BEH fermionic decays and combination

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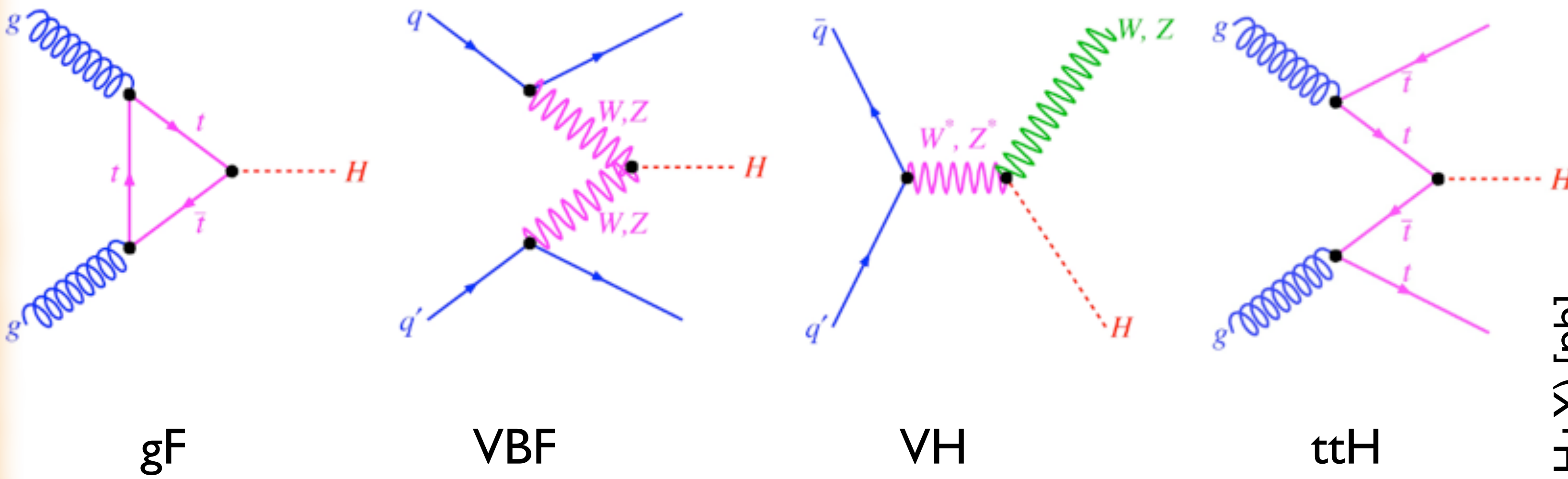
on behalf of the ATLAS and CMS Collaborations

Rencontres de Moriond - Electroweak Session
12-19.March.2016

Outline

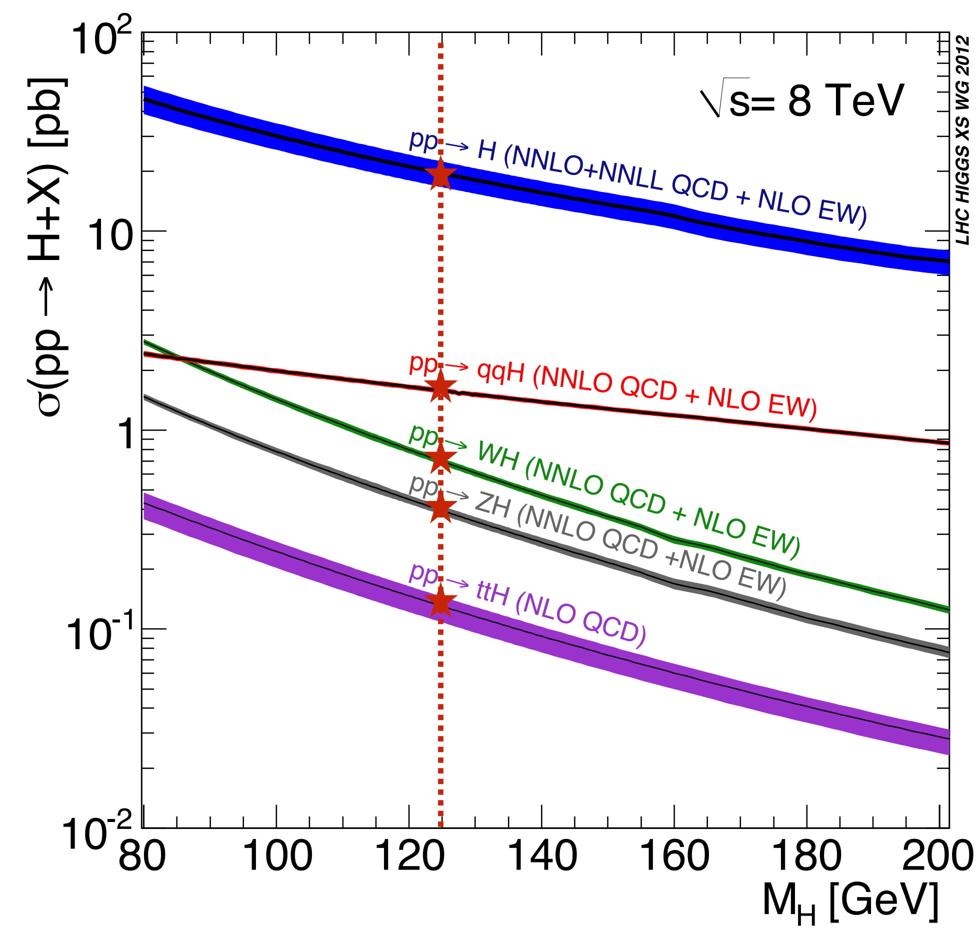
- Higgs boson production and decay
- Fermionic decays
  - $H \rightarrow \tau\tau$
  - $H \rightarrow \mu\mu$ and $H \rightarrow ee$
  - Lepton flavor violating decays
  - $H \rightarrow bb$
- ATLAS + CMS combination
- Conclusions

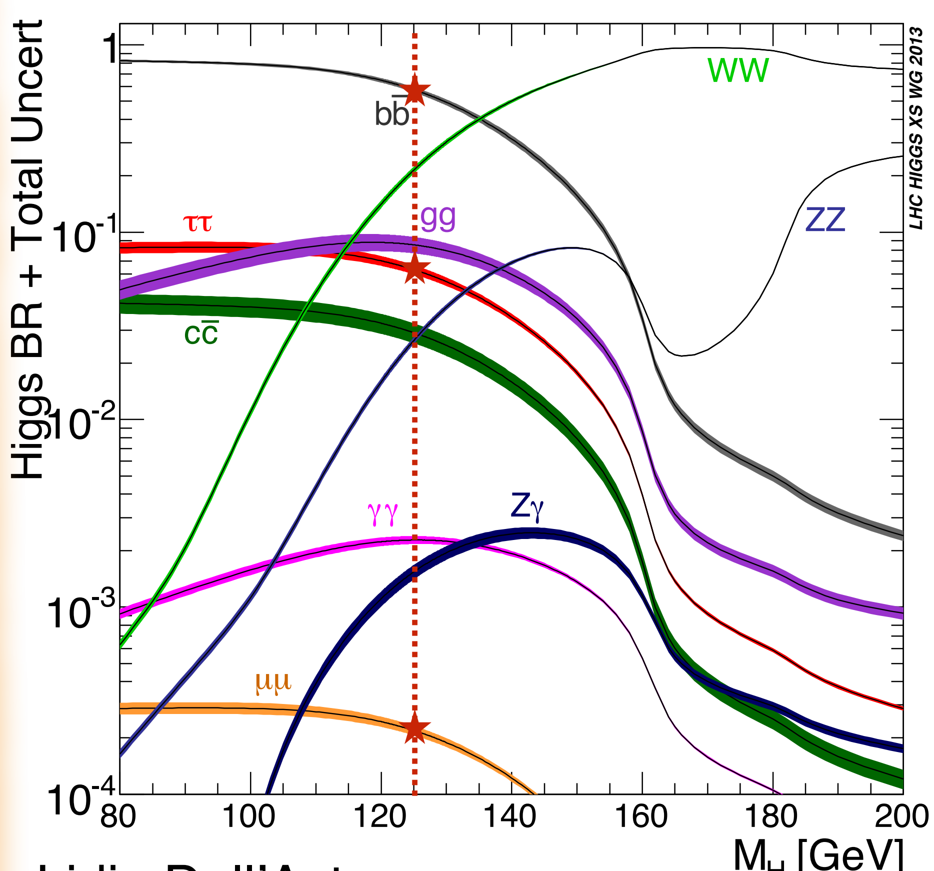
Higgs boson production and decay



Higgs boson **production** cross sections

m_H = 125 GeV	gF	VBF	WH	ZH	ttH
7 TeV	15.13 pb	1.22 pb	0.58 pb	0.34 pb	0.09 pb
8 TeV	19.27 pb	1.58 pb	0.70 pb	0.42 pb	0.13 pb
13 TeV	43.92 pb	3.75 pb	1.38 pb	0.87 pb	0.51 pb





BR for the **decay** of Higgs boson into **fermions**.

m_H = 125 GeV	$H \to bb$	$H \to \tau\tau$	$H \to \mu\mu$
BR	57.7%	6.32%	0.0219%

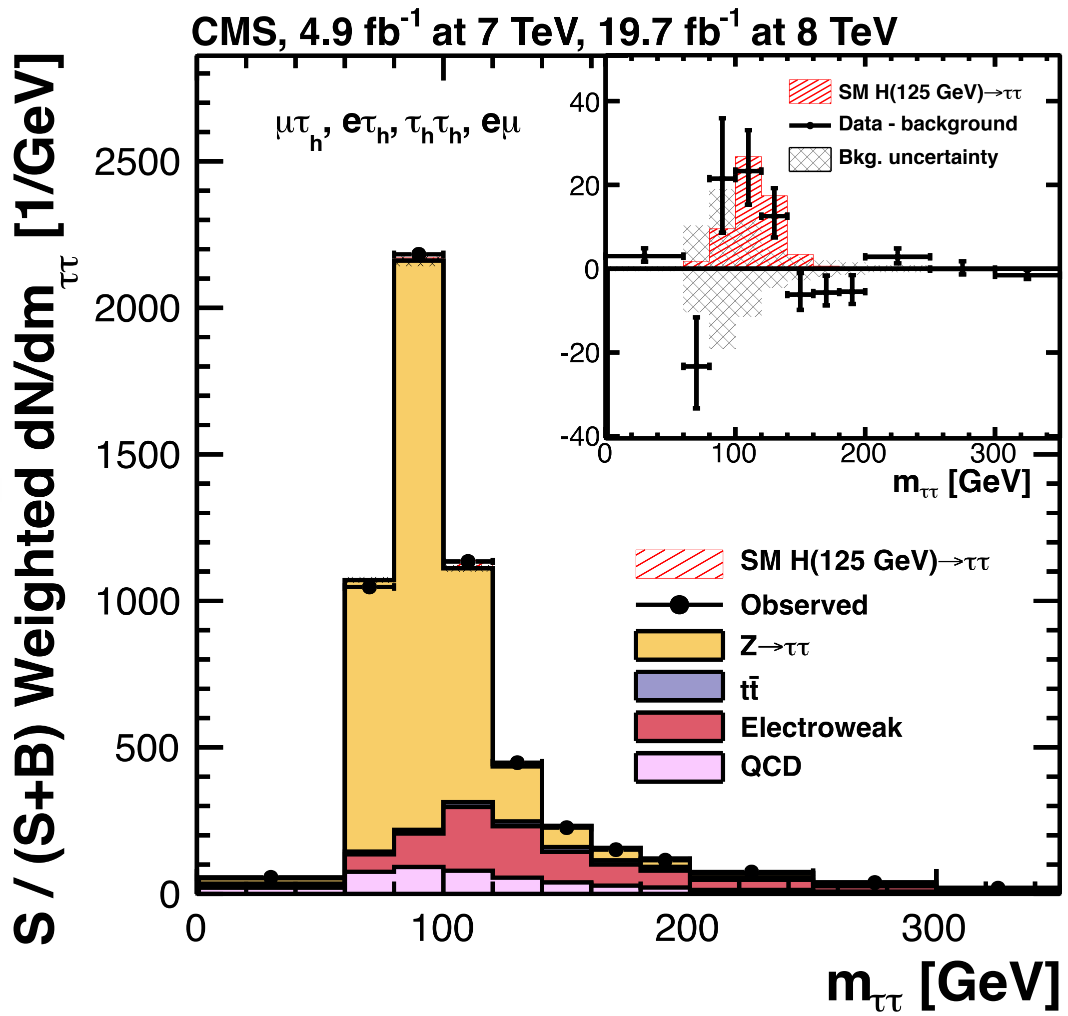
Trying to answer the **question**: what did we learn from the search and study of fermionic Higgs decays?

Disclaimer: covering here ~20 papers!
No time to go through analysis details…
Happy to discuss them over a 🍺 or a ⛷ break!

H→ττ

Evidence of Higgs boson **Yukawa** coupling to fermions.

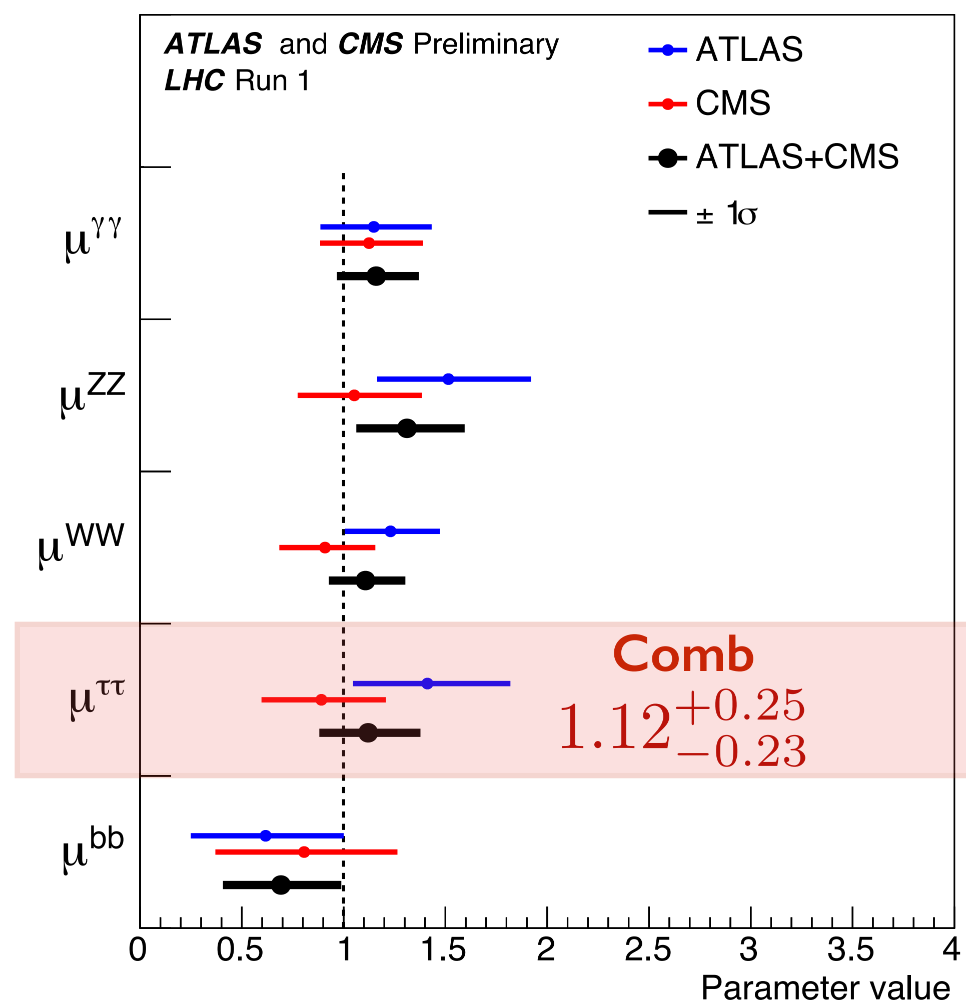
ATLAS: JHEP 04 (2015) 117 and ATLAS-CONF-2015-044
CMS: JHEP 05 (2014) 104 and CMS-PAS-HIG-15-002



- Lower BR than bb, but cleaner final state.
- Main **challenges**: mass resolution, triggering (fully hadronic channel) and controlling the $Z \to \tau\tau$ and multi-jet backgrounds.
- Event **categorization** based on jet multiplicity and $p_T(\tau\tau)$.
- Multivariate techniques with fit of final discriminant (ATLAS and CMS) or cut based analysis with fit of $m(\tau\tau)$ (CMS).

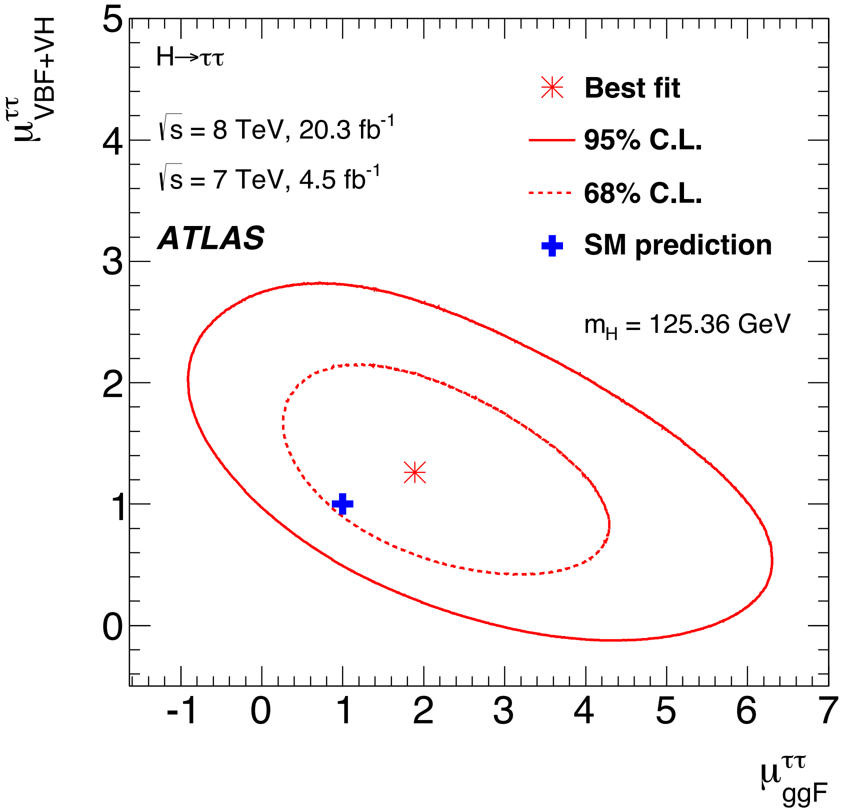
Channel	Signal strength [μ]		Signal significance [σ]	
	from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$ $\left(^{+0.37}_{-0.33}\right)$	$0.89^{+0.31}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.42}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	-0.7 ± 3.6 (± 3.6)	0.8 ± 3.5 (± 3.5)		

Comb 5.5 (5.0)



$H \to \tau\tau$

Looking at different **production** modes…



ATLAS: JHEP 04 (2015) 117

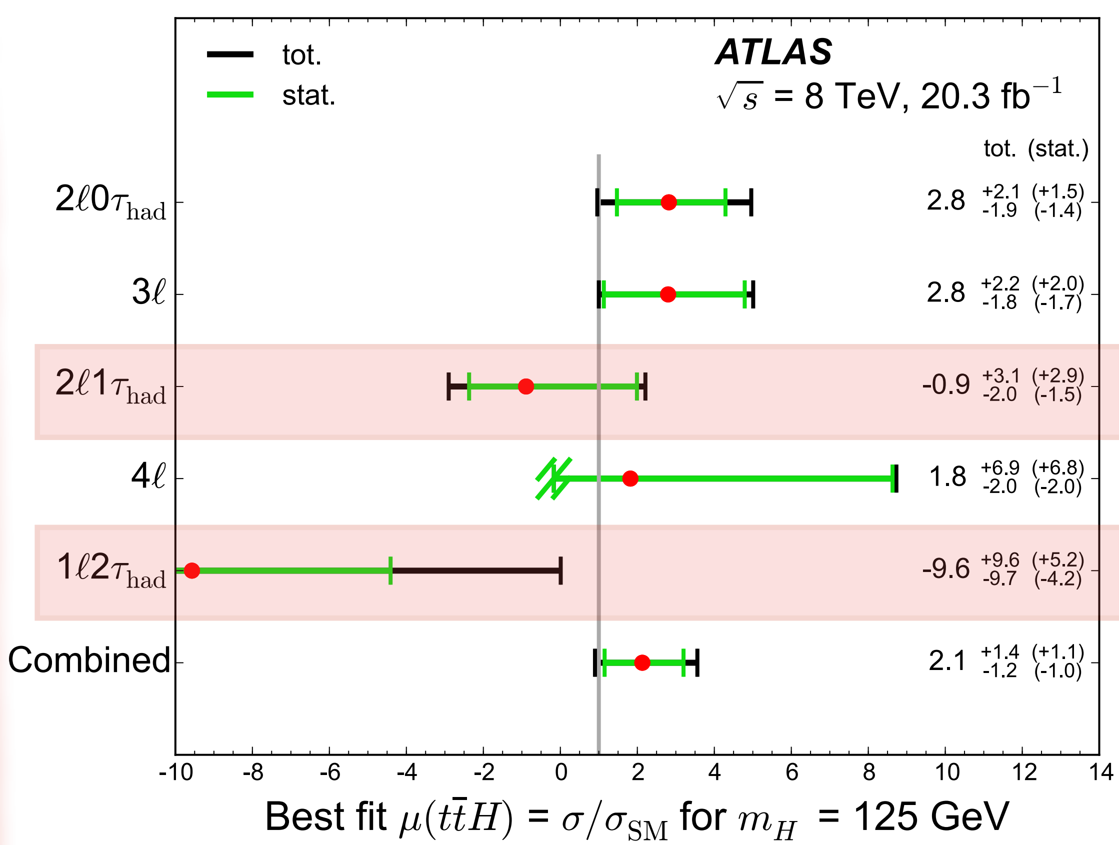
$$\mu^{\tau\tau}_{ggF} = 2.0 \ \pm 0.8(\text{stat.}) \ ^{+1.2}_{-0.8}(\text{syst.}) \ \pm 0.3(\text{theory syst.})$$

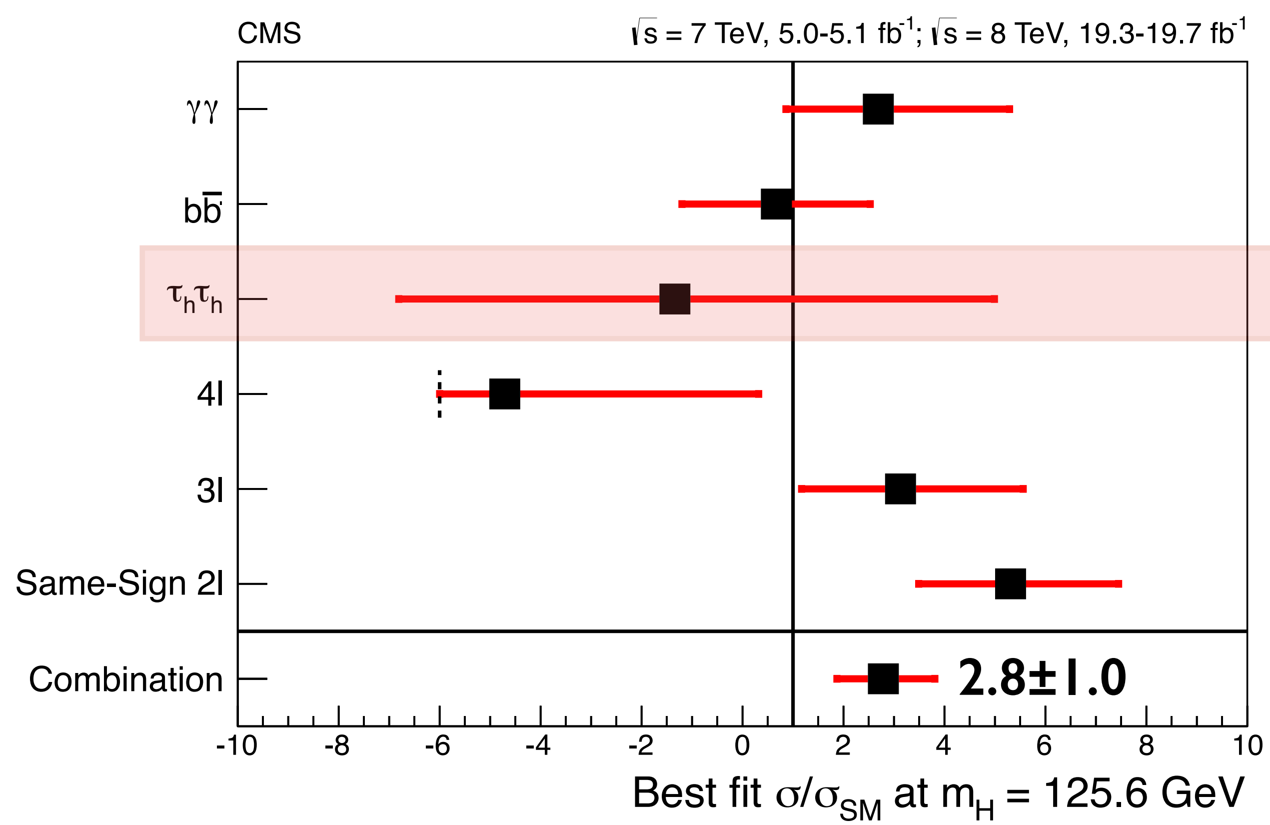
$$\mu^{\tau\tau}_{\text{VBF}+VH} = 1.24 \ ^{+0.49}_{-0.45}(\text{stat.}) \ ^{+0.31}_{-0.29}(\text{syst.}) \ \pm 0.08(\text{theory syst.})$$

obs (exp) signal significance @ 125 GeV:
ggF: 1.74σ (0.95σ)
VBF + VH: 2.25σ (1.72σ)

ttH

ATLAS: Phys. Lett. B 749 (2015) 519
CMS: JHEP 09 (2014) 087



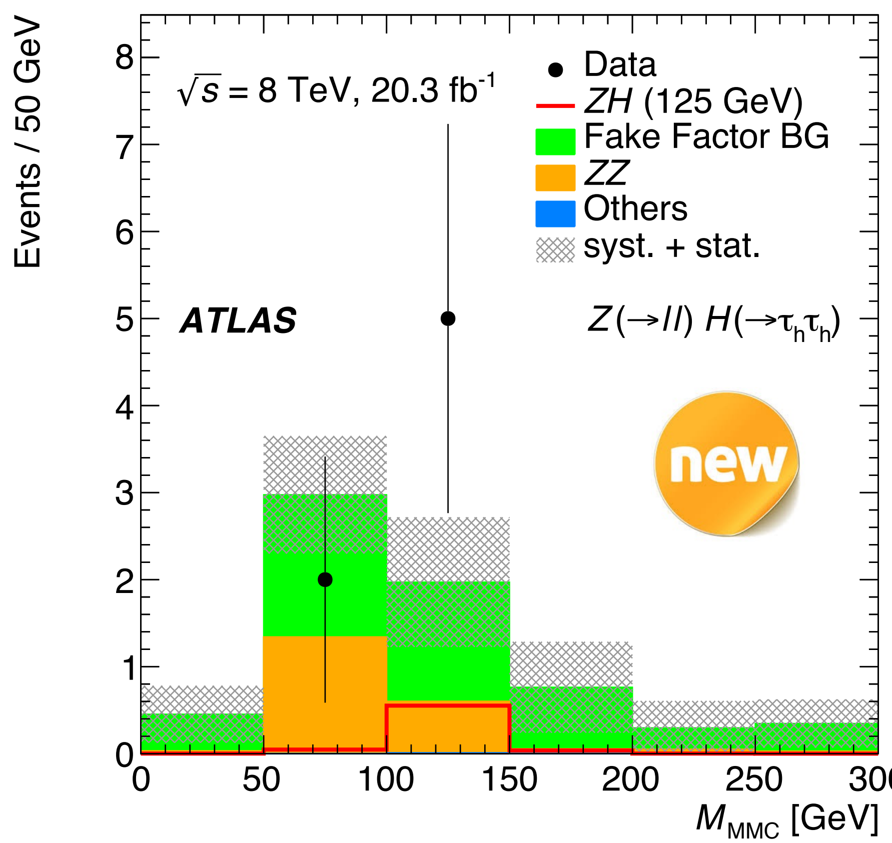


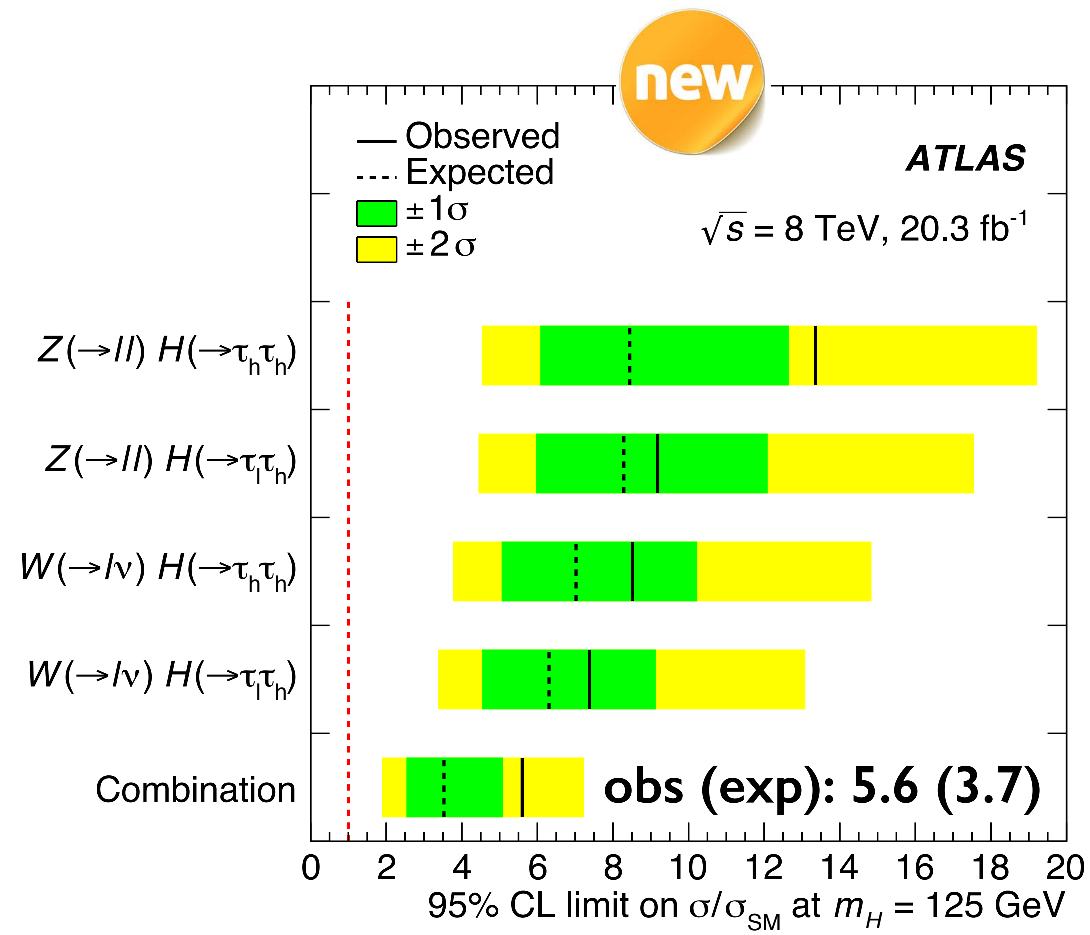
[Also bosonic decays included here!]

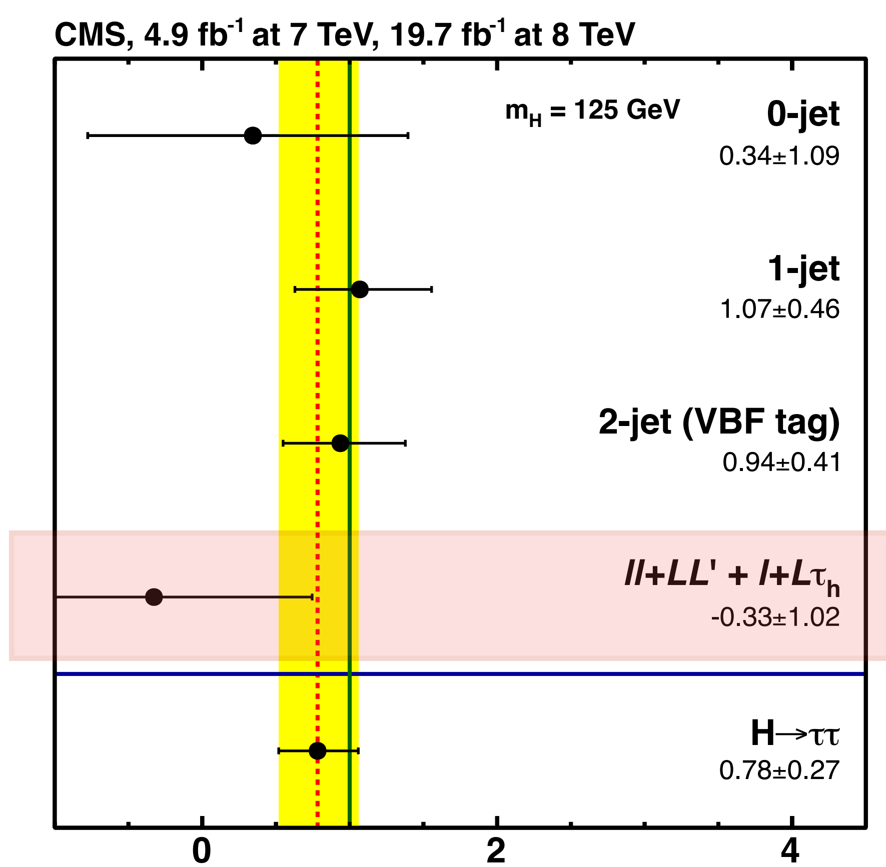
Looking at different **production** modes…

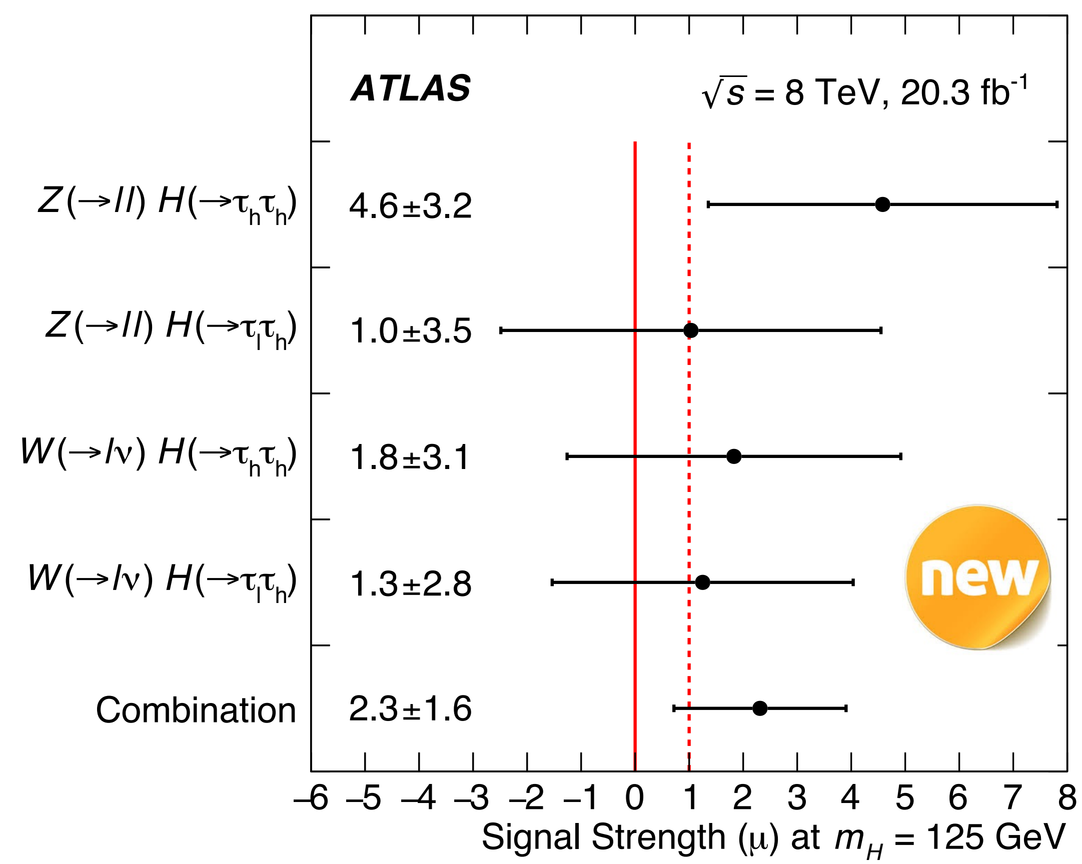
ATLAS: HIGG-2014-01 (Submitted to PRD)
CMS: JHEP 05 (2014) 104

VH





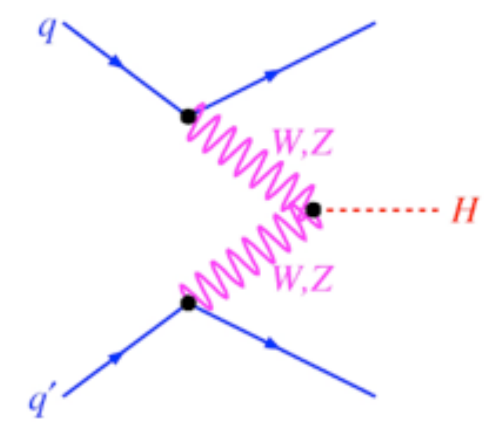




new

ATLAS: HIGG-2015-06 (Submitted to EPJC)

- Look for **CP-violating** HVV couplings.
  - Run1 studies in decay H→WW and H→ZZ and differential cross sections of H→γγ in EFT: no deviations from the SM.
  - **New**: use **VBF** production, perform **direct test of CP-invariance**.
- Possible signs of CP-odd contribution: clear indication of new physics.
- CP-mix parametrized in terms of $\tilde{d}$ parameter.
- **Optimal Observable** (OO): combines information into single variable.
  - CP-odd observable.
  - Highest sensitivity for small values of parameter of interest.



$$\mathcal{OO} = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$$

with: $\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}$

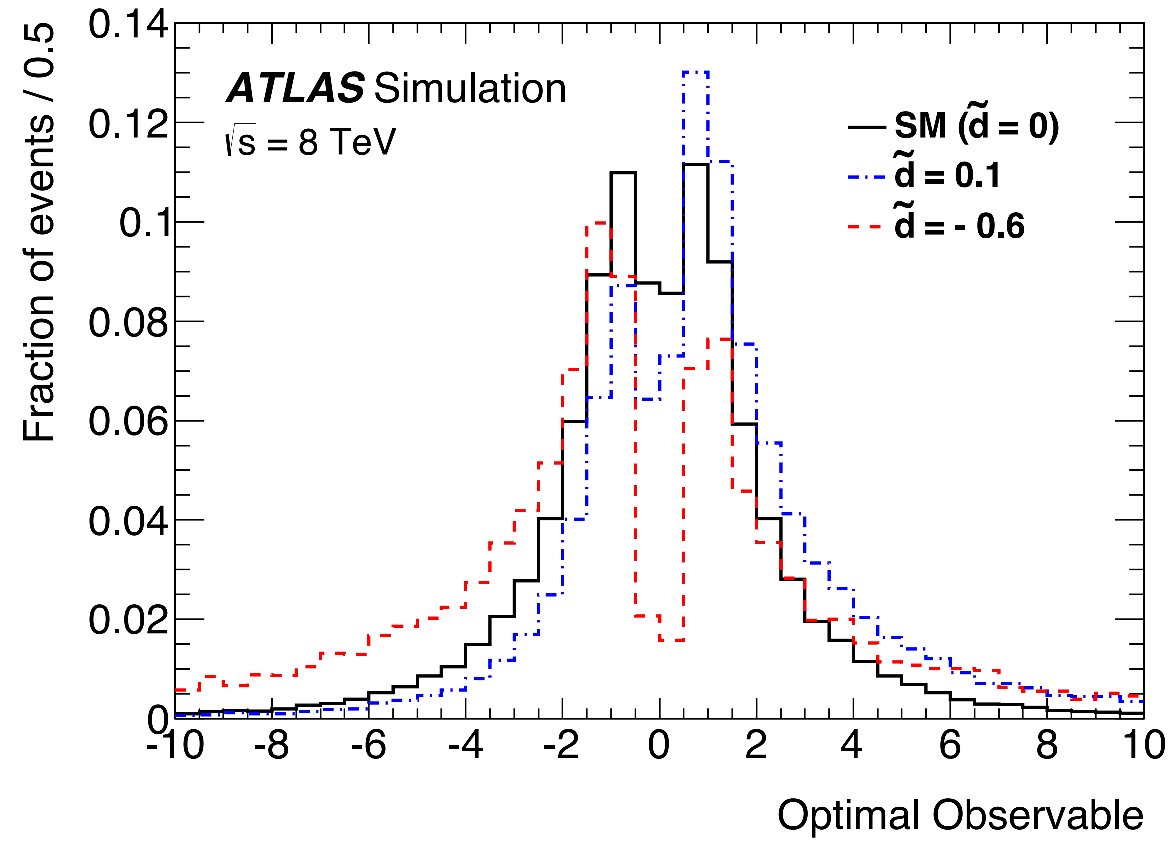
Considering CP-odd contributions, effective Lagrangian can be written as:

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \tilde{g}_{HAA}H\tilde{A}_{\mu\nu}A^{\mu\nu} + \tilde{g}_{HAZ}H\tilde{A}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HZZ}H\tilde{Z}_{\mu\nu}Z^{\mu\nu} + \tilde{g}_{HWW}H\tilde{W}^{+}_{\mu\nu}W^{-\mu\nu}$$

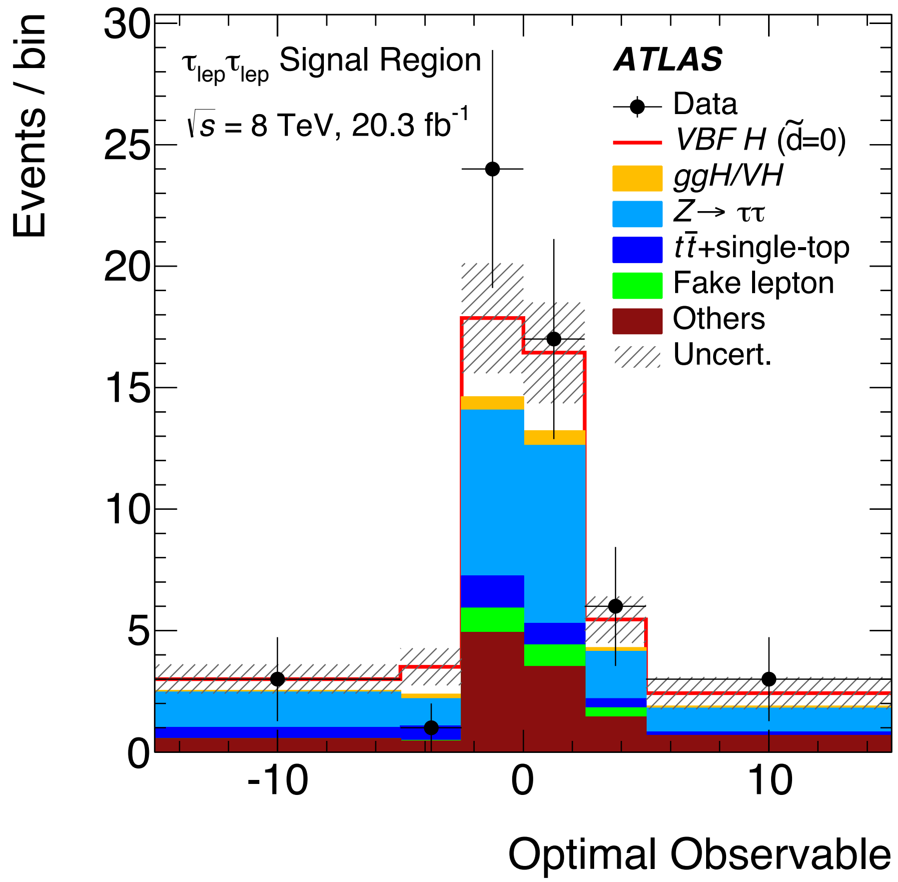
…and couplings can be parametrized as:

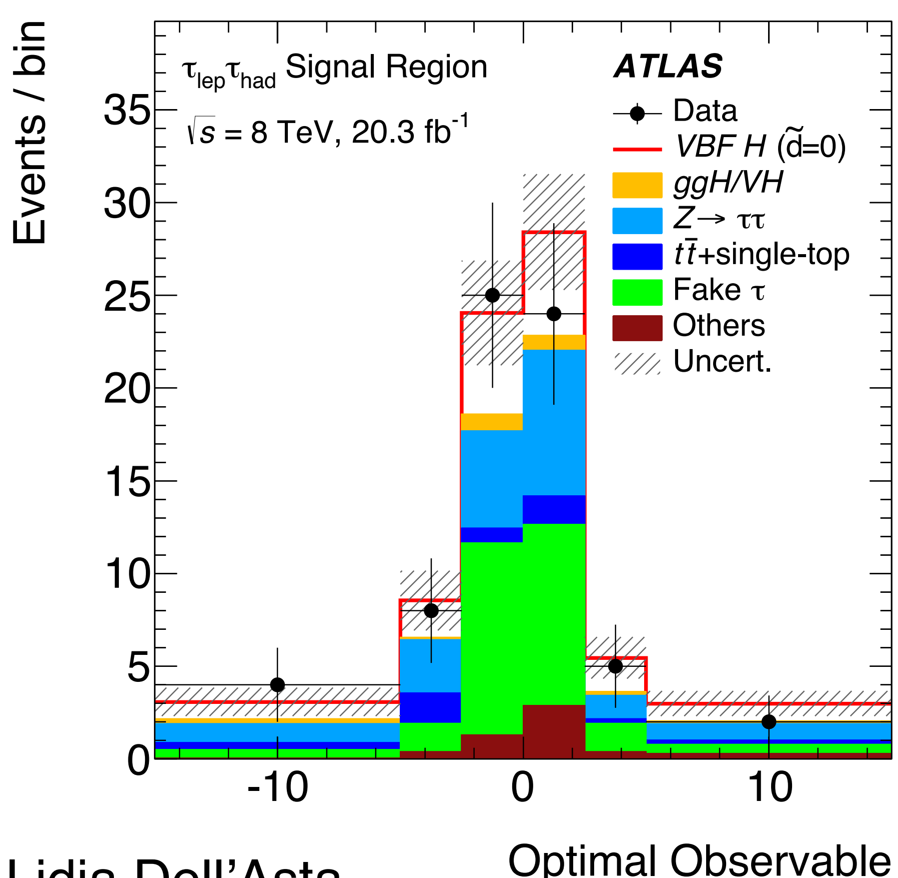
$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W) \qquad \tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$

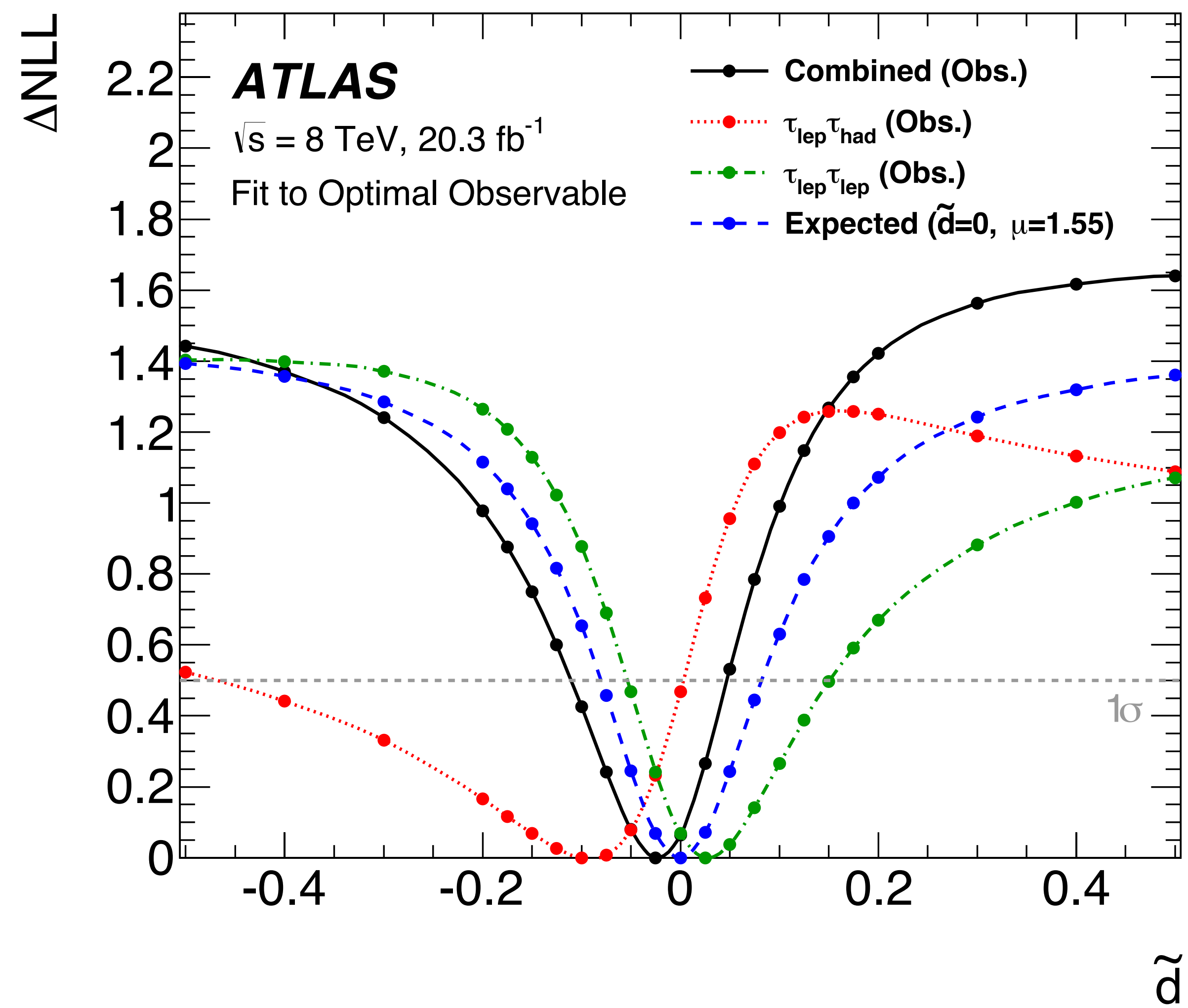
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W) \qquad \tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d}\,.$$



new







OO performs better than signΔφ(j,j).

$\tilde{d}$ outside [-0.11,0.05] excluded at 68% C.L..

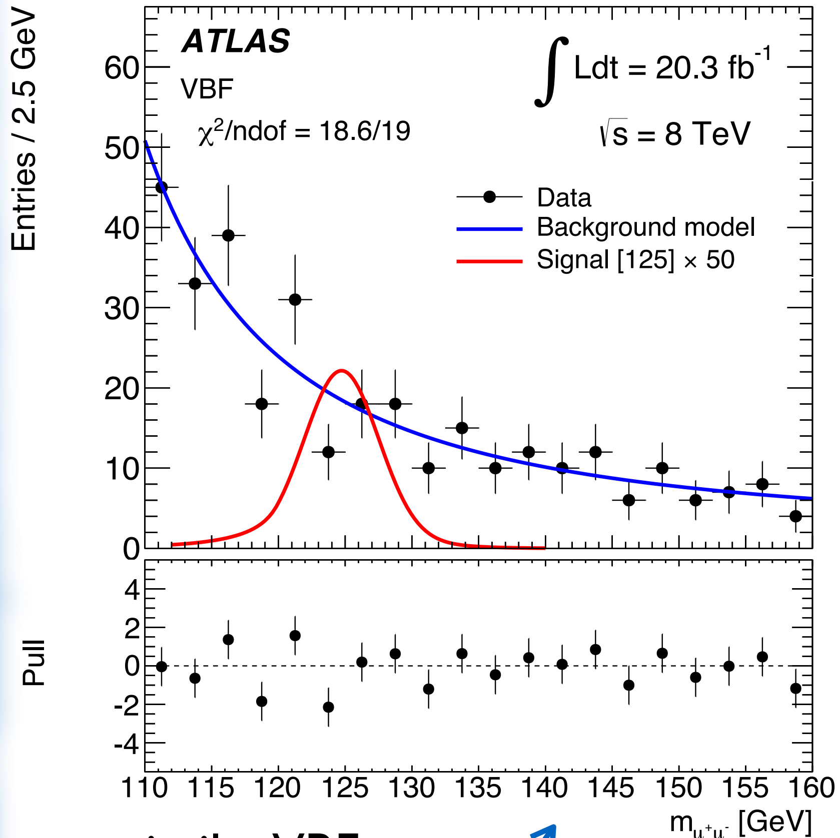
This 68% C.L. limit is a factor 10 better than the one from the ATLAS H→WW/ZZ combined CP analysis.

$H\to\mu\mu$ and $H\to ee$

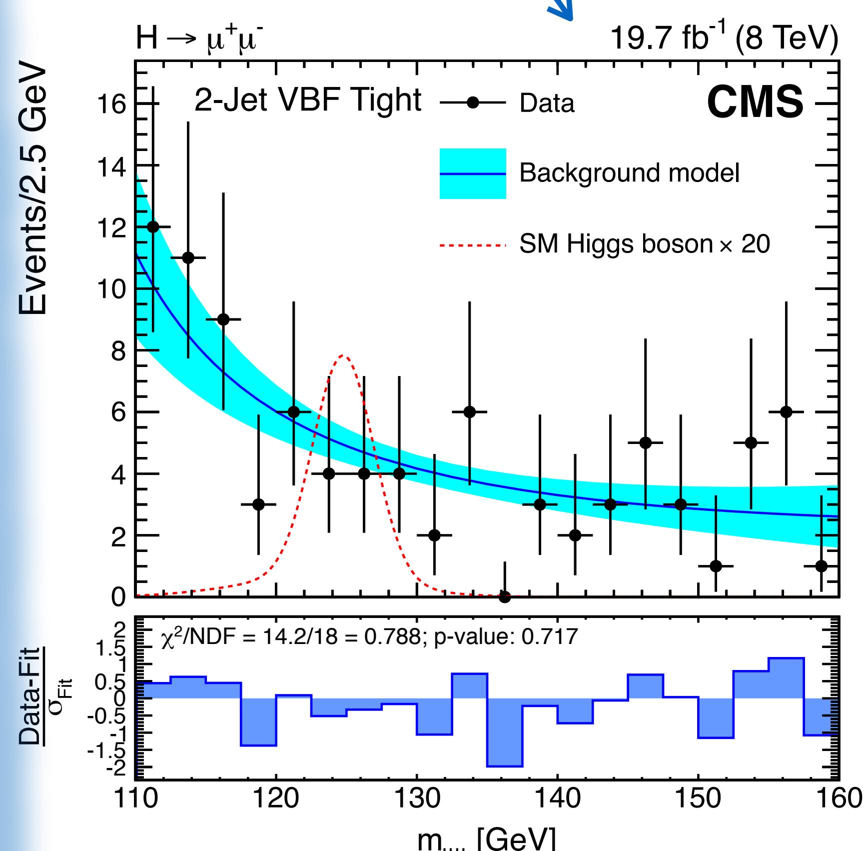
ATLAS: Phys. Lett. B 738 (2014) 68
CMS: Phys. Lett. B 744 (2015) 184

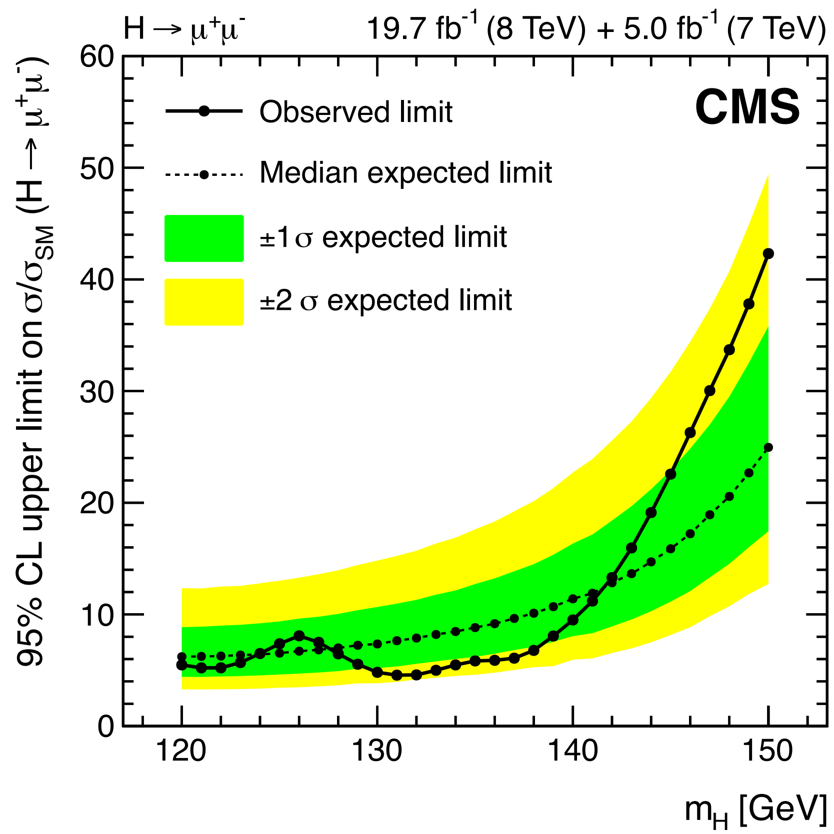
Higgs boson coupling to **second generation** fermions.
Test if the coupling is flavor universal or proportional to the lepton mass, as predicted by the SM.

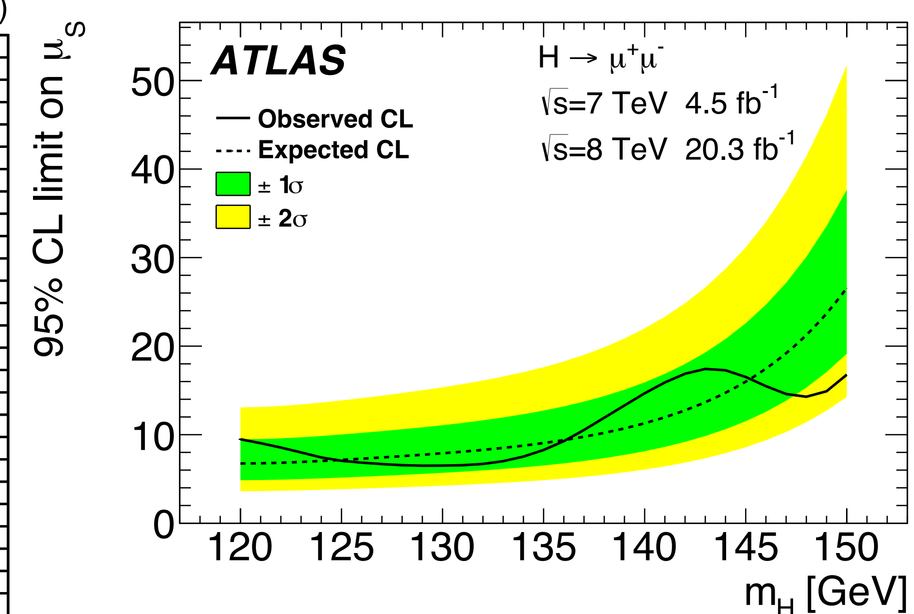
- **Clean** final state, but **small BR** and **overwhelming** $Z/\gamma^*\to\mu\mu$ **background**.
- Event **categorization** based on jet multiplicity, $p_T(\mu\mu)$ and $m(\mu\mu)$ resolution.
- Cut based analysis with fit of $m(\mu\mu)$ with analytical bkg/signal shapes.

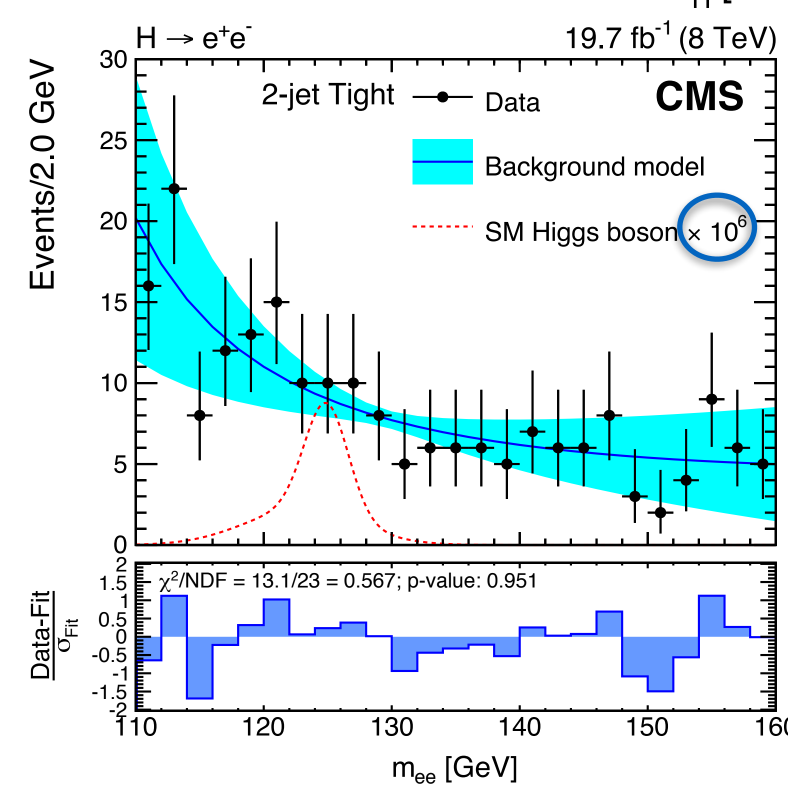


similar VBF categories









obs (exp) 95% CL limit on μ @ 125 GeV:
ATLAS: 7.0 (7.2) x SM
CMS: 7.4 (6.5) x SM

Lepton flavor violating decays

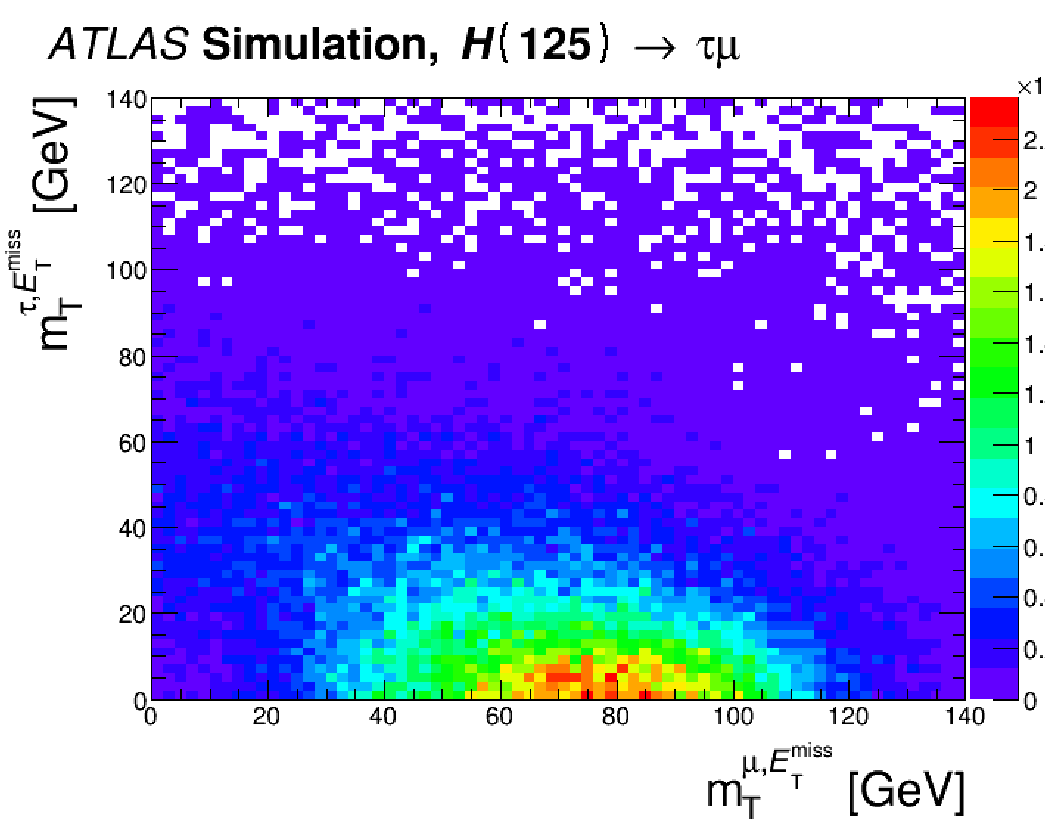
In the SM, lepton flavor violating (LFV) decays are forbidden.
If the theory is re-normalizable up to a finite mass scale, LFV couplings may be introduced.
LFV decays can occur naturally in several BSM models.

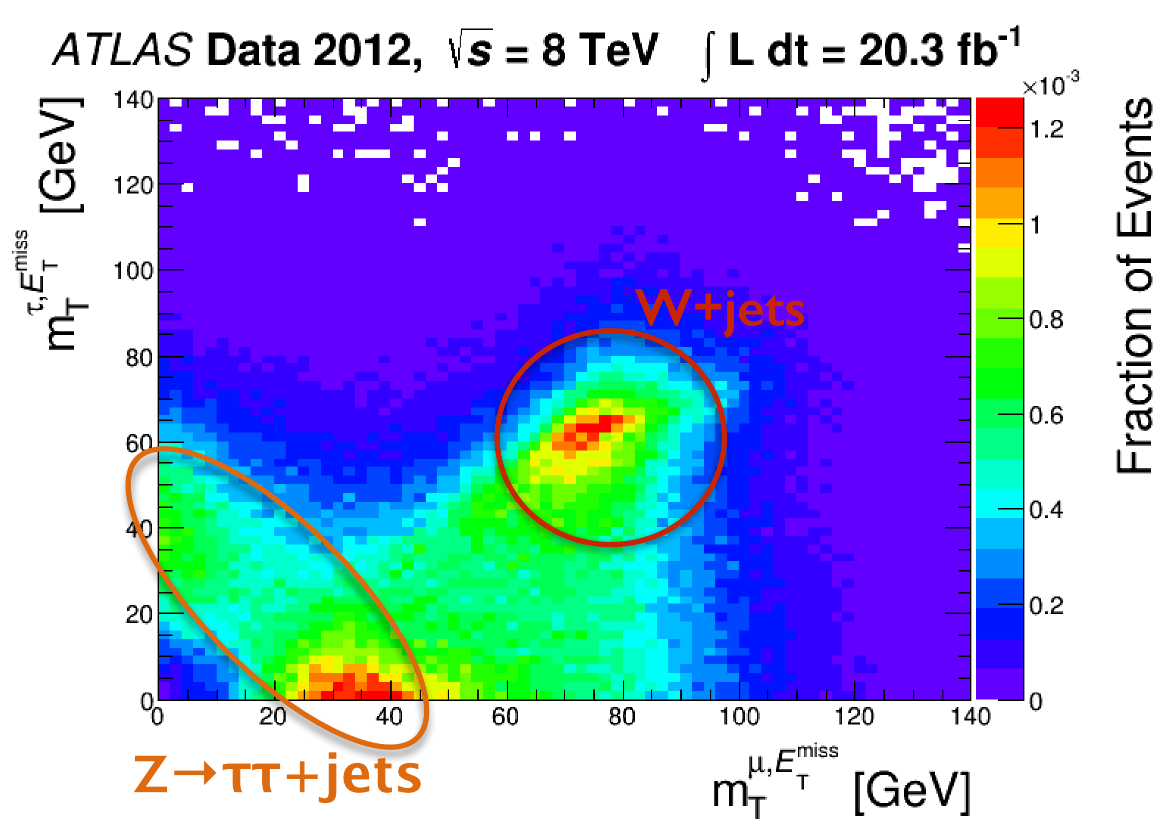
ATLAS: JHEP 11 (2015) 211 and new paper in preparation
CMS: Phys. Lett. B 749 (2015) 337 and CMS-PAS-HIG-14-040

LFV decay:
limits on BR

$BR(H \to \mu e) < O(10^{-8})$
$BR(H \to \tau e) < O(10\%)$
$BR(H \to \tau\mu) < O(10\%)$

- Signature very similar to SM $H \to \tau\tau$ decays, but:
  - lepton from LFV Higgs decay tends to have a larger momentum than in SM case
  - neutrinos are collinear with the tau decay products.
- Event categorization based on m_T (ATLAS) or number of jets (CMS).
- Fit of τ+lepton collinear mass or MMC.

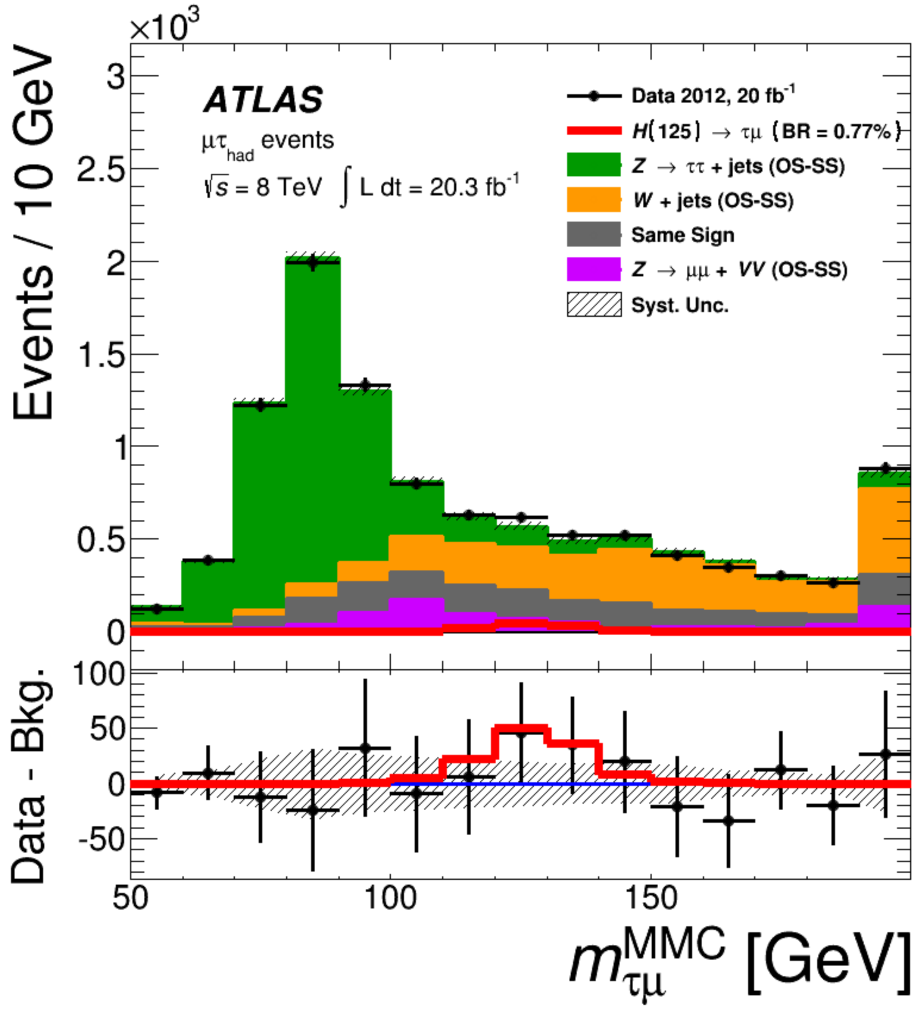


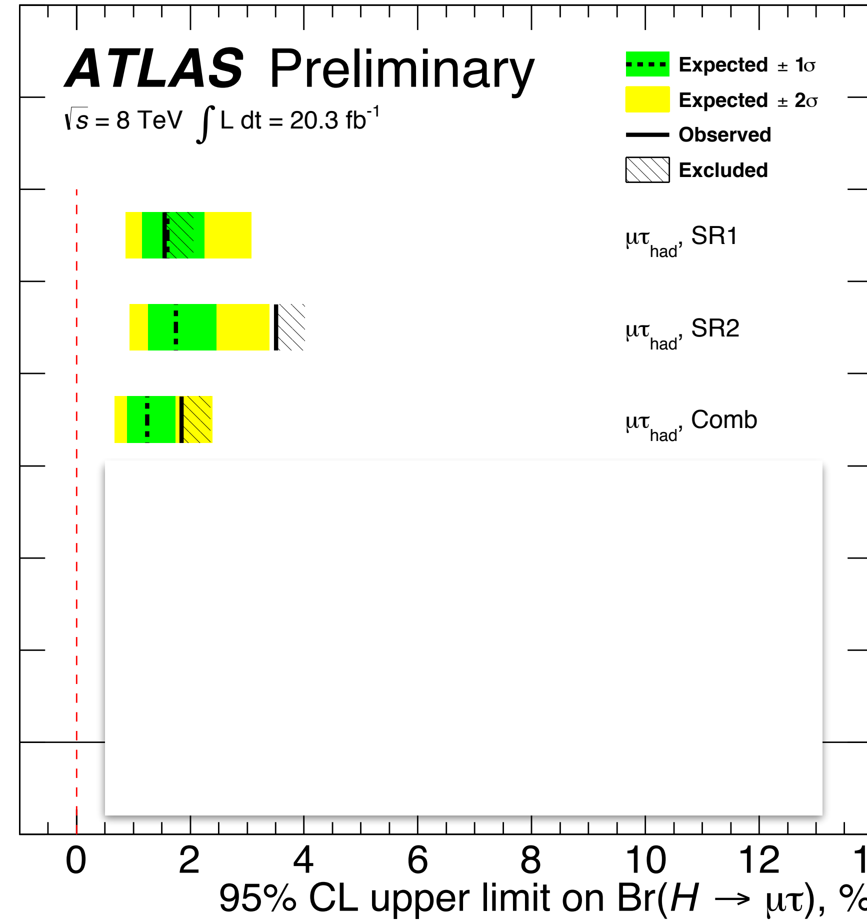


Channel summary: CMS & ATLAS

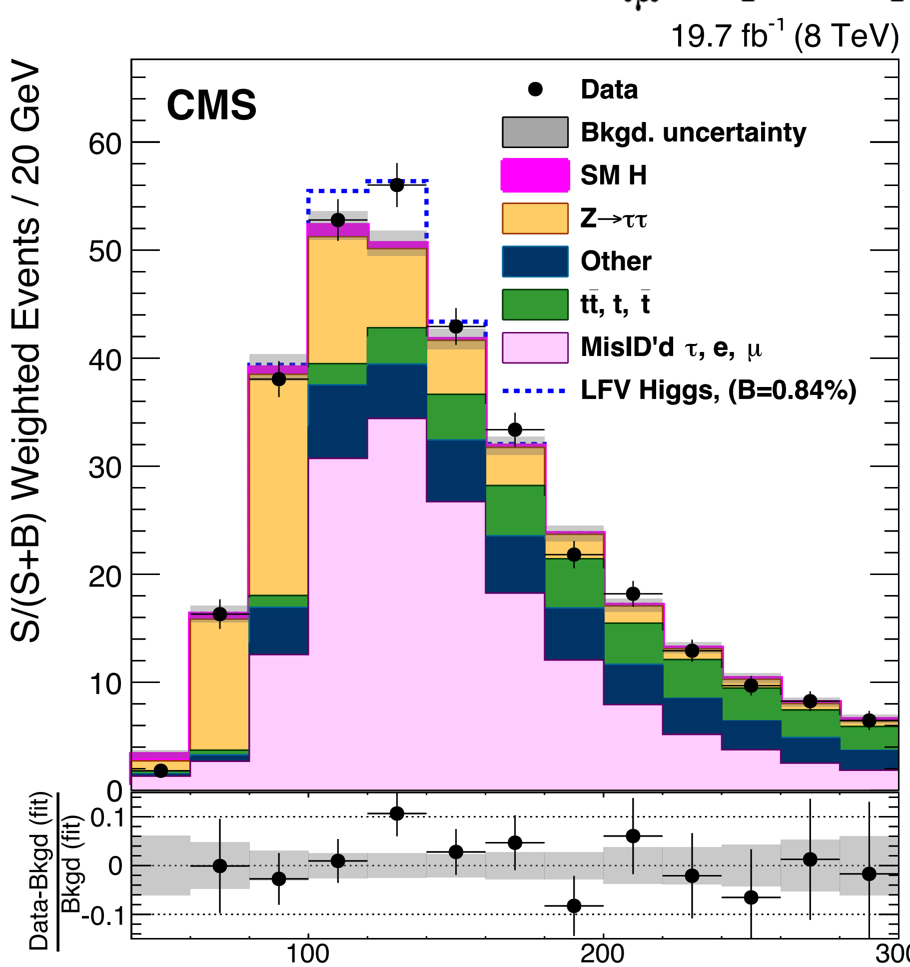
	e	μ
τ_l	τμ ✔✔ new	τe ✔✔ new
τ_h	✔✔ new	✔✔

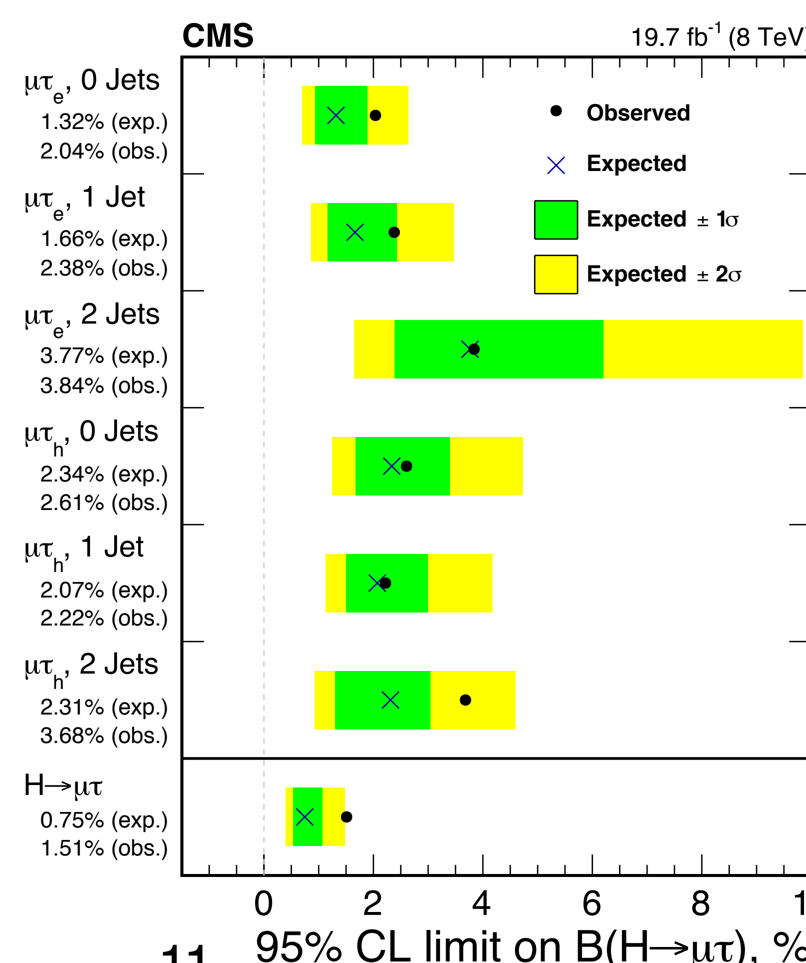
Lepton flavor violating decays





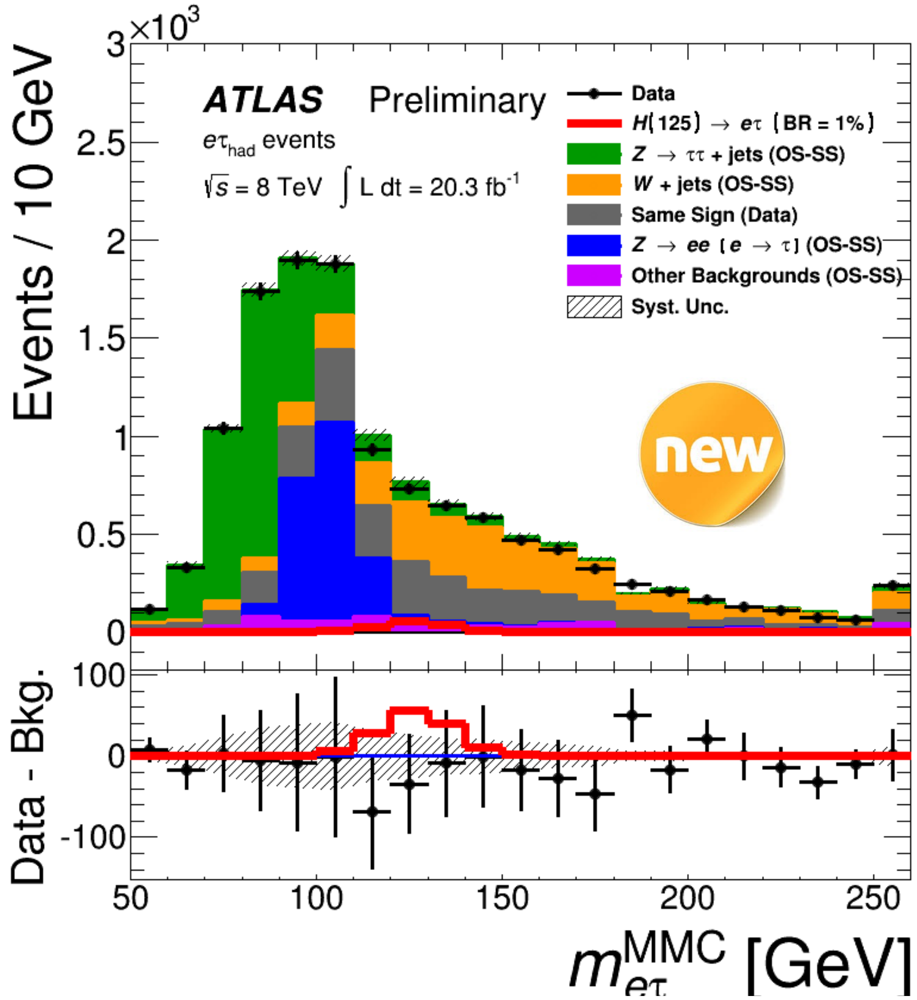
observed 95% CL upper limit on BR:
Br(H→μτ) < 1.85%

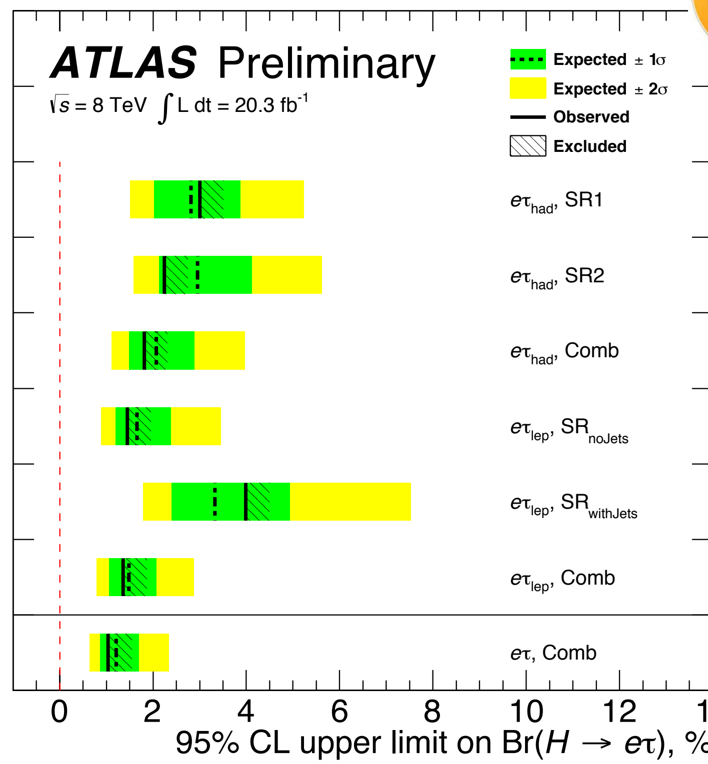


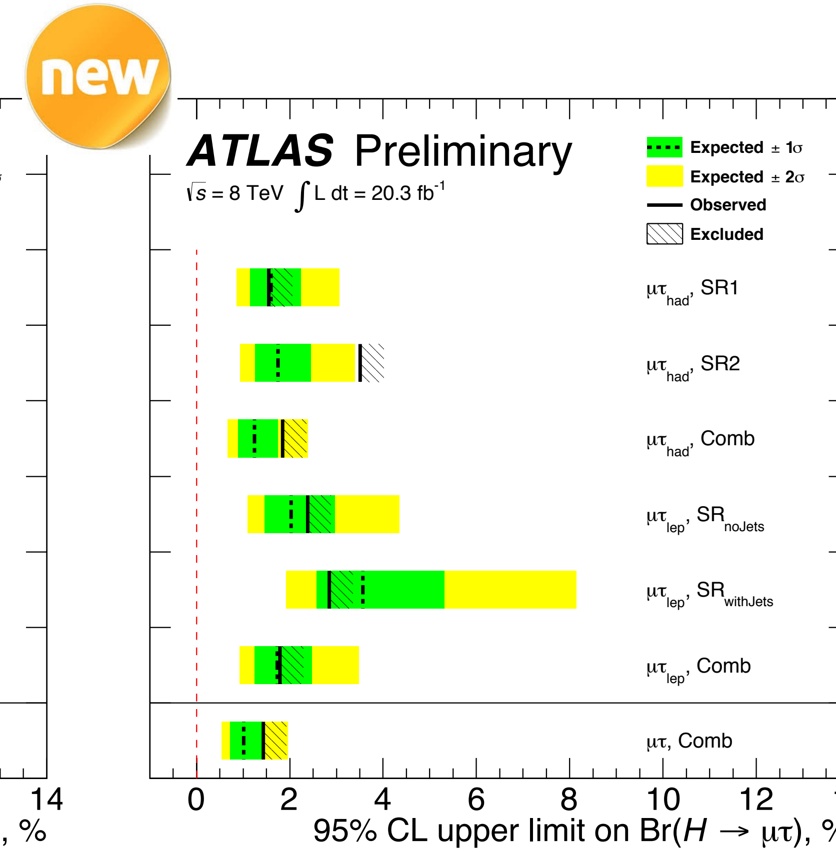


observed 95% CL upper limit on BR:
Br(H→μτ) < 1.51%

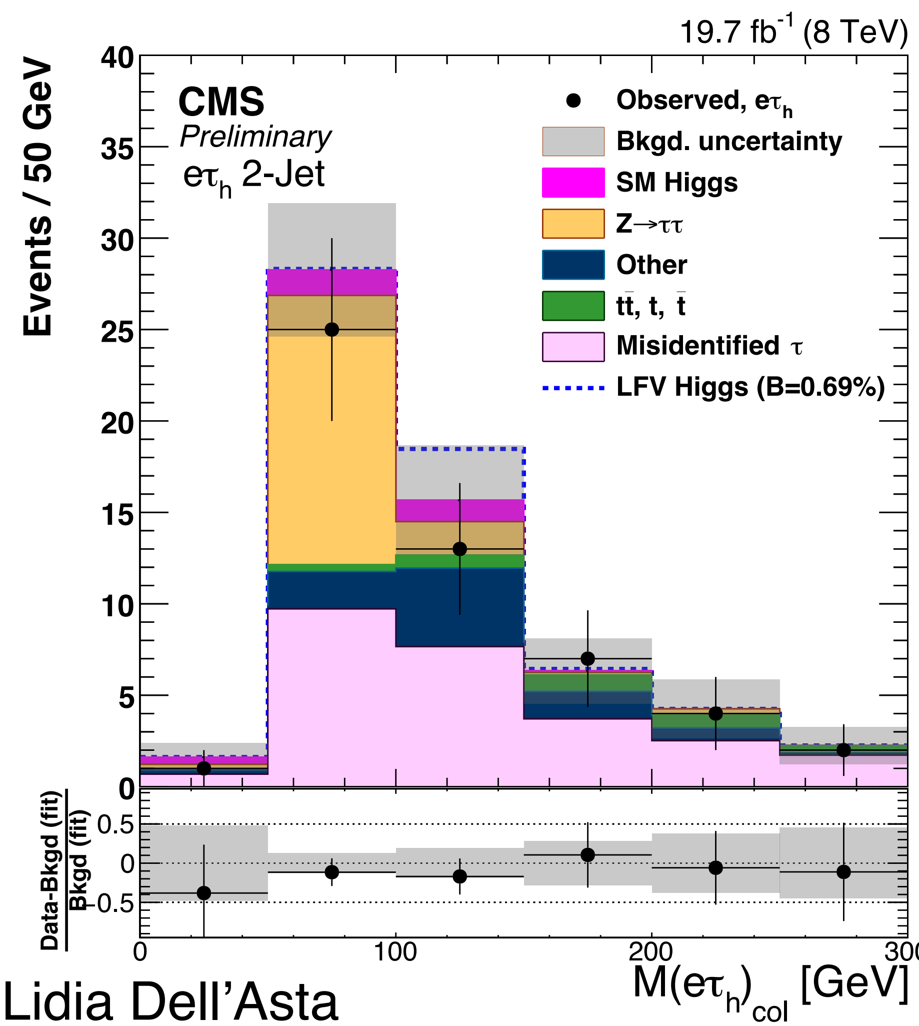
Lepton flavor violating decays

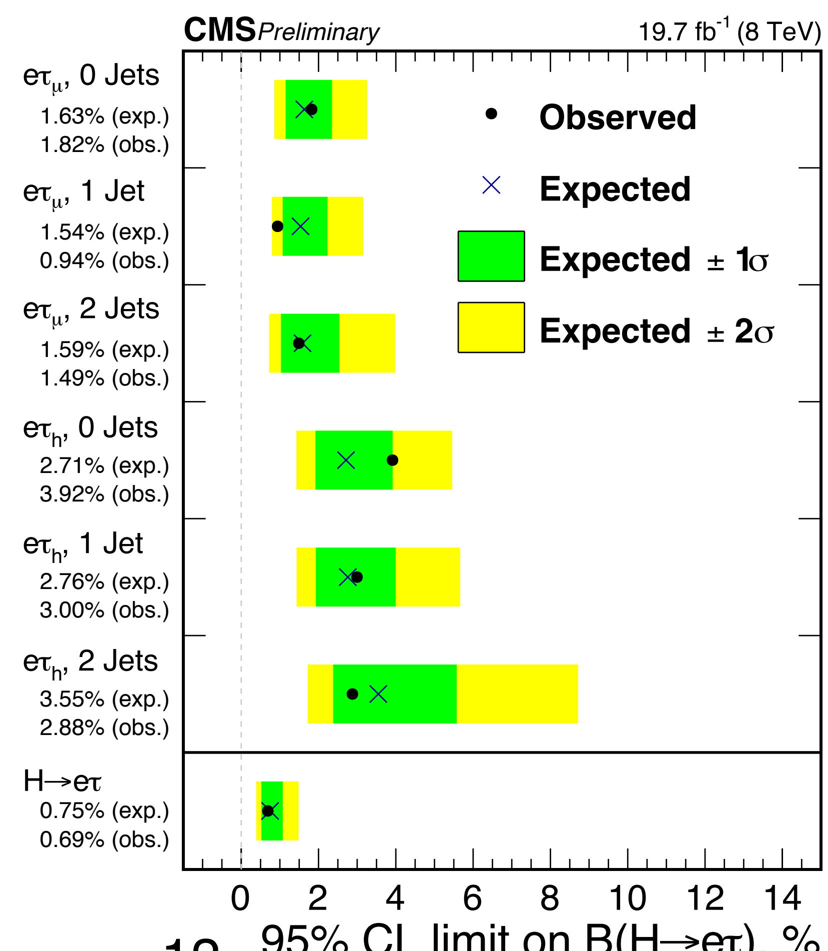






observed 95% CL upper limit on BR:
Br(H→eτ) < 1.04%
Br(H→μτ) < 1.43%





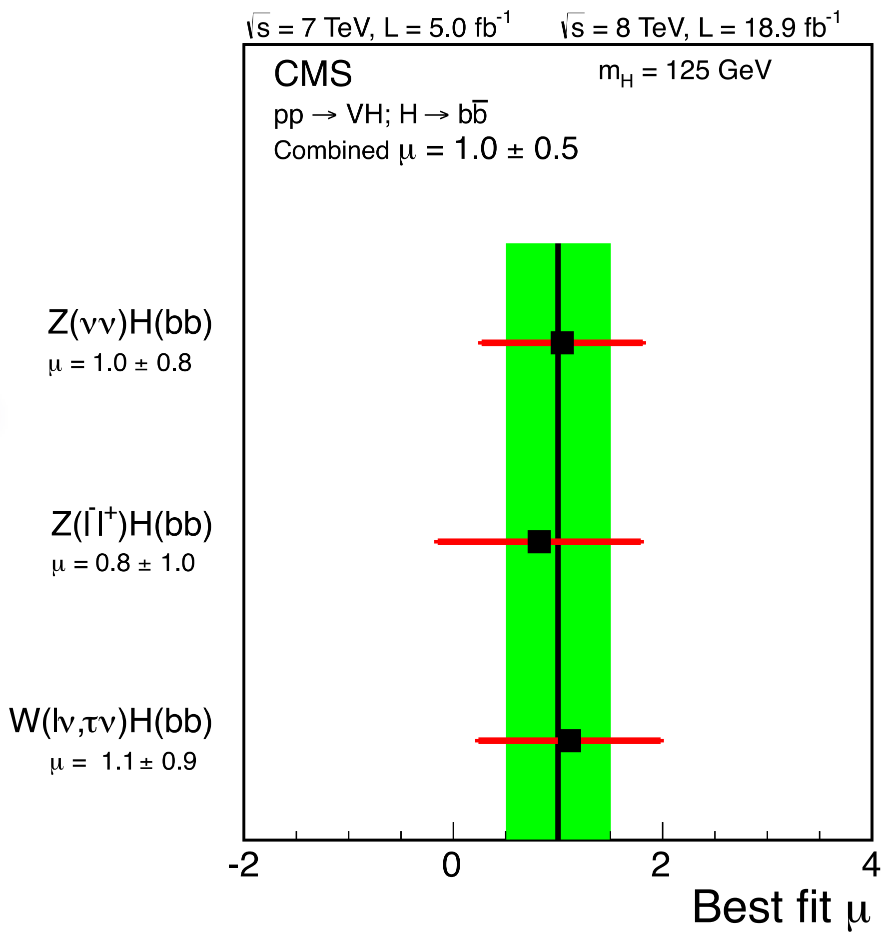
observed 95% CL upper limit on BR:
Br(H→eτ) < 0.69%

H→bb

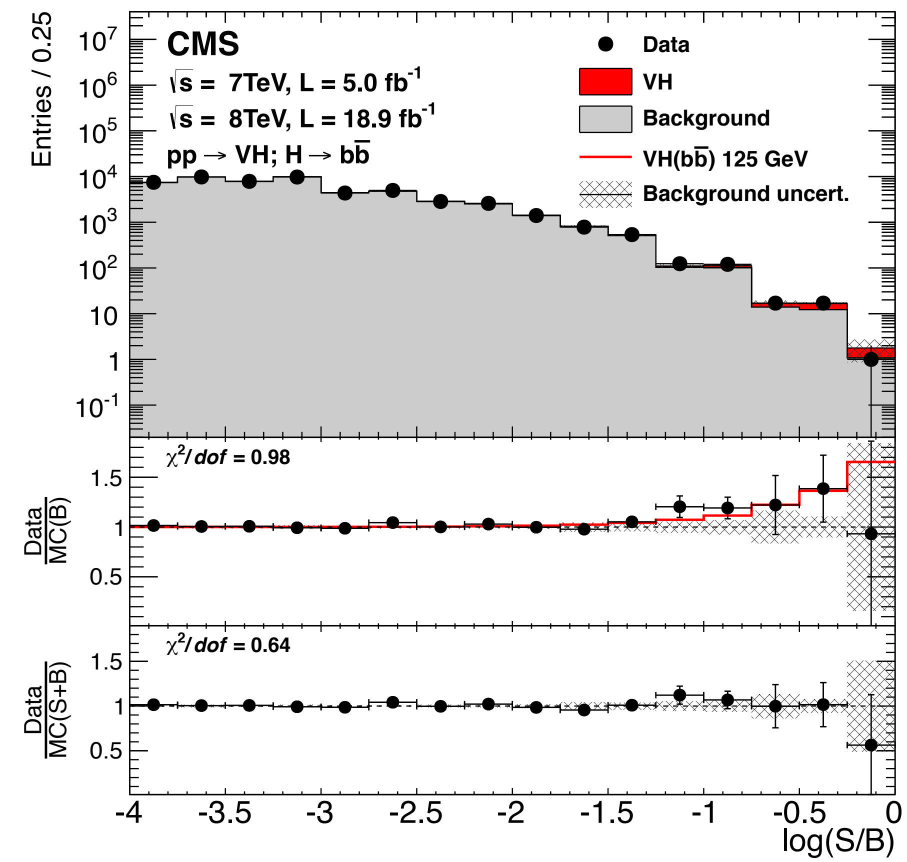
VH

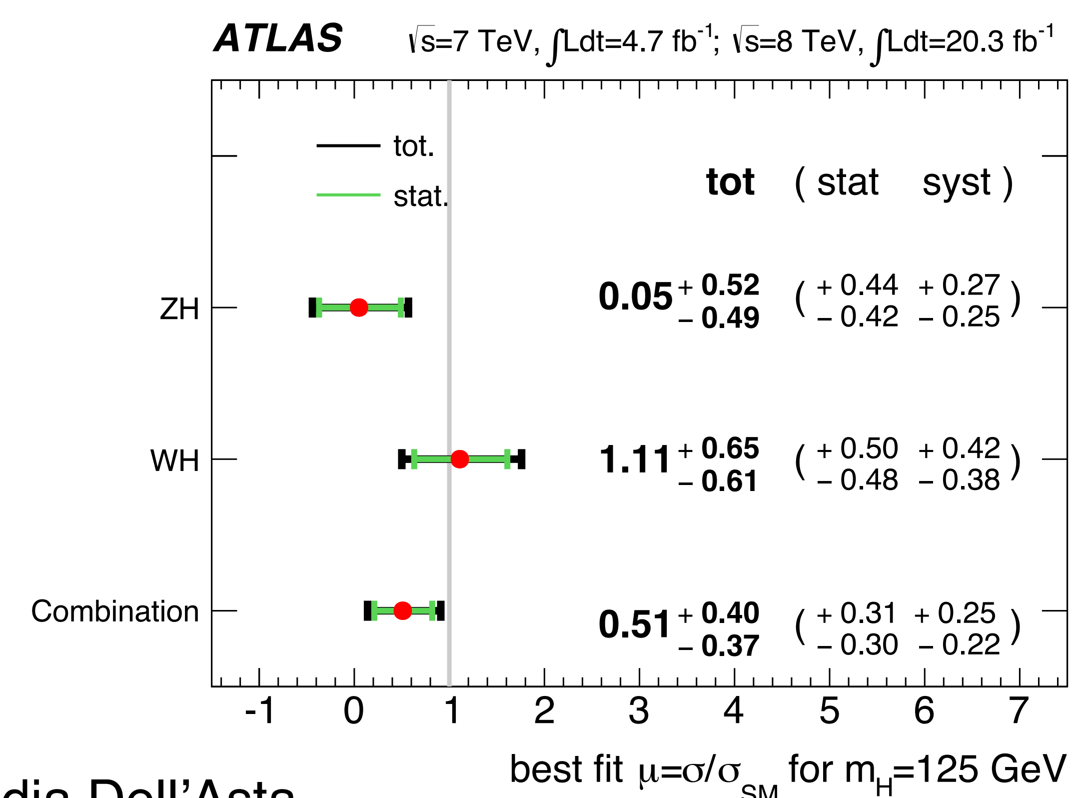
First direct test of interaction of the Higgs boson with the **quark sector**, as the coupling to the top quark has only been tested through loop effects.

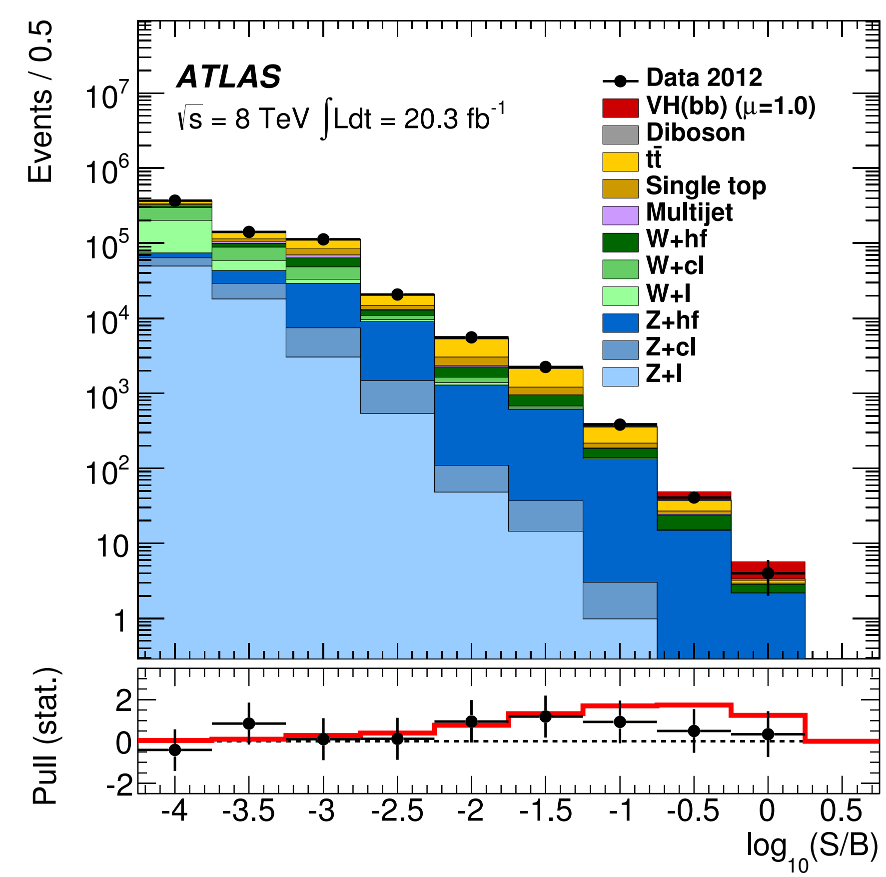
ATLAS: JHEP 01 (2015) 069
CMS: PRD 89 (2014) 012003



- Inclusive search for H→bb not feasible at hadron colliders because of the overwhelming background from multi-jet production.
- **Associated production** offers a viable alternative (can use leptons from W/Z for triggering and background suppression).
- Event **categorization** based on lepton, jet and b-tagged jet multiplicities.



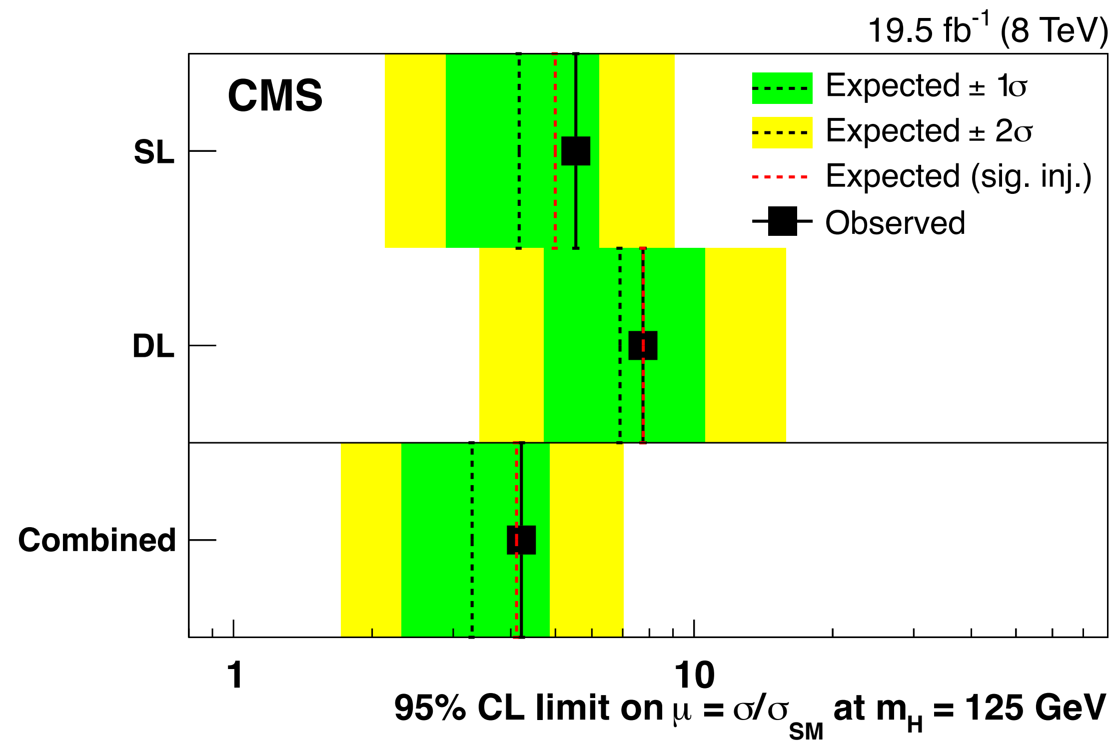


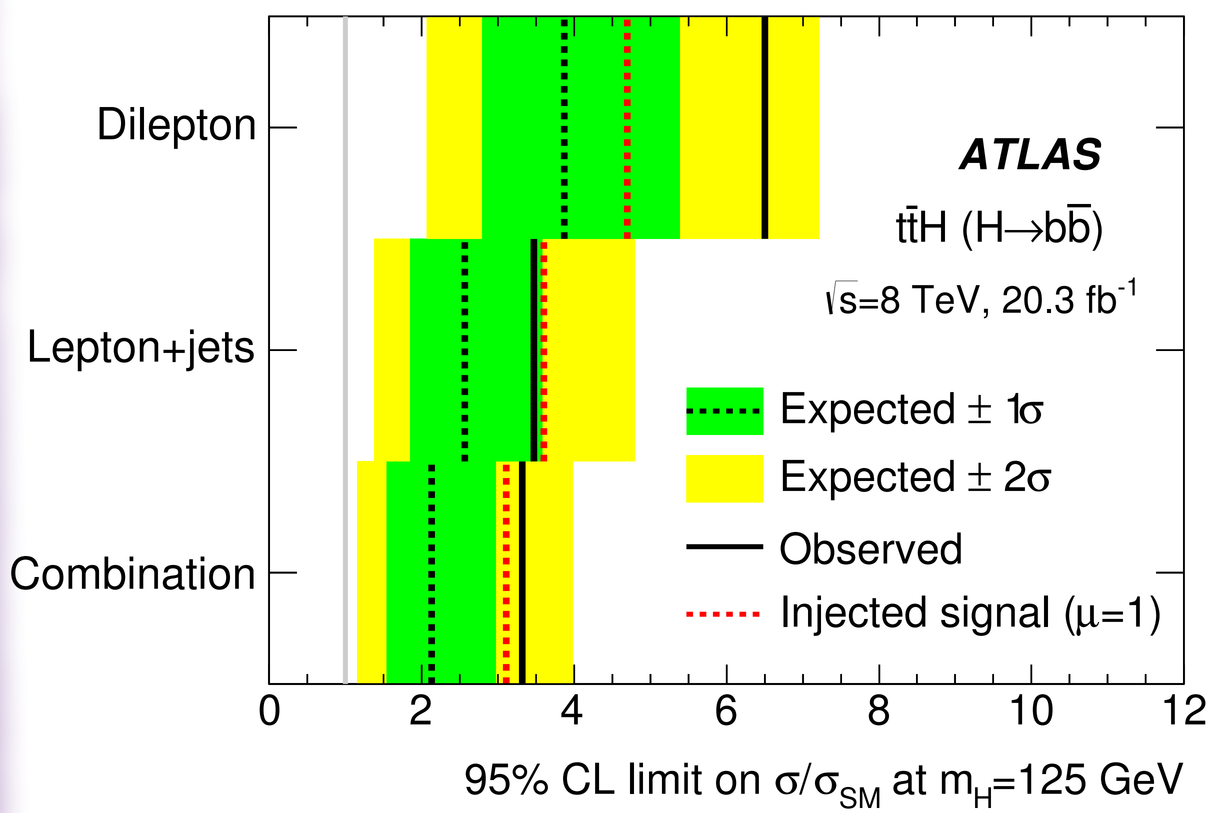


ttH

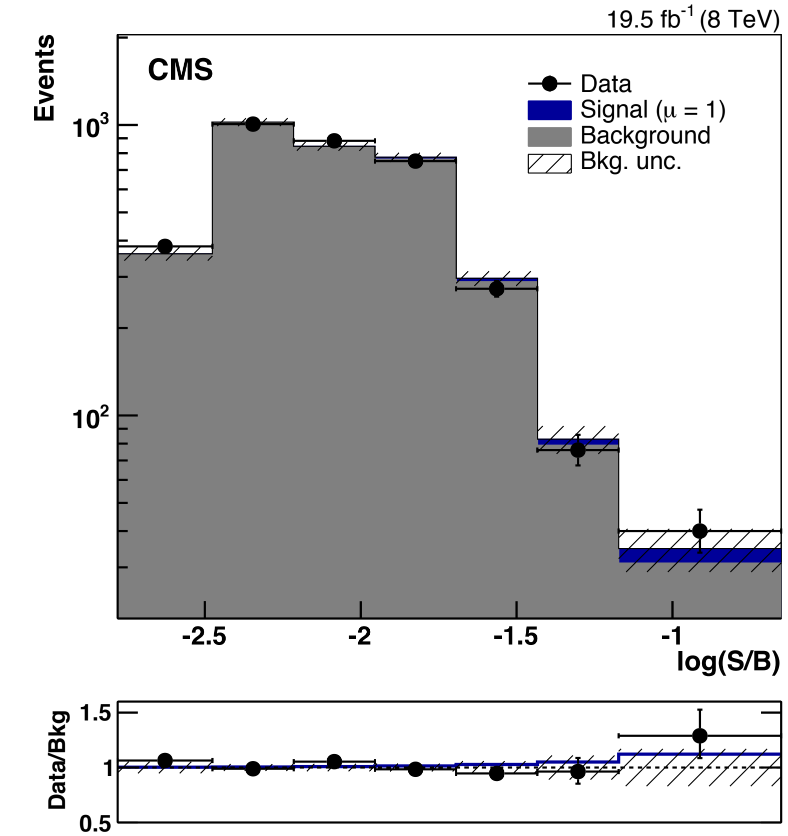
Heavy-quark couplings in both **production** and **decay**.

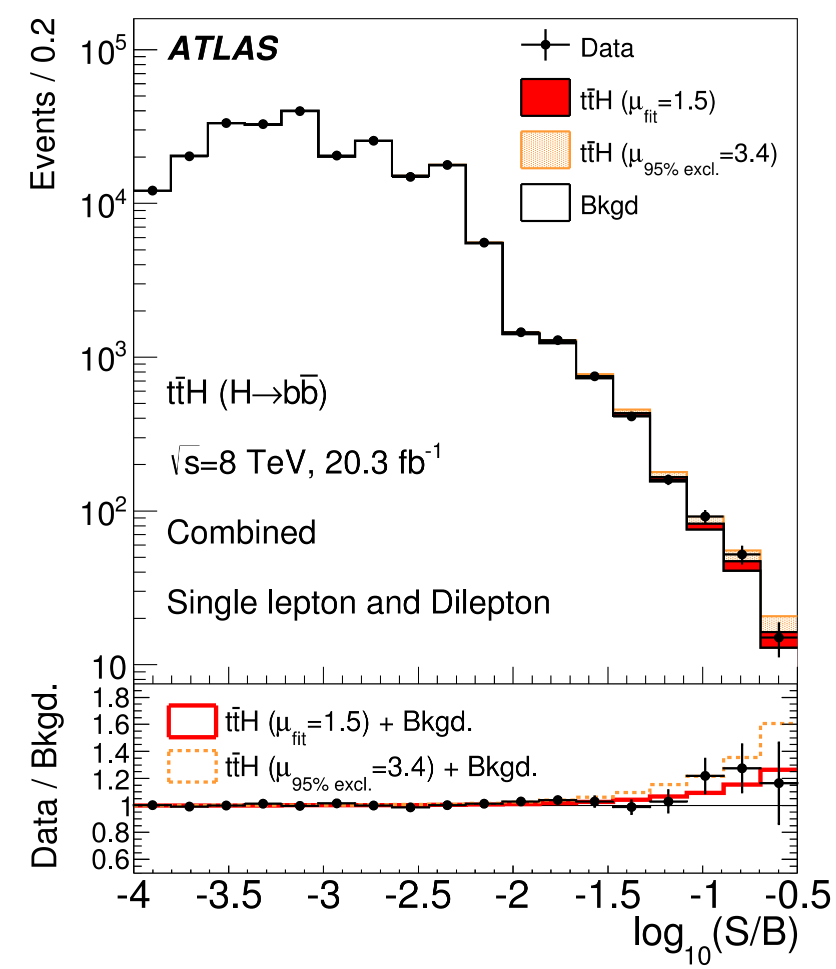
ATLAS: Eur. Phys. J. C 75 (2015) 349
CMS: Eur. Phys. J. C 75 (2015) 251





- Event **categorization** based on lepton, jet and b-tagged jet multiplicities.
- Multivariate techniques with fit of final discriminant for categories with larger S/B used by ATLAS. Analytical matrix element method (MEM) used by CMS.

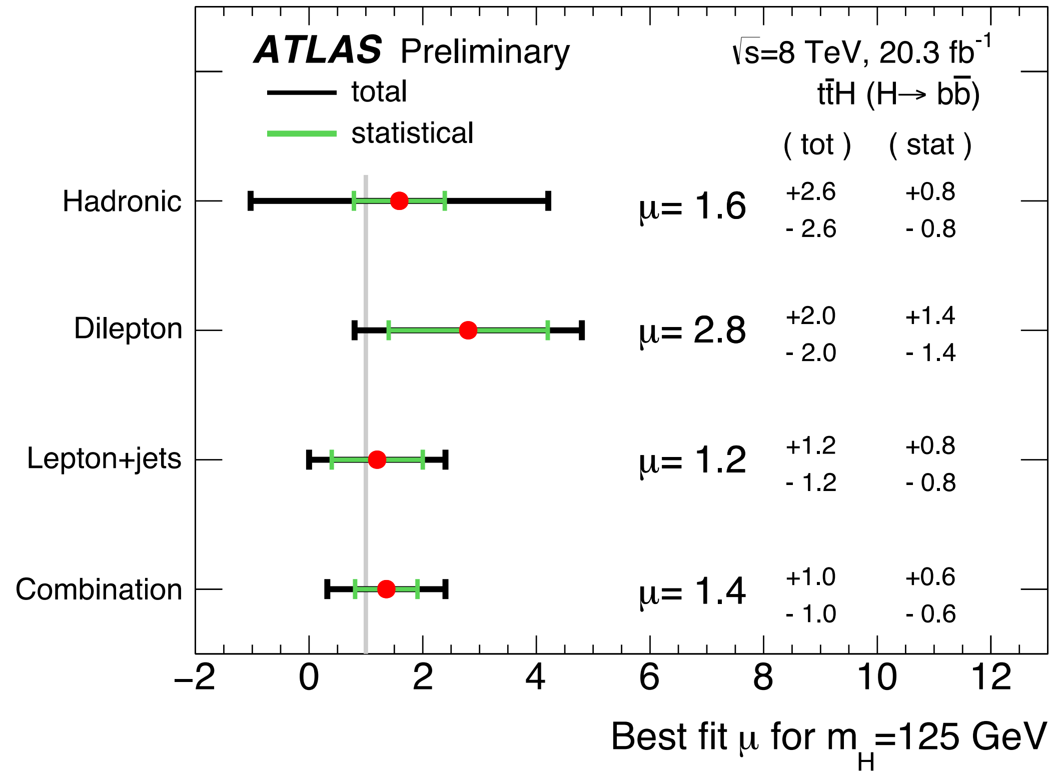




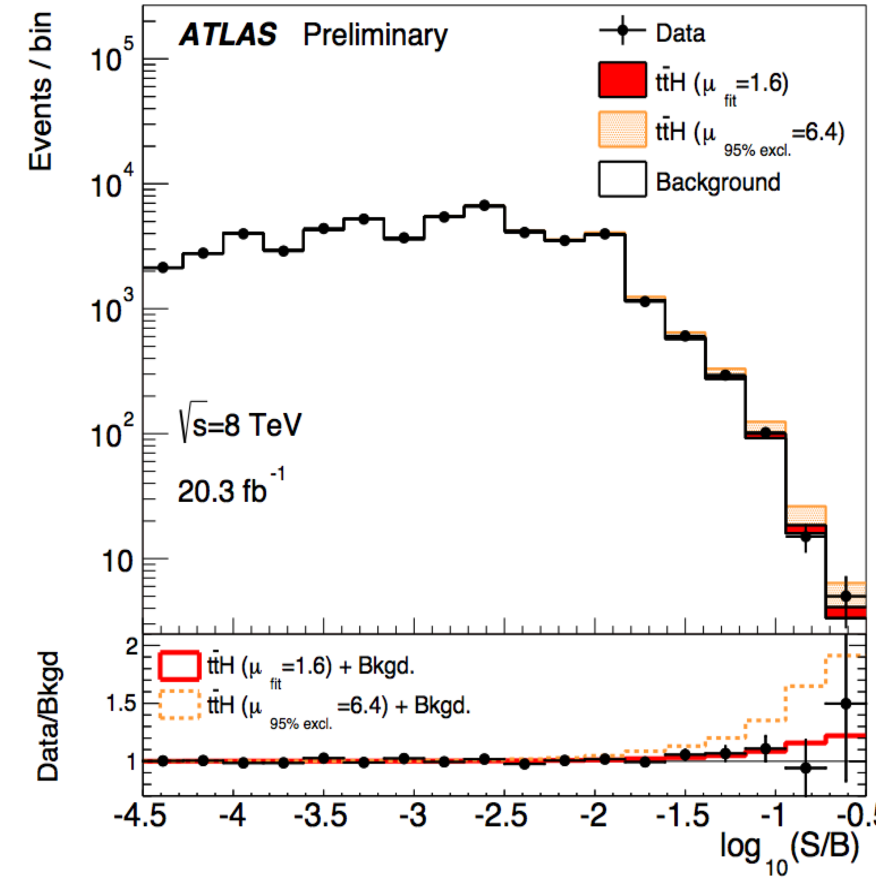
ATLAS: paper in preparation

ttH full hadronic

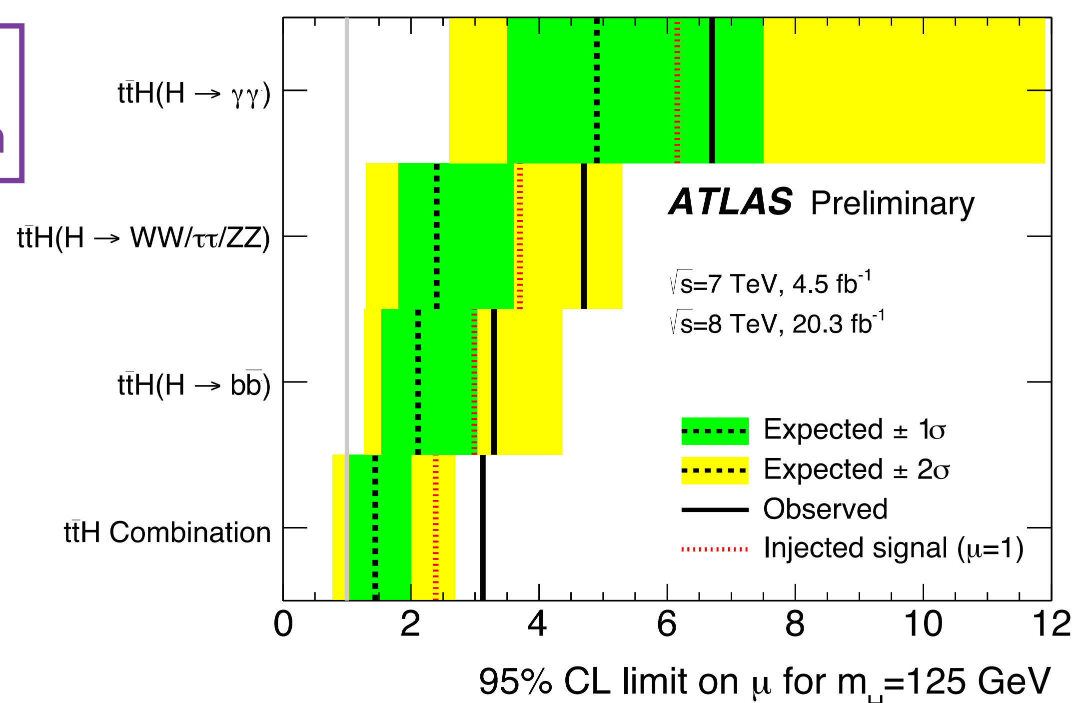
- The fully hadronic channel has the **highest BR** but the **least** signal **purity**.
- Event categorization based on number of jets and b-tagged jets.
- Multivariate analysis.
- Data-driven method for the extraction of main **background** from **multi-jet** events, using data sample with same jet multiplicity but lower b-tagged jet multiplicity.

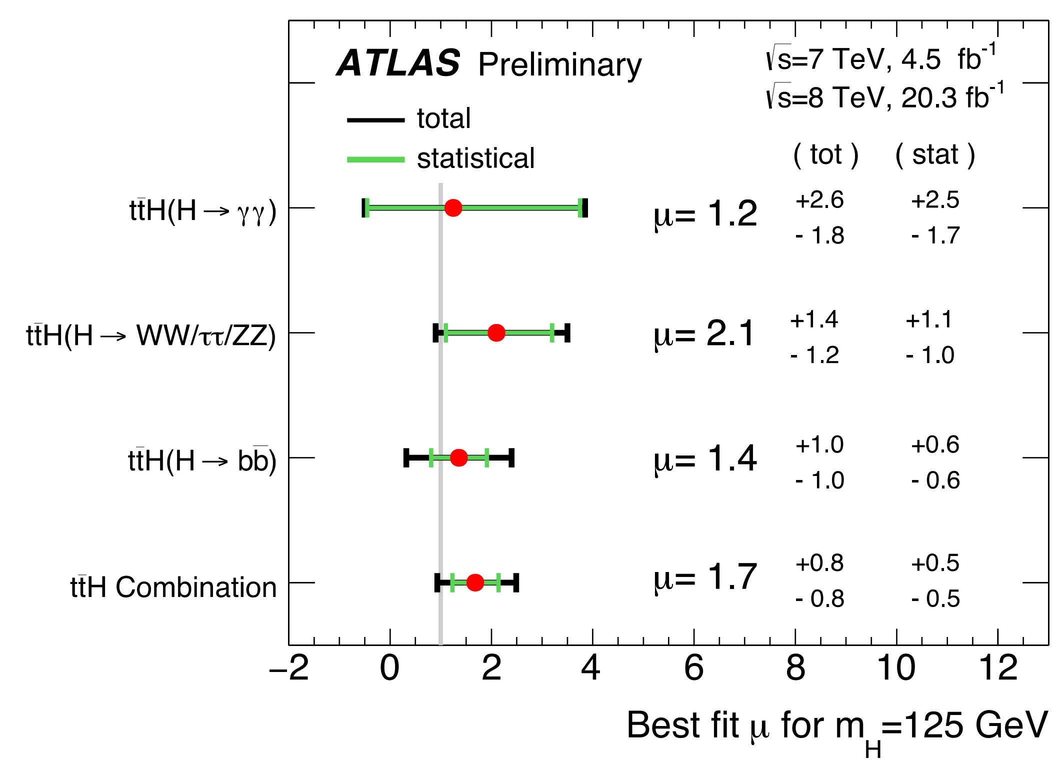


Combination of all ttH(bb) channels



new ttH combination





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

ATLAS and **CMS** combination for the measurement of Higgs boson production and decay rates and constraints on its couplings.
Full Run1 data sample: 5 fb^{-1} at 7 TeV and 20 fb^{-1} at 8 TeV.

Using gg→H→ZZ as a reference:

$$\sigma_i \cdot BR^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{BR^f}{BR^{ZZ}}\right)$$

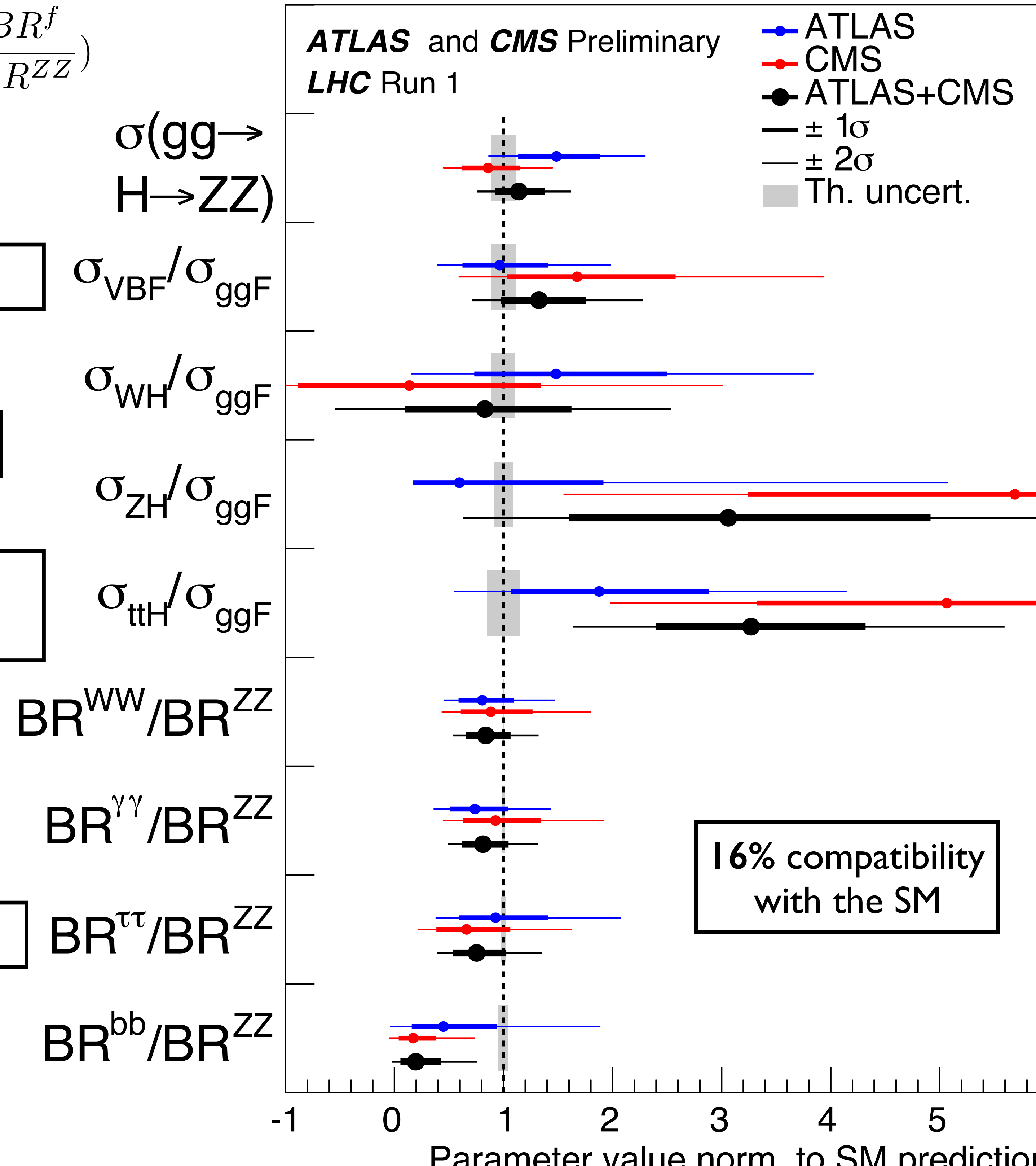
Observed with 5.4σ significance (4.7σ exp.)

VH: 3.5σ significance (4.2σ exp.)

2.4σ excess over SM prediction for ttH
(4.4σ obs. and 2.0σ exp.)

Observed with 5.5σ significance (5.0σ exp)

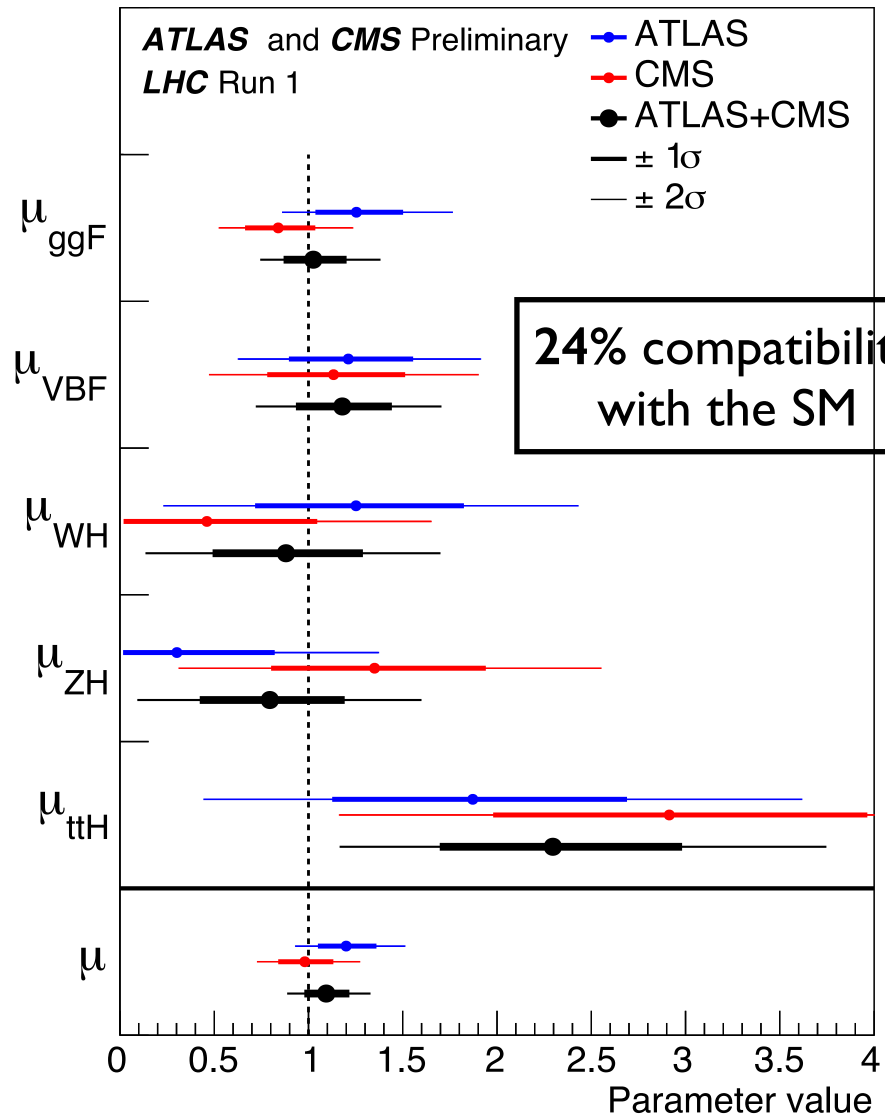
2.5σ deficit compared to SM prediction



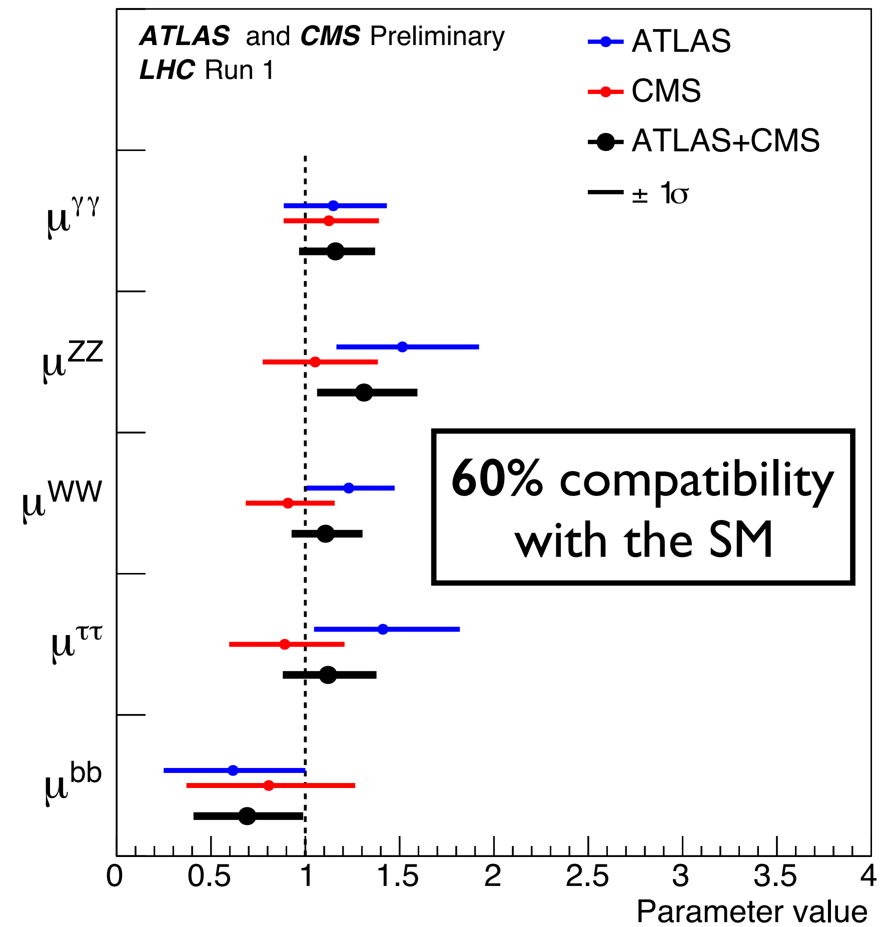
ATLAS+CMS Combination

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

Production modes



Decay modes



Production process	ATLAS+CMS	ATLAS	CMS
$\mu_{\rm ggF}$	$1.03^{+0.17}_{-0.15}$	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$
$\mu_{\rm VBF}$	$1.18^{+0.25}_{-0.23}$	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$
μ_{WH}	$0.88^{+0.40}_{-0.38}$	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$
μ_{ZH}	$0.80^{+0.39}_{-0.36}$	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$
μ_{ttH}	$2.3^{+0.7}_{-0.6}$	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.16^{+0.20}_{-0.18}$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$
μ^{ZZ}	$1.31^{+0.27}_{-0.24}$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$
μ^{WW}	$1.11^{+0.18}_{-0.17}$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$
$\mu^{\tau\tau}$	$1.12^{+0.25}_{-0.23}$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$
μ^{bb}	$0.69^{+0.29}_{-0.27}$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

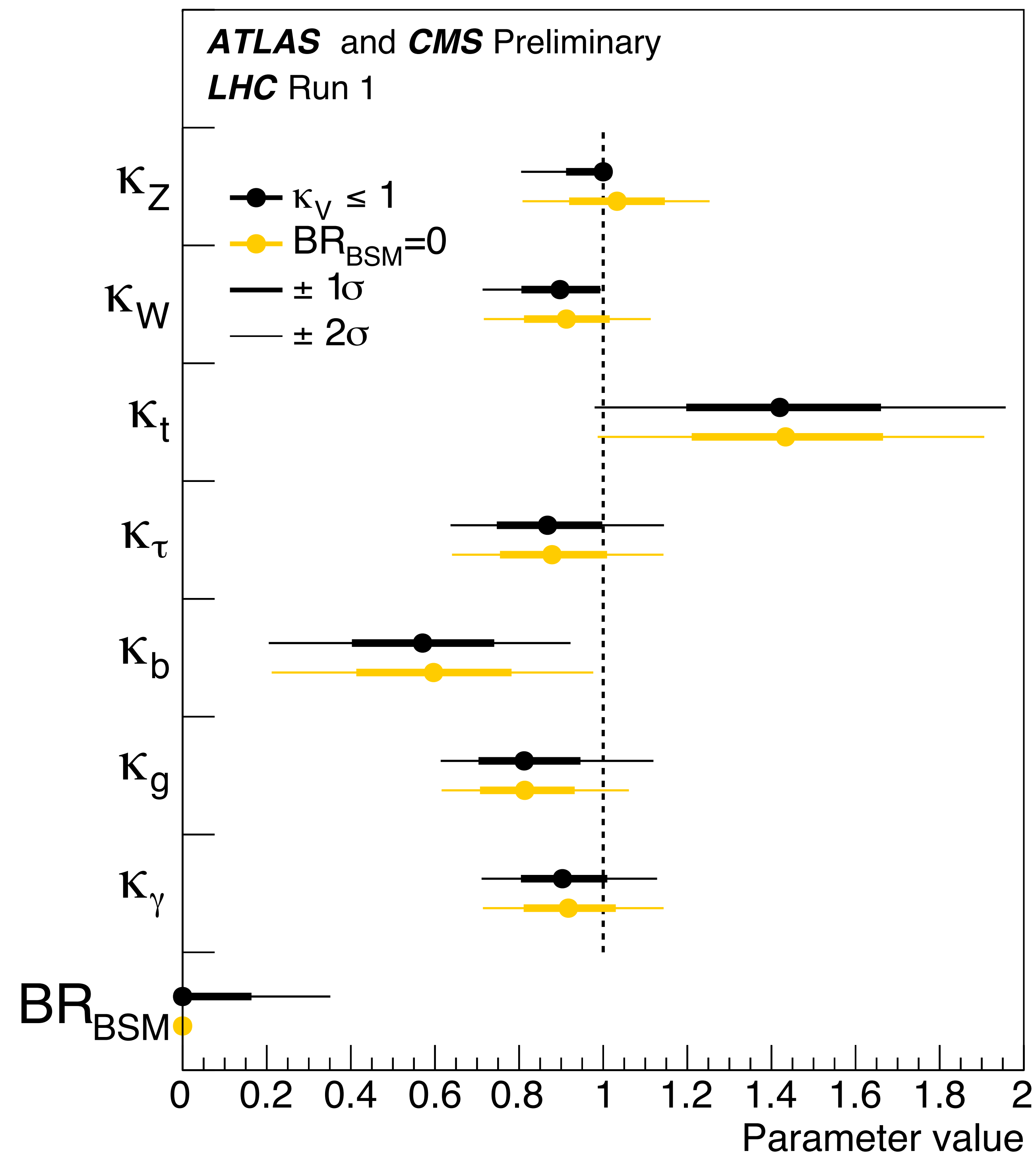
- Coupling modifiers have been proposed to interpret the LHC data using specific modifications of the Higgs boson couplings related to new physics beyond the SM.
- "k-framework":
  - assuming exactly same coupling structure as SM,
  - modify couplings with LO degrees of freedom.

$$\sigma_i = \kappa_i^2 \cdot \sigma_i(\mathrm{SM})$$

$$\Gamma_f = \kappa_f^2 \cdot \Gamma_f(\mathrm{SM})$$

$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{\sigma_i(\mathrm{SM}) \cdot BR^f(\mathrm{SM})} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\Gamma_\mathrm{H}/\Gamma_\mathrm{H}(\mathrm{SM})}$$

- Changes in the couplings will result in a variation of the Higgs boson width.
  - Assume no BSM contribution or allow additional BSM contribution to the width.
- Two scenarios considered:
  - BR(BSM) = 0
  - $k_V \leq 1$ and BR(BSM) free
    - upper limit of 0.34 at 95% CL is obtained for BR(BSM).



- The search for Higgs fermionic decays is an essential piece of the Higgs puzzle.
  - **$H\rightarrow\tau\tau$** decays have been observed.
    - Many measurements in this final state were done on Run1 data, looking at different production modes.
    - A new method to check the CP invariance in the VBF production has been established.
  - **$H\rightarrow\mu\mu$** and **$H\rightarrow bb$** have been looked for.
    - More data is needed for an observation.
  - **Lepton flavor violating** decays have been looked for and new upper limits on $Br(H\rightarrow e\tau)$ and $Br(H\rightarrow \mu\tau)$ have been set.

- Run1 data gave us the Higgs.
- Run2 will give us the opportunity to explore it even more.