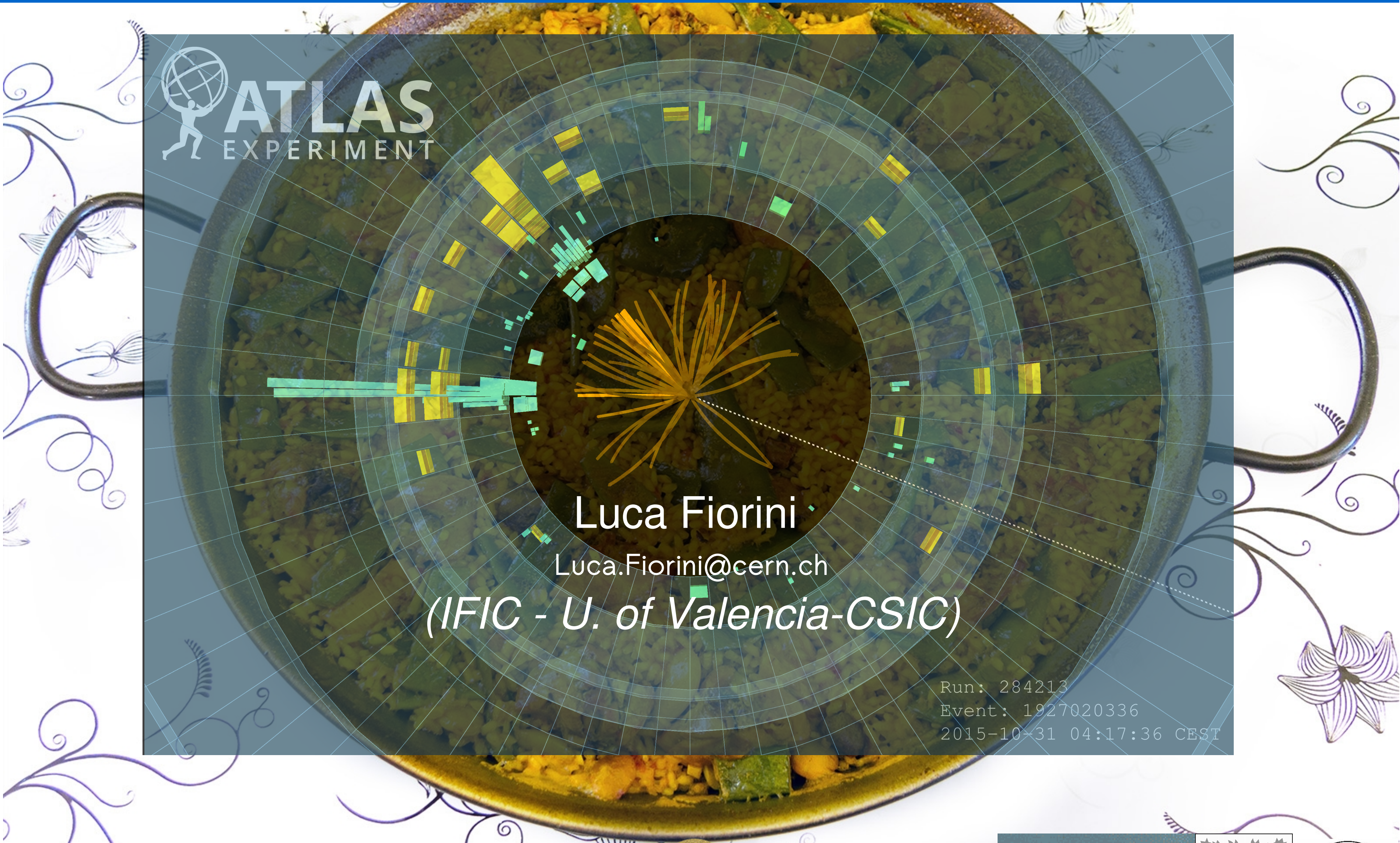
Experimental Higgs Physics (1)



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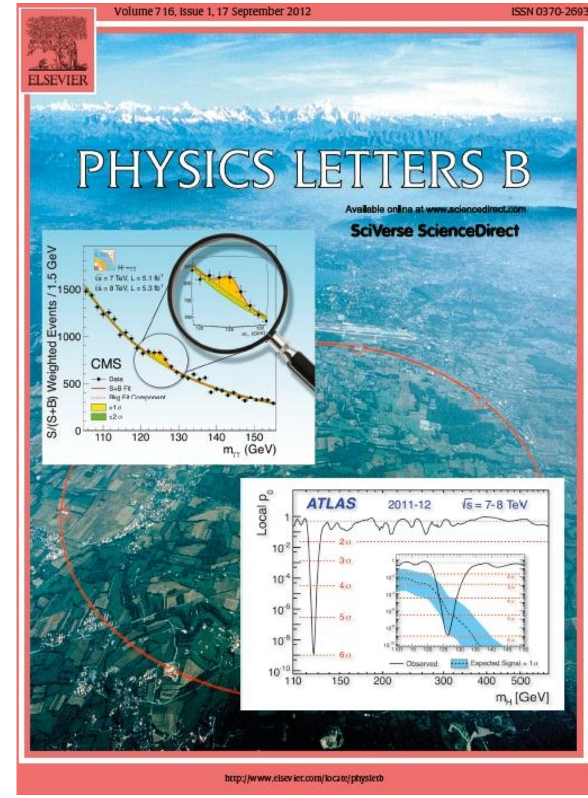
Outline

- Introduction
- Experimental Detectors performance
- End of Run 1 status
- Higgs results with ~36 fb^{-1} of data @LHC Run 2:
  - **Yukawa coupling to fermions:**
    - VH $H \rightarrow bb$
    - ttH production
    - $H \rightarrow \tau\tau$
    - Second generation fermions: $H \rightarrow \mu\mu$ and $H \rightarrow cc$
    - Lepton Flavor Violation $H \rightarrow \tau (e/\mu)$
  - **Bosonic channels:**
    - $H \rightarrow WW$
    - $H \rightarrow ZZ$
    - $H \rightarrow \gamma\gamma$
  - **Combination:**
    - Higgs boson mass measurement
    - Cross section measurements
  - **Self coupling:**
    - HH production mode



Higgs couplings

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

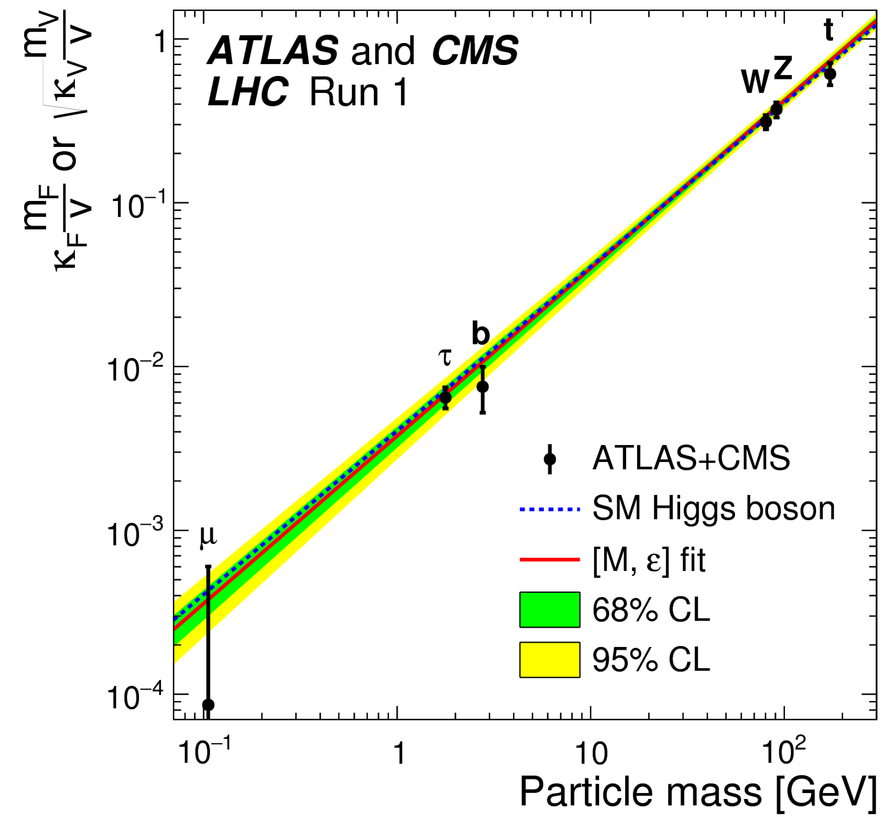
Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

A MODEL OF LEPTONS*

Steven Weinberg†
Laboratory for Nuclear Science and Physics Department,
Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 17 October 1967)



- Higgs boson couplings to EW bosons allows to normalize $WW \to WW$ scattering.
- In the SM the Higgs field couples to fermions through a Yukawa interaction, proportionally to the mass of the fermions.
- Deviation of couplings, asymmetries in up/down type quarks, evidence of (large) lepton flavour violation or flavour changing neutral current would be signs of new physics.

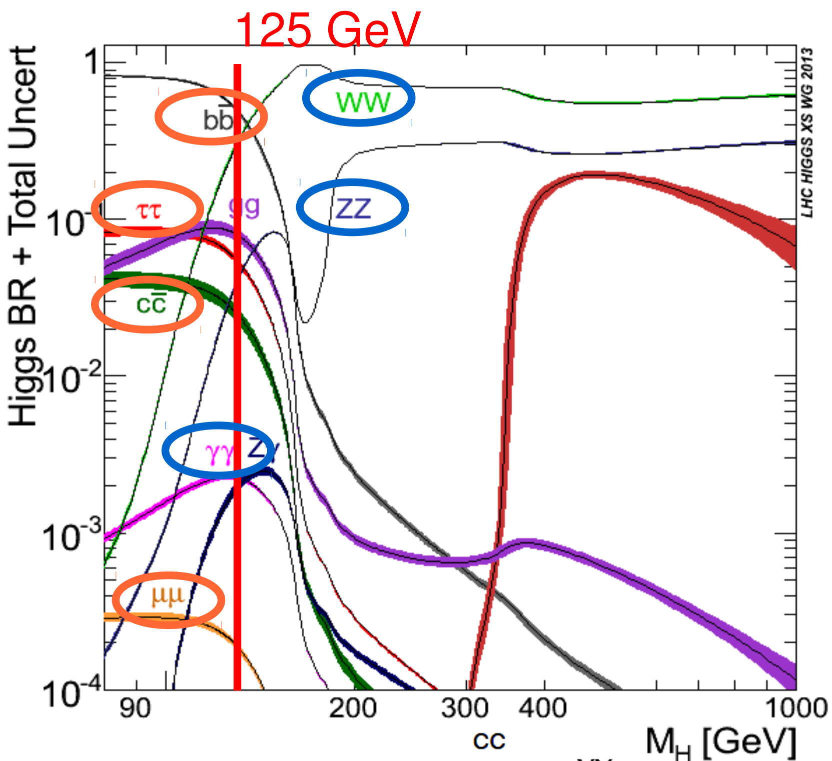
Higgs boson Discovery

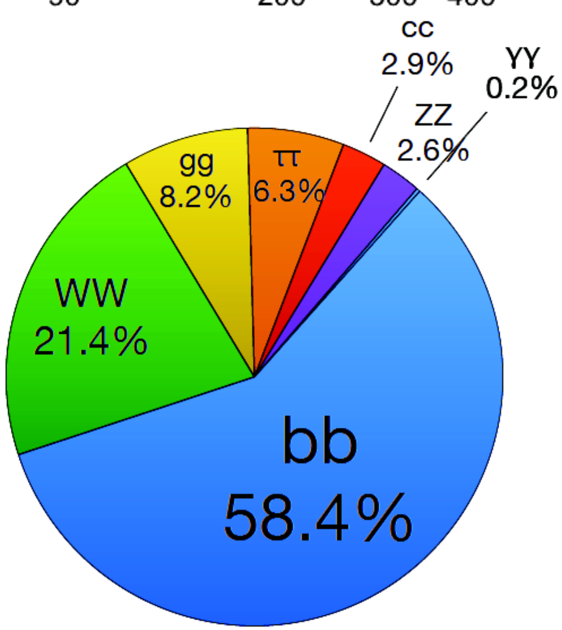
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs:

"*for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider*".

The 2013 Principe de Asturia award for technical and scientific research to: François Englert, Peter Higgs, CERN

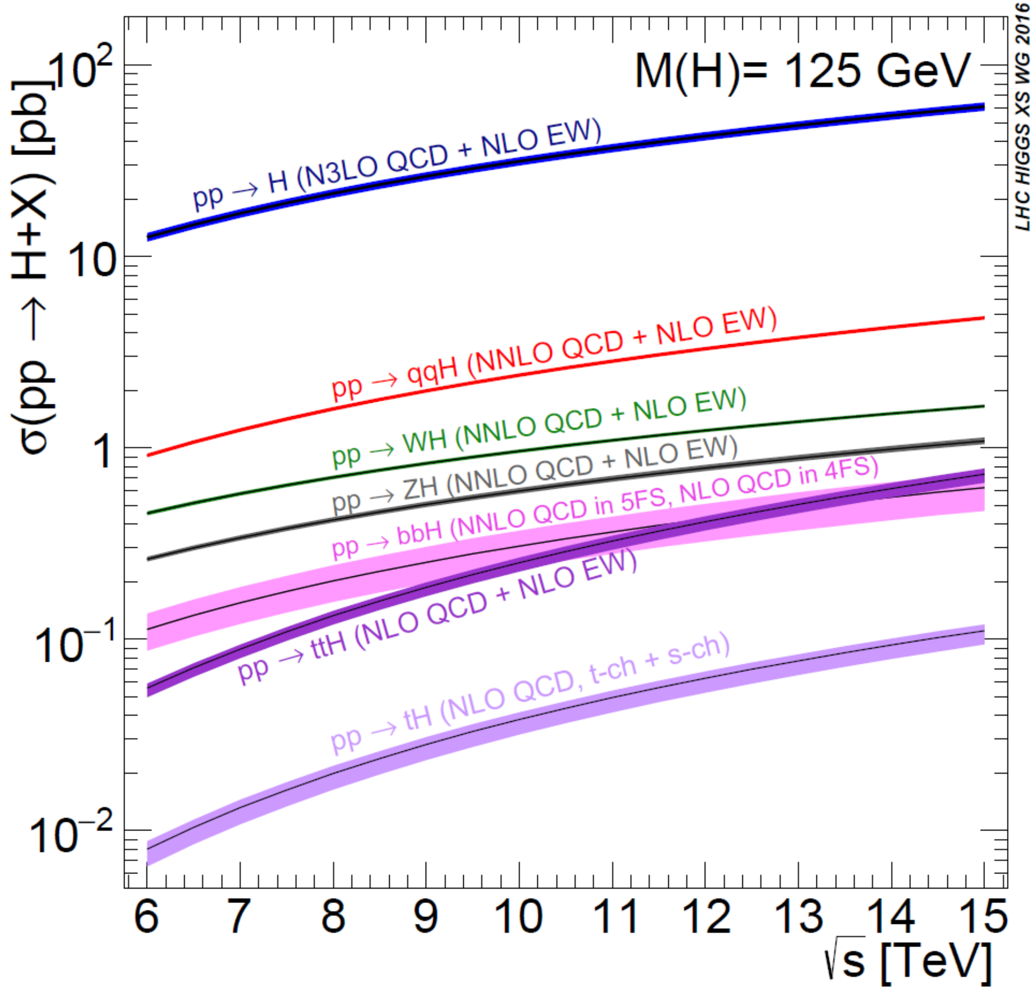
Higgs Decay Modes





- Higgs boson first discovered from the analysis of its decay to the bosonic channels.
- Fermionic decay modes provide direct measurement of the Yukawa couplings.
- $H \to \gamma\gamma$ can also provide indirect measurement of couplings to quarks at LHC (via virtual loops).

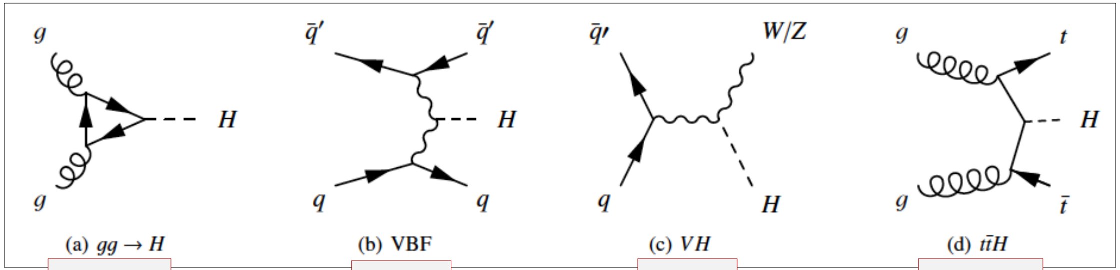
Higgs Production Modes at LHC



Total x-section:

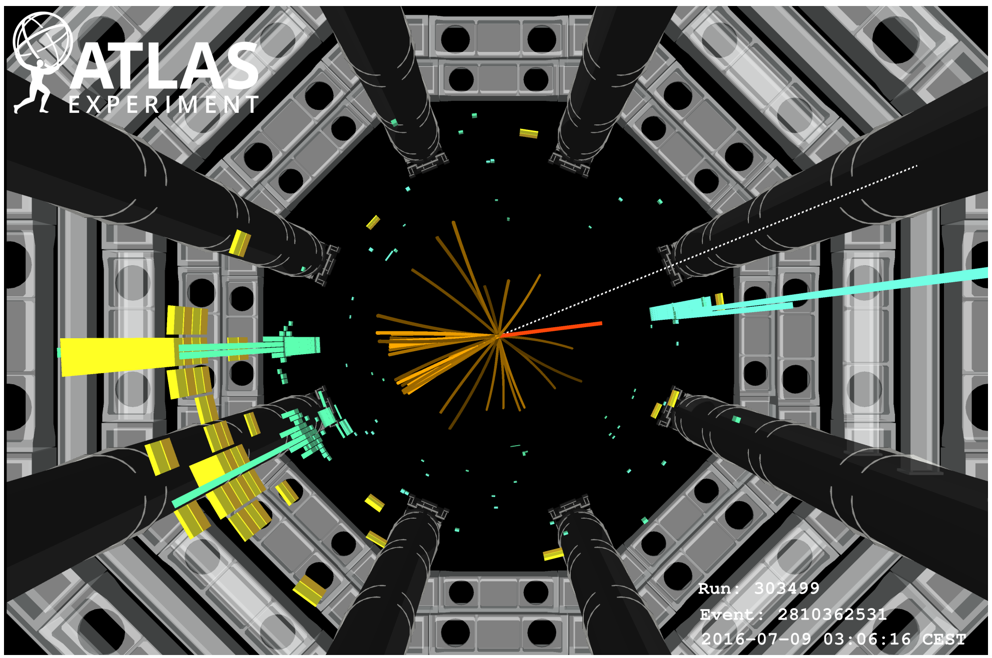
17 pb (17000 evts/fb^{-1}) @7 TeV
22 pb (22000 evts/fb^{-1}) @8 TeV
55 pb (55000 evts/fb^{-1}) @13TeV

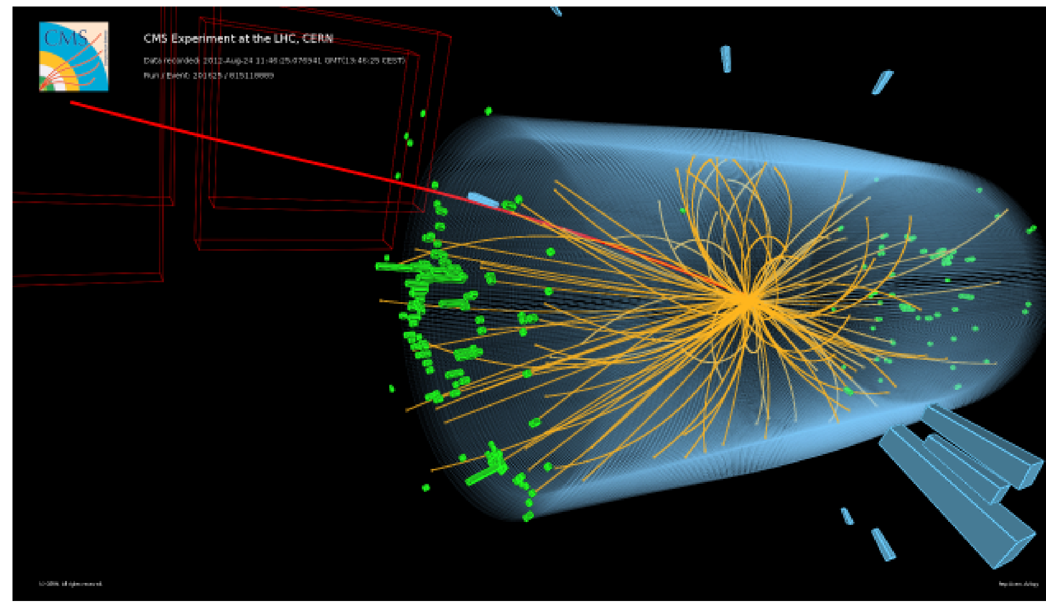
- ggH is the main production mode at LHC. Provides indirect measurement of couplings to quarks via virtual loops.
- ttH provides direct measurement of Yukawa coupling, but they are not easily accessible.



87%	7%	5%	<1%

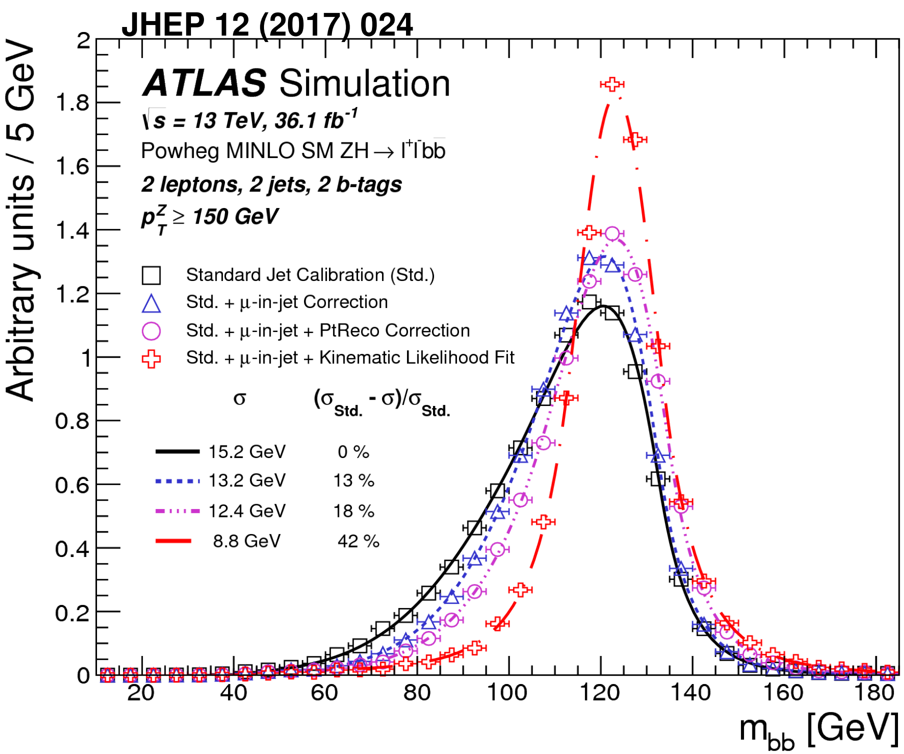
Higgs Run 2 Results

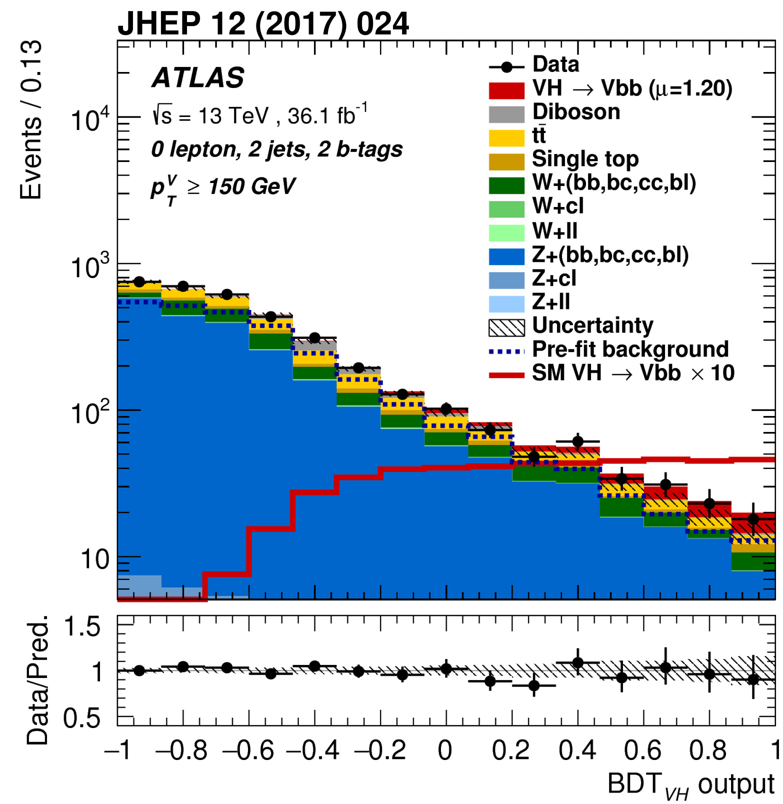




Run 2 VH → b-bar

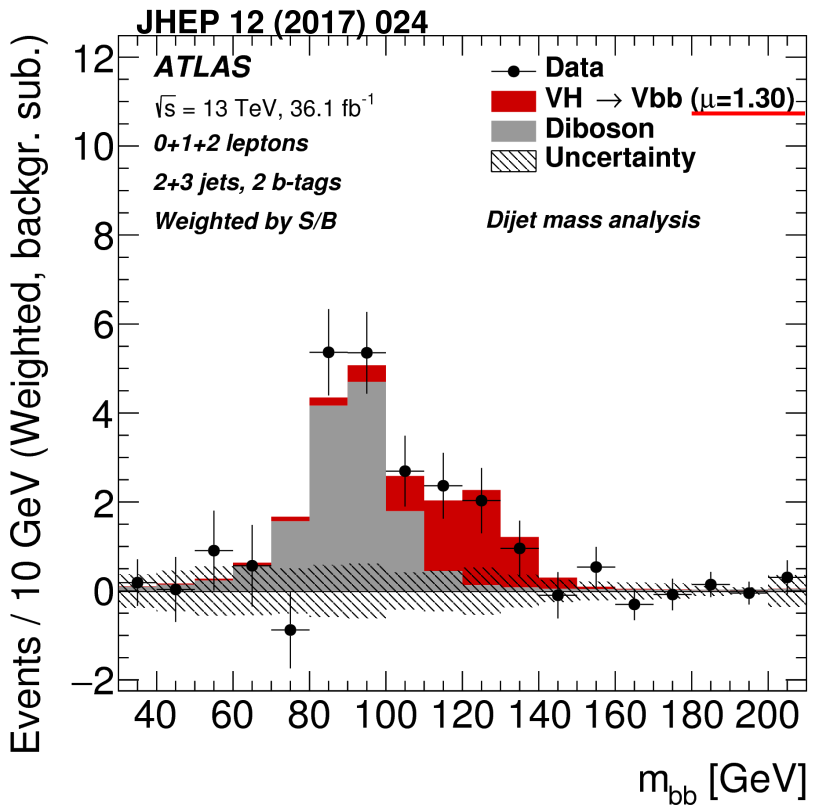
- Most abundant decay mode (58%), but challenging due to the multi-jet background.
- Tag VH production mode and use MVA analysis to boost sensitivity.
- VZ → bbar is used as benchmark.
- CMS added the search for boosted production q/gH(→bb) in Run 2.

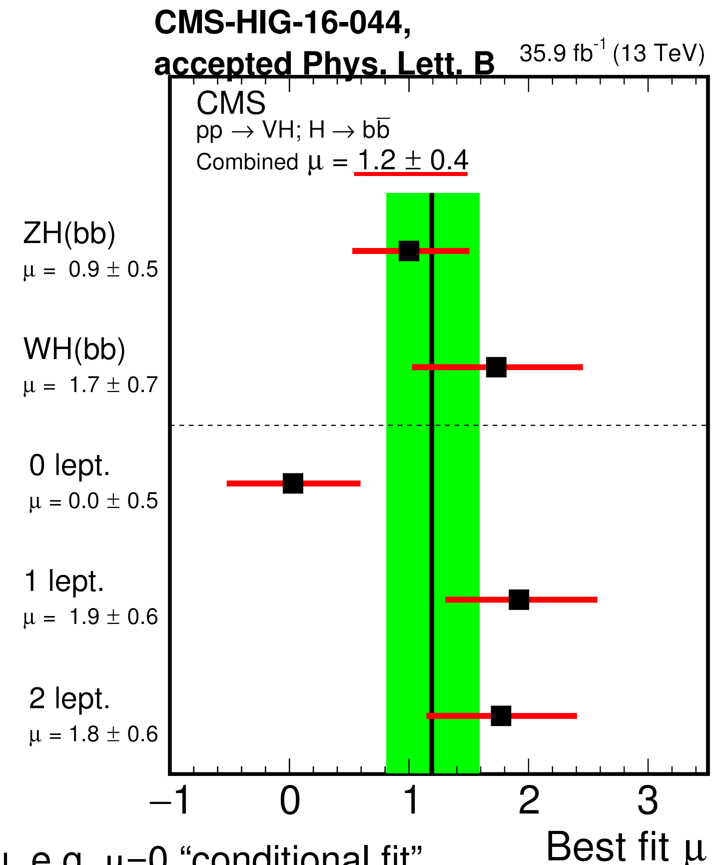




- Analyses target events where H → bb candidate recoils against V boson
- Channels: V decays to νν, lν and ll (l=e,μ)
- Boosted Decision Trees (BDT) to separate signal and ttbar and Z backgrounds
- Dedicated b-jet energy calibration to improve m_{bb} resolution

Run 2 VH → bbar





$$\lambda(\mu) = -2\ln\frac{\mathcal{L}(\mu,\hat{\hat{\theta}}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\theta})}$$

→ Best-fit fixing mu, e.g. μ=0 "conditional fit"

→ Best-fit max lh, "unconditional fit"

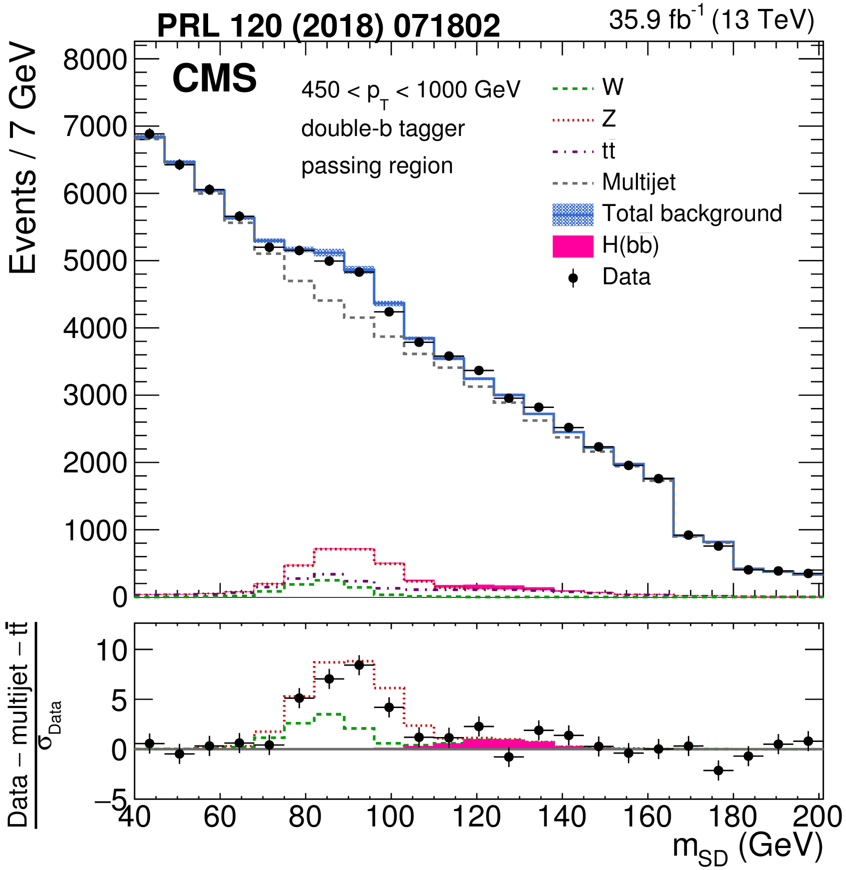
ATLAS Run 1+2 $\mu = 0.90 \pm 0.18(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$ $\mu := \sigma\cdot B/(\sigma\cdot B)_{SM}$

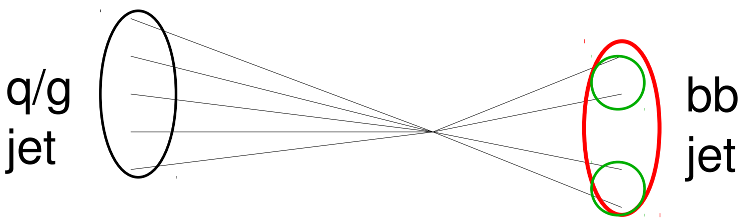
- Evidence of VH → bb production from both experiments

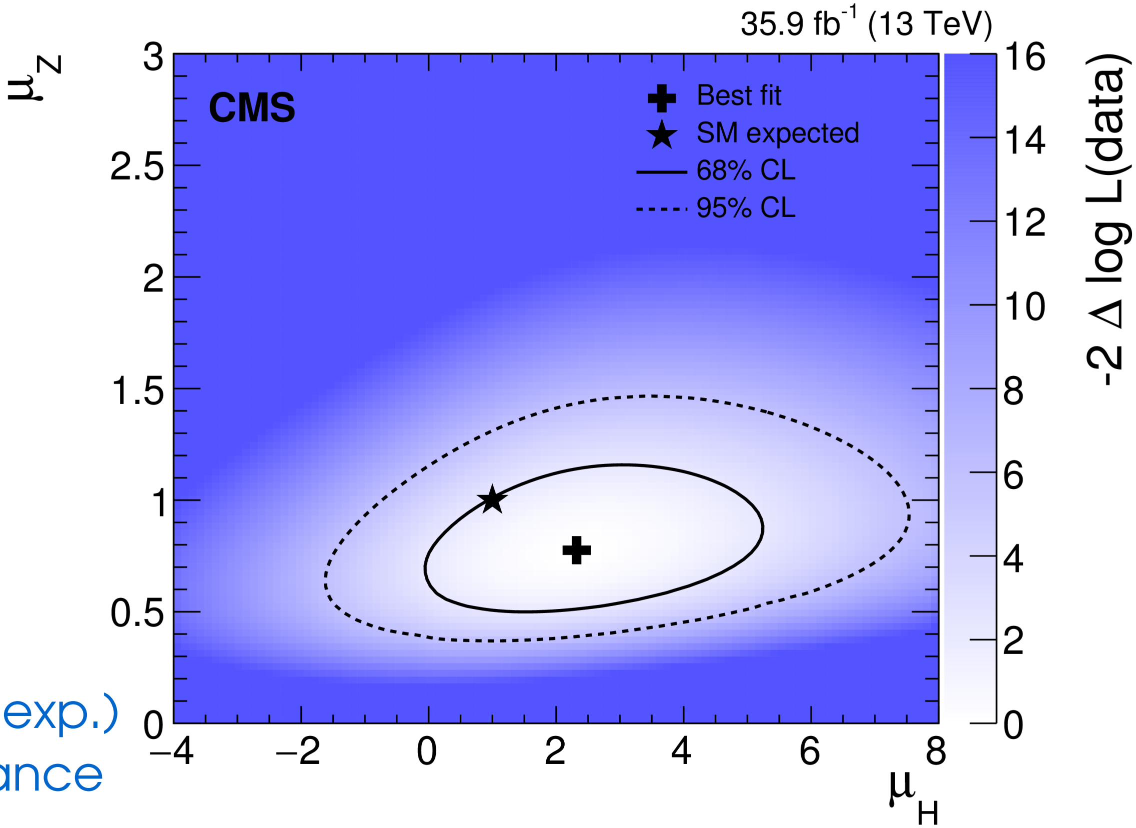
Observed (Expected significance)	Run 1+2 comb.
ATLAS	3.6 (4.0) σ
CMS	3.8 (3.8) σ

Run 2 q/g+H → b-bar

- Target inclusive production mode (mainly ggF) where a boosted H → bb candidate recoils against a high-p_T jet of large radius.
- "Soft-drop" dedicated jet substructure to tag large-radius jets containing two b-quarks



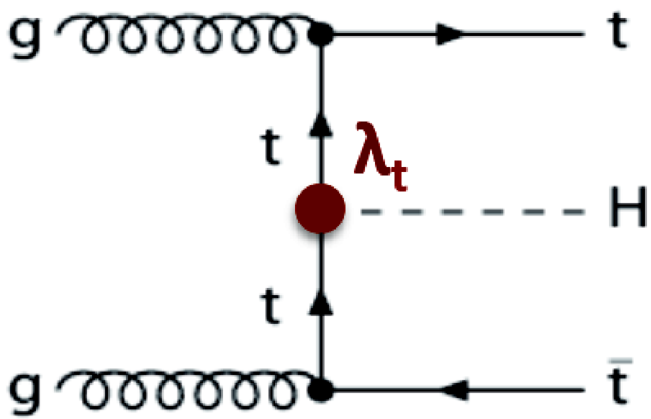


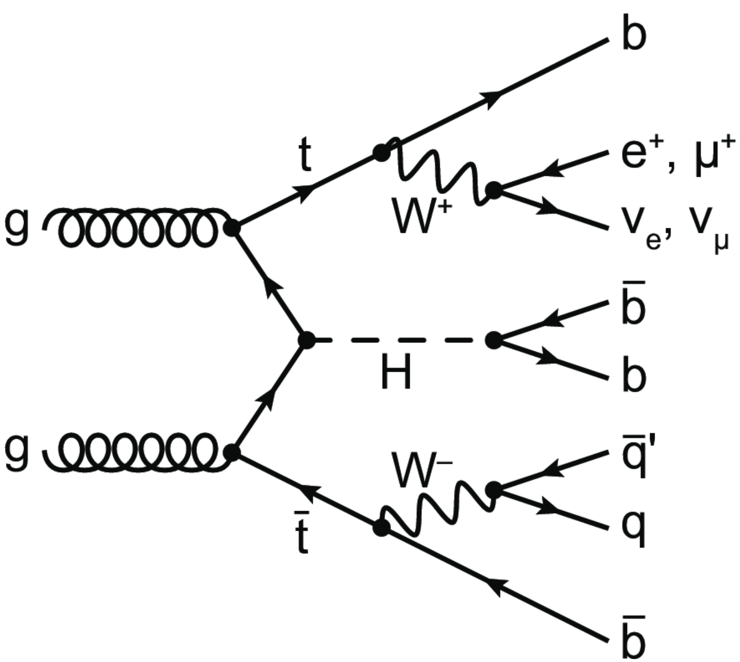


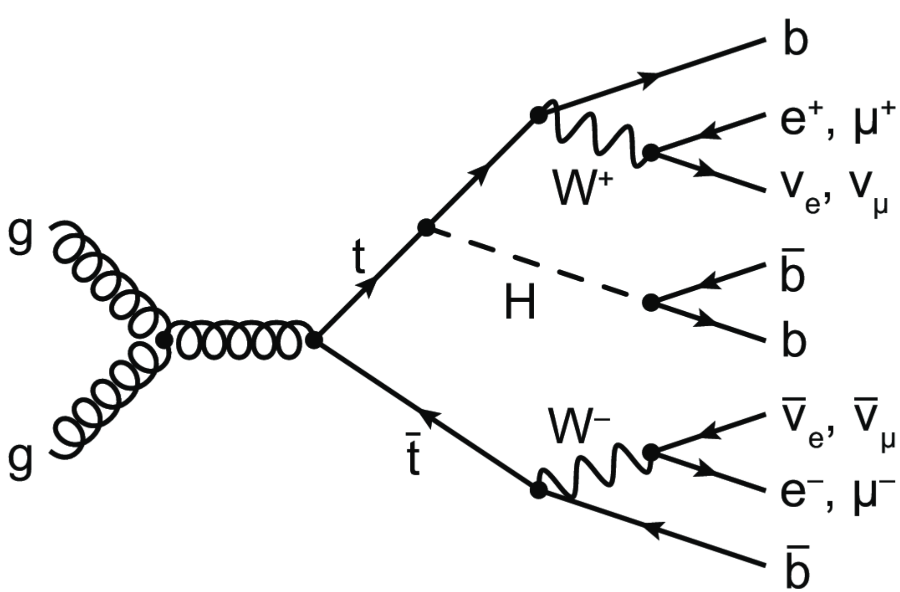
- Significance of H → bb: 1.5 σ (0.7 σ exp.)
- Z → bb observed with > 5 σ significance

Higgs ttH production

- 13TeV/8TeV Cross-section ~3.9: sensitive to potential new physics and quickly improving Run1 sensitivity for SM production.



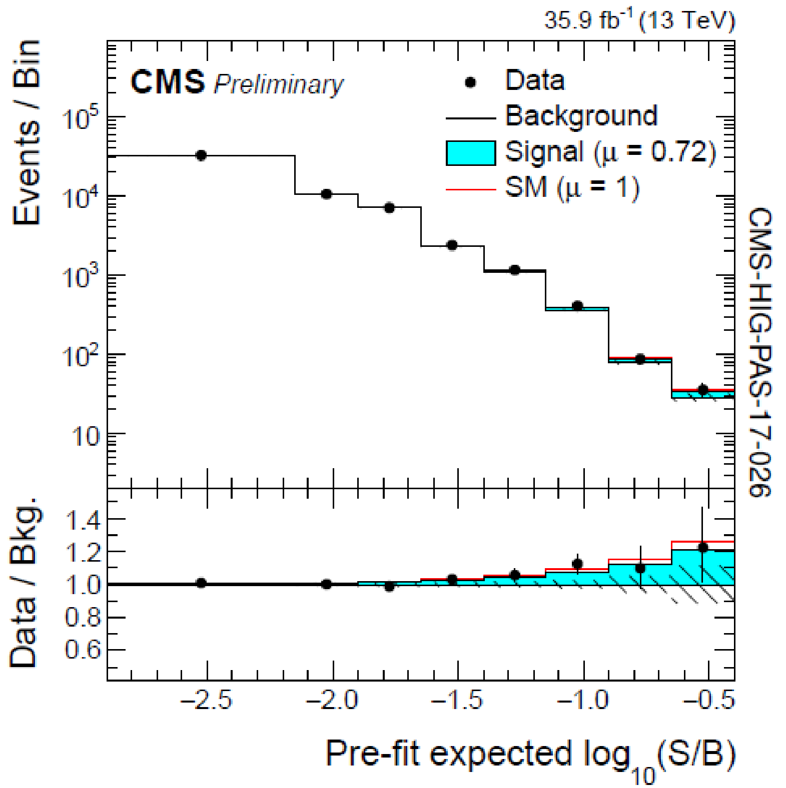




CMS ttH(bb) Results

- Profit from large H → bb BR. Leptonic ttbar have higher purity.
- Difficult final state due to huge combinatorics in event reconstruction and large tt + HF background with large theory uncertainties.

- Bkg. Discrimination from BDT, ME and DNN are used to extract signal.



Uncertainty source	$\pm\sigma_\mu$ (observed)
total experimental	+0.15/-0.16
b tagging	+0.11/-0.14
jet energy scale and resolution	+0.06/-0.07
total theory	+0.28/-0.29
$t\bar{t}$+hf cross-section and parton shower	+0.24/-0.28
size of MC samples	+0.14/-0.15
total systematic	+0.38/-0.38
statistical	+0.24/-0.24
total	+0.45/-0.45

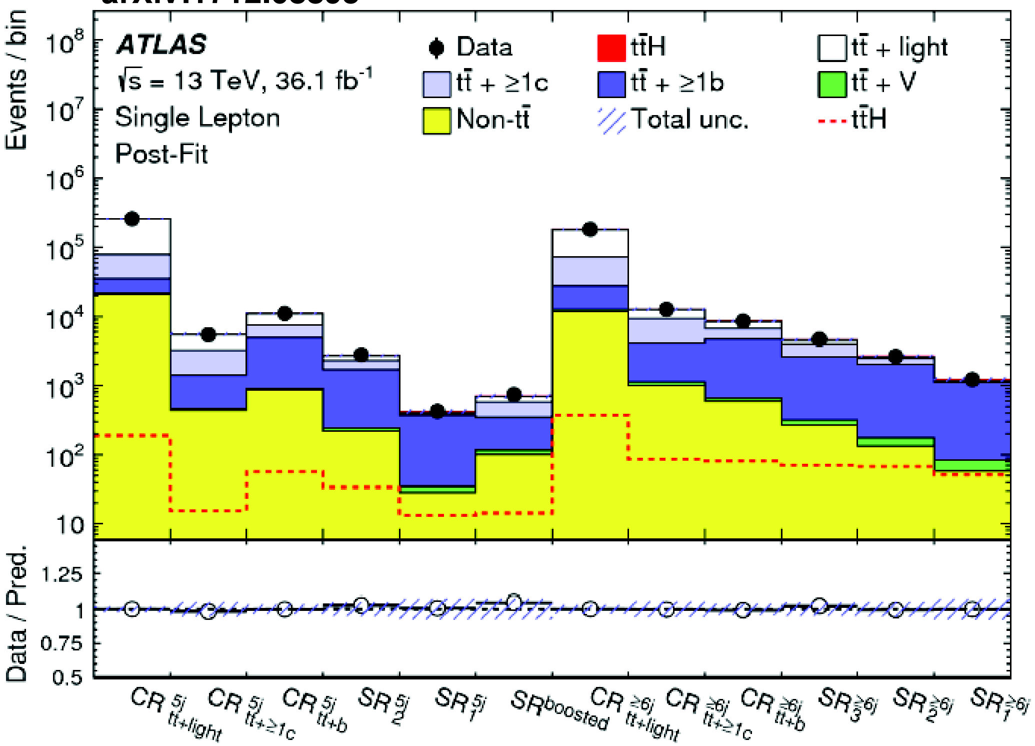
- Main systematics: ttbar+HF theory, b-tagging and jet energy calibration

μ=0.72±0:45 ; Obs (exp) significance: 1.6 (2.2) σ

ATLAS ttH(bb) Results

- BDT to decide jet assignment and separate signal from background.
- Signal extracted from combined fit of classification BDT output in SRs and event yields in most of CRs

arXiv:1712.08895

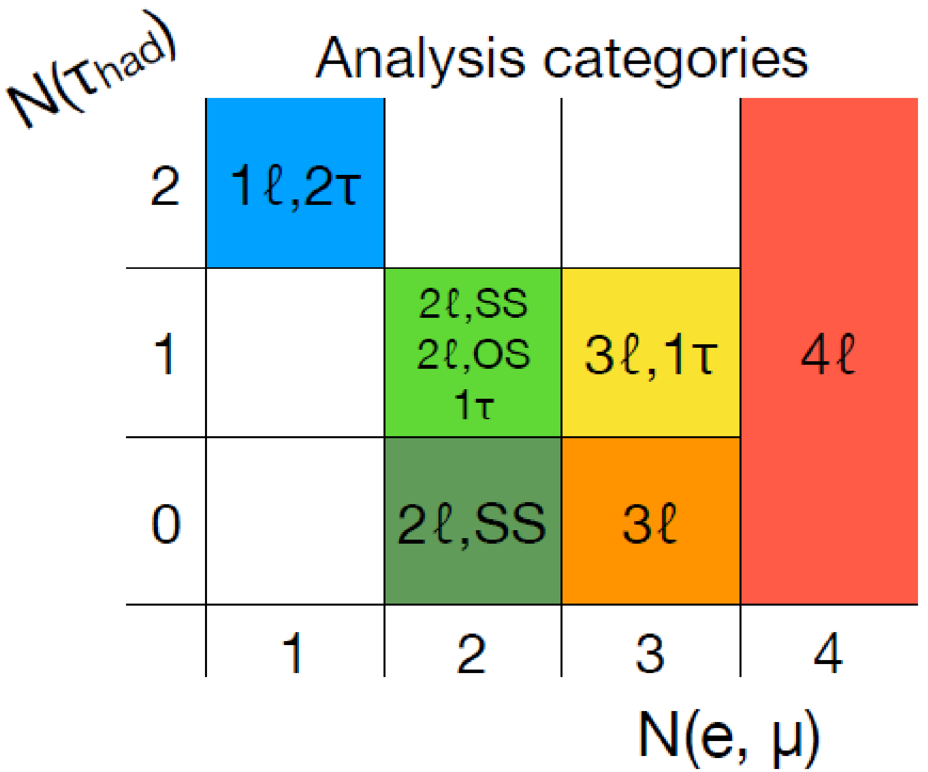


Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modeling	+0.46	−0.46
Background-model stat. unc.	+0.29	−0.31
b-tagging efficiency and mis-tag rates	+0.16	−0.16
Jet energy scale and resolution	+0.14	−0.14
$t\bar{t}H$ modeling	+0.22	−0.05
$t\bar{t}+\geq 1c$ modeling	+0.09	−0.11
JVT, pileup modeling	+0.03	−0.05
Other background modeling	+0.08	−0.08
$t\bar{t}$ + light modeling	+0.06	−0.03
Luminosity	+0.03	−0.02
Light lepton (e,μ) id., isolation, trigger	+0.03	−0.04
Total systematic uncertainty	+0.57	−0.54
$t\bar{t}+\geq 1b$ normalization	+0.09	−0.10
$t\bar{t}+\geq 1c$ normalization	+0.02	−0.03
Intrinsic statistical uncertainty	+0.21	−0.20
Total statistical uncertainty	+0.29	−0.29
Total uncertainty	+0.64	−0.61

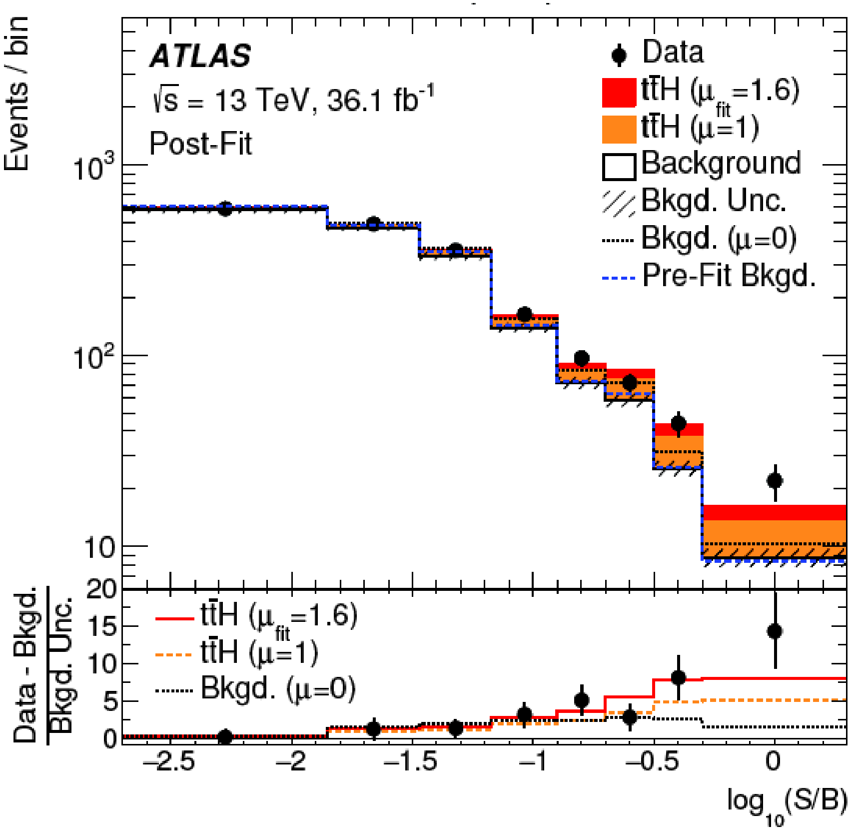
- Precision limited by systematic uncertainty on ttbar+≥1b simulation
- Best fit $\mu=0.84^{+0.64}_{-0.61}$; Obs (exp) significance 1.4 (1.6) σ

ATLAS ttH(H->WW, ZZ, ττ)

- 7 categories split by number and flavour of charged leptons
- Main backgrounds events from ttW/Z and tt with non-prompt leptons
- MVA to reject non-prompt and charge misid backgrounds.
- Event classified with MVA approaches



arXiv:1712.08891

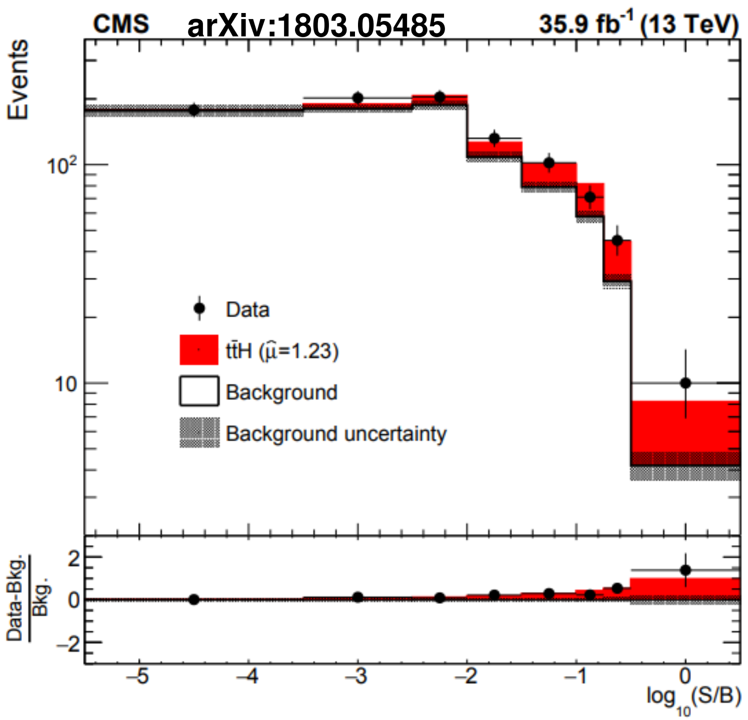


- Main systematics are signal and background modelling and jet energy scale.
- $\mu=1.6^{+0.5}_{-0.4}$; Obs (exp) significance: 4.1 (2.8) σ

CMS ttH(H->WW, ZZ, ττ)

- Event categorization in lepton flavor, charge and b-jet multiplicity
- Extensive usage of MVA methods:
- Lepton selection combining isolation, identification and vertex variables
- Resolved hadronic top decay and Higgs decay product taggers
- BDT discriminants based on kinematic variables, e.g. ΔR(l,jet)
- Matrix element calculations for $2l+1\tau_{had}$ and $3l+0\tau_{had}$

Source	Uncertainty [%]	$\Delta\mu/\mu$ [%]
e, μ selection efficiency	2–4	11
τ_h selection efficiency	5	4.5
b tagging efficiency	2–15 [57]	6
Reducible background estimate	10–40	11
Jet energy calibration	2–15 [65]	5
τ_h energy calibration	3	1
Theoretical sources	≈10	12
Integrated luminosity	2.5	5

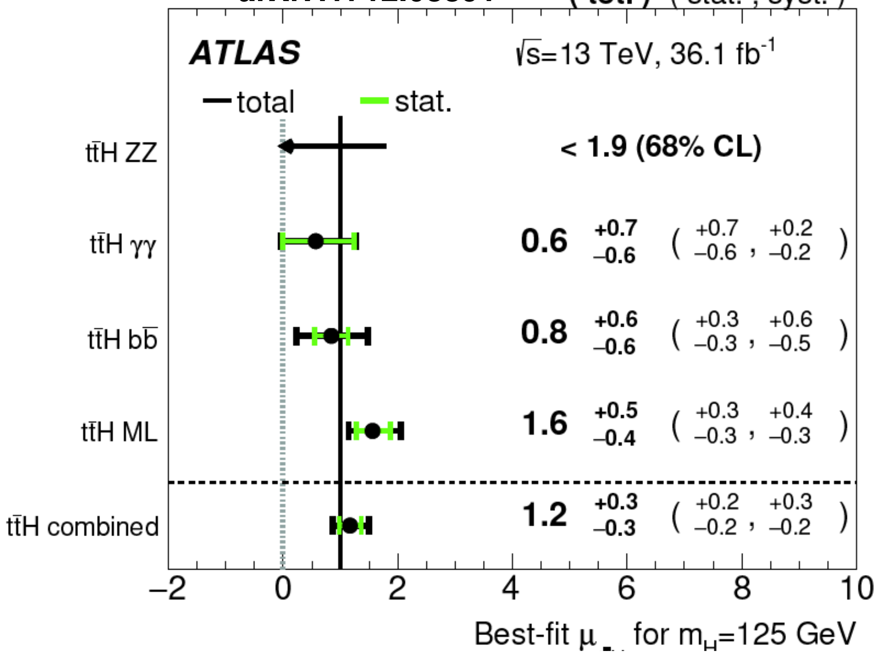


- Main experimental uncertainties: lepton efficiency, non-prompt background prediction, signal and background modelling
- $\mu=1.23^{+0.45}_{-0.43}$; Obs (exp) significance: 3.2 (2.8) σ

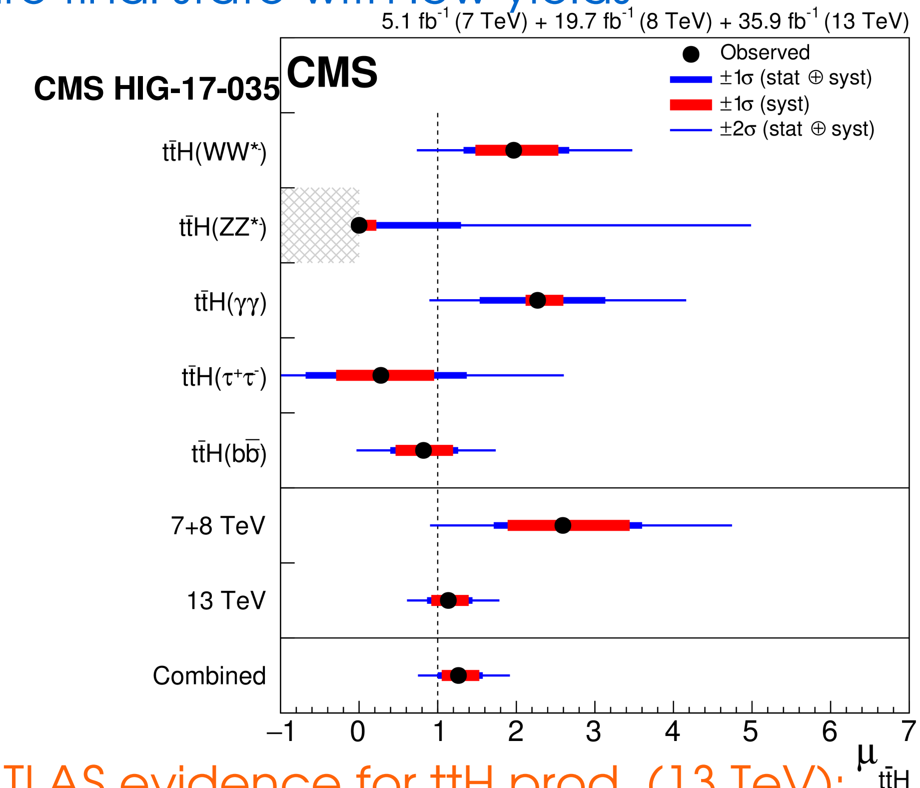
13 TeV ttH Combination

- Combined results include ttH(γγ), very pure final state with low yields

arXiv:1712.08891



CMS HIG-17-035



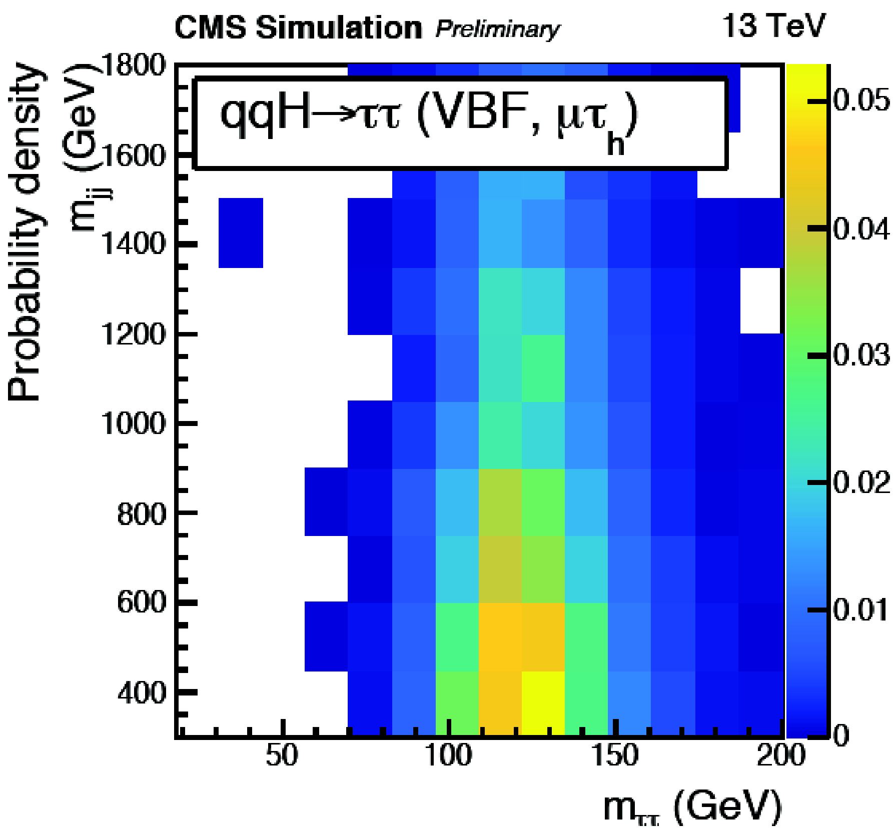
Uncertainty Source	$\Delta\mu$	
$t\bar{t}$ modeling in $H \to b\bar{b}$ analysis	+0.15	−0.14
$t\bar{t}H$ modeling (cross section)	+0.13	−0.06
Non-prompt light-lepton and fake τ_{had} estimates	+0.09	−0.09
Simulation statistics	+0.08	−0.08
Jet energy scale and resolution	+0.08	−0.07
$t\bar{t}V$ modeling	+0.07	−0.07
$t\bar{t}H$ modeling (acceptance)	+0.07	−0.04
Other non-Higgs boson backgrounds	+0.06	−0.05
Other experimental uncertainties	+0.05	−0.05
Luminosity	+0.05	−0.04
Jet flavor tagging	+0.03	−0.02
Modeling of other Higgs boson production modes	+0.01	−0.01
Total systematic uncertainty	+0.27	−0.23
Statistical uncertainty	+0.19	−0.19
Total uncertainty	+0.34	−0.30

- ATLAS evidence for ttH prod. (13 TeV):
  - Obs (exp) Signif.: 4.2 (3.8) σ
- **CMS observation (Run1+Run2):**
  - μ**=1.26$^{+0.31}_{-0.26}$**
  - **Obs (exp) Signif.: 5.2 (4.2) σ**
- Most sensitive channels limited by systematic uncertainties, mostly theoretical uncertainties.
- Other channels still statistically limited

Run 2 $H \rightarrow \tau\tau$ Analysis

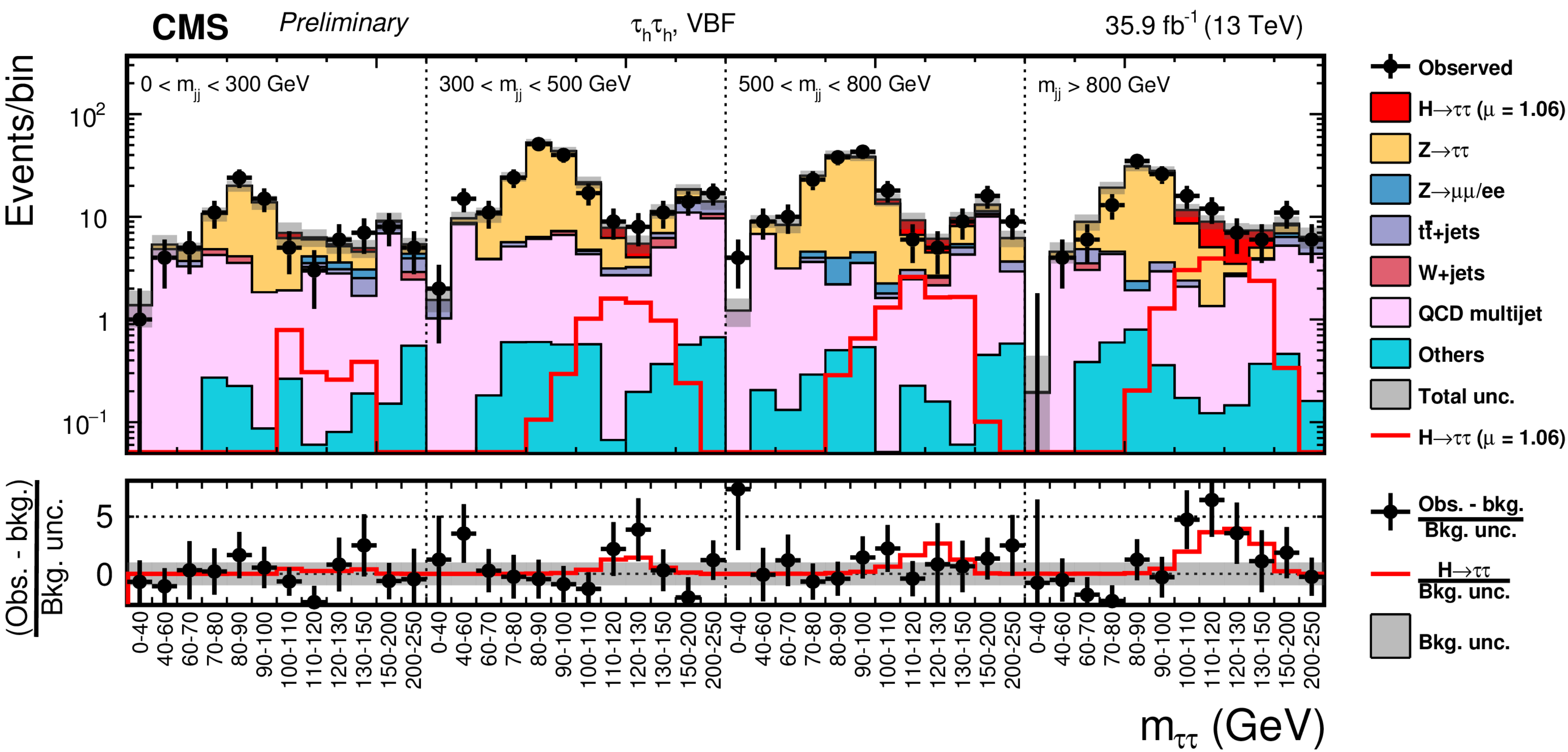
CMS PAS-HIG-16-043

- Main background is $Z \rightarrow \tau\tau$ modelled by MC simulation.
- Cut-based analysis employing 0-jet, boosted and VBF event categories
- Analysis includes leptonic and hadronic decay channels of the taus: ($e\tau_{had}$, $\mu\tau_{had}$, $e\mu$, $\tau_{had}\tau_{had}$)



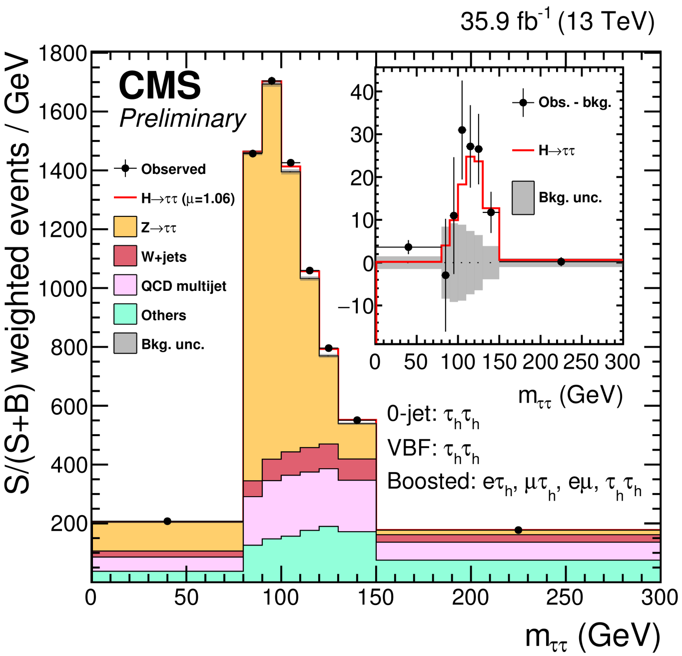
- Extracting the signal in 2-dimensions : one dim is always di-tau mass (m_{vis} for 0jet) and other dimension (tau decay mode,di-jet mass, higgs p_T, ...) is chosen targeting specific prod modes.

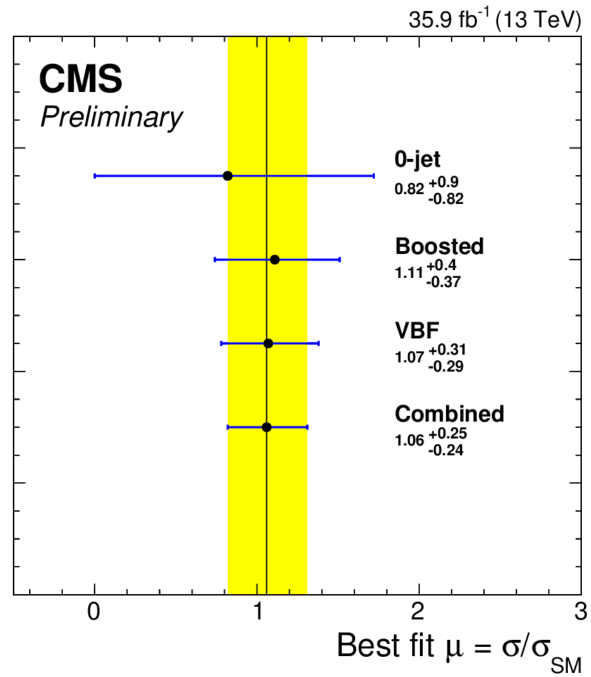
$H \rightarrow \tau\tau$ Background

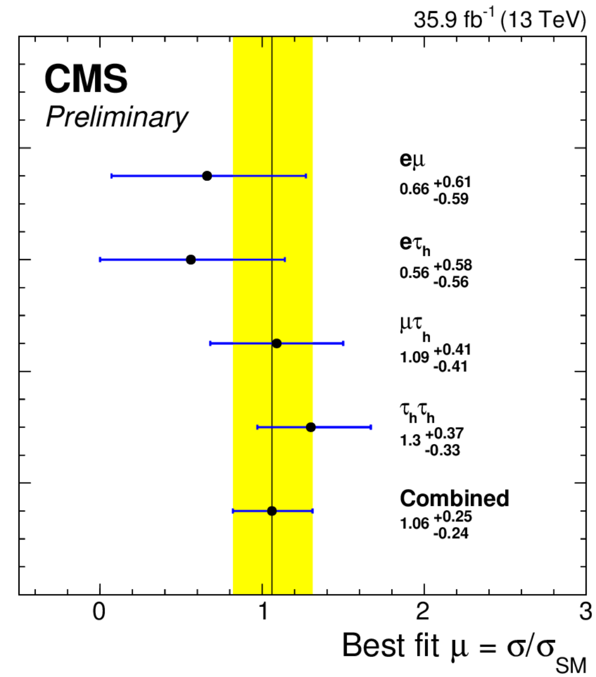


- $Z \rightarrow \tau\tau$: MadGraph MC, with corrections from $Z \rightarrow \mu\mu$ CR
- QCD MJ: data-driven from CR
- Other: lepton $\rightarrow \tau$ fake and EW

$H \rightarrow \tau\tau$ Results

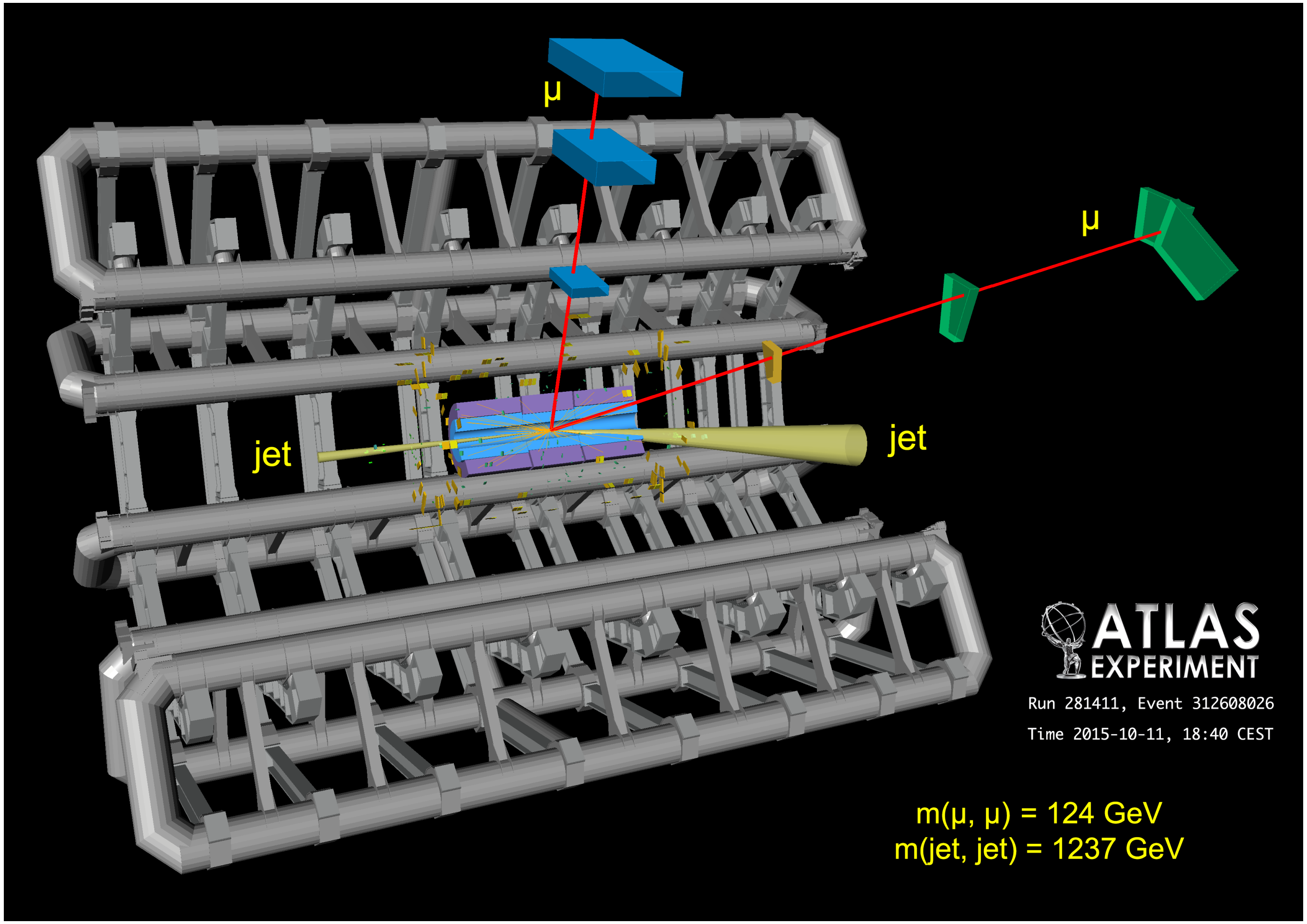






- Excess compatible with the 125 GeV SM Higgs
- Expected (postfit) significance is 4.7 σ
- Observed significance is 4.9 σ
- 0jet and boosted: mostly ggH, VBF: mostly qqH
- 0jet: little signal sensitivity, but it allows to control background and systematics.

Coupling to 2nd generation fermions



CMS $H \rightarrow \mu\mu$

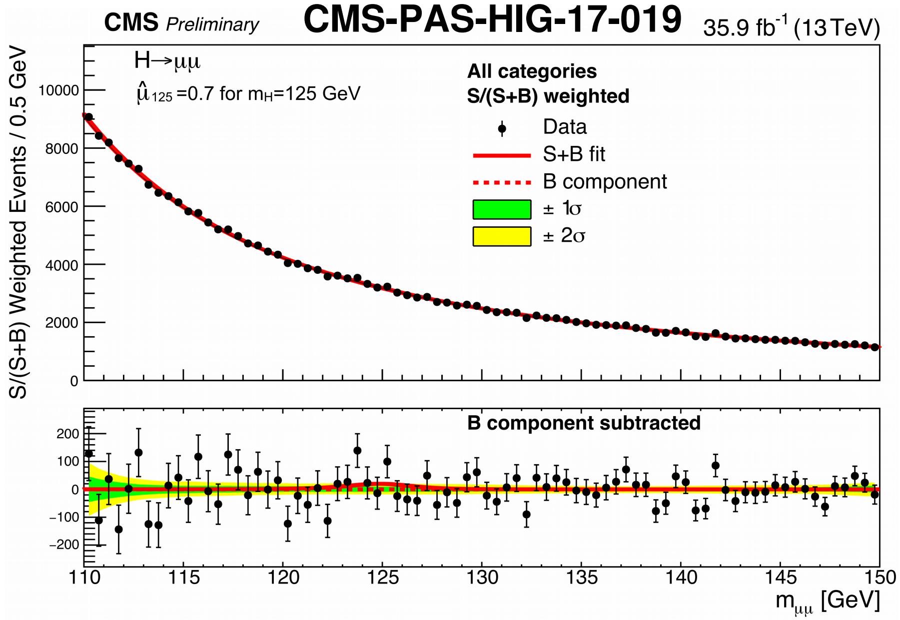
- Best channel to measure Higgs couplings to 2nd fermion generation.

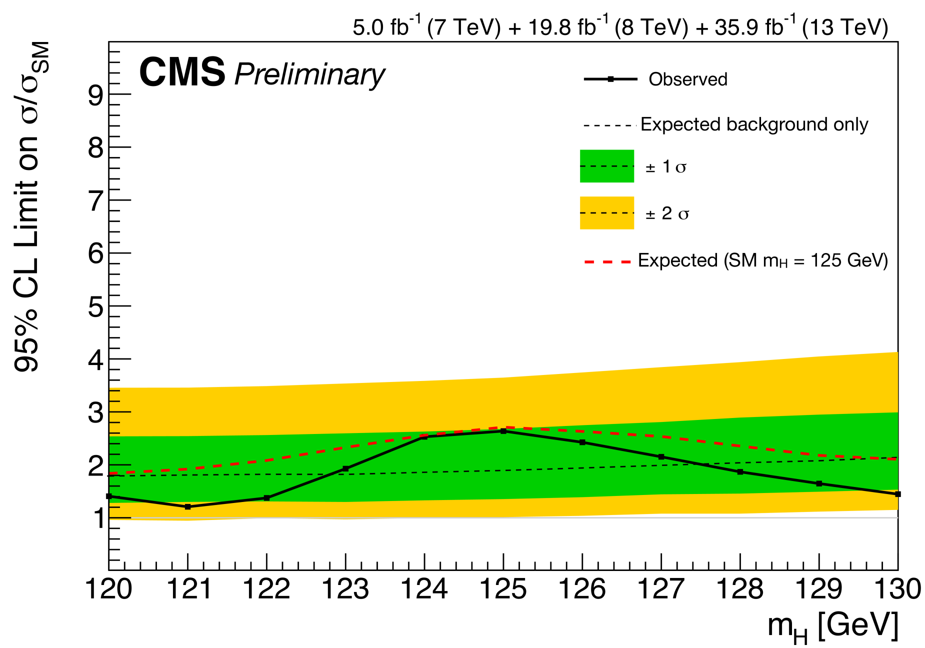
- SM BR: 2.2×10^{-4}
- Clean signature, benefits from good mass resolution

- Dominant background is $Z \rightarrow \mu\mu$, several order of magnitudes larger than Higgs signal, then ttbar

- Use of kinematic of the di-muon system to for optimal sensitivity: η_{μ}, $p_T^{\mu\mu}$ $\Delta\phi_{\mu\mu}$, $\Delta\eta_{\mu\mu}$ and BDT.

- Run1+2 combination upper limits on on obs (exp.) production rate:
    - <2.64 (1.89) xSM prediction @ 95% C.L.





ATLAS $H \to \mu\mu$

- Selection:
  - Two muons with p_T>15 GeV
  - E_T^{miss} < 80 GeV
  - b-jet veto
  - 110 < $m_{\mu\mu}$ < 160 GeV

- In Run 2, a BDT is used to define two VBF-enriched Signal Region (loose, tight). Event failing the selection are reused for 6 ggH categories, based on η_μ and $p_T^{\mu\mu}$

- Signal is parametrized with a Crystal-Ball+Gaussian shape.
- Background is parameterized with a Breit-Wigner+exponential fit to data in sidebands.

- Expect to measure $H \to \mu\mu$ (second generation fermions) during the lifetime of the LHC.

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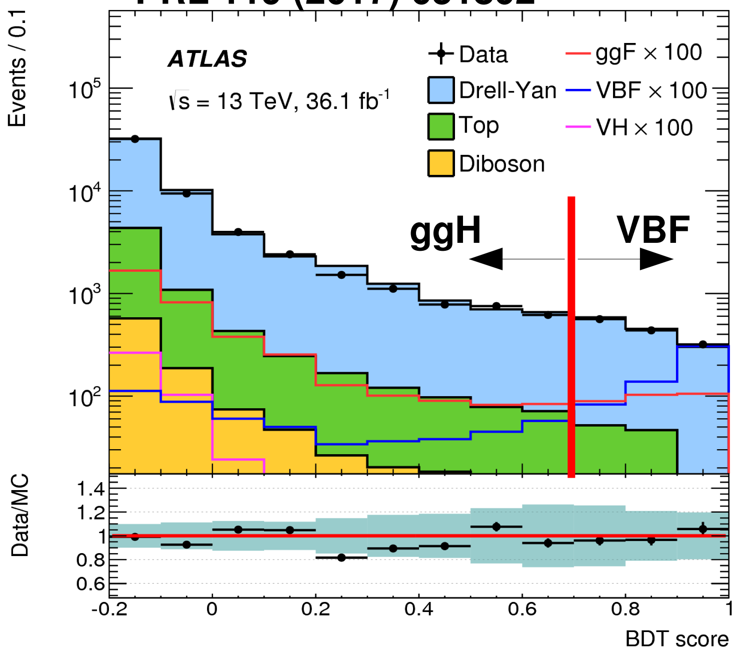


	best fit value for σ/σSM	95% CL upper limit on σ/σSM
Run 2	-0.1±1.5	3.0 (exp 3.1)
Run 1 + Run 2	-0.1±1.4	2.8 (2.9)

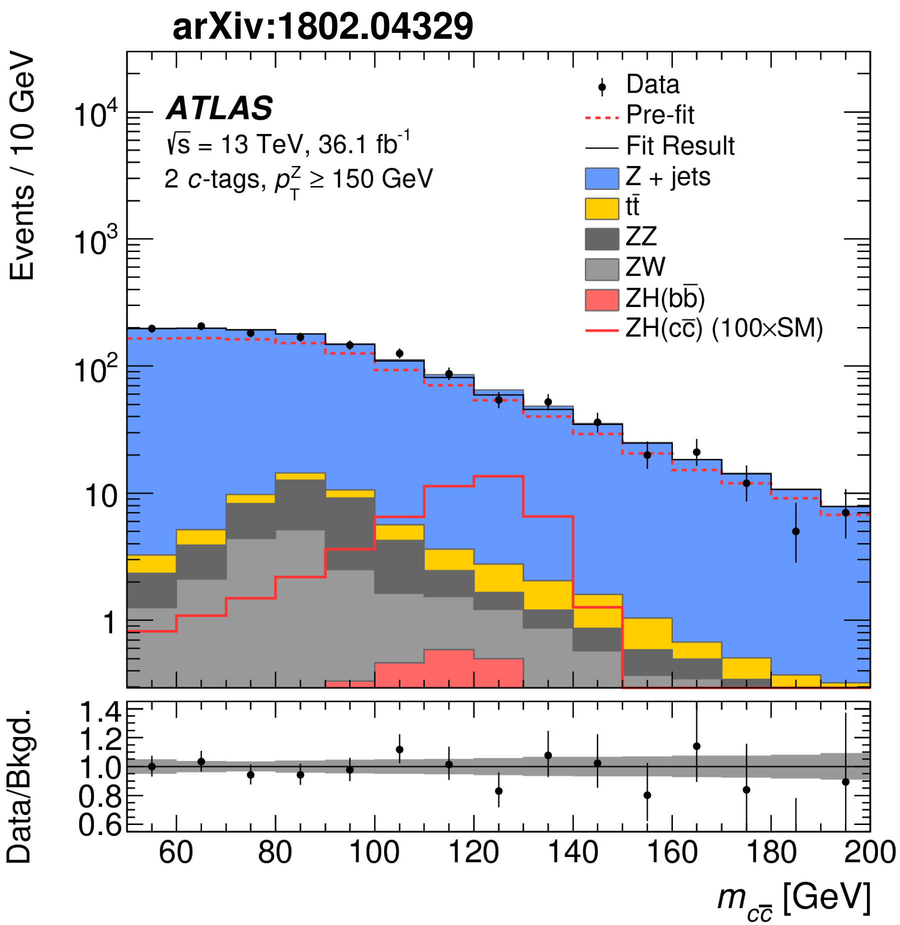
ATLAS ZH → ccbar

- Focus on on Z(→ ll)H(→cc) for simpler background composition

- Dedicated MVA discriminants to separate c-jets from light-jets and c-jets from b-jets

- Cut-based event selection with fit to m_{cc}

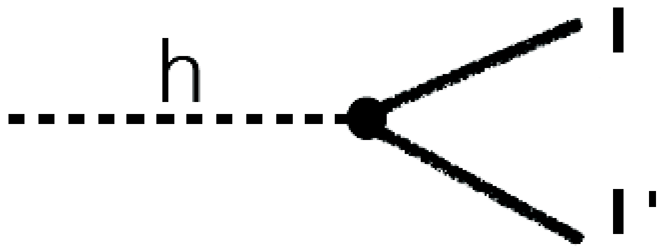
- Simultaneous fit of signal and Z+jets background



- Observed upper limit of 2.7 pb on σ(ZH)xBR(H → cc) >100 times the SM prediction of 26 fb @ 13 TeV)
- Cross-check $\mu_{ZV} = 0.6^{+0.5}_{-0.4}$ (1.4σ observed, 2.2σ expected)

- Flavor tagging uncertainty is the dominant uncertainty

Off-diagonal terms



$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij} (\bar{f}_L^i f_R^j) h + h.c. + \cdots ,$$

In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

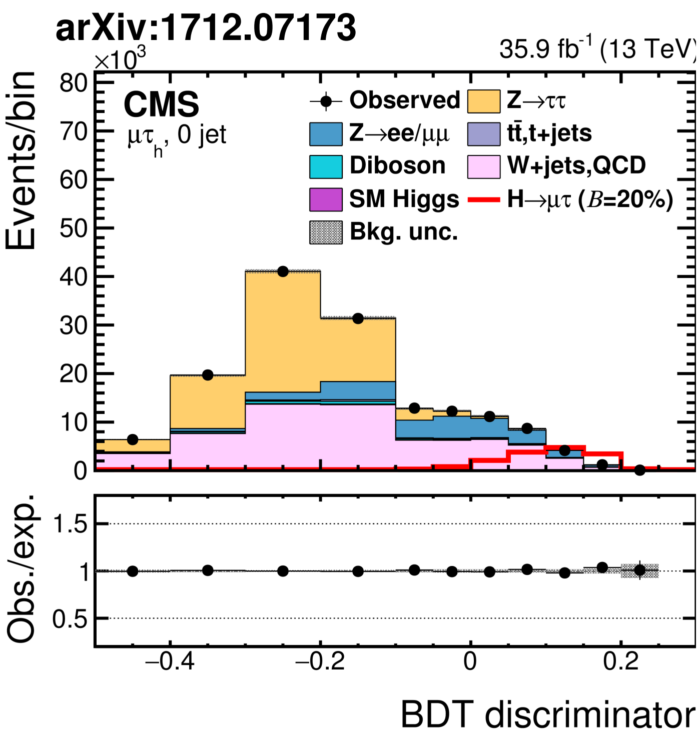
- Lepton flavor violation exists in Nature (neutrino oscillations), but LFV in the charged sector is extremely suppressed in the SM.

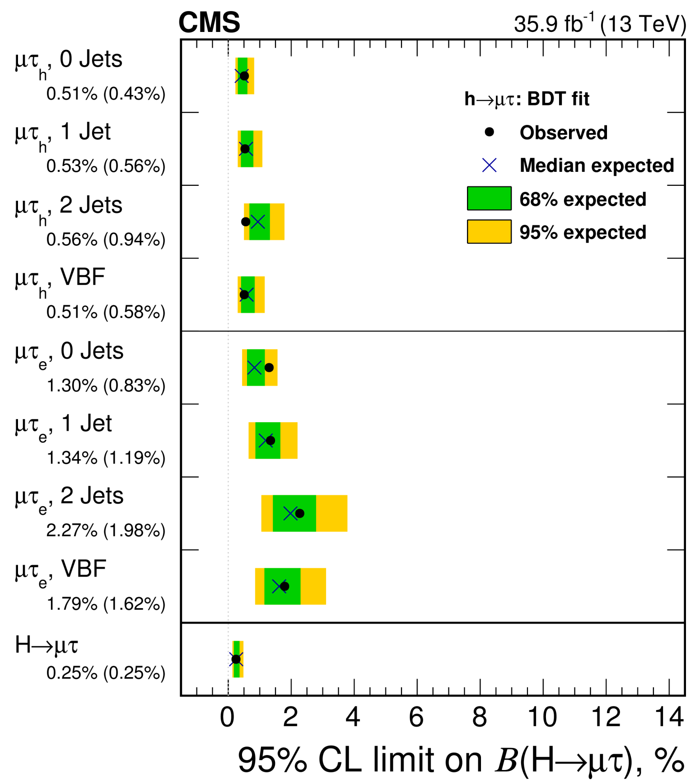
- A number of models beyond SM predict LFV in charged sector related to the Higgs sector at levels observable at LHC.

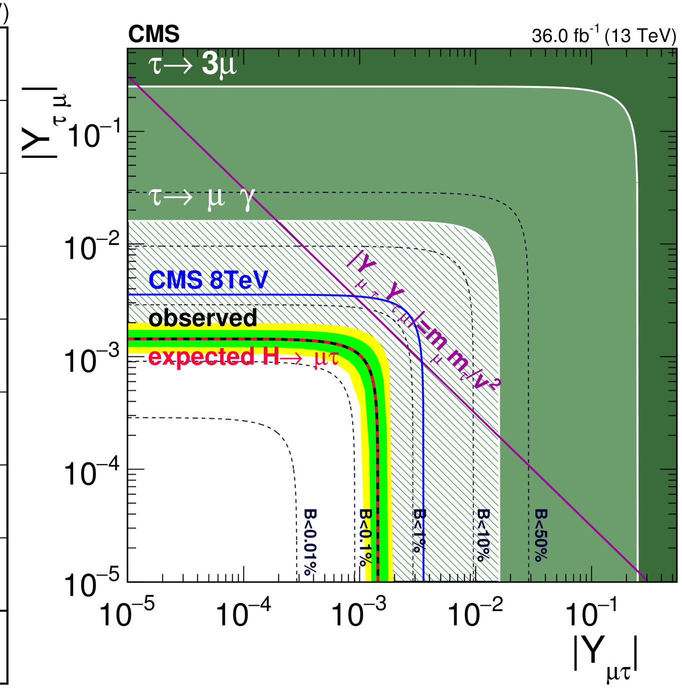
- Low energy results (e.g. $\mu \rightarrow e\gamma$, $\tau \rightarrow eee$, μ-e conversion, etc.) provide indirect constraints, but there are often assumptions.

Run 2 $H \to \tau\mu$ Search

- Main backgrounds are the $Z \to \tau\tau$, W+jets and QCD production.
- Analysis employs categorization in 0-jet, 1-jet, 2-jet VBF and no VBF final states
- Both BDT and collinear mass fit analyses are used.



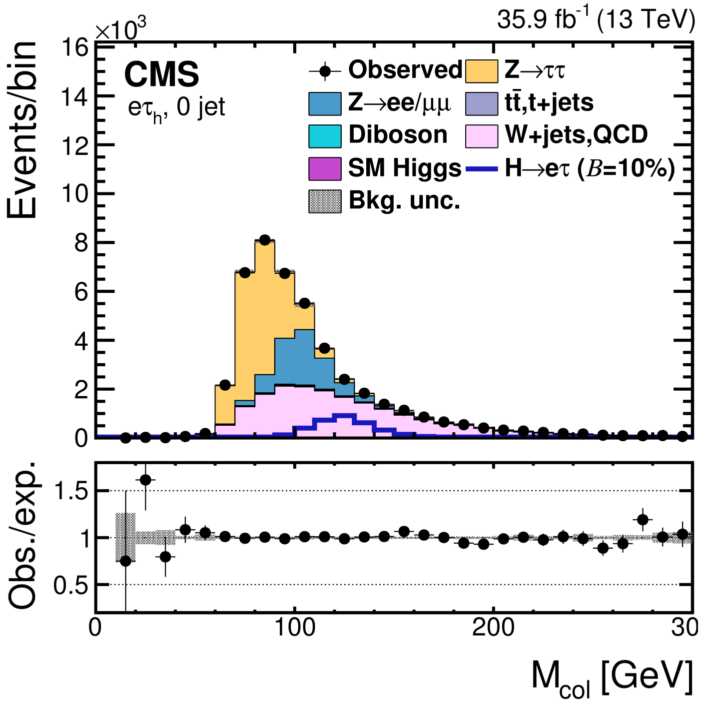


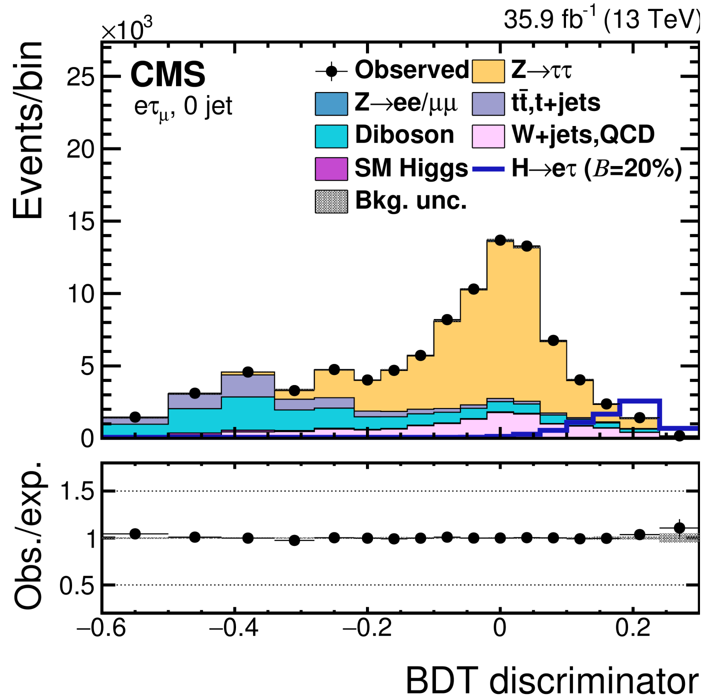


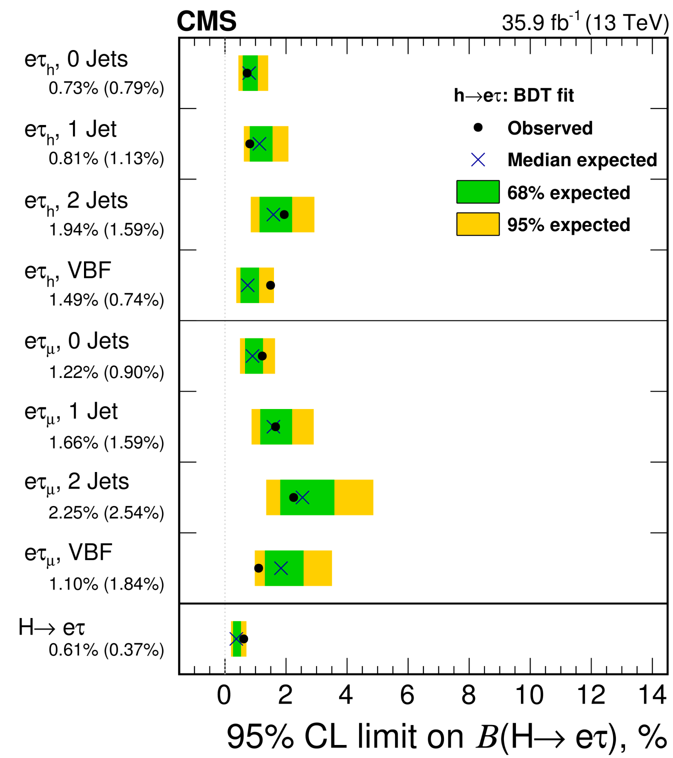
- BDT analysis significantly better than mass fit
- Best-fit BR($H \to \tau\mu$) = 0.00 ±0.12%
- No excess found, this result excludes the BR corresponding to the CMS Run 1 excess

Run 2 $H \to \tau e$ Search

- Same strategy used also for the $H \to \tau e$ search with only small differences in the choice of input variables to the BDT.
- With respect to $H \to \tau\mu$ search, additional $Z \to ee$ background



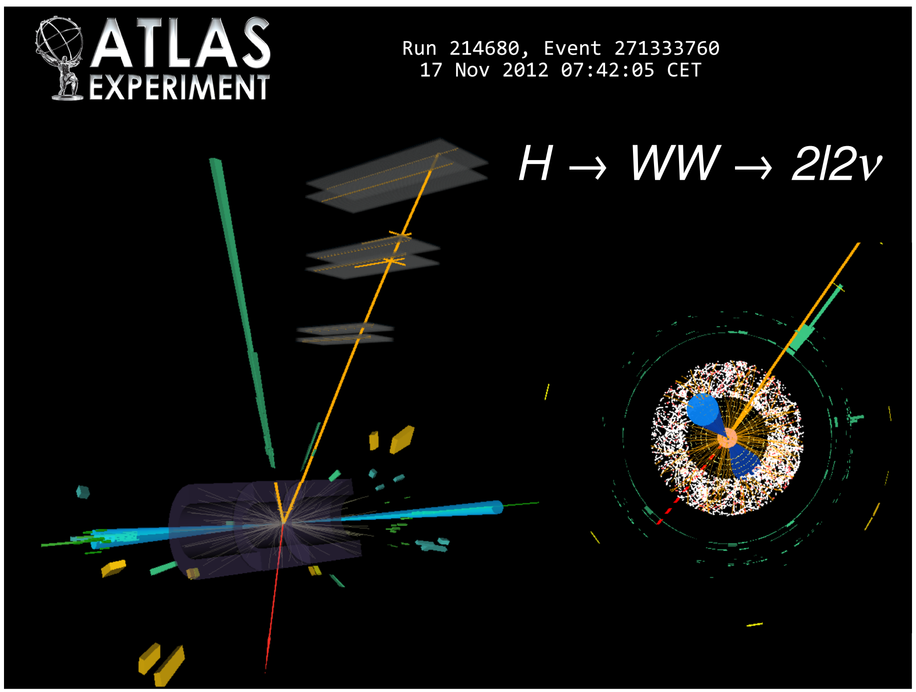


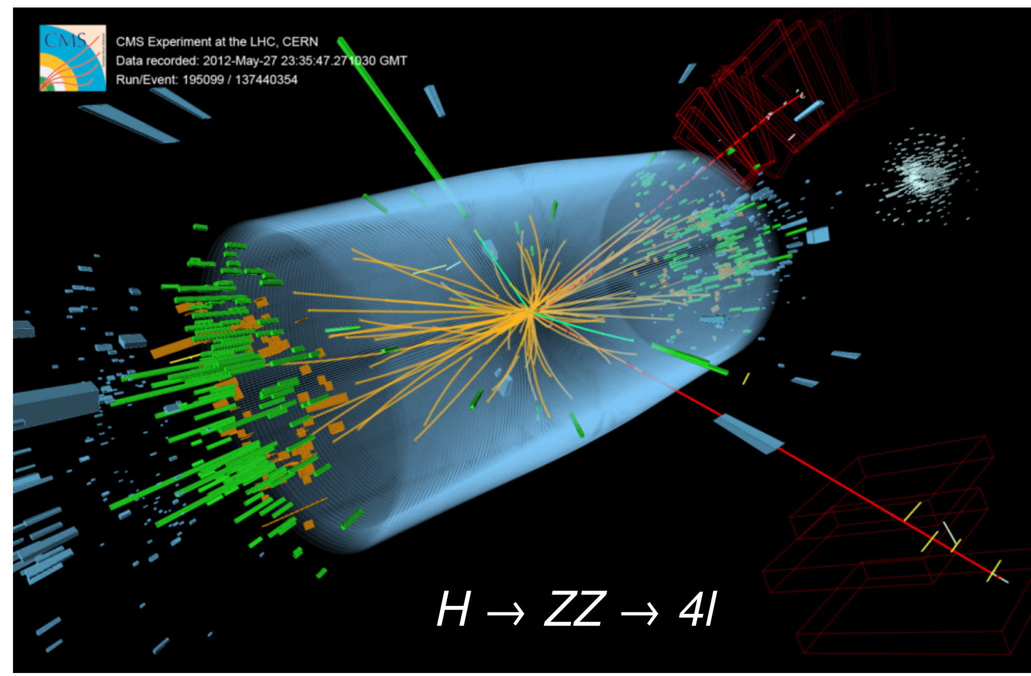


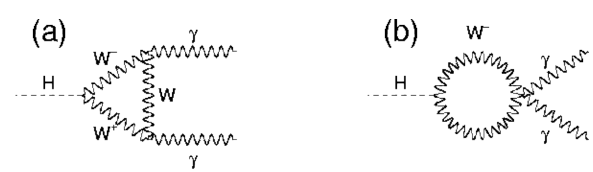
- Best-fit BR($H \to \tau e$) = 0.30 ±0.18%
- No excess found

Coupling to bosons

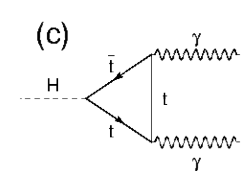
- Channels already established with $> 5\ \sigma$ significance during Run 1
- $H \rightarrow WW$ has a strong sensitivity to VBF production
- $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$ best channels for mass and fiducial and differential cross-section measurements.





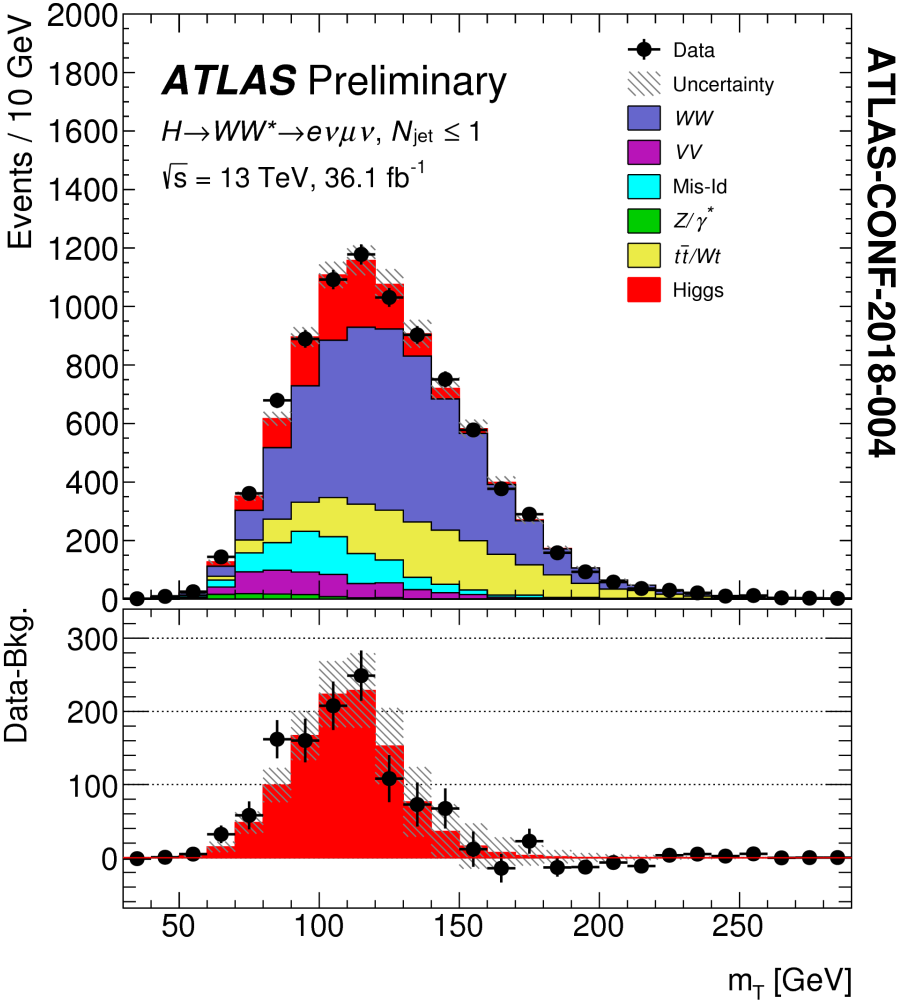


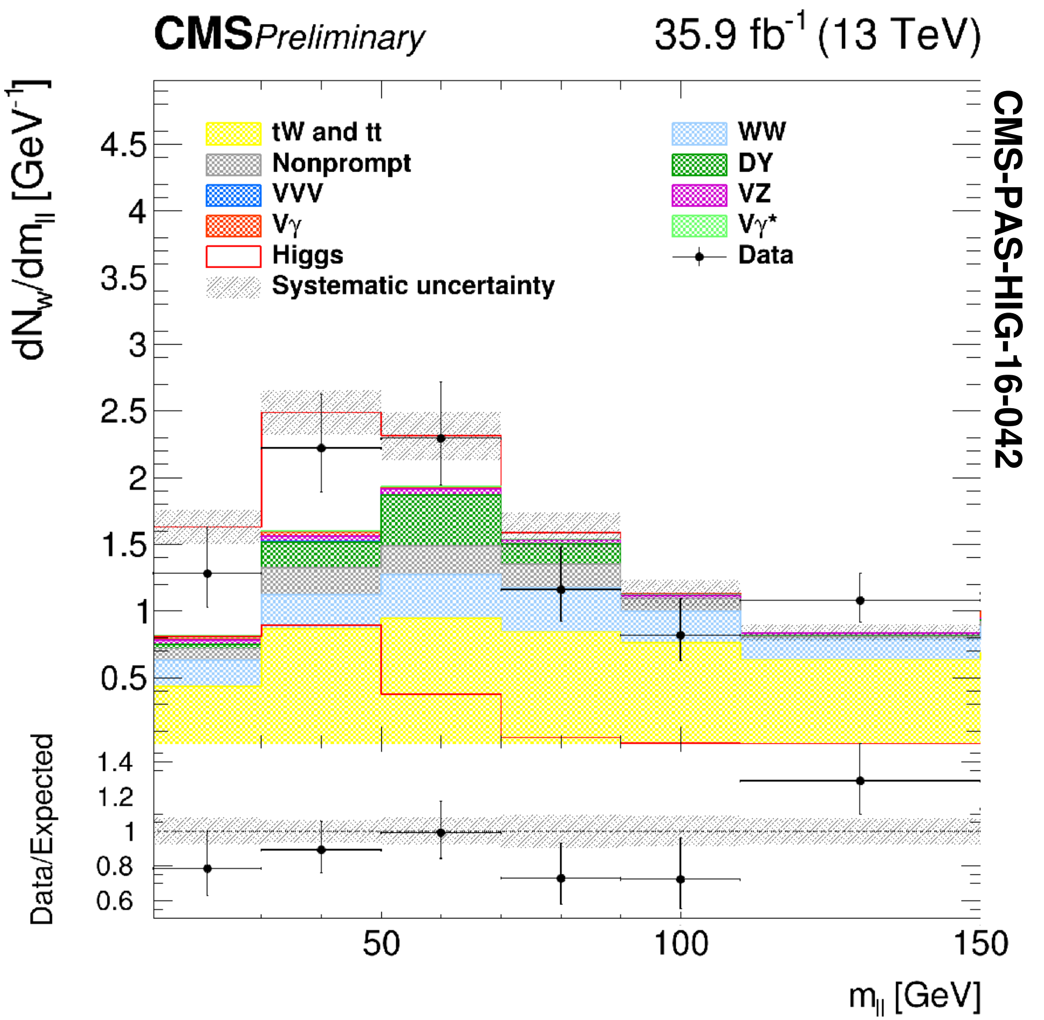
$H \rightarrow \gamma\gamma$



$H \rightarrow WW^* \rightarrow 2l2\nu$

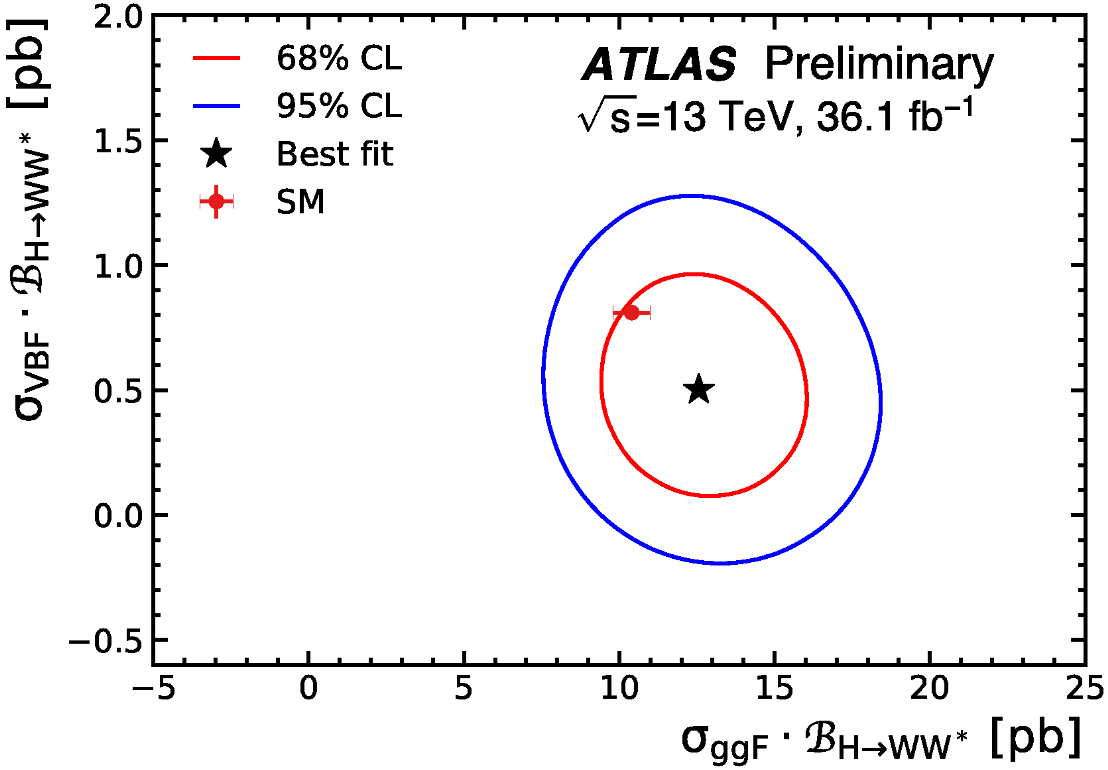
- Difficult final state due to presence of neutrinos and many sources of bkg.
- Major backgrounds are determined from data control regions: WW, ttbar, Z, backgrounds from mis-identified leptons.
- ATLAS and CMS divide the data in 0jet and 1jet and 2jet (VBF) categories.
- CMS includes categories for VH production. ATLAS uses BDT for VBF production

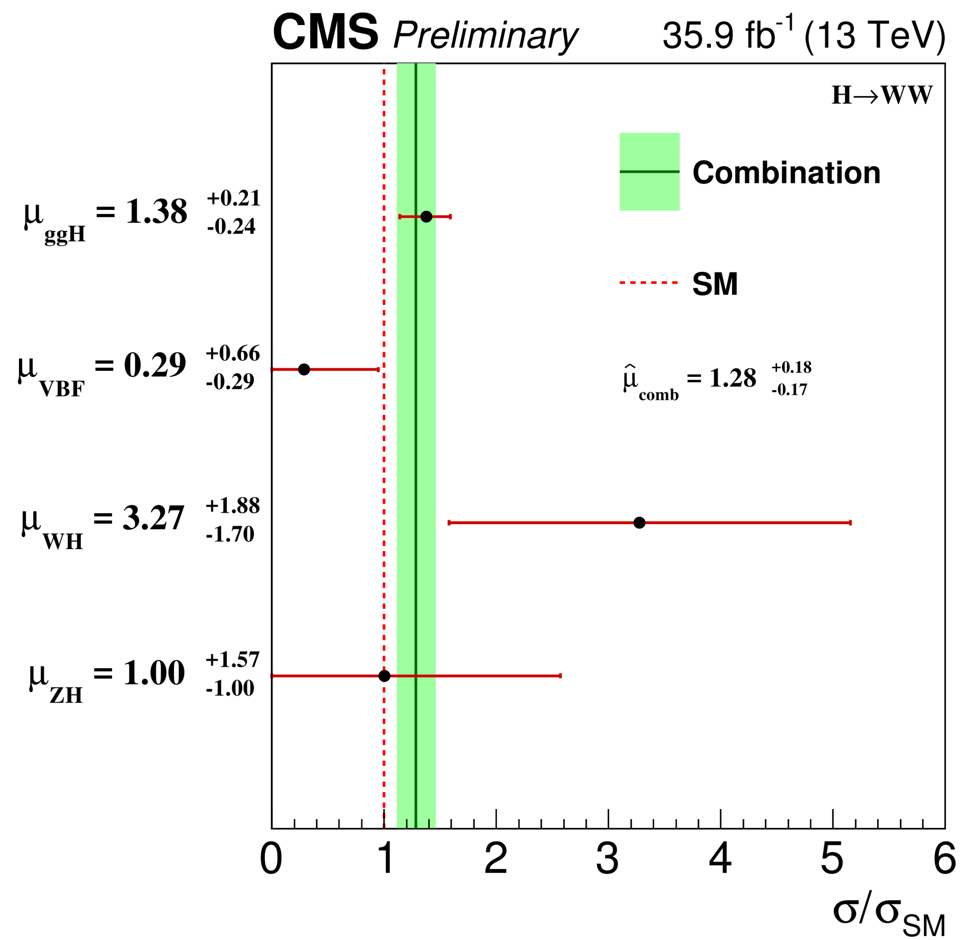




$H \rightarrow WW^* \rightarrow 2l2\nu$

- ATLAS and CMS re-established H → WW with > 5 σ significance in Run 2.
- Provides access to all Higgs production modes
- Good agreement with SM expectation





ATLAS Results

ggF Significance 6.3 obs (5.2 exp) σ

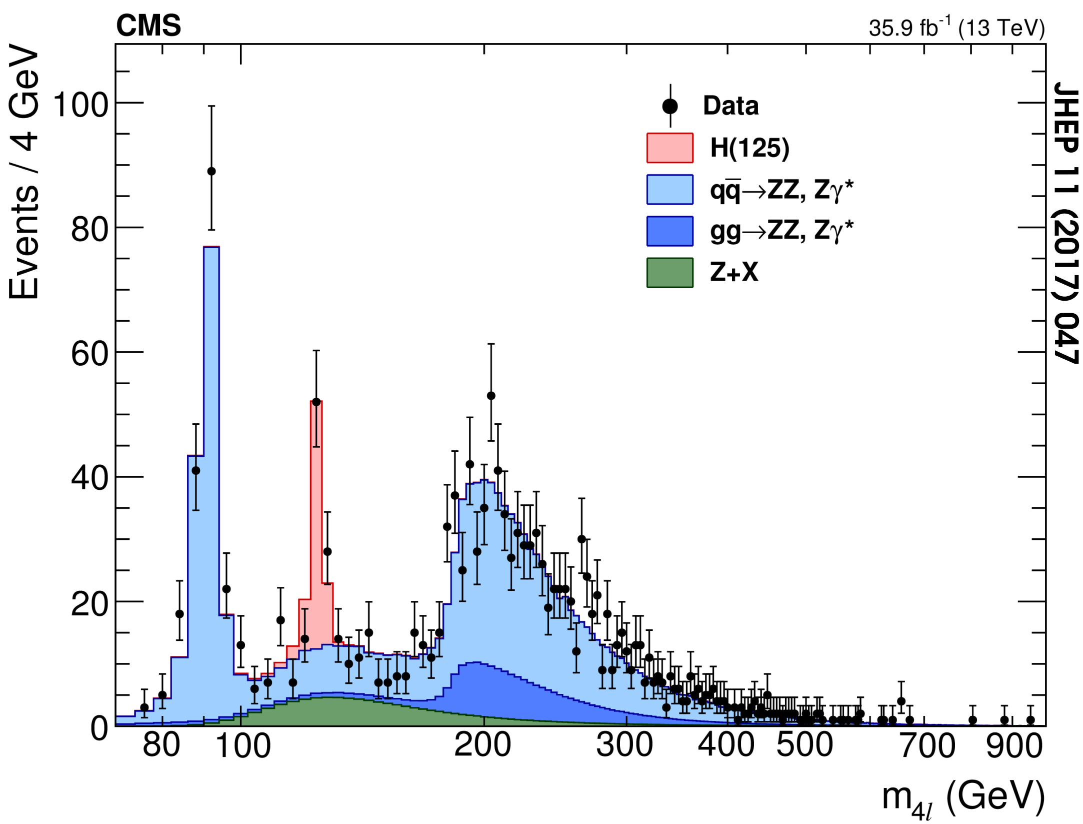
VBF Significance 1.9 obs (2.7 exp) σ

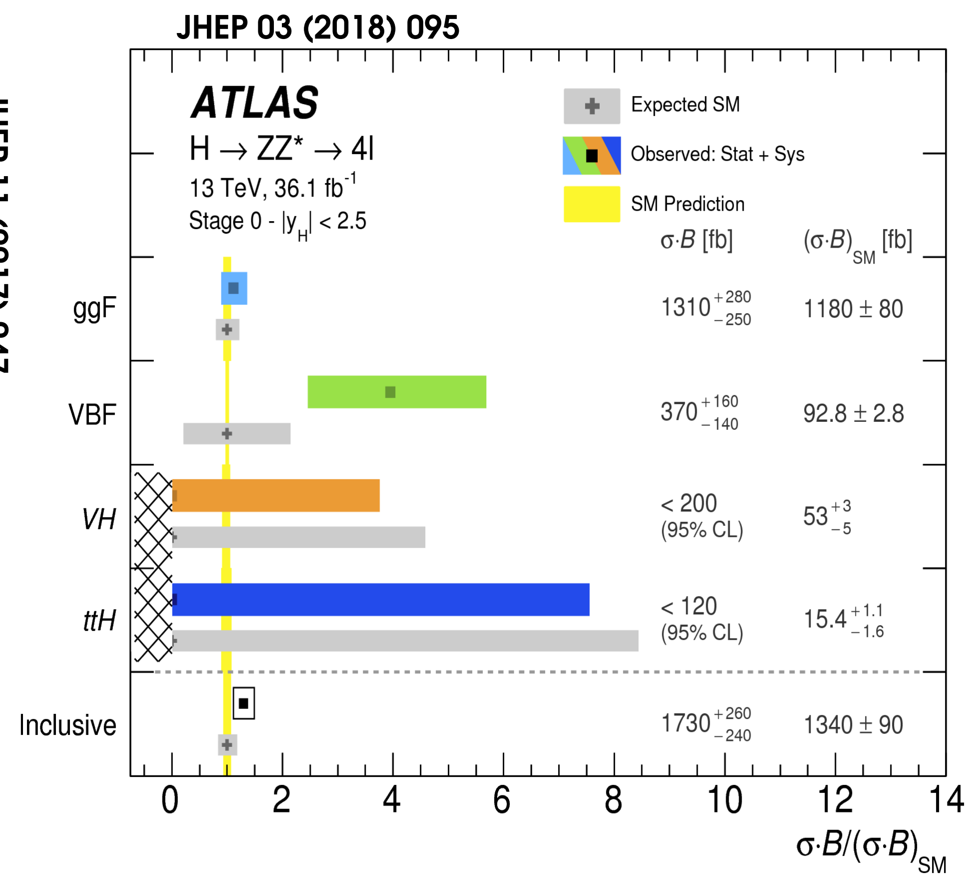
CMS Results

Significance 9.1 obs (7.1 exp) σ

13 TeV H → ZZ*→ 4l

- Clean, small rate and fully-reconstructable final state in 4 leptons
- Analysis separated by production mode and lepton flavour (4μ,4e,2e2μ)
- Small background from Z → 4l and diboson production ZZ → 4l

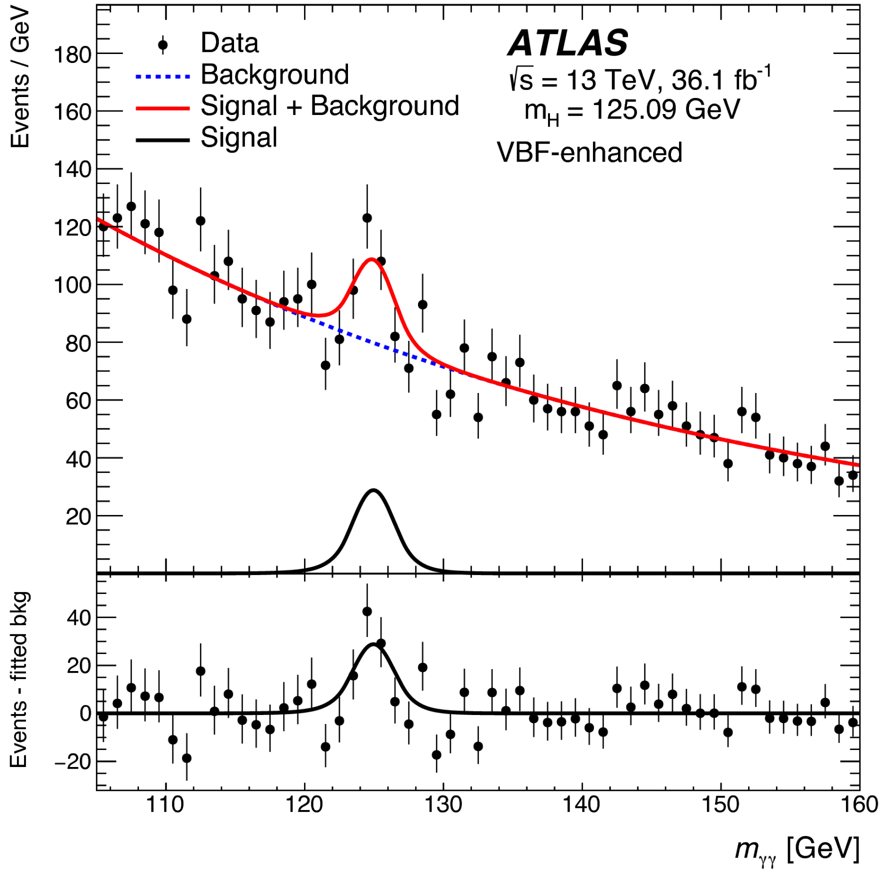


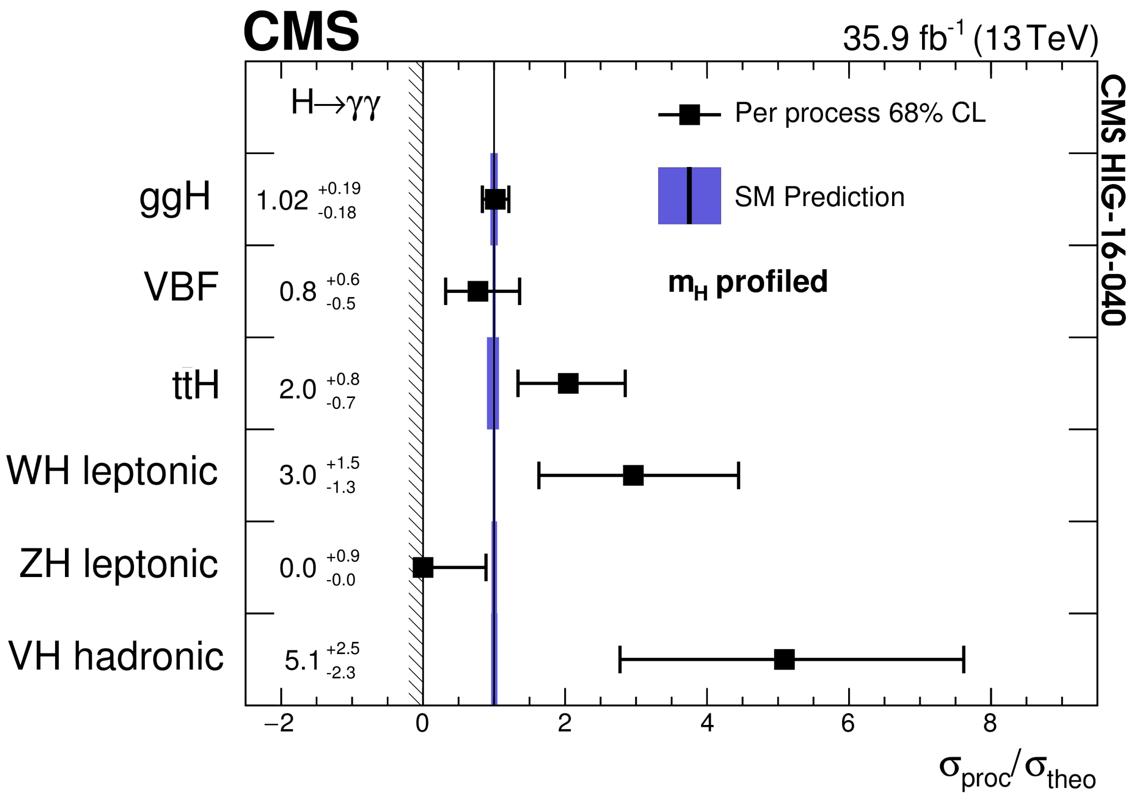


13 TeV $H \rightarrow \gamma\gamma$

- Good mass resolution and smooth background → signal extracted from a parametric function fit of the $m_{\gamma\gamma}$ distribution.
- Main backgrounds are $\gamma\gamma$ continoum and γ+jet
- Channel with fair sensitivity to all the main production modes.
- Categories defined by production mode and (di-)photon characteristics, CMS also uses BDT

arXiv:1802.04146



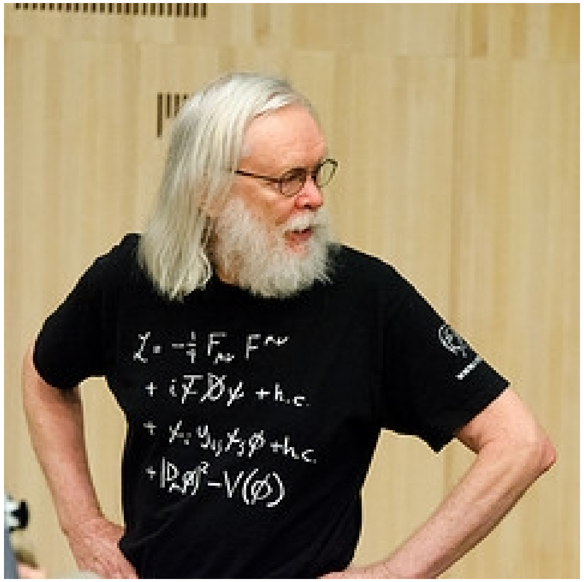


Higgs boson Mass and Cross-section

Higgs Mass?

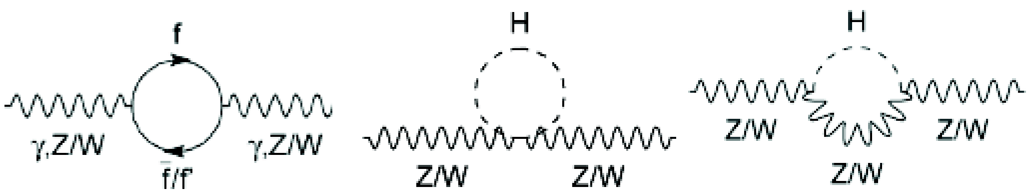
- The Model is capable of very precise predictions, but it has one free parameter not predicted by the theory:
the mass of the Higgs boson.
- J. Ellis et al., A Phenomenological Profile of the Higgs Boson(1976):

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

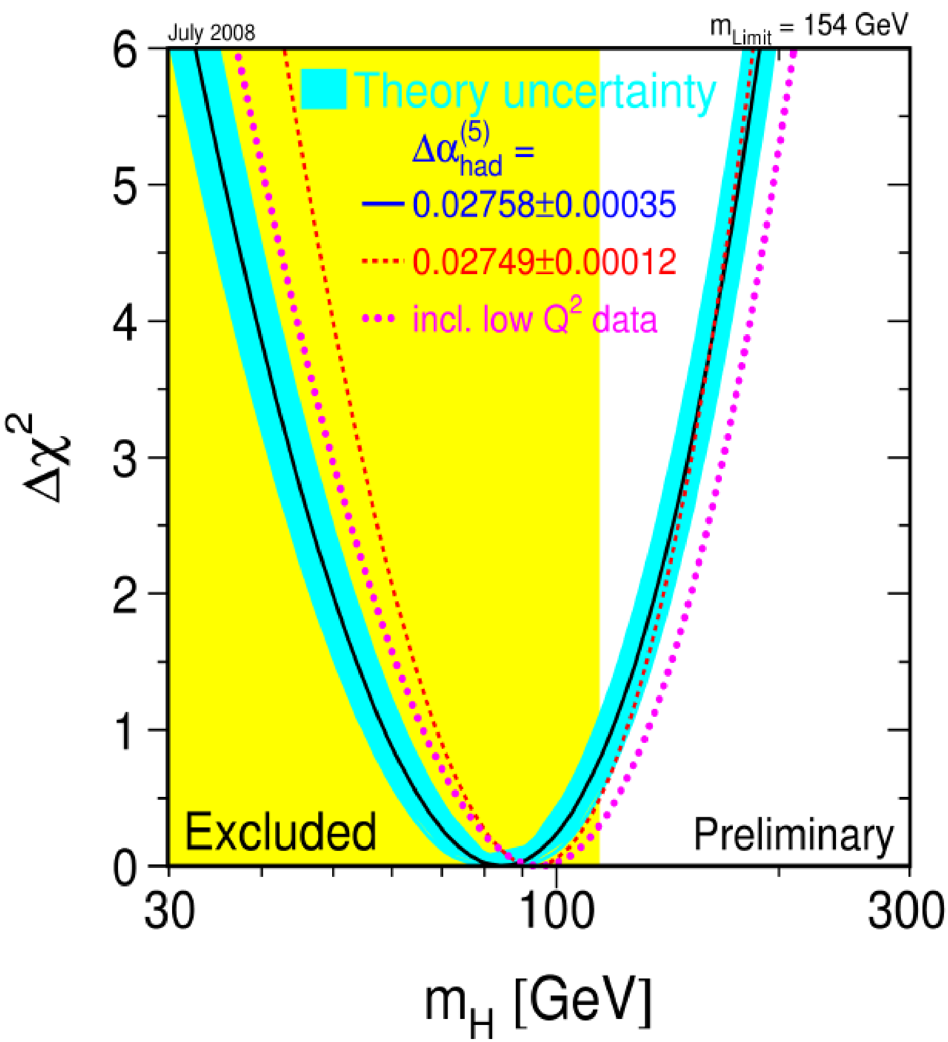


Indirect limits

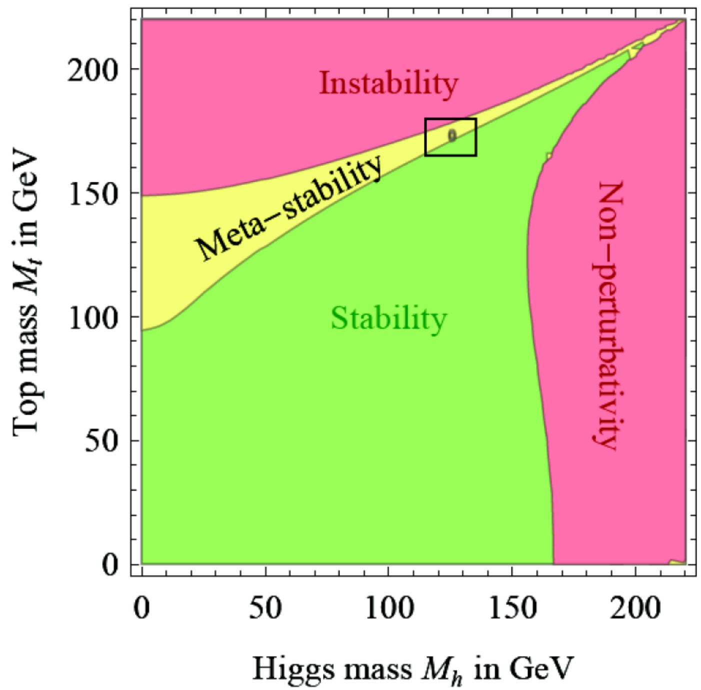
- Boundaries on the Higgs mass not only from direct searches, but also from EW fit of the SM measurements.
- Higgs mass is the only free parameter of the theory → possible to fit its value from measurements, such has M_W, M_Z, $Z \rightarrow ff$ cross section, G_F etc. where the Higgs radiative corrections can contribute.
- Problem: dependence is *weak*, e.g. moving the Higgs mass from 100 GeV to 1TeV affects M_W by only 150 MeV.
  Logarithmic dependence of M_W on M_H

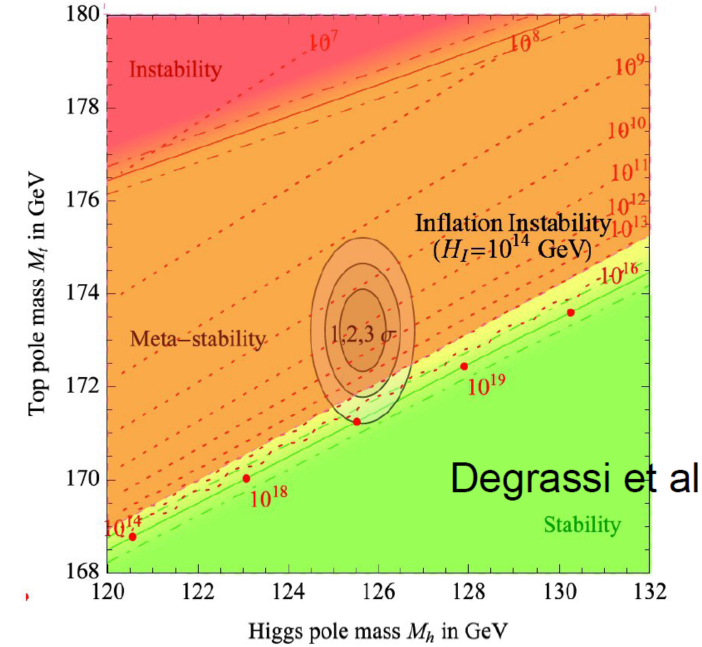


- Best EW fit for $M_H = 94^{+29}_{-24}$ GeV
- $M_H < 154$ GeV @ 95% CL



Higgs Mass measurement

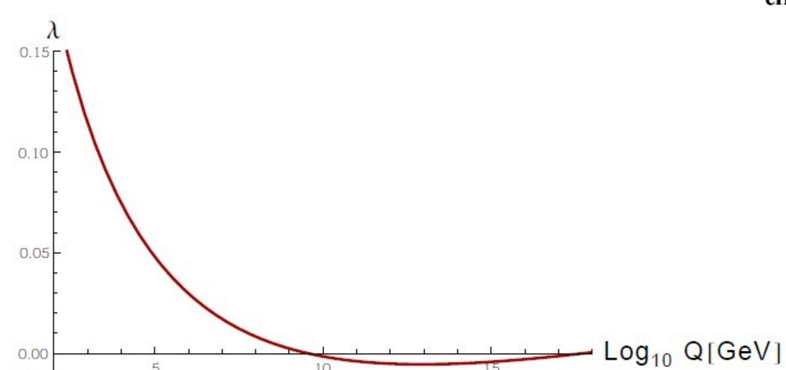


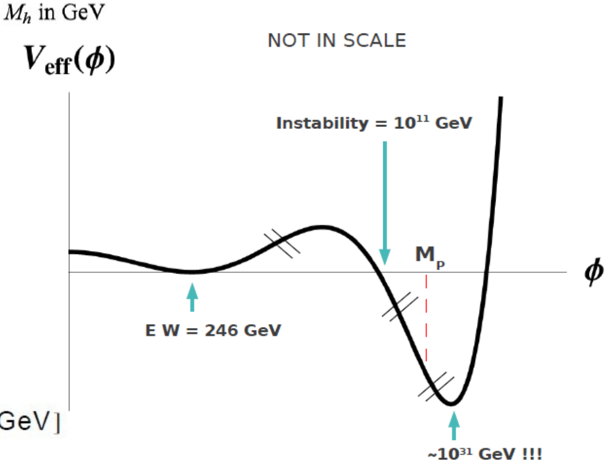


$$L = (\partial\Phi)(\partial\Phi^*) - V(\Phi)$$

$$V = \mu^2\Phi\Phi^* + \lambda(\Phi\Phi^*)^2$$

At EW scale λ~0.13



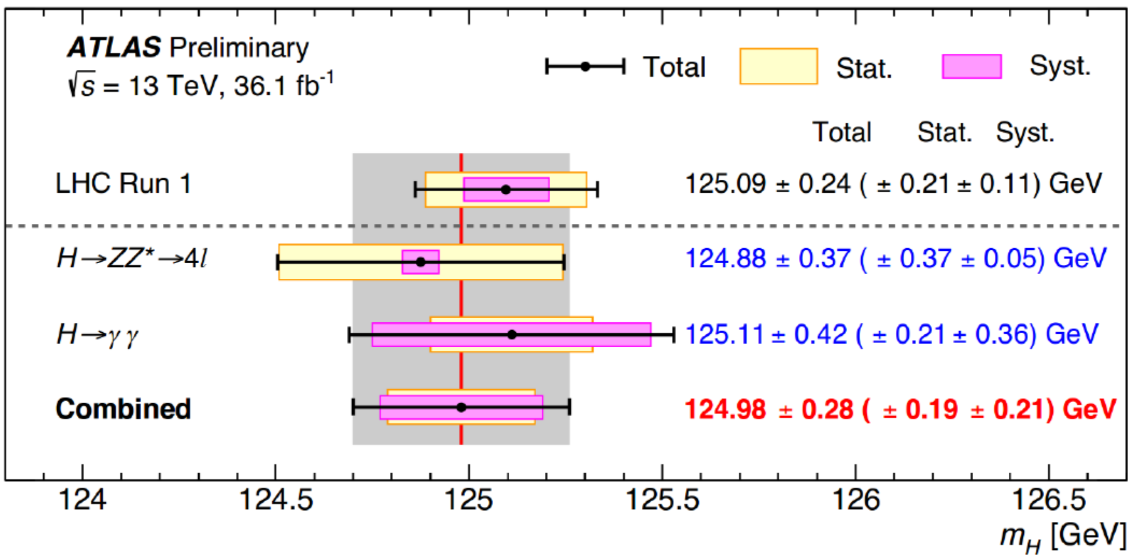


- Higgs quartic coupling λ can become negative for energies > O(10^{10}) GeV. Main corrections depends on m_{top} and m_H precise values.
- EW Vacuum stability up to Planck scale excluded @ 95 C.L. <u>without NP</u>
- G.Degrassi et al. (JHEP08(2012)098, JHEP12(2013)089)

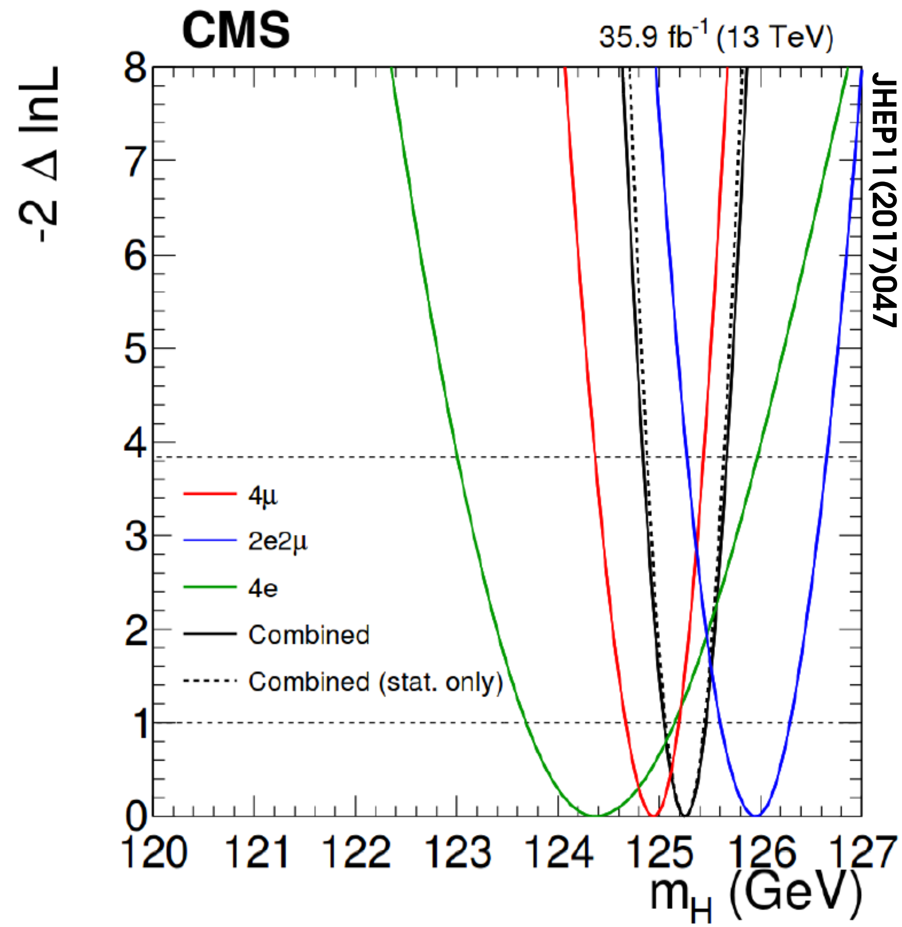
Combined Mass Measurement

- ATLAS and CMS mass measurement with Run 1 data after precise calibration:
- **m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV**
- Run 2 update is also based on H → γγ and H → ZZ(4l), having the best mass resolution

ATLAS-CONF-2017-046



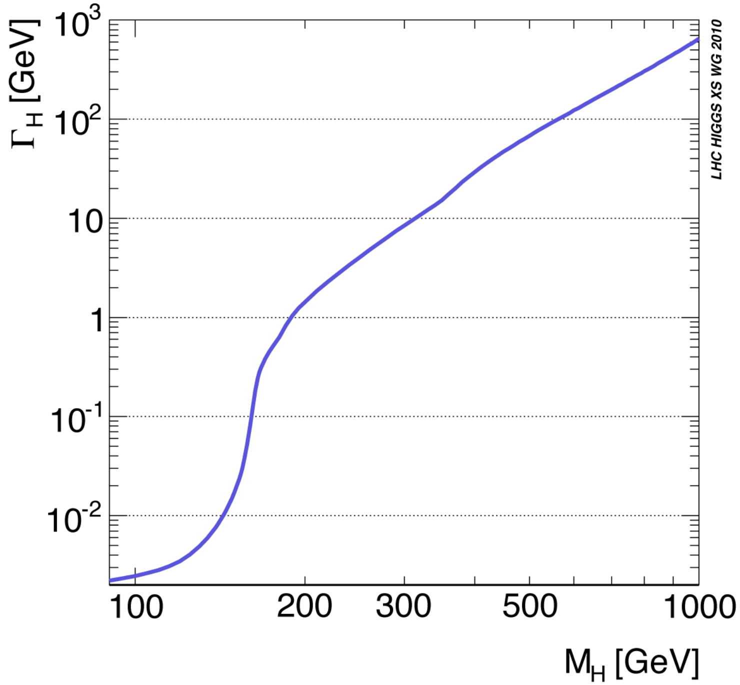
- H→ZZ(4l) is the most accurate channel and the result is still limited by statistics.
- CMS Run 2 result already better than LHC Run 1 combination.



$$m_{\mathrm{H}} = 125.26 \pm 0.21\ (\pm 0.20\ \mathrm{stat.} \pm 0.08\ \mathrm{sys.})\ \mathrm{GeV}$$

Higgs Mass width?

- The Higgs width also depends on its mass value, spanning several orders of magnitude:



For high mass, the width grows as

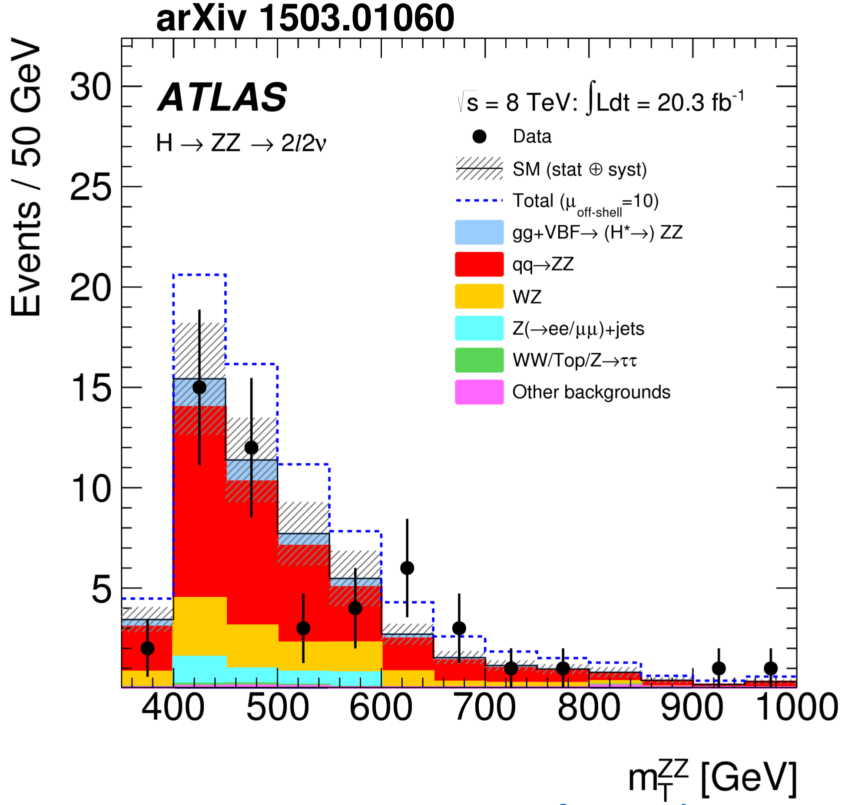
$$\Gamma_H = \frac{3g^2}{128\pi m_W^2} m_H{}^3 \simeq 0.5\ \mathrm{TeV}^{-2}\, m_H{}^3.$$

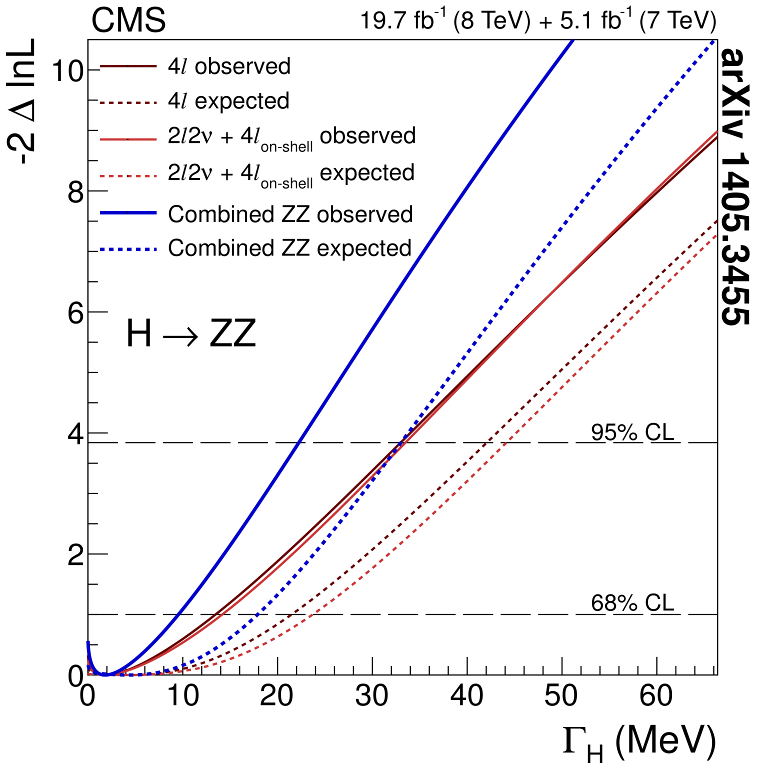
Width becomes equal to mass around 1.4 TeV
For mass >~1 TeV, the concept of Higgs resonance would disappear.

For mH=125 GeV, the width is about 4 MeV

Width Measurement

- SM Higgs width prediction is 4.2 MeV. Small expected value implies possible sensitivity to additional decay modes → tool for discovery.
- Direct measurement of the width performed but has no sensitivity to SM prediction.
- Higher sensitivity from indirect measurement from H → VV off-shell and background interference.
- Both experiments analyzed ZZ → 4l and 2l2ν final states. ATLAS also includes H → WW.





Assuming same on-shell and off-shell couplings:

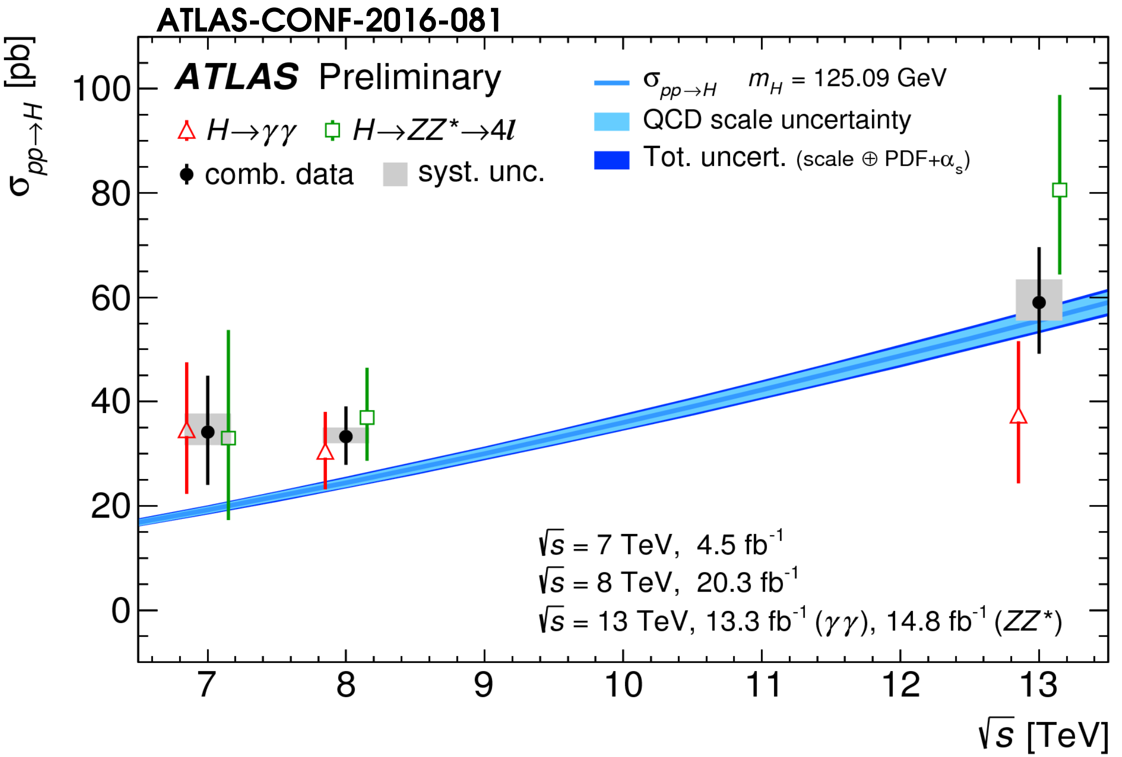
ATLAS:

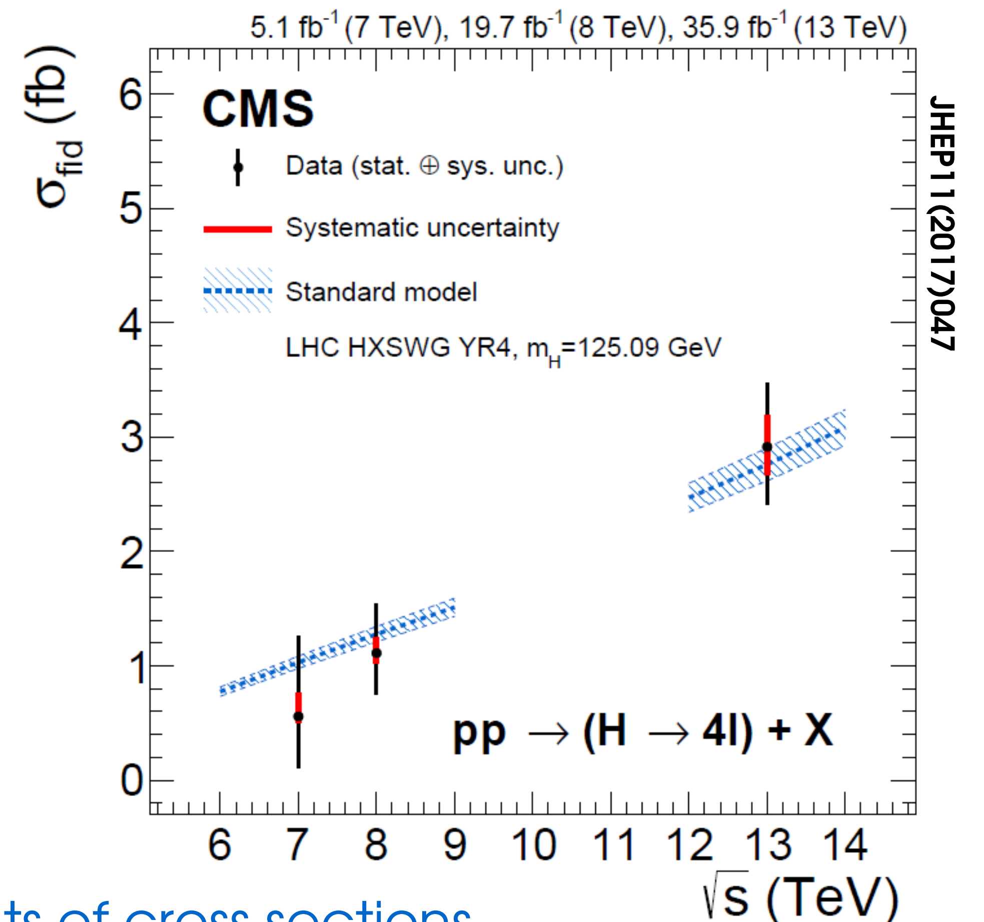
Γ < 22.7 (33) MeV @ 95% CL

CMS:

Γ < 22 (33) MeV @ 95% CL

13 TeV Higgs fiducial cross-section





- Fiducial and differential measurements of cross sections.
- Experimental and particle level selection as similar as possible to minimize theory uncertainties, with fiducial volume definition tuned to different fiducial volumes, based on detector and experiment.
- All measurements agree well with the SM prediction.

13 TeV Higgs differential cross-section

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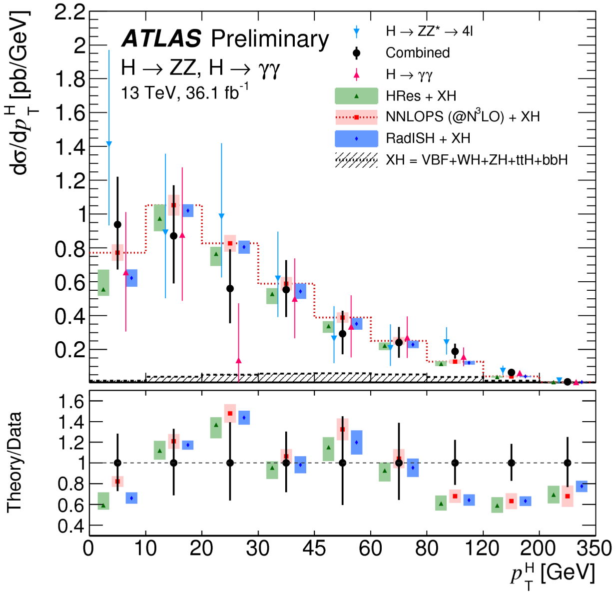
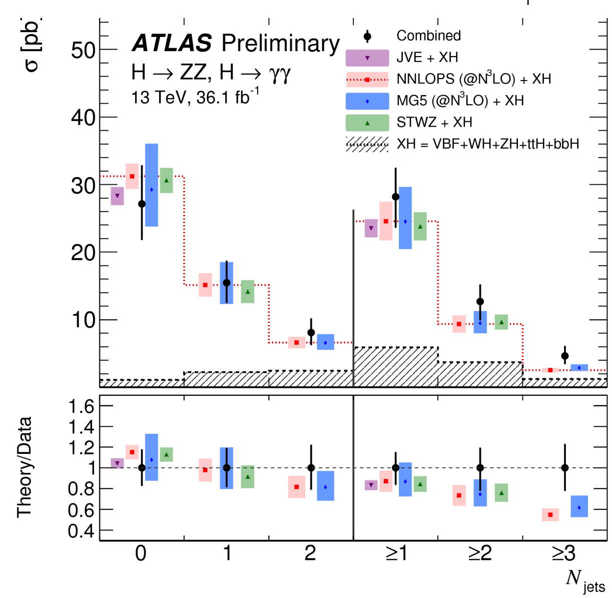
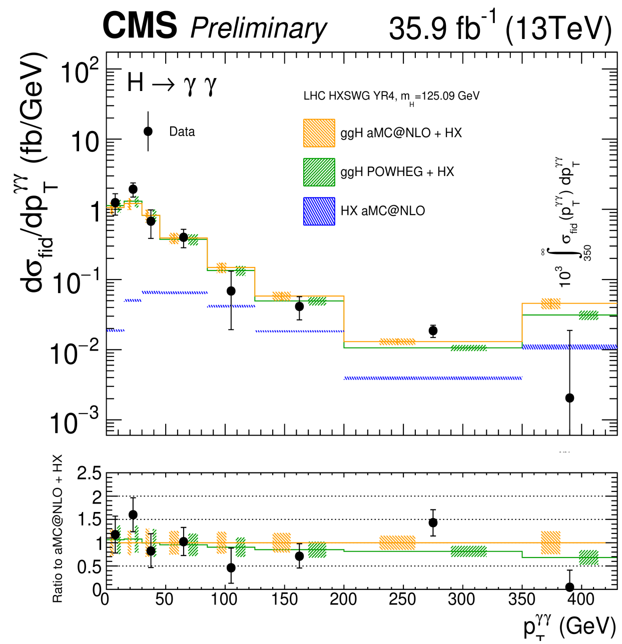
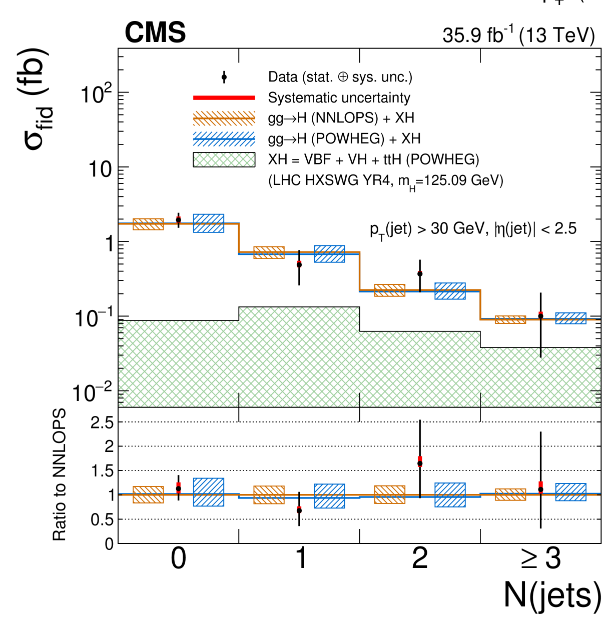




CMS-PAS-HIG-17-015

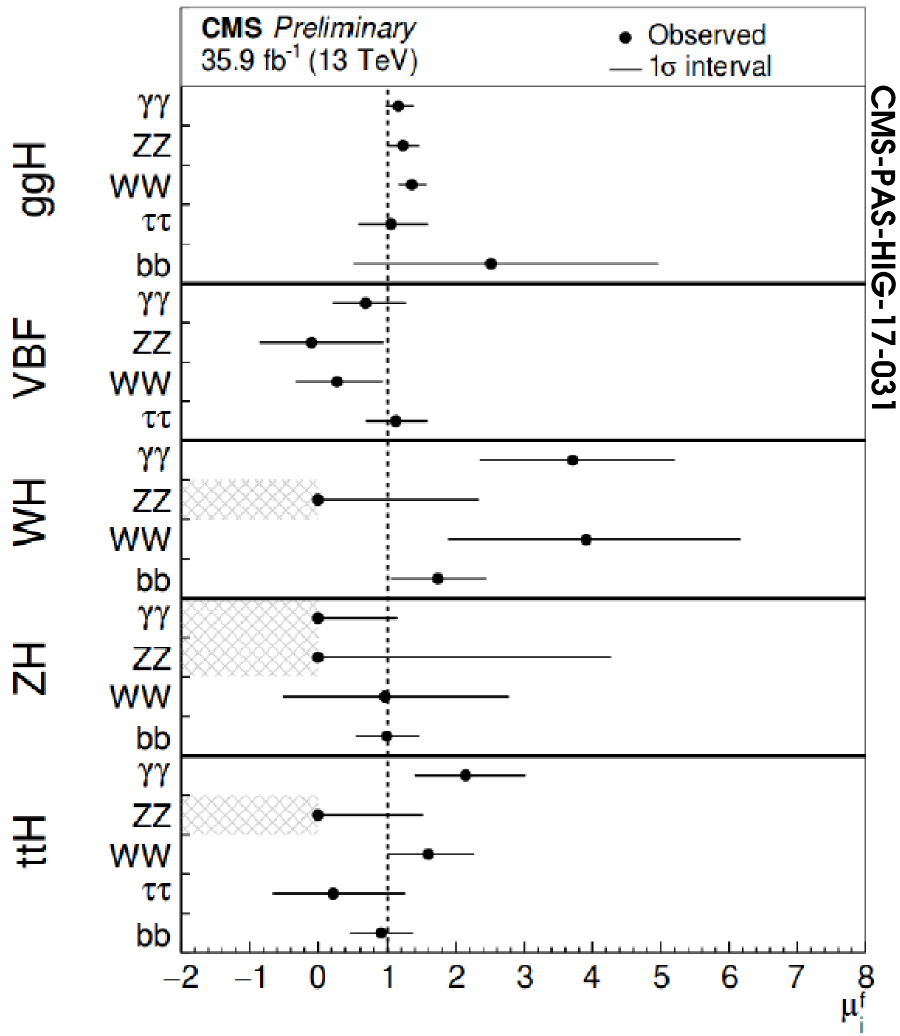


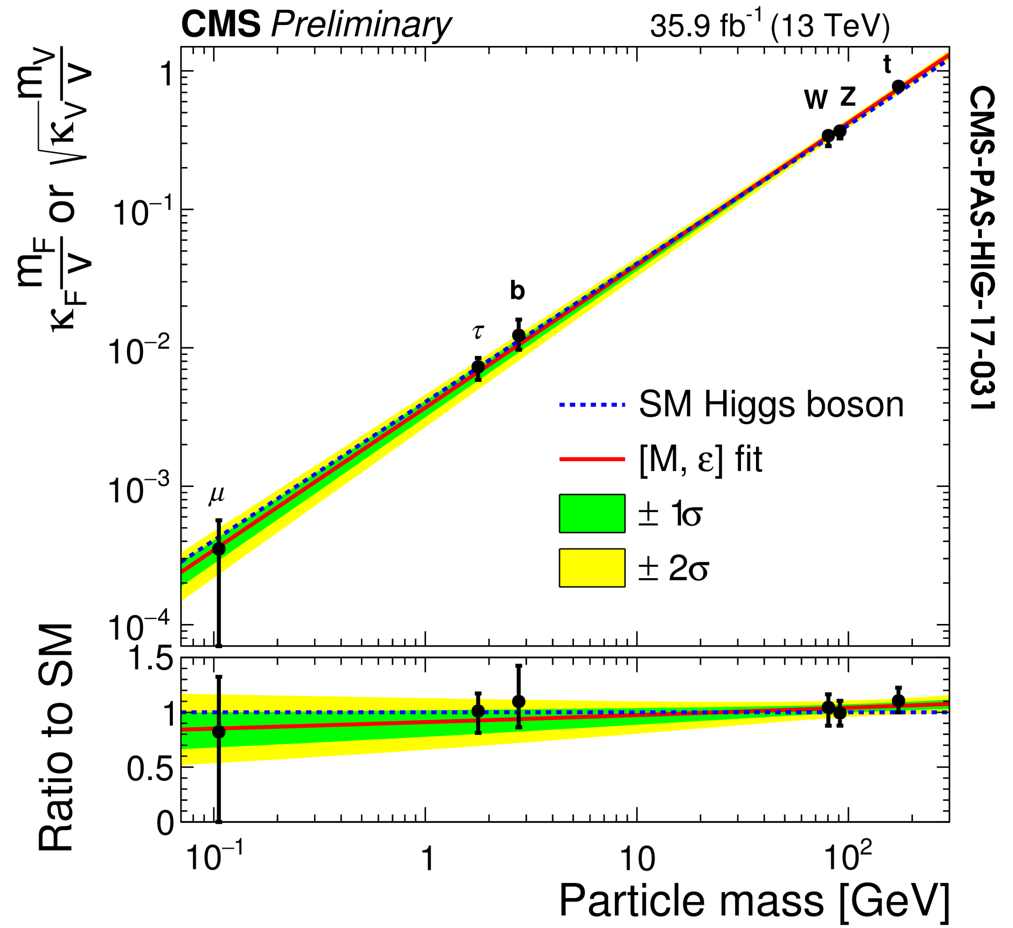
JHEP11(2017)047



- Overall good agreement with the SM calculations.

CMS combination





- Coupling measurement:

$$\mu = 1.17^{+0.10}_{-0.10} = 1.17^{+0.06}_{-0.06}\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{sig. th.})\ ^{+0.06}_{-0.06}\ (\text{other sys.})$$

- Within current precision Higgs couplings scale with particle masses

Summary

- Outstanding performance from the LHC team and experiments is allowing to deliver an impressive amount of updates on the Higgs measurements with Run 2 data.

- LHC Run 2 is the opportunity to improve Higgs measurements:
  - ttH and VH(bb) already more sensitive than Run 1.
  - Search for rare and forbidden channels and production modes continues:
    - $H \to \mu\mu$, $H \to cc$ and LFV decay modes

- Mass measurement already better than Run 1 combination and still limited by statistical uncertainties.

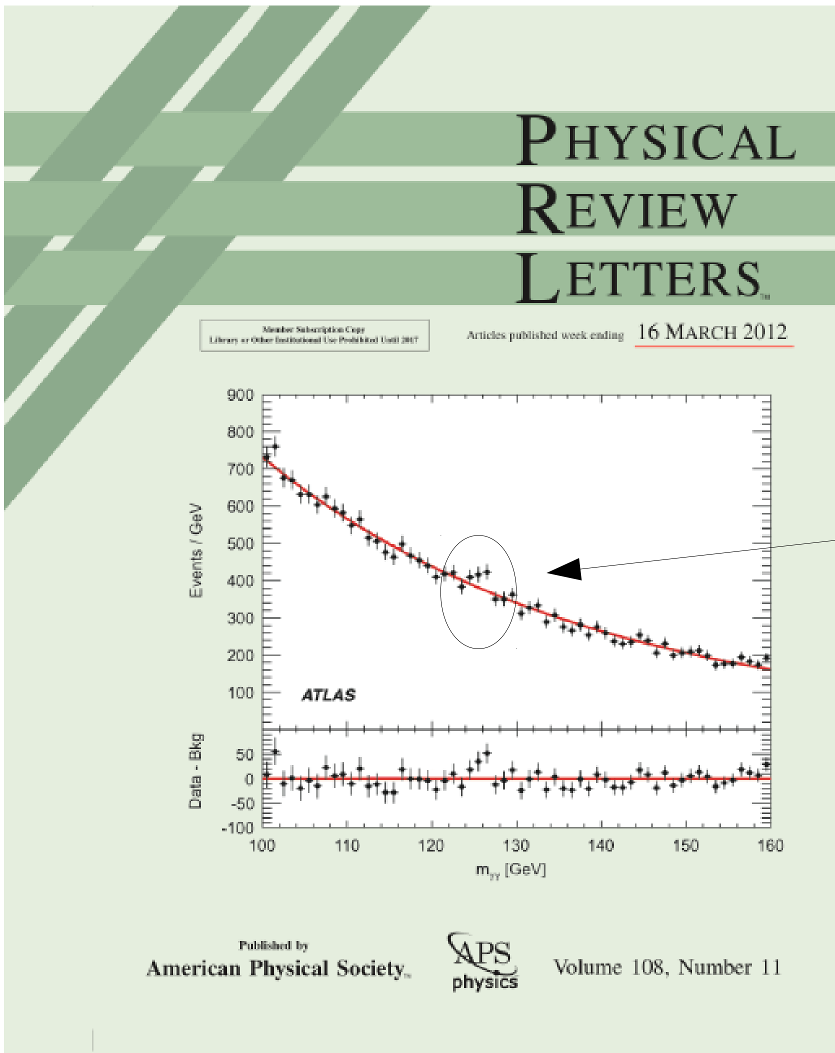
- Cross-section measurement:
  - Precise measurements in very specific phase space possible via combination of decay channels.

Thanks for the attention

Bonus Slides

Statistics Introduction

- How to quantify the compatibility of an excess with a fluctuation of the background or the signal of a new particle?



Excess or background fluctuation??

The Basics

Very basic introduction.

- Let's assume that we are doing a counting experiment and that only the statistical components matter.

- To prove that we have a significant excess, we must show that we have an excess in the data *incompatible* with the background-only hypothesis:
  - Number of observed events: N_{data}
  - Number of expected background events: N_{bkg}
  - Data fluctuates statistically: $\sqrt{N_{data}}$

  Statistical Significance for a signal process over the background: (a simplified version!): $=S/\sqrt{B}$
  The significance of a data excess over the expected background (considering only the stat. uncert. on data) $=(N_{data}-N_{bkg})/\sqrt{N_{data}}$
  - *Convention* for discovery: 5σ, corresponds to probability of statistical fluctuation of 2.9×10^{-7}
  - Increases with increasing luminosity: $S/\sqrt{B} \sim \sqrt{L} \rightarrow$ requires 4 times more data to increase significance by a factor 2, all the rest equal.

Statistical Model

- Let's build a model to take decisions about the nature of a process based on the measurement and our model
- L(N|H) is probability to obtain exactly the data observed:

$$L(\vec{N} \mid H_b) = \prod_i Poisson(N_i \mid \tilde{b}_i)$$

$$L(\vec{N} \mid H_{s+b}) = \prod_i Poisson(N_i \mid \tilde{s}_i + \tilde{b}_i)$$

$$L(\mu, \boldsymbol{\theta}) = \prod_{j=1}^{N} \frac{(\mu s_j + b_j)^{n_j}}{n_j!} e^{-(\mu s_j + b_j)} \prod_{k=1}^{M} C(\lambda_k)$$

$$\mathcal{C}(\lambda) = \frac{1}{\sqrt{2\pi}\sigma_{\lambda_e}} \exp\left(-\frac{(\lambda_e - \lambda)^2}{2\sigma_{\lambda_e}}\right)$$

- Need a way to quantify 'similarity' or 'extremity' of observed data

Quantify hypothesis likelihood

$$\lambda(\vec{N}) = \frac{L(\vec{N} \mid H_{s+b})}{L(\vec{N} \mid H_b)}$$

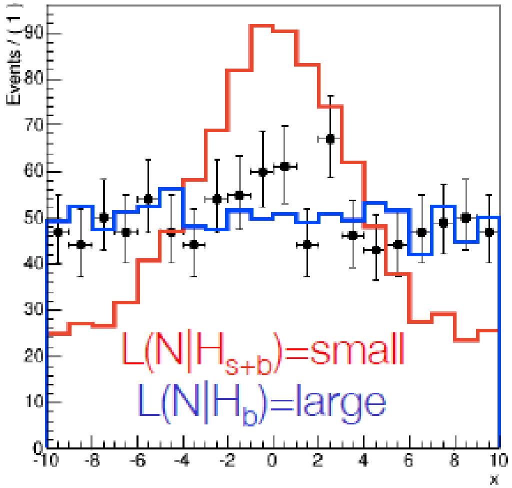
- Intuitive picture:

→ If data is likely under H_b, $L(N|H_b)$ is **large**, $L(N|H_{s+b})$ is smaller

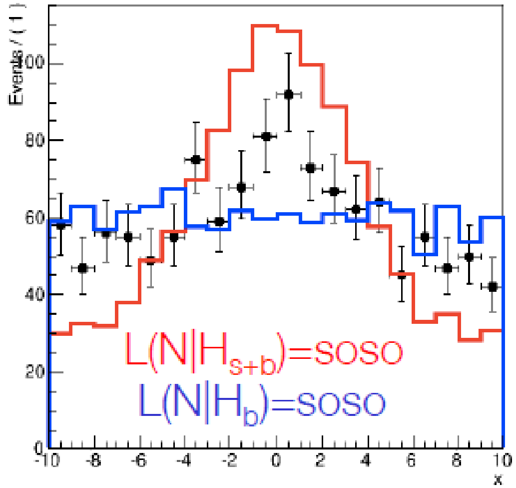
→ If data is likely under H_{s+b} $L(N|H_{s+b})$ is **large**, $L(N|H_b)$ is smaller

$$\lambda(\vec{N}) = \frac{\text{small}}{\text{large}} = \text{small}$$

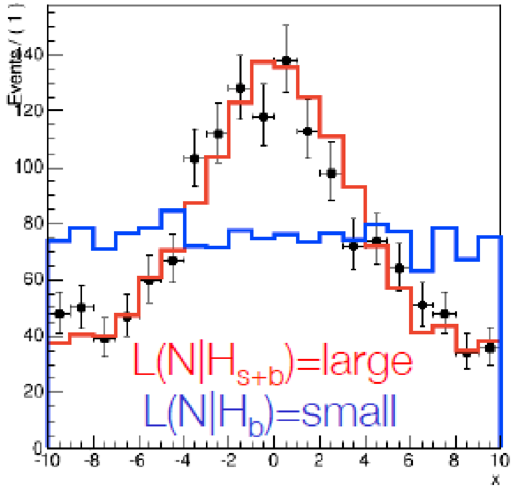
$$\lambda(\vec{N}) = \frac{\text{large}}{\text{small}} = \text{large}$$



λ(N)=0.0005



λ(N)=0.47



λ(N)=5000

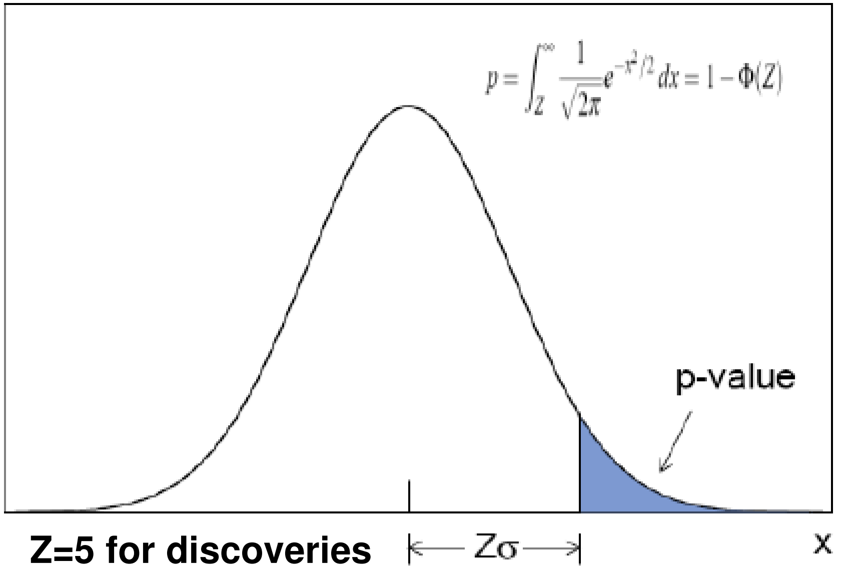
P-value and Test Statistics

- p-value: probability to realize the observed excess/deficit of data with only background fluctuations.

- μ: Signal strength. Global factor applied to the signal and fitted in the data.

$$n_s = \mu \sigma Br L \varepsilon$$

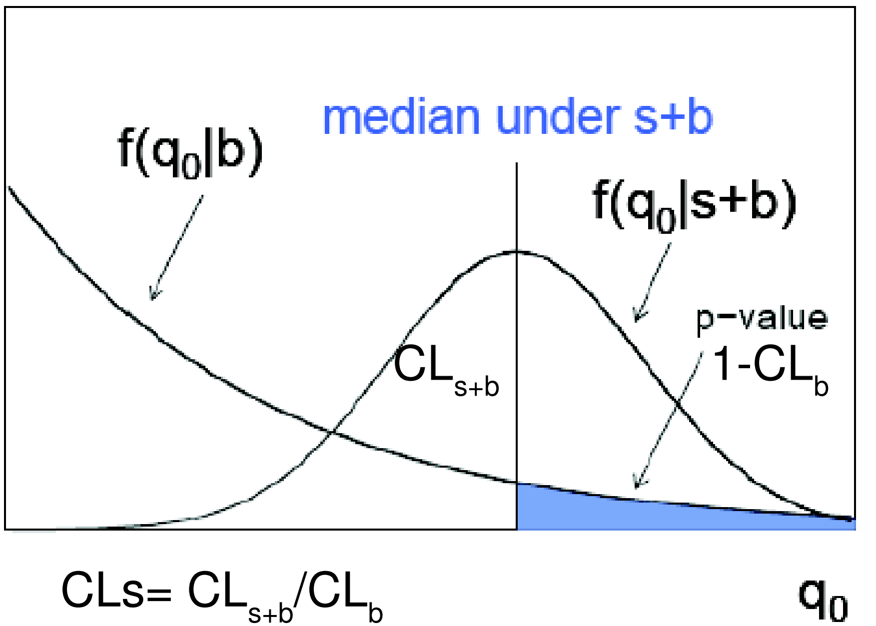
E.g. $\mu=0$ no Higgs, $\mu=1$ SM Higgs



- Test Statistics q_μ

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$

Optimal discriminant between two hypothesis:
- The best-fit mu-hat and nuisance parameters
- The alternative mu-value and its corresponding nuisance parameters



Statistics Details

$$\mathcal{L} = \prod_{i \in \text{obs.}} \text{Poisson}\left(n_i \,|\, \nu_i(\mu, \theta)\right) \cdot \prod_{j \in \text{nui.s}} \text{Constraint}(\theta_j, \tilde{\theta}_j)$$

θ are the nuisance parameters, e.g. systematics

$$\prod_i \frac{(\mu s_i + b_i)^{n_i}}{n_i!} \, e^{-\mu s_i - b_i}$$

Statistics constraints for binned likelihood

$$\rho(\theta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(\theta - \tilde{\theta})^2}{2\sigma^2}\right)$$

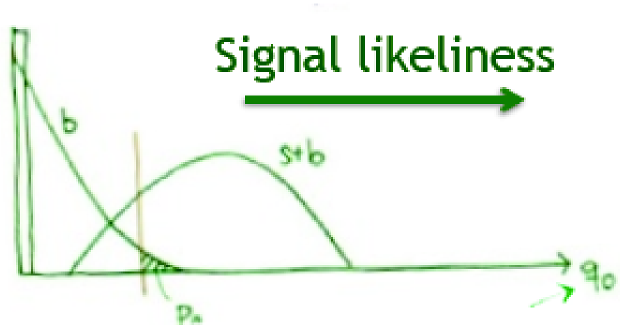
$$\rho(n) = \frac{1}{\alpha} \frac{(n/\alpha)^N}{N!} \exp(-n/\alpha)$$

Nuisance parameters constraints.
Typically gaussian.
Gamma function used for MC statistics.

P_0 plots

$$\lambda_0 = \lambda(0,\theta) = \frac{L(0,\hat{\hat{\theta}}(0))}{L(\hat{\mu},\hat{\theta})}$$

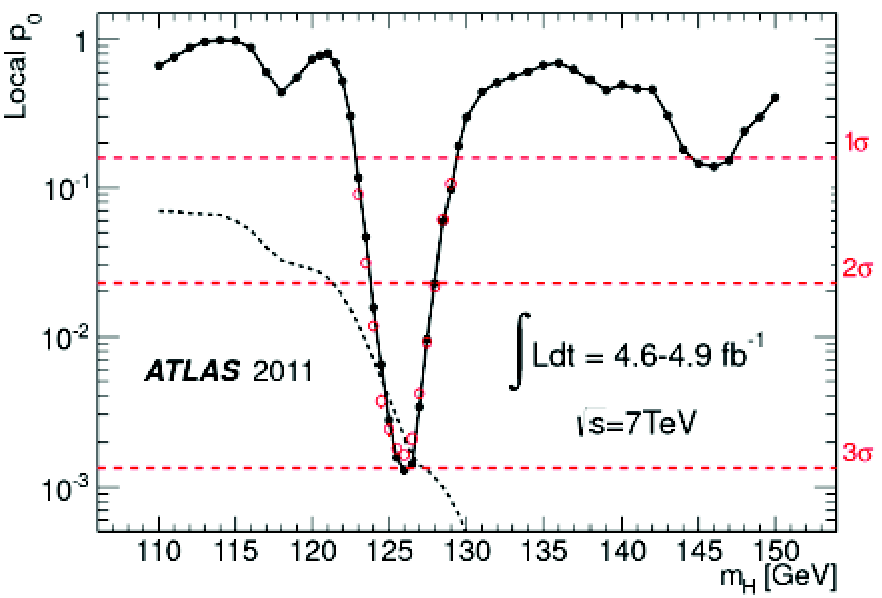
$$q_0 = -2\ln\lambda_0$$



p_0 Probability that a background only experiment be more signal like than observed

p_0: Typical test is between the best-fit value of the signal strength, μ-hat, and the background-only hypothesis μ=0.

- Compare how much more likely is the signal hypothesis compared to the background hypothesis.

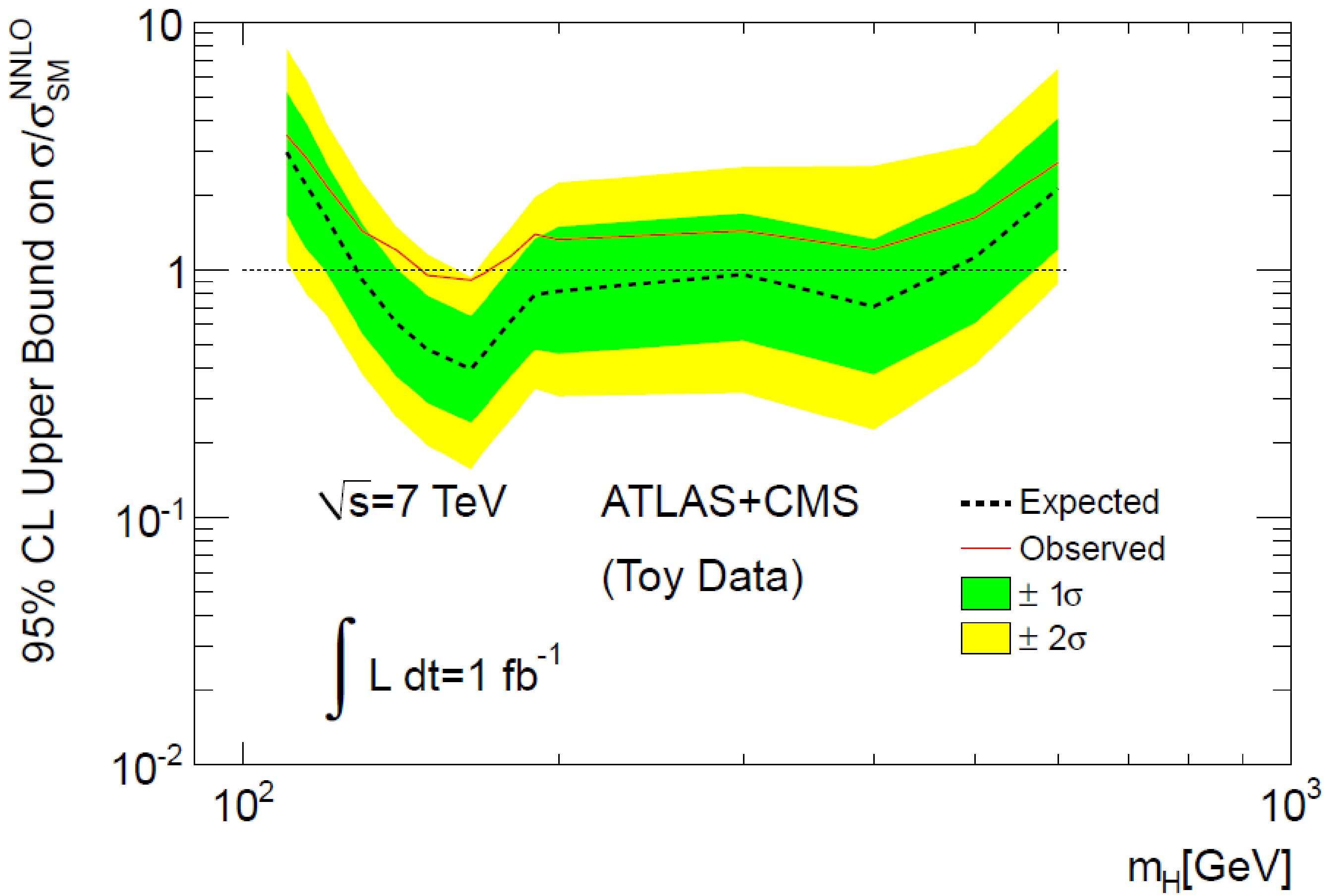


Limits

$$\mathrm{CL}_s = \frac{\mathrm{CL}_{s+b}}{\mathrm{CL}_b}. \qquad 1 - p_b = P(\tilde{q}_\mu \geq \tilde{q}_\mu^{obs} \,|\, \text{background-only}) = \int_{q_0^{\text{obs}}}^{\infty} f(\tilde{q}_\mu | 0, \hat{\theta}_0^{\text{obs}})\, d\tilde{q}_\mu$$

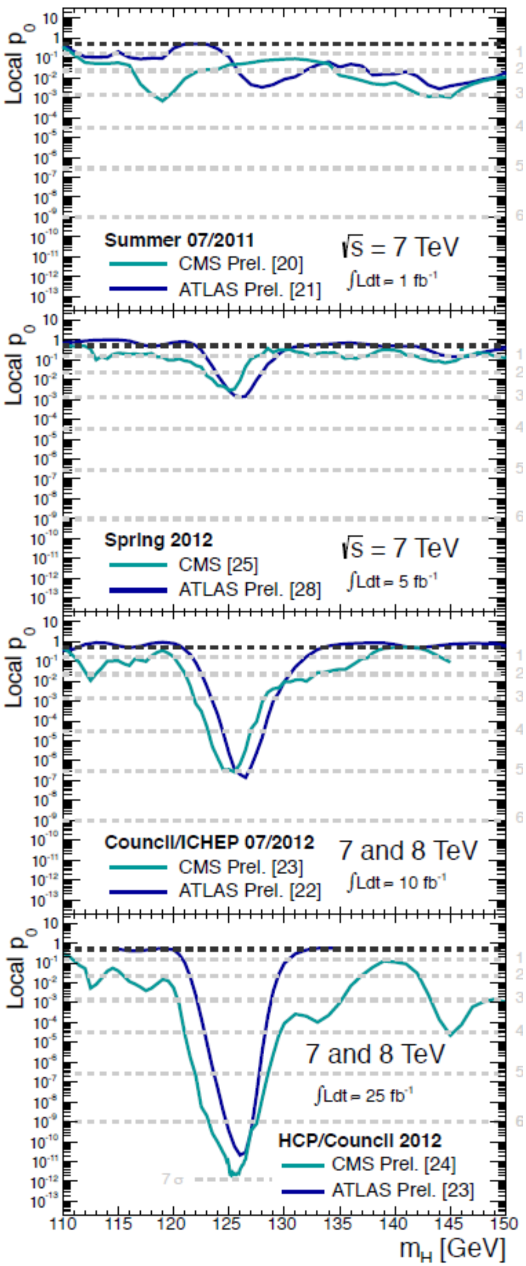
$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$

CLS=0.05 for 95% C.L. exclusions



Higgs Excess evidence

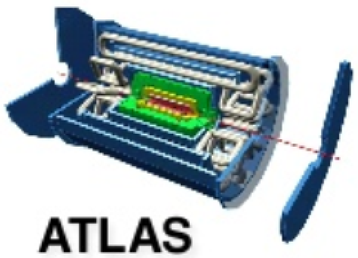
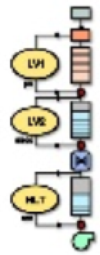
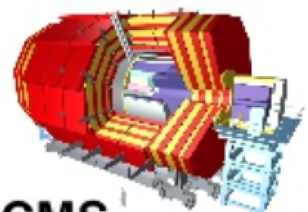
PDG, review of Particle Physics

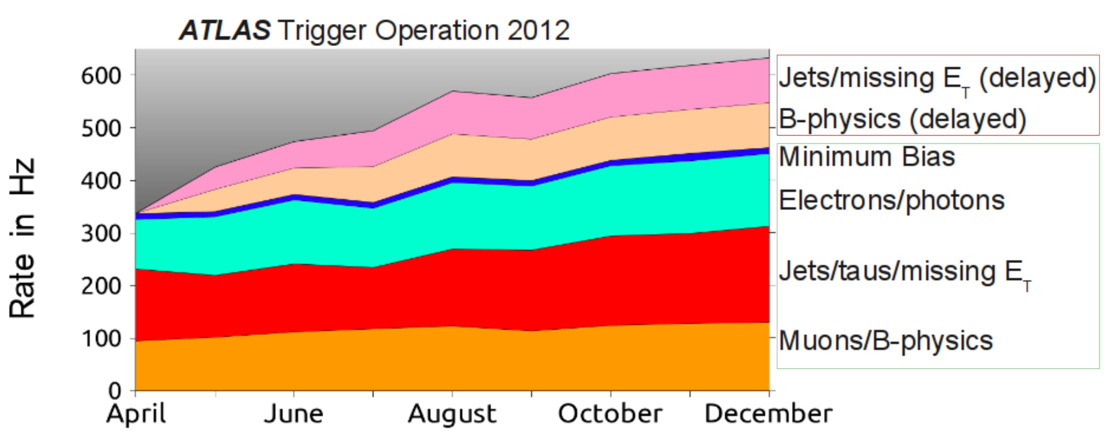


How the Higgs evidence increased in ~ 1 year from 1 ifb to 25 ifb.

From the growing evidence of a new particle to a new era of measurements

DAQ and Trigger

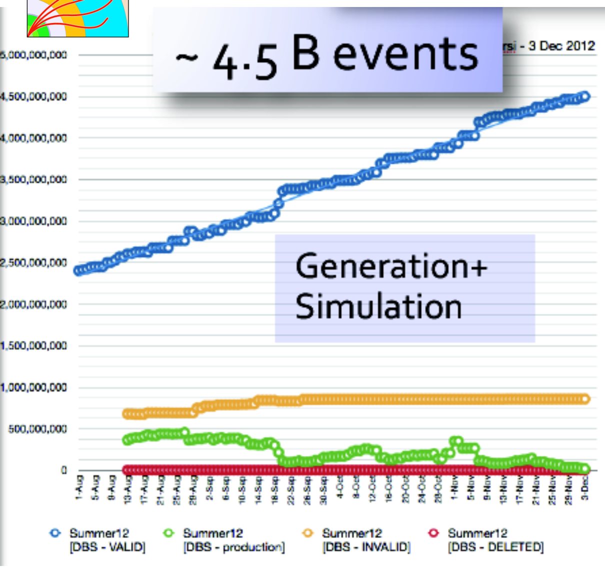
	Trigger No. Levels		Level-0,1,2 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	HLT Out MB/s (Event/s)
 ATLAS	3		LV-1 10^5 LV-2 $3x10^3$	$1.5x10^6$	4.5	**600+300** ($4x10^2+2x10^2$)
 CMS	2		LV-1 10^5	10^6	100	O(1000) (10^3)

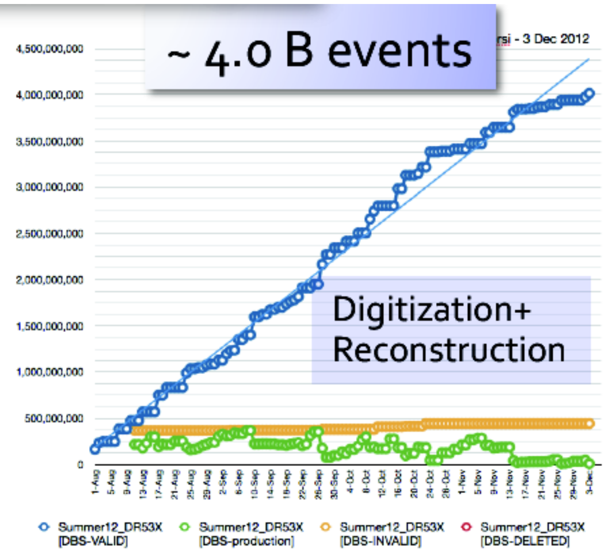


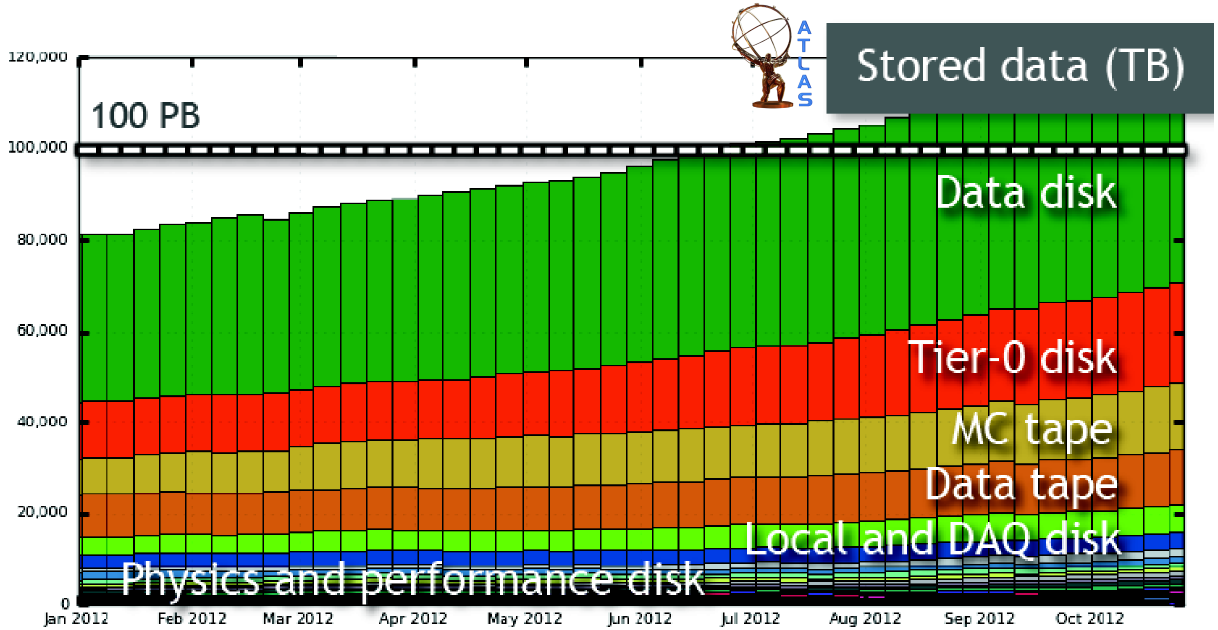
Both experiments have improved their DAQ and trigger systems for Run-2.
Current DAQ Performance
- >= 100 kHz at L1
- >= 1 kHz HLT output

Computing and Simulation

The fast duty cycle of the LHC analyses is possible thanks to the Tier0 and GRID resources





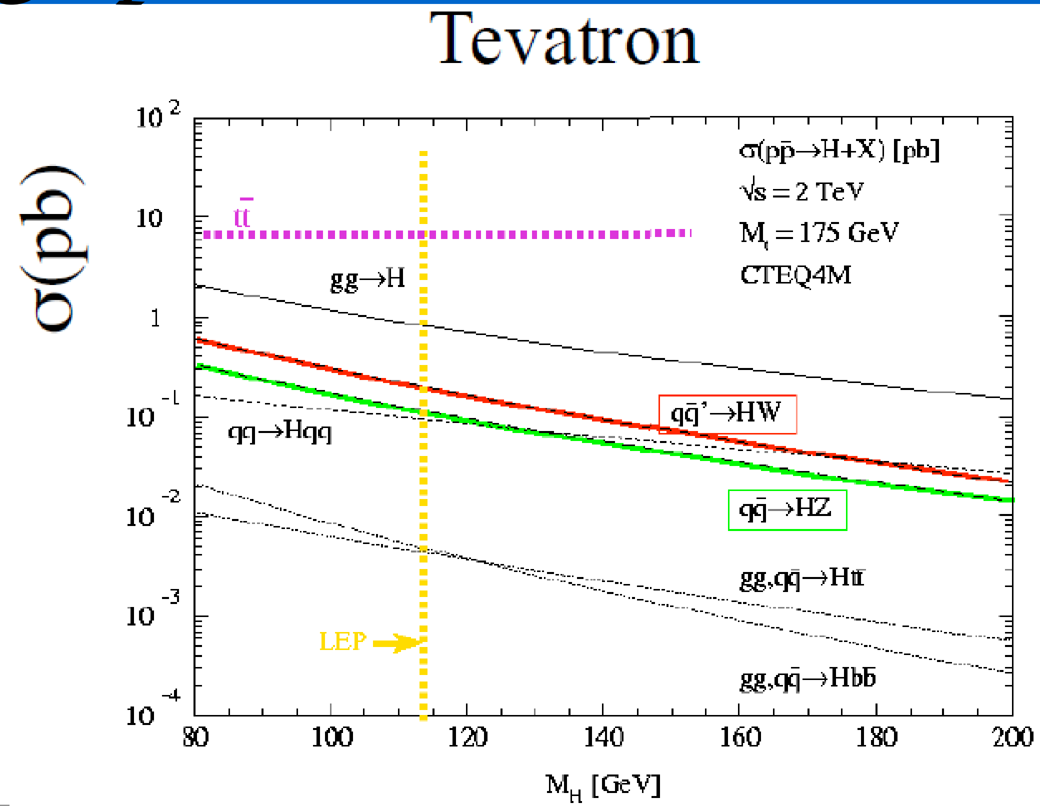


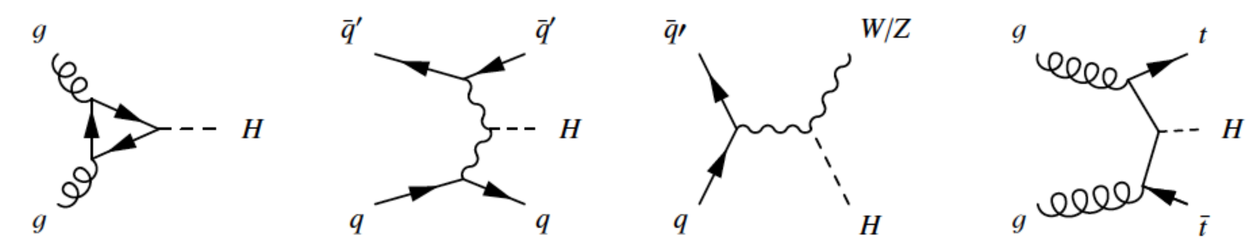
- Just in 2012, both CMS and ATLAS experiments have produced 3-4 billions of MC events on the GRID and processed ~3 billions of data events at Tier0.

- On a single machine, it would require more than 15 thousands years (without considering user and group analyses, calibrations, reprocessings, ...).

- GRID is a crucial asset of the LHC experiments to provide physics results in a timely manner.

Higgs prod. Rates at TeVatron





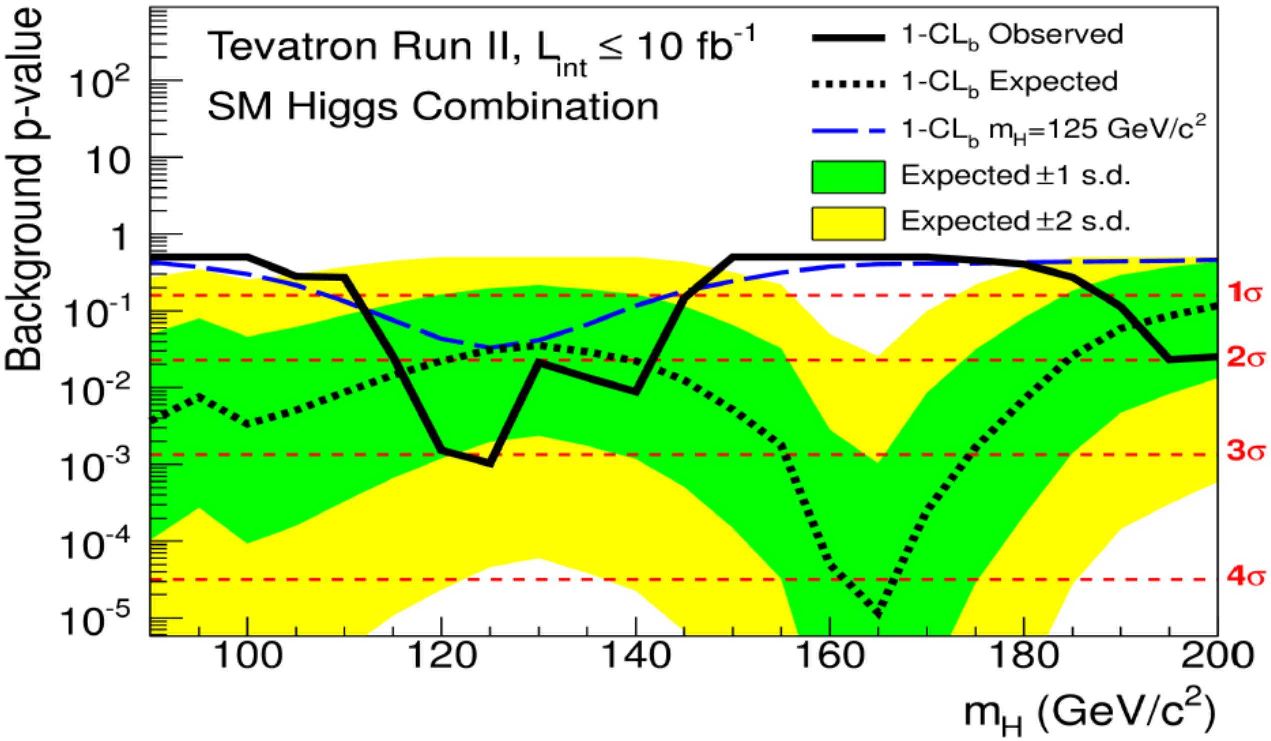
(a) $gg \to H$ (b) VBF (c) VH (d) $t\bar{t}H$

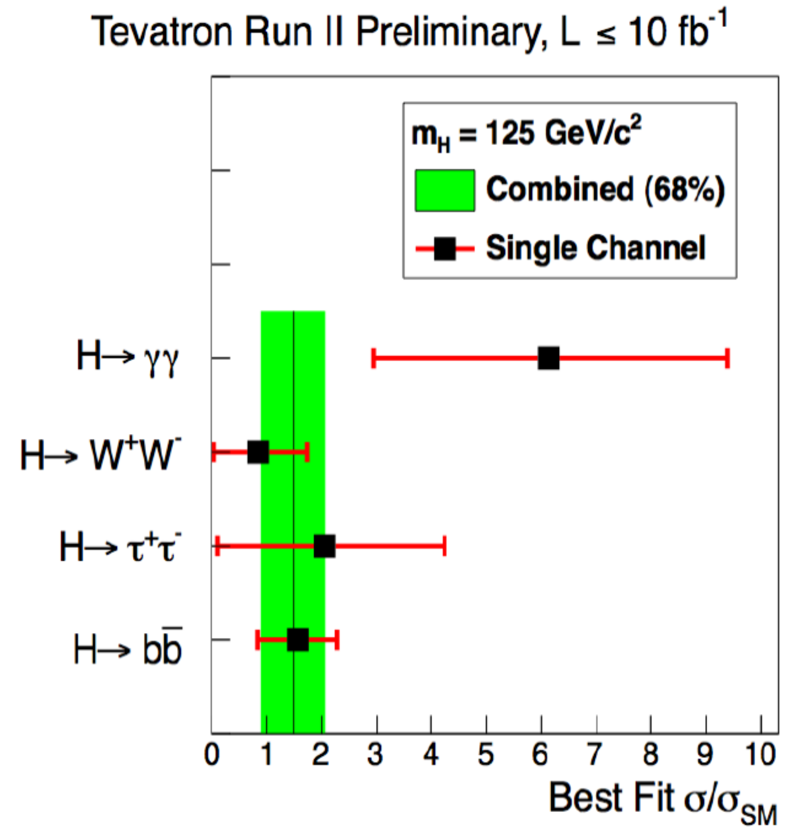
78% **7%** **15%** **<1%**

ggH is the dominant production mode.
VH is the subleading production mode

TeVatron Results

TeVatron updated their Higgs boson search results with ~10 fb^{-1}
Most sensitive channels are (V)H → (V)bb, H → WW. Analyses of H → γγ and H → ττ are also included.

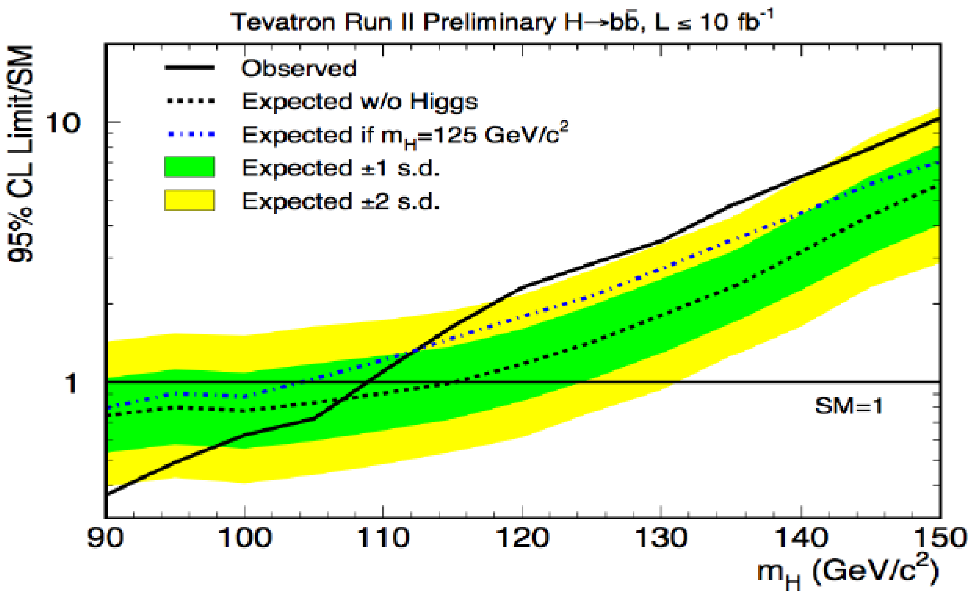


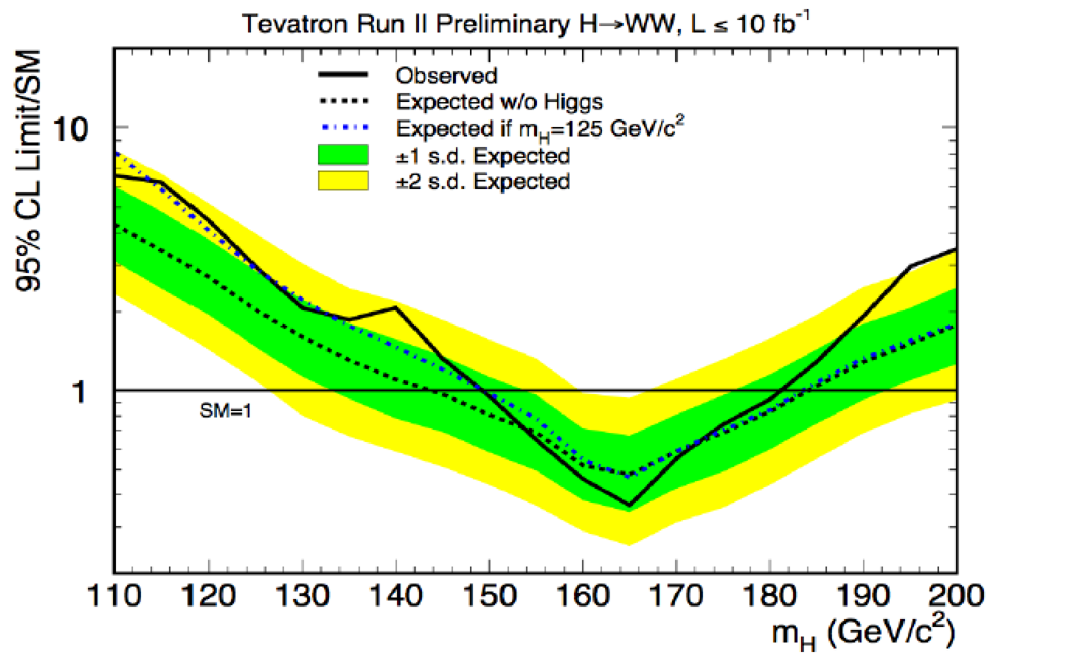


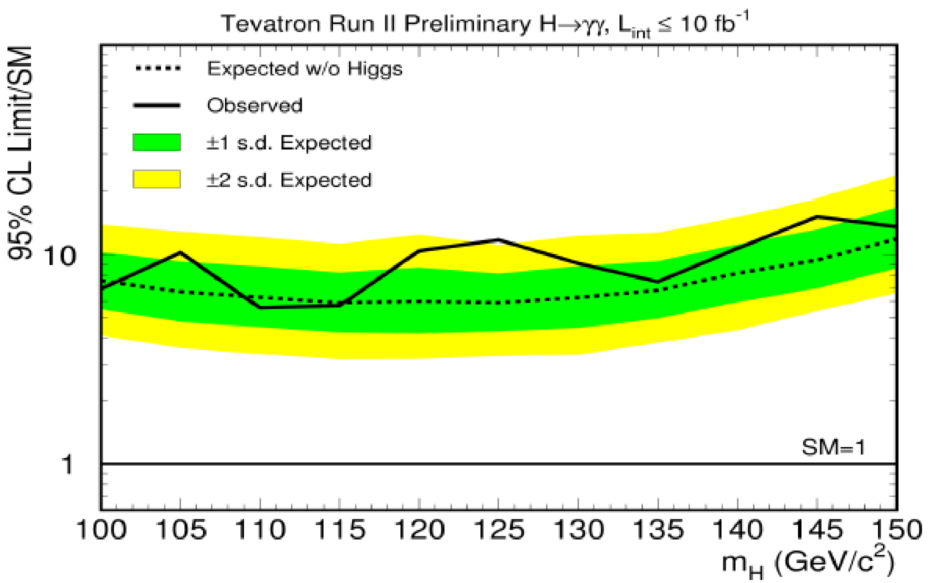
The minimum p-value is found to be 3.0σ at mH =125GeV.

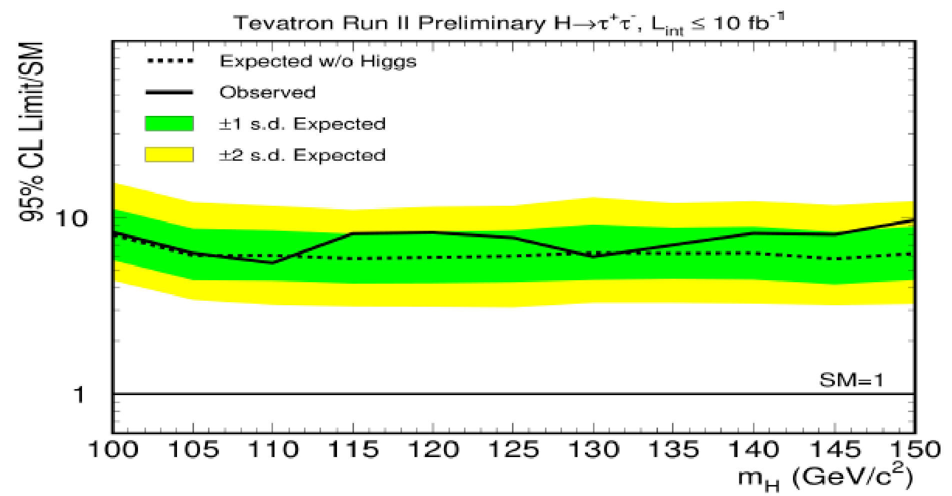
Fit to signal strength
(1.4±0.6)xSM @125 GeV

TeVatron Limits by channel

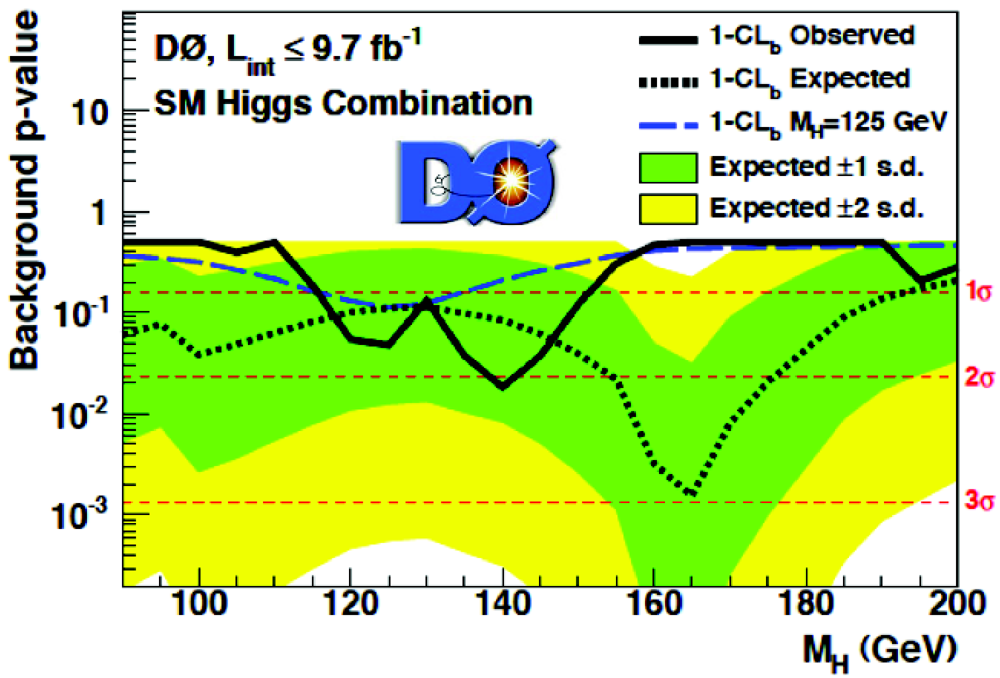


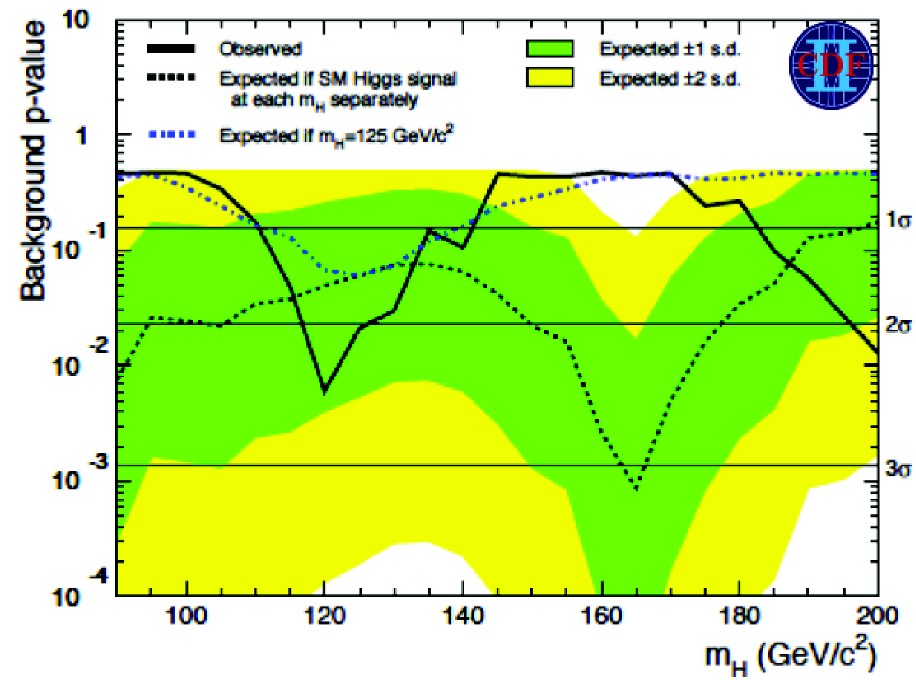






TeVatron Results by experiment

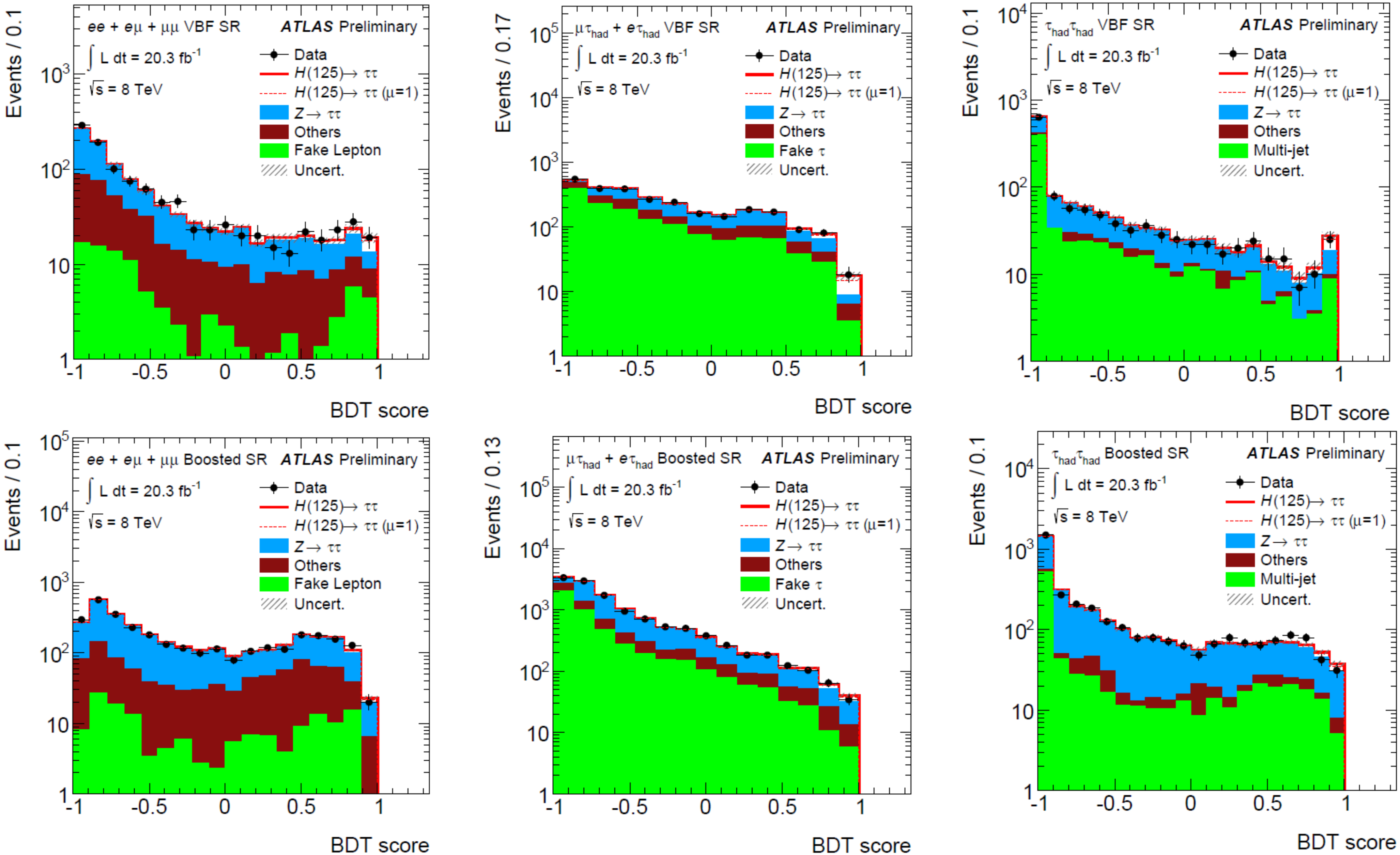




Local p-value distributions as a function of the Higgs mass for D0 and CDF experiments:

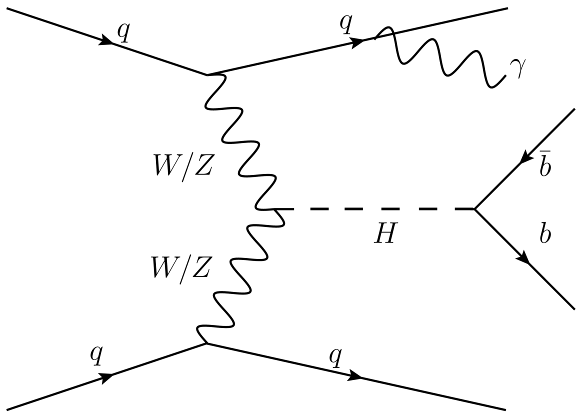
- D0: 1.7 σ @ m_H=125 GeV
- CDF: 2.0 σ @ m_H=125 GeV

$H \rightarrow \tau\tau$ Analysis BDT

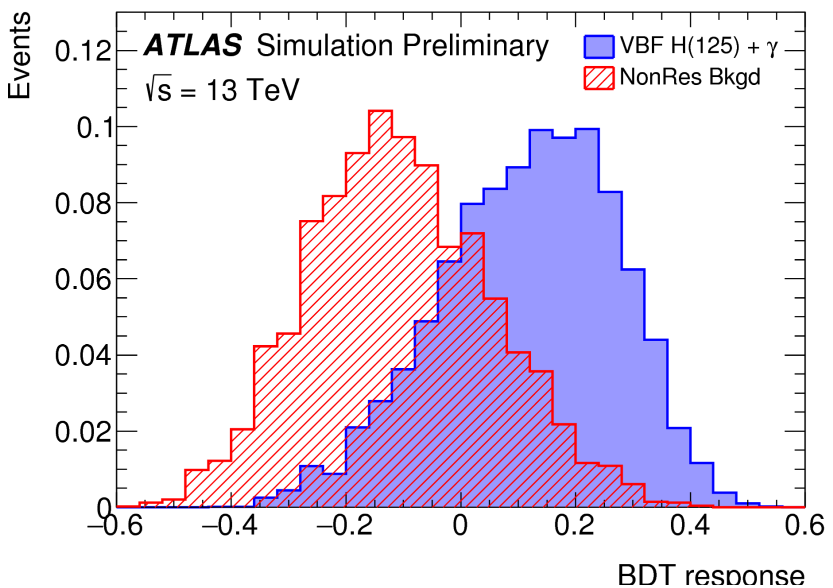


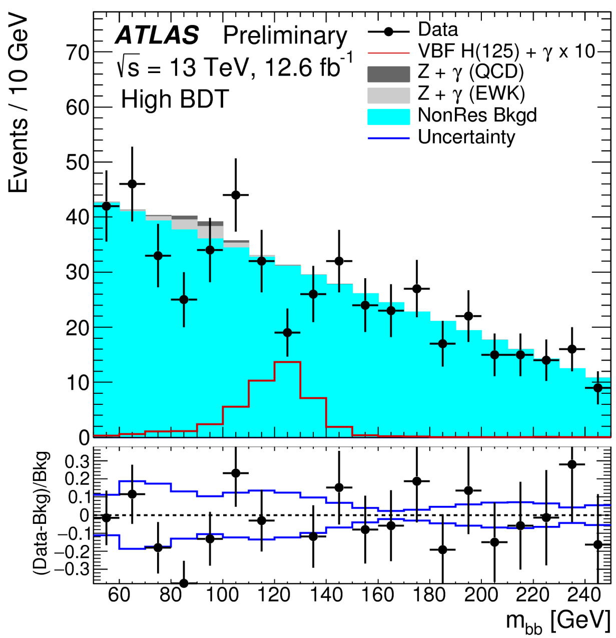
- Data is divided in 6 signal regions and 9 control region to simultaneously fit signal and backgs.

Run 2 $qqH \rightarrow bbar + \gamma$



ATLAS-CONF-2016-063





- Trigger on photons, 4 jets and mjj>700 GeV
- Main backgrounds are γ+4 jets production and Z → bb + jets
- BDT is used too reject multi-jet background
- Events are separated in 3 categories according to the BDT
- Signal is extracted from a fit of the m_{bb} mass, limited by statistical uncertainty.

ATLAS:

μ=-3.9±2.8 @125 GeV

95% CL Limit: 4.0 (6.0 exp.) x SM

Higgs Potential (2)

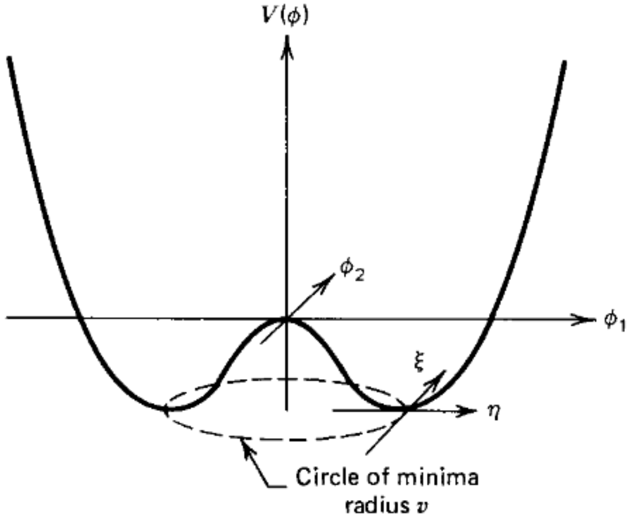
The minima of the potential are on a circumference of radius:

$$|\Phi| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv v/\sqrt{2}$$

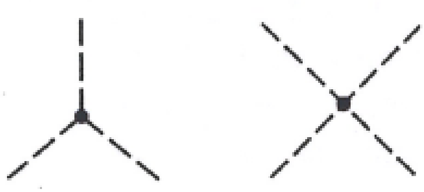
We rewrite the Lagrangian around a minimum: $\frac{v}{\sqrt{2}} + \eta(x)$

The Lagrangian now becomes:

$$\mathscr{L} = \tfrac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2\eta^2 \pm \mu\lambda\eta^3 - \tfrac{1}{4}\lambda^2\eta^4 + \tfrac{1}{4}(\mu^2/\lambda)^2$$



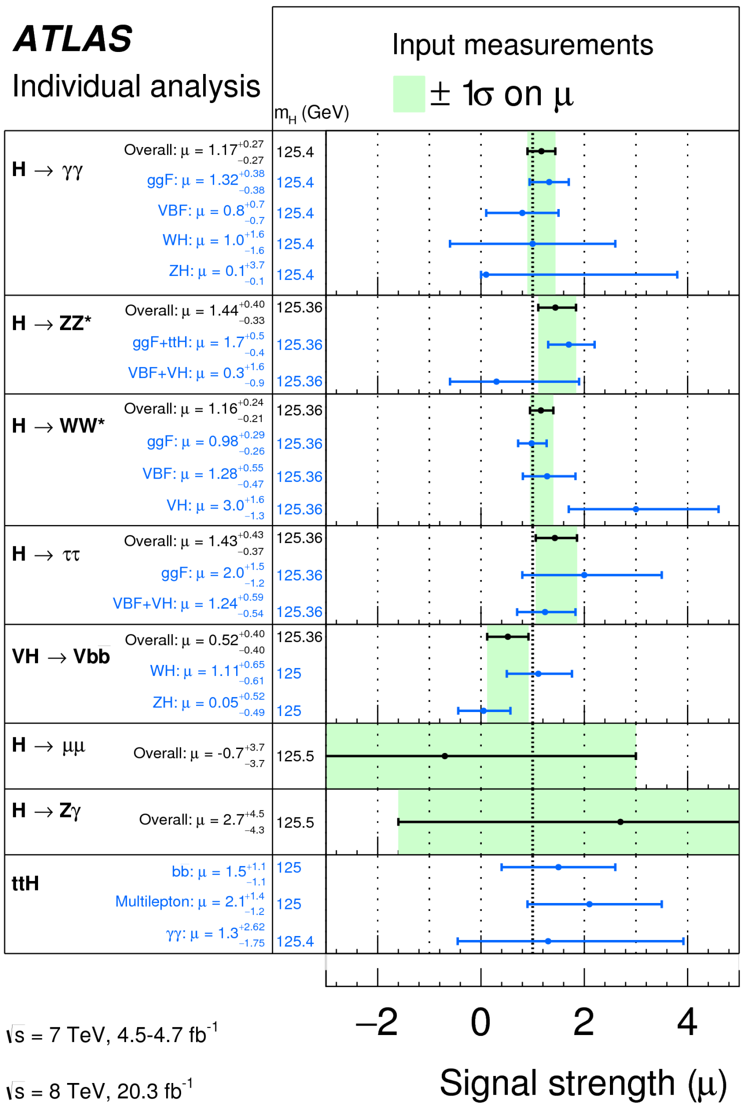
where the third and forth terms represent
the self coupling of the Higgs field:



22/05/18

LHC Couplings Combination

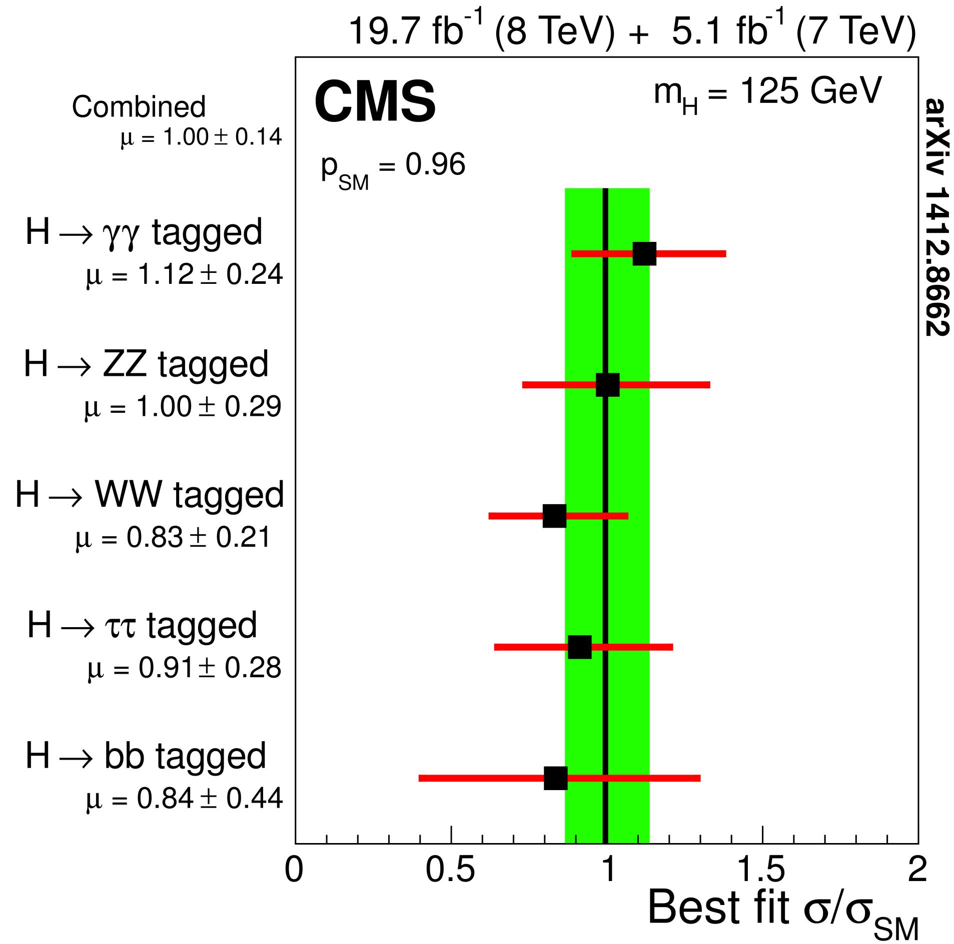
arXiv 1507.04548



$\mu=\sigma/\sigma_{SM}$

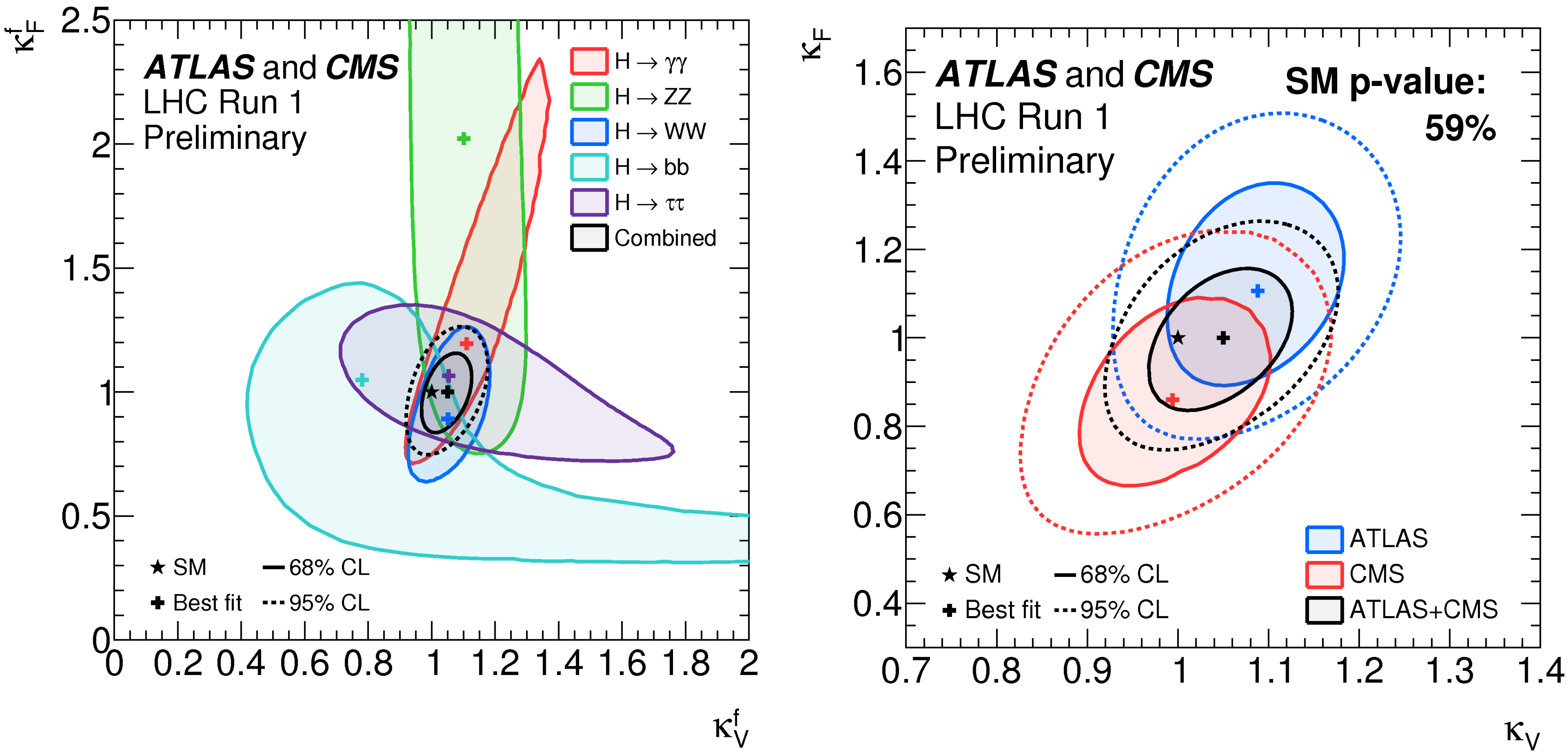
$\mu=0$ no Higgs

$\mu=1$ SM Higgs



- Combination of ATLAS and CMS coupling measurements.
- Inputs sensitive to ggF, VBF, W/ZH and ttH production modes and to $H \to \gamma\gamma$, $H \to ZZ$, $H \to WW$, $H \to \tau\tau$, $H \to \mu\mu$ and $H \to bb$ decay modes.

κ_V vs κ_F Contour



- Couplings are grouped: $\kappa_V = \kappa_W = \kappa_Z$; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Assumptions:

– gg → H and H → γγ only through SM particles

→ only SM particles contribute to decay

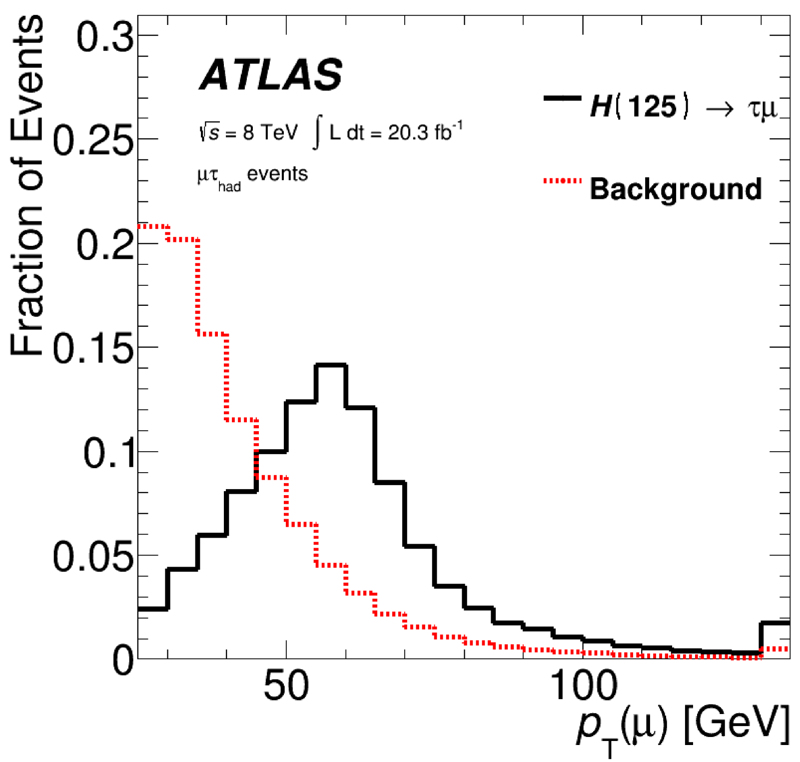
$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_H},$$

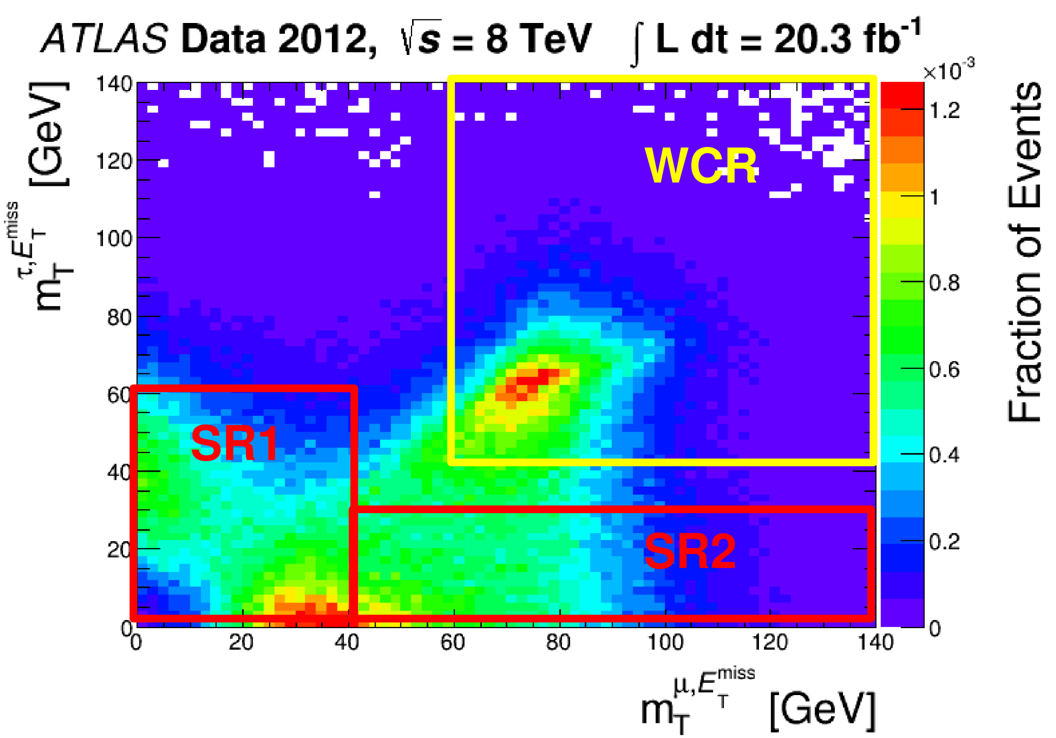
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \quad \text{or} \quad \kappa_j^2 = \Gamma^j/\Gamma_{SM}^j.$$

- All results in agreement with SM ($\kappa_V = \kappa_F = 1$) within 1σ

ATLAS $H \to \mu\tau$

- ATLAS analyzed the $\mu\tau_{had}$ final states
- Analysis employs 2 signal categories and 1 control region
- Using binned MMC (missing mass calculator) spectrum for the statistical analysis.
- Main backgrounds:
  - W+jets main backgrond in SR1
  - $Z \to \tau\tau$ main background in SR2





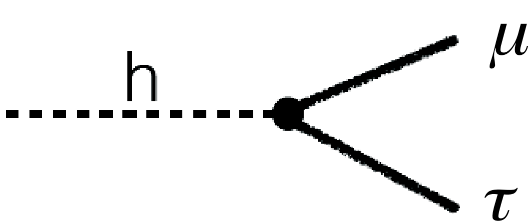
Run 1 search for $h \to \ell\ell'$

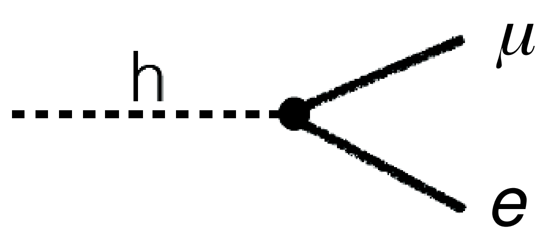
General Higgs interaction to fermions in mass basis.

$$\mathcal{L}_Y = -m_i \bar{f}_L^i f_R^i - Y_{ij}(\bar{f}_L^i f_R^j)h + h.c. + \cdots ,$$

In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

Indirect limit on BR($H \to \ell\tau$) are loose O(10%)
Stringent indirect limits on $Y_{e\mu}$ from $\mu \to e\gamma$ BR($H \to e\mu$)< 10^{-8}, but with assumptions on NP contributions in the loop.





e

τ

Phys. Lett. B 749 (2015) 337

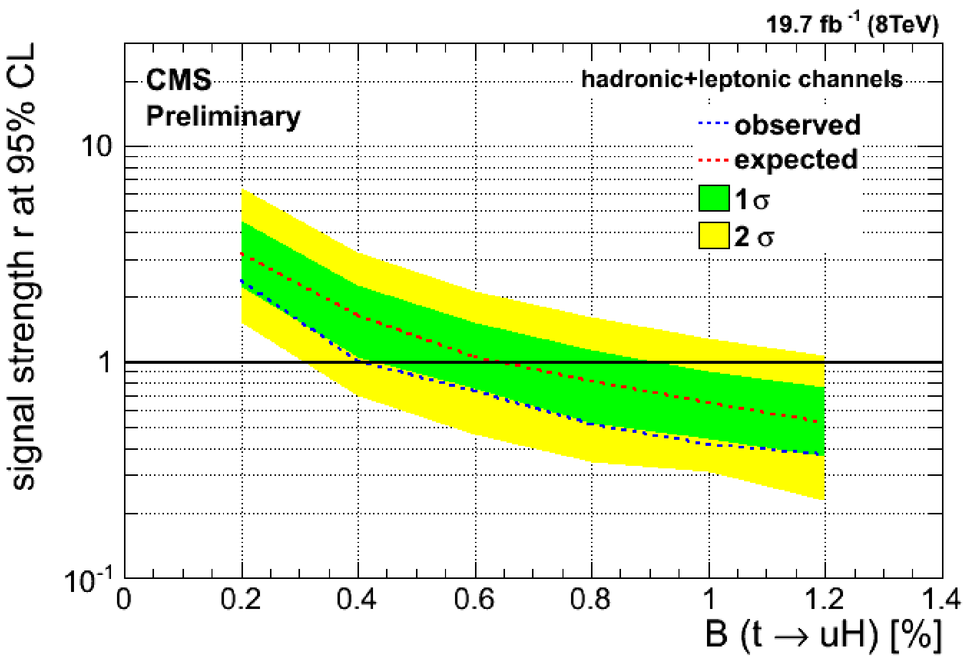
arXiv:1508.03372

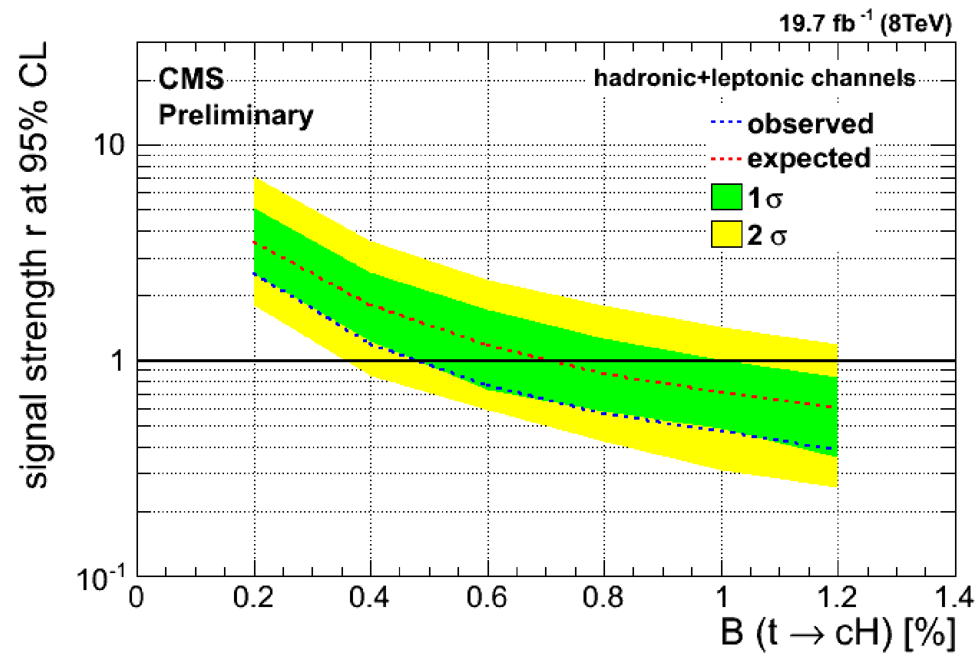
CMS-PAS-HIG-14-040

CMS-PAS-HIG-14-040

CMS FCNC $t \to u/c+H(\gamma\gamma)$

- 8 TeV datasets is used.
- Similar approach to ATLAS analysis, considering both hadronic and leptonic final states of the W decay:



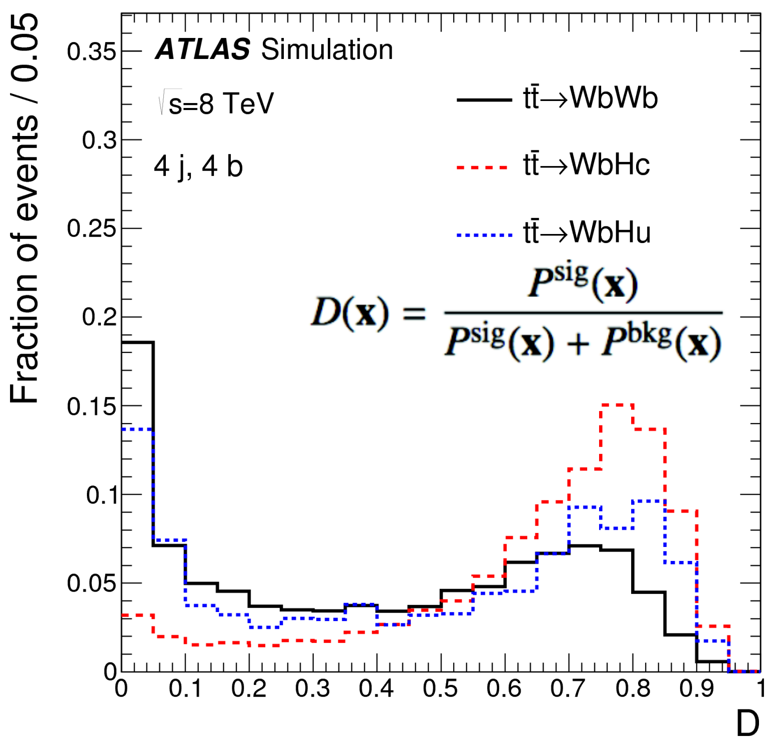


Observed (expected) 95% CL upper limits on the branching ratios:

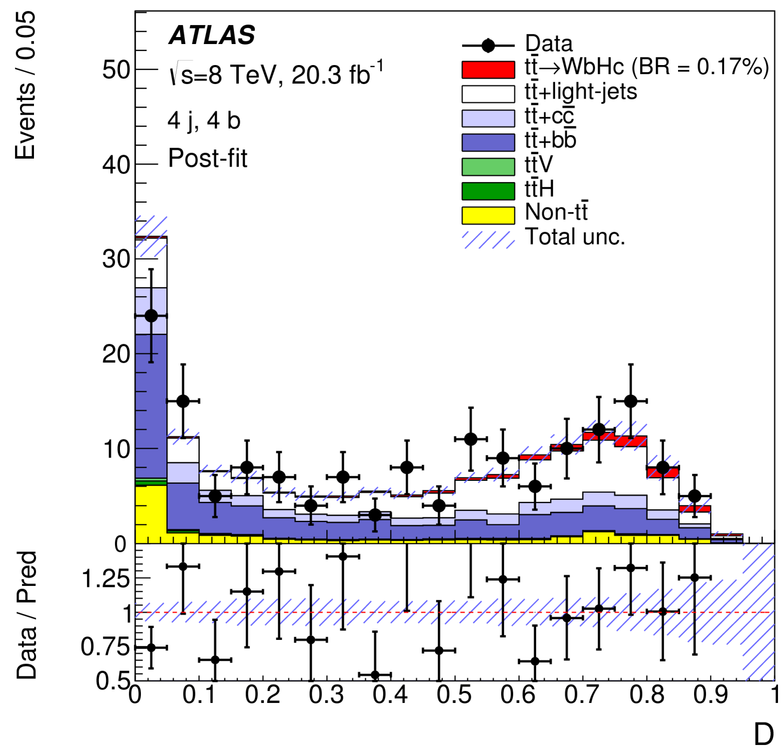
- BR($t \to Hu$) < 0.42% (0.65%)
- BR($t \to Hc$) < 0.47% (0.71%)

ATLAS FCNC $t \rightarrow u/c+H(bb)$

- Search for ttbar→WbHq→(ℓν)b(bb)q
- Requiring one light lepton, >= 4 jets and >=2 b-jets
- 9 signal- and bkg-enriched event categories:
  - (4j, 5j, ≥6j) x (2b, 3b, ≥4b)
- main background is SM ttbar(→WbWb)+jets
- Using Likelihood discriminant including mass constraints and b-tagging information for signal and bkg hypotheses.



$$D(\mathbf{x}) = \frac{P^{\mathrm{sig}}(\mathbf{x})}{P^{\mathrm{sig}}(\mathbf{x}) + P^{\mathrm{bkg}}(\mathbf{x})}$$

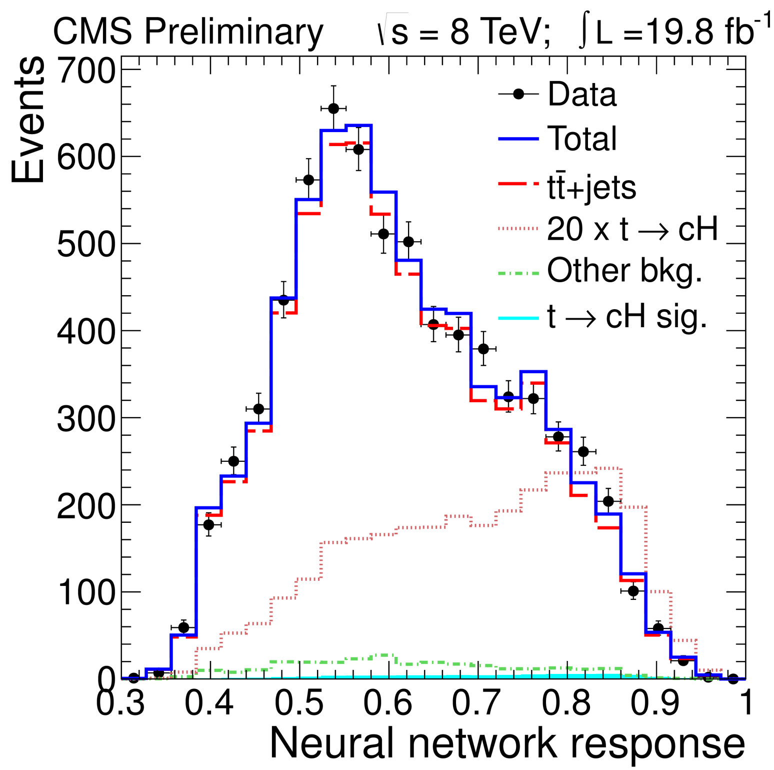


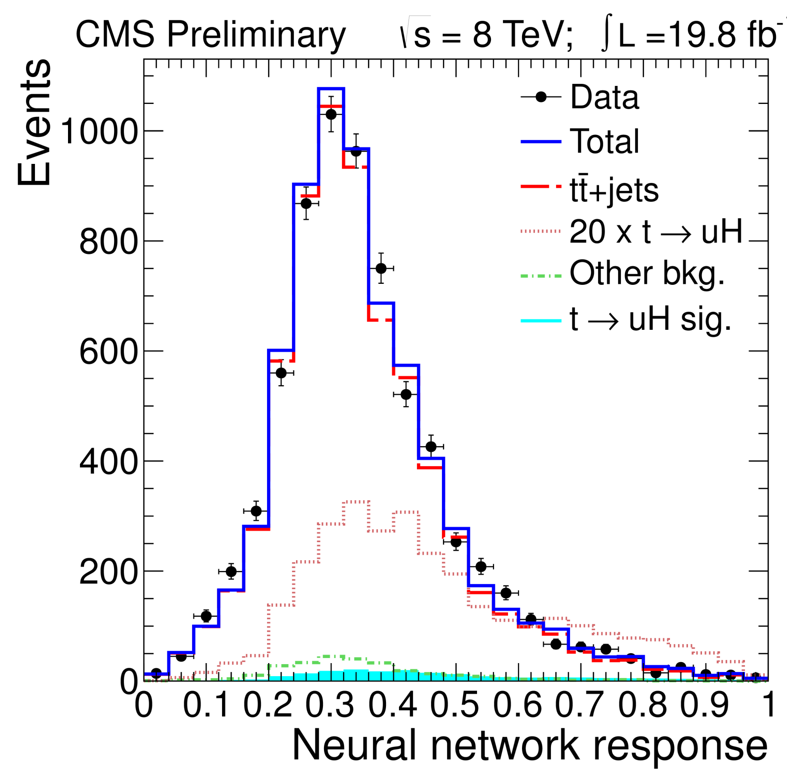
Observed (expected) 95% CL upper limits on the branching ratios:

- BR(t → Hu) < 0.61% (0.64%)   BR(t → Hc) < 0.56% (0.42%)

CMS FCNC $t \to u/c+H(bb)$

- Result released 5 days ago!
- Requiring one light lepton, >=4 jets and >= 2-bjets
- Using Boosted decision Tree discriminant with kinematic variables of the Higgs and top candidates and and combining it in a Neural-Network Likelihood discriminant including b-tagging information of the jets.

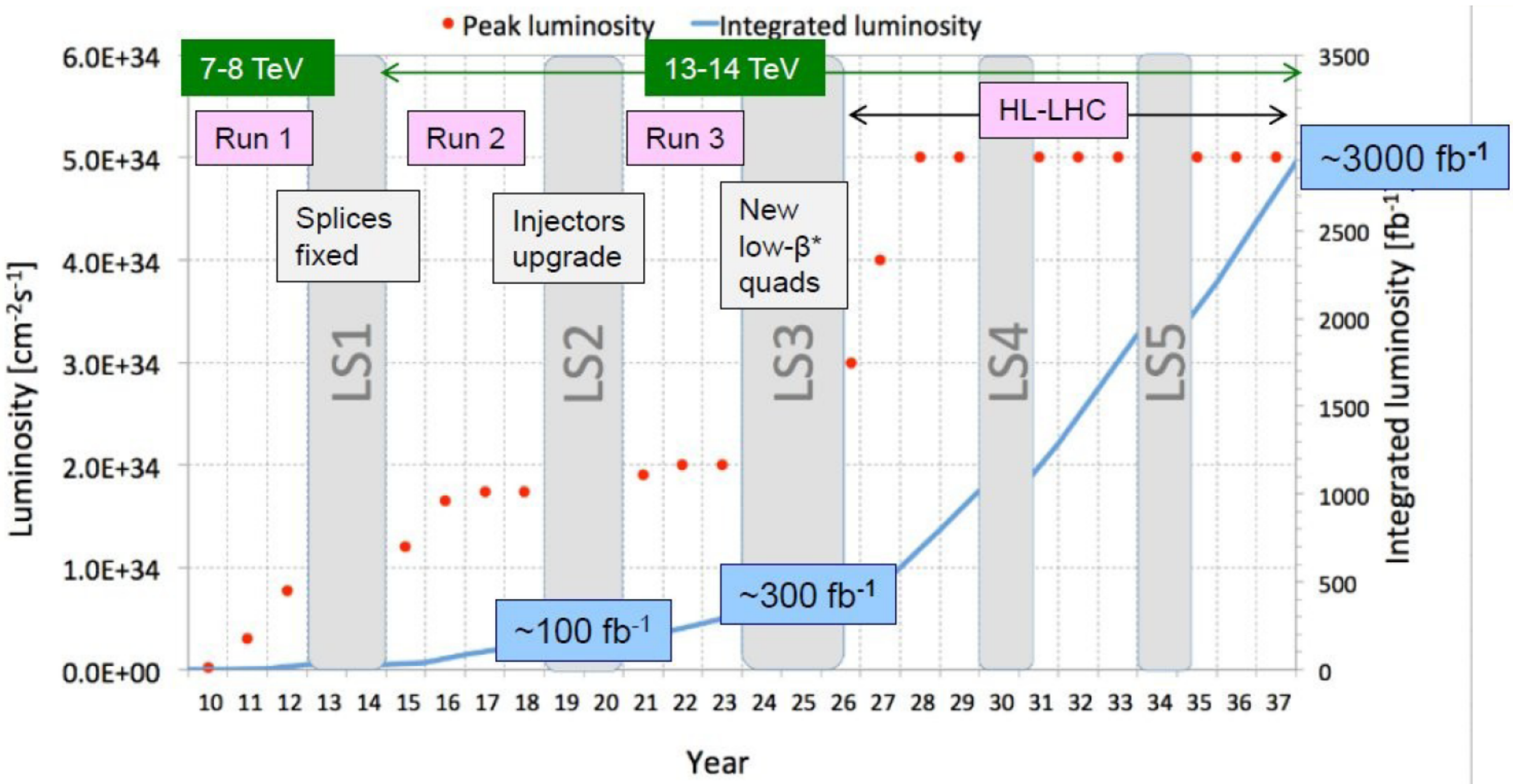




Observed (expected) 95% CL upper limits on the branching ratios:

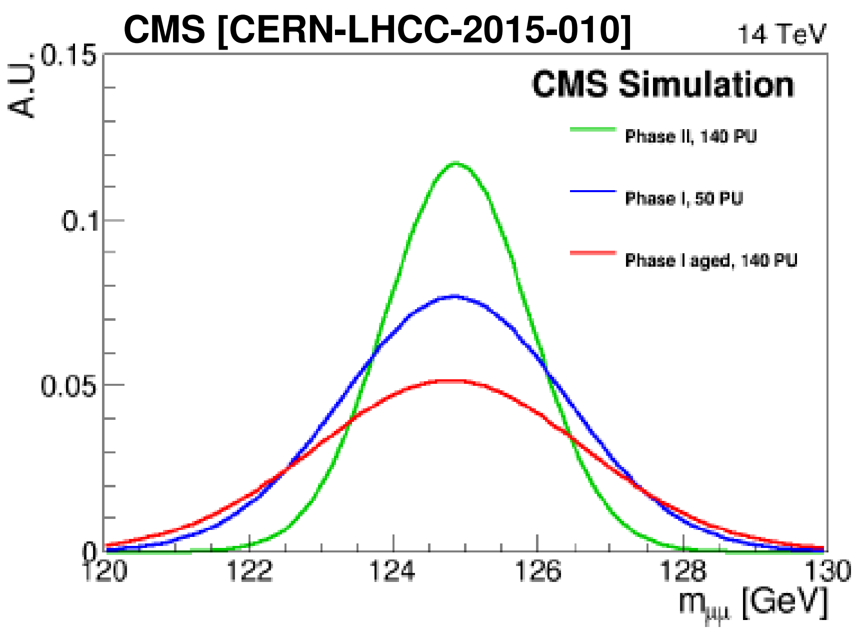
- $BR(t \to Hu) < 1.92\%$ (0.85%) $BR(t \to Hc) < 1.16\%$ (0.89%)

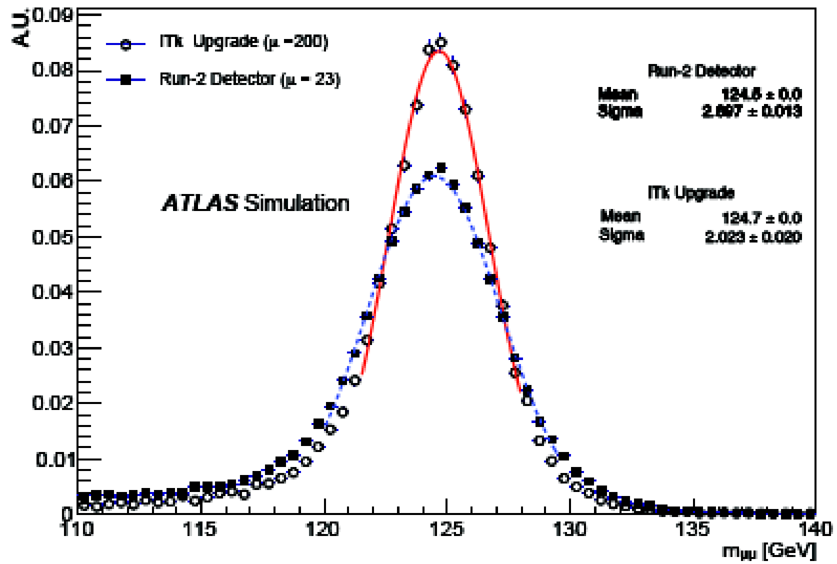
LHC Upgrade



- In parallel design of electron-positron linear colliders ILC, CLIC
- At CERN for >2035: HE-LHC, VHE-LHC, TLEP,...

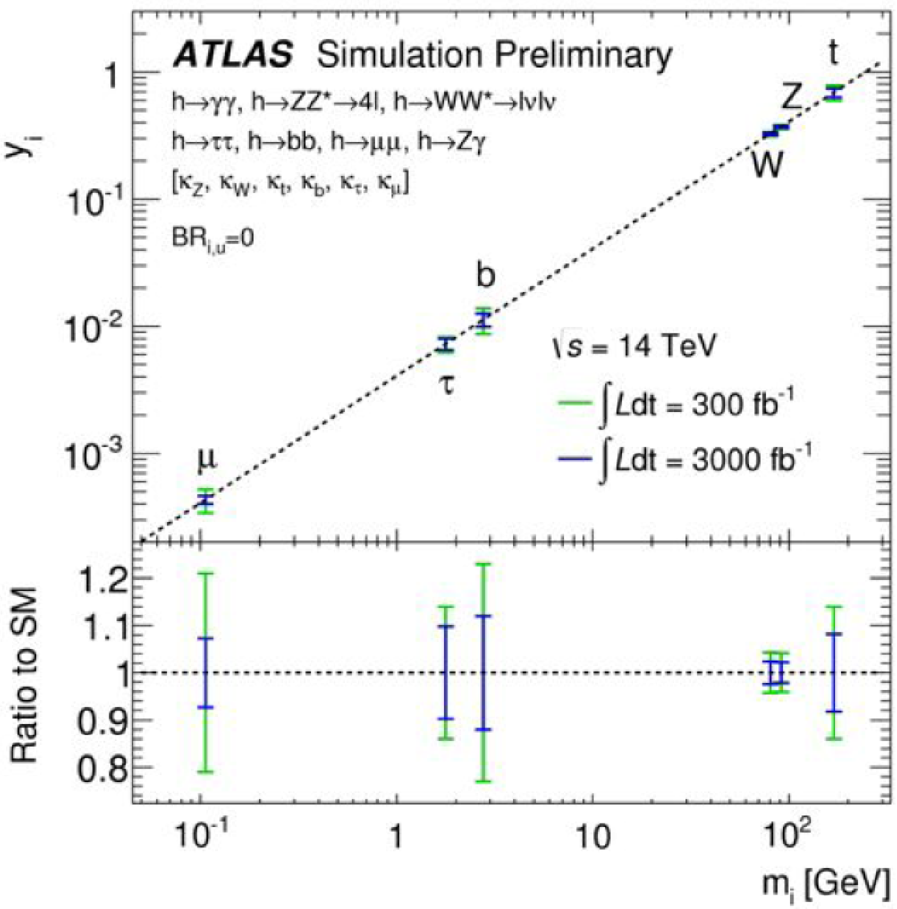
Projections of $H \rightarrow \mu\mu$

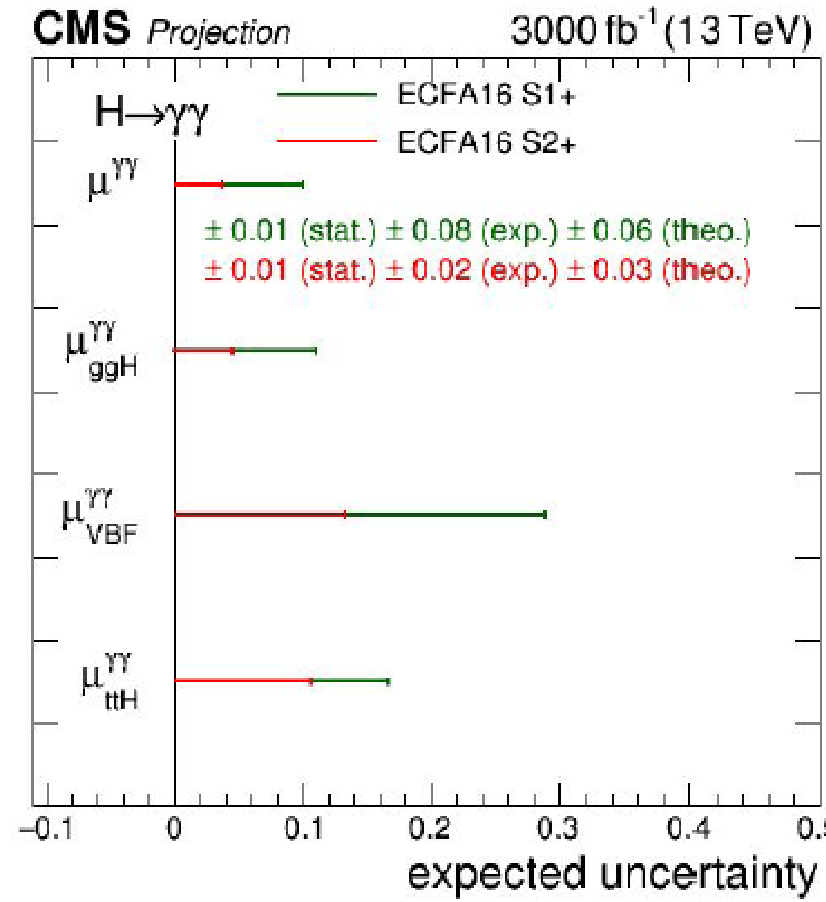




- CMS: revised projection, expect 5% uncertainty on $H \rightarrow \mu\mu$ coupling measurement at HL-LHC (only a few tens produced during LHC Run-1, according to SM prediction.

Sensitivity for Phase-1 and Phase-2

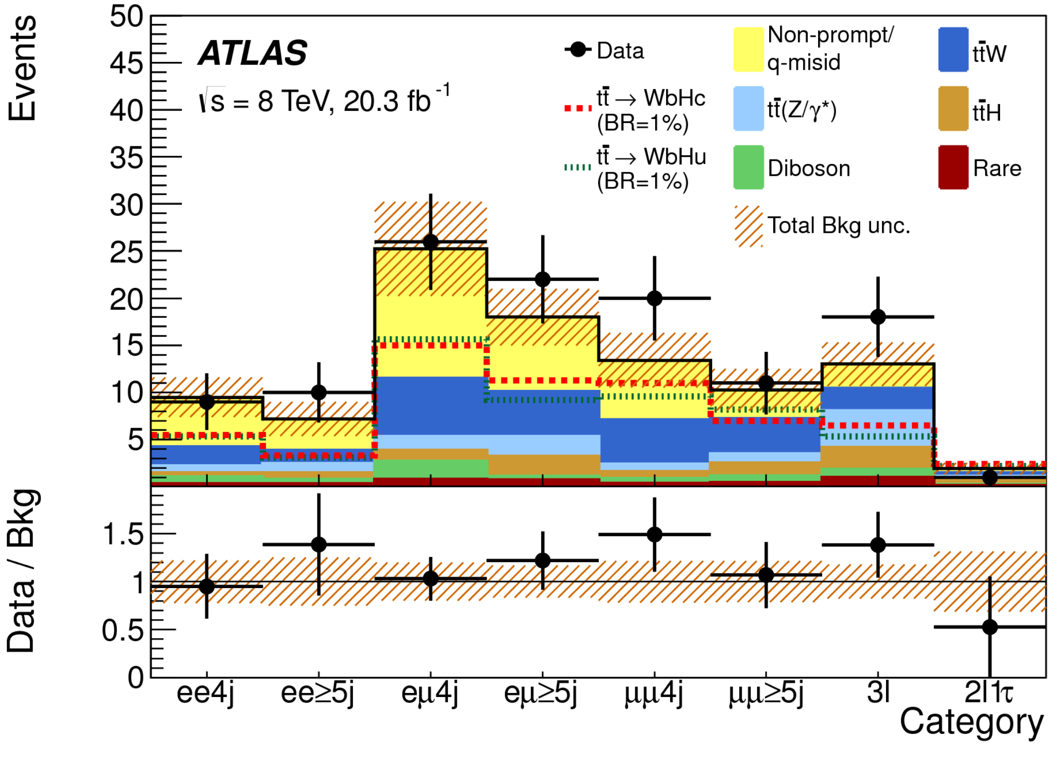




- Phase-1 and phase-2 will allow to measure rare decays ($H \rightarrow \mu\mu$) in addition to the main 5 and perhaps HH production.
- Some some production modes, projections indicate accuracy below 10% for the main decay modes.

ATLAS FCNC $t \rightarrow u/c+H$ (multi-lep)

- Re-interpretation of ATLAS ttH analysis in multi-lepton final states
- 8 different categories defined by lepton multiplicity and jet multiplicity:
  - (ee, μμ, eμ) x (4j,>=5j)
  - 3 light leptons
  - 2 light leptons + 1 tau



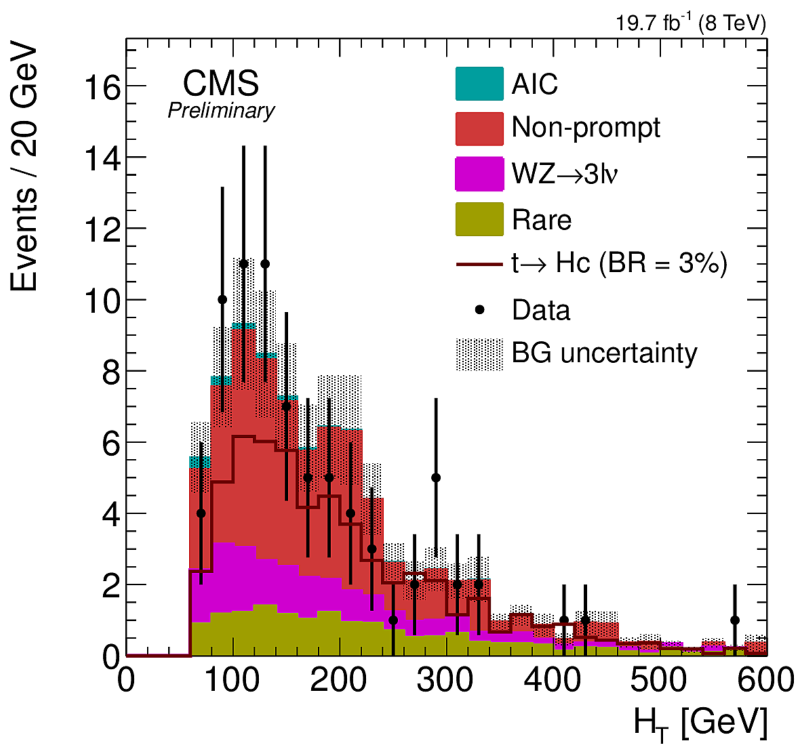
The observed (expected) 95% CL upper limits on the branching ratios are:

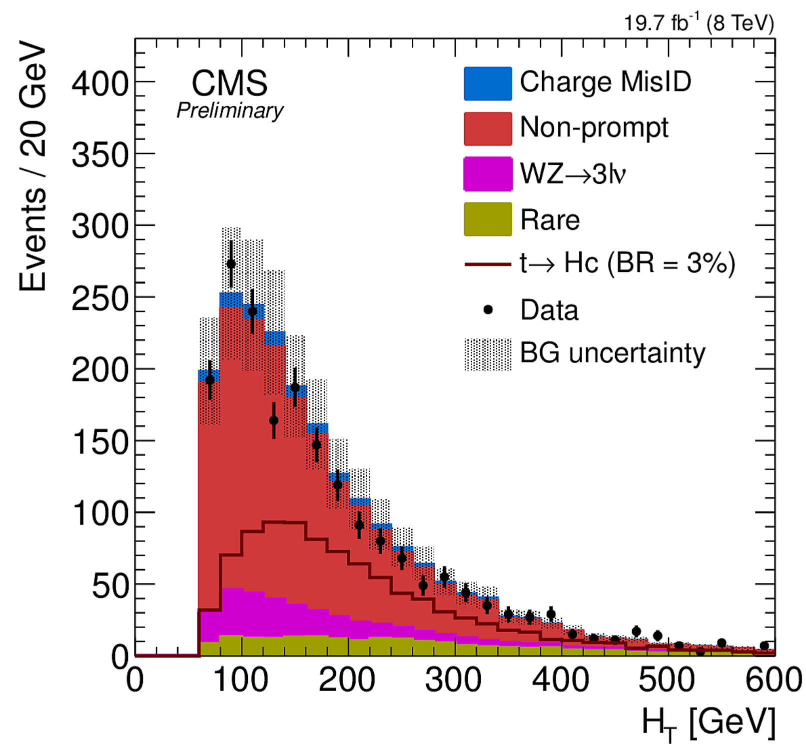
- BR($t \rightarrow Hc$) < 0.79% (0.54%)
- BR($t \rightarrow Hu$) < 0.78% (0.57%),

assuming BR($t \rightarrow Hu$), BR($t \rightarrow Hc$) =0 respectively

CMS FCNC $t \rightarrow c+H$

- Analysis of 3 light leptons or 2 same sign leptons events, selecting the final states ($H \rightarrow ZZ, WW, \tau\tau$) and $t \rightarrow bW(\rightarrow \ell\nu)$
- Two categories, no jet splitting:
  - 2 light leptons SS
  - 3 light leptons



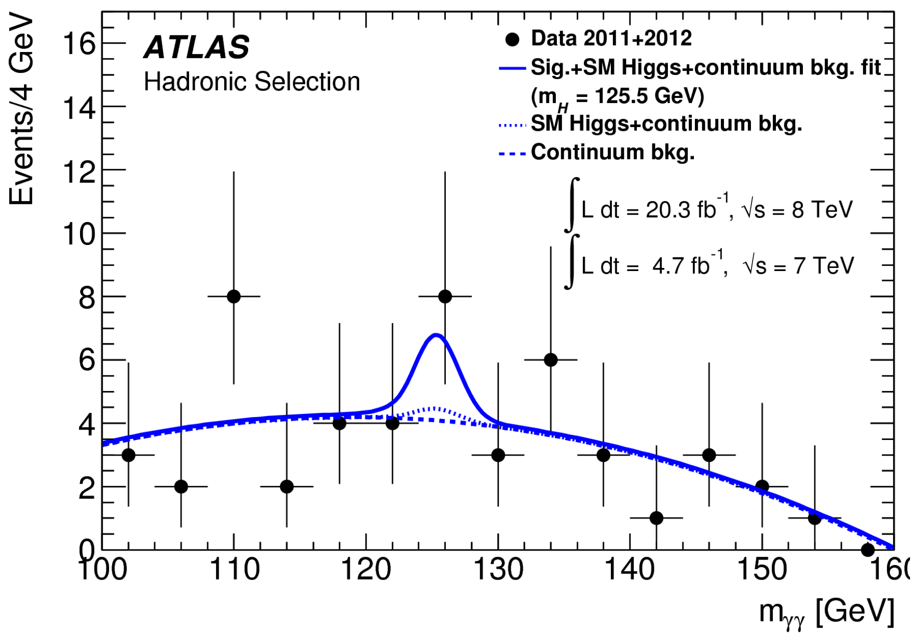


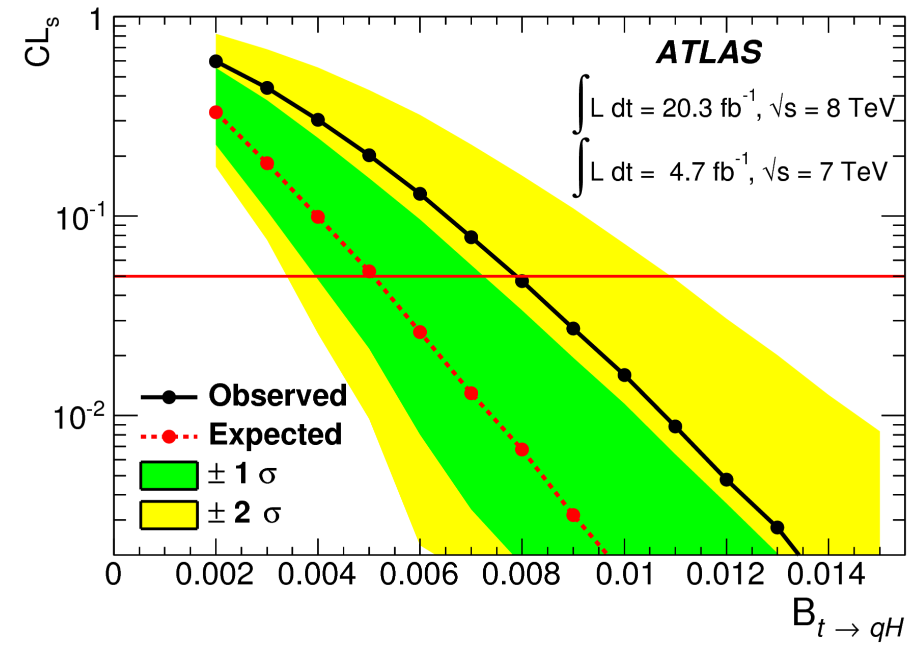
The observed (expected) 95% CL upper limits on the branching ratio is:

- $BR(t \rightarrow Hc) < 0.93\%$ (0.89%)

ATLAS FCNC $t \rightarrow u/c + H(\gamma\gamma)$

- 7 TeV and 8 TeV datasets are used.
- Main backgrounds are di-photon non-resonant background and ttH
- Analysis considers both hadronic and leptonic final states of the W decay:
  - diphoton+jets (cut on m_{top})
  - diphoton+lepton+jets (cut on $m_T(W)$)





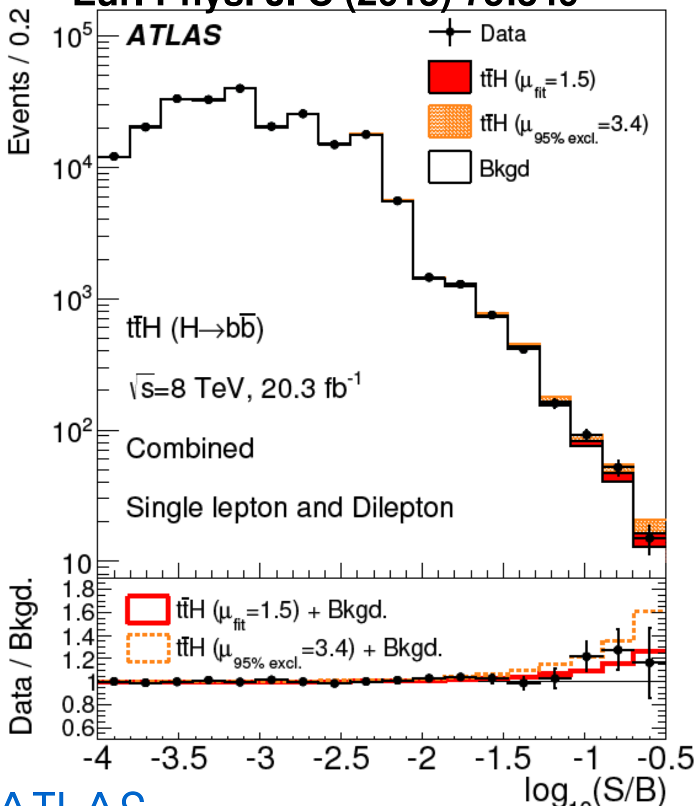
Observed (expected) 95% CL upper limits on the branching ratios:

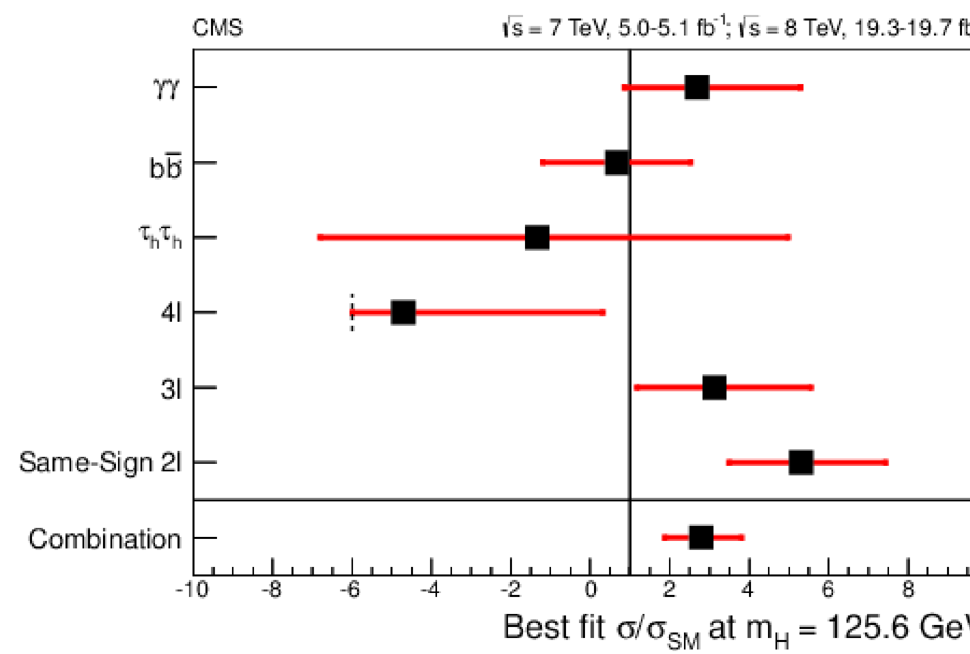
- BR($t \rightarrow Hq$) < 0.79% (0.51%)

Run 1ttH (H->bb, WW, ZZ, ττ, γγ)

- ATLAS and CMS covered broad range of Higgs boson final states and ttbar decay modes, grouped by decay products:
  - $H \to bb$, Multileptons (WW, ττ, ZZ), $H \to \gamma\gamma$
- b-tagging and top-tagging used to suppress backgrounds.
- The analyses are characterised by large number of categories and control region.
- These analyses require an excellent modelling and control of tt+HF and ttV

Eur. Phys. J. C (2015) 75:349





JHEP 09 (2014) 087

ATLAS

μ=1.7±0.8 @125.36 GeV

Local Significance: 2.5 obs (1.5 exp) σ

CMS

8 TeV: μ=2.8±1.0 @125.6 GeV

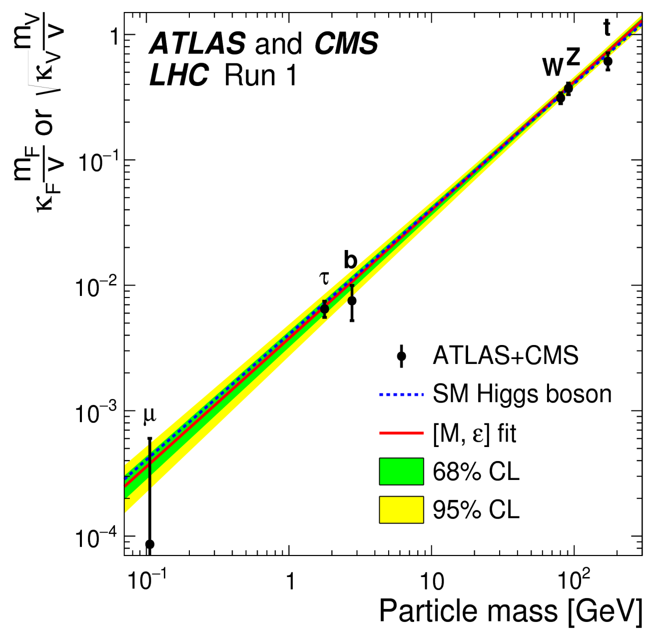
Local Significance: 3.4 obs (1.2 exp) σ

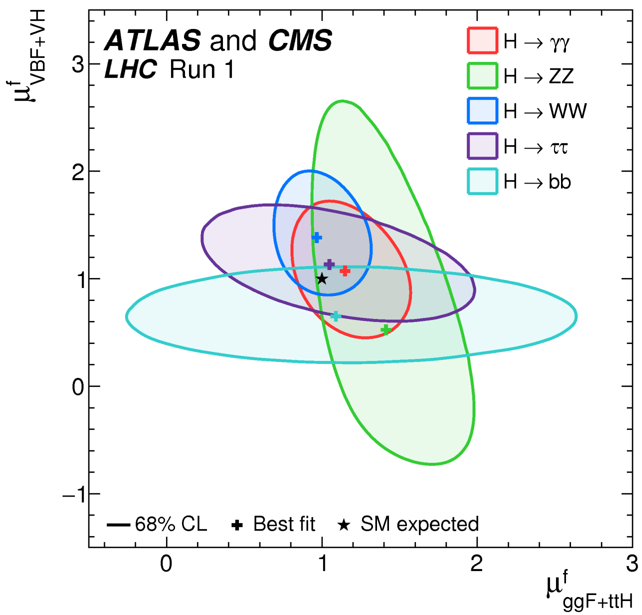
Run 1 Combined Measurements

- Higgs Yukawa couplings to ττ established already from Run 1.
- H → ττ is still the only leptonic channel accessible for few more years and it is the fermionic channel with the best sensitivity.
- ttH measurements are among the most interesting topics of LHC Run 2.
- H → bb sensitivity already above 3σ during Run 1, but observed value was lower than that.

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	5.0
H→bb	2.6	3.7

JHEP 1608 (2016) 045





Run 1 Combined Measurements (2)

$$\kappa = \frac{g}{g_{SM}}$$

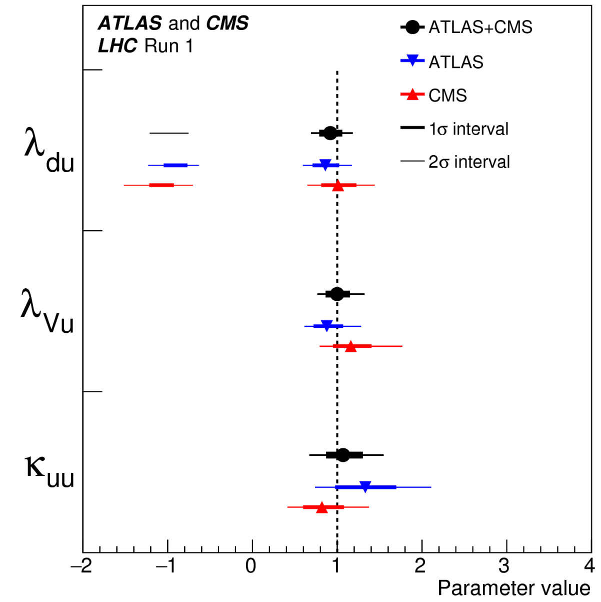
$$\sigma_i \times \mathrm{BF}^f = \frac{\sigma_i(\vec{\kappa}) \times \Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\lambda_{du} = \kappa_d / \kappa_u$$

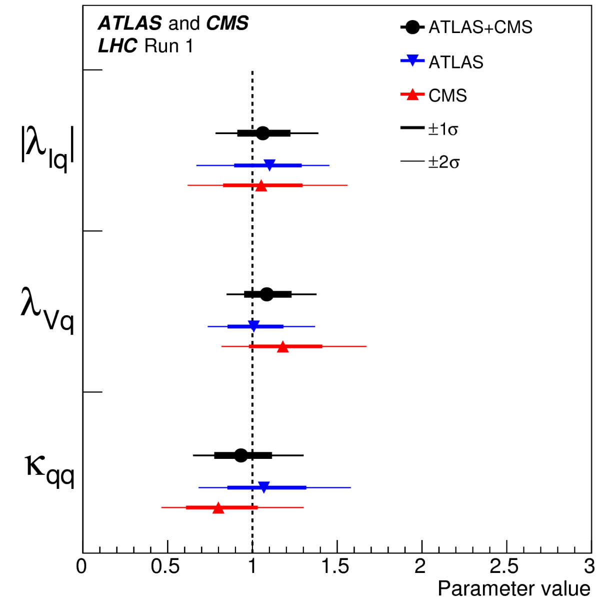
$$\lambda_{Vu} = \kappa_V / \kappa_u$$

$$\kappa_{uu} = \kappa_u \cdot \kappa_u / \kappa_H$$

$$\lambda_{\ell q} = \kappa_\ell / \kappa_q$$

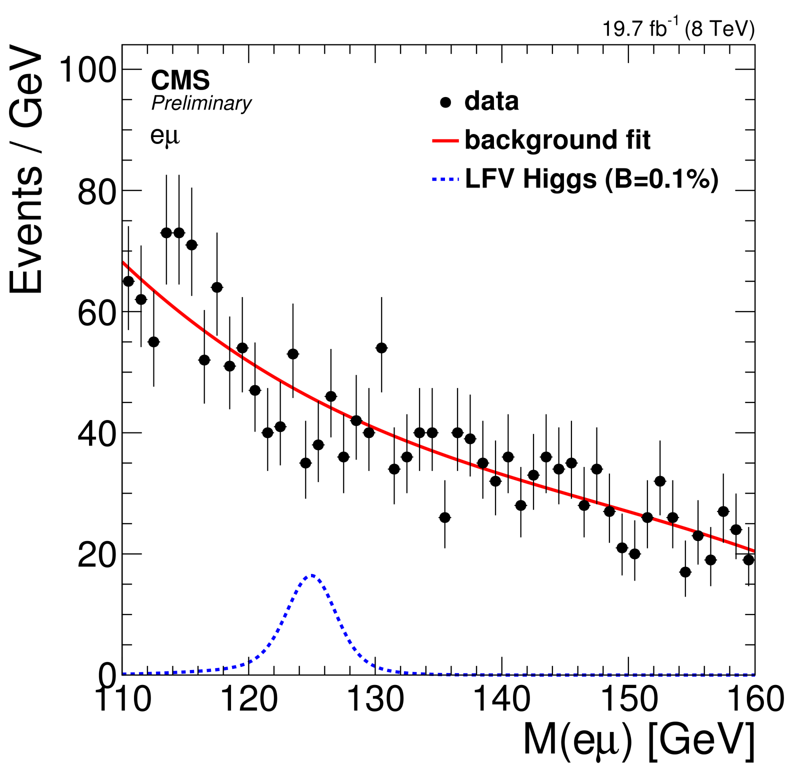


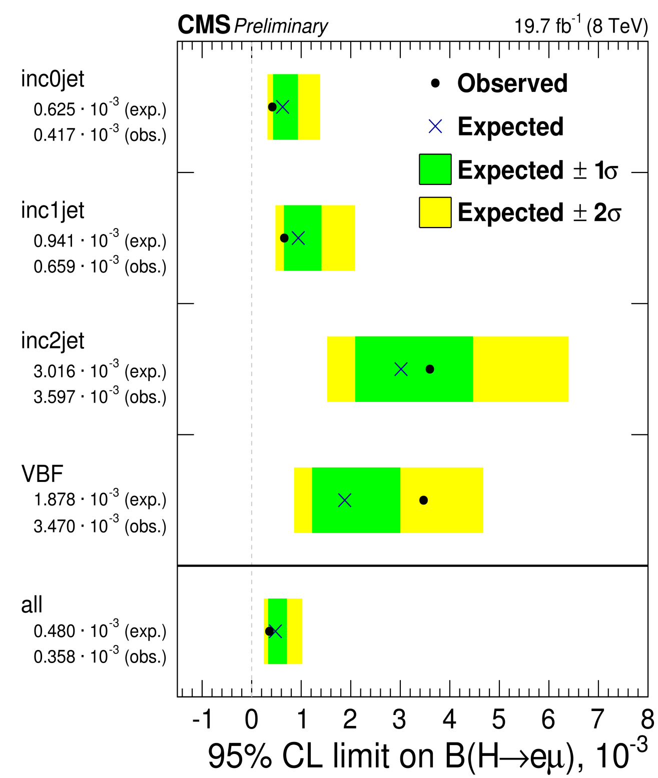
- Several BSM models predict λ_{lq} and $\lambda_{ud} \neq 1$
- Quark couplings probed mainly by ggH, H → bb
- Lepton couplings from H → ττ
- Precision:
  - $|\lambda_{ud}| \in (0.80, 1.04)$
  - $|\lambda_{ud}| \in (0.88, 1.21)$



Run 1 H →eμ

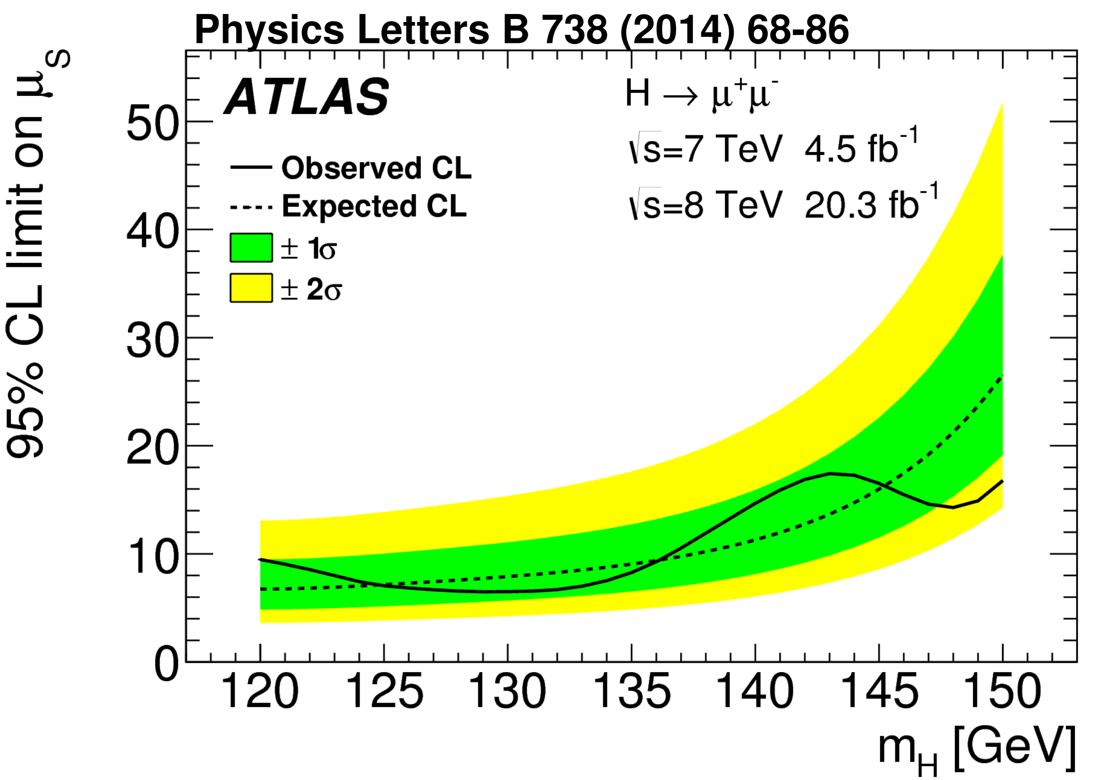
- CMS uses unbinned fit of the eμ mass spectrum.
- 11 categories (2 VBF + 3x3 barrel/endcap combination x number of jets), similar to H → μμ and H → γγ analyses
- Background modeled by polynomial, exponential and power law (category dependent).
- Signal modeled by the sum of two gaussians.

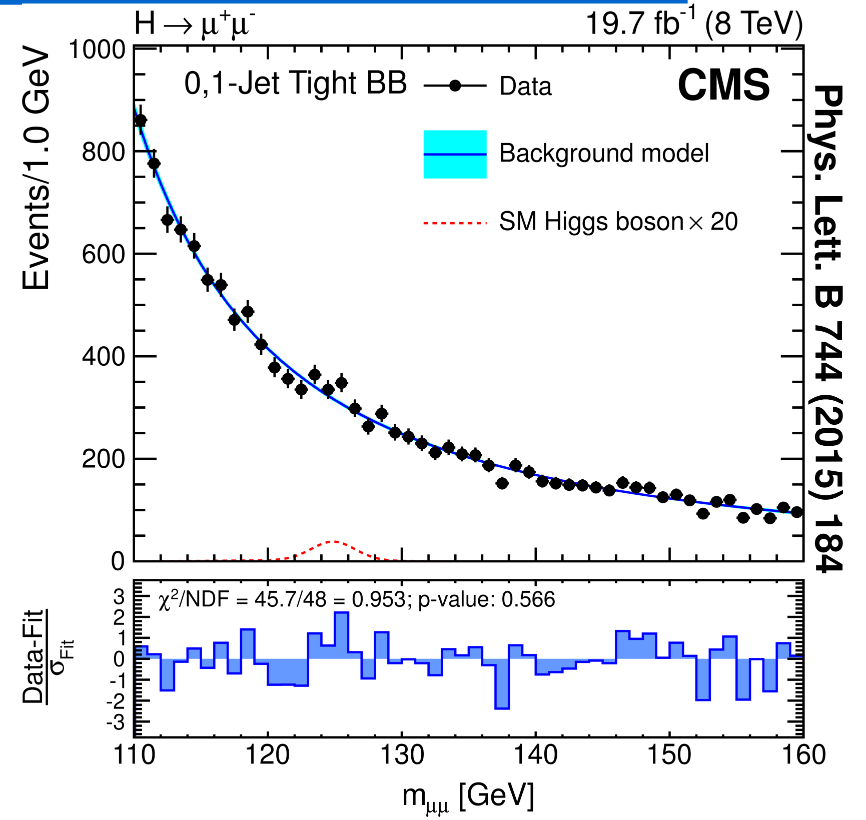




No excess observed: 95% CL limit is BR(H→eμ)<0.036%

Run 1 $H \rightarrow \mu\mu$





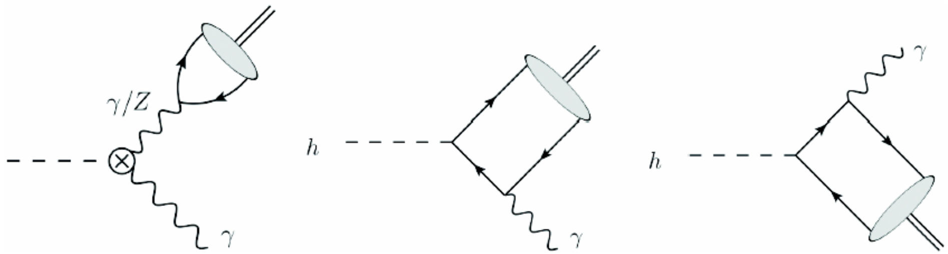
- Excellent mass resolution provides a clean signature.
- Result extracted from the fit of the $m_{\mu\mu}$ mass spectrum, similar to $H \rightarrow \gamma\gamma$
- Evidence of $H \rightarrow \tau\tau$ and limit on $H \rightarrow \mu\mu$ means no universal coupling of the Higgs to leptons, as expected.
- Need significantly more statistics to reach sensitivity to the SM rate of $H \rightarrow \mu\mu$

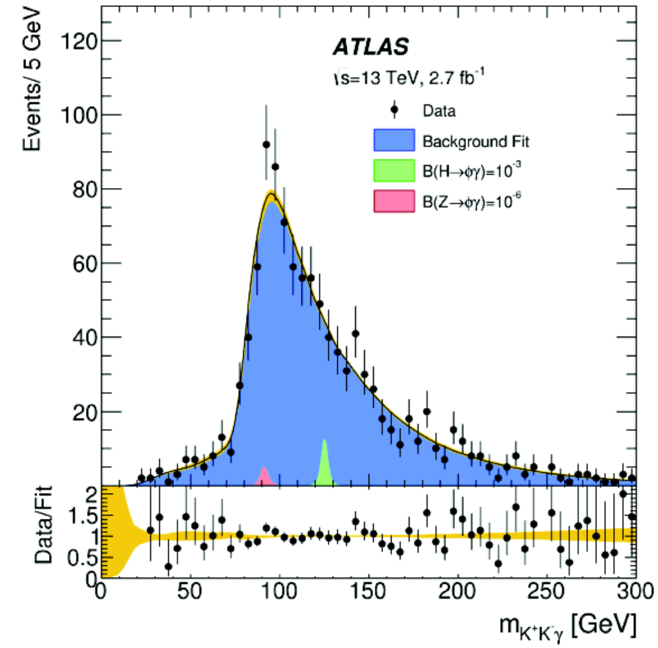
ATLAS:
Limit @ m_H=125 GeV: 7.0xSM
(7.2 exp)

CMS:
Limit @ m_H=125 GeV: 7.4xSM
(6.5 exp)

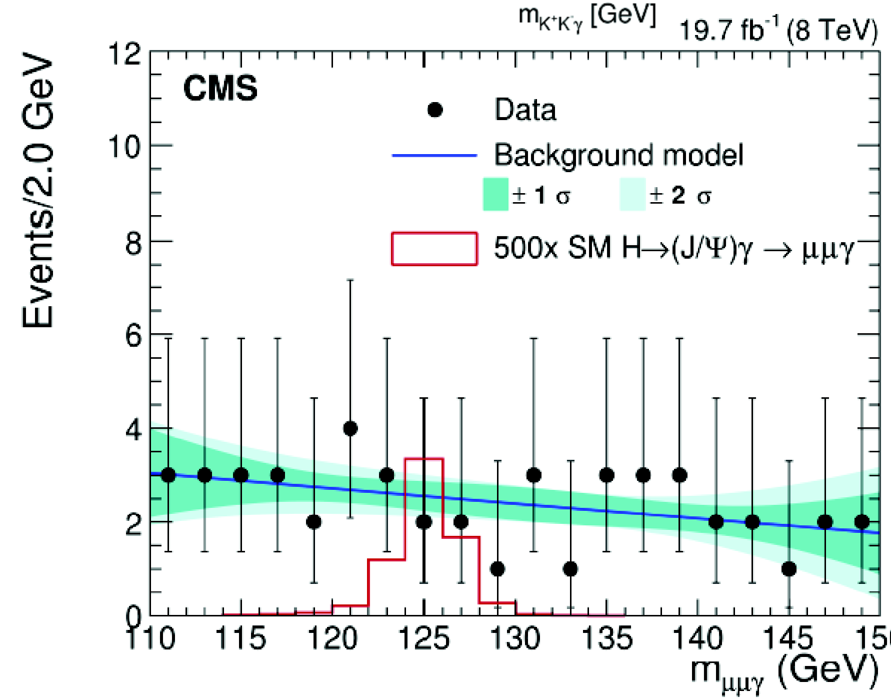
$H \to \gamma X\ (\to ff)$

ATLAS: Phys.Rev.Lett.117, 111802 (2016), Phys.Rev.Lett.114, 121801 (2015) CMS: Phys.Lett.B 753 (2016) 341





- Final states with ϕ, J/ψ and $\Upsilon(nS) + \gamma$ are sensitive to s,c,b-quark Yukawa couplings
- A dedicated trigger is used for the $H \to \gamma\phi(\to K^+K^-)$ search.
- $\mu\mu\gamma$ final state is used by both experiments, CMS also adds $ee\gamma$ events.



95% CL Limit ATLAS:

- BR ($H \to \gamma\phi$): 0.14%
- BR ($H \to \gamma J/\psi$): 0.15%
- BR ($H \to \gamma\Upsilon(1,2,3S)$): 0.13%, 0.19%, 0.13%

95% CL Limit CMS:

- BR ($H \to \gamma J/\psi$): 0.15%
- BR ($H \to \gamma^*\gamma$): 6.7xSM

Run 2 $H \to \mu\mu$ Results

- 2015+2016 limit greatly improves the Run 1 result.

- Results are in agreement with SM so far, some gap to be closed still to reach sensitivity to SM predicted cross-section.

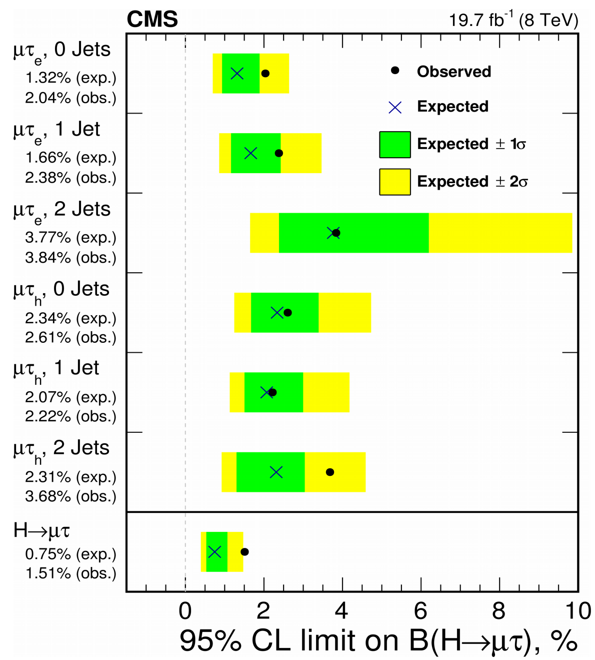
- Expect to measure H → μμ (second generation fermions) during the lifetime of the LHC.

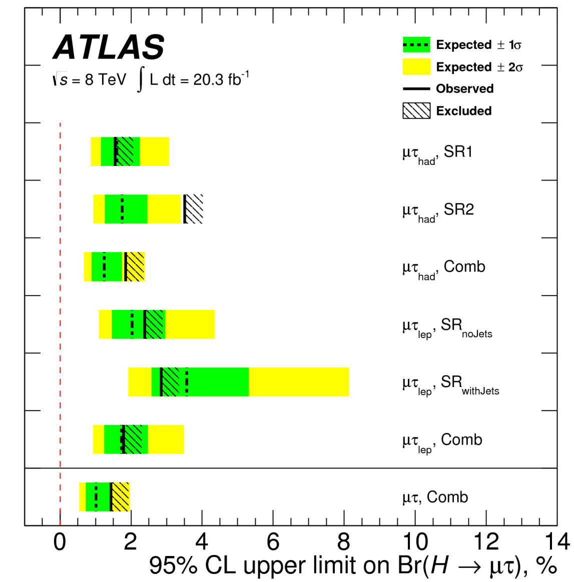
	S	B	$S/\sqrt{B}$	FWHM	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6 GeV	7885
Non-central low $p_T^{\mu\mu}$	32	38000	0.16	7.0 GeV	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7 GeV	6585
Non-central medium $p_T^{\mu\mu}$	66	31000	0.37	7.1 GeV	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3 GeV	3160
Non-central high $p_T^{\mu\mu}$	40	13000	0.35	7.7 GeV	12829
VBF loose	3.4	260	0.21	7.6 GeV	274
VBF tight	3.4	78	0.38	7.5 GeV	79

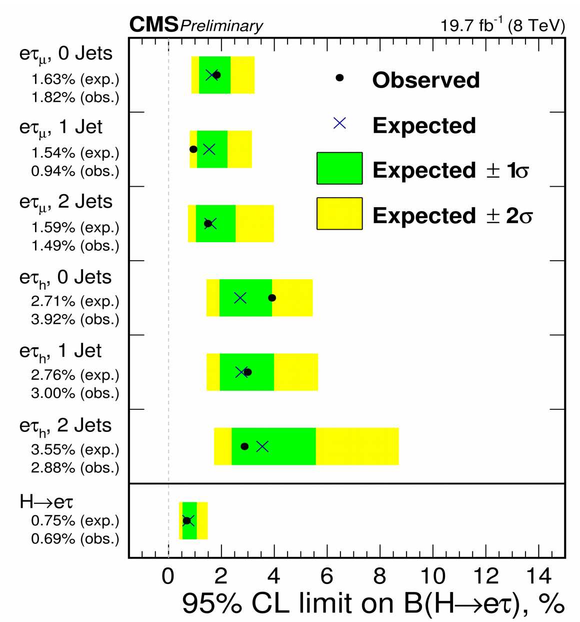
Run 1 search for $h \to \tau \ell'$

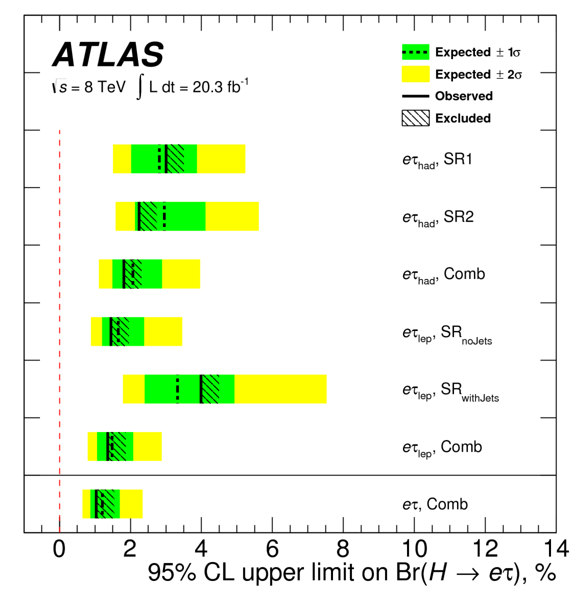
- The search for LFV decays of the Higgs boson are an interesting door to New Physics, $H \to \tau\mu$, τe.
- ATLAS searches for LFV $H \to \tau l$ decays are in part adapted from the $H \to \tau\tau$ analyses.
- A data-driven method is used by ATLAS for $l\tau_l$ channel, relying on symmetry of the SM bkg processes between eμ and μe final states.
- Collinear mass used by CMS and by ATLAS in $l\tau_l$ channel. ATLAS uses MMC reconstruction in the $l\tau_{had}$ channel.

- Small excess observed by CMS in 3 out of 6 categories:
  - 2.4 σ excess





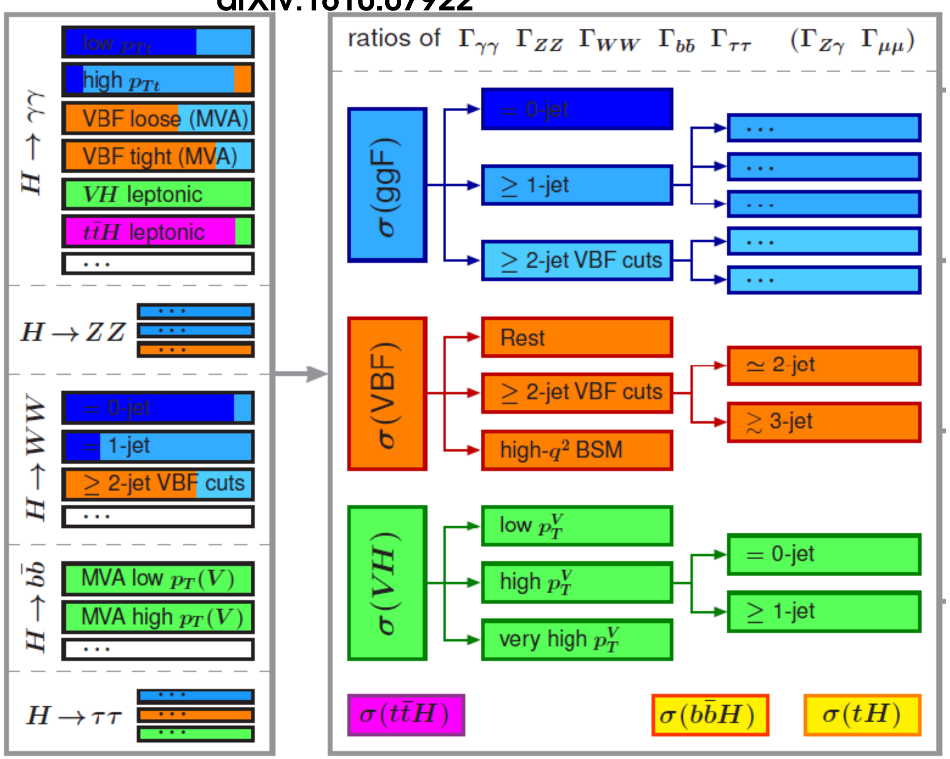




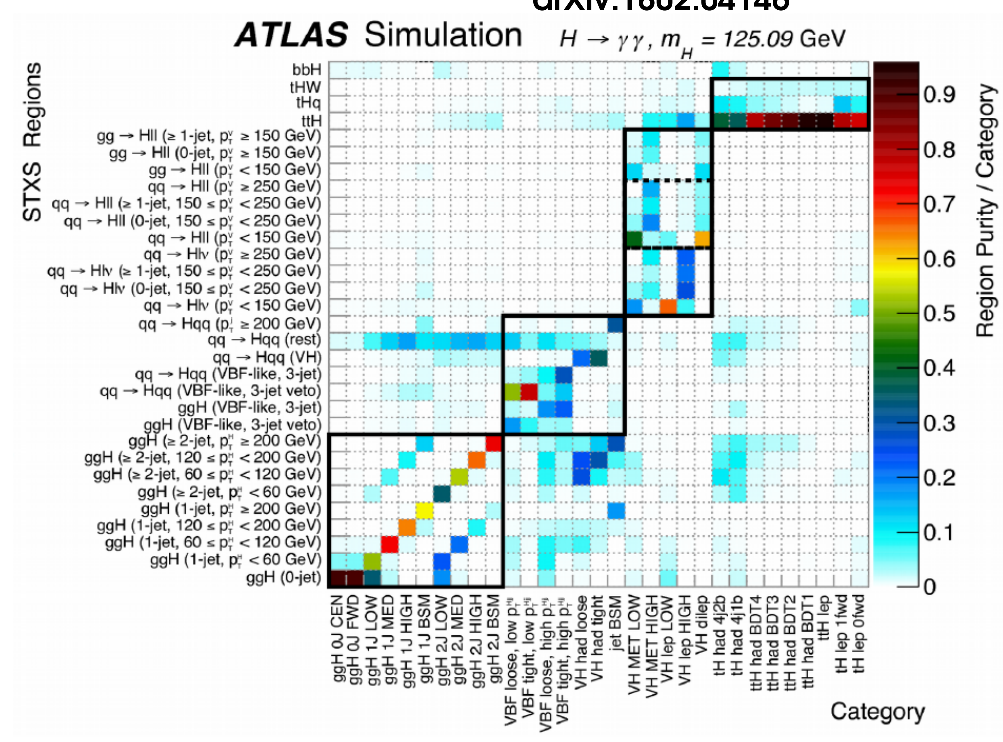
Simplified template cross sections

- **Simplified template cross sections (STXS):**
  - Aimed to balance experimental precision and theory uncertainties:
  - Independent very simple fiducial region definitions for each Higgs production mode based on Higgs kinematics and associated particles.
  - The experimental selection can be different and can use MVAs
  - STXS definitions are common for ATLAS, CMS and theory
- First (stage 0 and some stage 1) measurements done already in Run 2

arXiv:1610.07922



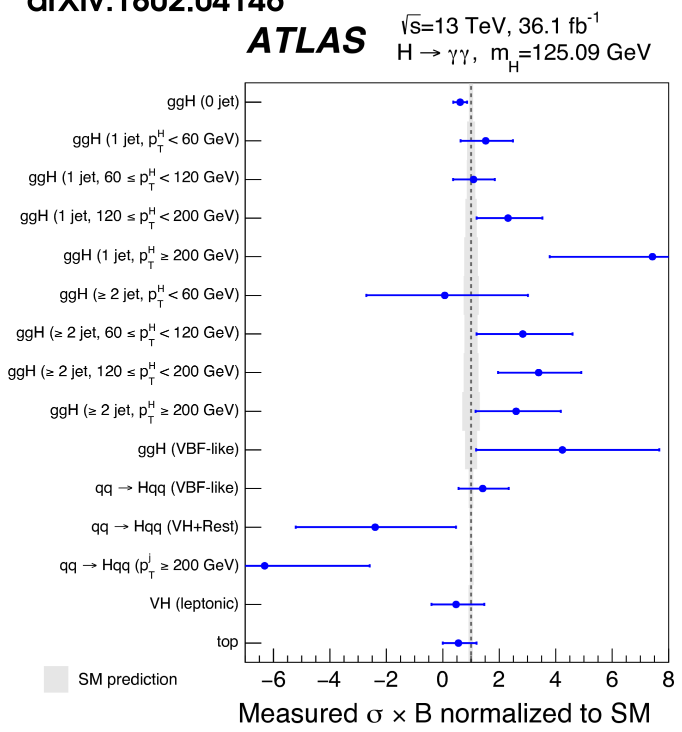
arXiv:1802.04146



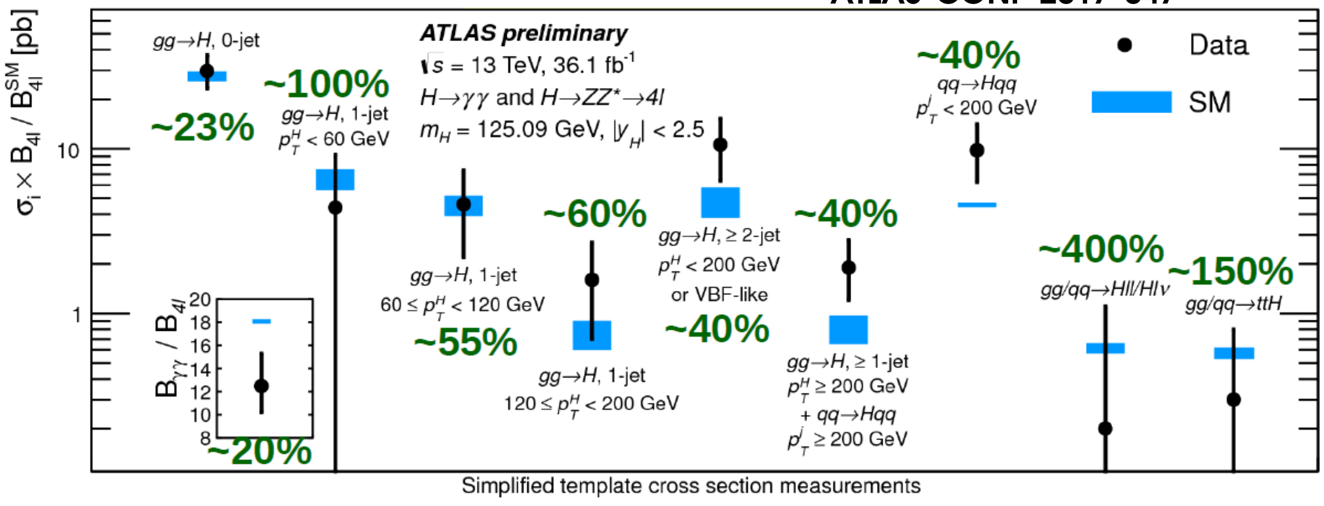
ATLAS STXS

- $H\rightarrow\gamma\gamma$: 31 experimental categories, roughly matching the STXS bins
  - Still too fine granularity for precise measurements in all STXS bins with just one channel, but can measure in combined bins.
  - ATLAS performed a combination of STXS measurements for the $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*$ channels.
  - In addition to cross section measurements for all production modes, also perform measurements of some kinematic bins
- Best precisions of ~20% reached

arXiv:1802.04146

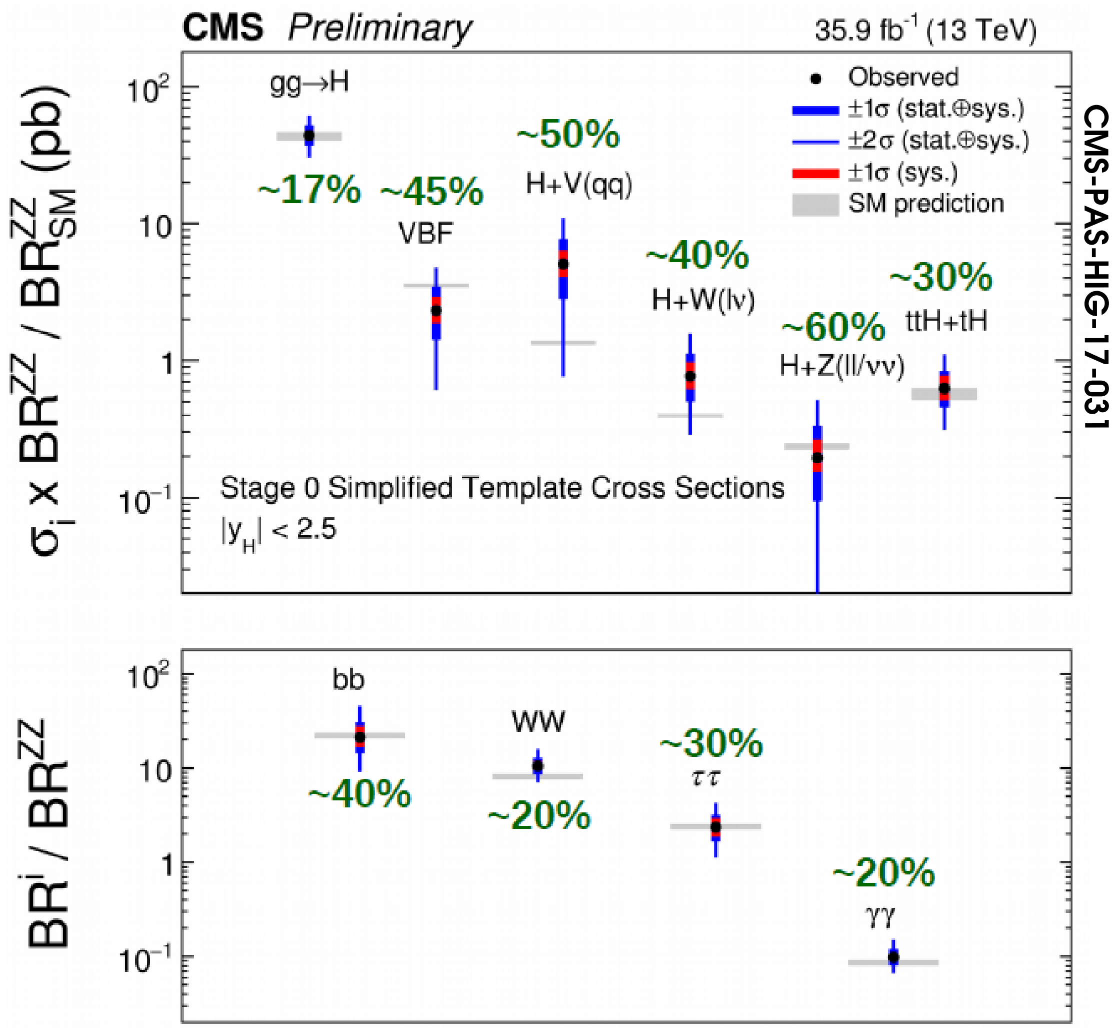


ATLAS-CONF-2017-047

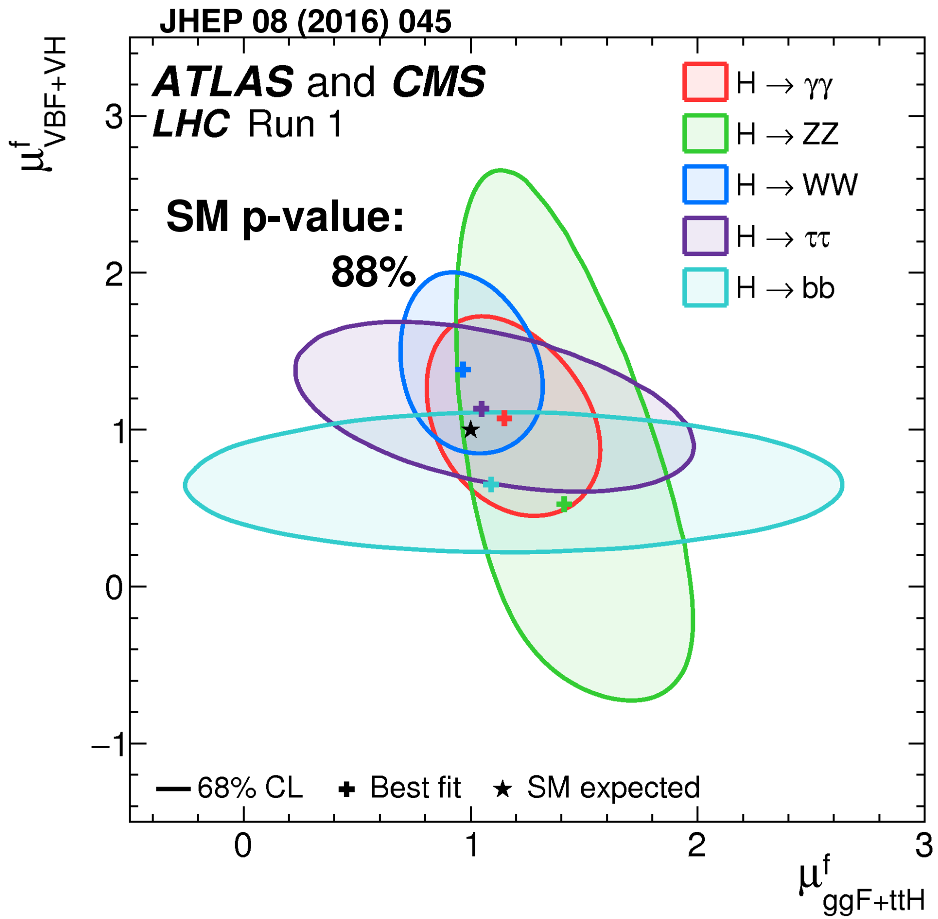


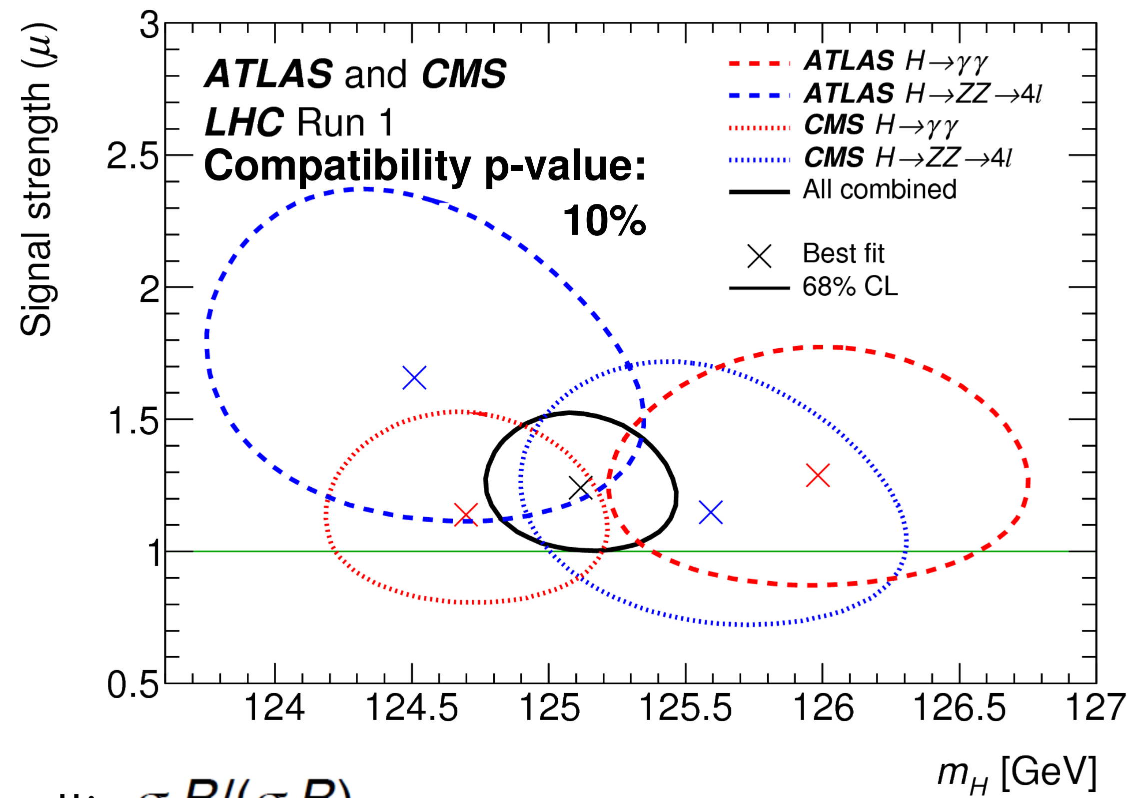
CMS STXS

- Results quoted for the conventional production modes
- VH split into V(ℓℓ) and V(qq)
- Th. uncs. in SM predictions (grey bands) separated from exp. and th. uncs. in the measurements
- STXS measurement using "big 5" decay channels
- Best precisions of <20% reached



Run 1 Higgs Summary





$\mu := \sigma \cdot B / (\sigma \cdot B)_{SM}$

- Measure ggF+ttH production and VBF+VH production for each decay mode
- Measurement of the combined ratio: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
- m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV
- Mass measurement uncertainty is dominated by the statistical error.

Run 1 Higgs Legacy

ATLAS+CMS Run 1 combination

Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	**5.5**	5.0
$H \rightarrow bb$	2.6	3.7

- Higgs mass measured with 0.4% accuracy
- ggF and $H \rightarrow ZZ, \gamma\gamma, WW$ observed by individual experiments
- VBF production and $H \rightarrow \tau\tau$ observed with $>5\sigma$ significance by ATLAS+CMS combination.
- ttH, VH production and $H \rightarrow bb$ not observed during Run1, they are among the most interesting topics of LHC Run 2.