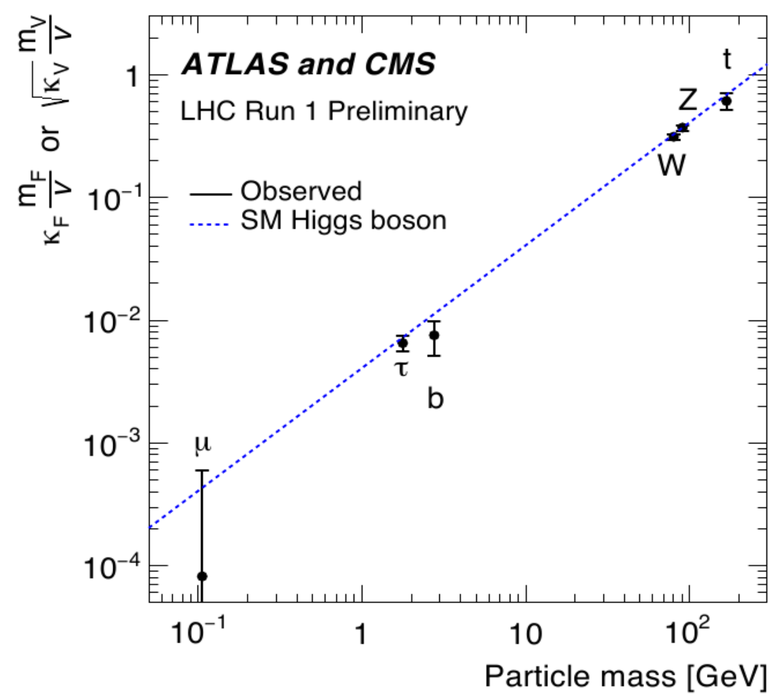
Higgs physics at the LHC: an experimental perspective

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\Psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$



Chris Hays,
Oxford University

Young experimentalist and theorist institute
13 January 2016

Overview

- Motivation
- SM Higgs boson measurements
  - Mass, width, spin, CP
  - Couplings to fermions and bosons
- BSM Higgs boson probes
  - EFT coefficients
  - Non-SM couplings
  - Additional Higgs bosons

Motivation

- The Higgs boson is the only fundamental scalar in the SM
  - Introduces ad-hoc terms in the Lagrangian
    - Not the result of an underlying symmetry in the SM

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\psi + h.c.$$

Fermion matter and gauge symmetry

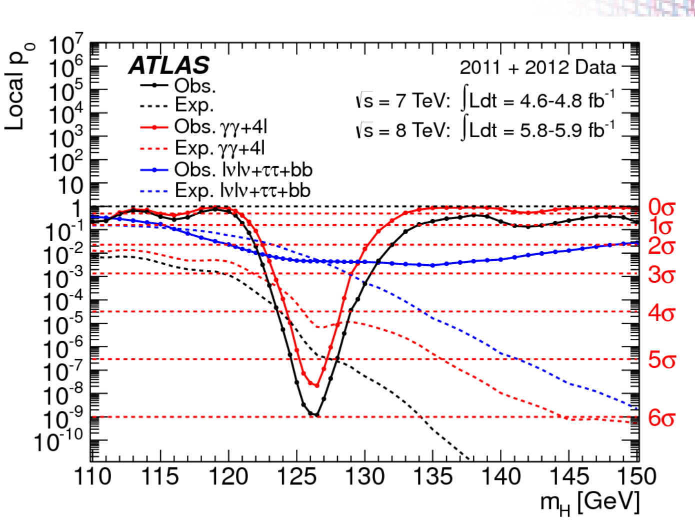
$$+ \bar{\Psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$

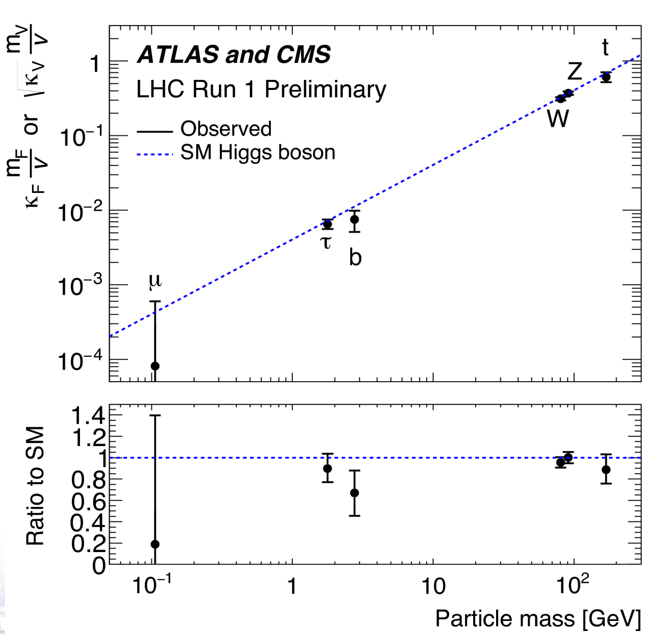
Destroys symmetry with non-zero scalar v.e.v.

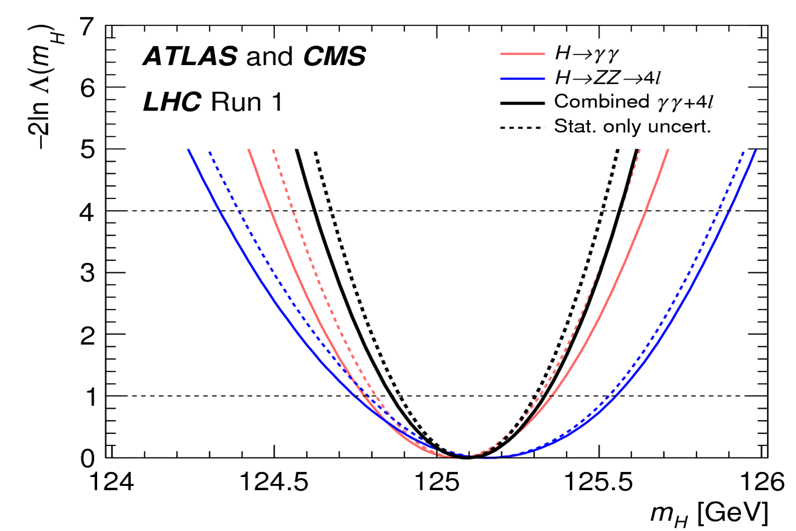
- Half the SM Lagrangian can now be studied directly!

SM Higgs boson measurements

- Steps in the SM Higgs boson measurement program
  - Discover
  - Measure mass, spin and CP
  - Measure width
  - Confirm mass-coupling correlation

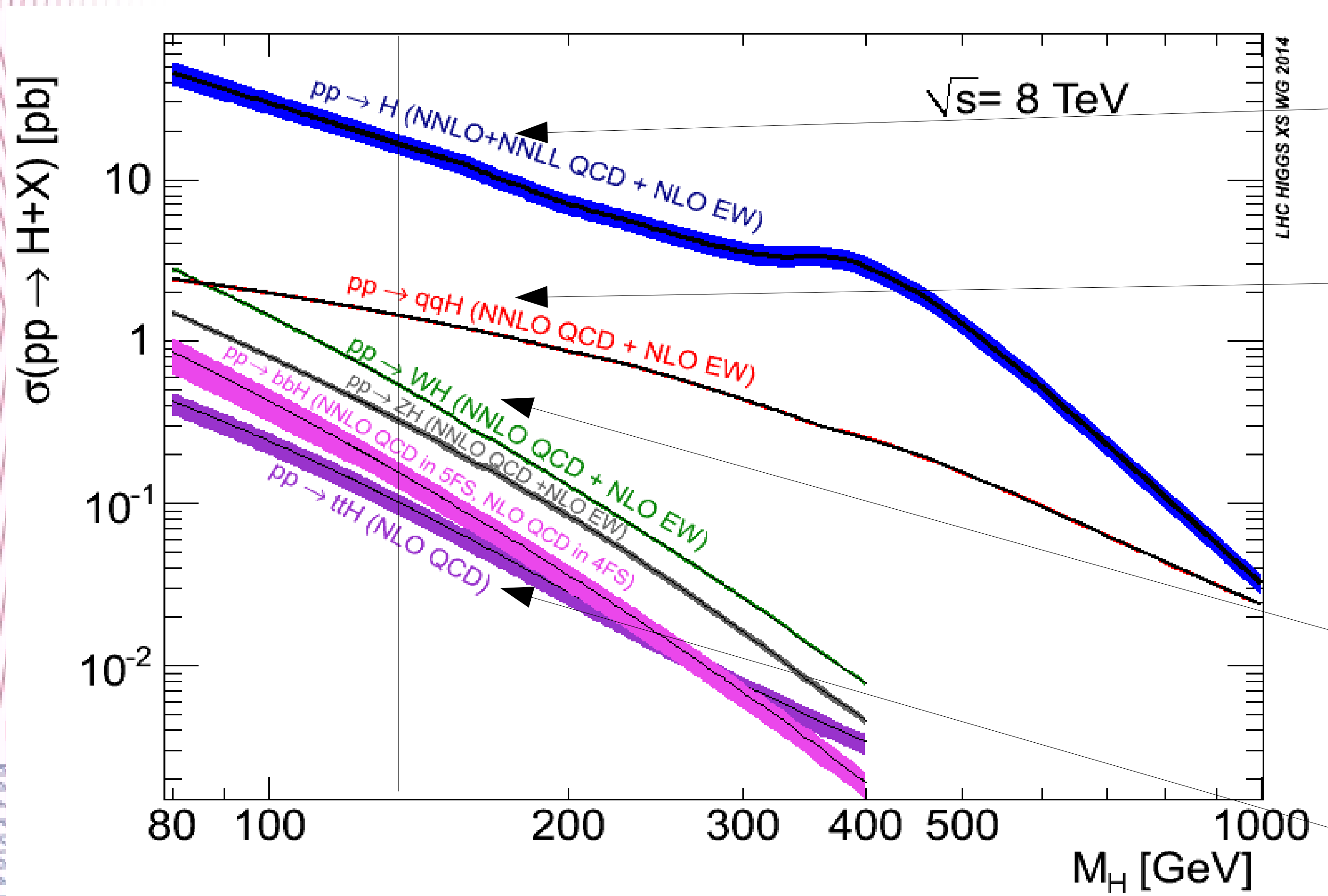


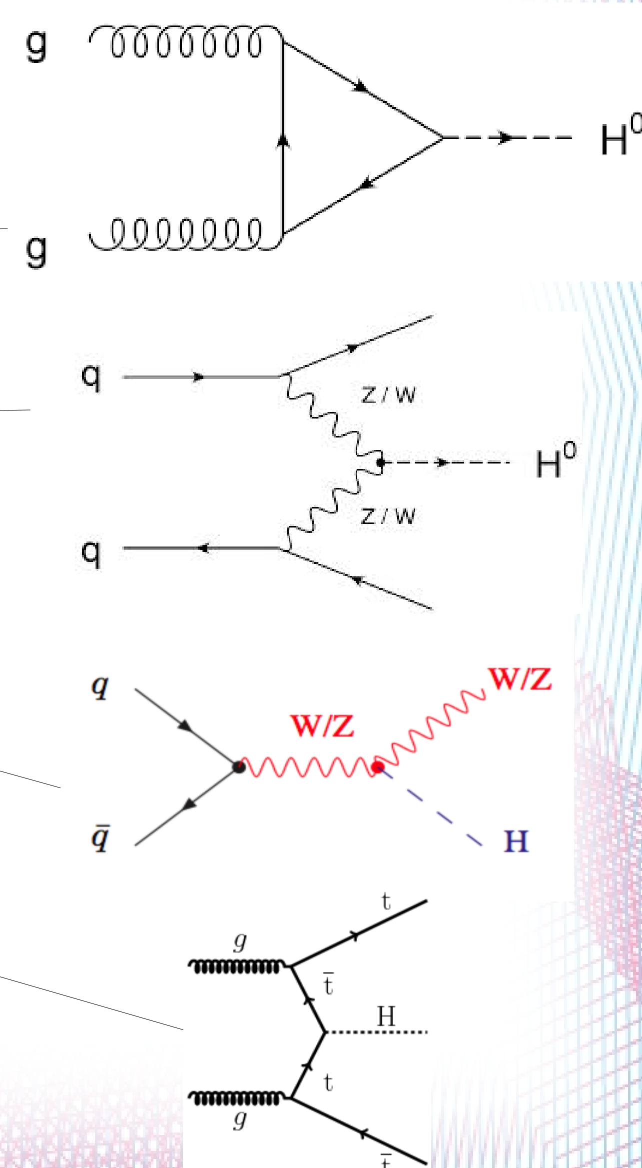




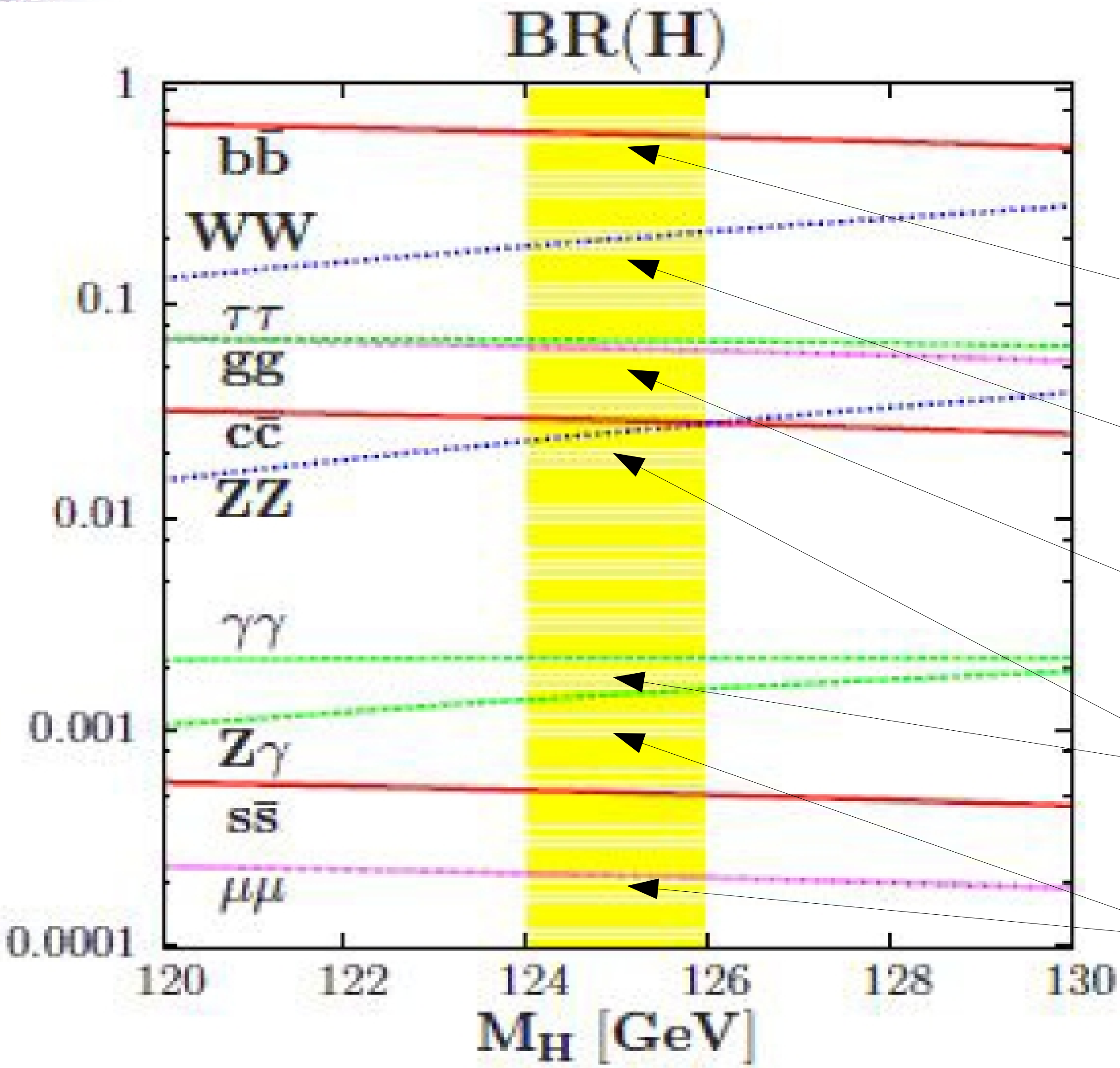
Higgs boson production

- Dominated by gluon fusion





Higgs boson decay



bb suffers from large QCD-induced background (e.g. g→bb)

Largest statistical precision from WW→lνlν

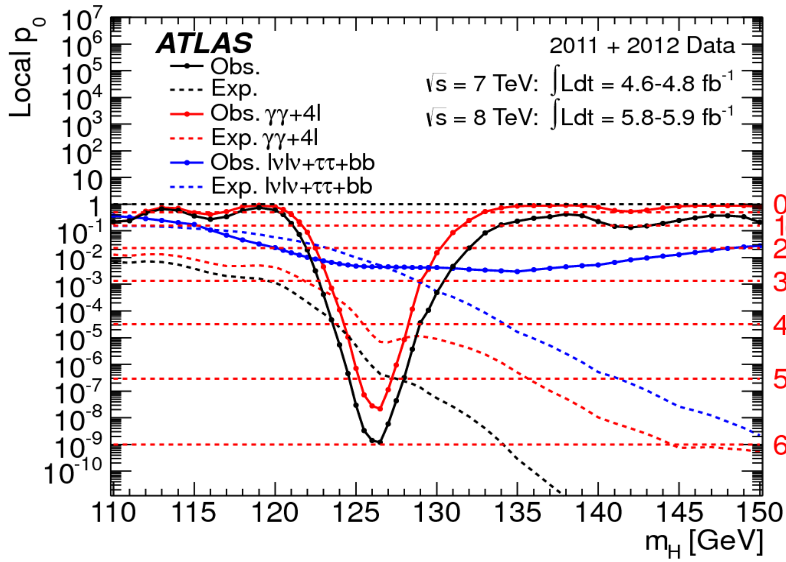
Approximate mass reconstruction possible in ττ

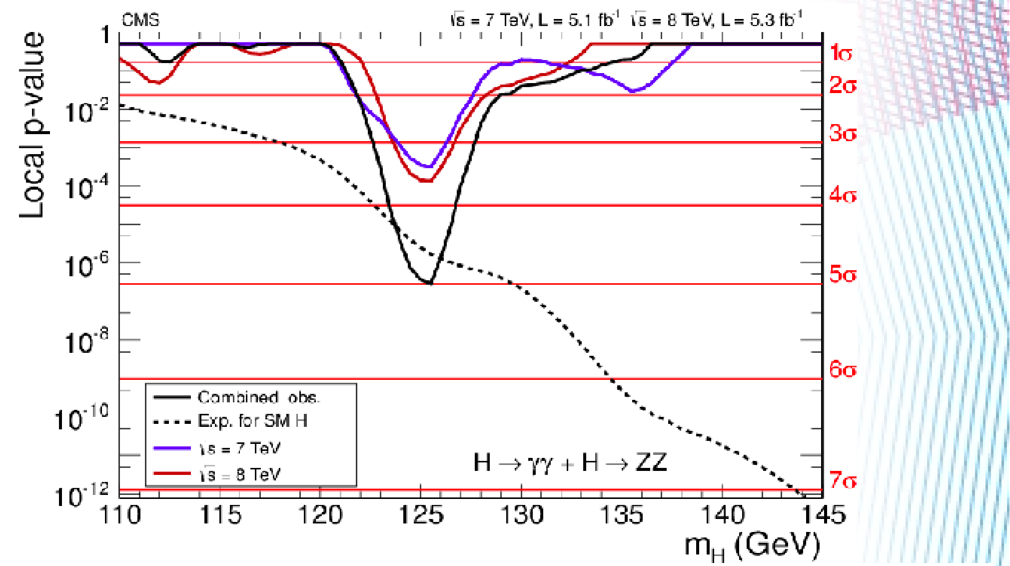
Fully reconstruct final state in ZZ→llll and γγ

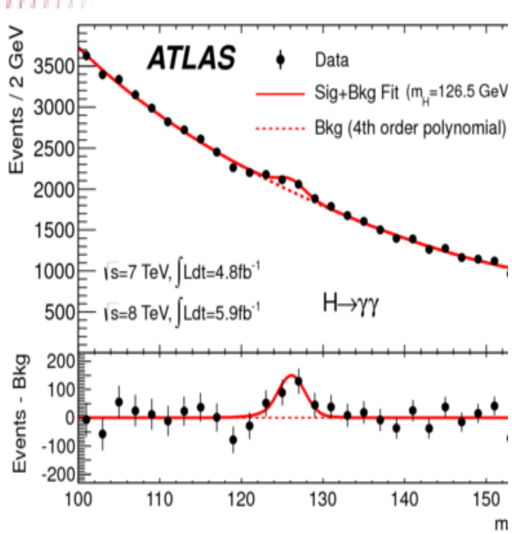
Rare decays to μμ, Zγ: need lots of data to observe

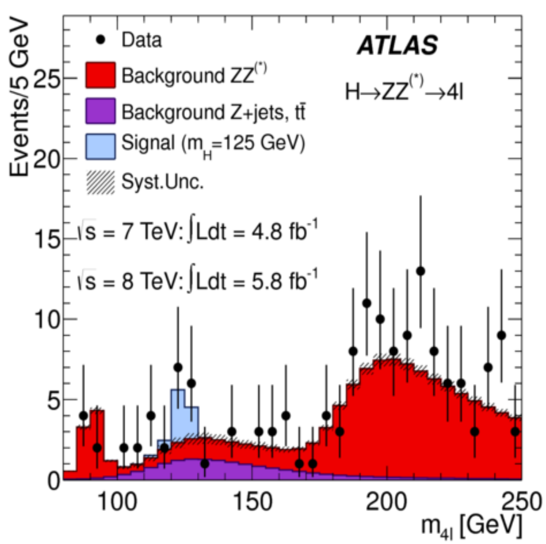
Higgs boson decays to ZZ→llll and γγ

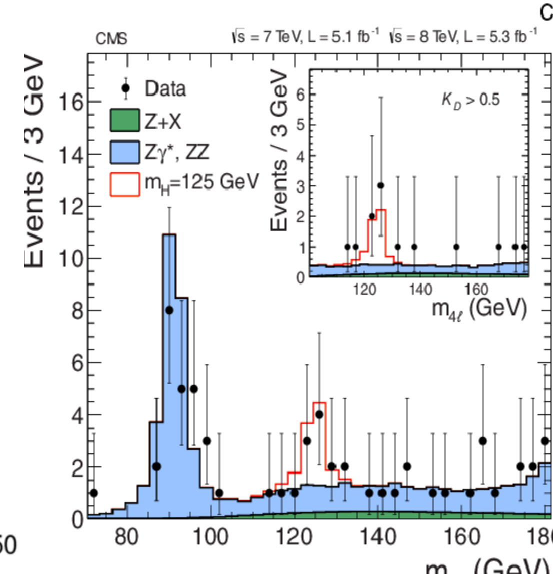
- Key contributors to discovery

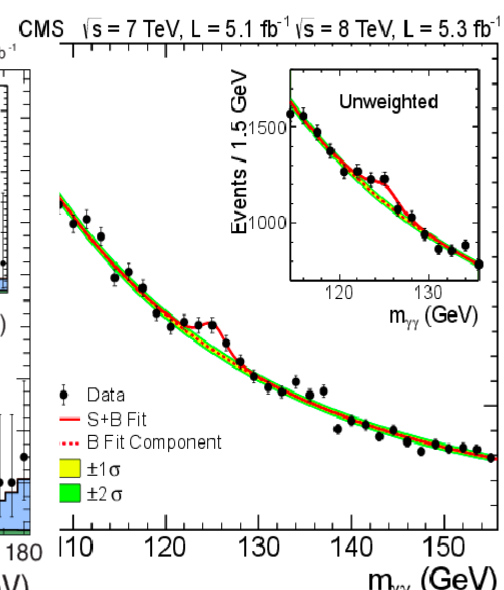








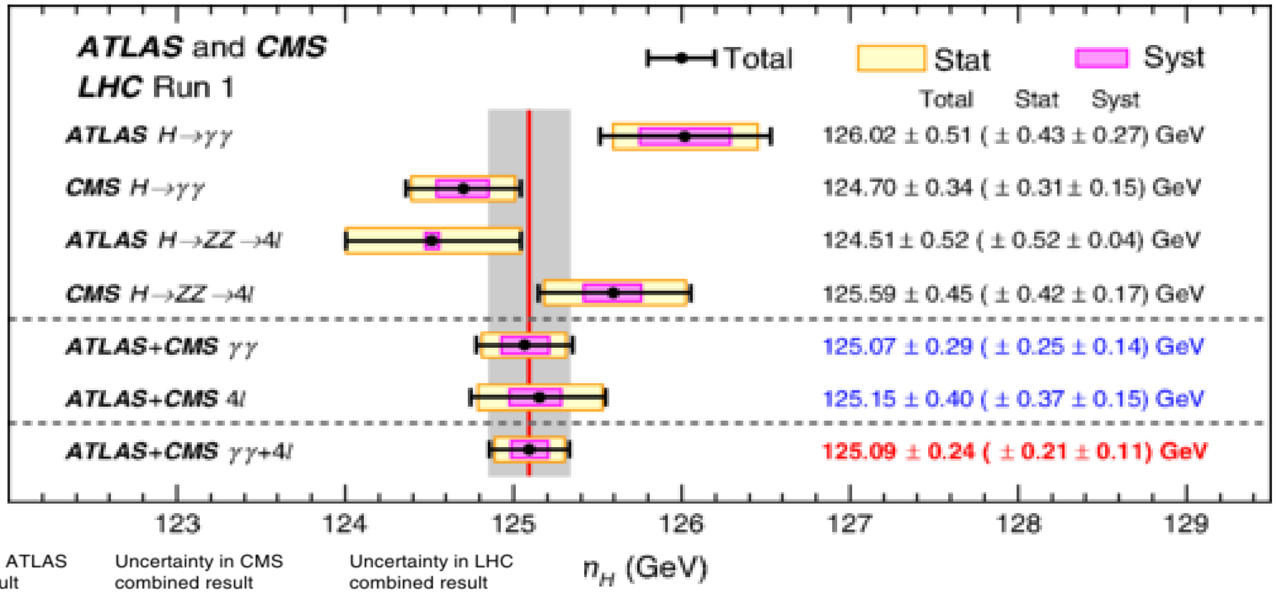




Higgs boson mass

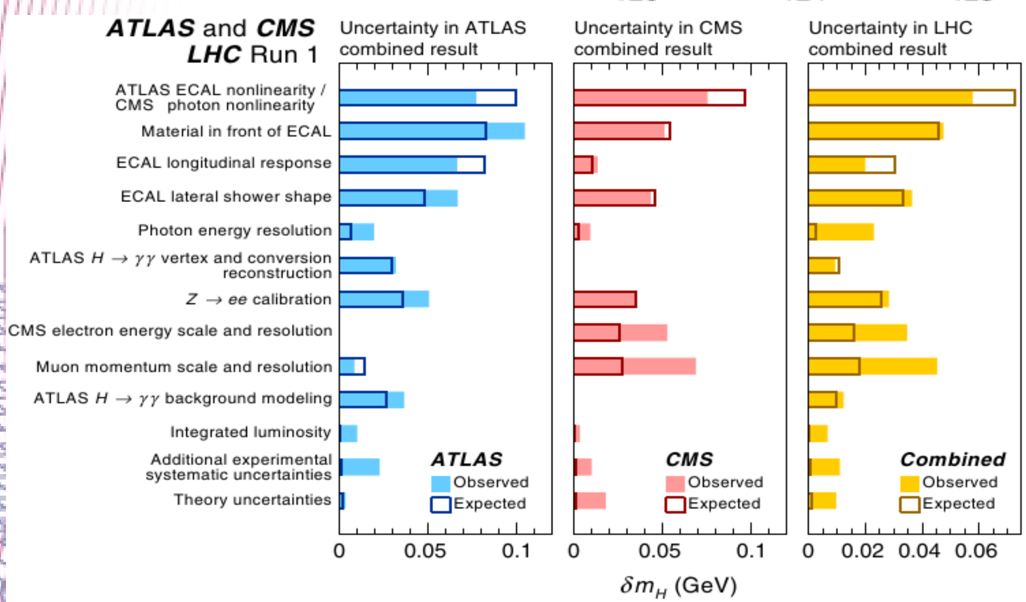
- Fully reconstructed final states allow precise mass measurement

(Mass an important parameter in supersymmetry)



PRL 114, 191803

Accuracy to 2 parts in 1000



Statistical uncertainty dominates; leading systematic uncertainty is photon energy calibration

Run 2 should reduce uncertainty by a factor of two

Will need some improvement in γ calibration

Higgs boson width

- Direct width measurements limited by experimental resolution

(Width sensitive to non-SM decays)

Channel	ATLAS	CMS
$H \rightarrow ZZ$	$\Gamma < 2.6$ GeV	$\Gamma < 3.4$ GeV
$H \rightarrow \gamma\gamma$	$\Gamma < 5.0$ GeV	$\Gamma < 2.4$ GeV

Standard Model prediction $\Gamma \sim 4$ MeV

Run 2 combined direct limit could achieve $\Gamma < 1$ GeV

Interference between Higgs production and background shifts the mass in the $\gamma\gamma$ channel
Shift is dependent on the width of the Higgs boson: SM predicts ~60 MeV shift

Difference in masses between $\gamma\gamma$ and ZZ channels sensitive to Higgs width

ATLAS+CMS combination: $m_{\gamma\gamma} - m_{ZZ} = -0.1 \pm 0.5$ GeV

Run 2 combined mass difference could have precision of ~200 MeV

Could translate into $\Gamma < 15$ MeV? Sensitive to higher order corrections

Higgs boson width

- Off-shell production indirectly sensitive to width

$$|\mathcal{M}_{i\to H\to f}|^2 = \frac{|\mathcal{M}_i|^2\,|\mathcal{M}_f|^2}{|p_H^2 - M_H^2 + iM_H\Gamma_H|^2}$$

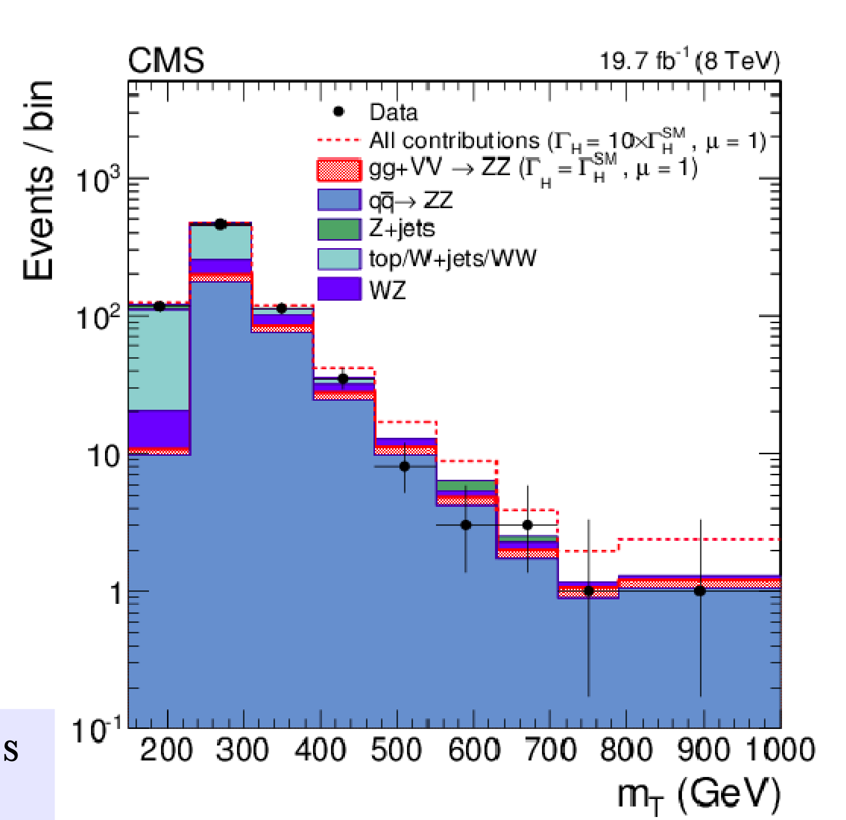
Most cross section is in the region $(p_H^{\ 2} - M_H^{\ 2}) \sim M_H\Gamma_H$: cross section inversely proportional to Γ_H

For $p_H^{\ 2} \gg M_H^{\ 2}$ cross section independent of Γ_H

CMS (ZZ) and ATLAS (ZZ & WW) set limits of $\Gamma < 22$ MeV

Model dependent:
new particles affecting the width could also affect
the high-p^2 measurement

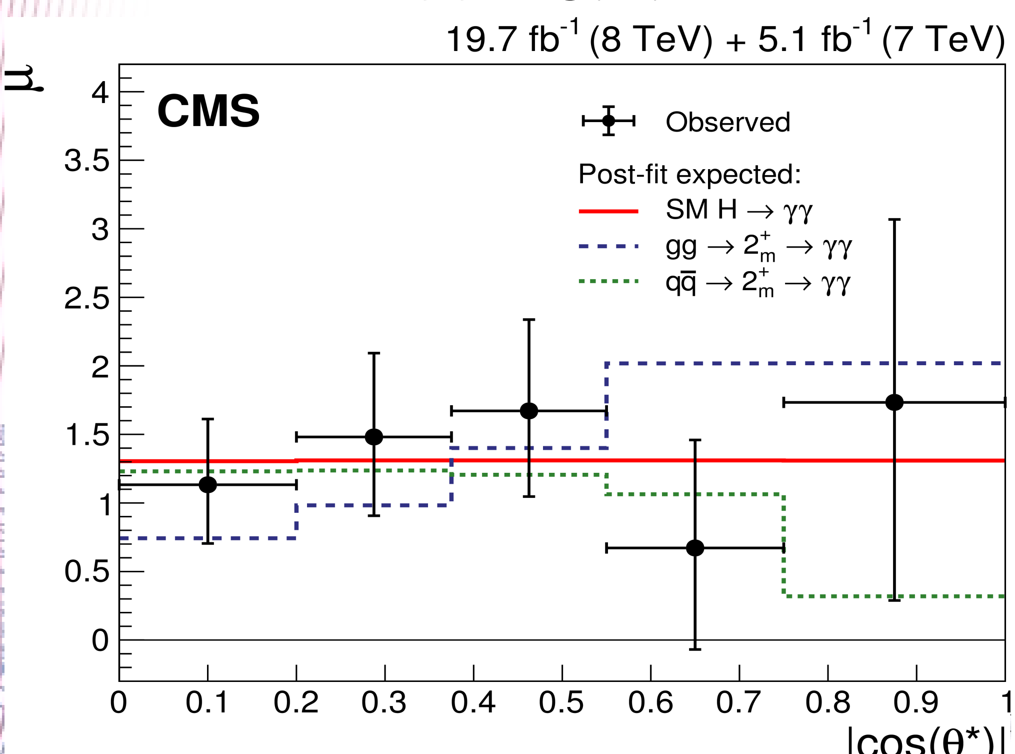
VBF production less model-dependent:
Expect first results in this channel in Run 2

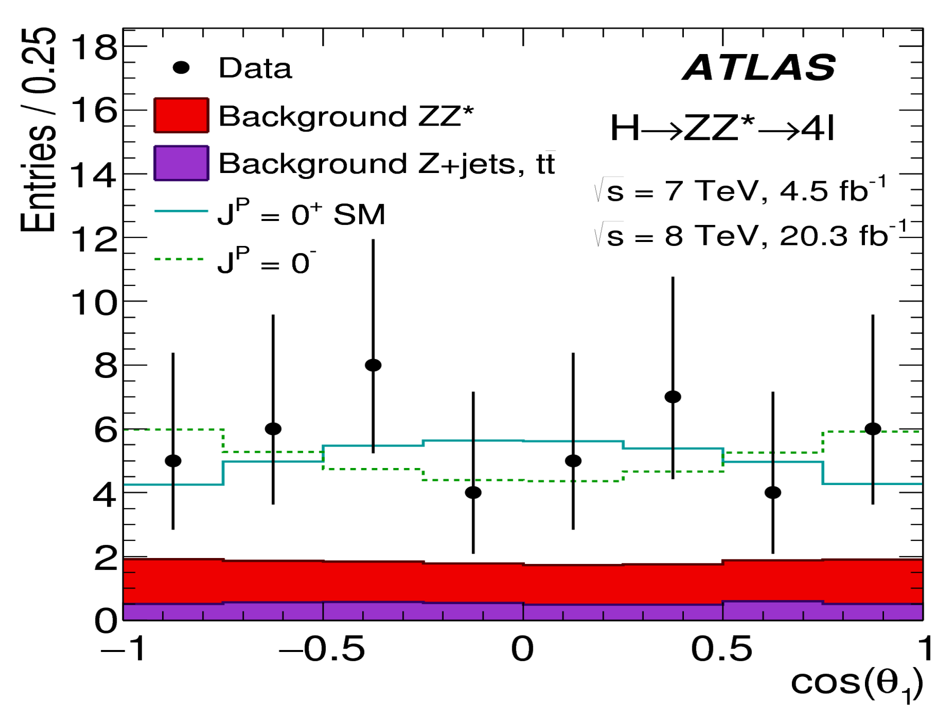


CMS also sets a lower bound by looking for displaced vertices
$\Gamma > 3.5 \times 10^{-9}$ MeV

Higgs boson spin and CP

- Must be a scalar to be called a Higgs boson
  - Study angular distributions of ZZ, γγ, and WW decays
    - Use multivariate analysis in each channel
  - Spin-0 CP-even state preferred to spin-2 or CP-odd state at ~99% C.L.





SM Higgs boson measurements

- Steps in the SM Higgs boson measurement program
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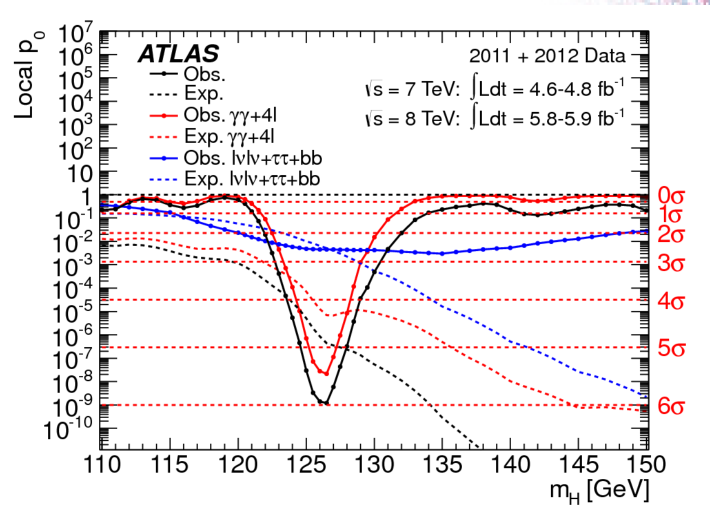
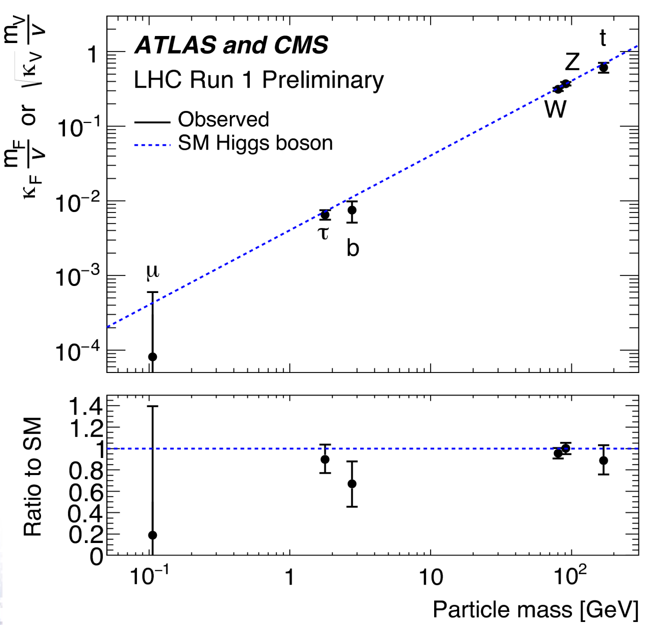
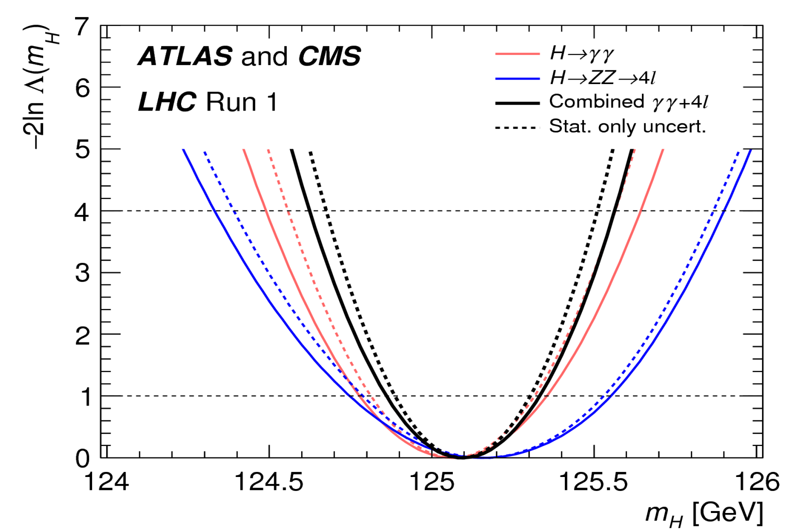
  - Confirm mass-coupling correlation







Higgs boson production

- Run 1 coupling results use "kappa" framework
  - Multiplicative factors for Higgs terms in the Lagrangian

For a given production process or decay channel:

$$\kappa_j^2 = \sigma_j / \sigma_j^{\mathrm{SM}} \qquad \kappa_j^2 = \Gamma^j / \Gamma^j_{\mathrm{SM}}$$

Connect to measurements via "μ" factors (notation: i→H→f)

$$\mu_i = \frac{\sigma_i}{(\sigma_i)_{\mathrm{SM}}} \quad \text{and} \quad \mu^f = \frac{\mathrm{BR}^f}{(\mathrm{BR}^f)_{\mathrm{SM}}}.$$

$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

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}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $\mathrm{BR}_{\mathrm{BSM}} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

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

Higgs boson coupling to EW bosons

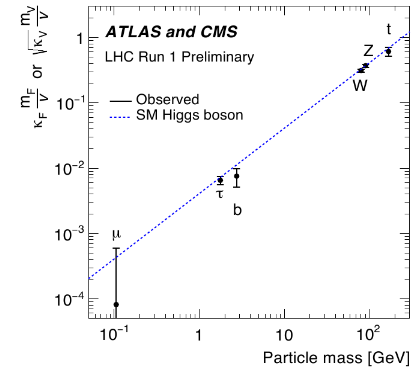
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \psi + h.c.$$

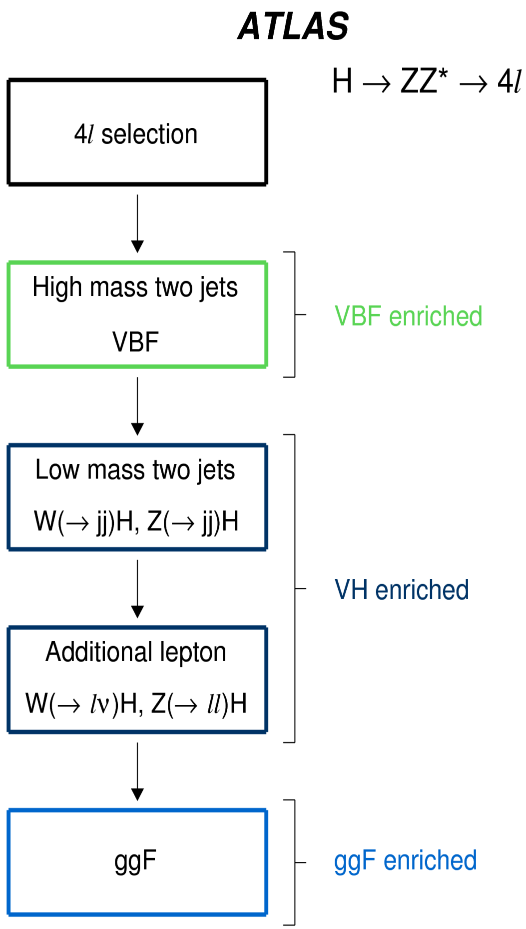
$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$

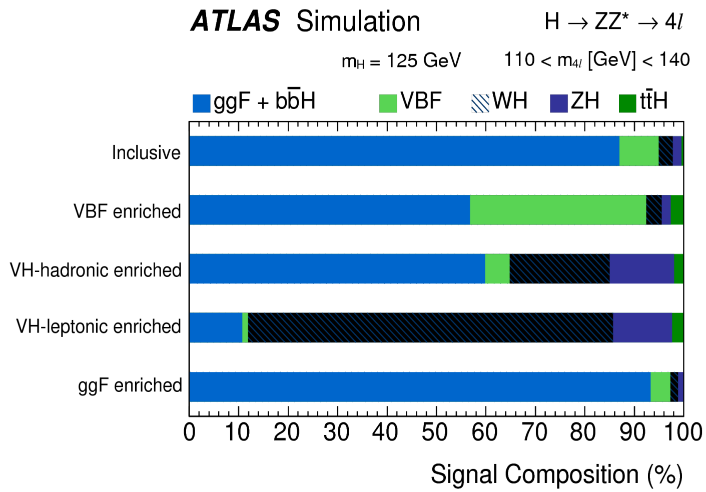
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs boson decay to ZZ



- Uncertainty statistics dominated
  - Loosely split by production mode





ATLAS

$$\mu_{ggF+b\bar{b}H+t\bar{t}H} \times B/B_{SM} = 1.66\,^{+0.45}_{-0.41}(\text{stat})\,^{+0.25}_{-0.15}(\text{syst})$$

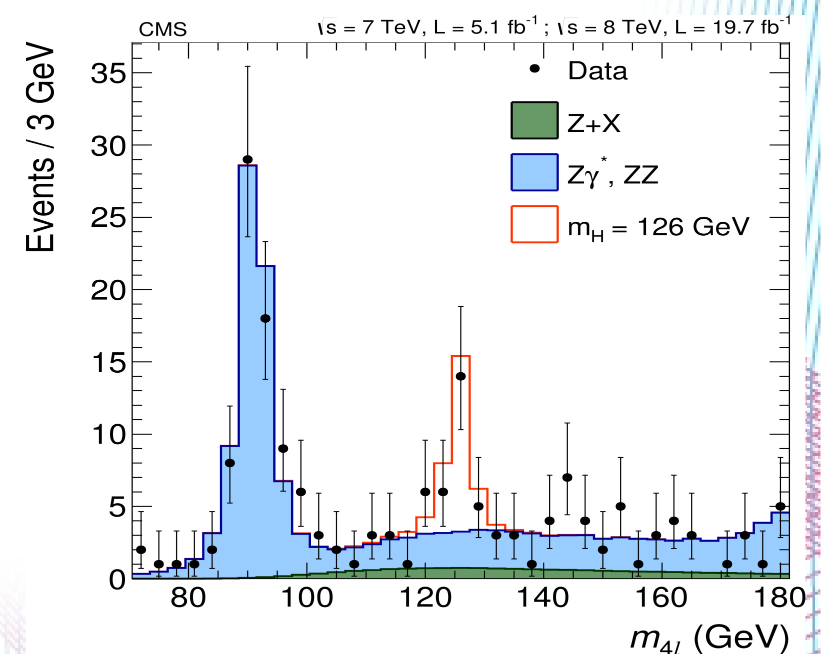
$$\mu_{VBF+VH} \times B/B_{SM} = 0.26\,^{+1.60}_{-0.91}(\text{stat})\,^{+0.36}_{-0.23}(\text{syst})$$

CMS

$$\mu_{ggH,t\bar{t}H} = 0.80^{+0.46}_{-0.36}$$

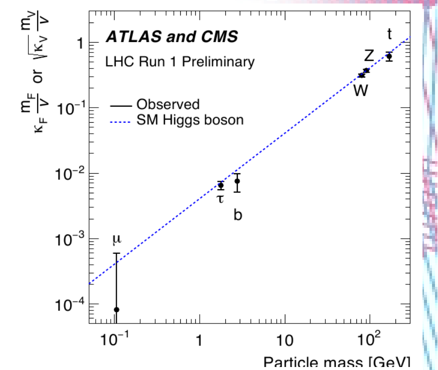
$$\mu_{VBF,VH} = 1.7^{+2.2}_{-2.1}$$

Reconstruction of Z→4l
an important validation



Expect ~20% uncertainty in Run 2

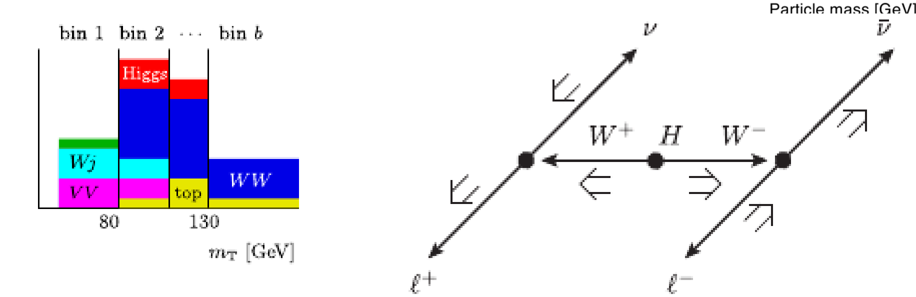
Higgs boson decay to WW

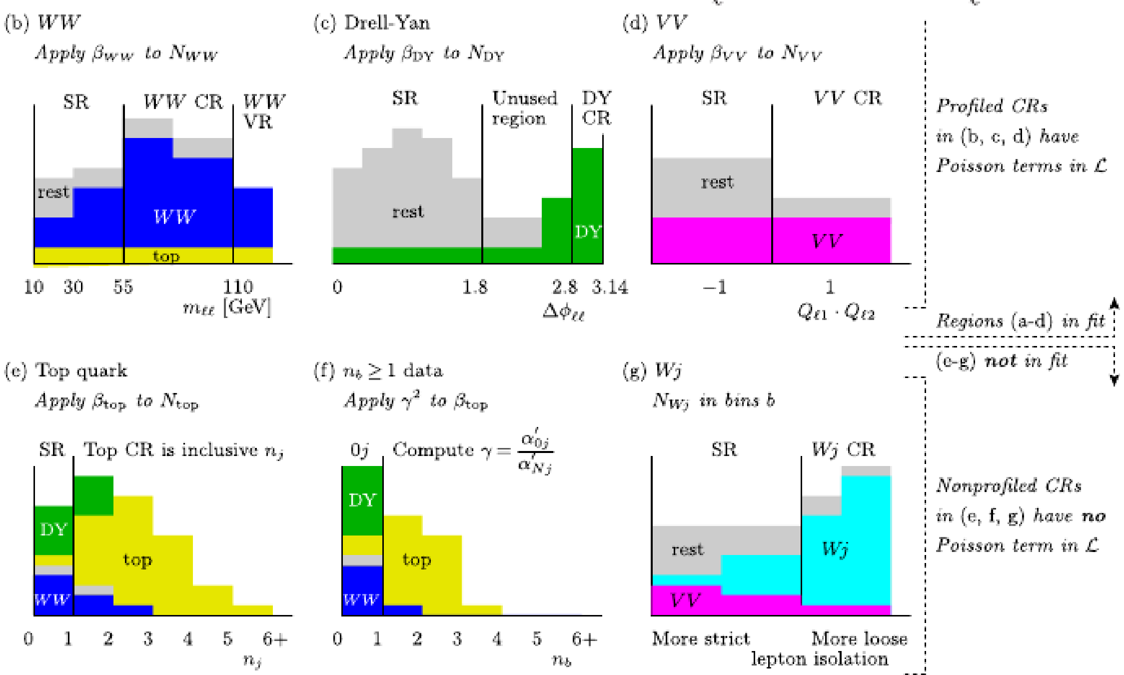


- Most complicated of the measured channels
  - Constrain cocktail of backgrounds with data

Name	Process	Feature(s)
WW	WW	Irreducible
Top quarks		
$t\bar{t}$	$t\bar{t} \to WbW\bar{b}$	Unidentified b-quarks
t	tW	Unidentified b-quark
	$t\bar{b}, tq\bar{b}$	q or b misidentified as ℓ; unidentified b-quarks
Misidentified leptons (Misid)		
Wj	W + jet(s)	j misidentified as ℓ
jj	Multijet production	jj misidentified as $\ell\ell$; misidentified neutrinos
Other dibosons		
VV	$W\gamma$	γ misidentified as e
	$W\gamma^*$, WZ, $ZZ \to \ell\ell\ell\ell$	Unidentified lepton(s)
	$ZZ \to \ell\ell\nu\nu$	Irreducible
	$Z\gamma$	γ misidentified as e; unidentified lepton
Drell-Yan (DY)		
$ee/\mu\mu$	$Z/\gamma^* \to ee, \mu\mu$	Misidentified neutrinos
$\tau\tau$	$Z/\gamma^* \to \tau\tau \to \ell\nu\nu\ell\nu\nu$	Irreducible

PRD 92, 012006





Higgs boson decay to WW

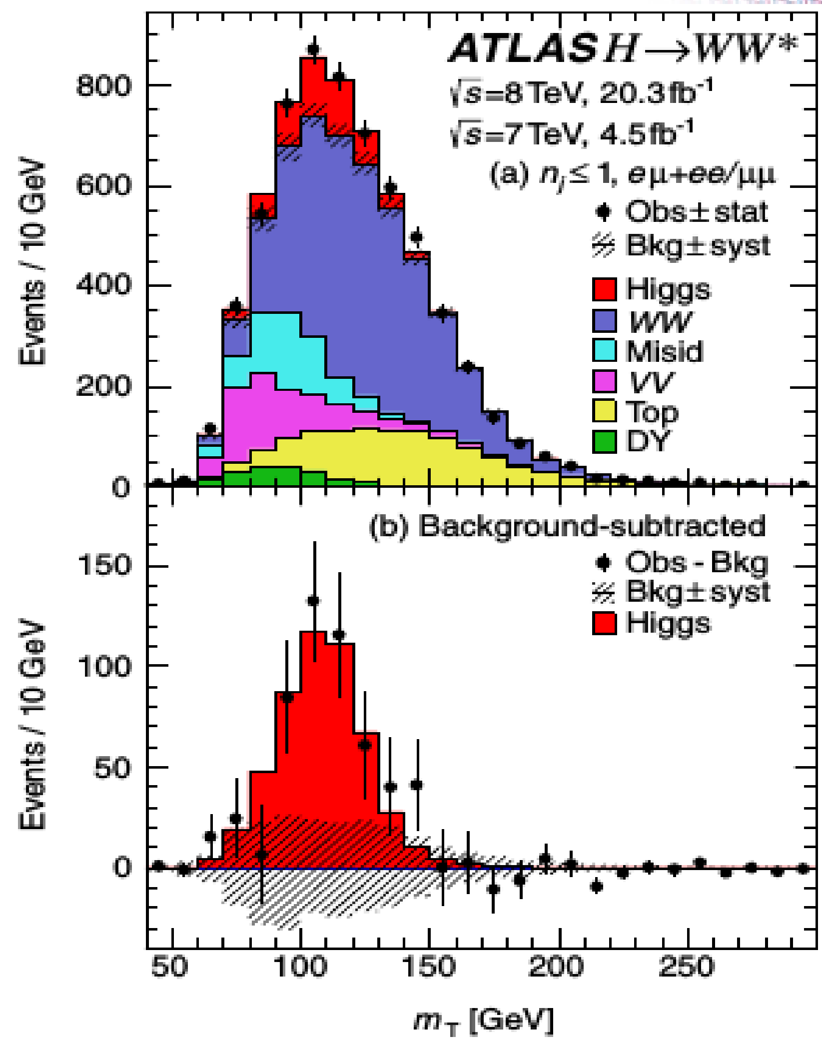
- Fit mass-based discriminant in multiple measurement bins

$$m_T = \sqrt{(E_T^{\ell\ell} + p_T^{\nu\nu})^2 - |\mathbf{p}_T^{\ell\ell} + \mathbf{p}_T^{\nu\nu}|^2}$$

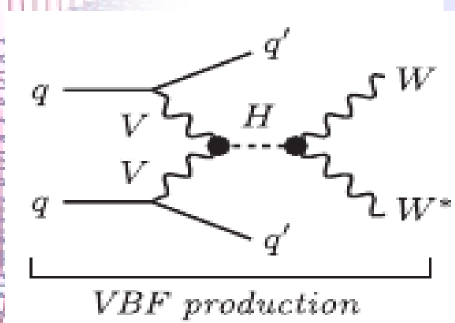
ATLAS gg→H→WW measurement has smallest relative production uncertainty in any single channel (27%)

Expect <20% ggF uncertainty in Run 2

$$\mu_{ggF} = 1.02 \pm 0.19 \ {}^{+0.22}_{-0.18} = 1.02 \ {}^{+0.29}_{-0.26}$$
$$\mu_{VBF} = 1.27 \ {}^{+0.44}_{-0.40} \ {}^{+0.30}_{-0.21} = 1.27 \ {}^{+0.53}_{-0.45}$$
$$\text{(stat)} \quad \text{(syst)}$$



Measurement of vector-boson fusion optimizes selection and discriminant using the radiating jets

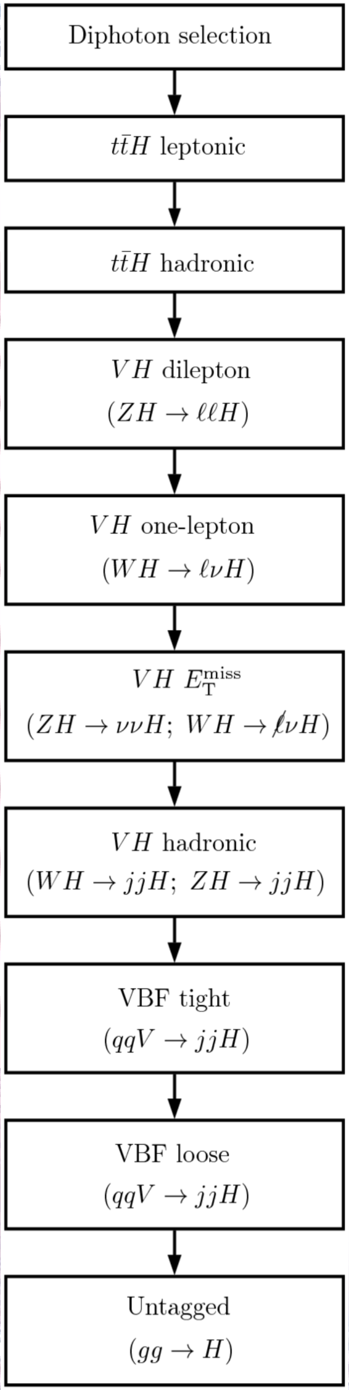


Uncertainty statistics-dominated:

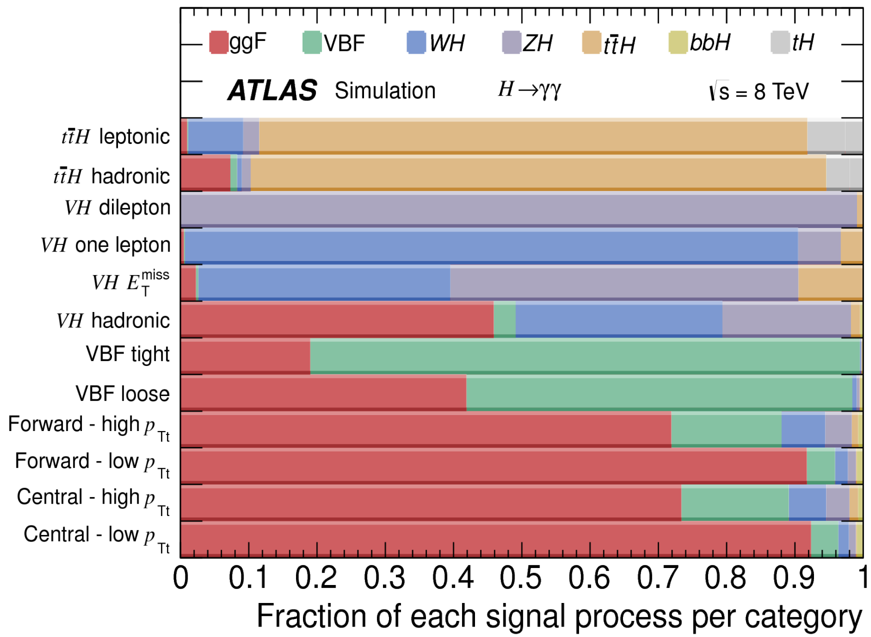
~25% precision per experiment possible for VBF in Run 2

~50% precision possible for VH in Run 2

Higgs boson decay to γγ



Loose split by production mode

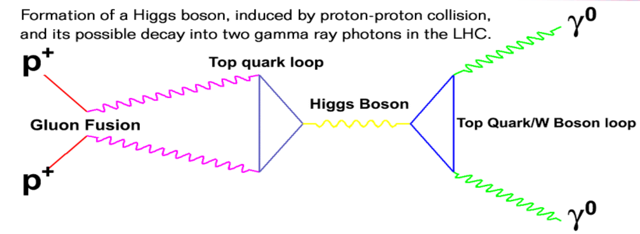


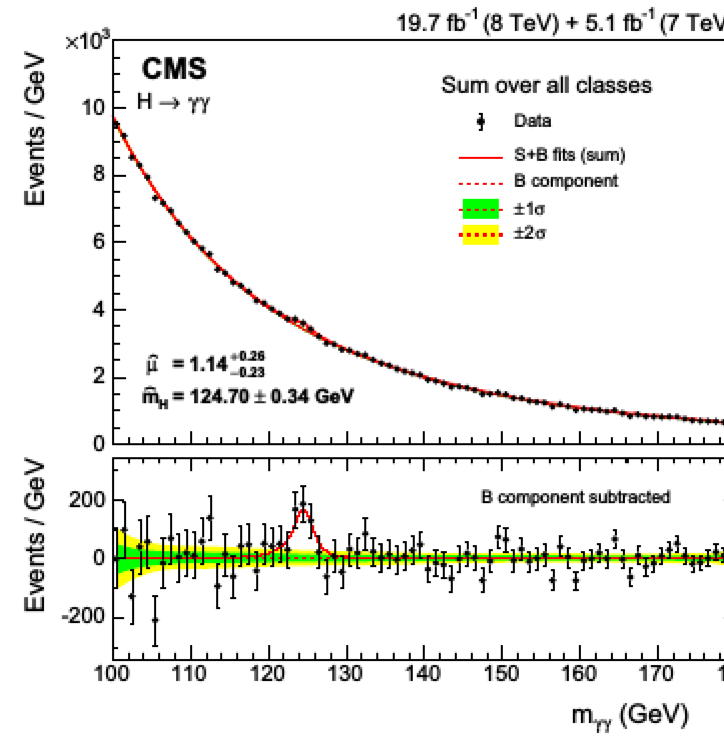
ATLAS

$$\mu_{\mathrm{ggF}} = 1.32 \pm 0.32(\mathrm{stat})^{+0.13}_{-0.09}(\mathrm{syst})^{+0.19}_{-0.11}(\mathrm{theory})$$

$$\mu_{\mathrm{VBF}} = 0.8 \pm 0.7(\mathrm{stat})^{+0.2}_{-0.1}(\mathrm{syst})^{+0.2}_{-0.3}(\mathrm{theory})$$

Expect <20% uncertainty in ggF, <35% in VBF, in Run 2



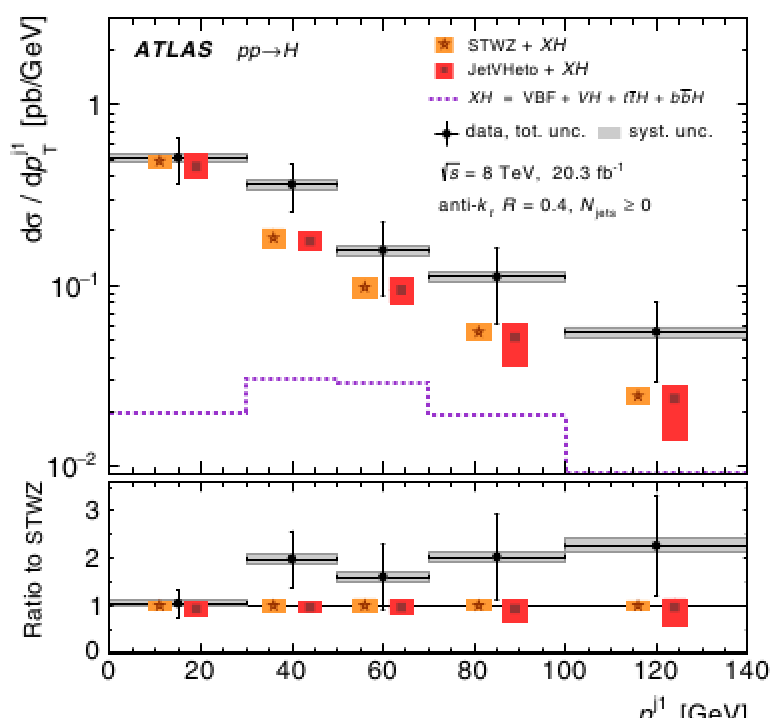


CMS

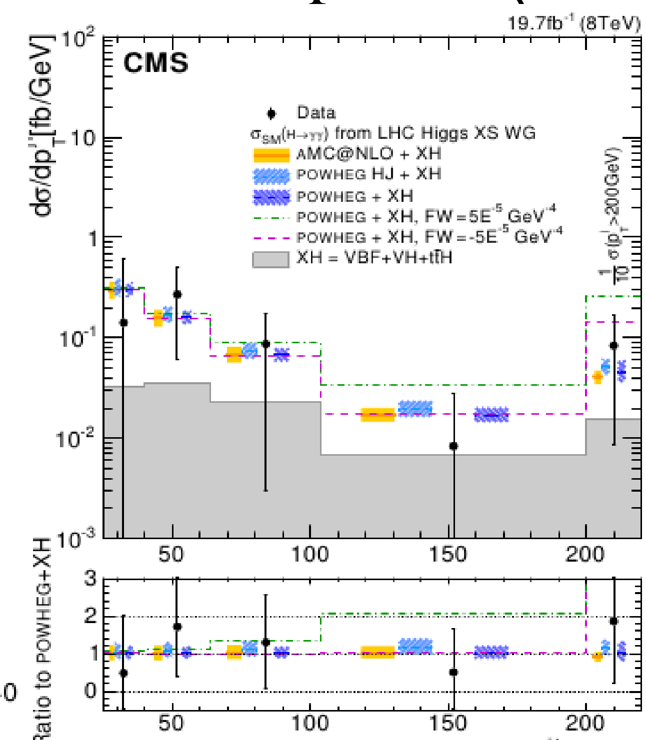
	Expected	Observed
$\hat{\mu}_{\mathrm{ggH,t\bar{t}H}}$	$1.00^{+0.34}_{-0.30}$	$1.13^{+0.37}_{-0.31}$
$\hat{\mu}_{\mathrm{VBF,\,VH}}$	$1.00^{+0.57}_{-0.51}$	$1.16^{+0.63}_{-0.58}$

Differential Higgs boson production

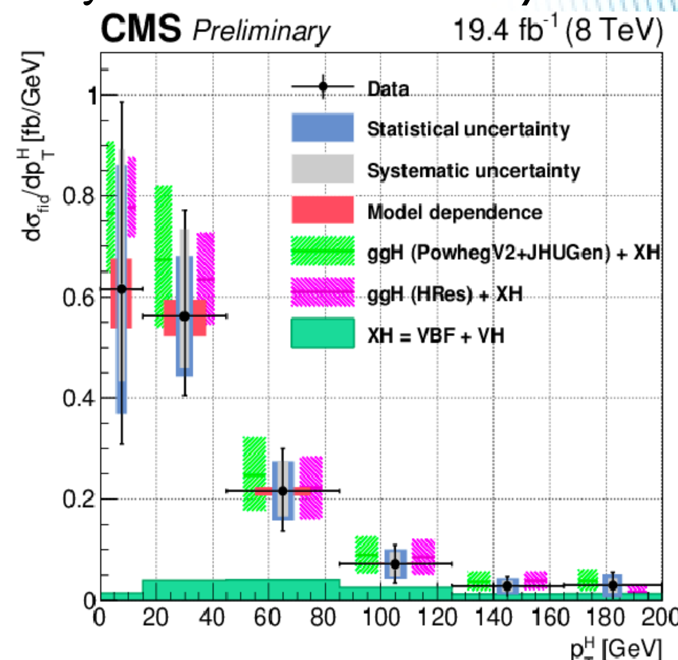
- Sufficient number of events in ZZ, γγ, and WW for single-differential cross section measurements
  - ZZ+γγ combined; WW separate (not fully reconstructed)



PRL 115, 091801



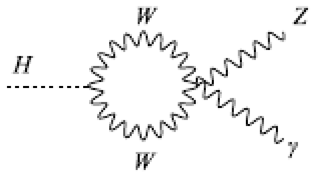
arxiv:1508.07819

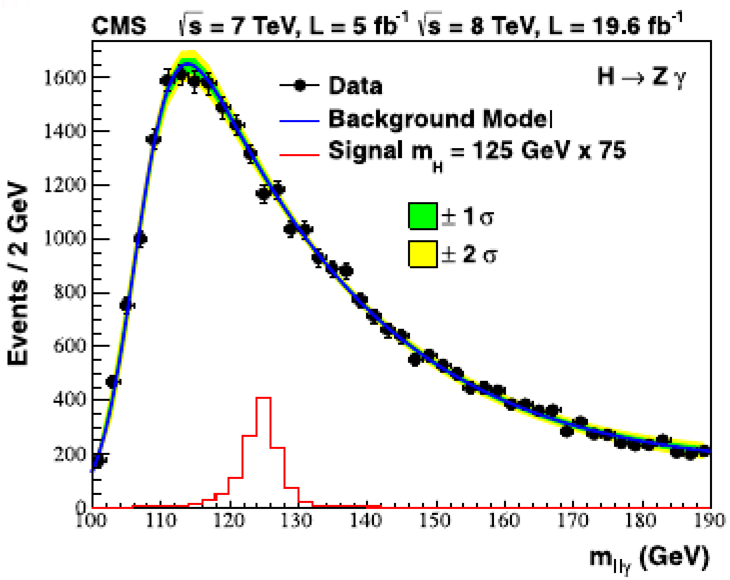


Fiducial task force in LHC Higgs working group to define standard binning, allowing ATLAS+CMS combination in Run 2

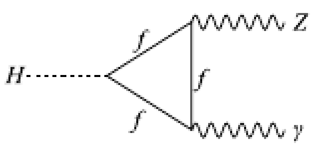
Higgs boson decay to Zγ

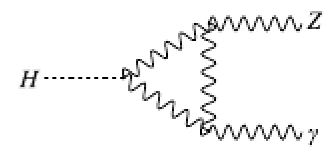
- Sensitive to similar loop contributions to γγ

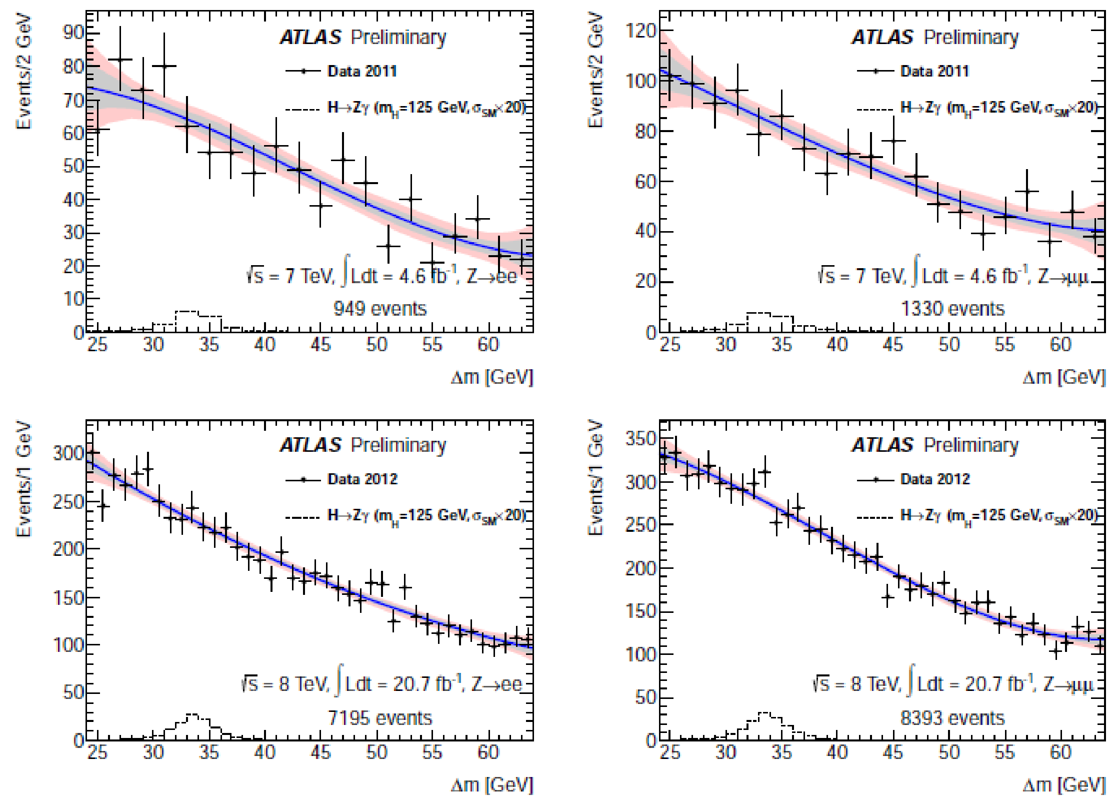




ATLAS probes mass difference $m_{ll\gamma}$ - m_{ll}







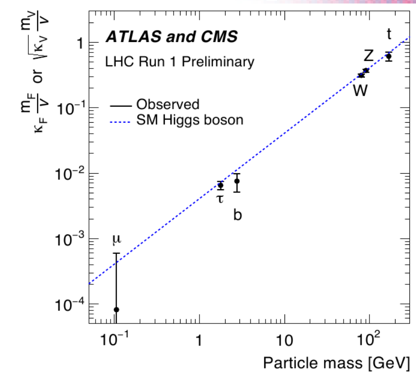
CMS limits 10x SM
ATLAS limits 19x SM

Combined ATLAS & CMS could get to 4x SM prediction in Run 2

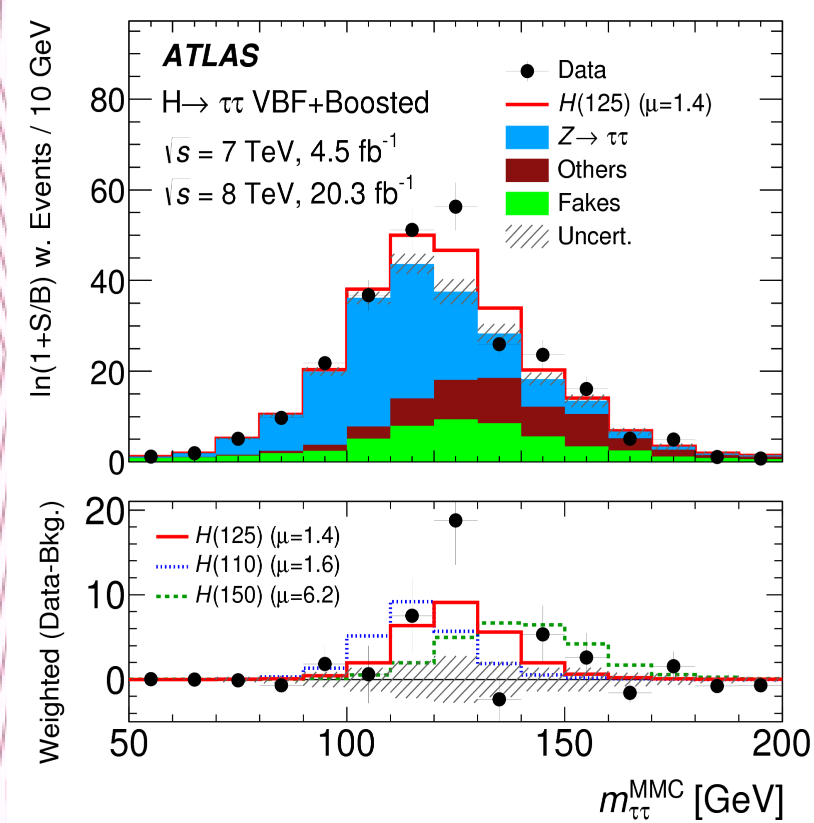
Higgs boson coupling to fermions

$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$

Higgs boson decay to ττ



- Challenge to reconstruct invariant mass



If the tau pair does not fall along a line, the mass can be resolved (neutrinos from the tau decay are approximately collinear)

Gluon fusion measured by requiring the ditau p_T to be large ("boosted")

$\mu = 1.0 \pm 0.5$

Dominant Z→ττ background modelled byreplacing muons in Z→μμ data with taus from simulaiton

ATLAS:

$$\mu^{\tau\tau}_{ggF} = 2.0 \ \pm 0.8(\text{stat.}) \ {}^{+1.2}_{-0.8}(\text{syst.}) \ \pm 0.3(\text{theory syst.})$$

$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24 \ {}^{+0.49}_{-0.45}(\text{stat.}) \ {}^{+0.31}_{-0.29}(\text{syst.}) \ \pm 0.08(\text{theory syst.})$$

$$\mu = 1.43 \ {}^{+0.27}_{-0.26}(\text{stat.}) \ {}^{+0.32}_{-0.25}(\text{syst.}) \ \pm 0.09(\text{theory syst.})$$

CMS: combined μ=0.78 ± 0.27

Run 2: Expect ~60% ggF and ~30% VBF uncertainty

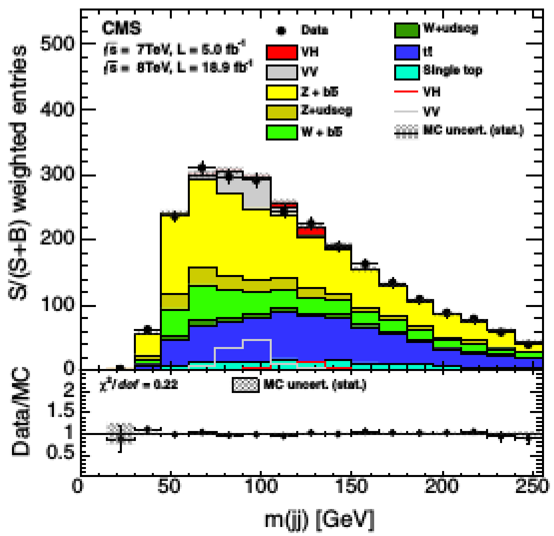
Higgs boson decay to bb

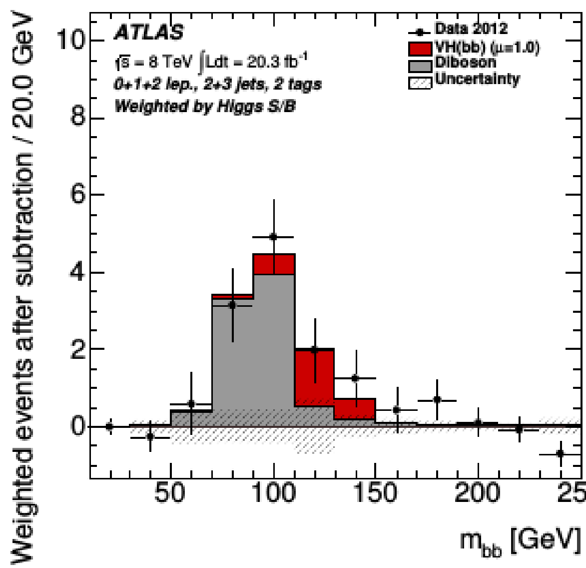
- Use VH production to suppress QCD b-jet production

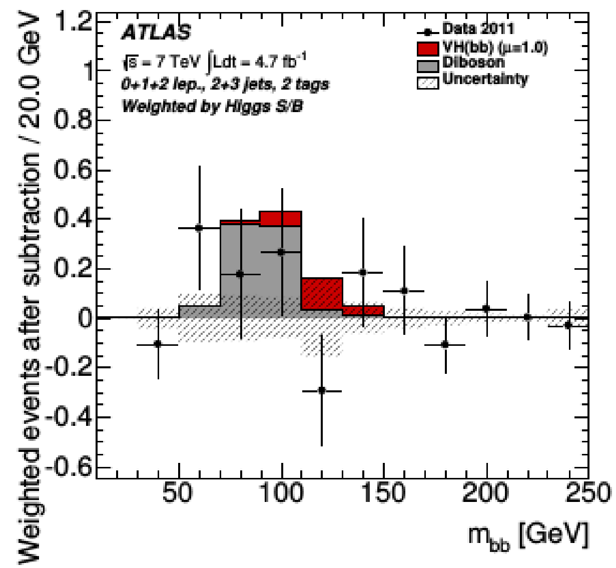
Need careful understanding of V+jets backgrounds

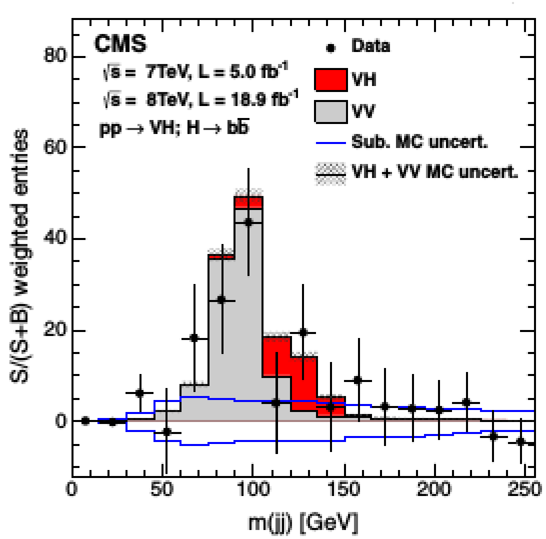
Multivariate analyses to squeeze out small signal

Observation of dibosons an important validation





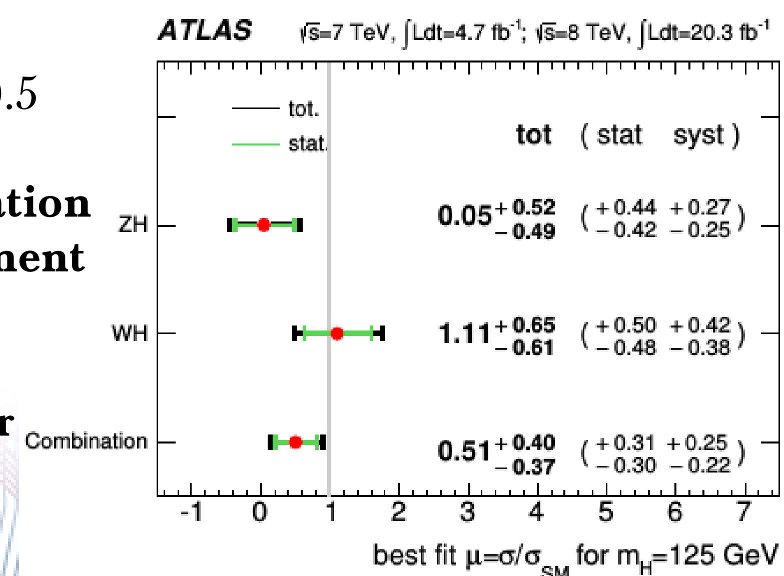




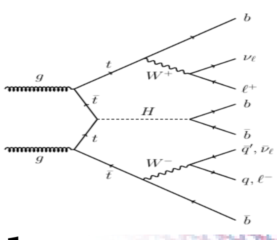
CMS:
combined μ=1.0 ± 0.5

Expect first observation and ~25% measurement in Run 2

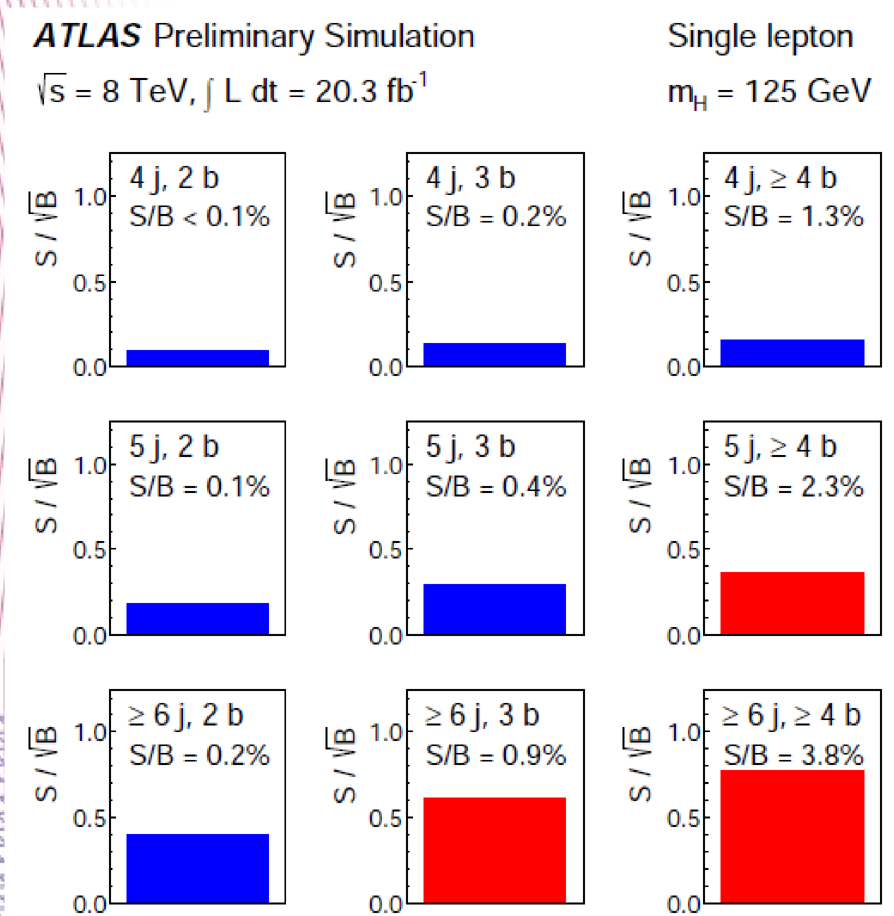
Also evidence for VBF production

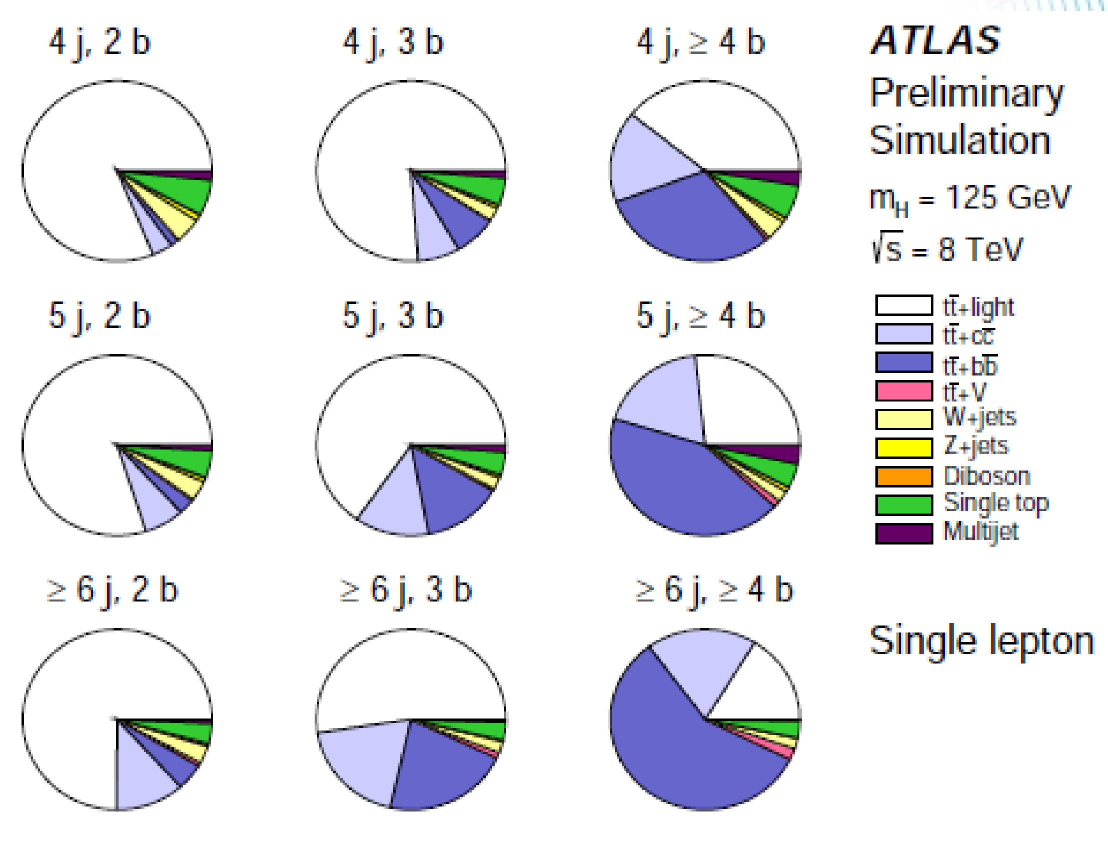


ttH production with decay to b quarks



- Many possible final states depending on tt decay
  - One/two leptons; categorize by number of jets and b-jets

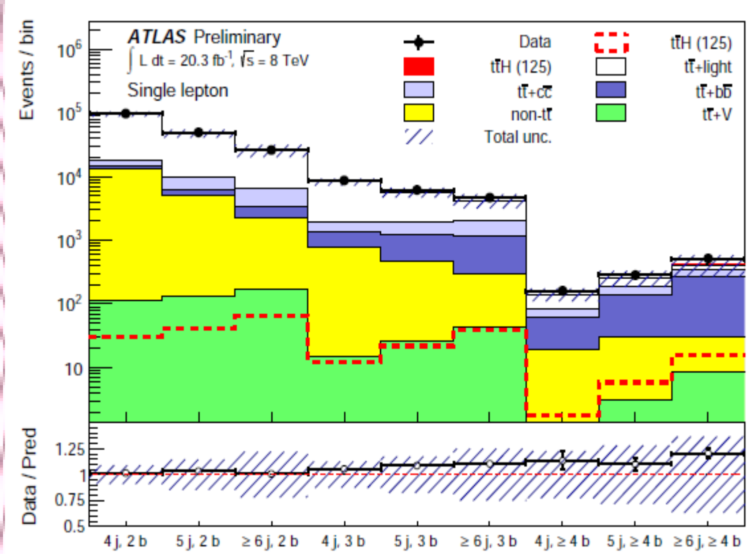


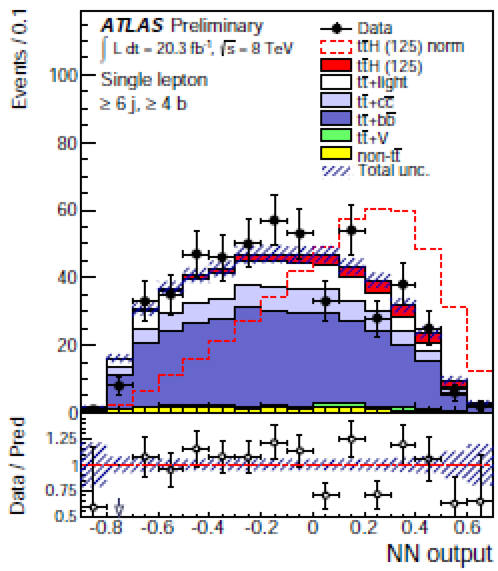


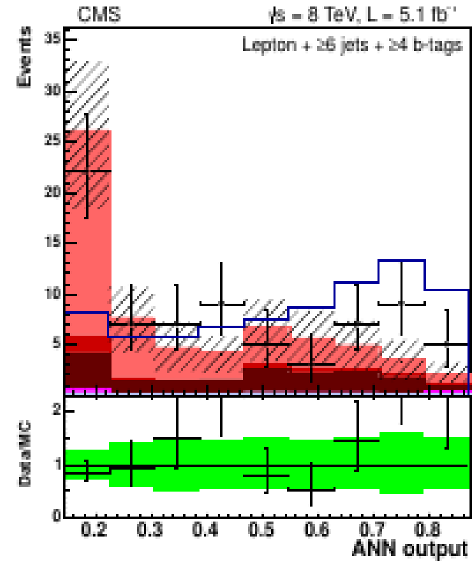
Flavour composition of jets

ttH production with decay to b quarks

- Fit multivariate distribution in each final state

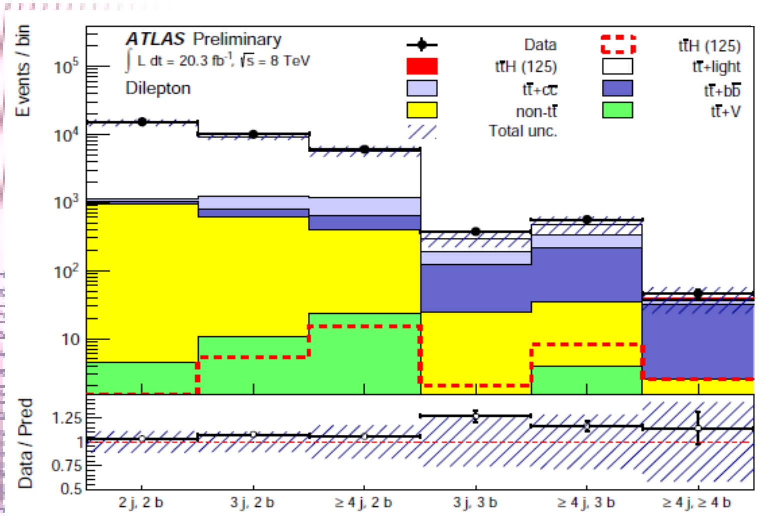


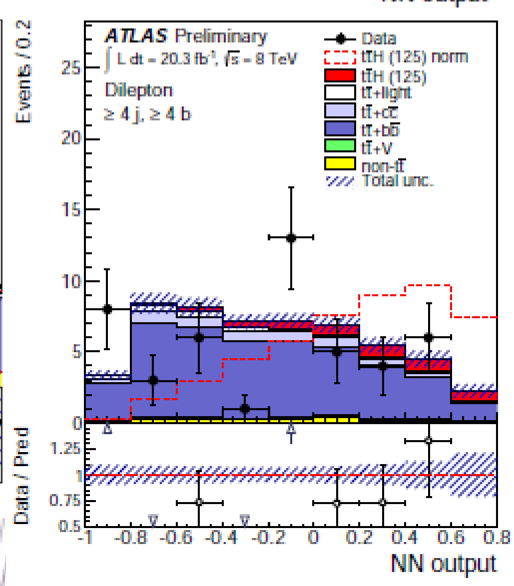


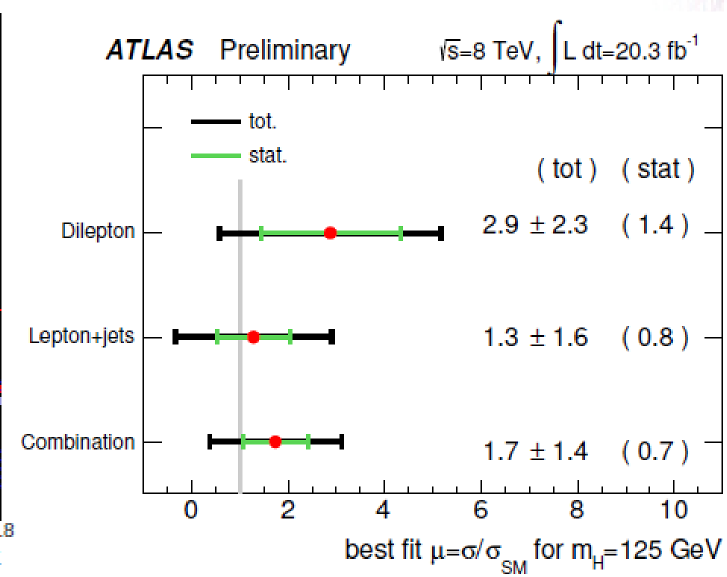


CMS limit:
$\mu < 4.3$

Run 2: Expect evidence of ttH production

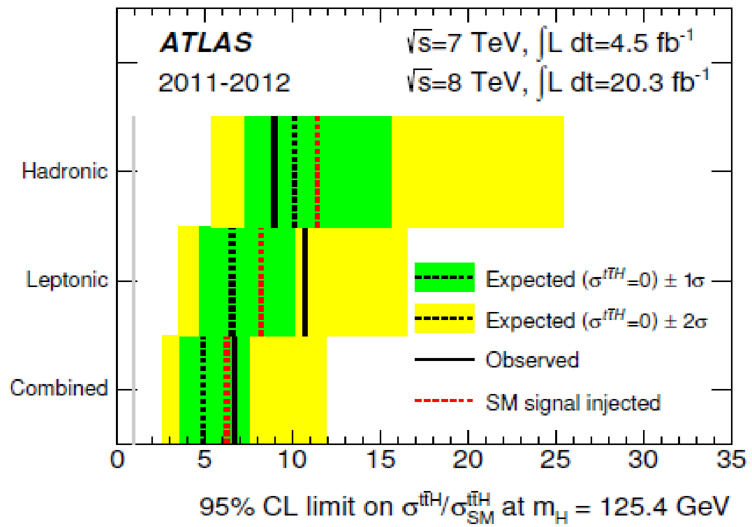


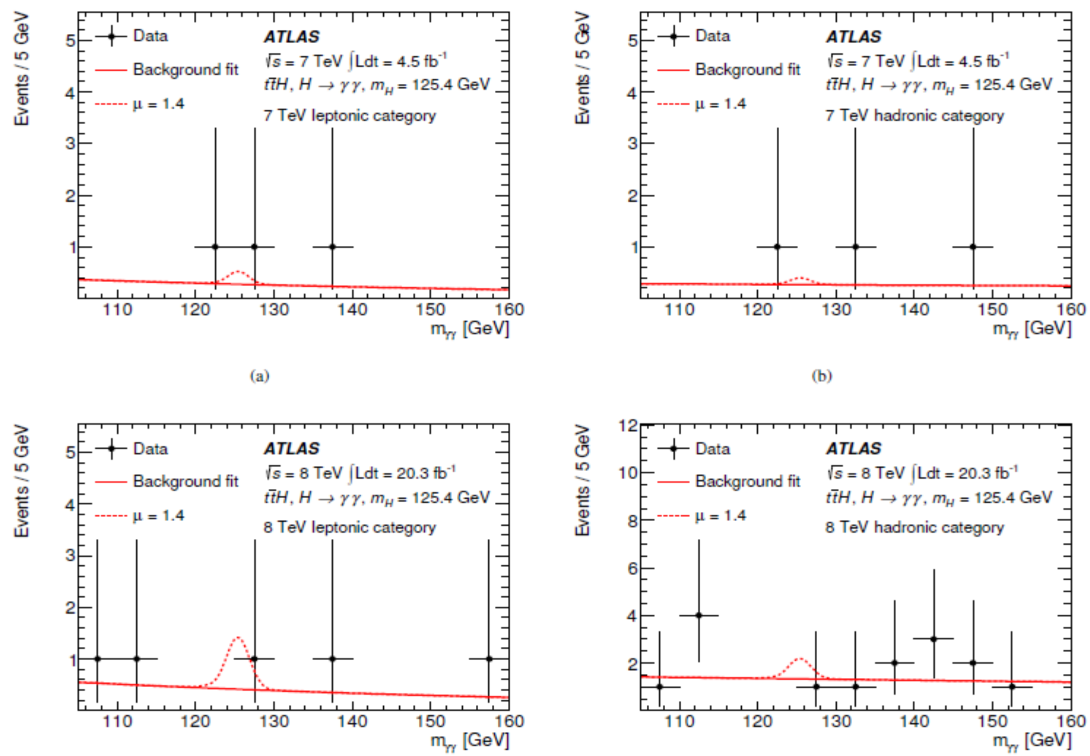


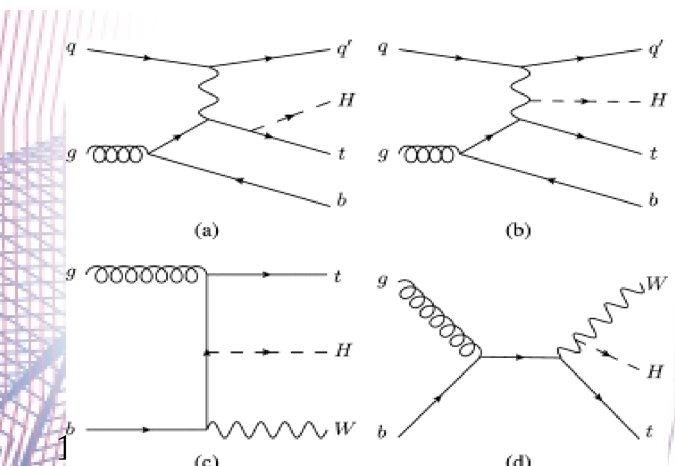


ttH production with decay to photons

- ATLAS and CMS limits are ~7x SM cross section
  - Expect to be within a factor of ~2 in Run 2





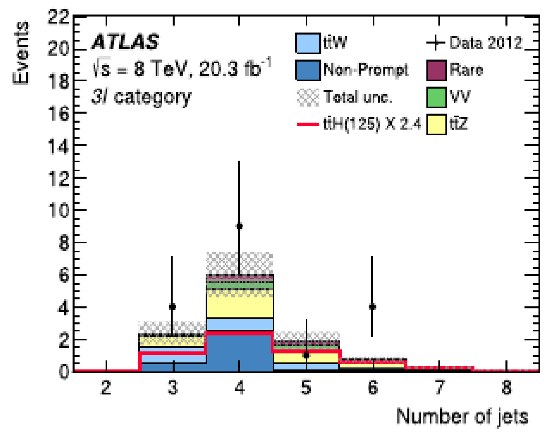


ATLAS search also sensitive to tH production
Probes the sign of the ttH coupling

ttH production with leptons in decay

- Combine Higgs boson decays to WW, ττ and ZZ
  - Categorize by leptonic combinations in the event

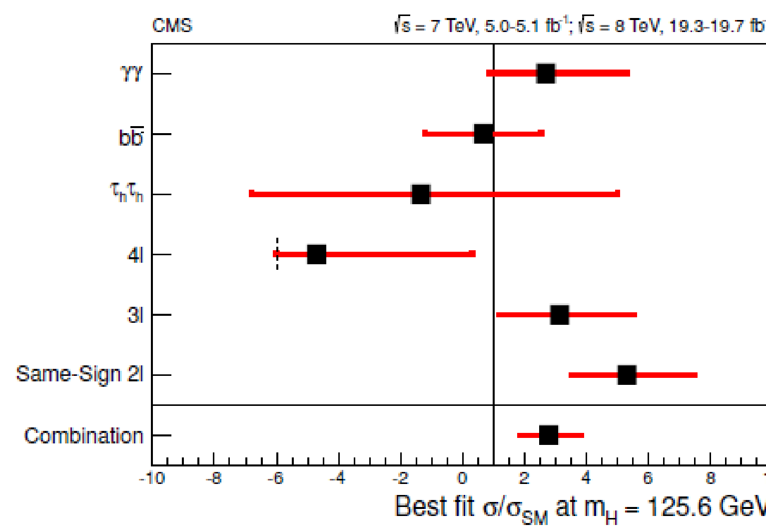
Category	Higgs boson decay mode			
	WW^*	$\tau\tau$	ZZ^*	Other
$2\ell 0\tau_{\rm had}$	80%	15%	3%	2%
3ℓ	74%	15%	7%	4%
$2\ell 1\tau_{\rm had}$	35%	62%	2%	1%
4ℓ	69%	14%	14%	4%
$1\ell 2\tau_{\rm had}$	4%	93%	0%	3%



ATLAS and CMS have excesses beyond SM prediction

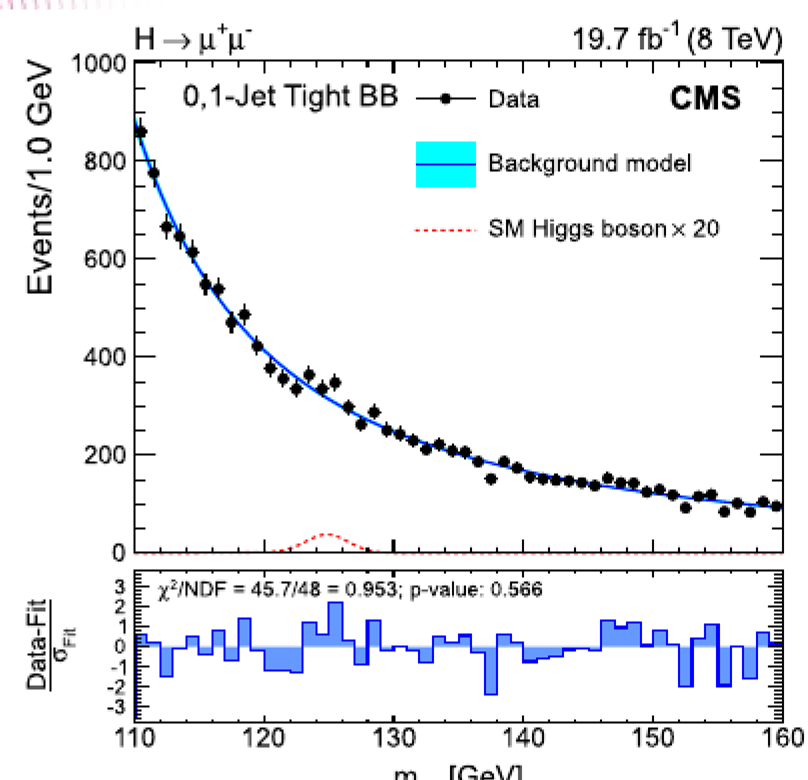
Evidence for ttH production expected in these channels in Run 2

	ee	$e\mu$	$\mu\mu$	3ℓ	4ℓ
$t\bar{t}$H, H → WW	1.0 ± 0.1	3.2 ± 0.4	2.4 ± 0.3	3.4 ± 0.5	0.29 ± 0.04
$t\bar{t}$H, H → ZZ	—	0.1 ± 0.0	0.1 ± 0.0	0.2 ± 0.0	0.09 ± 0.02
$t\bar{t}$H, H → $\tau\tau$	0.3 ± 0.0	1.0 ± 0.1	0.7 ± 0.1	1.1 ± 0.2	0.15 ± 0.02
$t\bar{t}$ W	4.3 ± 0.6	16.5 ± 2.3	10.4 ± 1.5	10.3 ± 1.9	—
$t\bar{t}$ Z/γ^*	1.8 ± 0.4	4.9 ± 0.9	2.9 ± 0.5	8.4 ± 1.7	1.12 ± 0.62
$t\bar{t}$ WW	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.0	0.4 ± 0.1	0.04 ± 0.02
$t\bar{t}$ γ	1.3 ± 0.3	1.9 ± 0.5	—	2.6 ± 0.6	—
WZ	0.6 ± 0.6	1.5 ± 1.7	1.0 ± 1.1	3.9 ± 0.7	—
ZZ	—	0.1 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	0.47 ± 0.10
Rare SM bkg.	0.4 ± 0.1	1.6 ± 0.4	1.1 ± 0.3	0.8 ± 0.3	0.01 ± 0.00
Non-prompt	7.6 ± 2.5	20.0 ± 4.4	11.9 ± 4.2	33.3 ± 7.5	0.43 ± 0.22
Charge misidentified	1.8 ± 0.5	2.3 ± 0.7	—	—	—
All signals	1.4 ± 0.2	4.3 ± 0.6	3.1 ± 0.4	4.7 ± 0.7	0.54 ± 0.08
All backgrounds	18.0 ± 2.7	49.3 ± 5.4	27.7 ± 4.7	59.8 ± 8.0	2.07 ± 0.67
Data	19	51	41	68	1



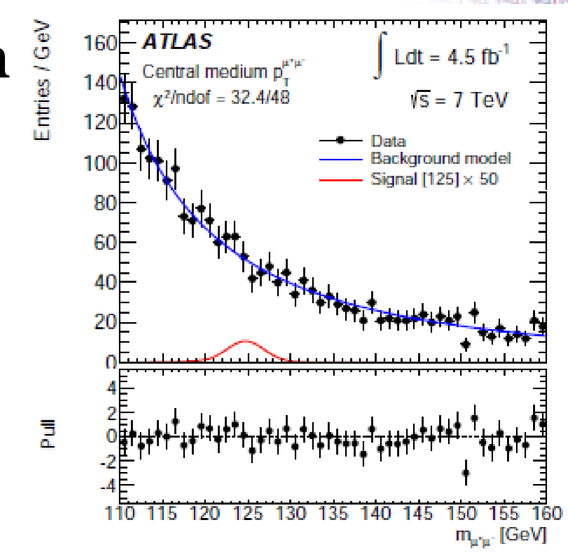
Higgs boson decay to μμ

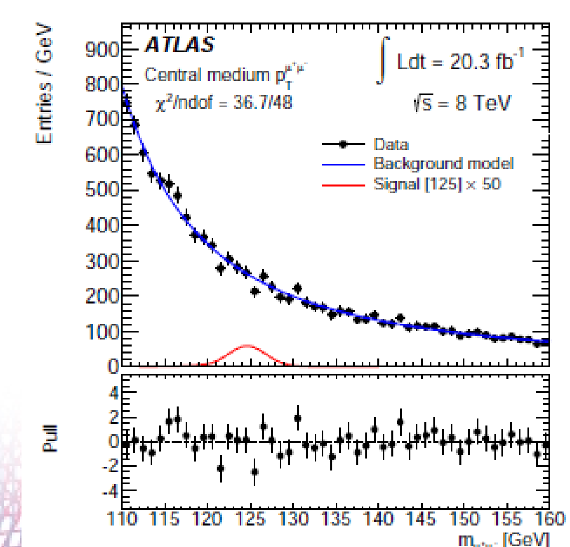
- Directly test Higgs couplings to second generation fermions
  - ATLAS & CMS limits ~7x SM prediction
  - CMS also constrains decay to ee
    - 37000x SM prediction



ATLAS splits into seven categories based on dimuon momentum and rapidity, and on production mechanism

Combined ATLAS & CMS could get to 2x SM prediction in Run 2

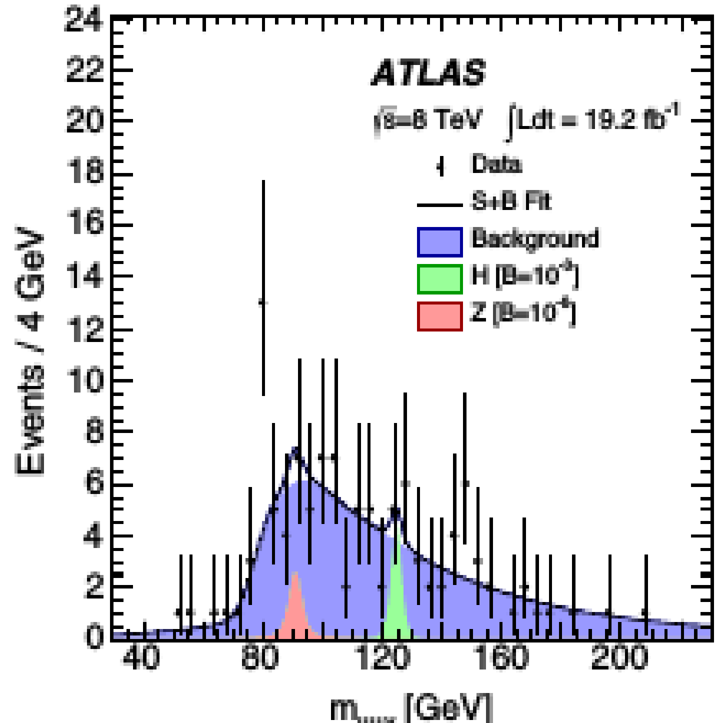




Higgs boson decay to J/ψ γ

- Sensitive to Hcc coupling
  - Predicted branching ratio 2.8×10^{-6}

	95% C.L. upper limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
	$\mathcal{B}(Z \to \mathcal{Q}\gamma)$ $[10^{-6}]$				
Expected	$2.0^{+1.0}_{-0.6}$	$4.9^{+2.5}_{-1.4}$	$6.2^{+3.2}_{-1.8}$	$5.4^{+2.7}_{-1.5}$	$8.8^{+4.7}_{-2.5}$
Observed	2.6	3.4	6.5	5.4	7.9
	$\mathcal{B}(H \to \mathcal{Q}\gamma)$ $[10^{-3}]$				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma(pp \to H) \times \mathcal{B}(H \to \mathcal{Q}\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44



ATLAS searches for decays both to J/ψγ and Υγ

Expect Run 2 limits to reach 5×10^{-4} (~180x SM)

Could also probe Hcc coupling using charm tagging in VH production

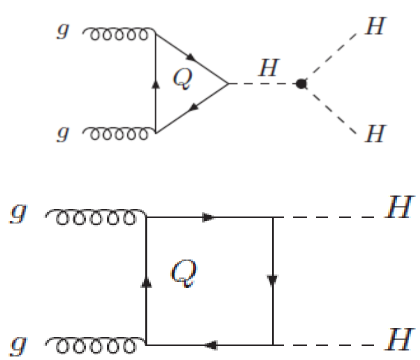
Higgs boson self-coupling

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\Psi} \not{D} \psi + h.c.$$
$$+ \bar{\Psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs boson pair production

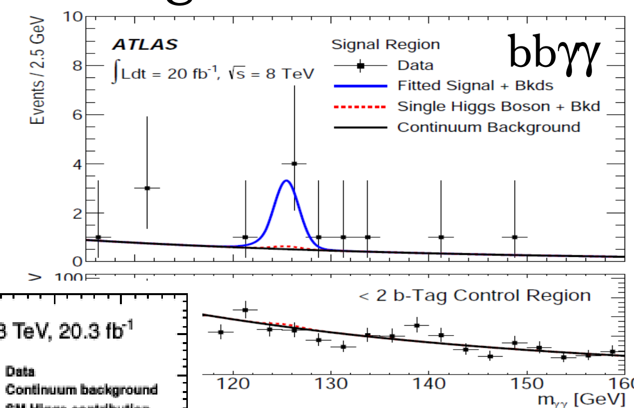
- Destructively interfering diagrams leads to very low rates
  - Many channels to study

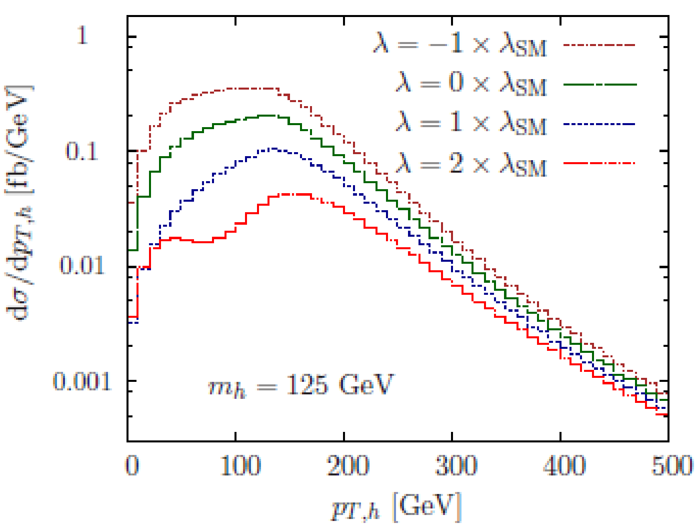
(a) gg double-Higgs fusion: $gg \to HH$

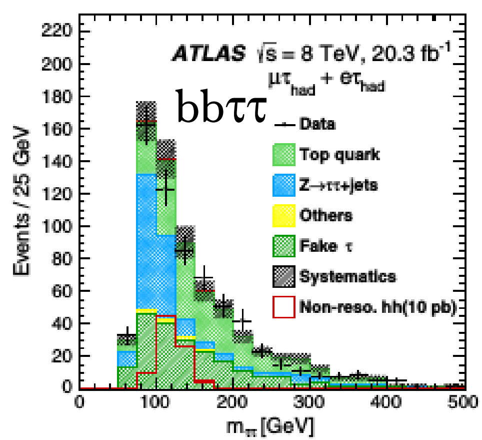


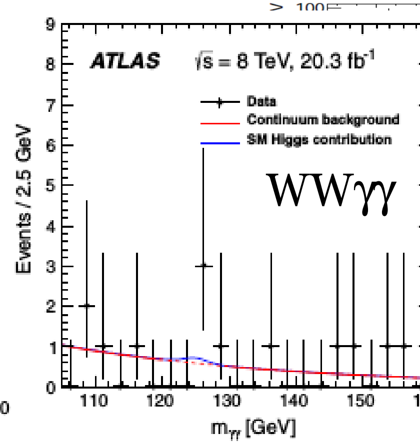
- ATLAS analysis combines four promising channels

hh	Nonresonant search	
Final state	Categories	Discriminant
$\gamma\gamma b\bar{b}$	1	$m_{\gamma\gamma}$
$\gamma\gamma WW^*$	1	event yields
$b\bar{b}\tau\tau$	4	$m_{\tau\tau}$
$b\bar{b}b\bar{b}$	1	event yields







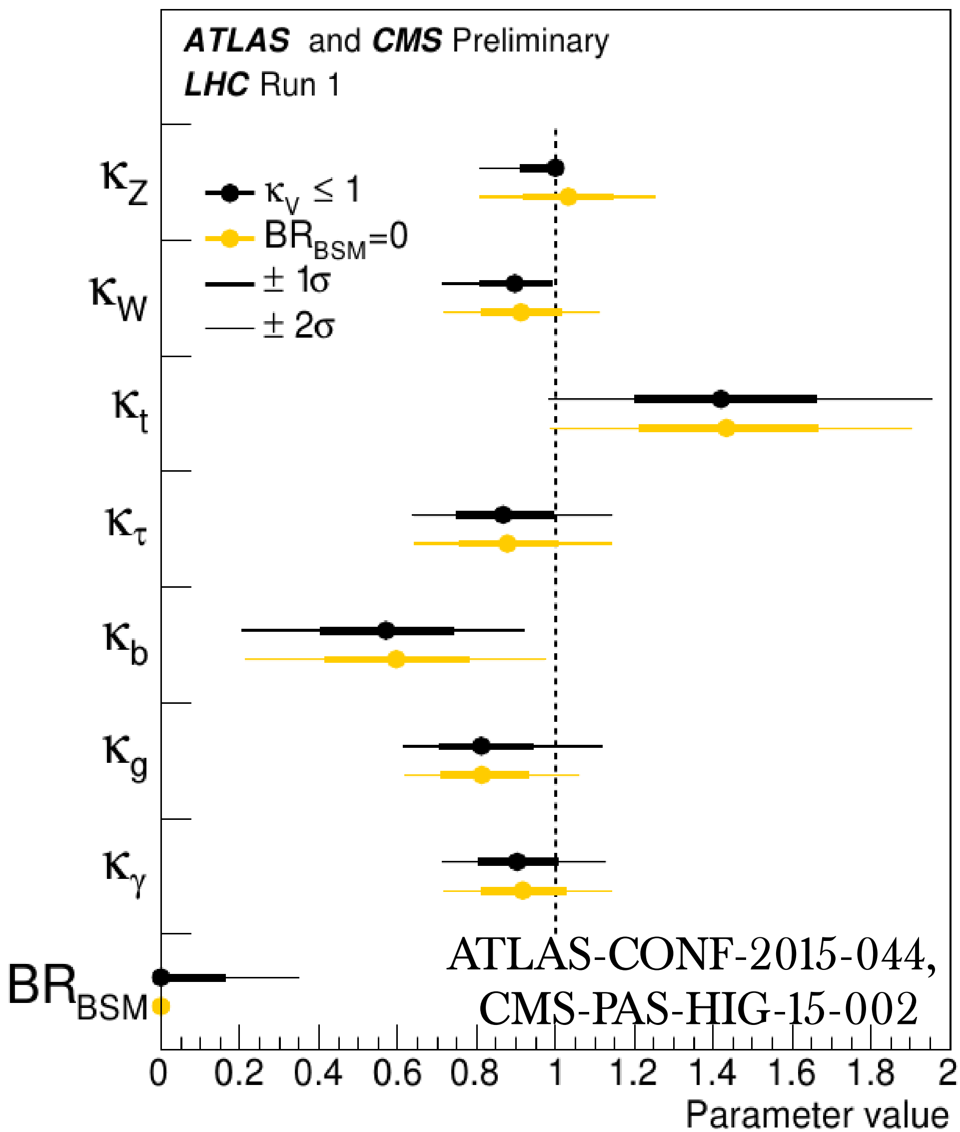


Should get to better than 30x SM prediction in Run 2

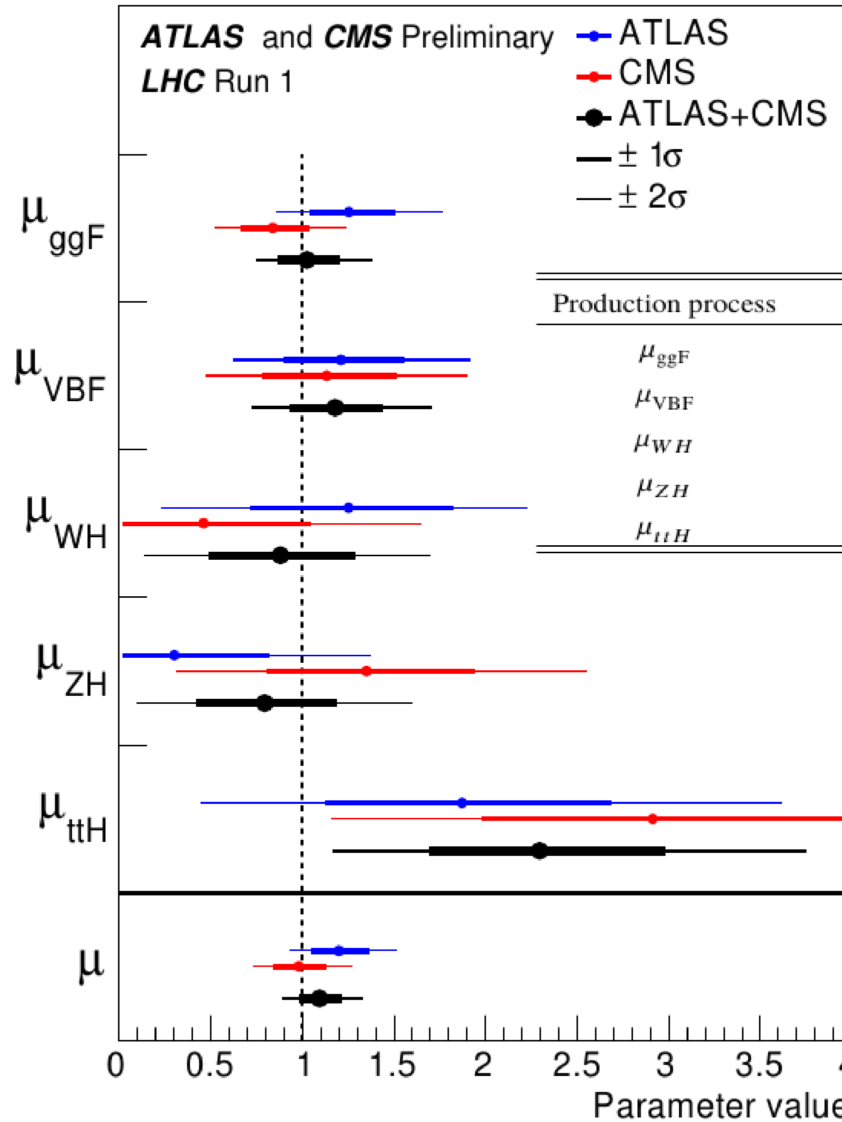
Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
Upper limit on the cross section [pb]					
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69
Upper limit on the cross section relative to the SM prediction					
Expected	100	680	130	63	48
Observed	220	1150	160	63	70

Combined Run 1 results

- ATLAS+CMS κ and μ constraints



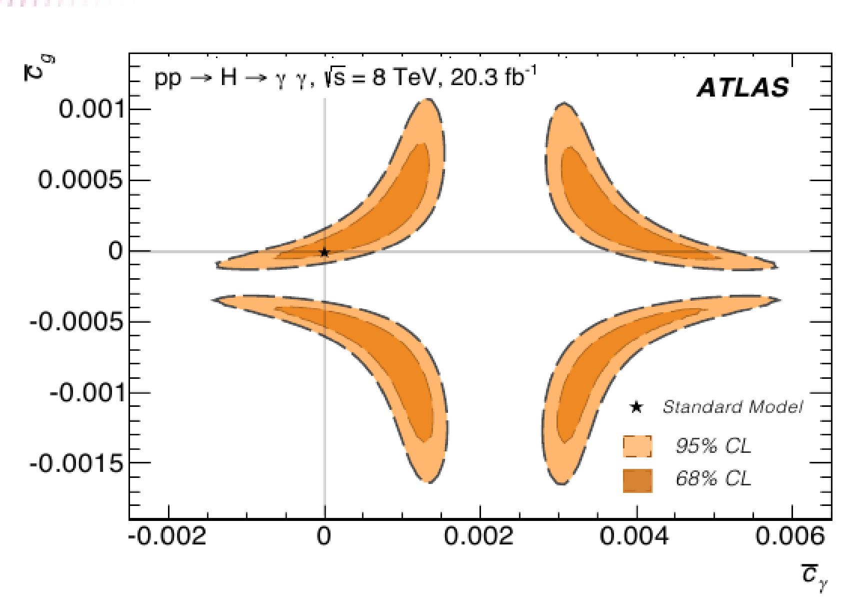
ATLAS-CONF-2015-044,
CMS-PAS-HIG-15-002

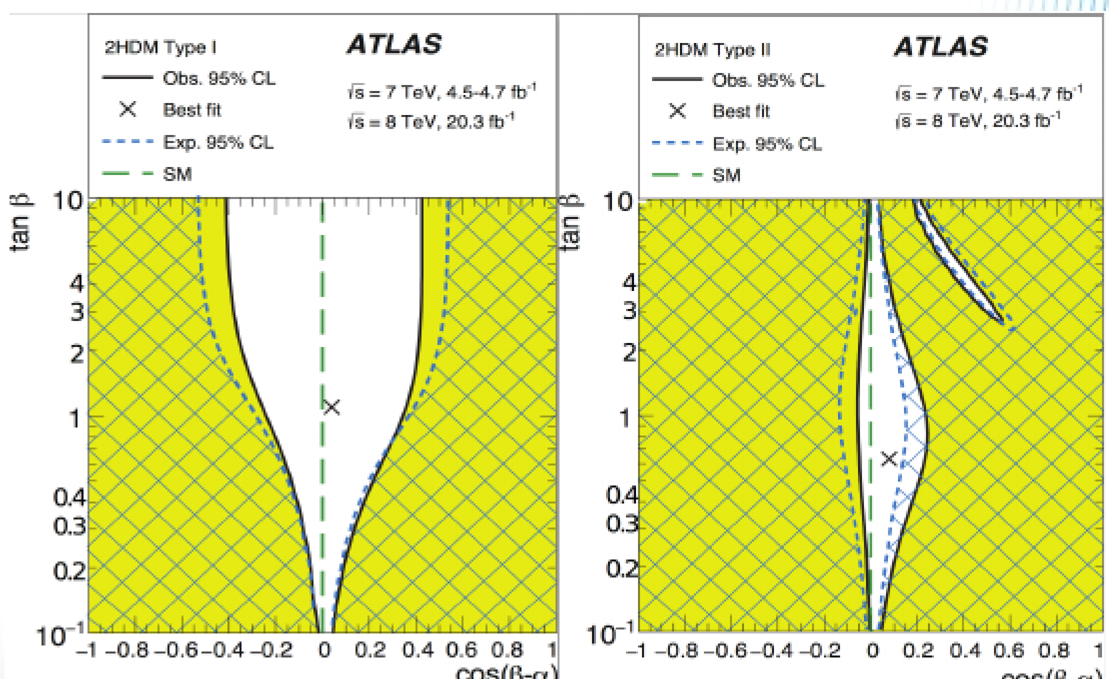


Production process	ATLAS+CMS
μ_{ggF}	$1.03^{+0.17}_{-0.15}$
μ_{VBF}	$1.18^{+0.25}_{-0.23}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$

Higgs boson beyond the SM

- Concurrent effort along various tracks
  - Parameterize deviations in SM measurements
  - Search for BSM decays
  - Search for additional Higgs bosons





Parametrizing deviations

- Run 2 to probe more terms in the Lagrangian
  - Current tools include ≤6 dimensional operators to LO
    - For example, single-Higgs couplings to the SM:

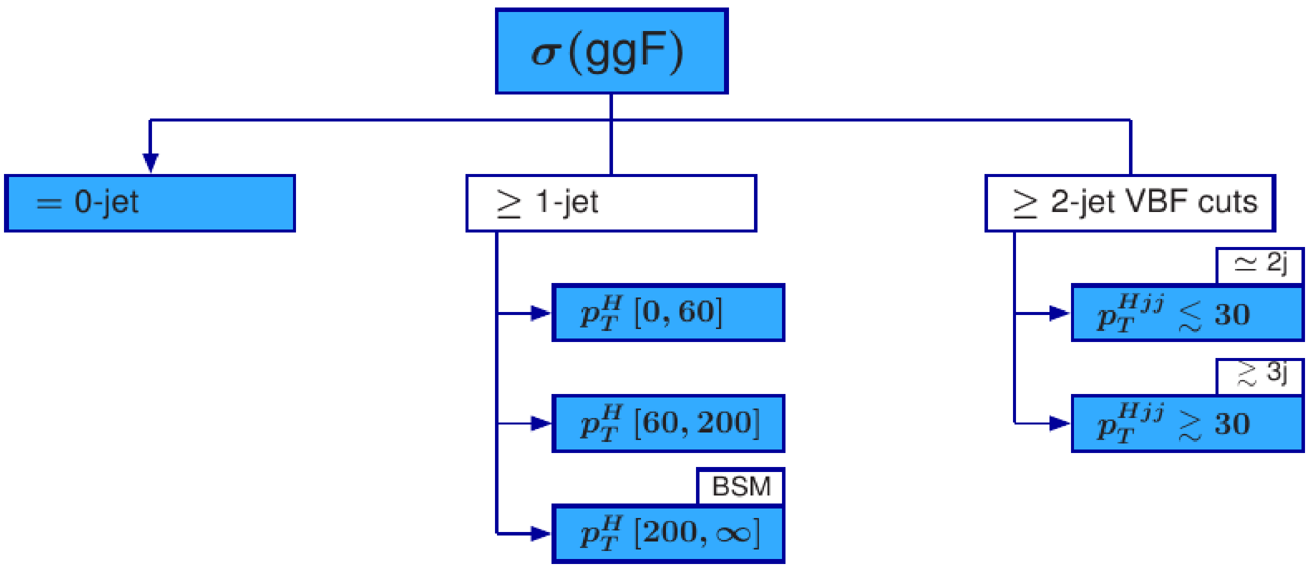
LHCHXSWG-INT-2015-001

$$\begin{aligned}
\Delta\mathcal{L}_{\mathrm{h}} &= \frac{h}{v}\Big[2\delta c_w m_W^2 W_\mu^+ W_\mu^- + \delta c_z m_Z^2 Z_\mu Z_\mu \\
&- \sum_{f\in u,d,e}\sum_{ij}\sqrt{m_{f_i}m_{f_j}}[\delta y_f]_{ij}\left[\cos\phi_{ij}^f \bar{f}_i f_j - i\sin\phi_{ij}^f \bar{f}_i\gamma_5 f_j\right] \\
&+ c_{ww}\frac{g^2}{2}W_{\mu\nu}^+ W_{\mu\nu}^- + \tilde{c}_{ww}\frac{g^2}{2}W_{\mu\nu}^+\tilde{W}_{\mu\nu}^- + c_{w\Box}g^2\left(W_\mu^-\partial_\nu W_{\mu\nu}^+ + \mathrm{h.c.}\right) \\
&+ c_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a G_{\mu\nu}^a + c_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}A_{\mu\nu} + c_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}A_{\mu\nu} + c_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}Z_{\mu\nu} \\
&+ c_{z\Box}g^2 Z_\mu\partial_\nu Z_{\mu\nu} + c_{\gamma\Box}gg'Z_\mu\partial_\nu A_{\mu\nu} \\
&+ \tilde{c}_{gg}\frac{g_s^2}{4}G_{\mu\nu}^a\tilde{G}_{\mu\nu}^a + \tilde{c}_{\gamma\gamma}\frac{e^2}{4}A_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{z\gamma}\frac{e\sqrt{g^2+g'^2}}{2}Z_{\mu\nu}\tilde{A}_{\mu\nu} + \tilde{c}_{zz}\frac{g^2+g'^2}{4}Z_{\mu\nu}\tilde{Z}_{\mu\nu}\Big]
\end{aligned}$$

- Derive from measurements of exclusive cross sections
  - e.g. σ(0-jet), σ(high-p_T^H)

Parametrizing deviations

- Run 2 experimental focus will be on binned cross sections
  - Effectively production-level fiducial cross sections
    - Extrapolate back to decay vertex



Ongoing discussion in LHC Higgs WG about binning

Likely several stages for measurements to choose from
Use the finest binning feasible for the measurement

Post-decay fiducial cross sections measured in Run 1

Type	$n_j = 0$	$n_j = 1$
Preselection	$p_T^{\ell 1} > 22$ $p_T^{\ell 2} > 10$ opposite-charge ℓ $m_{\ell\ell} > 10$ $p_T^{\nu\nu} > 20$	
n_j dependent	$\Delta\phi_{\ell\ell,\nu\nu} > \pi/2$	-
	$p_T^{\ell\ell} > 30$	-
	-	$m_T^{\ell} > 50$
	-	$m_{\tau\tau} < 66$
	$m_{\ell\ell} < 55$	$m_{\ell\ell} < 55$
	$\Delta\phi_{\ell\ell} < 1.8$	$\Delta\phi_{\ell\ell} < 1.8$

ATLAS
H→WW

$$\mu^{ggF}_{0j,e\mu} = 1.39 \quad \pm 0.27 \quad {}^{+0.21}_{-0.19} \quad {}^{+0.27}_{-0.17}$$
$$\mu^{ggF}_{1j,e\mu} = 1.14 \quad {}^{+0.42}_{-0.41} \quad {}^{+0.27}_{-0.26} \quad {}^{+0.42}_{-0.17}$$
(stat) (syst) (sig)

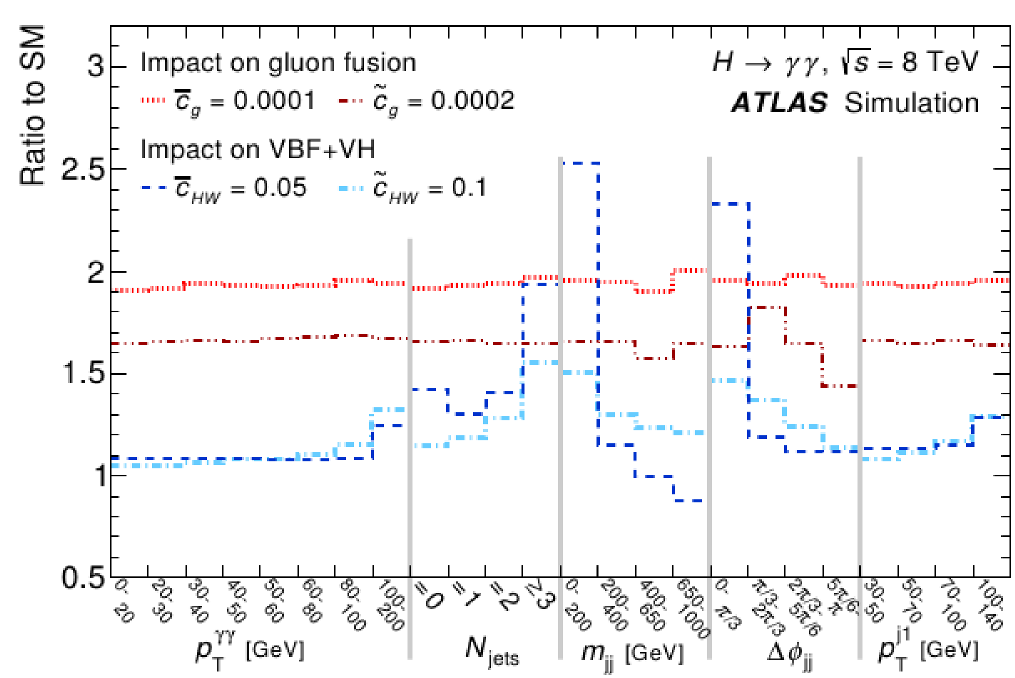
$$\sigma^{ggF}_{\mathrm{fid},0j} = 27.6 \quad {}^{+5.4}_{-5.3} \quad {}^{+4.1}_{-3.9} = 27.6 \quad {}^{+6.8}_{-6.6} \text{ fb}$$
$$\sigma^{ggF}_{\mathrm{fid},1j} = 8.3 \quad {}^{+3.1}_{-3.0} \quad {}^{+2.0}_{-1.9} = 8.3 \quad {}^{+3.7}_{-3.5} \text{ fb.}$$
(stat) (syst)

Parametrizing deviations

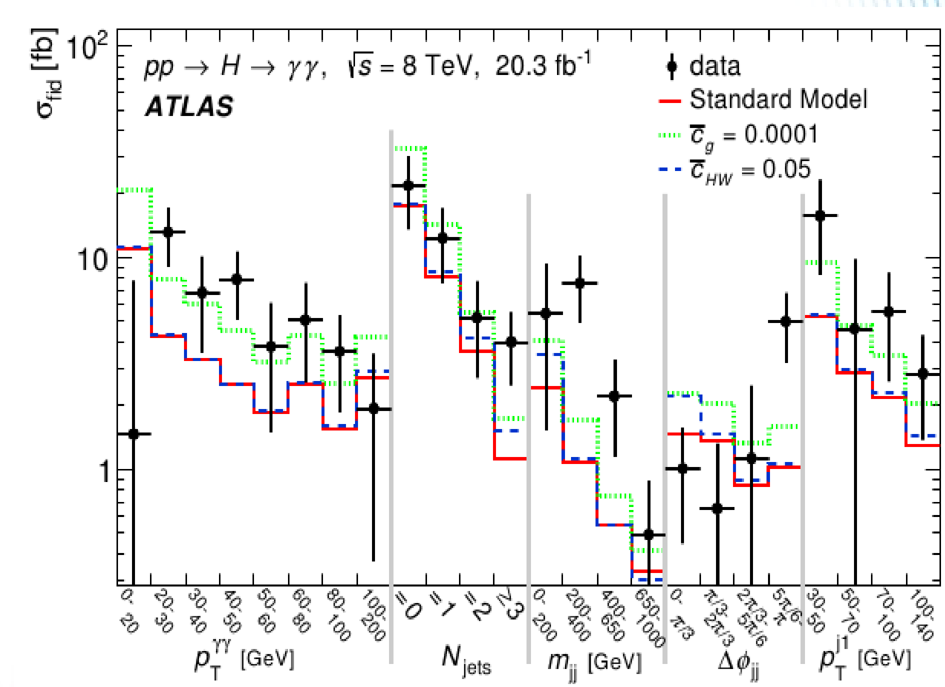
- Run 1 results with effective Lagrangian from ATLAS H→γγ
  - Consider only terms relevant for ggF and VBF production

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

arxiv:1508.02507



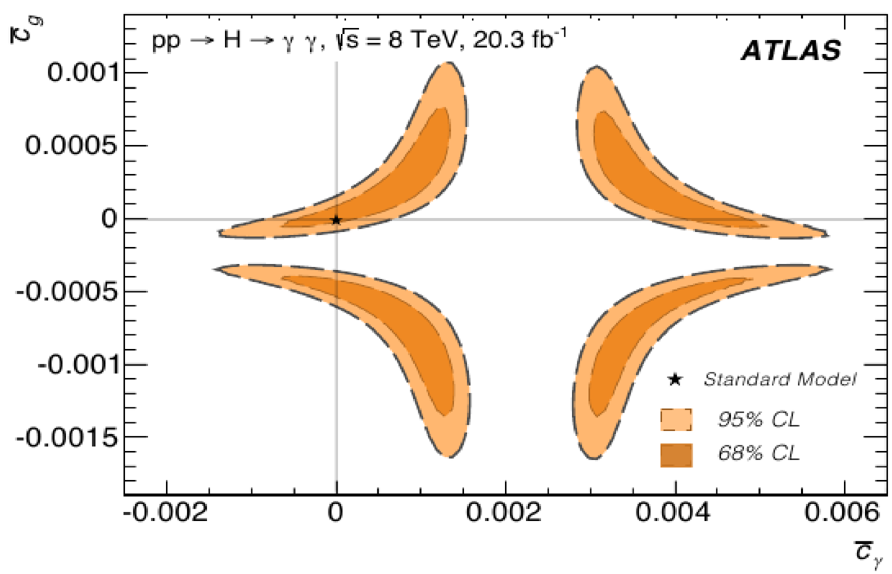
Impact of effective couplings

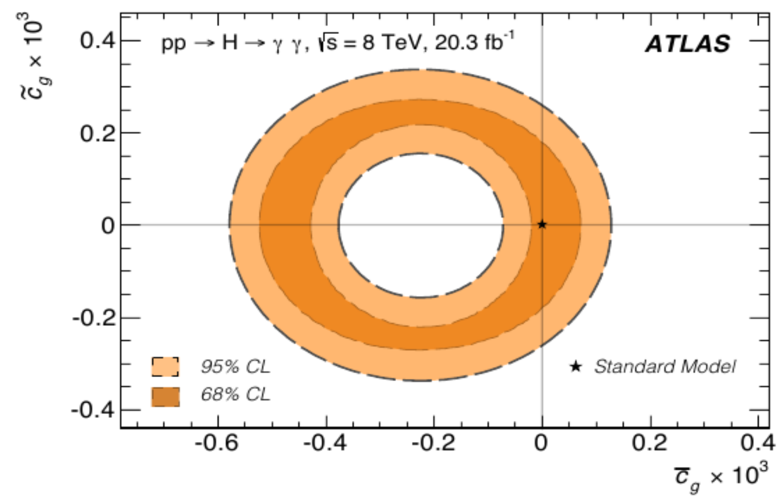


Measured results

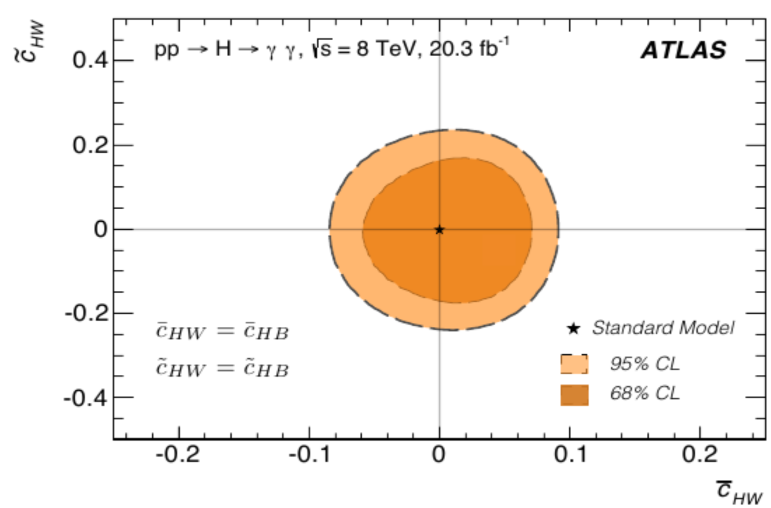
Parametrizing deviations

- Run 1 results with effective Lagrangian from ATLAS H→γγ
  - Obtain constraints in 1- & 2-dimensional coupling planes



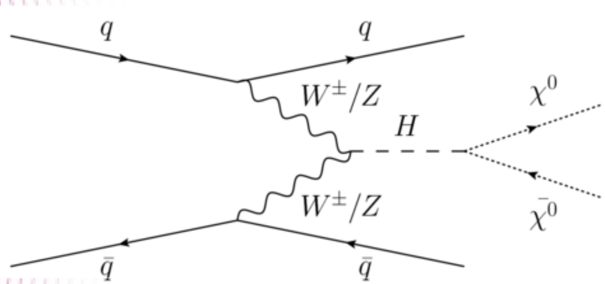


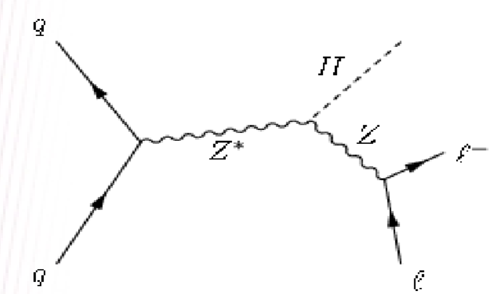
Coefficient	95% $1 - CL$ limit
$\bar{c}_\gamma$	$[-7.4, 5.7]\times10^{-4} \cup [3.8, 5.1]\times10^{-3}$
$\tilde{c}_\gamma$	$[-1.8, 1.8]\times10^{-3}$
$\bar{c}_g$	$[-0.7, 1.3]\times10^{-4} \cup [-5.8, -3.8]\times10^{-4}$
$\tilde{c}_g$	$[-2.4, 2.4]\times10^{-4}$
$\bar{c}_{HW}$	$[-8.6, 9.2]\times10^{-2}$
$\tilde{c}_{HW}$	$[-0.23, 0.23]$

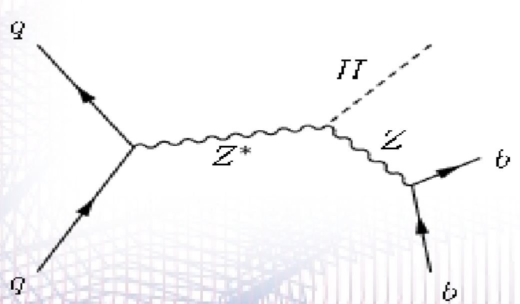


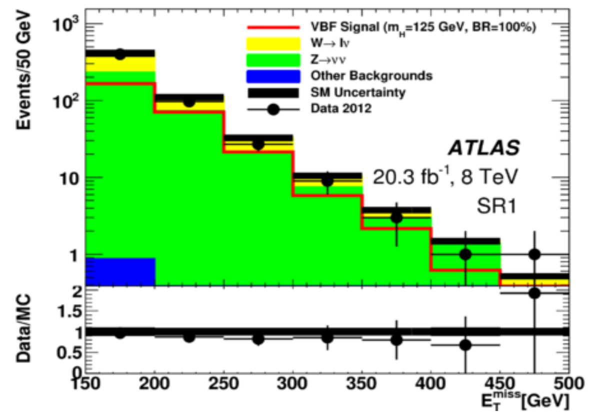
Higgs boson decays to BSM particles

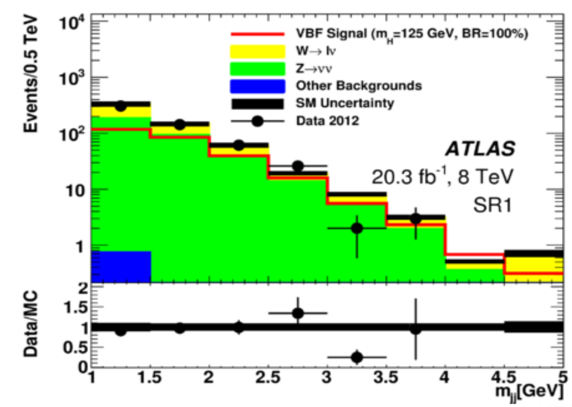
- Decays to a low-mass scalar (“a”) or invisible/dark matter (“χ”)
  - Dark matter needs to be produced with objects (VBF, VH)







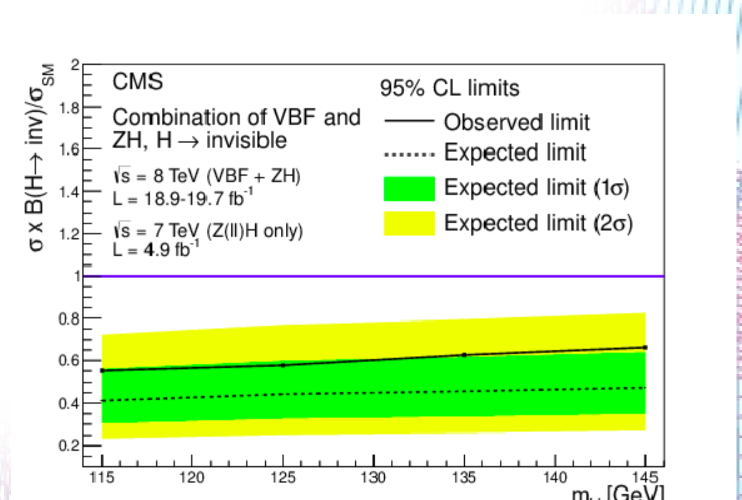




VBF production most sensitive

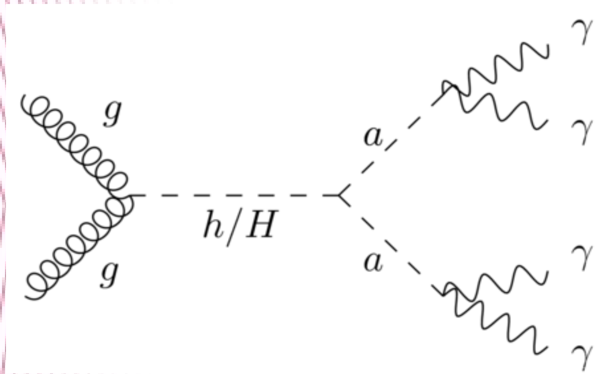
ATLAS sets limit of BR < 25%

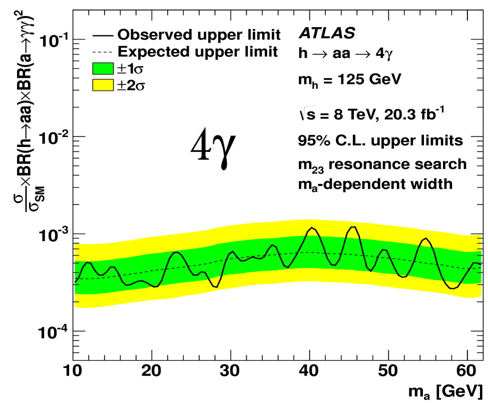
Could achieve combined BR < 10% in Run 2

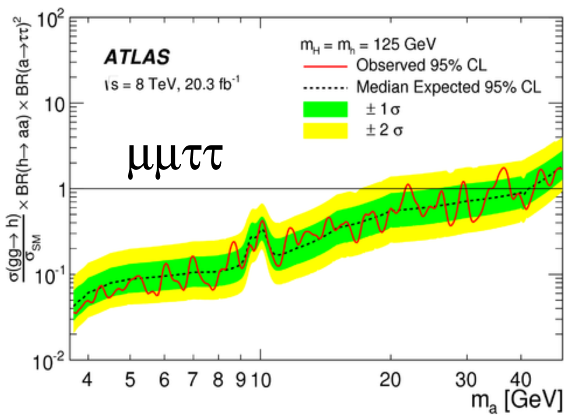


Higgs boson decays to BSM particles

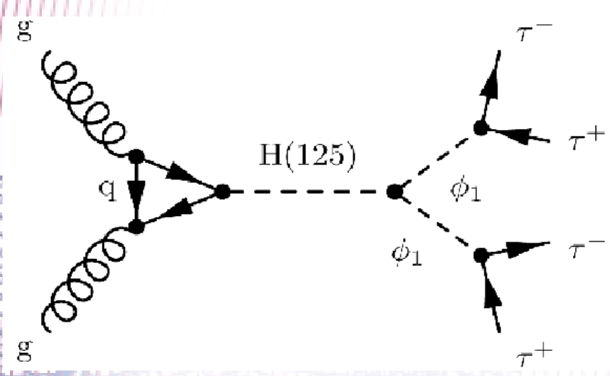
- Decays to a low-mass scalar (“a”) or invisible/dark matter (“χ”)
  - Low-mass scalar: many possible decays, broad mass range

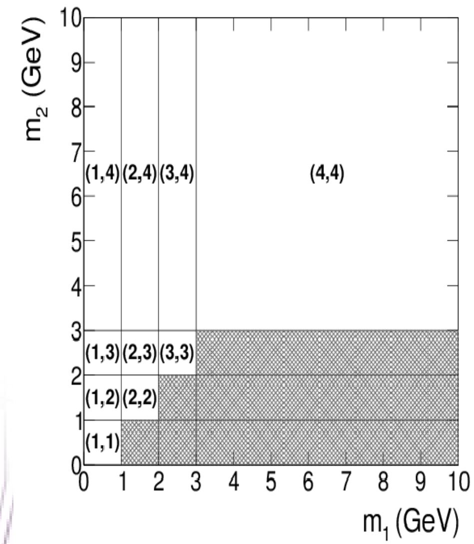


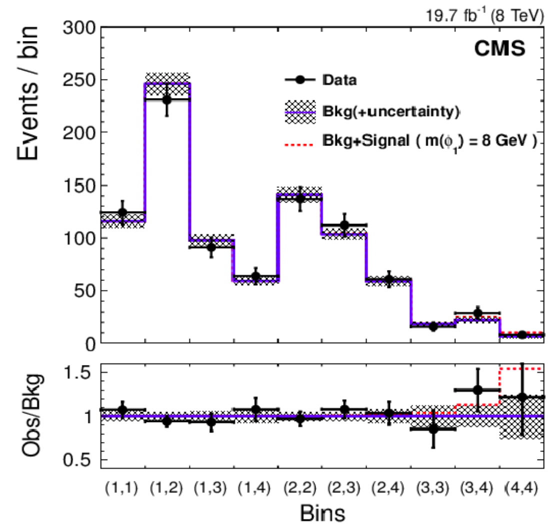




ATLAS limits in 4γ and μμττ probe branching fractions < 1







CMS limits in ττττ not sensitive to BF<1 with SM production

Additional Higgs bosons

- Probe additional EW singlets, doublets, triplets
  - Type II two-Higgs doublet model appears in supersymmetry
  - Contribution of second Higgs to particle masses small

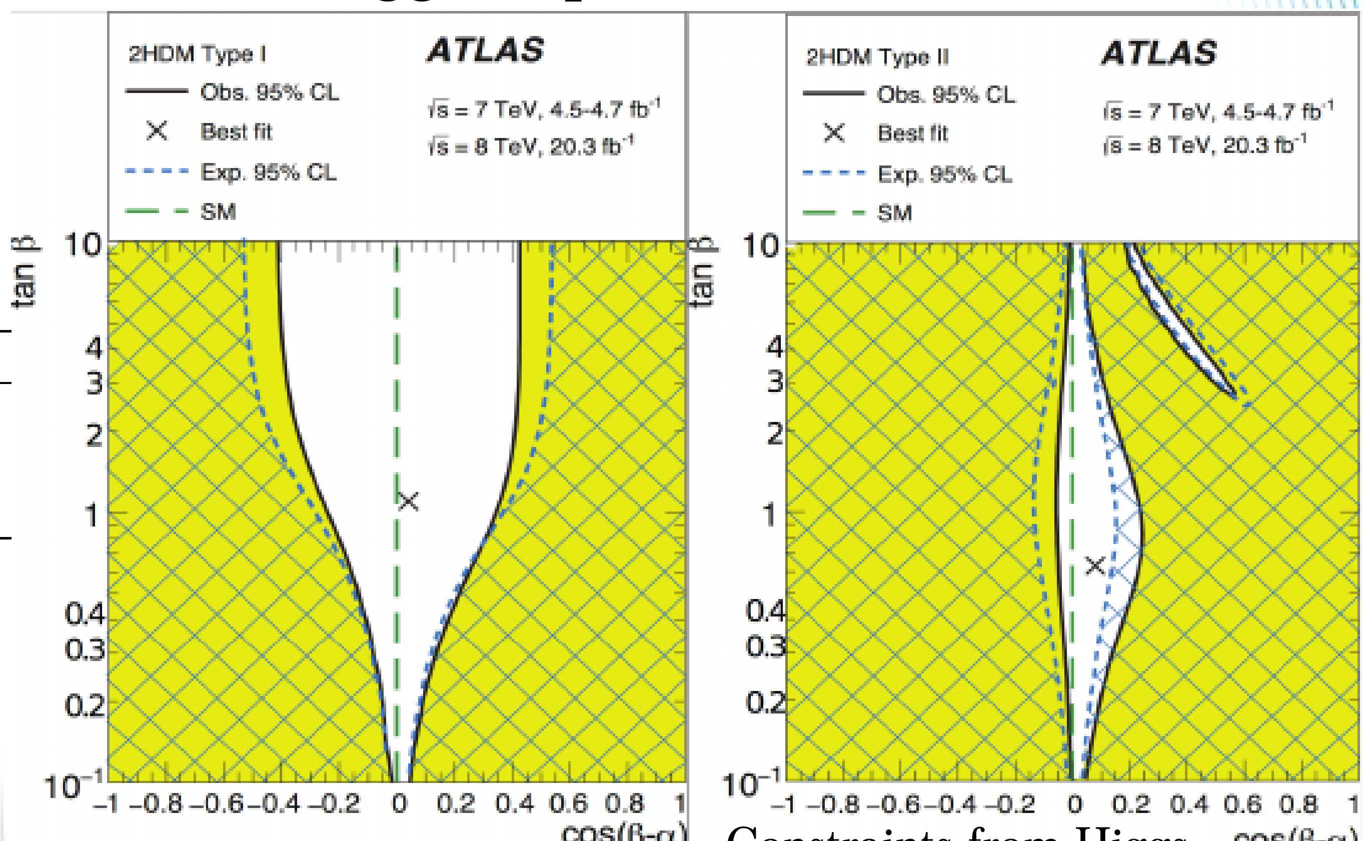
$$\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \qquad \langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}$$

$$\tan\beta \equiv \frac{v_2}{v_1}$$

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

$$\begin{aligned} h &= \rho_1 \sin\alpha - \rho_2 \cos\alpha, \\ H &= -\rho_1 \cos\alpha - \rho_2 \sin\alpha \end{aligned}$$

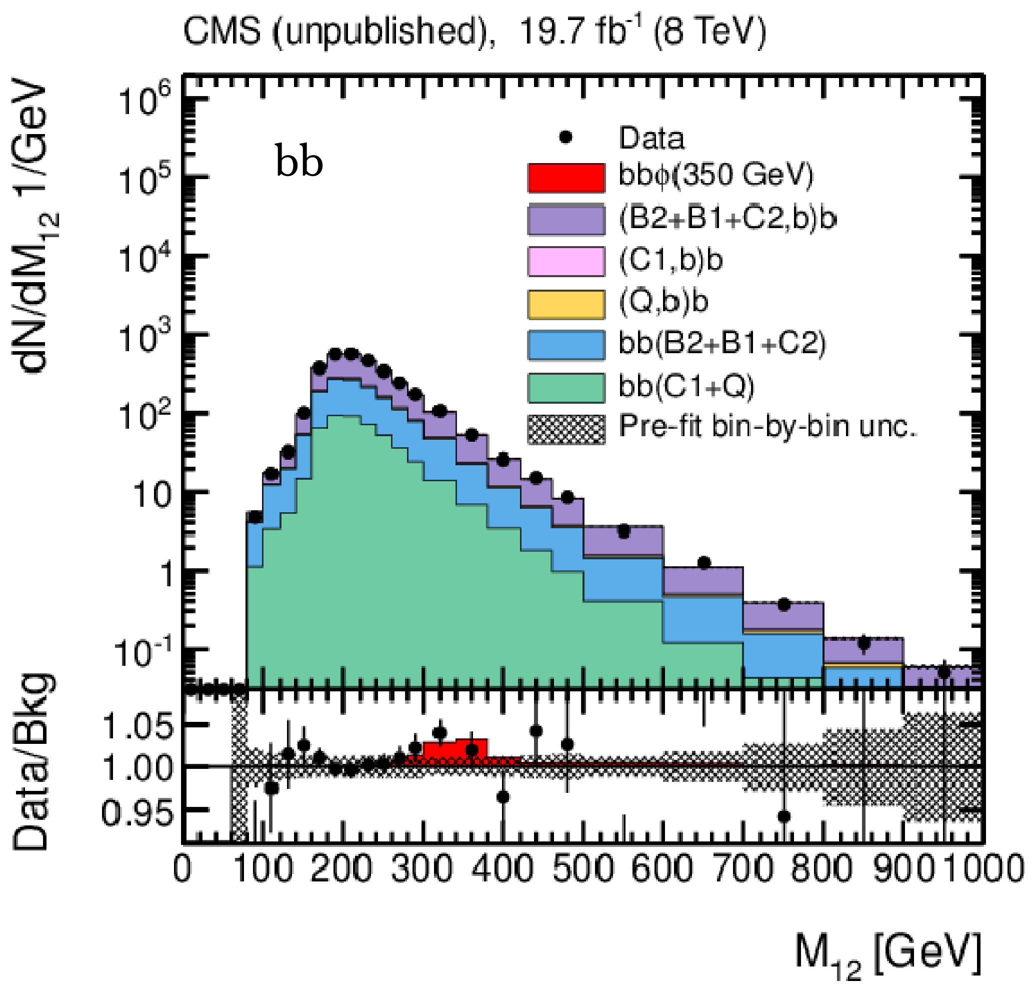
$$\begin{aligned} H^{SM} &= \rho_1 \cos\beta + \rho_2 \sin\beta \\ &= h \sin(\alpha - \beta) - H \cos(\alpha - \beta) \end{aligned}$$

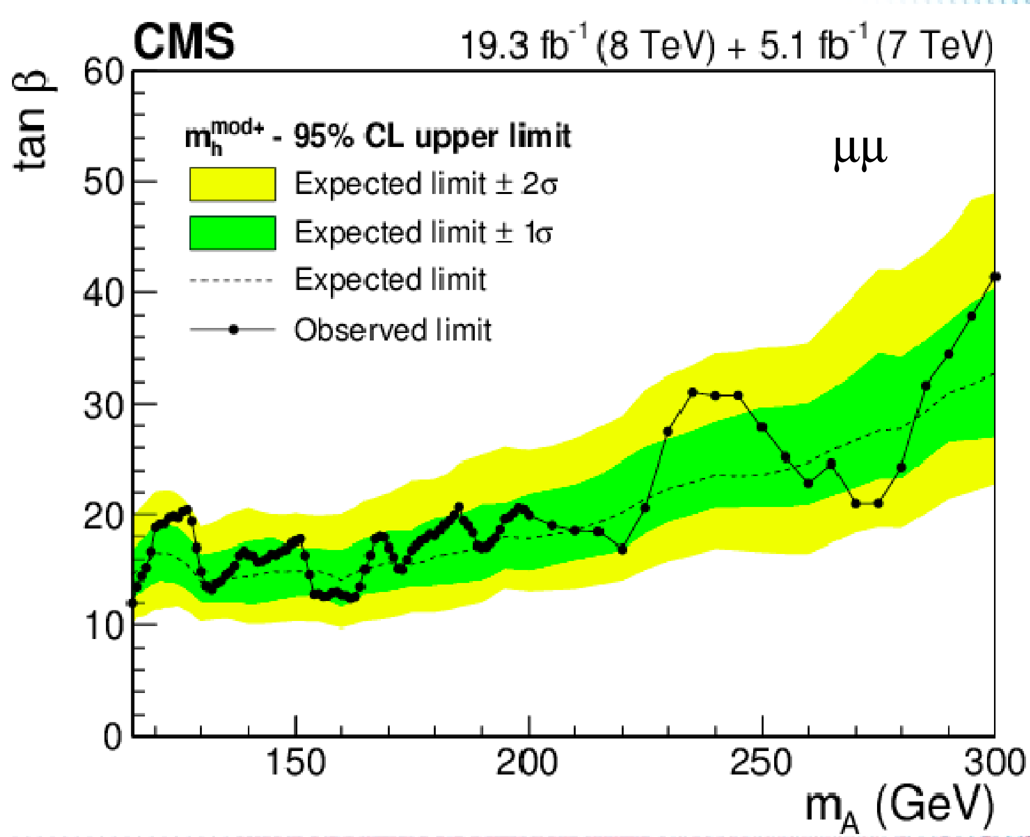


Constraints from Higgs coupling measurements

Additional Higgs bosons

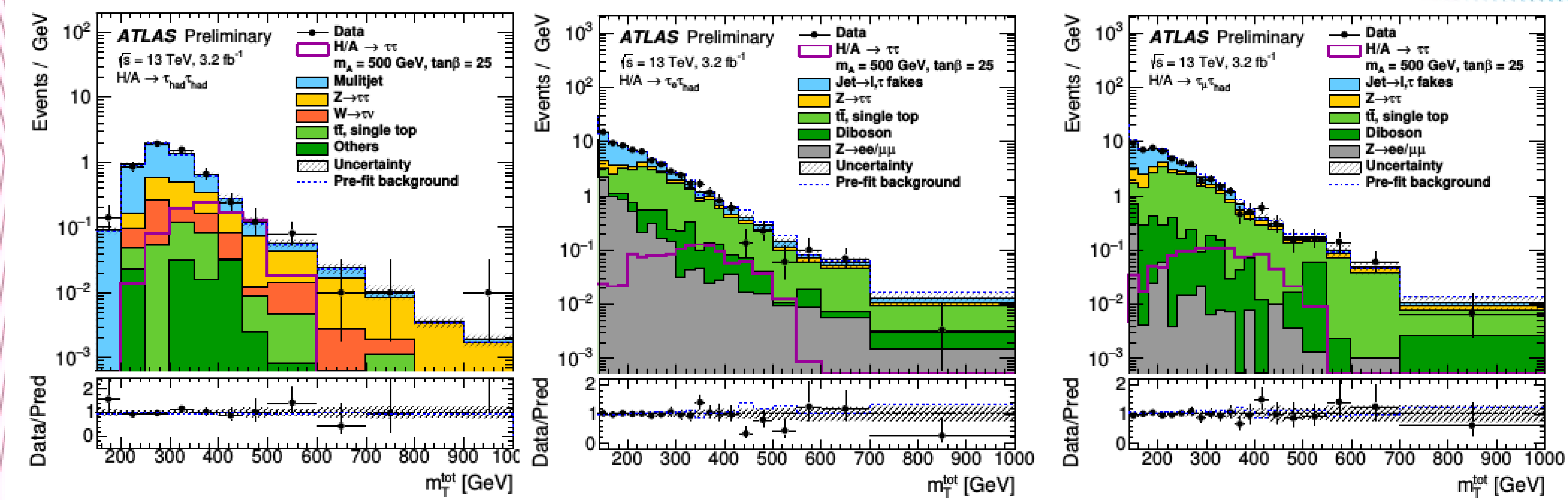
- New bosons are charged and neutral (CP-even and CP-odd)
  - High tanβ: preferentially decay to bb, ττ, μμ





Additional Higgs bosons

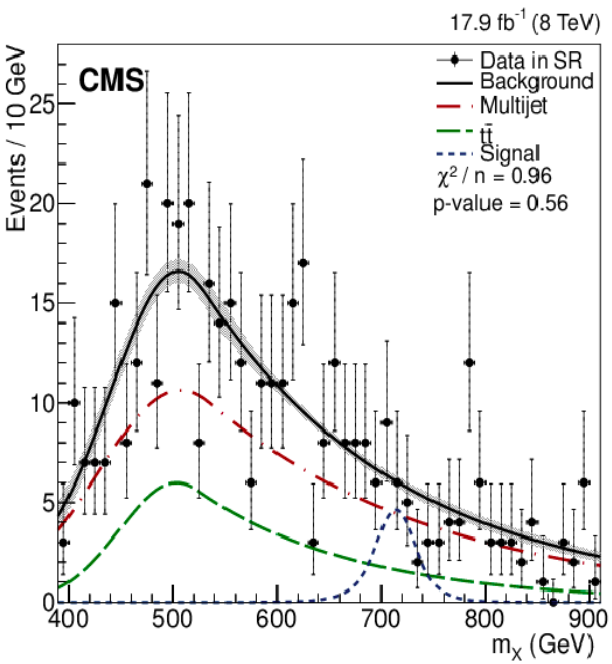
- Best sensitivity from ττ decay at high tanβ
  - First results from Run 2

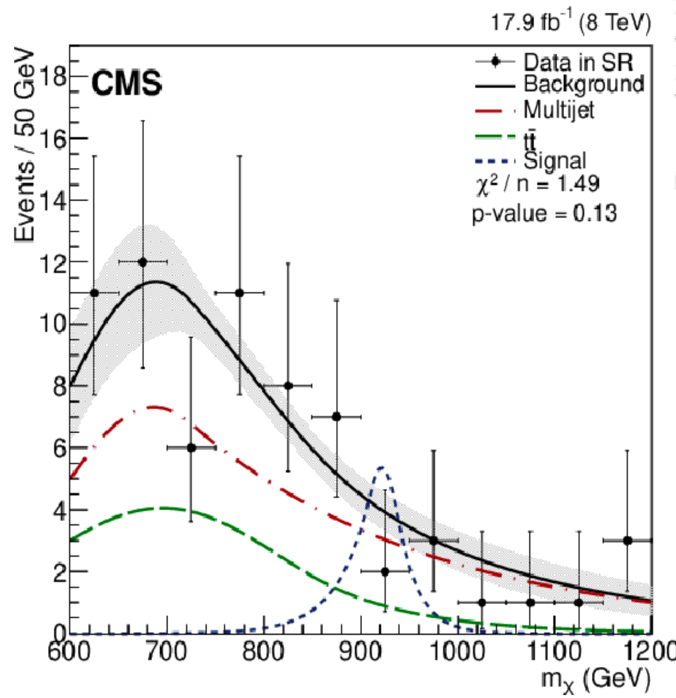


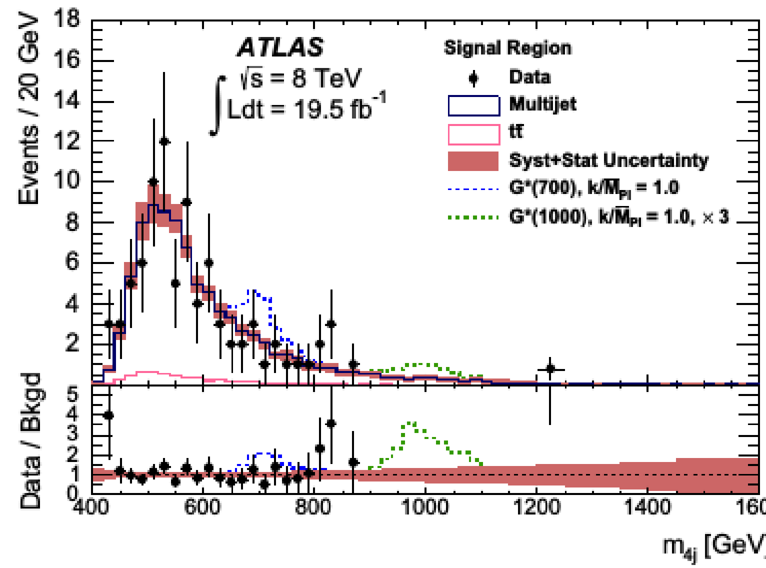
No excesses observed

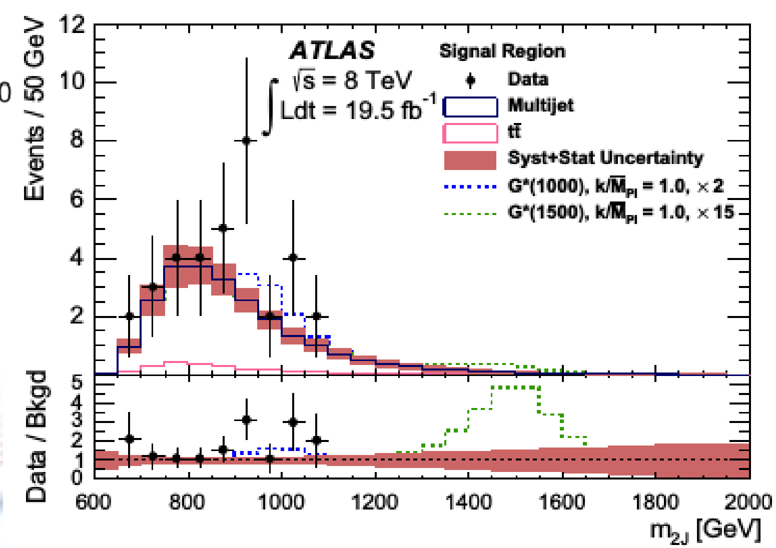
Additional Higgs bosons

- Additional CP-even Higgs boson can decay to SM Higgs pairs



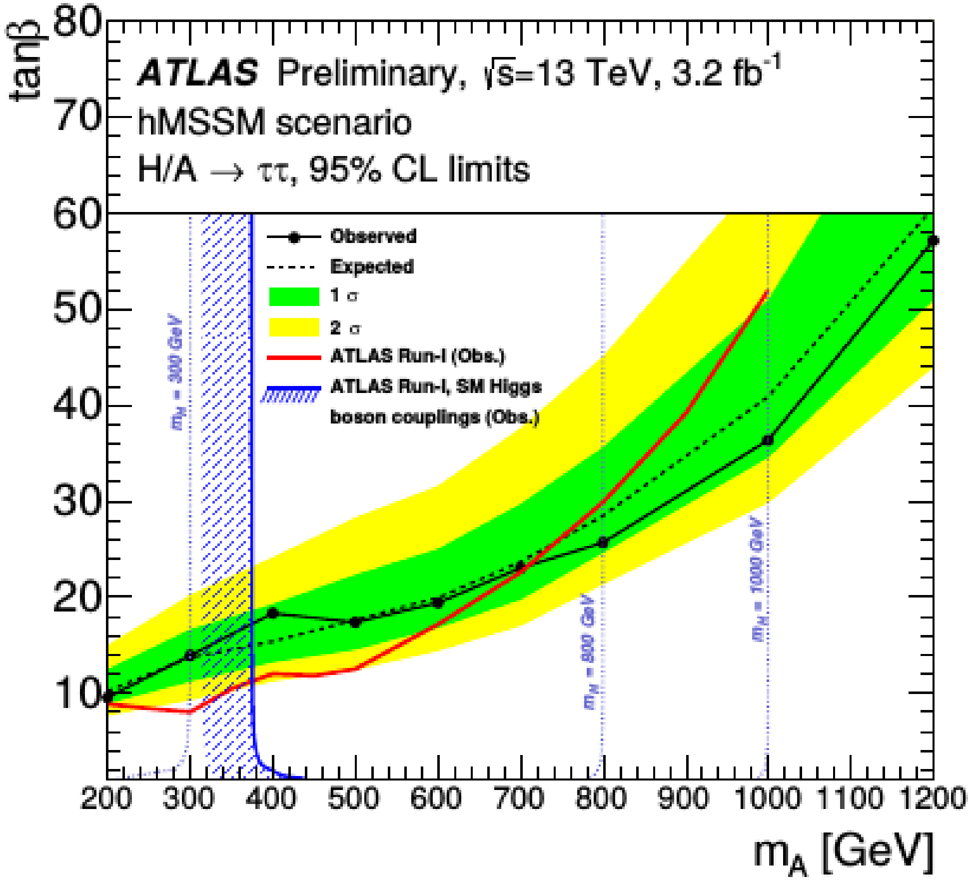




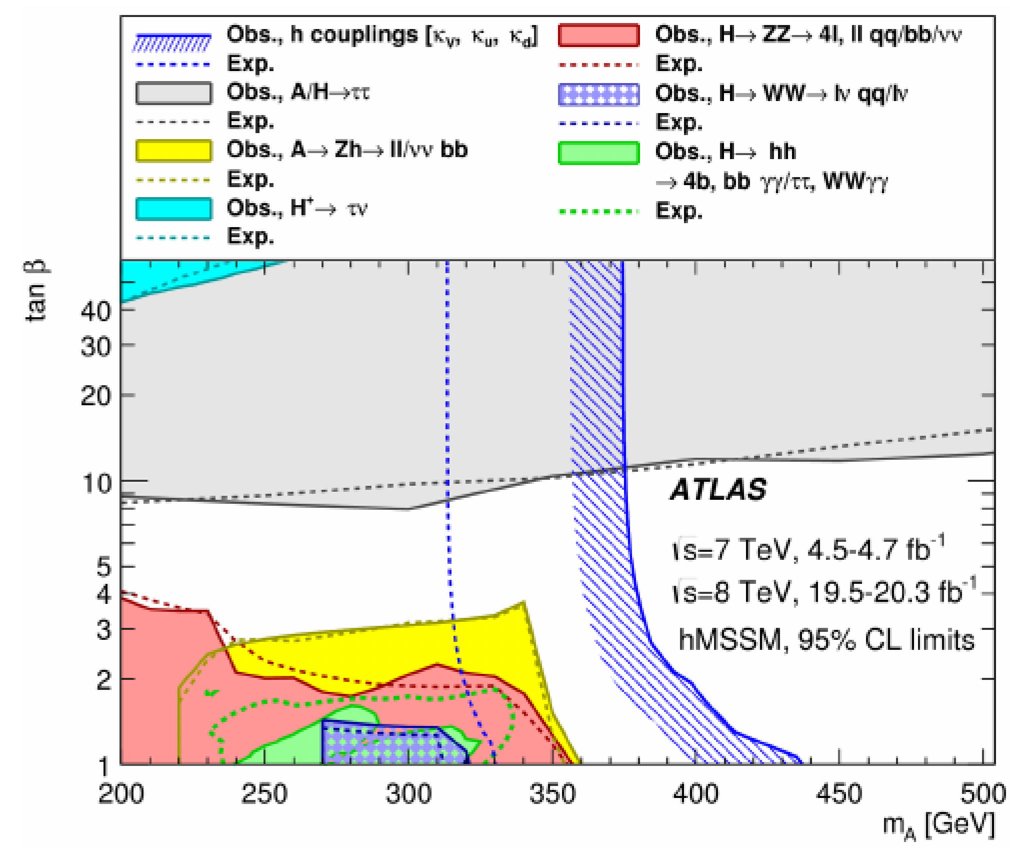


Best sensitivity in 4b final state

Additional Higgs bosons



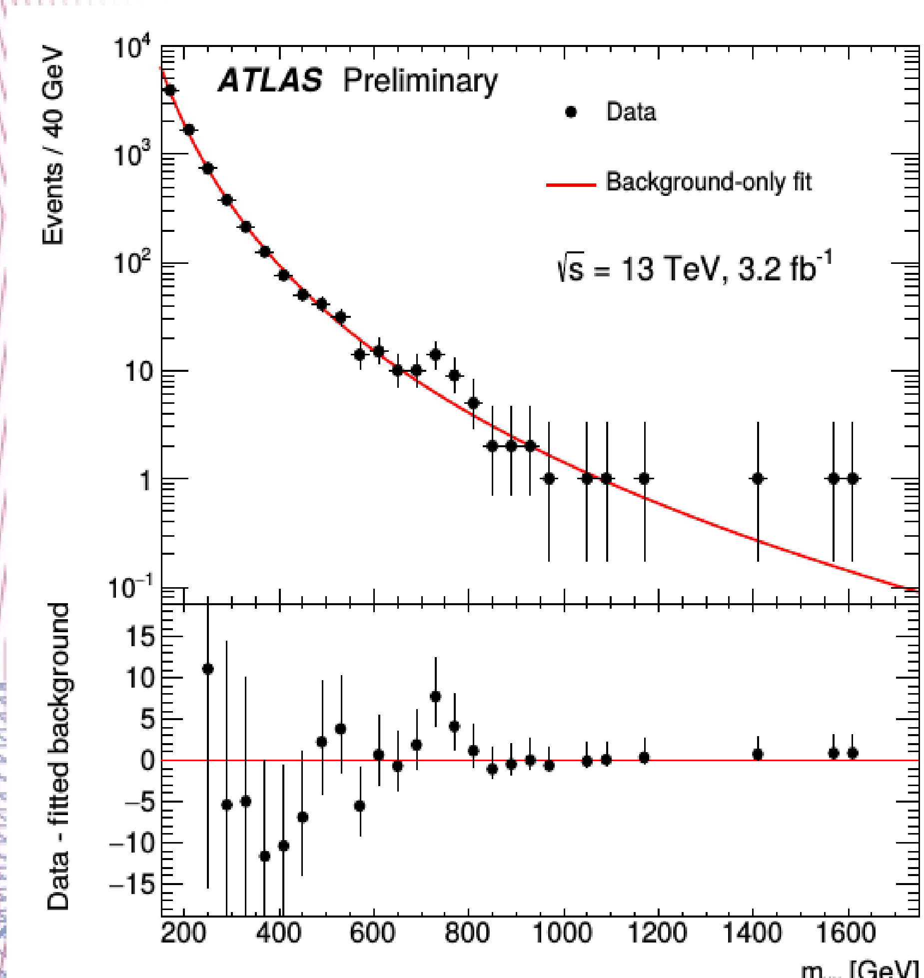
Run 2

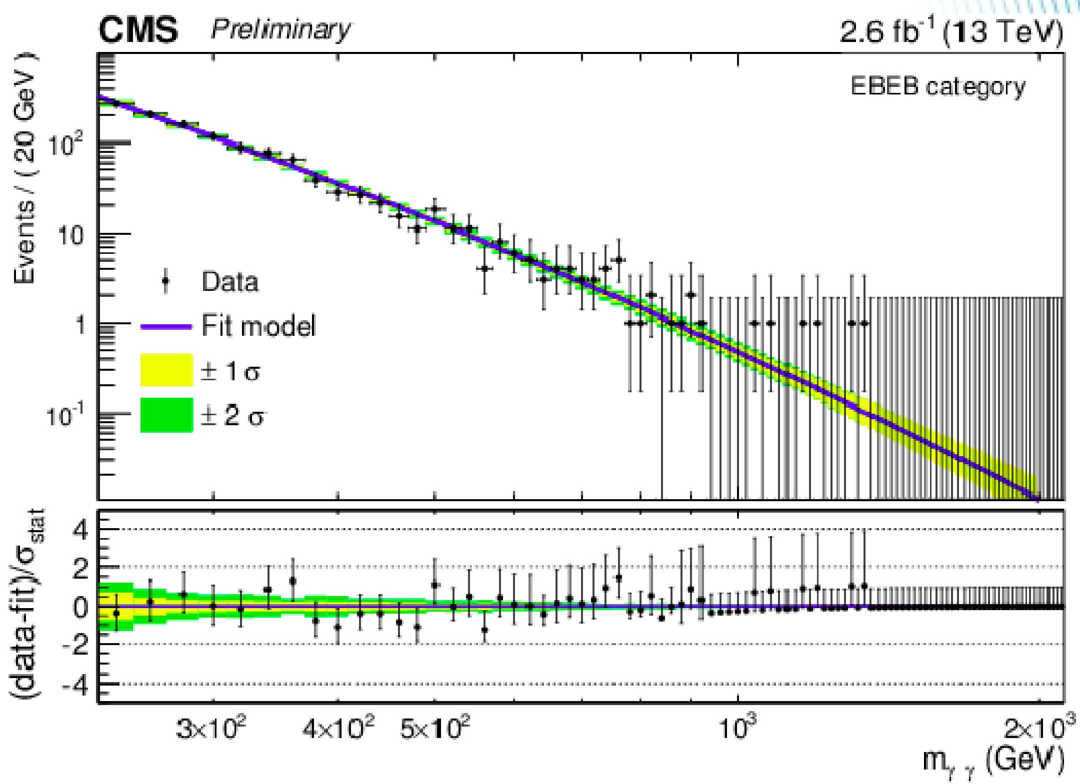


Combined Run 1

Additional Higgs bosons

- Possible to have enhanced production and decay in loops
  - Interesting Run 2 excesses in $\gamma\gamma$ mass distribution





Summary

- Run 1 saw the discovery of the Higgs boson and a comprehensive program to measure its properties
- Run 2 will probe new processes, search for small deviations in old processes, and expand the reach for additional scalars
- There is a parallel joint experimental and theoretical effort in the context of the LHC Higgs working group: a new yellow report to be released in the summer

Higgs boson production

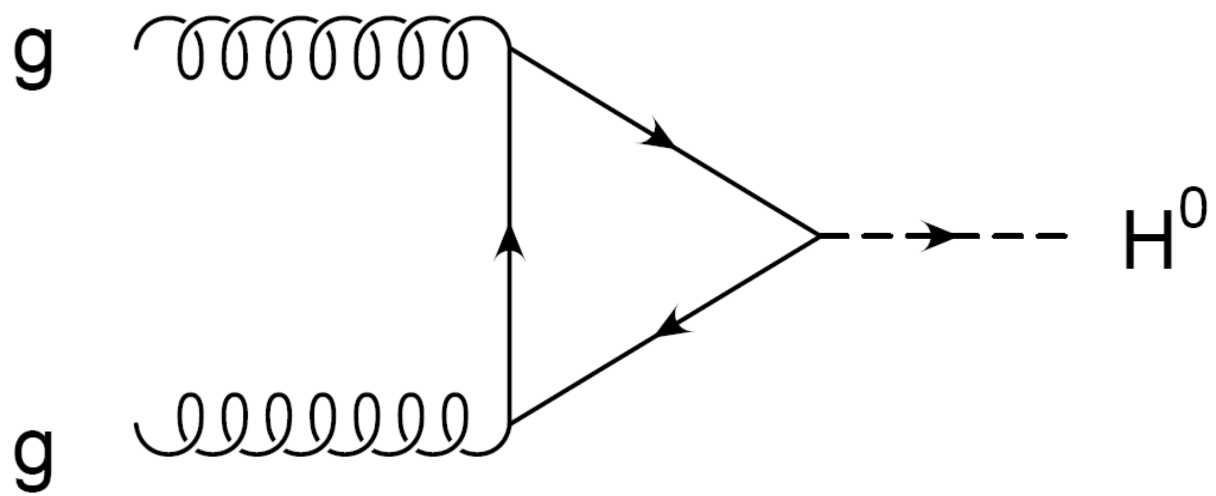
- Leading-order effective Lagrangian has limitations
  - Parameters have no sensitivity to e.g. pTH

- Ongoing work to extend to NLO and to add dimension-8 operators
  - already 59 operators at dimension-6

- Yellow report will also have prescription for connecting experimental constraints on EFT parameters to specific models

Higgs boson production

- At the LHC Higgs bosons are produced via the same kind of radiative corrections that affect the Higgs mass



Two additional gluon vertices, one fewer Higgs vertex:
sensitive to new strongly charged particles contributing to the Higgs mass

Higgs boson mass

- Supersymmetry possible solution to hierarchy problem

$$\Delta m_H^{\ 2} = -2|y_t|^2/(16\pi)\ [\Lambda^2 + \ldots]$$

The quadratic divergence cancels, leaving:

$$\Delta(m_{h^0}^2) = \frac{3}{4\pi^2}\cos^2\alpha\ \ y_t^2 m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right)$$

This adds to the tree-level expression $m_H^{\ 2} = m_Z^{\ 2}\cos^2 2\beta$