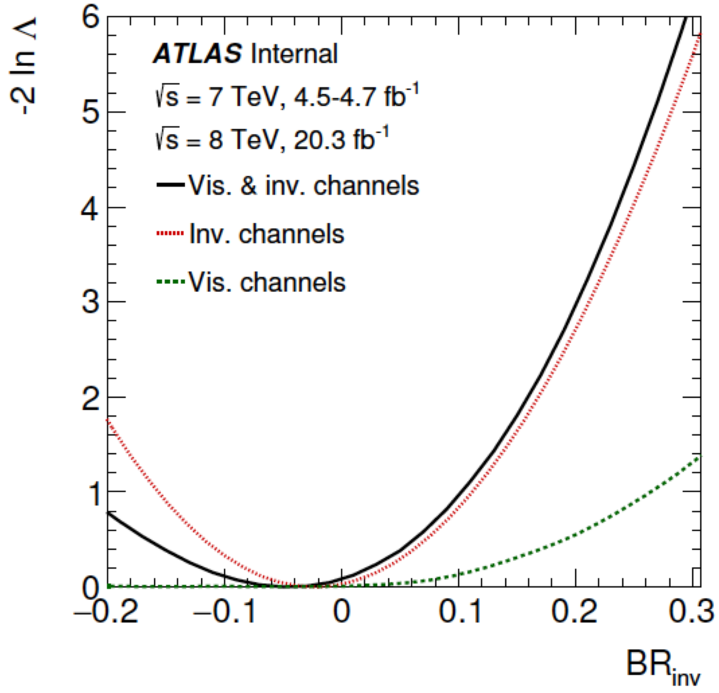


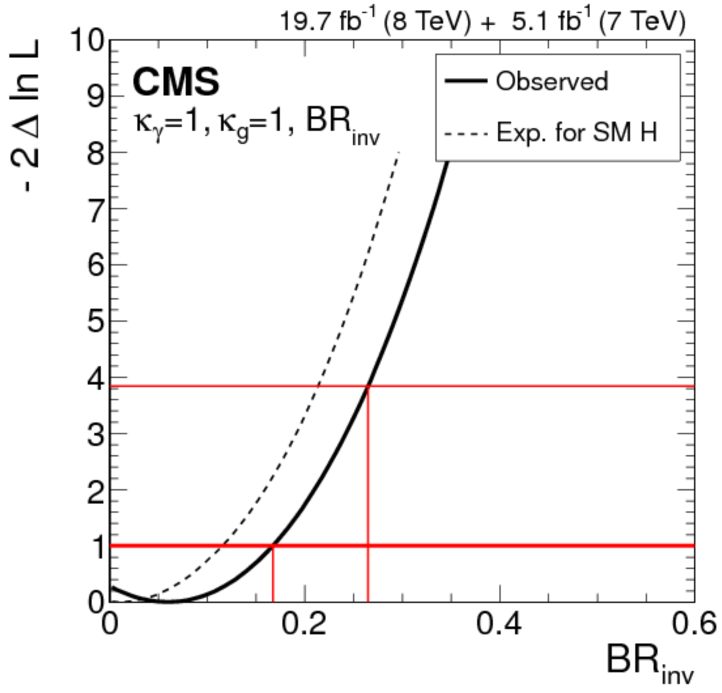
NEW PHYSICS IN PRODUCTION OR DECAY?

Allow for contributions from BSM particles with mass < $m_H/2$

- Relax assumption on the width
- Right plots : include direct limits







Run 3 and Beyond

Ongoing studies of Higgs physics potential at high luminosity