Higgs anomalous couplings, FCNC and LFV decays

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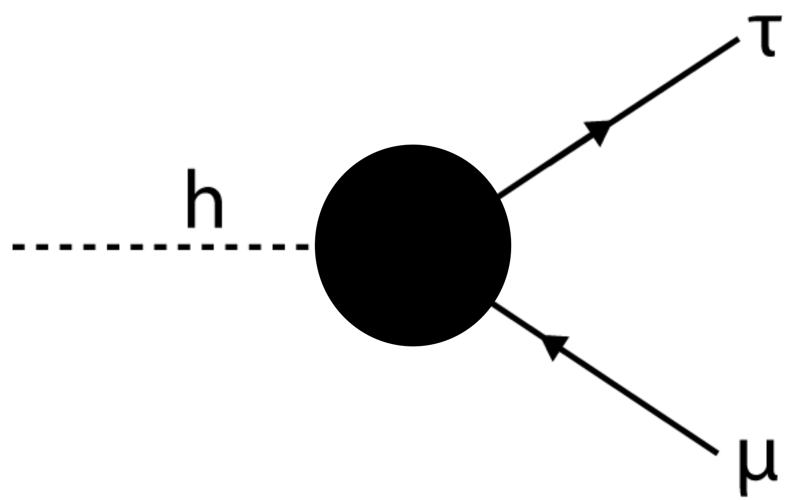
CKM 2018

Higgs LFV decay studies



Overview of results

CMS

→ Prior $H \rightarrow \mu\tau$ study using Run 1 data, 19.7 fb^{-1} @ 8 TeV showed a slight excess of events with the result

$BR(H \rightarrow \mu\tau) = 0.84^{+0.39}_{-0.37}\%$ at 68% CL

$BR(H \rightarrow \mu\tau) < 1.51\%$ at 95% CL

→ Using Run 2 data, 35.9 fb^{-1} @ 13 TeV, decay modes used to search for $H \rightarrow \mu\tau, e\tau$:

$\mu\tau_h, e\tau_h, \mu\tau_l + e\tau_l$ joint search

→ Results obtained are

$BR(H \rightarrow \mu\tau) < 0.25\%$ at 95% CL

$BR(H \rightarrow e\tau) < 0.61\%$ at 95% CL

→ JHEP 06 (2018) 001

ATLAS

→ Using Run 1 data, 20.3 fb^{-1} @ 8 TeV

→ Decay modes to search for $H \rightarrow \mu\tau, e\tau$:

$\mu\tau_h, e\tau_h, \mu\tau_e + e\tau_\mu$ joint search

→ Results obtained are

$BR(H \rightarrow \mu\tau) < 1.43\%$ at 95% CL

$BR(H \rightarrow e\tau) < 1.04\%$ at 95% CL

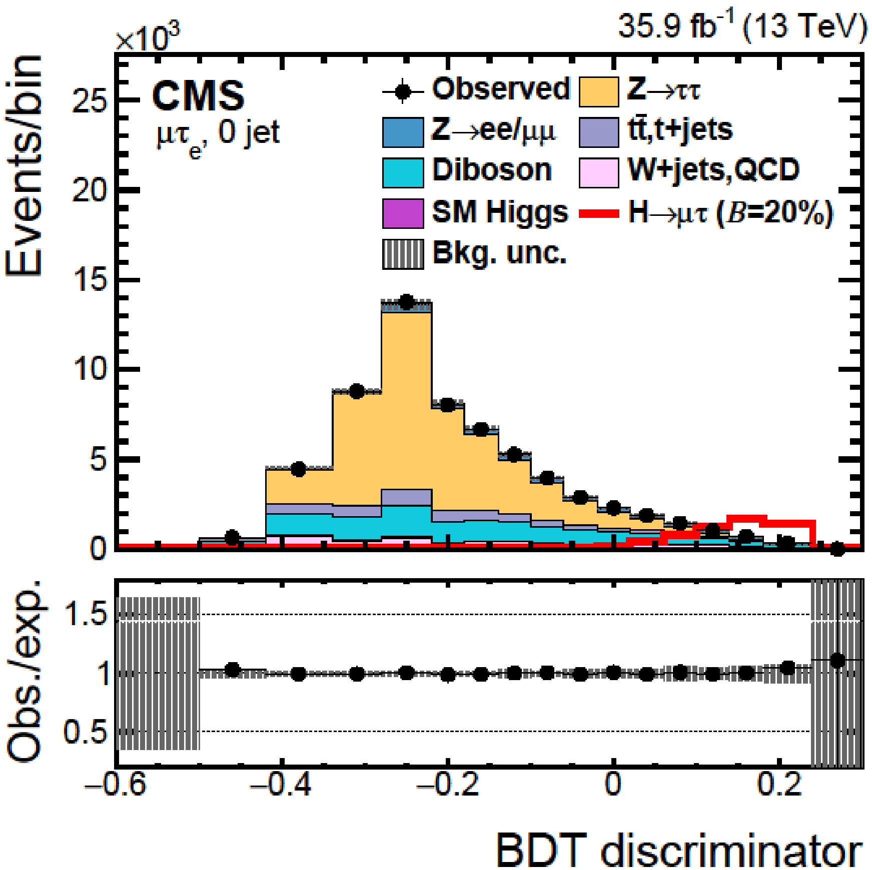
→ JHEP 11 (2015) 211

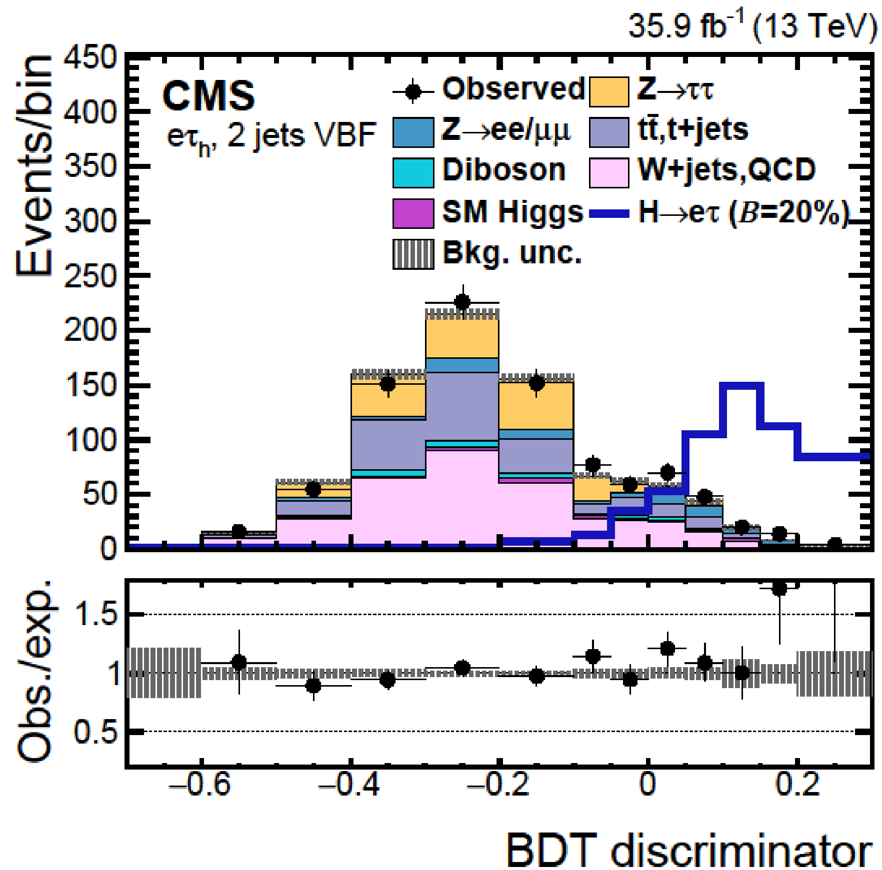
→ EPJ C 77 (2017) 70 latest, includes combination with above.

CMS analysis: Strategy

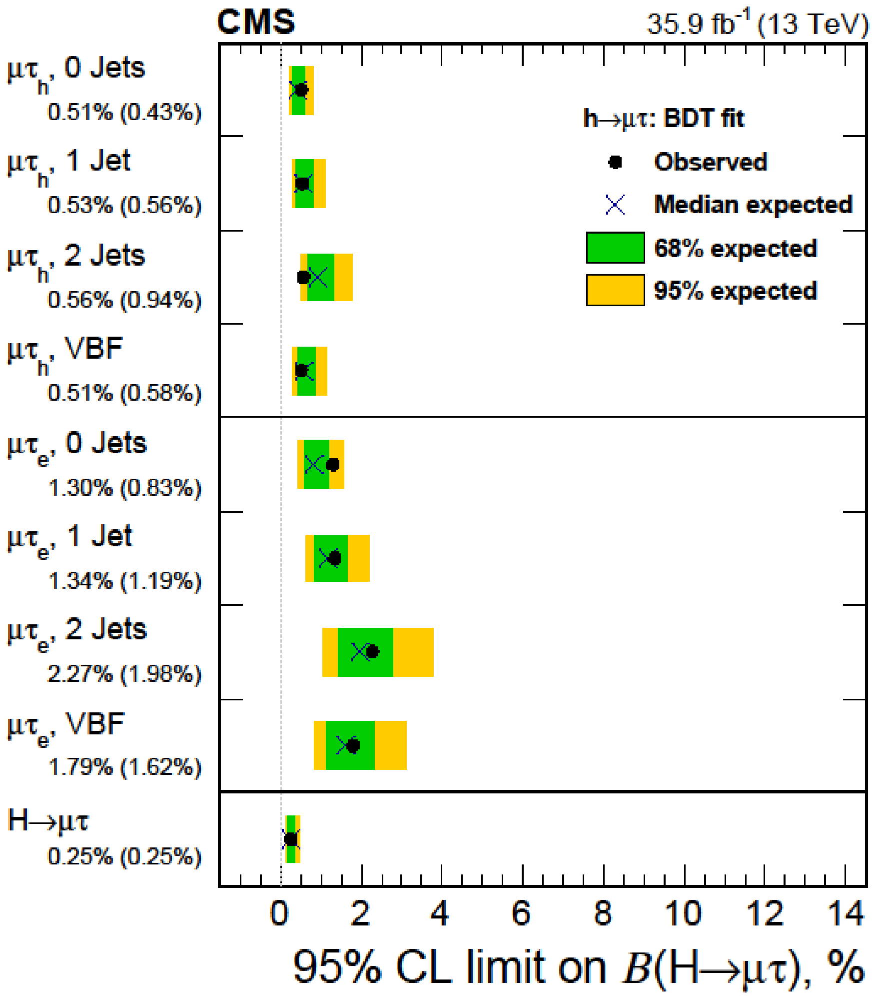
→ Main improvement since previous results is the inclusion of signal vs bkg. BDTs in likelihood. Tighter cuts and the use of M_{col} is used as a cross-check method.

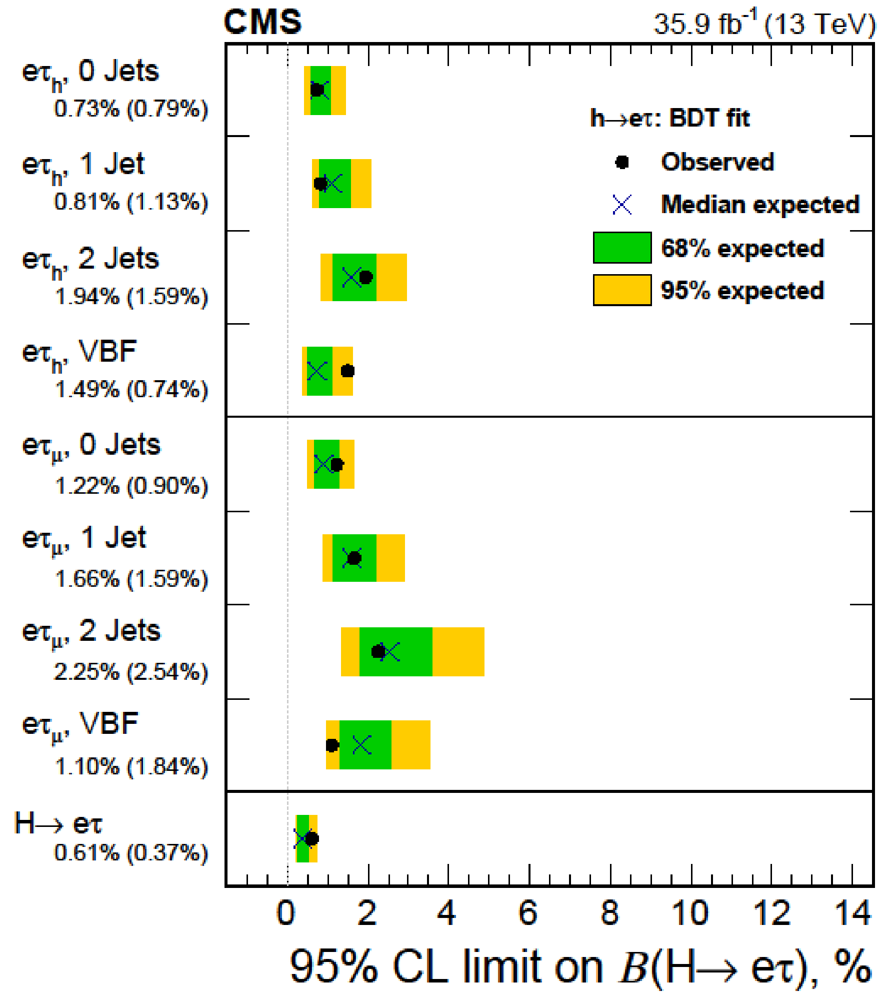
→ Categorization based on associated jets: 0-jet, 1-jet, 2-jet ggH ($m_{jj} < 550$ GeV), and 2-jet VBF ($m_{jj} > 550$ GeV)





CMS analysis: Results

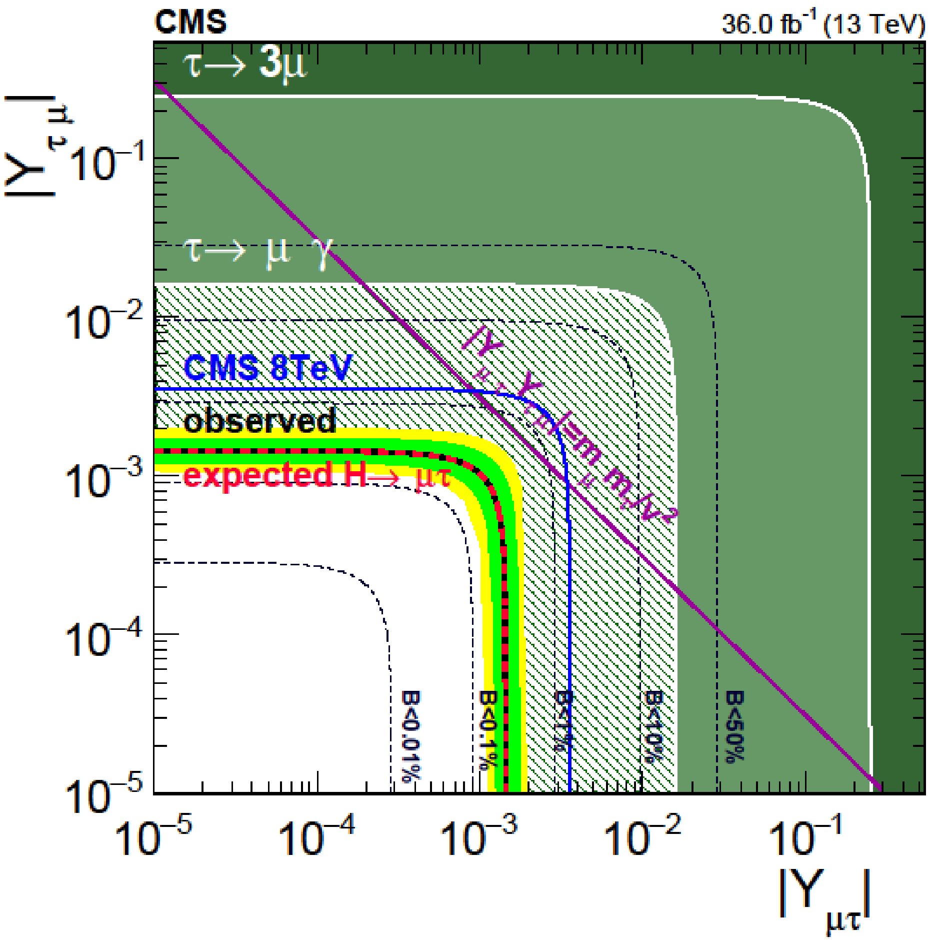


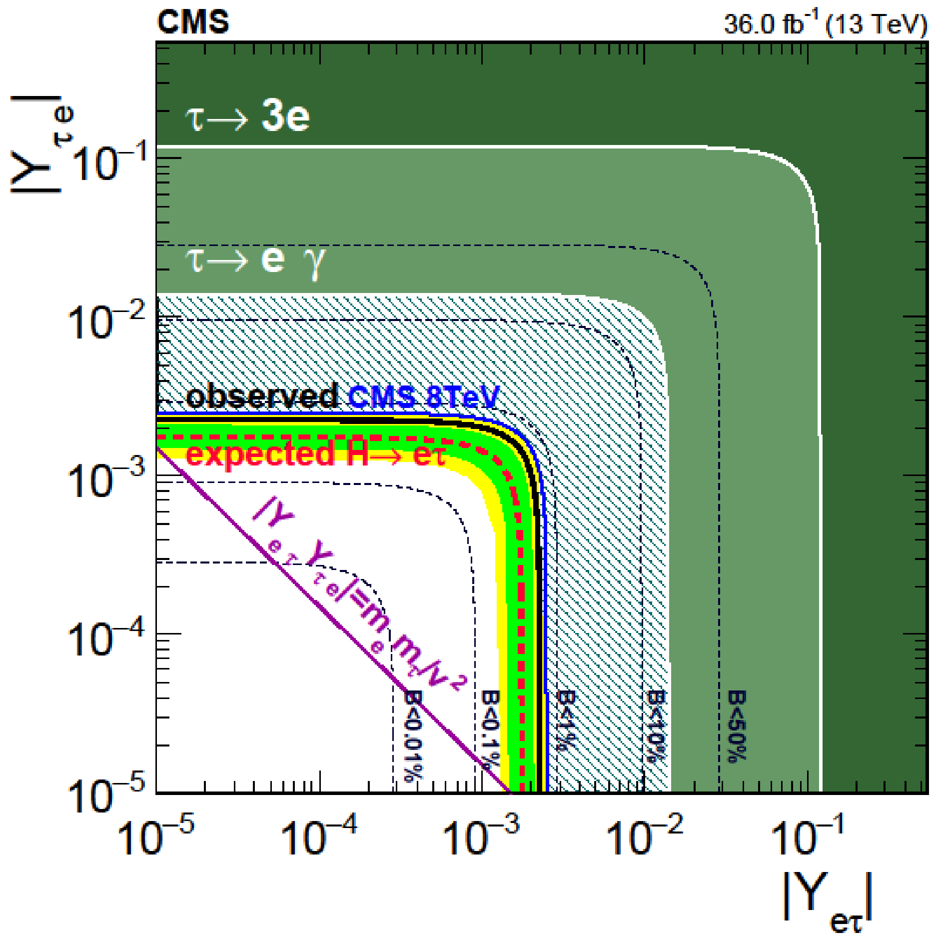


$BR(H \to \mu\tau) < 0.25\%$ at 95% CL

$BR(H \to e\tau) < 0.61\%$ at 95% CL

CMS analysis: Interpretation





$$\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{m_\mathrm{H}}{8\pi}\left(|Y_{\ell^\beta \ell^\alpha}|^2 + |Y_{\ell^\alpha \ell^\beta}|^2\right)$$

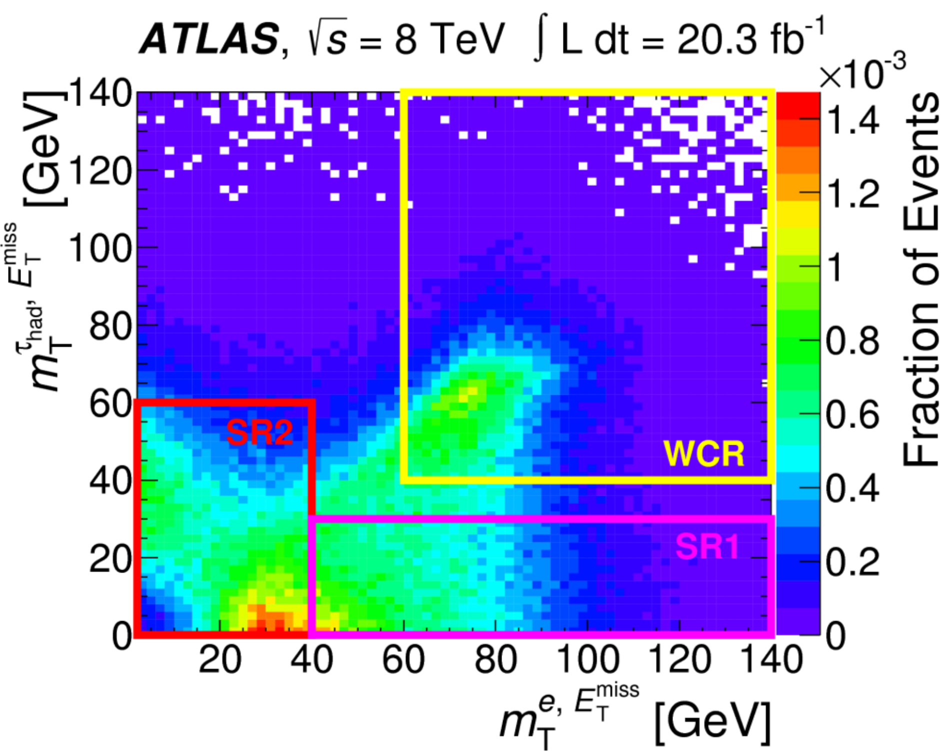
$$\mathcal{B}(\mathrm{H} \to \ell^\alpha \ell^\beta) = \frac{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta)}{\Gamma(\mathrm{H} \to \ell^\alpha \ell^\beta) + \Gamma_\mathrm{SM}}$$

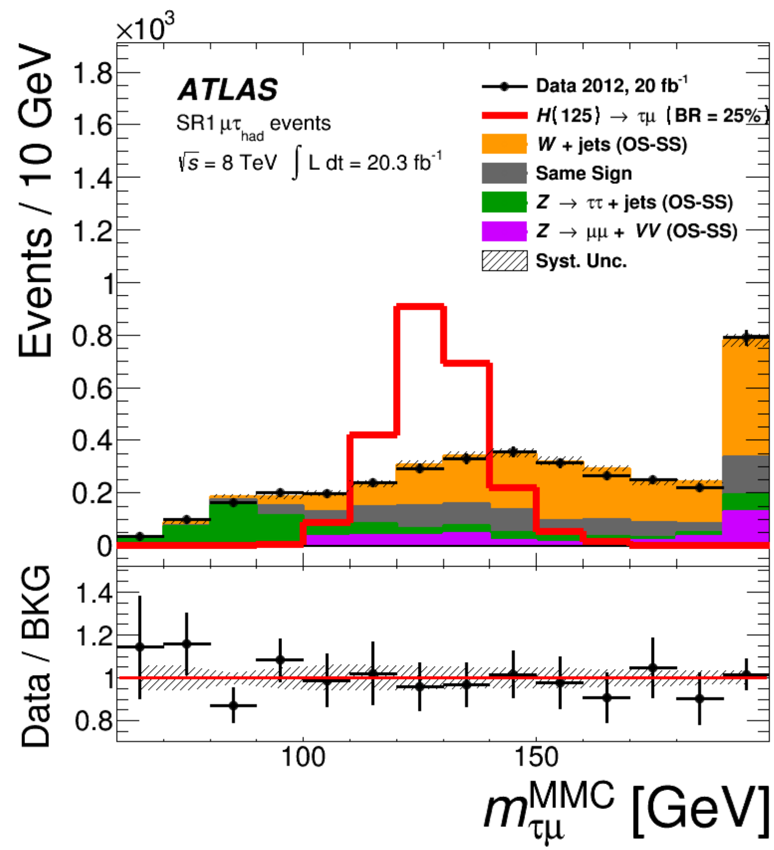
	BDT fit
$\sqrt{\lvert Y_{\mu\tau}\rvert^2 + \lvert Y_{\tau\mu}\rvert^2}$	$< 1.43 \times 10^{-3}$
$\sqrt{\lvert Y_{e\tau}\rvert^2 + \lvert Y_{\tau e}\rvert^2}$	$< 2.26 \times 10^{-3}$

ATLAS analysis: $\mu\tau_h$ and $e\tau_h$ strategy

→ Events are divided into two signal regions and a W+jets control region in the $m_T^{l,E_T^{miss}}$ - $m_T^{\tau_h,E_T^{miss}}$ plane ($m_T^{l,E_T^{miss}} = \sqrt{2p_T^l E_T^{miss}(1-cos\phi)}$)

→ The likelihood is constructed as a function of the Missing Mass Calculator Mass $m_{l\tau}^{MMC}$.



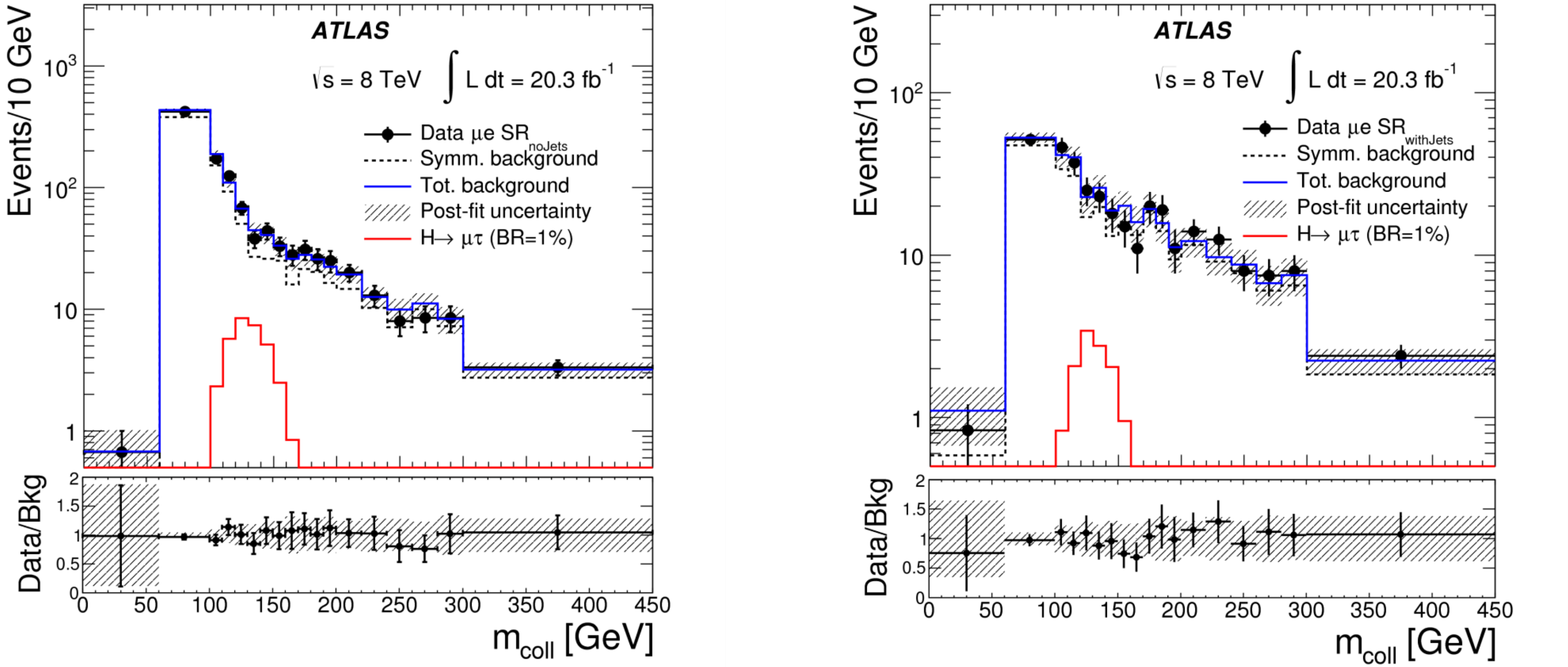


ATLAS analysis: $\mu\tau_e$ and $e\tau_\mu$ strategy

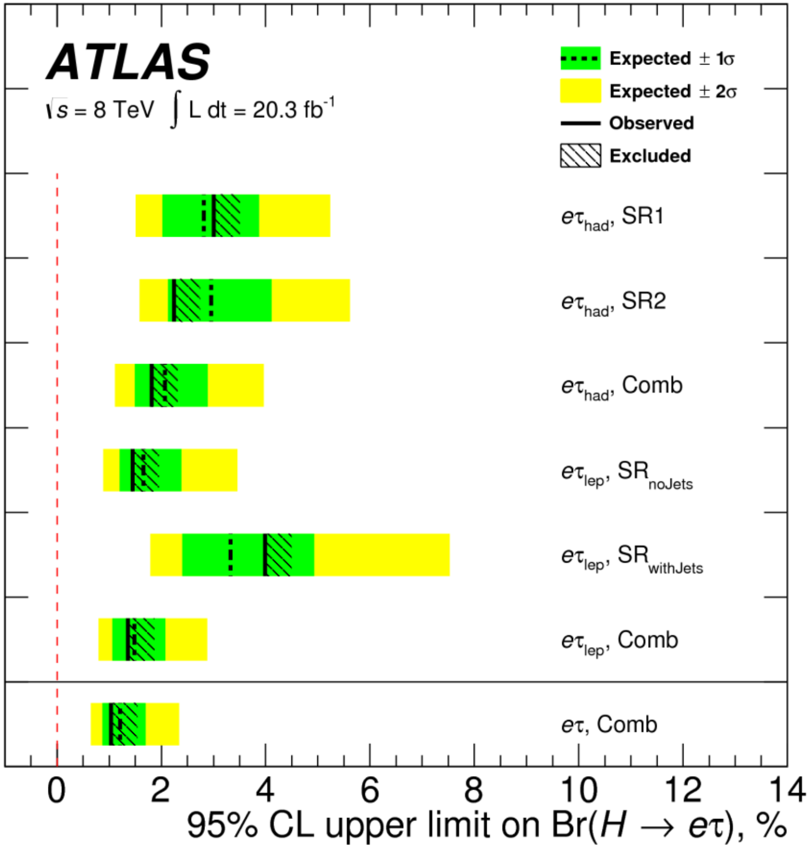
→ Events are divided in two signal regions: SR_{noJets} with no central ($|\eta_j| < 2.4$) jets, and $SR_{withJets}$ with ≥ 1 central jets with no b-tag.

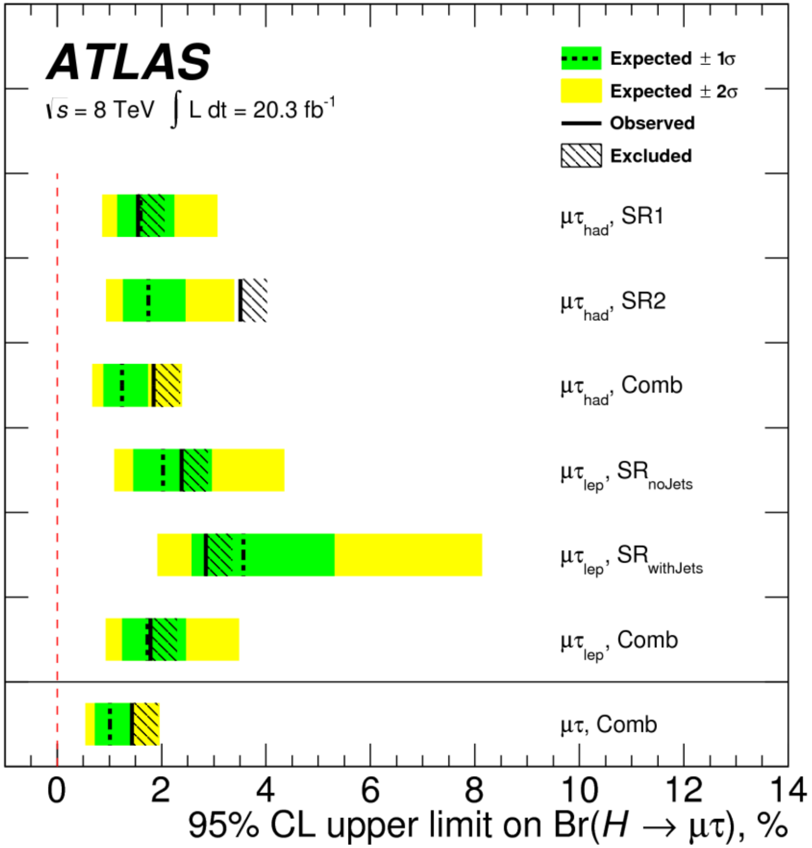
→ The likelihood is constructed as a function of the collinear mass m_{coll}.

→ Data-driven method exploiting symmetry of SM background μe and $e\mu$ processes, up to corrections for mis-id leptons or trigger efficiency.



ATLAS analysis: Results

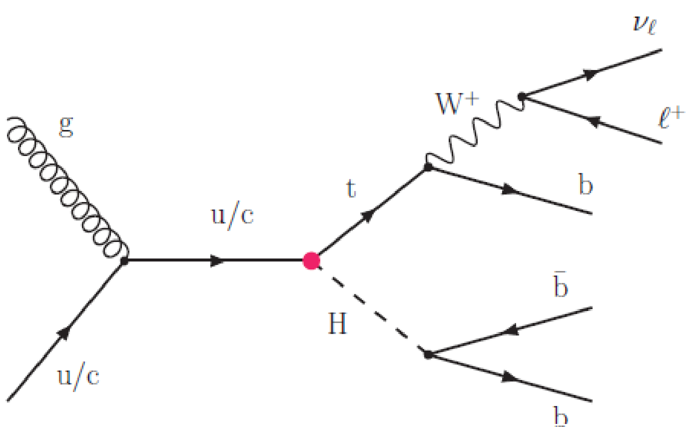


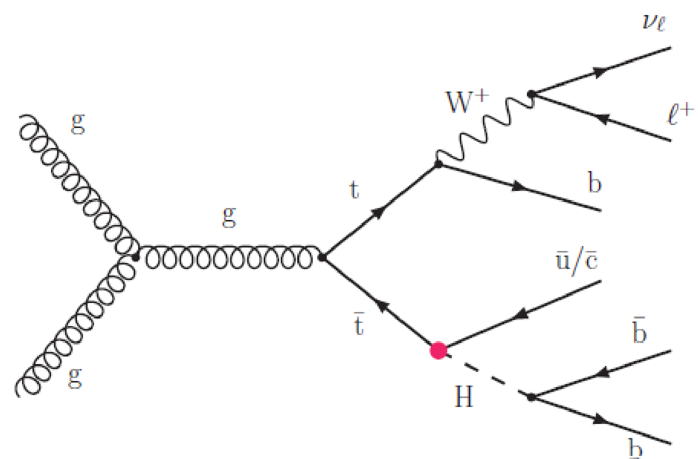


$BR(H \to e\tau) < 1.04\%$ at 95% CL

$BR(H \to \mu\tau) < 1.43\%$ at 95% CL

Higgs FCNC studies





Overview of results

CMS

→ Prior study on $t \to Hq$ $(q = c, u)$ via $t\bar{t}$ pair production using Run 1 data, 19.7 fb^{-1} @ 8 TeV showed no excess of events with the results

$BR(t \to Hu) < 0.55\%$ at 95% CL

$BR(t \to Hc) < 0.40\%$ at 95% CL

→ Run 2 result using 35.9 fb^{-1} @ 13 TeV via single top and top pair production with $H \to b\bar{b}$ decay

→ Results obtained are

$BR(t \to Hu) < 0.47\%$ at 95% CL

$BR(t \to Hc) < 0.47\%$ at 95% CL

→ JHEP 06 (2018) 102

ATLAS

→ Prior study on $t \to Hq$ $(q = c, u)$ via $t\bar{t}$ pair production using Run 1 data, 20.3 fb^{-1} @ 8 TeV showed no excess of events with the results

$BR(t \to Hu) < 0.45\%$ at 95% CL

$BR(t \to Hc) < 0.46\%$ at 95% CL

→ Run 2 result using 36.1 fb^{-1} @ 13 TeV via top pair production with $H \to \gamma\gamma$ decay

→ Results obtained are

$BR(t \to Hu) < 0.24\%$ at 95% CL

$BR(t \to Hc) < 0.22\%$ at 95% CL

→ Also using multi-lepton final states WW, ZZ and $\tau\tau$:

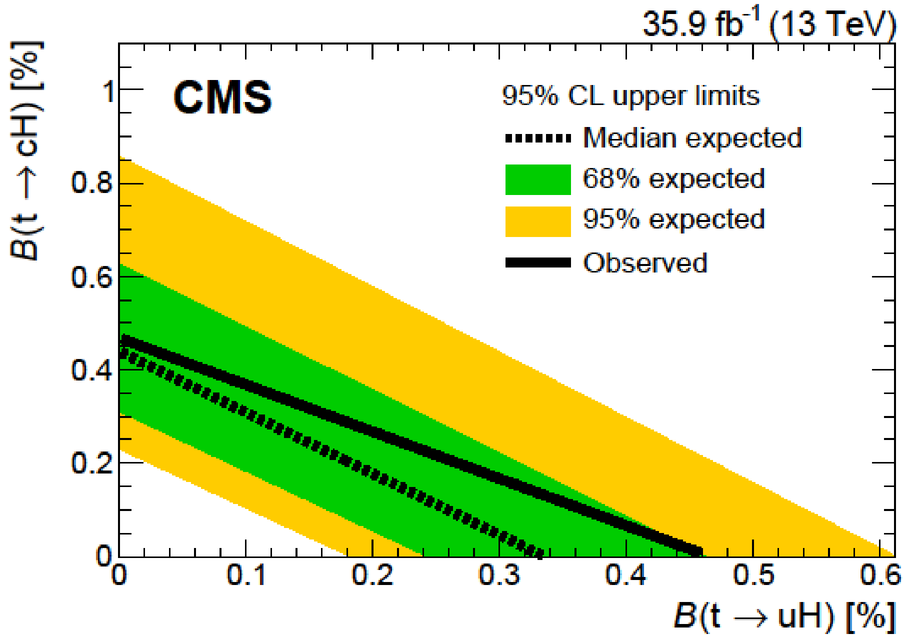
$BR(t \to Hu) < 0.19\%$ at 95% CL

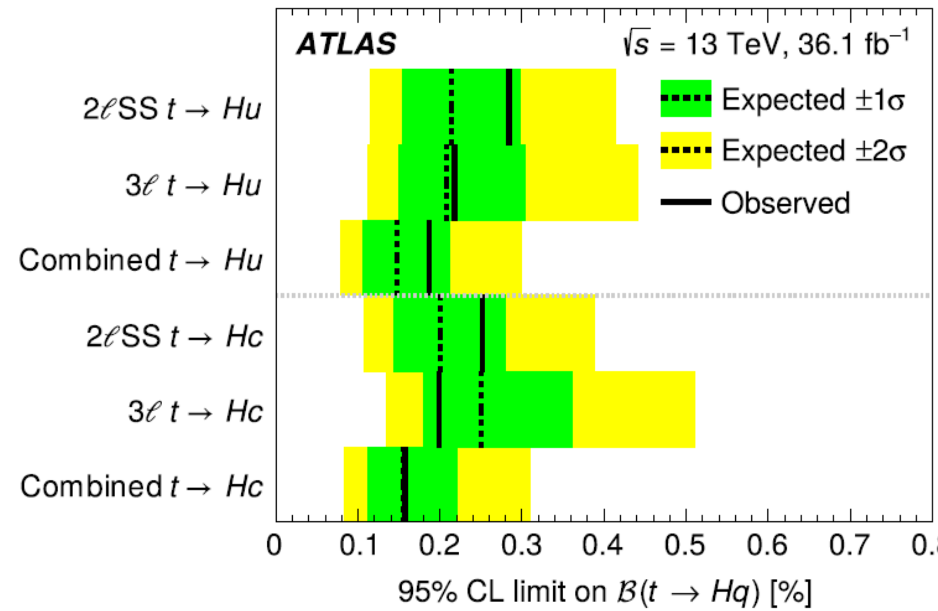
$BR(t \to Hc) < 0.16\%$ at 95% CL

→ JHEP 10 (2017) 129

→ Phys. Rev. D 98 (2018) 032002

Overview of results





→ Results obtained are

$BR(t \to Hu) < 0.47\%$ at 95% CL

$BR(t \to Hc) < 0.47\%$ at 95% CL

→ JHEP 06 (2018) 102

See Gagan Mohanty's talk for more details

→ $\gamma\gamma$ results:

$BR(t \to Hu) < 0.24\%$ at 95% CL

$BR(t \to Hc) < 0.22\%$ at 95% CL

→ Multi-lepton final states WW, ZZ and $\tau\tau$:

$BR(t \to Hu) < 0.19\%$ at 95% CL

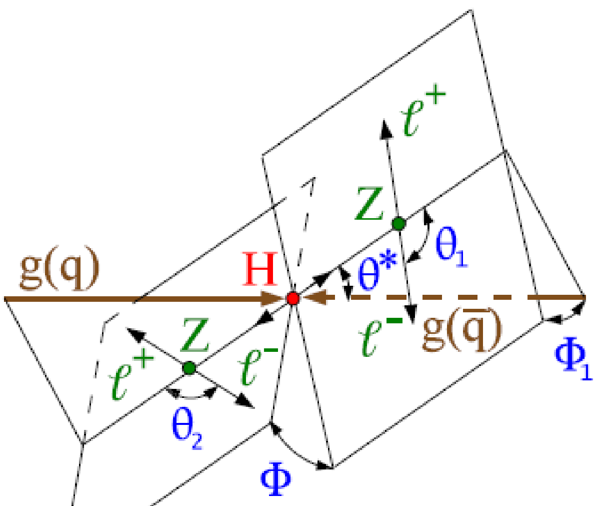
$BR(t \to Hc) < 0.16\%$ at 95% CL

→ JHEP 10 (2017) 129

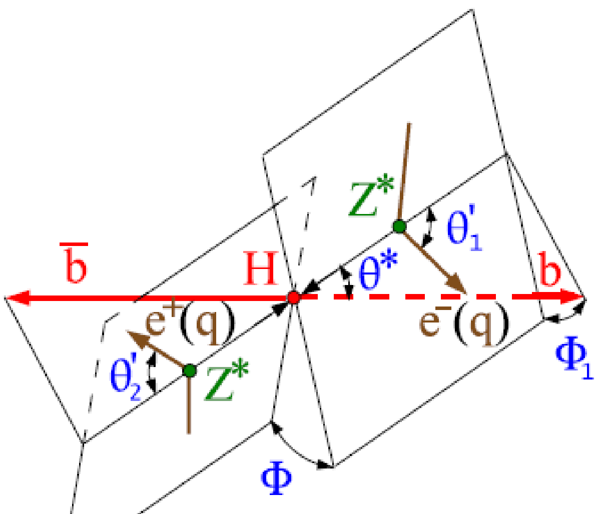
→ Phys. Rev. D 98 (2018) 032002

→ See also Markus's talk for tighter results

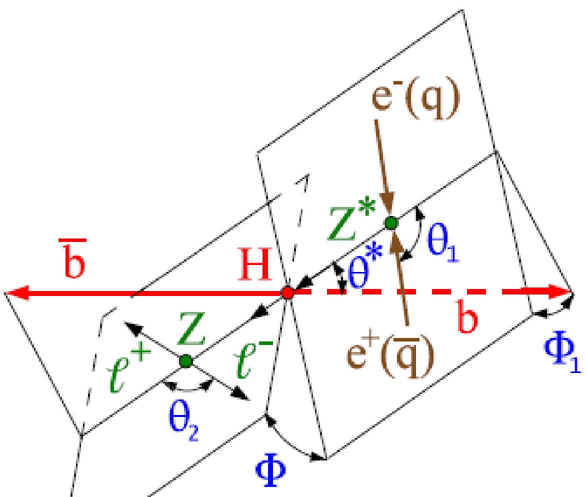
Anomalous couplings studies



$H \to VV$



$VV \to H$ (VBF)



$V^* \to VH$

Overview of results

CMS

→ Different measurements done using production or decay information in Run 1, e.g. $VH(\rightarrow b\bar{b})$

→ Run 2 result using 80.2 fb^{-1} @ 13 TeV with Run 1 combination most recent result using dedicated amplitude formalism

→ Tests fraction of anomalous HVV couplings in on-shell Higgs production with decay to $4l$

→ Joint treatment with Higgs total width Γ_H constraints using the off-shell technique

→ CMS-PAS-HIG-18-002 very recent

ATLAS

→ Different measurements done using production or decay in Run 1, e.g. VBF $H(\rightarrow \tau\tau)$

→ Run 2 results using 36.1 fb^{-1} @ 13 TeV using $H \rightarrow \gamma\gamma$ or $H \rightarrow 4l$ decay

→ Results are obtained as part of differential cross section measurements (fiducial cross sections, simplified template cross sections - STXS) and the Effective Field Theory approaches Pseudo-Observables - PO, Higgs characterization frameworks or in terms of Wilson coefficients.

→ $4l$ inclusive and differential cross section: JHEP 10 (2017) 132
→ $4l$ couplings: JHEP 03 (2018) 095
→ $\gamma\gamma$ couplings: arxiv1802.04146

CMS analysis: HVV couplings

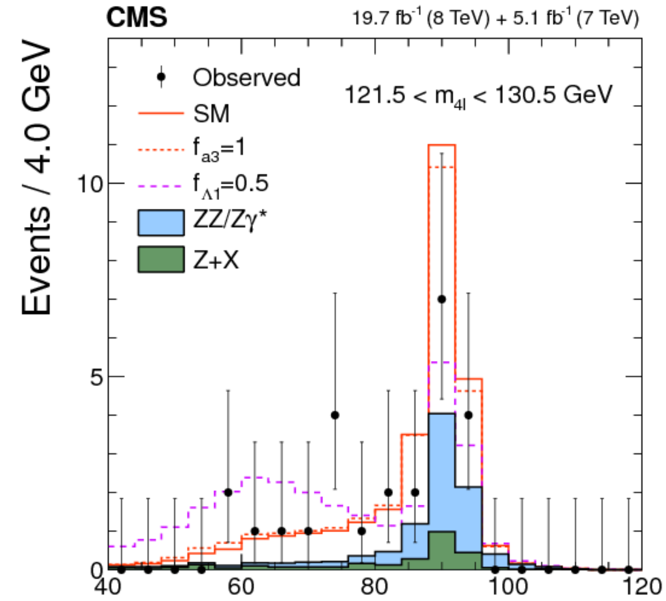
$$A(HVV) \sim \left[\boldsymbol{a_1} - e^{i\phi_{\Lambda Q}} \frac{q_H^2}{\Lambda_Q^2} - e^{i\phi_{\Lambda 1}^{VV'}} \frac{(\kappa_1 q_{V1}^2 + \kappa_2 q_{V2}^2)}{\Lambda_1^2} \right] m_V^2 \epsilon_{V1}^* \epsilon_{V2}^*$$
$$+ \mathrm{a}_2 \mathrm{f}_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \mathrm{a}_3 \mathrm{f}_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}$$

→ Any anomalous coupling can be described with an effective on-shell cross sectional fraction and a phase defined for $2f2f'$ decay:

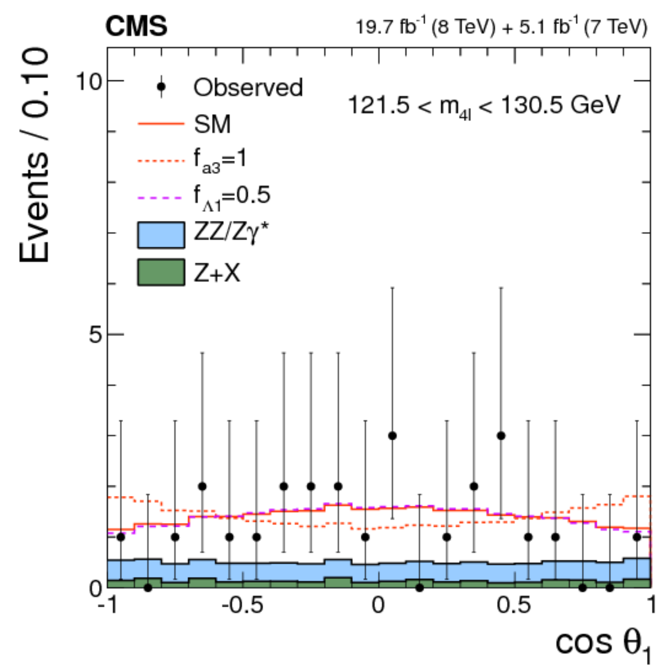
$$f_{\mathrm{ai}} = \frac{|a_i|^2 \sigma_i}{\sum_j |a_j|^2 \sigma_j} \qquad \phi_{\mathrm{ai}} = \tan^{-1}(a_i/a_1)$$

→ $f_{\Lambda Q}$ observable only from off-shell. Others can be measured from either on-shell or off-shell.

→ Formalisms used by ATLAS are equivalent with different ways of parameterizing AC couplings



Phys. Rev. D 92 (2015) 012004



CMS analysis: Off-shell technique

On−shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{m_H^2 \Gamma_H^2} dq_H^2 \propto \mu_{prod}$

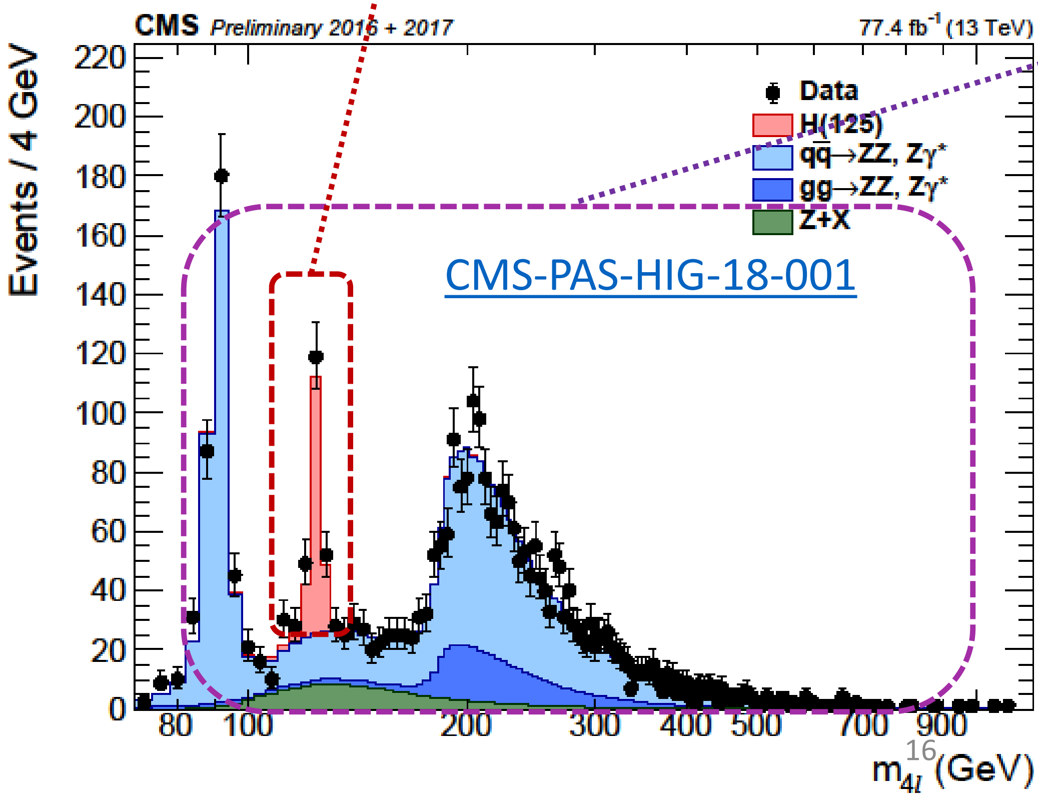
→ $\Gamma_H \lesssim 1$ GeV, limited by resolution

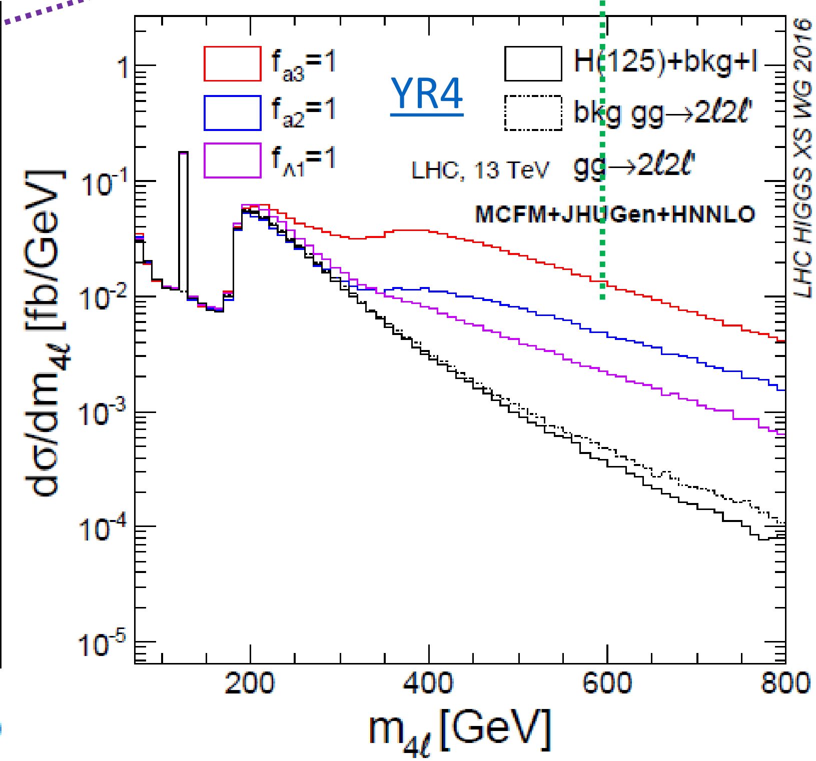
→ Very sensitive to production and decay kinematics

Off−shell: $\rightarrow \frac{g_{prod}^2 g_{dec}^2}{(q_H^2 - m_H^2)^2} dq_H^2 \propto \mu_{prod} \cdot \Gamma_H$

→ Resolution is not very important, $\Gamma_H \lesssim 10$ MeV feasible

→ AC enhance off-shell yield, change m_{4l} and other kinematics





CMS analysis: Distributions

When full kinematic information available ($m_{H^*}, m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1$), once can extract the ME $|\mathcal{M}|^2$, where $d\sigma = |\mathcal{M}|^2 d\Pi$, and construct either of

$$D_{A\ vs\ B} = \frac{|\mathcal{M}_A|^2}{|\mathcal{M}_A|^2+|\mathcal{M}_B|^2} \quad D_{A-B\ int.} = \frac{|\mathcal{M}_{A+B}|^2-|\mathcal{M}_A|^2-|\mathcal{M}_B|^2}{|\mathcal{M}_A|^2+|\mathcal{M}_B|^2} \quad w = \frac{|\mathcal{M}_{target}|^2}{|\mathcal{M}_{sample}|^2}$$

→ Examples:

For background discrimination,

$$D_{bkg}^{kin} = \frac{P_{sig}(\{q_l\})}{P_{sig}(\{q_l\})+P_{q\bar{q}\ bkg}(\{q_l\})}$$

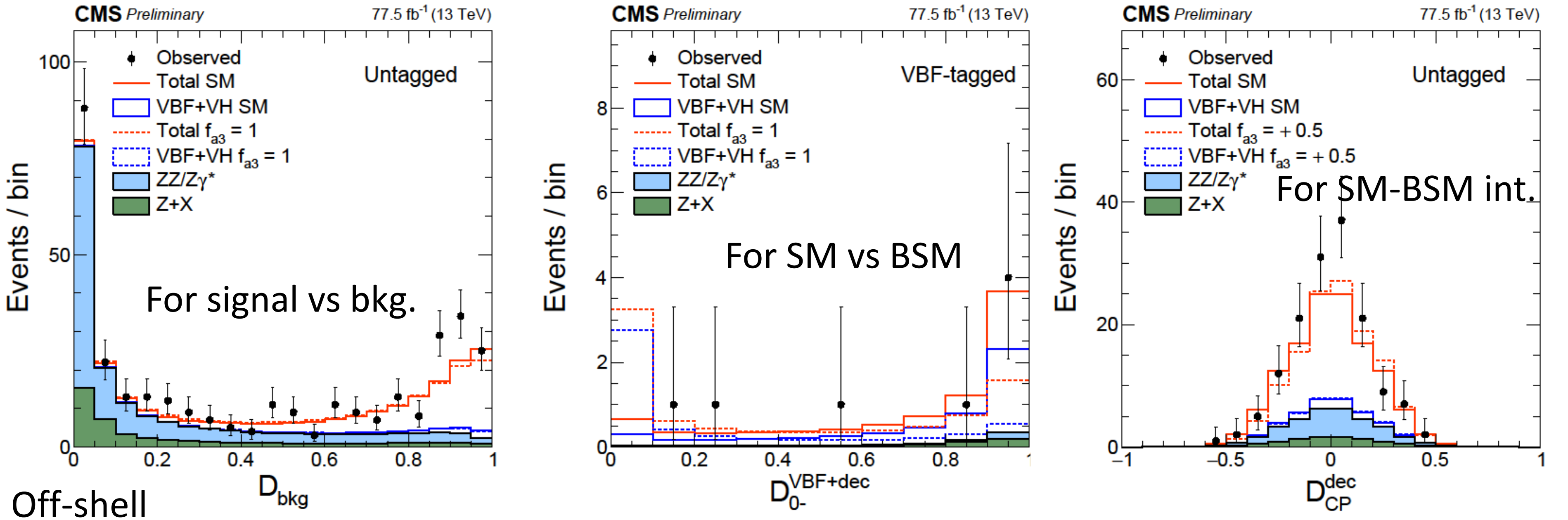
For categorization,

$$D_{2jet} = \frac{P_{jj}^{VBF}(\{q_l\})}{P_{jj}^{VBF}(\{q_l\})+P_{jj}^{HJJ}(\{q_l\})}$$

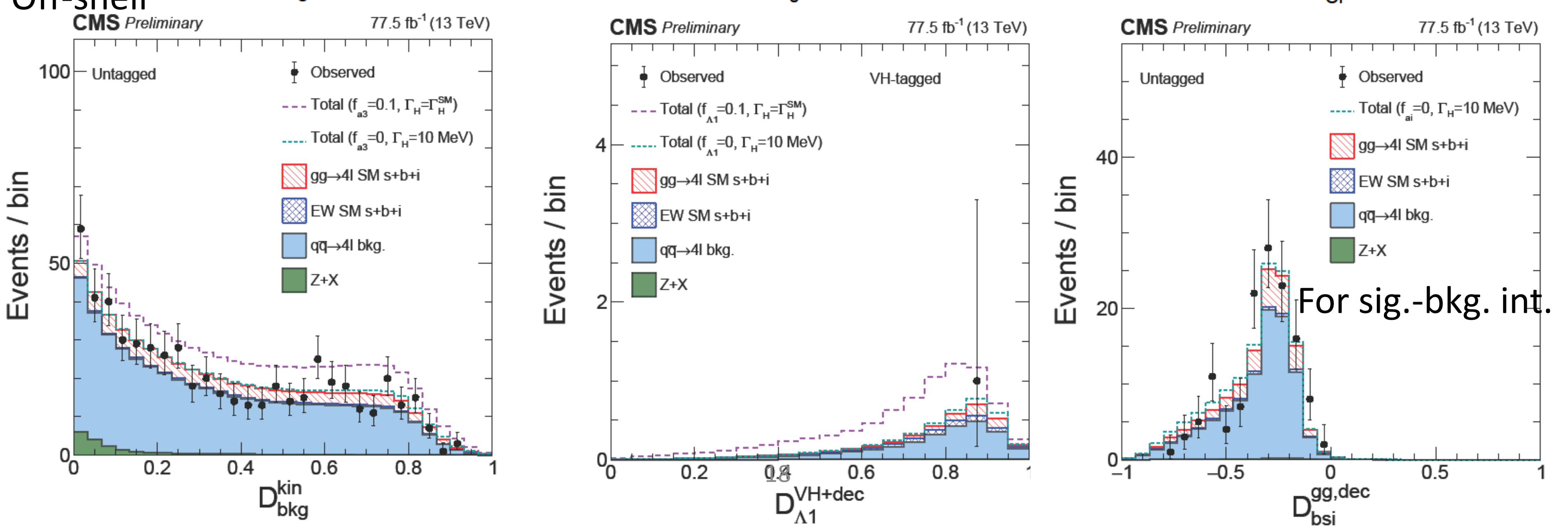
→ The CMS $4l$ analysis uses MEs from JHUGen/MCFM package for Matrix Element Likelihood Approach (MELA).

CMS analysis: Distributions

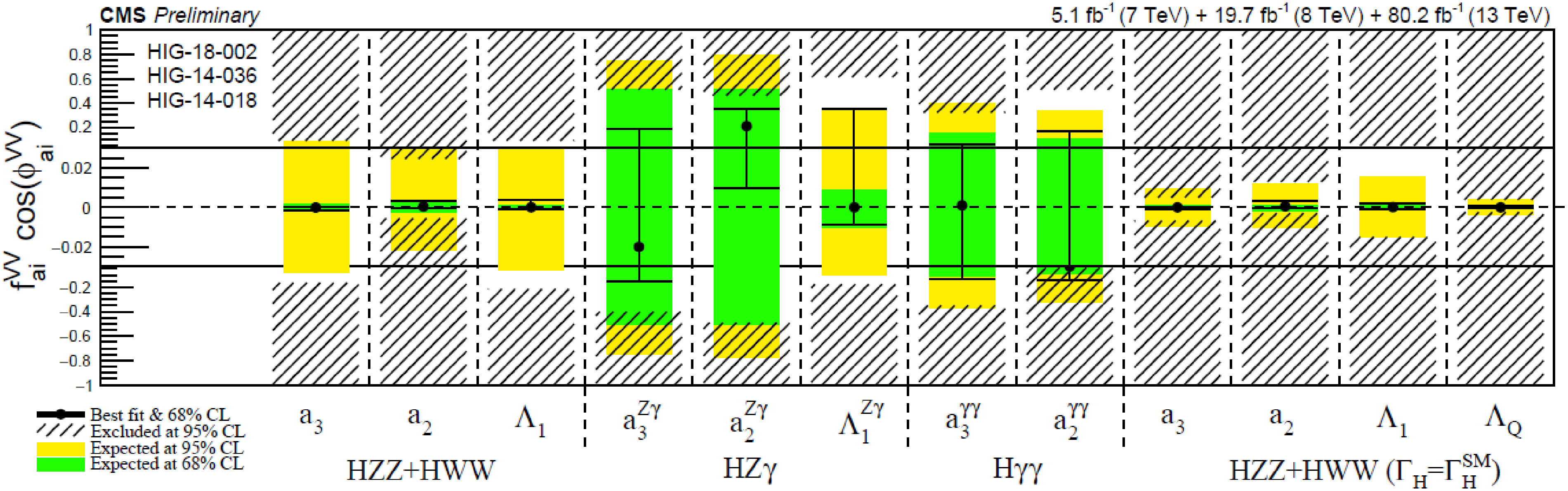
On-shell



Off-shell



CMS results: $f_{ai}\cos(\phi_{ai})$



CMS results: $f_{ai}\cos(\phi_{ai})$

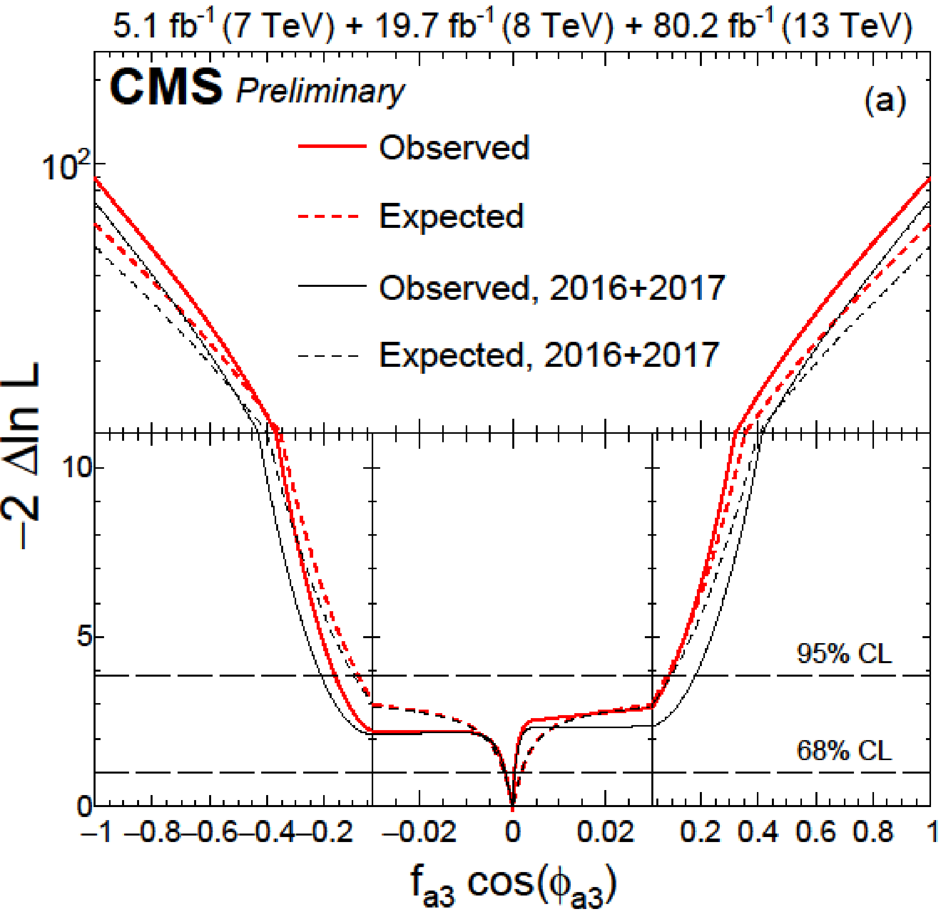
Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$-0.0001^{+0.0005}_{-0.0015}$ $[-0.16, 0.09]$	$0.0000^{+0.0019}_{-0.0019}$ $[-0.082, 0.082]$
$f_{a2}\cos(\phi_{a2})$	$0.0004^{+0.0026}_{-0.0007}$ $[-0.006, 0.025]$	$0.0000^{+0.0030}_{-0.0023}$ $[-0.021, 0.035]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.0000^{+0.0035}_{-0.0008}$ $[-0.21, 0.09]$	$0.0000^{+0.0012}_{-0.0006}$ $[-0.059, 0.032]$
$f_{\Lambda1}^{Z\gamma}\cos\left(\phi_{\Lambda1}^{Z\gamma}\right)$	$0.000^{+0.355}_{-0.009}$ $[-0.17, 0.61]$	$0.000^{+0.009}_{-0.010}$ $[-0.10, 0.34]$

On-shell results

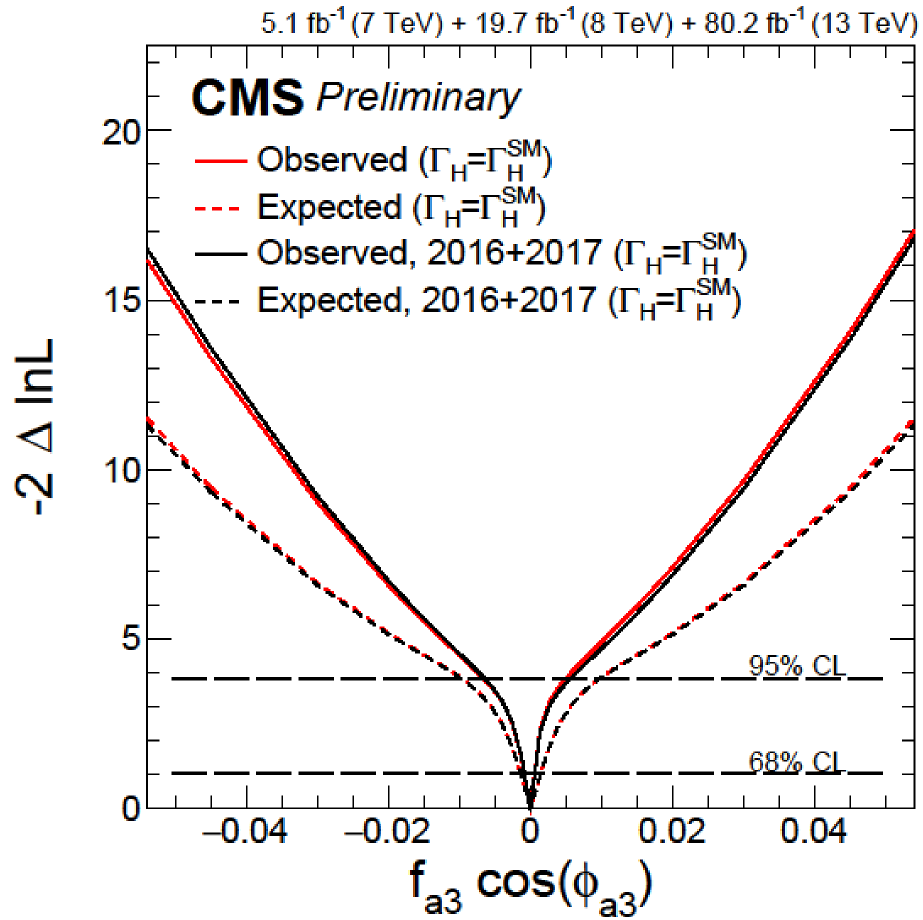
On-shell + off-shell combination

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	$0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$	$0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$

CMS results: $f_{a3}\cos(\phi_{a3})$

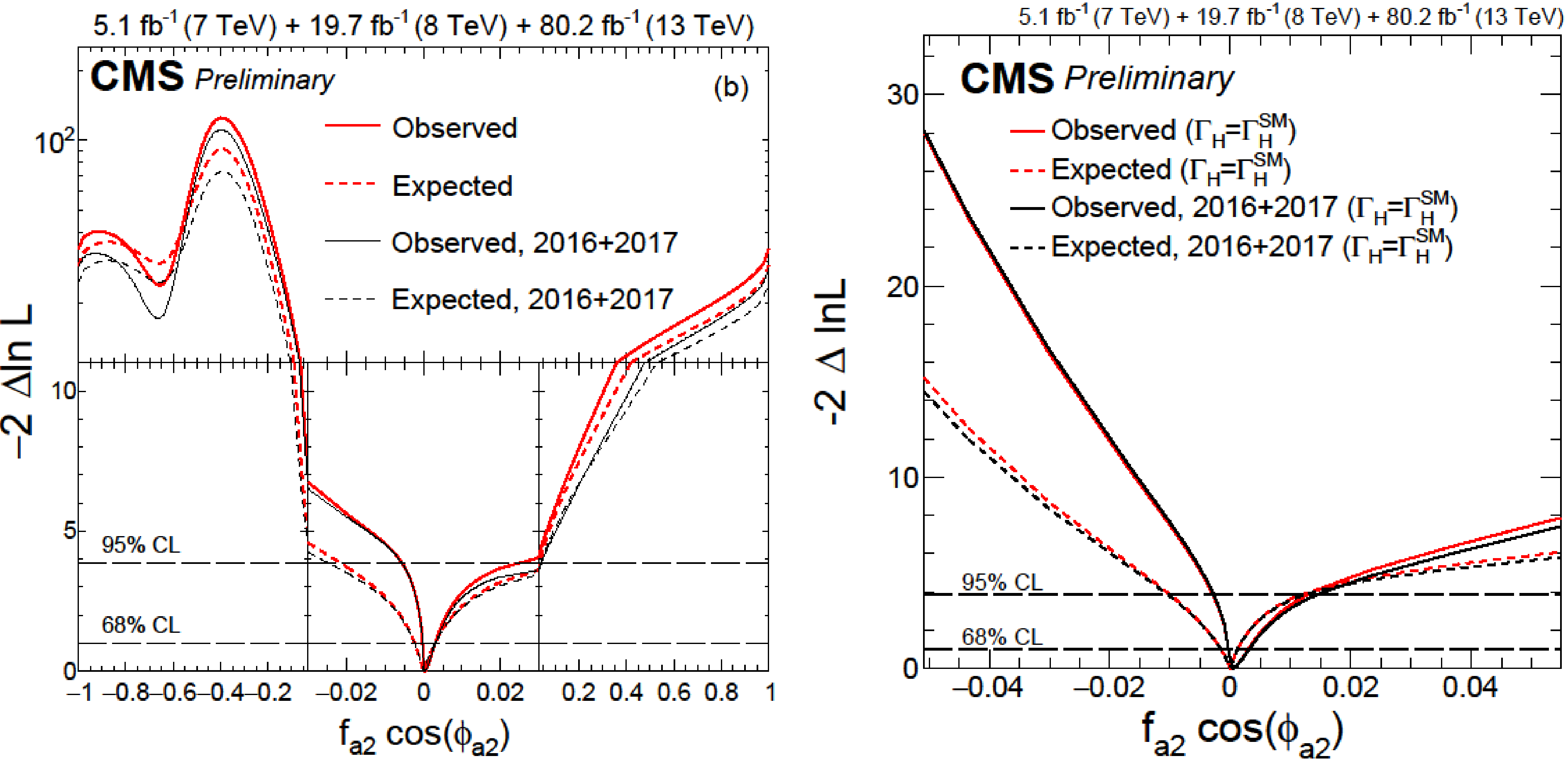


On-shell result



On-shell + off-shell

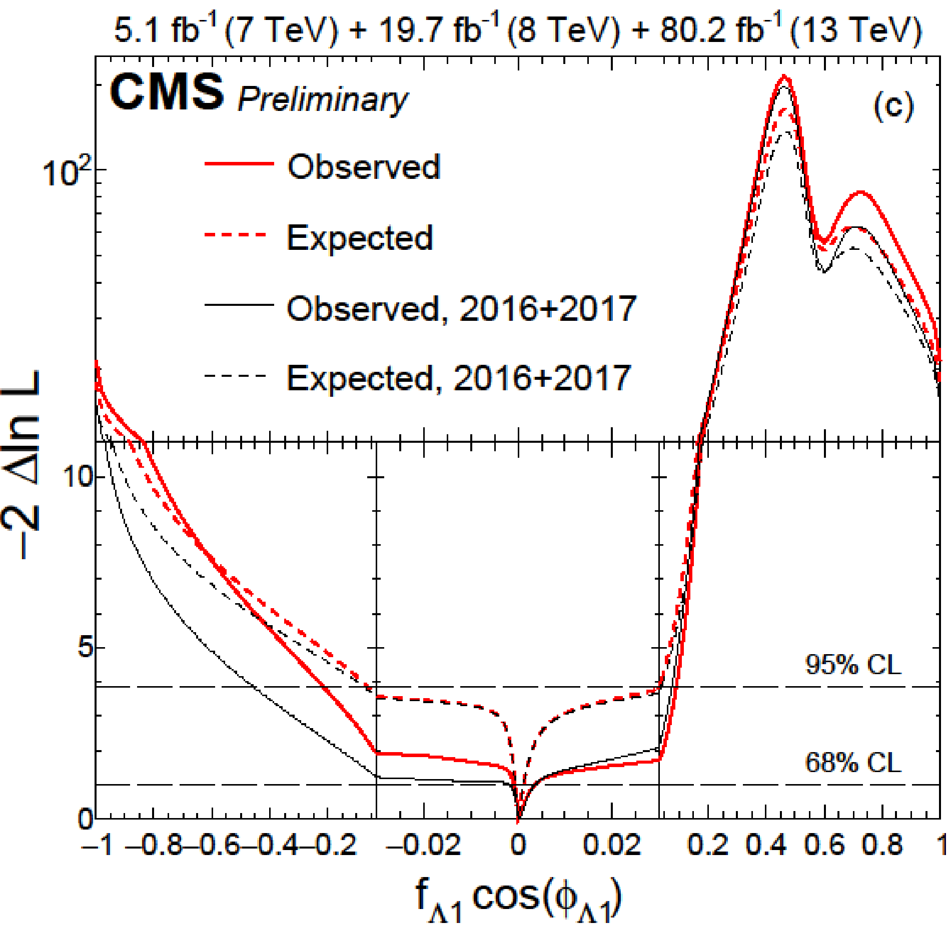
CMS results: $f_{a2}\cos(\phi_{a2})$

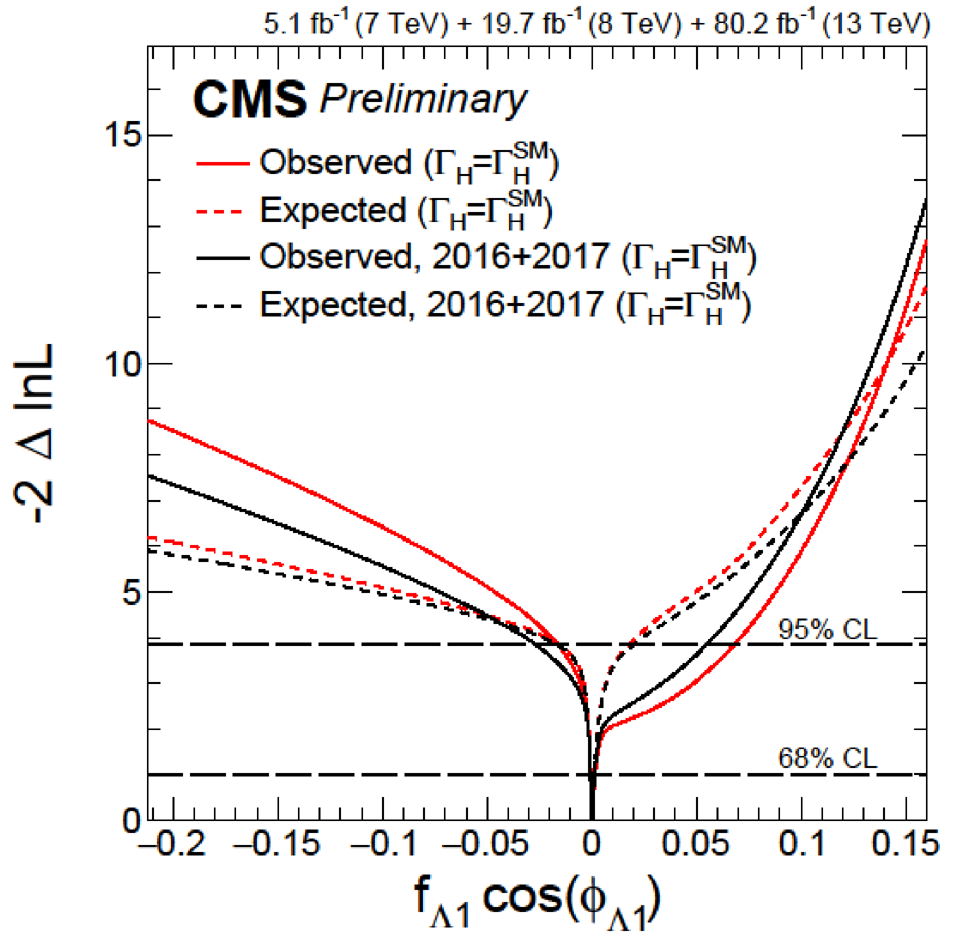


On-shell result

On-shell + off-shell

CMS results: $f_{\Lambda 1}\cos(\phi_{\Lambda 1})$

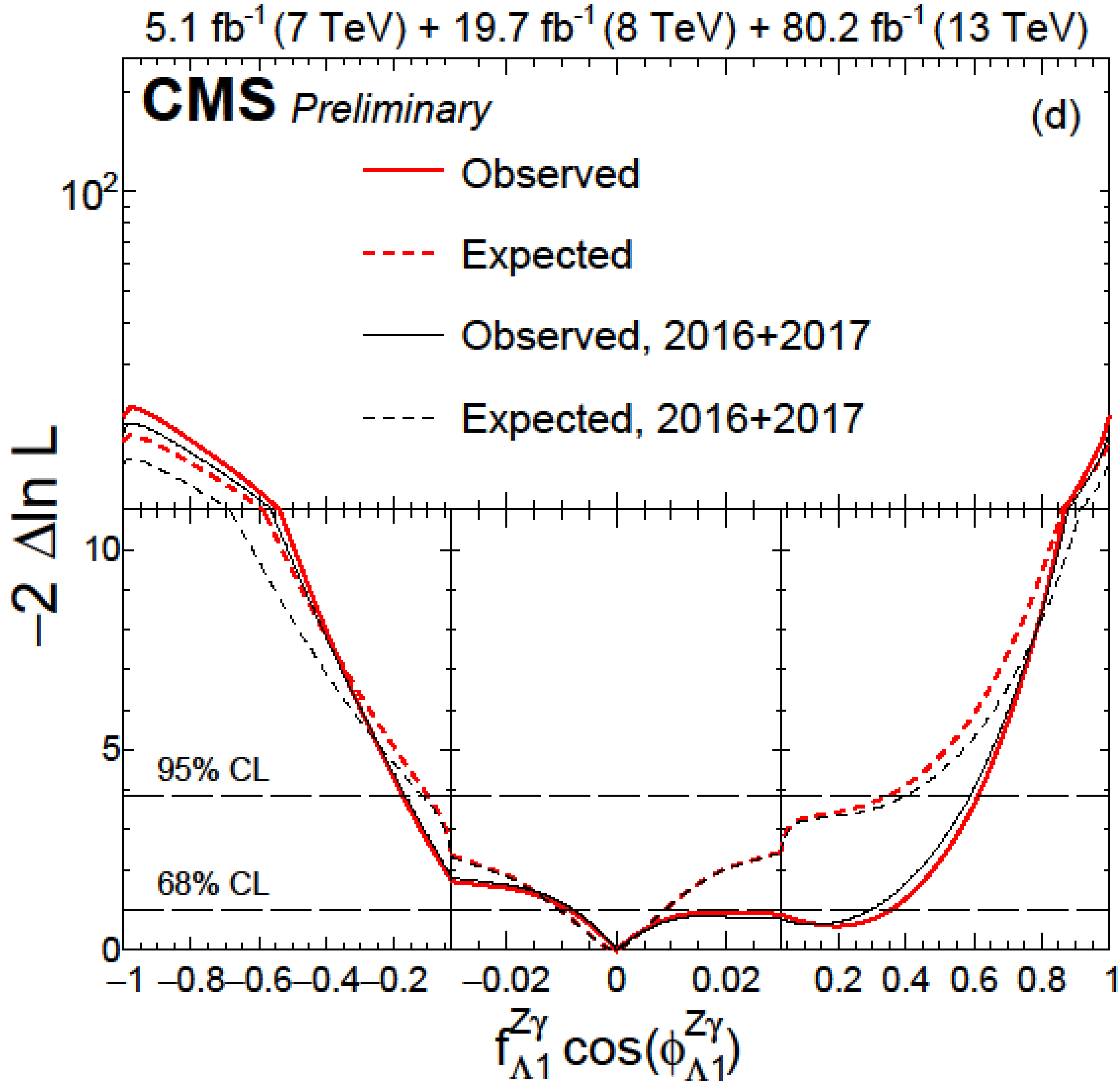




On-shell result

On-shell + off-shell

CMS results: $f_{\Lambda 1}^{Z\gamma} \cos(\phi_{\Lambda 1}^{Z\gamma})$



Only on-shell

CMS results: Γ_H and f_{ai} summary

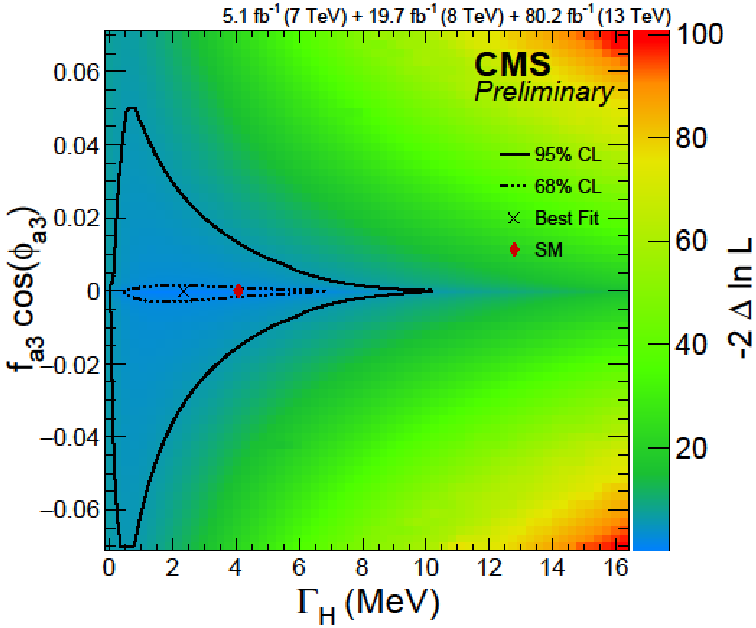
Parameter	Observed	Expected
Γ_H (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

SM-like couplings

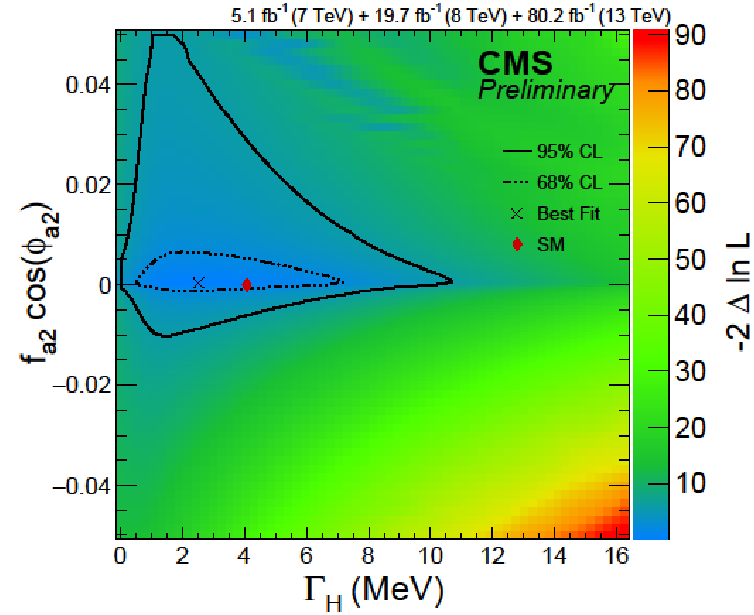
Different HVV couplings

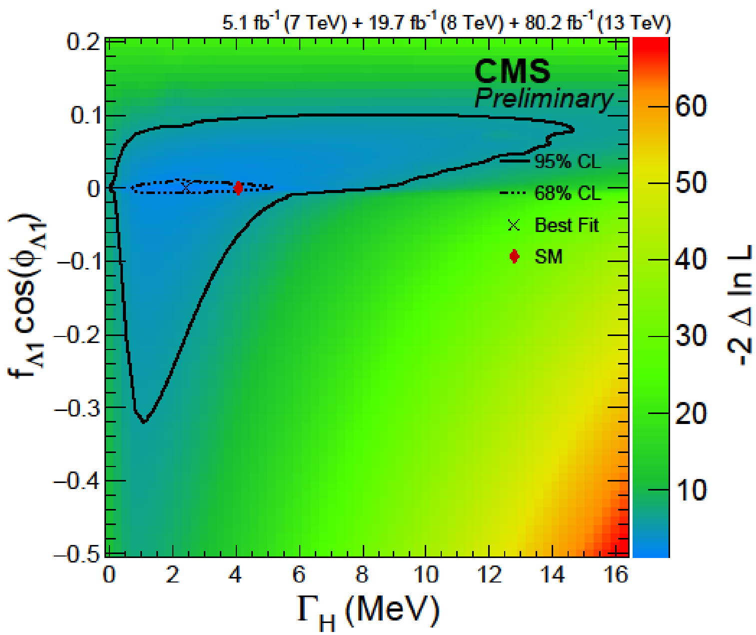
Parameter	Unconstrained Parameter	Observed	Expected
Γ_H (MeV)	$f_{a3} \cos(\phi_{a3})$	$2.4^{+2.7}_{-1.8}$ [0.02, 8.38]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]
Γ_H (MeV)	$f_{a2} \cos(\phi_{a2})$	$2.5^{+2.9}_{-1.8}$ [0.02, 8.76]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]
Γ_H (MeV)	$f_{\Lambda 1} \cos(\phi_{\Lambda 1})$	$2.4^{+2.5}_{-1.6}$ [0.06, 7.84]	$4.1^{+5.2}_{-4.1}$ [0.0, 13.9]

CMS results: Γ_H and f_{ai} joint constraints

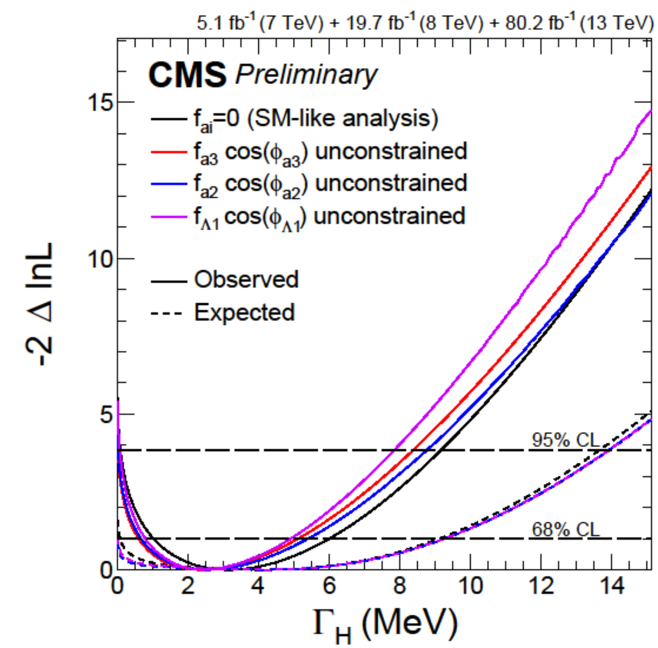


Joint constraints on-shell + off-shell





Γ_H constraints under different assumptions



ATLAS analyses

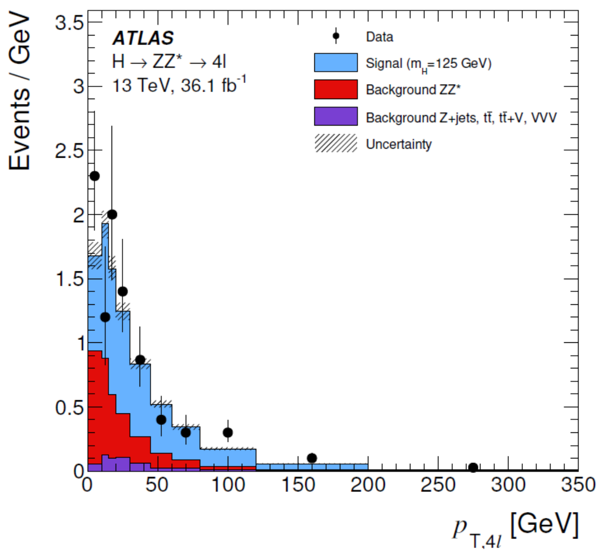
→ Both $4l$ and $\gamma\gamma$ analyses follow differential cross section measurements.

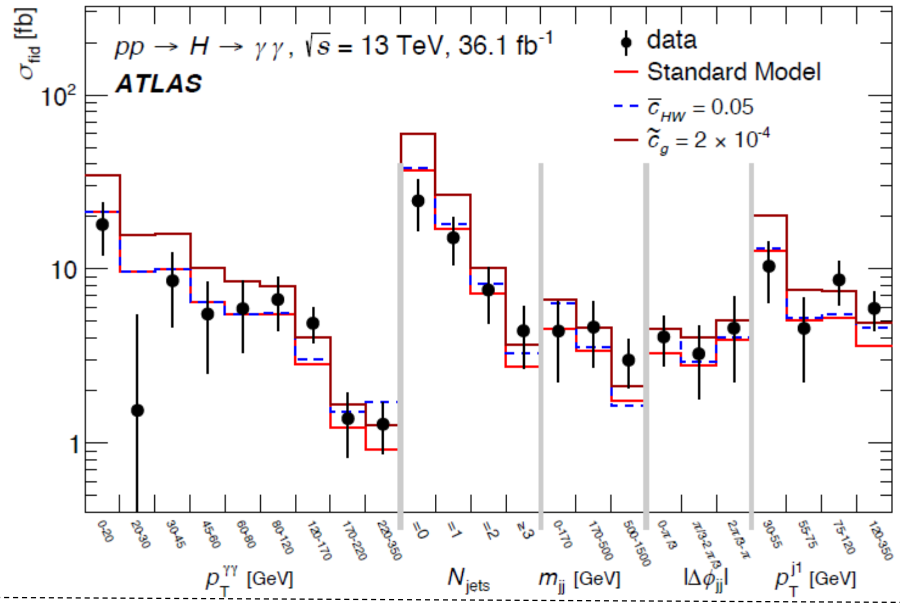
→ First $4l$ analysis mentioned places limits on POs ϵ_L, ϵ_R and total signal strength κ pairwise, where ϵ_L and ϵ_R are contact interaction left- and right-handed couplings.

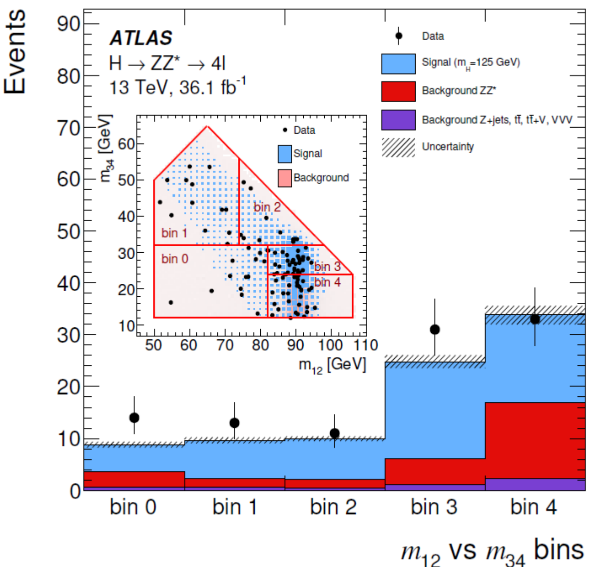
→ Second $4l$ analysis mentioned places limits on κ_{Agg}, κ_{Hvv} and κ_{Avv} being the coupling strengths of CP-odd Higgs to gluons, CP-even Higgs to EW bosons and CP-odd Higgs to EW bosons.

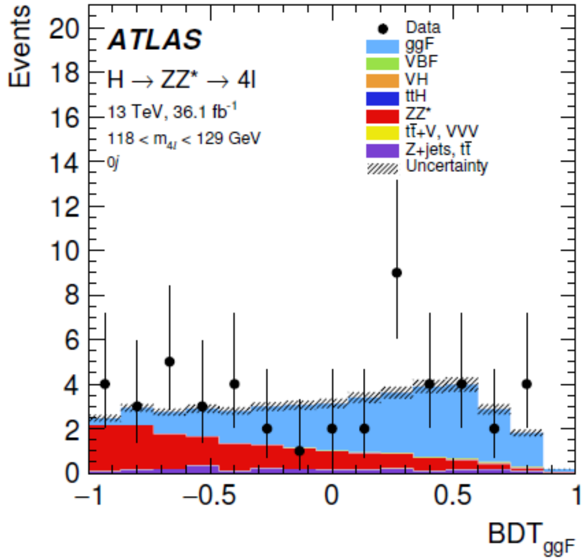
→ $\gamma\gamma$ analysis places limits on Wilson coefficients $\bar{c}_g$, $\tilde{c}_g$, $\bar{c}_{HW}$ and $\tilde{c}_{HW}$.

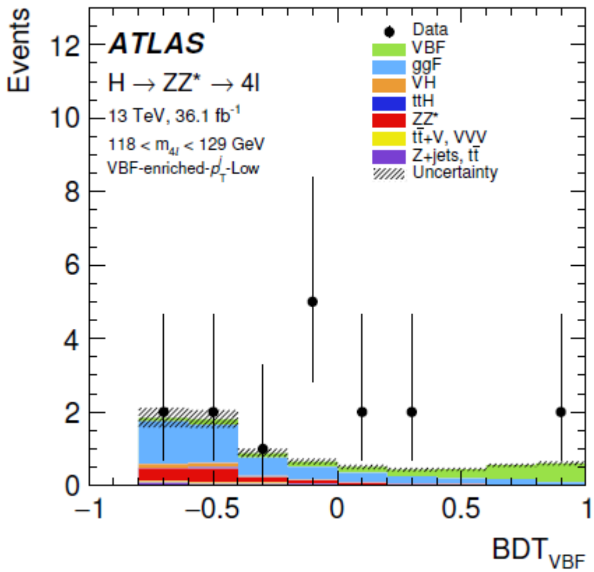
ATLAS analyses: Distributions



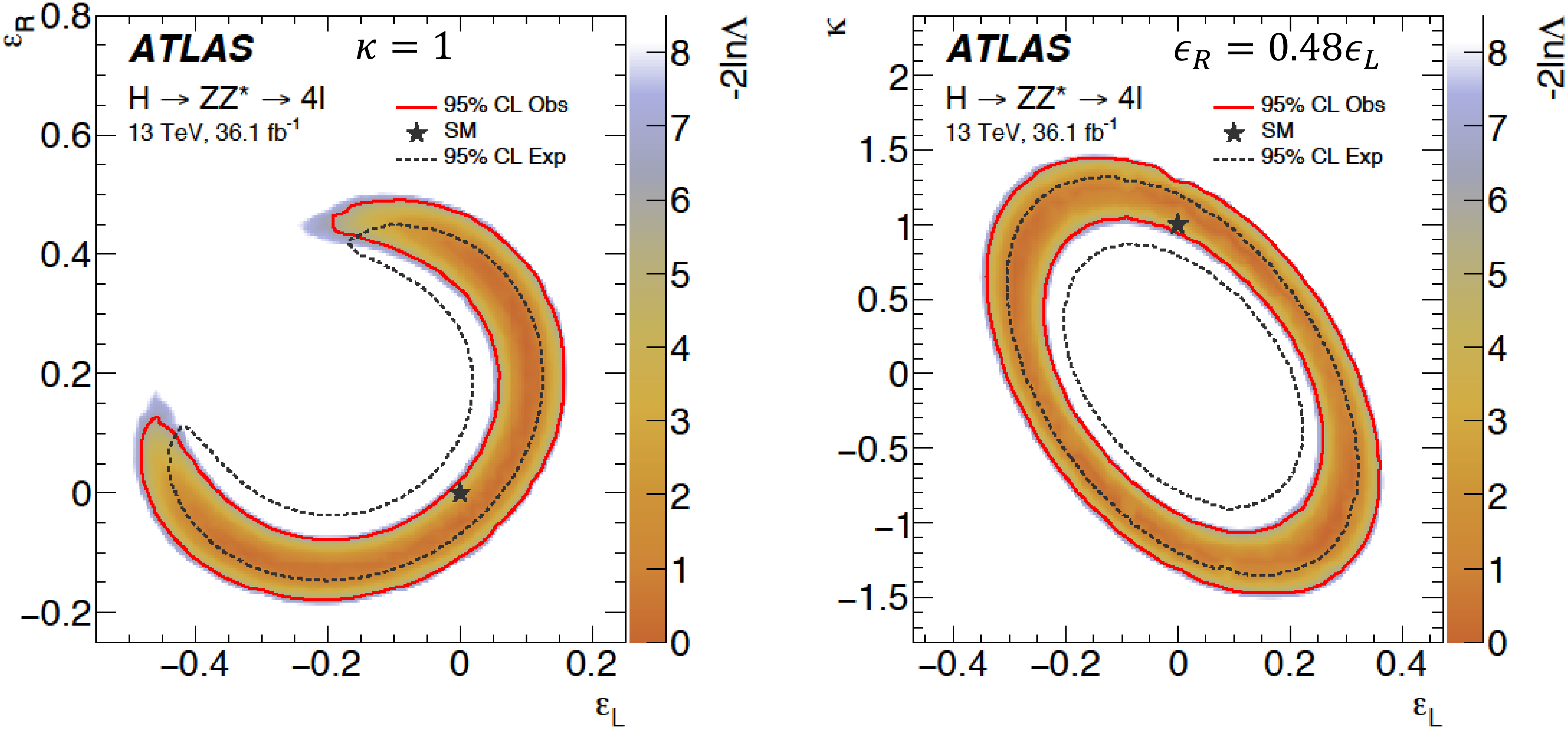




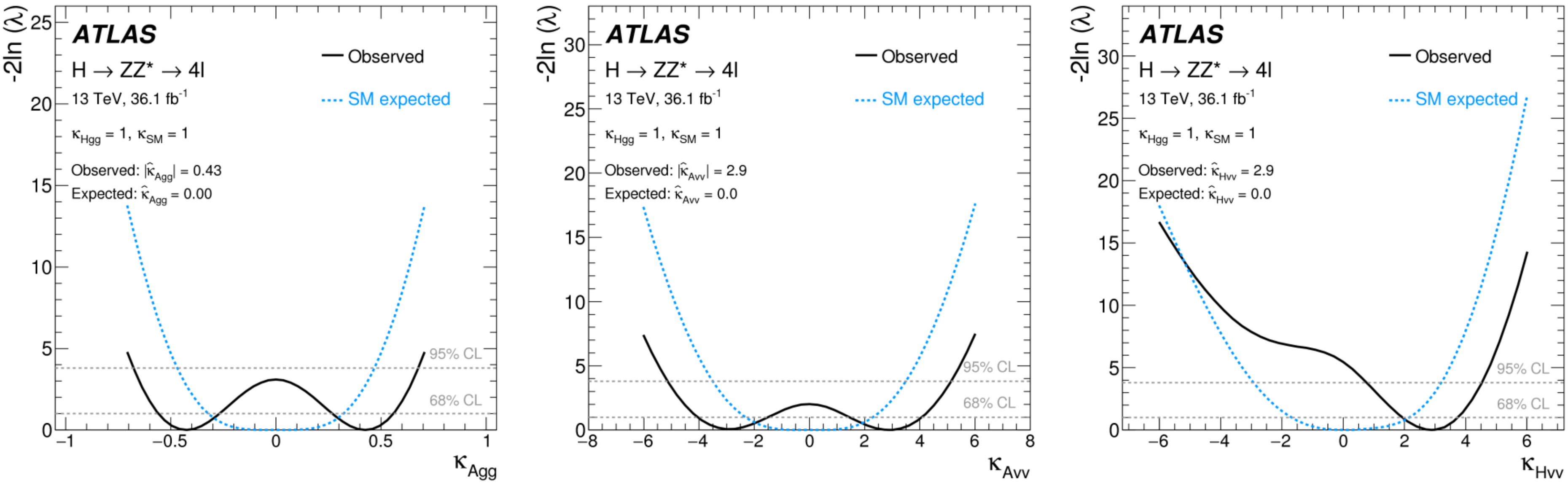




ATLAS analysis: $4l$ POs

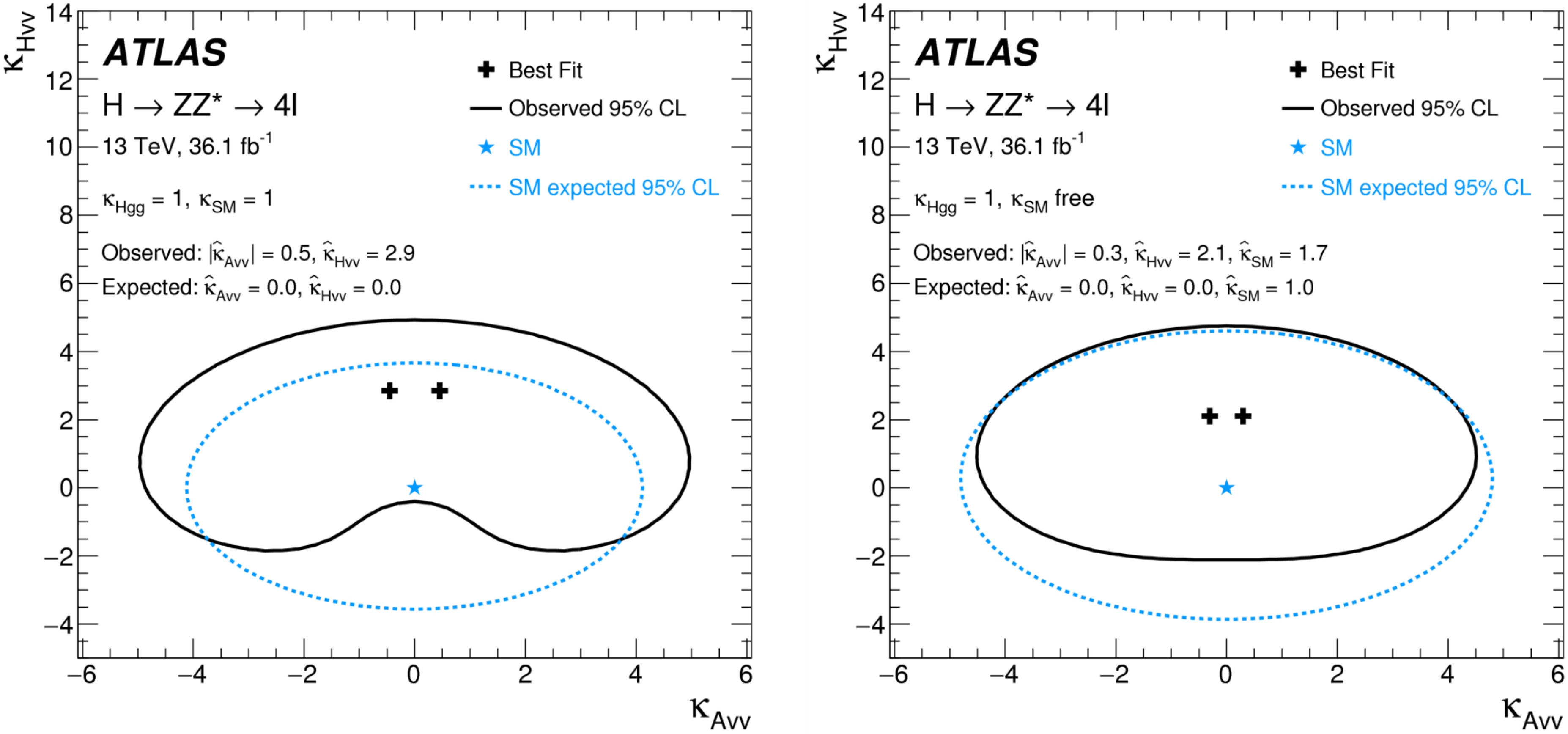


ATLAS analysis: $4l\ \kappa$

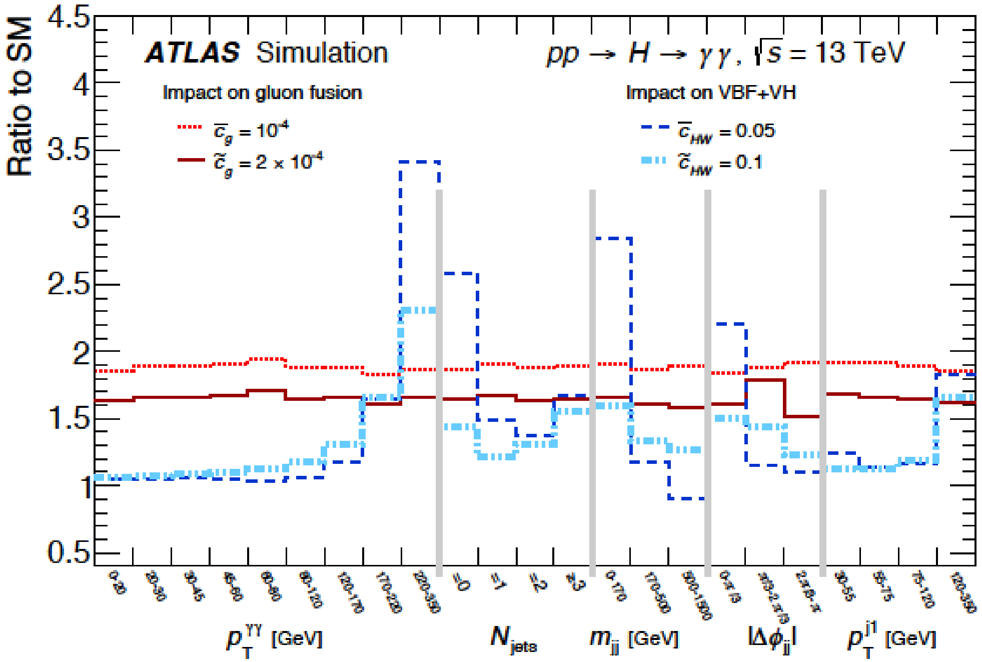


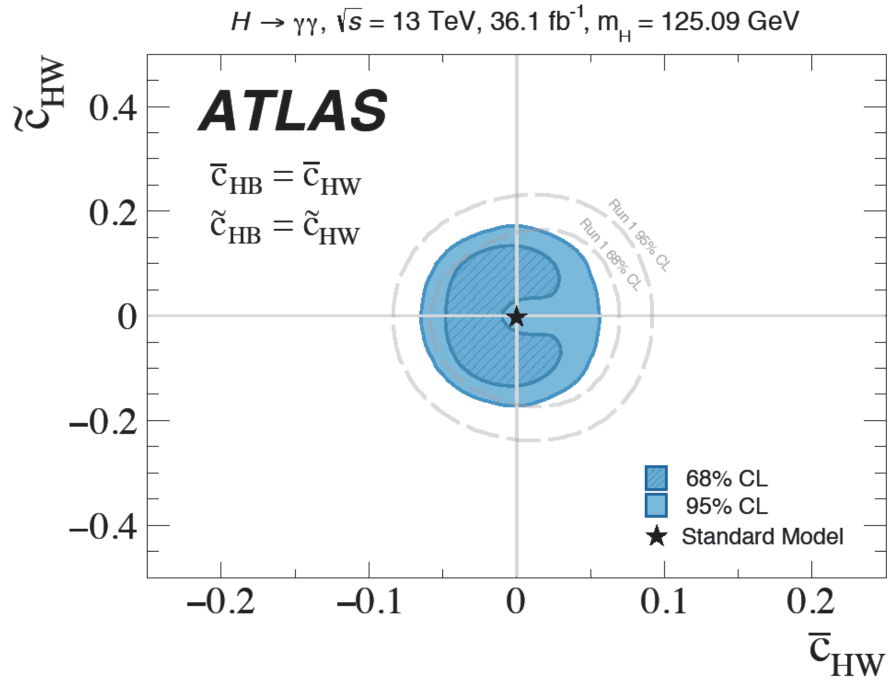
BSM coupling κ_{BSM}	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{\mathrm{BSM}}$	Best-fit $\hat{\kappa}_{\mathrm{SM}}$	Deviation from SM
κ_{Agg}	$(\kappa_{Hgg} = 1,\ \kappa_{\mathrm{SM}} = 1)$	$[-0.47,\ 0.47]$	$[-0.68,\ 0.68]$	± 0.43	-	1.8σ
κ_{HVV}	$(\kappa_{Hgg} = 1,\ \kappa_{\mathrm{SM}} = 1)$	$[-2.9,\ 3.2]$	$[0.8,\ 4.5]$	2.9	-	2.3σ
κ_{HVV}	$(\kappa_{Hgg} = 1,\ \kappa_{\mathrm{SM}}$ free$)$	$[-3.1,\ 4.0]$	$[-0.6,\ 4.2]$	2.2	1.2	1.7σ
κ_{AVV}	$(\kappa_{Hgg} = 1,\ \kappa_{\mathrm{SM}} = 1)$	$[-3.5,\ 3.5]$	$[-5.2,\ 5.2]$	± 2.9	-	1.4σ
κ_{AVV}	$(\kappa_{Hgg} = 1,\ \kappa_{\mathrm{SM}}$ free$)$	$[-4.0,\ 4.0]$	$[-4.4,\ 4.4]$	± 1.5	1.2	0.5σ

ATLAS analysis: $4l$ κ joint constraints



ATLAS analysis: $\gamma\gamma$ results





Coefficient	Observed 95% CL limit	Expected 95% CL limit
$\bar{c}_g$	$[-0.8, 0.1] \times 10^{-4} \cup [-4.6, -3.8] \times 10^{-4}$	$[-0.4, 0.5] \times 10^{-4} \cup [-4.9, -4.1] \times 10^{-4}$
$\tilde{c}_g$	$[-1.0, 0.9] \times 10^{-4}$	$[-1.4, 1.3] \times 10^{-4}$
$\bar{c}_{HW}$	$[-5.7, 5.1] \times 10^{-2}$	$[-5.0, 5.0] \times 10^{-2}$
$\tilde{c}_{HW}$	$[-0.16, 0.16]$	$[-0.14, 0.14]$

Summary

Presented Higgs decay and anomalous couplings studies

→ LFV studies using $\mu\tau$ and eτ:

→ Run 2 results from CMS

→ Run 1 studies from ATLAS

→ FCNC is studied using Run 2 data for both experiments:

→ CMS includes single-top channels, using $H \rightarrow b\bar{b}$

→ ATLAS uses $H \rightarrow \gamma\gamma, WW, ZZ, \tau\tau$ for increased sensitivity

→ See Gagan Mohanty's talk for more details

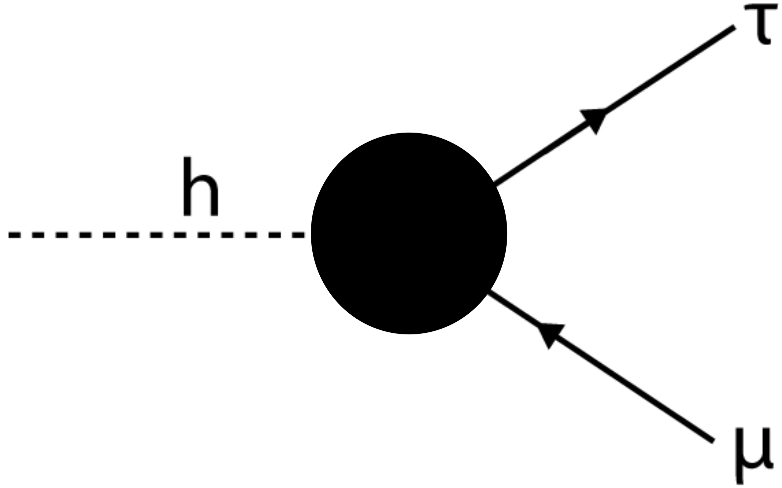
→ Anomalous Higgs couplings from Run 2 data:

→ HVV anomalous couplings from CMS using production and decay

→ ATLAS utilizing differential cross section measurements to place constraints on different HVV, Hgg or contact interaction couplings

Backup

Higgs LFV decay studies



CMS LFV analysis: Results

Expected limits (%)

	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	<0.83	<1.19	<1.98	<1.62	<0.59
$\mu\tau_h$	<0.43	<0.56	<0.94	<0.58	<0.29
$\mu\tau$			<0.25		

Observed limits (%)

	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	<1.30	<1.34	<2.27	<1.79	<0.86
$\mu\tau_h$	<0.51	<0.53	<0.56	<0.51	<0.27
$\mu\tau$			<0.25		

Best fit branching fractions (%)

	0-jet	1-jet	2-jets	VBF	Combined
$\mu\tau_e$	0.61 ± 0.36	0.22 ± 0.46	0.39 ± 0.83	0.10 ± 1.37	0.35 ± 0.26
$\mu\tau_h$	0.12 ± 0.20	-0.05 ± 0.25	-0.72 ± 0.43	-0.22 ± 0.31	-0.04 ± 0.14
$\mu\tau$			0.00 ± 0.12		

Expected limits (%)

	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	<0.90	<1.59	<2.54	<1.84	<0.64
$e\tau_h$	<0.79	<1.13	<1.59	<0.74	<0.49
$e\tau$			<0.37		

Observed limits (%)

	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	<1.22	<1.66	<2.25	<1.10	<0.78
$e\tau_h$	<0.73	<0.81	<1.94	<1.49	<0.72
$e\tau$			<0.61		

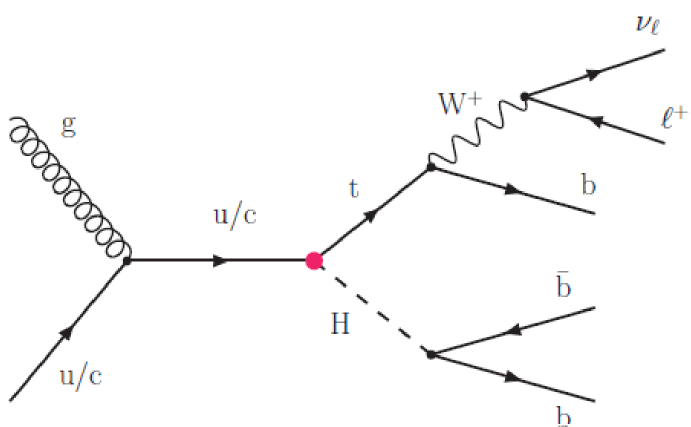
Best fit branching fractions (%)

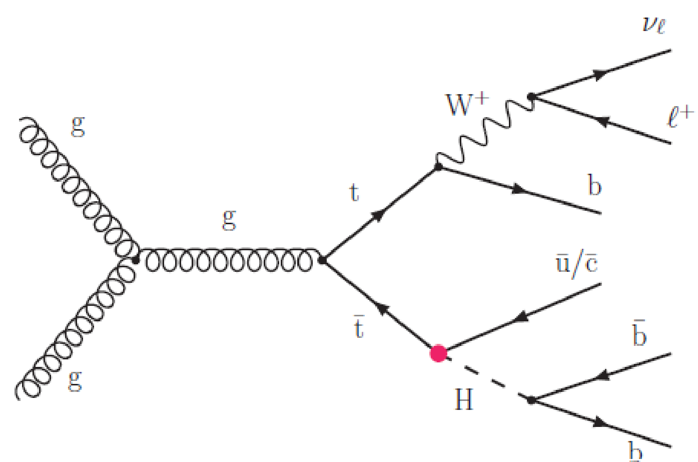
	0-jet	1-jet	2-jets	VBF	Combined
$e\tau_\mu$	0.47 ± 0.42	0.17 ± 0.79	-0.42 ± 1.01	-1.54 ± 0.44	0.18 ± 0.32
$e\tau_h$	-0.13 ± 0.39	-0.63 ± 0.40	0.54 ± 0.53	0.70 ± 0.38	0.33 ± 0.24
$e\tau$			0.30 ± 0.18		

ATLAS LFV analysis: Results

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{\rm had}$	SR1	$2.81^{+1.08}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.18}_{-0.82}$	2.24	$-1.33^{+1.58}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{\rm lep}$	$\rm SR_{noJets}$	$1.66^{+0.72}_{-0.48}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$\rm SR_{withJets}$	$3.33^{+1.60}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.60}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$
$H \to \mu\tau_{\rm had}$	SR1	$1.60^{+0.64}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{\rm lep}$	$\rm SR_{noJets}$	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$\rm SR_{withJets}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$

Higgs FCNC studies





CMS analysis: Strategy

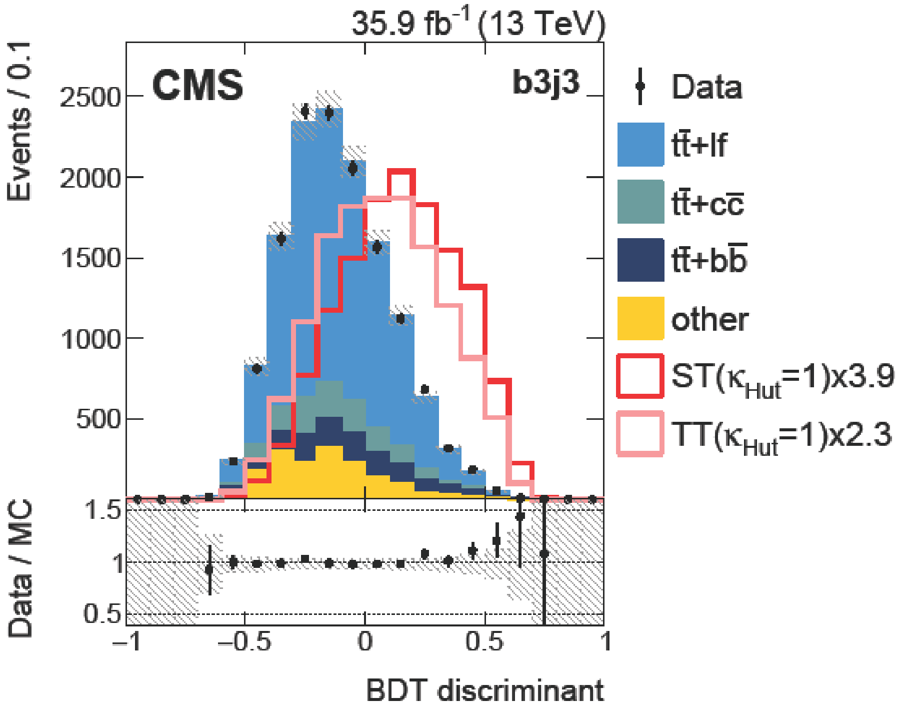
→ Analysis considers one top with leptonic decay + H (ST) or + t($\rightarrow Hq$) (TT), where the Higgs boson decays to $b\bar{b}$.

→ Event categorization based on jet multiplicity and how many b-tagged jets:
b2j3, b3j3, b2j4, b3j4, b4j4 (not used in Hut analysis)

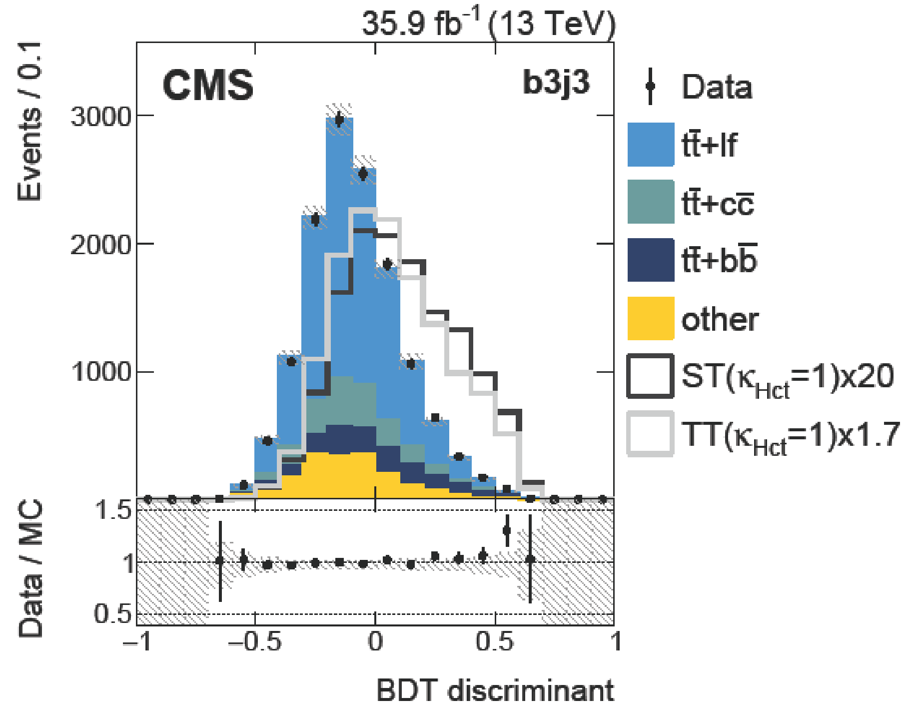
→ Two BDTs are trained:
- Using $m_{b\bar{b}}, m(t^l), p_T(t^l)$ in the signal hypothesis, and also $m(t^h), \Delta R(t^l, t^h)$ for background $t\bar{t}$ hypothesis, where t^h is the reconstructed hadronic top decay with one b-tagged jet and two untagged jets. This is to ensure ~75% correct assignment of b jets
- Charge of the lepton (Hut BDTs), CSVv2 discriminant value of the b jet from the Higgs boson with lower p_T, $m_{b\bar{b}}$, and the value of BDT from above. This is to use in the likelihood analysis.

→ Final likelihood fit is performed for Hut and Hct couplings, and the $t\bar{t} + b\bar{b}$, $t\bar{t} + c\bar{c}$ and $t\bar{t} + lf$ (light jets) contributions.

CMS analysis: Example BDT distributions

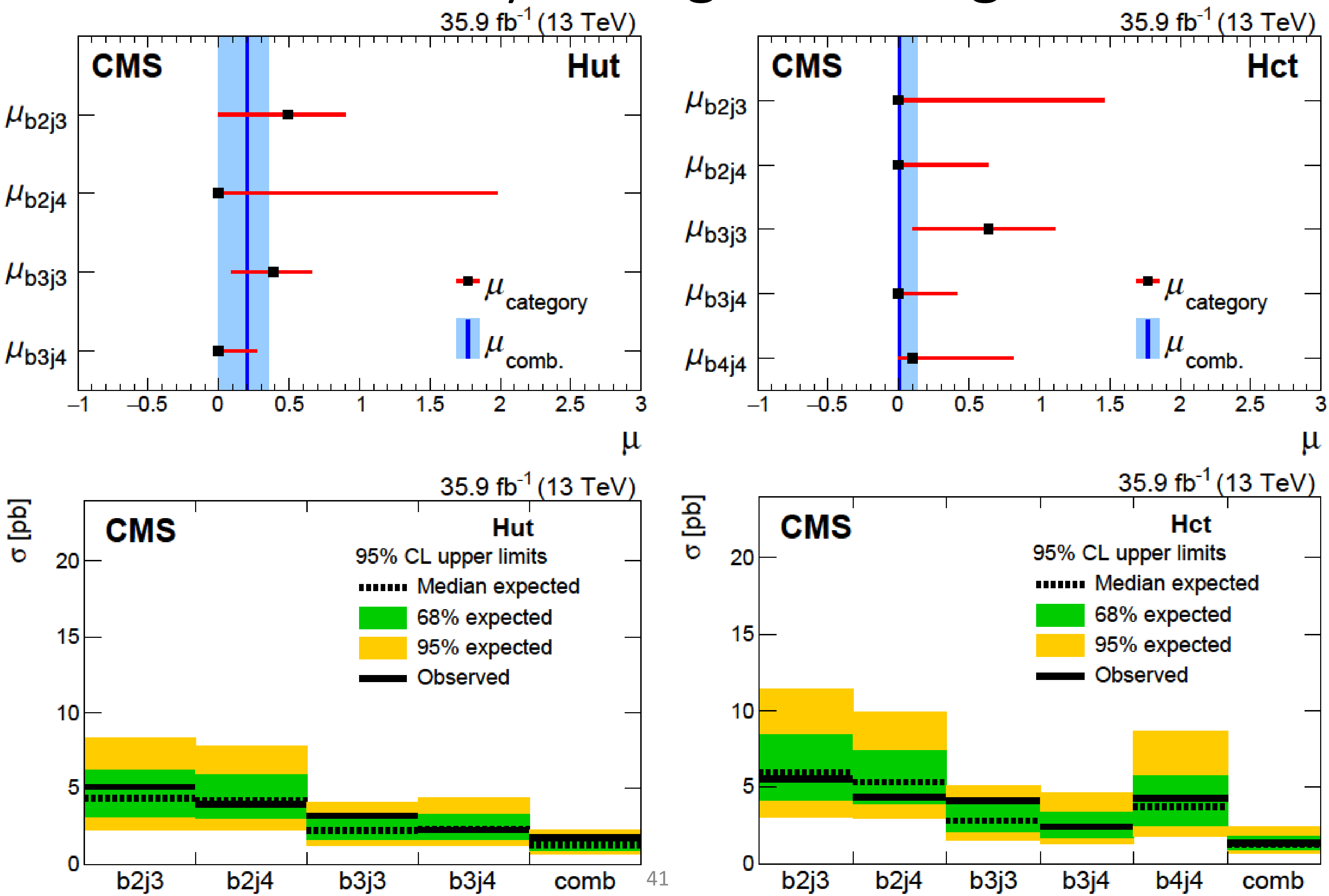


Hut BDT

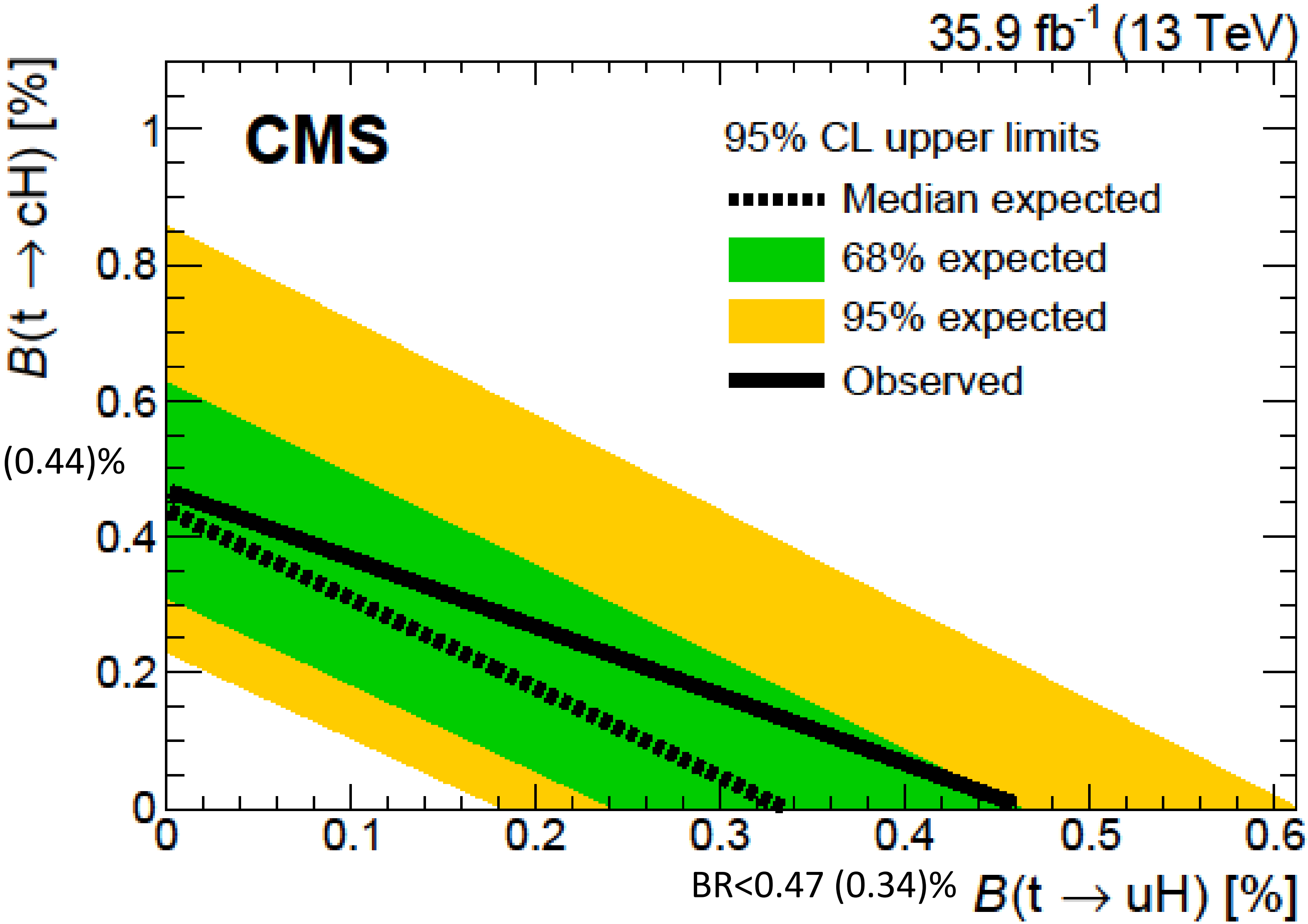


Hct BDT

CMS analysis: Signal strength



CMS analysis: BR constraints



BR<0.47 (0.44)%

BR<0.47 (0.34)%

ATLAS analysis: $\gamma\gamma$ strategy

→ Analysis considers one top with leptonic or hadronic decay + t($\rightarrow Hq$), where the Higgs boson decays to $\gamma\gamma$.

→ Both top decay channels are categorized into Category 1 for events satisfying top mass window requirements in both top pairs, Category 2 for those satisfying only the top mass window requirement for the Hq system.

→ In the hadronic top decay channel, smooth parameterizations of $m_{\gamma\gamma}$ are used in the final likelihood parameterization with full treatment of nuisances.

→ Leptonic channel is statistically limited, so only two bins in $m_{\gamma\gamma}$ are used (SR vs two-sided sidebands), and the ratio of backgrounds in the SR and sidebands is varied with a free parameter.

→ Likelihood scan is done for $t \rightarrow Hc$ and is re-interpreted for $t \rightarrow Hu$ with 8% lower acceptance (due to b-tagging).

ATLAS analysis: Multi-lepton strategy

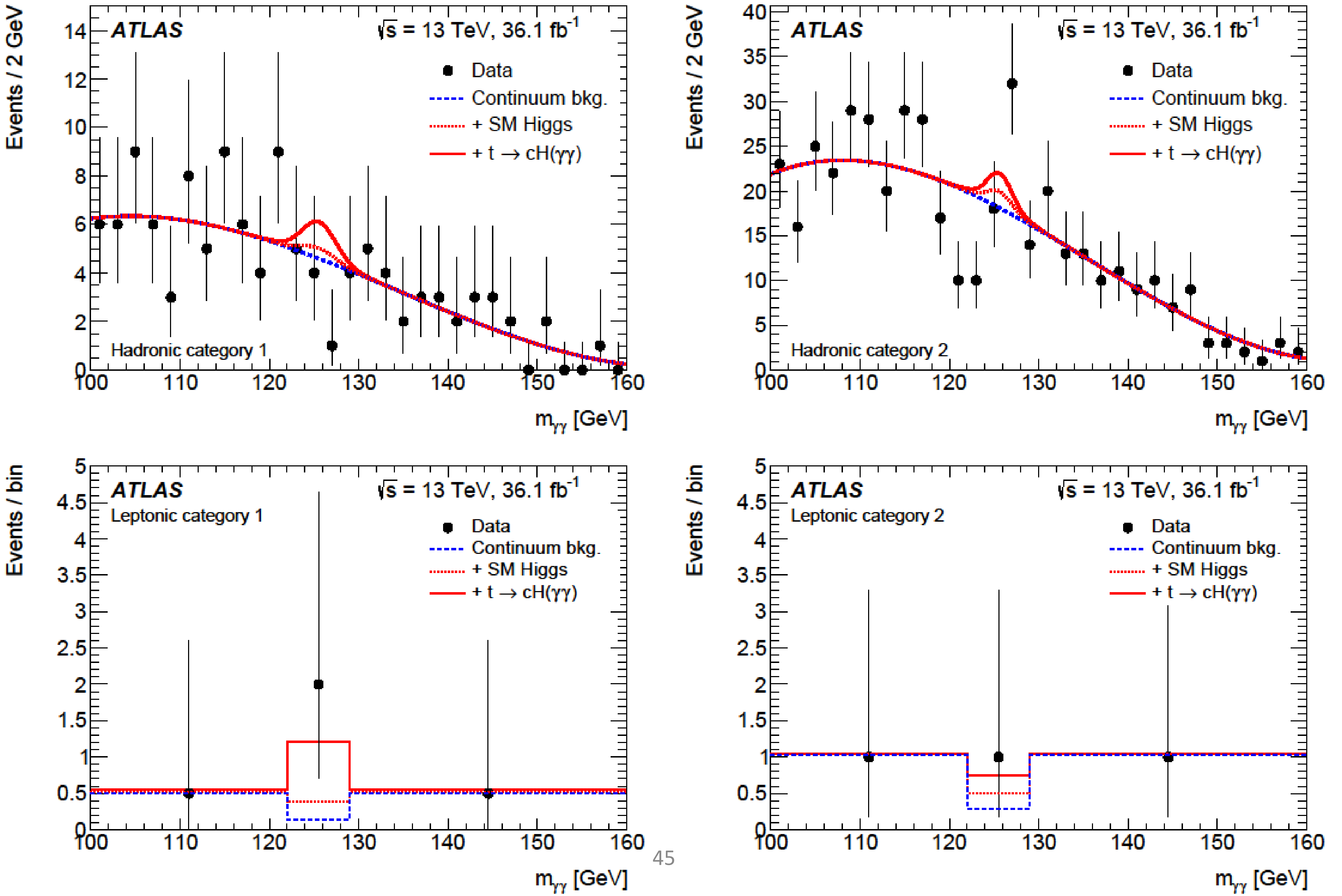
→ Events categorized into $2lSS$ (≥ 4 jets of which one or two b-tagged, two SS leptons) and $3l$ (≥ 2 jets of which at least one b-tagged, three leptons with sum of charges ± 1)

→ Dominant contribution (85% $2lSS$ and 71% $3l$) from $H \rightarrow WW$.

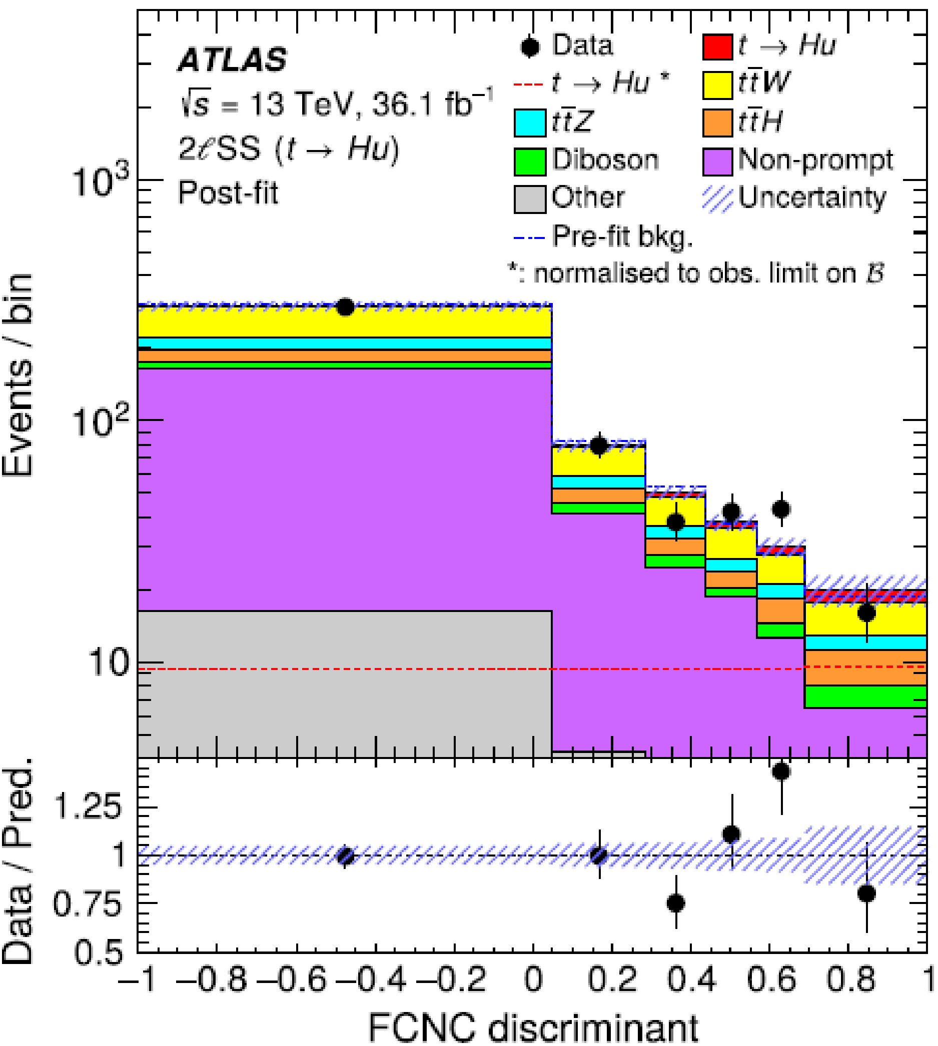
→ Limits placed using a BDT discriminant

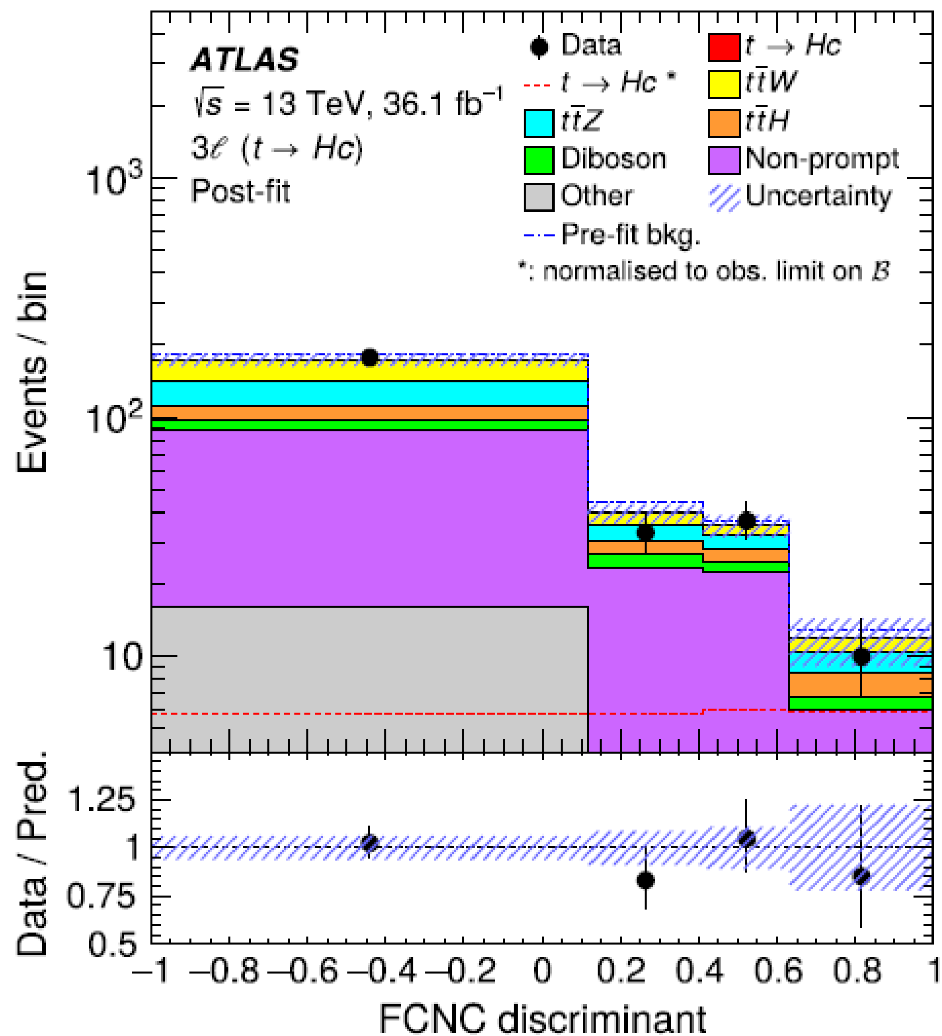
Variable	$2\ell SS$	3ℓ
p_T of higher-p_T lepton	×	
p_T of lower-p_T lepton	×	
p_T of lepton ℓ_0		×
p_T of lepton ℓ_1		×
p_T of lepton ℓ_2		×
Dilepton invariant masses (all combinations)	×	×
Trilepton invariant mass		×
Best Z candidate invariant mass		×
Maximum lepton $\lvert\eta\rvert$	×	
Lepton flavor	×	
Number of jets	×	×
Number of b-tagged jets	×	×
p_T of highest-p_T jet		×
p_T of second highest-p_T jet		×
p_T of highest-p_T b-tagged jet		×
$\Delta R(\ell_0, \ell_1)$		×
$\Delta R(\ell_0, \ell_2)$		×
ΔR(higher-p_T lepton, closest jet)	×	
ΔR(lower-p_T lepton, closest jet)	×	
$\Delta R(\ell_1$, closest jet)		×
Smallest $\Delta R(\ell_0$, b-tagged jet)		×
E_T^{miss}	×	
m_{eff}	×	×

ATLAS analysis: $m_{\gamma\gamma}$ distributions

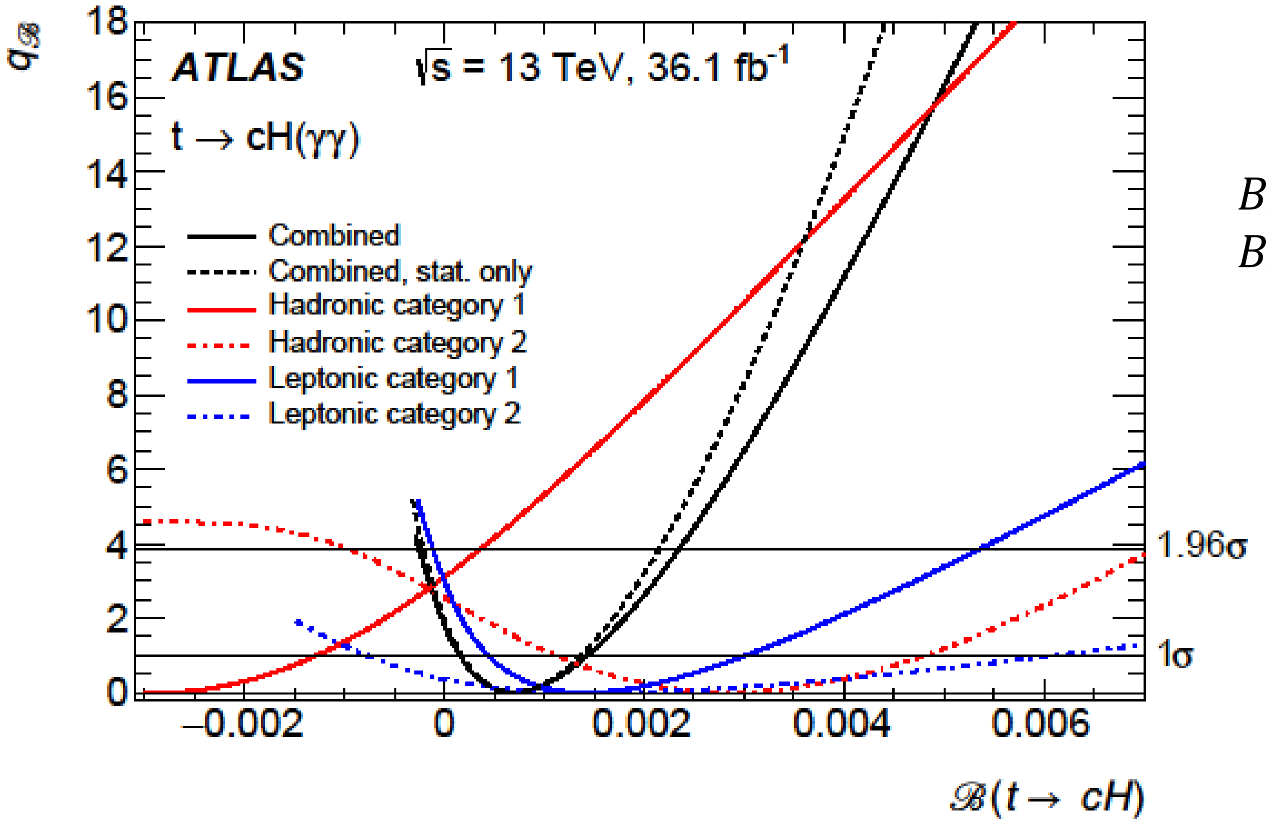


ATLAS analysis: Multi-lepton distributions





ATLAS analysis: $\gamma\gamma$ results



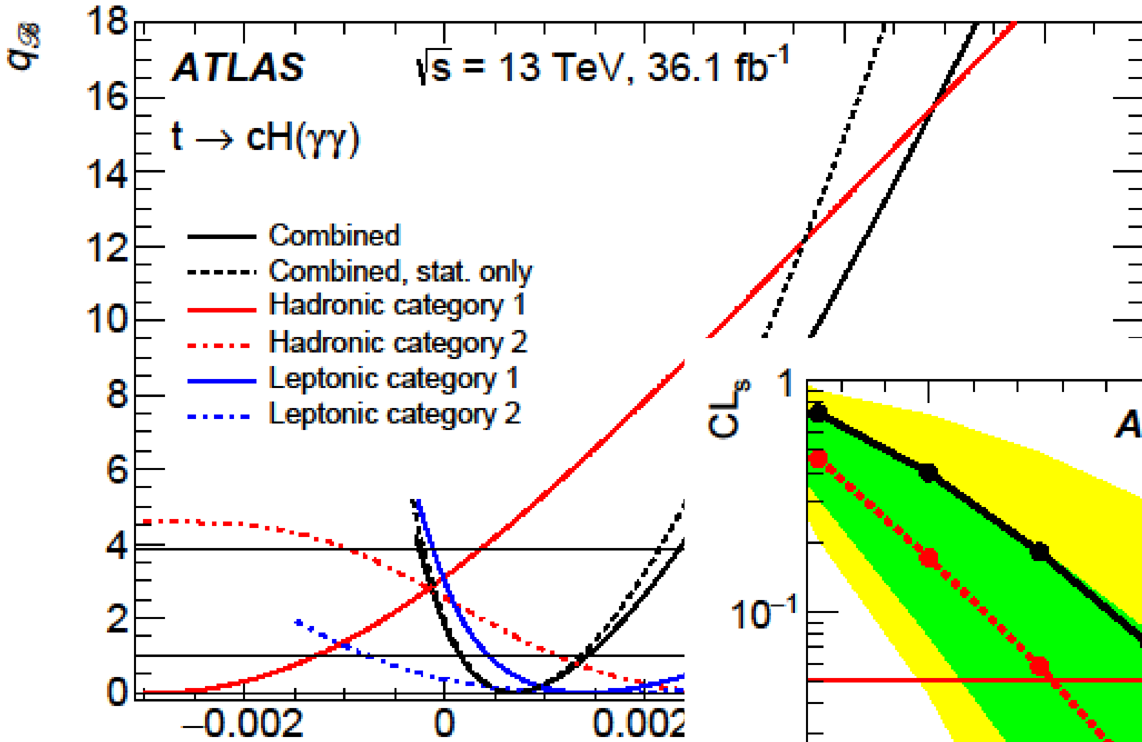
$BR(t \to Hc) < 0.22\%$ at 95% CL

$BR(t \to Hu) < 0.24\%$ at 95% CL

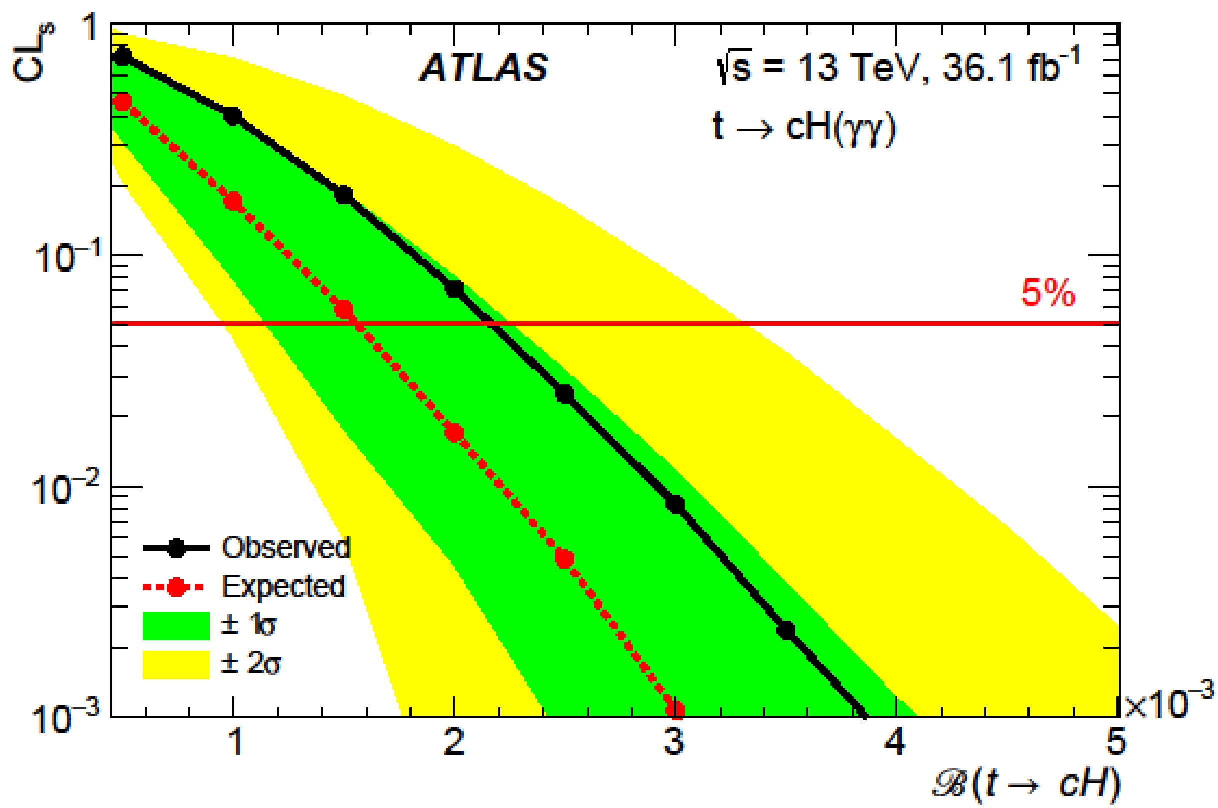
$\lambda_{tcH} < 0.090\ (0.077)$ at 95% CL

$\lambda_{tuH} < 0.094\ (0.079)$ at 95% CL

ATLAS analysis: $\gamma\gamma$ results

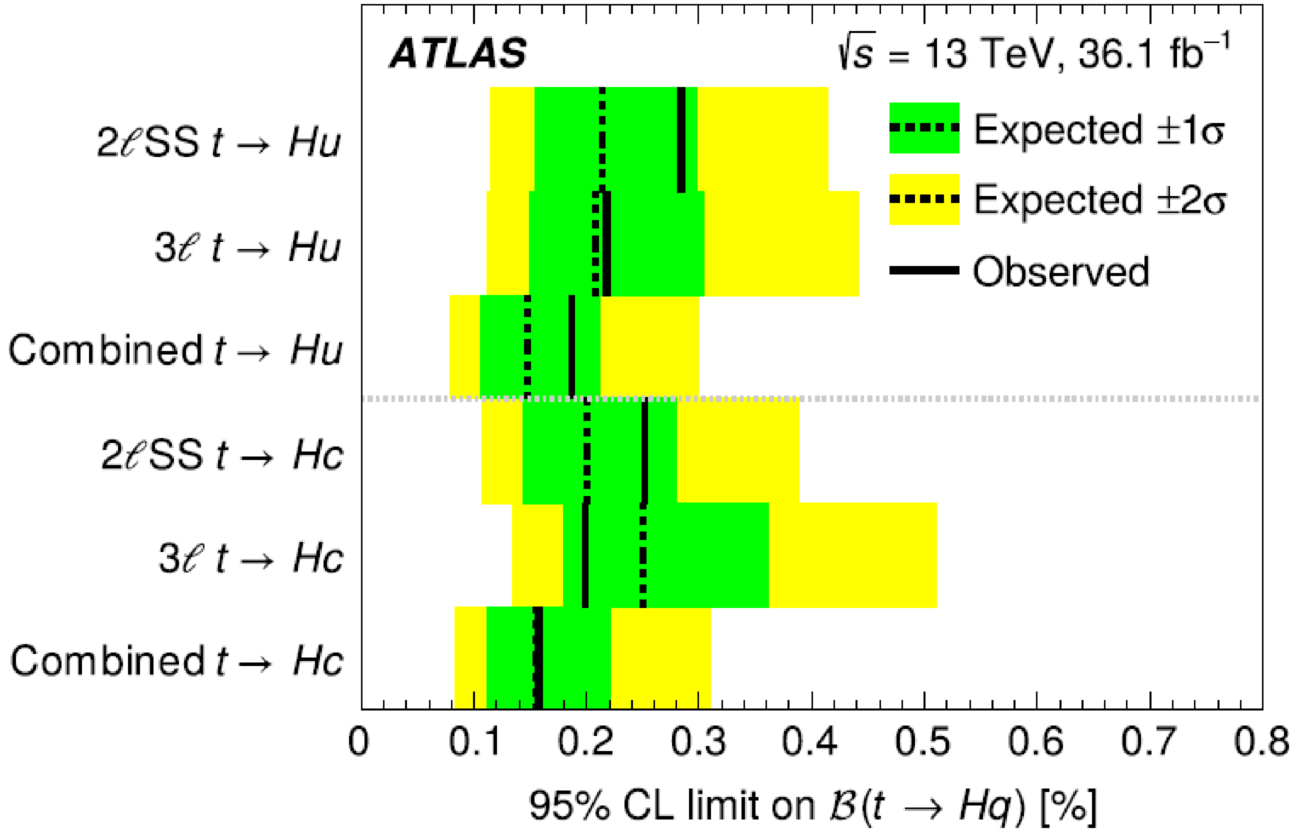


$BR(t \to Hc) < 0.22\%$ at 95% CL
$BR(t \to Hu) < 0.24\%$ at 95% CL



$\lambda_{tcH} < 0.090\ (0.077)$ at 95% CL
$\lambda_{tuH} < 0.094\ (0.079)$ at 95% CL

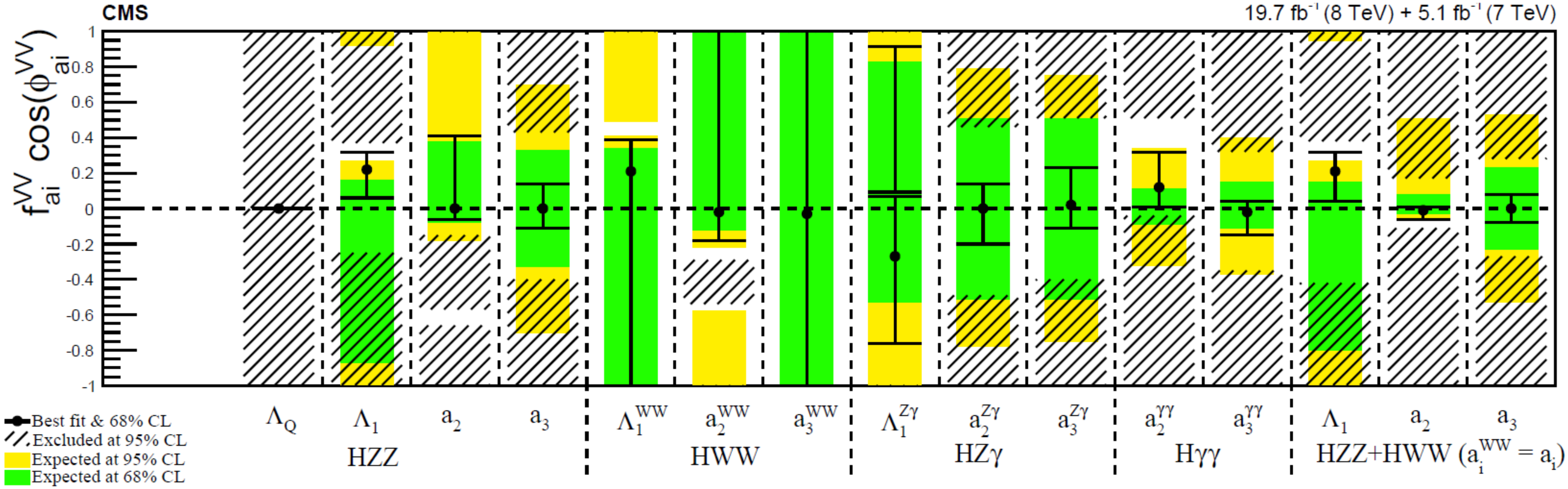
ATLAS analysis: Multi-lepton results



$BR(t \to Hc) < 0.16\%$ at 95% CL
$BR(t \to Hu) < 0.19\%$ at 95% CL

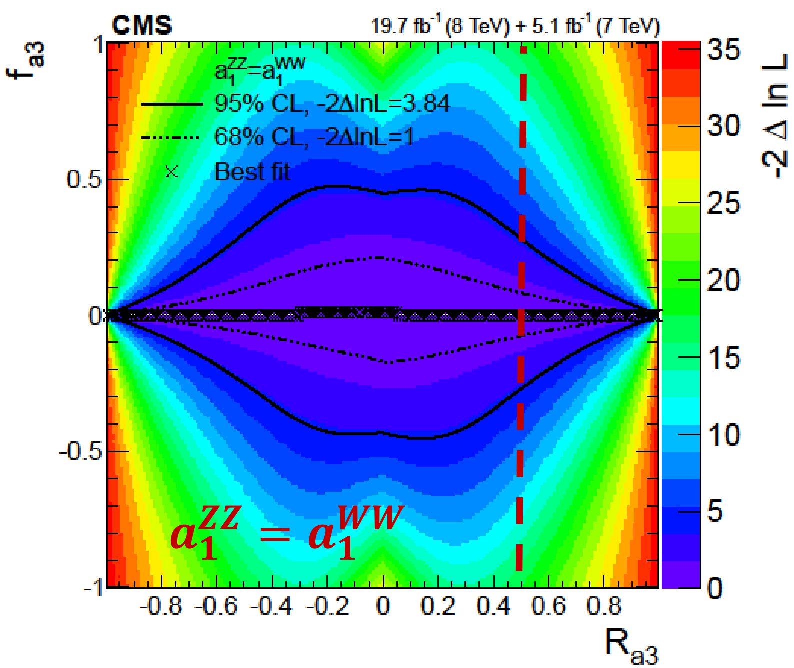
Anomalous couplings studies

Run I AC combination

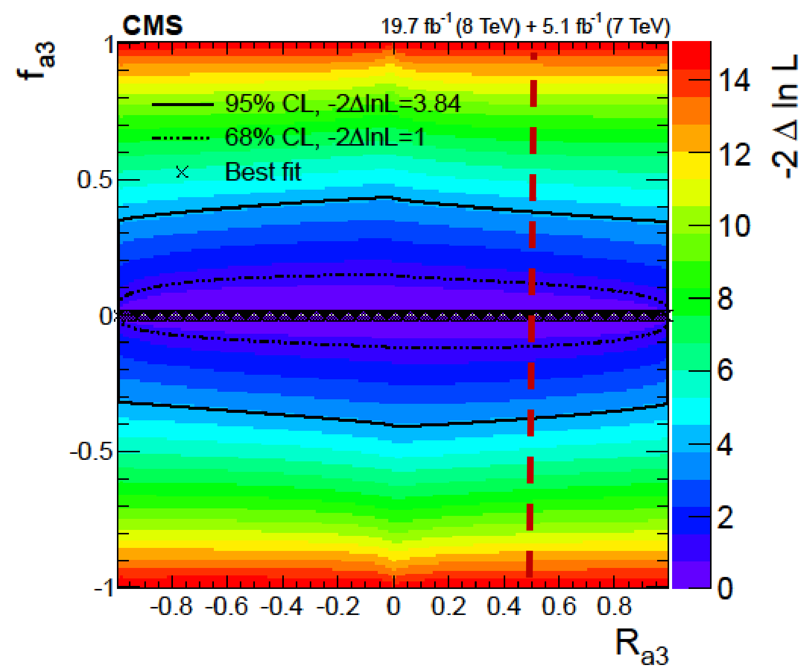


[Phys. Rev. D 92 (2015) 012004]

4l+$WW \rightarrow 2l2\nu$ combination (+$\gamma\gamma$ for spin-2 couplings)



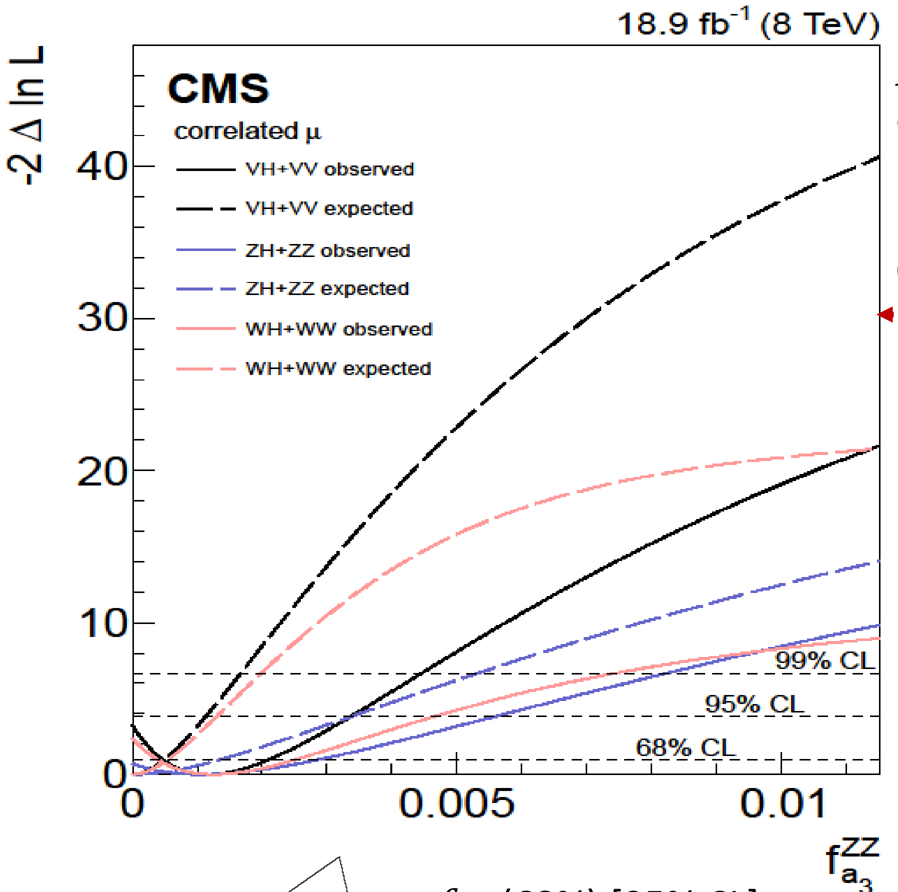
R_{ai}



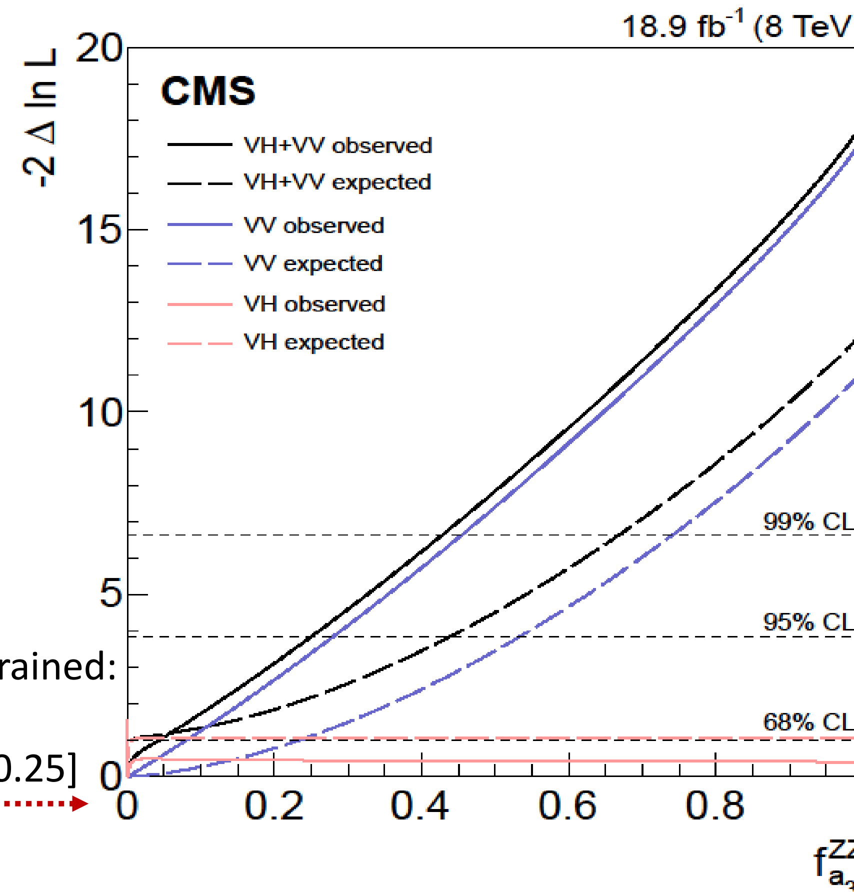
Run I a_3 AC using associated production

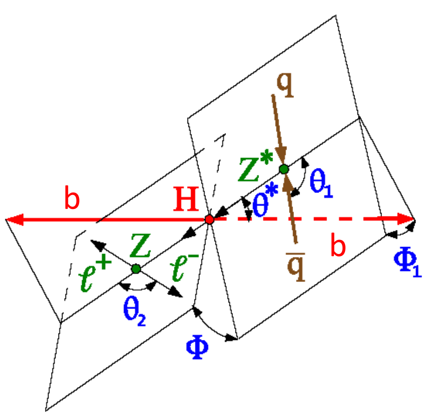
Phys. Lett. B 759 (2016) 672

$VH \rightarrow b\bar{b}$
combination with
$H \rightarrow VV$



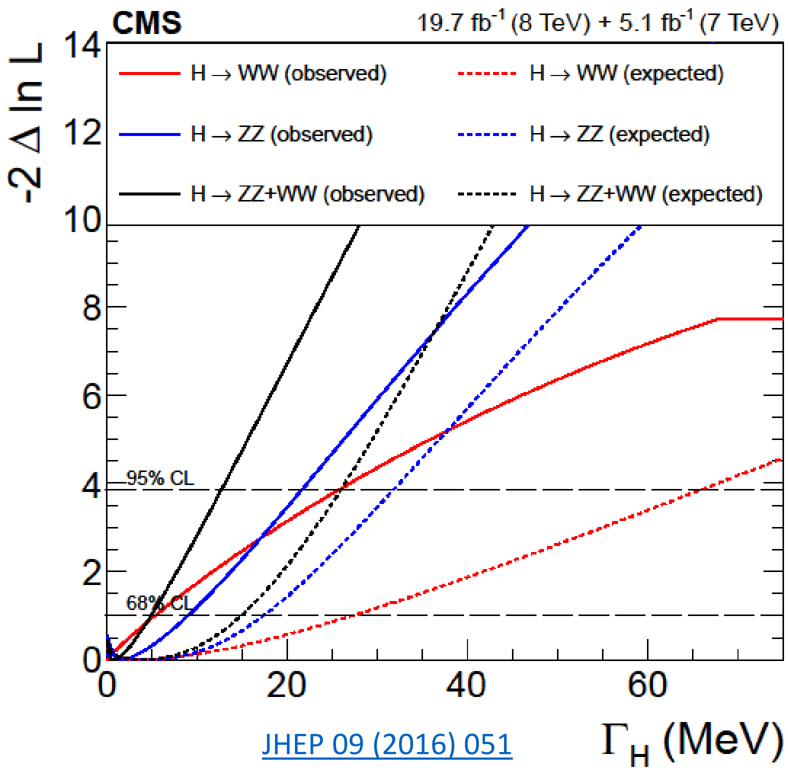
f_{a3} (68%) [95% CL]
$a_3^{ZZ}/a_1^{ZZ} = a_3^{WW}/a_1^{WW}$
$t\bar{t}H$ and $b\bar{b}H$ couplings ratio as in SM:
Expected: (0, 0.00050) [0,0.0011]
Observed: (0.00047, 0.0021) [0,0.0034]





f_{a3} (68%) [95% CL]
$a_3^{ZZ}/a_1^{ZZ} = a_3^{WW}/a_1^{WW}$
$t\bar{t}H$ and $b\bar{b}H$ couplings unconstrained:
Expected: (0, 0.0062) [0,0.44]
Observed: (0.00011, 0.0021) [0,0.25]

Run I width from off-shell Higgs boson



JHEP 09 (2016) 051

Expected $\Gamma_H < 26$ MeV
Observed $\Gamma_H < 13$ MeV

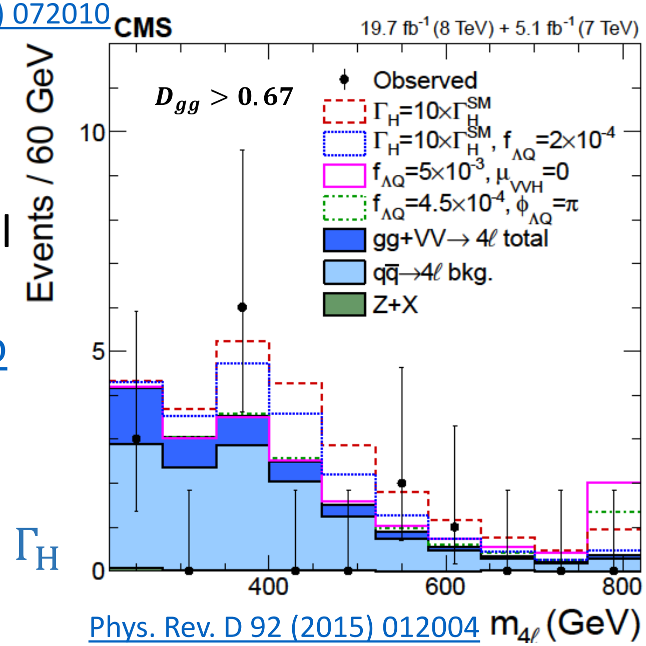
Combination using $4l$, and WW or $ZZ \rightarrow 2l2\nu$ using on-shell + off-shell combination of events

Phys. Rev. D 92 (2015) 072010

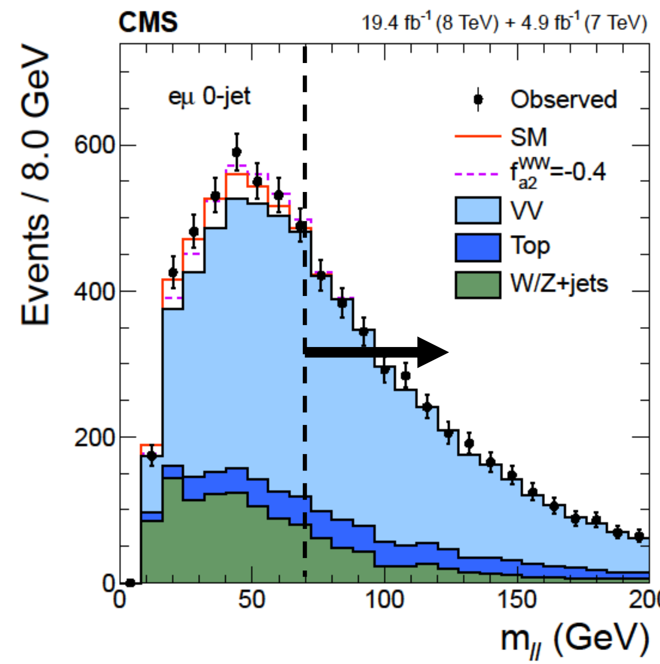
Proposed by F. Caola and K. Melnikov using the large off-shell tail pointed out by N. Kauer and G. Passarino

$$\sigma^{on-shell}_{vv\rightarrow H\rightarrow ZZ} \sim \mu_{vvH}$$
$$\Rightarrow \sigma^{off-shell}_{vv\rightarrow H\rightarrow ZZ} \sim \mu_{vvH} \times \Gamma_H$$

- Tight constraints on Γ_H with SM-like tensor structure
- Significant interference effects with background
- New probe for BSM physics



Phys. Rev. D 92 (2015) 012004



CMS HVV main uncertainties

Migration uncertainties:
- → Signal 4-20%, largest in ggH in VBF 2-jet tagged category
- → 3-20% in irreducible background, similar composition

Overall yield:
- → NNLO K factor uncertainty for gg processes
- → 10% additional uncertainty in gg background
- → 2% BR

Reducible background:
- → 36-43%

Lepton momentum scale:
- → 0.04, 0.3 and 0.1% for $4\mu, 4e, 2e2\mu$

Lepton energy resolution:
- → 20% on mass measurement

Lepton ID and reco. efficiency:
- → 2.5-9%

Luminosity:
- → 2.3-2.6%