Recent Higgs Boson Results from the LHC

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on behalf of the ATLAS and CMS collaborations
Aspen 11/01/2016

Introduction

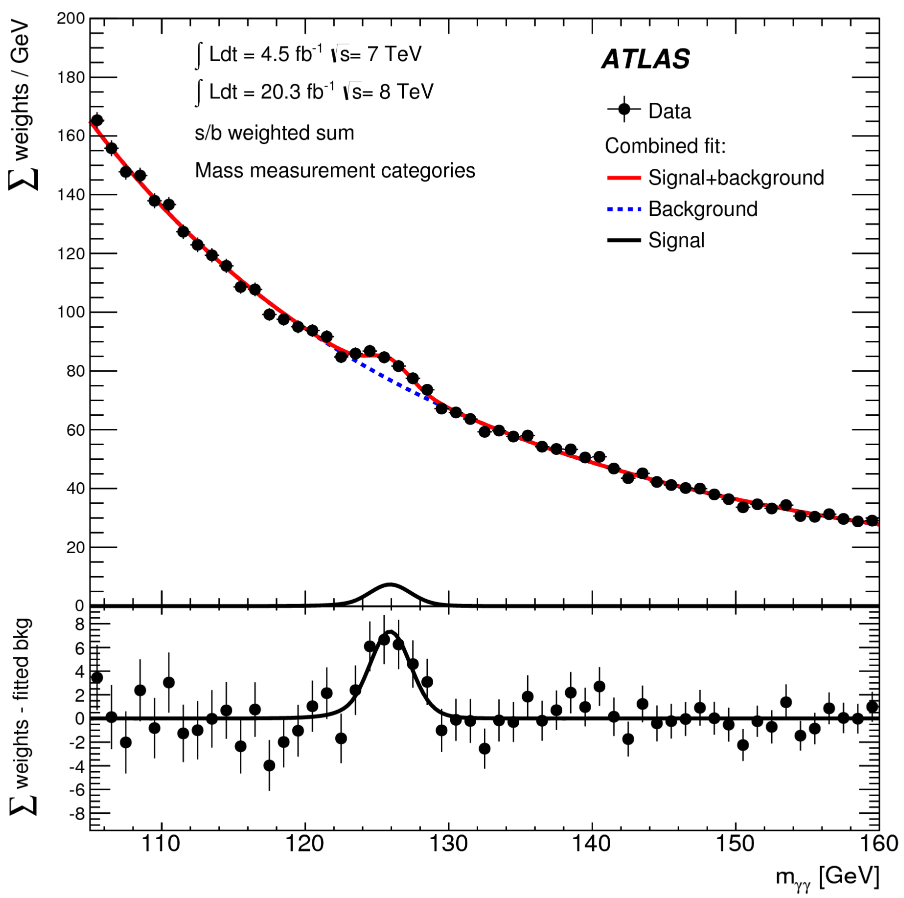
- After the discovery in July 2012, the emphasis shifted towards measurements to characterize the newly discovered boson
  - Mass: this is the only missing value to fully characterize the Higgs boson in the SM
  - Width: very challenging to measure in the SM (~4 MeV)
  - Spin/Parity: Is it 0+ as expected ?
  - Couplings: Several extensions of the SM (for instance MSSM) can predict deviations (often small) in the couplings between the Higgs boson and other particles
  - Search for "non standard" decay modes
- In addition, searches for heavier scalar particles were also pursued
- In this talk, will review the latest run 1 result (20+5 fb^{-1} at $\sqrt{s}$ = 8 or 7 TeV), with emphasis on the recent coupling combination
- Will also mention some first run 2 results (~3 fb^{-1} at $\sqrt{s}$=13 TeV in 2015 data). The sensitivity for H(125) is still significantly lower than run 1 results but can become competitive at higher masses (>= ~ 800 GeV)

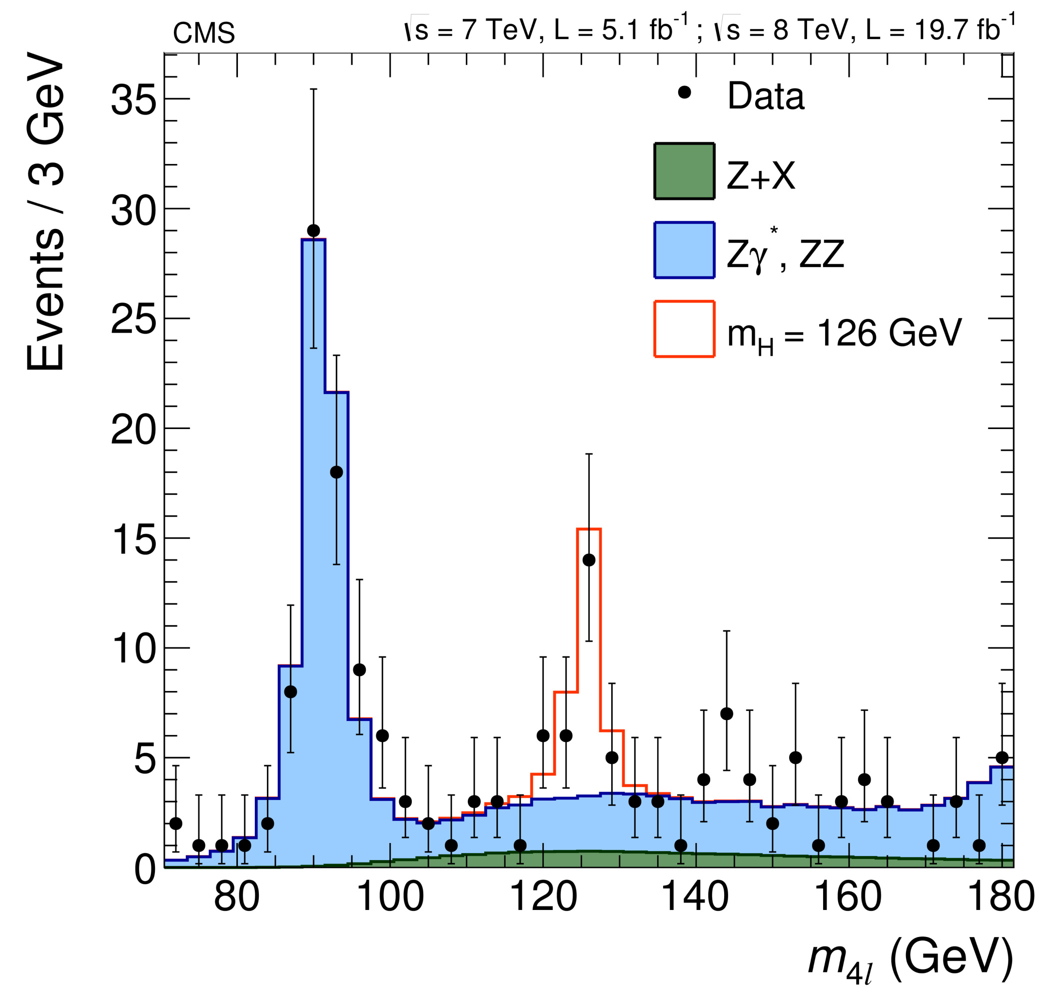
Mass measurement

Use the 2 channels with the best mass resolution

$H \rightarrow \gamma\gamma$

$H \rightarrow ZZ^* \rightarrow 4l$ (l=e ou μ)



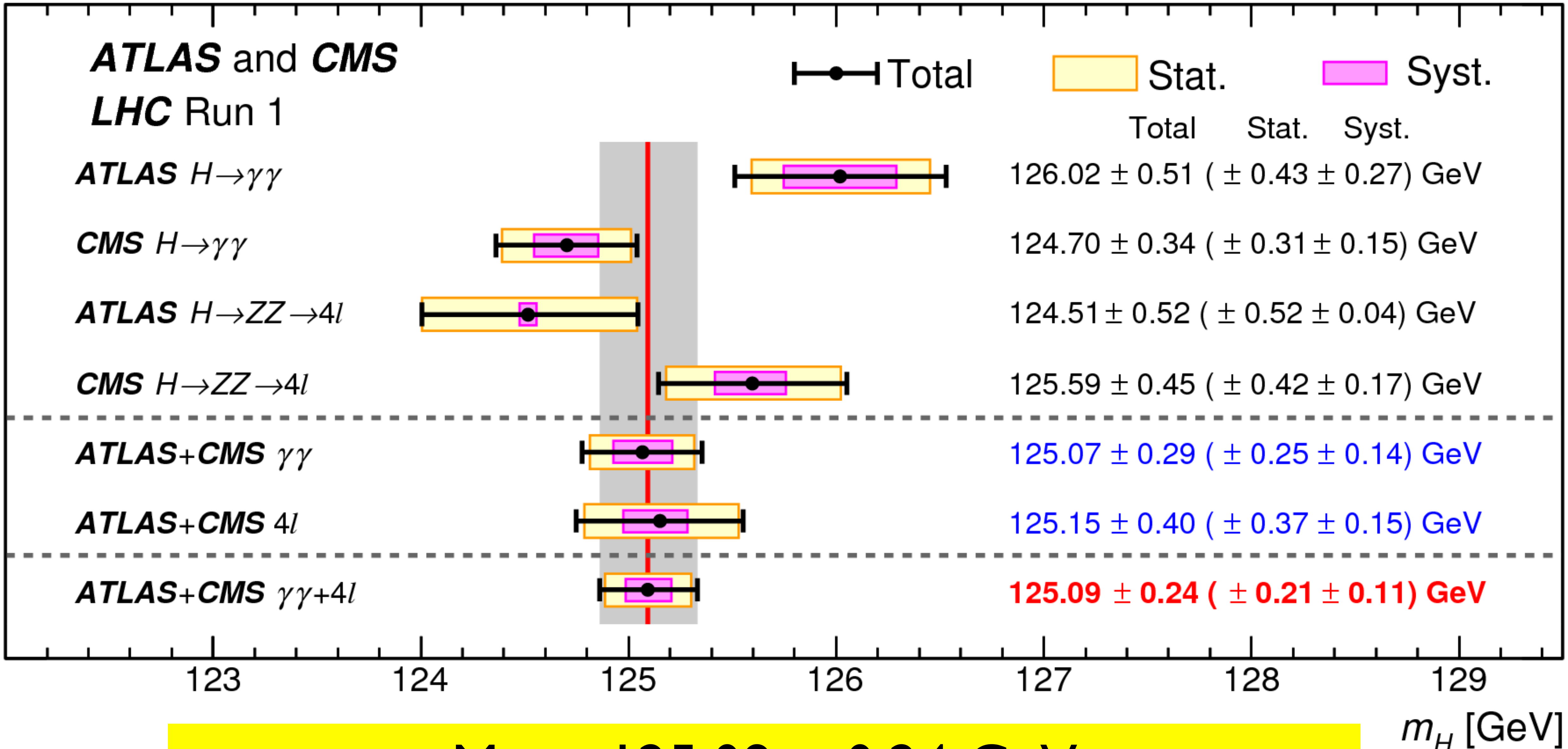


Exploit data as much as possible with event categorization (different S/B, different resolutions)

Very detailed studies of energy and momentum calibration using for instance large datasets of $Z \rightarrow ll$ decays

Results for the mass measurement

ATLAS-CMS PRL 114 (2015) 191803



Mass=125.09 +-0.24 GeV
Accuracy < 0.2% (main uncertainty is statistical)

p-value of consistency of 4 measurements ~ 10%
Syst. uncertainty dominated by photon energy scale uncertainty

Width studies

Γ(SM) ~4 MeV

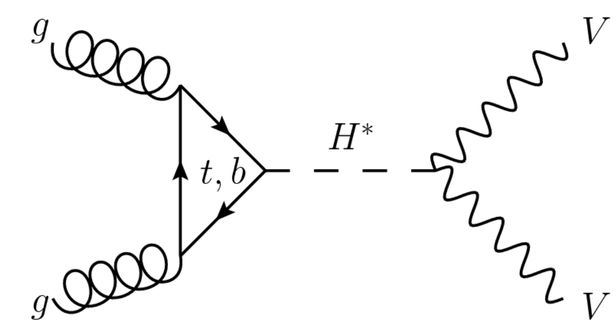
Direct upper limit from mass distribution: Γ< 1.7 GeV (CMS EPJC 75 (2015) 212)

Direct lower limit from lifetime in 4l: Γ> 3.5 10^{-9} MeV (CMS PRD92 (2015) 072010)

q ~M_H (on shell) σ~1/Γ_H *(couplings)

q>>M_H (off shell) σ~(couplings)

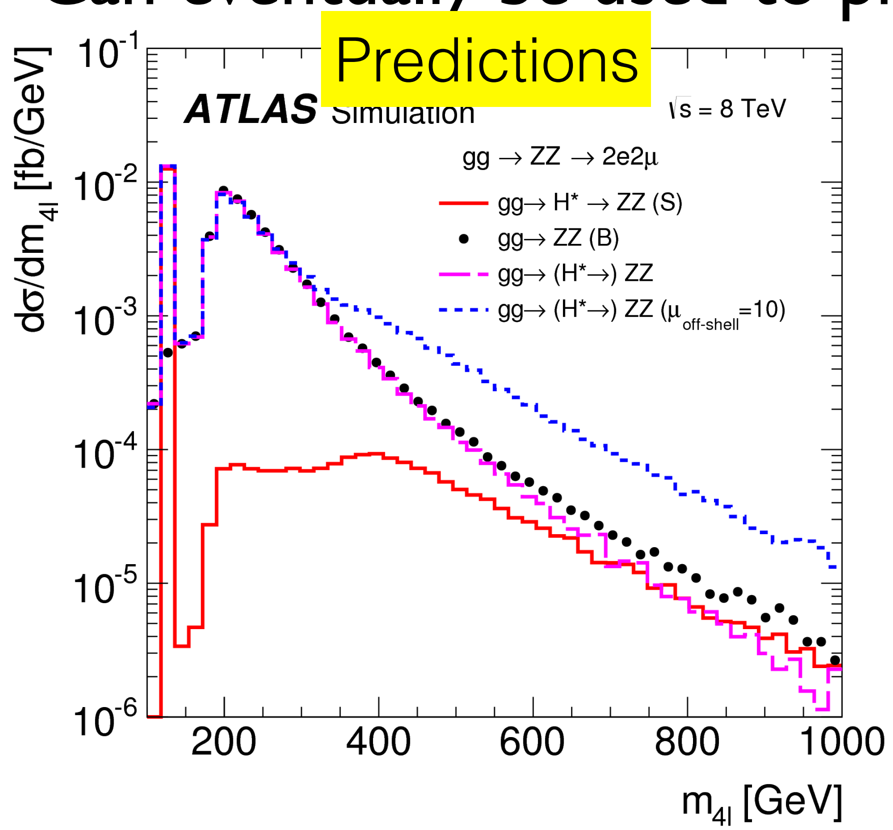
⇒Ratio ~Γ_H

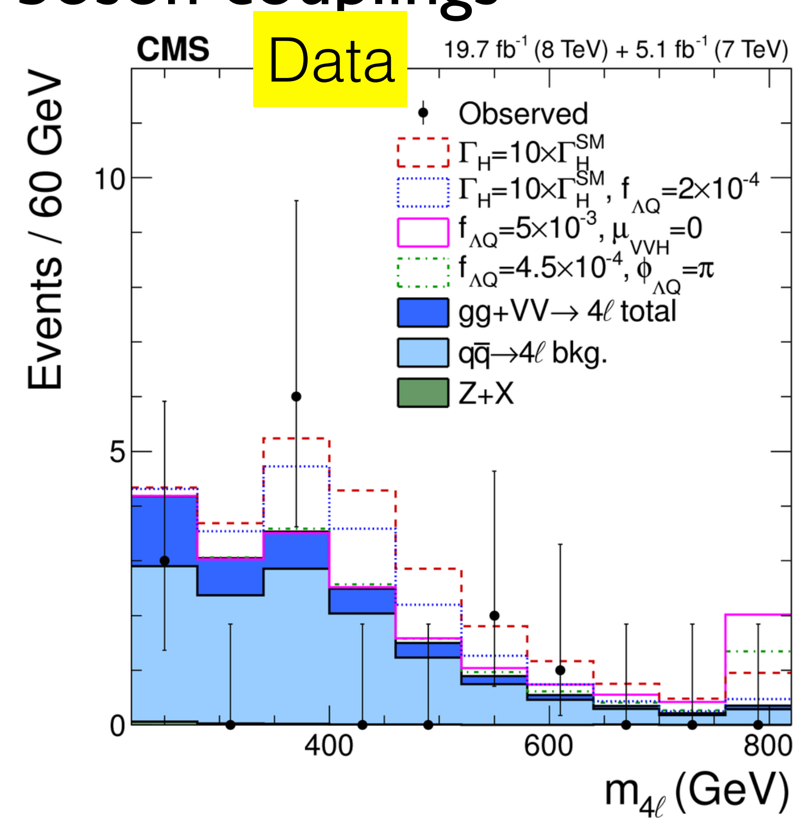


Interference with gg->ZZ taken into account

Γ< 22.7 MeV (ATLAS EPJ C75 (2015) 335), 26 MeV (CMS PRD92 (2015) 072010) assuming no change in coupling and no new physics at high VV mass (expected 33 and 41 MeV resp.)

Can eventually be used to probe off-shell Higgs boson couplings



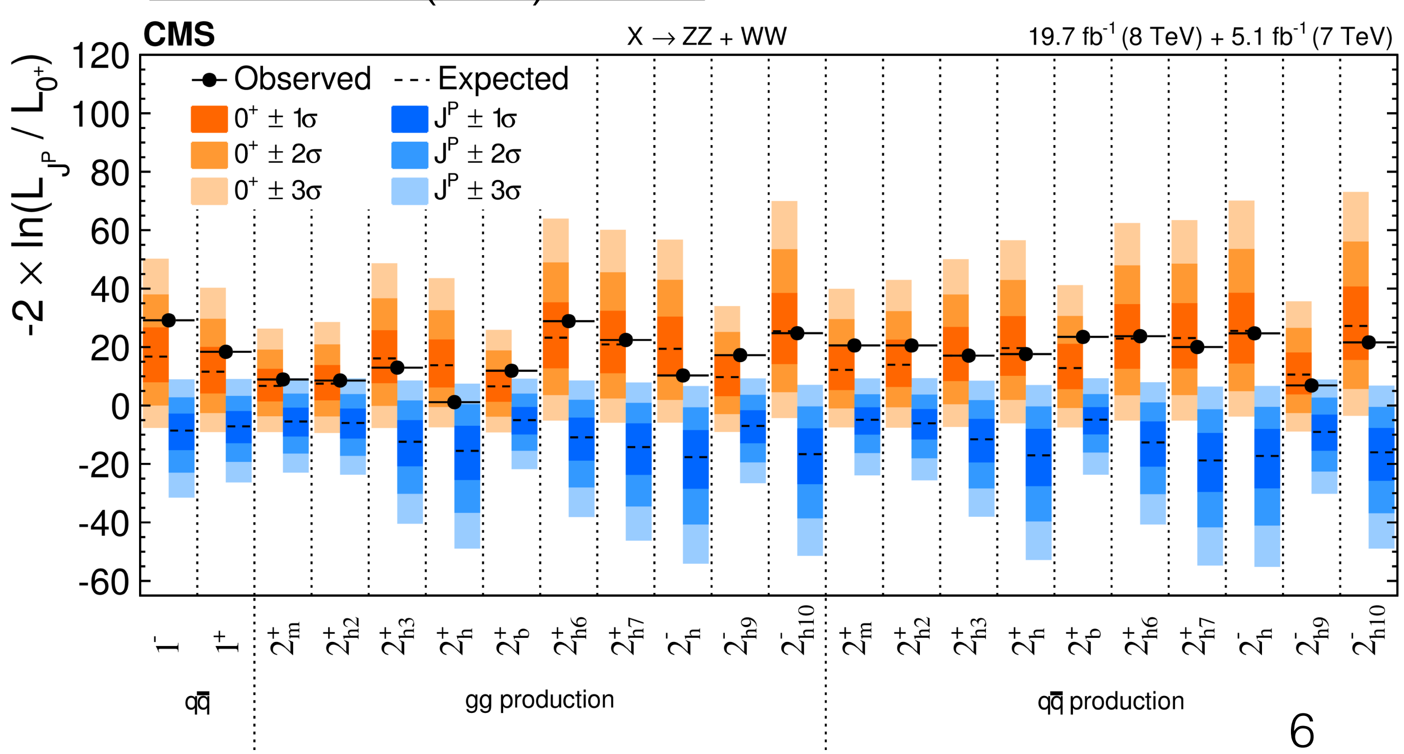


Spin/CP studies

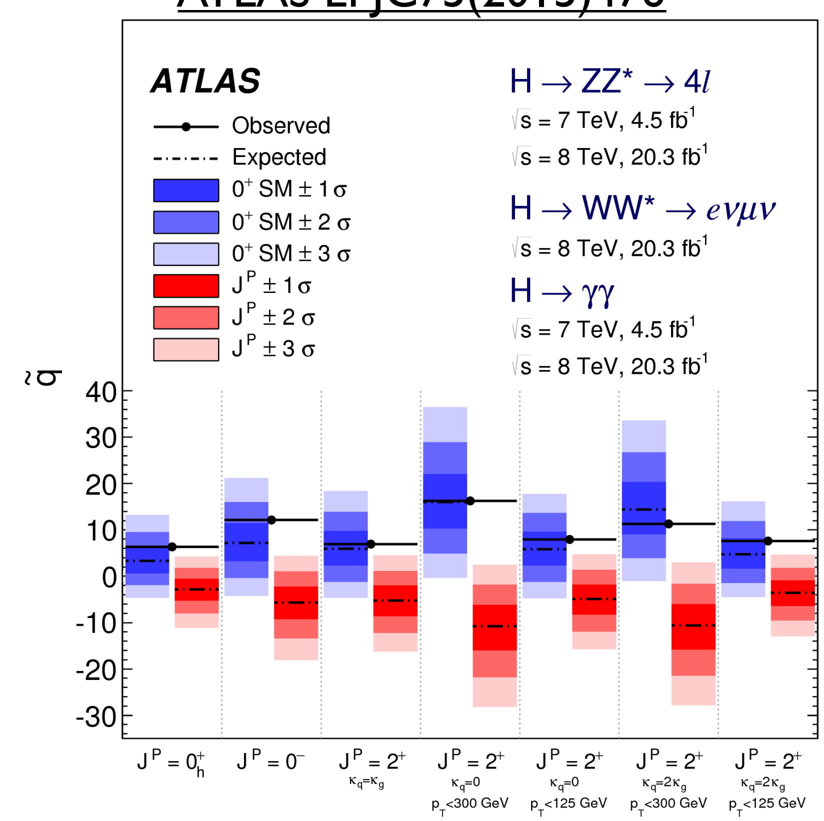
Studied mostly in di-boson events up to now

All pure alternatives tested against 0+ strongly rejected
(more details in backup)

CMS PRD 92 (2015) 012004

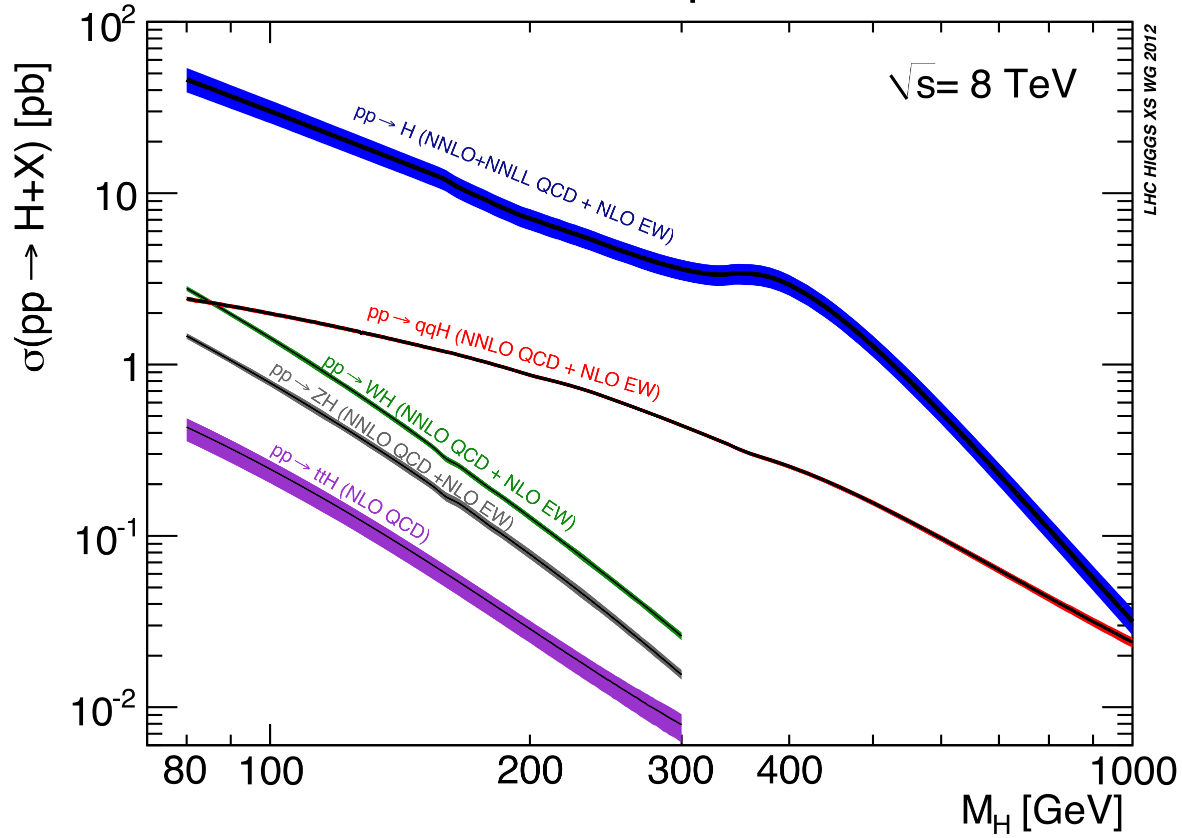


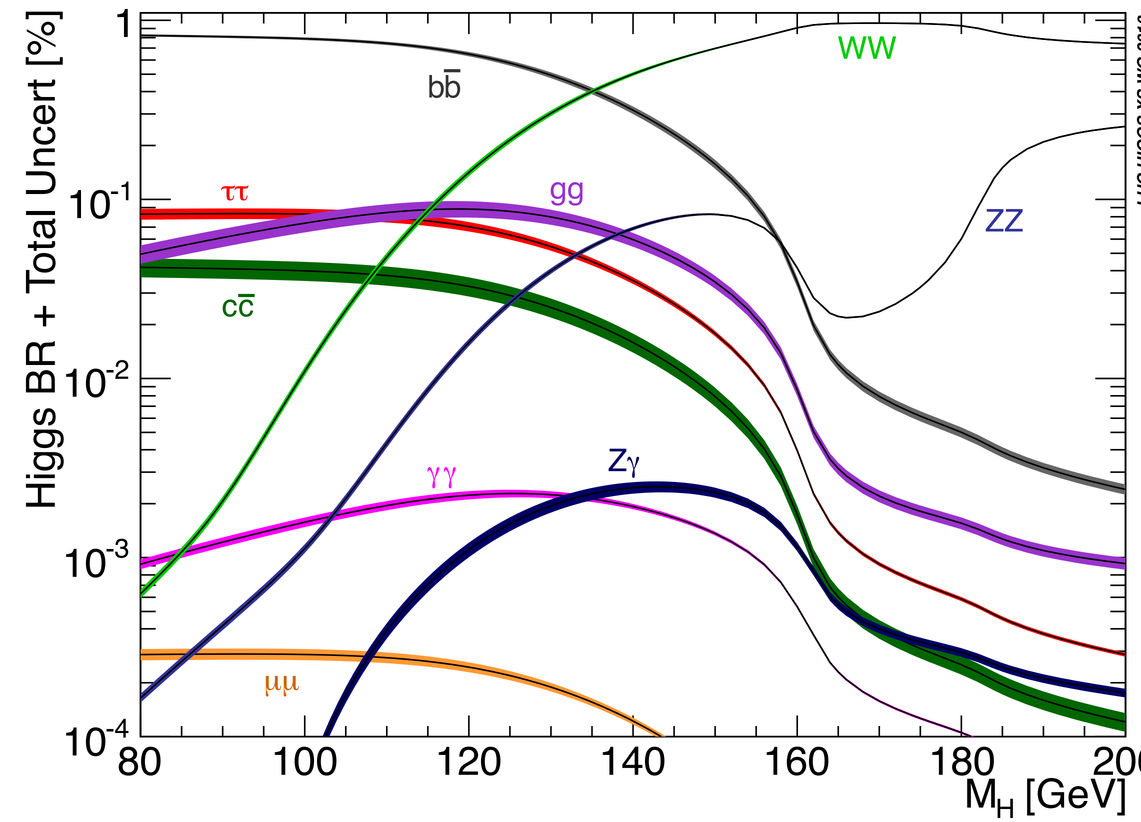
ATLAS EPJC75(2015)476

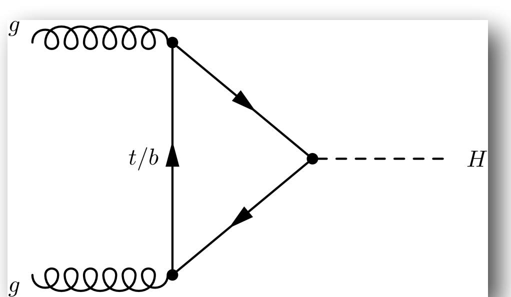


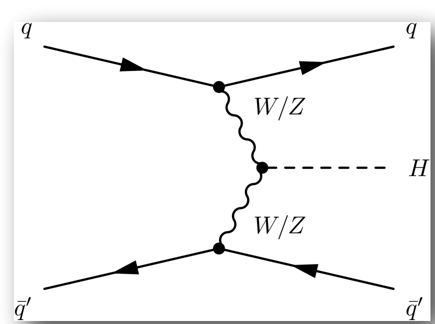
Production and decay in the SM

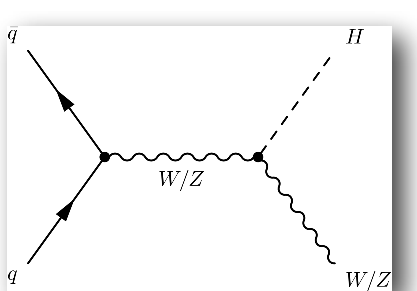
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

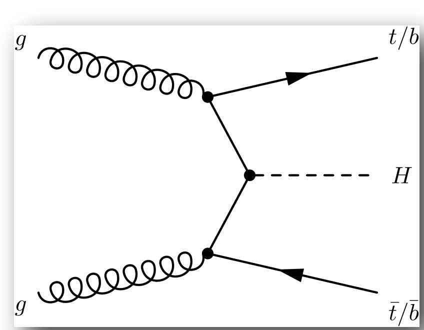












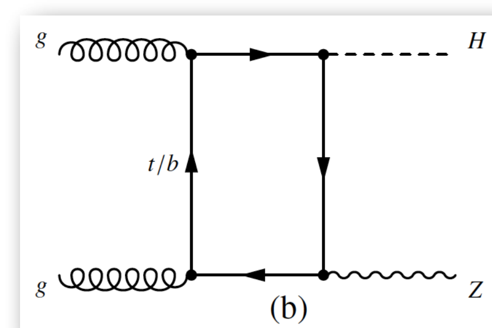
Theoretical predictions of cross-section as used in ATLAS-CMS combination

Use NNLO ggF, N3LO becoming available

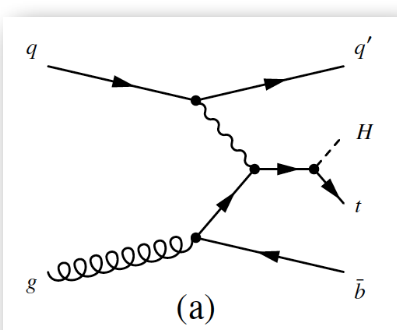
Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

Some subtleties to take into account for coupling studies

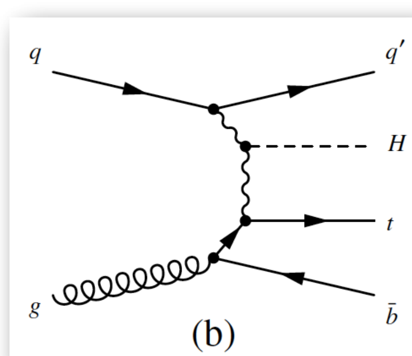
- gluon box contribution to ZH production
- tH production



(b)



(a)



(b)

Coupling studies

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

For each "bin" (experiment, production mode i, decay j, analysis category k) compare measured rate to expectations

$$Luminosity*\sigma_i*BR_j*Acceptance_{ijk}*\varepsilon_{ijk} + background_{ijk}$$

$Acceptance_{ijk}*\varepsilon_{ijk}$ from simulation => **Assume Standard Model kinematics**

Systematic uncertainties (theory and experimental) propagated in profile likelihood fit as well as background uncertainties

Theoretical signal uncertainties and part of luminosity correlated between ATLAS and CMS, other not

	Untagged (ggF mostly)	VBF	VH	ttH
H→γγ	combined	combined	combined	combined
H→ZZ*→4l	combined	combined	combined	combined
H→WW*→2l2ν	combined	combined	combined	combined
H→ττ	combined	combined	combined	combined
H→bb		(CMS, not combined)	combined	combined
H→μμ	combined	combined		
H→Zγ	(ATLAS and CMS limits, not combined)			
H->invisible		not combined	not combined	

$Acceptance_{ijk} * \varepsilon_{ijk}$ from simulation => **Assume Standard Model kinematics**

MC generators used for acceptance*efficiency

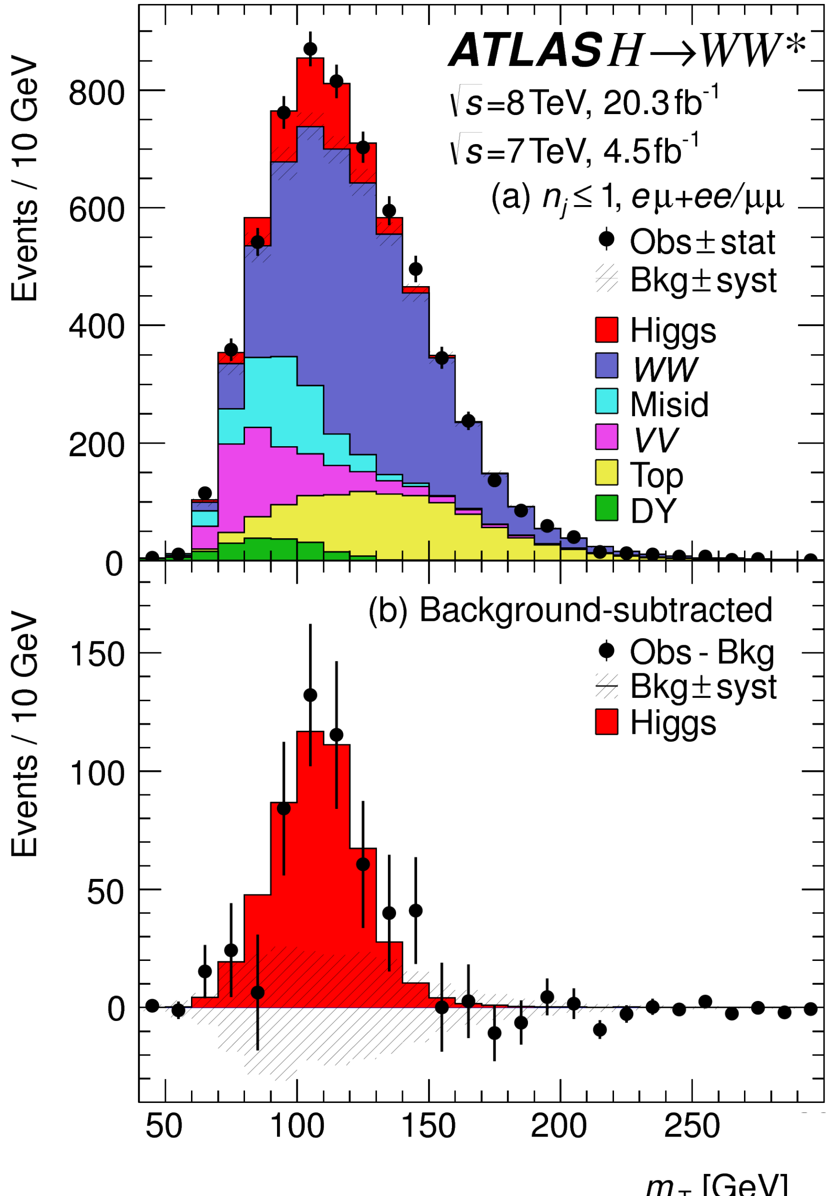
Production process	Event generator	
	ATLAS	CMS
ggF	POWHEG [29–33]	POWHEG
VBF	POWHEG	POWHEG
WH	PYTHIA8 [34]	PYTHIA6.4 [35]
ZH ($qq \to ZH$ or $qg \to ZH$)	PYTHIA8	PYTHIA6.4
$ggZH$ ($gg \to ZH$)	POWHEG	See text
ttH	POWHEL [43]	PYTHIA6.4
tHq ($qb \to tHq$)	MADGRAPH [45]	aMC@NLO [28]
tHW ($gb \to tHW$)	aMC@NLO	aMC@NLO
bbH	PYTHIA8	PYTHIA6, aMC@NLO

Pt(H) reweighted to HiRes2.1

Starting point: Analysis in each of the decay (and production) mode
Optimize signal extraction using MVA tools and/or categories
Normalize background using control regions

H→WW→lνlν

Clearly observed but
needs careful background estimation

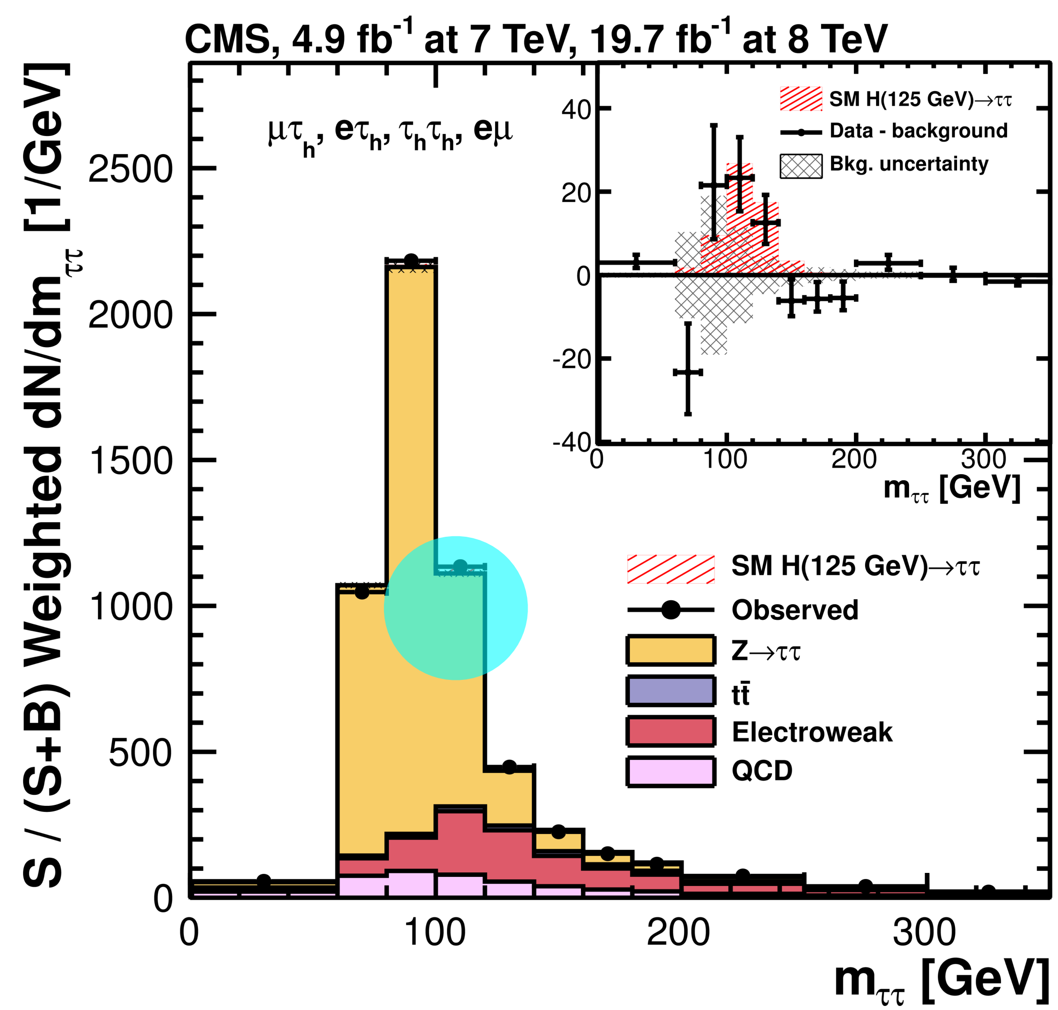


ATLAS PRD92 (2015) 012006

CMS JHEP 01 (2014) 096

H→ττ

Need to separate signal from main Z background (data driven)



CMS JHEP 05 (2014) 104

ATLAS JHEP 1504 (2015) 117

H→bb: Look in associated production with W,Z or ttbar

Use multivariate techniques to enhance sensitivity

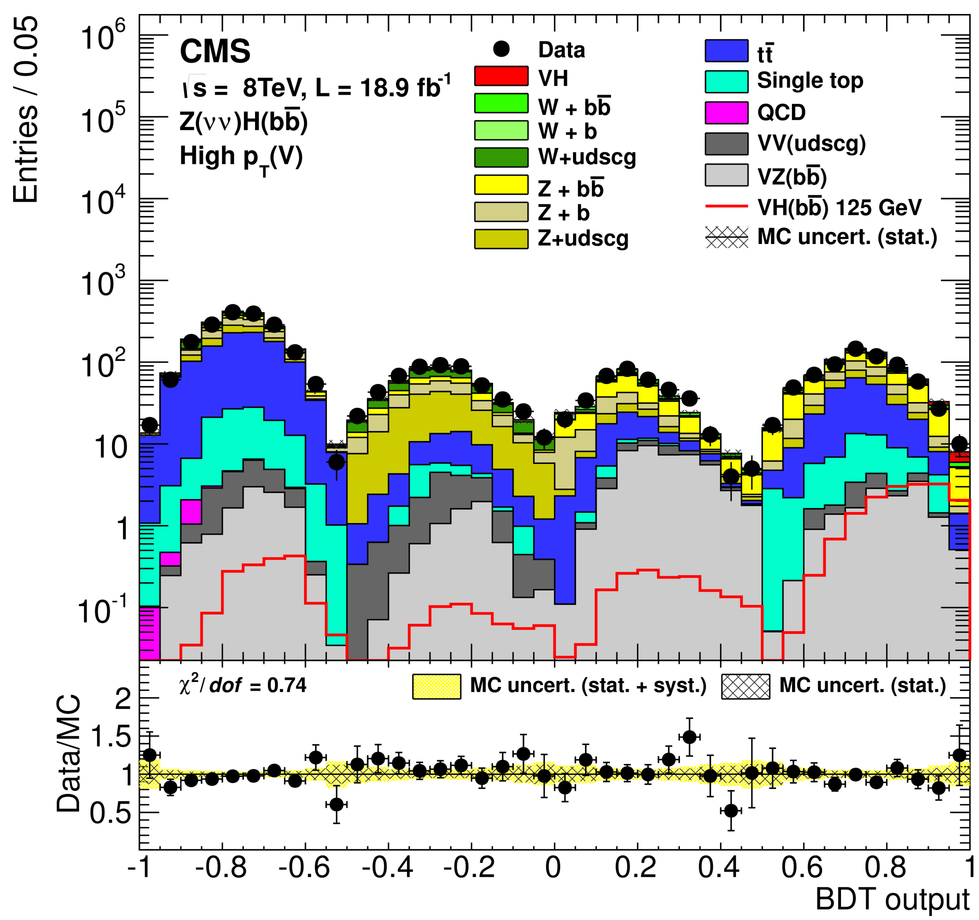
Categories according to Njets, Nb-jets, Pt(V), etc..

Perform simultaneous fit to control and signal regions to constrain background

CMS PRD 89 (2014) 012003

ATLAS JHEP 1501 (2015) 069

Example VH CMS analysis

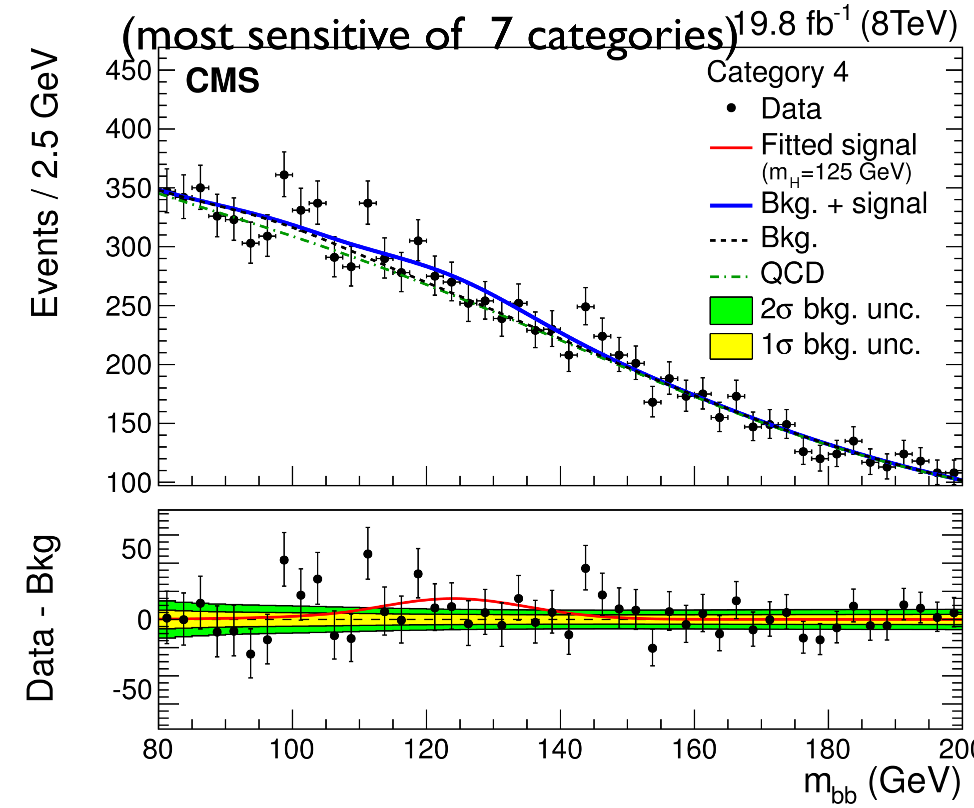


~2.5σ expected significance (combined VH, ttH)

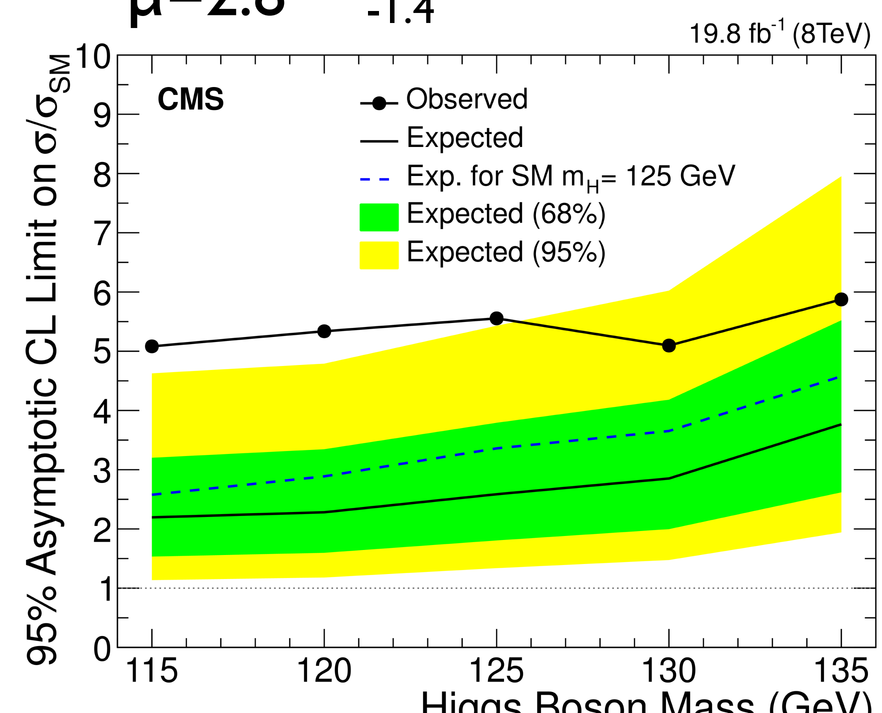
Also search in VBF production by CMS (not used in combination)

CMS PRD 92 (2015) 032008

(most sensitive of 7 categories)

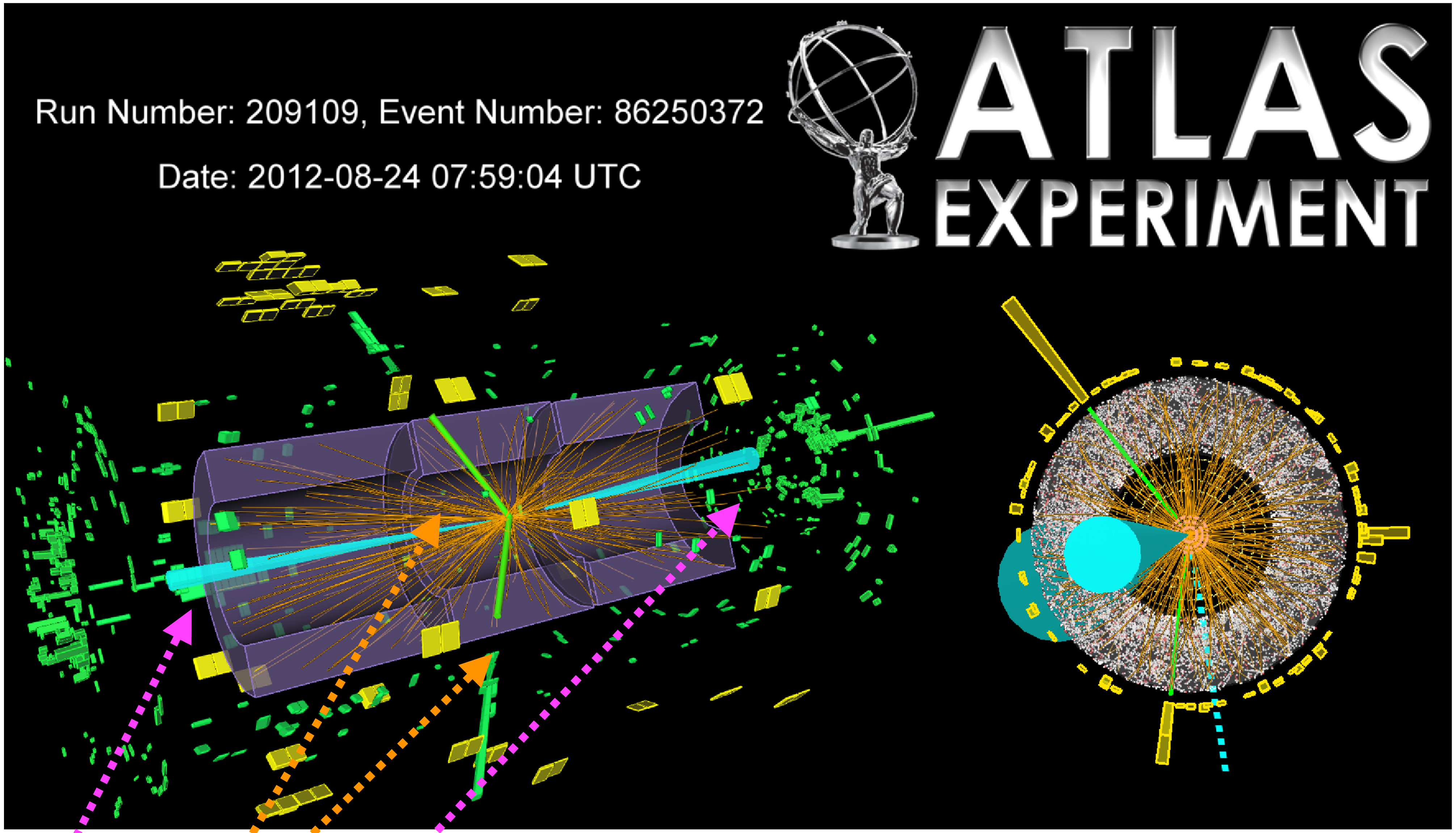


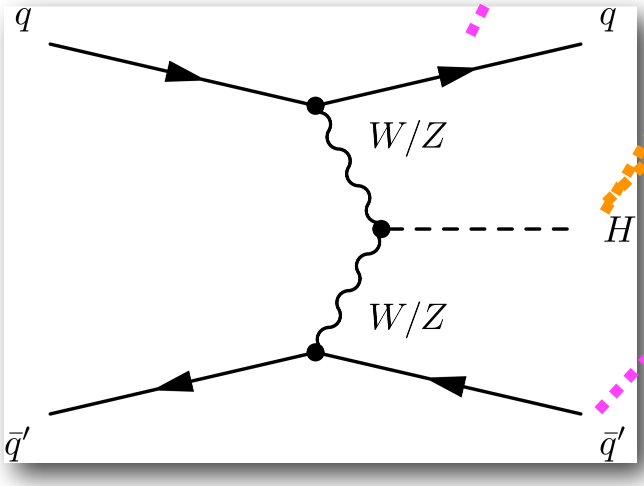
$\mu=2.8^{+1.6}_{-1.4}$



Split by production mode

Example of a candidate for H(→ττ) produced by vector boson fusion





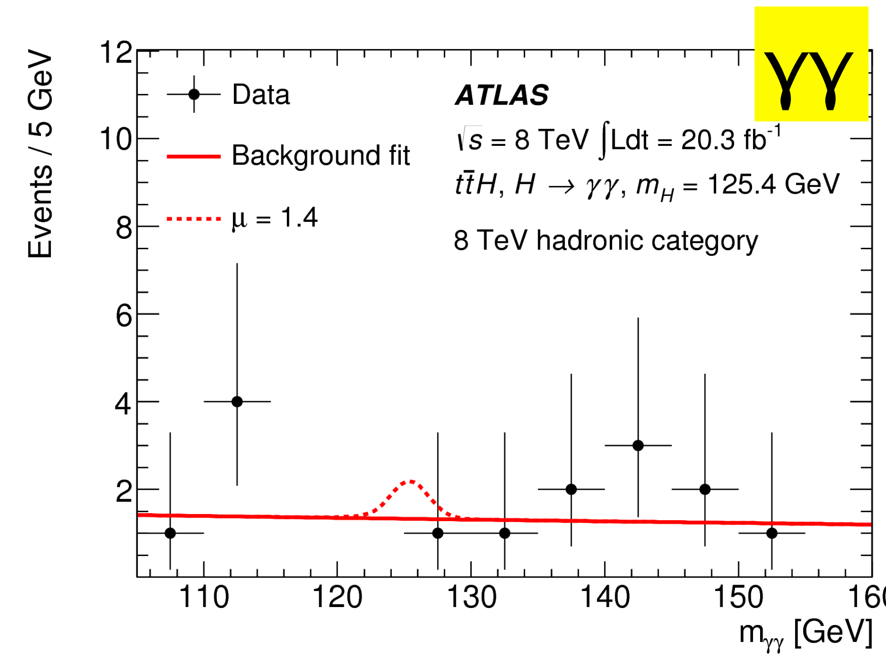
Main complication: take correctly into account the cross-contamination between different production modes and its uncertainty

For instance ~20 % ggF contribution to tight VBF selection with up to ~50% relative uncertainty

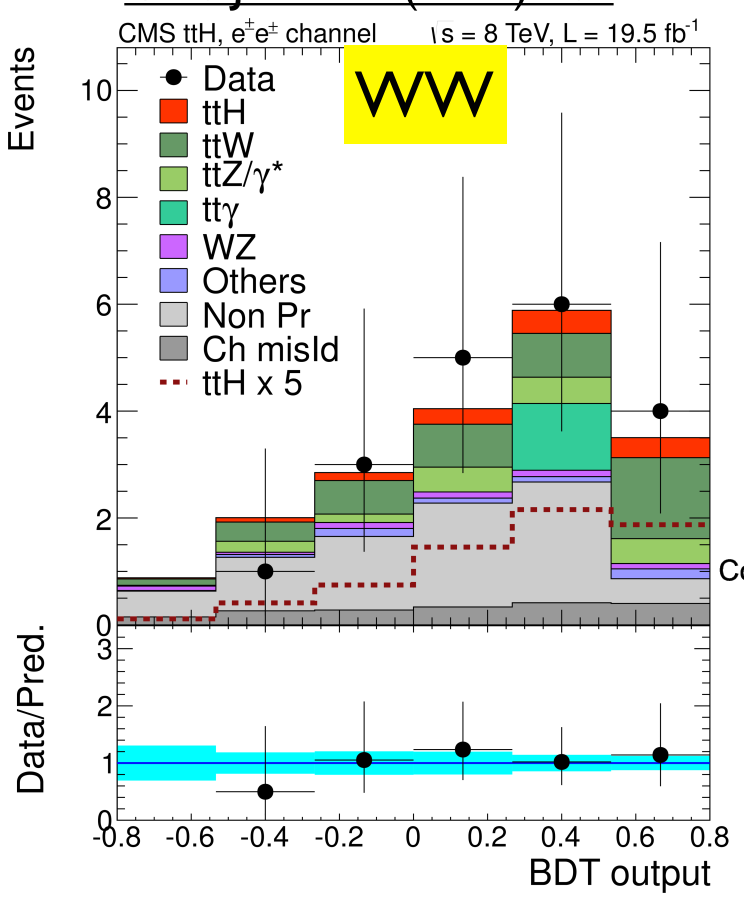
ttH channel: several decay modes investigated

- bbbar : larger rate but complicated final state (4b) with combinatoric background and theoretically difficult t-tbar + heavy flavor bkg
- γγ : cleaner but lower statistics
- WW leading to multi lepton final state (2 same sign or 3) : best sensitivity. Need to control ttV background and instrumental background
- ττ

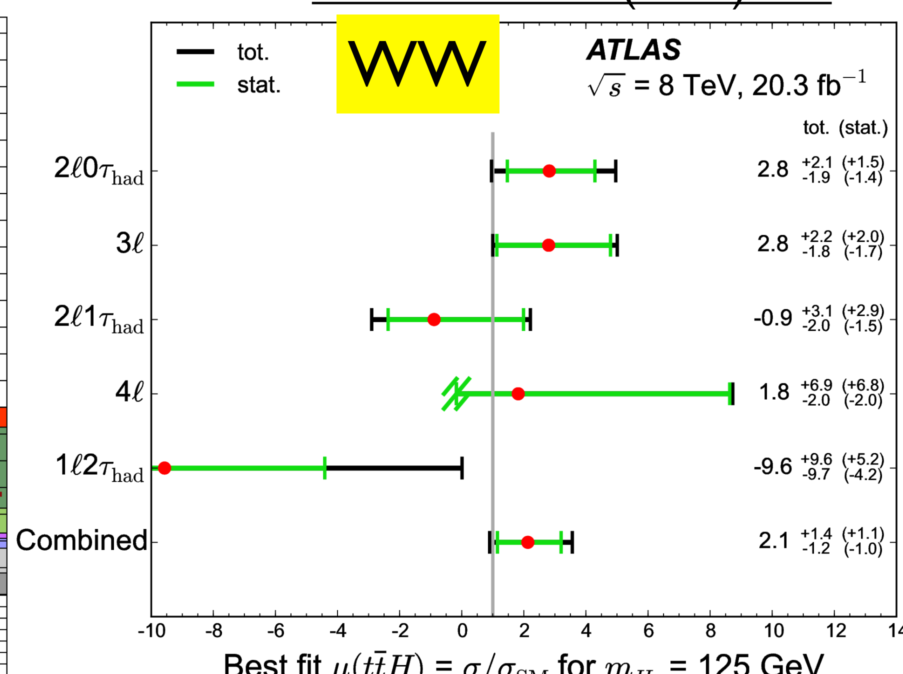
ATLAS PLB740 (2015) 222



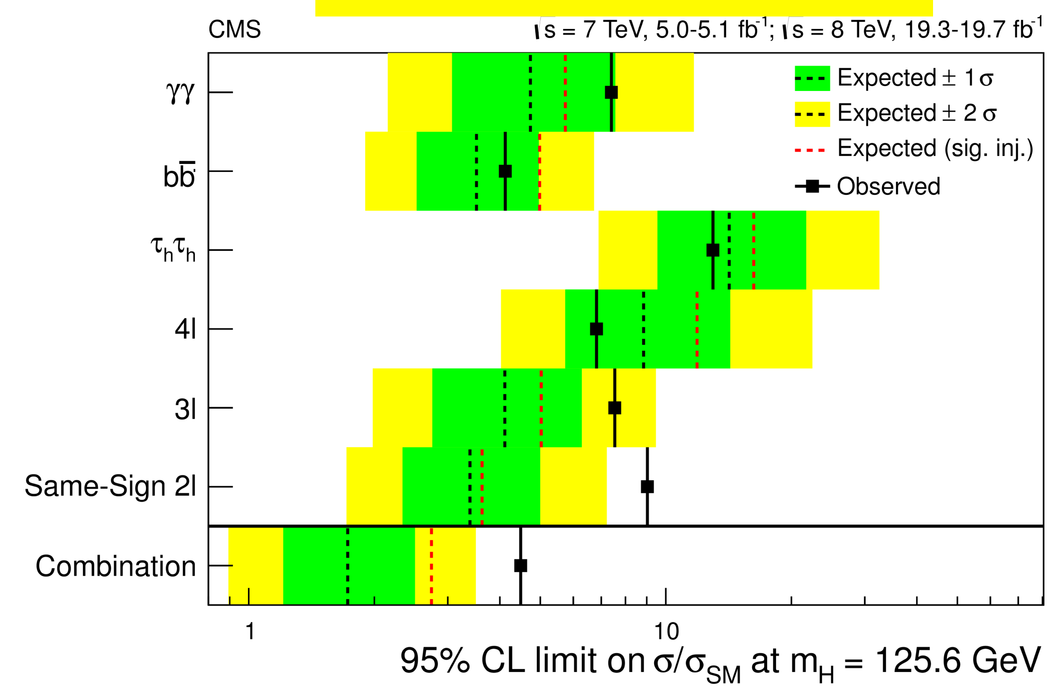
CMS JHEP 09 (2014) 087



ATLAS PLB749 (2015) 519

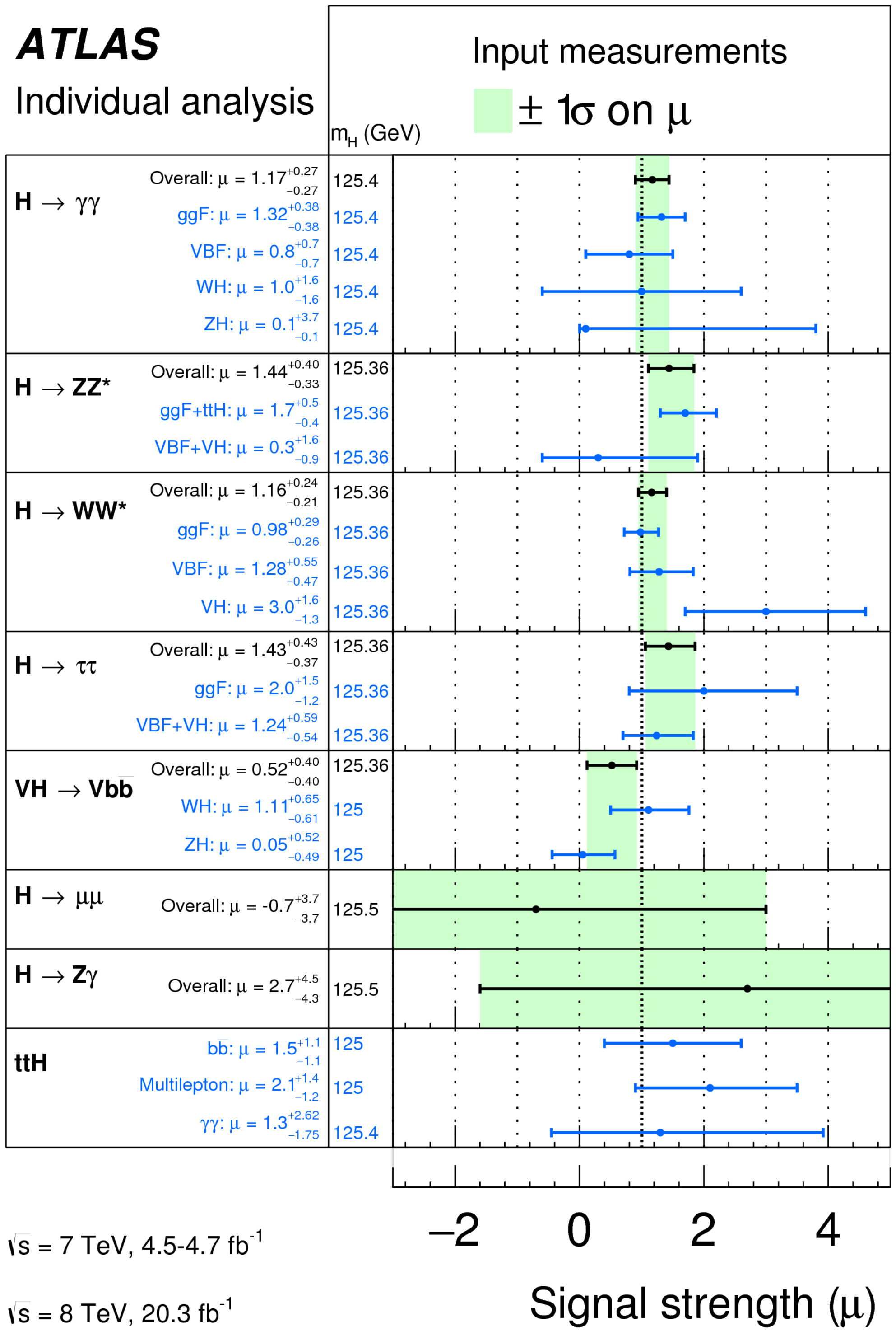


CMS ttH combination

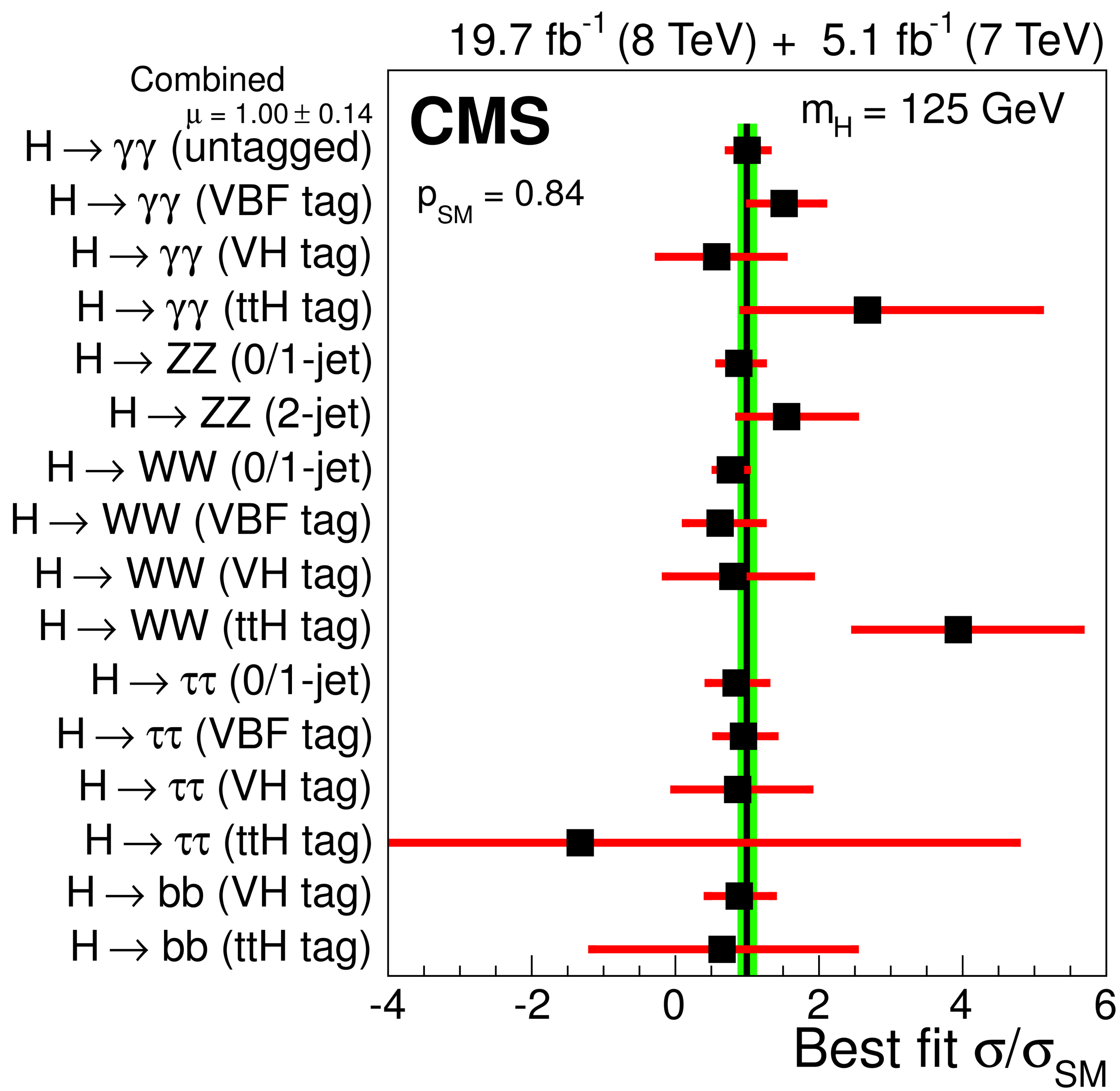


ATLAS and CMS inputs

ATLAS 1507.04548



CMS EPJ C 75 (2015) 212



Most model independent (assuming narrow width): Measure ratio of cross-section and of BR

$$(\sigma_i . BR_j) = \sigma(gg \to H \to ZZ) \frac{\sigma_i}{\sigma_{ggF}} \frac{BR^j}{BR^{ZZ}}$$

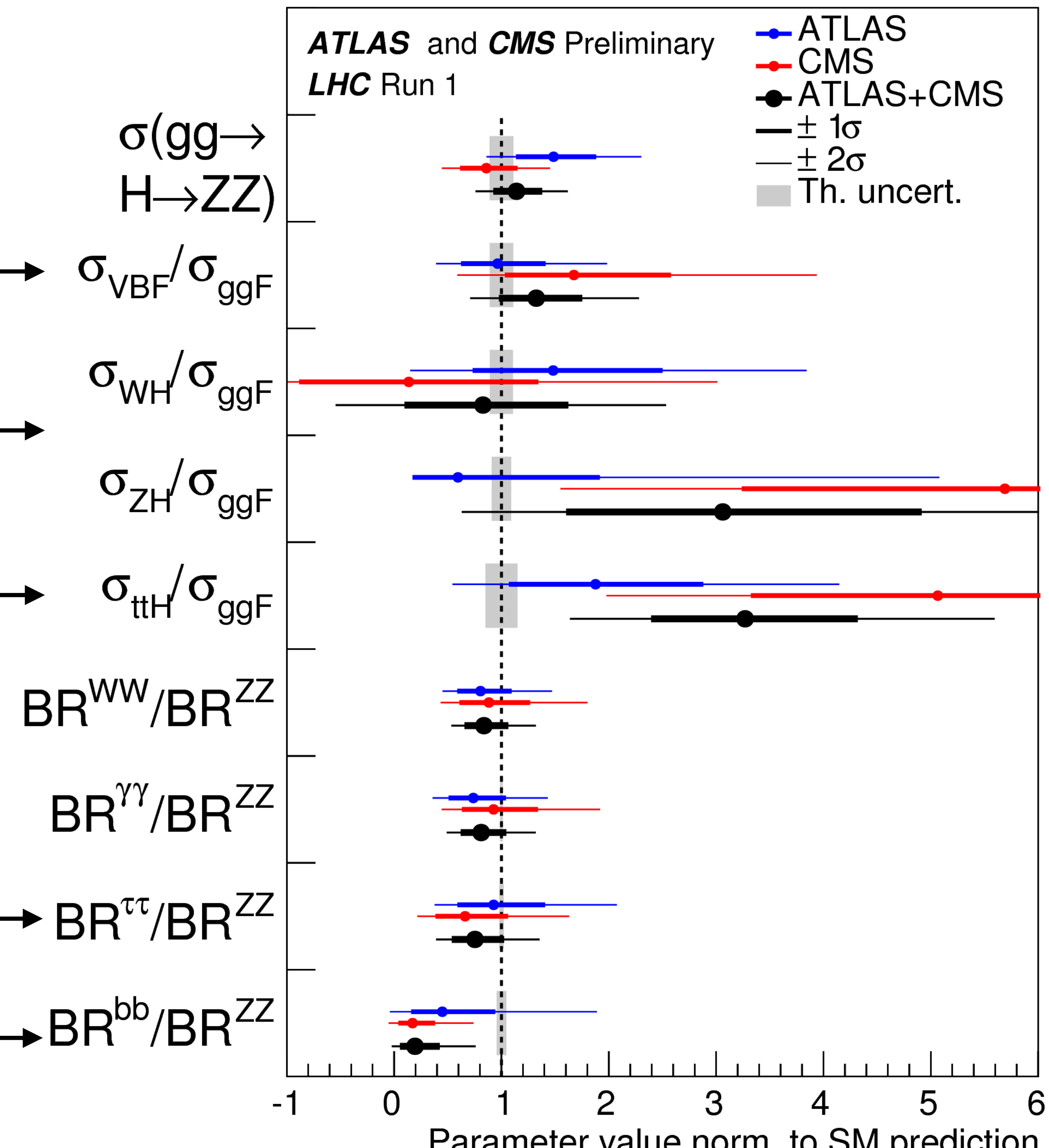
Observed with 5.4 σ significance (exp 4.7) → $\sigma_{VBF}/\sigma_{ggF}$

3.5 σ for combined WH+ZH production (exp. 4.2) → σ_{WH}/σ_{ggF}, σ_{ZH}/σ_{ggF}

~2.4 σ excess over SM prediction for ttH (4.4 observed, 2.0 expected) → $\sigma_{ttH}/\sigma_{ggF}$

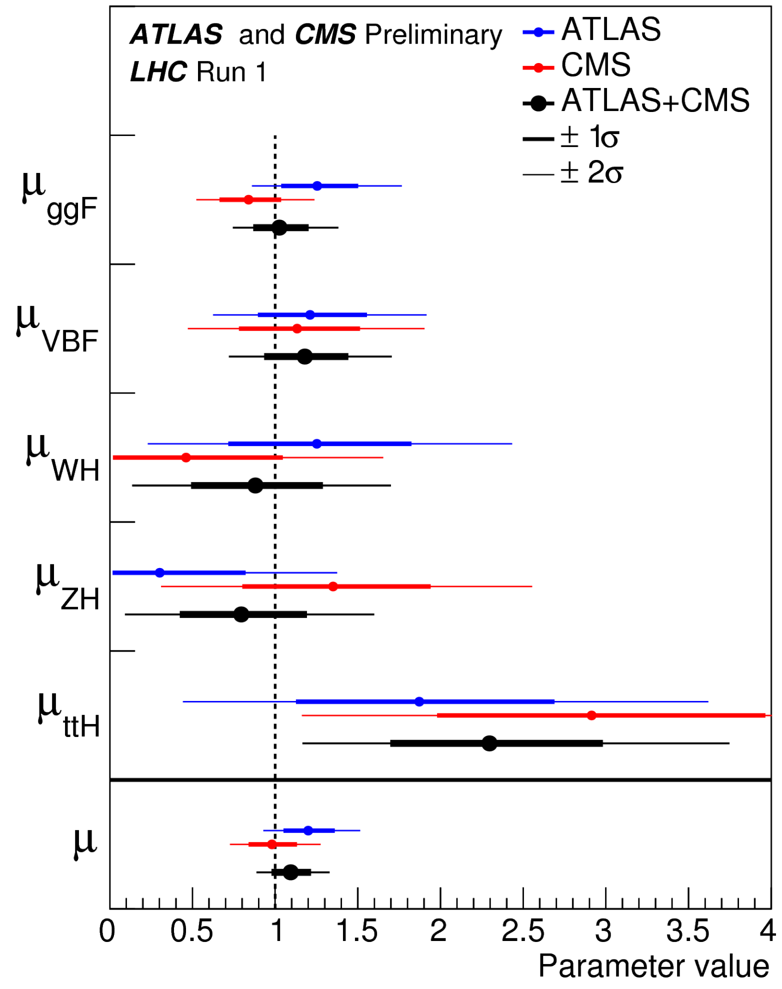
Observed with 5.5 σ significance (exp. 5.0) → $BR^{\tau\tau}/BR^{ZZ}$

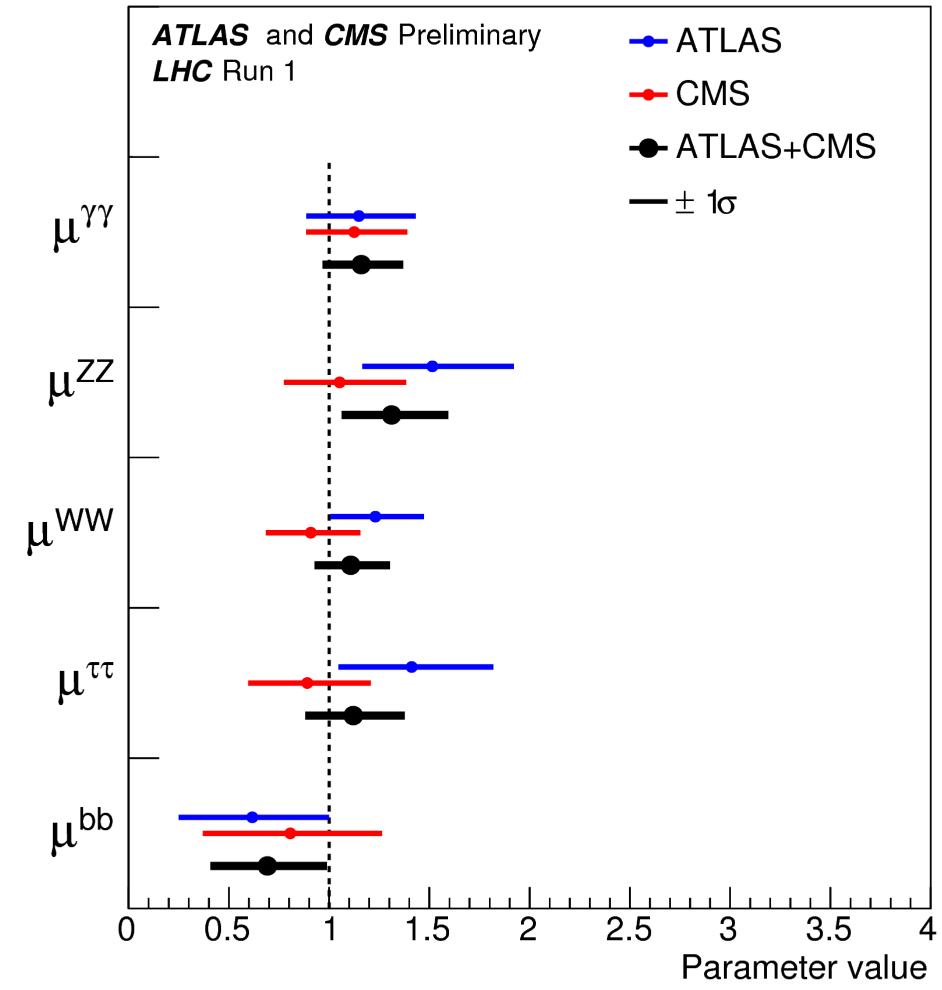
Driven low by "excess" in ZH and ttH production modes in other decay channels than bb → BR^{bb}/BR^{ZZ}



Signal strength $\mu_i^f = (\sigma_i.BR_f)_{meas} / (\sigma_i.BR_f)_{theo} = \mu_i \cdot \mu^f$

Cross-section per production mode (assuming SM BR) compared to theory prediction	Branching ratio per decay mode (assuming SM cross-section) compared to theory prediction





Global signal strength assuming SM ratio for all production and decay (~10% accuracy):

$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}} +0.07 -0.06_{\text{th. sigma}}$

The "kappa" framework

Assuming exactly same coupling structure as SM

Modify couplings with LO degrees of freedom

$$\sigma_i = \kappa_i^2 * \sigma_i(SM) \quad \Gamma_f = \kappa_f^2 * \Gamma_f(SM) \quad \Rightarrow \mu_i^f = \kappa_i^2 . \kappa_f^2 \, / \, (\Gamma_H / \Gamma_H(SM))$$

Loops (g and γ): either resolved with SM content (assuming no other particles) or write as effective κ_g, κ_γ

Total width: SM contributions rescaled by appropriate κ's. Assume no BSM contribution or allow additional BSM contribution to the width

Handbook of LHC Higgs Cross Sections: 3. Higgs Properties" (arXiv:1307.1347)

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $+ 0.06 \cdot \kappa^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $+ 0.0023 \cdot \kappa^2 + 0.0016 \cdot \kappa_Z^2 +$ $+ 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa^2$

All κ free

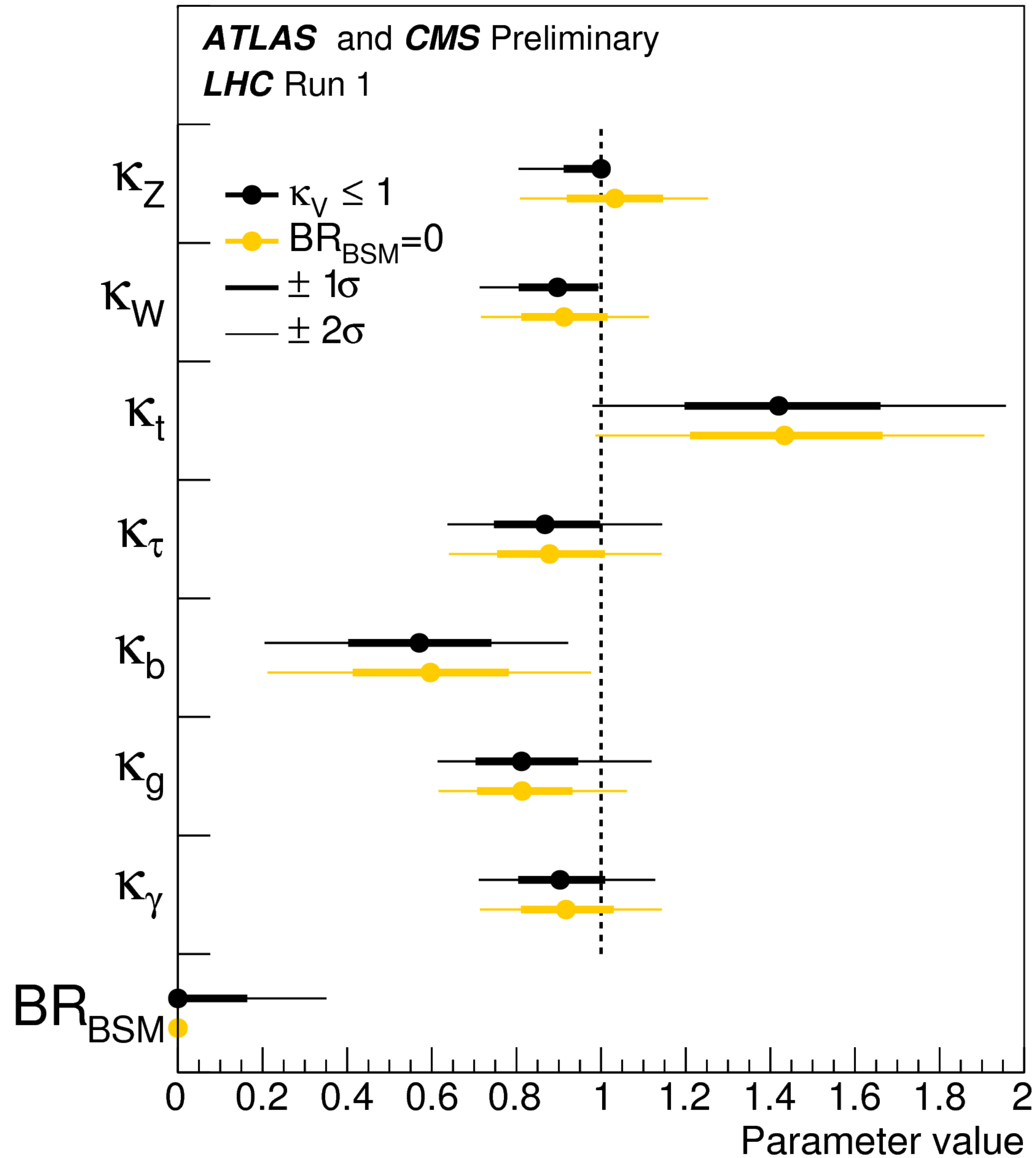
Effective loop couplings for g and γ

Total width $\Gamma = \Gamma(\boldsymbol{\kappa})/(1\text{-}BR_{BSM})$

Need some assumption to remove degeneracy between κ and Γ : For this scenario assume $\kappa_V \leq 1$ if BR_{BSM} is free

$BR_{BSM} < 0.34$ (95%CL) if $\kappa_V \leq 1$

Large uncertainty on κ_t which is only constrained by ttH mode in this scenario



Constraints on tree-level Higgs boson couplings

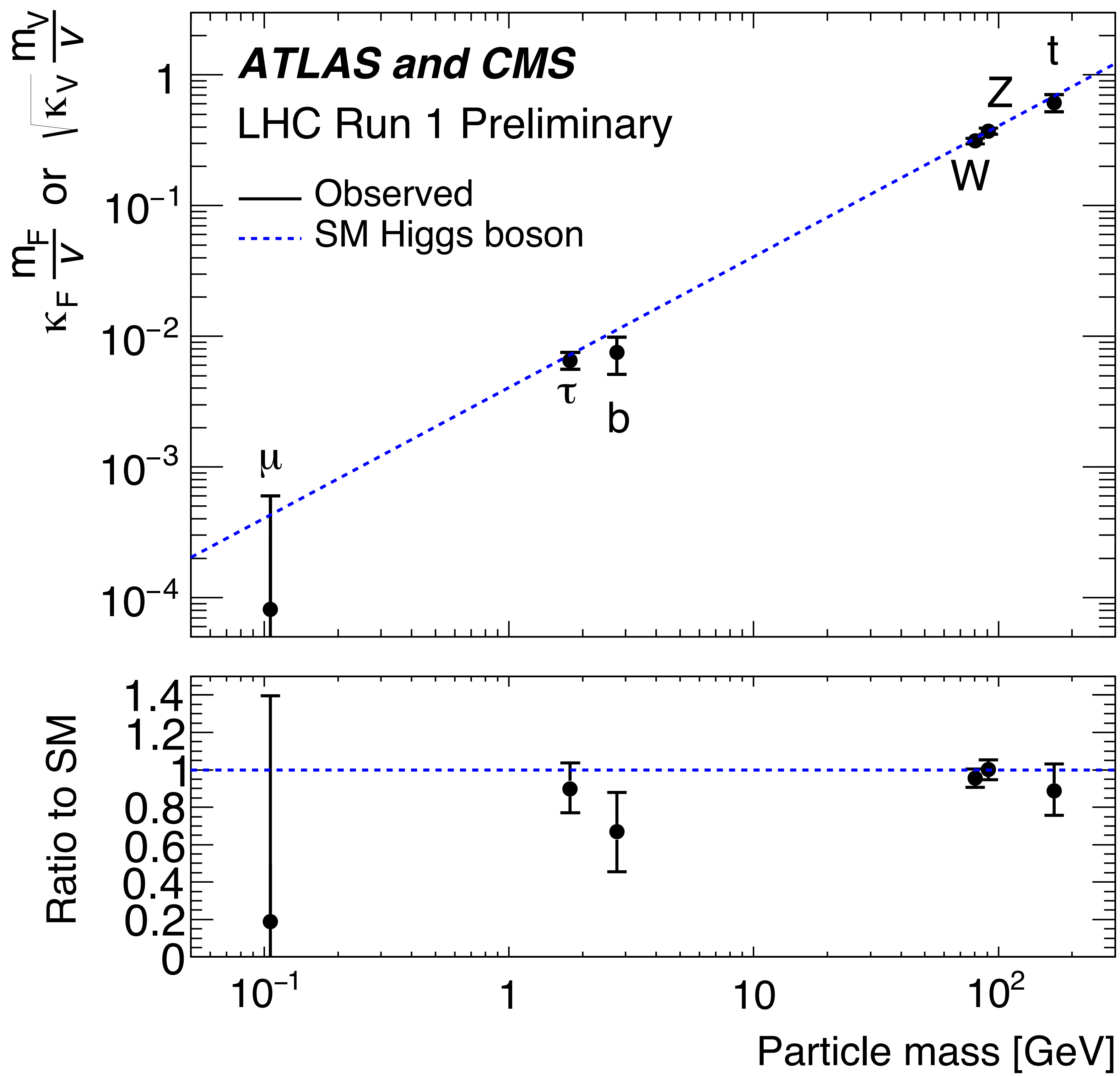
More assumptions:

Resolve loops with SM content

$BR_{BSM} = 0$

=> Measure couplings to the SM particles

Good precision for top from loop induced gluon fusion rate

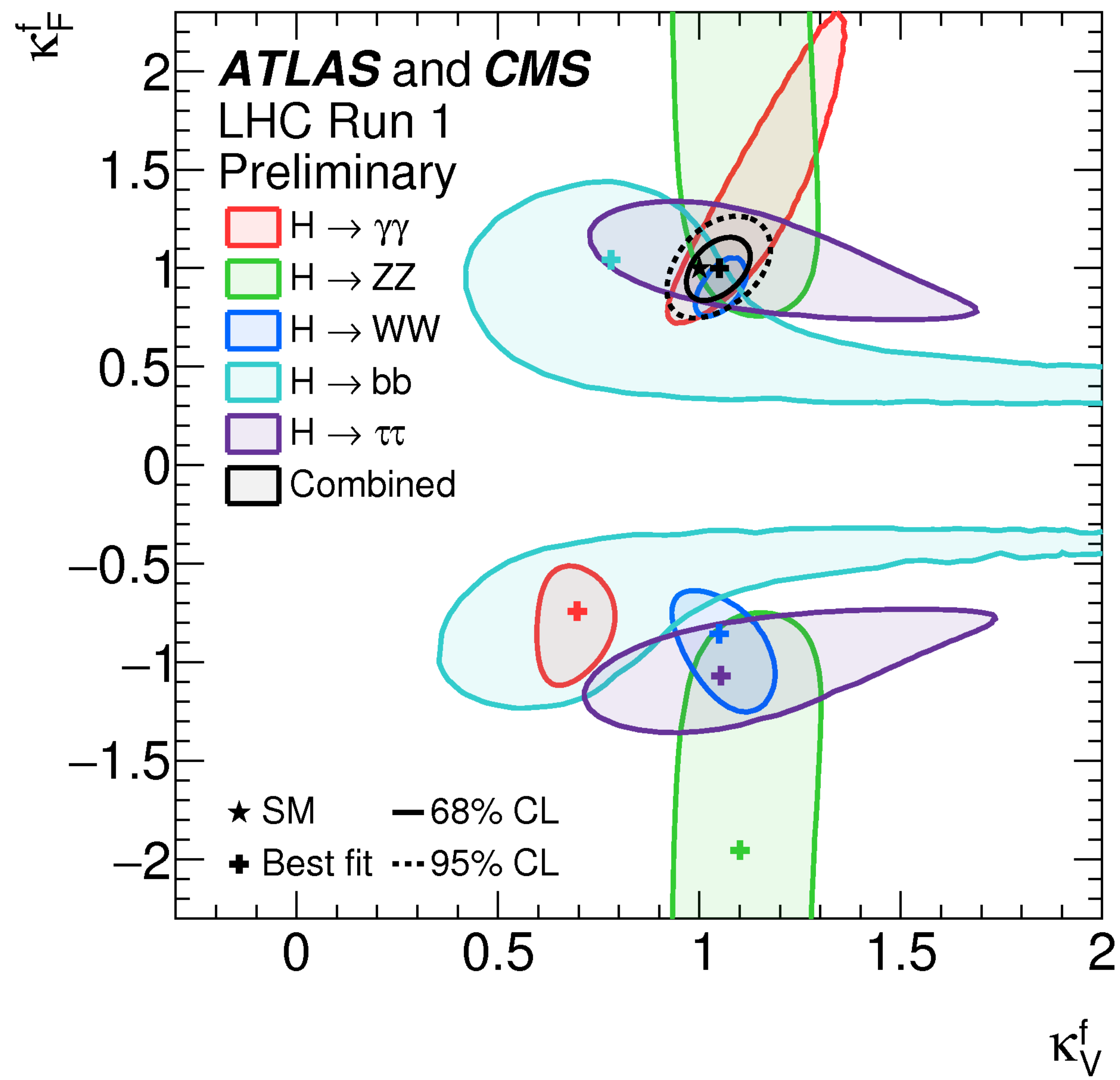


Fermion and Bosons:

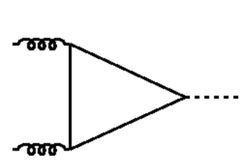
Only two independent κ for all fermions and all bosons

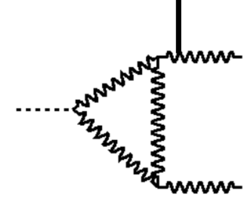
Resolve loops, $BR_{BSM}=0$

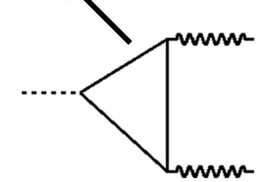
Interference effects (like in $H\rightarrow\gamma\gamma$ decays) allow to probe the relative sign of κ_V and κ_F



Example: Rate ($gg\rightarrow H\rightarrow\gamma\gamma$) ~ $\kappa_F^2 * (1.6\,\kappa_V^2+0.07\,\kappa_F^2-0.66\,\kappa_F\,\kappa_V) / (0.75^*\,\kappa_F^2+0.25^*\,\kappa_V^2)$







Γ(H)

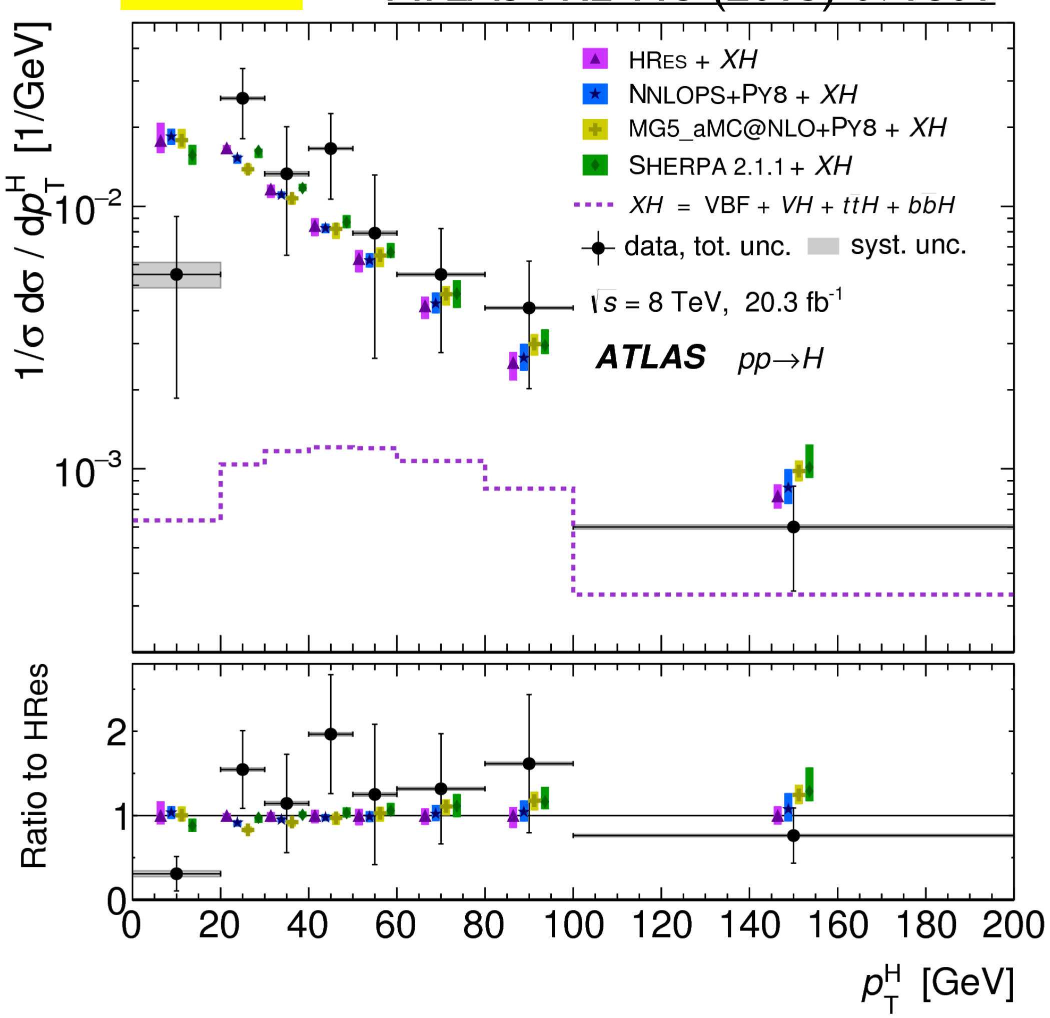
Differential cross-sections

Measure differential cross-sections with "minimal" model assumption for quantities like PT(H), number of jets, etc..

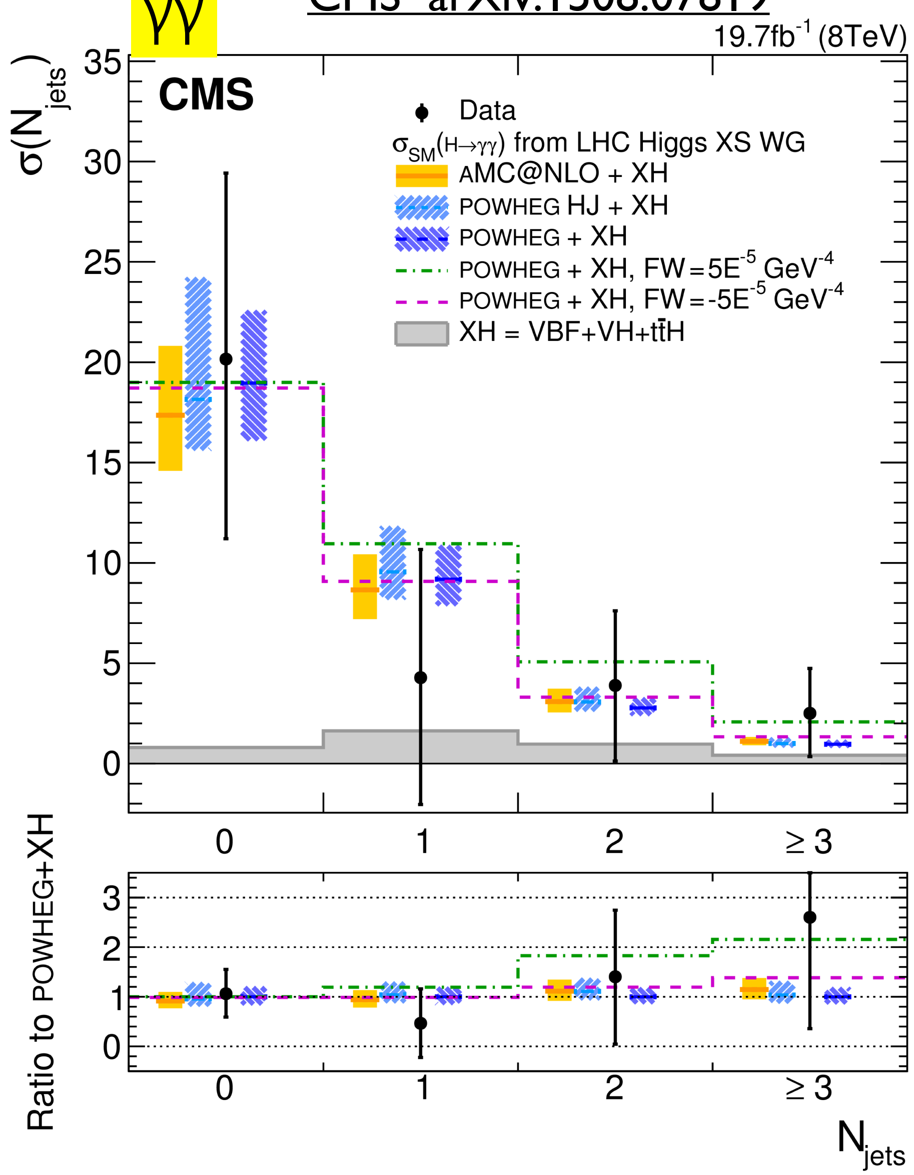
Relatively easy in γγ and 4l decay mode (can have ~inclusive selection with "simple" background subtraction procedure)

Can check that QCD effects in H production kinematic properties are consistent with SM

γγ+4l ATLAS PRL 115 (2015) 091801

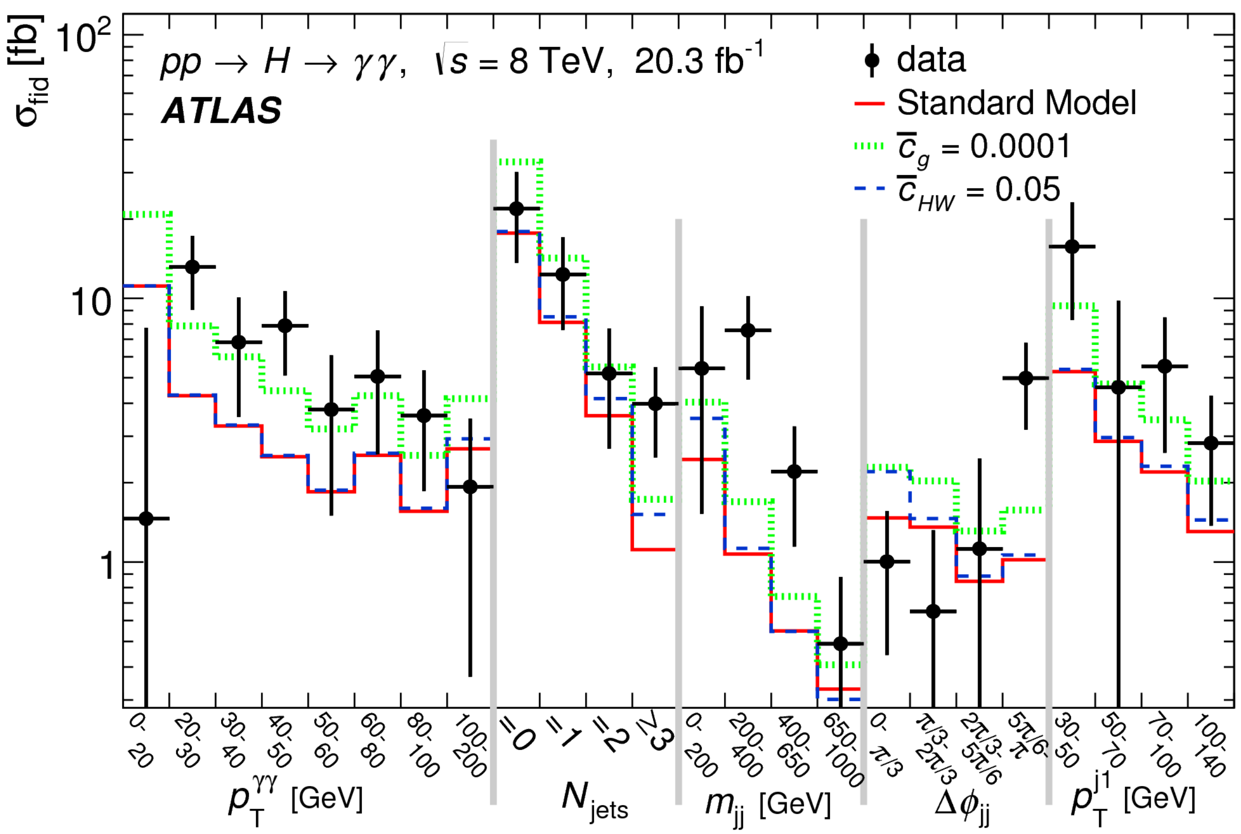


γγ CMS arXiv:1508.07819



EFT study with differential cross-sections

ATLAS Phys.Lett. B753 (2016) 69



Add dimension 6 operators to Lagrangian

H→γγ potentially sensitive to 8 operators modifying couplings to photons, gluons and vector bosons

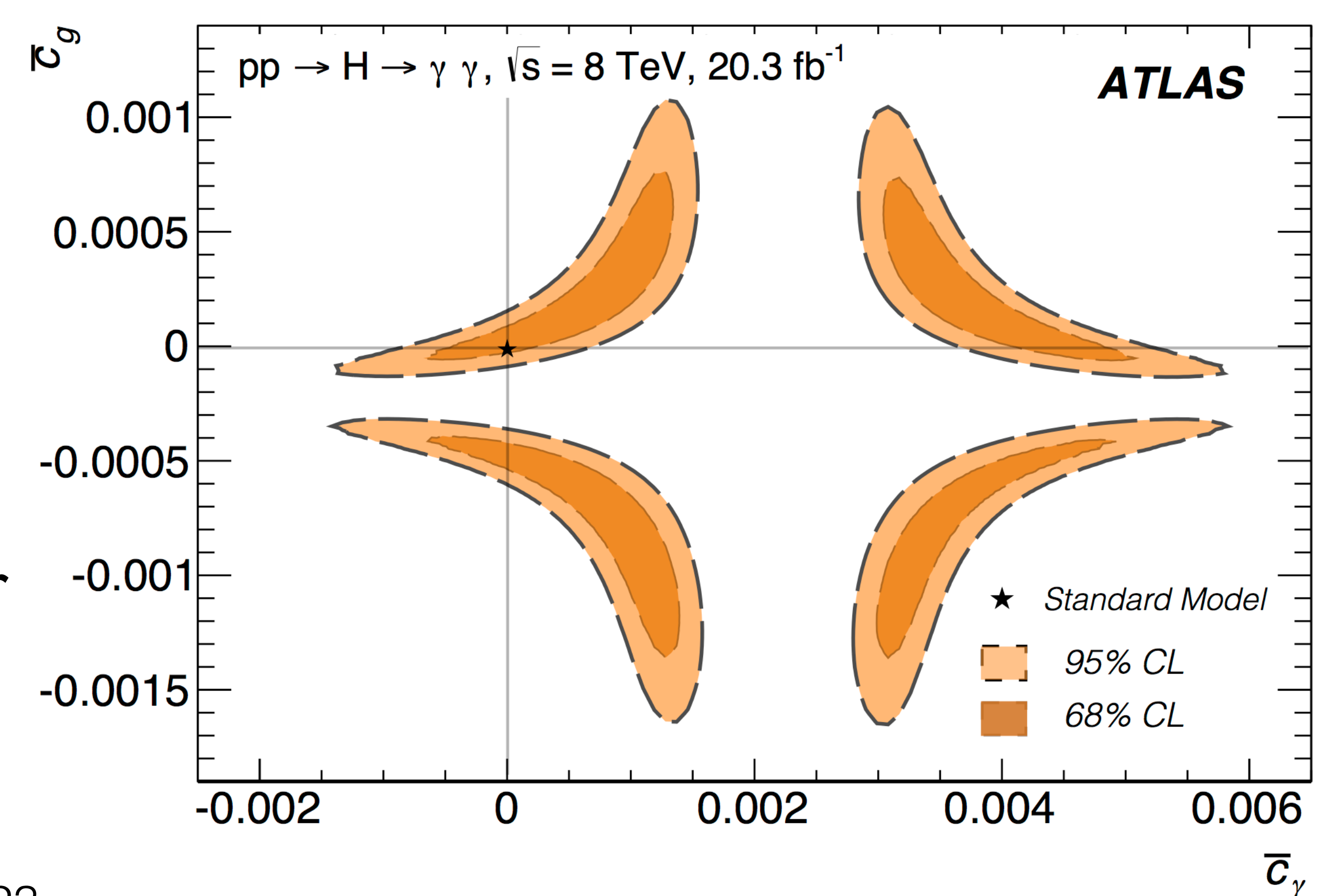
These anomalous couplings would change the rate and kinematics of the observed H→γγ events

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

see JHEP 07 (2013) 035

Example limit on 2 couplings, assuming 0 for the others

(assumes higher order QCD corrections factorize from new physics effect)



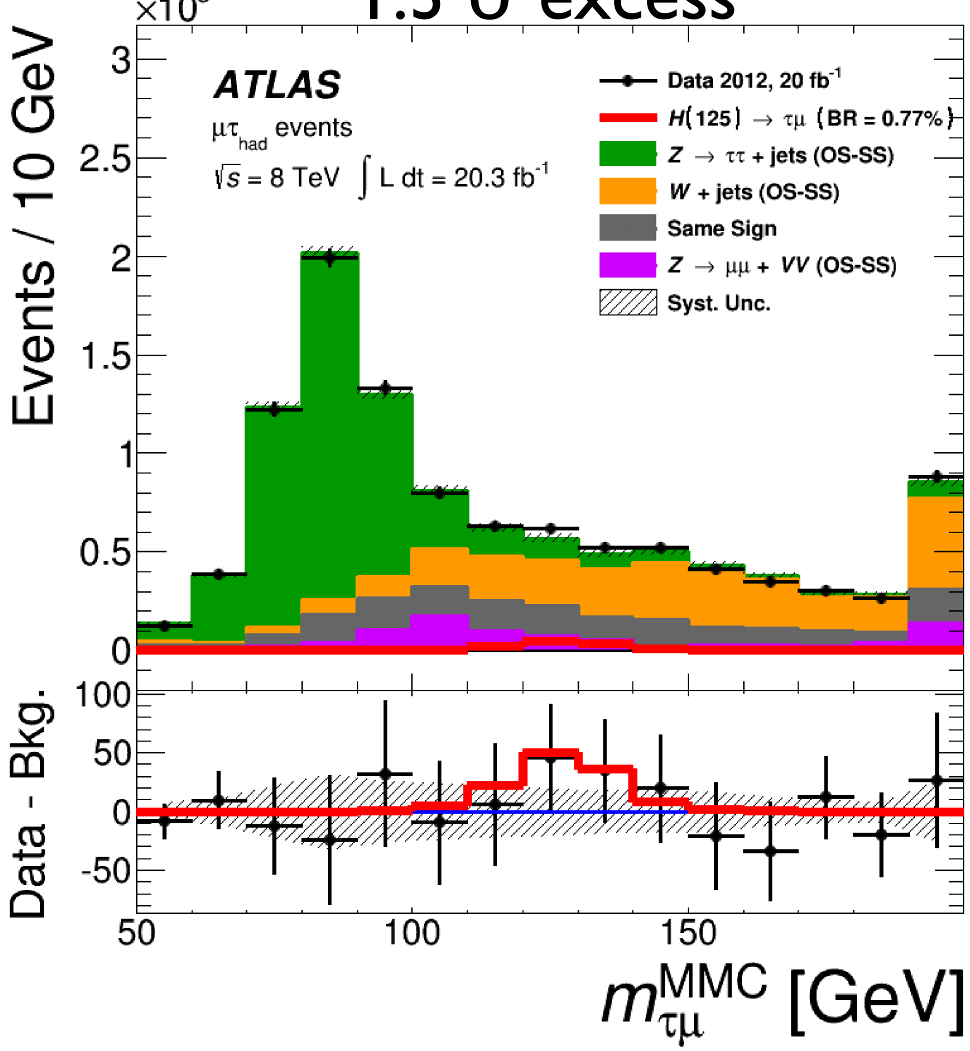
Rare BSM H(125) decay: LFV

Study of Higgs boson couplings still leave room for sizable non SM decay mode
Probe lepton flavor violation in decay looking for H→τμ (or τe or eμ)
Final state similar to H→ττ but with higher momentum muon

ATLAS JHEP 1511 (2015) 211

BR(τμ)<1.85% (exp 1.24%)

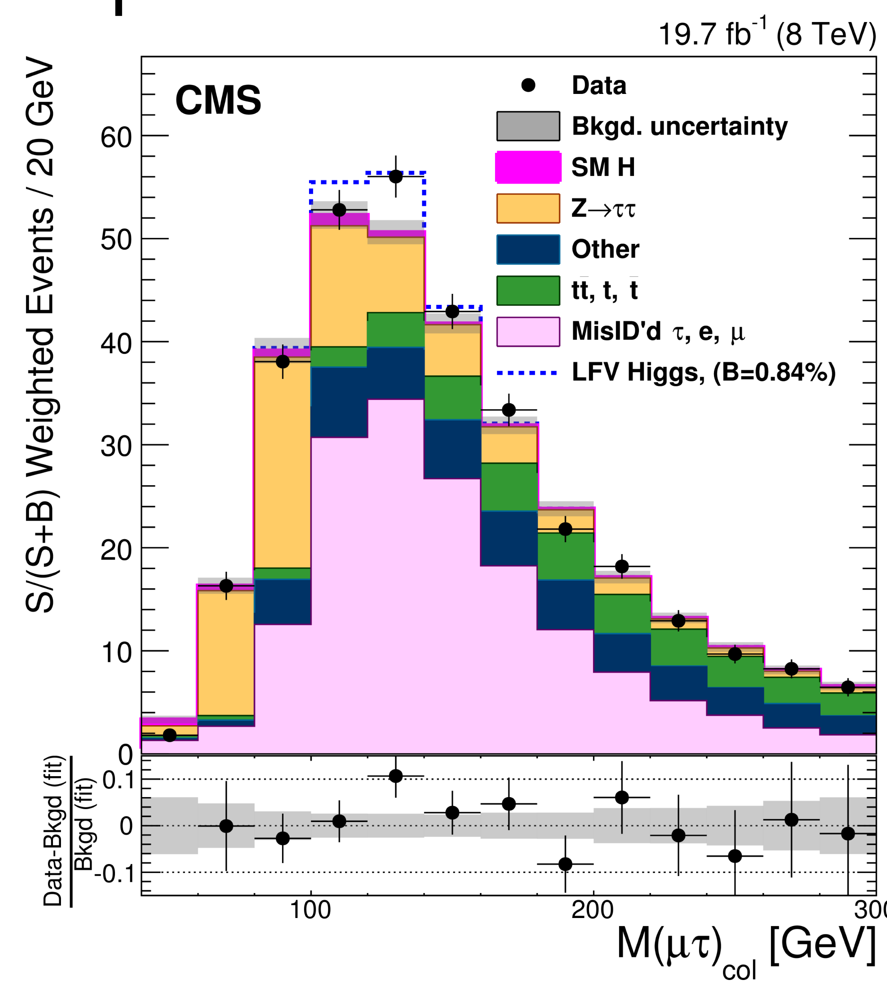
1.3 σ excess



CMS Phys. Lett. B 749 (2015) 337

BR(τμ) = 0.84+0.39-0.37% (<1.51%)

p-value of BR=0 is 0.01

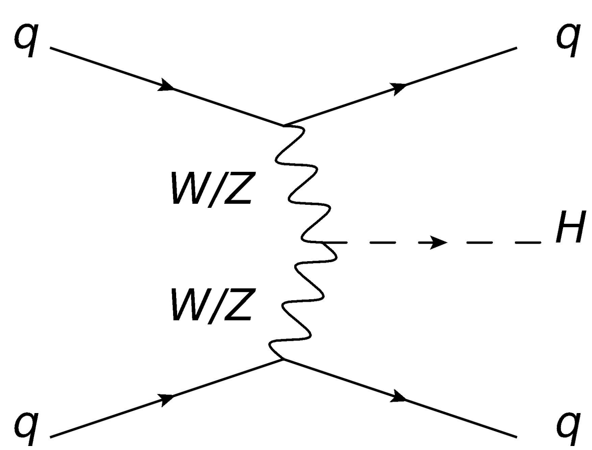


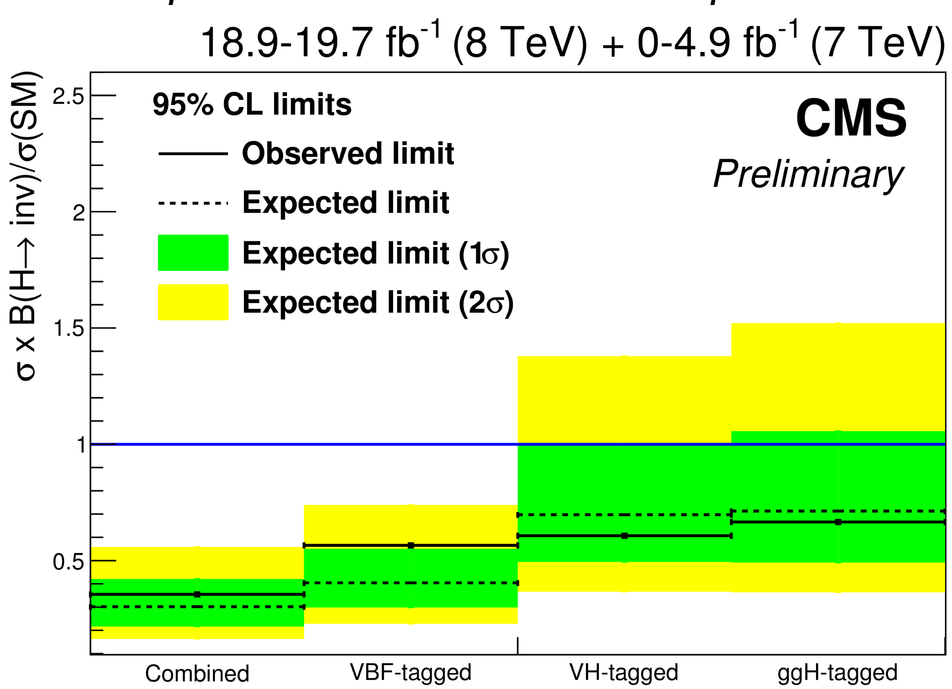
BR(τe)< 0.70% BR(eμ)<0.036%

Rare BSM H(125) decay: Invisible or partially invisible

Invisible Higgs boson decay search using "tagged" production modes. Most sensitive is VBF production

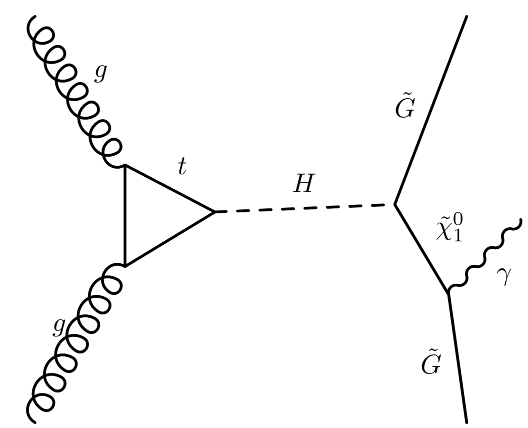
CMS-PAS-HIG-2015-12
ATLAS JHEP 1511 (2015) 206



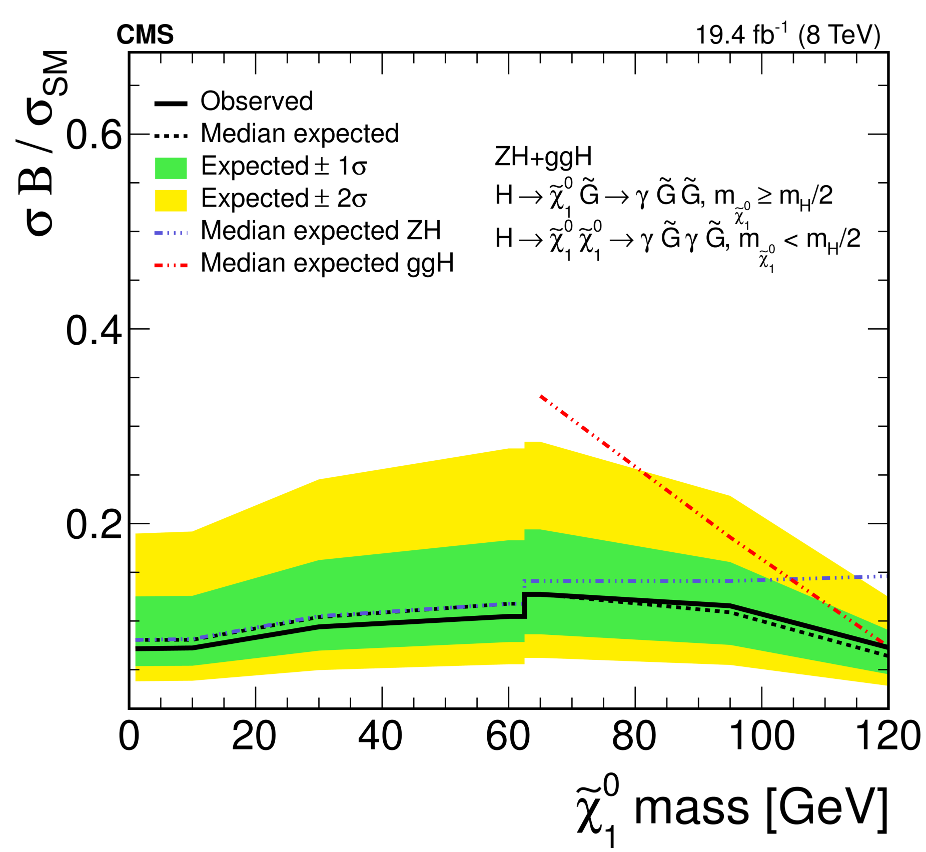


CMS BR<0.36 (0.30 exp.)
ATLAS BR<0.25 (0.27 exp.)

Higgs boson decay to one or two photons + invisible particles
(inspired by neutralino-> gravitino+photon)



CMS arXiv:1507.00359



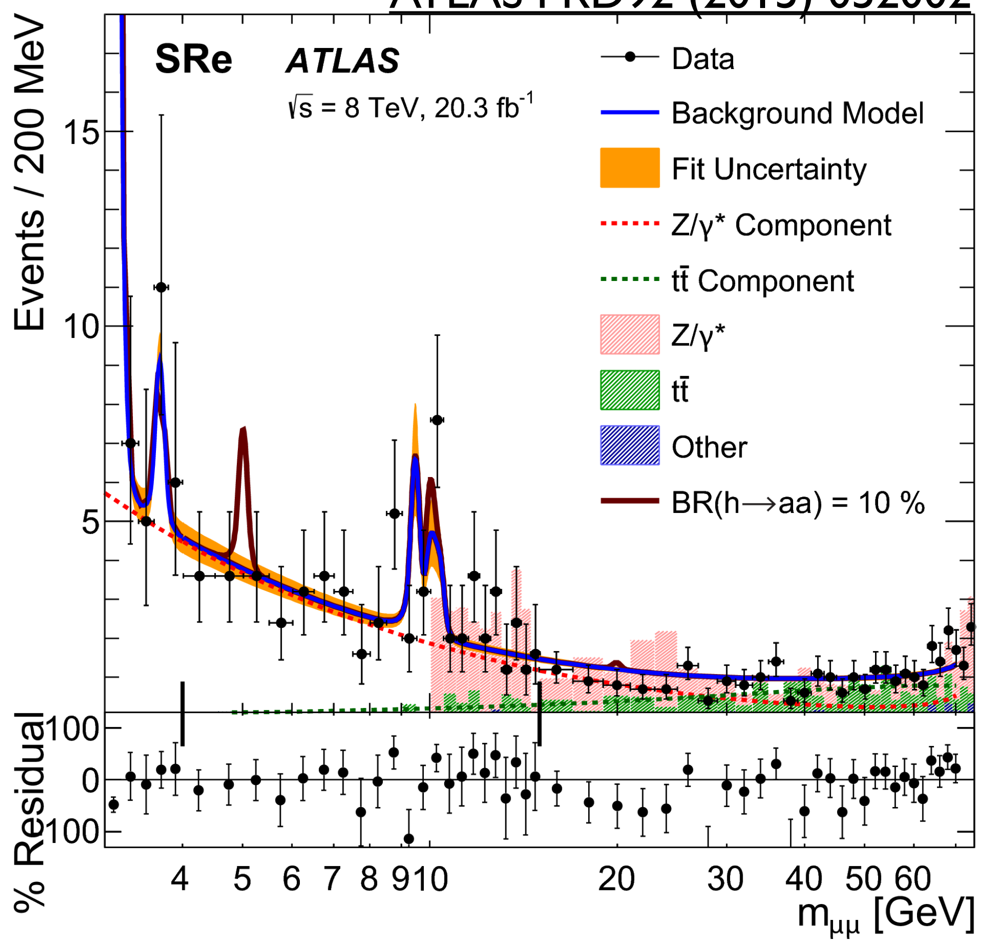
Rare BSM H(125) decay: $H \to aa$

Inspired by NMSSM: can have pseudoscalar state a much lighter than H(125)

$H \to aa \to \tau\tau\mu\mu$

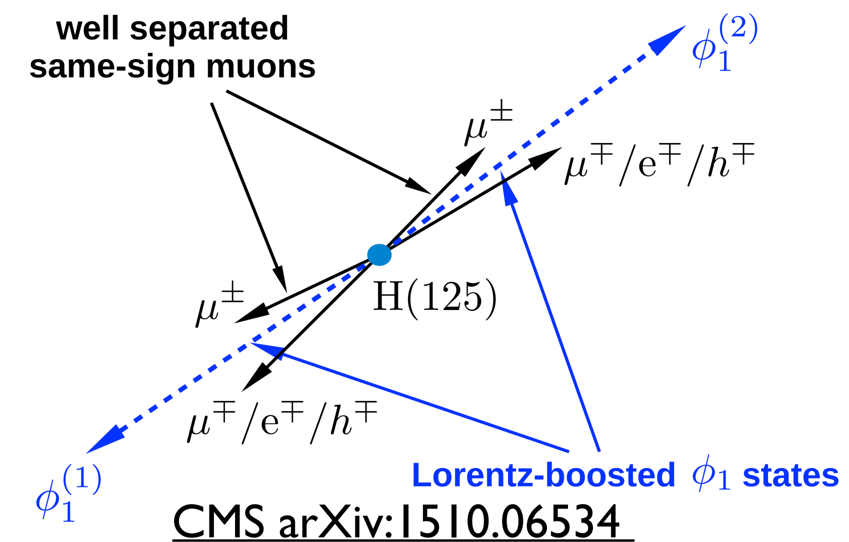
Look for peak in $M_{\mu\mu}$ in events select with leptonic + hadronic taus

ATLAS PRD92 (2015) 052002



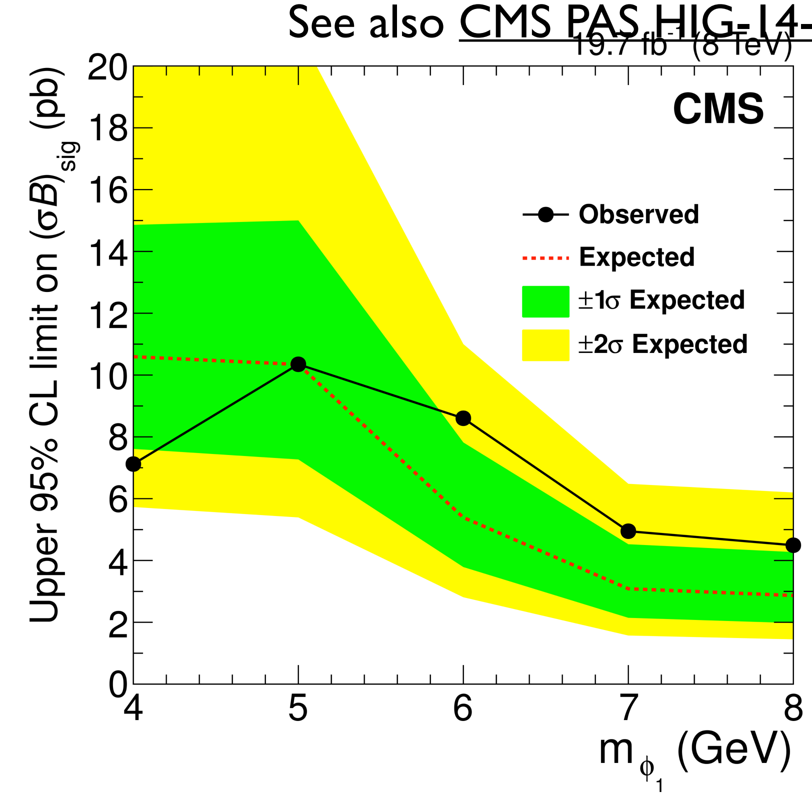
BR($H \to aa$).BR($a \to \tau\tau$)^2 < 3.5% for m_a=3.75 GeV (assuming SM cross-section for H)

$H \to aa \to \tau\tau\tau\tau$



CMS arXiv:1510.06534

See also CMS PAS HIG-14-022



see also $H \to aa \to 4\mu$ in CMS PLB 752 (2016) 146

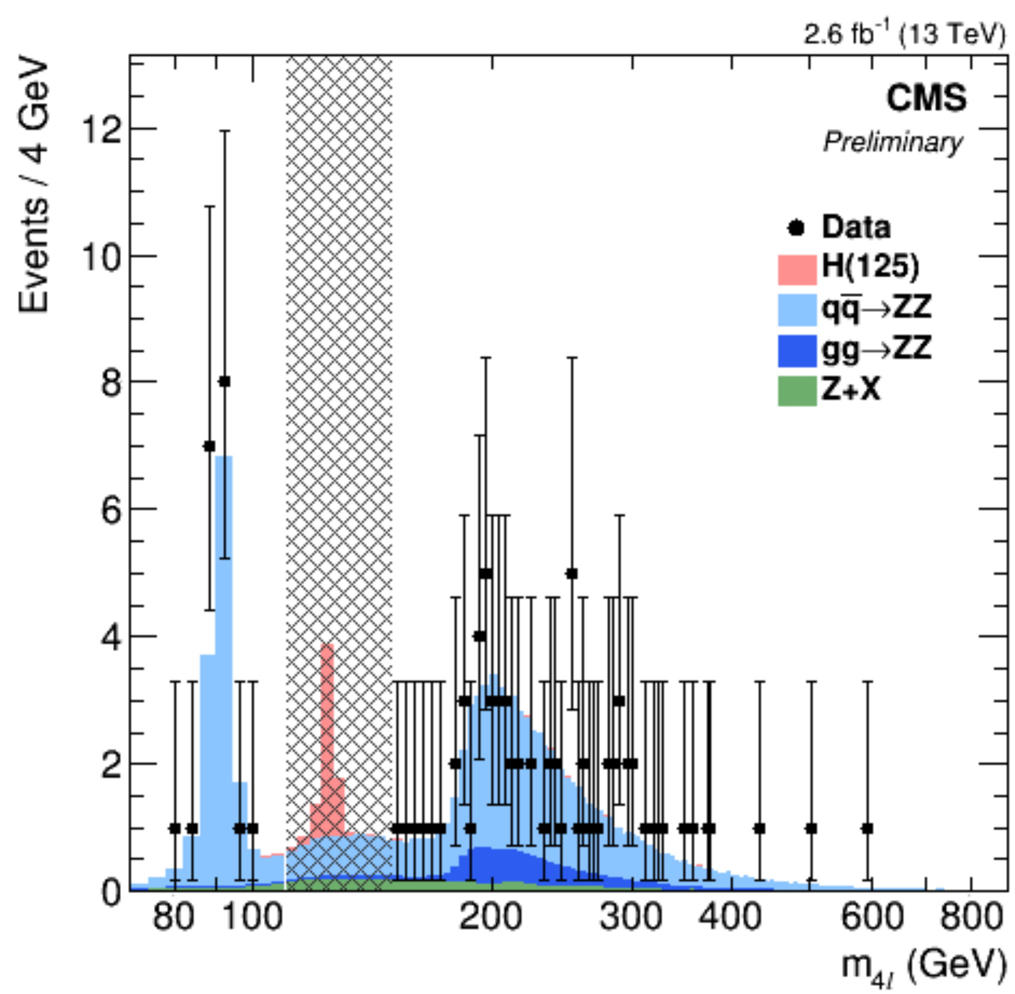
A first glimpse at 2015 data for H(125)

Luminosity ~ 3 fb^{-1} at 13 TeV not enough to reach run 1 sensitivity for H(125)

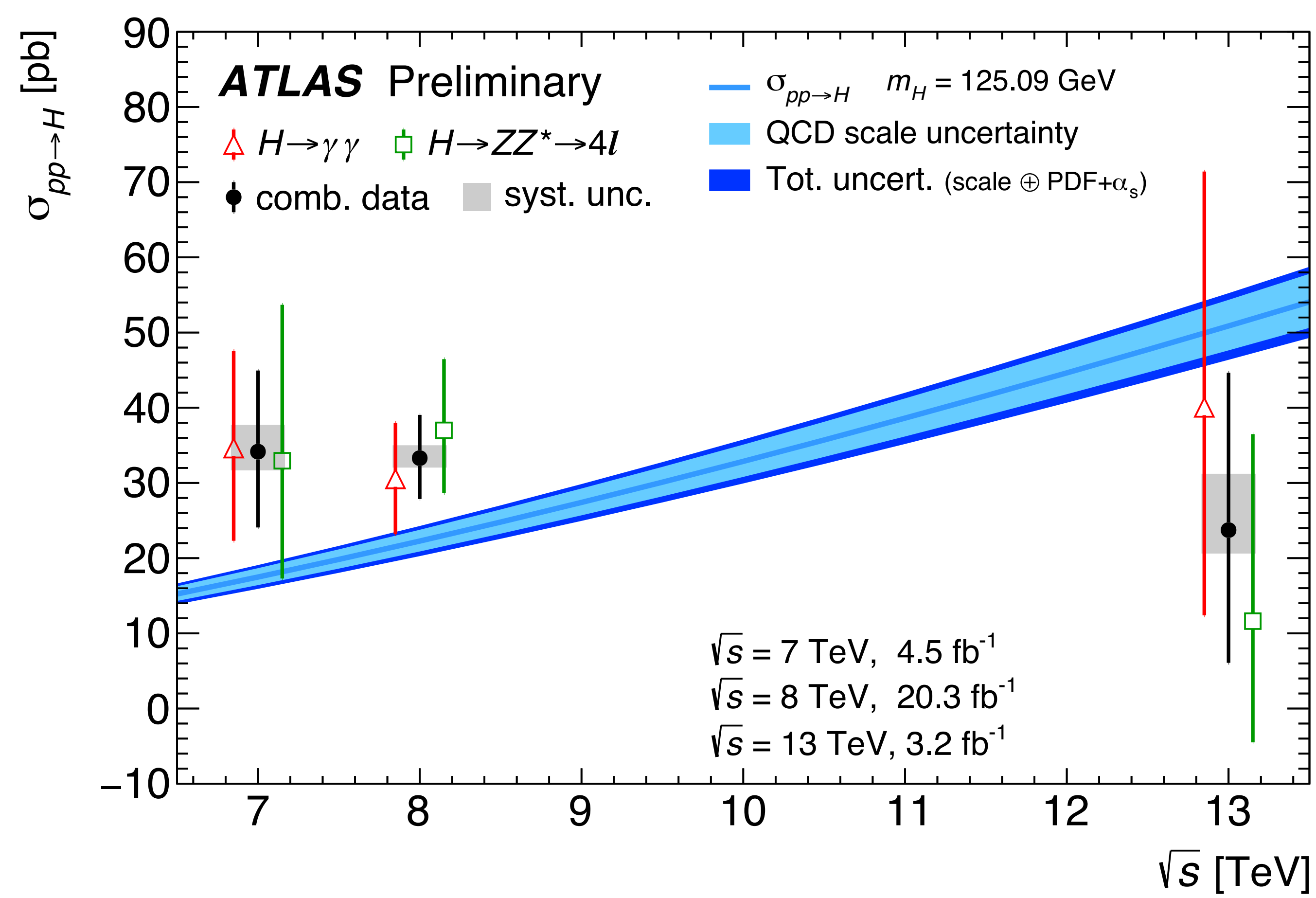
Nevertheless CMS and ATLAS re-established Higgs analysis with 2015 data

CMS preferred to stay blinded and released analysis performance studies
ATLAS performed fiducial cross-section measurements in 4l and γγ channels
(3.4σ combined sensitivity expected, 1.4σ observed)

https://twiki.cern.ern.ch/twiki/bin/view/CMSPublic/HigPagDec2015



ATLAS-CONF-2015-069



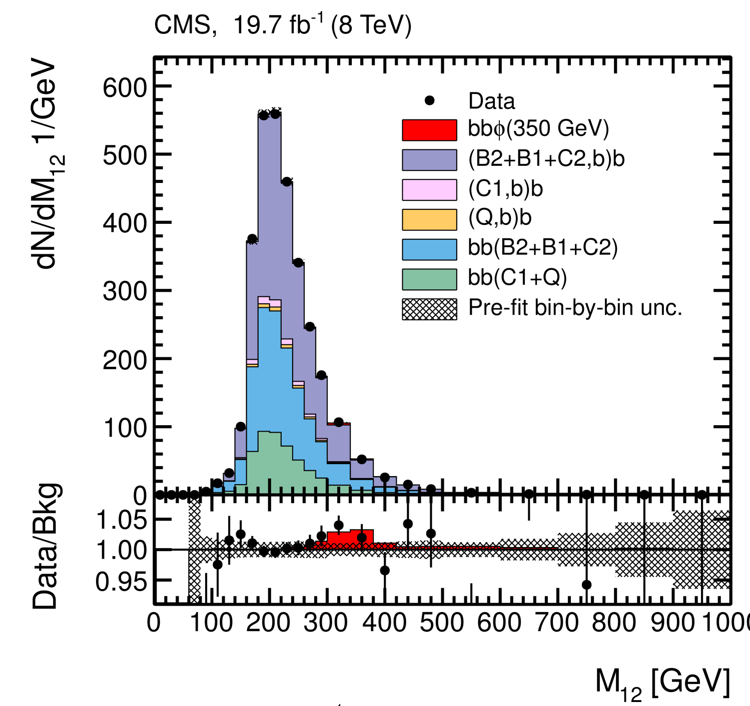
Direct searches for heavier neutral scalars

Several extensions of the SM predicts a richer scalar sector
For instance 2 Higgs doublet model => 5 states h,H,A,H+-
Search for high mass H,A done in several final states

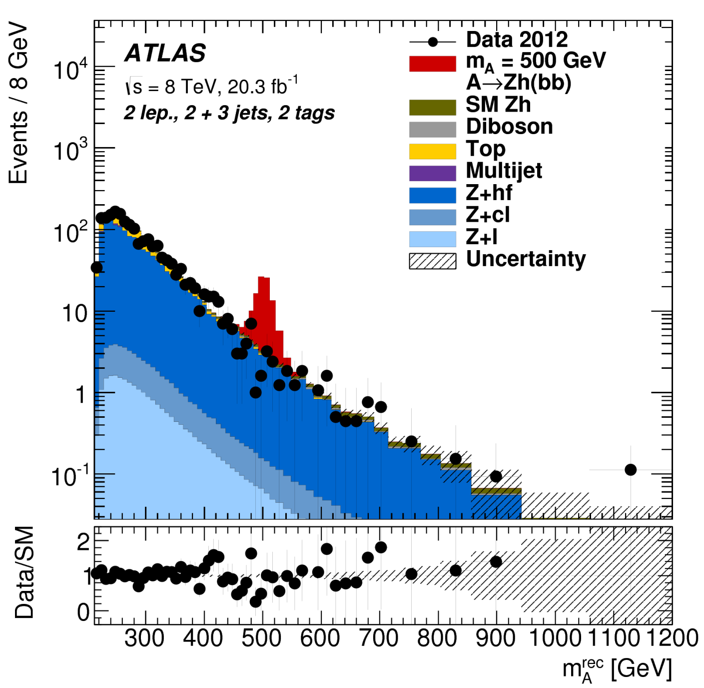
- hh pairs *(see backup)*
- ττ (and μμ) *(see backup)*
- bbbar
- ZZ *(see backup)*
- Zh (→ll bb , also νν bb and ll ττ)

No excess observed => constraints on 2HDM parameter space

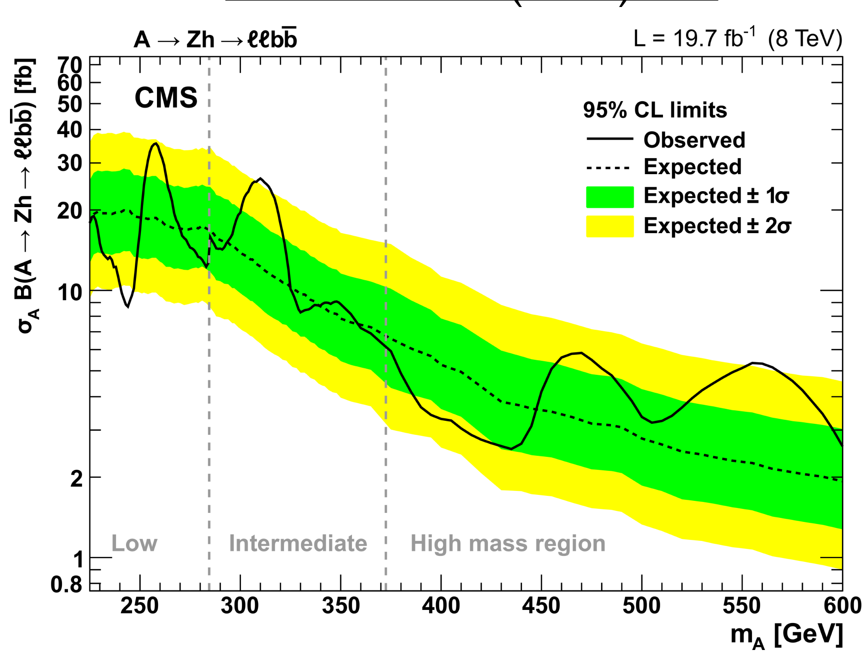
CMS arXiv:1506.08329

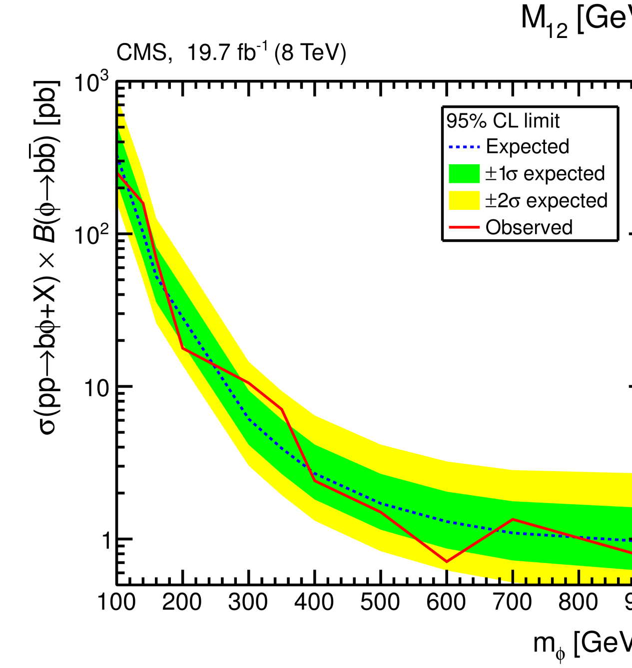


ATLAS PLB744 (2015) 163



CMS PLB 748 (2015) 221

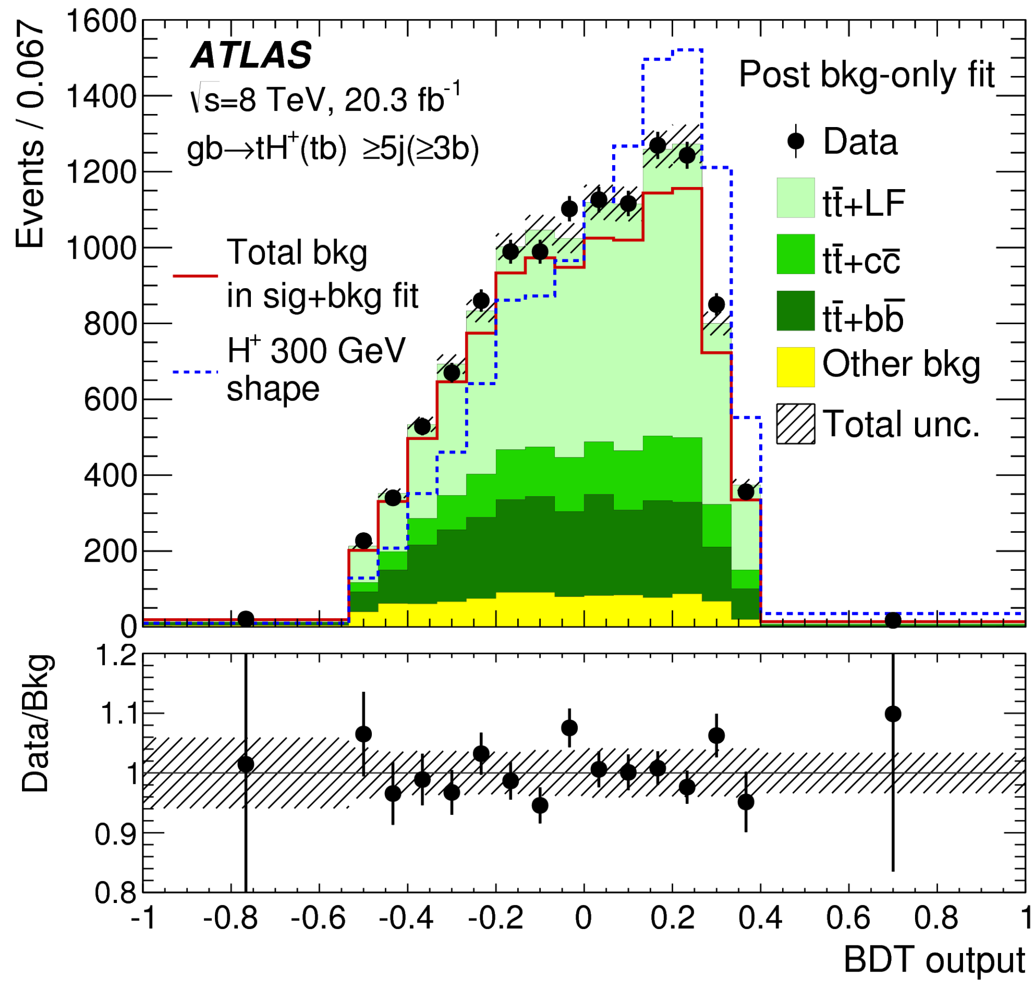




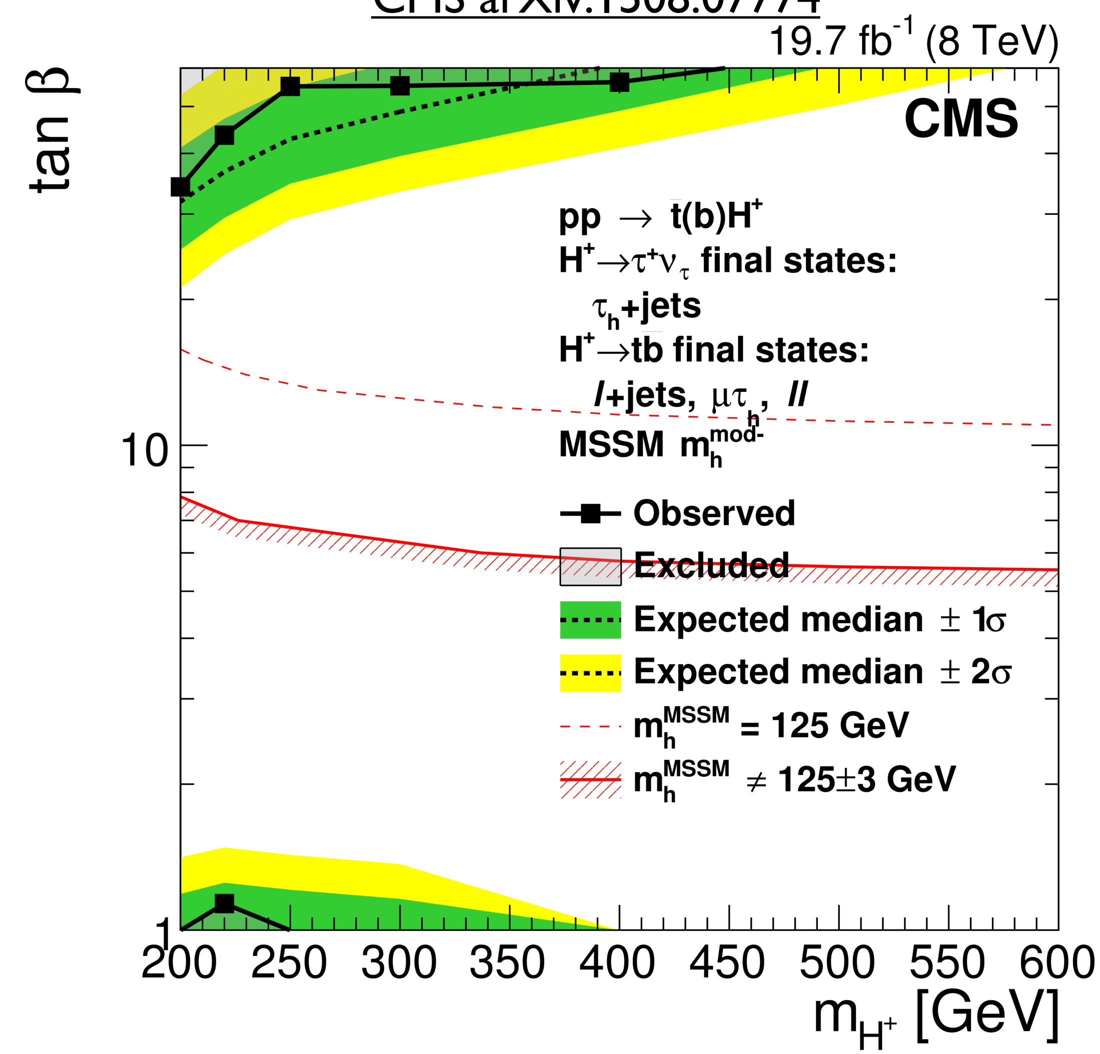
Direct searches for heavier charged scalars

- In top decays at low mass, with $H^{\pm}\to\tau\nu$
- t b $H^{\pm}$ production at high mass
  - $H^{\pm}\to\tau\nu$ (high tanβ) : look for instance at hadronic tau+jets final state
  - $H^{\pm}\to tb$ (low tanβ) : complicated final state with combinatoric and tt+heavy flavor background

ATLAS arXiv:1512.03704



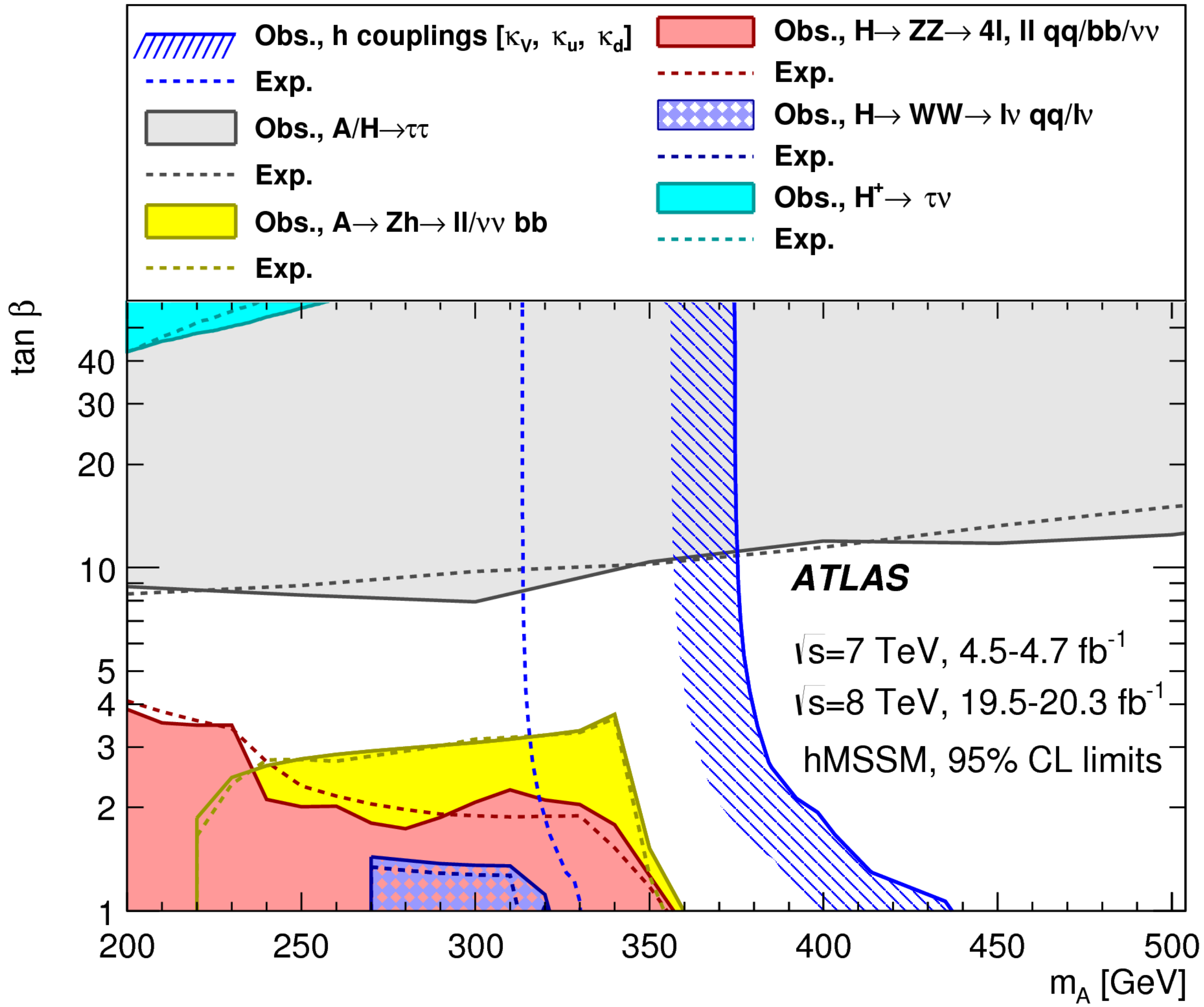
CMS arXiv:1508.07774



~2-2.4 σ excess over bkg prediction

no excess seen in $H^{\pm}\to tb$

Complementarity of direct searches and coupling measurements



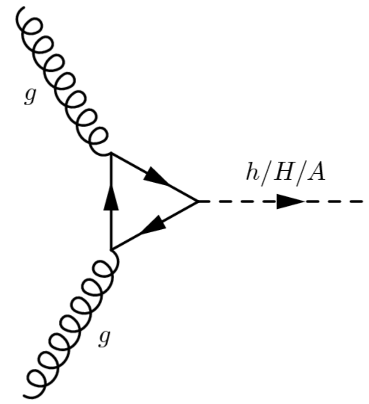
ATLAS JHEP 1511 (2015) 206

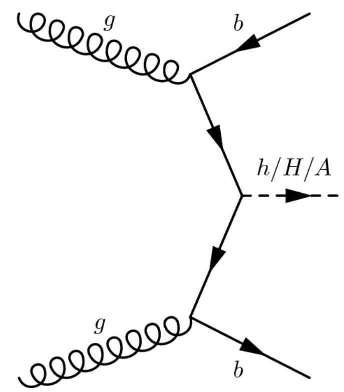
First glimpse at A/H→ττ in run 2

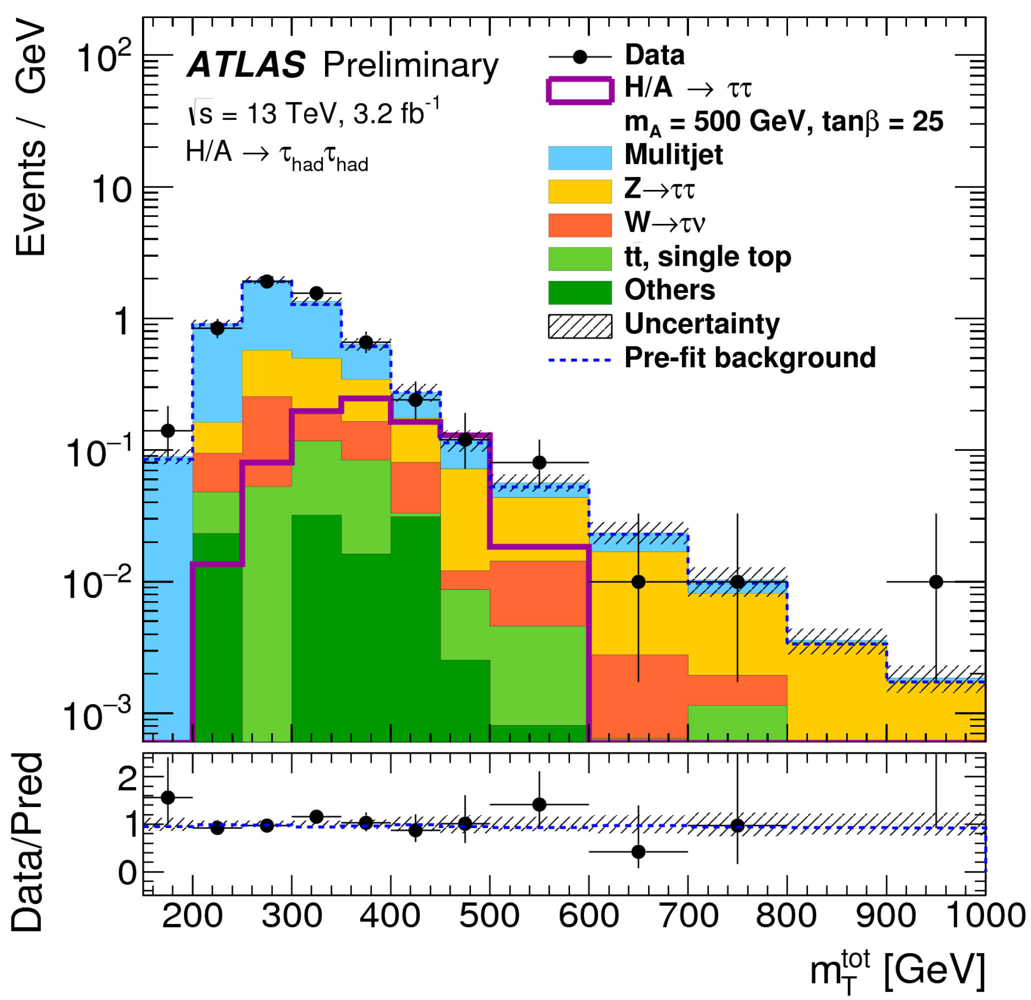
2 channels τ_{lep}-τ_{had} and τ_{had}-τ_{had}

- τ_{lep}-τ_{had}: Z and top bkg from MC, W+jets and multijets from τ_{had} fake rate method
- τ_{had}-τ_{had}: dominant background from multijets with fake rate method (checked in same sign events)

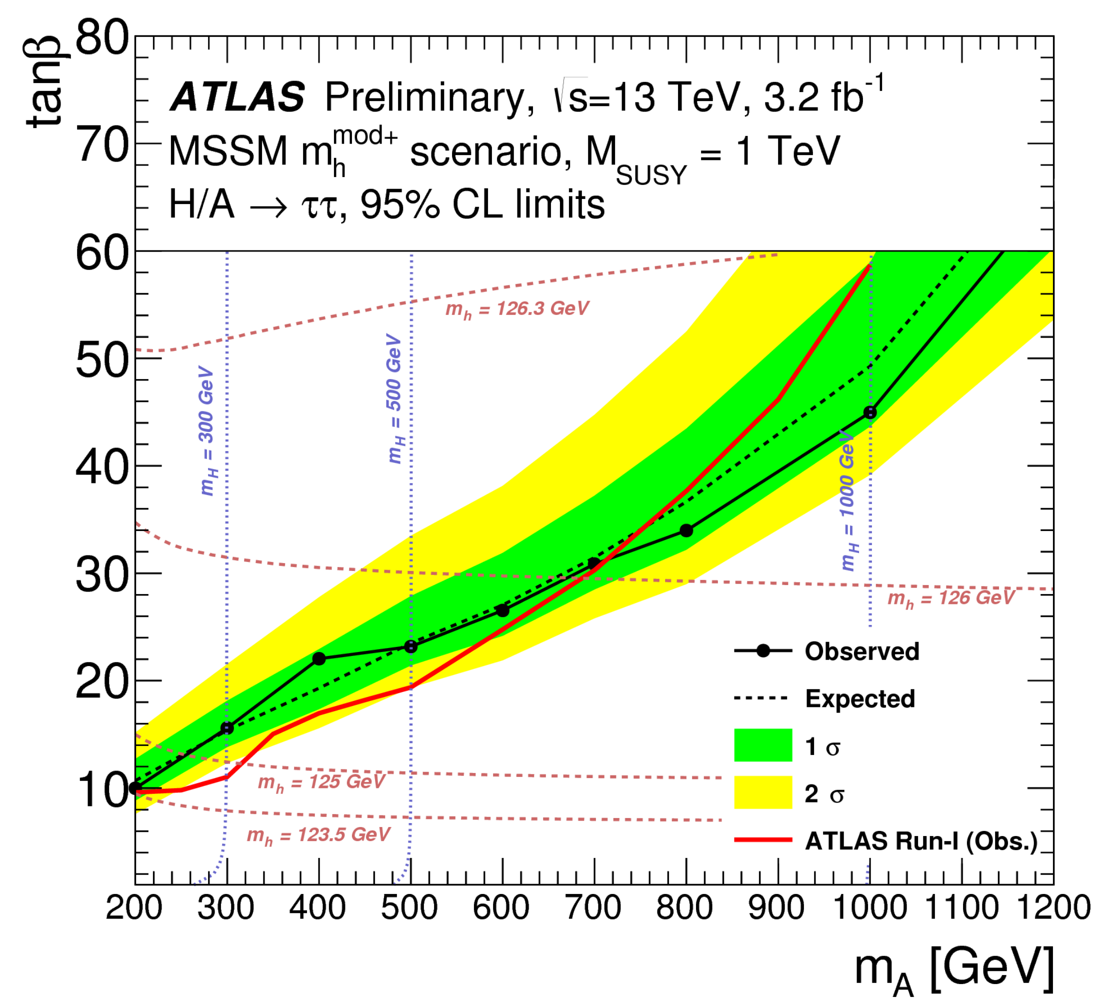
Limit better than run 1 for M > ~700 GeV







ATLAS-CONF-2015-061



Conclusions

- From run 1 data, H(125) properties are consistent with Standard Model predictions
  - ggF and VBF production modes observed at > 5σ level
  - 4 decay modes also observed at > 5σ level (not yet b-bbar)
  - Typical accuracy ~10-20% on coupling measurements, depending on scenario and assumptions
  - ttH a little high in run 1 => to check in run 2
  - No BSM decay observed, small excess in LFV search to be investigated in run 2
  - No other high mass scalar particle observed
- 2015 data does not have the sensitivity of run 1 data for H(125) but have been used by ATLAS and CMS to search for high mass scalar states (see other talks in this conference) and to re-establish analysis for H(125) measurements
- With 2016 data (~35 fb^{-1} expected) sensitivity will significantly improve over run 1

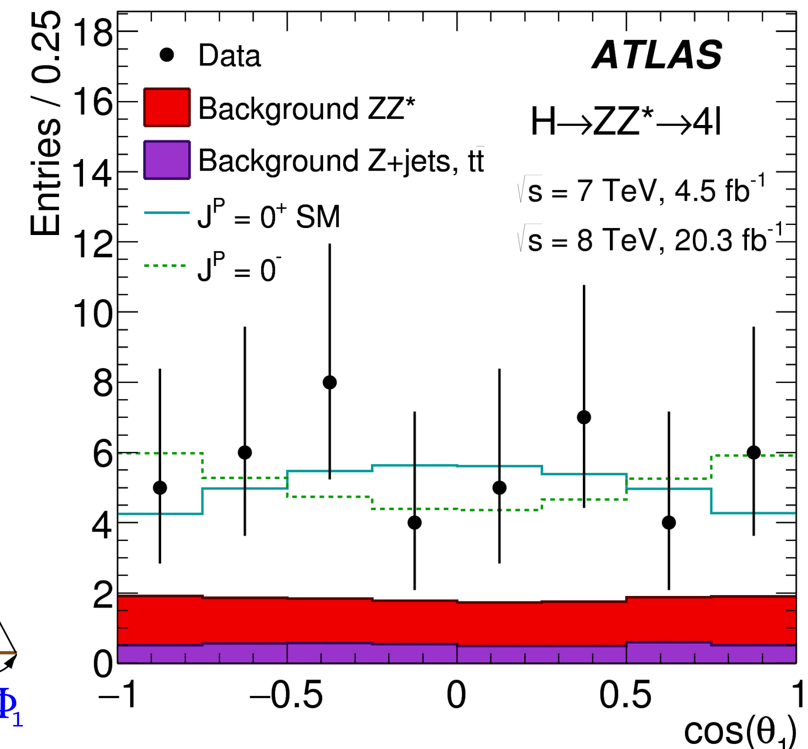
Backup

Spin/CP studies

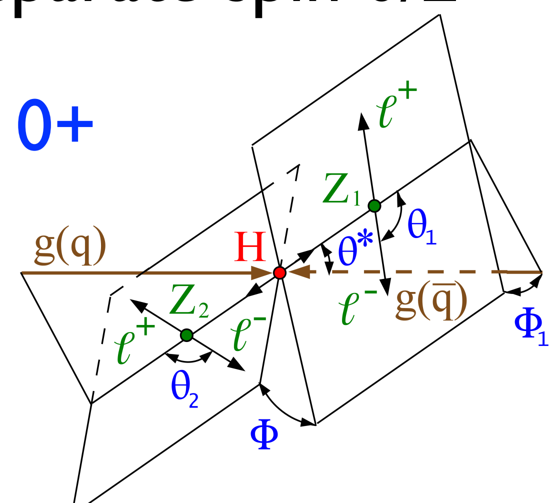
Studied mostly in di-boson events up to now
4 lepton final state provides rich set of information to discriminate between spin and parity hypothesis combined in multivariate analysis

Di-photon events can also help to separate spin 0/2

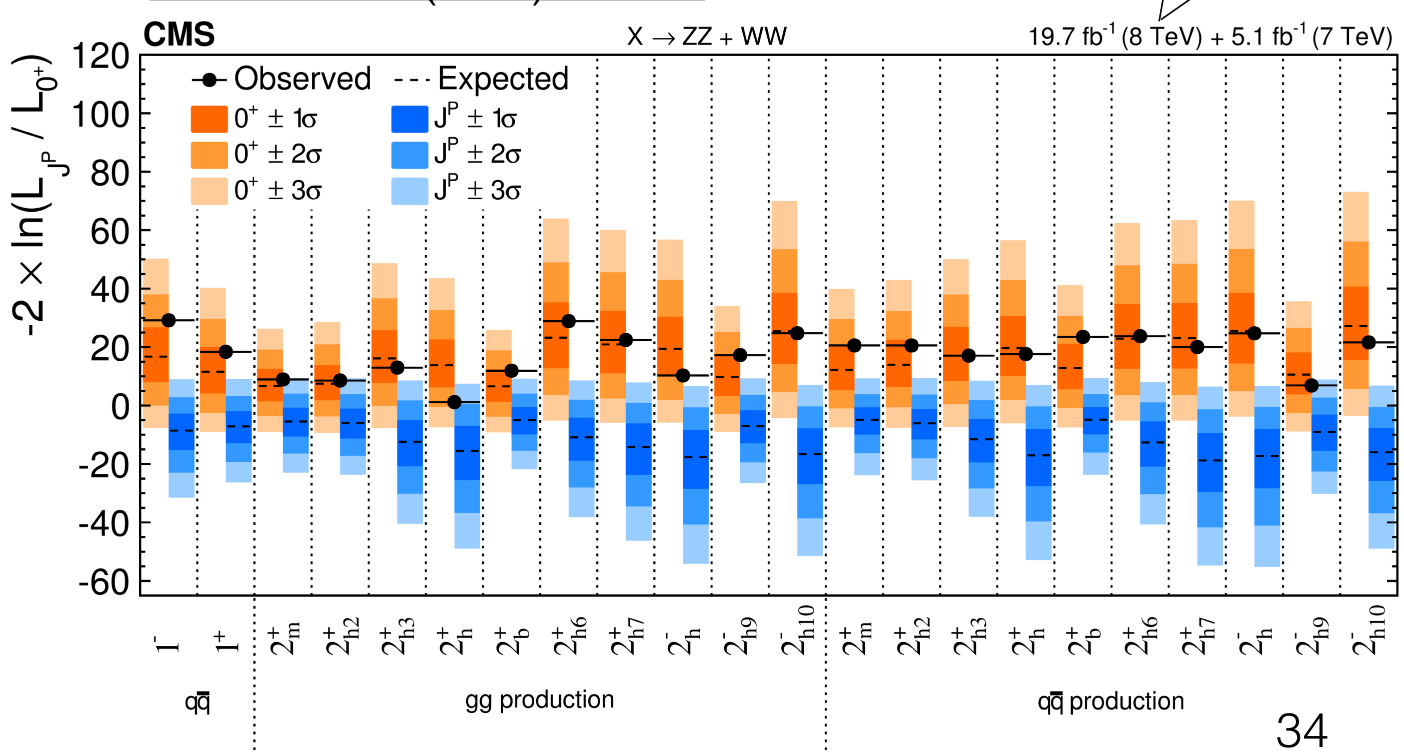
All pure alternatives tested against 0+ strongly rejected

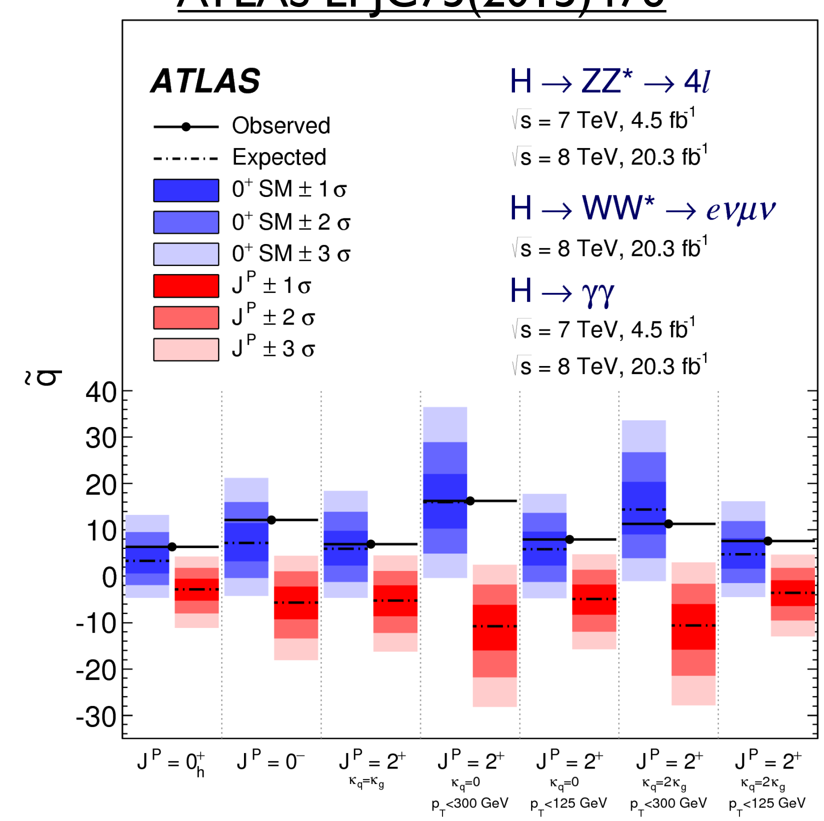


ATLAS EPJC75(2015)476



CMS PRD 92 (2015) 012004

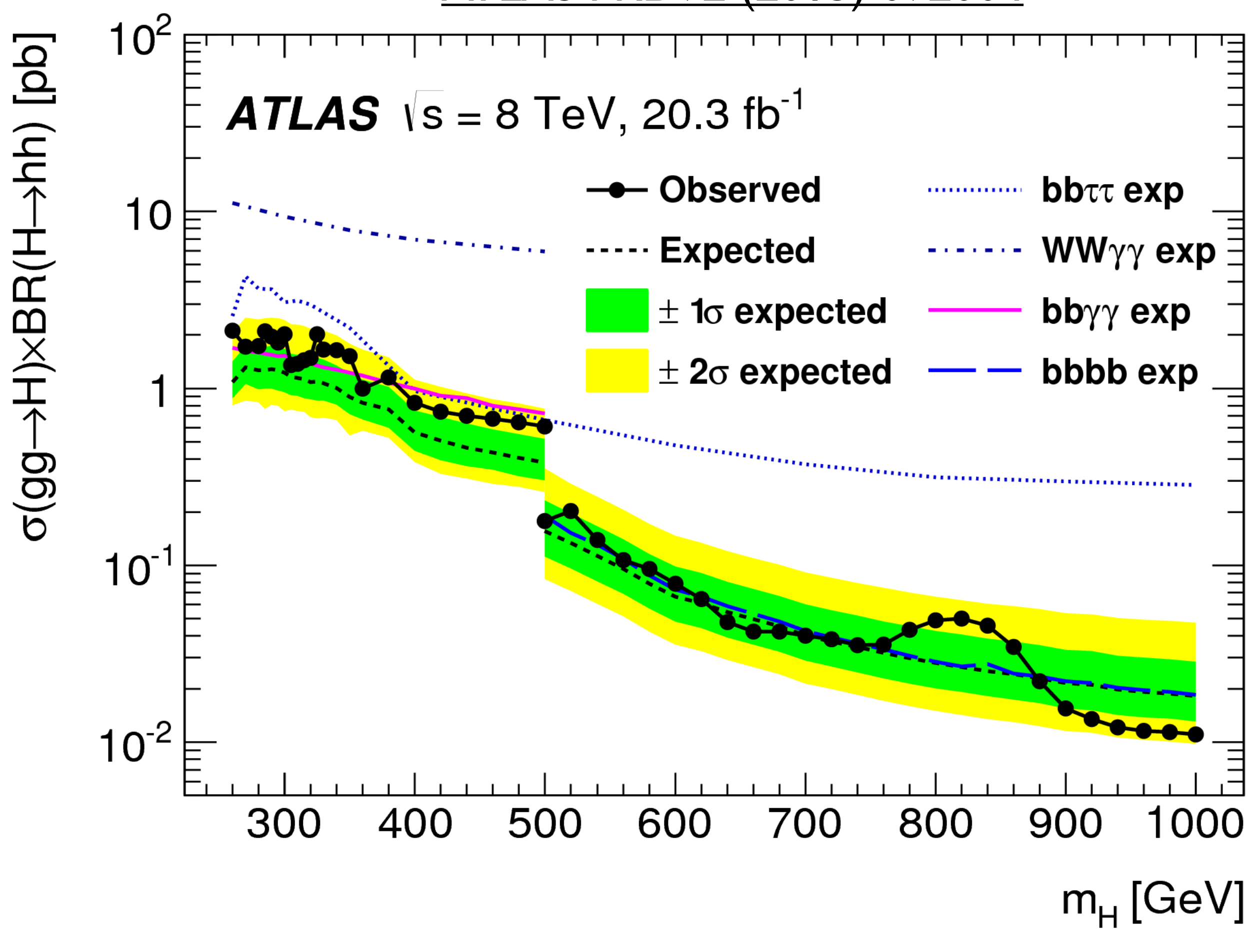




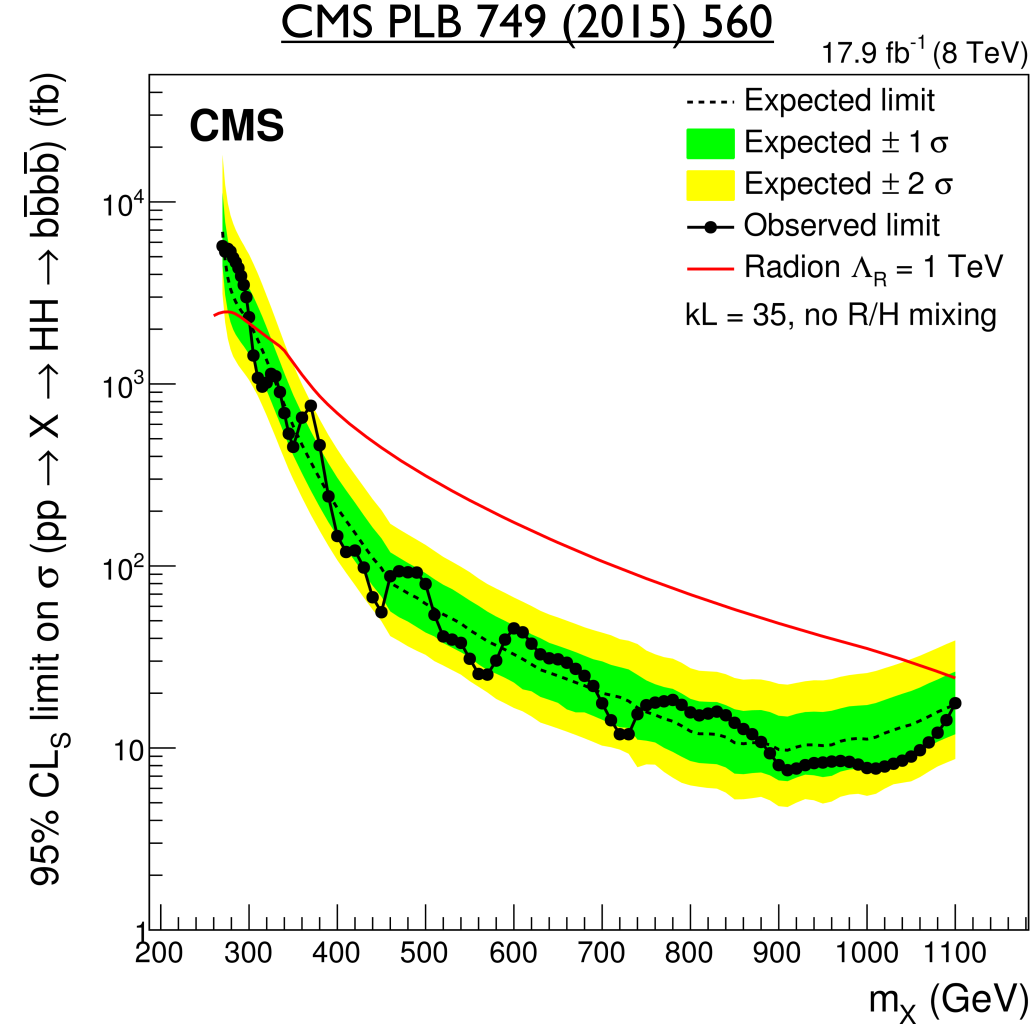
Direct searches for decays to h pairs

4b final state most sensitive at high mass
Use other h decays modes at lower mass
Sensitive to X=H in some MSSM space
Also compare to more exotic scenario for X
Also investigating hh continuum production but sensitivity still far beyond SM

ATLAS PRD92 (2015) 092004

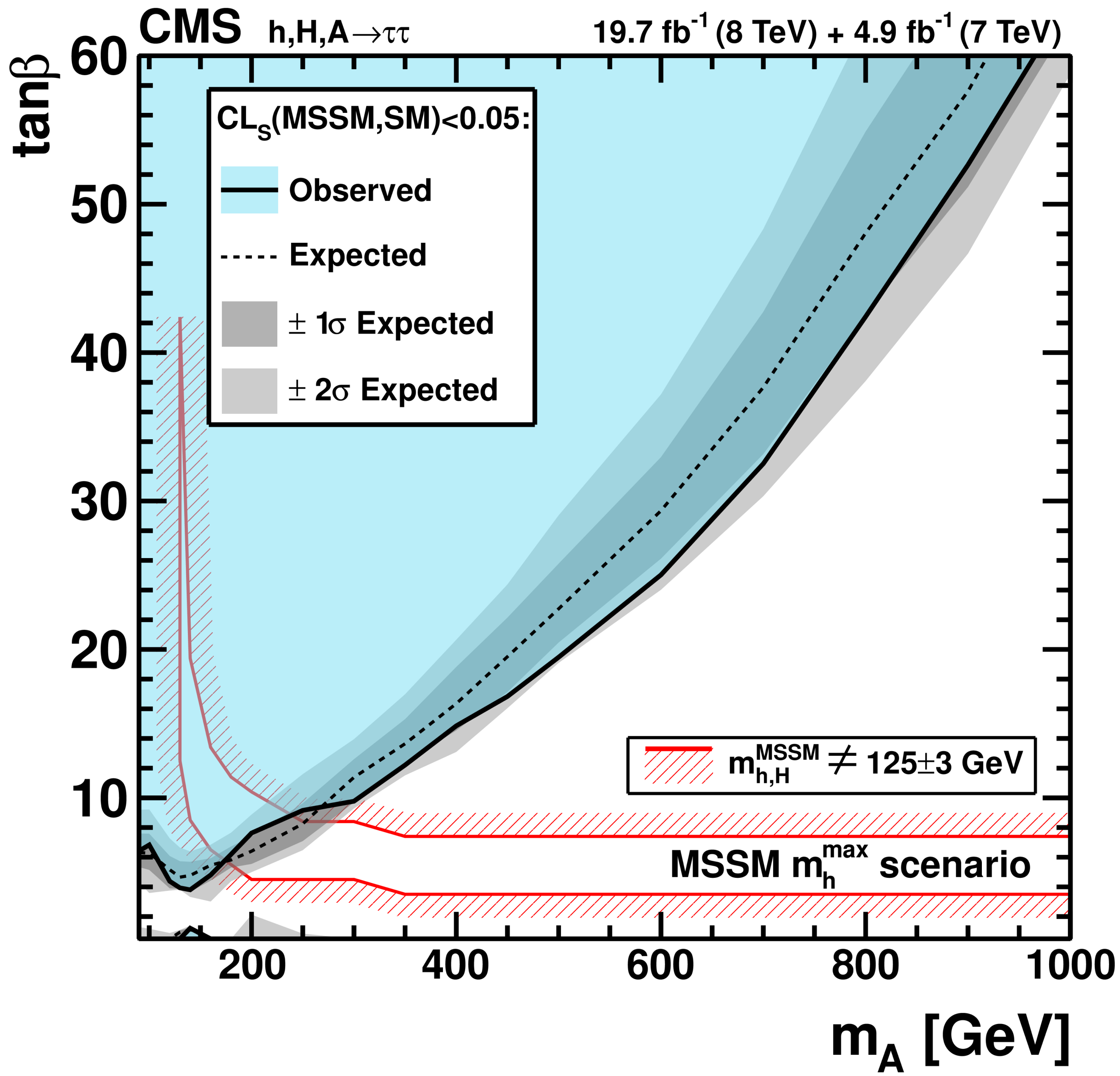


CMS PLB 749 (2015) 560

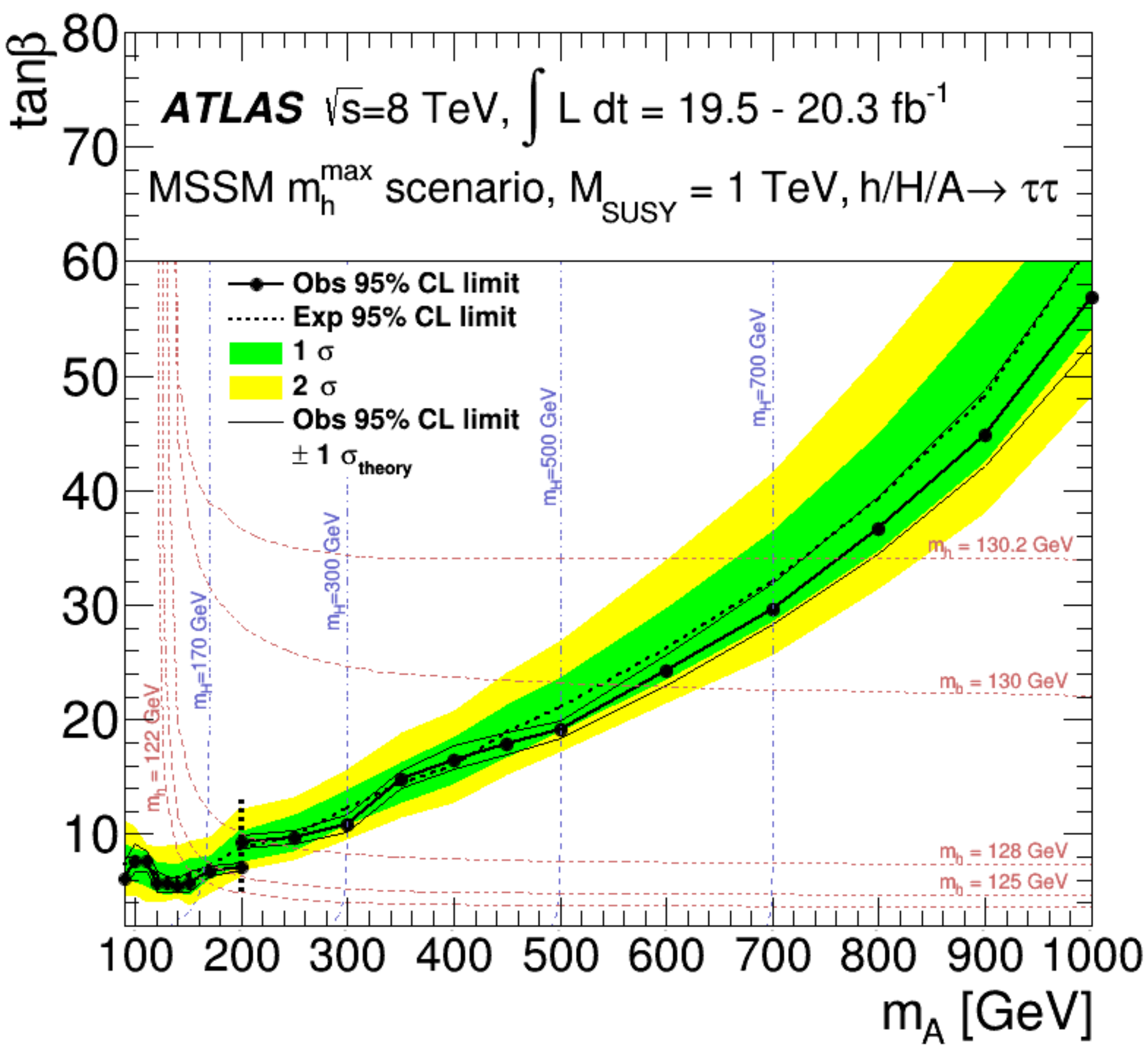


Searches for heavy H/A→ττ

CMS JHEP10 (2014) 160

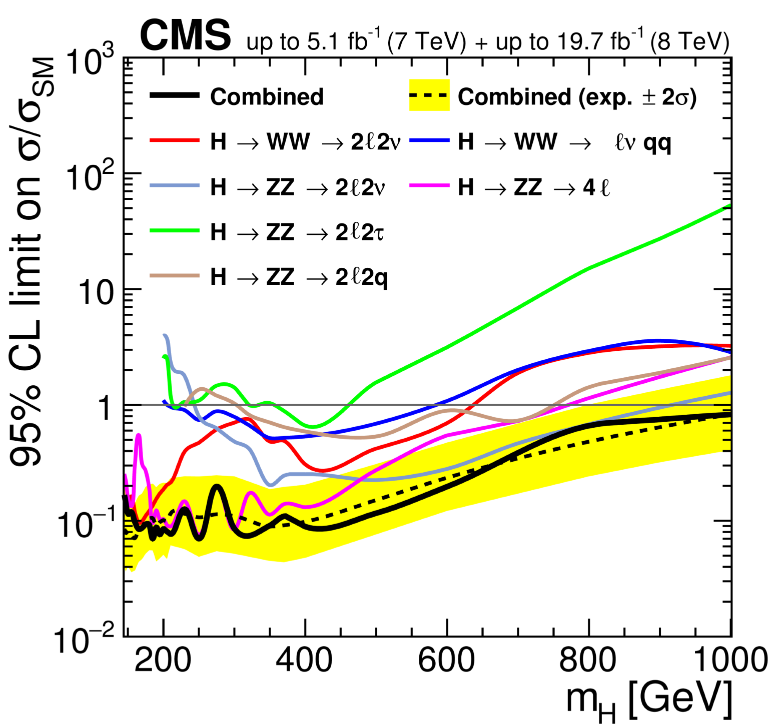


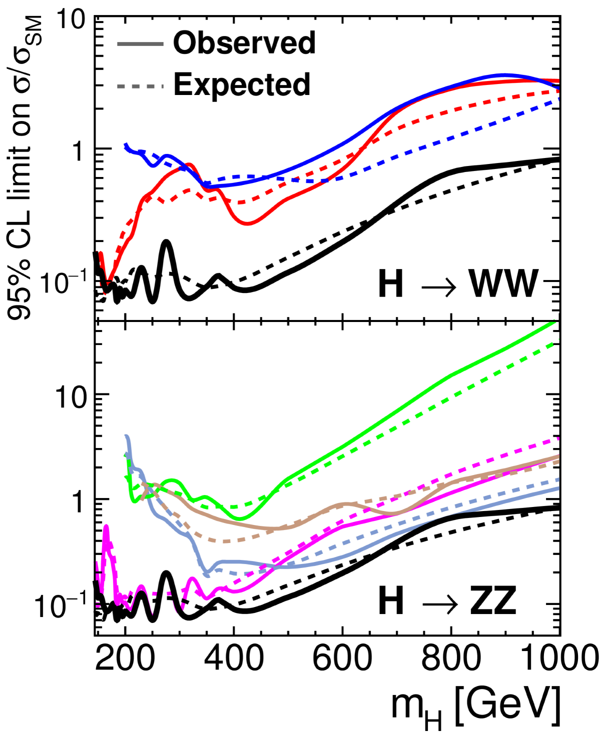
ATLAS JHEP 1411 (2014) 056



Searches for heavy H→WW/ZZ

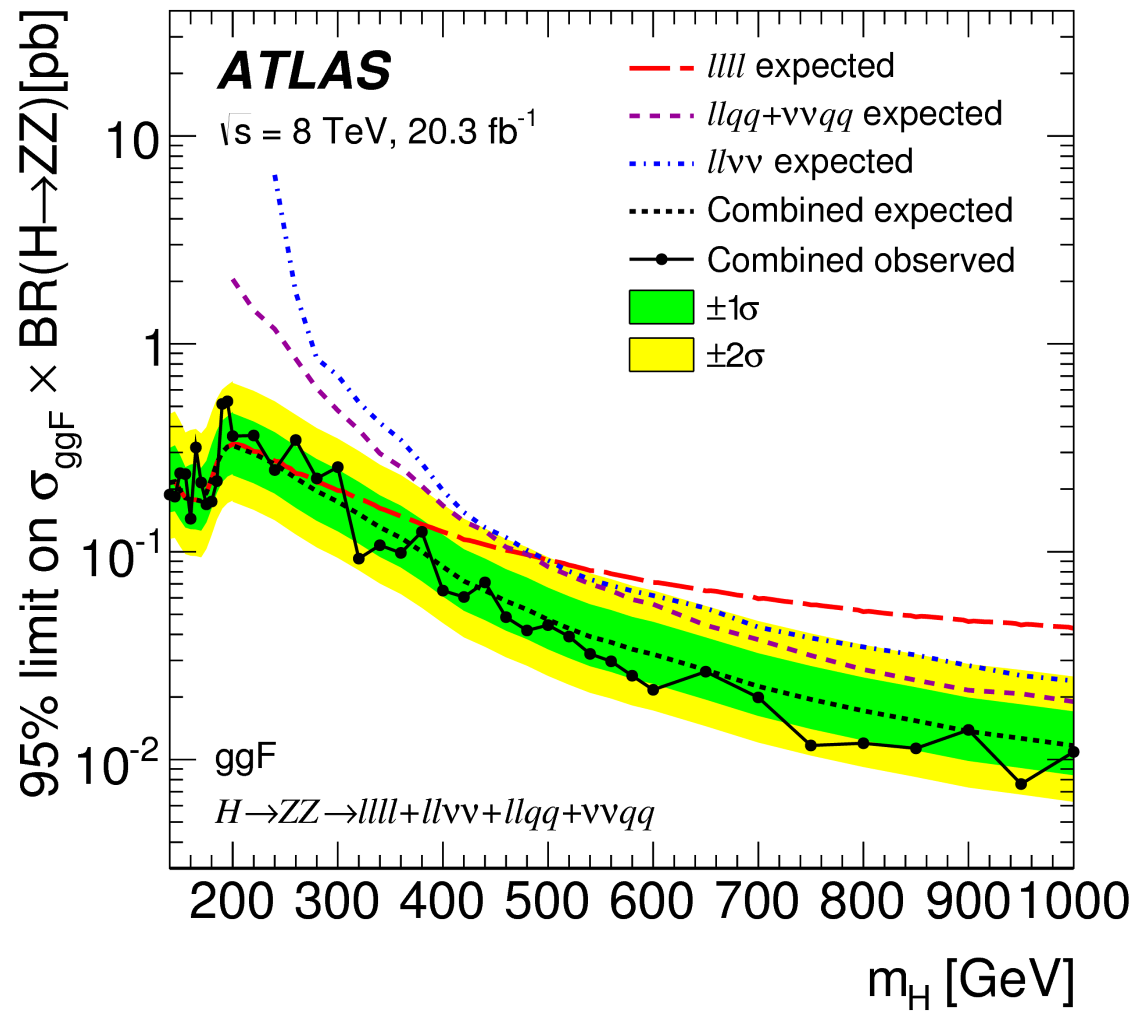
CMS JHEP 10 (2015) 144





ATLAS 1507.05930

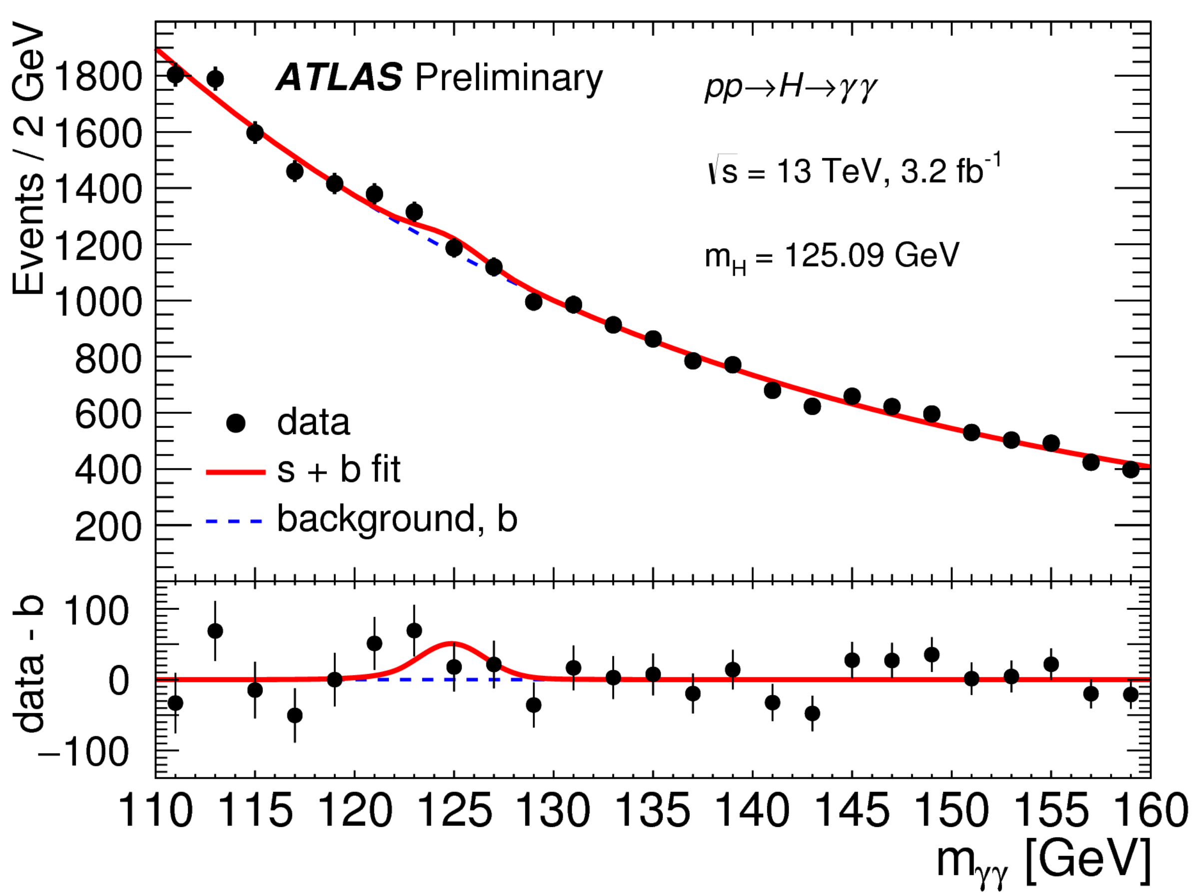
ATLAS 1509.00389



A first glimpse at 2015 data for H(125)

Mass distributions (ATLAS) in gamma-gamma and 4l in 3.2 fb-1 of 13 TeV data

ATLAS-CONF-2015-060



ATLAS-CONF-2015-059