Recent Higgs Boson Results from the LHC

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Vulcano Workshop 2016 - FRONTIER OBJECTS IN ASTROPHYSICS AND PARTICLE PHYSICS

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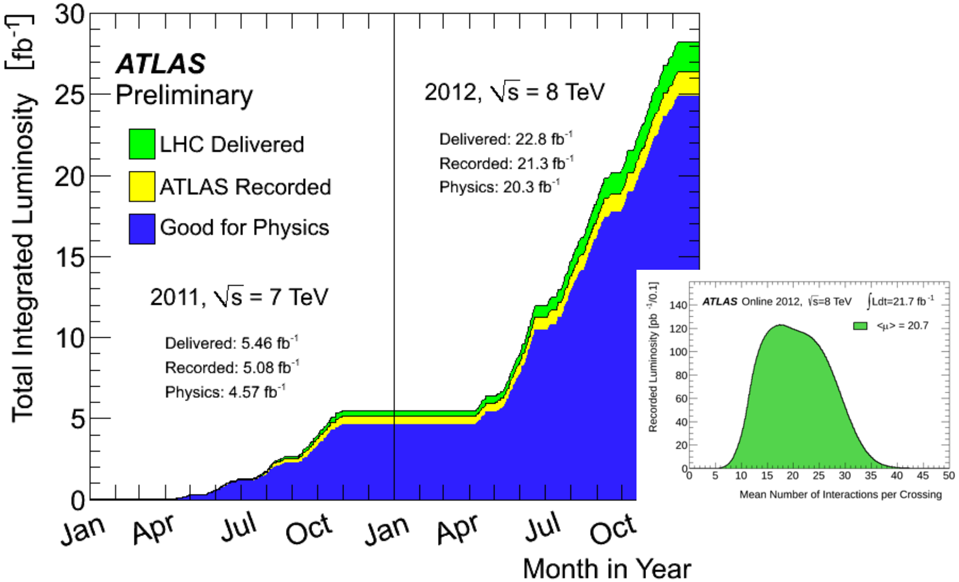
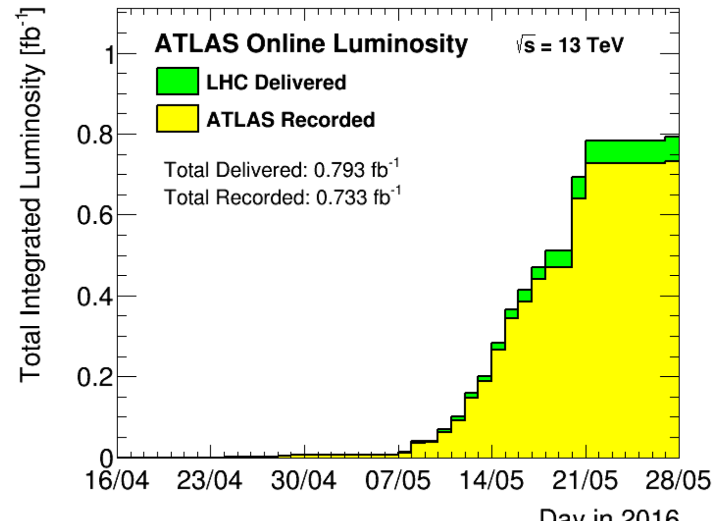
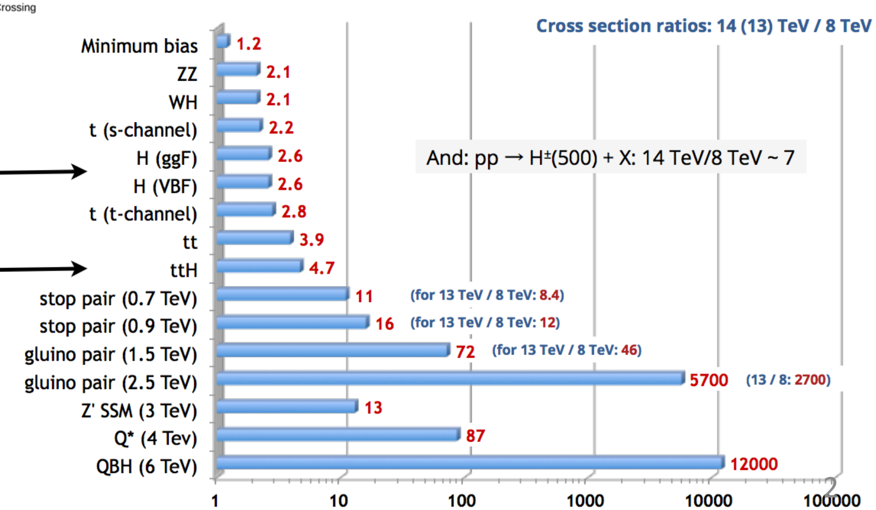
Welcome to the LHC run2

- Very successful LHC RUN1, with ~25fb^{-1} delivered at $\sqrt{s}$=7,8 TeV
  - Allowed to great results: Higgs boson discovery , B^0_s->μμ observation
- LHC RUN2 started at $\sqrt{s}$=13TeV in 2015 delivering ~3fb^{-1}
  - Final RUN2 expectation is 100fb^{-1}, ~30fb^{-1} at the end of this year

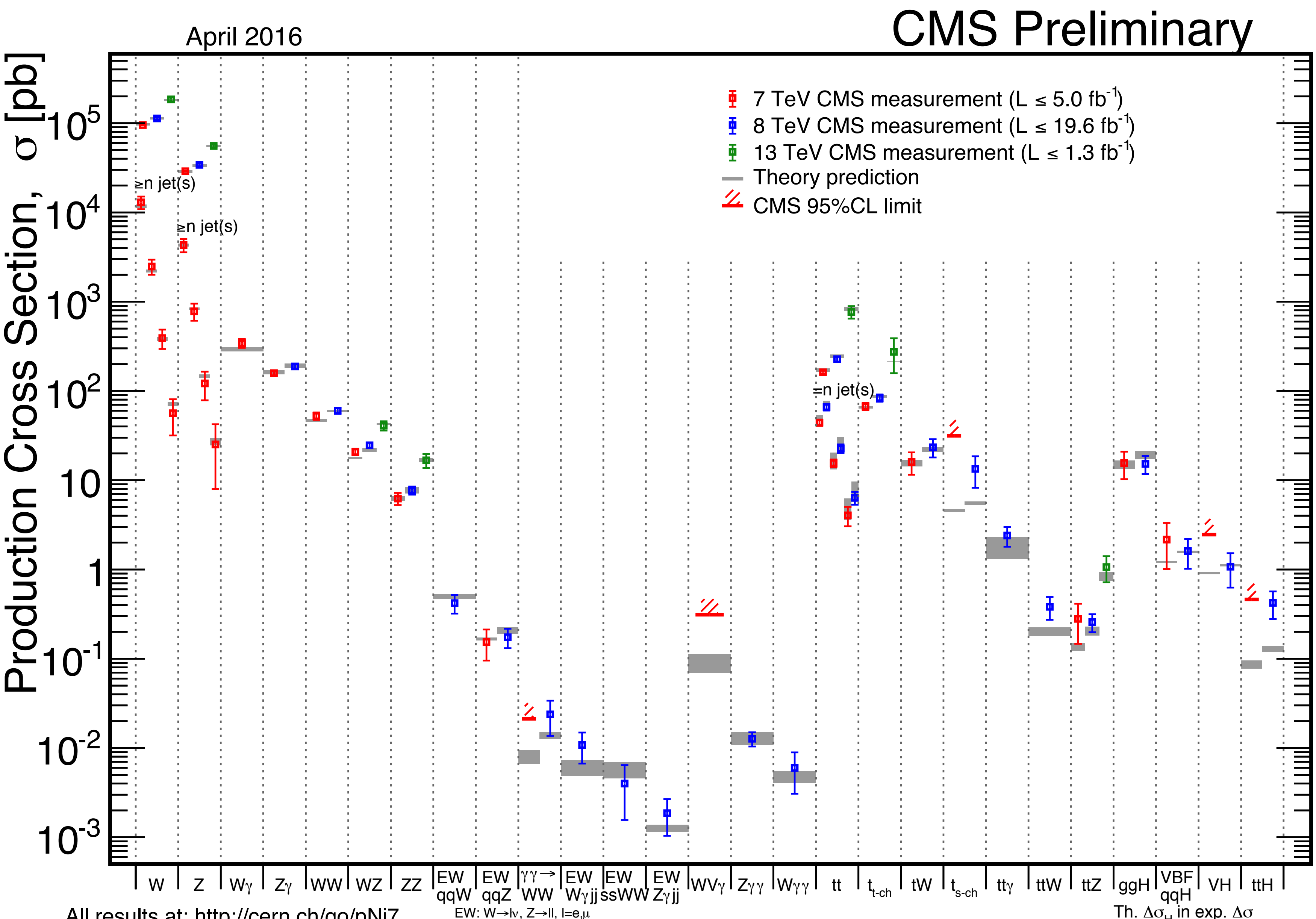




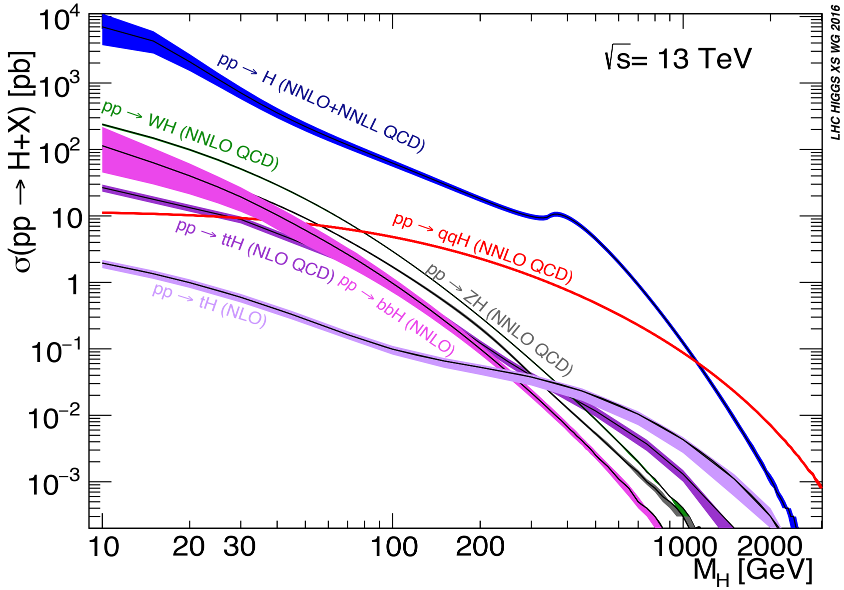
- Hugely increased potential for discovery of heavy BSM particles thanks to the higher $\sqrt{s}$

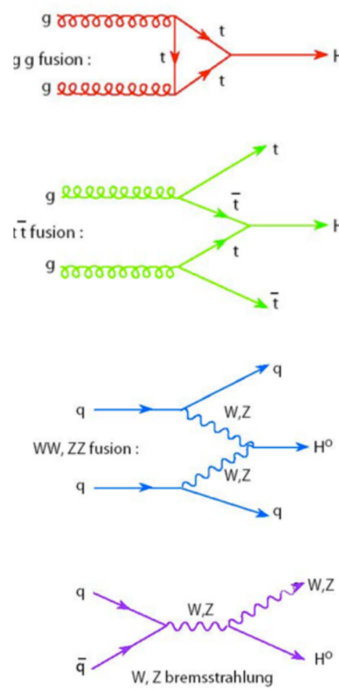


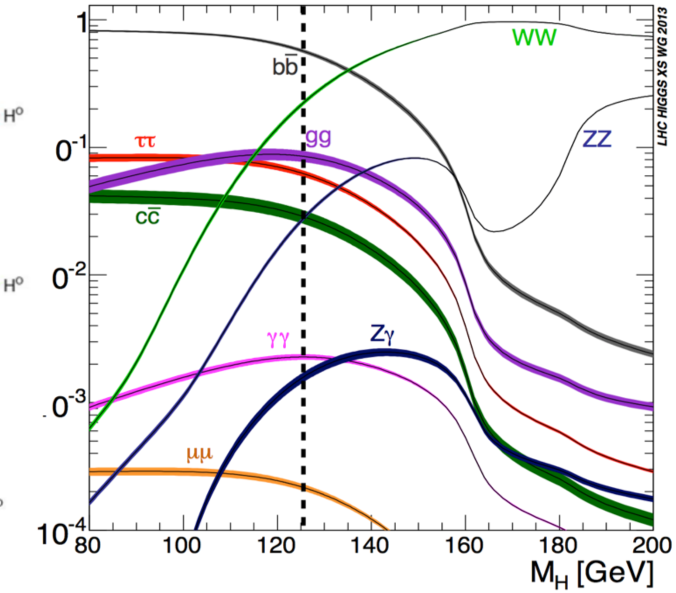
The Standard Model in its full glory

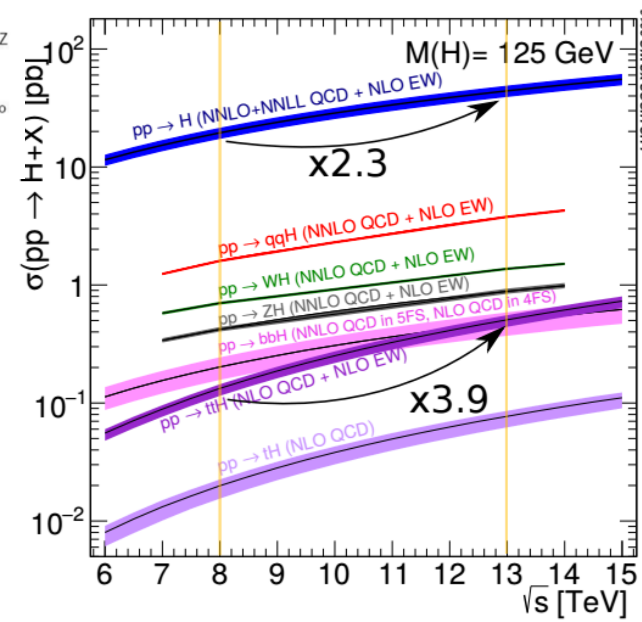


Higgs Boson at LHC





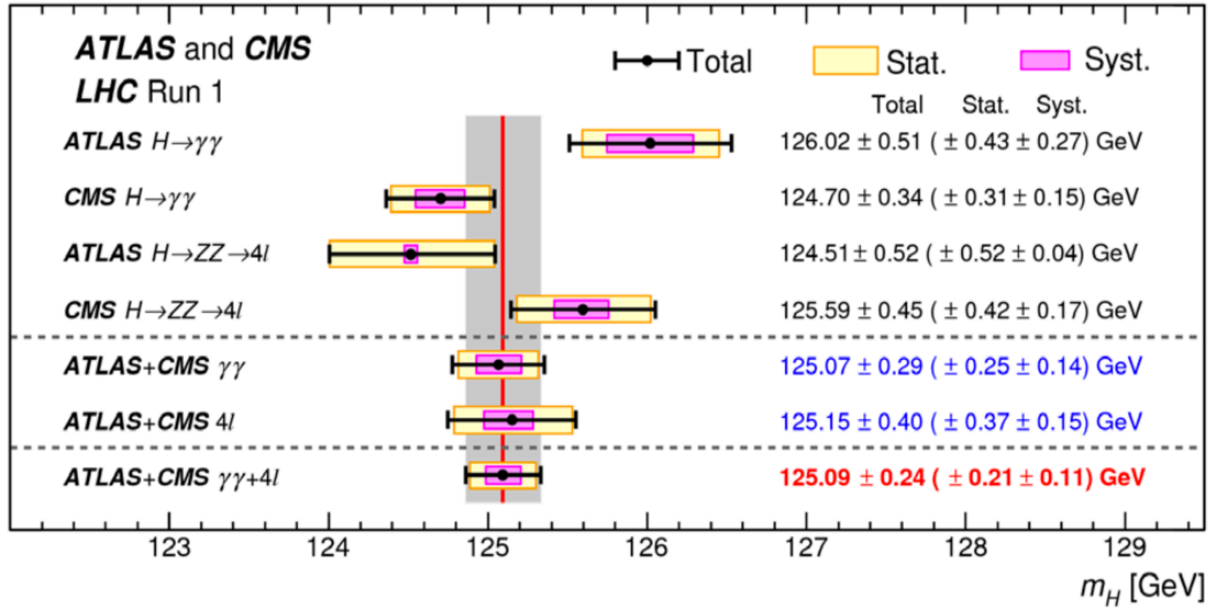


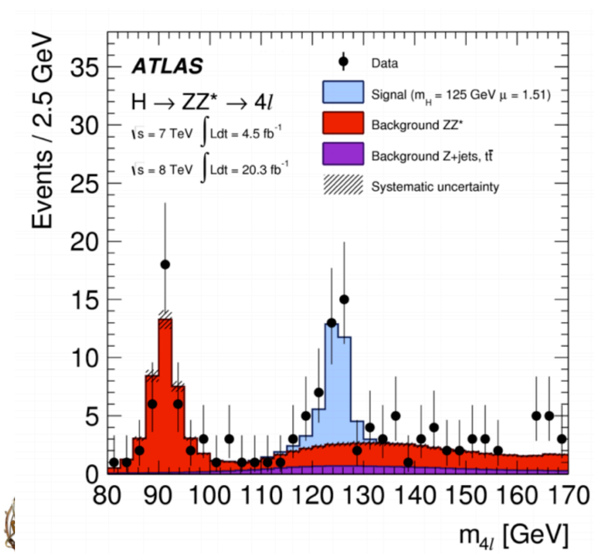


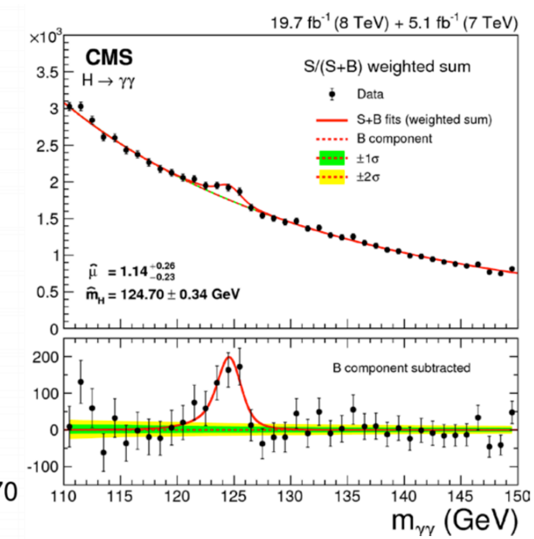
- Run 2 : the Higgs precision era
  - σ_{ggH} (13 TeV)/ σ_{ggH} (8 TeV) = 2.3
    - factor 3.9 increase for σ_{ttH}
    - σ_{ggH} (13 TeV) ~ 50pb
  - Improvements in detectors for Run2
    - (e.g. ATLAS IBL) and analysis techniques
  - Currently only ≈ 15% of int. luminosity @8TeV

Mass of the Higgs boson

- H->γγ and H->ZZ*->4l combined
  - 1-2% mass resolution
- Largest systematics from determination of energy/ momentum scales of photons and leptons







$m_H = 125.09 \pm 0.24$ GeV

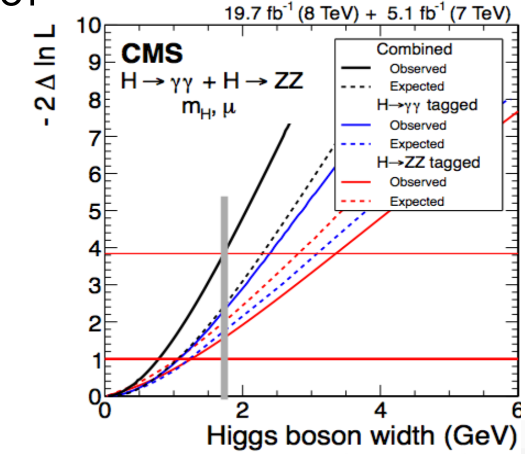
- Already a per-mil precision
  - Small tensions between individual measurements

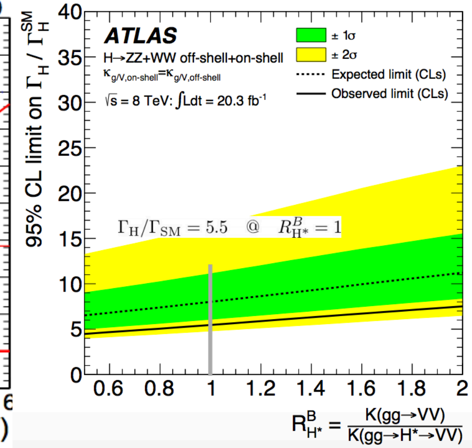
$$m_{\gamma\gamma}^{ATLAS} - m_{\gamma\gamma}^{CMS} = 1.3 \pm 0.6 \text{ GeV } (2.1\sigma)$$

$$m_{4\ell}^{ATLAS} - m_{4\ell}^{CMS} = -0.9 \pm 0.7 \text{ GeV } (1.3\sigma)$$

Width of the Higgs boson

- SM width ~ 4 MeV @ 125 GeV —> precision of direct measurements at LHC is limited by instrumental resolution
  - direct upper limit from mass distribution: **Γ_H< 1.7 GeV @ 95% CL**
  - direct lower limit from lifetime in 4l: **τ_H<190 fs => Γ_H>3.5 10^{-9} MeV**



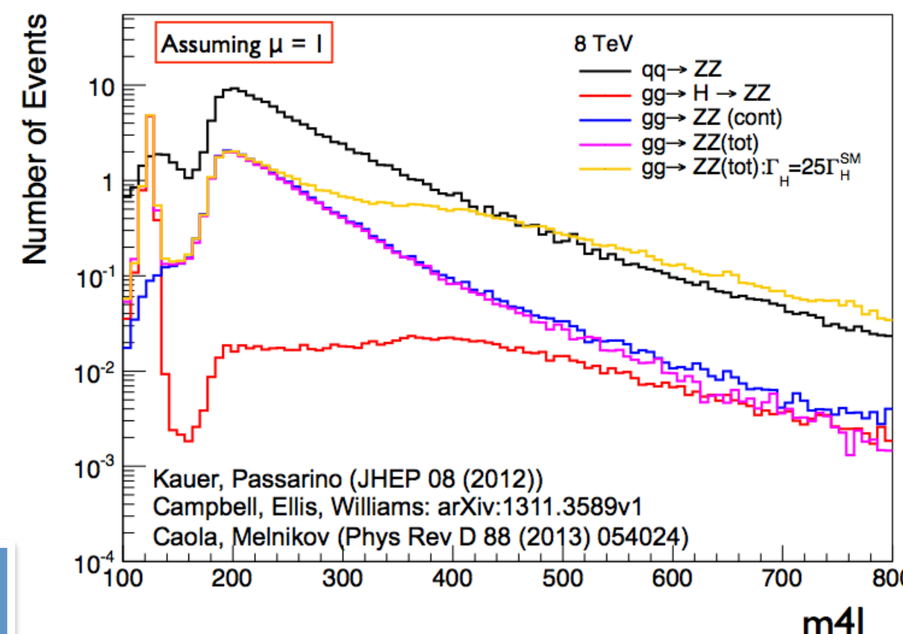


- Indirect constraint through the on-shell/off-shell production ratio of gg->H->VV

$$\frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell, SM}}} = \mu_{\text{off-shell}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{V,\text{off-shell}}$$

$$\frac{\sigma^{gg\to H\to ZZ}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ}_{\text{on-shell, SM}}} = \mu_{\text{on-shell}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{V,\text{on-shell}}}{\Gamma_H/\Gamma_H^{SM}}$$

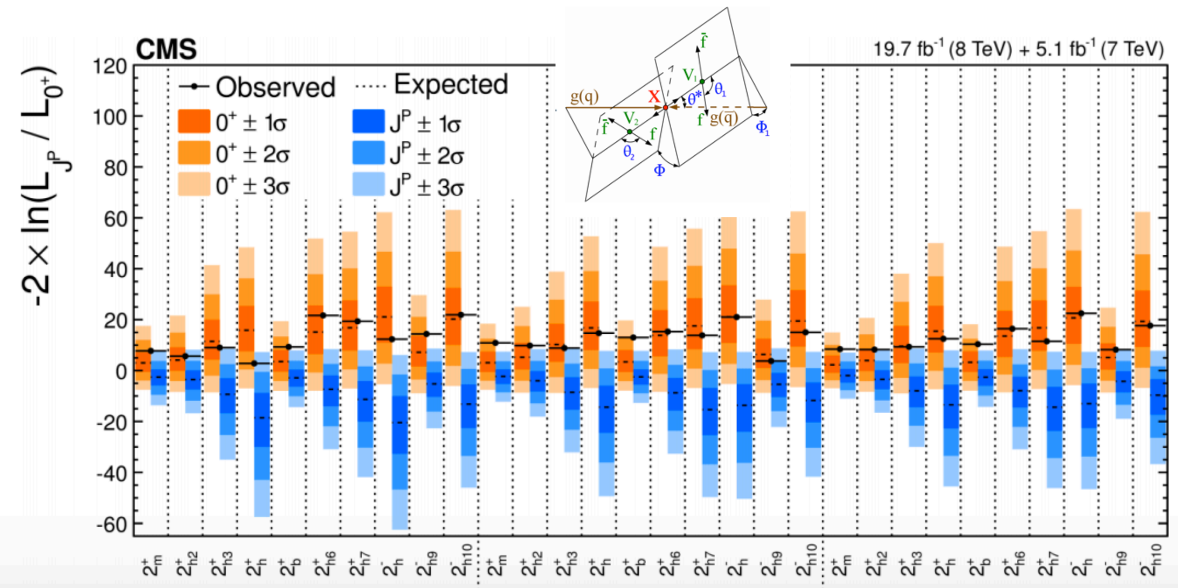
- ATLAS and CMS combined ZZ and WW channels
- Large negative interference with gg->VV enters in the game

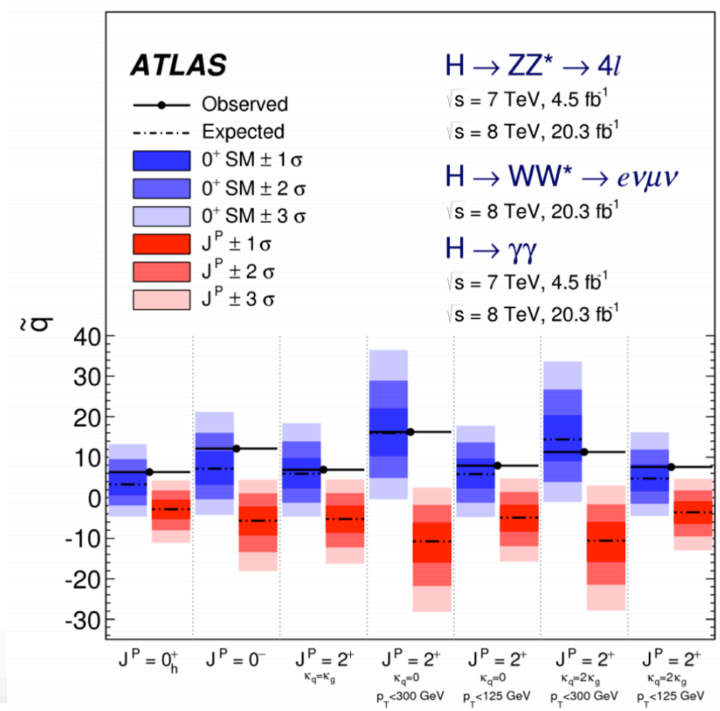


Γ_H/Γ_H (SM) < 3.1 (6.2) obs (exp)
@ 95% CL

Spin and Parity

- Diboson decay modes of the Higgs boson (γγ,WW,ZZ) used to test Spin/CP properties. The data strongly prefer the SM hypothesis $J^P=0^+$. Almost all alternative hypotheses studied have been excluded at 95% CL



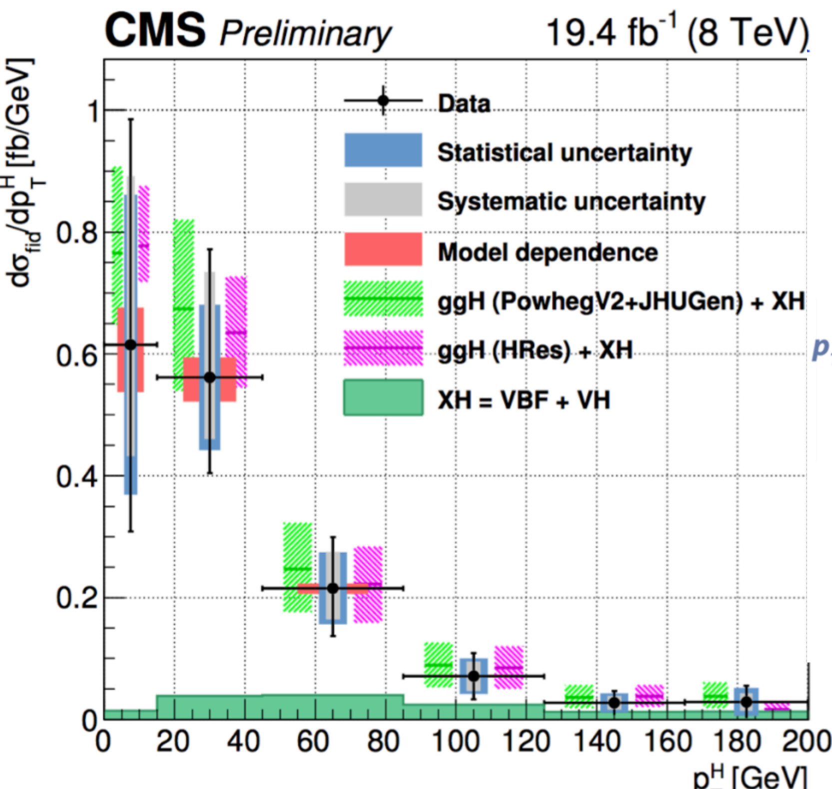


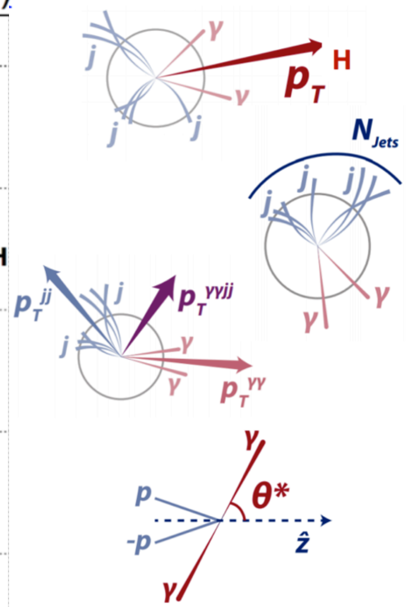
Eur. Phys. J. C (2015) 75:476

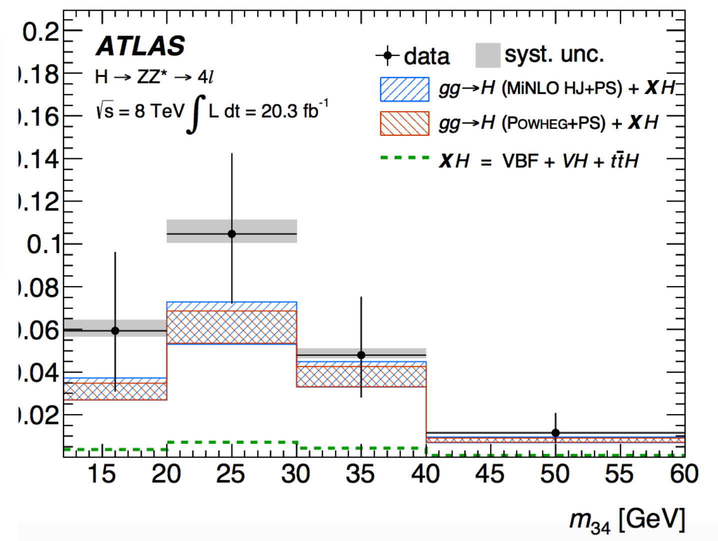
Tensor structure and CP-invariance of the couplings are also studied in ZZ, WW and ττ decays, no deviations from the SM expectations have been found.

Fiducial and differential cross section @ 8TeV

- The most model independent way to study the Higgs Boson properties
  - Test SM predictions and look for hints of bsm physics







- Measurements are statistically limited, but no significant deviations from SM

ATLAS+CMS couplings combination: inputs

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

- More than 600 experimental categories
  - Each can receive contributions from different processes
  - Each can bring information about different couplings

	ggF	VBF	VH	$t\bar{t}H$
$H \to \gamma\gamma$	✓	✓	✓	✓
$H \to ZZ^* \to 4l$	✓	✓	✓	✓
$H \to WW^* \to 2l2\nu$	✓	✓	✓	✓
$H \to \tau\tau$	✓	✓	✓	✓
$H \to b\bar{b}$	✗	✗	✓	✓
$H \to \mu\mu$	✓	✓	✗	✗

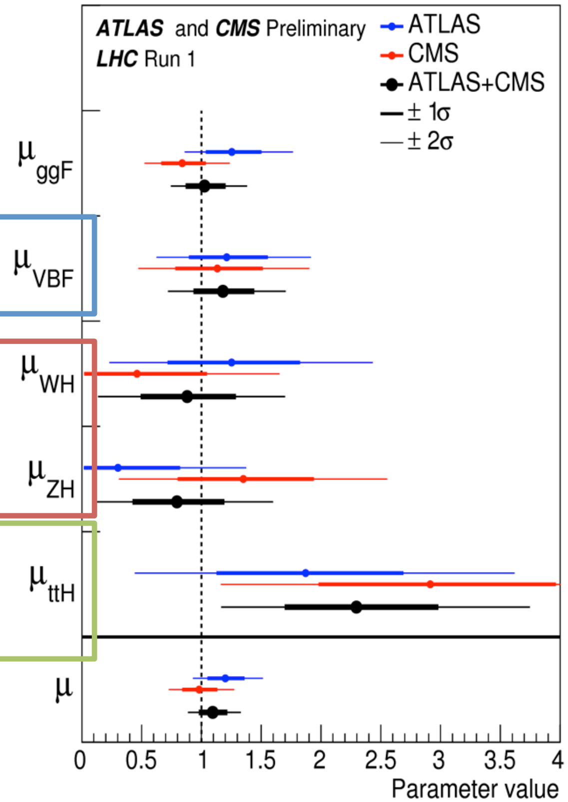
Assumptions:

- Assume SM tensor structure (→ SM kinematics)
- and Narrow Width Approximation : $\sigma(i \to H \to f) = \sigma_i \, \Gamma_f / \Gamma_{tot}$

ATLAS+CMS combination

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

Production modes

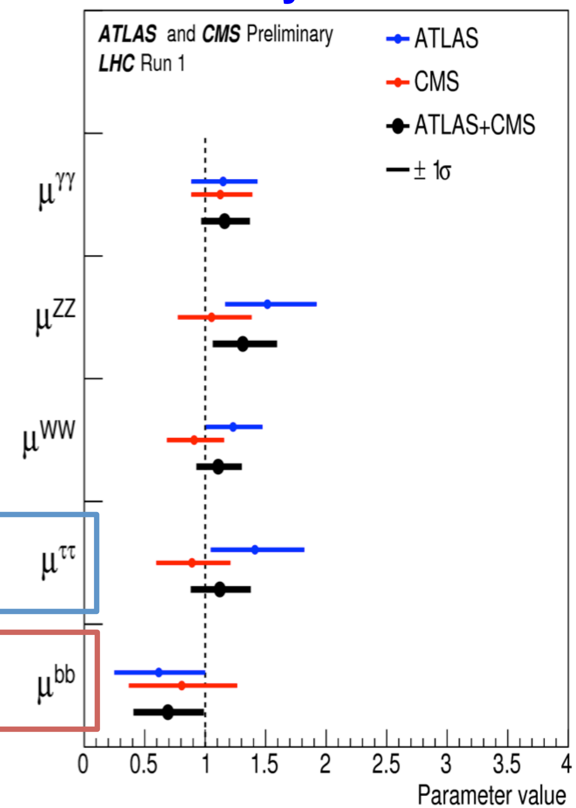


Observed with 5.4σ significance (4.7σ exp)

3.5σ significance (4.2σ exp.)

2.4σ excess over SM prediction (4.4σ obs, 2.0σ exp)

Decay modes



Observed with 5.5σ significance (5.0σ exp)

2.5σ deficit wrt SM predictions

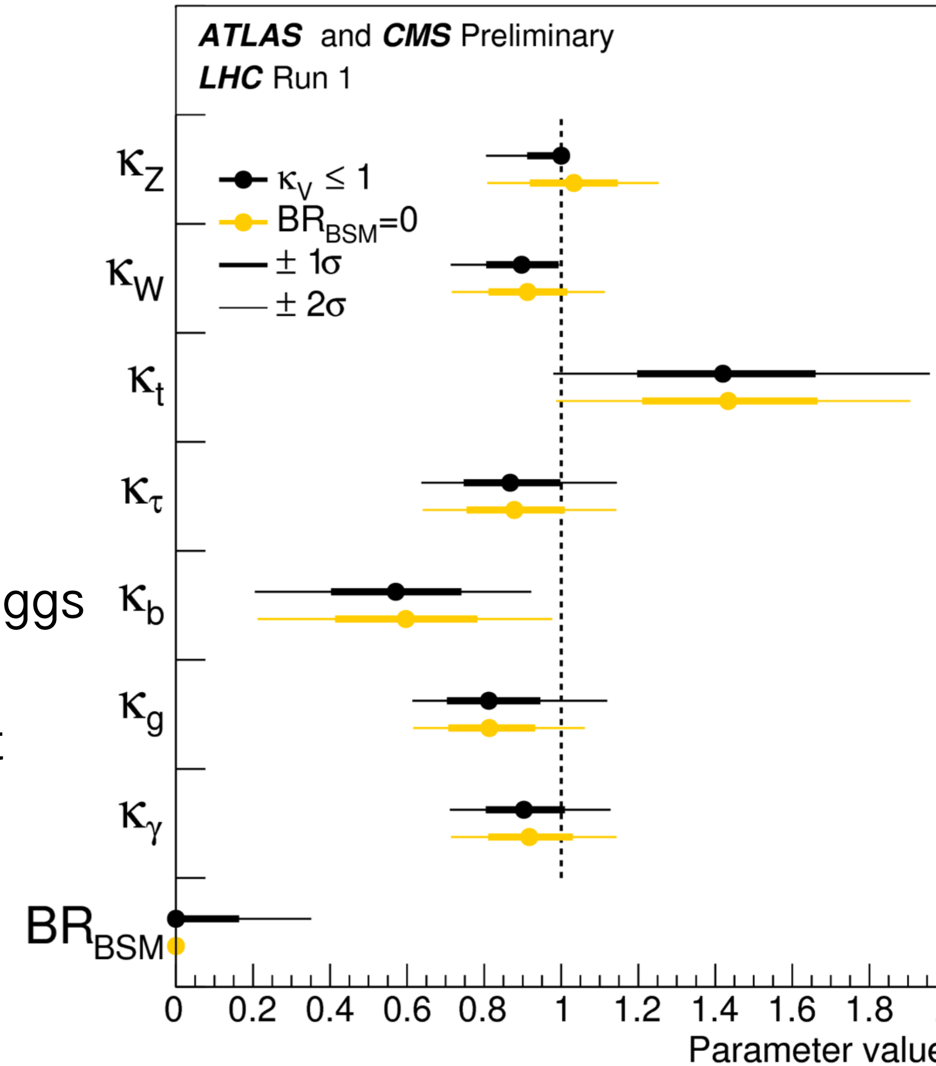
$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})\ ^{+0.07}_{-0.06}\ (\text{thsig})$$

ATLAS+CMS combination

- Coupling strength modifier introduced to probe new physics BSM
  - Same coupling structure as in SM
  - modify couplings with LO degree of freedom

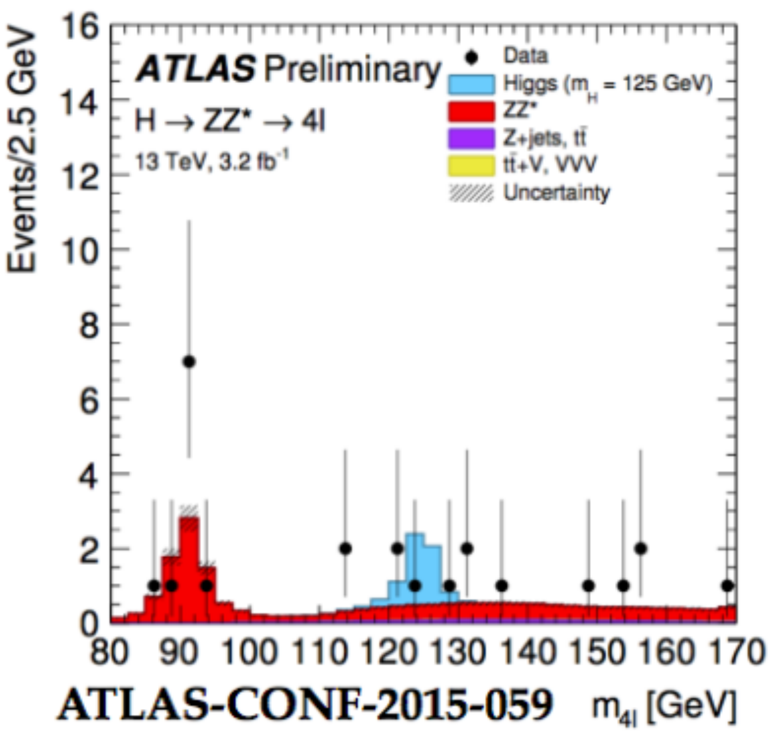
$$\sigma_i = \kappa_i^2 \cdot \sigma_i(\mathrm{SM})$$
$$\Gamma_f = \kappa_f^2 \cdot \Gamma_f(\mathrm{SM})$$
$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{\sigma_i(\mathrm{SM}) \cdot BR^f(\mathrm{SM})} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\Gamma_\mathrm{H}/\Gamma_\mathrm{H}(\mathrm{SM})}$$

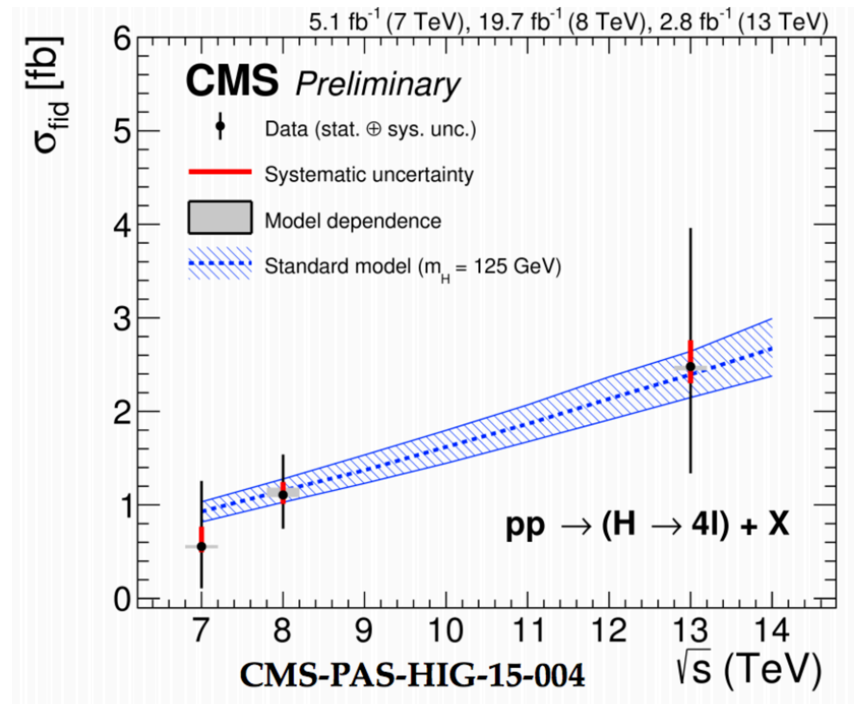
- Changing the couplings variation of Higgs boson width
- 2 possible approaches: allowing or not extra BSM contribution in the width
  - BR_{BSM}=0
  - $k_V \leq 1$ (N-HDM) and BR_{BSM} free
    - $BR_{BSM}<0.34$ at 95% CL



First results @ 13 TeV : ZZ

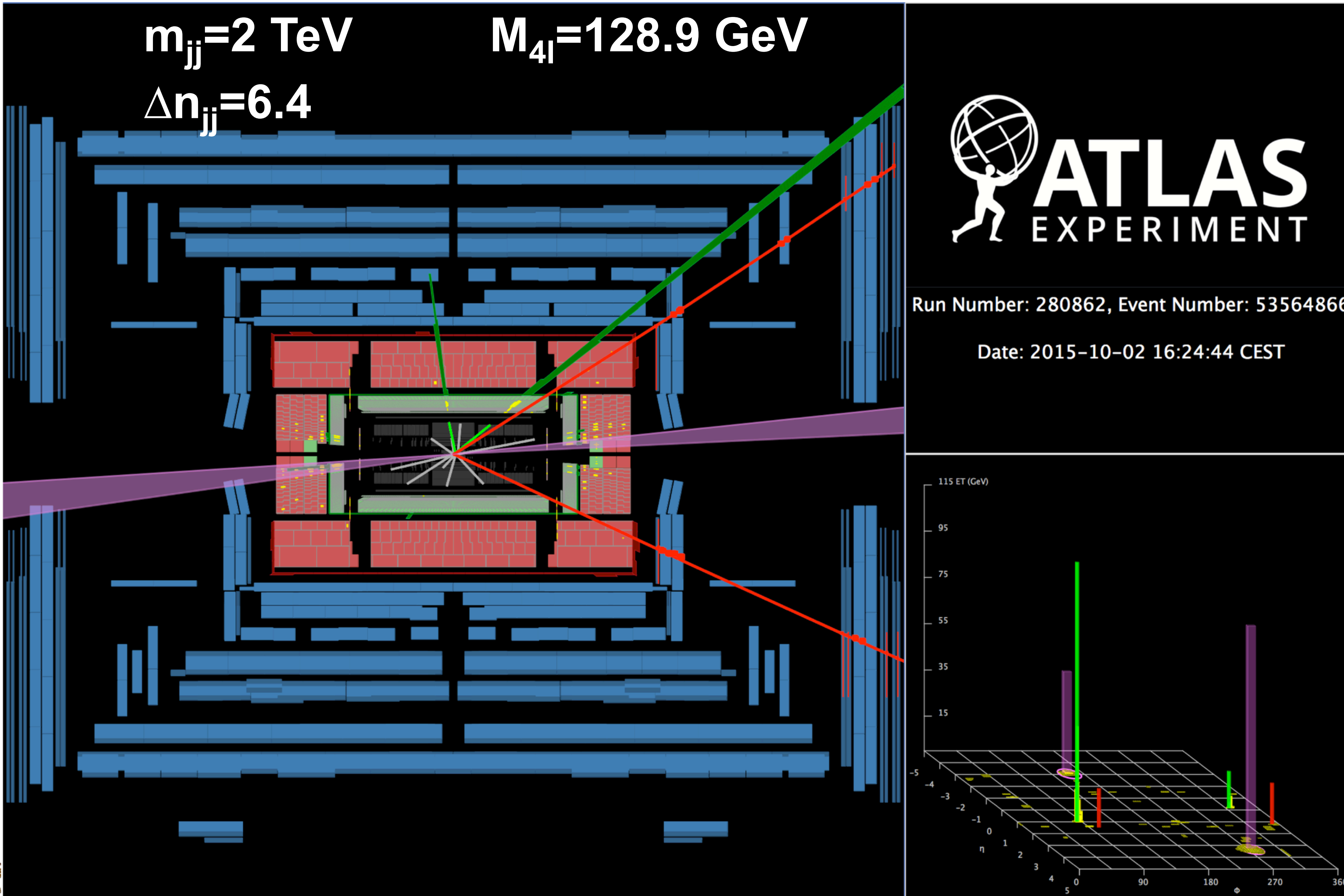
- First 2015 data still not enough to reach run1 sensitivities
  - Used mainly to re-establish a signal √s=13 TeV





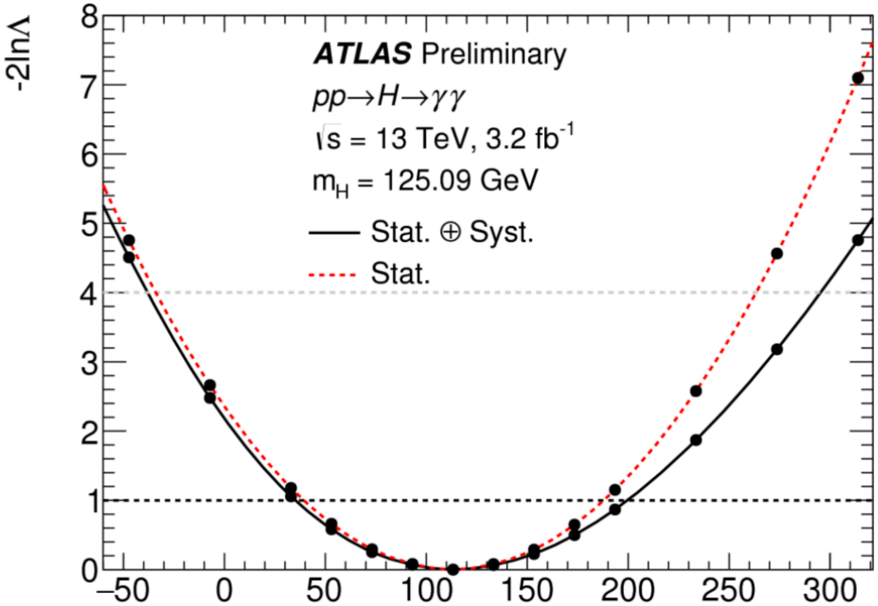
- Signal extraction for mH=125.1 GeV using m4l
  - Cms also included a first categorization for VBF
  - Expected significances above 3s , observed strength μ ~1 for cms, μ 0.3 for ATLAS

A peculiar H->ZZ->4l candidate

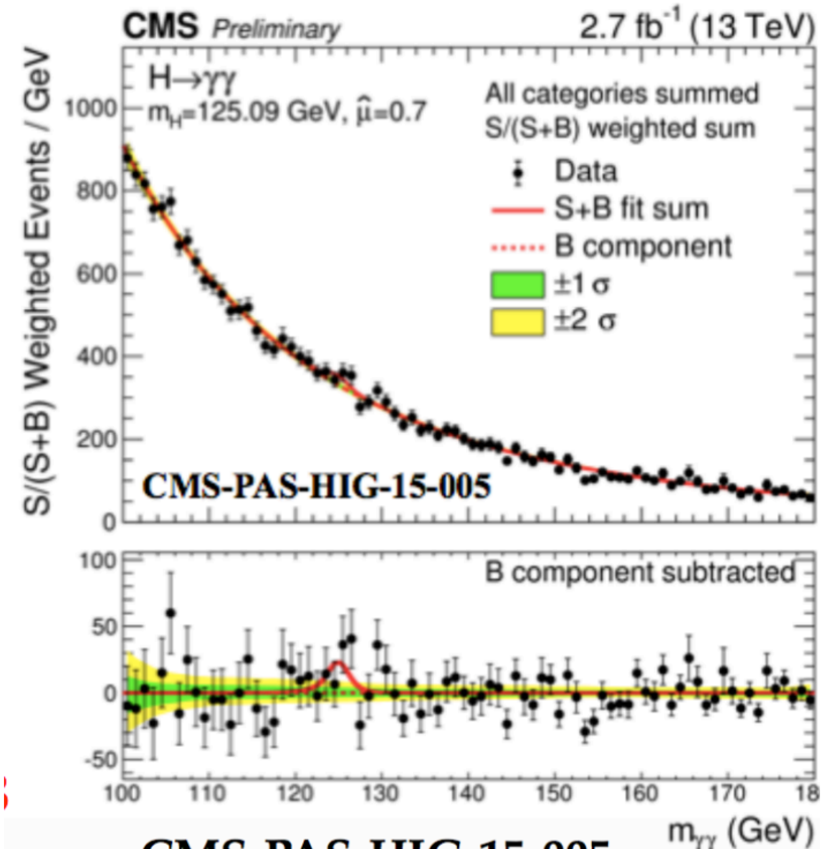


First results @ 13 TeV : γγ

- Requires good photon identification and reconstruction
- Several improvements wrt RUN1
  - ie. PU stability of photon isolation
- Bkg from diphoton production and fakes



ATLAS-CONF-2015-060



CMS-PAS-HIG-15-005

- ATLAS: fiducial xsec measurement

Cross section result

$\sigma_{\text{fid.}} = 52 \pm 34 \text{ (stat.) } ^{+21}_{-13} \text{ (syst.) } \pm 3 \text{ (lumi.) fb}$

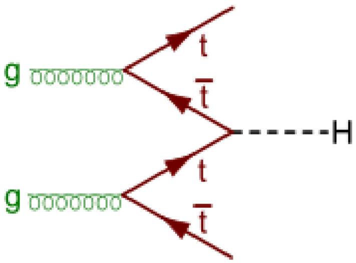
$\sigma^{\text{SM}}_{\text{fid.}} = 66.1^{+6.8}_{-6.6} \text{ fb}$

- CMS: full prod. Mode categorization

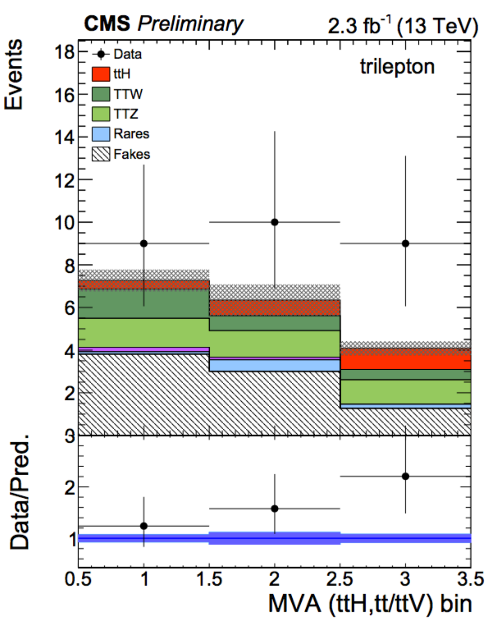
Signal Strength

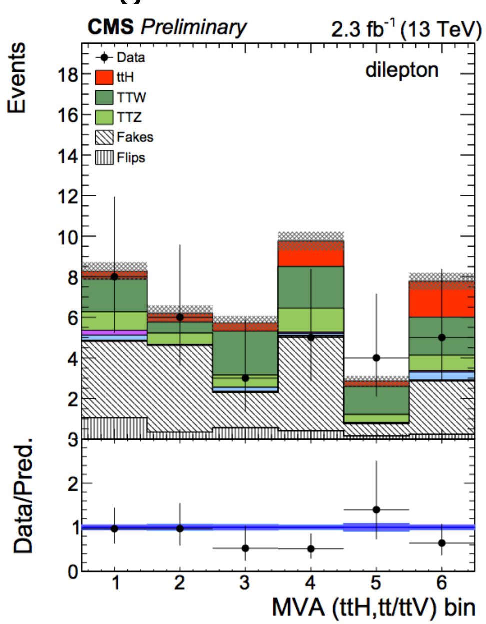
- $\mu = 0.69^{+0.47}_{-0.42}$ at $m_H = 125.09$ GeV
- 1.7σ significance (2.7σ expected)

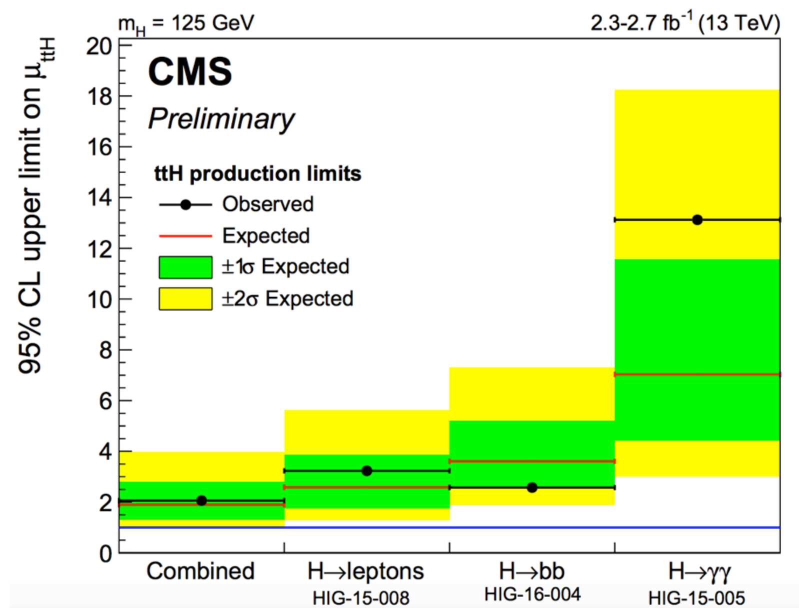
First results @ 13 TeV : ttH



- Quite complex final state, investigated in several H decay channels
  - H → bb: high statistics, large background and systematics, combinatory
  - H → γγ: low background and low statistics
  - H → WW/ZZ/ττ with same sign or ≥3 leptons: fake lepton and ttV background





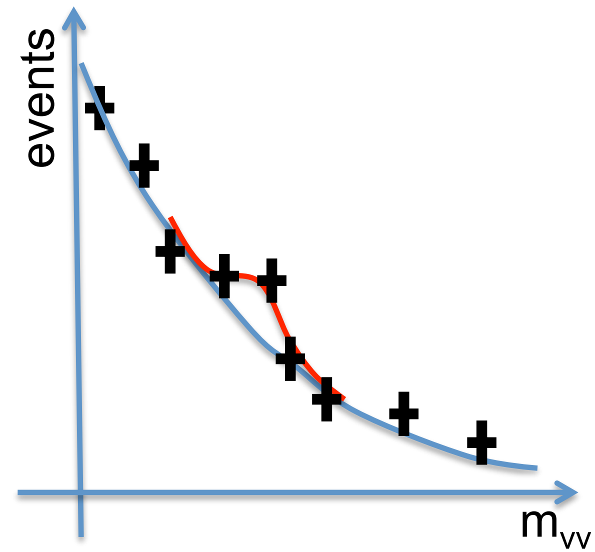


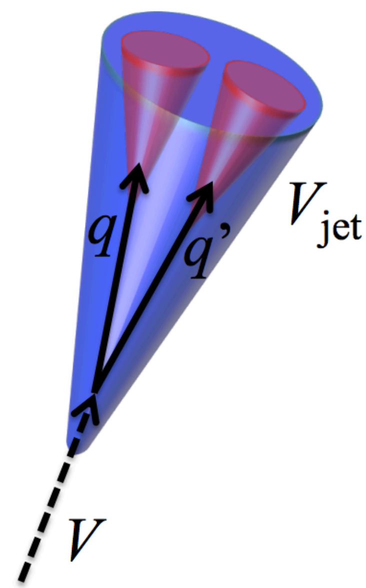
- Best fit: μ = 0.15+0.95—0.81
- Limit: μ < 2.1 (1.9 expected for no ttH)
- Close to run 1 sensitivity

Going beyond the SM: High mass resonance searches

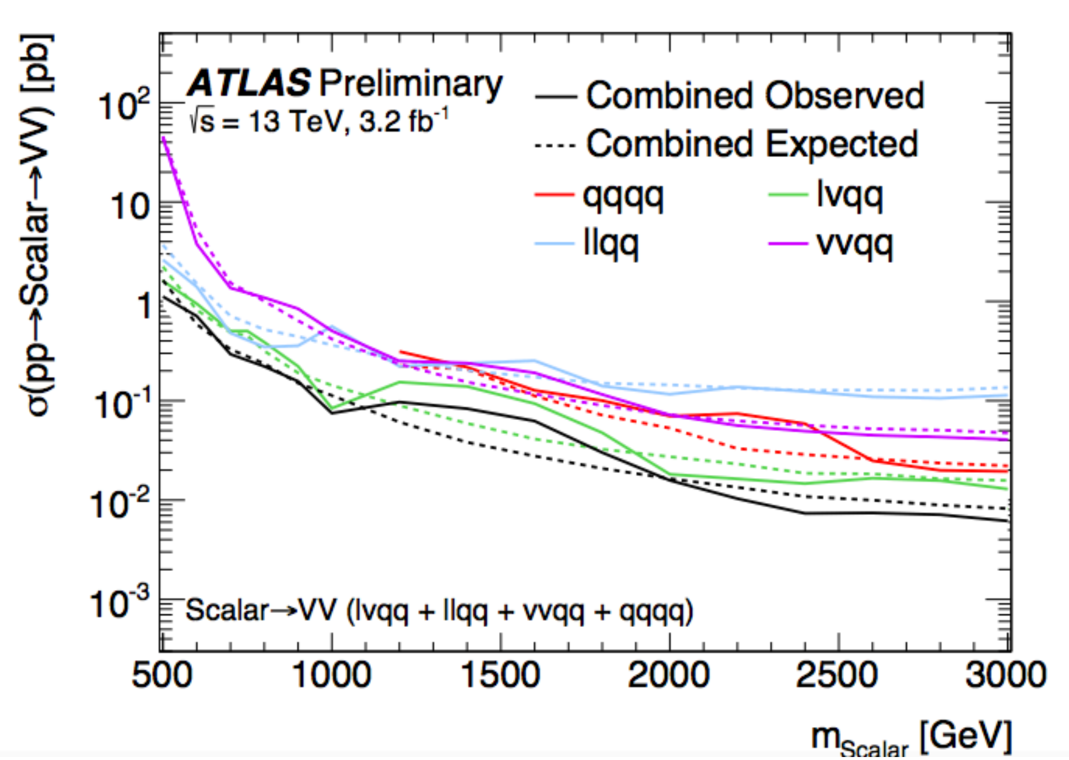
How to find a new resonance

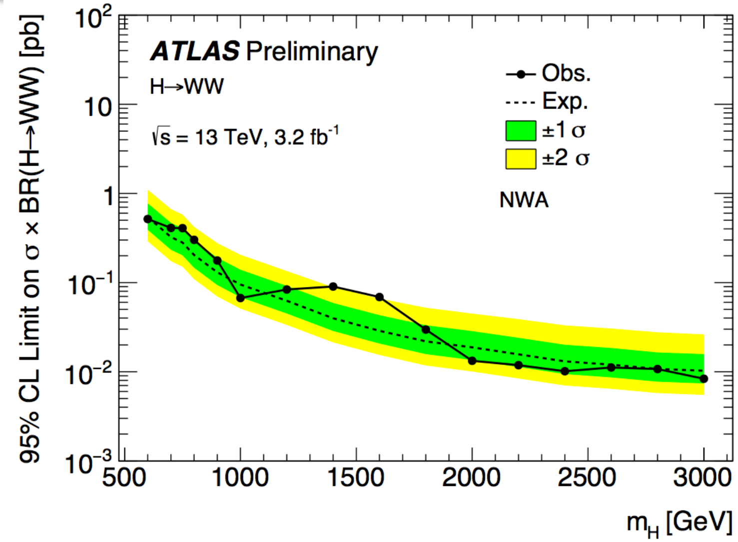
- Several ATLAS and CMS analyses designed to be sensitive to possible BSM physics
  - Sequential Standard Model (Z',W', spin-1);
  - Randall-Sundrum graviton (RS G*, spin-2);
  - Bulk RS graviton (Bulk G*, spin-2)
  - HVT Model
  - extended Higgs sectors (spin-0)
- Simplest way is to search for excess (bumps) over smooth background
  - Usually bkg fitted using functions or predicted with MC simulations
  - Considered various final states
- For high mass scalar (& graviton) searches mainly focus on diboson decays
  - Above mX~1TeV boosted topologies of Vector boson decays are extensively investigated

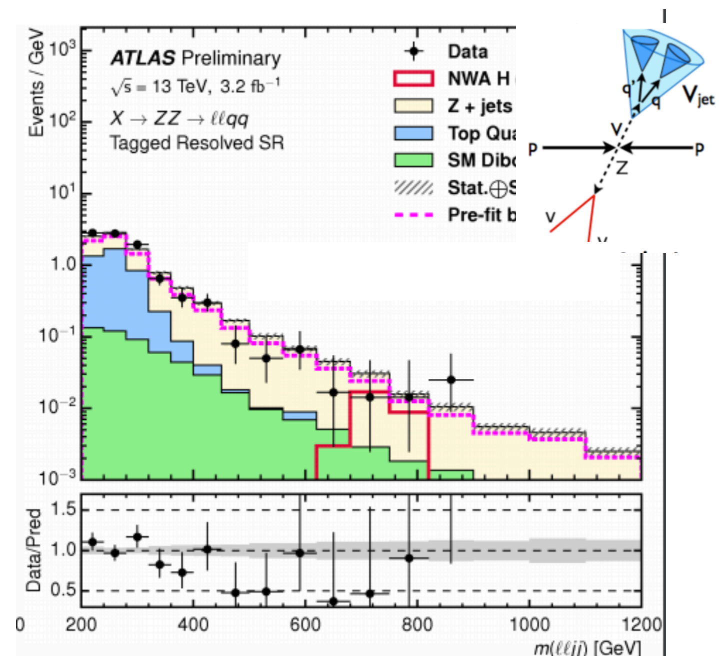




Scalar searches in diboson: ZZ and WW



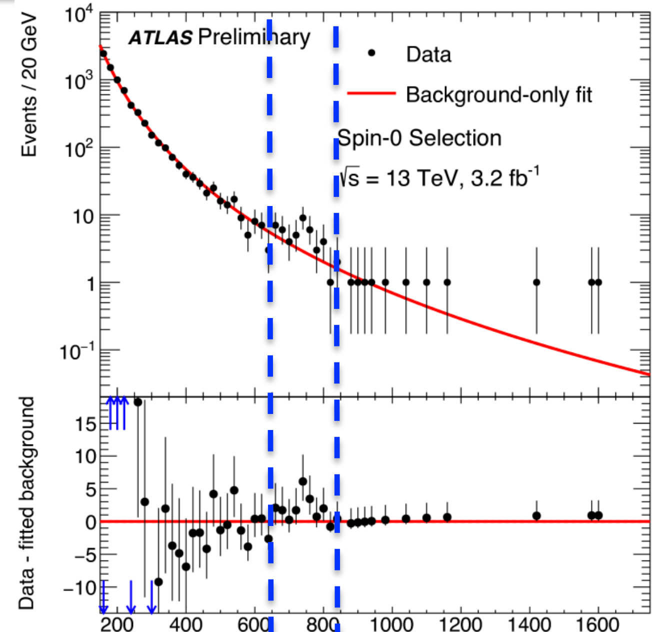


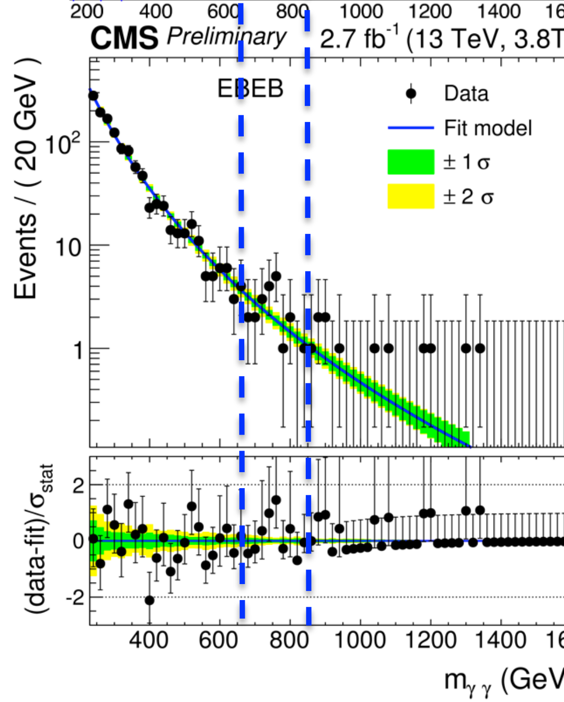


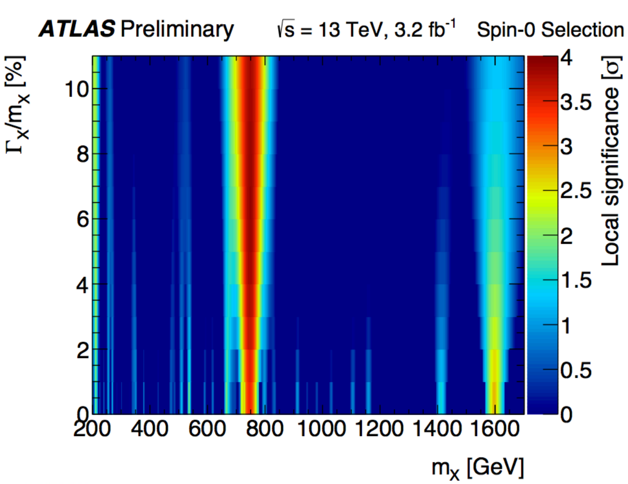
- Pletora of new results exploiting the power of the 13 TeV c.m.e.
  - Up to now no evidence of excess in a wide mX range
    - ATLAS 2TeV run1 excess not confirmed, replaced by a mild excess @ 1.6TeV

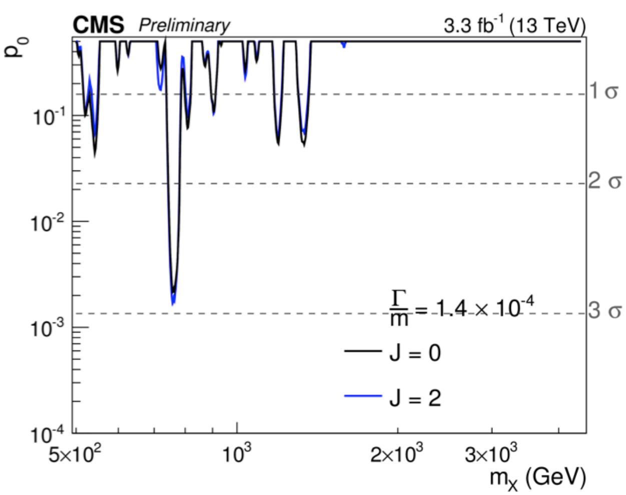
Diphoton final state

- Very clean final state
  - 2 isolated high pT photons reconstructed in the EM calorimeters
- ATLAS : Largest deviations ~ 750 GeV
  - spin 0 and $\Gamma X = 45$ GeV (6%): **3.9 σ** local significance, z-global =2.0 σ
  - spin 2 and k/MPl=0.2 ($\Gamma_G = 6\%\ m_G$), 3.6 σ local significance, z-global =1.8 σ
- CMS: Largest deviations ~ 760 GeV
  - spin 2 and Γ/m=1.4%, 2.9 σ local significance (2.8 σ ,spin 0), global significance <1 σ
  - mostly from EBEB categories, driven by 3.8T

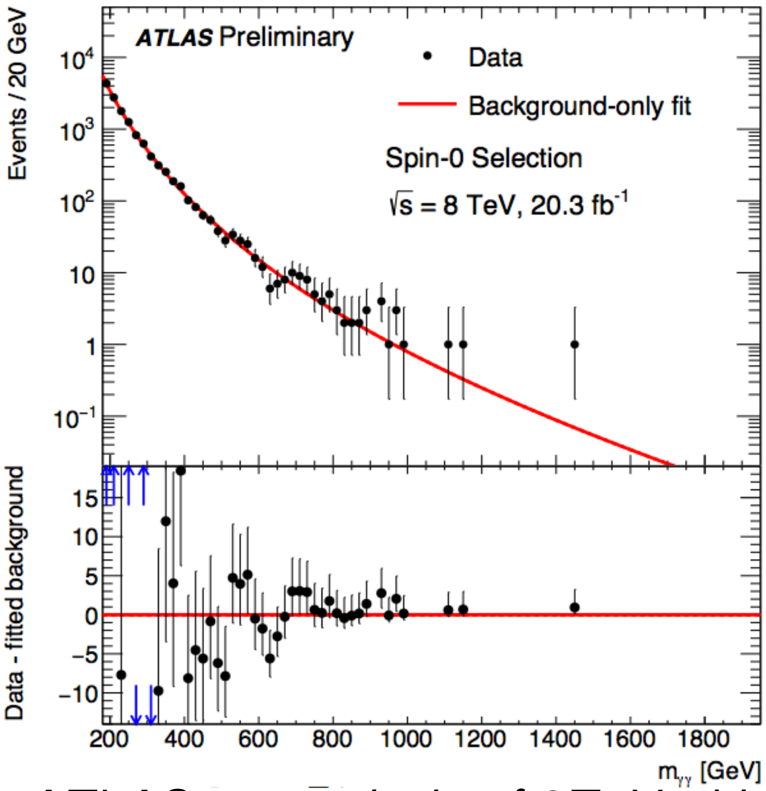


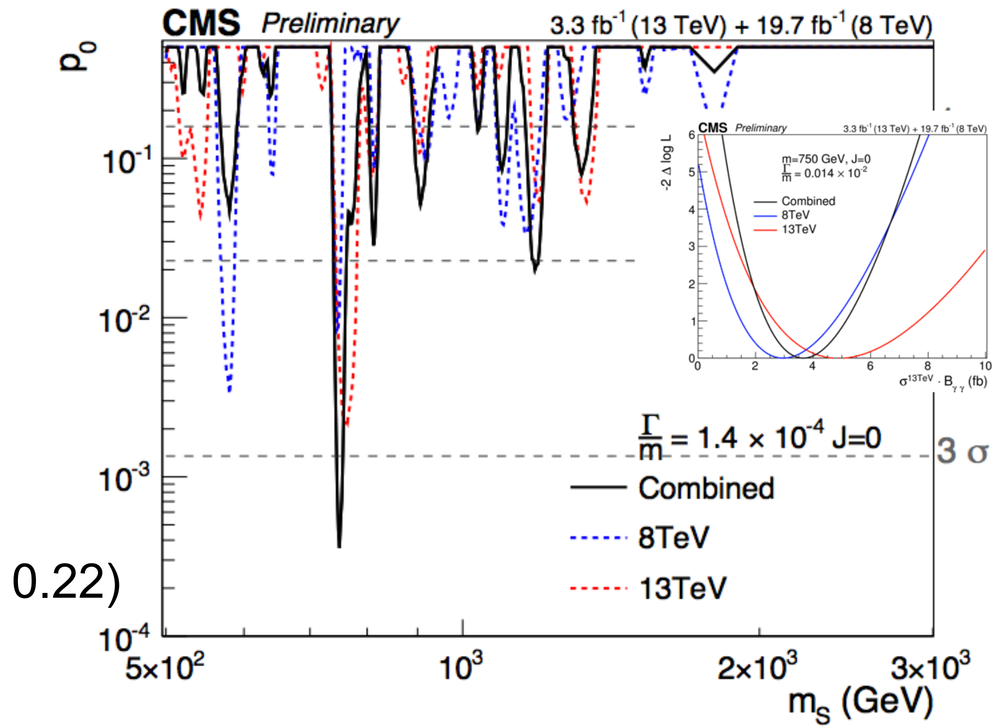






Compatibility and combination with Run1



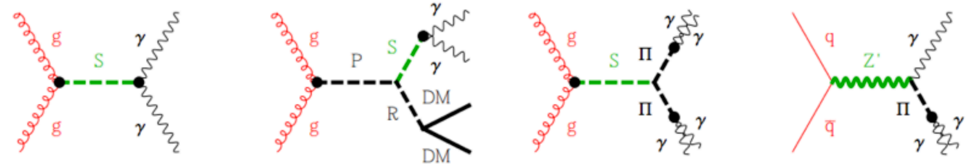


- ATLAS: re-analysis of 8TeV with latest run1 calibrations
  – 1.9 σ at 750 GeV, Γ/m=6%
- Compatibility with 13 TeV scalar
  – gg (scaling: 4.7) →compatibility: 1.2 σ
  – qq (scaling: 2.7)→compatibility: 2.1 σ

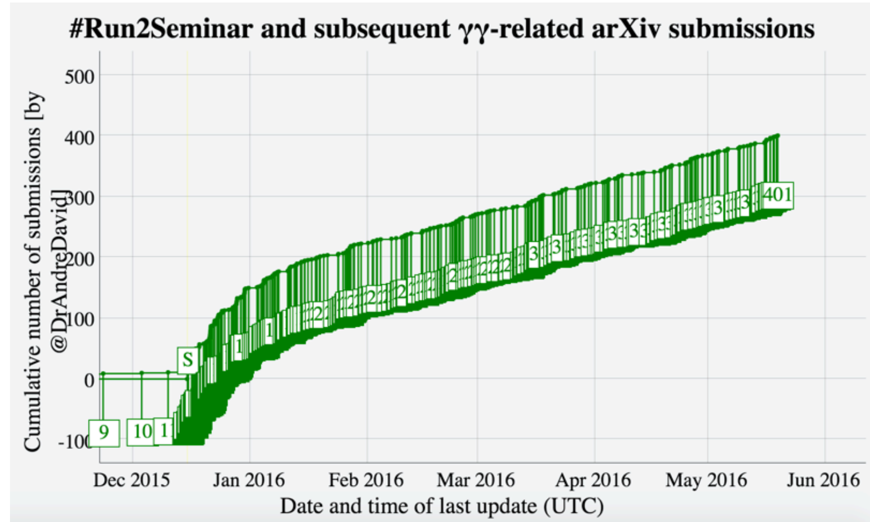
- CMS: Largest excess observed at 750 GeV and for narrow width.
  – Local significance: 3.4 σ
  – global significance 1.6 σ
- Combined xsec (8/13TeV ratio 0.22):
  – $\sigma BR(\gamma\gamma)\sim 4 \pm 1.5$ fb

Possible interpretation?

- A lot of ideas from theorists since December 2015 to explain the excess



- gg production mode preferred to conciliate with run1 observation
  - Achievable also assuming a parent resonance (extra activity should be present)
- In case of just SM+750 resonance, hard to explain such high γγ rate (tt,WW open)
  - Easier if include vector-like fermions
- Large width scenario very intriguing
  - Difficult to achieve in vanilla models
  - Portal to DM (invisible decays)



$\sigma(pp \to \gamma\gamma)$	$\sqrt{s} = 8\,\text{TeV}$ narrow	$\sqrt{s} = 8\,\text{TeV}$ broad	$\sqrt{s} = 13\,\text{TeV}$ narrow	$\sqrt{s} = 13\,\text{TeV}$ broad
CMS	$0.63 \pm 0.31\,\text{fb}$	$0.99 \pm 1.05\,\text{fb}$	$4.8 \pm 2.1\,\text{fb}$	$7.7 \pm 4.8\,\text{fb}$
ATLAS	$0.21 \pm 0.22\,\text{fb}$	$0.88 \pm 0.46\,\text{fb}$	$5.5 \pm 1.5\,\text{fb}$	$7.6 \pm 1.9\,\text{fb}$

final state f	σ at $\sqrt{s} = 8\,\text{TeV}$ observed	expected	ref.	σ at $\sqrt{s} = 13\,\text{TeV}$ observed	expected	ref.
$e^+e^-, \mu^+\mu^-$	< 1.2 fb	< 1.2 fb	[3]	< 5 fb	< 5 fb	[78]
$\tau^+\tau^-$	< 12 fb	< 15 fb	[3]	< 60 fb	< 67 fb	[79]
$Z\gamma$	< 11 fb	< 11 fb	[3]	< 28 fb	< 40 fb	[80]
ZZ	< 12 fb	< 20 fb	[3]	< 200 fb	< 220 fb	[81]
Zh	< 19 fb	< 28 fb	[3]	< 116 fb	< 116 fb	[82]
hh	< 39 fb	< 42 fb	[3]	< 120 fb	< 110 fb	[83]
W^+W^-	< 40 fb	< 70 fb	[3]	< 300 fb	< 300 fb	[84]
$t\bar{t}$	< 450 fb	< 600 fb	[3]			
invisible	< 0.8 pb	-	[3]			
$b\bar{b}$	$\lesssim 1$ pb	$\lesssim 1$ pb	[3]			
jj	$\lesssim 2.5$ pb	-	[3]			

channel	$u\bar{u}$	$d\bar{d}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$	$\gamma\gamma$	gg
$\frac{\sigma_{13\text{TeV}}}{\sigma_{8\text{TeV}}}$	2.5	2.7	4.3	5.1	5.4	2	4.7

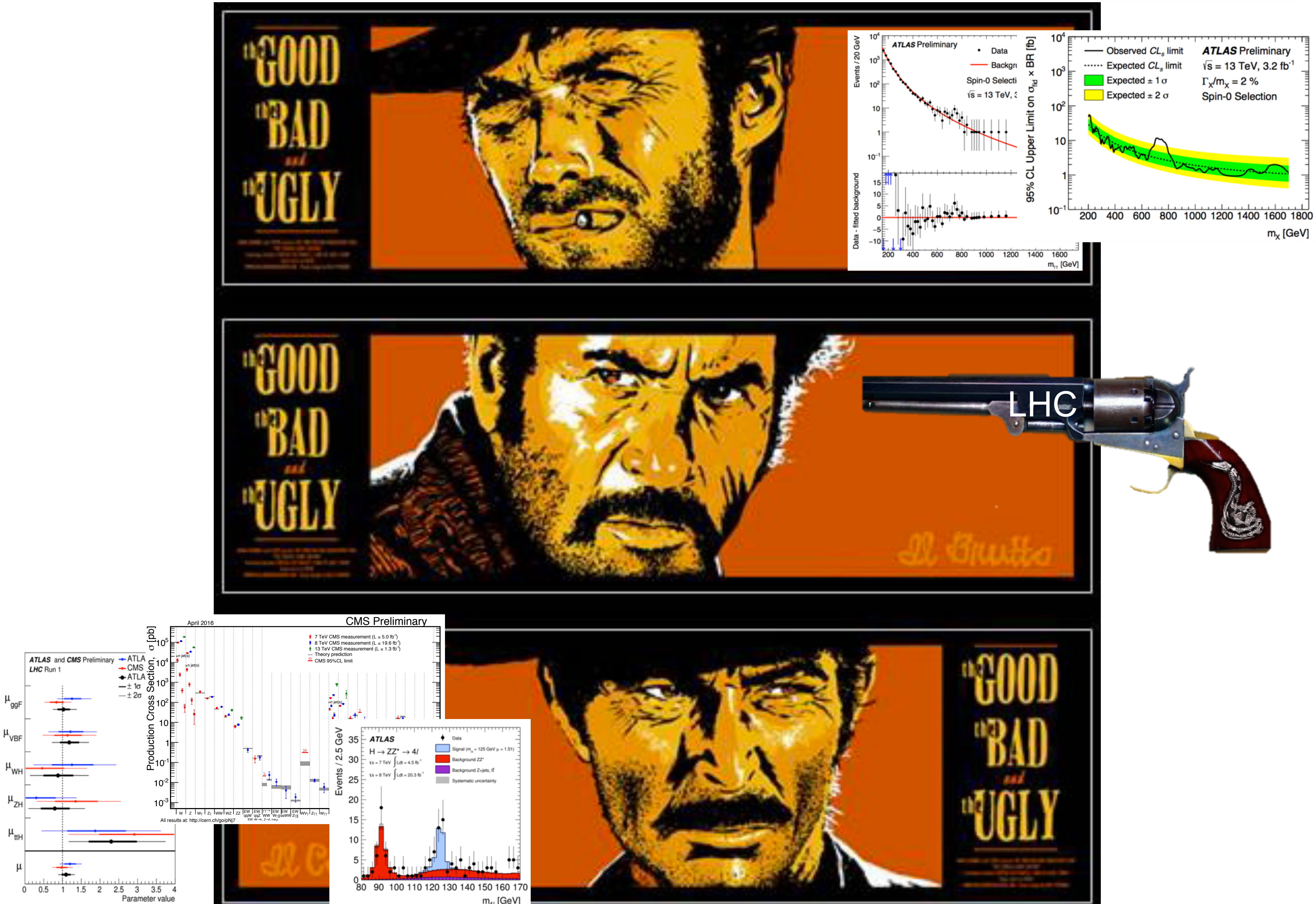
Conclusions

- LHC run1 very successful Higgs physics program
  - After the Higgs boson discovery, clear transition from the discovery to the "precision" measurements mode
  - Big effort spent to characterize as much as possible the Higgs boson with the available data
    - Mass, couplings, spin and parity, width…
- Run 2 started in 2015
  - Collected already ~4 fb^{-1} of dataat 13 TeV used to already re-asses the h(125)
    - Already first measurements in diboson decay channels and ttH prod mode
  - By the end of this year expected ~30fb^{-1} of data
    - This will allow to improve the precision of current Higgs related measurements
  - News about the 750GeV $\gamma\gamma$ "mild" excess already expected for summer conferences

We will know soon who will be the survivor of the LHC western

The LHC western

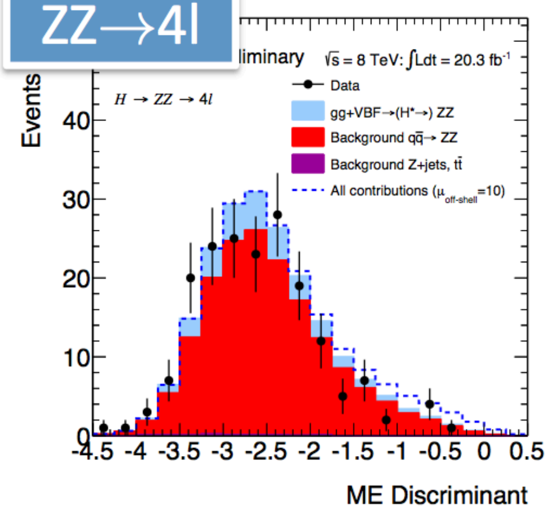
The LHC western



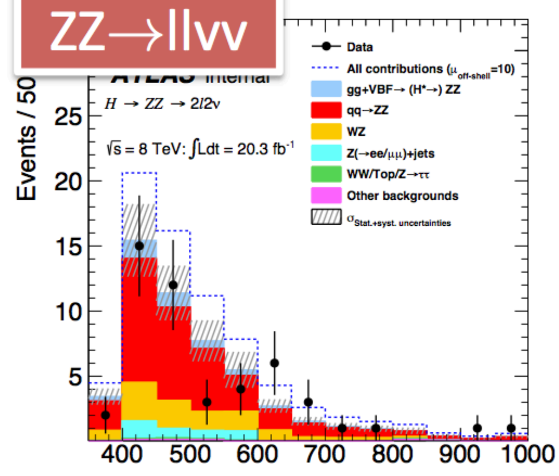
Backup

- Combination of ZZ→4l, ZZ→llνν and WW→eνμν final states
- **ZZ→4l** : ML fit to ME-based discriminant used to enhance separation between gg→H*→ZZ and gg→ZZ , qq→ZZ backgrounds in the m_{4l} range 220-1000GeV
- **ZZ→llνν** : ML fit to the m_T^{ZZ} used as discriminating variable to enhance sensitivity to gg→H*→ZZ signal in the m_T^{ZZ} range 380-1000GeV
- **WW→eνμν** : ML fit on the yield in the signal region defined by $R8 = \sqrt{m_{ll}^2 + (0.8 m_T^{WW})^2} > 450$ GeV
  Main qq→WW and top backgrounds normalized from control regions
- Main **systematic** uncertainties from **theoretical** knowledge of gg→H*→VV signal gg→VV background and their interference and of the qq→VV background

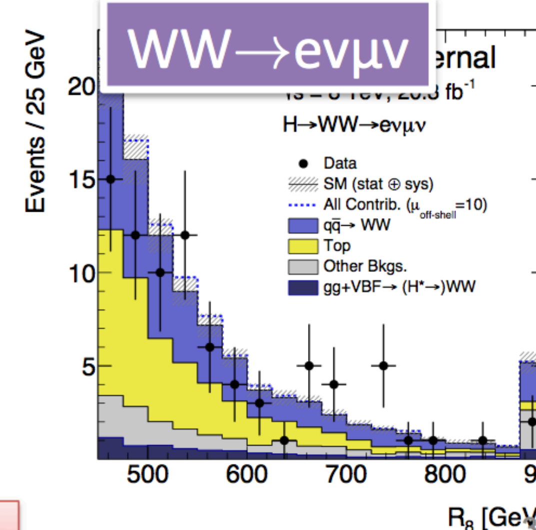
ZZ→4l



ZZ→llνν

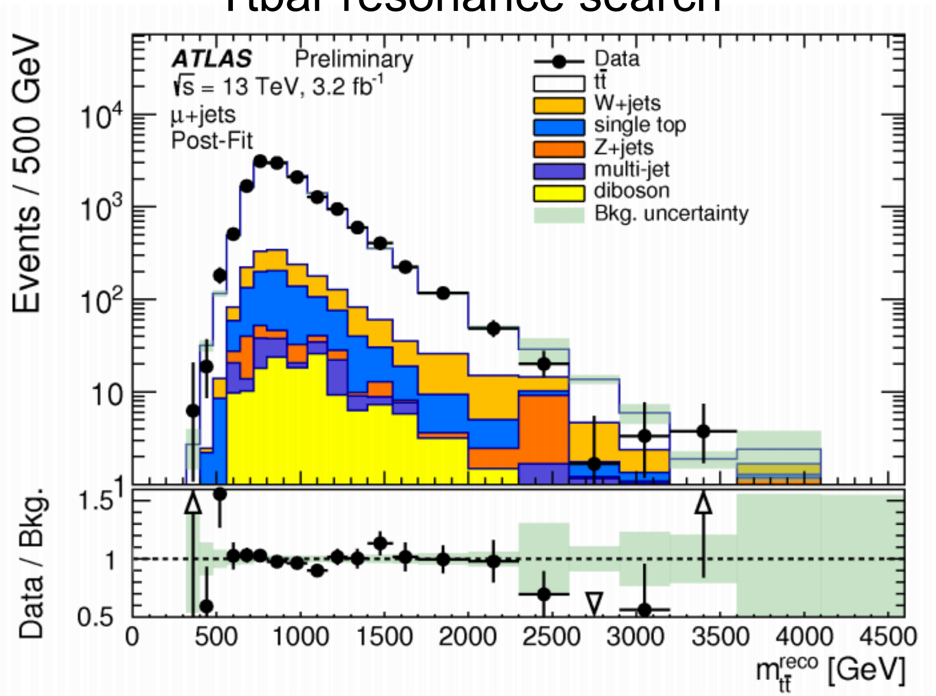


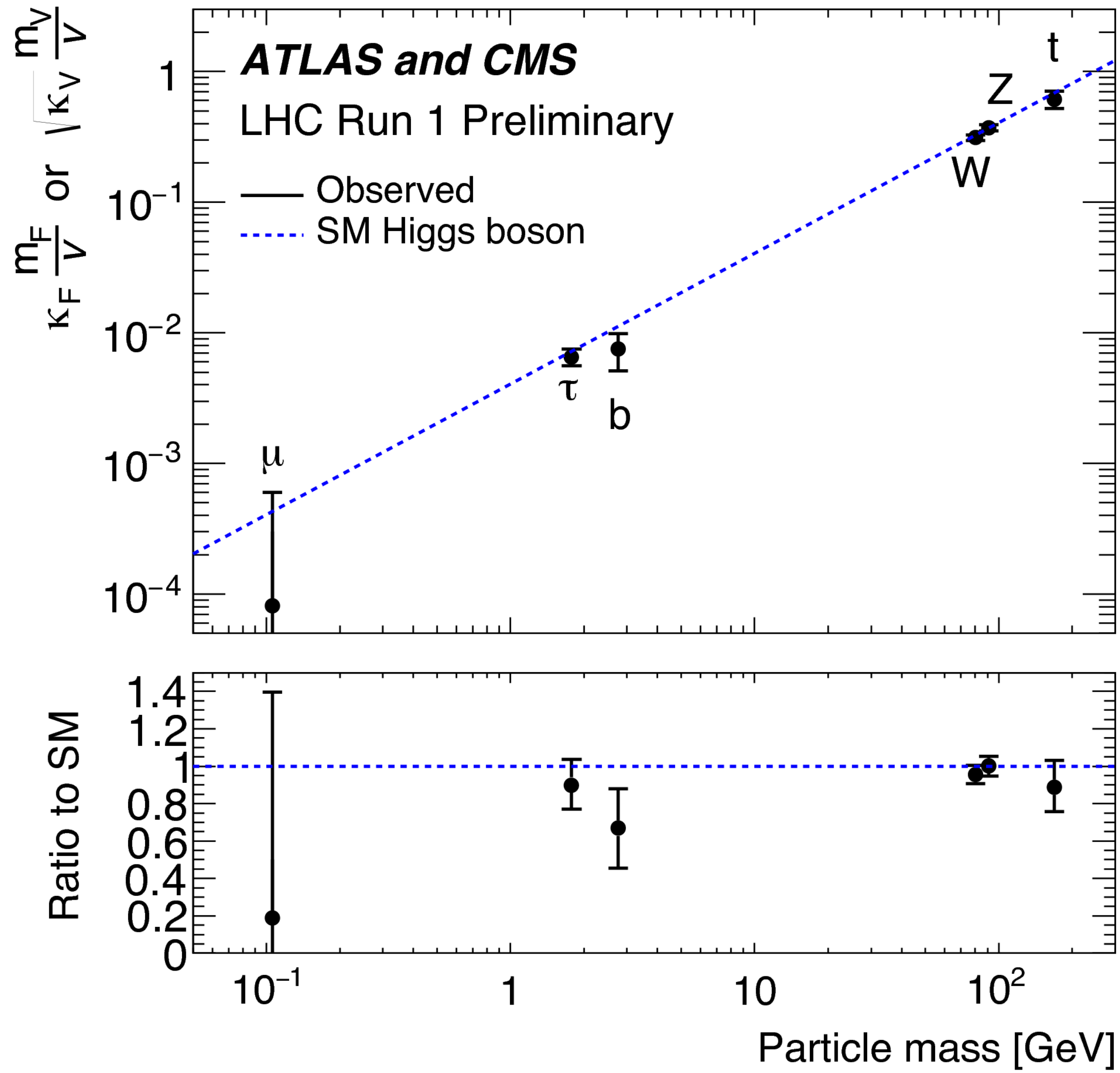
WW→eνμν



Agreement with SM expectations

Ttbar resonance search




ATLAS and CMS
LHC Run 1 Preliminary
Observed
SM Higgs boson
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V} \frac{m_V}{v}$
Ratio to SM
Particle mass [GeV]
μ
τ
b
W
Z
t