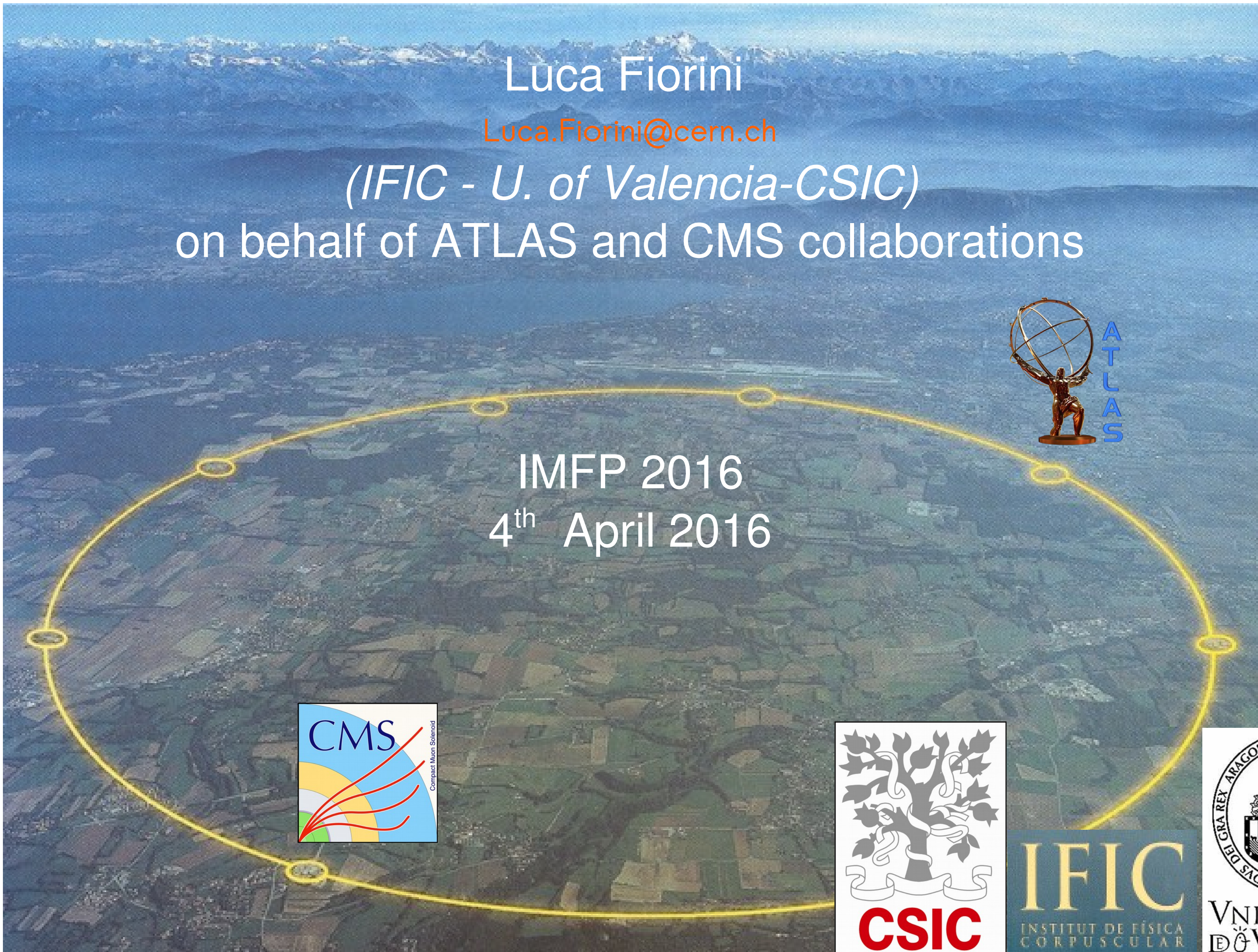
Status of the 125 GeV Higgs boson physics at LHC



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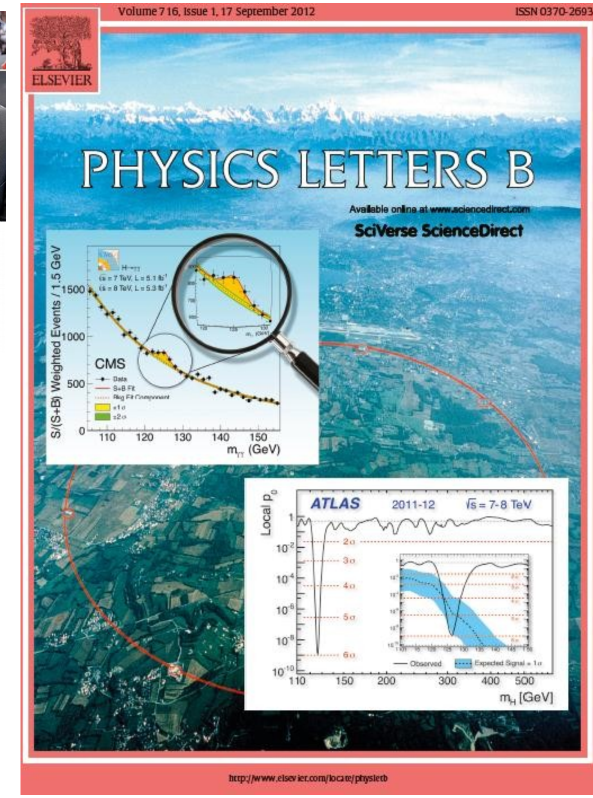
(IFIC - U. of Valencia-CSIC)

on behalf of ATLAS and CMS collaborations

IMFP 2016

4th April 2016

Outline



- LHC performance
- Experiments performance
- Higgs production and decay
- Individual Higgs Physics Results:
  - **H → ZZ(4l)**
  - **H → $\gamma\gamma$**

  First 13 TeV Higgs results

  - **H → WW (2l2ν)**
  - **VH(bb)**
  - **H → $\tau\tau$**
  - **H → $\mu\mu$**
  - **LFV H → $\tau\ell$**
  - **ttH production**

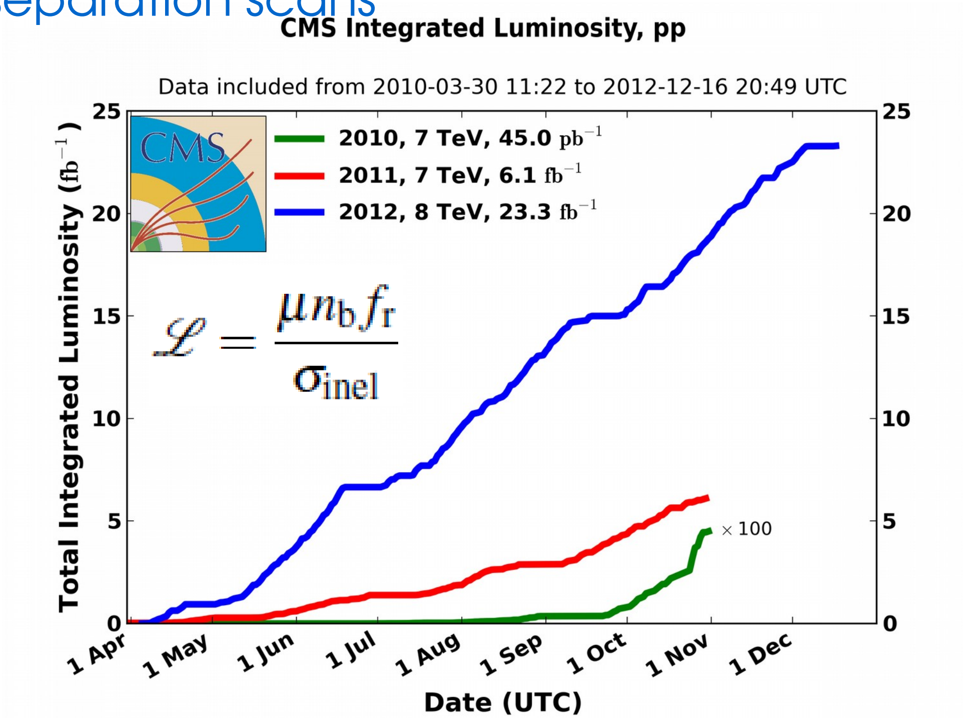
  First 13 TeV Higgs results
- Properties:
  - **Mass**
  - **Width**
  - **Spin/CP**
  - **Couplings**
- Future Prospects for LHC upgrades

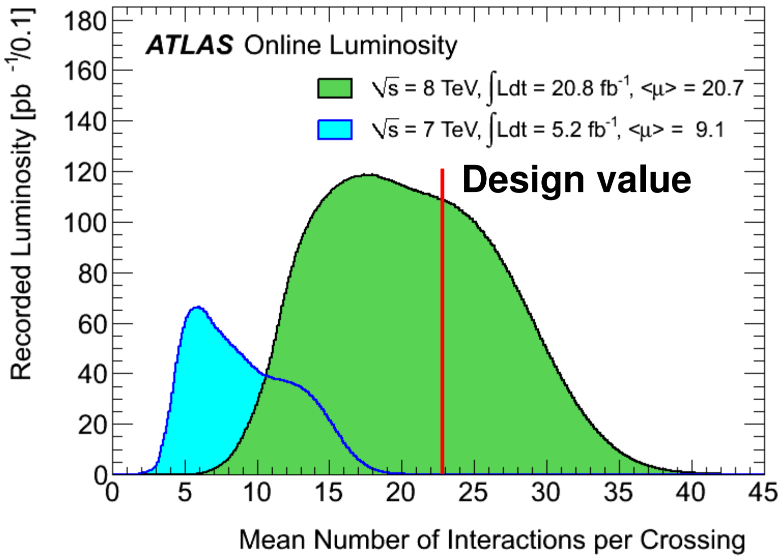
Many more Higgs results produced by LHC, but not possible to present all of them in this talk.

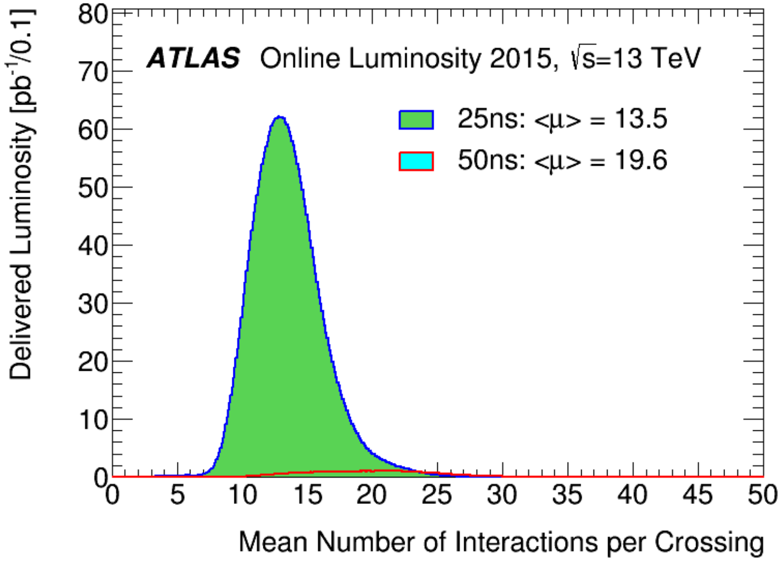
LHC Luminosity and interactions per bunch crossing

Run-1 Results based on 2011+2012 data

Luminosity is measured with forward/tracking detectors and calibrated with beam separation scans







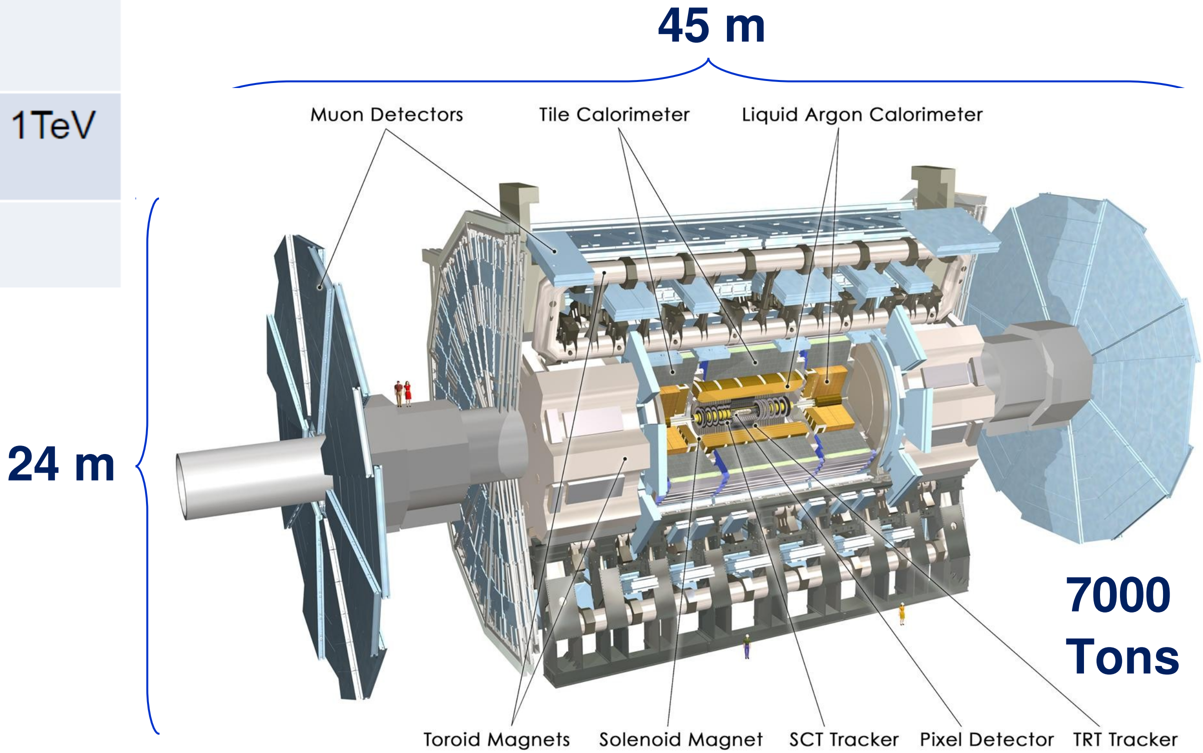
- Pileup already at the design level and above during 2012, thanks to excellent performance of the LHC.
- Peak luminosity ($cm^{-2} s^{-1}$): 7.7×10^{33} (2012), 5.2×10^{33} (2015).

~29 fb^{-1} of data delivered during Run1and about 4 fb^{-1} during 2015 and up to 25 fb^{-1} expected in 2016.

ATLAS Detector

	ATLAS
Magnetic field	2 T solenoid + toroid: 0.5 T (barrel), 1 T (endcap)
Tracker	Silicon pixels and strips + transition radiation tracker $\sigma/p_T \approx 5 \cdot 10^{-4} p_T + 0.01$
EM calorimeter	Liquid argon + Pb absorbers $\sigma/E \approx 10\%/\sqrt{E} + 0.007$
Hadronic calorimeter	Fe + scintillator / Cu+LAr (10λ) $\sigma/E \approx 50\%/\sqrt{E} + 0.03$ GeV
Muon	$\sigma/p_T \approx 2\%$ @ 50GeV to 10% @ 1TeV (Inner Tracker + muon system)
Trigger	L1 + HLT (L2+EF)

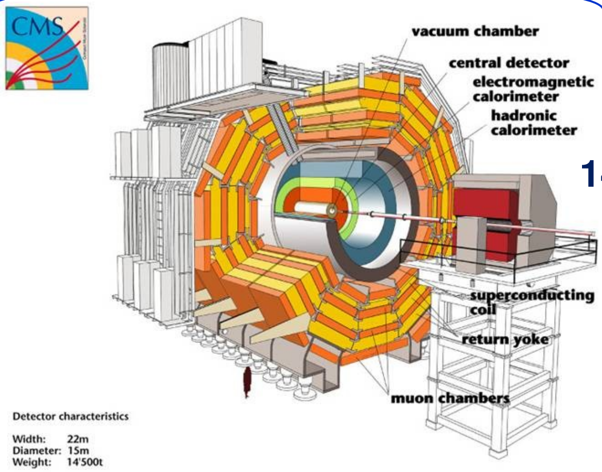
ATLAS Collaboration
38 Countries
175 Institutions
3000 Scientific Authors total
(~2000 with a PhD)



CMS Detector

29 m

15 m



14000 Tons

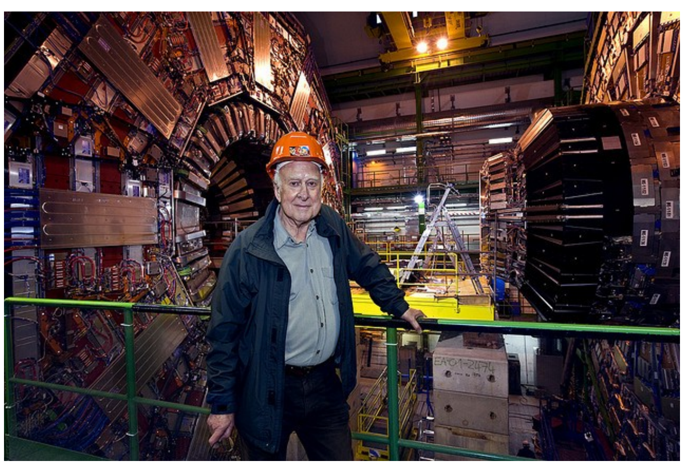
CMS Collaboration

42 Countries

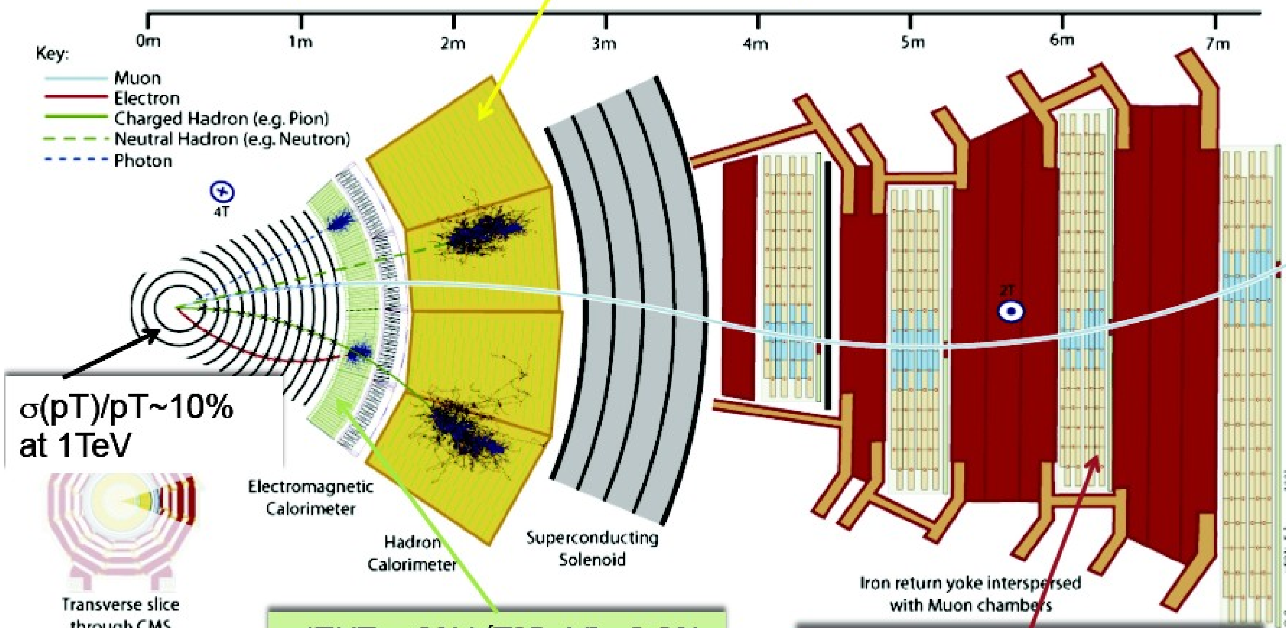
182 Institutions

3300 Scientific Authors total

(~900 students)



$\sigma(E_T)/E_T \sim 100\%/\sqrt{E_T[GeV]} + 5\%$



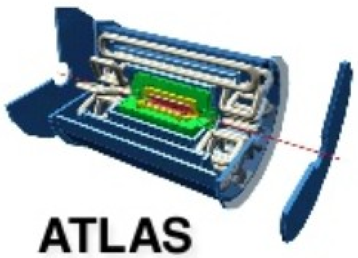
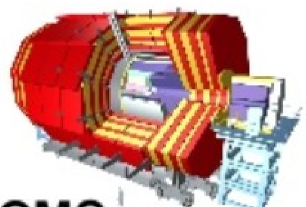
$\sigma(pT)/pT \sim 10\%$ at 1TeV

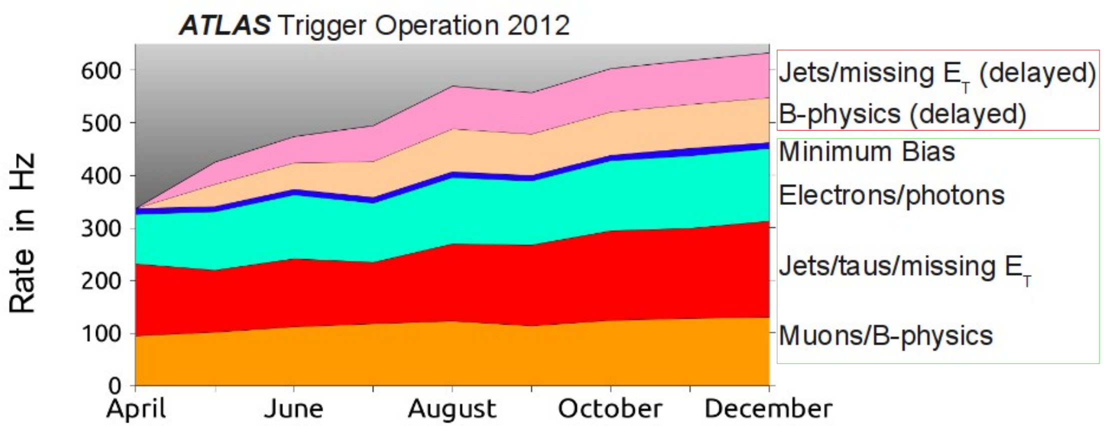
$\sigma(E)/E \sim 3\%/\sqrt{E[GeV]} + 0.3\%$

$\sigma(pT)/pT \sim 1\%$ @ 100GeV

$\sigma(pT)/pT \sim 10\%$ @1 TeV

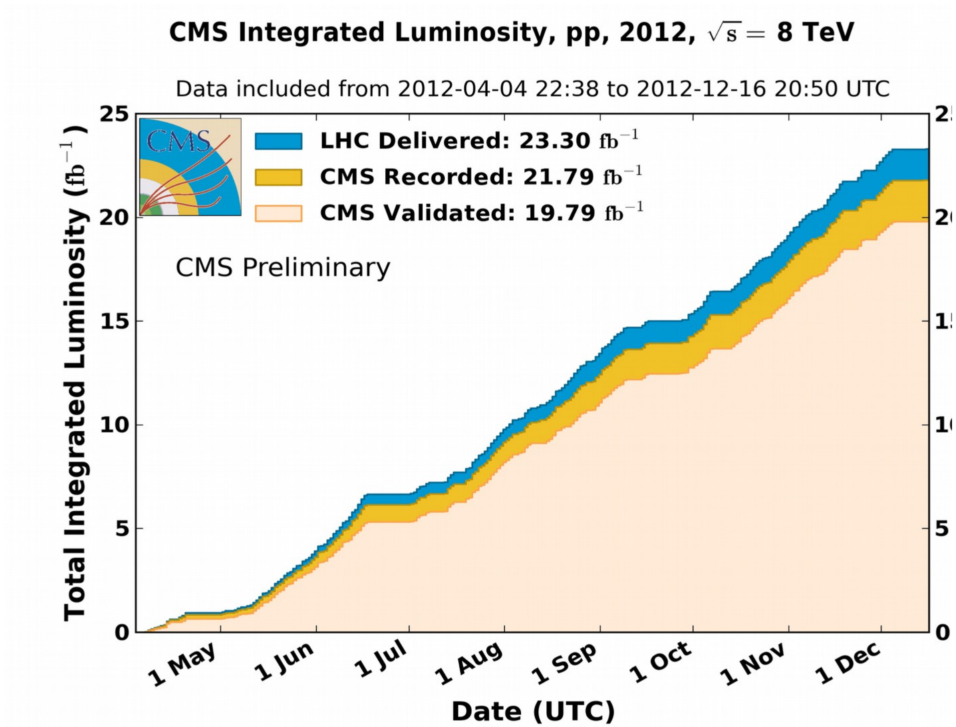
DAQ and Trigger

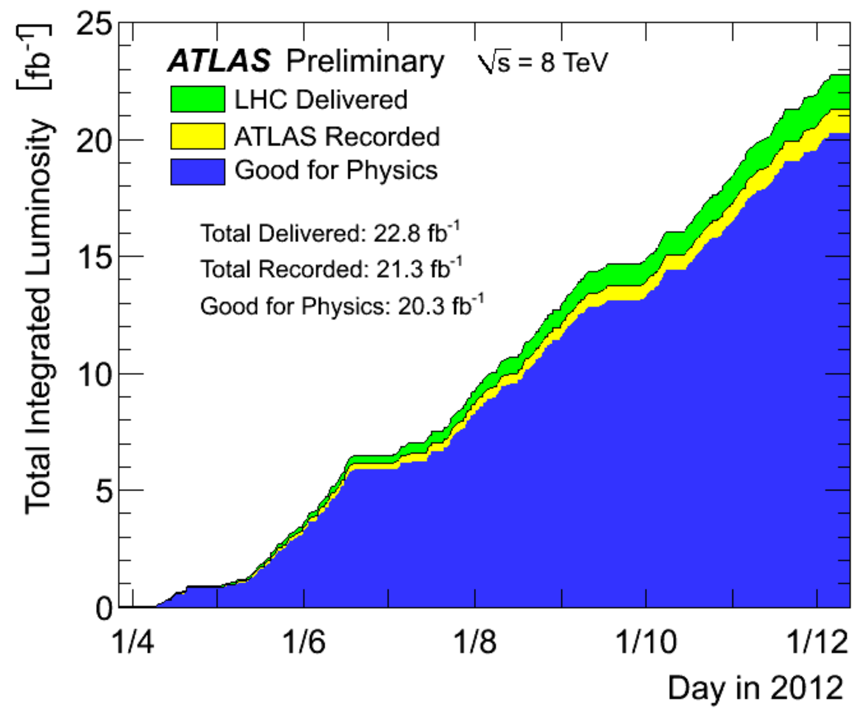
	Trigger No. Levels	Level-0,1,2 Rate (Hz)	Event Size (Byte)	Readout Bandw.(GB/s)	HLT Out MB/s (Event/s)
 ATLAS	3 	LV-1 10^5 LV-2 $3x10^3$	$1.5x10^6$	4.5	600+300 ($4x10^2+2x10^2$)
 CMS	2 	LV-1 10^5	10^6	100	O(1000) (10^3)



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

Data taking & Quality efficiency



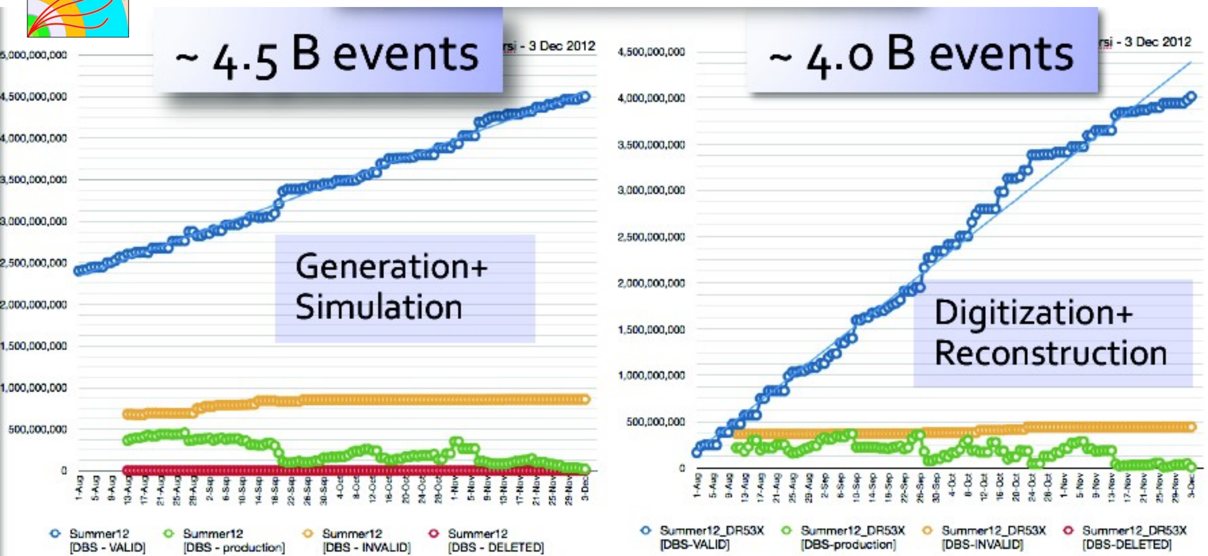


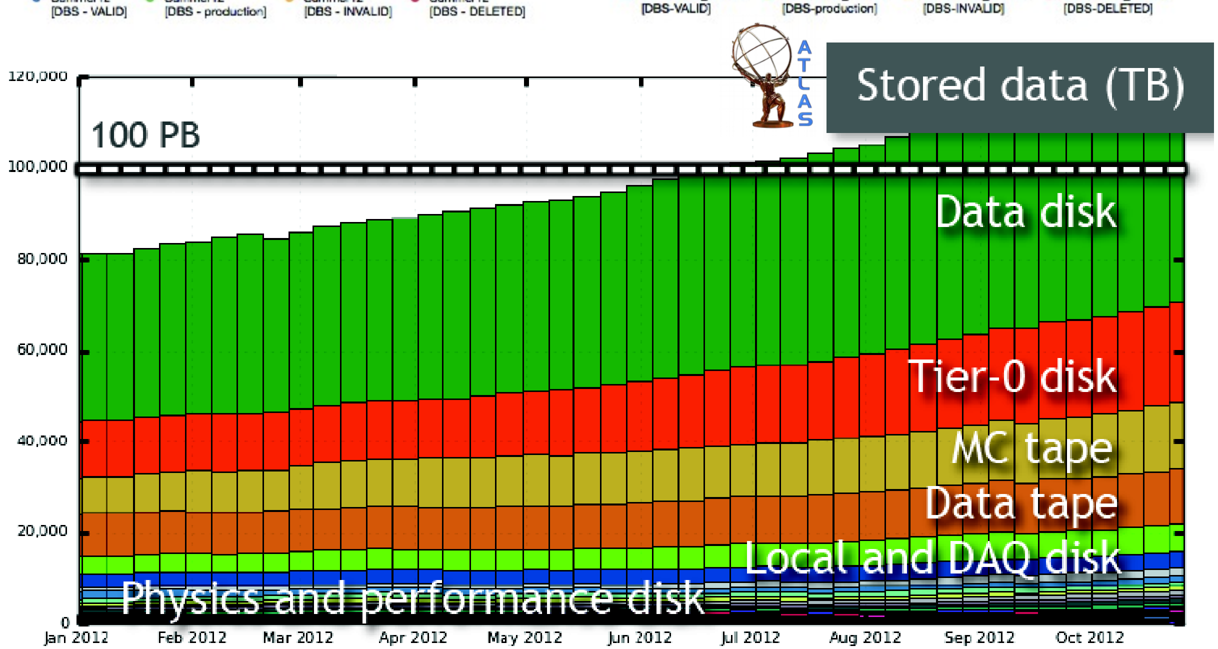
- ATLAS (CMS) data-taking efficiency for 2012 run was 93.1% (93.5%)
- The ATLAS (CMS) good quality data was 95.8% (91%) of the recorded data
  - High DQ also thanks to efficiency recovery from large data reprocessing

Overall ~88% (85%) of delivered luminosity is used for ATLAS and CMS physics analysis.

Computing and Simulation

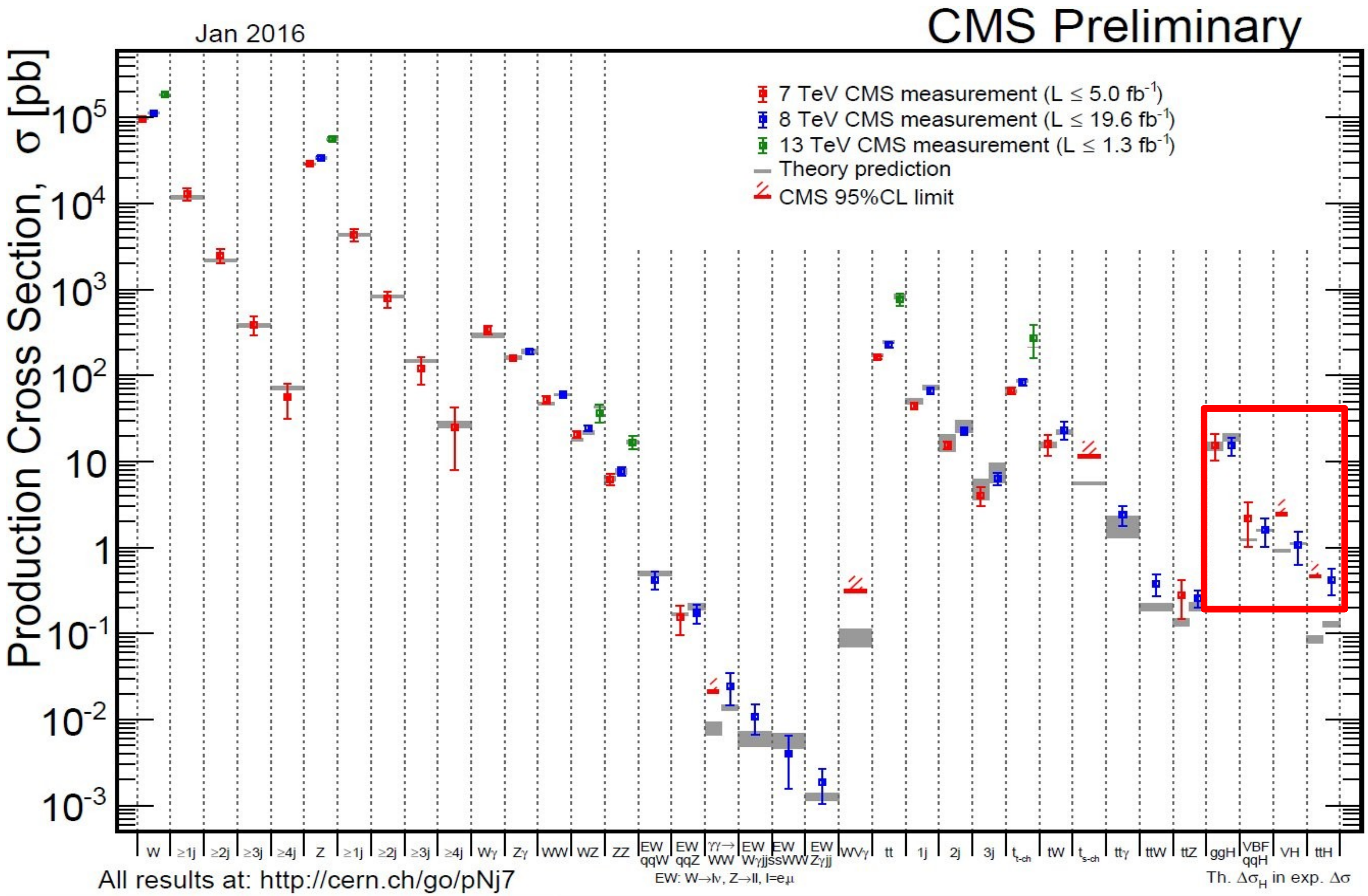
The fast duty cycle of the LHC analyses is possible thanks to the Tier0 and GRID resources





- 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.

Summary of SM results



- Good agreement with SM expectations within uncertainties.
- Experimental uncertainties are in some cases at the level of the theor. predictions

Preliminary measurements of the cross-sections down to few pb (~tens of fb in some cases if we include also the BR).
Comparable to Higgs production σ_{total}

Higgs Mechanism Birth

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

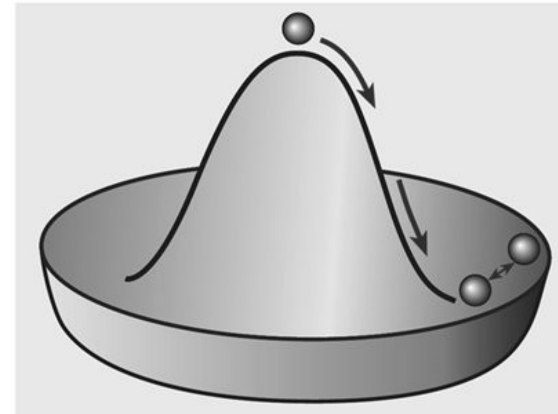
VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

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*

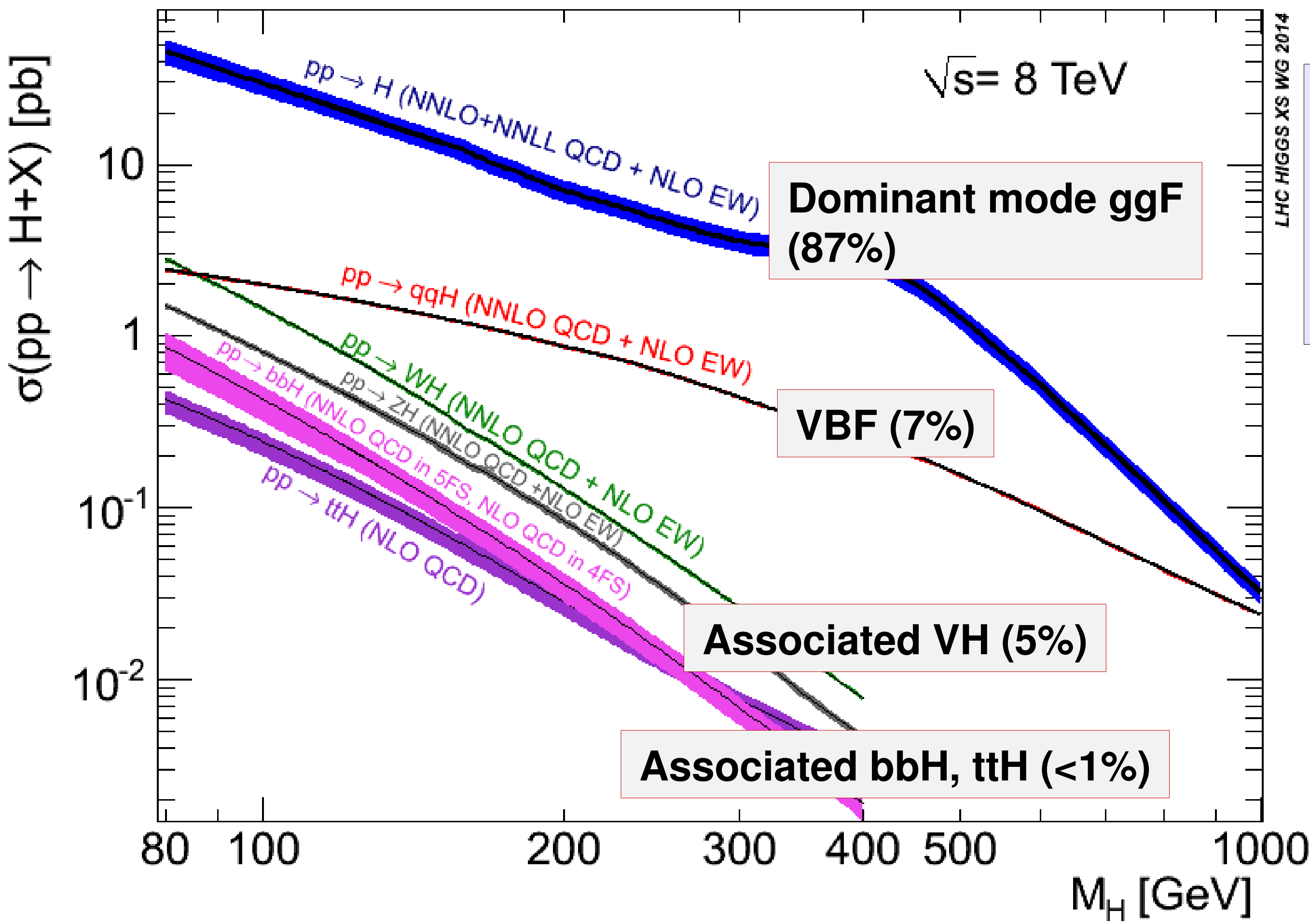
G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)



- EW Gauge bosons in previous formulation of the SM were massless.
- Four seminal papers in 1964 proposed a spontaneous symmetry breaking mechanism in relativistic gauge theory.

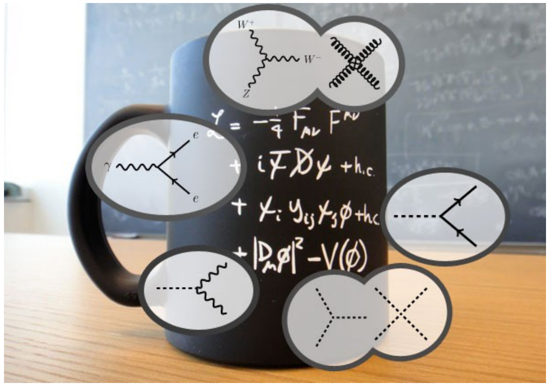
- The introduction of a complex scalar doublet allow to give mass to the *W* and *Z* bosons after symmetry breaking.
- 3 deg. of freedom go in the longitudinal polarizations of the $W^{\pm}$ and Z
- Remaining d.o.f. is a new scalar particle → the Higgs boson
- Yukawa couplings to fermions was later introduced in the formulation of the SM
- In the SM, all Higgs parameters are determined once the Higgs mass is known.

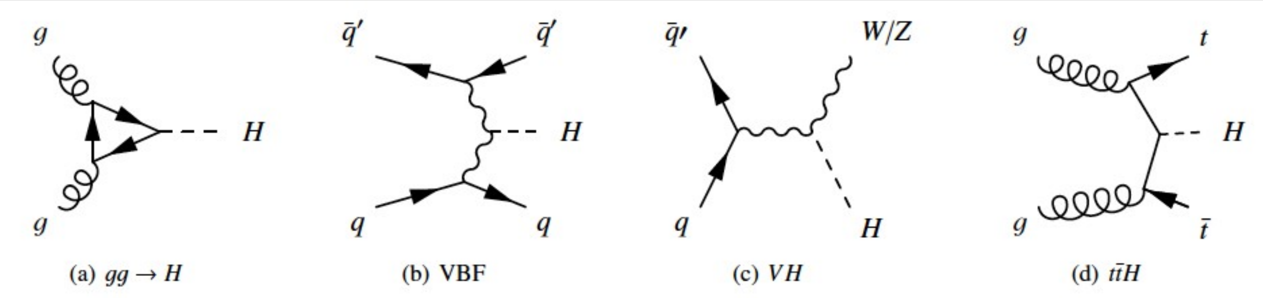
Higgs Production Modes at LHC



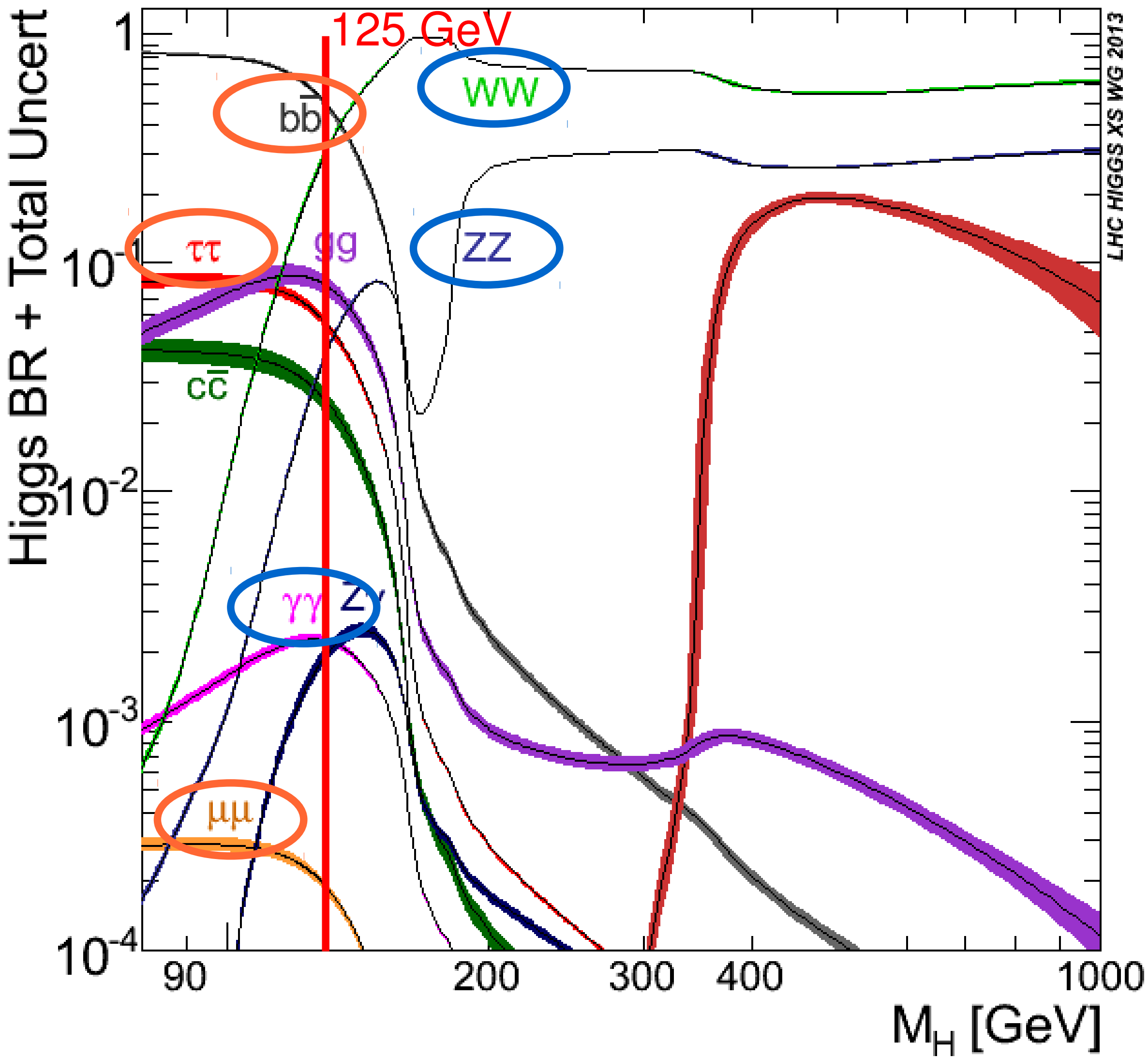
Total x-section:

17 pb (17000 evts/fb^{-1}) @7 TeV
22 pb (22000 evts/fb^{-1}) @8 TeV
51 pb (51000 evts/fb^{-1}) @13TeV

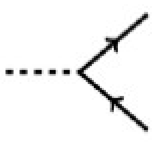




Higgs Decay Modes

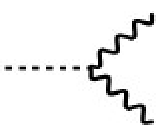


Fermionic modes: *ττ, μμ, bb*



$$\propto \frac{m_f}{v}$$

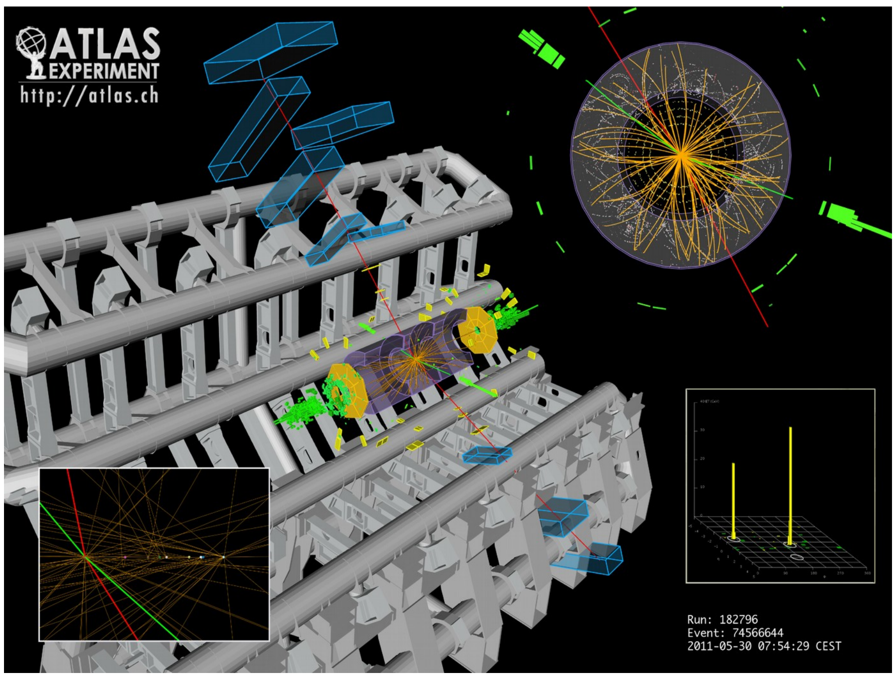
Bosonic modes: *γγ, ZZ, WW*

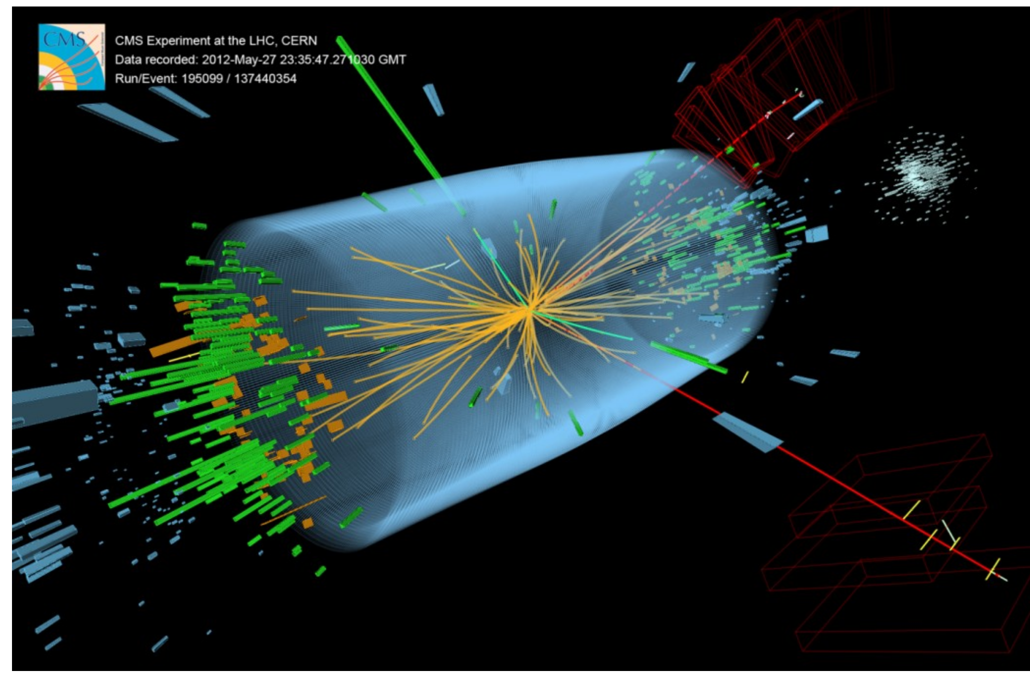


$$\propto \frac{m_V^2}{v}$$

They can also provide indirect measurement of couplings to quarks at LHC (via virtual loops)

$$\mathcal{H} \to ZZ^* \to 4\ell$$





$\mathcal{H} \to ZZ^* \to 4\ell$

"Golden channel"

- Three different channels: 4e, 4μ, 2e2μ
- Very high S/B
- Used to study mass, spin, couplings, width and fiducial and differential cross-sections.

Main backgrounds:

- ZZ* (irreducible)
- ttbar, Z+jets

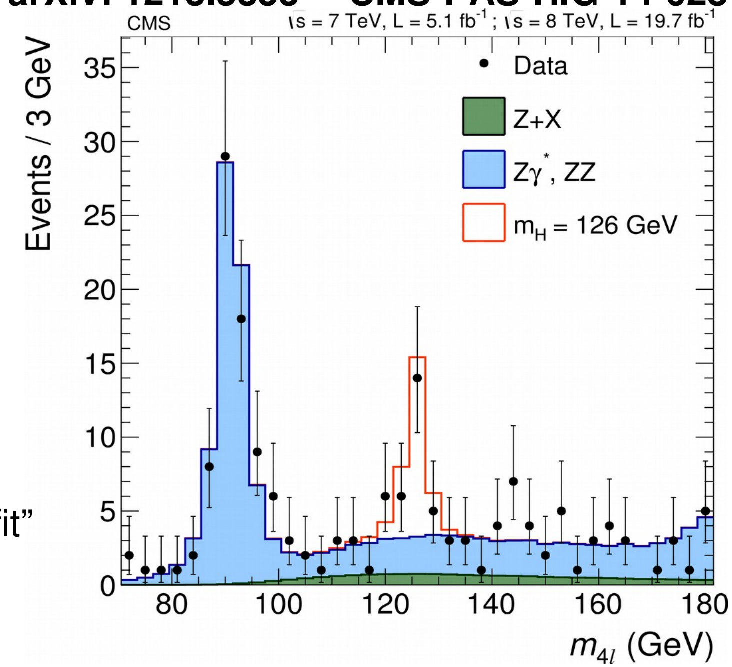
- Signal Extracted with Profile Likelihood Ratio

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

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

Denominator → Best-fit max lh, "unconditional fit"

arXiv: 1213.5353 CMS-PAS-HIG-14-028



ATLAS 8 TeV Results

Significance 8.1 obs (6.2 exp) σ

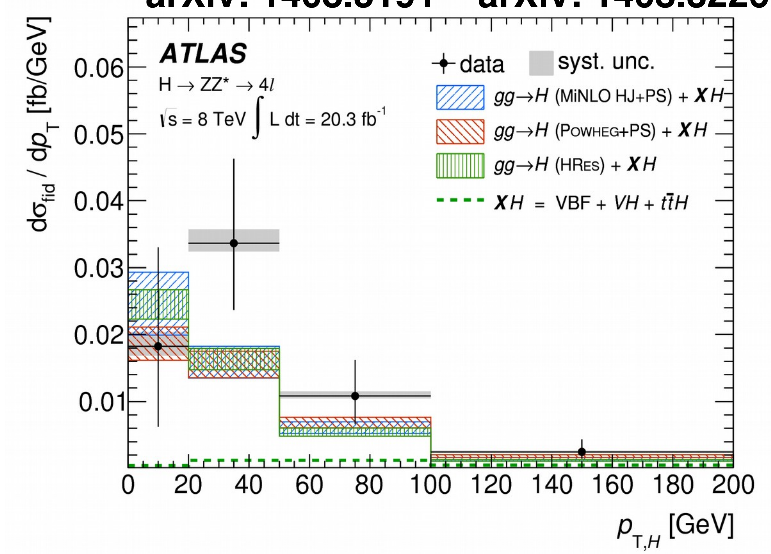
$\mu = \sigma/\sigma_{SM}$ @ 125.36 GeV = $1.4^{+0.4}_{-0.3}$

CMS 8 TeV Results

Significance 6.5 obs (6.3 exp) σ

$\mu = \sigma/\sigma_{SM}$ @ 125.0 GeV = 1.0 ±0.3

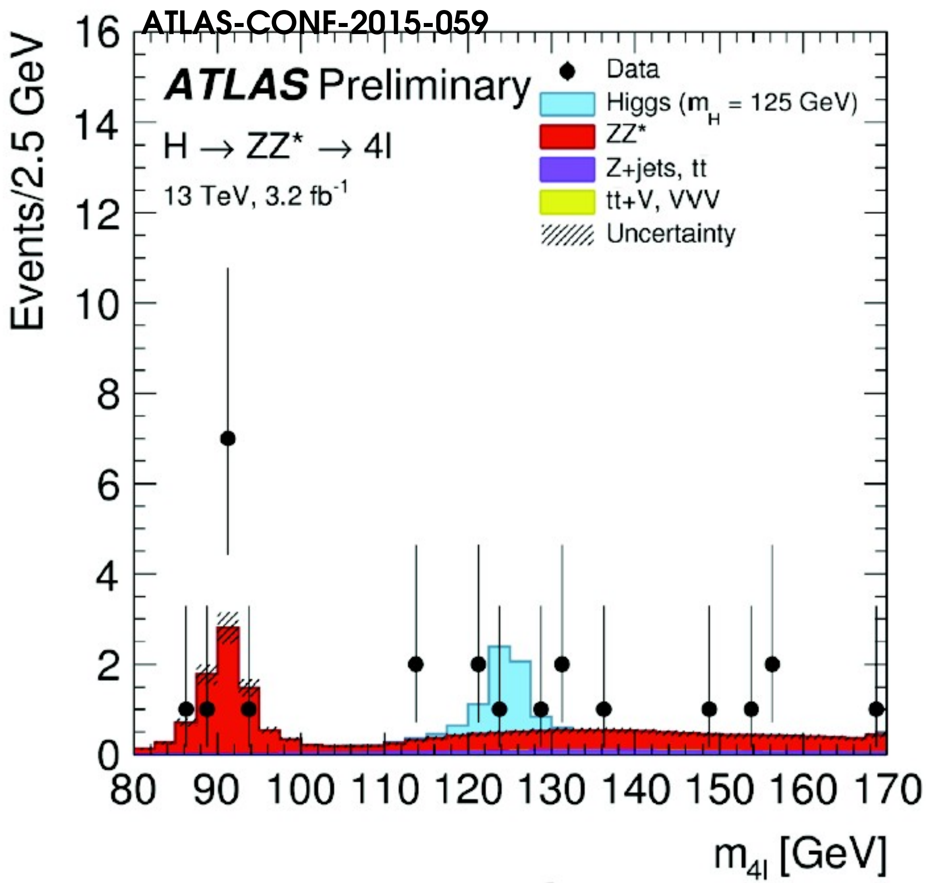
arXiv: 1408.5191 arXiv: 1408.3226

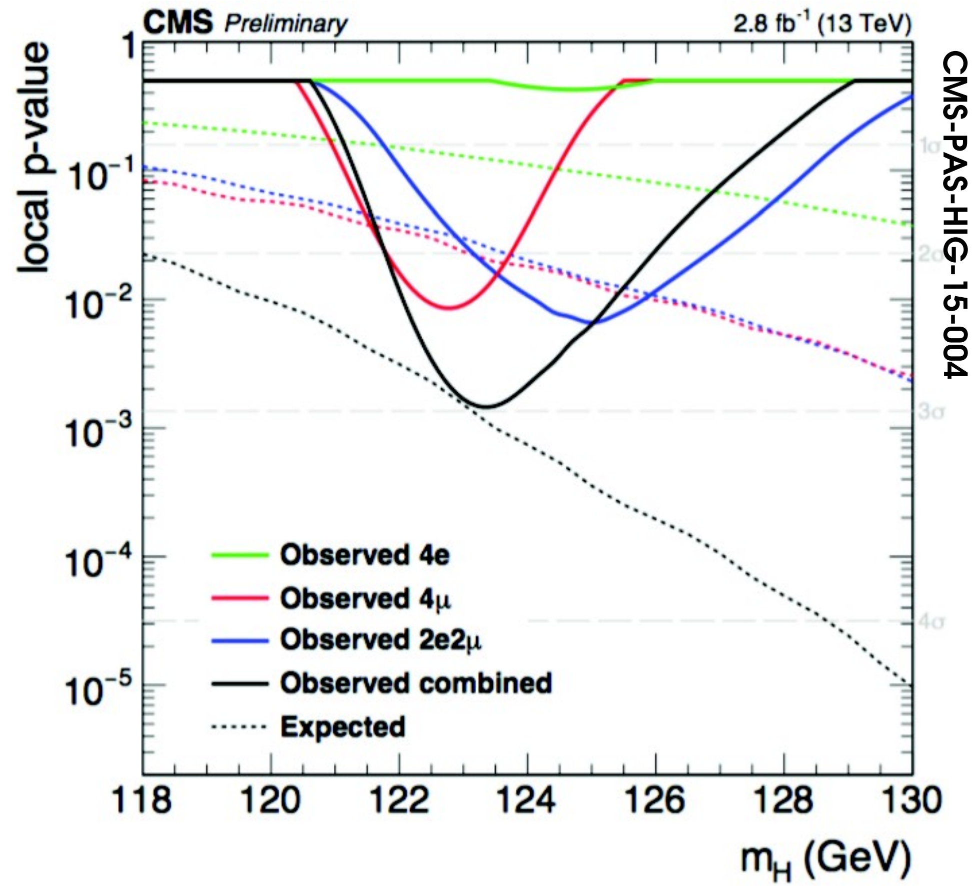


No significant deviation from SM observed in the fiducial cross section measurement.

13 TeV $H \rightarrow ZZ^* \rightarrow 4l$

First cross-section measurements at 13 TeV





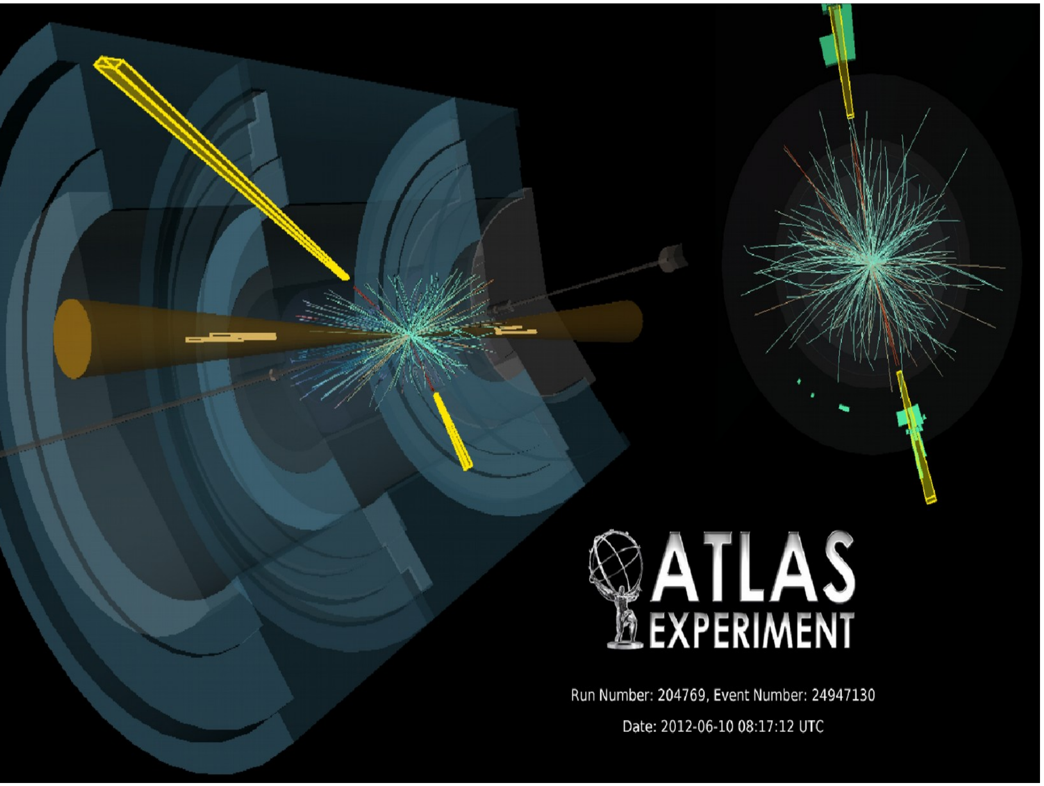
ATLAS 118-129 GeV

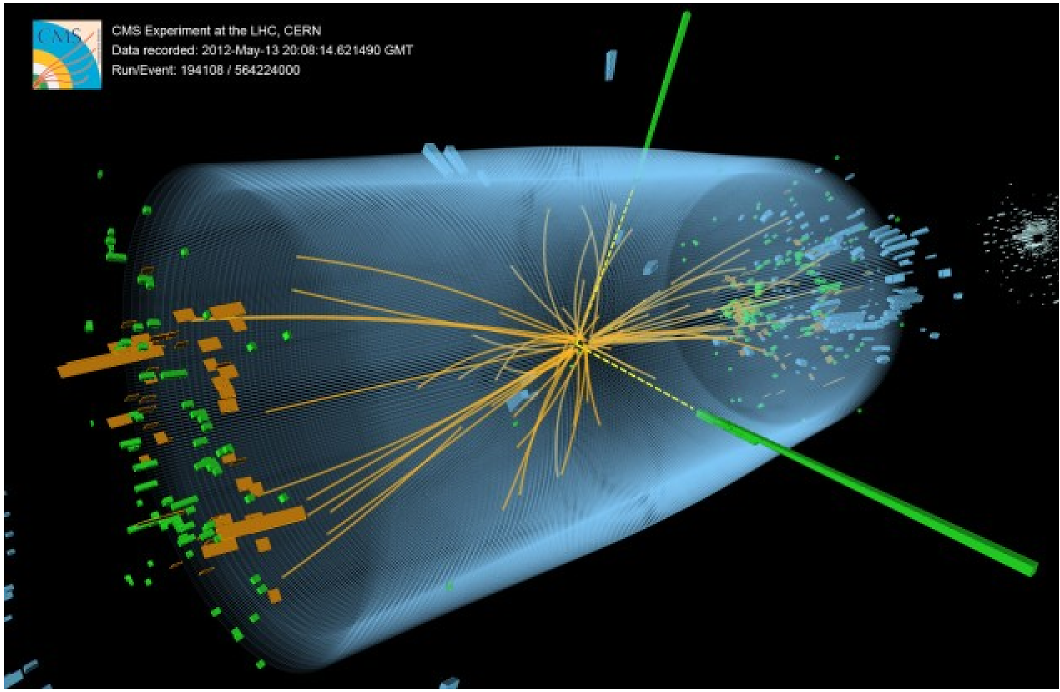
Final state	Signal full mass range	Signal	ZZ^*	$Z+jets$, $t\bar{t}$ $t\bar{t}V$, VVV, WZ	S/B	Expected	Observed
4μ	1.79 ± 0.21	1.67 ± 0.20	0.64 ± 0.06	0.08 ± 0.03	2.3	2.39 ± 0.21	1
$2e2\mu$	1.19 ± 0.14	1.06 ± 0.13	0.44 ± 0.04	0.07 ± 0.03	2.1	1.57 ± 0.14	1
$2\mu 2e$	1.07 ± 0.16	0.96 ± 0.15	0.34 ± 0.05	0.09 ± 0.02	2.2	1.40 ± 0.16	2
$4e$	1.01 ± 0.15	0.88 ± 0.13	0.32 ± 0.05	0.09 ± 0.02	2.1	1.30 ± 0.14	0
Total	5.06 ± 0.60	4.57 ± 0.54	1.74 ± 0.19	0.34 ± 0.06	2.2	6.65 ± 0.58	4

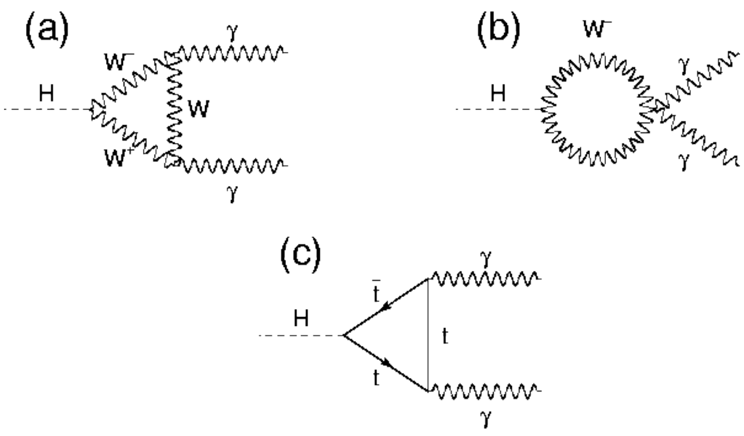
CMS 118-130 GeV

Channel	4e	4μ	$2e2\mu$	4ℓ
$q\bar{q} \rightarrow ZZ$	0.33 ± 0.03	0.75 ± 0.05	0.92 ± 0.07	2.00 ± 0.14
$gg \rightarrow ZZ$	0.04 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	$0.18^{+0.03}_{-0.02}$
Z+X	$0.17^{+0.15}_{-0.09}$	0.19 ± 0.08	0.26 ± 0.10	$0.62^{+0.20}_{-0.16}$
Sum of backgrounds	$0.54^{+0.16}_{-0.10}$	1.02 ± 0.09	1.25 ± 0.13	$2.80^{+0.25}_{-0.22}$
Signal ($m_H = 125$ GeV)	$0.91^{+0.11}_{-0.10}$	1.70 ± 0.15	2.21 ± 0.22	$4.82^{+0.44}_{-0.45}$
Total expected	$1.45^{+0.21}_{-0.16}$	2.72 ± 0.20	3.45 ± 0.29	$7.62^{+0.58}_{-0.56}$
Observed	1	3	4	8

$\mathcal{H} \to \gamma\gamma$





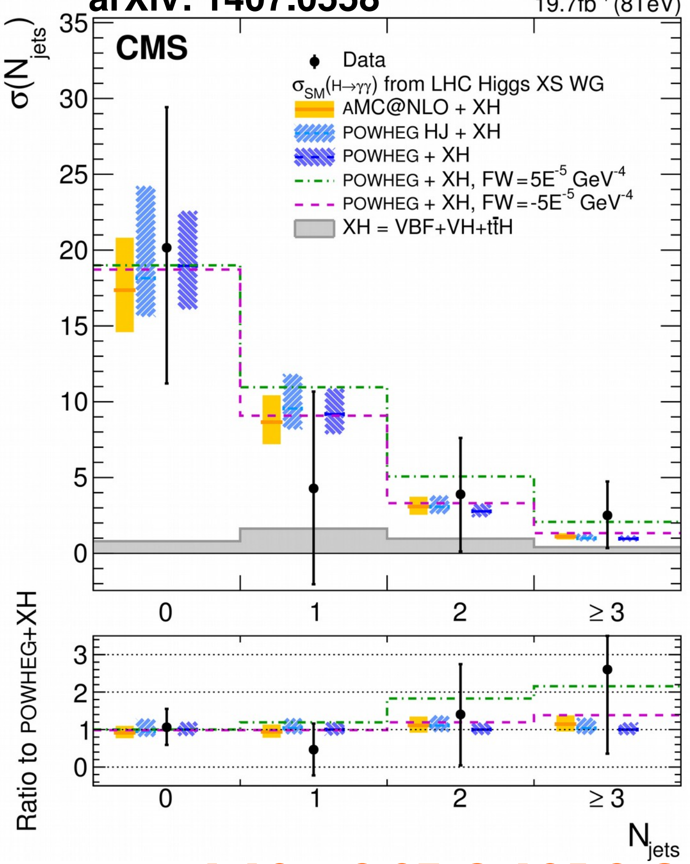


8 TeV $H \rightarrow \gamma\gamma$

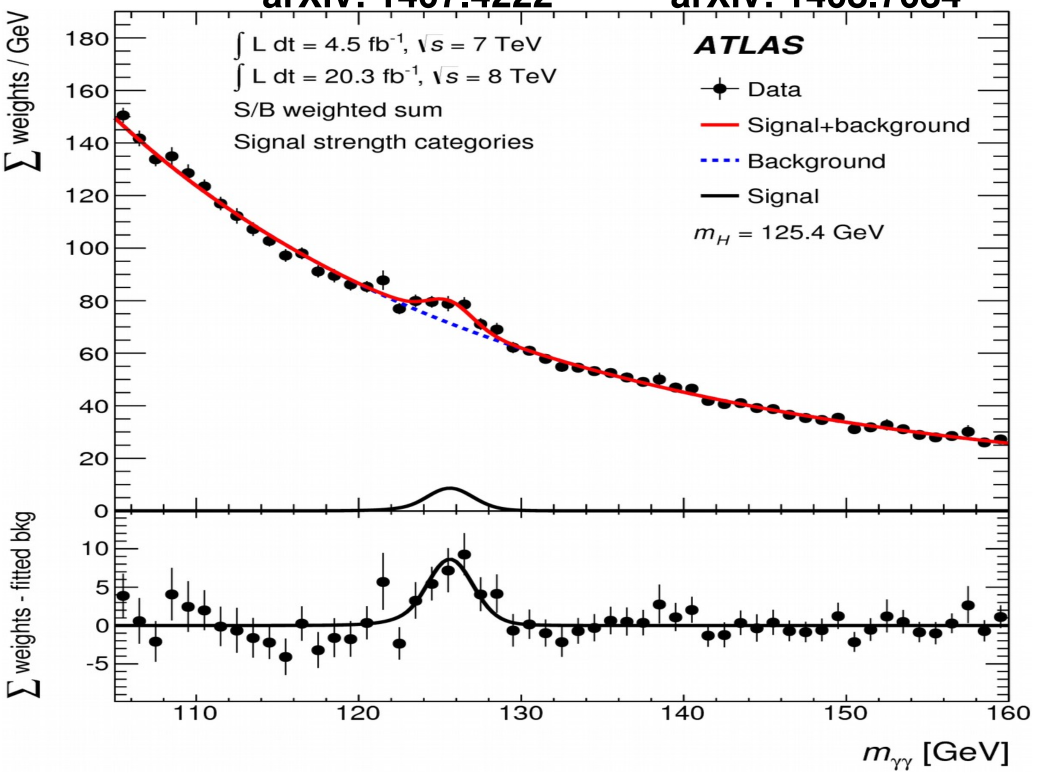
Final results from both ATLAS and CMS in 2014-2015 after impressive improvement of calibration and energy scales.

arXiv: 1508.7819

arXiv: 1407.0558



arXiv: 1407.4222 **arXiv: 1408.7084**



$\mu = 1.12 \pm 0.27$ @ 125.0 GeV

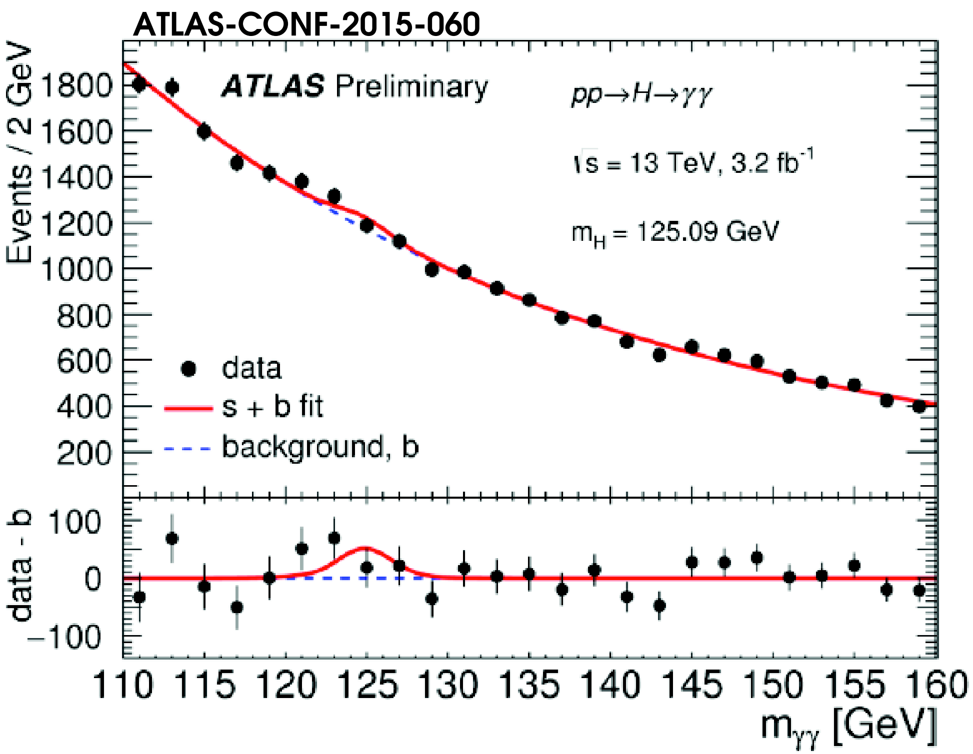
- Main syst. Uncertainties are PDF, theory uncertainties and showe shape model.
- Fiducial xsec measured for 12 variables in 2 fiducial regions.

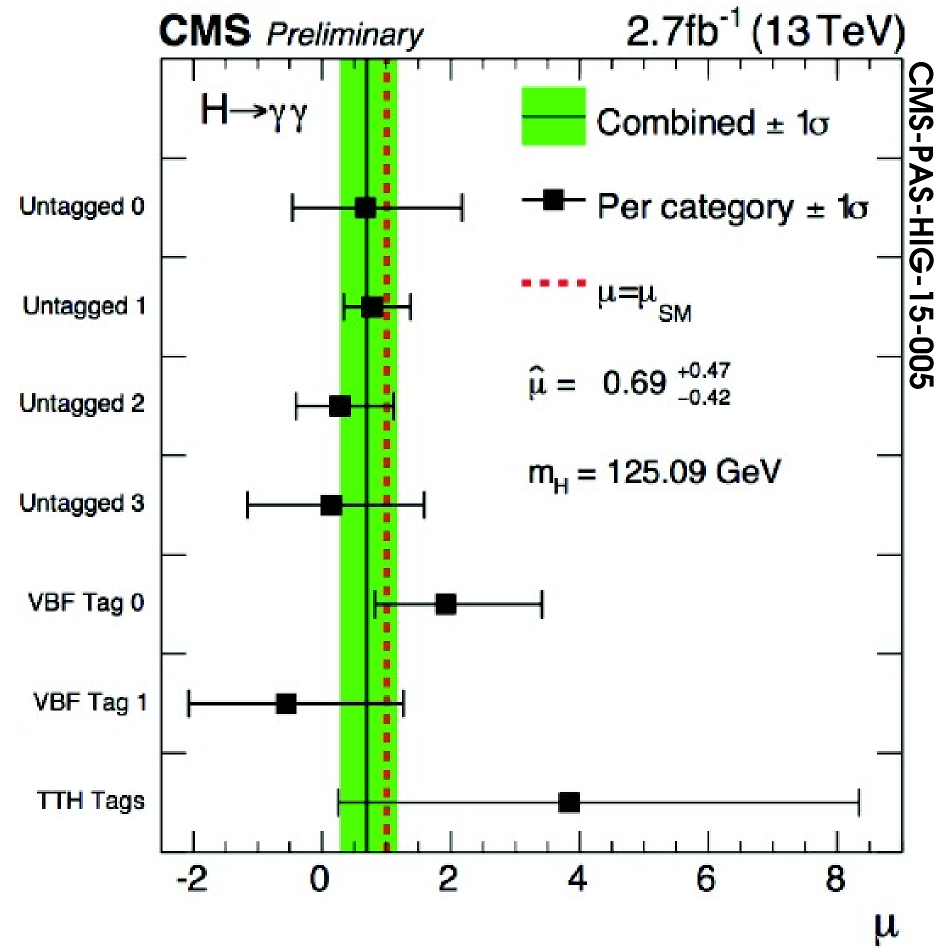
$\mu = 1.17 \pm 0.27$ @ 125.36 GeV

- Main syst. uncertainty related to luminosity meas. and photon isolation.
- Differential xsec measured in 7 fiducial regions and 12 different variables.

$13\ TeV\ H \to \gamma\gamma$

First Results with 2015 data





Both experiments fix mass to the Run-1 measurement, stronger constraint than with Run-2 data

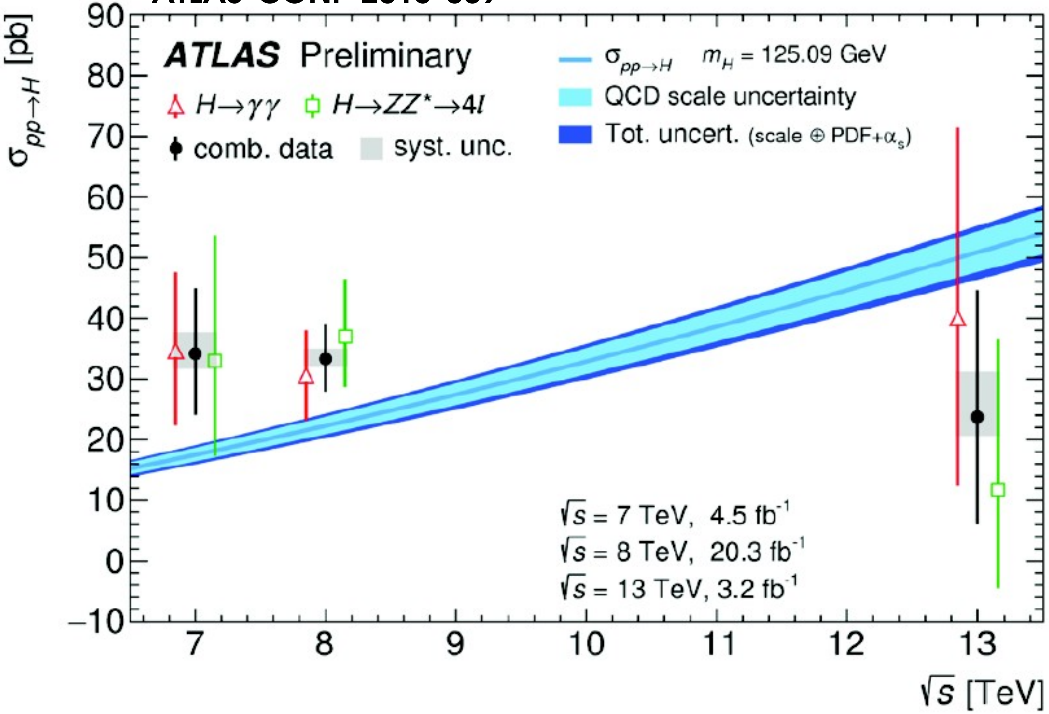
ATLAS provides a fiducial cross-section measurement

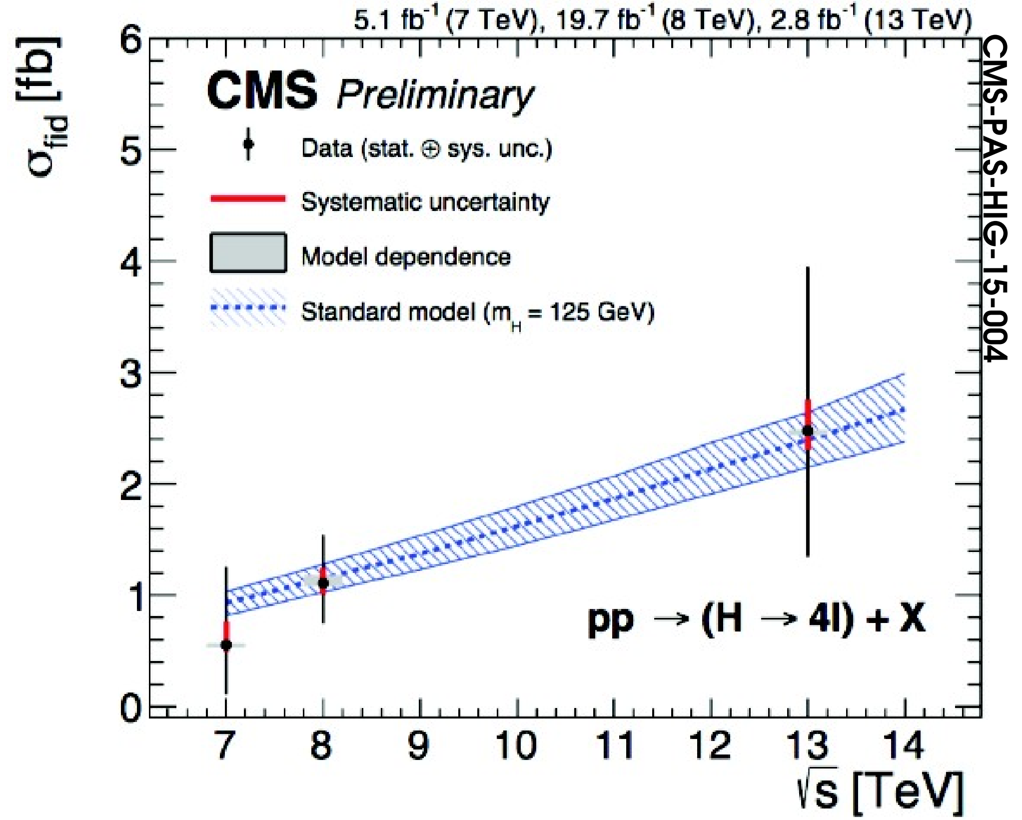
CMS 4 main categories are selected with a MultiVariate Analysis (MVA) classifier.

2 additional VBF categories and ttH tag category

13 TeV Higgs cross-section

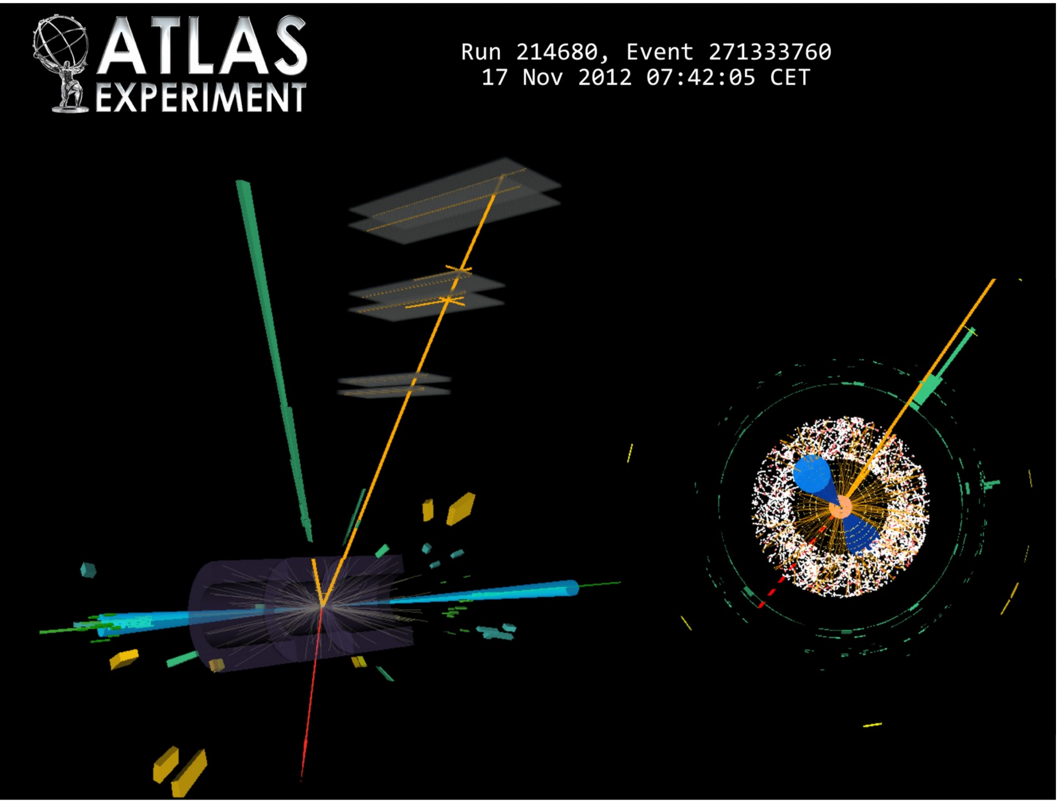
ATLAS-CONF-2015-069

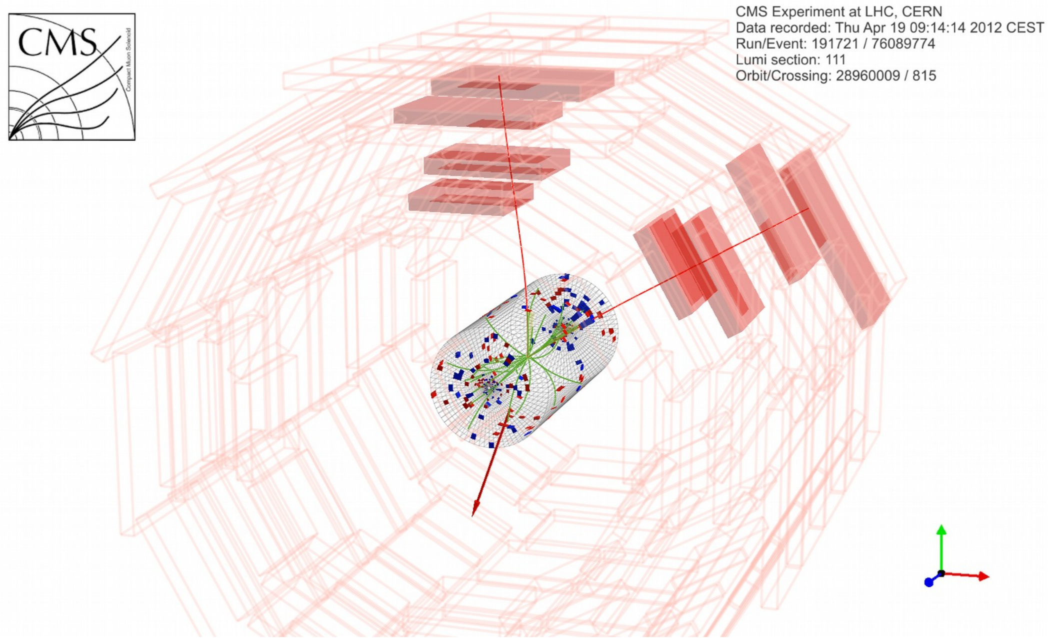




First Higgs fiducial and total cross-section measurements @13 TeV

$\mathcal{H} \to W^*W$

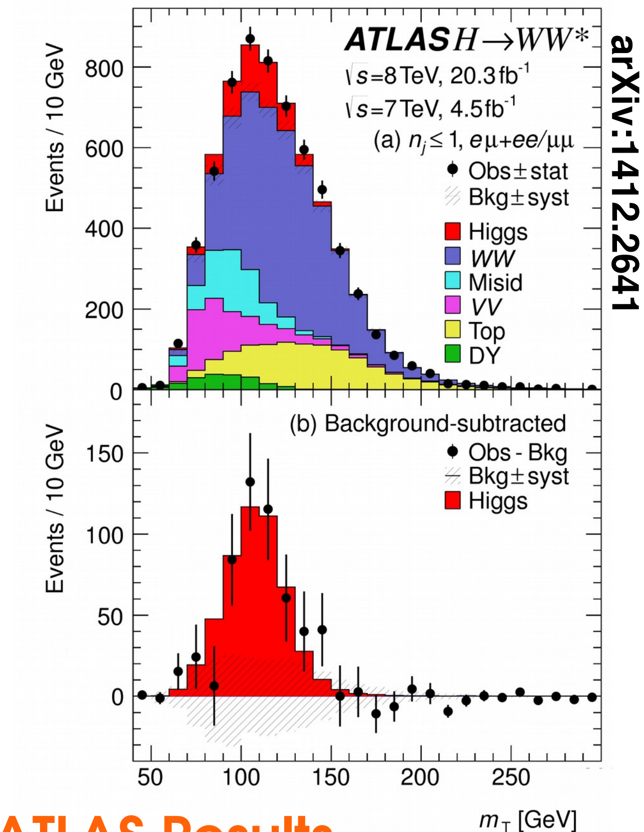


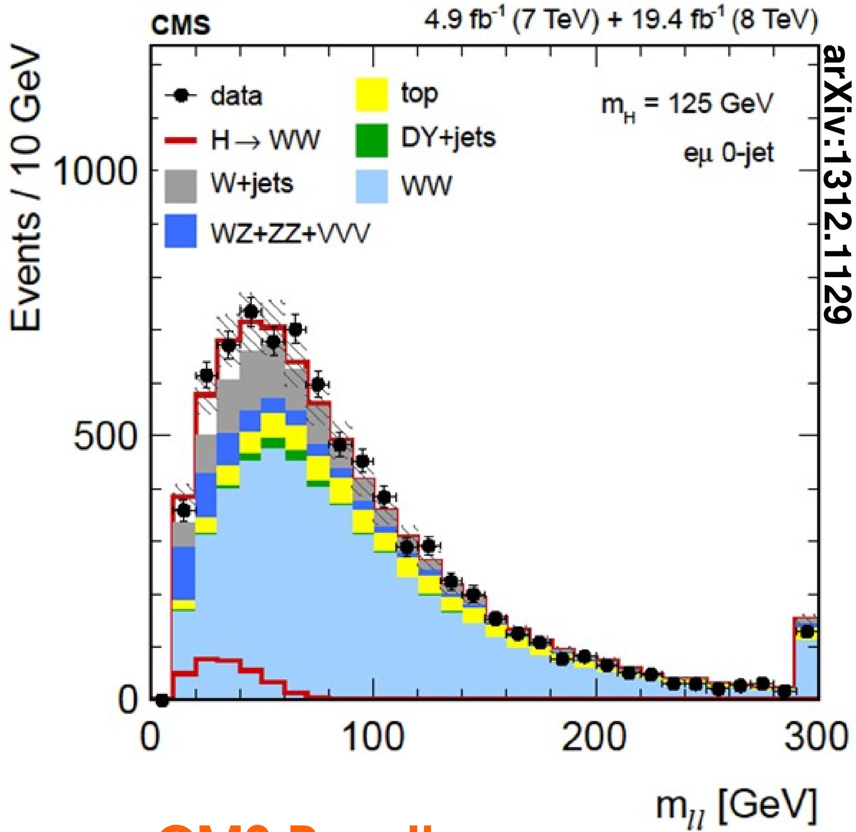


$H \rightarrow WW^* \rightarrow 2l2\nu$

Features:

- ATLAS divides the data in 0jet and 1jet and 2jet (VBF) categories.
- CMS extracts signal from a 2D fit techniques of m_{ll} vs m_T in 0/1jet and 2jet (VBF, VH) categories.
- CMS includes VH production. ATLAS has a separate search (arXiv:1506.06641)





ATLAS Results

Significance 6.5 obs (5.9 exp) σ

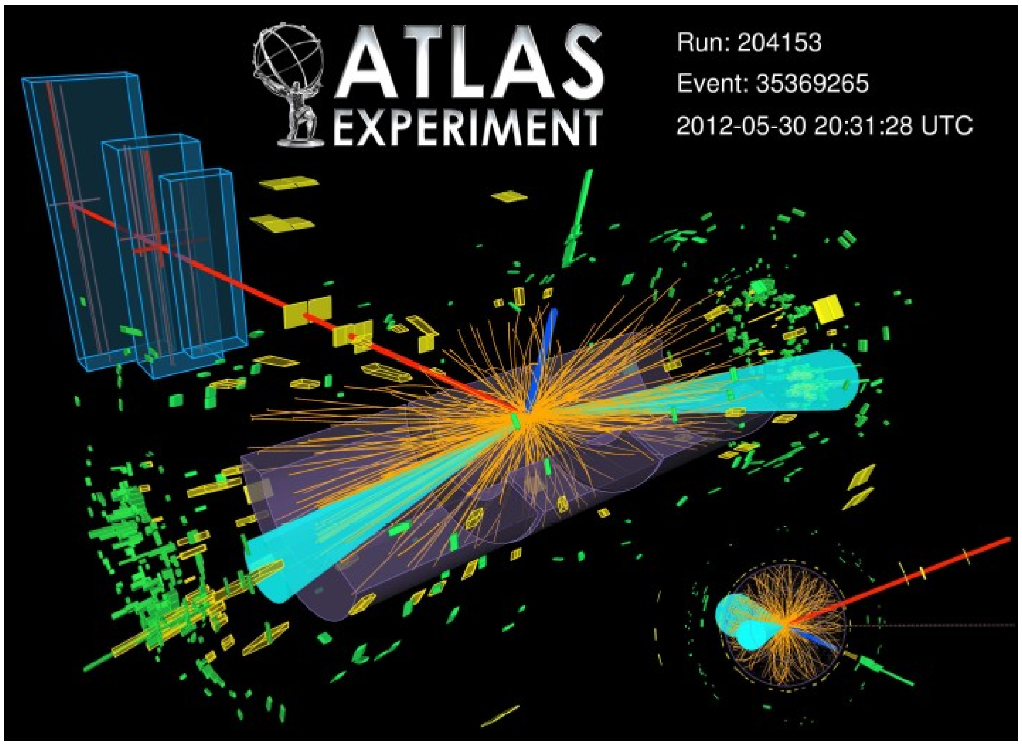
Signal Strength $\mu = 1.16^{+0.24}_{-0.21}$

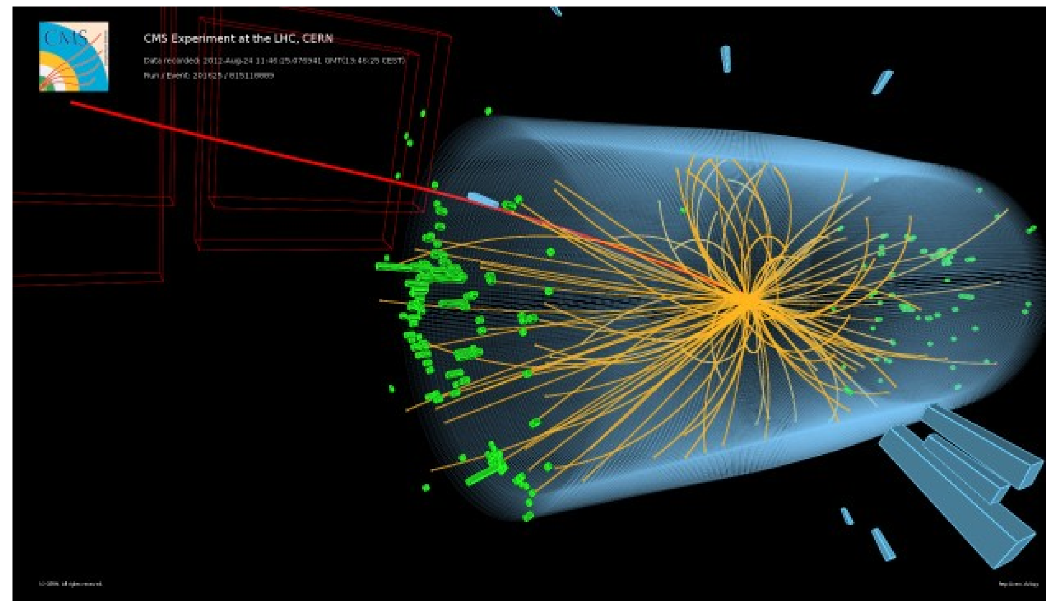
CMS Results

Significance 4.7 obs (5.4 exp) σ

$\mu = 0.83 \pm 0.21$

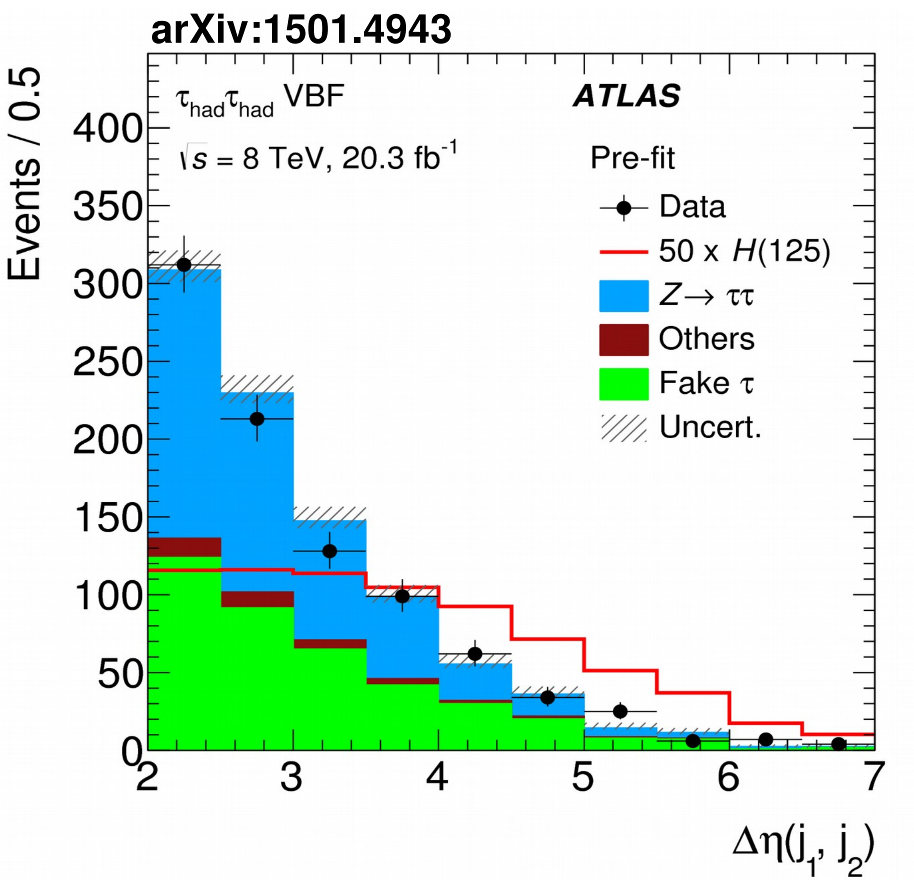
$\mathcal{H} \rightarrow \tau\tau$

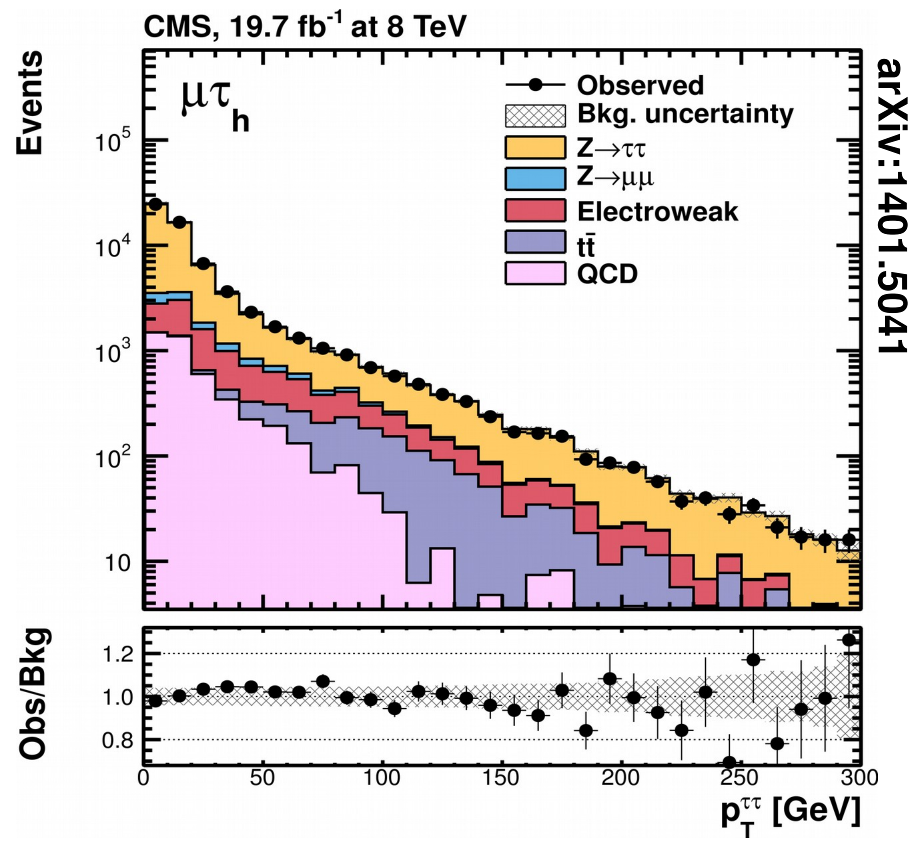




$H \to \tau\tau$ Analysis

- Main background is $Z \to \tau\tau$ modelled by tau-embedding of data $Z \to \mu\mu$
- ATLAS employs MVA analysis. CMS cut-based analysis includes VH. ATLAS has a separate analysis.



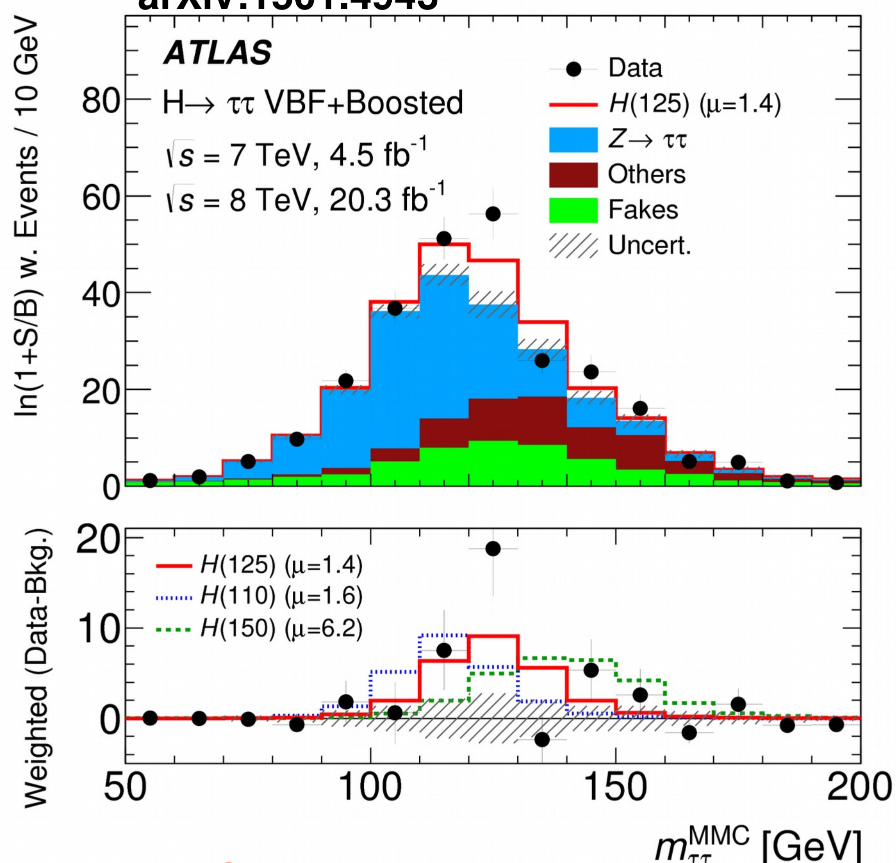


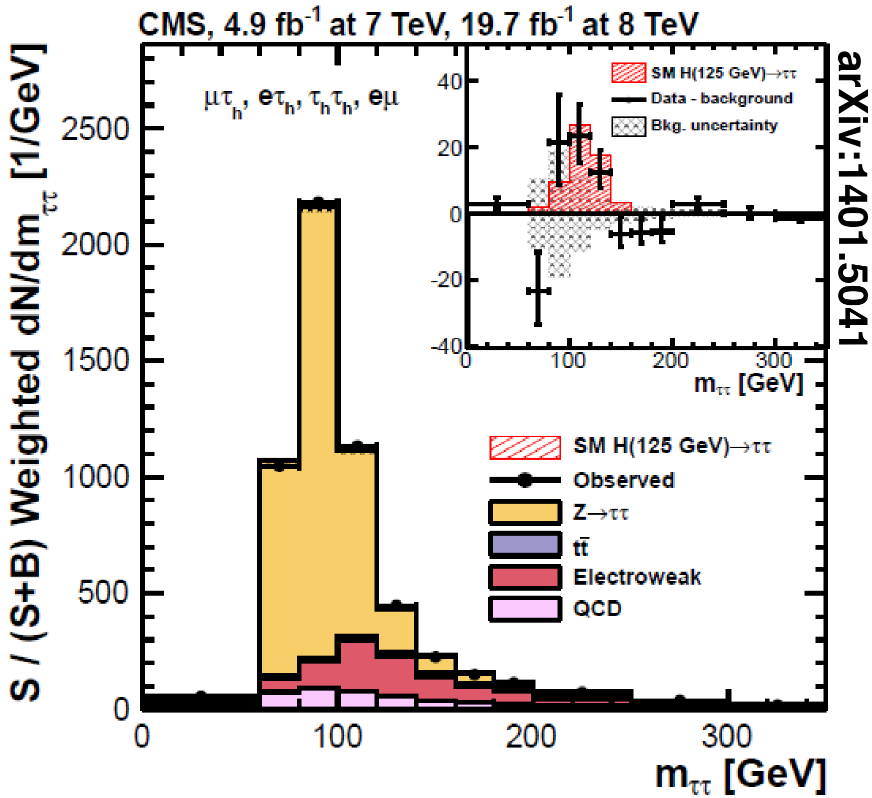
Analysis includes leptonic and hadronic decay channels of the taus.
Events are divided in 0-jet, 1-jet and 2-jet categories to enhance sensitivity to the VBF production mode and to ggF production of highly boosted Higgs bosons.

$H \to \tau\tau$ Results

- Evidence of Higgs fermionic decays:
  - Excess wrt expected background observed by both experiments
  - Highest significance among fermionic channels thanks to sensitivity to VBF process.

arXiv:1501.4943





ATLAS Results

Significance 4.5 obs (3.4 exp) σ

$$\mu = 1.43\ ^{+0.43}_{-0.37}$$

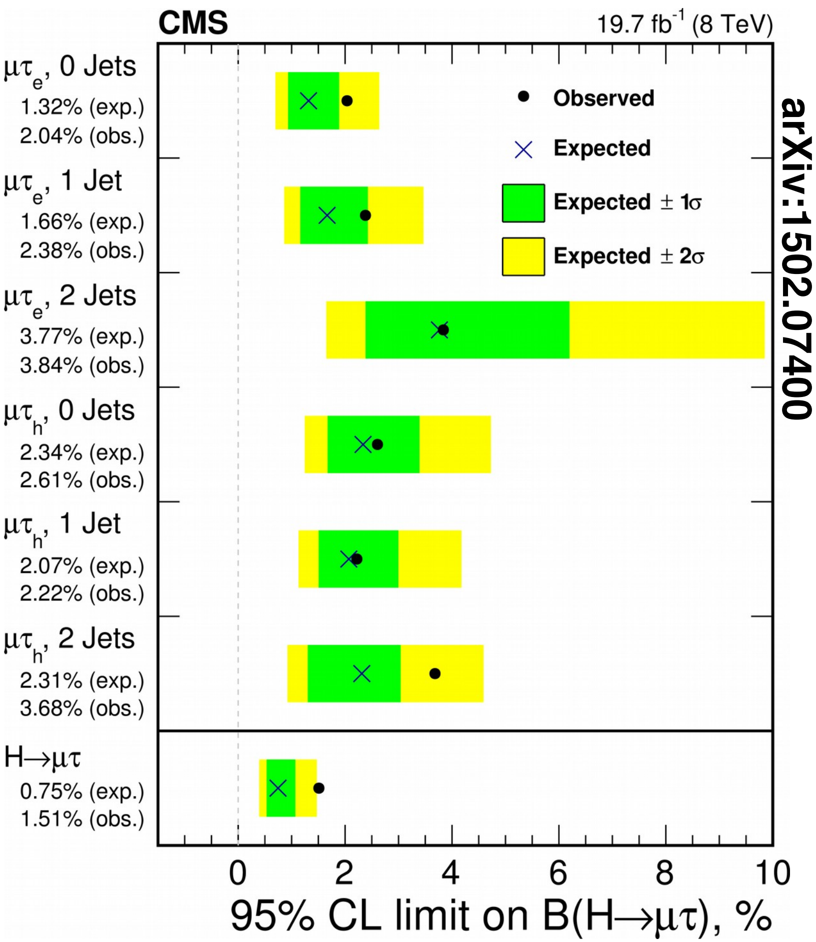
CMS Results

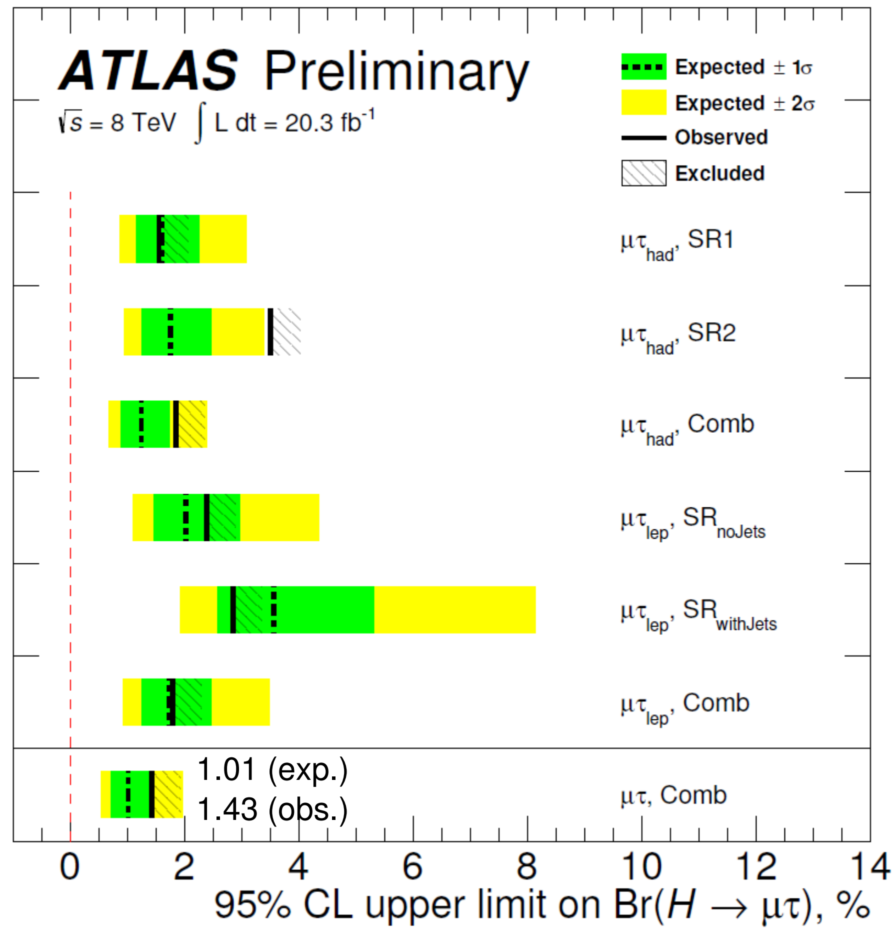
Significance 3.2 obs (3.7 exp) σ

$\mu = 0.78 \pm 0.27$

LFV $H \to \tau\mu$ Search

- CMS and ATLAS searches for LFV $H \to \tau\mu$ decay are adapted from the $H \to \tau\tau$ analyses.
  - Main backgrounds are the $Z \to \tau\tau$, W+jets and QCD production.

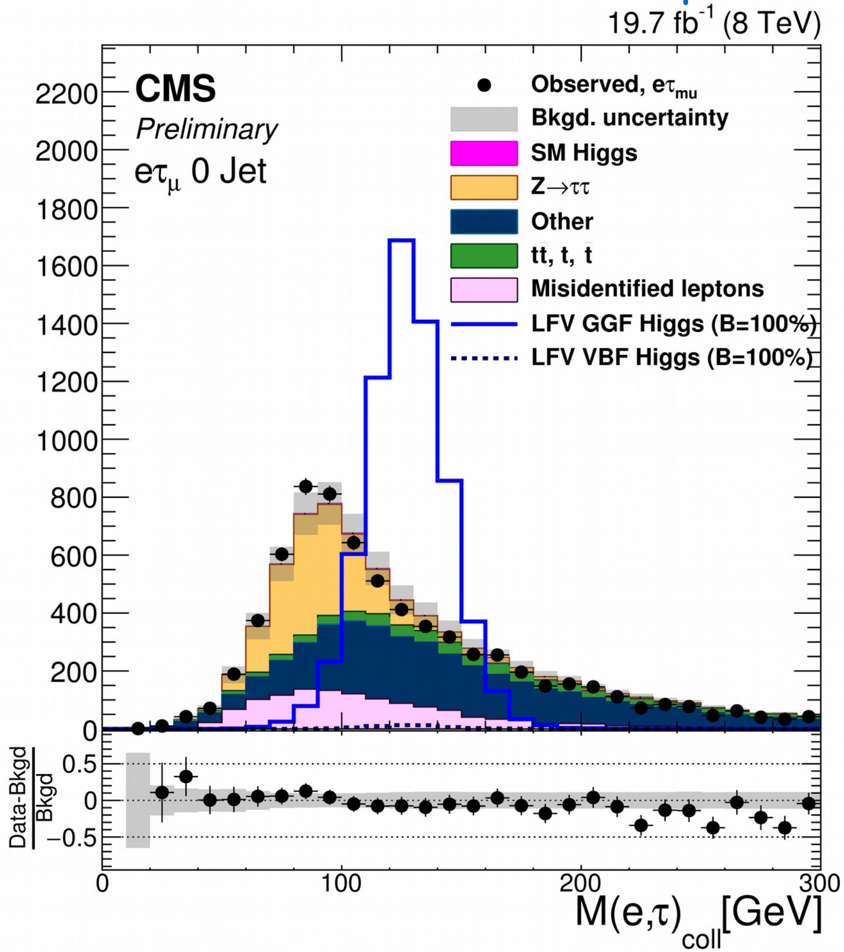


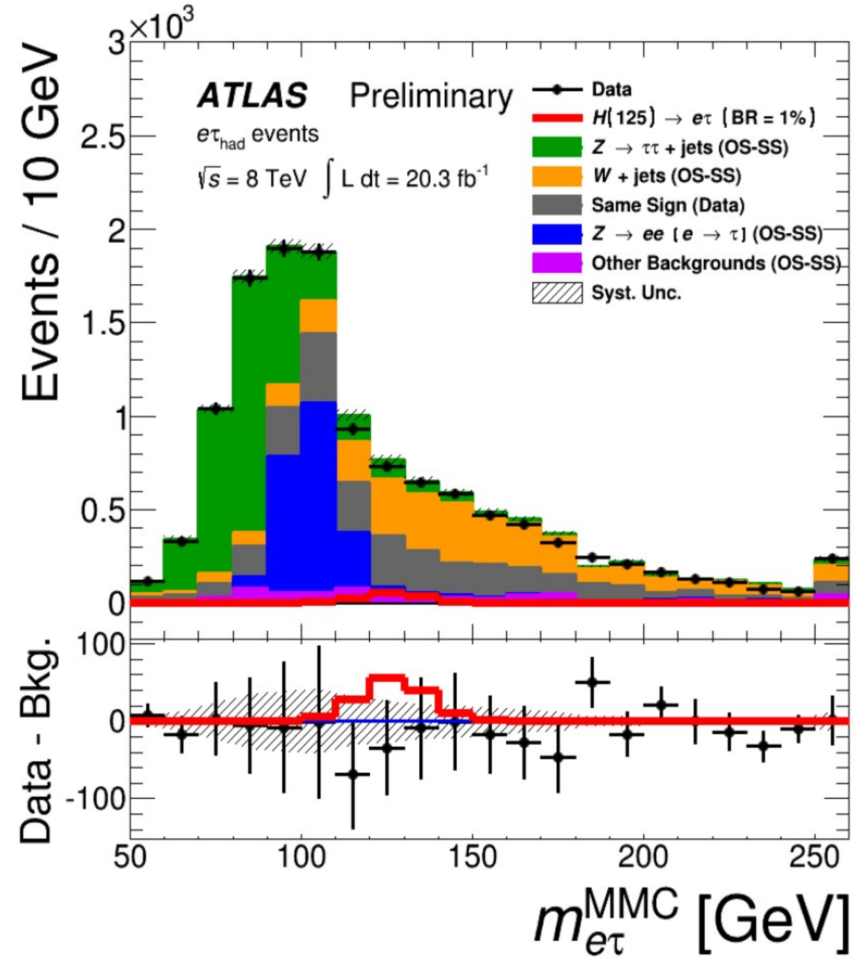


- CMS found 2.4σ excess corresponding to best fit $BR(H \to \tau\mu) = (0.84^{+0.39}_{-0.37})\%$
- ATLAS recently added $\tau_e\,\mu$ to $\tau_{had}\,\mu$ previous result. Best fit $BR(H \to \tau\mu) = (0.53 \pm 0.51)\%$

LFV $H \to \tau e$ Search

- Both experiments exploit final states with an electron and a tau decays to hadrons or muon.
- CMS also has results for $H \to e\mu$ search, no excess obseved.





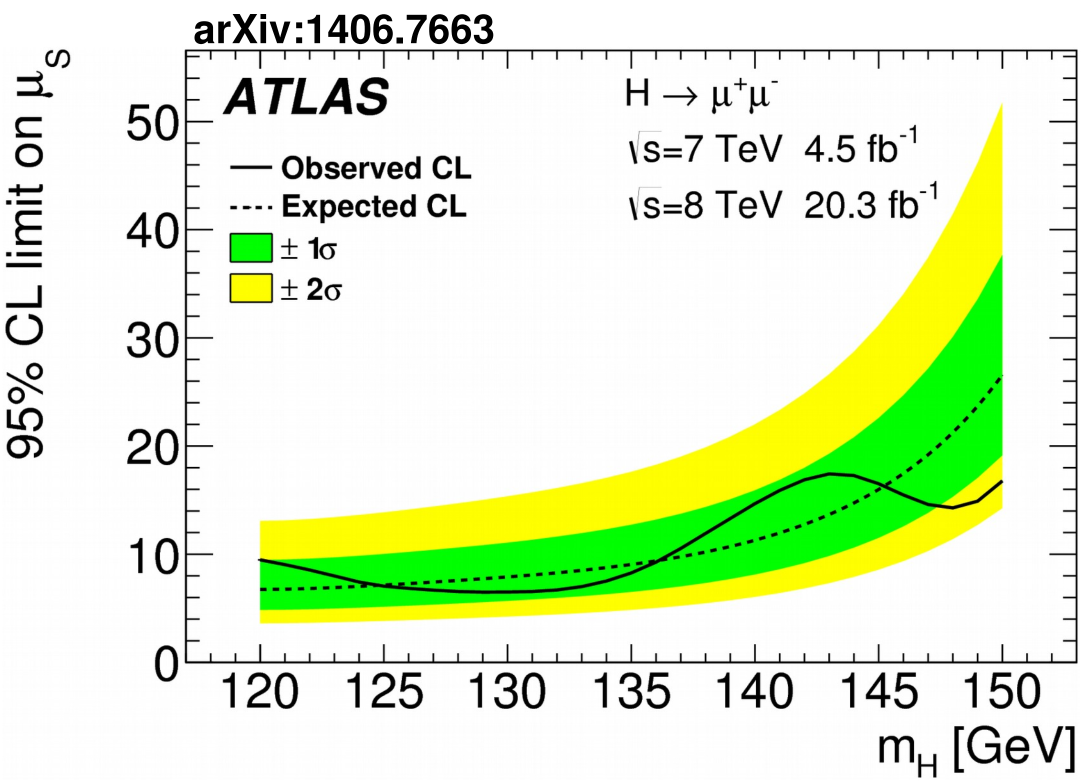
CMS Result

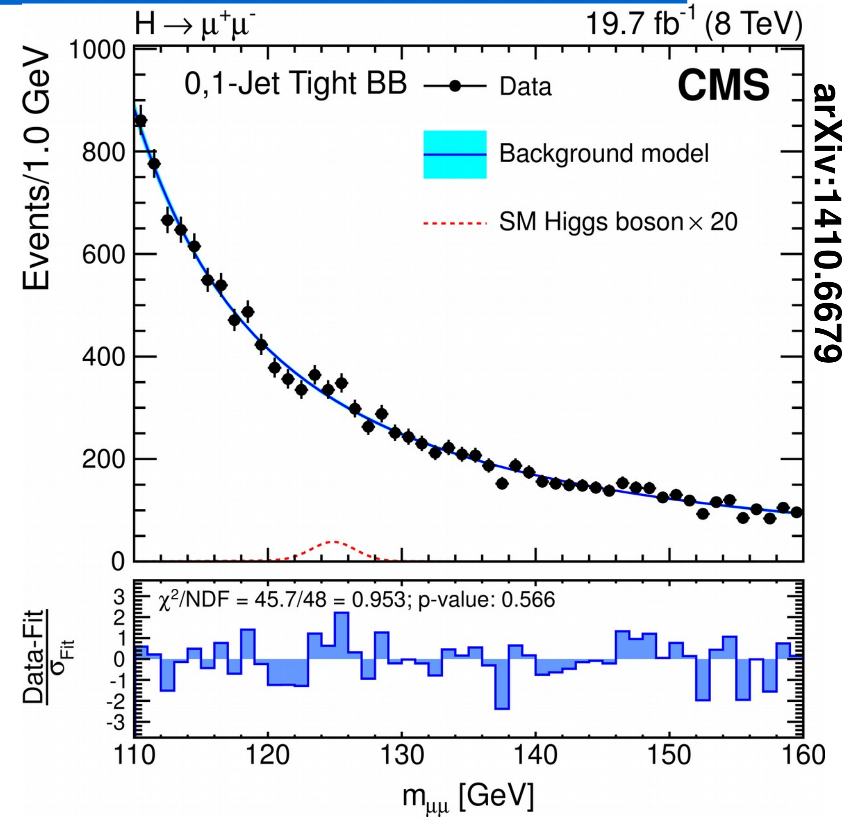
BR($H \to \tau e$) < 0.7%, 95% CL (exp. 0.75%)

ATLAS Result

BR($H \to \tau e$) < 1.0%, 95% CL (exp. 1.2%)

$H \rightarrow \mu\mu$





- Excellent mass resolution provides a clean signature.
- Result extracted from the fit of the $m_{\mu\mu}$ mass spectrum.
- 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 $H \rightarrow \mu\mu$

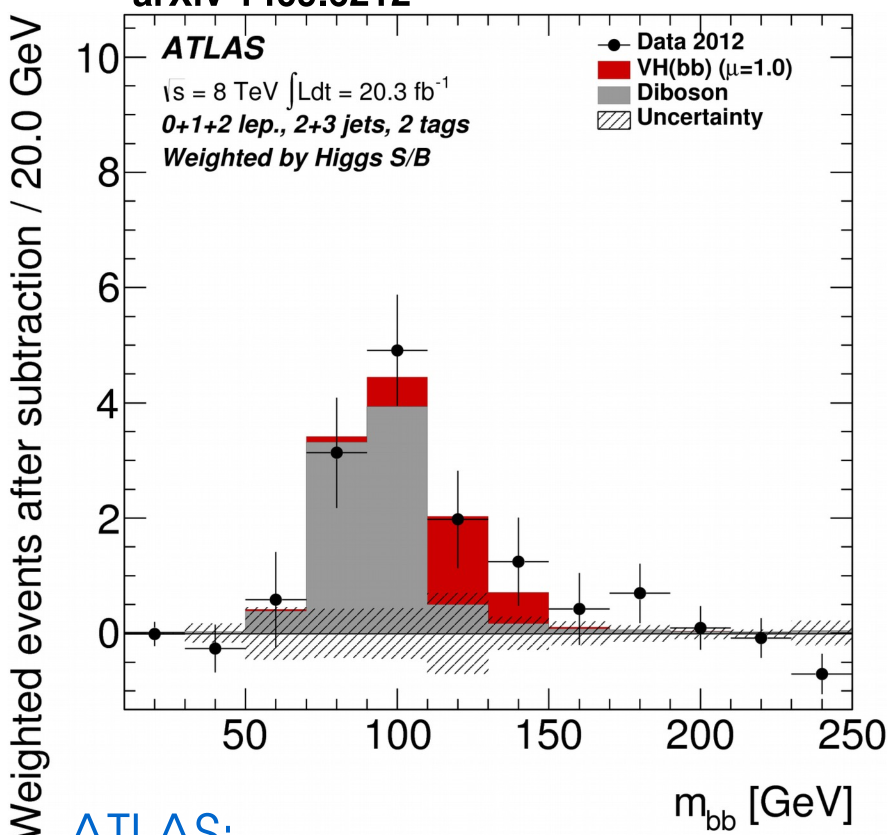
ATLAS:
Limit @ m_H=125 GeV: 7.0xSM
(7.2 exp)

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

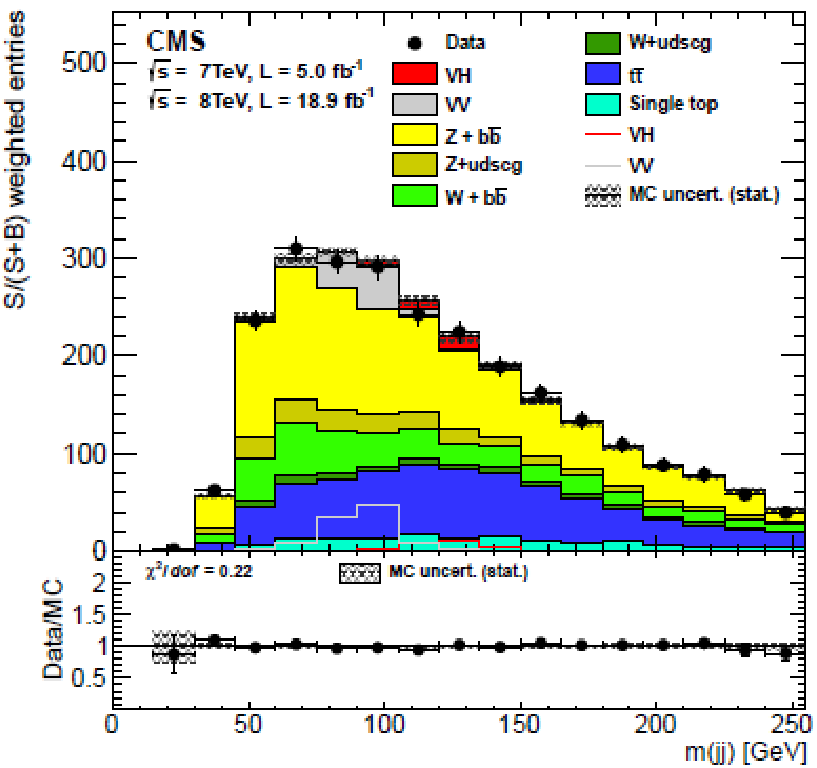
$VH \to bbar$

- Most abundant decay mode, 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 recently added a search for VBF production qqH(→bb).
- TeVatron has a combined significance of 2.8σ @125 GeV in the H → bb channel.

arXiv 1409.6212



arXiv:1310.3687 arXiv:1510.01010



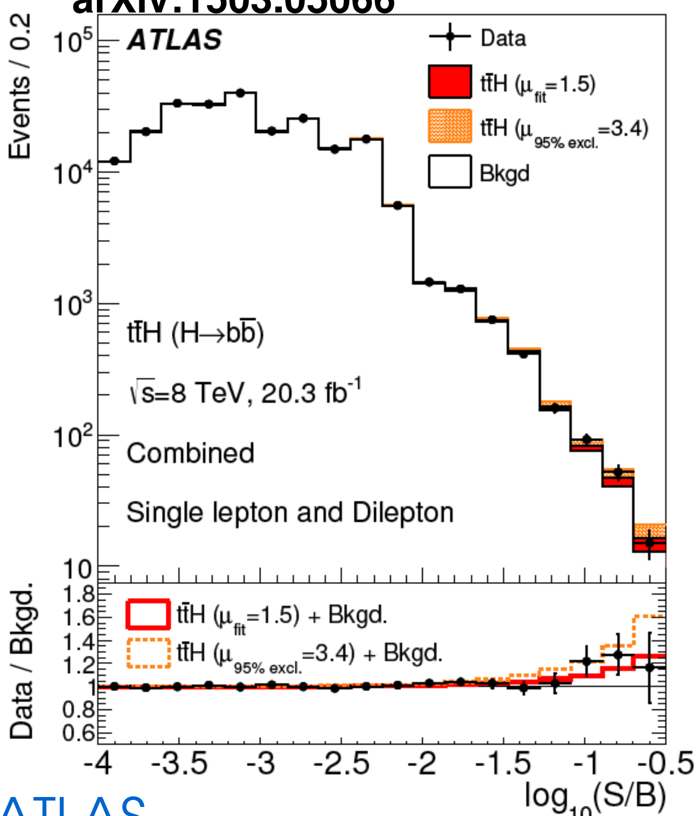
ATLAS:
$\mu=0.52\pm0.32(stat)\pm0.26(syst)$ @125.36 GeV
Significance 1.4 (2.6) σ

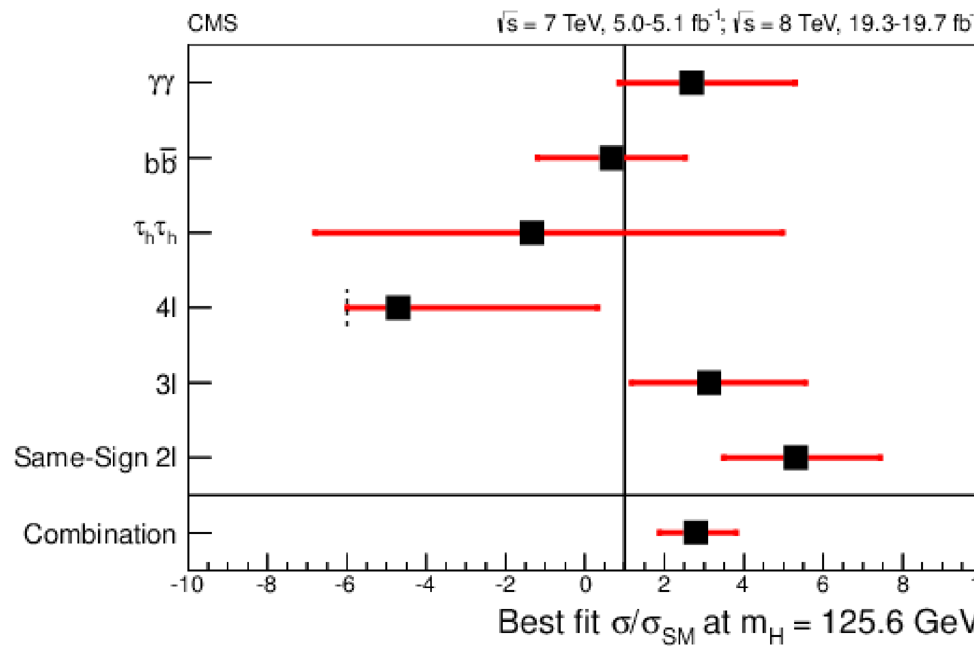
CMS (VH and VBF combination):
$\mu=1.0\pm0.4$ @125.0 GeV
Significance 2.0 (2.7) σ

ttH (H->bb, WW, ZZ, ττ, γγ)

- ATLAS and CMS covered broad range of Higgs boson final states and ttbar decay modes.
- b-tagging and top-tagging used to suppress backgrounds.
- The analyses are characterised by large number of categories and control region.
- CMS recently added a new search for single top tqH production

arXiv:1503.05066





arXiv 1408.1682

ATLAS

μ=1.7±0.8 @125.36 GeV

Local Significance: 2.5 obs (1.5 exp) σ

CMS

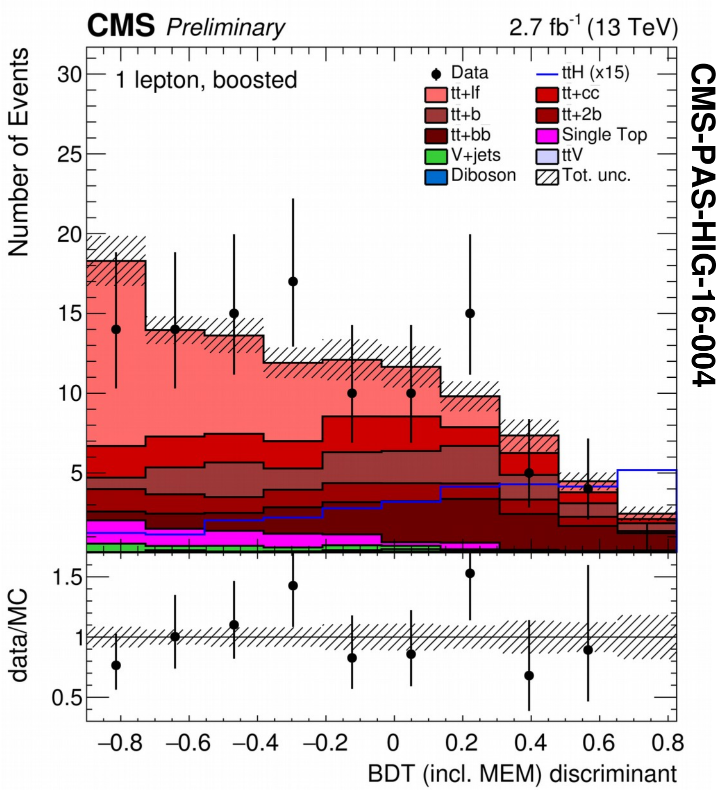
8 TeV: μ=2.8±1.0 @125.6 GeV

Local Significance: 3.4 obs (1.2 exp) σ

13 TeV ttH Results

- 13TeV/8TeV Cross-section ~3.9: sensitive to potential new physics and quickly approaching Run-1 sensitivity to SM production.

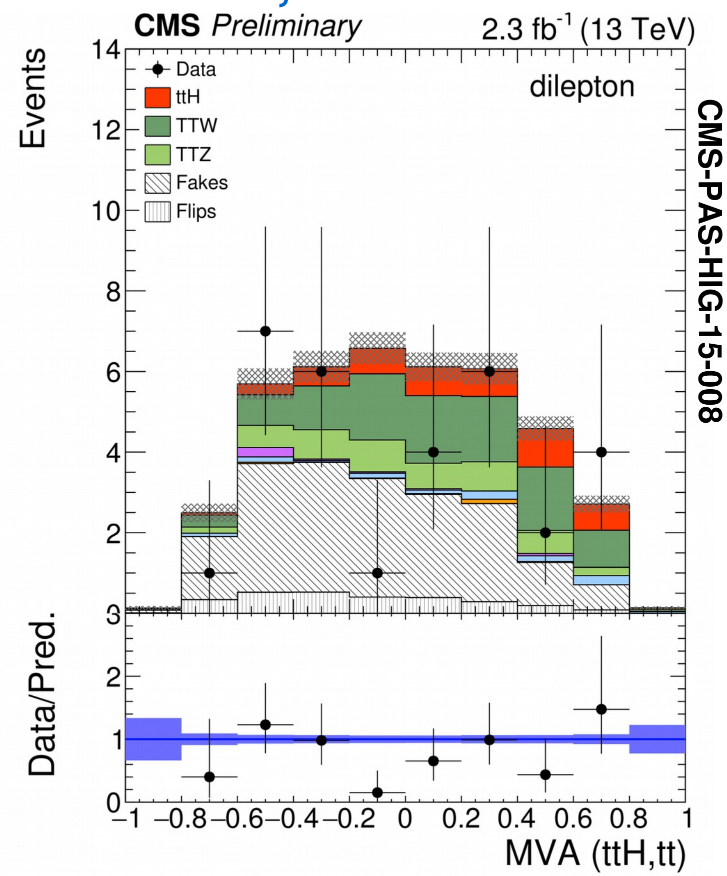
CMS ttH(bb)
- Event categories:
  - 11 (5) for lepton+jets (dilepton)
  - Bkg. Discrimination from BDT and ME



CMS ttH(bb) @13 TeV

μ=-2.0±1.8

CMS ttH multipleptons
- SS dilepton and trilepton channels
- 2 BDTs to reject ttbar and ttV



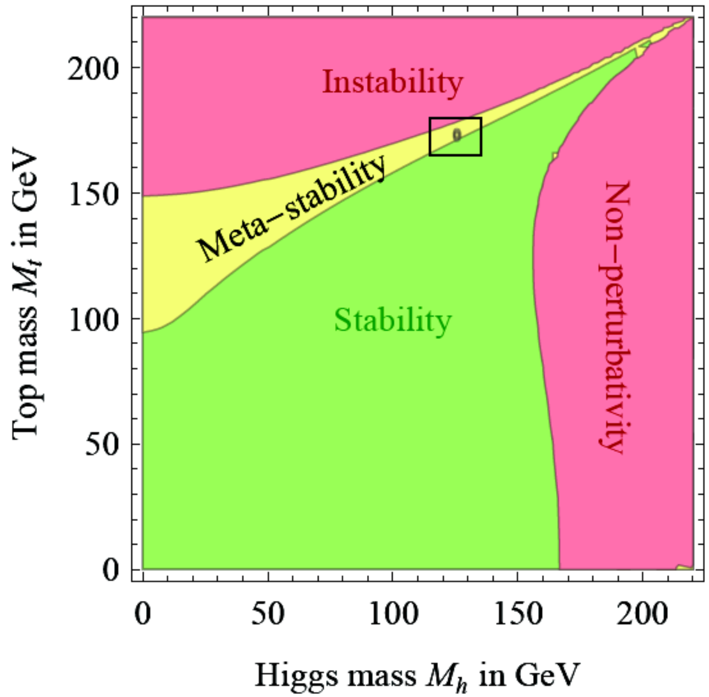
CMS ttH(multileptons) @13TeV

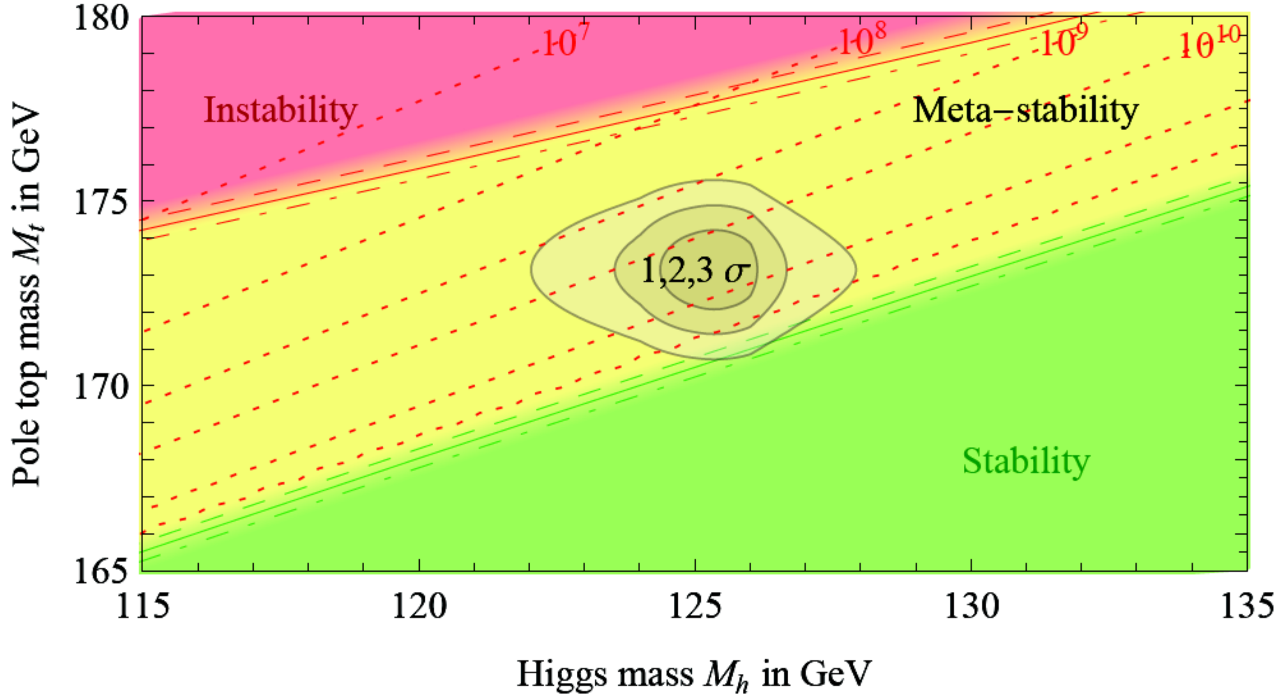
$\mu=0.6^{+1.4}_{-1.1}$

Higgs Mass and Width
Spin/Parity
Couplings

Why we call the new particle a Higgs Boson with high C.L.

Higgs Mass measurement

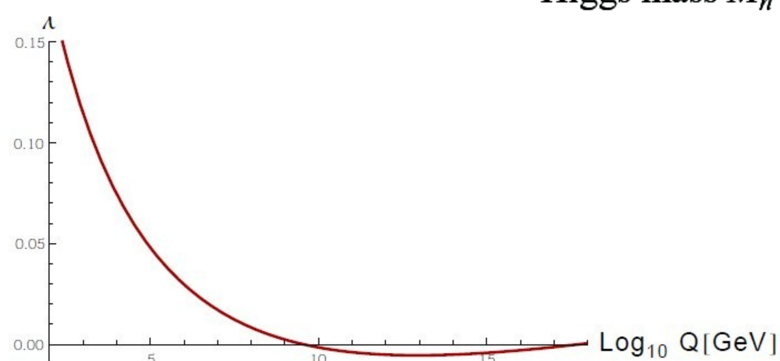


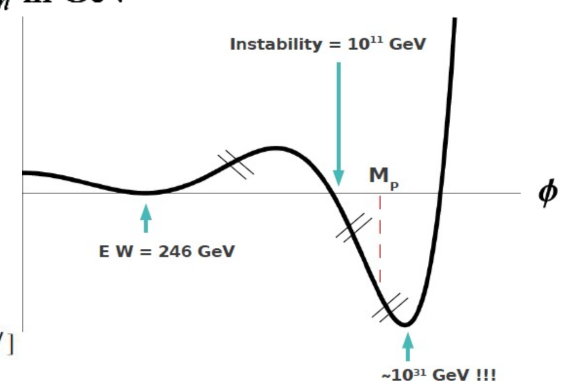


$$L = (\partial\Phi)(\partial\Phi^*) - V(\Phi)$$

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

At EW scale λ~0.13

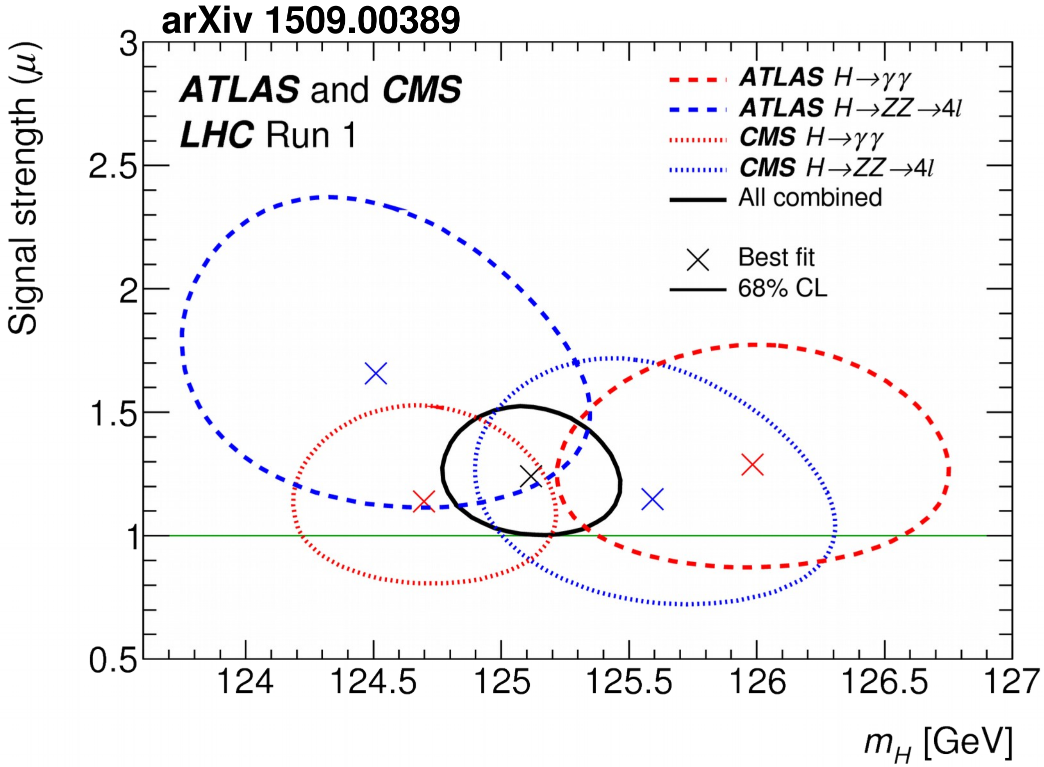


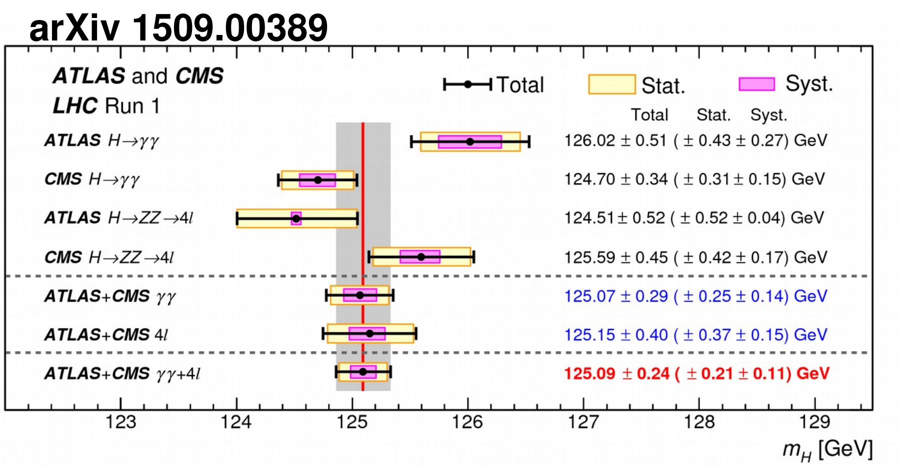


- Higgs quartic coupling λ can become negative for energies of O(10^{10}) GeV. Main corrections depends on m_{top} and m_H precise values.
- EW Vacuum stability up to Planck scaled excluded @ 95 C.L. without NP
- G.Degrassi et al. (arXiv:1205.6497, arXiv:1307.3536)

Combined Mass Measurement

- ATLAS and CMS finalized the mass measurement with Run-1 data after precise calibration of the detector.
- Combined measurement of the Higgs boson mass is performed in the two channels with the best mass resolution: $H \to \gamma\gamma$ and $H \to ZZ(4l)$ channels
- Signal strength is left free to avoid bias in the mass measurement.



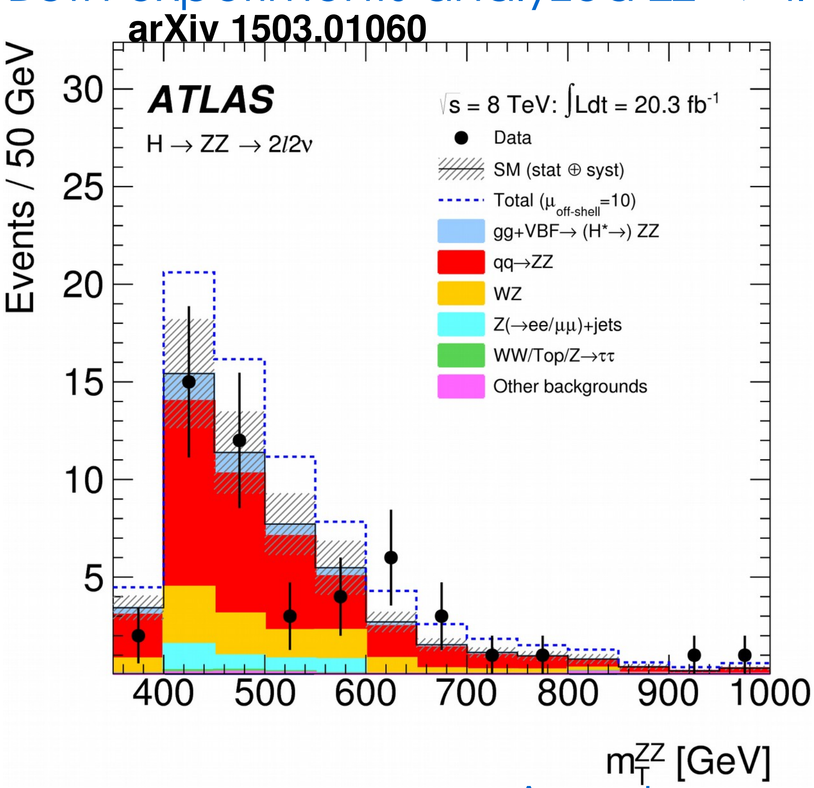


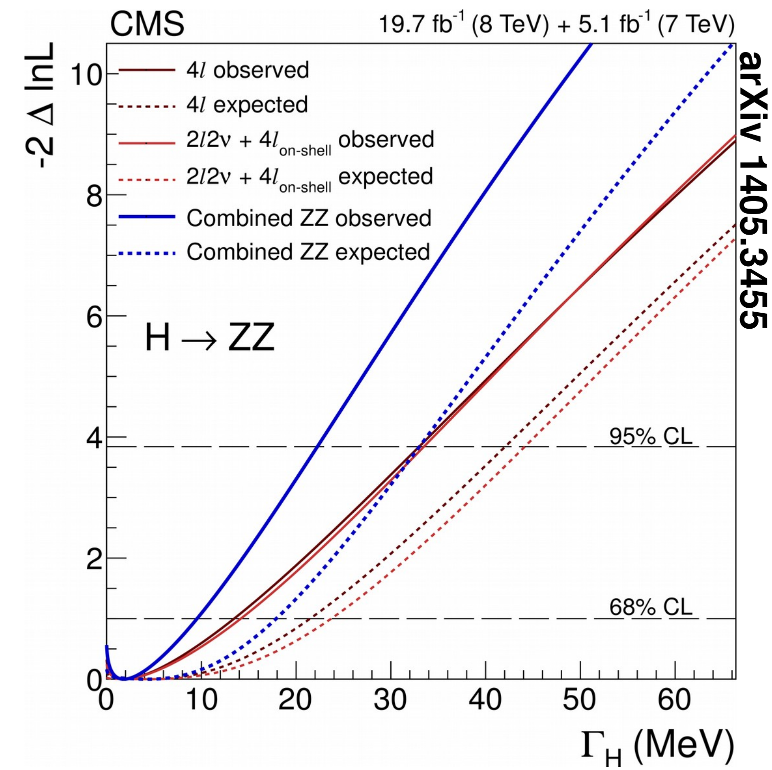
- Compatibility of the 4 measurements is 10%
- Uncertainty is dominated by the statistical error.
- Main syst. uncertainty related to photon and leptons energy scale

m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV

Width Measurement

- SM Higgs width prediction is 4.2 MeV. 1000 smaller vaue than W/Z bosons implies possible sensitivity to additional decay modes → tool for discovery.
- Direct measurement of the width performed but has no sensitivity to SM prediction ($3.5\ 10^{-12} < m_H < 1.7$ GeV).
- 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 obs (33 exp) MeV @ 95% CL

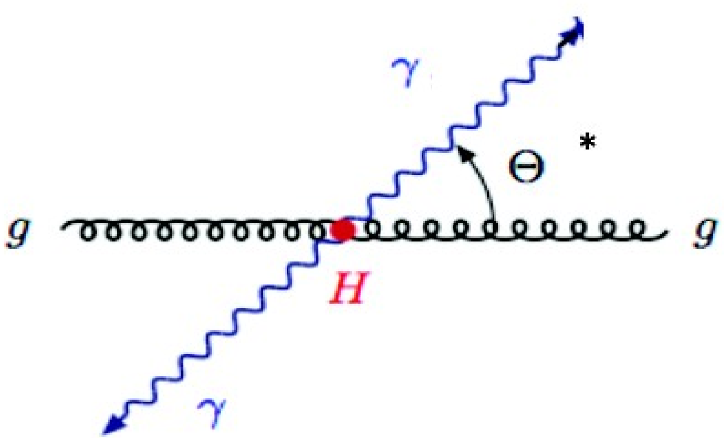
CMS:

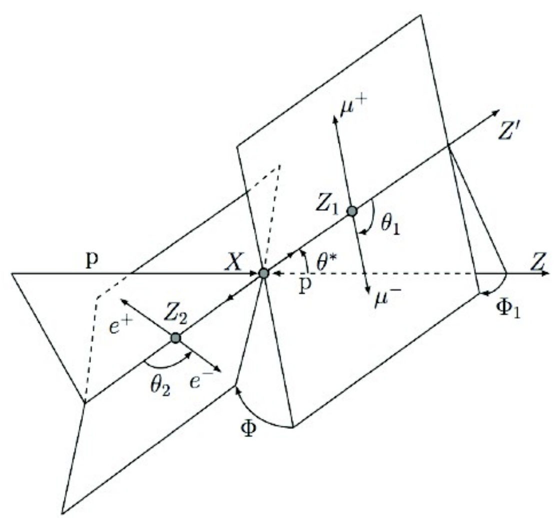
Γ < 22 obs (33 exp) MeV @ 95% CL

Spin-Parity Measurement

- Establish J^P of the new boson to verify SM prediction of 0^+
- Kinematic distributions are used to distinguish different signal models
  - Probe different amplitude structures.
- Test compatibility of data with distinct simple models.
- ATLAS and CMS results from $H \to ZZ$, $H \to WW$ and $H \to \gamma\gamma$ analyses

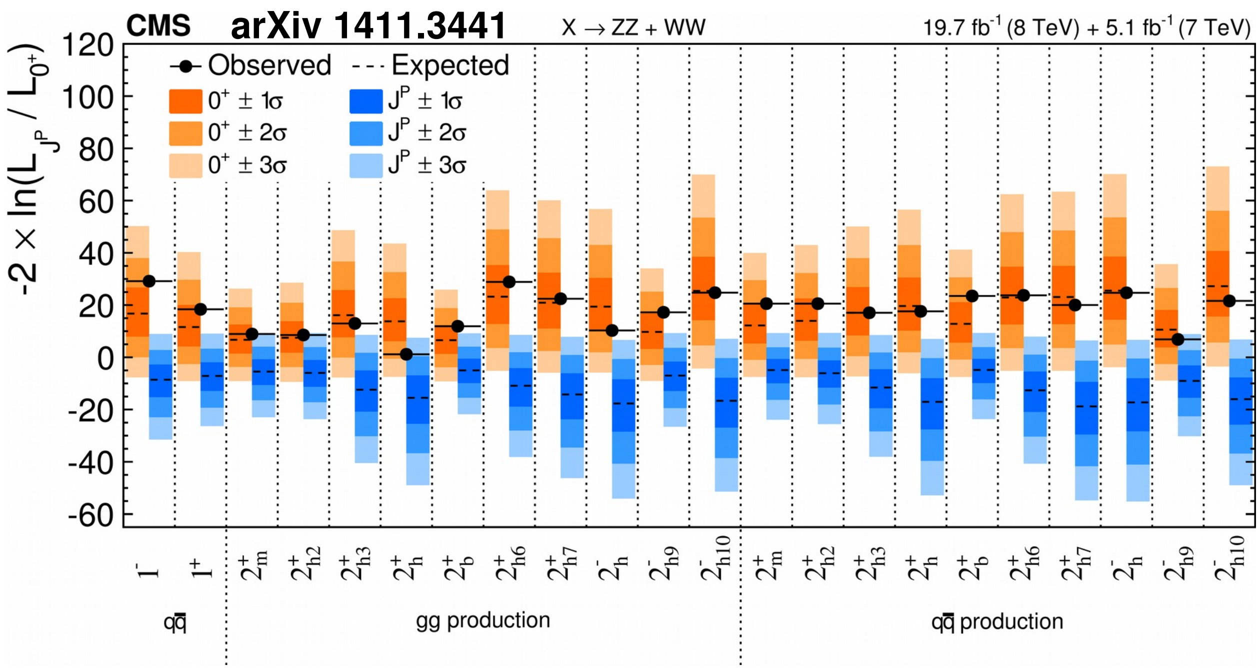
J^P	Description
0^-	CP-odd scalar
0_h+	CP-even w/ HD operators
1^+	Axial-vector
1^-	Vector
2_m^+ (gg)	gg -> min coupling grav
2_m^+(qq)	qq->min coupling grav

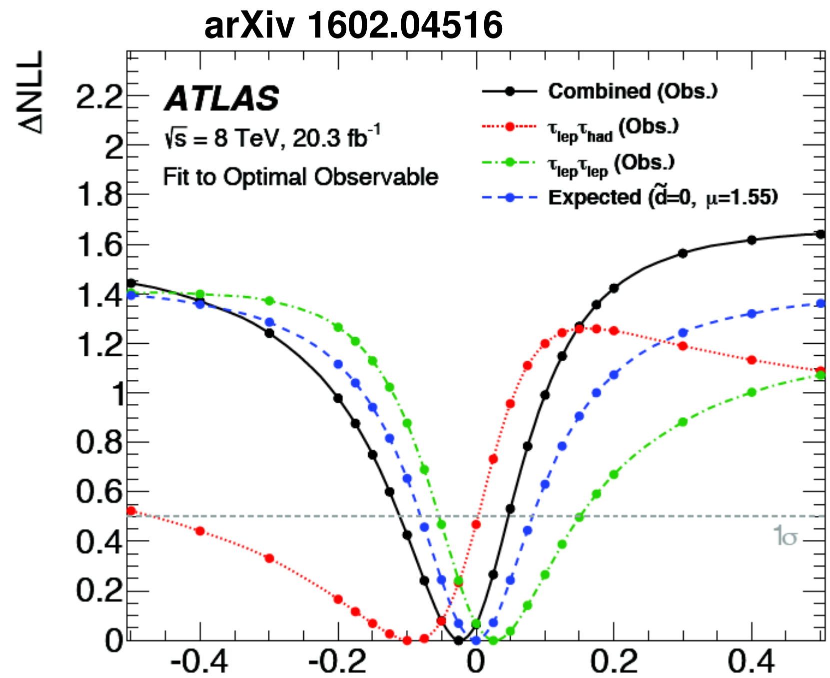




- Test statistics: $q = -2\ln\frac{\mathcal{L}(J^P_{\rm alt})}{\mathcal{L}(J^P{=}0^+)}$
- exclusion level $1-\alpha$: $\mathrm{CL}_s = \frac{P(q{>}q_{\rm obs}|J^P_{\rm alt}{+}\mathrm{bkg})}{P(q{>}q_{\rm obs}|0^+{+}\mathrm{bkg})} < \alpha$

Spin-Parity Results

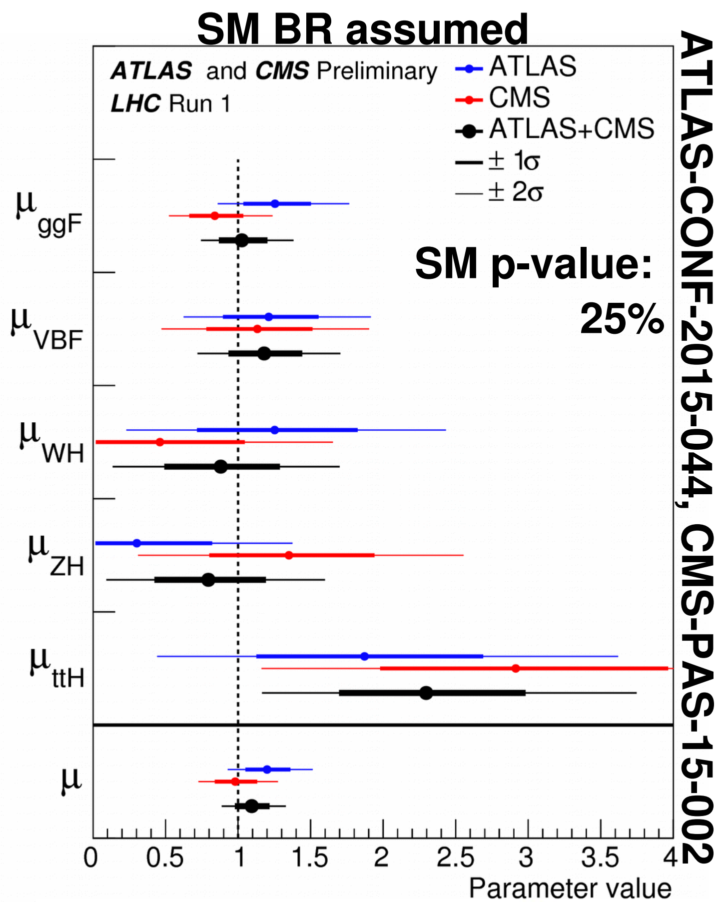


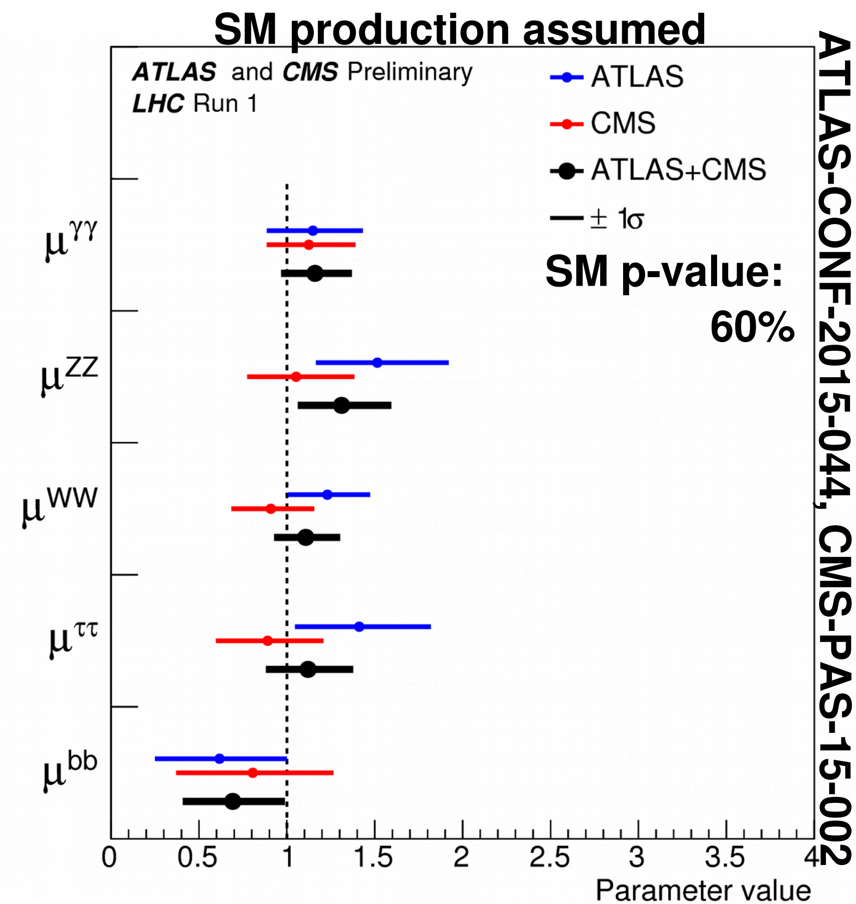


$$\mathcal{OO} = \frac{2\,\mathrm{Re}(\mathcal{M}^{*}_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2} \qquad \mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}} \qquad \tilde{d}$$

- Analyses are re-optimized for spin analysis. Alternative spin hypotheses are disfavored by ATLAS and CMS at >3σ combining H → ZZ, H → WW and H → γγ (ATLAS) final states.
- ATLAS H → ZZ and H → WW are used to probe the tensor structure of the of the interaction between the spin-0 boson and the SM vector bosons, including CP-odd BSM contributions.
- Recently constraints on CP measurements from VBF H → ττ. Strong sensitivity to parameter of interest dtilde → results are compatible with the SM hypothesis.

Signal Strength: Production and Decay





- $\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}$ and $\mu^f = \frac{BR^f}{BR^f_{SM}}$. $\mu_i^f \equiv \frac{\sigma_i \cdot BR^f}{(\sigma_i \cdot BR^f)_{SM}} = \mu_i \times \mu^f$
- $\mu = 1.09^{+0.11}_{-0.10} \quad = 1.09^{+0.07}_{-0.07}\text{ (stat) }^{+0.04}_{-0.04}\text{ (expt) }^{+0.03}_{-0.03}\text{ (thbgd)}^{+0.07}_{-0.06}\text{ (thsig)}$

$\mu=\sigma/\sigma_{SM}$
$\mu=0$ no Higgs
$\mu=1$ SM Higgs

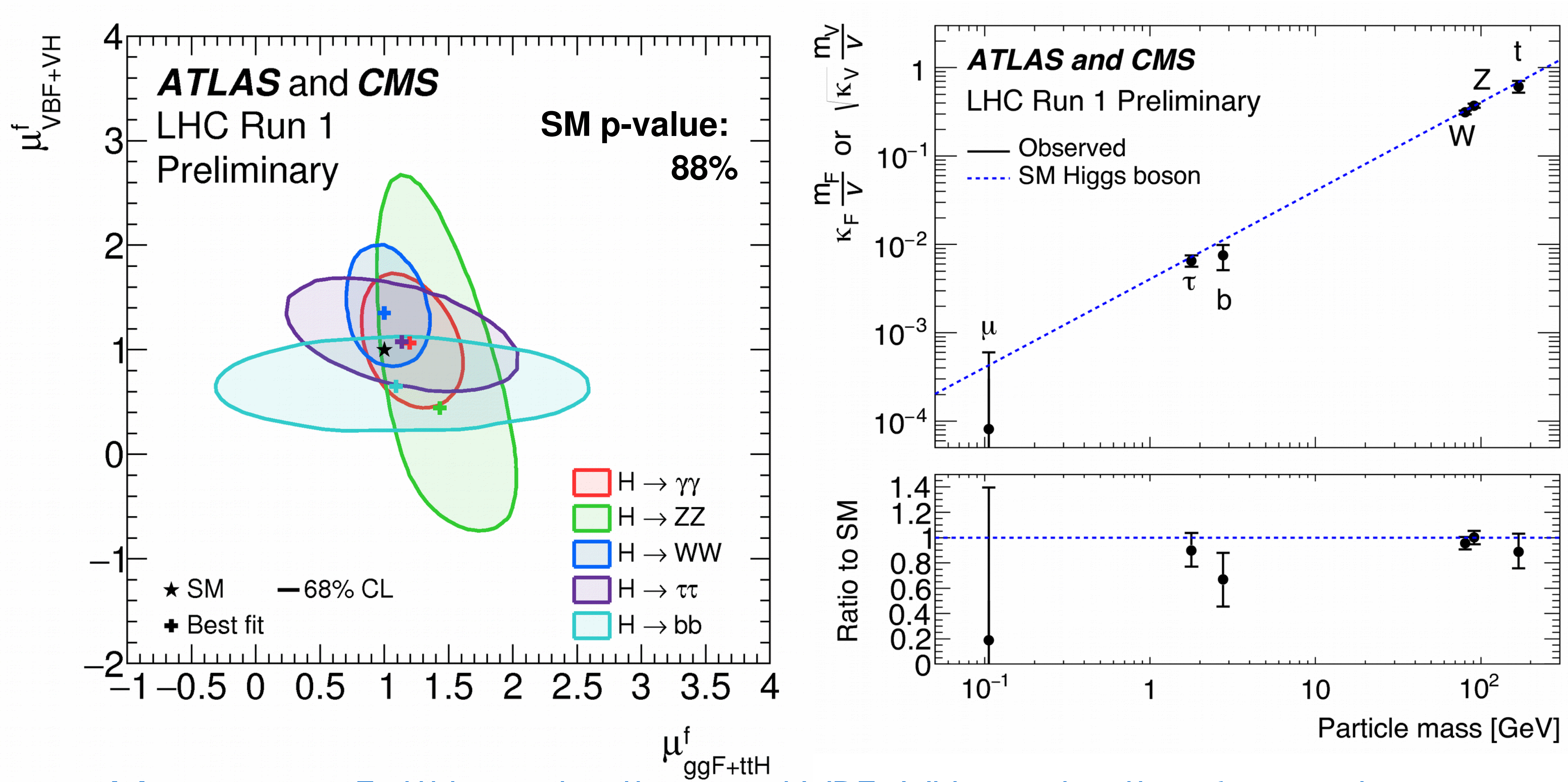
- Stat and Th.Sig terms are of comparable size, th.Sig dominated by ggF cross-section uncertainty.
- Largest difference in μ_{ttH}: 2.3σ excess with respect to SM

Significance of Combined Measurements

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		
$H \to \tau\tau$	**5.5**	5.0
$H \to bb$	2.6	3.7

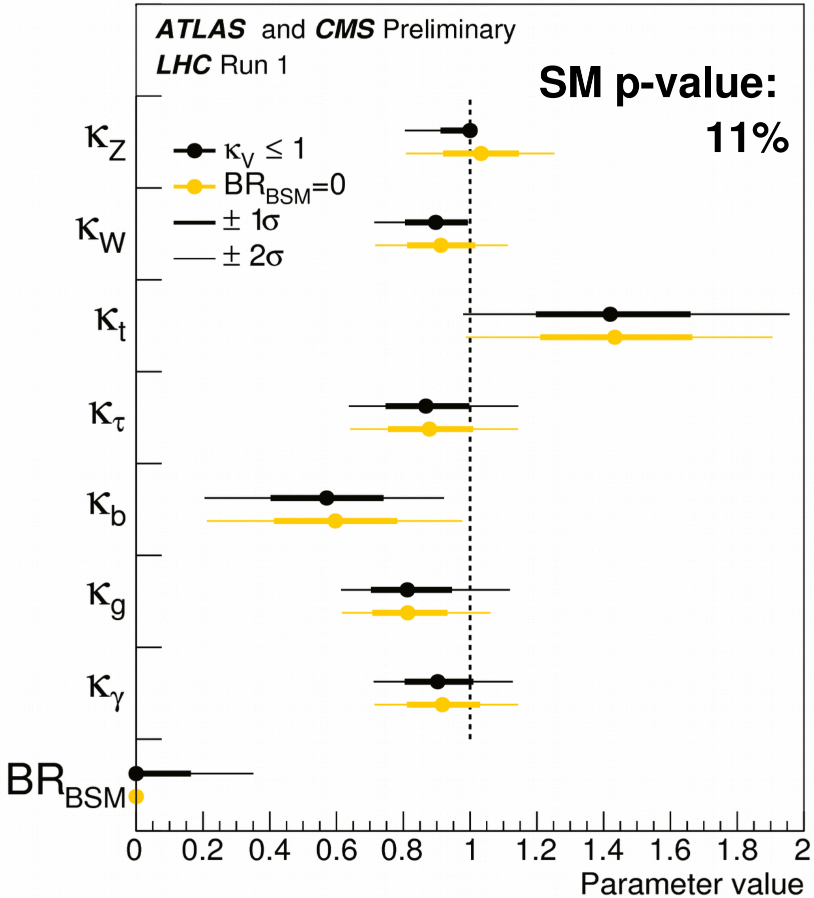
- Improved sensitivity thanks to the combination
- Comparing likelihood of the best-fit with the μ_{prod}=0 and μ_{decay}=0 hypothesis we obtain:
  - VBF production and $H \to \tau\tau$ now established with more than 5σ significance.
  - ggF and $H \to ZZ,\gamma\gamma,WW$ already established by individual experiments

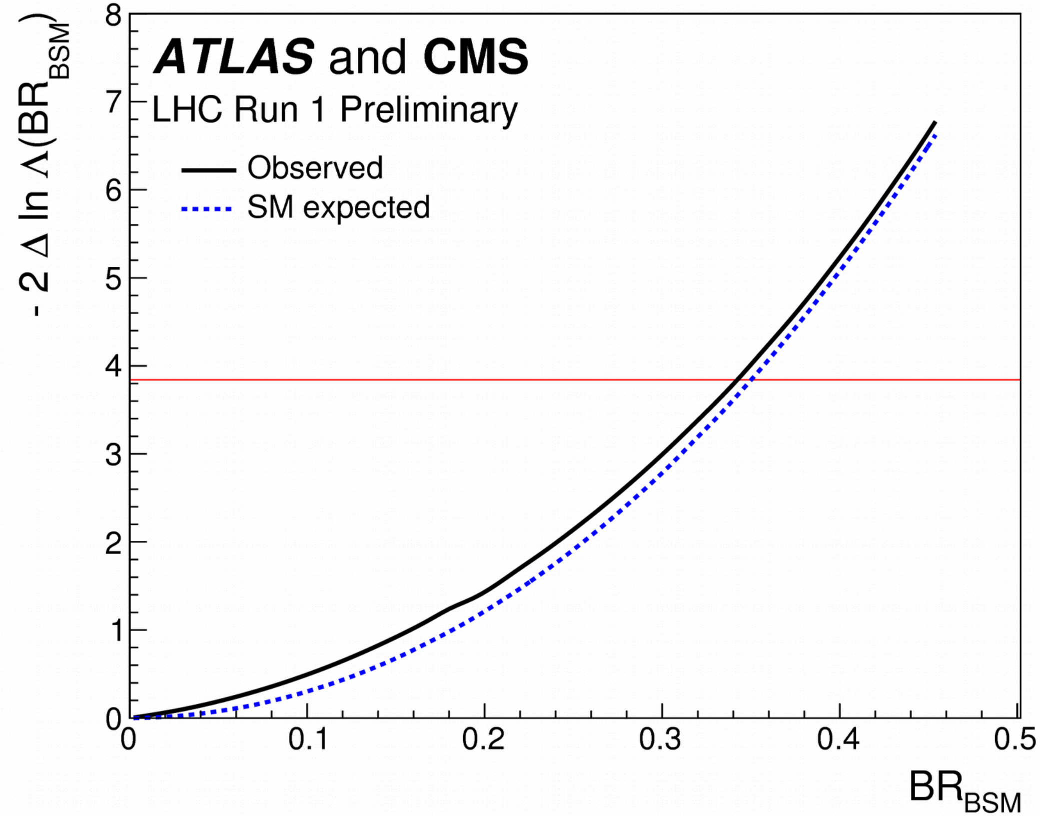
μ_V vs μ_F and Couplings scaling



- Measure ggF+ttH production and VBF+VH production for each decay mode (No assumption on SM production or decay rates needed for individual channels).
- Measurement of the combined ratio: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
- Within current precision Higgs couplings scale with particle masses

Constraints on BSM couplings





- Only σ x BRs can be measured, without further assumptions on the width of the Higgs boson cannot be measured: assume $k_V \leq 1$ (as in 2HDM). H → Dark Matter would contribute to BR_{BSM}

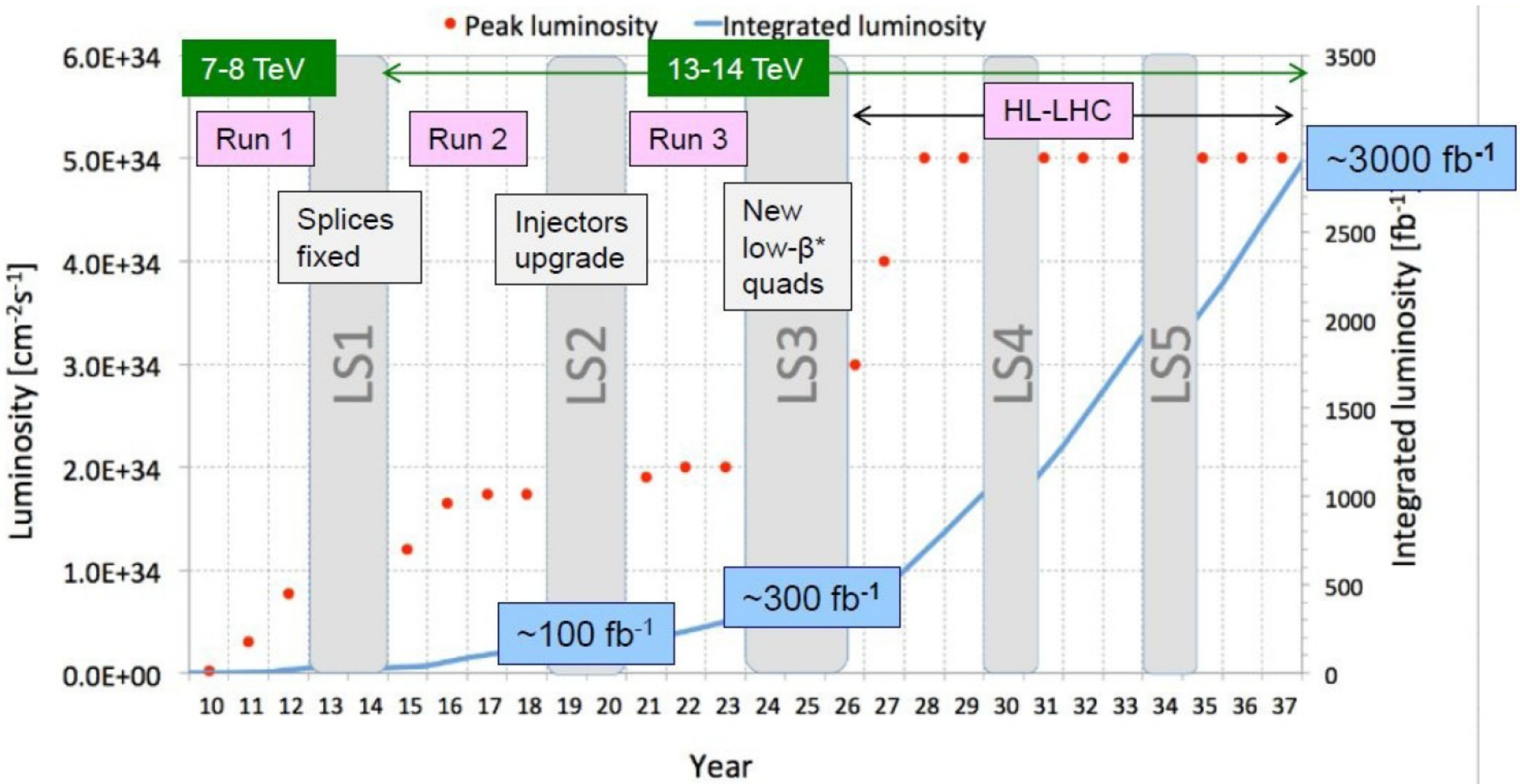
$$\sigma_i \cdot \mathrm{BR}^f = \frac{\sigma_i(\vec{\kappa}) \cdot \Gamma^f(\vec{\kappa})}{\Gamma_\mathrm{H}},$$

$$\Gamma_\mathrm{H} = \frac{\kappa_H^2 \cdot \Gamma_H^{\mathrm{SM}}}{1 - \mathrm{BR}_{\mathrm{BSM}}},$$

- k_t dominated by ttH process
- BR_{BSM} < 0.34 at 95% C.L. (assuming $k_V \leq 1$)

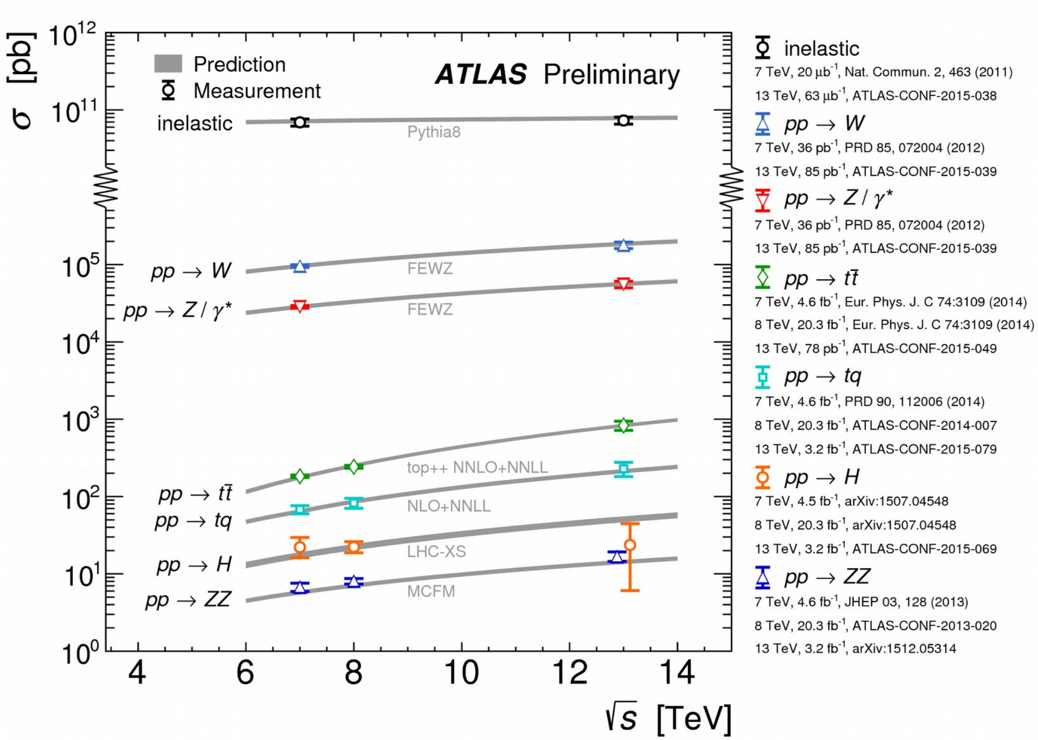
Higgs Sector Measurements Prospects

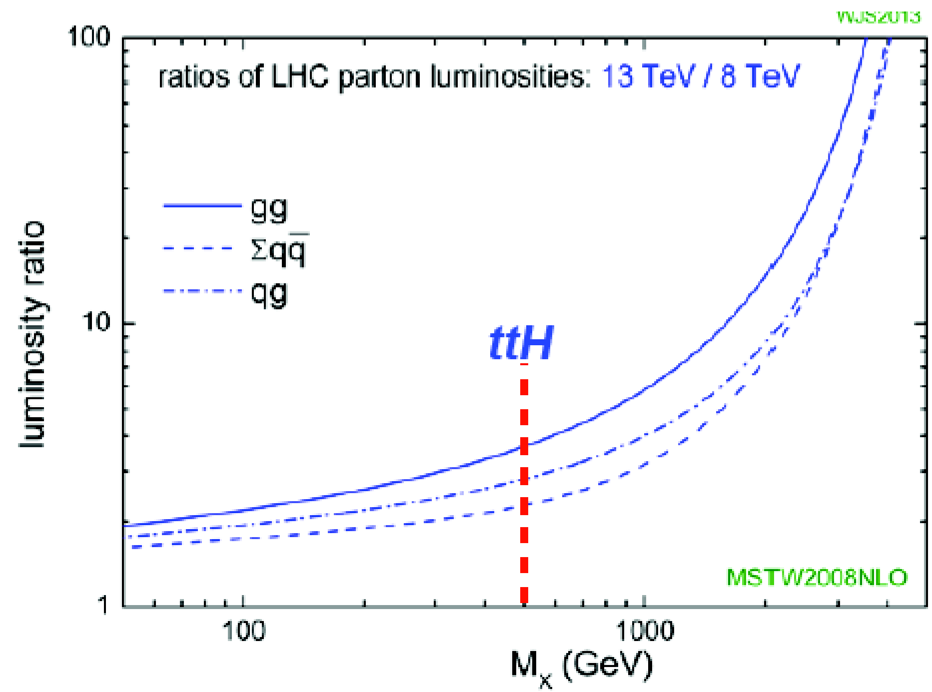
LHC Upgrade



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

LHC Run2 so far

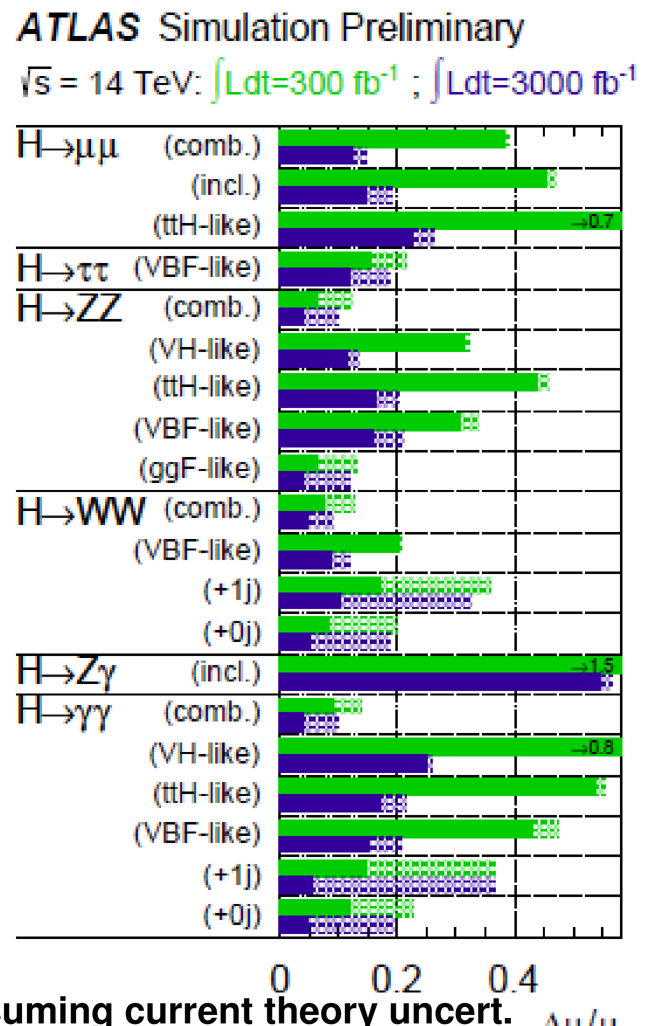




- Run-2 Milestones in Higgs Physics:

- Improvement of mass and couplings measurements (e.g. observe H → bb and VH prod.)
- Study Higgs boson fiducial, differential cross sections and CP-spin.
- Search for forbidden searches.
- Observation of ttH crucial to investigate the top quark Yukawa coupling
- Cross section increase (8TeV → 13TeV):
  - tt H: x3.9, The largest increase of all Higgs boson production modes
  - But large increase also of the main backgrounds tt+X increase x3.3

Sensitivity for Phase-1 and Phase-2



Assuming current theory uncert.
Exp. uncert. evaluated with Run-1 software

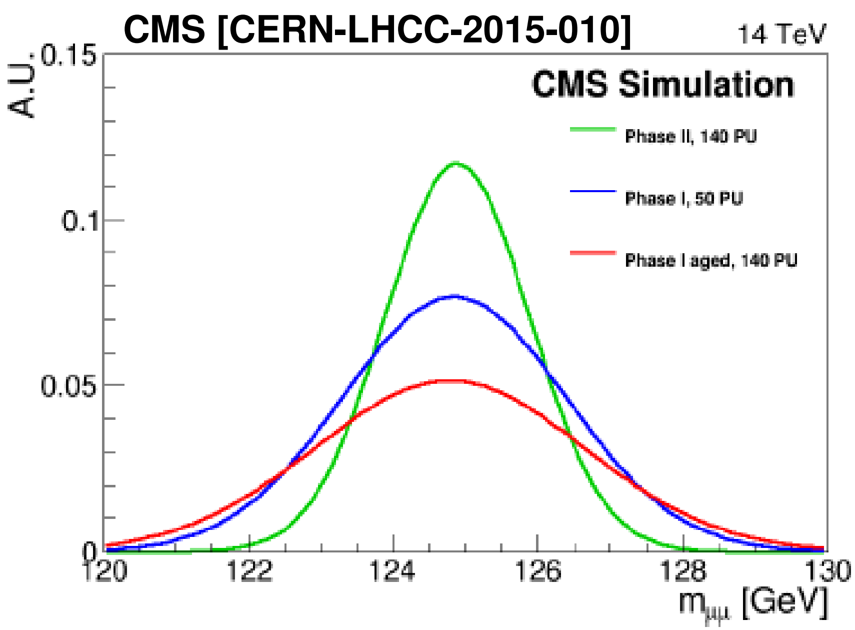
Assuming theory uncert. reduced by 50%, Run-1 exp. uncert.

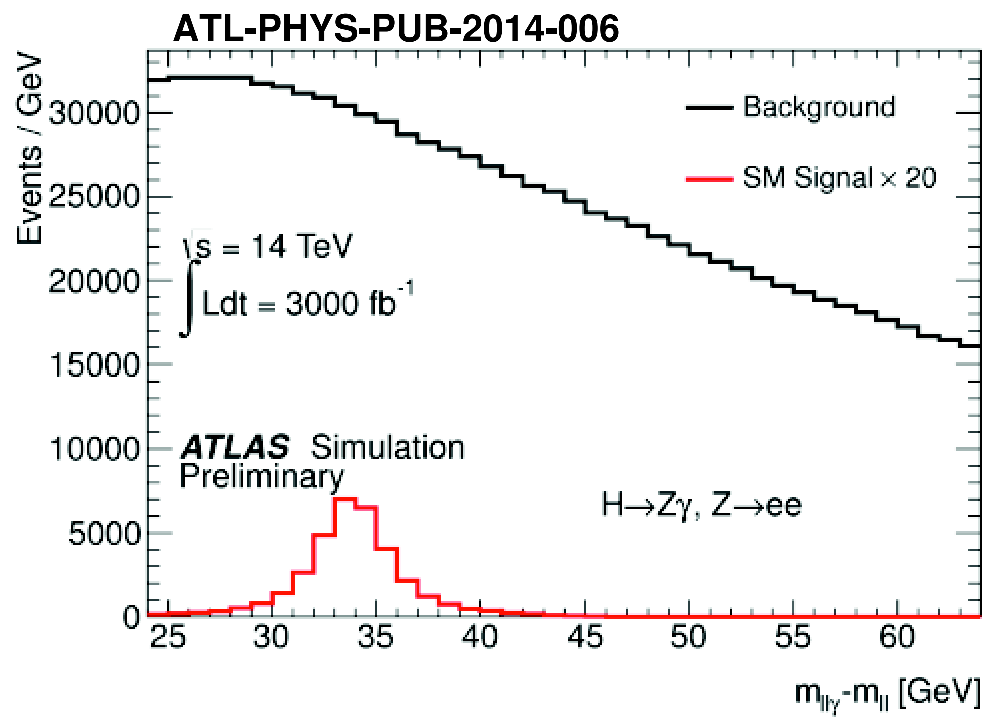
Coupling modifier	300 fb^{-1}	3000 fb^{-1}	
$k_{W,Z}$, $k_{\gamma,}$	6%	3%	
k_b	12%	5%	down-quark type
k_t	15%	7%	Top Yukawa coup.
k_τ	10%	5%	lepton coupling
k_μ	22%	7%	2nd generation

Measurement accuracy per experiment from projections in:
CMS: arXiv: 1307.7135
ATLAS: ATL-PHYS-PUB-2014-016

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

Projections of $H \to \mu\mu$ and $H \to Z\gamma$





- CMS: revised projection, expect 5% uncertainty on $H \to \mu\mu$ coupling measurement at HL-LHC (only a few tens produced during LHC Run-1, according to SM prediction.
- $H \to Z\gamma$: In Standard Model, this decay proceeds entirely via loops predominantly involving heavy charged particles:
  - Sensitive to possible new physics
  - Observation of the SM decay is possible at HL-LHC

Summary

• Outstanding performance from the LHC team and experiments is allowing to deliver an impressive amount of results on the Higgs sector.

• 136 papers published so far by ATLAS and CMS on Higgs physics (including BSM Higgs searches).

• We are currently at the beginning of Run-2 of the LHC and many properties of the Higgs boson have been already measured precisely. In some cases beyond expectations (e.g. Higgs width).

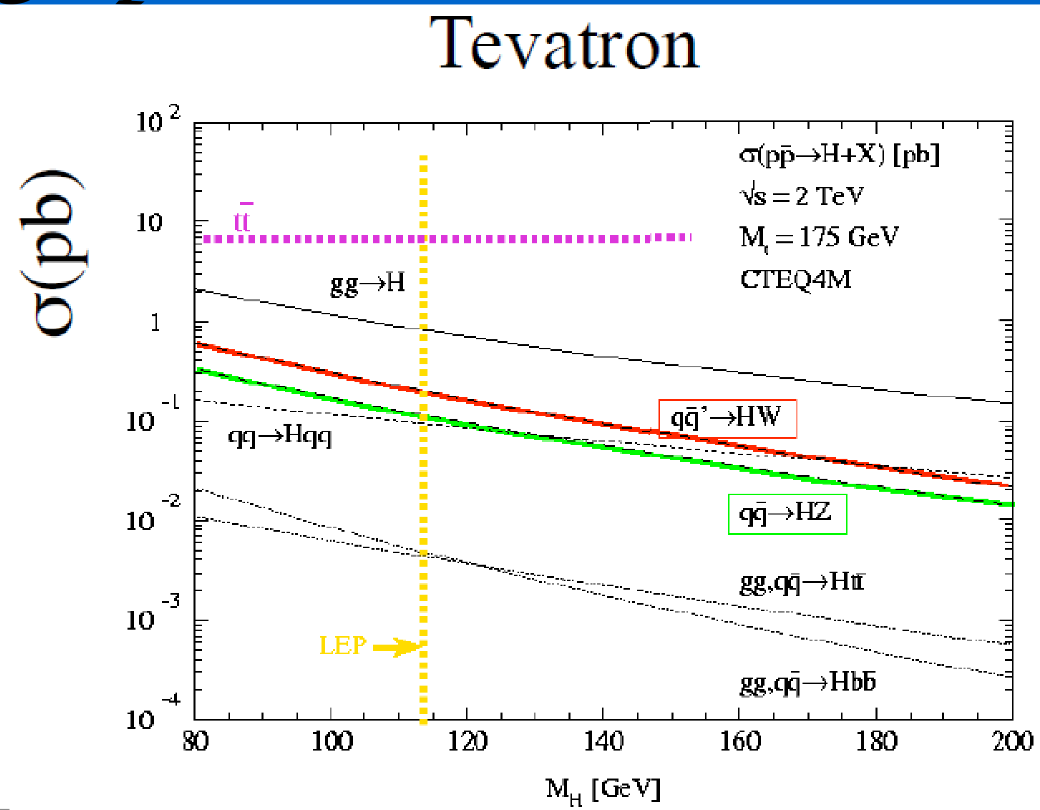
•Good connection between experimental and theoretical physicists was the key in many cases of this success.

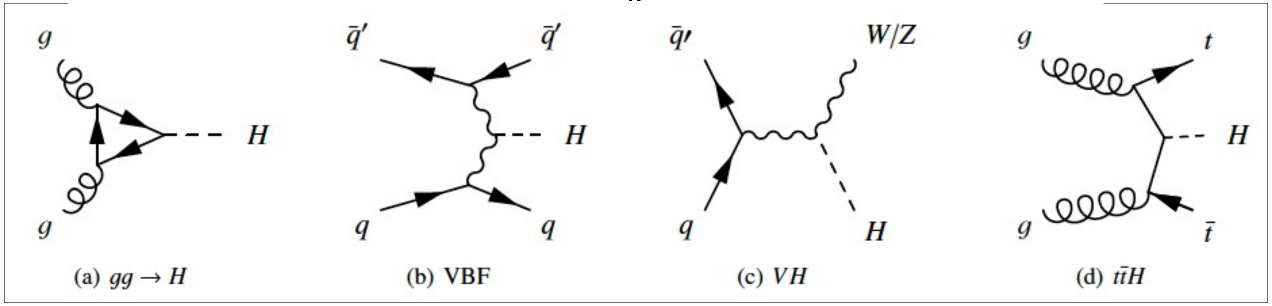
• LHC restarted delivering p-p collisions in 2015 with unprecedented center of mass energy:
  - Opportunity to perform searches for productions and decays suppressed in the SM.
  - Measurement of rare channels and production modes: $H \rightarrow \mu\mu$, VH(bb) and ttH
  - Better measurement of H(125) properties.

Thanks for the attention

Bonus Slides

Higgs prod. Rates at TeVatron





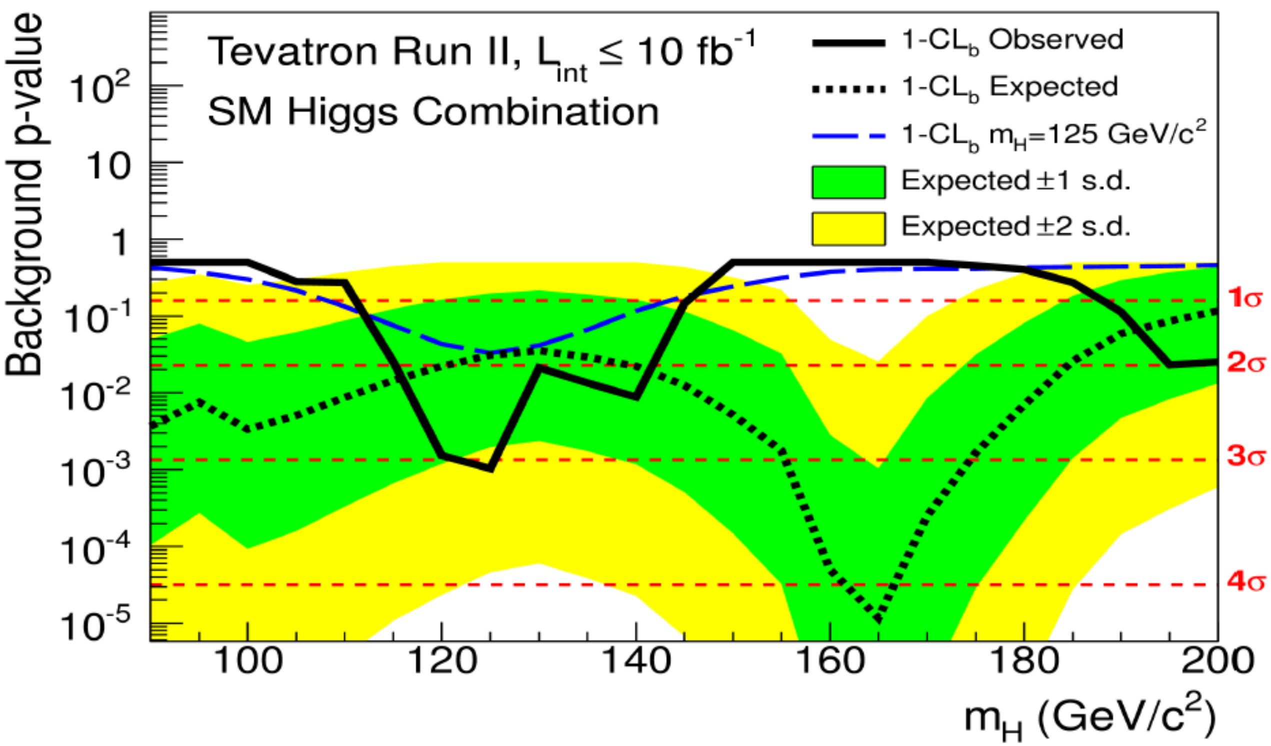
78% 7% 15% <1%

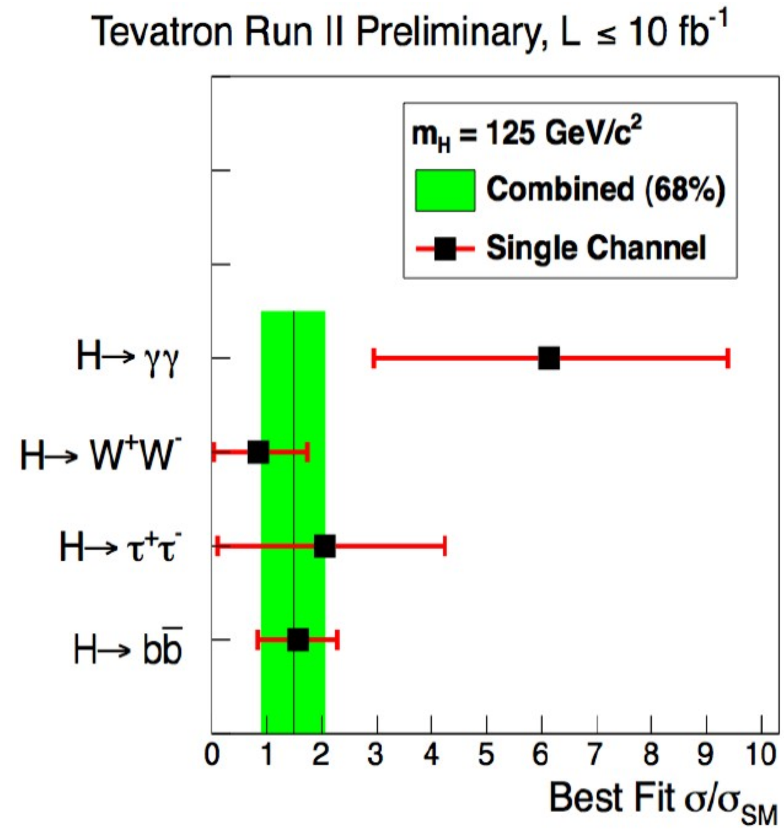
ggH is the dominant production mode.
VH is the subleading production mode

TeVatron Results

TeVatron updated their Higgs boson search results with ~10 fb^{-1}

Most sensitive channels are (V)H $\rightarrow$ (V)bb, H $\rightarrow$ WW. Analyses of H $\rightarrow \gamma\gamma$ and H $\rightarrow \tau\tau$ are also included.

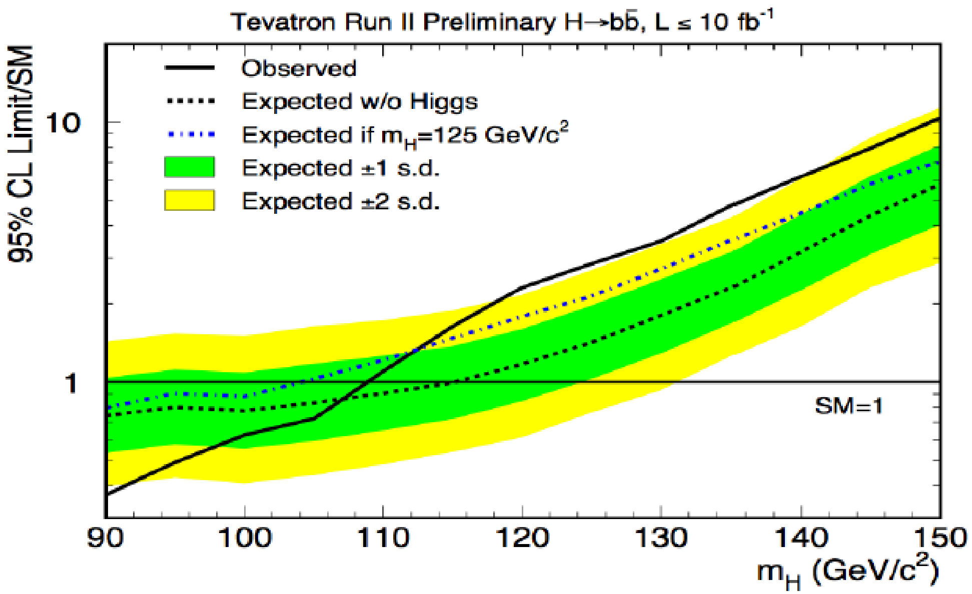


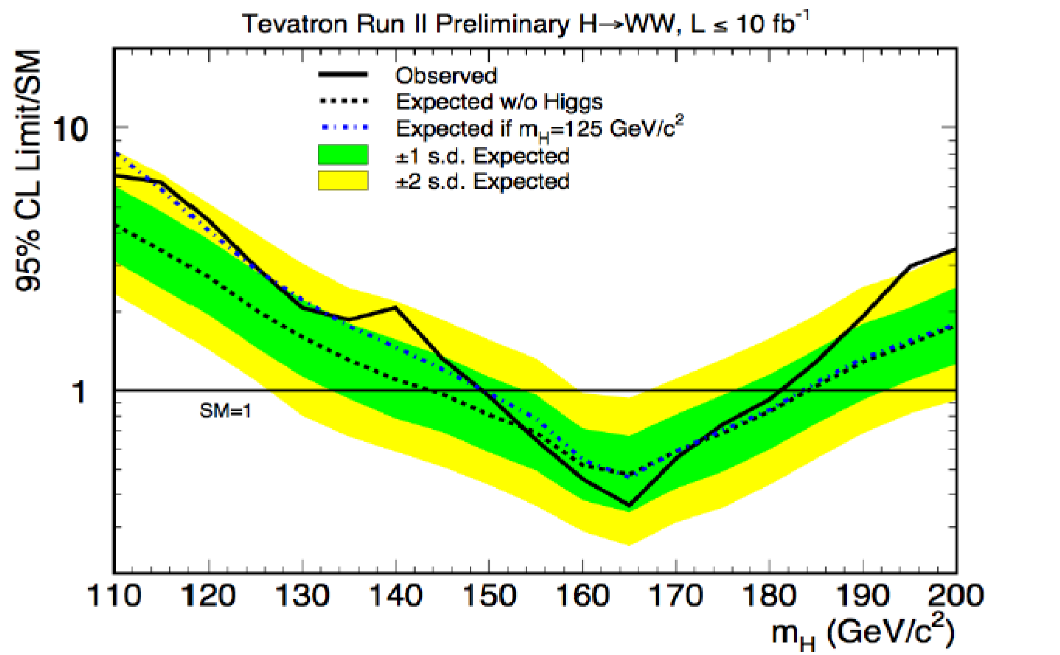


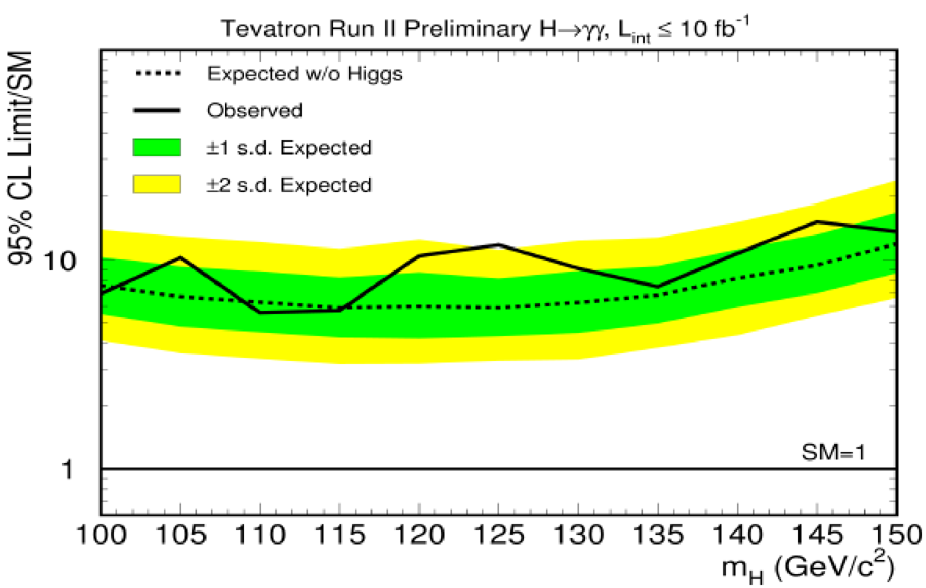
The minimum p-value is found to be 3.0σ at mH =125GeV.

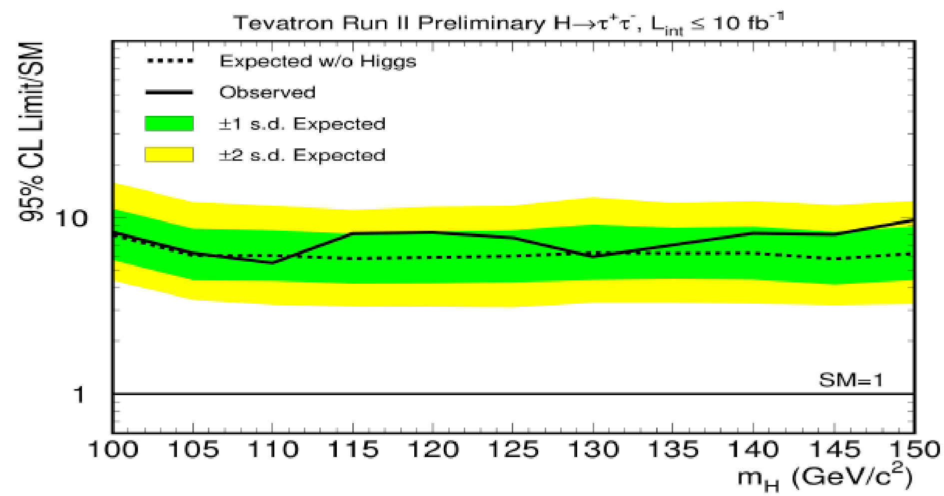
Fit to signal strength (1.4±0.6)xSM @125 GeV

TeVatron Limits by channel

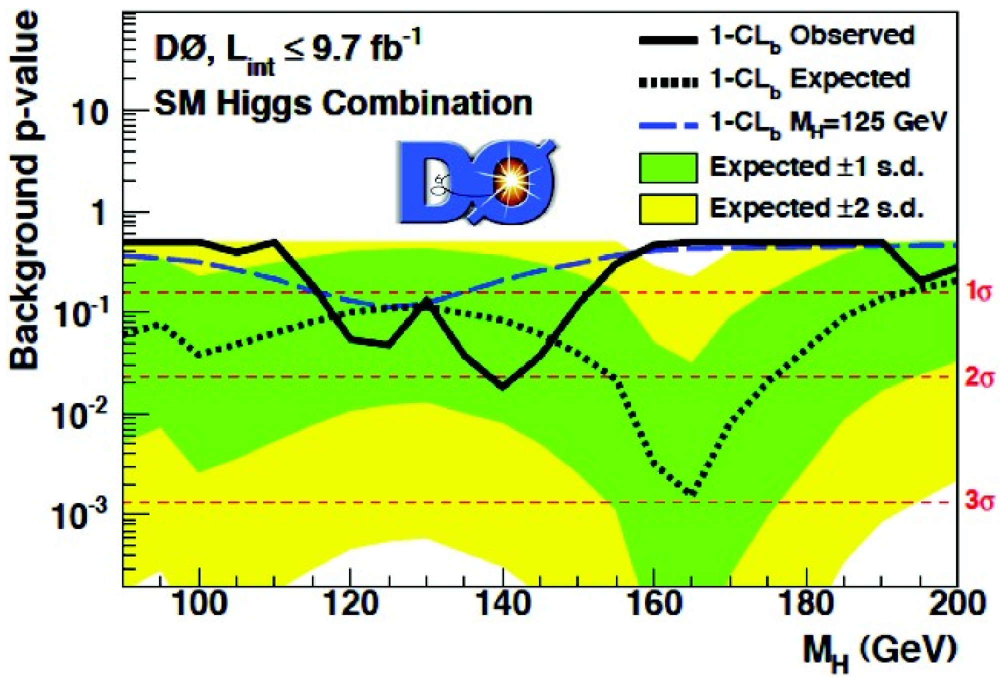


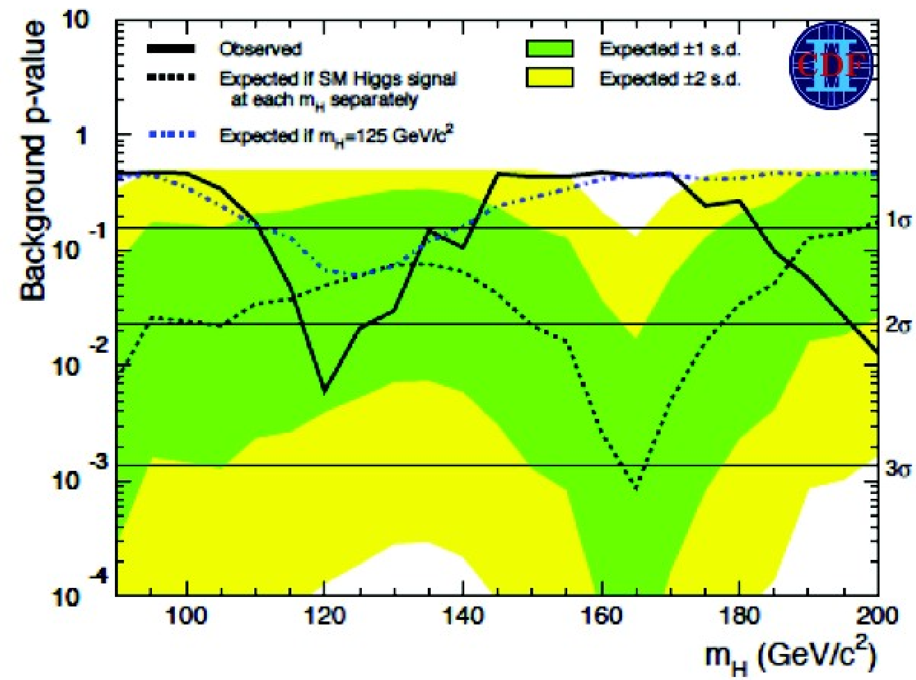






TeVatron Results by experiment





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

$\mathcal{H} \to \gamma\gamma$

Features:

- Data sample divided in exclusive final states and the analysis is further optimized to sub-leading production modes (VBF and VH).
- Robust cut-based selection is used to define the categories.

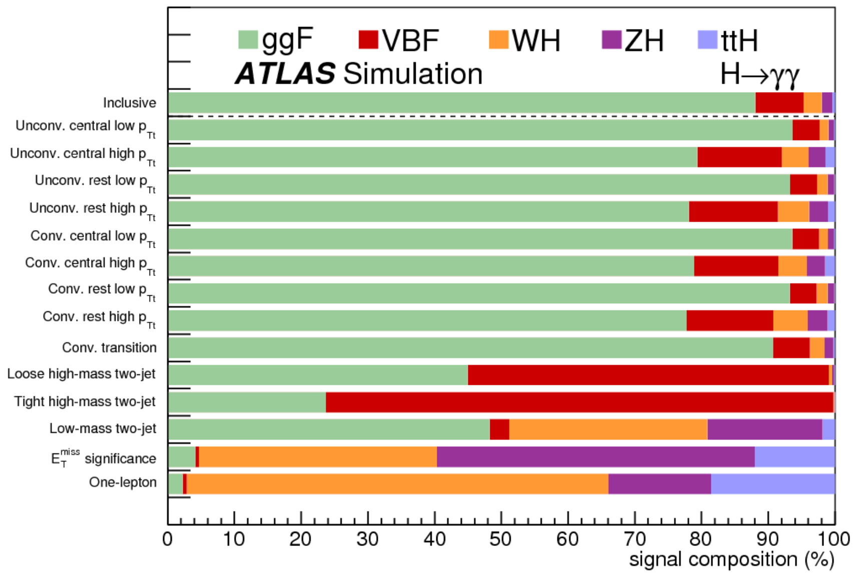
The main backgrounds:

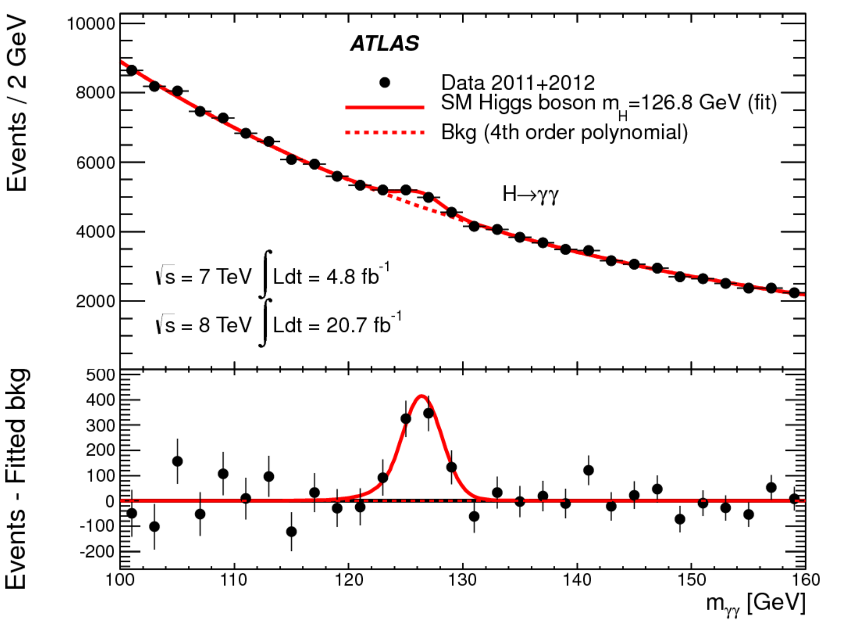
- **Irreducible**: Di-photon $\gamma\gamma$
- **Reducible**: Photon + jets, di-jets (jet is misidentified as γ), EW

Main Discriminant variable:

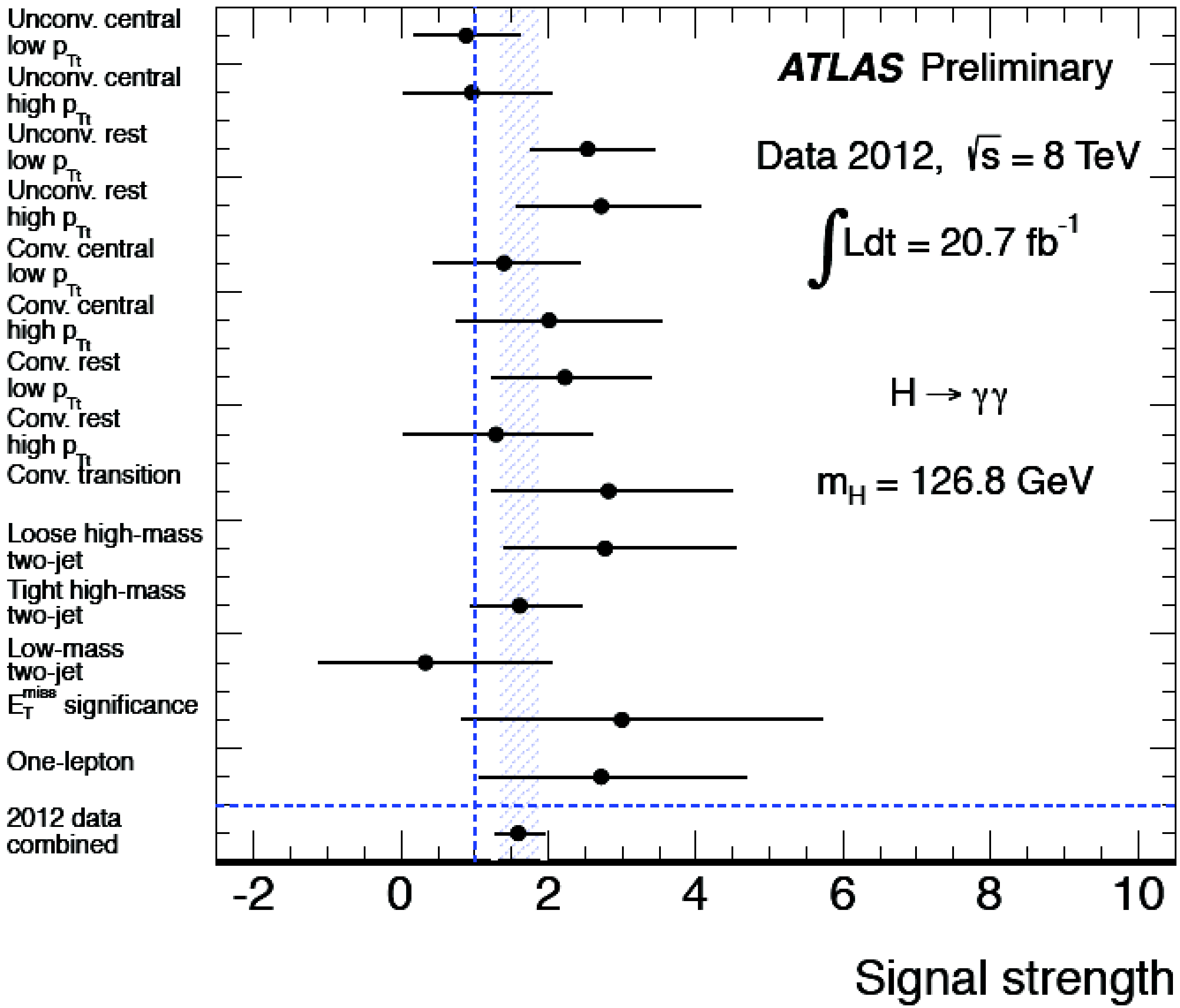
$m_{\gamma\gamma}$, narrow resonance on a steep falling background.

$$m_{\gamma\gamma} = \sqrt{E_1^{\gamma} E_2^{\gamma}(1 - \cos\alpha_{12})}$$

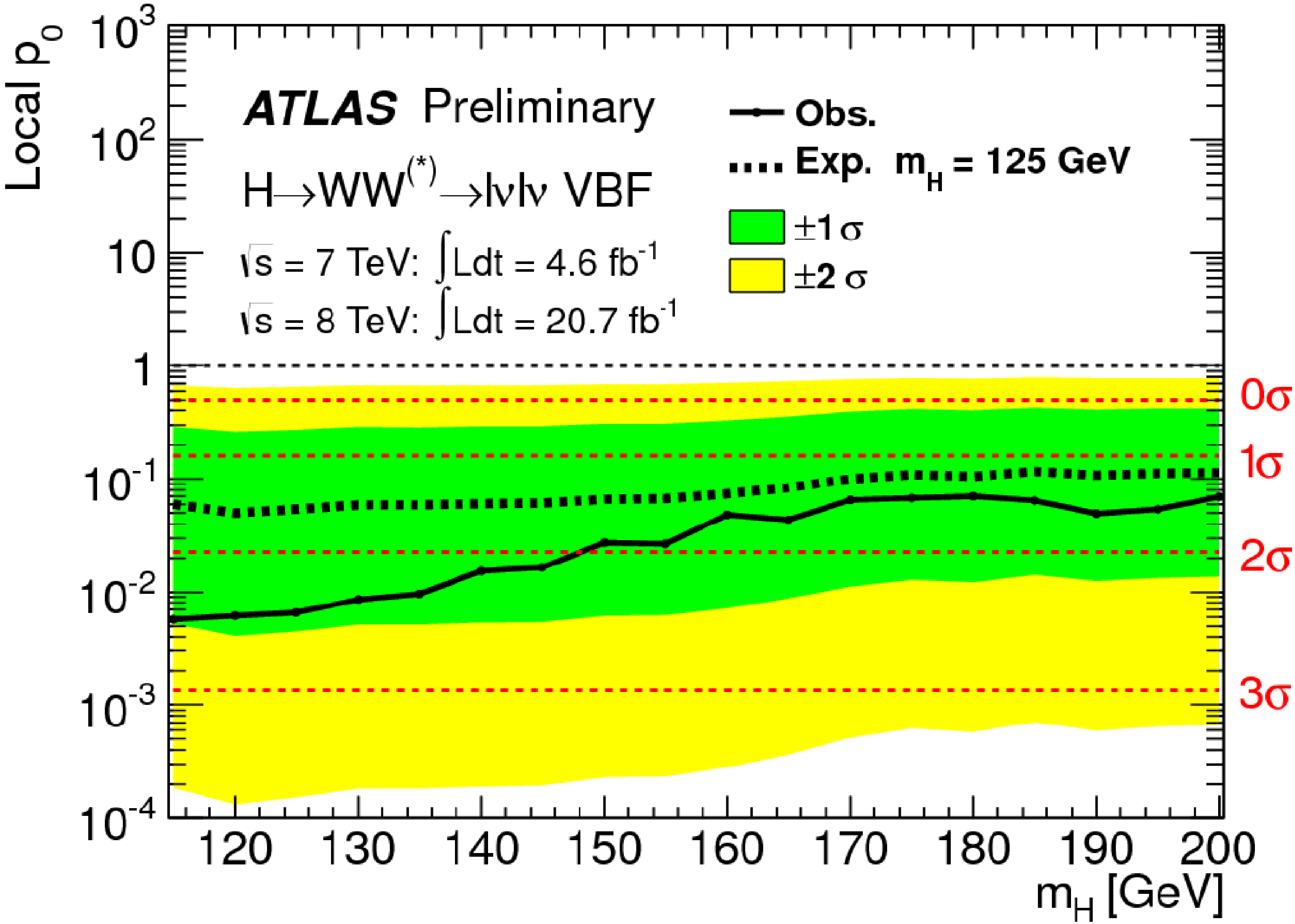




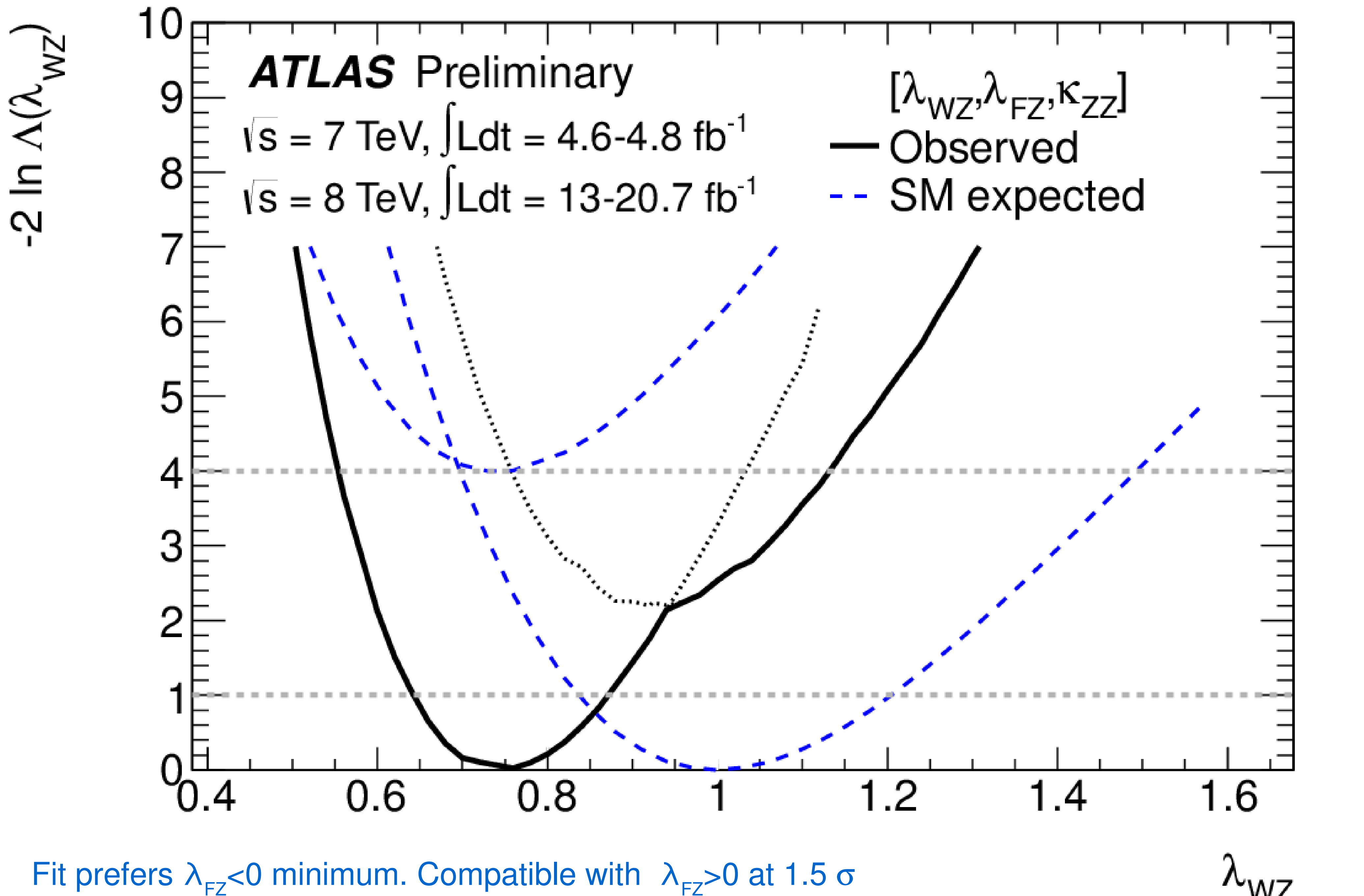
$\mathcal{H} \rightarrow \gamma\gamma$ categories



$\mathcal{H} \rightarrow \mathcal{WW}\ \mathcal{VBF}$

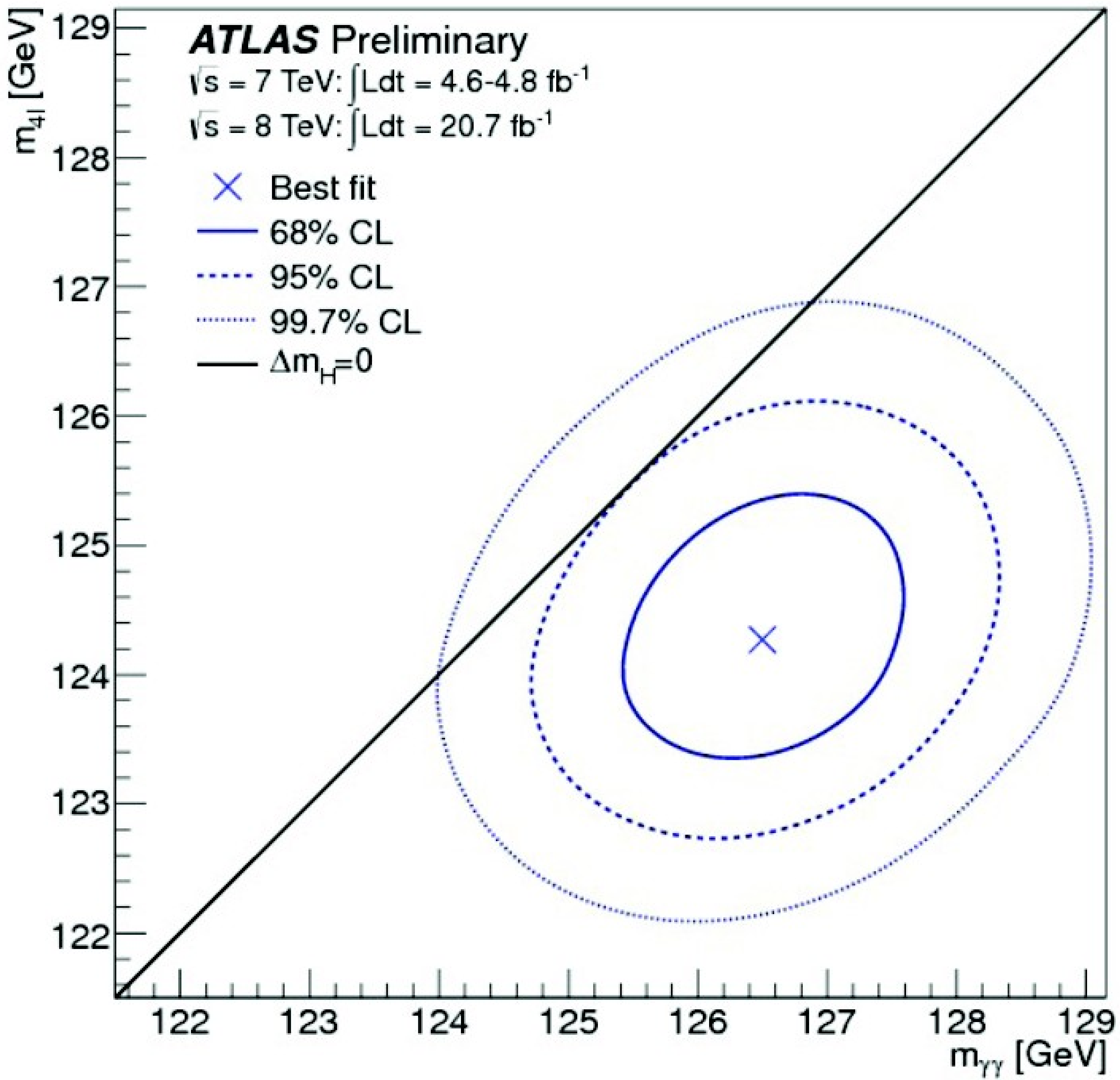


Custodial Symmetry

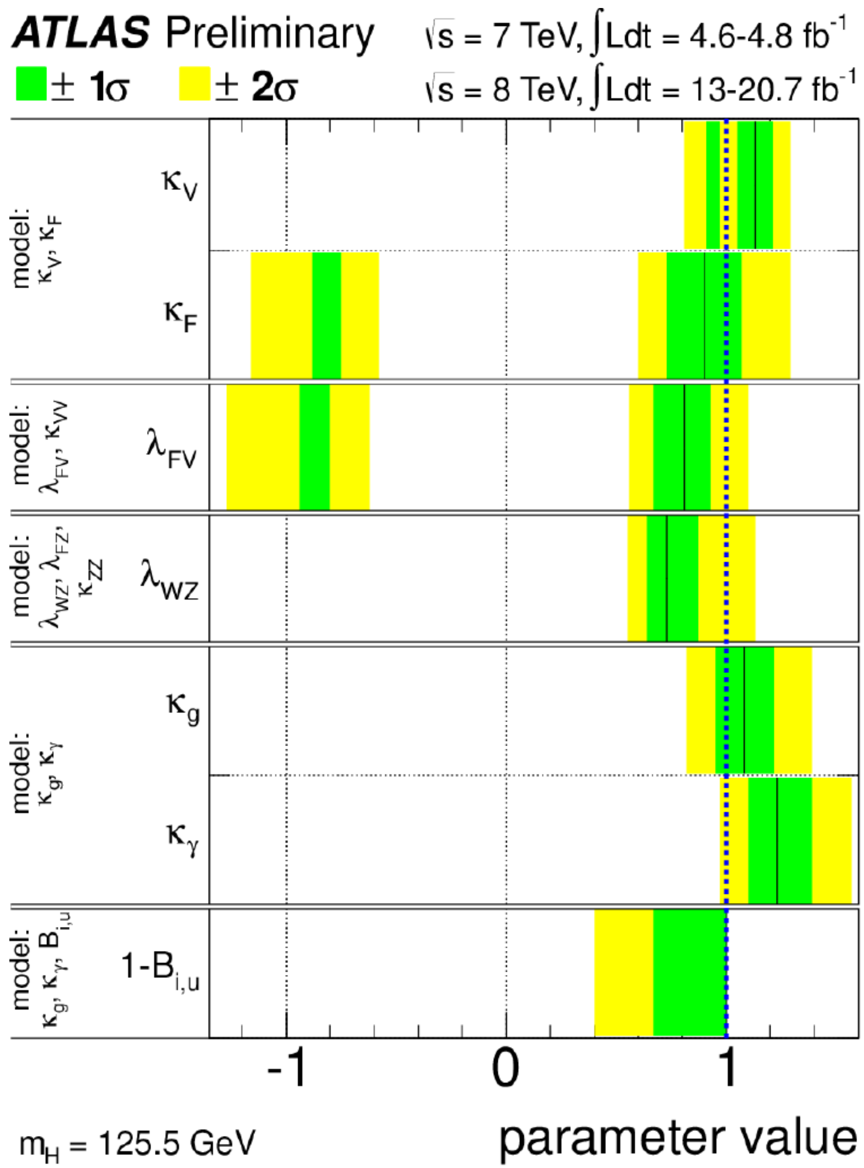


Fit prefers $\lambda_{FZ}<0$ minimum. Compatible with $\lambda_{FZ}>0$ at 1.5 σ

Mass difference



Summary of couplings



Parameter measurements are correlated

Spin Models

Table 1: Choice of coupling parameters for the spin-2 model considered in the current analysis. The notation follows the one adopted in [12]. (from JHU)

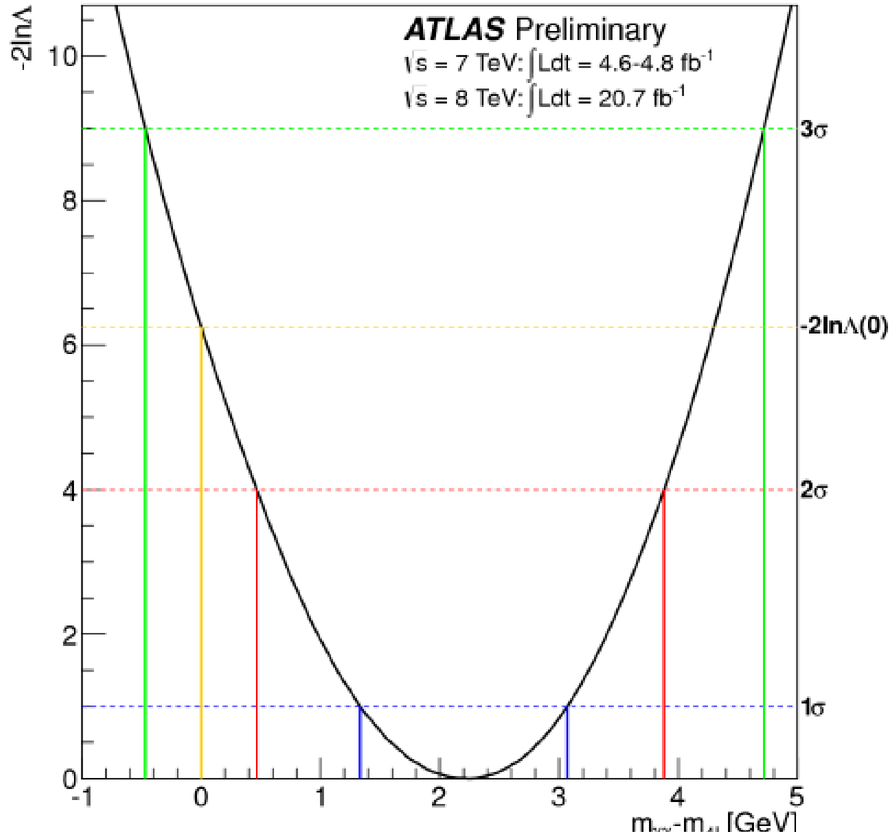
J^P	Production configuration	Decay configuration	Comments
2_m^+	$gg \to X: \ g_1 = 1$ $qq \to X: \ g_1 = 1$	$g_1 = g_5 = 1$	Graviton-like tensor with minimal couplings

General amplitude for spin-2 H→VV

$$A(X \to VV) = \Lambda^{-1}\left[\boxed{2g_1^{(2)} t_{\mu\nu} f^{*1,\mu\alpha} f^{*2,\nu\alpha}} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*1,\mu\alpha} f^{*2,\nu,\beta}\right.$$
$$+ g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}\left(f^{*1,\mu\nu} f^{*2}_{\mu\alpha} + f^{*2,\mu\nu} f^{*1}_{\mu\alpha}\right) + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} f^{*(2)}_{\alpha\beta}$$
$$+ m_V^2 \left(\boxed{2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu}} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu}\right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^*\right)$$
$$\left. + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*1,\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + g_9^{(2)} t_{\mu\alpha} \tilde{q}^\alpha \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\right]$$

Cannot exclude generic spin-2 with current data set

Mass measurement



H → ZZ: $m_H = 124.3\ ^{+0.6}_{-0.5}(\text{stat})\ ^{+0.5}_{-0.3}(\text{syst})$ GeV

H → γγ: 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

- ATLAS mass difference is reduced: $\Delta m_H = 2.3\ ^{+0.6}_{-0.7}$ (stat) ± 0.6 (sys) GeV, 2.4 σ from $\Delta m_H = 0$ (p = 1.5%). Δm_H was 3.0 GeV and 2.8 σ in Dec. 2012
- $m_{\gamma\gamma}$ sysematics dominated by the photon energy scale.
- m_{4l} mainly from muon momentum scale.

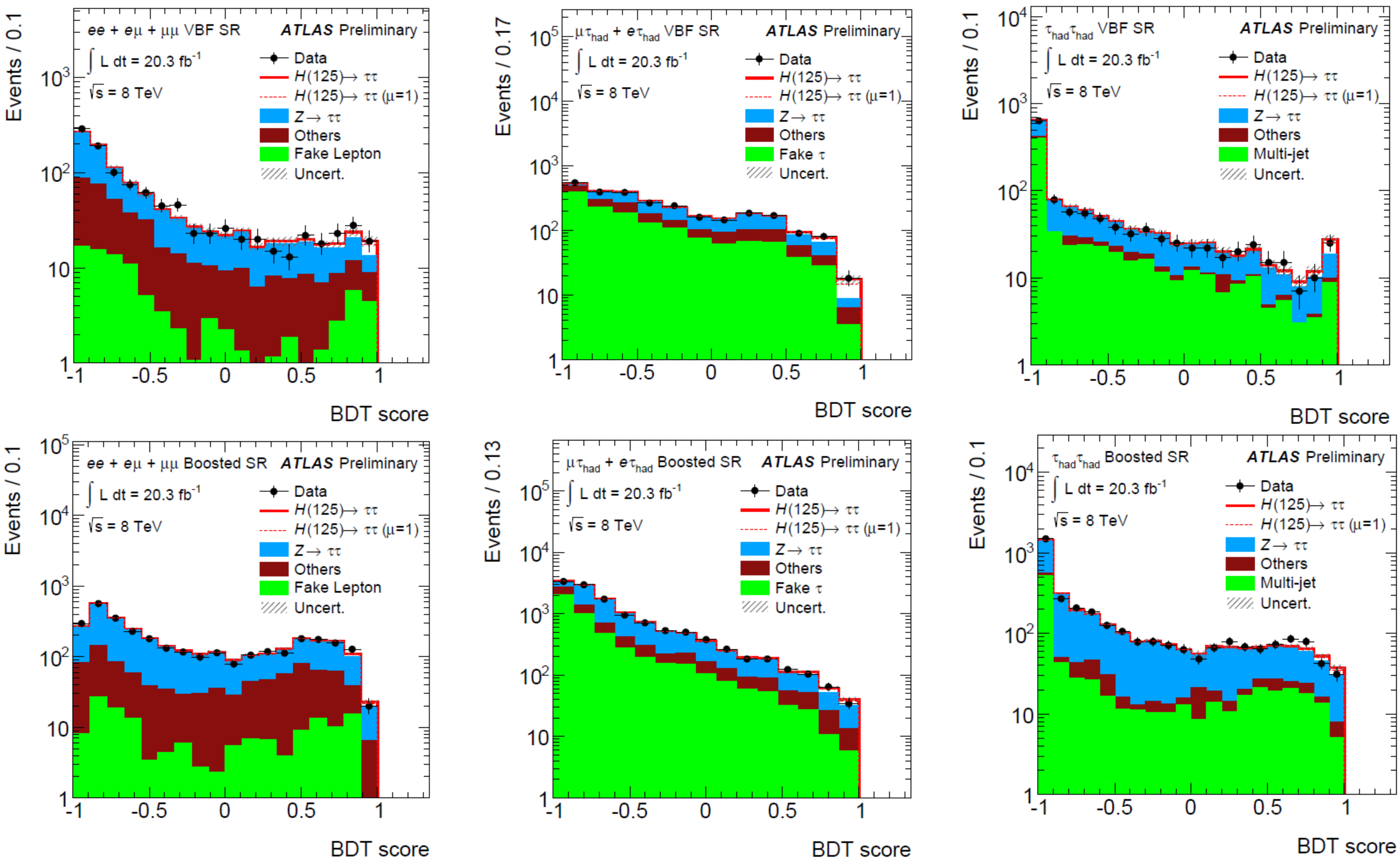
ATLAS Mass Systematics

- ***4 leptons***
  - Dominated by 4 muons (best resolution, less background)
    - Muon momentum-scale uncertainty : 0.2% (from Z, $J/\psi \rightarrow \mu\mu$)
  - electron E-scale = > see below

- ***$\gamma\gamma$***
  - Per category systematic uncertainties:
    - method ~ 0.3 % : (mainly from $Z \rightarrow ee$ MC/data)
    - material in front of calorimeter: ~ 0.3%, up to 0.7%
    - relative calibration presampler/calorimeter : ~ 0.1%

    In each of the above: extrapolation in E $\oplus$ transfer from e to γ
  - Additional (global) syst uncertainties:
    - E1/E2, linearity, lateral leakage, conversion fraction … 0.32%
  - Global mass systematic uncertainty: 0.55% = 0.7 GeV

$H \rightarrow \tau\tau$ Analysis BDT



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

Higgs Potential (2)

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

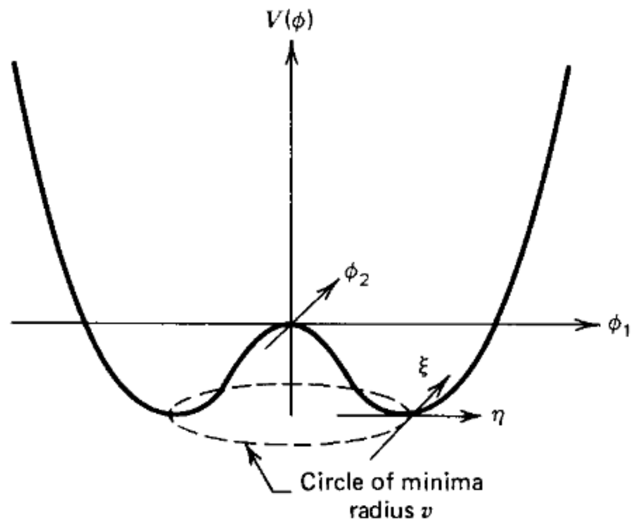
$$|\Phi| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv v/\sqrt{2}$$

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

The Lagrangian now becomes:

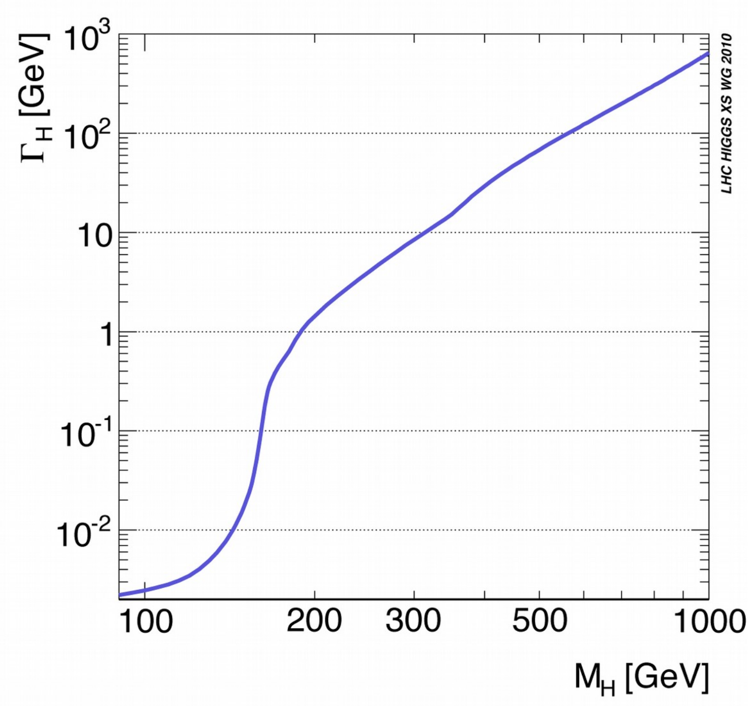
$$\mathscr{L} = \tfrac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \mu^2\eta^2 \pm \mu\lambda\eta^3 - \tfrac{1}{4}\lambda^2\eta^4 + \tfrac{1}{4}(\mu^2/\lambda)^2$$

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



Higgs Mass width

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



For high mass, the width grows as

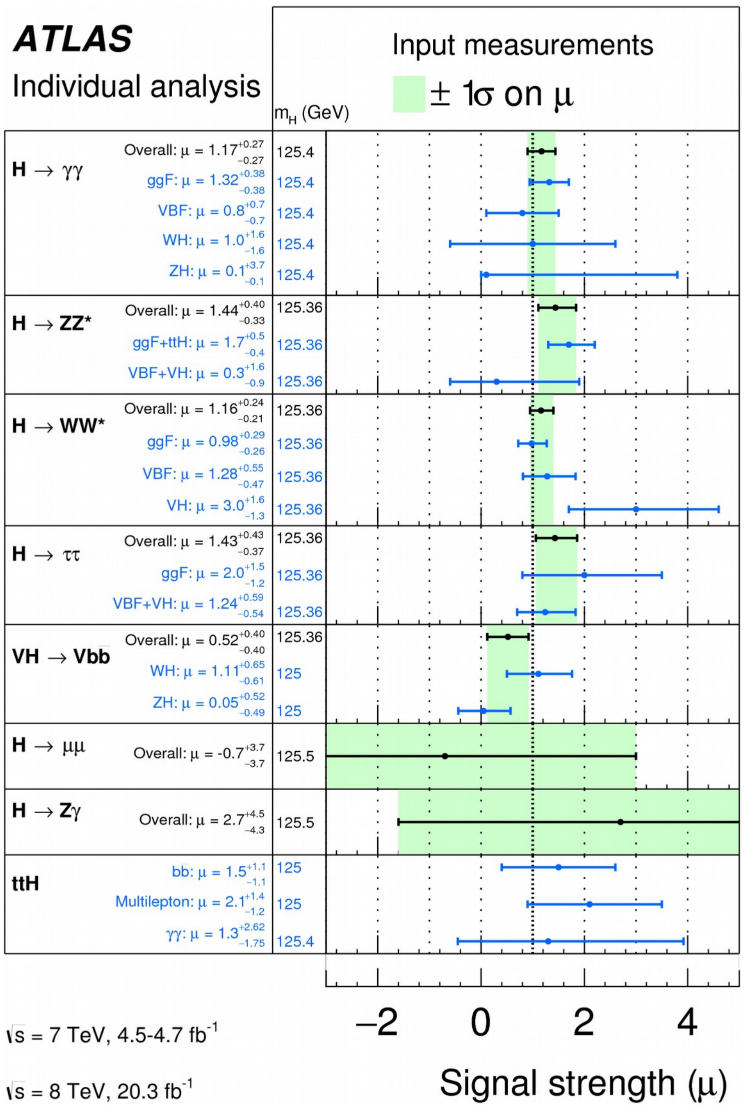
$$\Gamma_H = \frac{3g^2}{128\pi m_W^2} m_H{}^3 \simeq 0.5\ \mathrm{TeV}^{-2}\ m_H{}^3.$$

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

LHC Couplings Combination

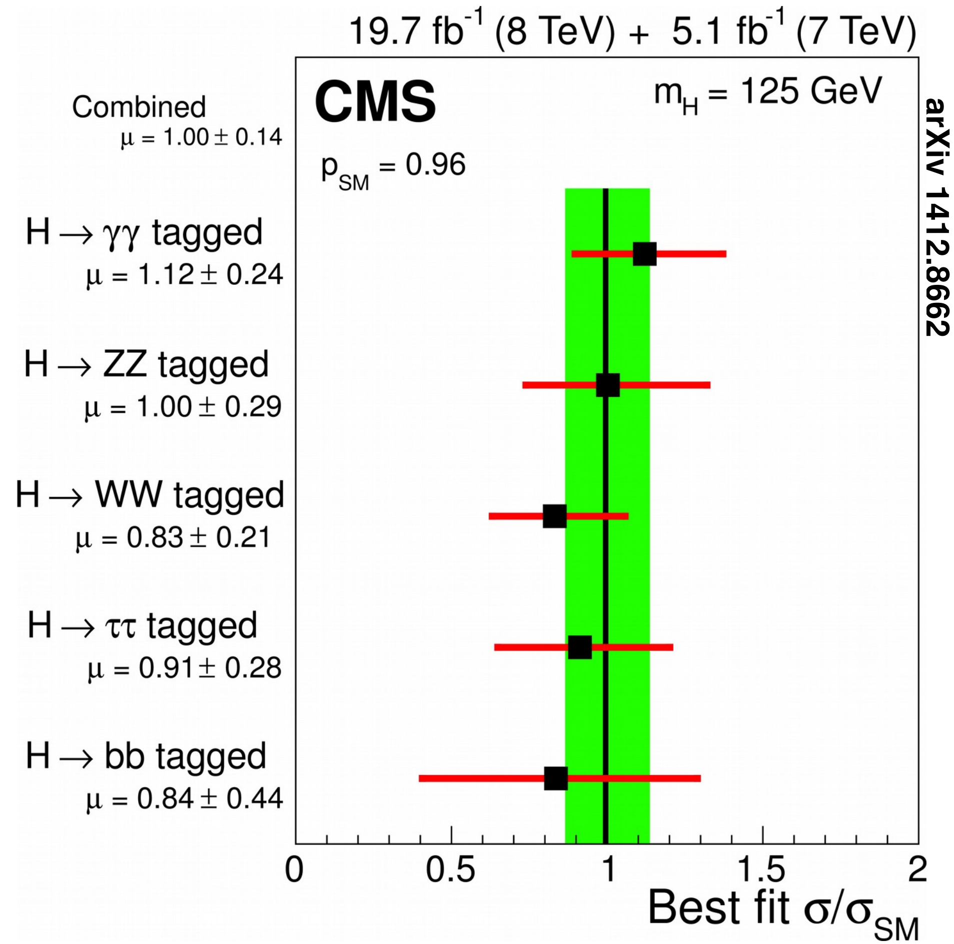
arXiv 1507.04548



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

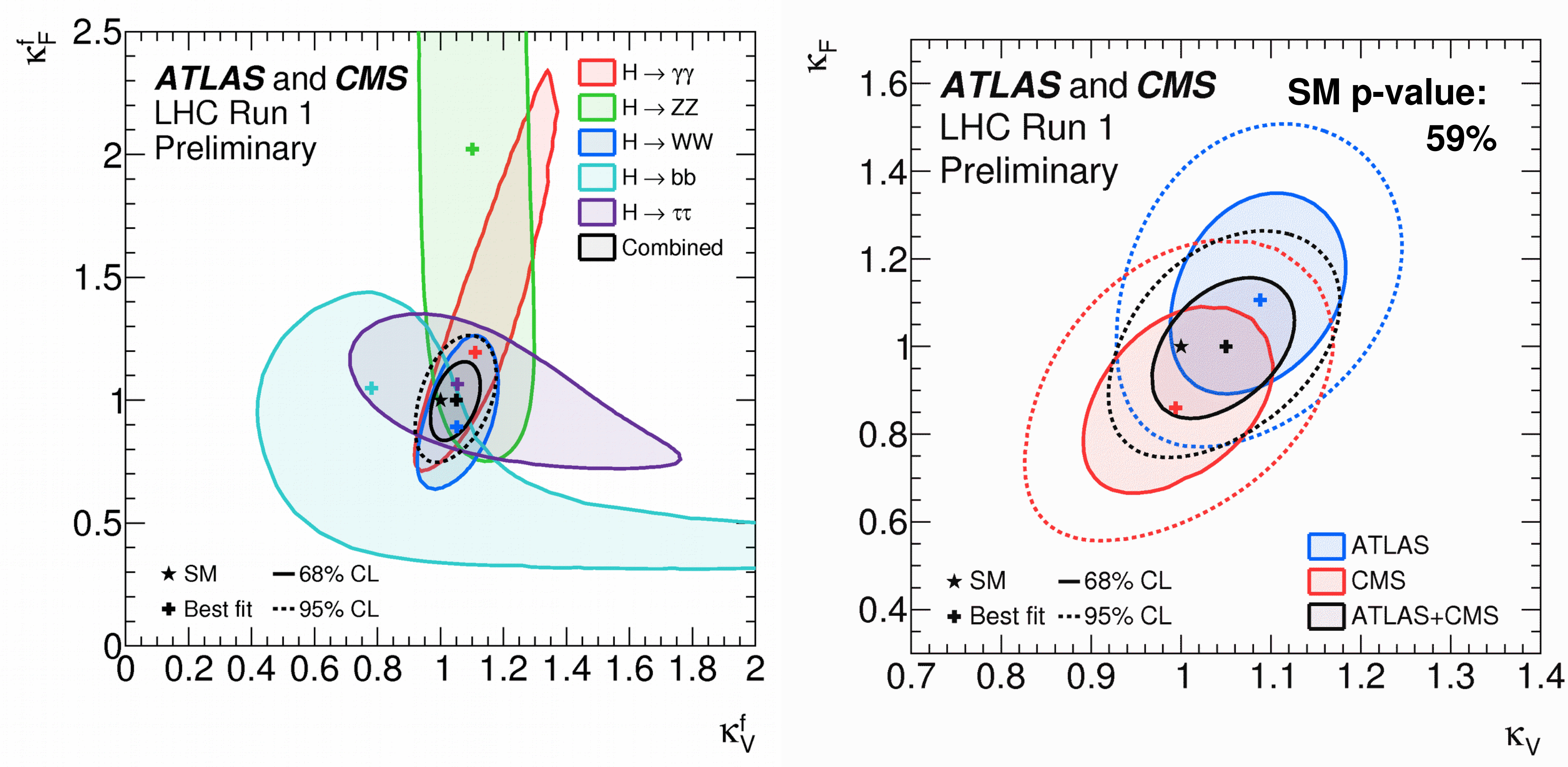
$\mu=0$ no Higgs

$\mu=1$ 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

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

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

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