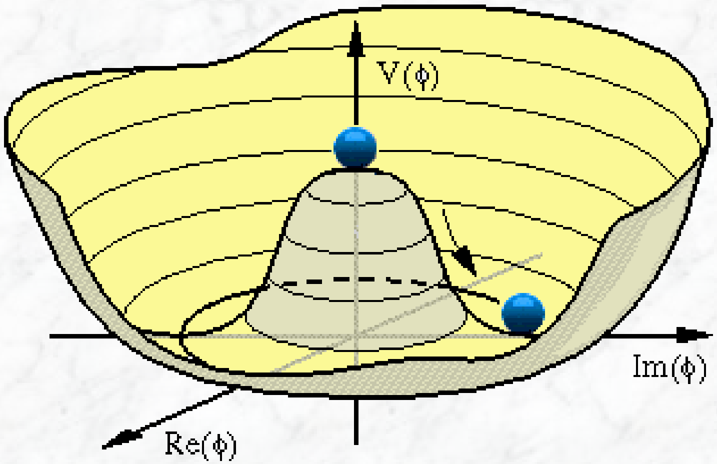
12. Status of Higgs Boson physics at the LHC

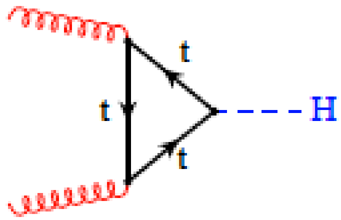
12.1 Higgs boson production at hadron colliders

12.2 The search for and discovery of a
Higgs boson at the LHC

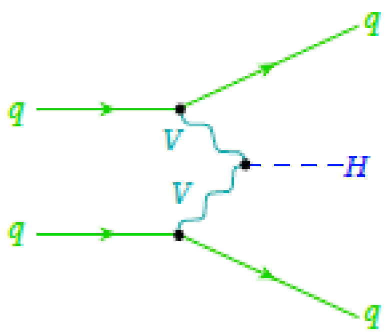
12.3 What are its properties?
Is it the Higgs boson of the Standard Model?



12.1 Higgs Boson production at Hadron Colliders

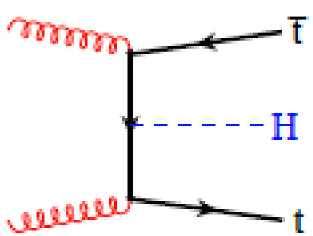


Gluon Fusion

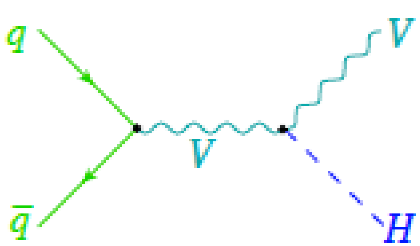


Vector boson fusion

Relative importance of the various processes is different at the LHC and at the Tevatron

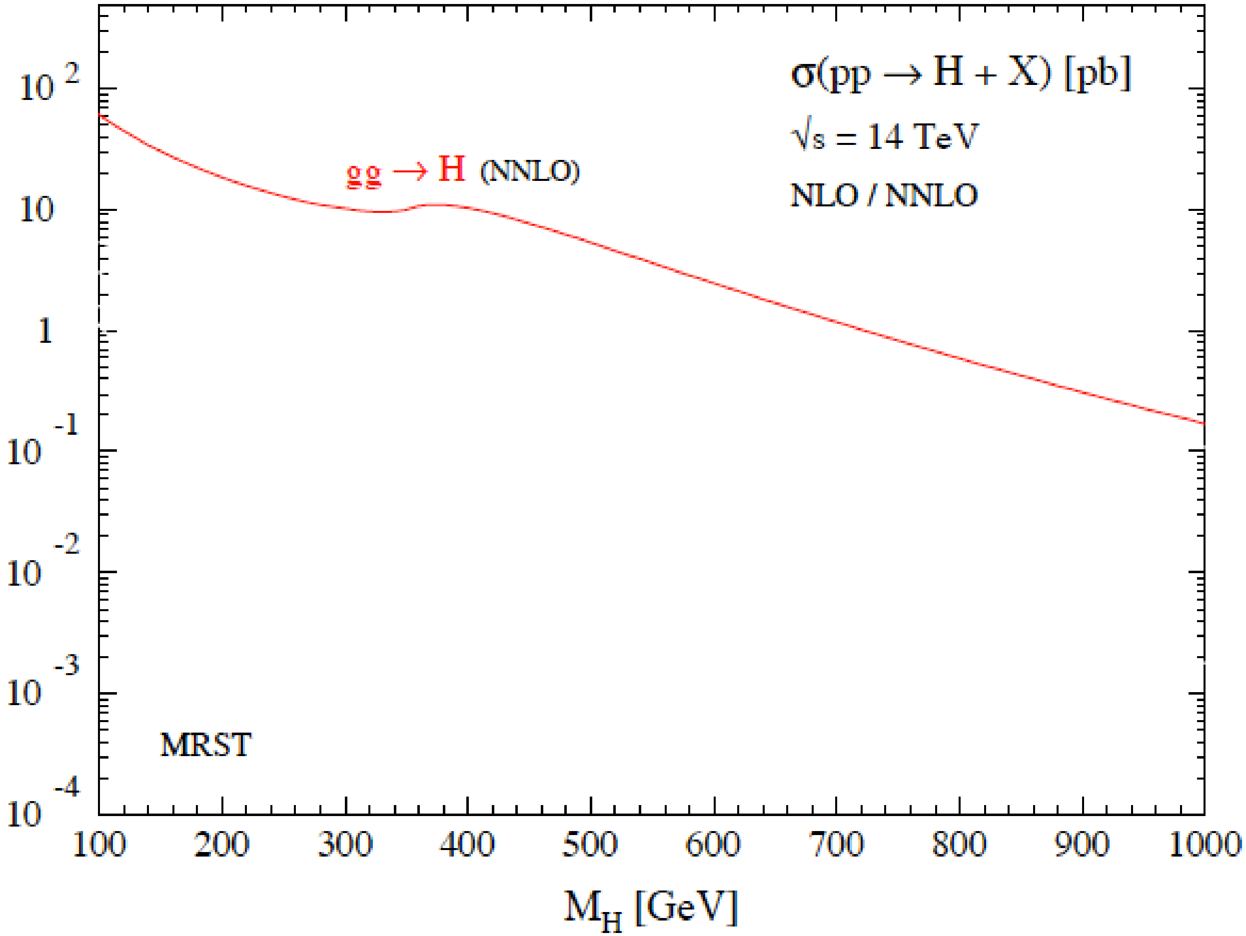


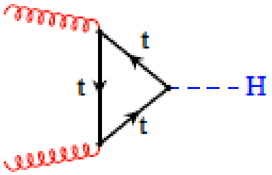
tt associated production



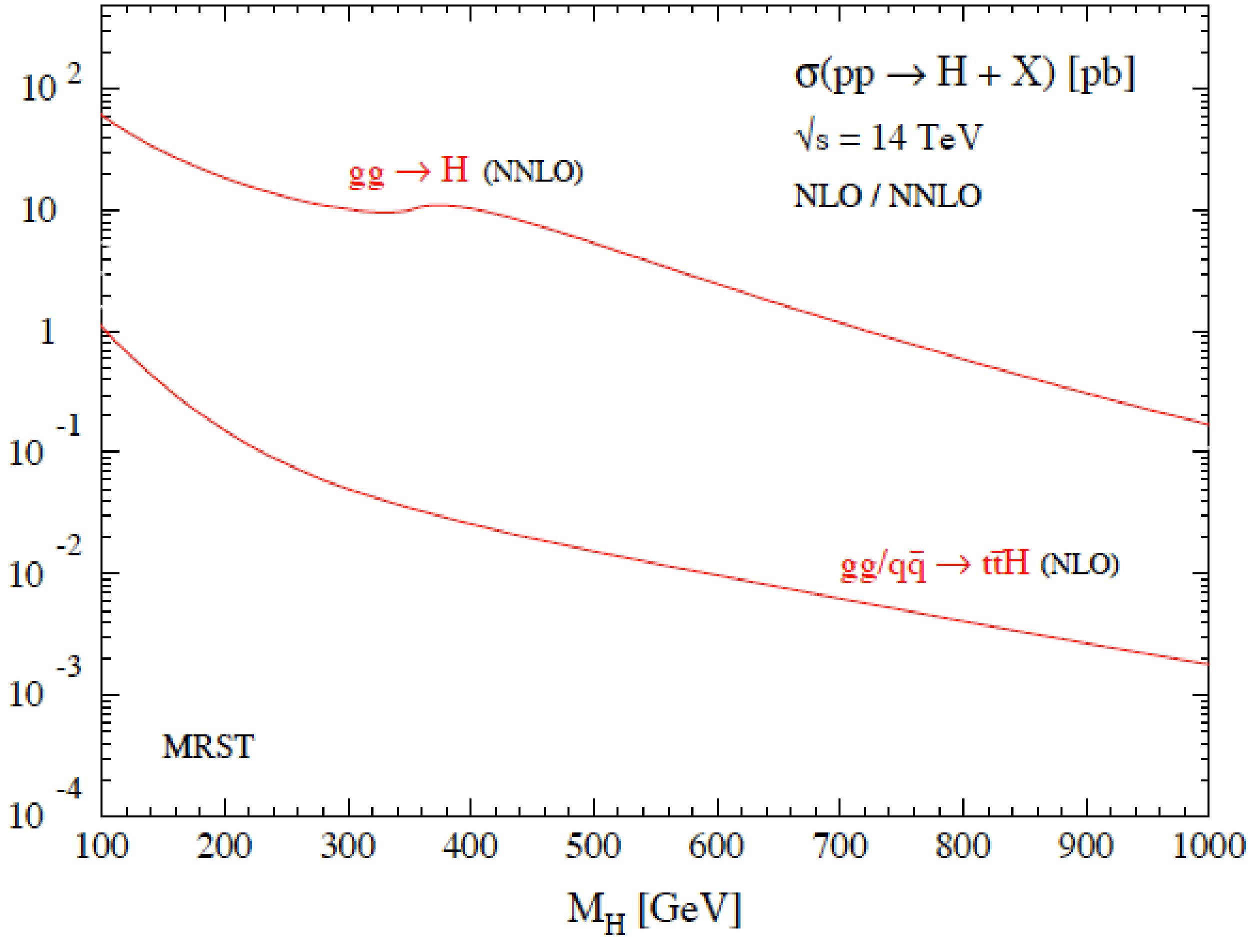
WH/ZH associated production

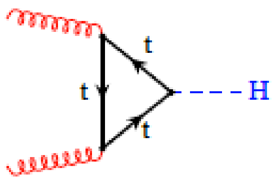
Production cross sections at the LHC

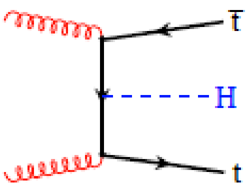




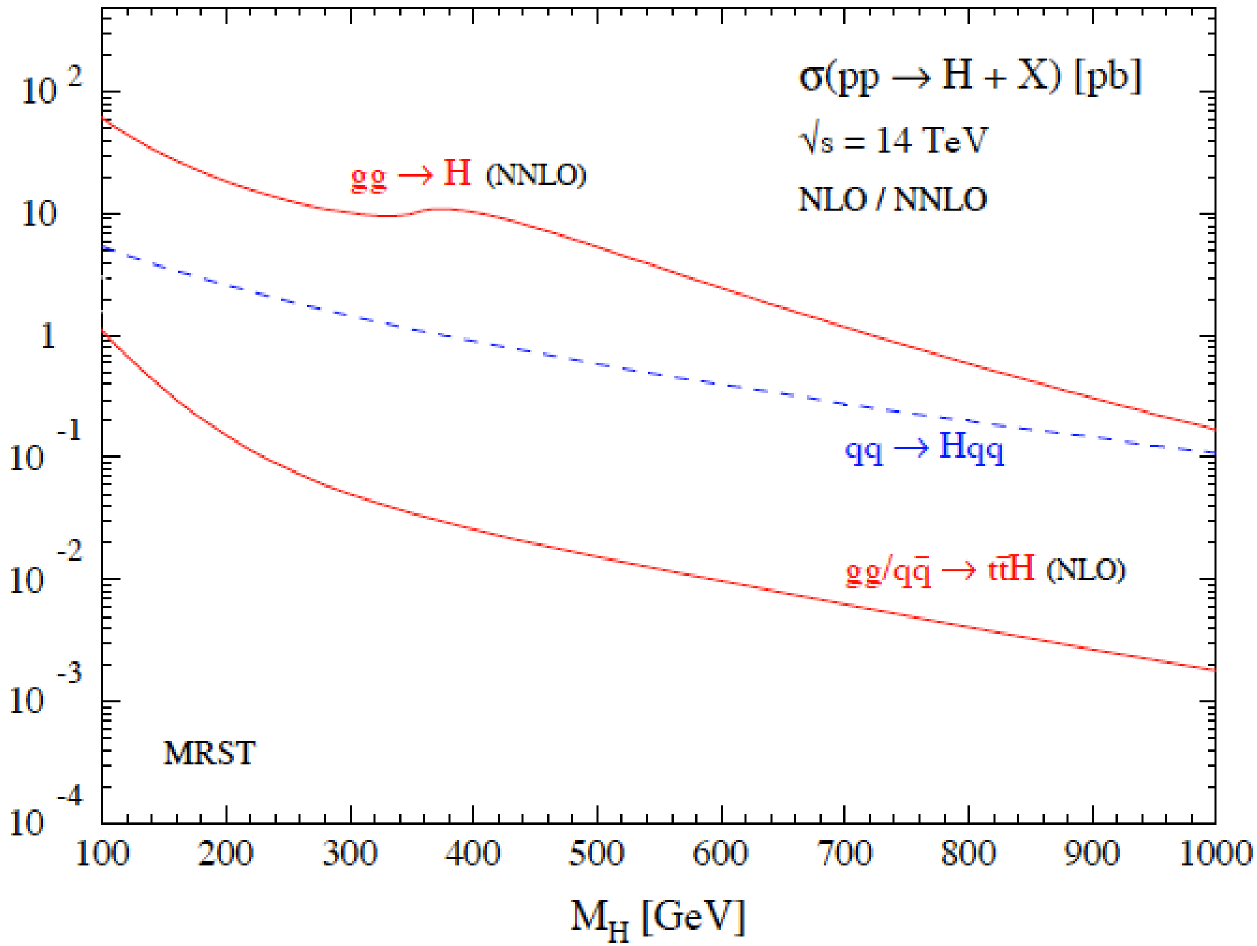
Production cross sections at the LHC

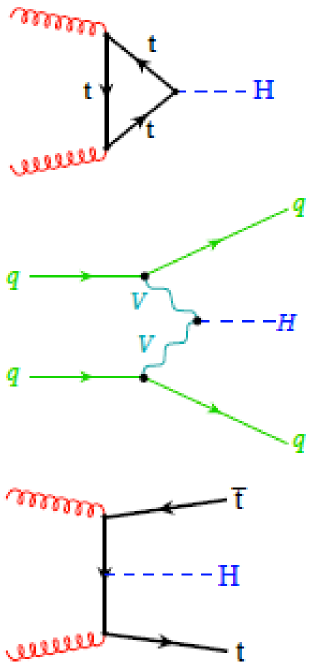




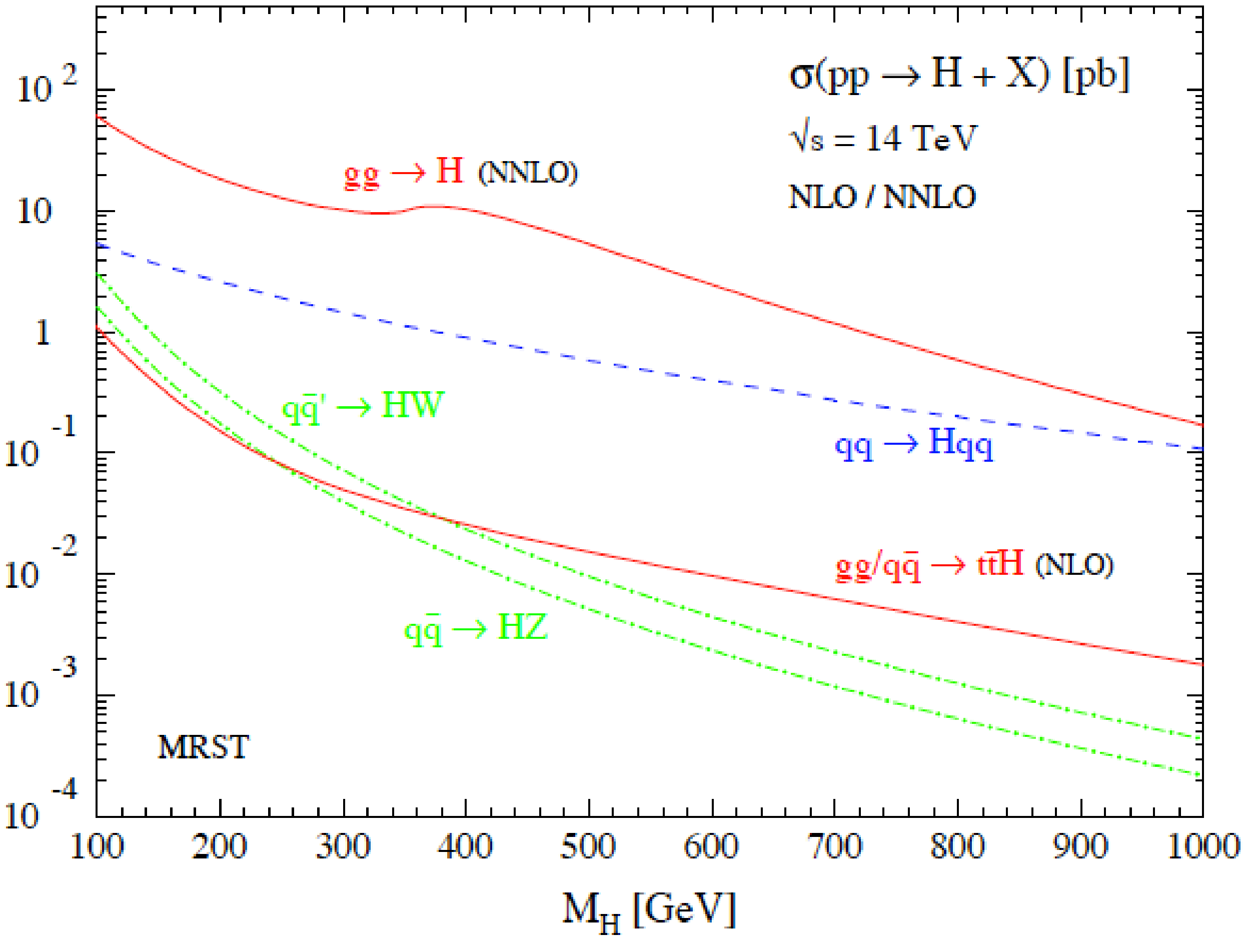


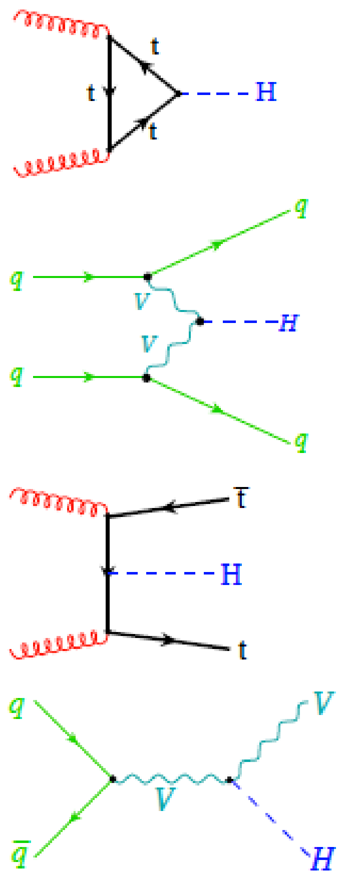
Production cross sections at the LHC



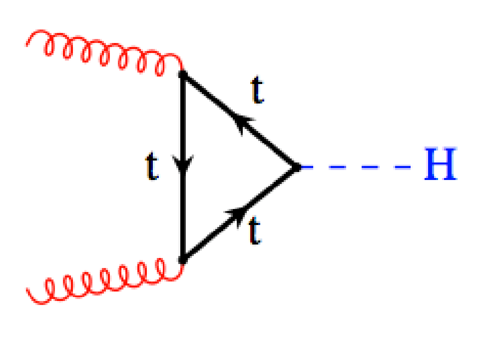


Production cross sections at the LHC





Gluon fusion:

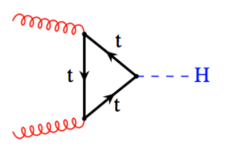


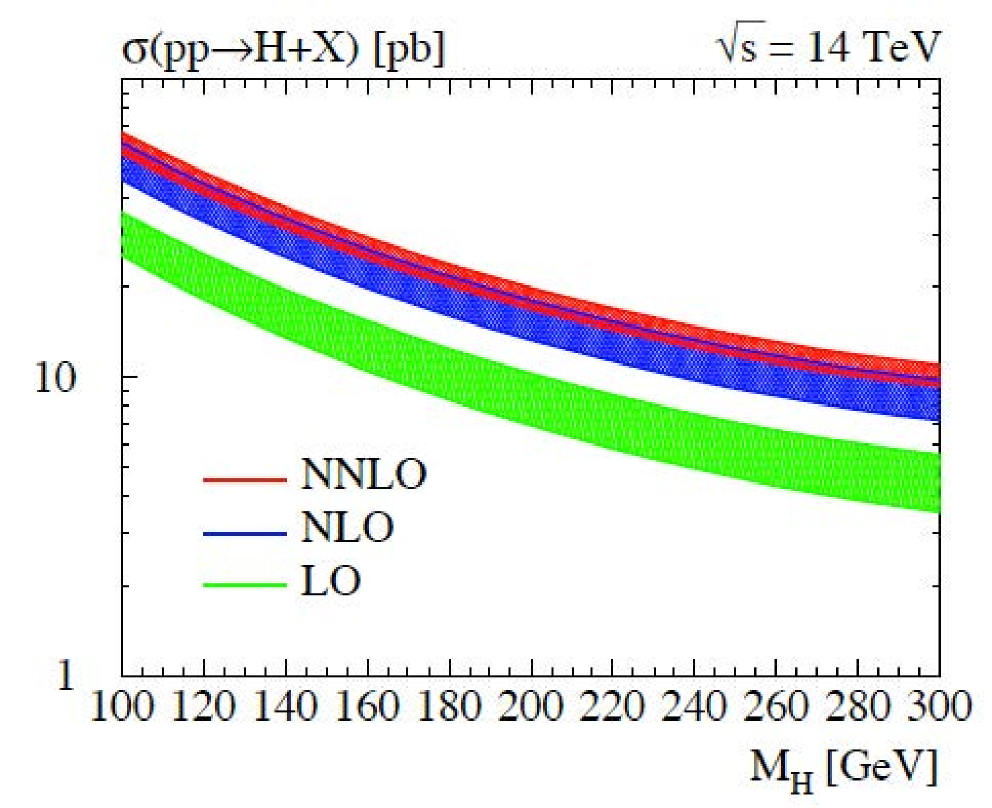
- Dominant production mode

- Sensitive to heavy particle spectrum …
  (e.g. 4th generation quarks)
  …and the corresponding Yukawa couplings
  (important for coupling measurements, top Yukawa coupling)

- Large K-factors (NLO, NNLO corrections)
  - Difficult to calculate, loop already at leading order
    (calculation with infinite top mass is used as an approximation, however, this seems to be a good approximation)
  - Nicely converging perturbative series

Higher order corrections:



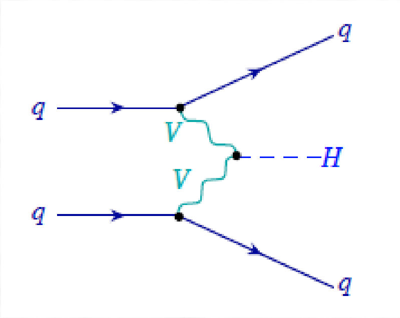


- Spira, Djouadi, Graudenz, Zerwas (1991)
- Dawson (1991)

- Harlander, Kilgore (2002)
- Anastasiou, Melnikov (2002)
- Ravindran, Smith, van Neerven (2003)

Independent variation of renormalization and factorization scales (with $0.5\ m_H < \mu_F, \mu_R < 2\ m_H$)

Vector boson fusion:



- Second largest production mode,
  Distinctive signature
  (forward jets, little jet activity in the central region)

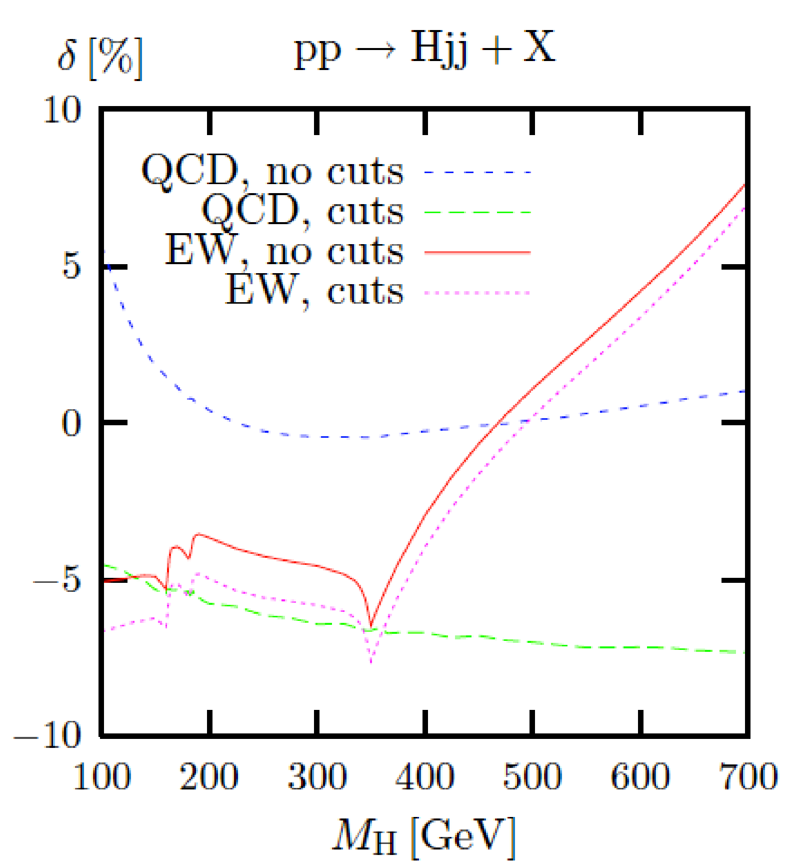
- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

  Both NLO QCD and el.weak have been calculated

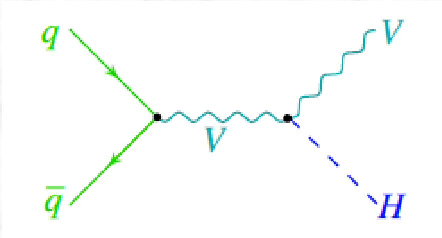
- Effective K-factor depends on experimental cuts

  Example: typical VBF cuts
  P_T(jet) > 20 GeV
  η < 4.5, $\Delta\eta$ > 4, $\eta_1 \cdot \eta_2 < 0$



Ciccolini, Denner, Dittmaier (2008)

WH / ZH associated production:



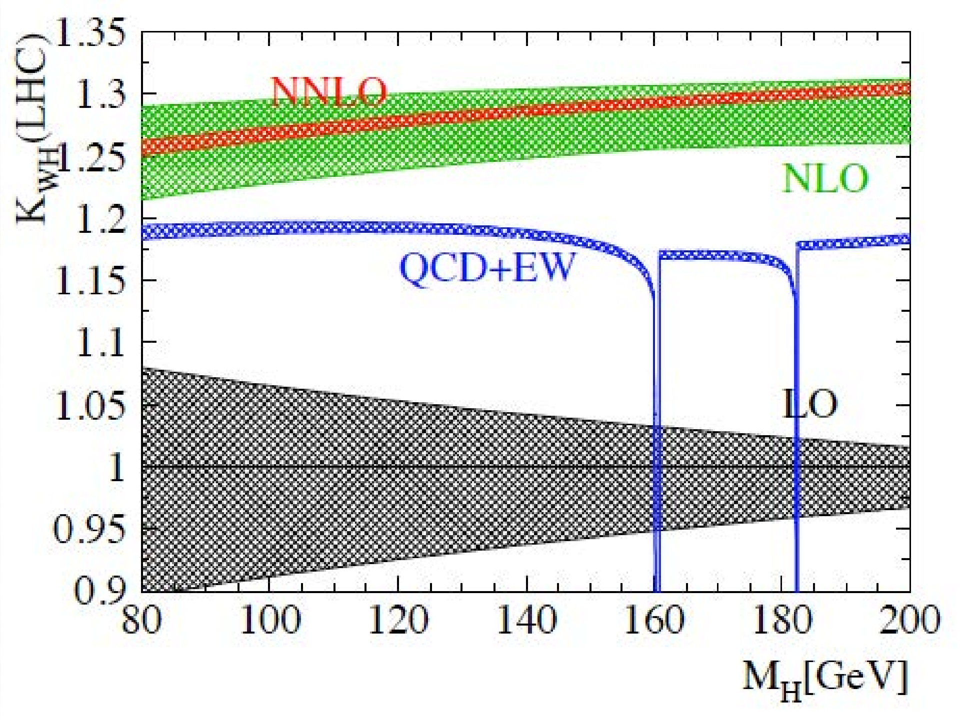
- Weak at the LHC,
  Relatively stronger at the Tevatron

- Allows for a decay-independent trigger
  W → lν, Z → ll

- Sensitivity to W/Z couplings

- Moderate K-factors
  (NLO corrections)

Both NLO QCD and el.weak
corrections available

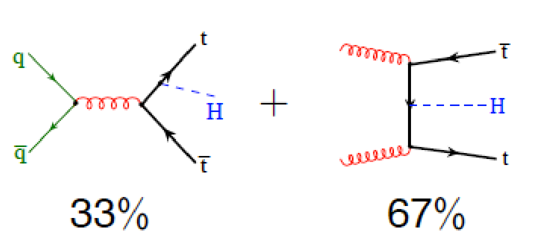


Brein, Djouadi, Harlander, (2003)

Han, Willenbrock (1990)

Ciccolini, Dittmaier, Krämer (2003)

ttH associated production:

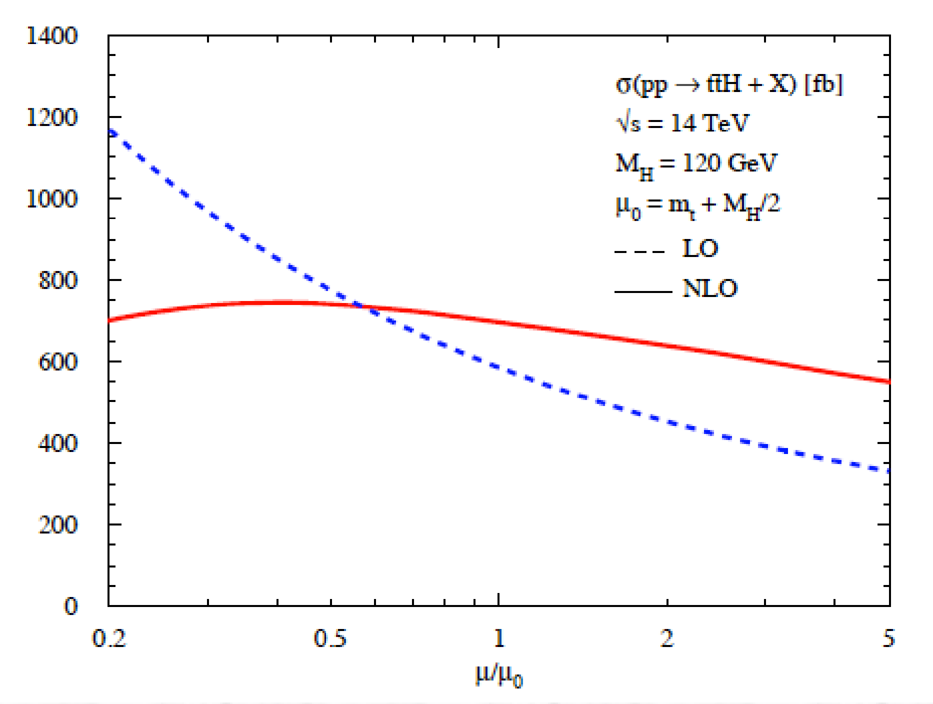


- Weak and difficult at the LHC
- Sensitivity to top-Yukawa coupling
- Moderate K-factors (NLO corrections)

NLO QCD corrections available, scale uncertainty drastically reduced

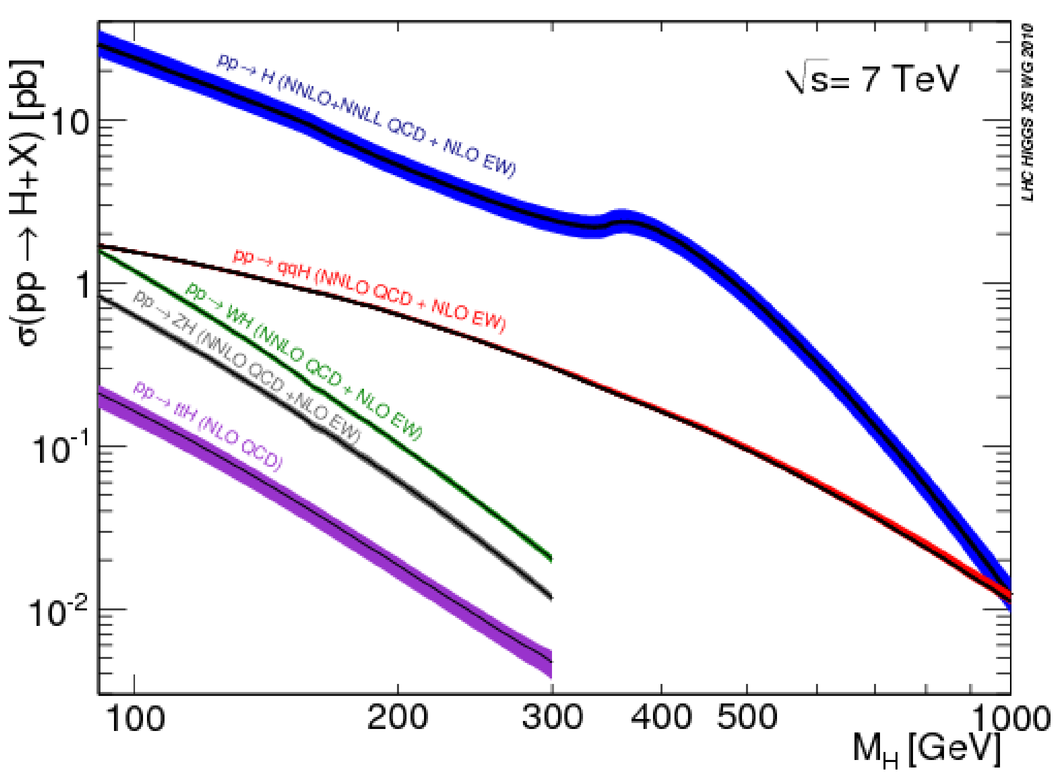
scale: $\mu_0 = m_t + m_H/2$

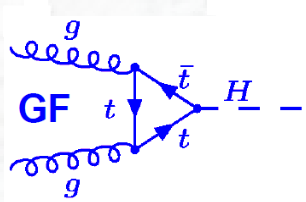
LHC: $K \sim 1.2$
Tevatron: $K \sim 0.8$



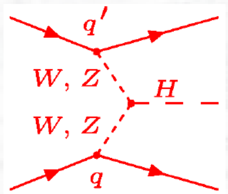
Beenakker, Dittmaier, Krämer, Plümper, Spira, Zerwas (2001)
Dawson, Reina, Wackeroth, Orr, Jackson (2001, 2003)

Higgs Boson Production at √s = 7 TeV

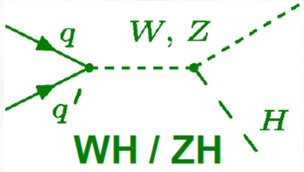




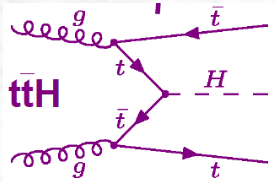
Gluon fusion



Vector boson fusion



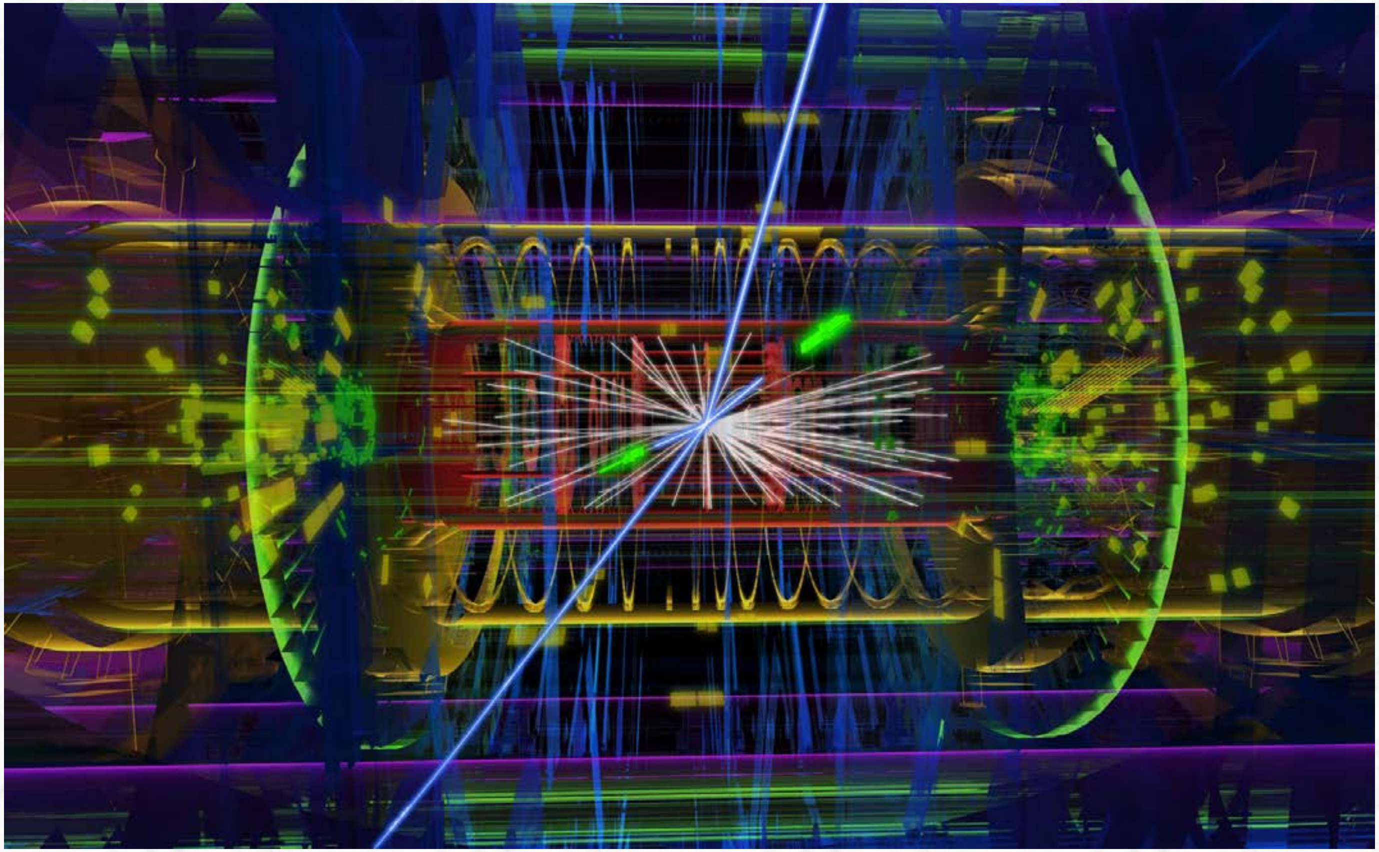
WH/ZH associated production



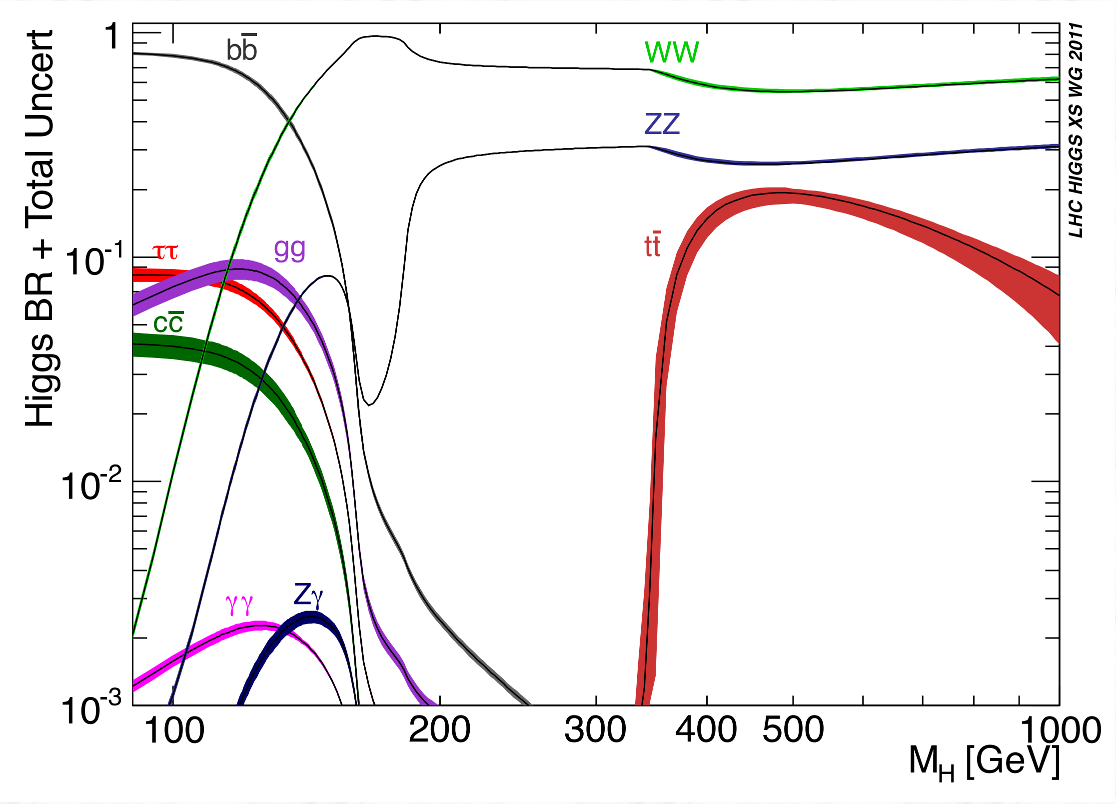
tt associated production

*) LHC Higgs cross-section working group
Large theory effort

12.2 The search for and discovery of a Higgs boson at the LHC



Useful Higgs Boson Decays at Hadron Colliders



at high mass:

Lepton final states
(via H → WW , ZZ)

at low mass:

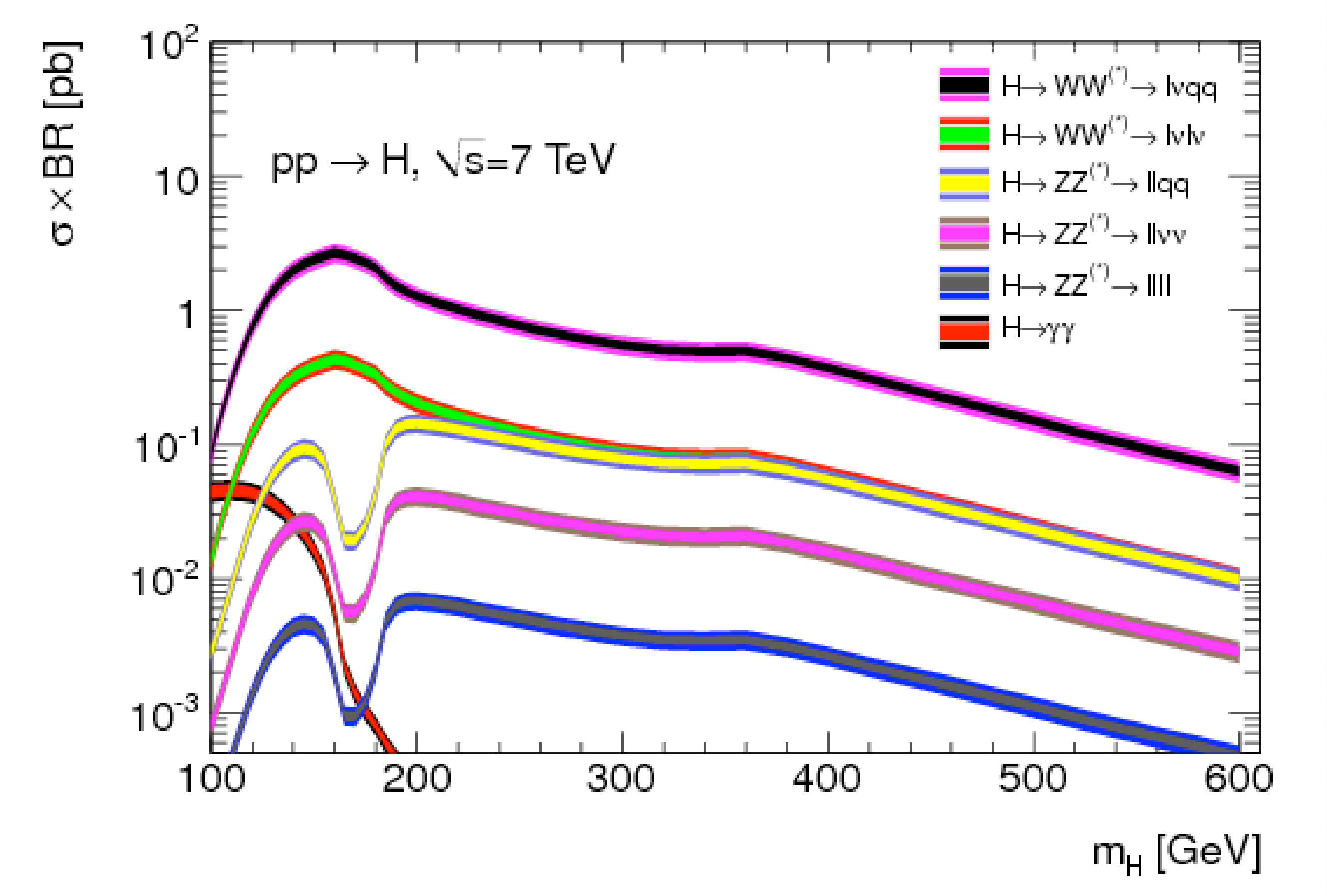
Lepton and Photon final states
(via H → WW*, ZZ*)

Tau final states

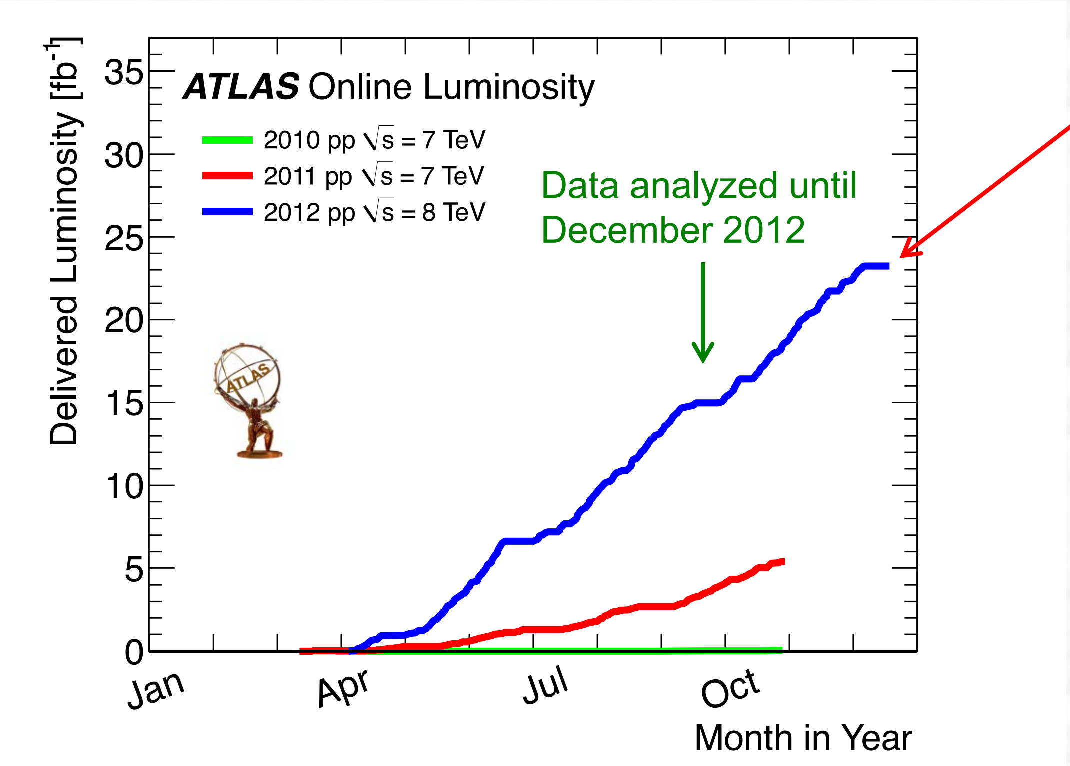
The dominant **bb decay mode** is only useable in the associated production mode (ttH, W/Z H)

(due to the huge QCD jet background, leptons from W/Z or tt decays)

Expected cross sections times production rates at √s = 7 TeV



Data taking in 2011/ 2012



Today: results with the full dataset

Until end 2012:

> 10^{15} pp collisions

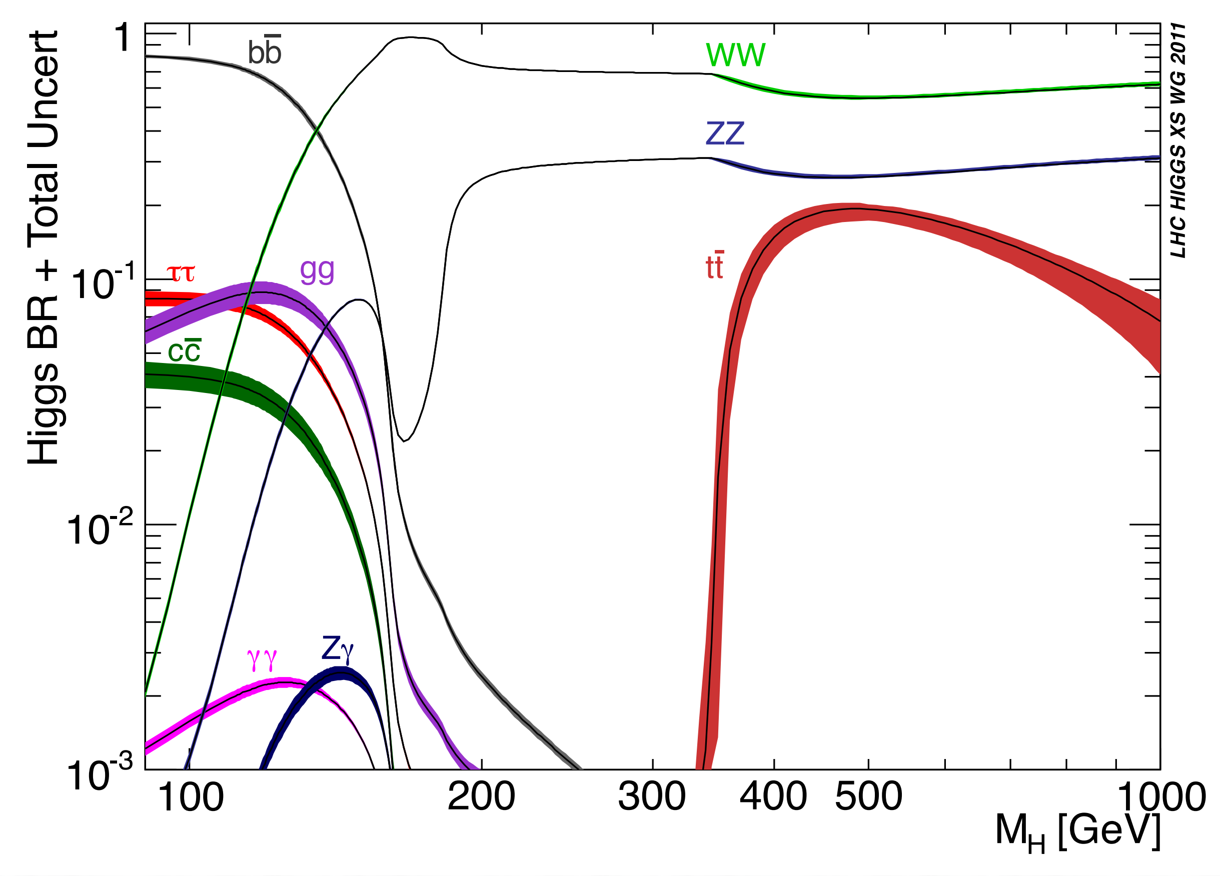
~10^{10} pp collisions recorded

25 ·10^6 Z → $\mu\mu$ decays produced

- Excellent LHC performance
  Peak luminosities > 7 10^{33} cm^{-2} s^{-1} (world record, 2012)

- Excellent performance of the experiments:
  - Data recording efficiency ~93.5%
  - Working detector channels >99%
  - Speed of data analysis

Higgs Boson Decays

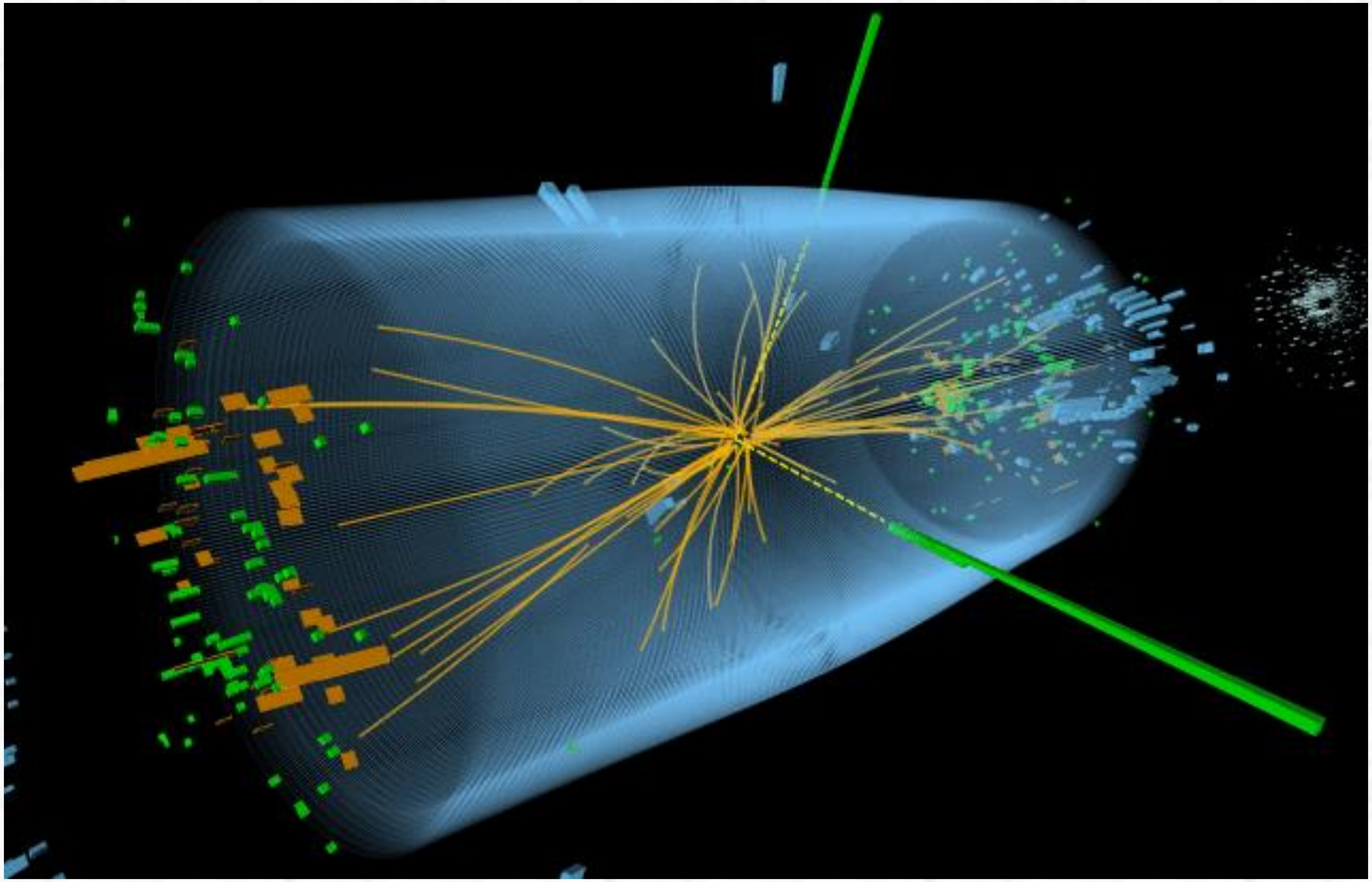


Important channels at hadron colliders: H → WW → ℓν ℓν

H → γγ

H → ZZ → $\ell^+\ell^-$ $\ell^+\ell^-$

Discovery of a Higgs-like particle

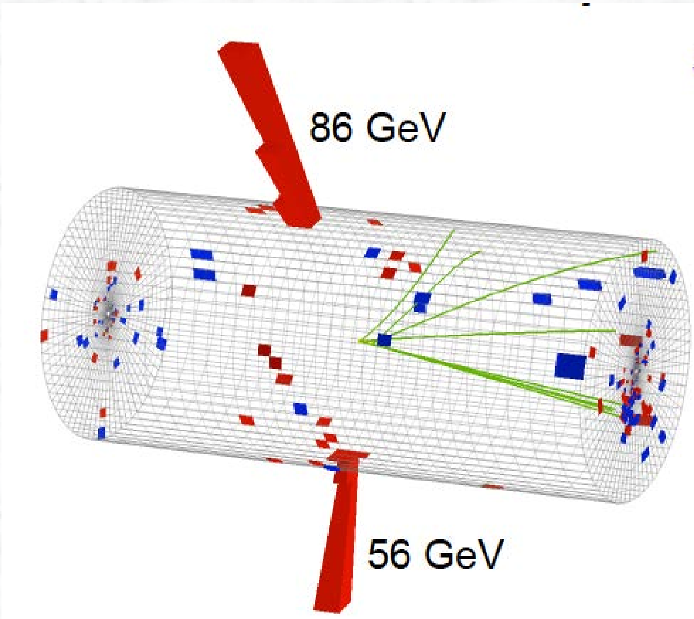


Expected number of decays in data: ~ 950 $H \rightarrow \gamma\gamma$

m_H = 125 GeV ~ 60 $H \rightarrow ZZ \rightarrow 4\ell$

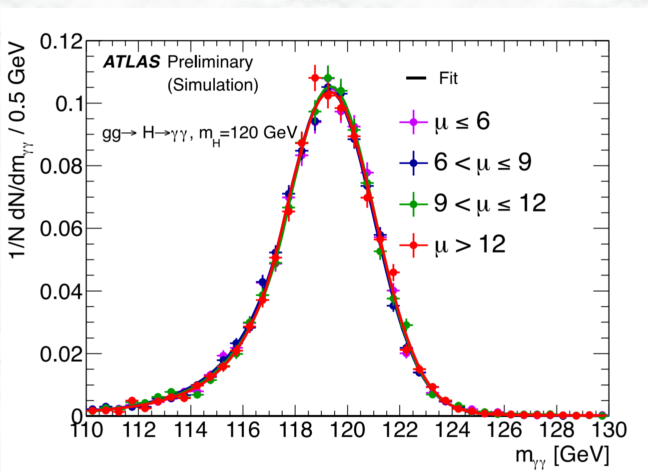
~ 9000 $H \rightarrow WW \rightarrow \ell\nu\,\ell\nu$

Search for the H → γγ decay

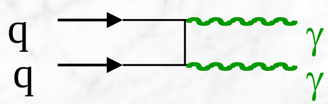


- 2 photons (isolated) with large transverse momenta
- Mass of the Higgs boson can be reconstructed $m_{\gamma\gamma}$

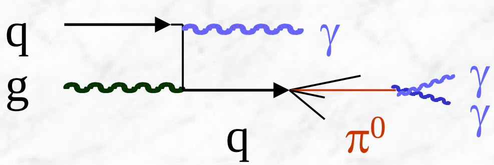
  Both experiments have a good mass resolution
  ATLAS: ~1.7 GeV/c^2 for m_H ~120 GeV/c^2



- Challenges:
  - signal-to-background ratio
    (small, but smooth irreducible γγ background)

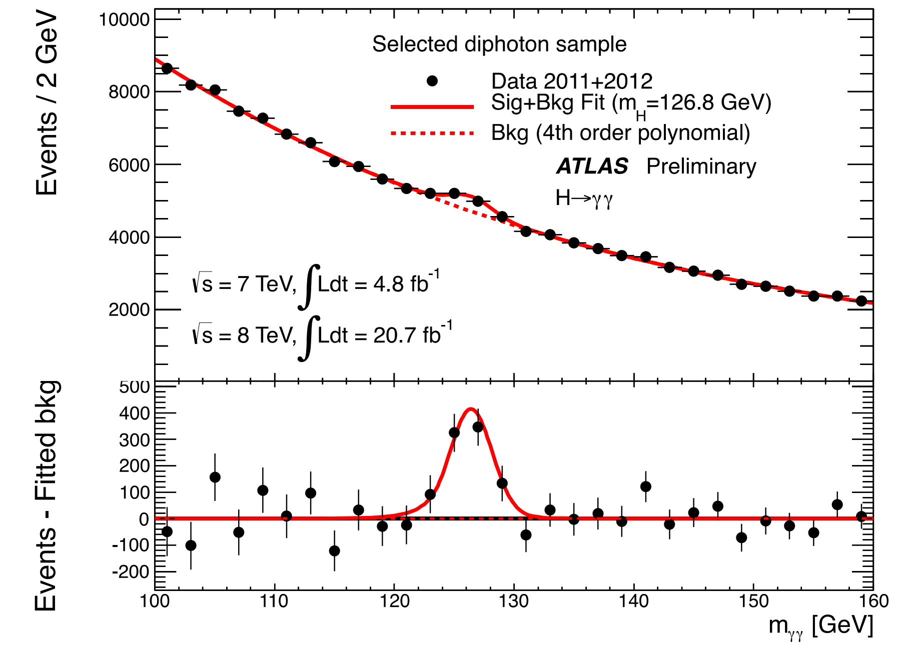


  - reducible backgrounds from γj and jj
    (several orders of magnitude larger than irreducible one)



Result of the ATLAS search for H → γγ

Full dataset ATLAS-CONF-2013-012

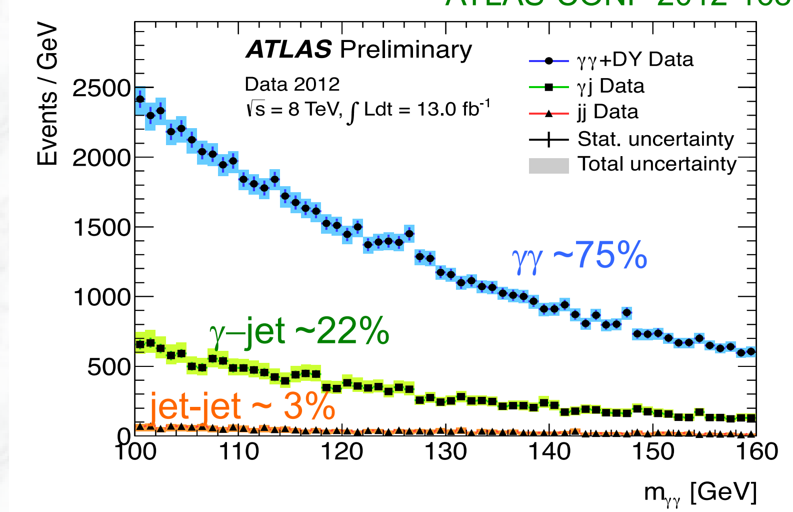


100 GeV < $m_{\gamma\gamma}$ < 160 GeV:

$\sqrt{s}$ = 7 TeV 23.788 events

$\sqrt{s}$ = 8 TeV 118.893 events

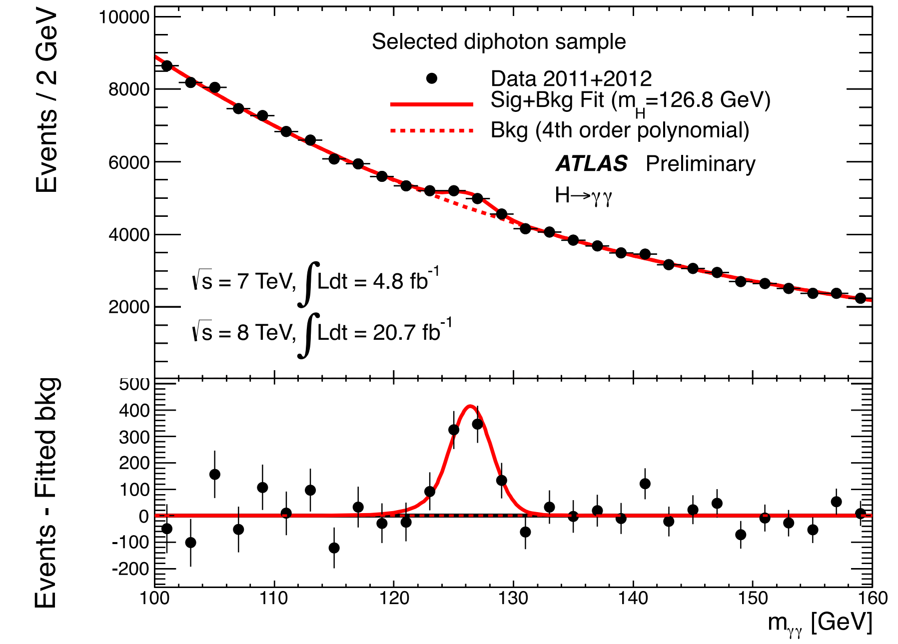
ATLAS-CONF-2012-168



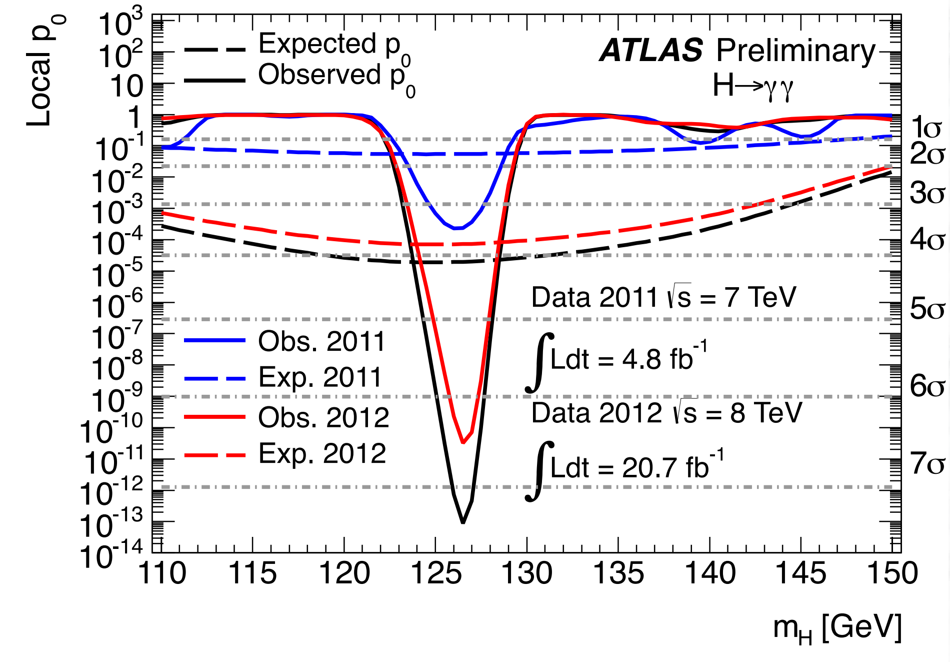
- Reducible γ-jet and jet-jet background at the level of 25%
- Background extrapolation below the excess from sidebands (4th order polynomial)

Result of the ATLAS search for H → $\gamma\gamma$

Full dataset ATLAS-CONF-2013-012



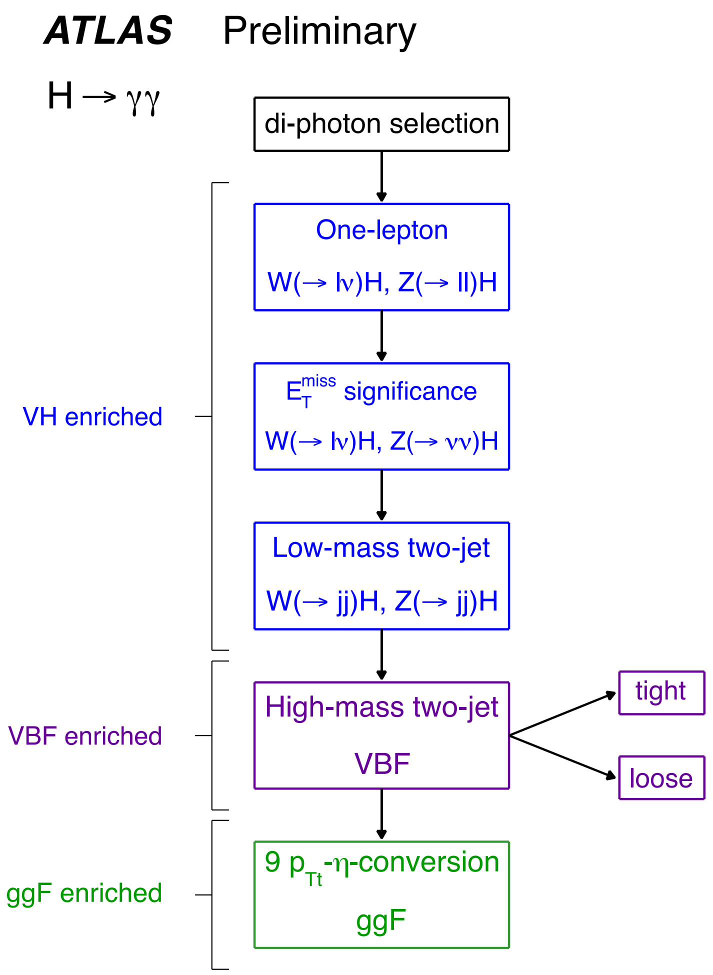
ATLAS-CONF-2013-012

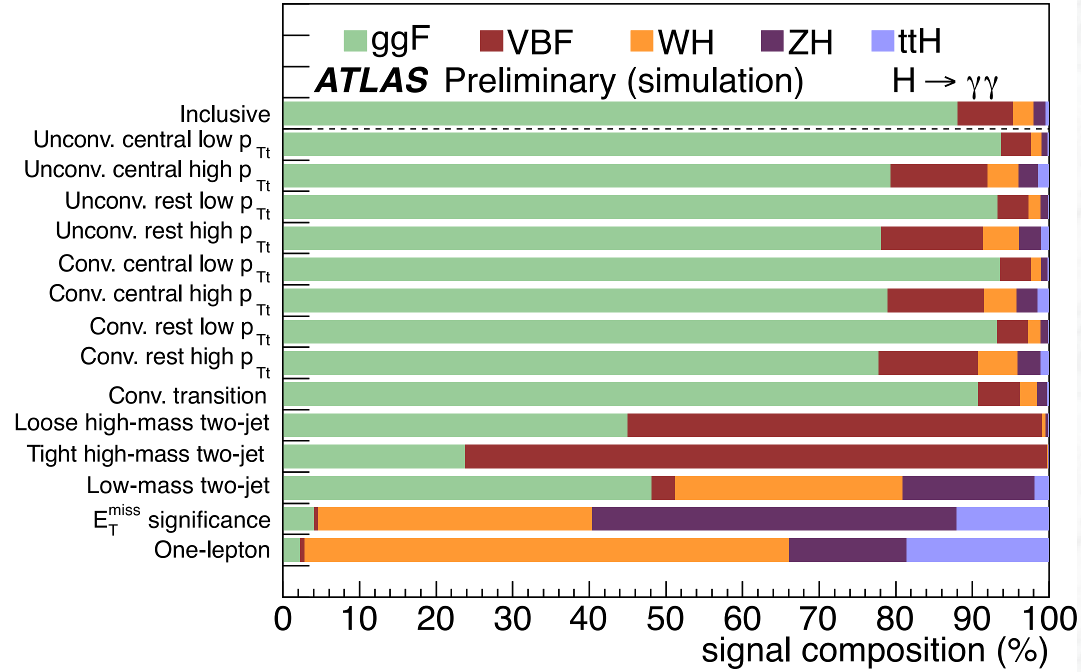


- p_0 value for consistency of data with background-only: ~ 10^{-13} (7.4σ observed) for the combined 7 TeV and 8 TeV data (4.3σ expected)
- Establishes the discovery of the new particle in the $\gamma\gamma$ channel alone

Categorisation of H → γγ candidate events

ATLAS-CONF-2013-012





Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)

- VH enriched: one-lepton, E_T^{miss}
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: 9 categories, exploit different mass resolution for different detector regions, $\gamma\gamma$ conversion status and p_{Tt}

Categorisation of H → γγ candidate events, √s = 8 TeV

$\sqrt{s}$	8 TeV				
Category	σ_{CB}(GeV)	Observed	N_S	N_B	N_S/N_B
Unconv. central, low p_{Tt}	1.50	911	46.6	881	0.05
Unconv. central, high p_{Tt}	1.40	49	7.1	44	0.16
Unconv. rest, low p_{Tt}	1.74	4611	97.1	4347	0.02
Unconv. rest, high p_{Tt}	1.69	292	14.4	247	0.06
Conv. central, low p_{Tt}	1.68	722	29.8	687	0.04
Conv. central, high p_{Tt}	1.54	39	4.6	31	0.15
Conv. rest, low p_{Tt}	2.01	4865	88.0	4657	0.02
Conv. rest, high p_{Tt}	1.87	276	12.9	266	0.05
Conv. transition	2.52	2554	36.1	2499	0.01
Loose High-mass two-jet	1.71	40	4.8	28	0.17
Tight High-mass two-jet	1.64	24	7.3	13	0.57
Low-mass two-jet	1.62	21	3.0	21	0.14
E_T^{miss} significance	1.74	8	1.1	4	0.24
One-lepton	1.75	19	2.6	12	0.20
Inclusive	1.77	14025	355.5	13280	0.03

Signal mass resolution (σ_{CB}), signal (N_S) and background (N_B) numbers in a mass window around m_H = 126.5 GeV containing 90% of the expected signal events

Statistical procedure, Higgs boson signal strength

- Parameter of interest: signal strength factor μ
  (acts as scale factor on the total number of events predicted by the Standard Model for a Higgs boson signal)

  $\mu = 0$ background-only hypothesis
  $\mu = 1$ Standard Model Higgs boson signal strength (in addition to background)

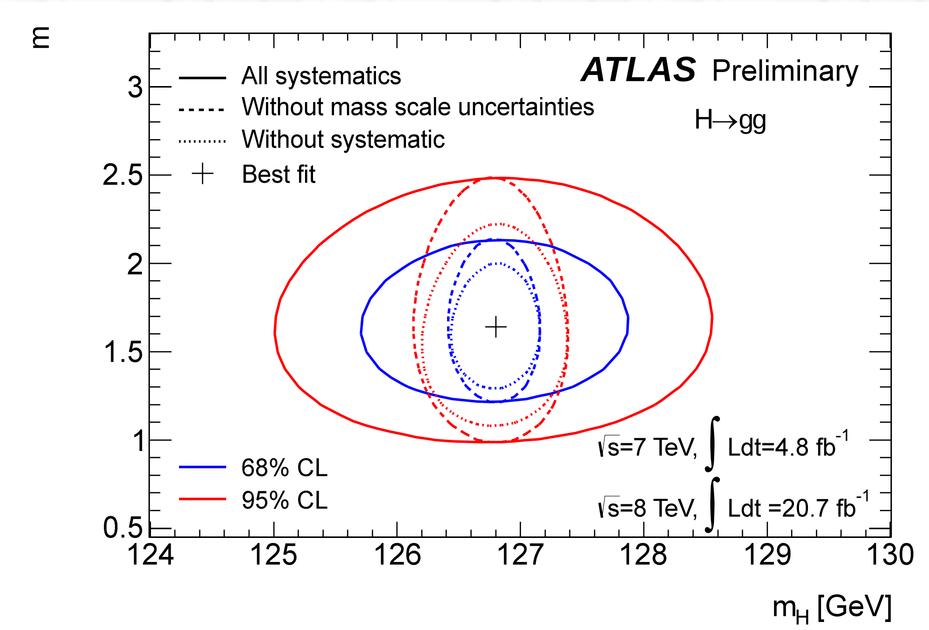
- Hypothesized values of μ are tested with a statistics $\Lambda(\mu)$ based on the profile likelihood ratio (→ lectures by Kyle Cranmer)

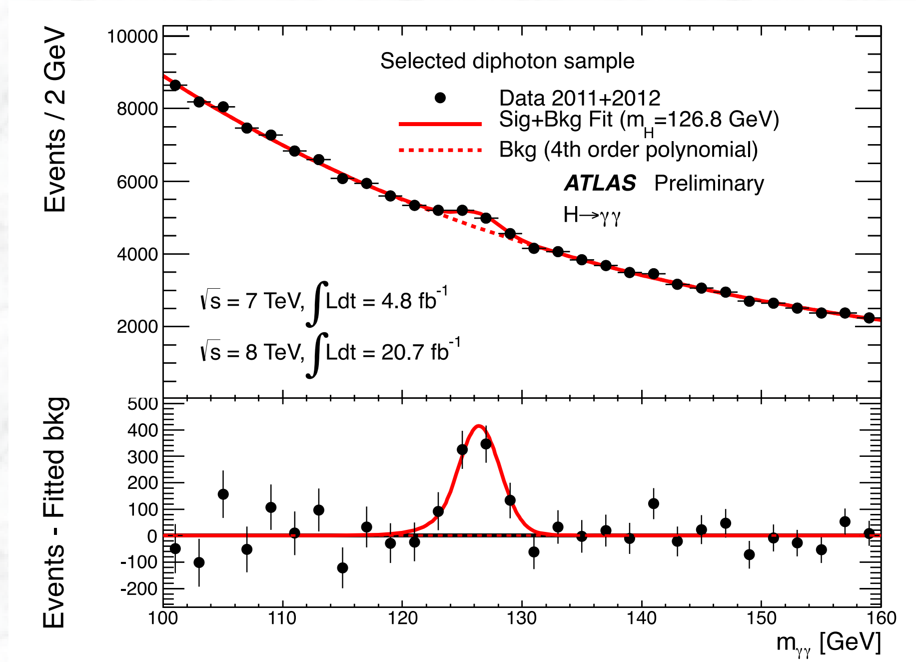
- The test statistics is based on likelihood functions

  (using signal and background models,
  systematic uncertainties are introduced as nuisance parameters with constraints (e.g. Gaussian))

Result of the ATLAS search for H → γγ

-mass and signal strength-



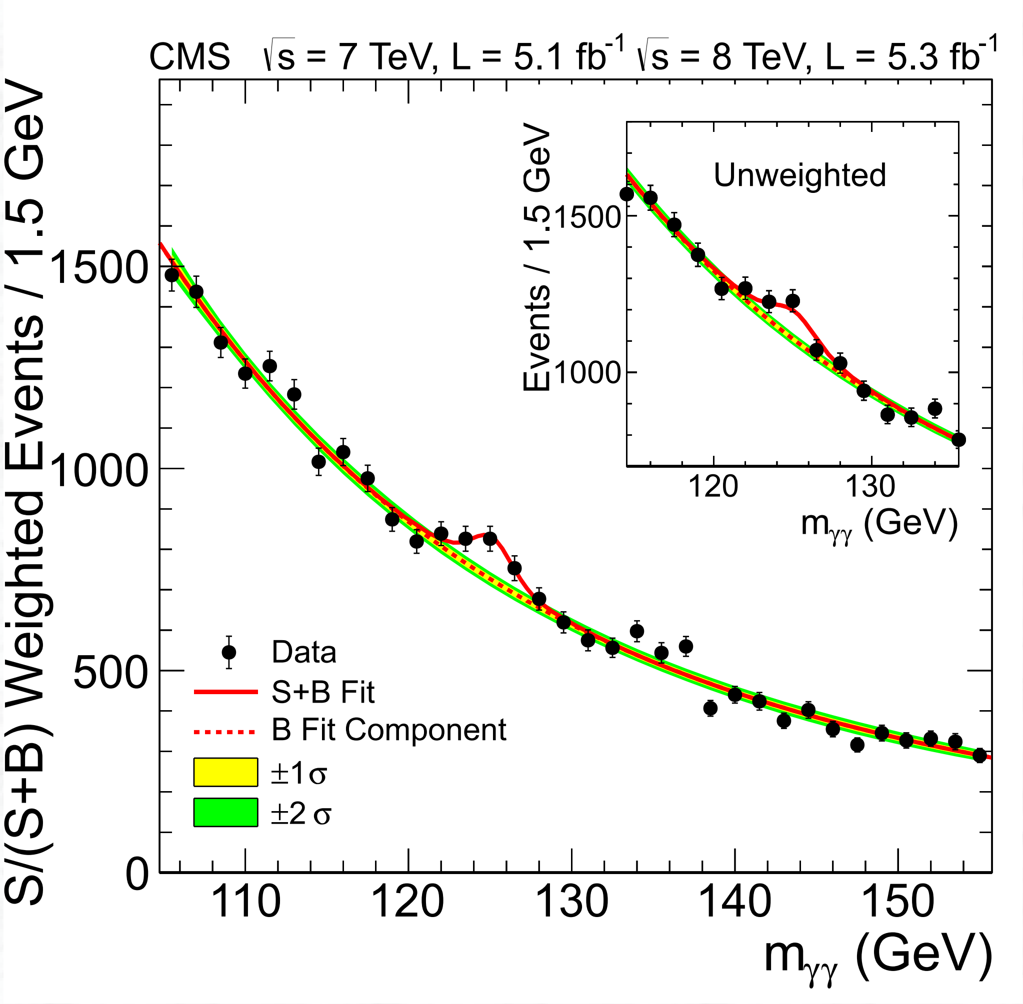


Mass: m_H = 126.8 ± 0.2 (stat) ± 0.7 (syst) GeV

Signal strength: $m := s / s_{SM} = 1.57 \pm 0.22 (stat)^{+0.24}_{-0.18} (syst)$

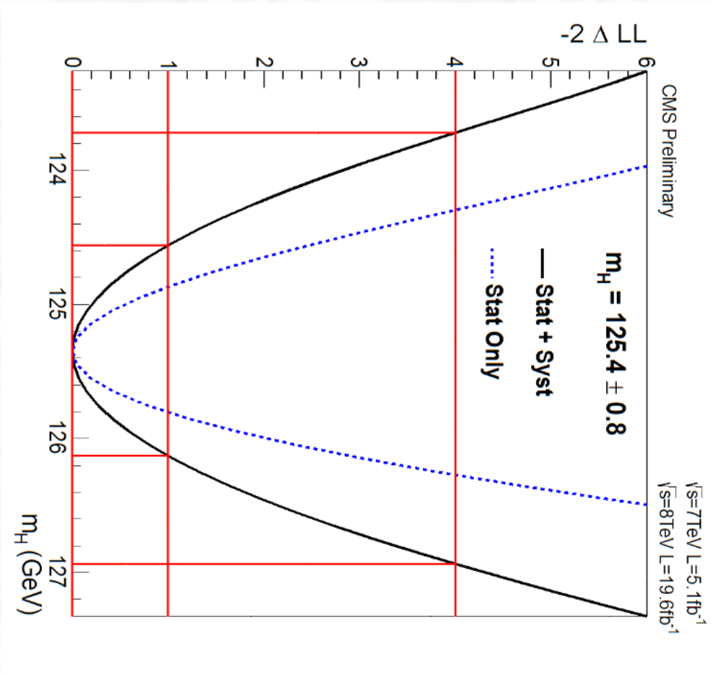
Result of the CMS search for H → γγ

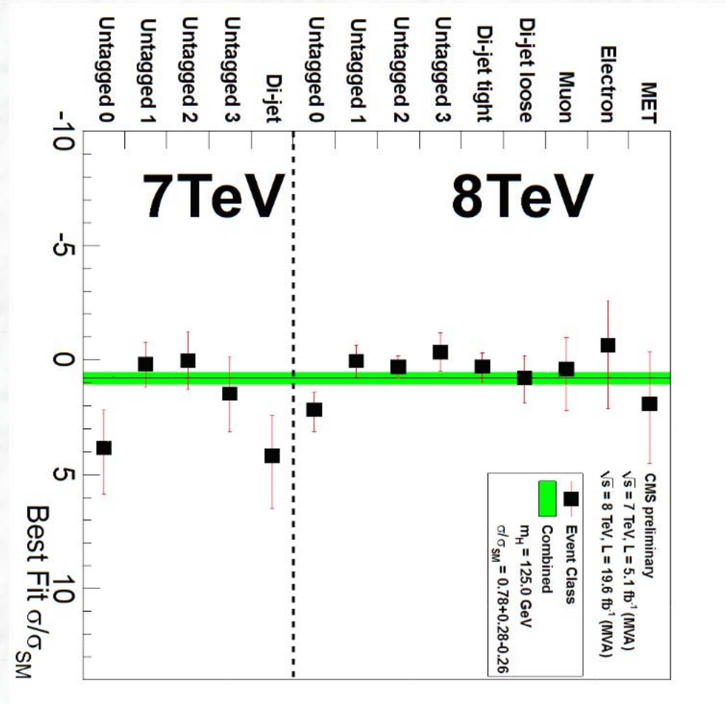
July 2012



Result of the CMS search for H → γγ

-mass and signal strength (MVA analysis)-

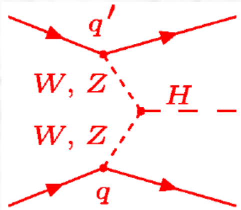


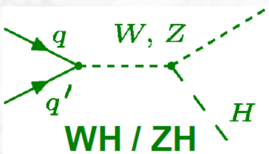


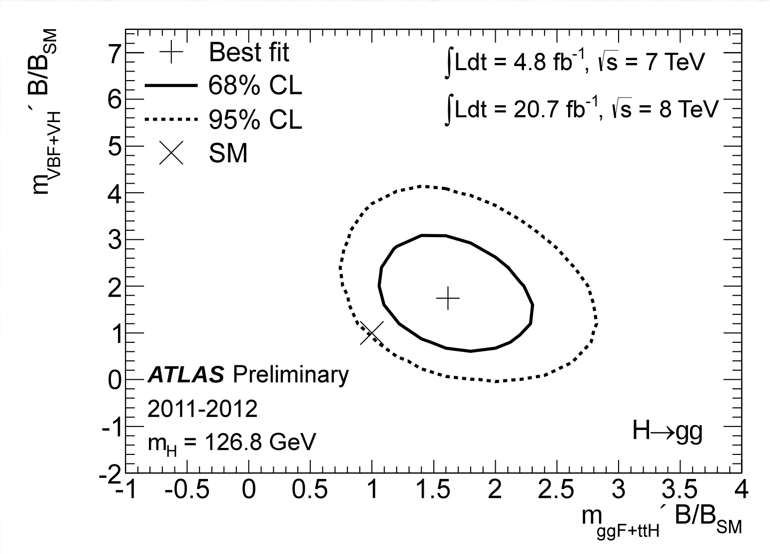
Mass: m_H = 125.4 ± 0.5 (stat) ± 0.6 (syst) GeV

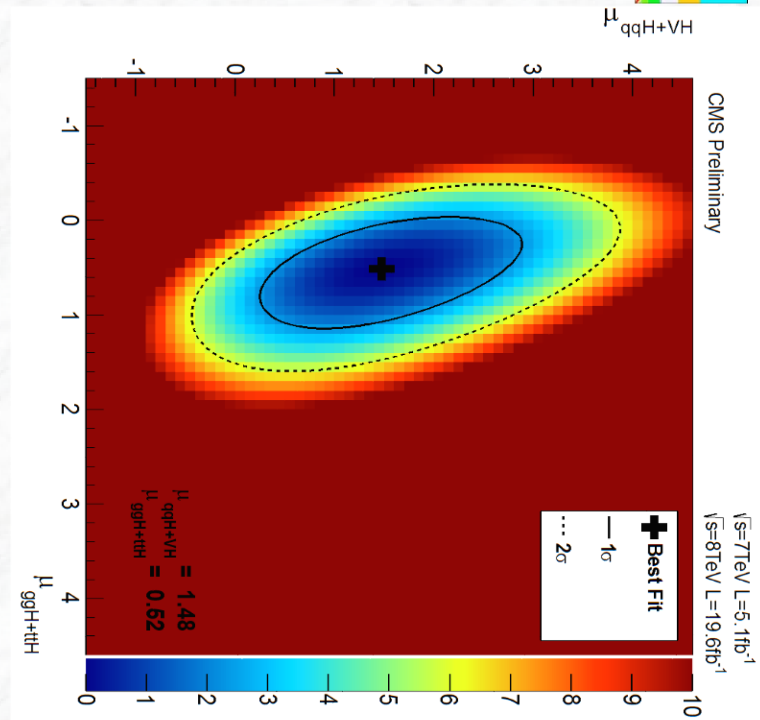
Signal strength: $m\!: = s\ /\ s_{SM} = 0.78^{+0.28}_{-0.26}$ (syst)

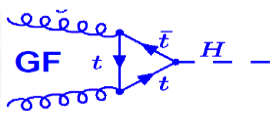
Separation of different production processes for H → γγ

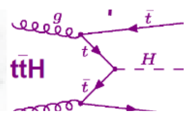


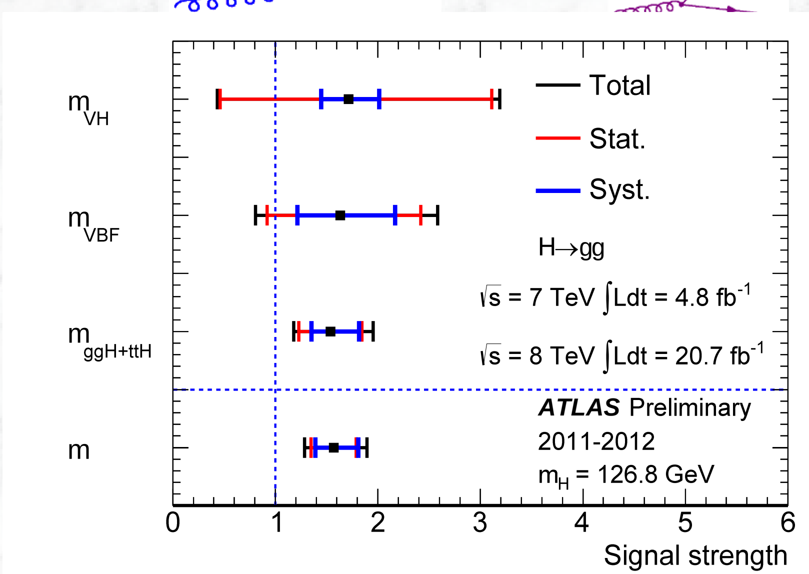






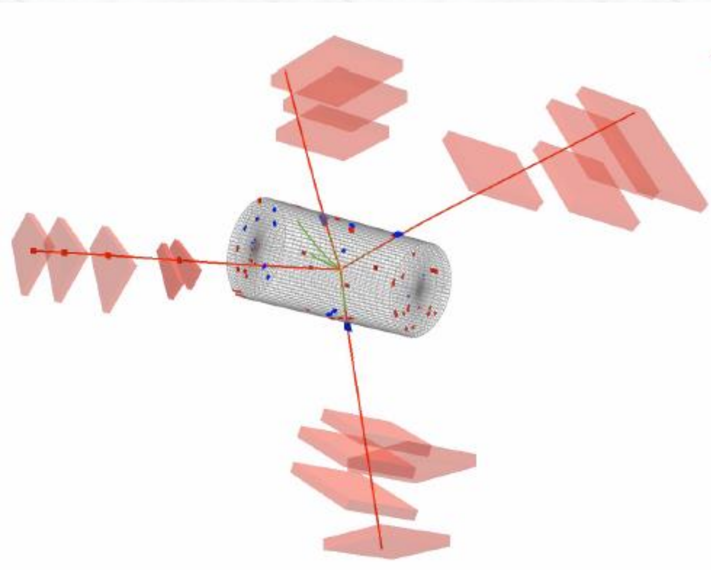


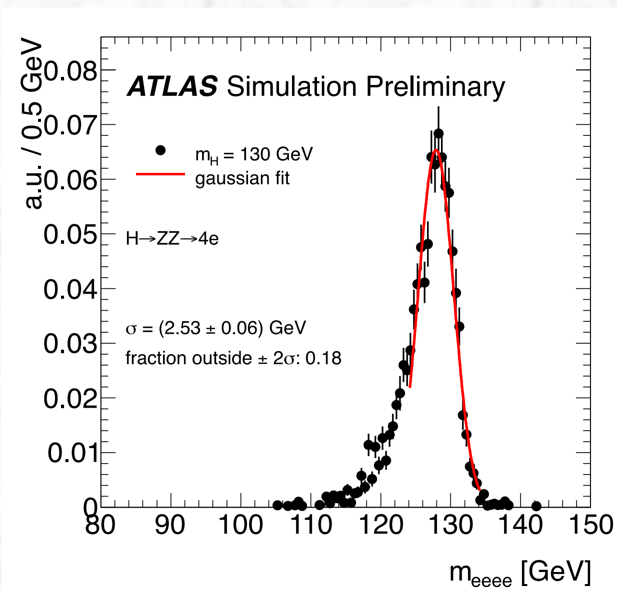




Important “evidence” for VBF production in both experiments

Search for the H → ZZ$^{(*)}$ → ℓ⁺ℓ⁻ ℓ⁺ℓ⁻ decay



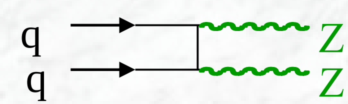


- The "golden mode"
  4 leptons (isolated) with large transverse momenta

- Mass of the Higgs boson can be reconstructed $m_{4\ell}$

  Both experiments have a good mass resolution
  ATLAS: ~2.5 GeV/c^2 (4e) for m_H ~130 GeV/c^2
  ~2.0 GeV/c^2 (4μ) for m_H ~130 GeV/c^2

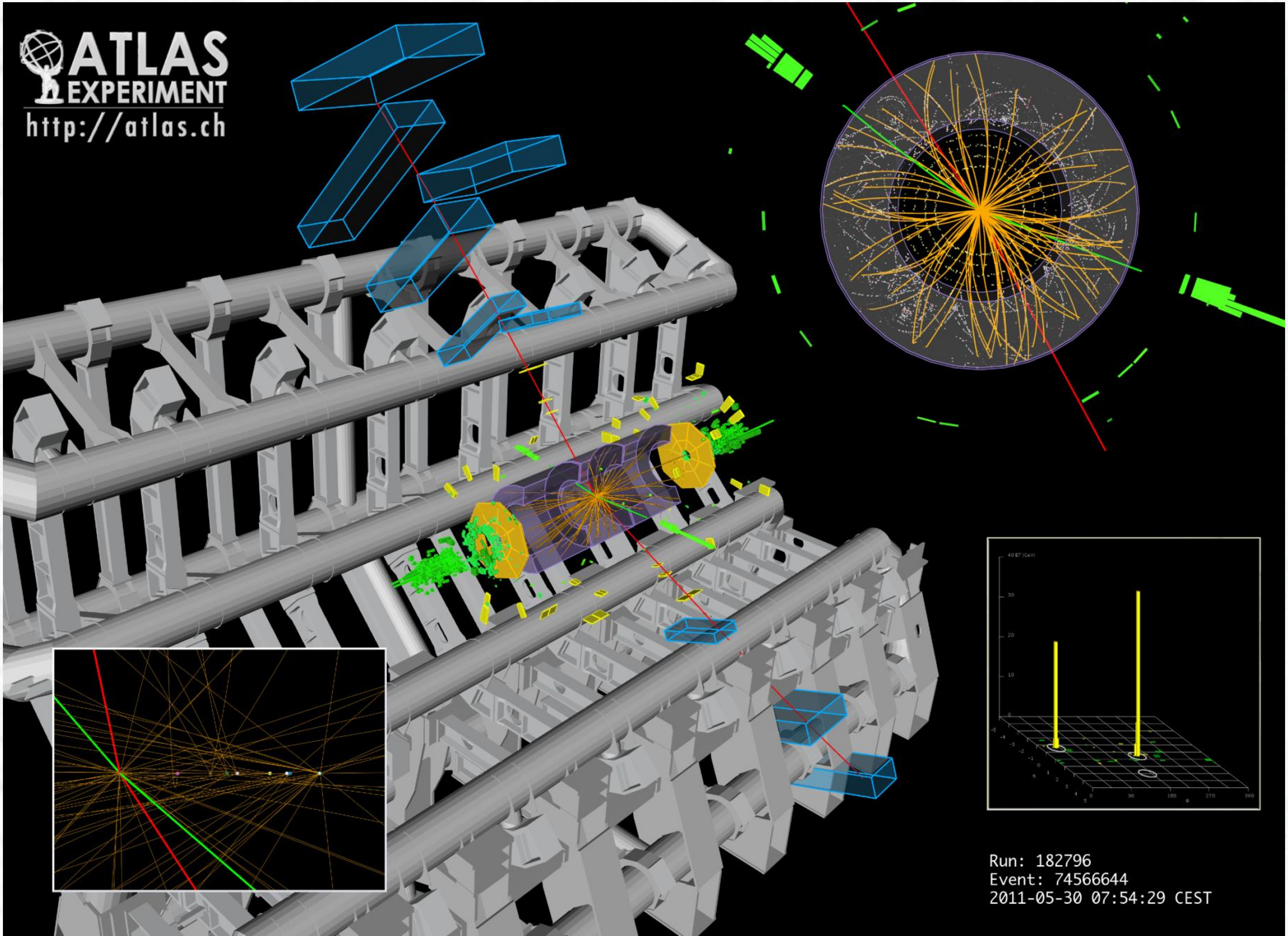
- Low signal rate, but also low background
  - Mainly from ZZ continuum



- In addition from tt and Zbb events:

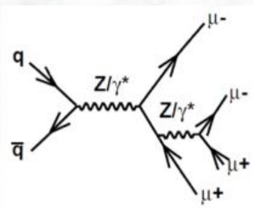
  tt → Wb Wb → ℓν cℓν ℓν cℓν
  Z bb → ℓℓ cℓν cℓν

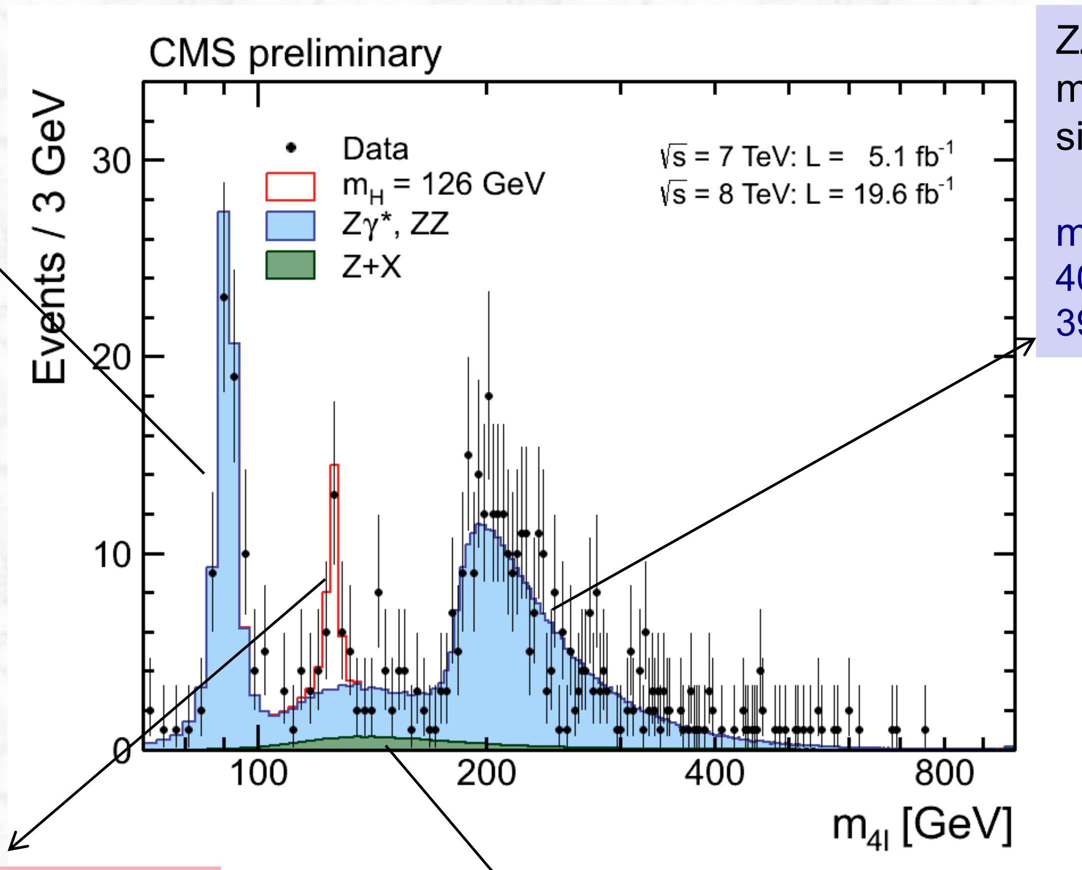
Candidate event for a H → ZZ → $e^+e^- \mu^+ \mu^-$ decay



CMS: 4ℓ invariant mass spectrum

Z → 4ℓ peak
(good data / MC agreement)





ZZ continuum background, modelled by Monte Carlo simulation (NLO)

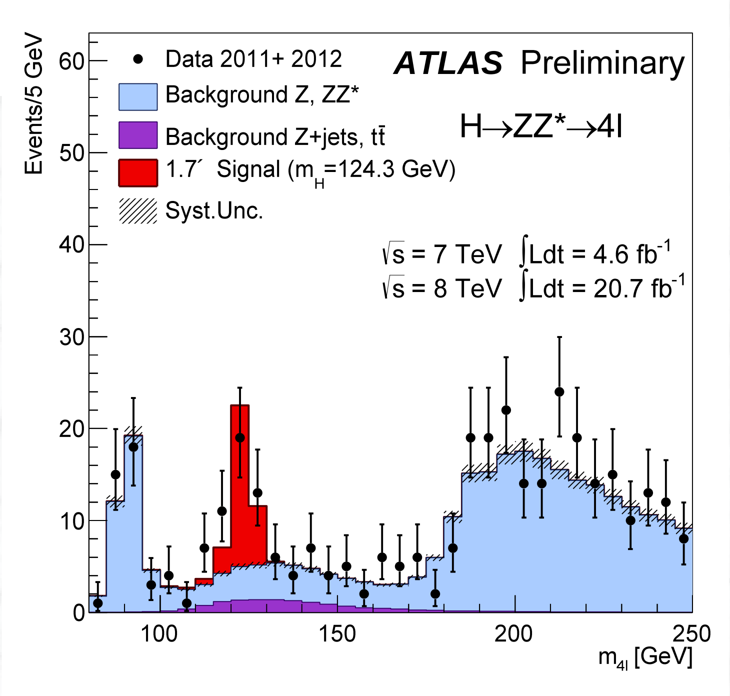
m(4ℓ) > 140 GeV:
403 events observed
390 events expected

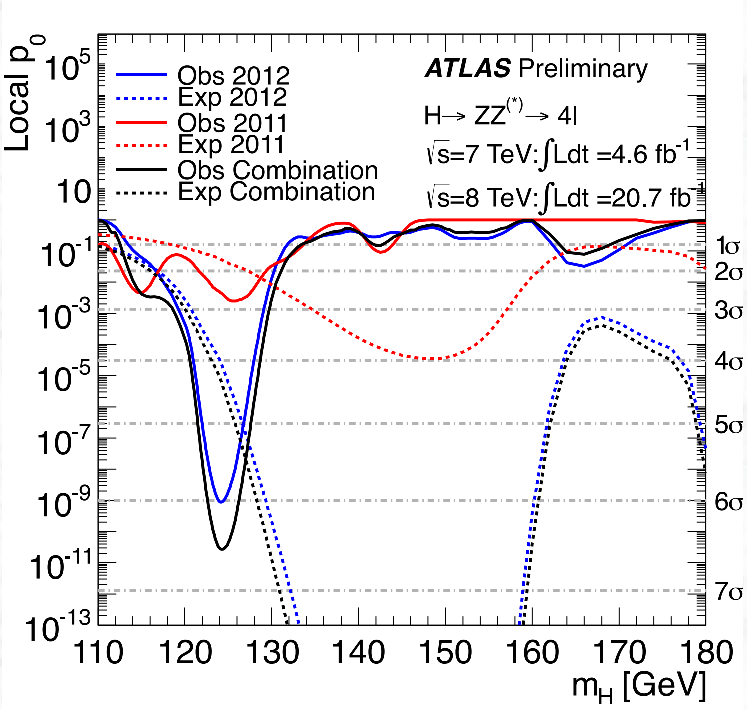
H → ZZ signal

121.5 < m(4ℓ) > 130.5 GeV:
S+B: 28 events expected
25 events observed

Reducible tt and Zbb, Z+jets background, data driven estimates

ATLAS: 4ℓ invariant mass spectra



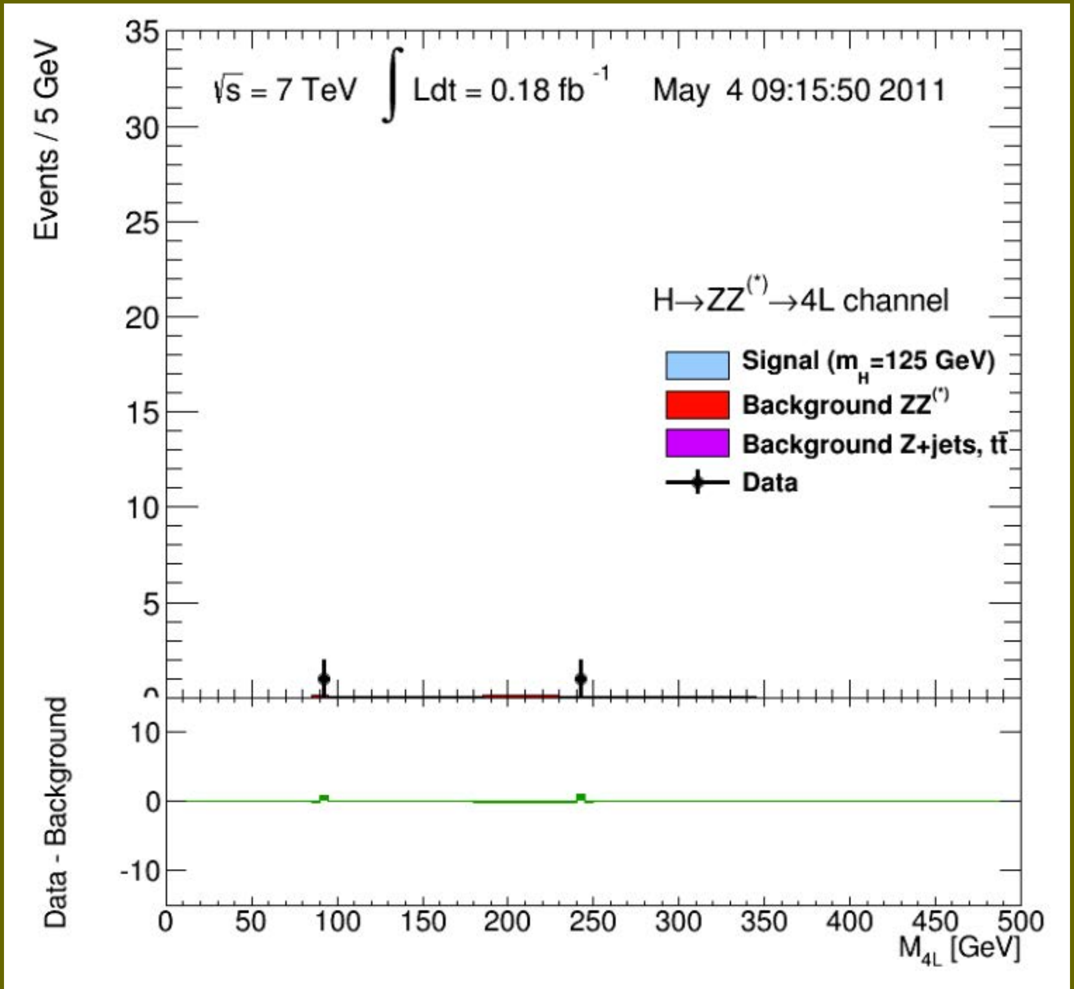


Mass range 120 – 130 GeV	Expected signal	Background	Data
√s = 7 TeV	2.2	2.3	5
√s = 8 TeV	13.7	8.8	27

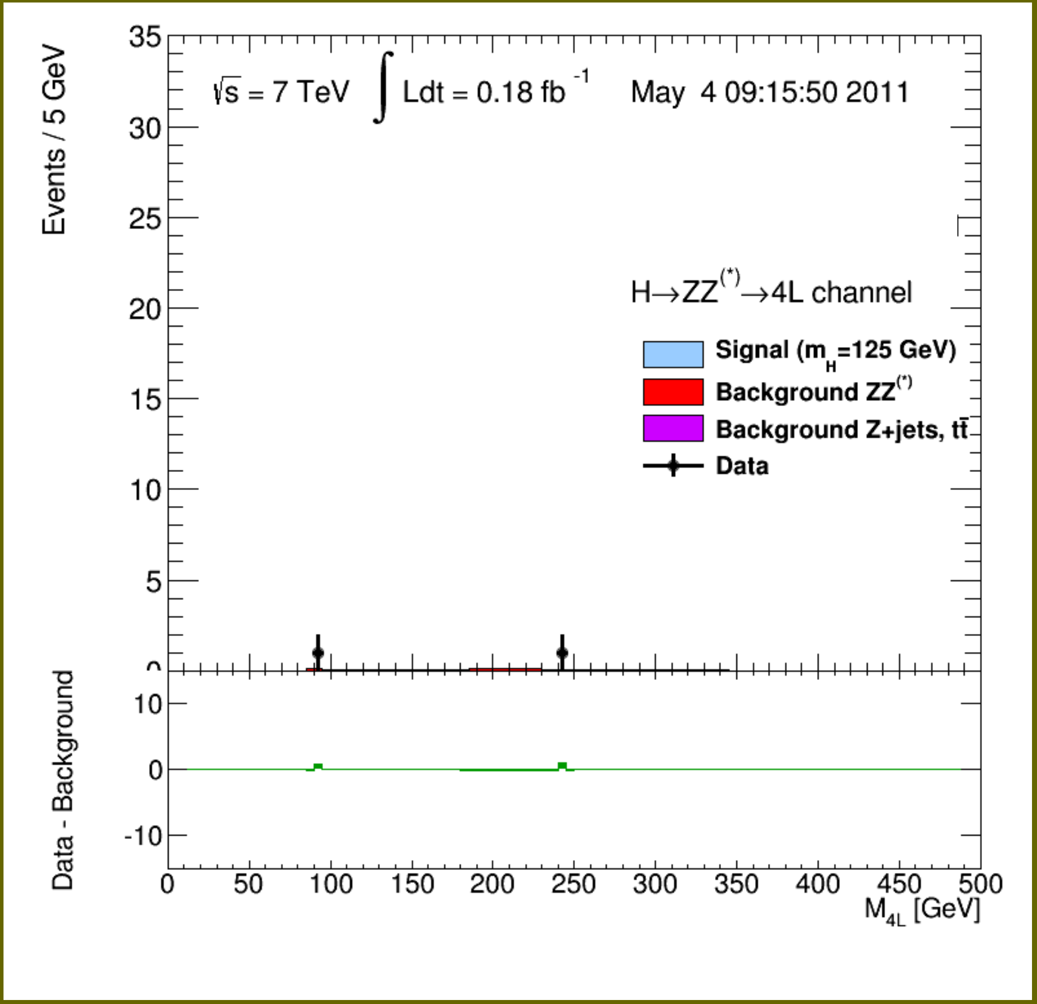
$m_{4\ell}$ > 160 GeV: 376 events observed
348 ± 26 expected from
√s = 7 + 8 TeV background (mainly ZZ)

- maximum deviation at 124.3 GeV
  p_0 value: ~2.7 10^{-11} (6.6σ obs.)
  (4.4σ exp.)
- Independent discovery-level observation

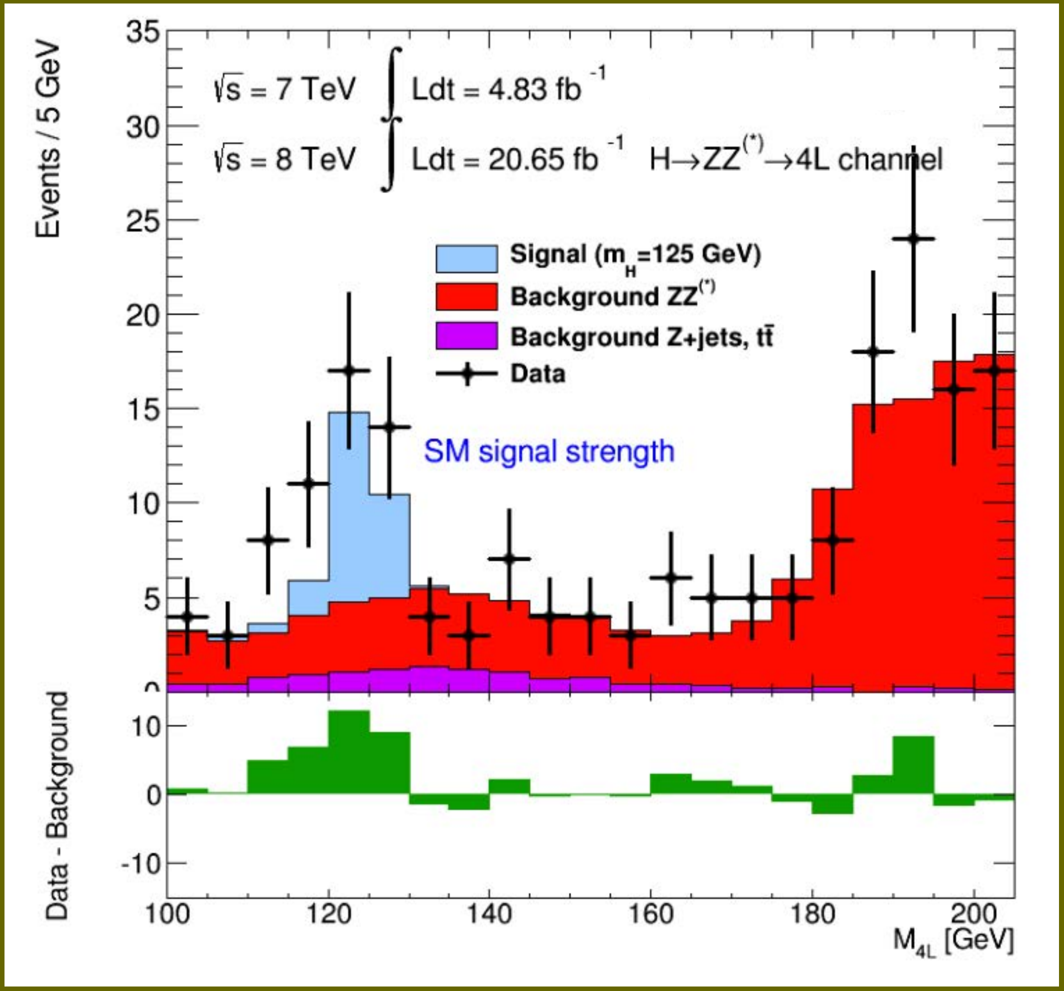
Time evolution of the H → ZZ → 4ℓ signal



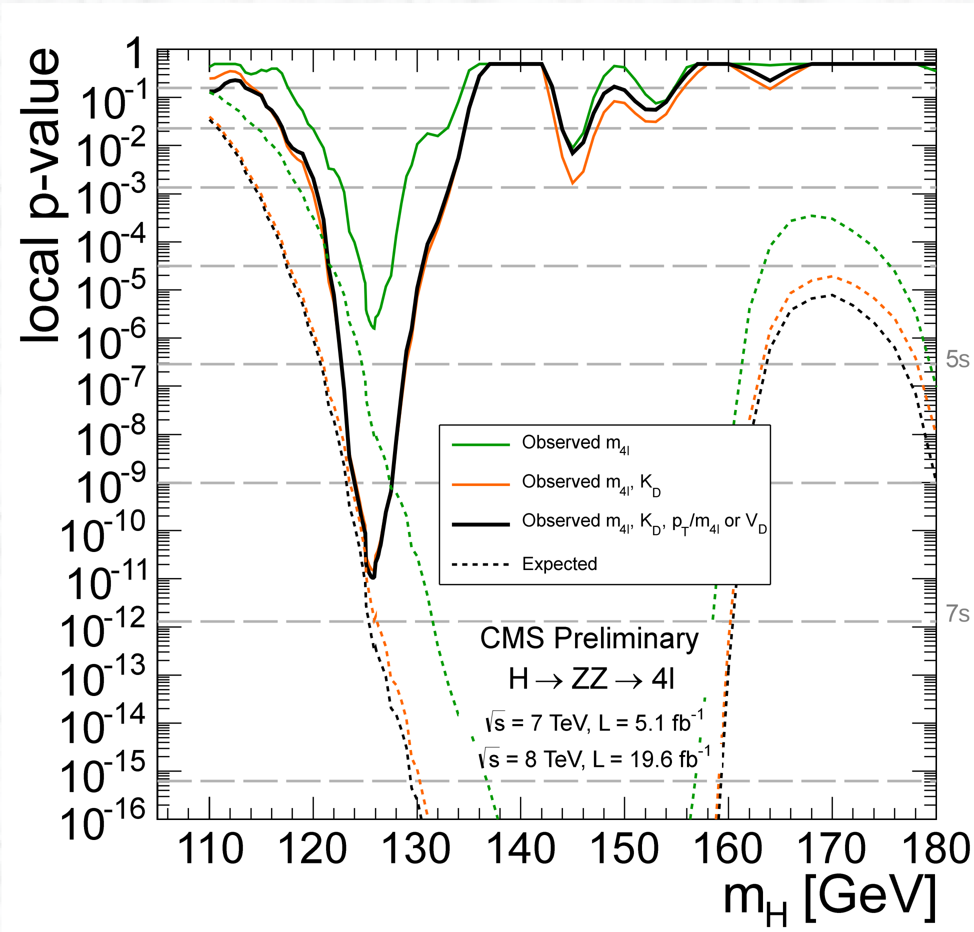
Time evolution of the H → ZZ → 4ℓ signal



Time evolution of the H → ZZ → 4ℓ signal



CMS $H \rightarrow ZZ$ significance



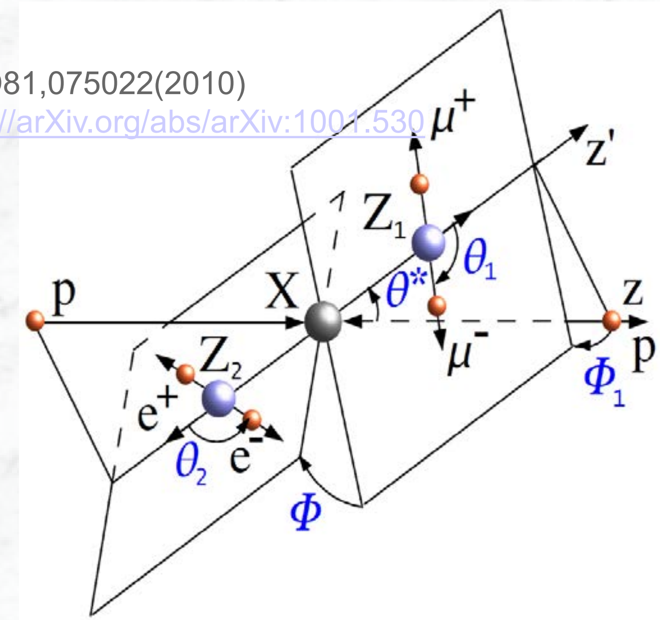
	Expected	Observed
3D (m_{4l}, K_D, V_D or p_T/m_{4l})	7.2 σ	6.7 σ
2D (m_{4l}, K_D)	6.9 σ	6.6 σ
1D(m_{4l})	5.6 σ	4.7 σ

at 125.8 GeV (minimum of local p value)

- Stand-alone discovery in the $H \rightarrow ZZ$ – 4l channel
- Additional discriminants improve sensitivity, as expected

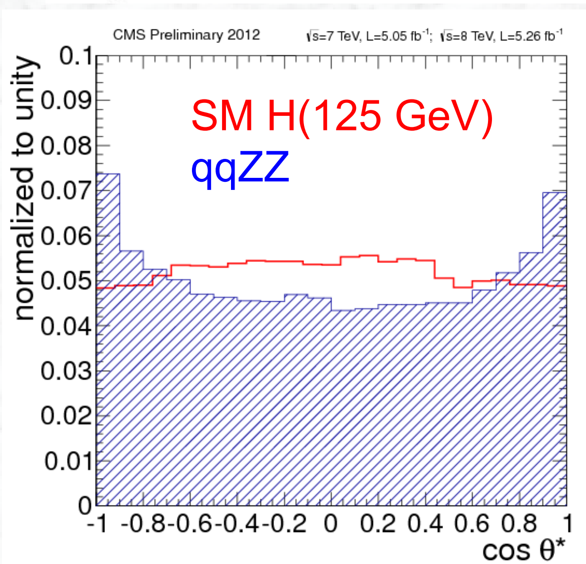
CMS: use additional information on decay kinematics, MELA discriminant

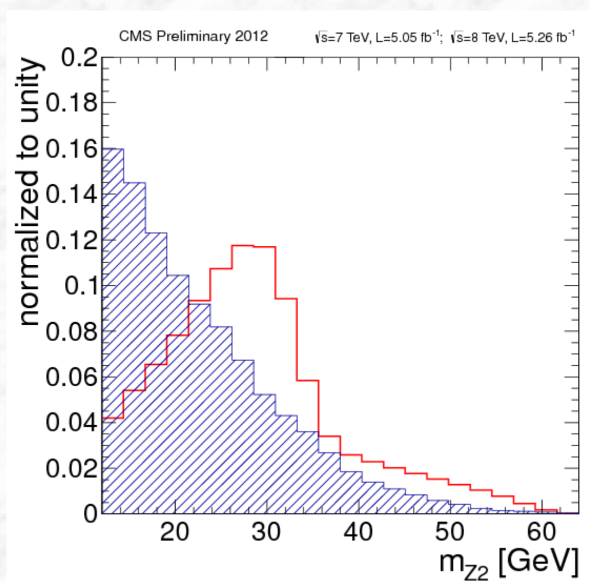
PRD81,075022(2010)
http://arXiv.org/abs/arXiv:1001.5300

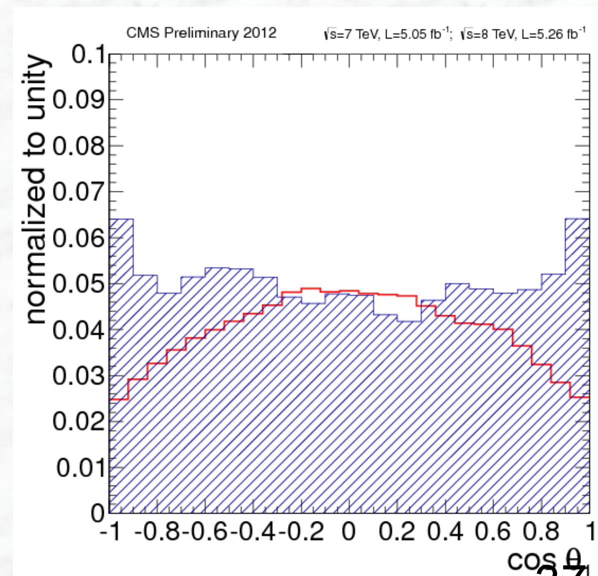


Matrix Element Likelihood Analysis:
uses kinematic inputs for
signal to background discrimination
$\{m_1, m_2, \theta_1, \theta_2, \theta^*, \Phi, \Phi_1\}$

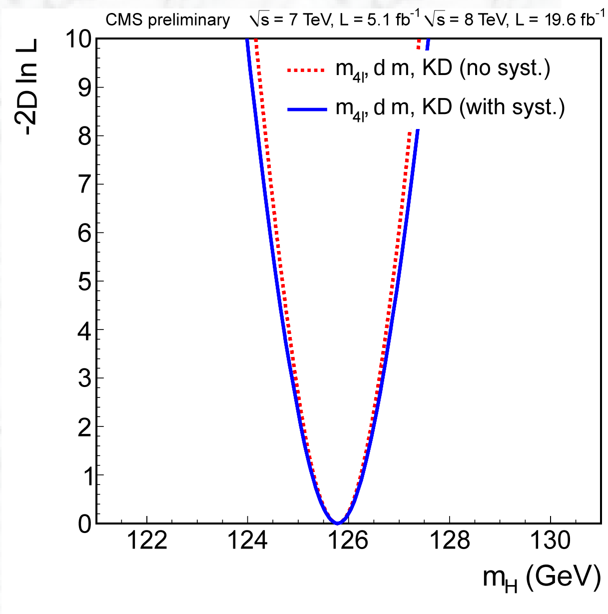
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

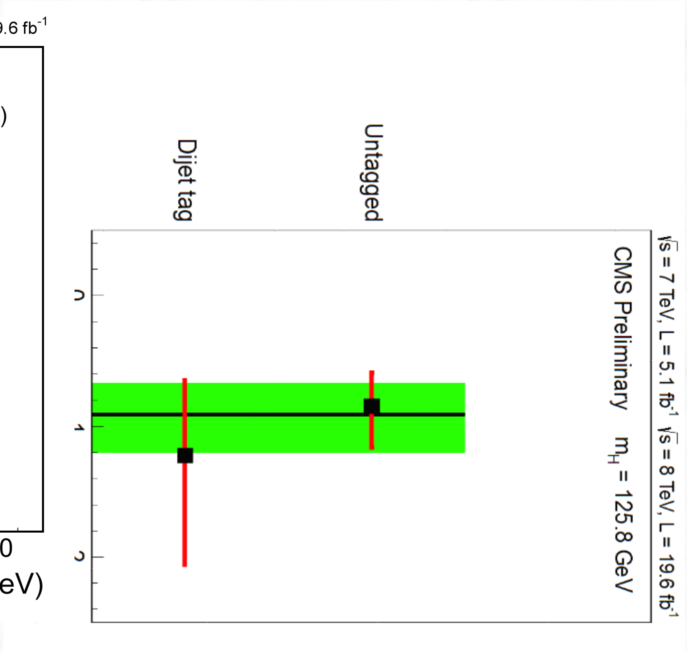


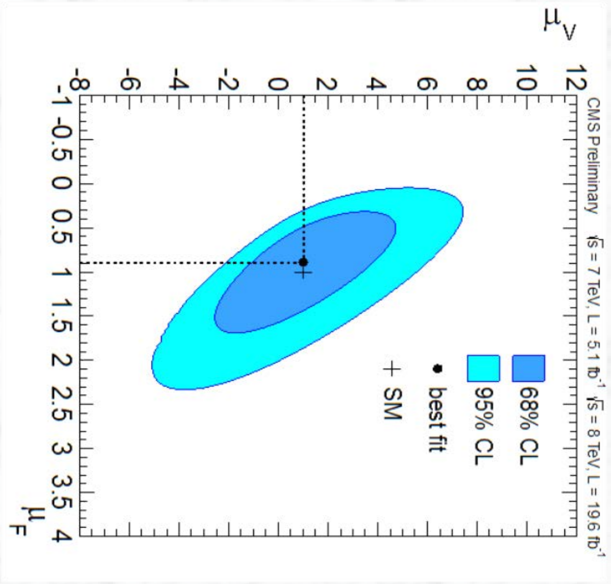




Mass and signal strength for H → ZZ*







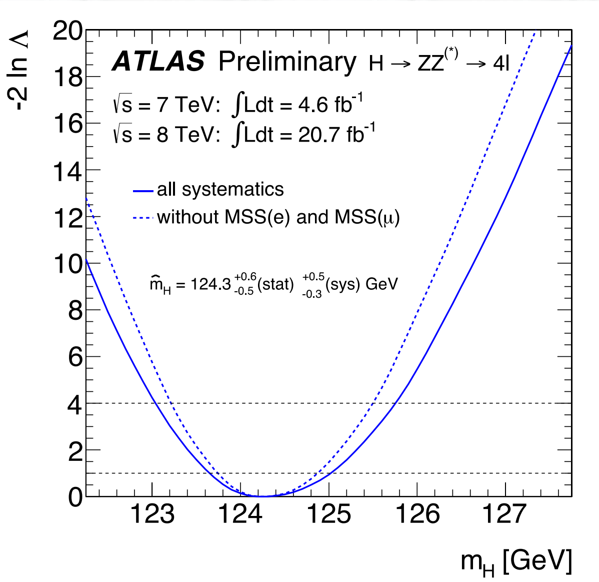
Mass: $m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{syst})$ GeV

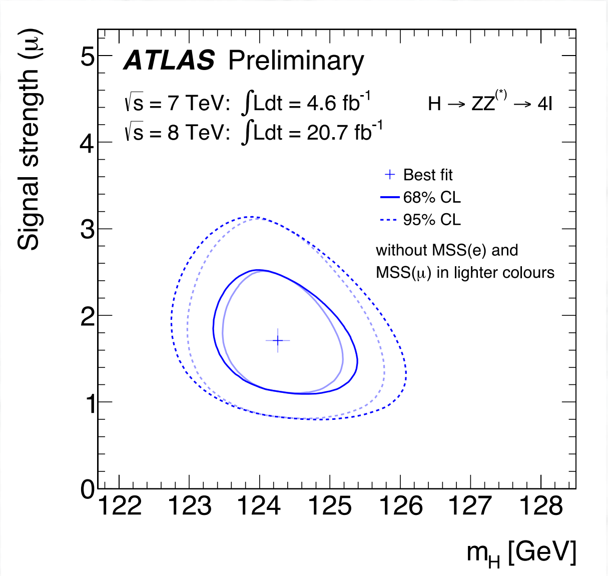
Signal strength: $\mu = 0.9^{+0.3}_{-0.2}$

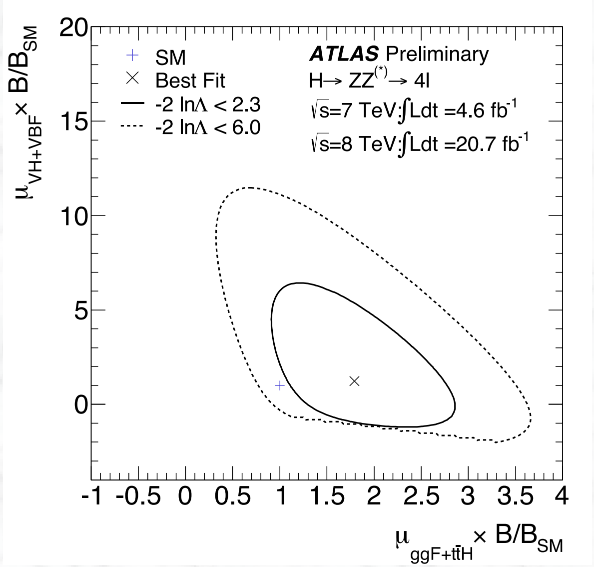
(m_H = 125.8 GeV)

Mass and signal strength for H → ZZ*

ATLAS-CONF-2013-013



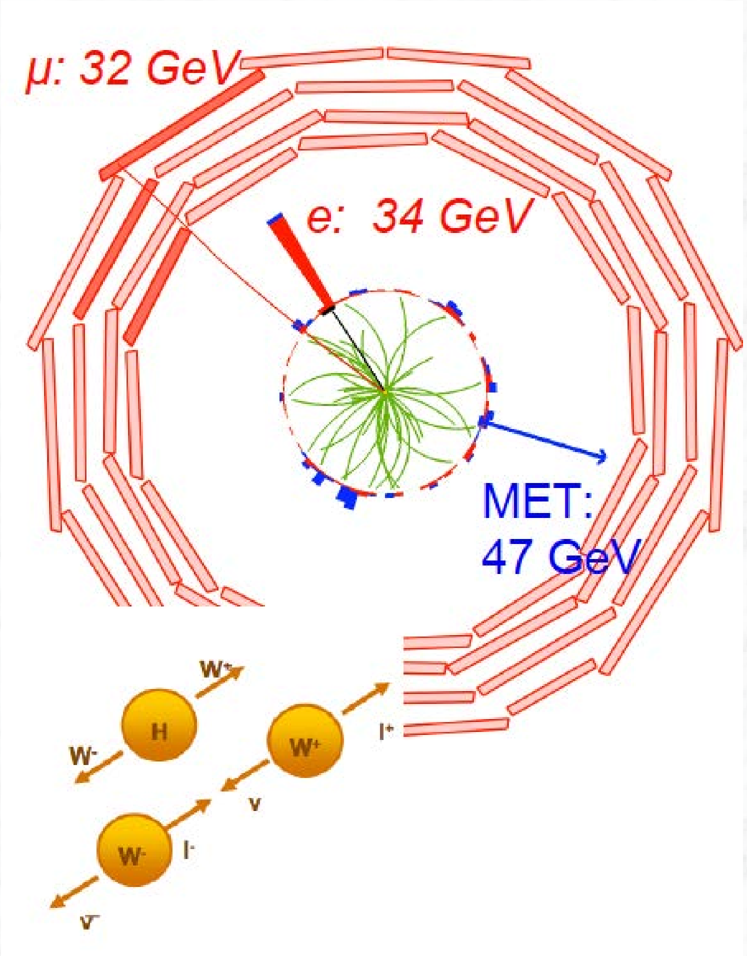




Mass: $m_H = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ GeV

Signal strength:
(m_H = 124.3 GeV) $\mu = 1.7 \pm 0.5$

Search for H → WW → ℓν ℓν decay



- Two high p_T leptons (e or μ)

  Leptons from Higgs decay (spin-0 particle) are expected to have a small angular separation

- Two neutrinos

  → large missing transverse energy

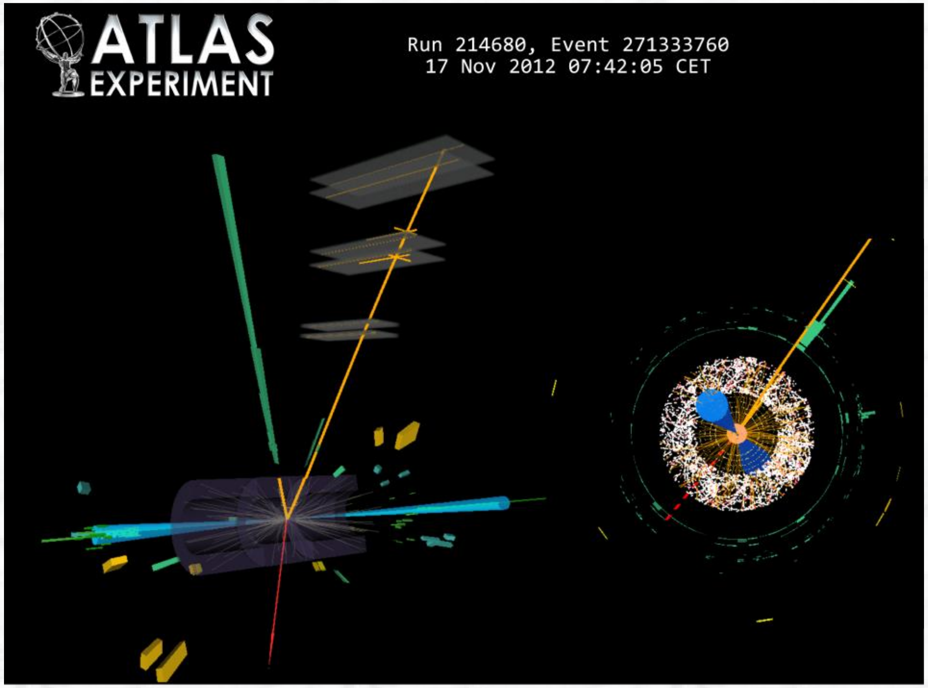
  → Higgs boson mass cannot be reconstructed, use transverse mass

- Highest sensitivity around 160 GeV

  (nearly 100% H → WW branching ratio)

  → Tevatron sensitivity and early LHC sensitivity in that mass region

What are the main backgrounds?



Final state signature:

- Two isolated, high p_T leptons;
  use all combinations: eμ, μe, ee, $\mu\mu$
- Missing transverse momentum
- Jets
  Depend on production process:
  gluon fusion (0, 1 jets), VBF: 2 jets

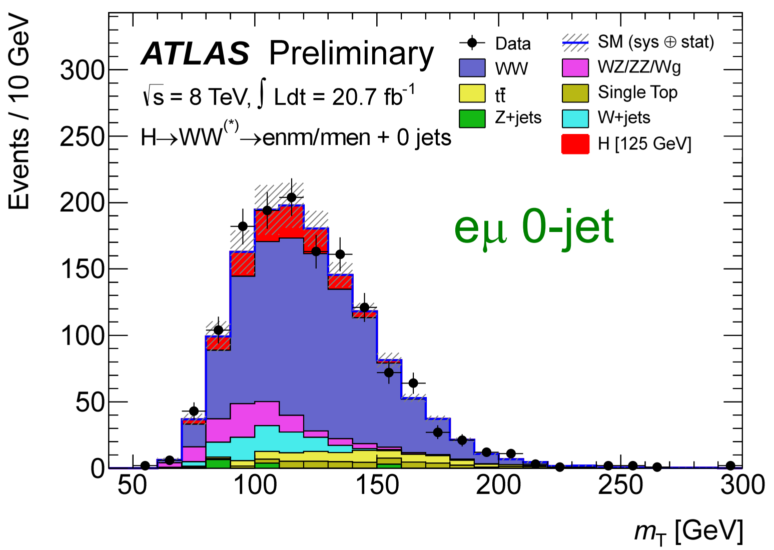
→ Split analysis in jet multiplicity 0,1 and 2 jets

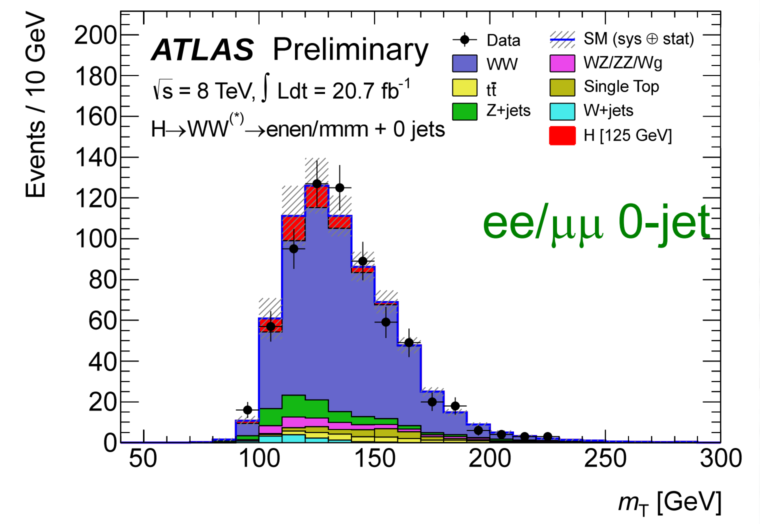
Major backgrounds:

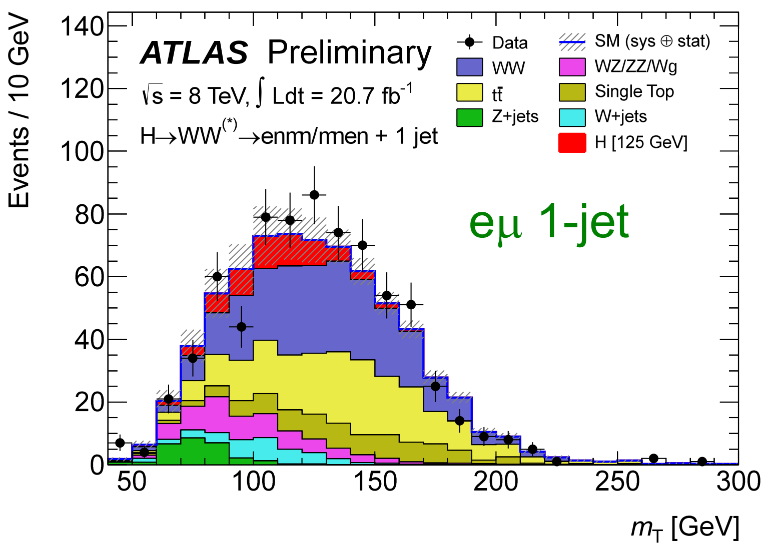
- Di-boson production, in particular WW production (0 jet, 1 jet)
- tt background (1, 2 jets)
- Z+jets [Drell-Yan], in particular for ee/$\mu\mu$ pairs;
  More difficult to reject at high luminosity

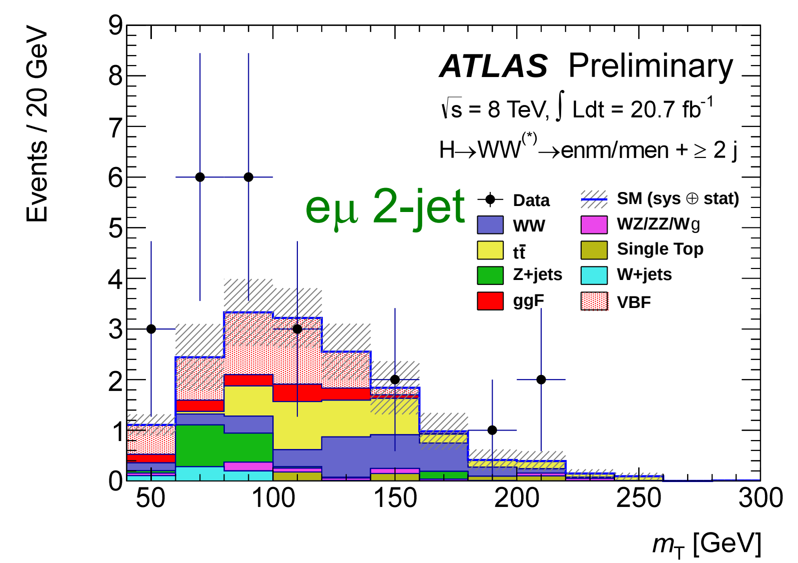
Transverse mass distributions

ATLAS-CONF-2013-030









Clear excess above backgrounds in all sub-channels (jet multiplicities)

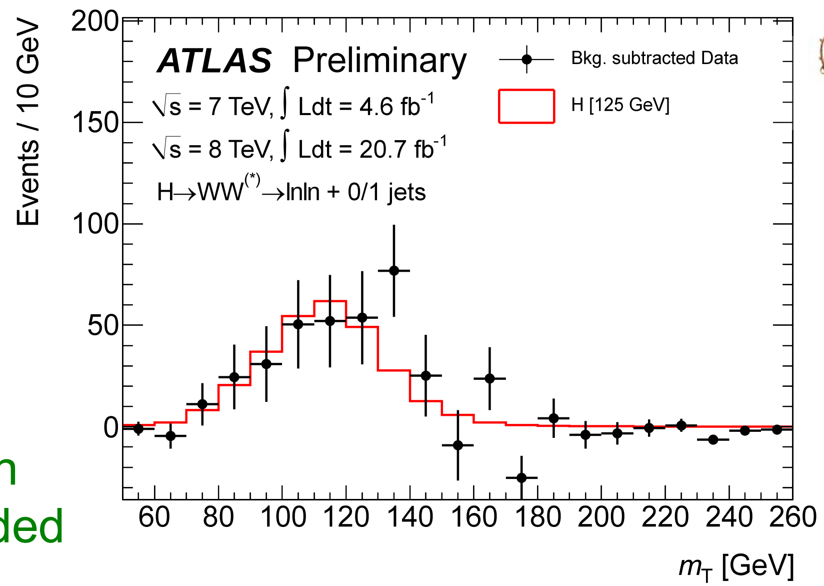
Search for H → WW → ℓν ℓν (cont.)
- number of estimated background and expected signal events (after final cuts)

$\sqrt{s}$ = 7 TeV, L = 4.6 fb^{-1}

N_{jet}	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	N_{W+jets}
= 0	154	161 ± 11	25 ± 5	113 ± 10	12 ± 2	5 ± 1	4 ± 1	6 ± 2	21 ± 5
= 1	62	47 ± 6	7 ± 2	16 ± 6	5 ± 1	10 ± 3	6 ± 2	5 ± 2	5 ± 1
≥ 2	2	4.6 ± 0.8	1.4 ± 0.2	0.7 ± 0.2	-	0.7 ± 0.5	0.1 ± 0.1	2.4 ± 0.6	0.3 ± 0.1

$\sqrt{s}$ = 8 TeV, L = 20.7 fb^{-1}

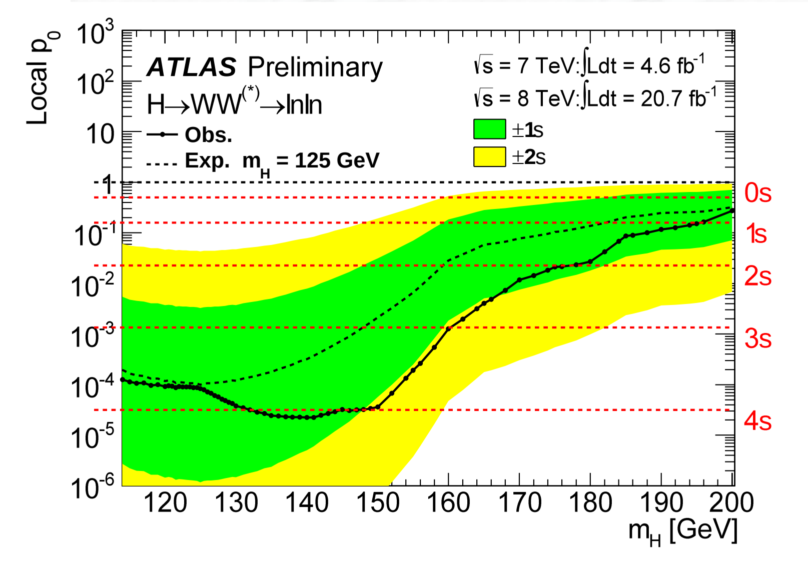
N_{jet}	N_{obs}	N_{bkg}	N_{sig}	N_{WW}	N_{VV}	$N_{t\bar{t}}$	N_t	N_{Z/γ^*}	N_{W+jets}
= 0	831	739 ± 39	97 ± 20	551 ± 41	58 ± 8	23 ± 3	16 ± 2	30 ± 10	61 ± 21
= 1	309	261 ± 28	40 ± 13	108 ± 40	27 ± 6	68 ± 18	27 ± 10	12 ± 6	20 ± 5
≥ 2	55	36 ± 4	10.6 ± 1.4	4.1 ± 1.5	1.9 ± 0.4	4.6 ± 1.7	0.8 ± 0.4	22 ± 3	0.7 ± 0.2



Background-subtracted m_T distribution for N_{jet} =0,1 and 7 and 8 TeV data added

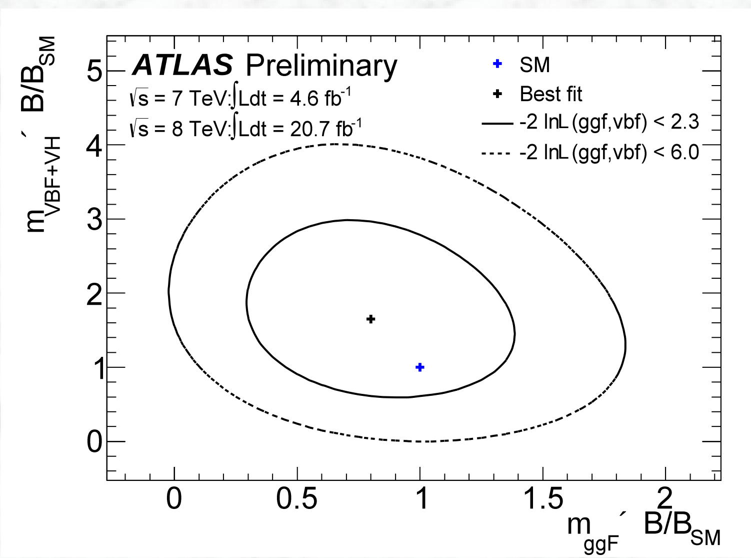
Results on the search for H → WW → ℓν ℓν decays

ATLAS-CONF-2013-030



Shallow minimum of p_0 value at 140 GeV

p_0 (125 GeV) = $8\ 10^{-5}$ (3.8σ observed)
(3.7σ expected)



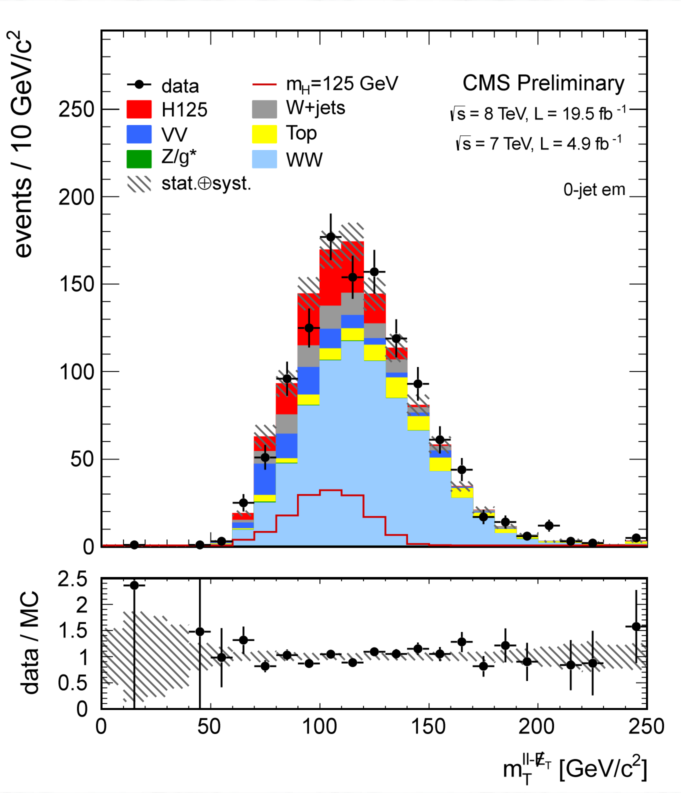
Signal strength:
(combination of 7 TeV and 8 TeV data, at 125 GeV)

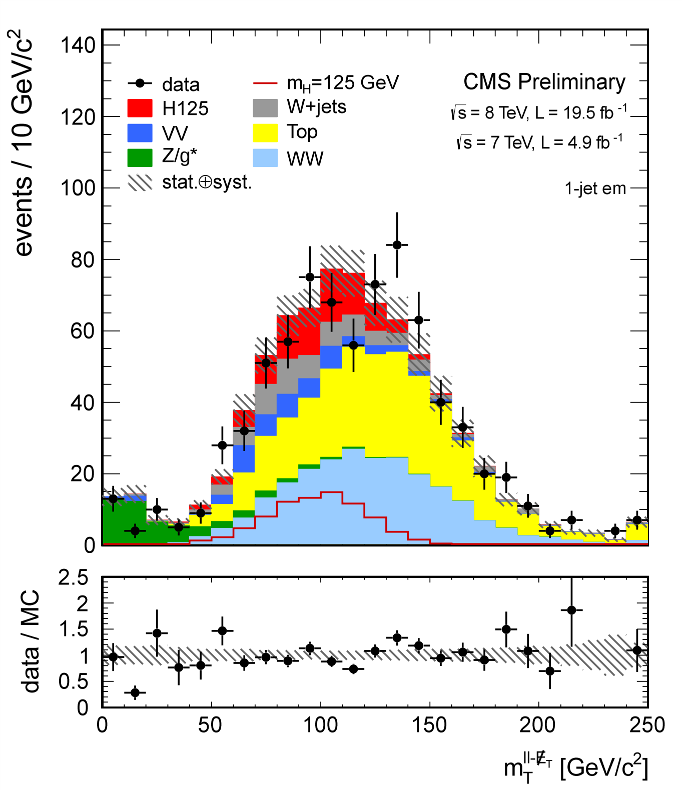
μ = 1.01 ± 0.21 (stat) ± 0.12 (syst) ± 0.19 (theo)

μ_{VBF} = 1.66 ± 0.79

μ_{ggF} = 0.82 ± 0.36

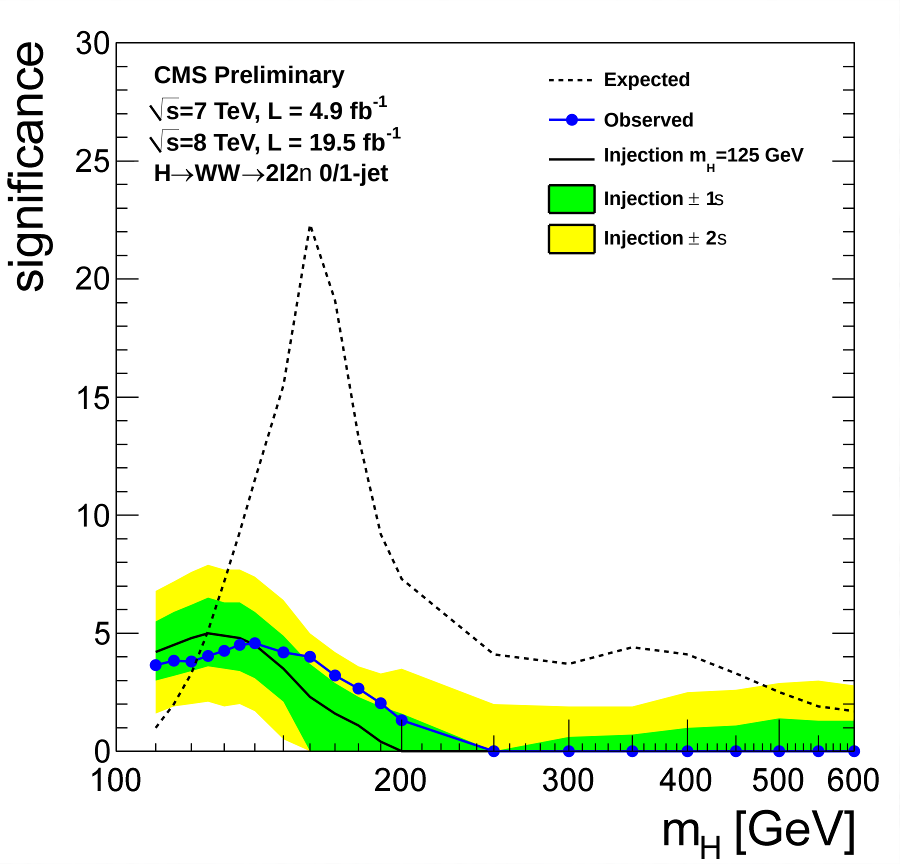
Transverse mass distributions after final cuts for the H → WW → ℓν ℓν search

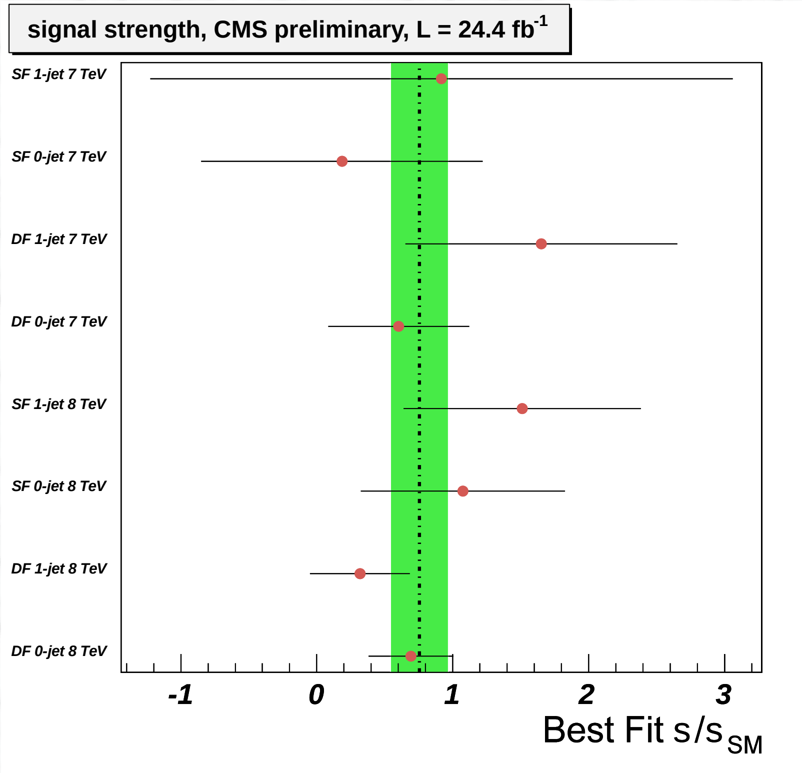




- Clear excess visible in both channels

H → WW → ℓν ℓν: signal significance and signal strength





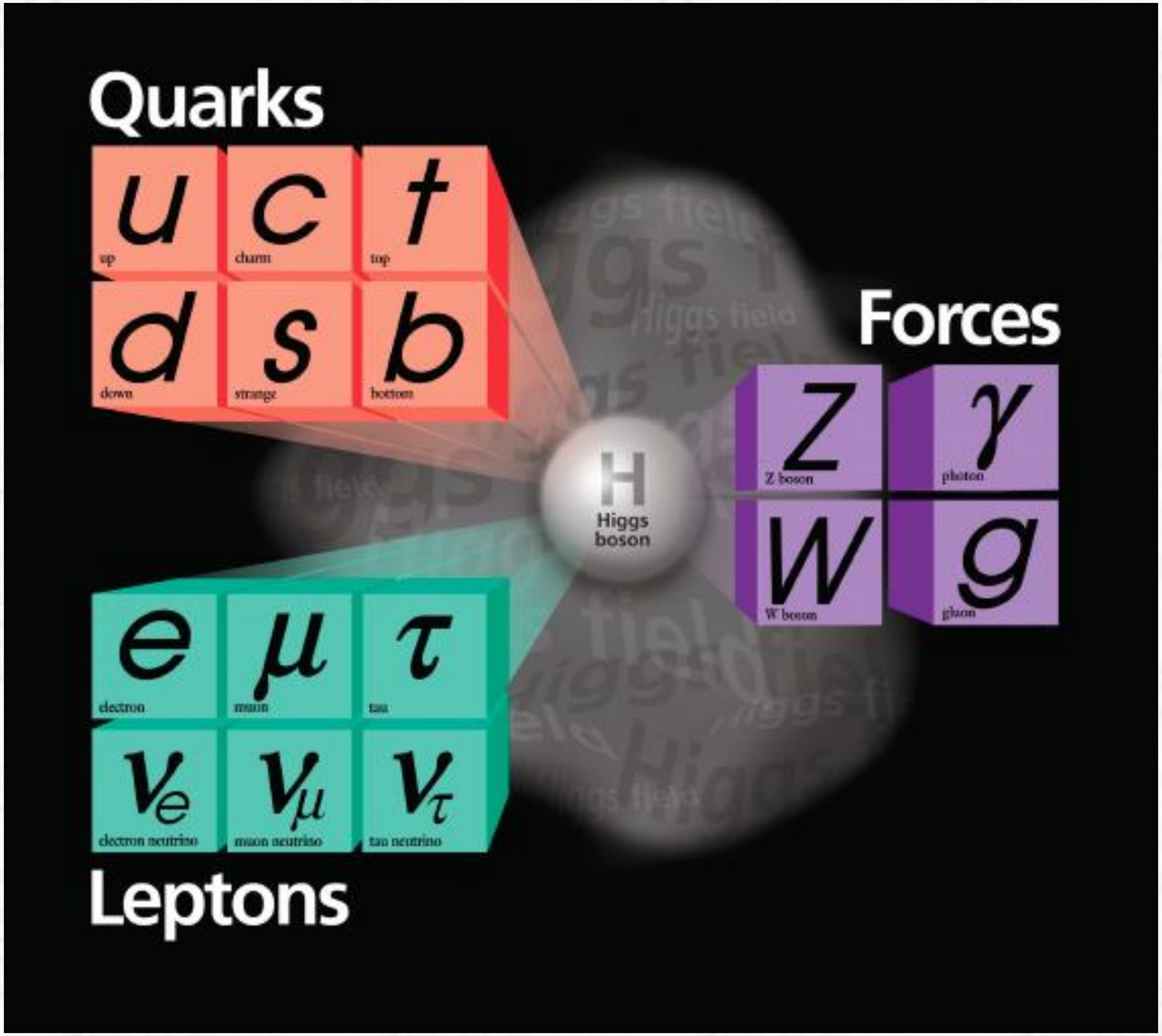
Expected for m_H = 125 GeV: 5.1σ

Observed at 125 GeV: 4.0σ

$\mu = 0.8 \pm 0.2$

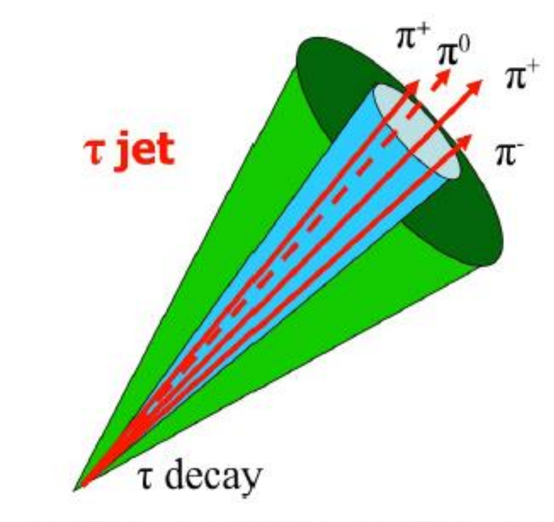
Sub-channels give consistent results

Couplings to quarks and leptons ?



Search for H → ττ and H → bb decays

Why is the search in these decay modes so challenging?



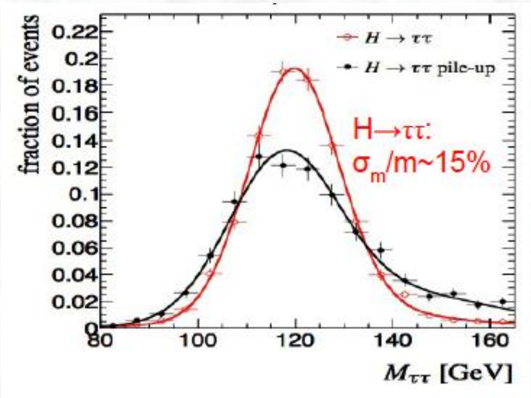
- The τ lepton is the heaviest lepton

  m_τ = 1.78 GeV /c^2, lifetime 2.9 10^{-13} s

  Decays into hadrons $\tau \rightarrow$ hadrons ν_τ (65%)
  $\tau \rightarrow e\nu_e\nu_\tau$, $\mu\nu_\mu\nu_\tau$ (35%)

- Challenge: distinguish hadronic τ decays from hadronic jet activity

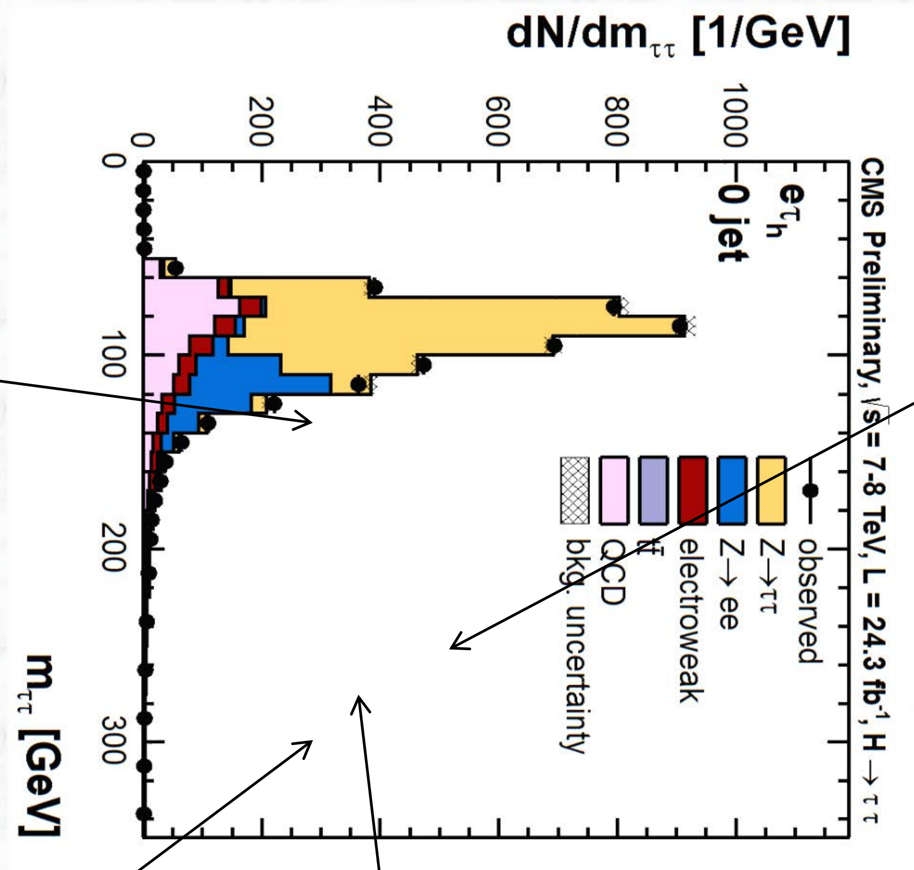
- Neutrinos in the final state, poor mass resolution



H → ττ background conditions/normalizations

Z → ττ

embedding



Z → ℓℓ (ℓ fakes a τ_h)

shape from Monte Carlo simulation

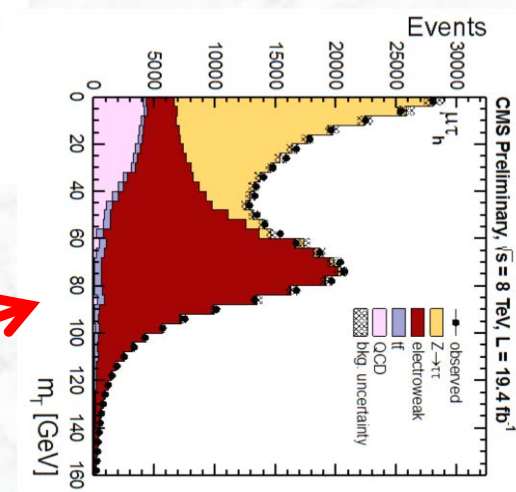
normalization from peak in visible mass region

Multijet background (QCD)

l / τ_h fakes:

- use same-sign data
- variation of isolation

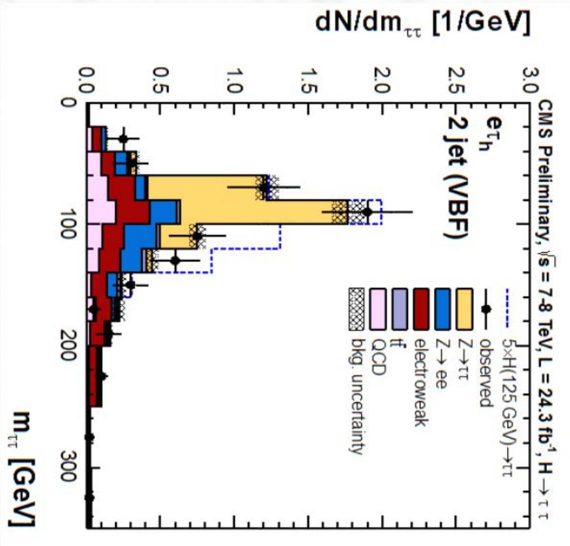
W+jets
mainly jet → τ_h fakes;
use transverse mass distribution for normalization



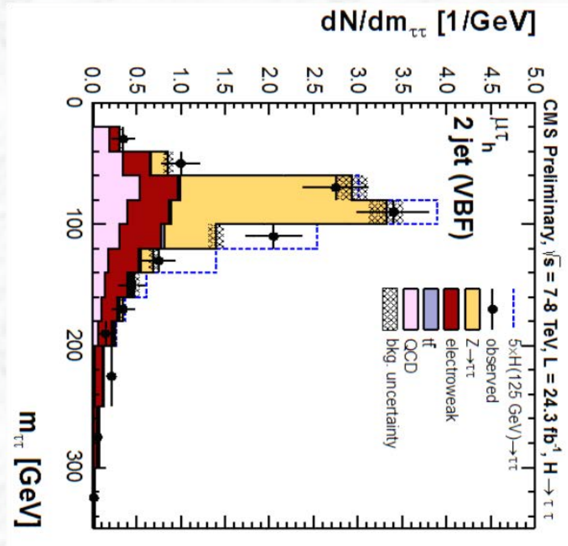
Reconstructed mass distributions

Full data set

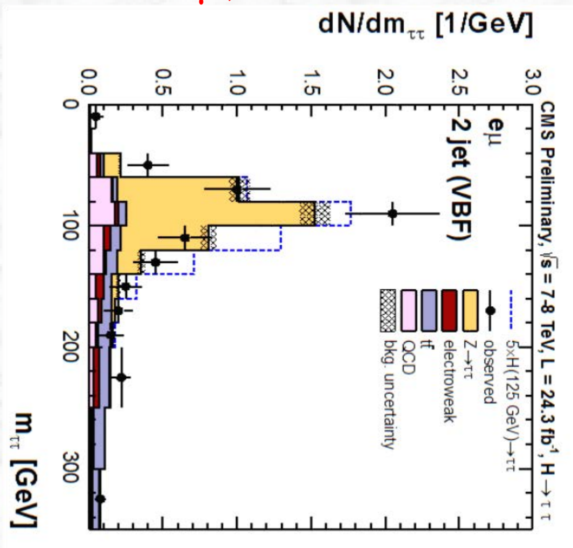
eτ, VBF



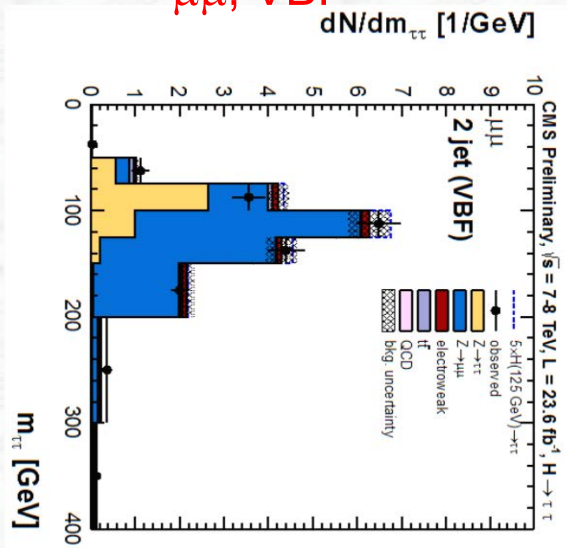
μτ, VBF



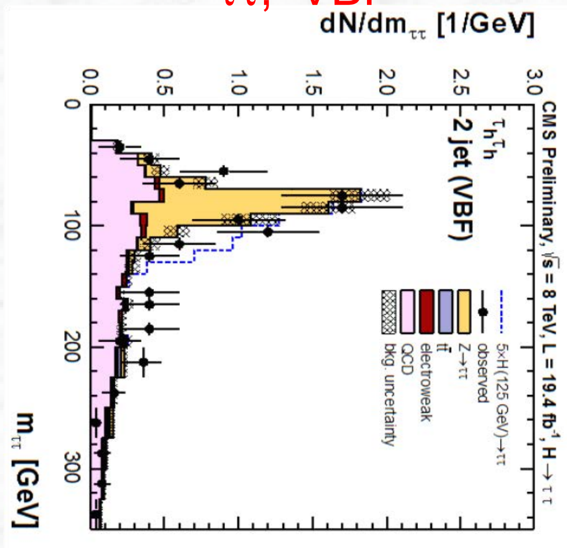
eμ, VBF



μμ, VBF



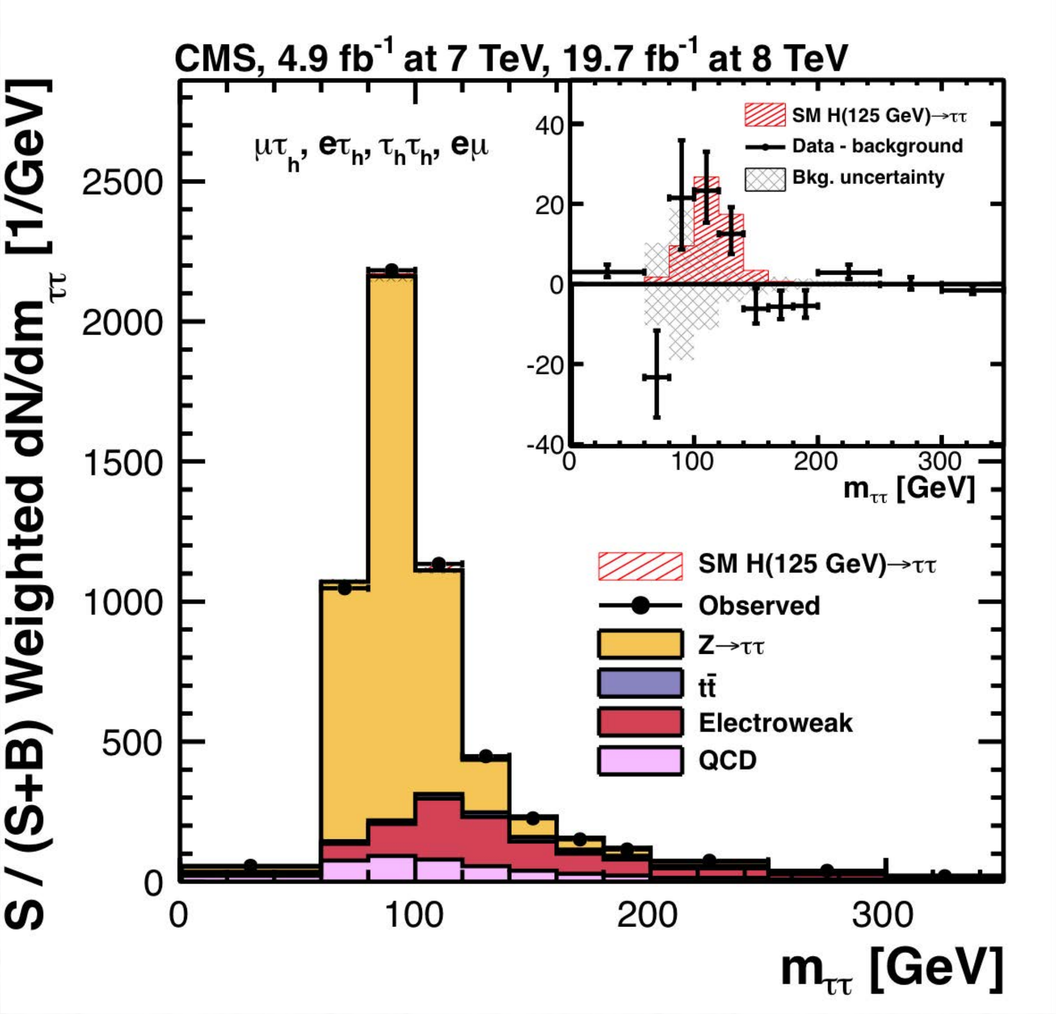
ττ, VBF



Standard Model Higgs boson signal multiplied by factor 5

CMS PAS HIG-13-004

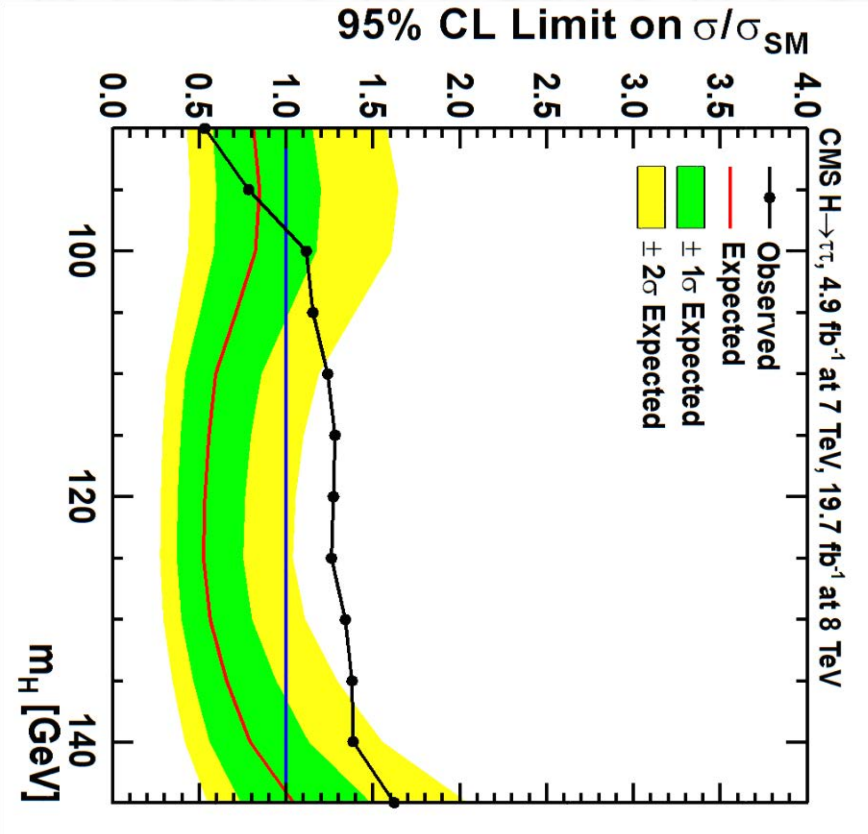
Combined reconstructed mass distribution

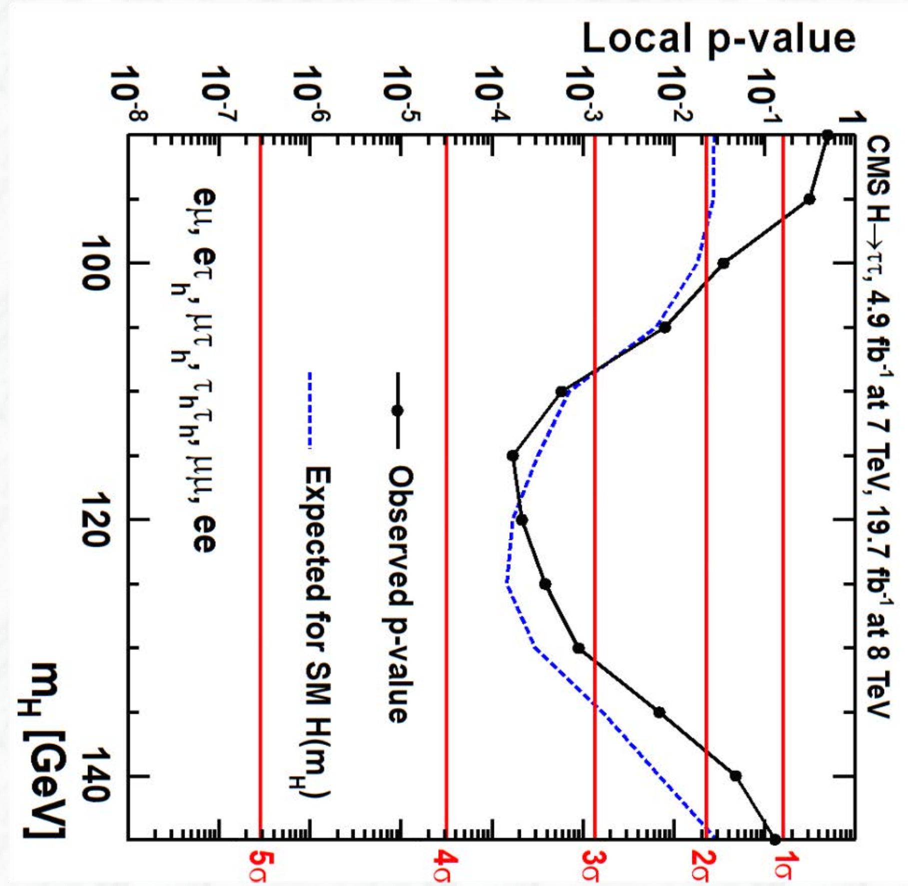


Combined observed and expected $m_{\tau\tau}$ distributions; The distributions obtained in each category are weighted by the ratio between the expected S/B yields in the category.

Combined CMS results (incl. VH)

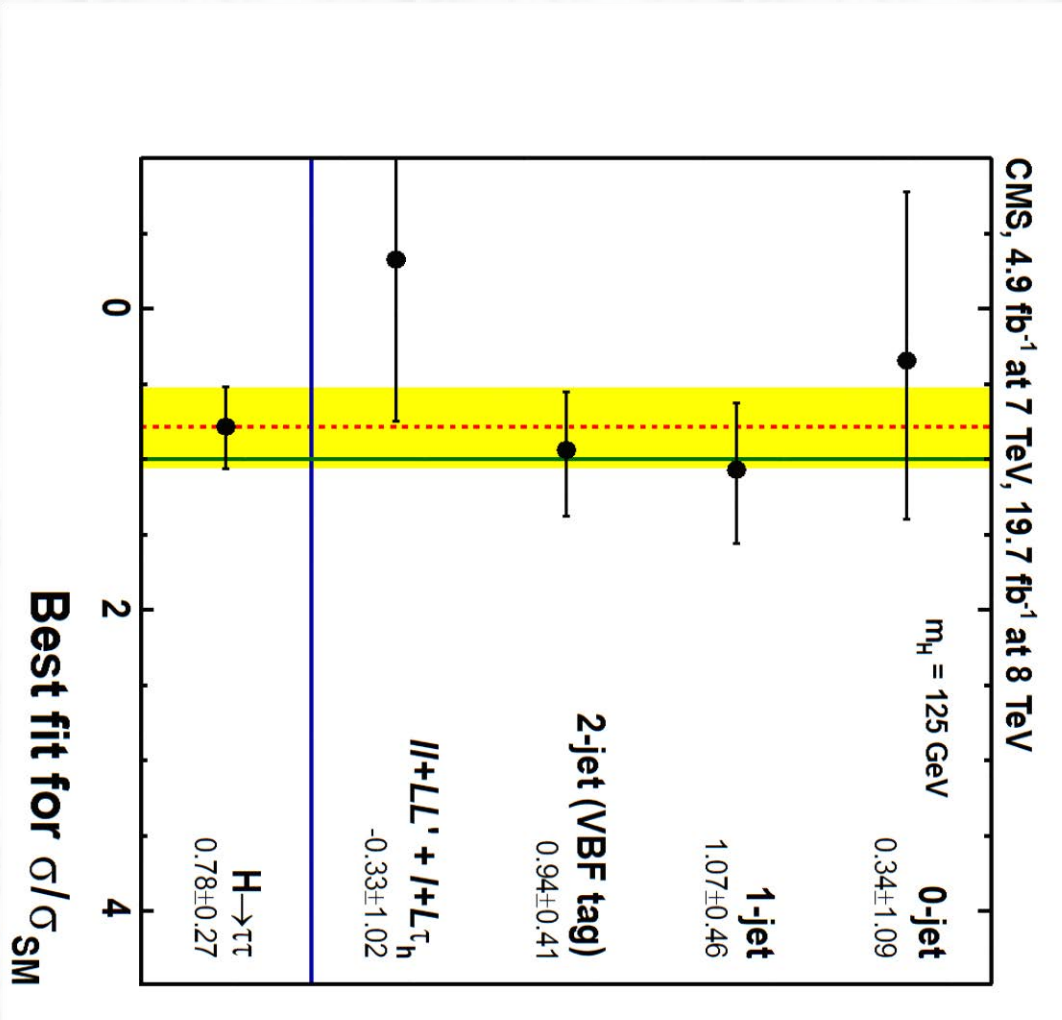
- First “evidence” for direct fermionic ($H\tau\tau$) coupling





Combined CMS results (incl. VH)

- First “evidence” for direct fermionic ($H\tau\tau$) coupling



Fitted signal strength (all sub-channels):

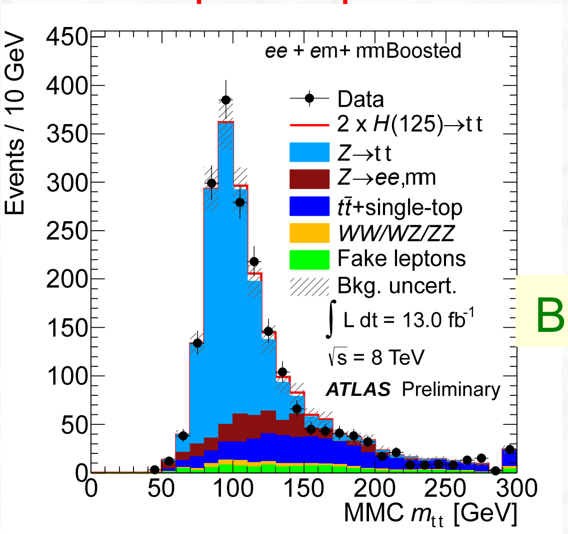
$\mu = 0.78 \pm 0.27$

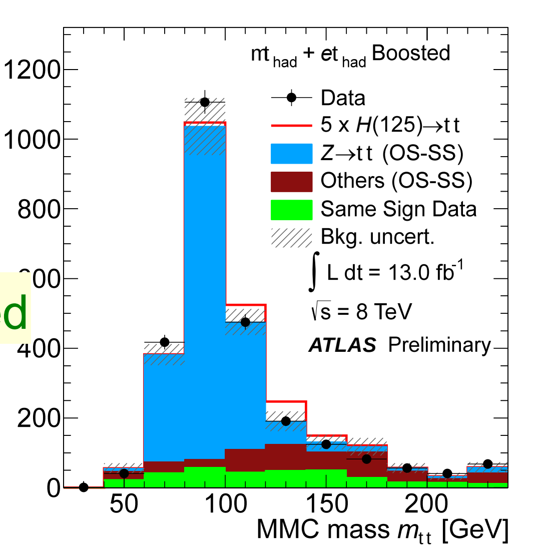
Reconstructed mass distributions

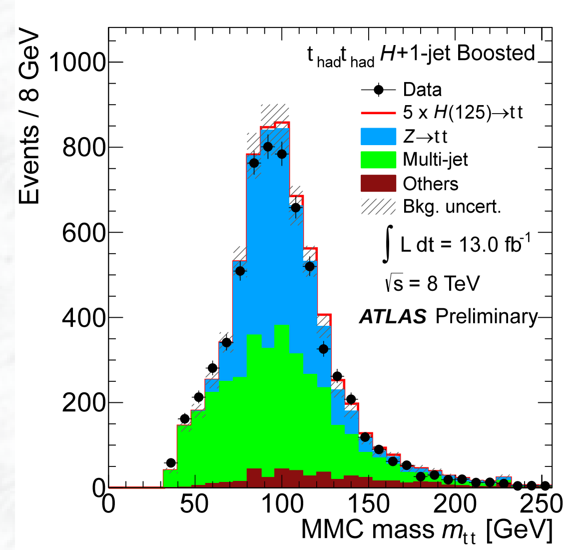
L = 13 fb^{-1} (2012)

lepton-lepton | e/μ – hadron | hadron – hadron

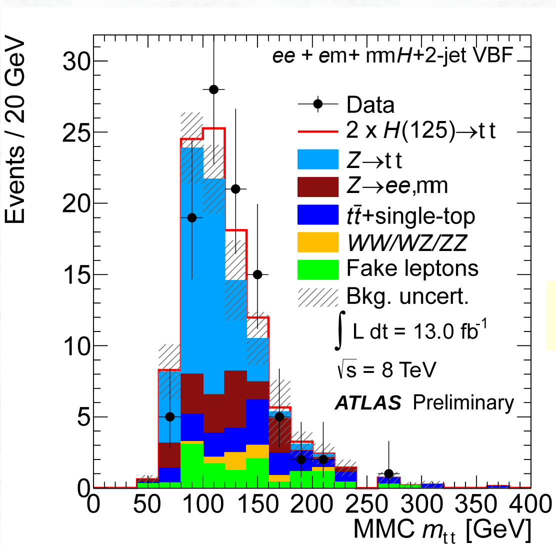
Boosted

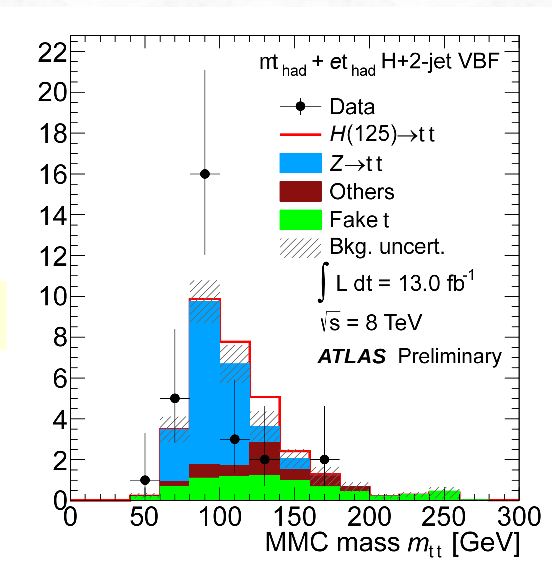


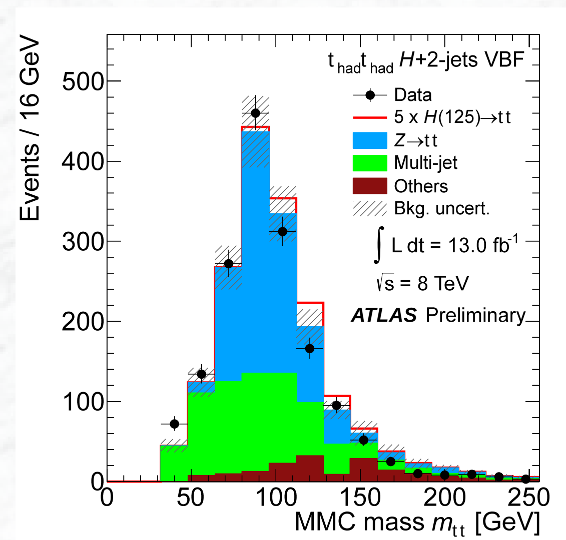




VBF



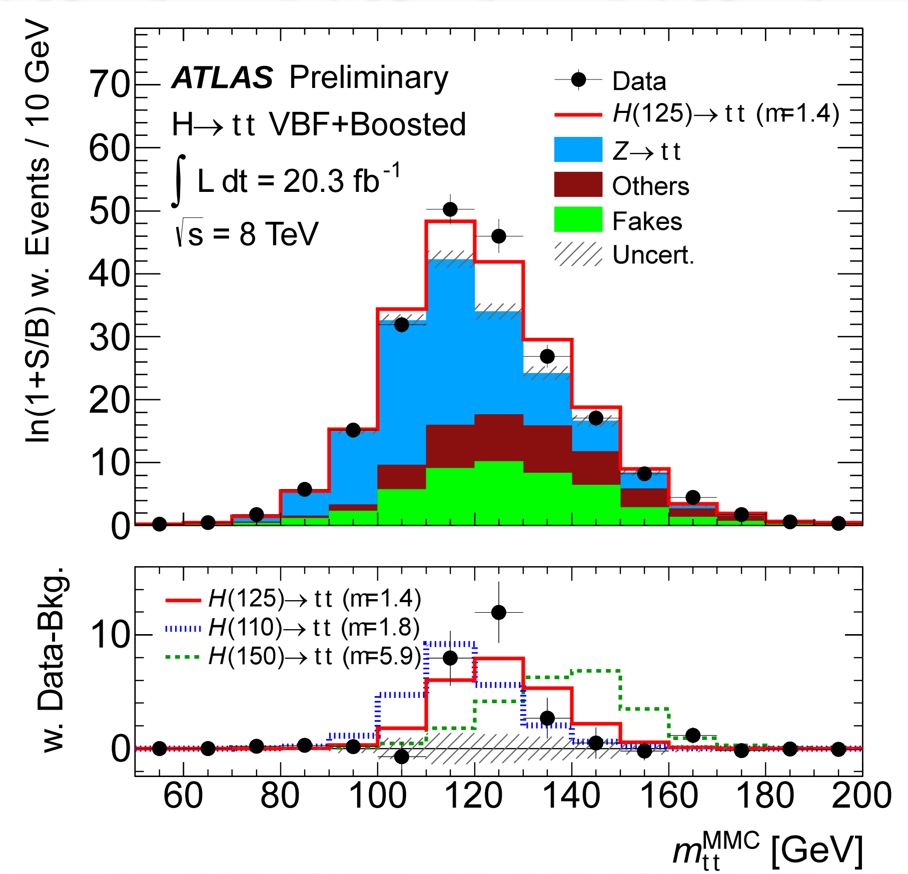


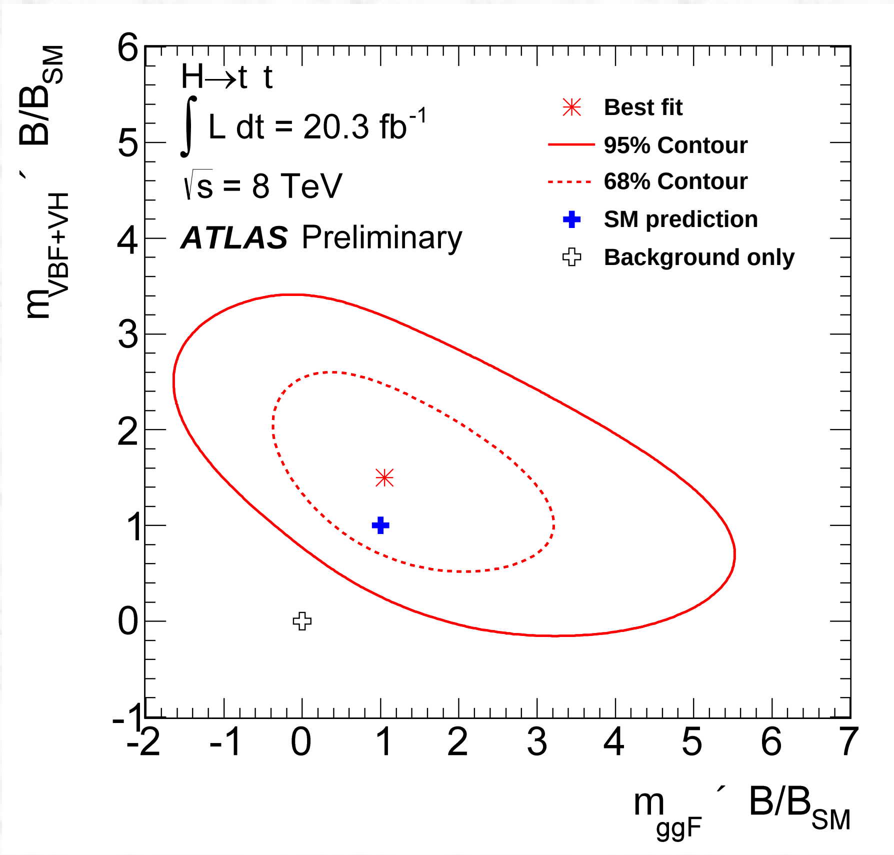


SM Higgs signal (multiplied by factors)

ATLAS-CONF-2012-16

Results on the search for H → ττ decays

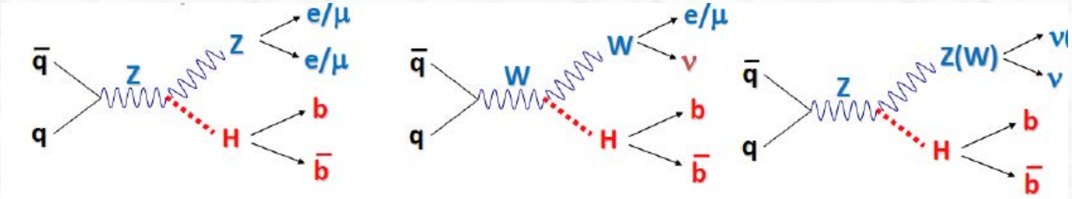




Fitted signal strength
(all sub-channels):

$\mu = 1.5 \pm 0.4$

Search for VH production with H → bb decays



- Exploit three leptonic vector boson decay modes
  → split analysis in 0, 1, and 2-lepton categories

- Require 2 b-tagged jets
  (working point for 70% efficiency)

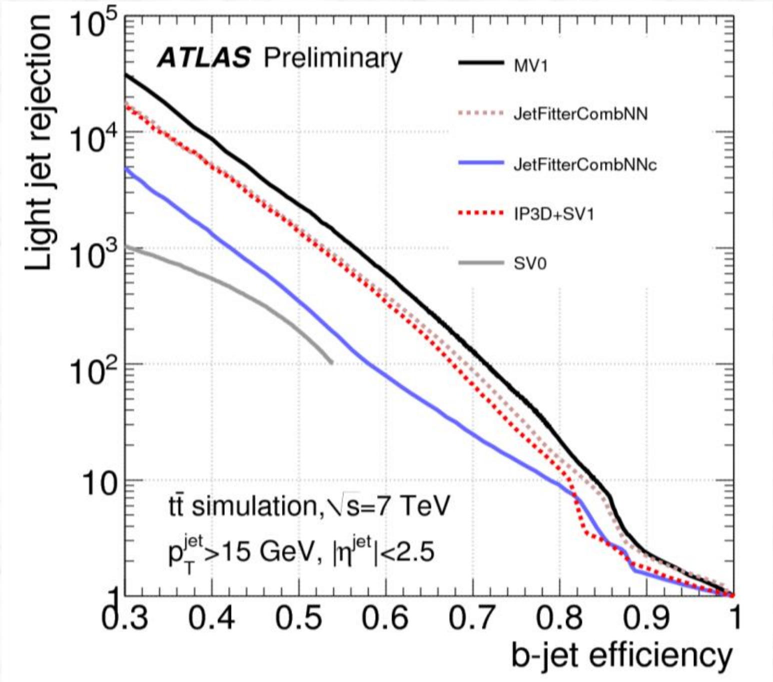
- Major background: W/Z bb, W+jets, tt

- Signal-to-background ratio improves for "boosted Higgs boson",
  split analysis in bins of $p_T(V)$

  ATLAS: in total 15 categories
  (0,1,2 jets × p_T bins)

  CMS: multivariate analysis

ATLAS-CONF-2012-161



Event selection for H → bb analyses

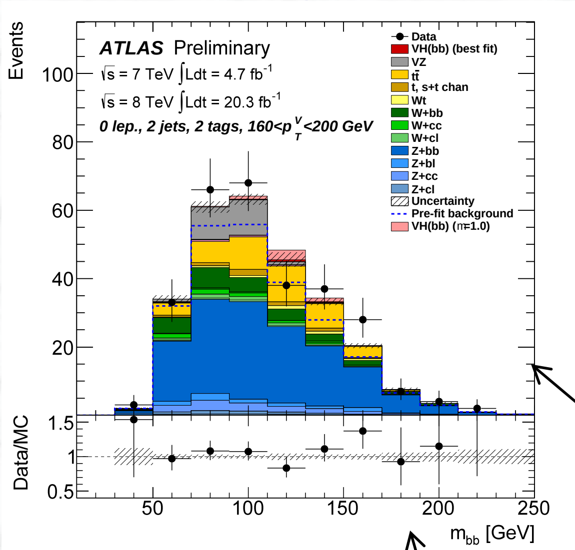
(i) Basic event selection for the three channels

Object	0-lepton	1-lepton	2-lepton
Leptons	0 loose leptons	1 tight lepton + 0 loose leptons	1 medium lepton + 1 loose lepton
Jets	2 b-tags $p_{\mathrm{T}}^{\mathrm{jet}_1} > 45$ GeV $p_{\mathrm{T}}^{\mathrm{jet}_2} > 20$ GeV $+ \leq 1$ extra jets		
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\min[\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	$E_{\mathrm{T}}^{\mathrm{miss}} > 25$ Gev	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

(ii) Further topological criteria in intervals of $p_T(V)$

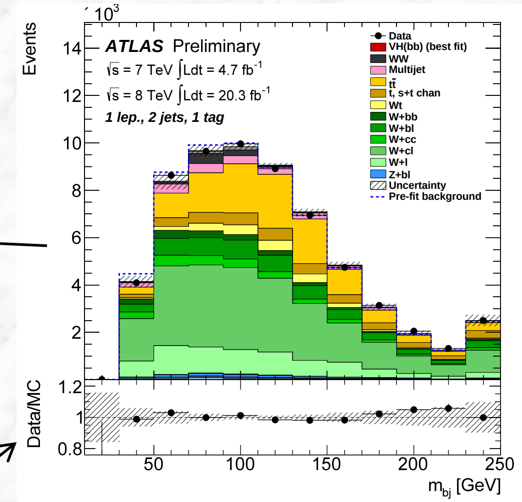
	p_{T}^{V} [GeV]	0-90	90-120	120-160	160-200	>200
All Channels	$\Delta R(b, \bar{b})$	0.7-3.4	0.7-3.0	0.7-2.3	0.7-1.8	<1.4
1-lepton	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	>25				>50
	m_{T}^{W} [GeV]	40-120			<120	

Background normalization, interplay of regions



Signal region: 0 leptons, 2 jets, 2 b-tags

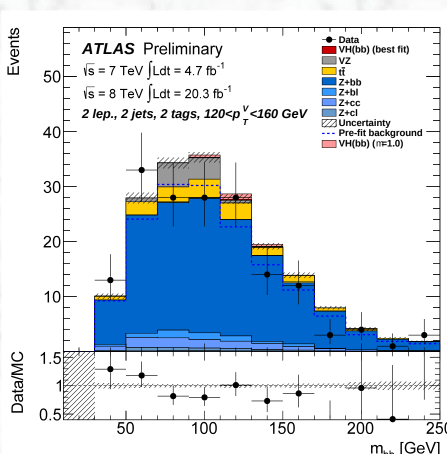
W+jets



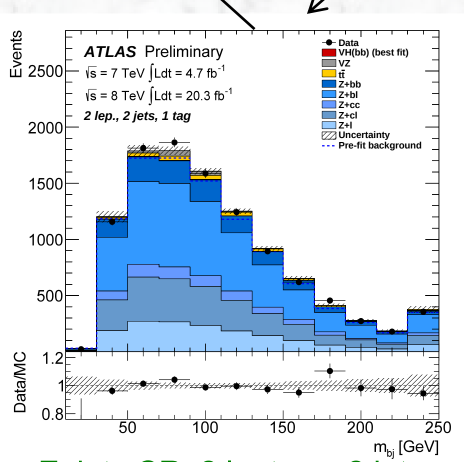
W+jets CR: 1 leptons, 2 jets, 1 b-tag

Z+jets, Zbb

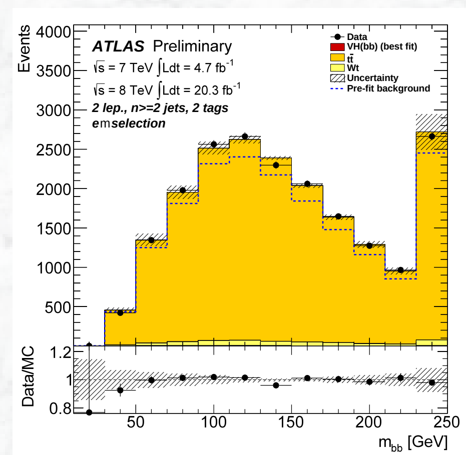
Top



Zbb SR: 2 leptons, 2 jets, 2 b-tags



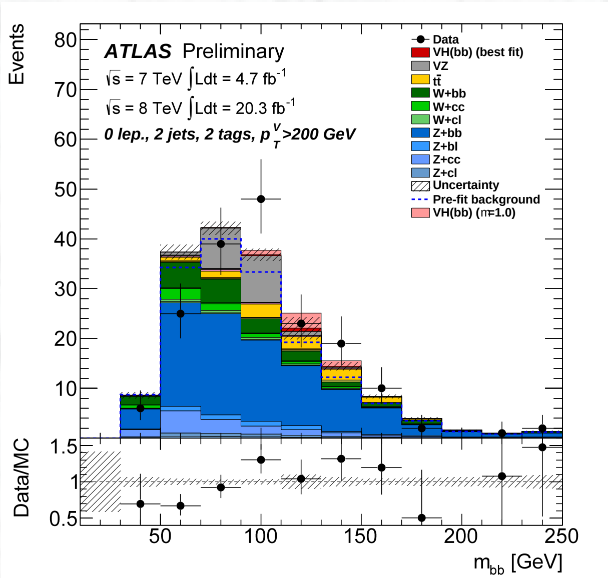
Z+jets CR: 2 leptons, 2 jets, 1 b-tags



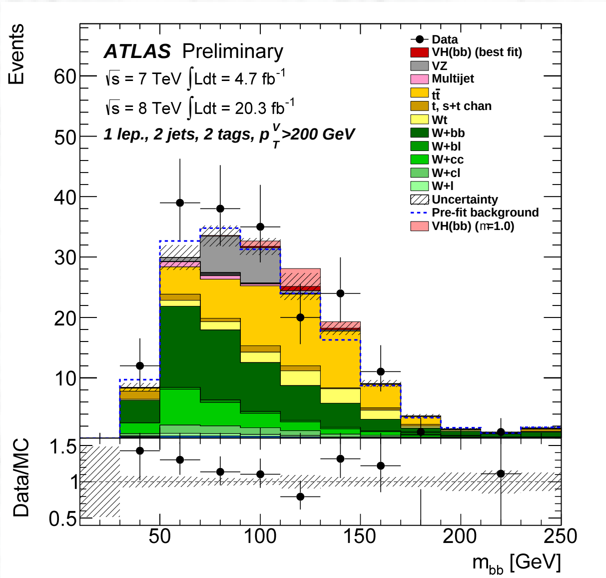
Top CR: 2 leptons, >=2 jets, 2 b-tags

Reconstructed mass distributions

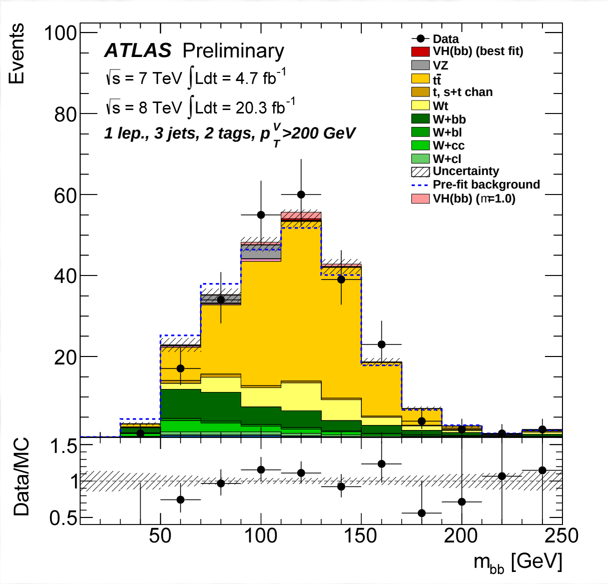
-full data set, 7 and 8 TeV (a selection, high p_T bins)-



0 lepton



1 lepton

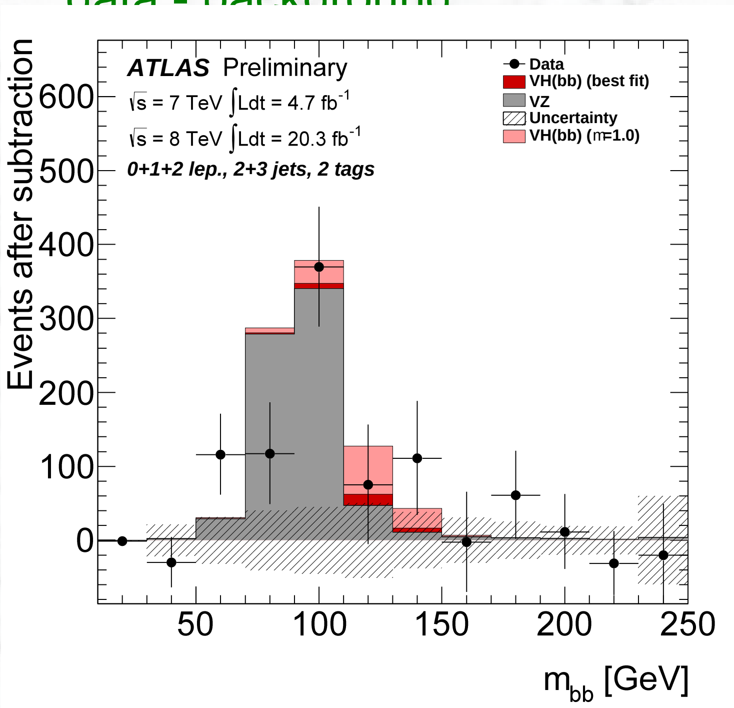


2 leptons

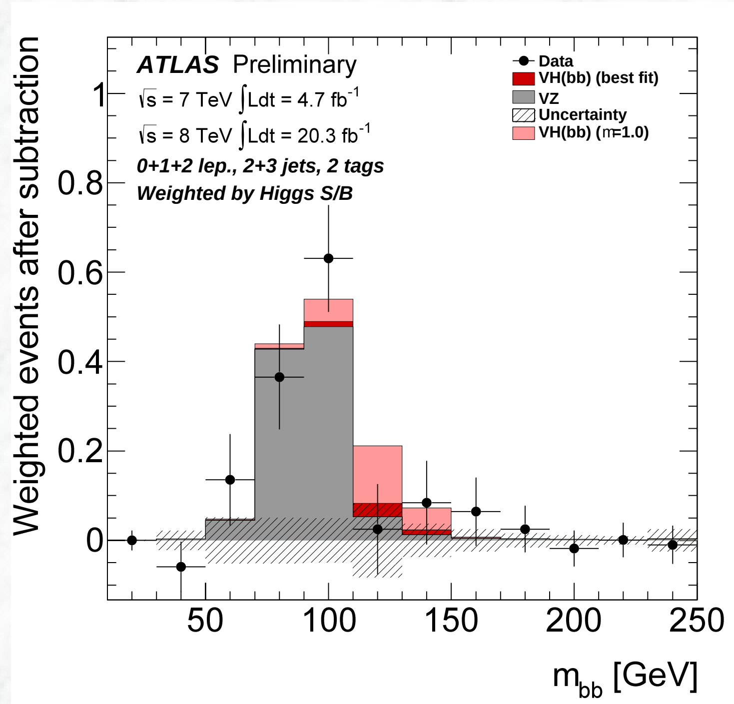
ATLAS-CONF-2013-079

Demonstration of di-boson production with Z → bb in ATLAS

combination (all bins, channels)
data - background



weighted distribution, by S/B ratio



Di-boson signal established
(important "calibration" signal; a Standard Model Higgs boson signal is included as background)

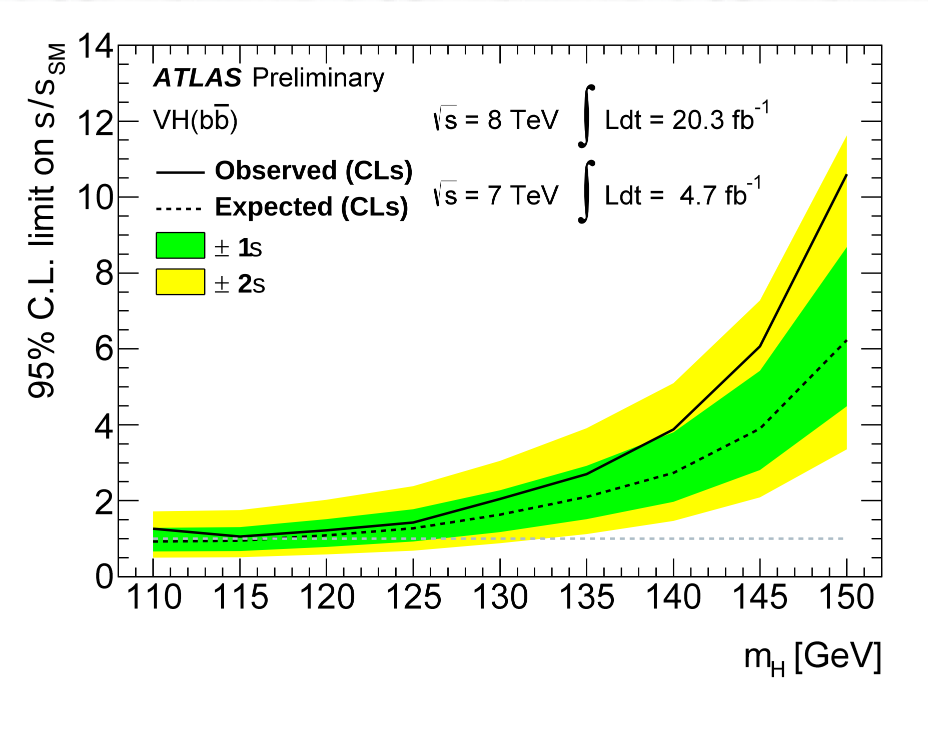
Significance 5.1σ

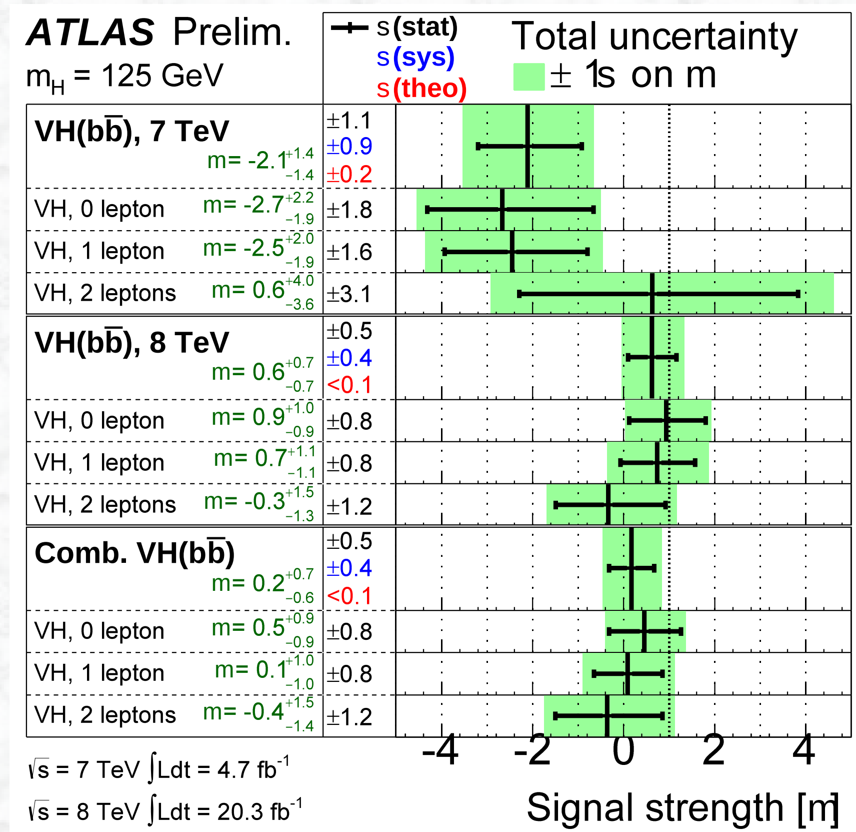
$\mu_{WZ+WW} = 0.90 \pm 0.20$

ATLAS-CONF-2013-079

ATLAS results on the search for VH, H → bb decays

ATLAS-CONF-2013-079





m_H = 125 GeV:

Observed 95% CL: 1.4 σ_{SM}

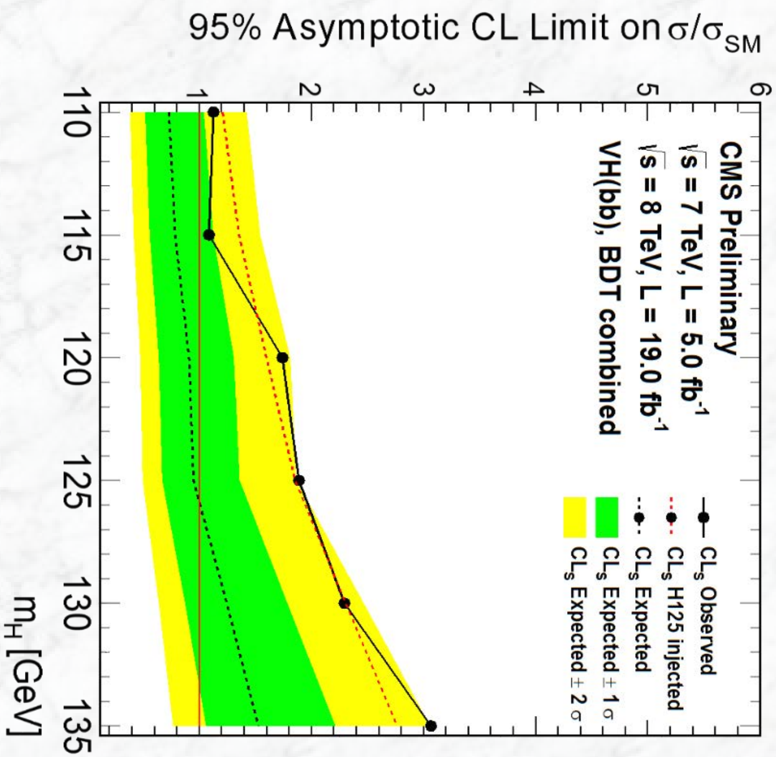
Expected (no Higgs): 1.3 σ_{SM}

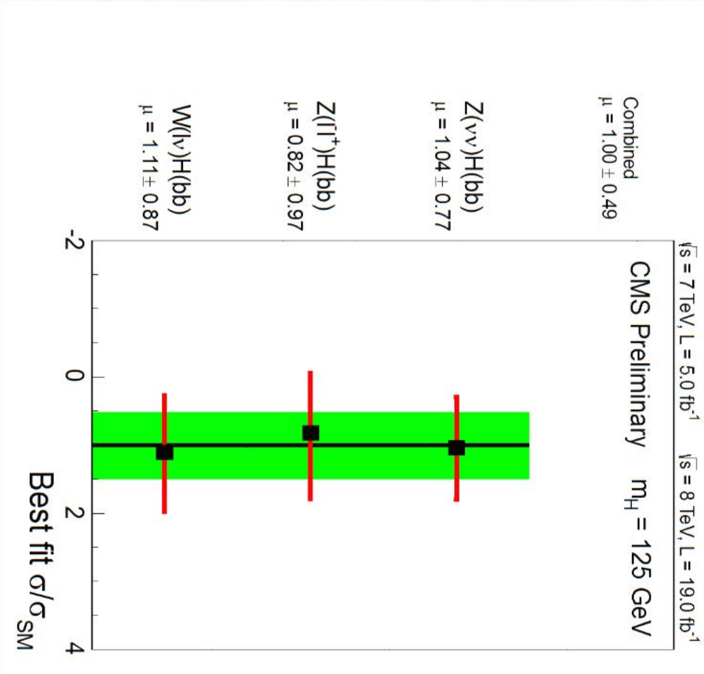
μ_H = 0.2 ± 0.5 (stat) ± 0.4 (syst)

Probability of obtaining a result more background-like than the observed in the presence of a SM signal (μ=1) is 0.11

CMS results on the search for VH, H → bb decays

CMS PAS HIG-13-012





m_H = 125 GeV:

Observed 95% CL: 1.89 σ_{SM}

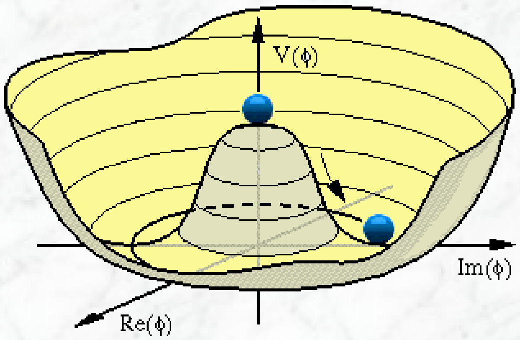
Expected (no Higgs): 0.95 σ_{SM}

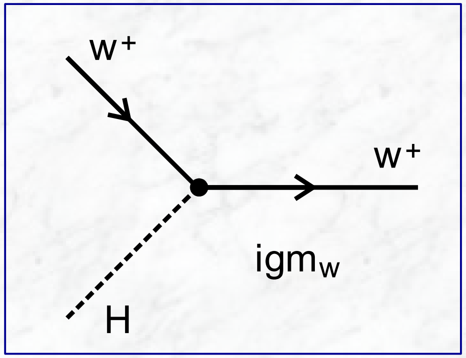
μ_H = 1.00 ± 0.49

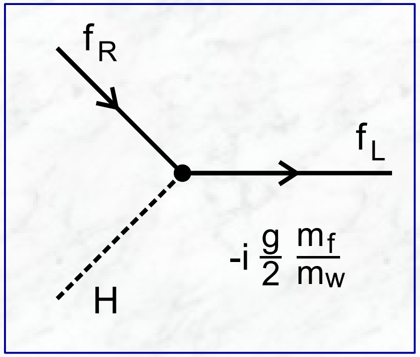
12.3 Is the new particle the Higgs Boson ?

- Production rates ?

  Couplings to bosons and fermions







- Spin, J^P quantum number

Higgs boson parameters

- After the discovery of the new boson, the most important question is:

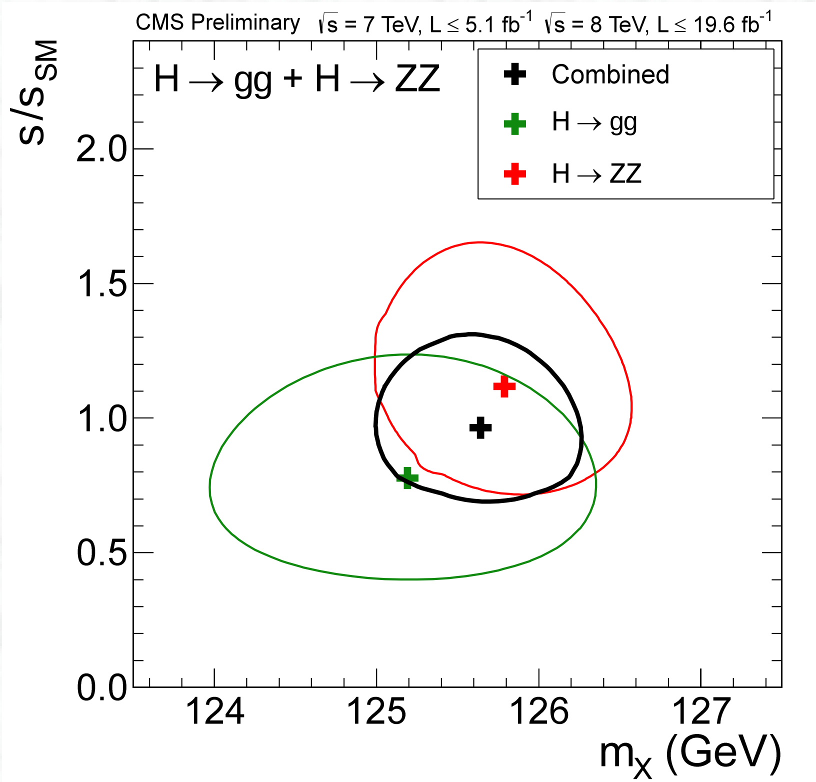
  - What are its properties ?
    (mass, spin, couplings, …)

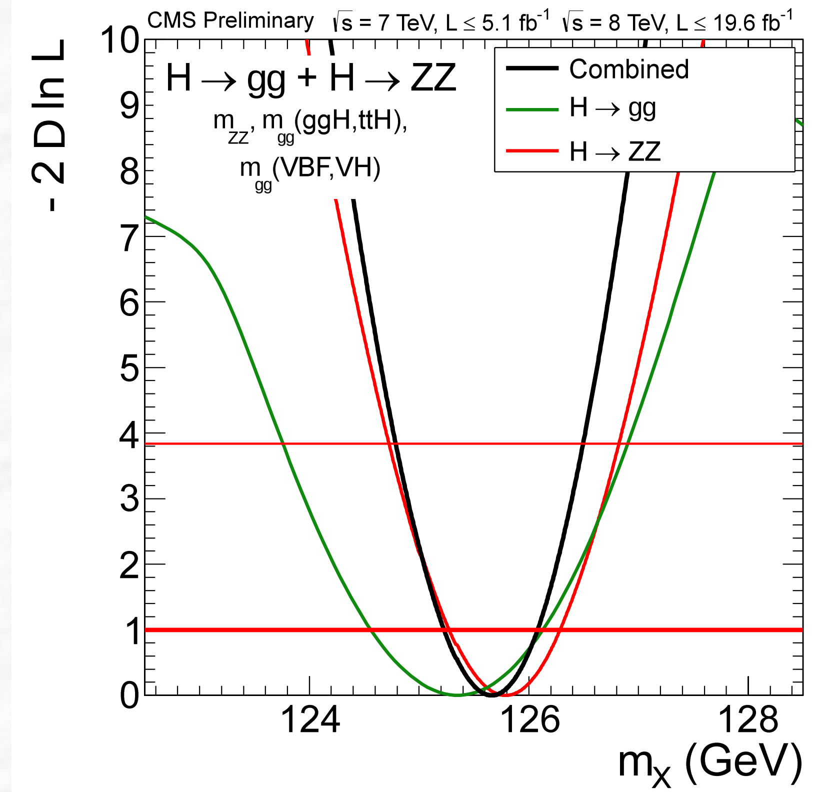
  - Is it the Higgs boson of the Standard Model?
    Or can we finds signs of Physics Beyond the Standard Model by studying its properties?

- Much attention of the LHC (and Tevatron) collaborations and from the theory community has been devoted to these questions during the past year.

Higgs boson mass: results from CMS

CMS PAS HIG-13-005



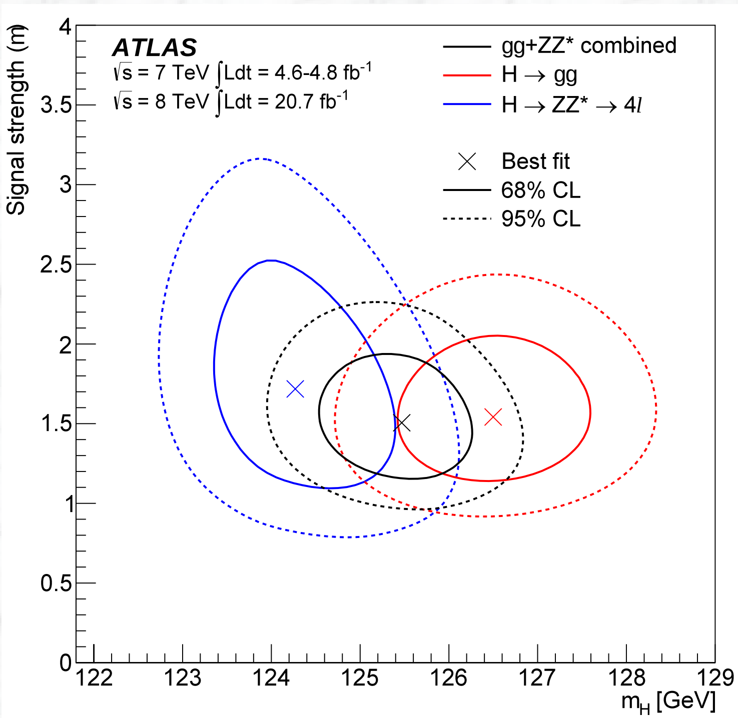


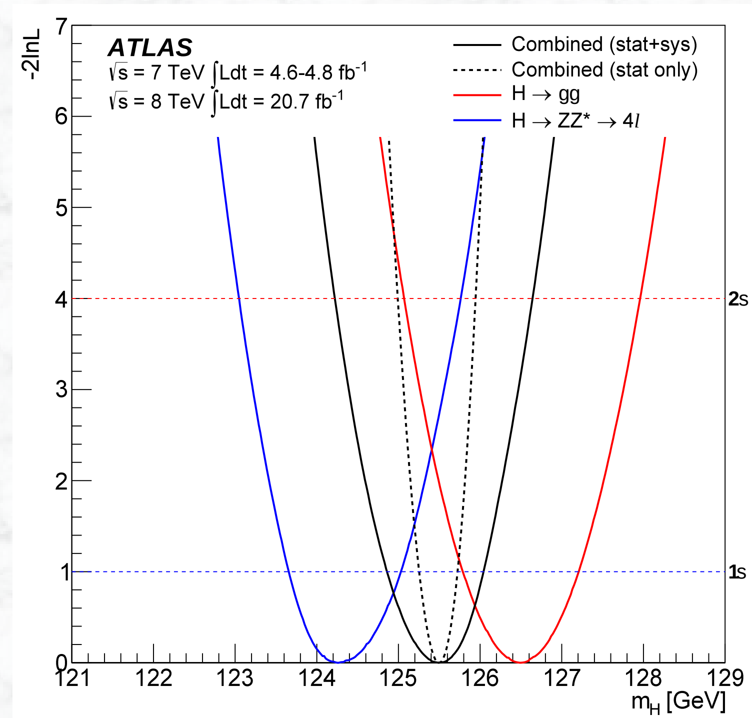
$$m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{syst})\ \text{GeV}$$

In the combination the relative signal strength for the two decay modes is constrained by the SM values

Higgs boson mass: results from ATLAS

ATLAS arXiv:1307.1427

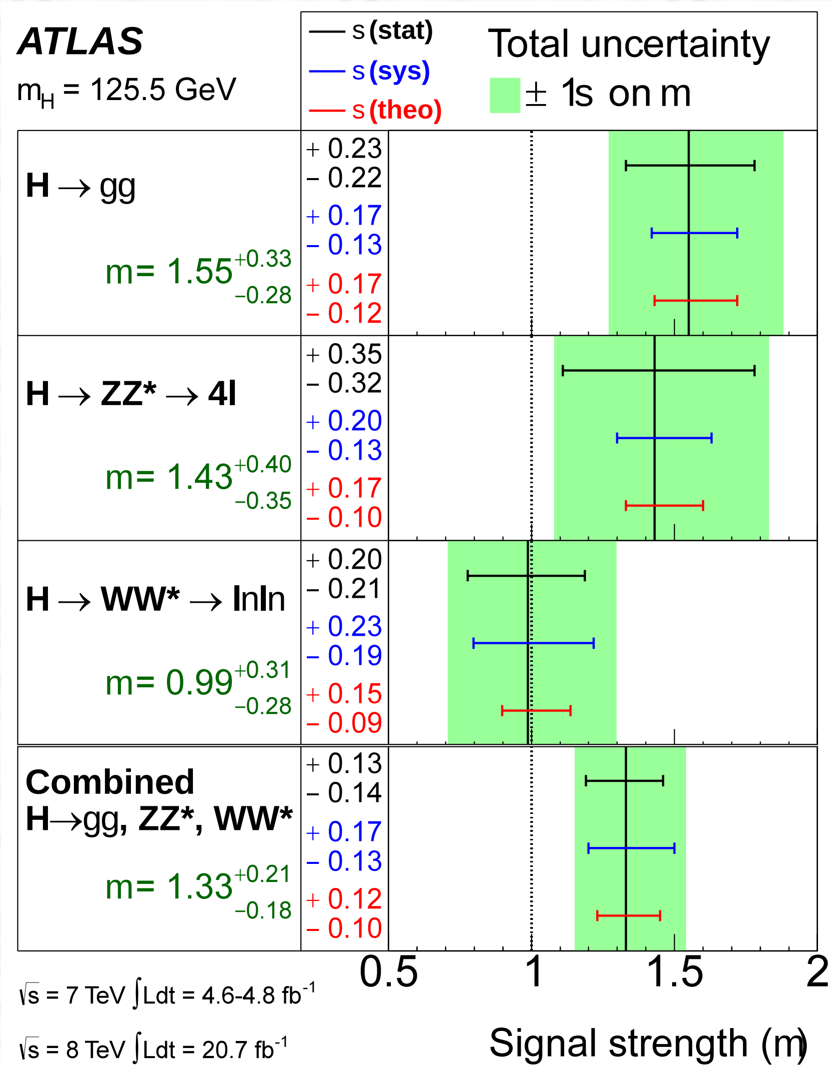




$$m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})\ \text{GeV}$$

Signal strength in di-boson decay modes

-including full data set-



- Data are consistent with the hypothesis of a Standard Model Higgs boson:

$$m = 1.33^{+0.21}_{-0.18}$$

- Experimental uncertainties are still too large to get excited about "high" γγ signal strength

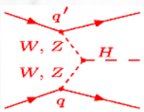
- Signal strengths in fermionic decay modes have large uncertainties, but are compatible with SM value of 1;

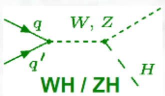
  If preliminary H → ττ and H → bb results are included:

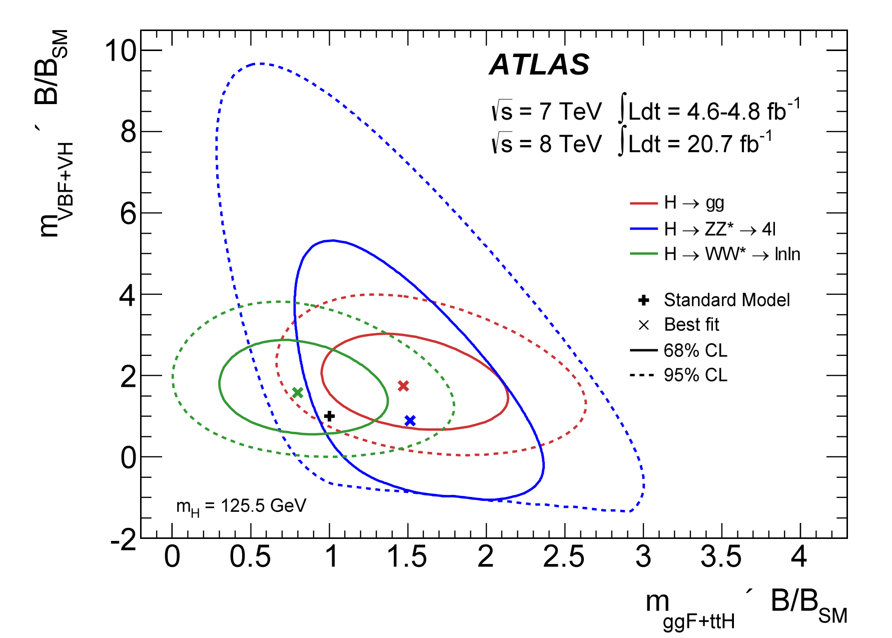
$$m = 1.23 \pm 0.18$$

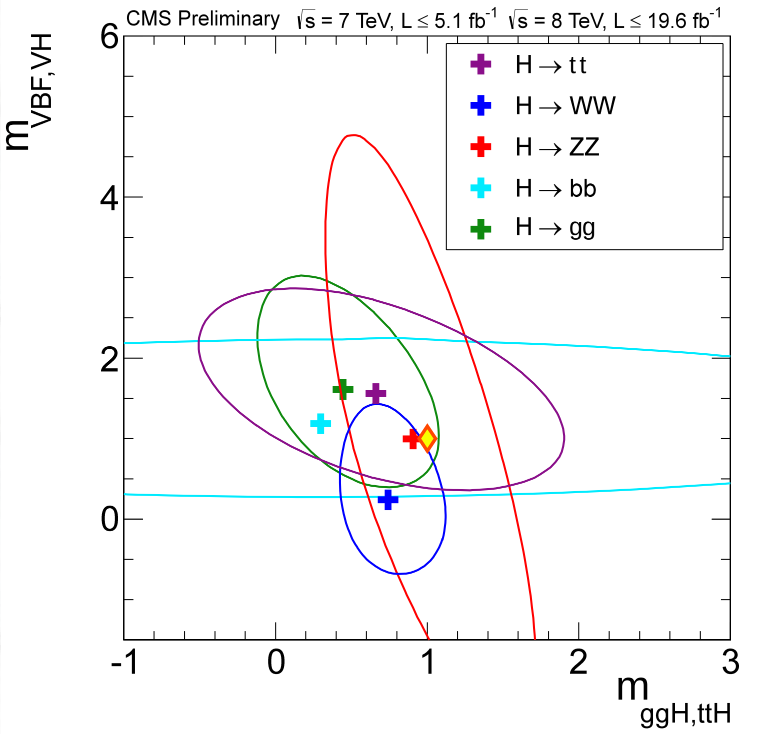
Ratios of production cross sections for the various processes (ggF, VBF,..) fixed to SM values

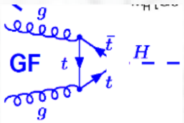
Gluon fusion versus vector-boson fusion

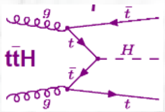








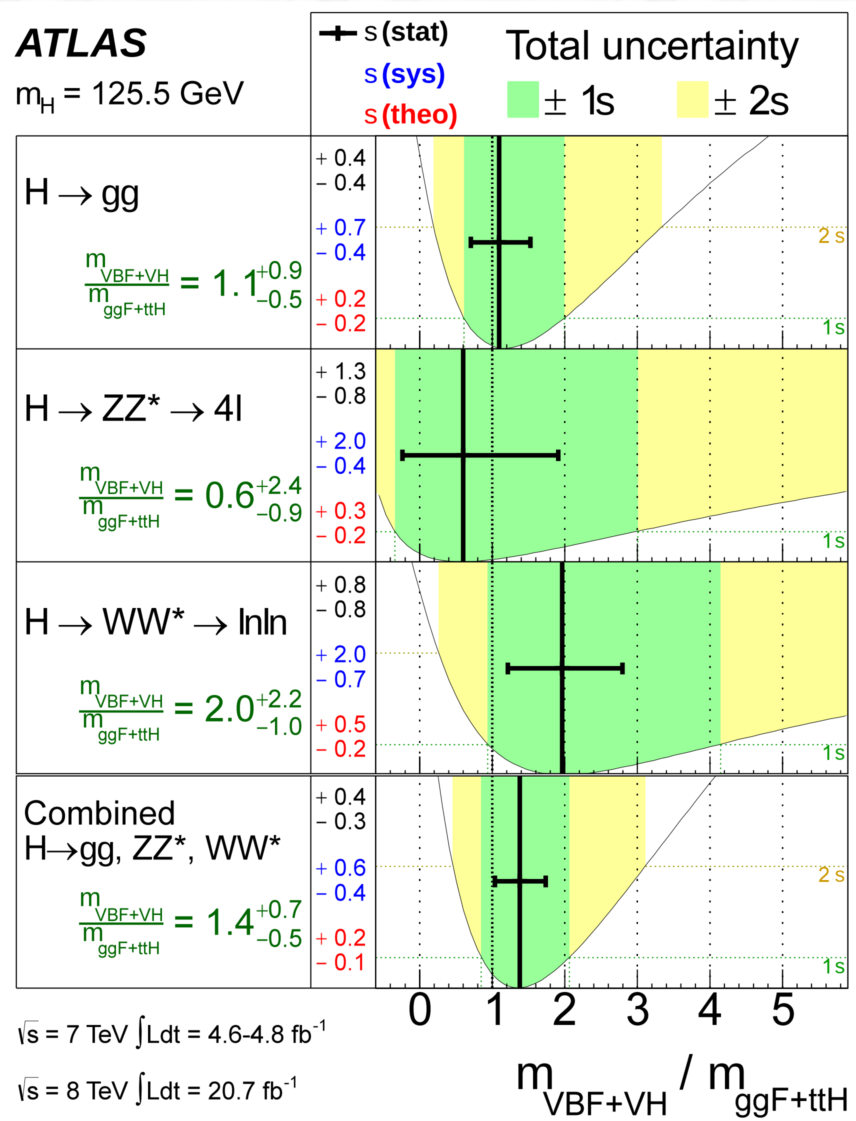




- Sensitivity to (ggF + ttH) and (VBF+VH) production fractions, modulo branching ratio factors B/B_{SM}
- Good agreement with the Standard Model, within the large uncertainties

- A combination of the different decay modes is not performed, since it would require introducing hypotheses on the relative branching ratios;

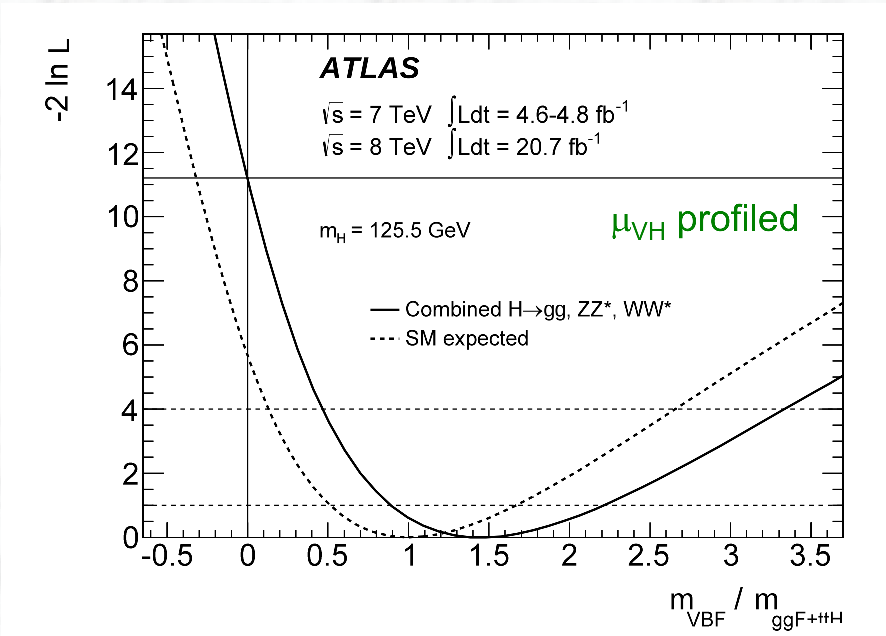
Evidence for production via vector boson fusion

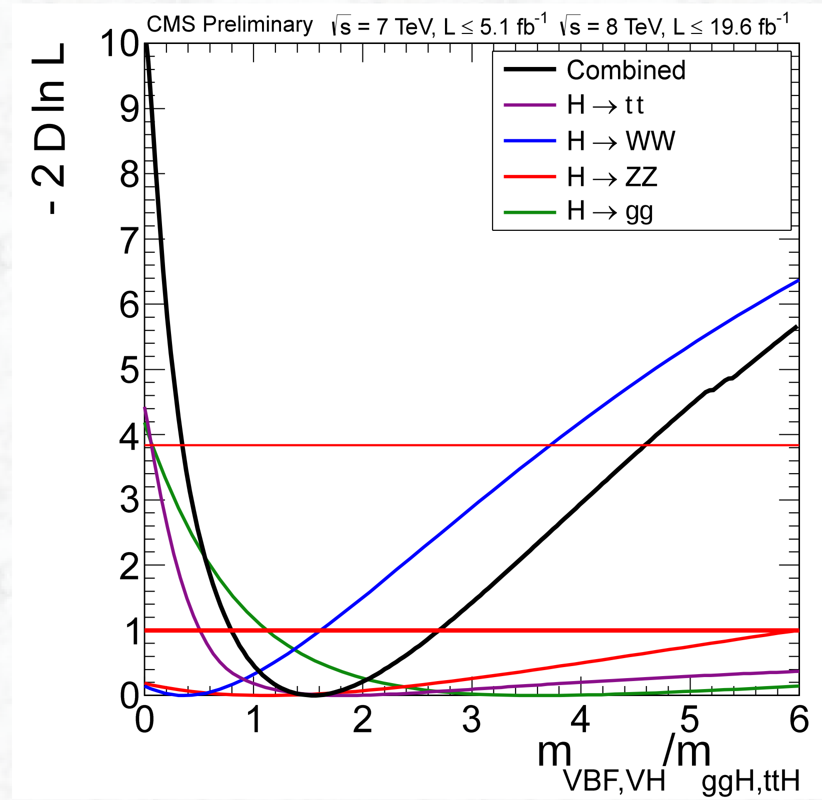


- Fit for the ratio of μ_{VBF+VH} / $\mu_{ggF+ttH}$ for the individual channels (model independent)
- Good agreement with SM expectation for individual channels and the combination

Next step: combination of results

Evidence for production via vector boson fusion





$$m_{VBF} / m_{ggF+ttH} = 1.4^{+0.4}_{-0.3}\,(stat)\,^{+0.6}_{-0.4}\,(syst)$$

3.3σ evidence for VBF production

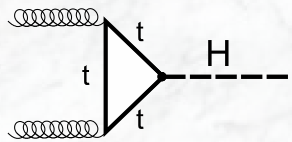
3.2σ evidence for V-boson mediated production

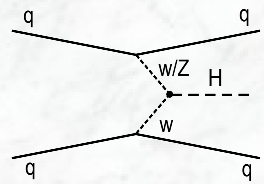
Higgs boson couplings

- Production and decay involve several couplings

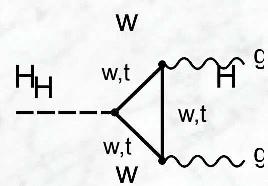
H t t t g g

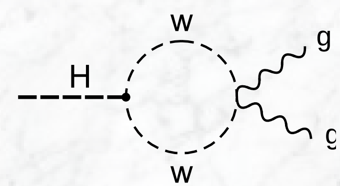
Production:





Decays: e.g. H → γγ (best example)
(Decay widths depends on W and top coupling,
destructive interference)





- Standard Model couplings are tested by introducing coupling scale factors κ

$$g_i = \kappa g_i^{SM}$$

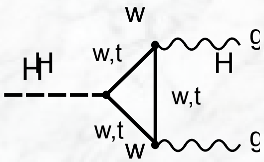
- Standard Model tree level amplitudes:

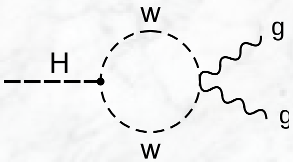
$$\Gamma_{ff} \propto \left(\kappa_f \frac{m_f}{v} \right)^2 = \kappa_f^2 \cdot \Gamma_{ff}^{SM}$$

$$\Gamma_{VV} \propto \left(\kappa_f \frac{m_V^2}{v} \right)^2 = \kappa_V^2 \cdot \Gamma_{VV}^{SM}$$

Higgs boson couplings

- Example: H → γγ $\Gamma_{\gamma\gamma} \propto \left|1.28k_W - 0.28k_t\right|^2 \times \Gamma_{\gamma\gamma}^{SM}$





  – Loop scaling factors can be expressed in terms of κ_f and κ_V

  - The analysis is also done in terms of effective loop couplings κ_g and κ_γ

Higgs boson couplings

- Benchmarks defined by LHC cross section working group (leading-order tree-level framework):

  - Signals observed originate from a single resonance; (mass assumed here is 125.5 GeV)

  - Narrow width approximation: → rates for given channels can be decomposed as:

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i, f = initial, final state
Γ_f, Γ_H = partial, total width

  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

Scaling of cross sections with κ_F and κ_V factors

$$\sigma \cdot \mathrm{BR}\,(gg \to H \to \gamma\gamma) \;=\; \sigma_{SM}(gg \to H) \cdot \mathrm{BR}_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \to H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * \mathrm{BR}(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * \mathrm{BR}(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

(i) Couplings to fermions and bosons

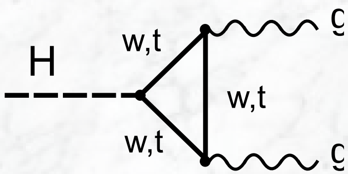
- Assume only one scale factor for fermion and vector couplings:

$\kappa_V = \kappa_W = \kappa_Z$
$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

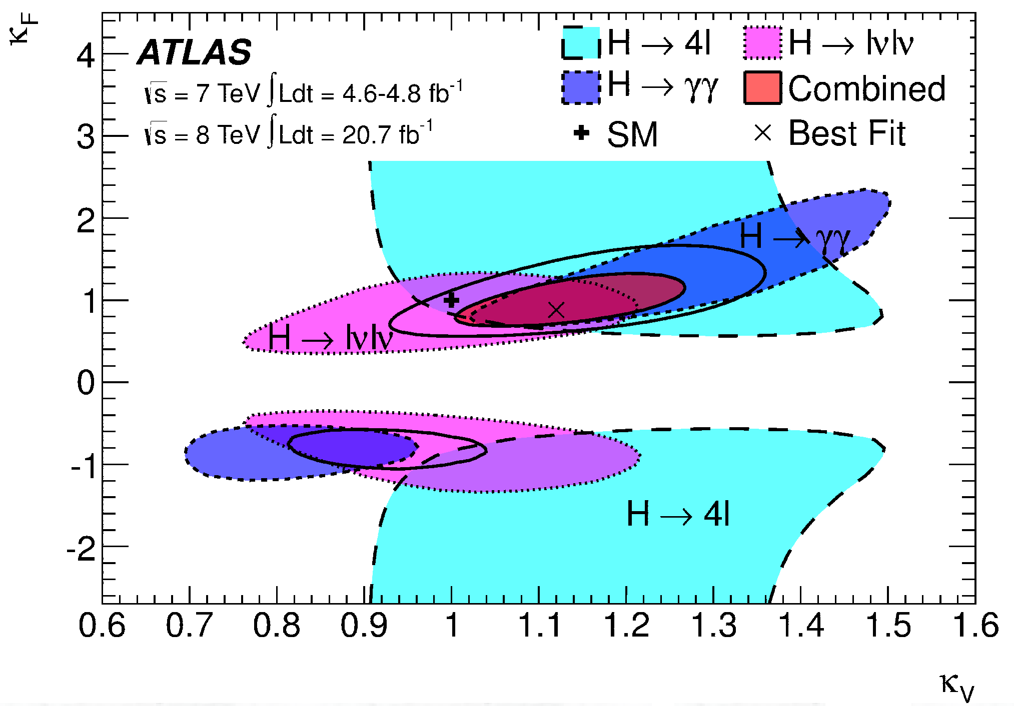
The size of the current data set is insufficient to quantify all parameters

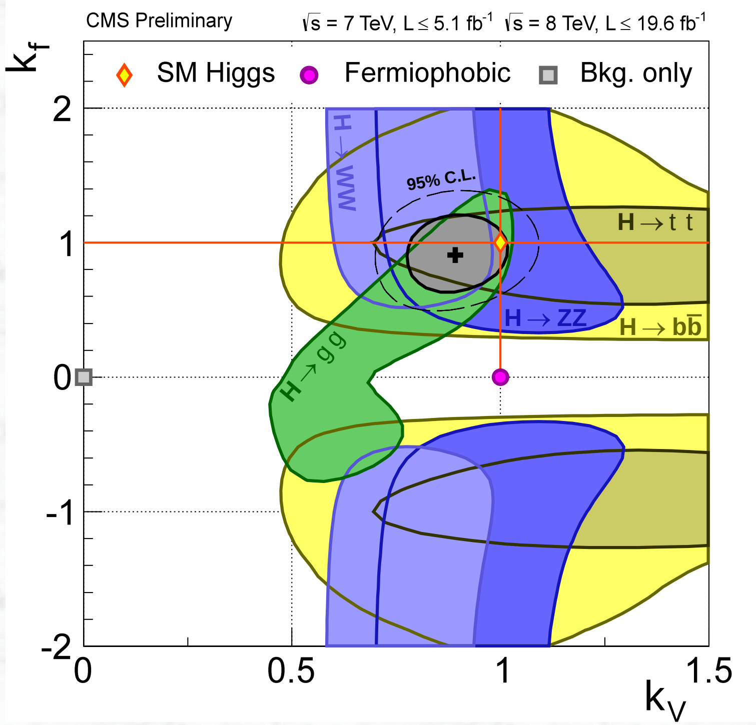
- Assume that H → $\gamma\gamma$ and gg → H loops and the total Higgs boson width depend only on κ_V and κ_F
(no contributions from physics beyond the Standard Model)

- Sensitivity to relative sign between κ_F and κ_V only from interference term in H → $\gamma\gamma$ decays (assume $\kappa_V > 0$)



(i) Couplings to fermions and bosons (cont).





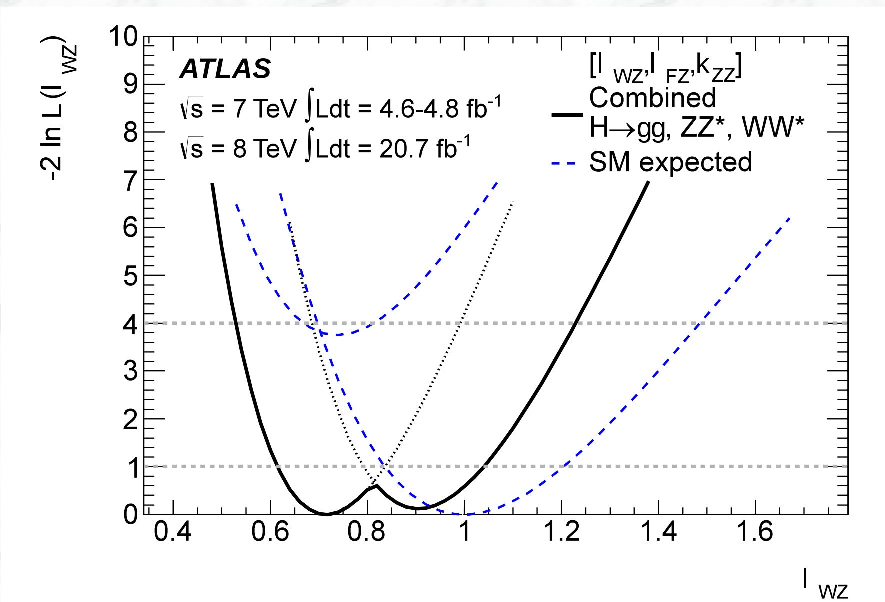
Results: Data are consistent with the SM expectation;

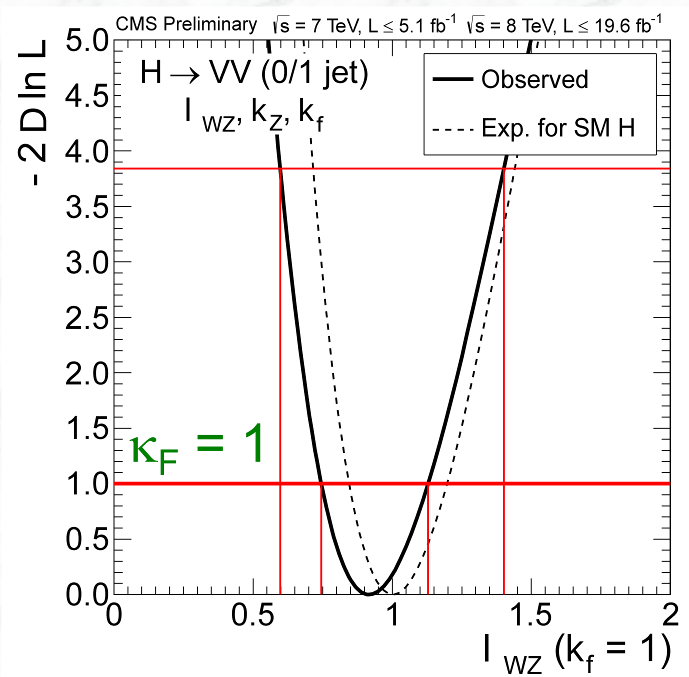
68% CL intervals: $\kappa_F \in [0.76, 1.18]$
(ATLAS) $\kappa_V \in [1.05, 1.22]$

95% CL intervals: $\kappa_F \in [0.61, 1.31]$
(CMS) $\kappa_V \in [0.74, 1.06]$

(ii) Ratio of couplings to the W and Z bosons

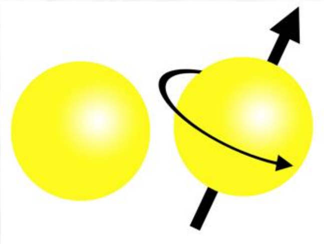
- Relation between m_W and m_Z in the Standard Model requires $\lambda_{WZ} := \kappa_W/\kappa_Z = 1$ (ρ parameter required to be 1)
- Sensitivity via VBF and VH production and H → WW and H → ZZ rates





68% CL intervals: $\lambda_{WZ} \in [0.61, 1.04]$

Spin and Parity



Wolfgang Pauli and Niels Bohr studying the motion of a gyro (1952, at the opening of the institute for theoretical physics in Lund /Sweden)

Standard Model Higgs boson: $J^P = 0^+$

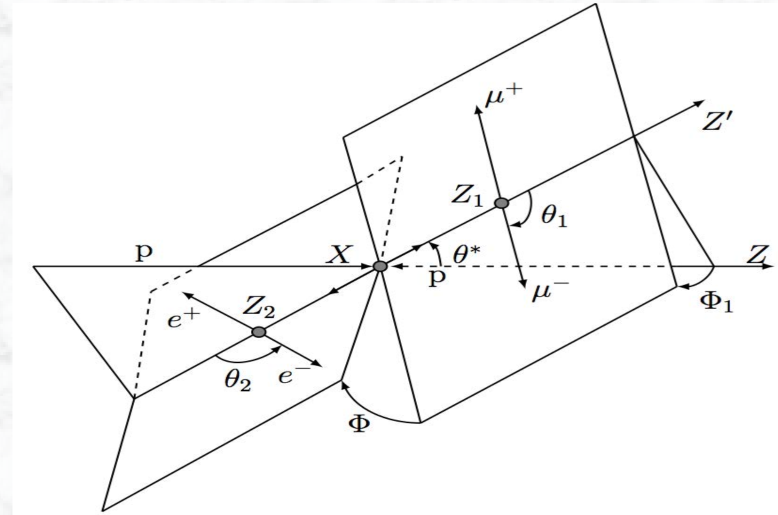
→ strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

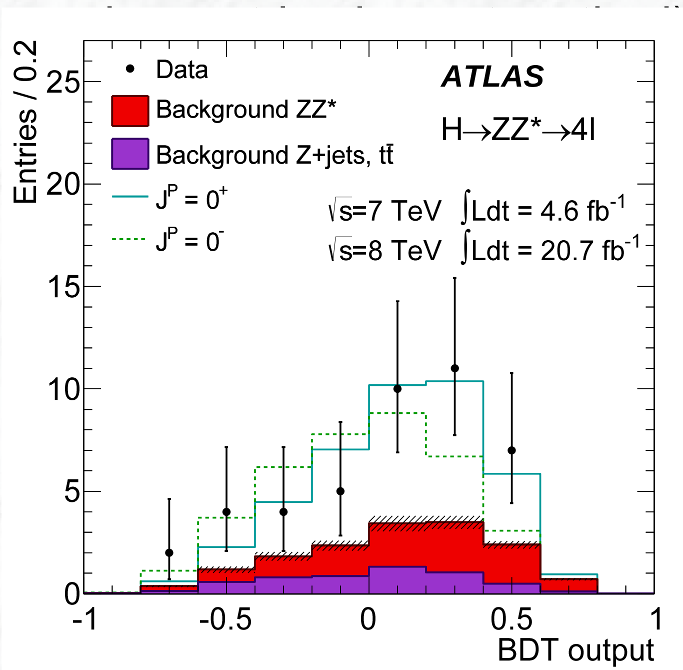
and demonstrate consistency with the 0^+ hypothesis

Spin 1: strongly dis-favoured by observed $H \rightarrow \gamma\gamma$ decays, Landau-Yang theorem

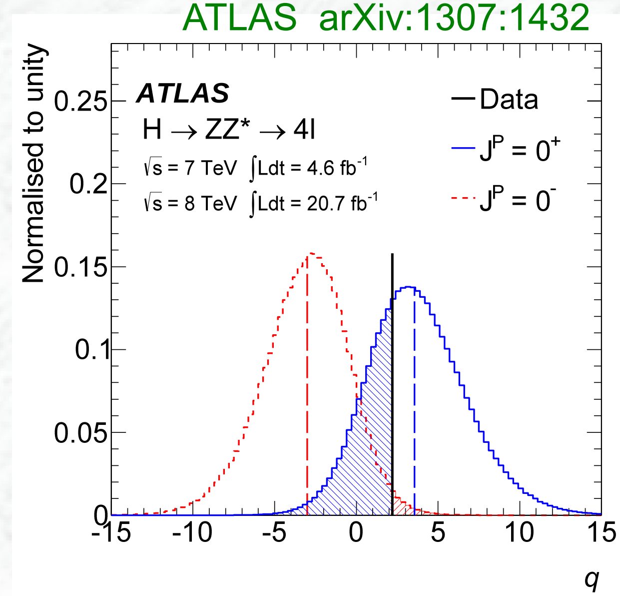
$J^P = 0^-$ versus $J^P=0^+$ (H → $ZZ^{(*)}$ → 4ℓ events)

- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle θ^*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2
- Perform multivariate analysis (Boosted decision tree, similar sensitivity





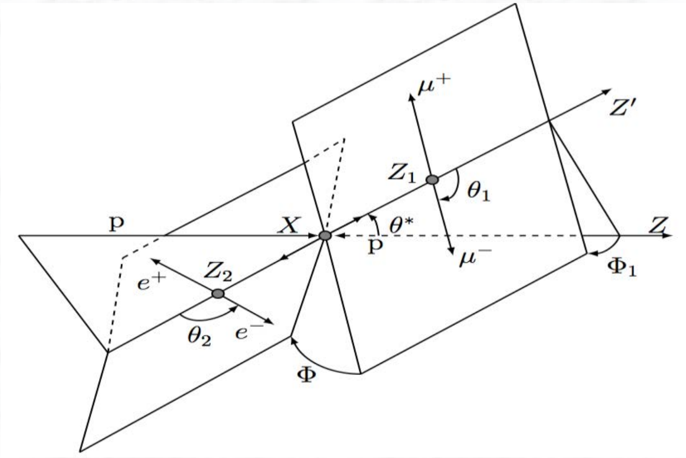
ATLAS arXiv:1307:1432

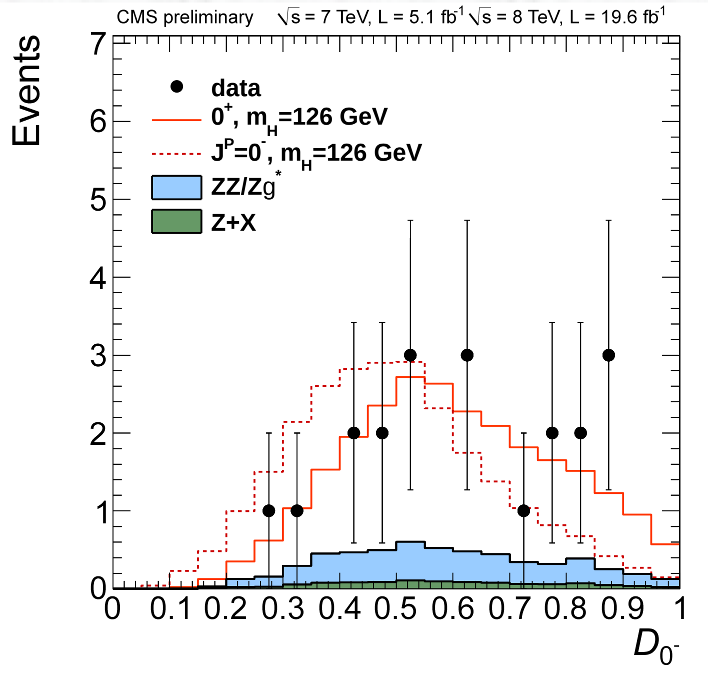


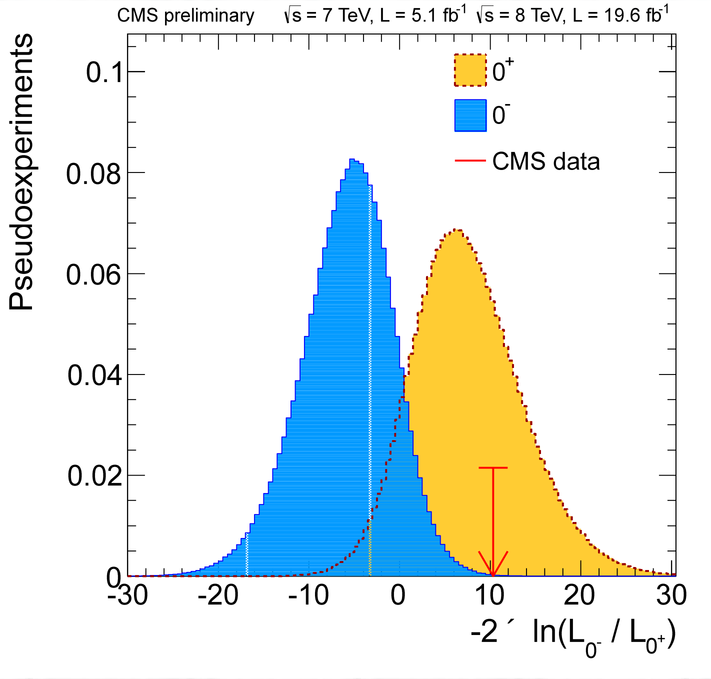
Exclude $J^P=0^-$ (vs. 0^+) with 97.8% CL

$J^P = 0^-$ versus $J^P=0^+$ (H → $ZZ^{(*)}$ → 4ℓ events)

- Sensitive variables:
  - Masses of the two Z bosons
  - Production angle θ*
  - Four decay angles Φ_1, Φ, θ_1 and θ_2
- Matrix-Element based discriminant D_{JP}







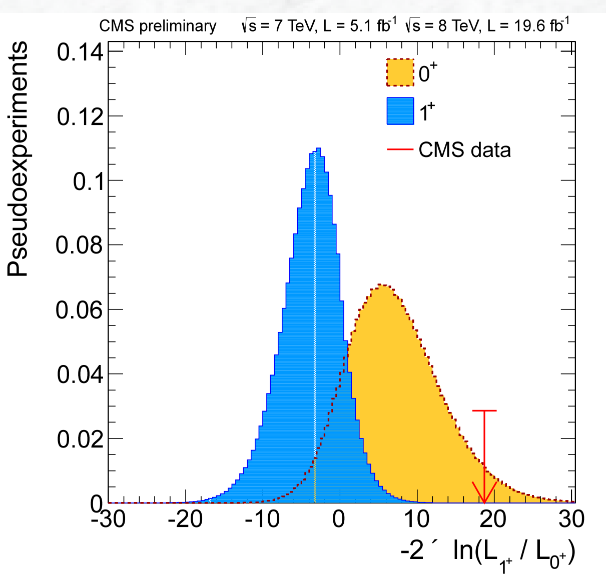
CMS PAS HIG-13-005

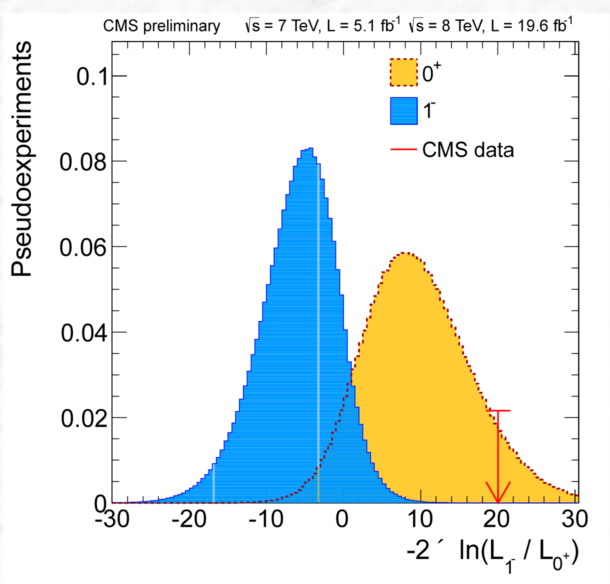
Exclude $J^P=0^-$ (vs. 0^+) with 99.8% CL

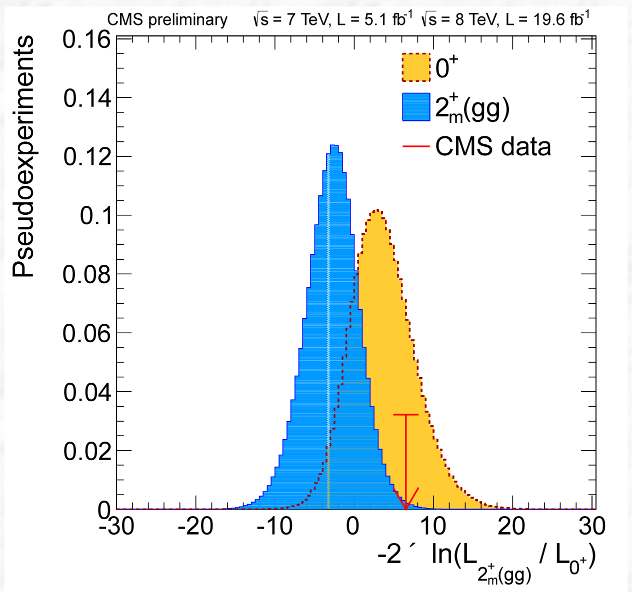
Further CMS results based on H → ZZ$^{(*)}$ → 4ℓ decays

CMS PAS HIG-13-005

J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL$_s$
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0_h^+	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%



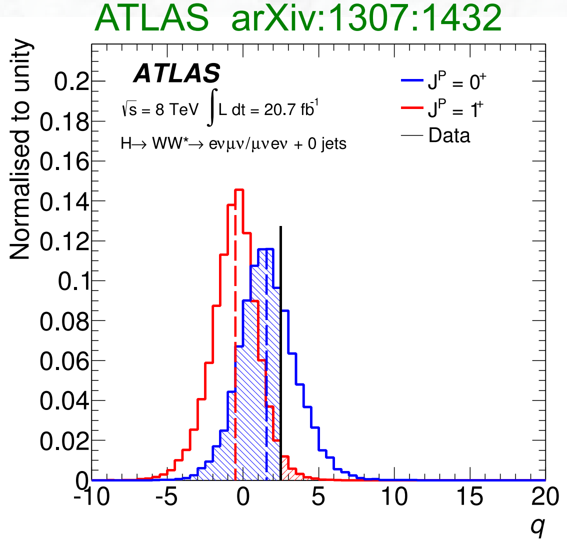


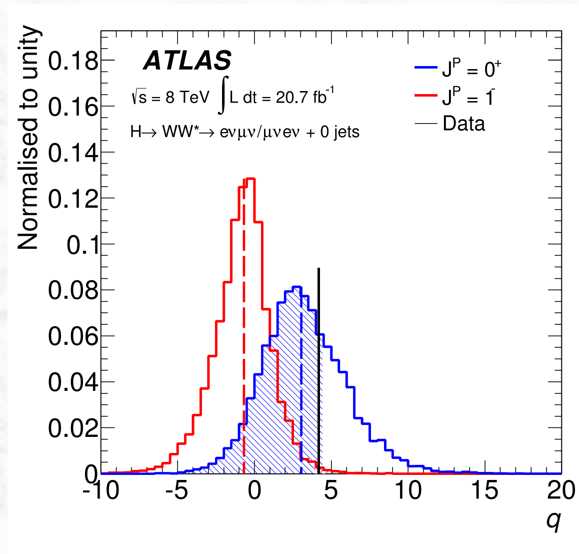


$J^P = 1^{+/-}$ versus $J^P=0^+$ (H → ZZ^* and H → WW^* events)

- H → ZZ*, as before: BDT separation based on masses and angles
- H → WW*: $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $p_T(\ell\ell)$, m_T carry information on spin, combine these variables using a BDT analysis

ATLAS arXiv:1307:1432





H → WW*

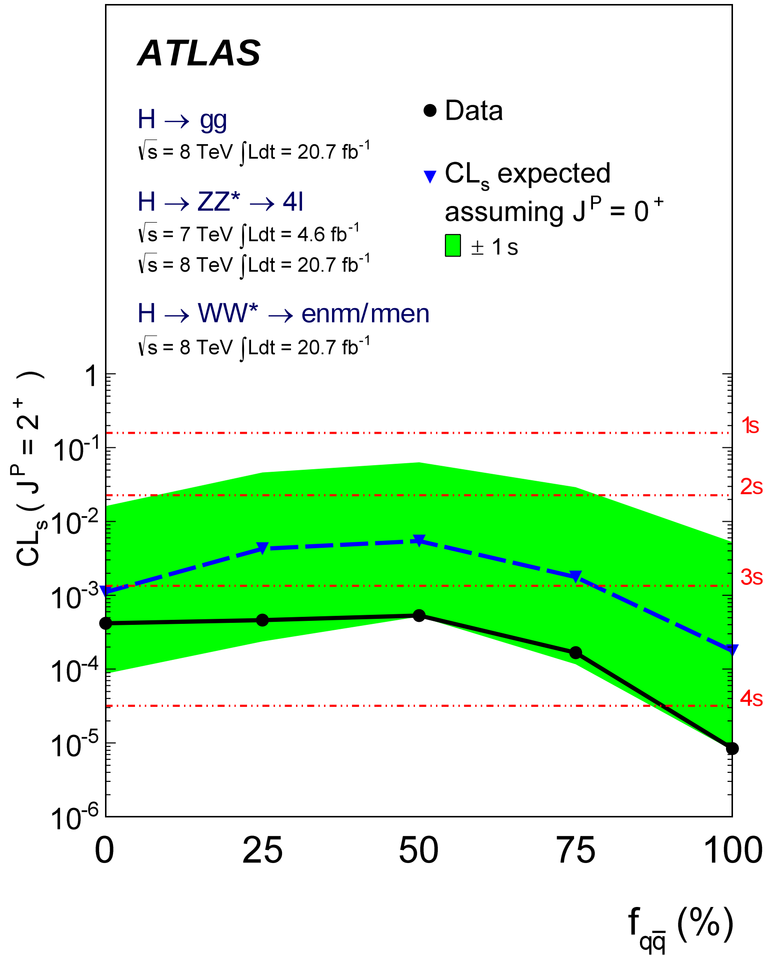
$$q = \log \frac{\mathcal{L}(J^P = 0^+, \hat{\hat{\mu}}_{0^+}, \hat{\hat{\theta}}_{0^+})}{\mathcal{L}(J^P_{\mathrm{alt}}, \hat{\hat{\mu}}_{J^P_{\mathrm{alt}}}, \hat{\hat{\theta}}_{J^P_{\mathrm{alt}}})}$$

q = test statistics to discriminate between two spin hypotheses

	p_0 (0^+)	CL (1^+) Exclusion	p_0 (0^+)	CL (1^-) Exclusion
H → ZZ*	0.55	99.8%	0.1	94%
H → WW*	0.70	92%	0.66	98%
Combination	0.62	99.97%	0.33	99.7%

$J^P = 2^+$ versus $J^P=0^+$ ($H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, and $H \rightarrow WW^*$ events)

ATLAS arXiv:1307:1432



- Spin 2: consider graviton-like tensor, equivalent to a Kaluza-Klein graviton

  (Y. Gao et al, Phys. Rev. D81 (2010) 075022)

- Production via gluon fusion and qq annihilation possible;
  Studies are performed as a function of the qq annihilation fraction (f_{qq})

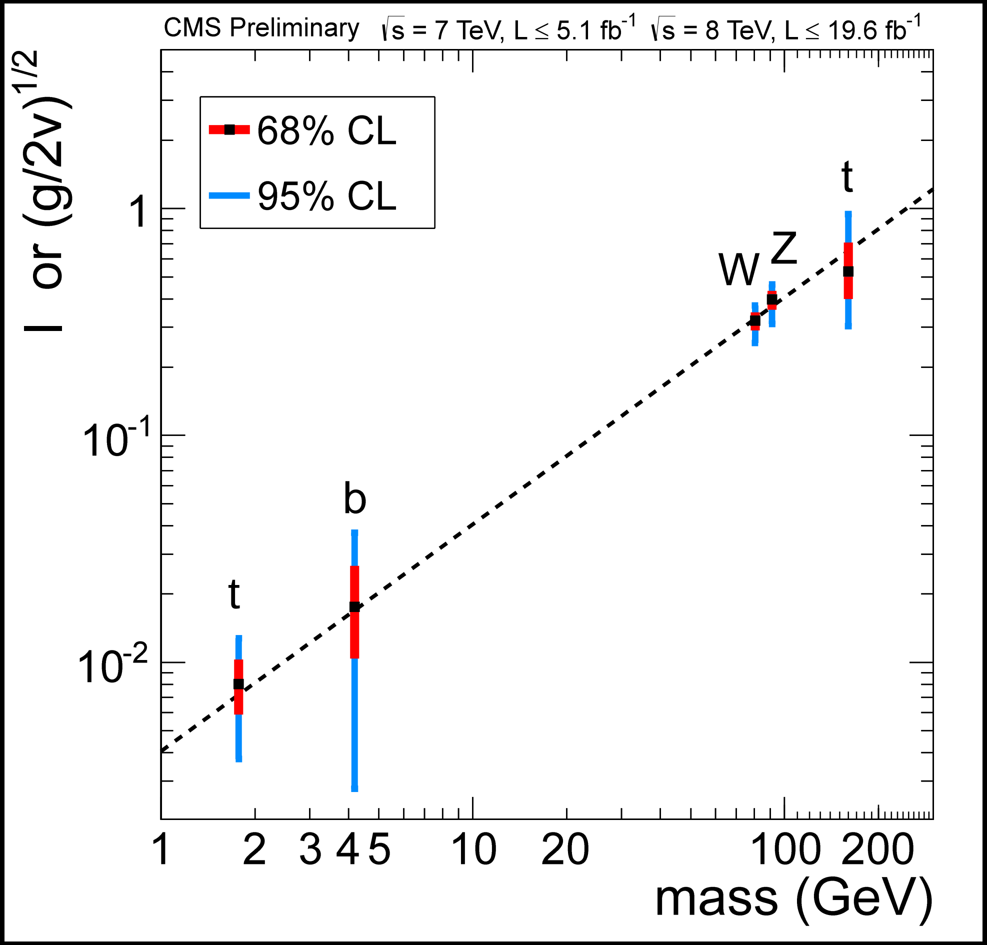
- Specific model 2^+_m:
  minimal couplings to SM particles

  (f_{qq} = 4% at LO, however, large uncertainties)

- Observed exclusion (combination of $\gamma\gamma$, ZZ* and WW*) of $J^P = 2^+$ (versus the SM $J^P = 0^+$) exceeds 99.9%, independent of f_{qq};
  Complementary behaviour of the different channels

CMS summary on coupling results

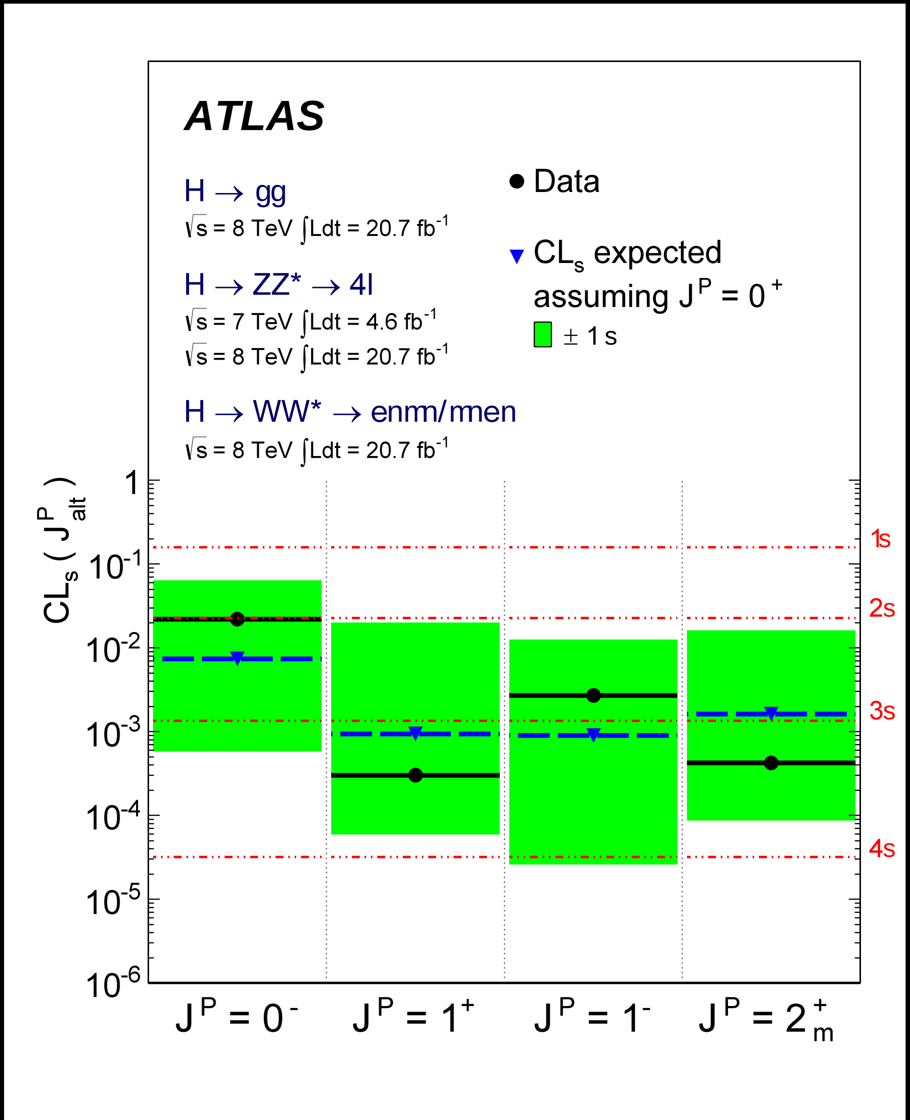
CMS PAS HIG-13-005



"The consistency of the couplings of the observed boson with those predicted for the Standard Model Higgs boson is tested in various ways, and no significant deviations are found."

ATLAS summary on spin results

ATLAS arXiv:1307:1432



"These studies provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred."

Summary

- A milestone discovery announced in July 2012

- Signals have been impressively confirmed with additional data;
  The discovery phase has turned into the measurement phase

- ATLAS and CMS data are consistent with the expectations for the Standard Model Higgs boson (within present uncertainties)

  - Production rates and coupling strengths
  - Evidence for VBF production
  - Evidence for spin-0 (0^- disfavoured)

- Exciting times ahead of us to study the Higgs boson with higher precision (> 2015) and to look for surprises (deviations? more Higgs bosons? …)