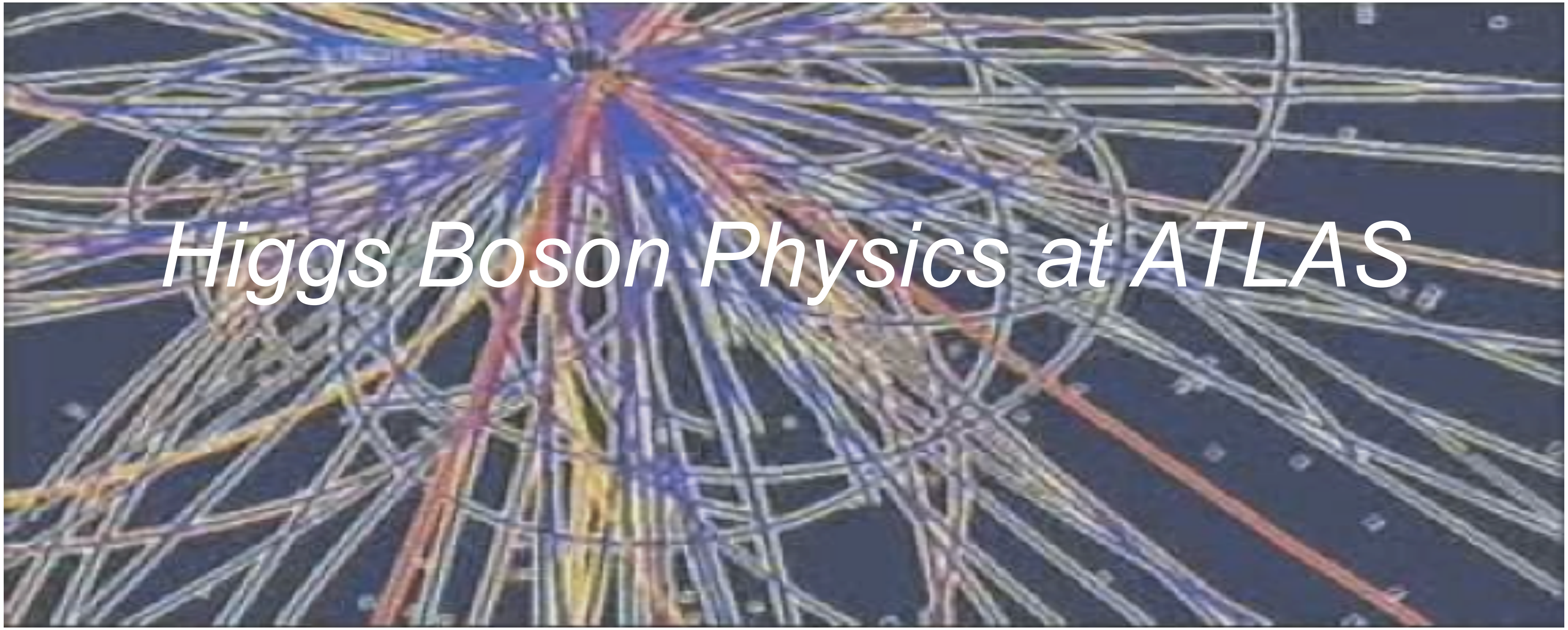
LHC-The First Part of the Journey, KITP, UC Santa Barbara, Jul 8-12, 2013



Higgs Boson Physics at ATLAS

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For the ATLAS Collaboration

Today's Presentation

- Introduction
  - LHC and ATLAS detectors
  - Search strategies

- Overview of Standard Model Higgs boson searches
  - Bosonic decay modes
  - Fermionic decay modes

- Higgs boson properties
  - Mass
  - Production and decay rates
  - Couplings to fermions and bosons
  - Spin/parity

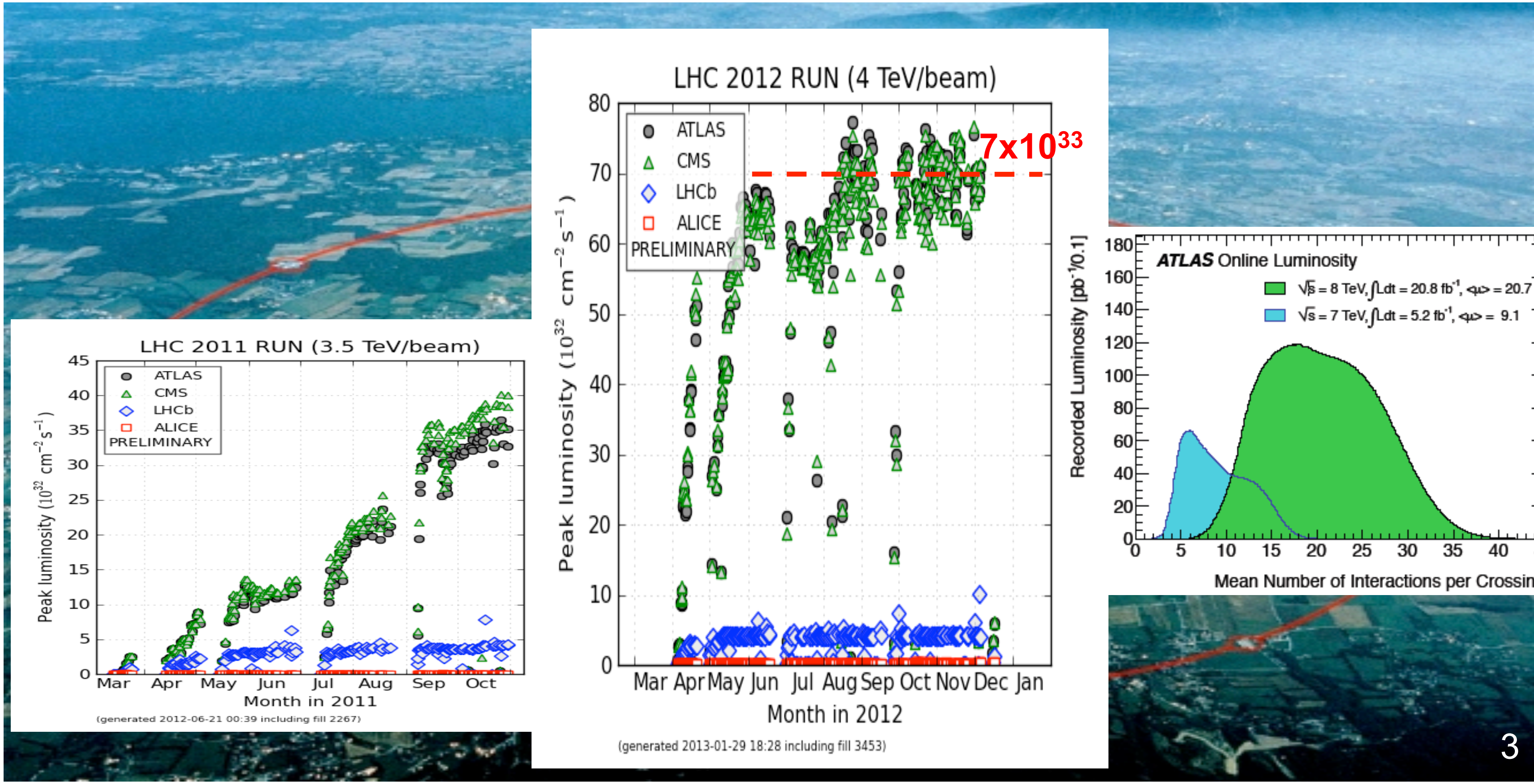
- Summary and conclusions

Large Hadron Collider

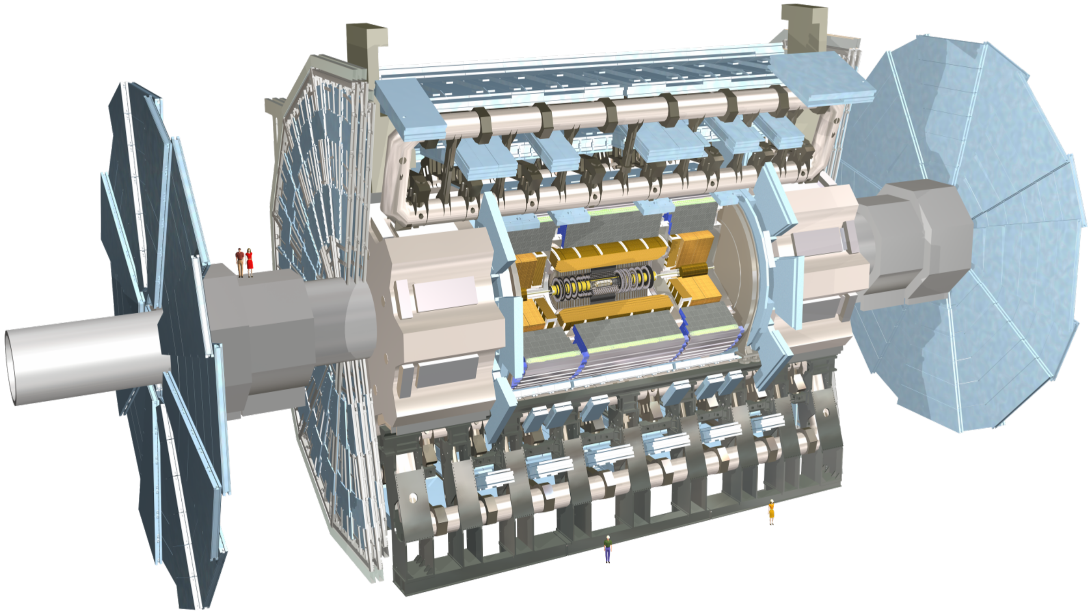
- Outstanding performance of the LHC over the last two years:
  - 2011: pp collisions at $\sqrt{s}$=7 TeV, ~5.8 fb^{-1}
  - 2012: pp collisions at $\sqrt{s}$=8 TeV, ~23.3 fb^{-1}

  (delivered to ATLAS and CMS)
- Collisions to resume in 2015 at $\sqrt{s}\geq$13 TeV and L$\geq 10^{34}$ $cm^{-2}s^{-1}$

  ➔ projecting ~25-45 fb^{-1}/year!



ATLAS Experiment



Inner tracking system in 2T solenoidal field:

- Pixel detector
- Silicon tracker
- Transition radiation tracker

Hermetic calorimetry:

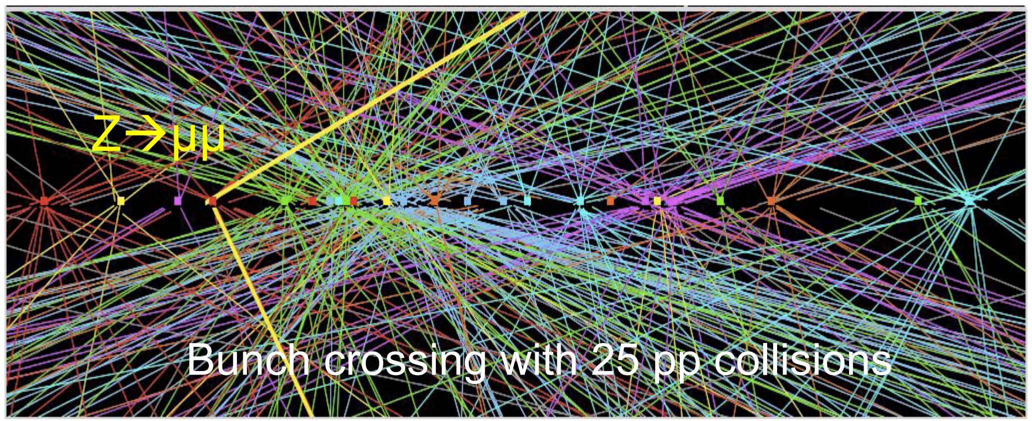
- Lead/LAr electromagnetic calorimeter.
- Hadronic calorimeter.

Muon spectrometer (supercond. toroid system).

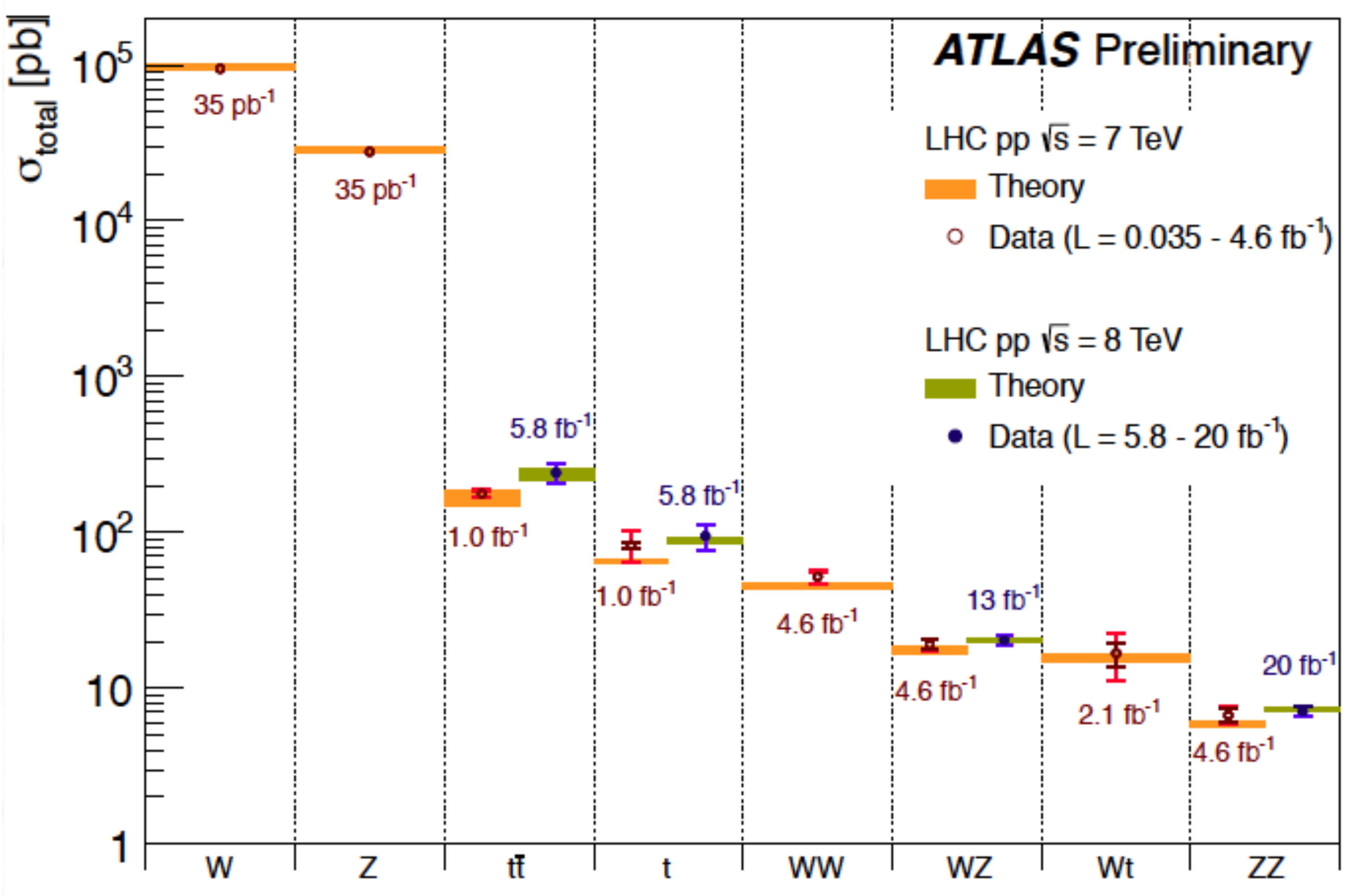
>99% working channels for most subdetectors.

- Excellent performance up to the highest instantaneous luminosities delivered by the LHC. ~94% data-taking efficiency

- Most results shown use the full 2011 dataset (~ 5 fb^{-1} at $\sqrt{s}$=7 TeV) and the full 2012 dataset (~20 fb^{-1} at $\sqrt{s}$=8 TeV).



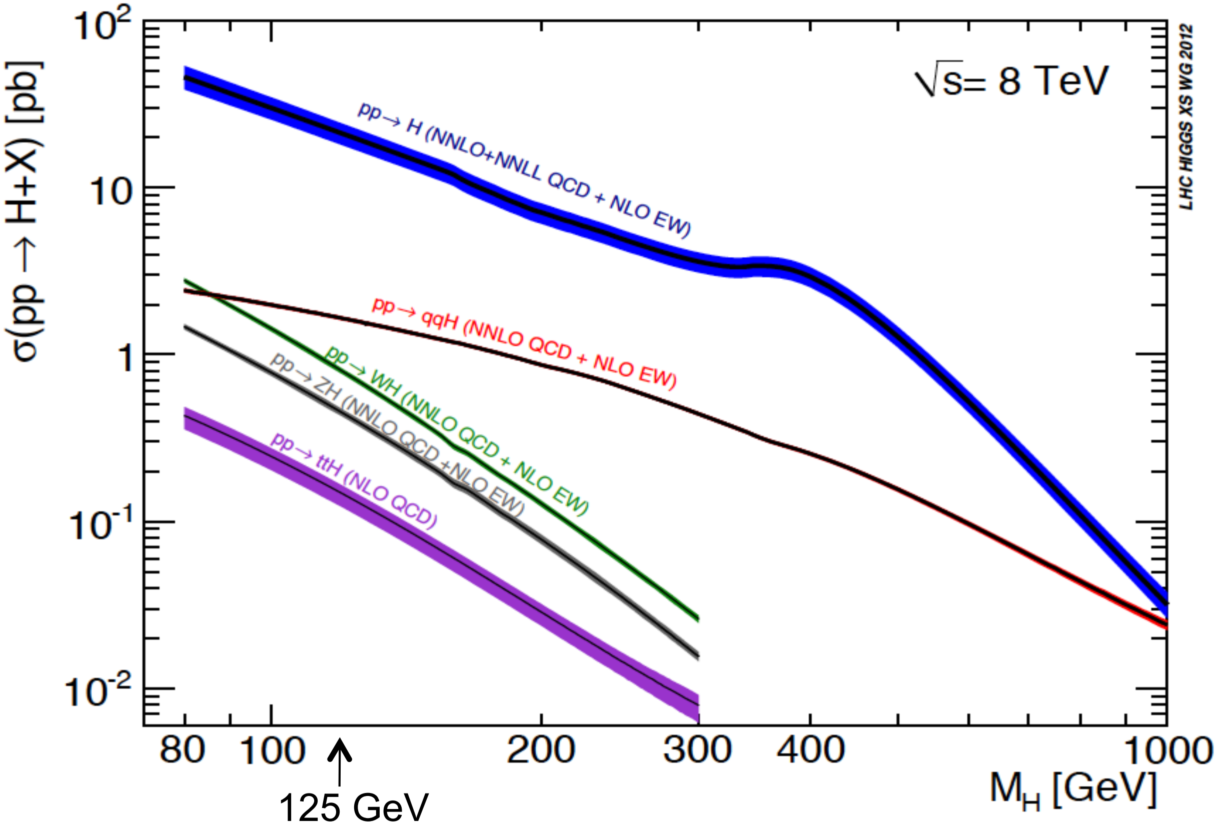
Rediscovering the Standard Model



- Performing precise measurements of SM processes over many orders of magnitude in production cross section.

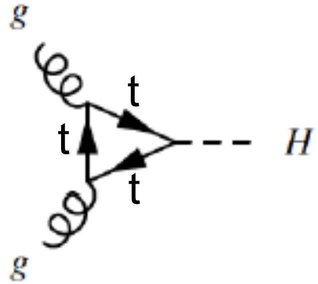
  ➔ good understanding of the backgrounds to the Higgs signal.

SM Higgs Production at the LHC

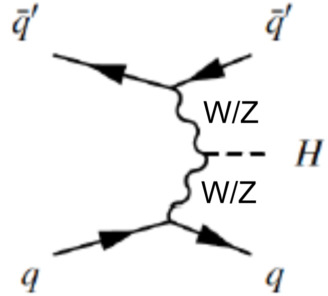


The LHC is a Higgs factory!

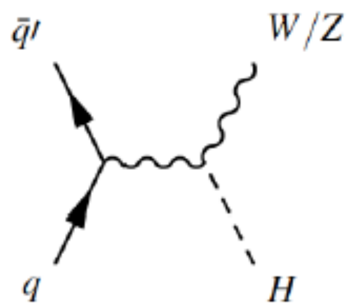
~600k Higgs events produced at each experiment in 2012!



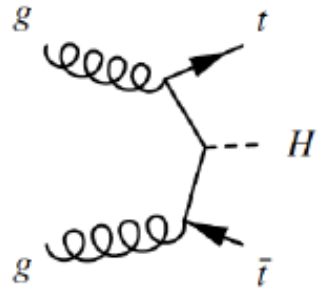
Gluon fusion (~87%)



Vector-boson fusion (~7%)

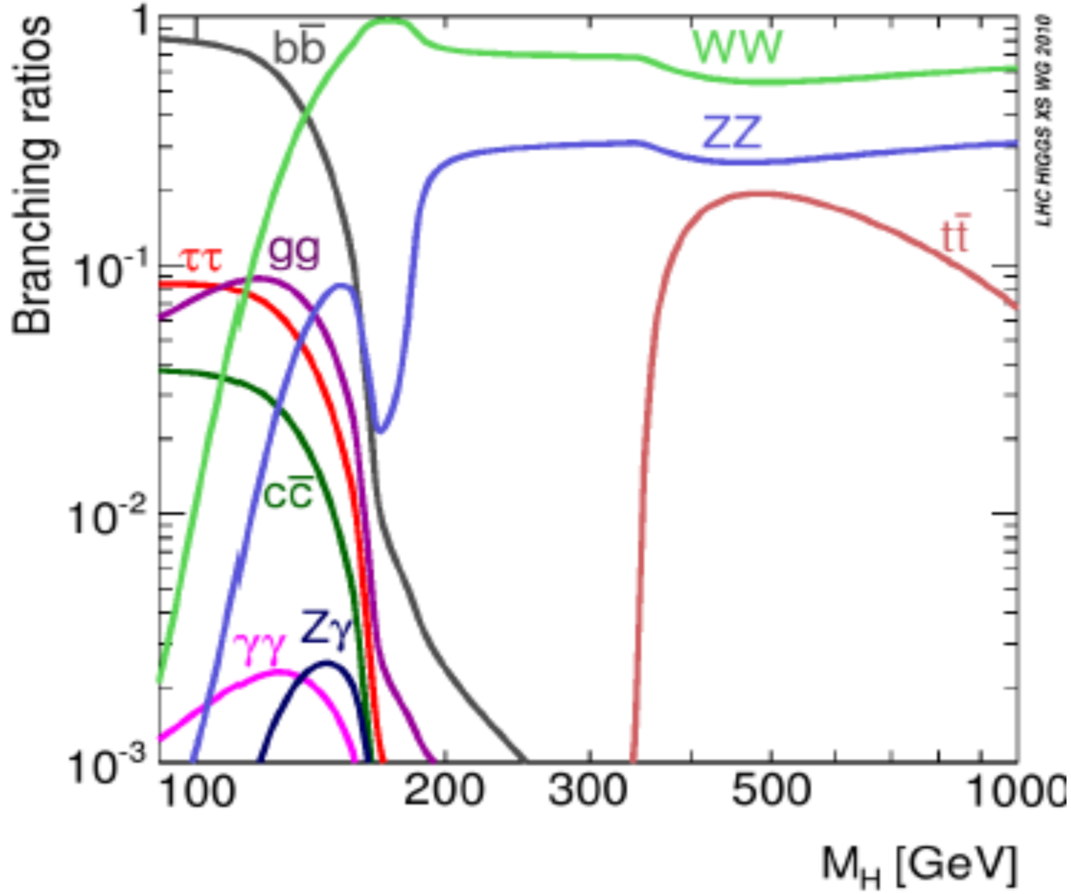


Associated production (~5%)



$t\bar{t}H$ production (~1%)

SM Higgs Decay Modes



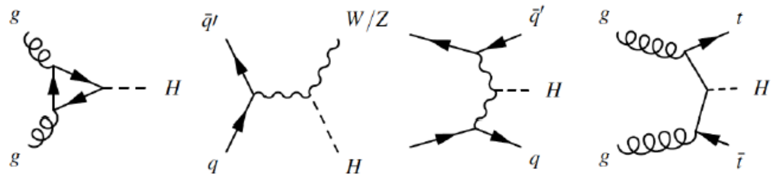
SM predictions (m_H = 125.5 GeV):

BR(H→WW) = 22.3%	BR(H→$b\bar{b}$)=56.9%
BR(H→ZZ) = 2.8%	BR(H→$\tau\tau$)=6.2%
BR(H→$\gamma\gamma$)=0.24%	BR(H→$\mu\mu$)=0.022%

➔ Only ~11% of decays not observable (i.e. H→gg, $c\bar{c}$)

Search Strategies

- Defined by a combination of theoretical and experimental considerations: e.g. expected signal rate, ability to trigger, signal-to-background ratio,…



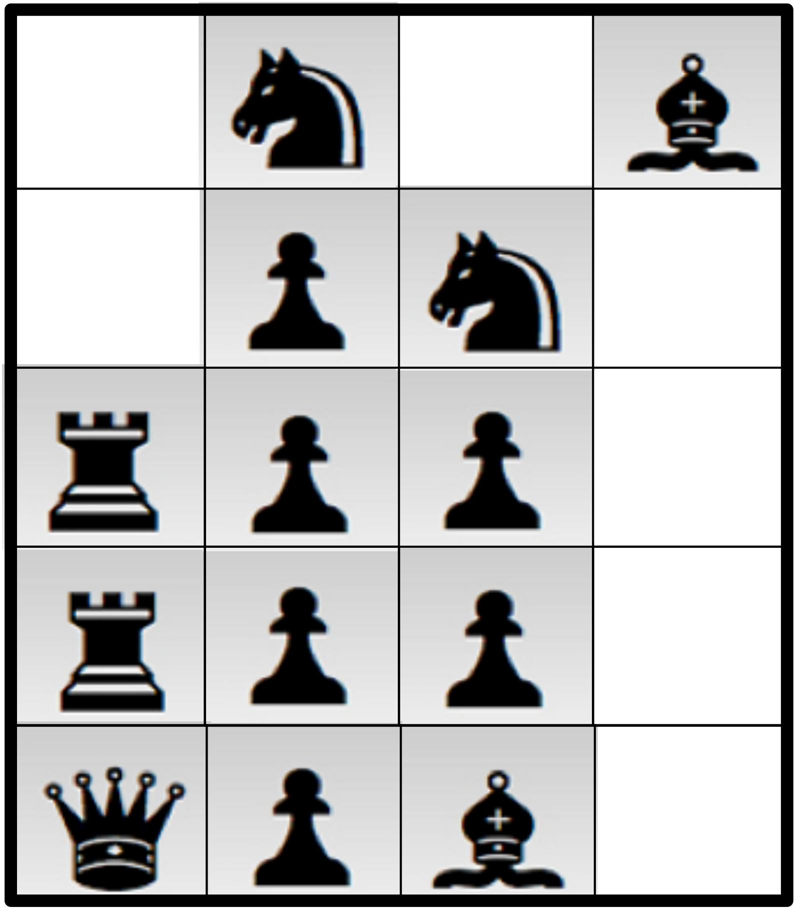
$H \rightarrow b\bar{b}$

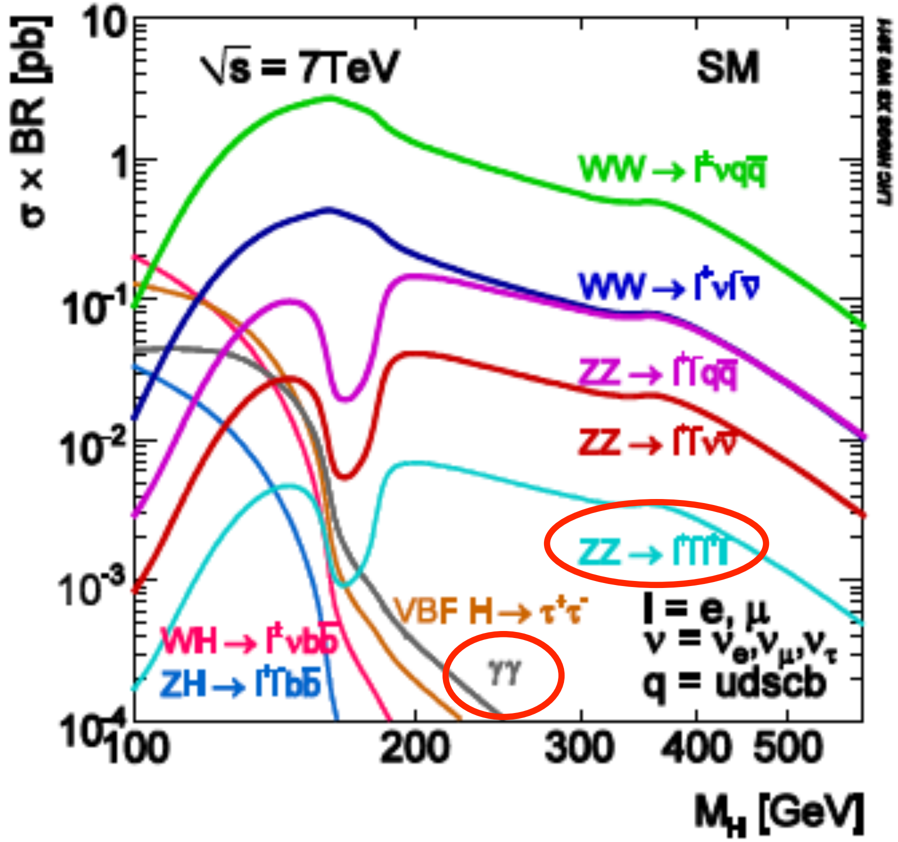
$H \rightarrow \tau^+\tau^-$

$H \rightarrow W^+W^-$

$H \rightarrow ZZ$

$H \rightarrow \gamma\gamma$

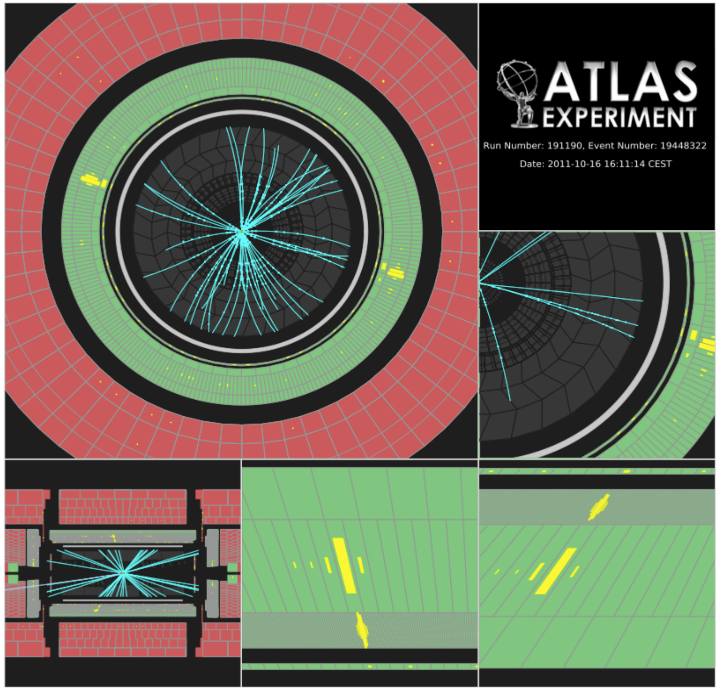




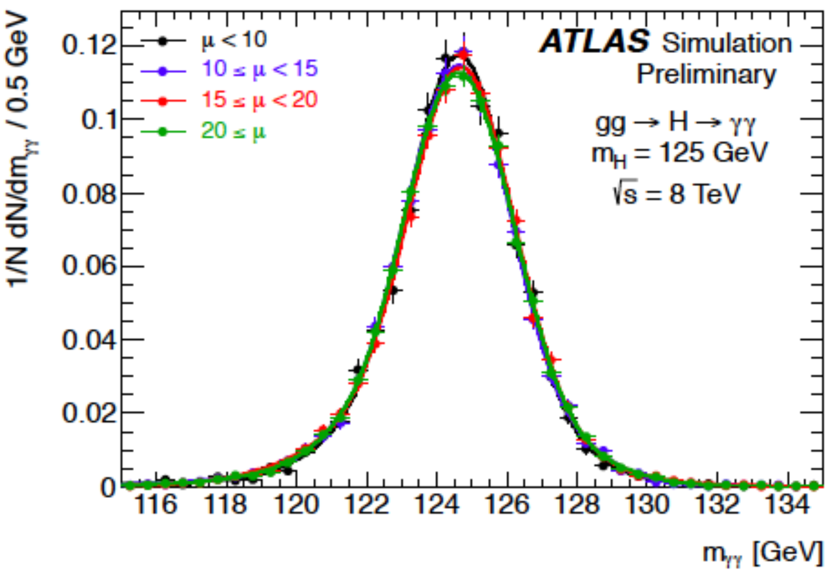
Bosonic Decay Modes

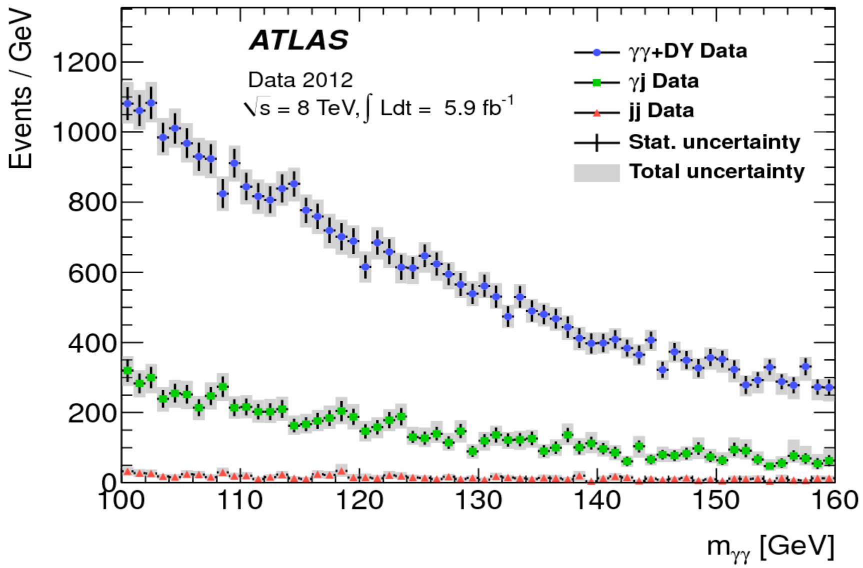
Searching for H→γγ

- A rare Higgs decay mode but most sensitive search at m_H<125 GeV!
  BR(H→γγ)~0.2%



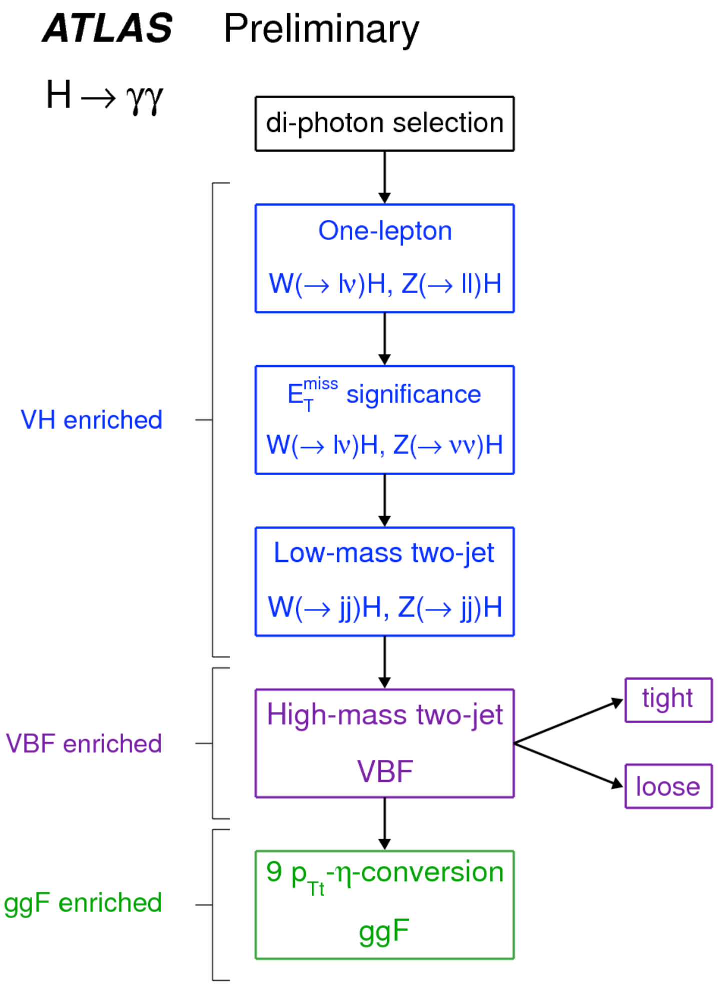
- Two high-p_T isolated photons (p_T>40, 30 GeV).
- Higgs mass reconstructed as $m_{\gamma\gamma}$
  - Good mass resolution ~1.4% (robust against pileup).
- Challenge: large background from non-resonant γγ production (irreducible, dominant), and γ+jet and dijet production (reducible).

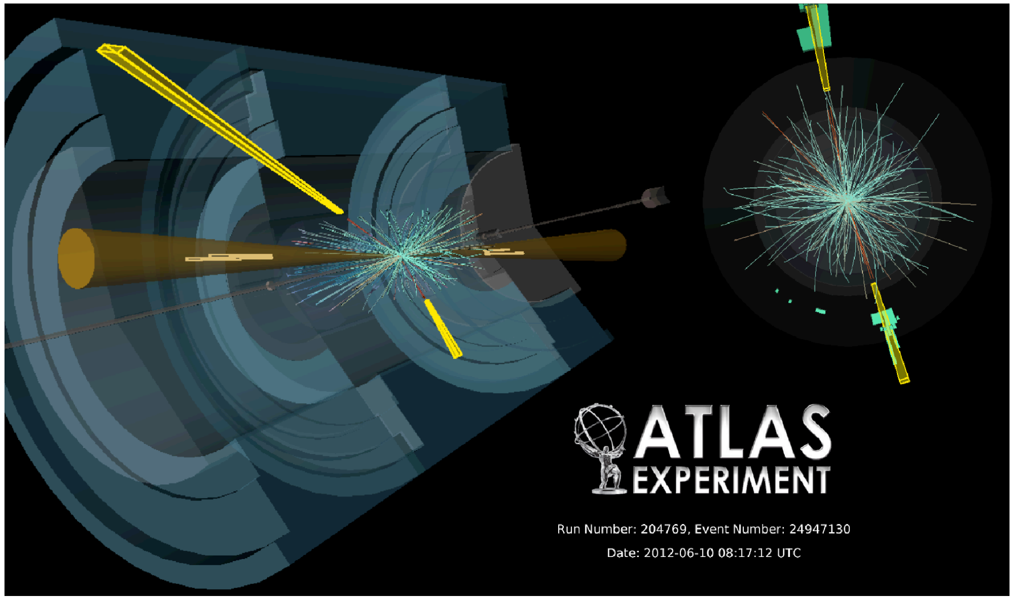


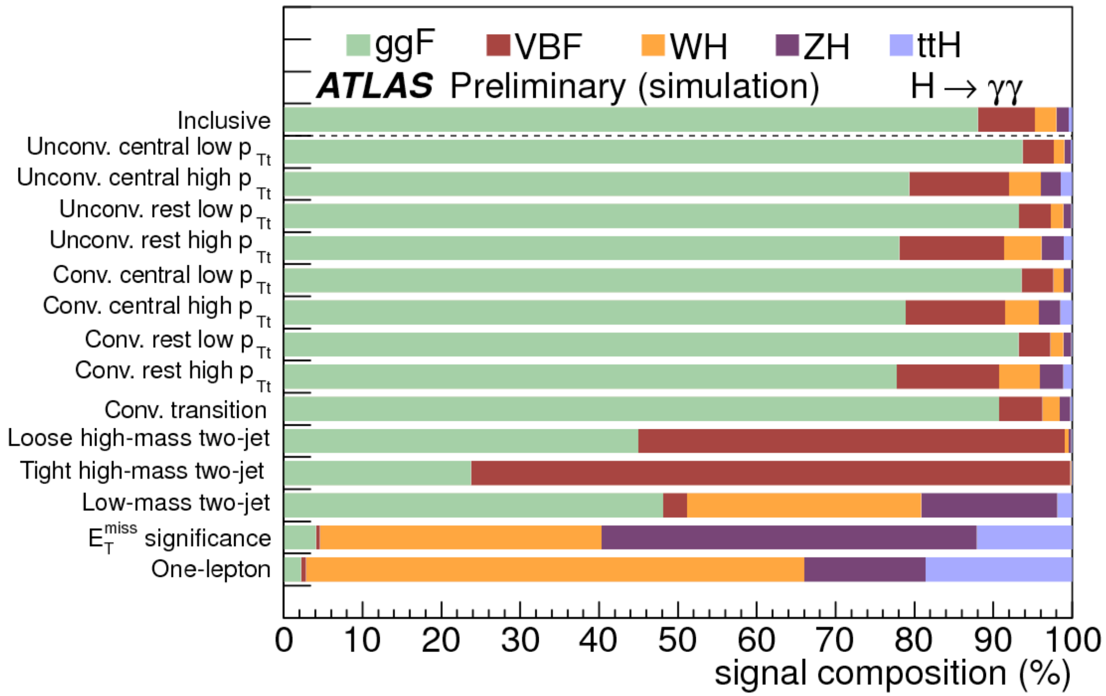


Searching for H→γγ

- Event categorization to increase overall sensitivity and sensitivity to individual production modes (VH, VBF).

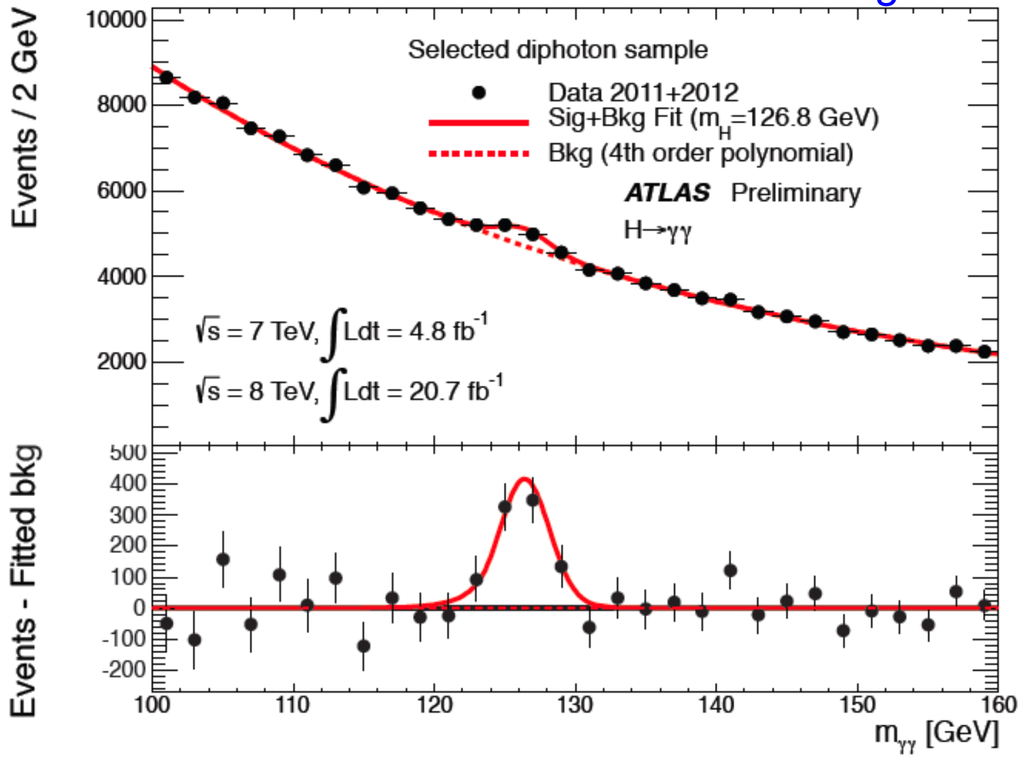




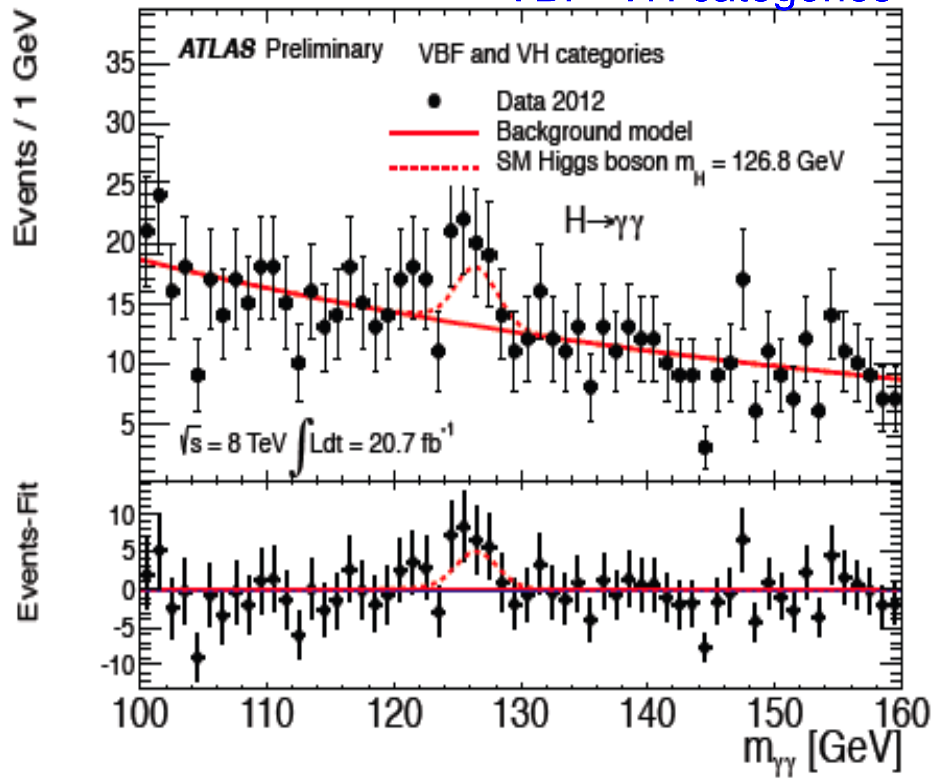


Searching for H→γγ

ATLAS-CONF-2013-012 All categories



VBF+VH categories



- Background interpolation in the region of the excess (obtained from sidebands) for each of the categories.
- Reducible γ+jet and dijet background at the level of 25%.

Searching for H→γγ

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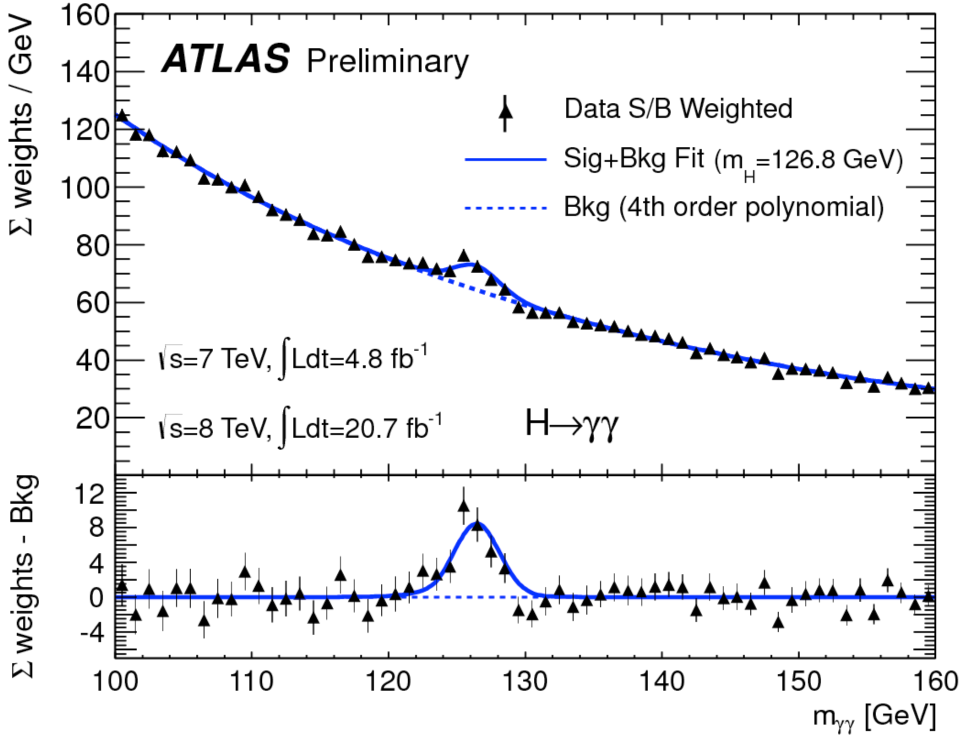
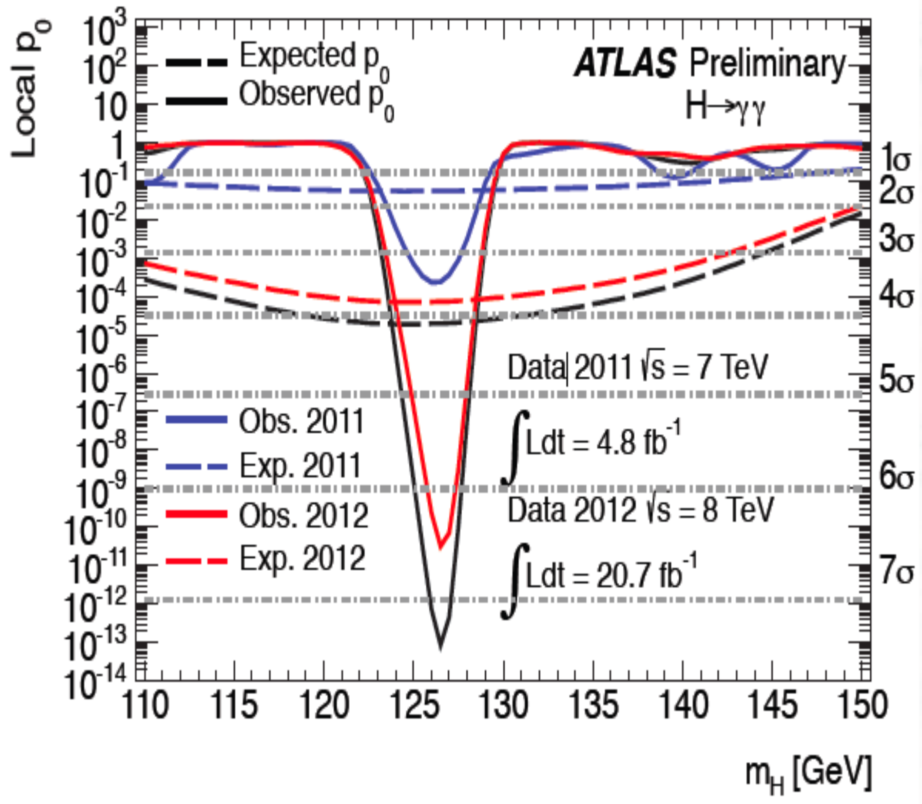


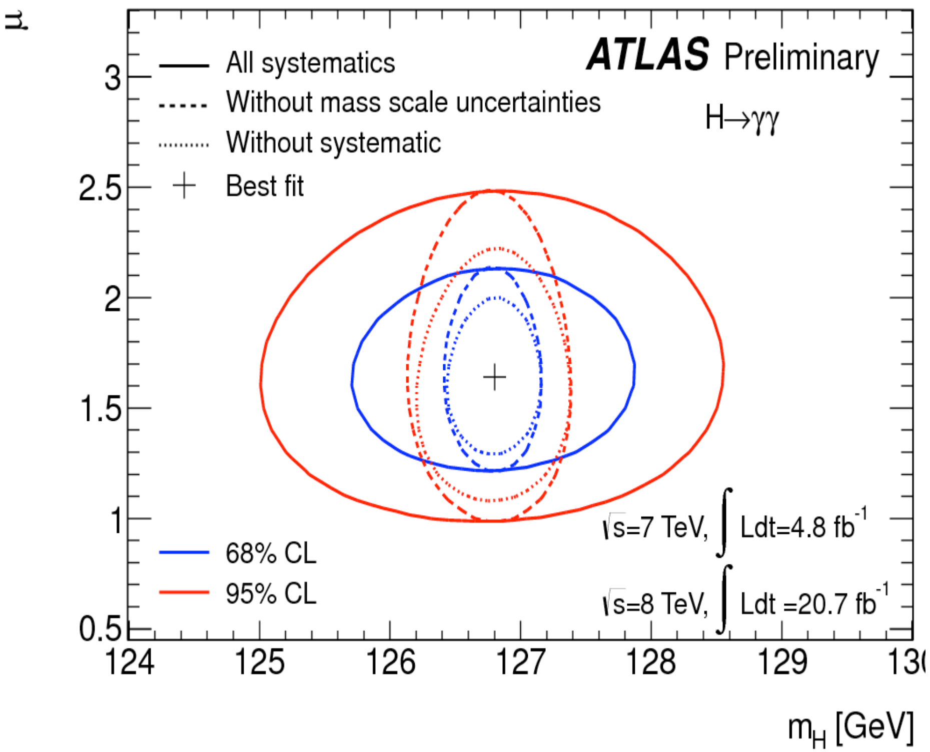


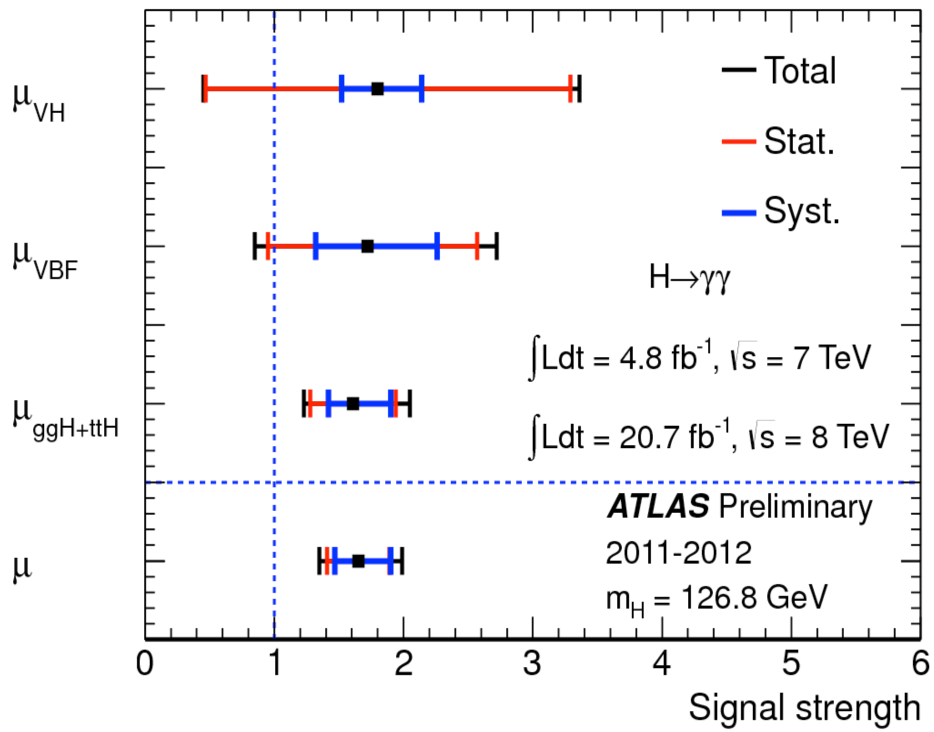
$w_i = \ln(1 + S_i/B_i)$

- Smallest p_0 value with consistency with background-only hypothesis: ~10^{-13}
  Minimum at m_H=126.5 GeV, 7.4σ (observed), 4.3σ (expected)

- Establishes the discovery of the new particle in the γγ channel alone!

Searching for H→γγ





Mass:

$$m_H = 126.8 \pm 0.2(stat) \pm 0.7(syst)\ \text{GeV}$$

- Dominant uncertainty from photon energy scale

Signal strength (at m_H=126.8 GeV):

$$\mu = 1.65^{+0.24}_{-0.24}(stat)^{+0.25}_{-0.18}(syst)$$

$$\mu_{VH} = 1.8^{+1.5}_{-1.3}(stat)^{+0.3}_{-0.3}(syst)$$

$$\mu_{VBF} = 1.7^{+0.8}_{-0.8}(stat)^{+0.5}_{-0.4}(syst)$$

$$\mu_{ggF+ttH} = 1.6^{+0.3}_{-0.3}(stat)^{+0.3}_{-0.2}(syst)$$

Searching for H→Zγ

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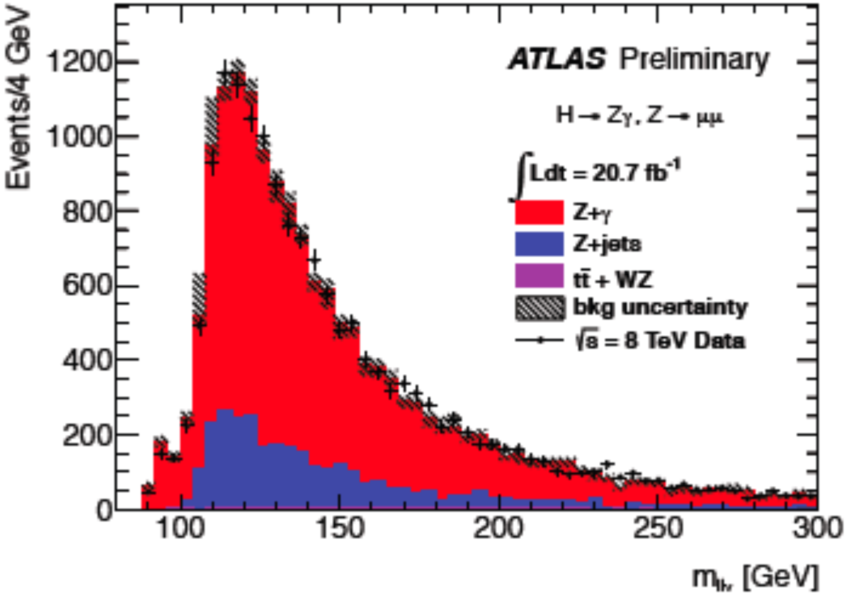


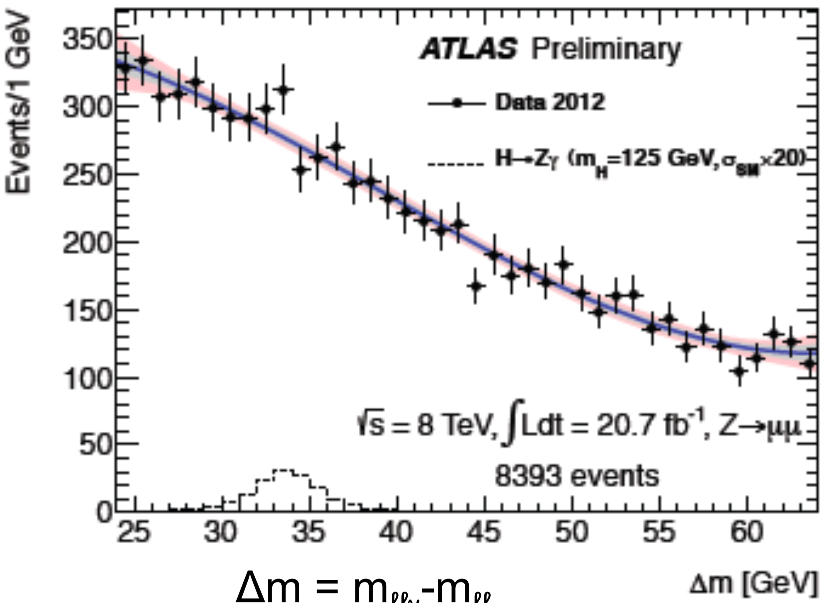
- Another loop-mediated decay.

  Measurement/limit can constrain BSM models.
- B(H→Zγ) ~ BR(H→γγ) but requirement of Z→ll reduces the sensitivity by x15.
- Search for a narrow llγ reasonance on top of a falling background, as for H→γγ.
- No significant excess observed.

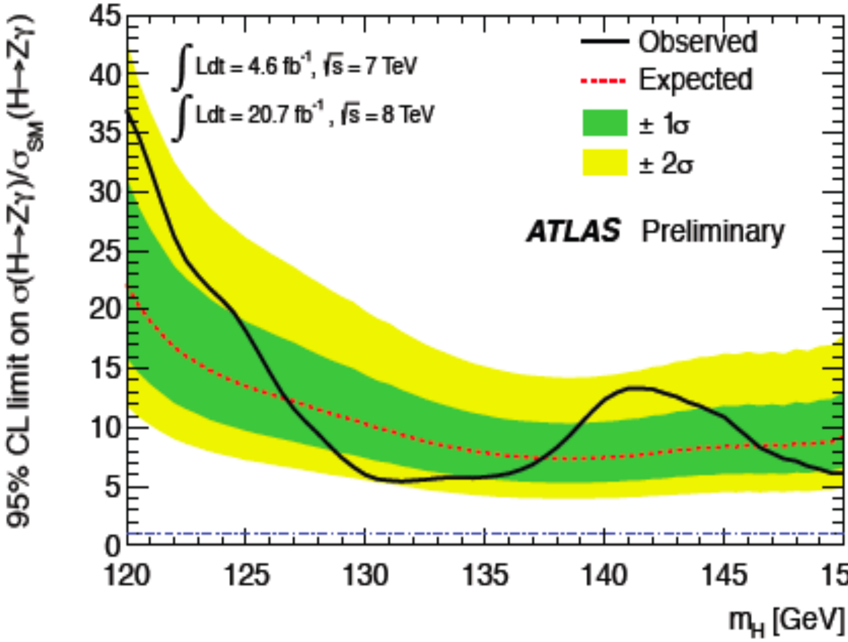
At m_H=125 GeV:

Observed limit: 18.2xSM

Expected limit: 13.5xSM



$\Delta m = m_{\ell\ell\gamma} - m_{\ell\ell}$



Searching for H→ZZ(*)→4l

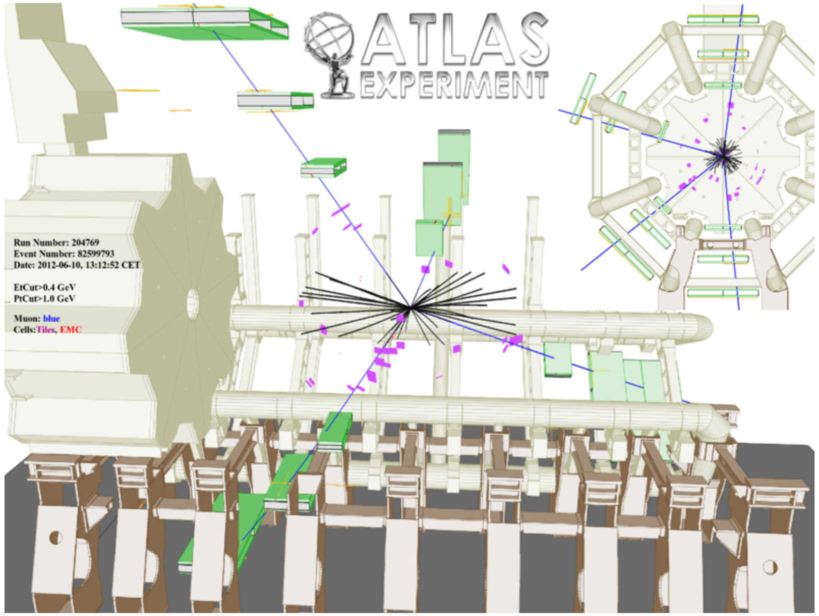
- An even rarer Higgs decay mode if both Z bosons are required to decay into ee or μμ!
  BR(H→ZZ→4e, 4μ or 2e2μ)~0.01%

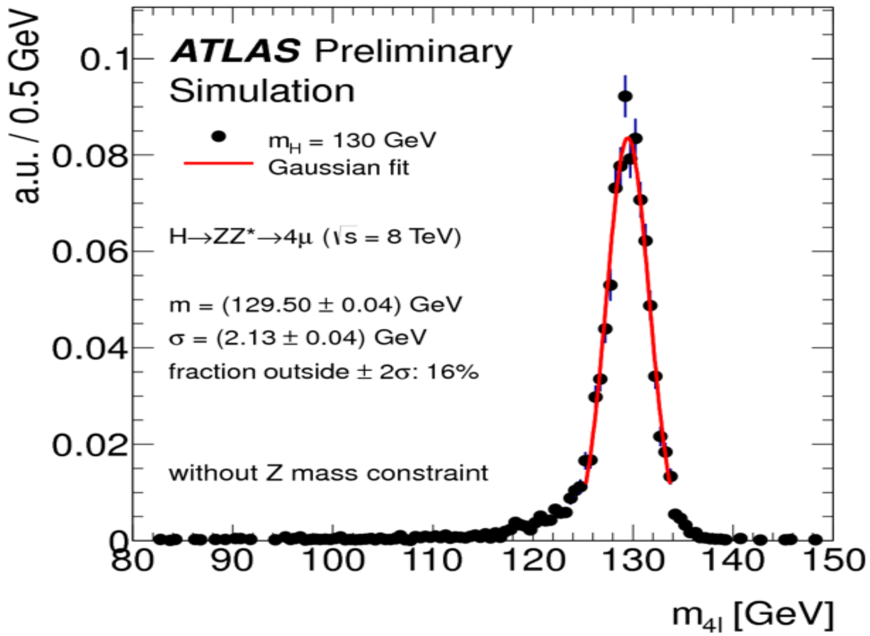
- The “golden mode”: 4 isolated leptons
  e: p_T>20, 15, 10, 7 GeV, |η|<2.47
  μ: p_T>20, 15, 10, 6 GeV, |η|<2.7
  At least one pair consistent with Z mass.

- Low rate but clean signature with very small background:
  - Mainly from non-resonant (Z/γ*)(Z/γ*)
  - Small contribution from $t\bar{t}$ and Z+jets

- Higgs mass reconstructed as $m_{4\ell}$
  - Good mass resolution ~1.3%-1.9% (depending on the channel)

- Event categories also defined (VH-like, VBF-like and ggF-like).





Searching for H→ZZ$^{(*)}$→4l

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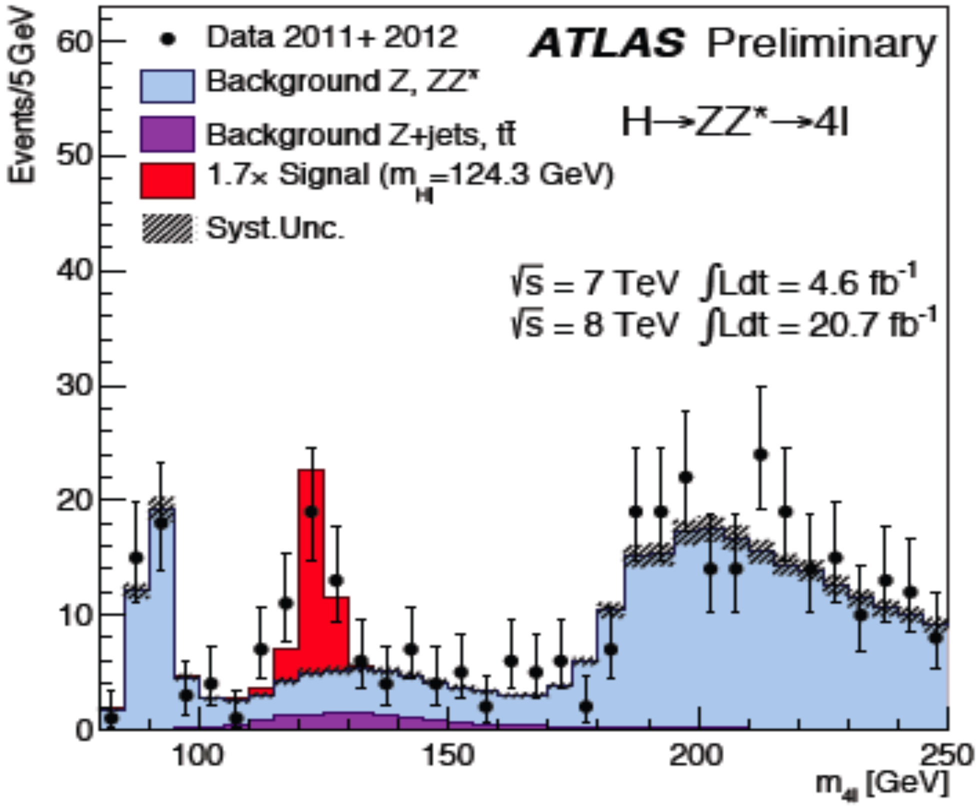
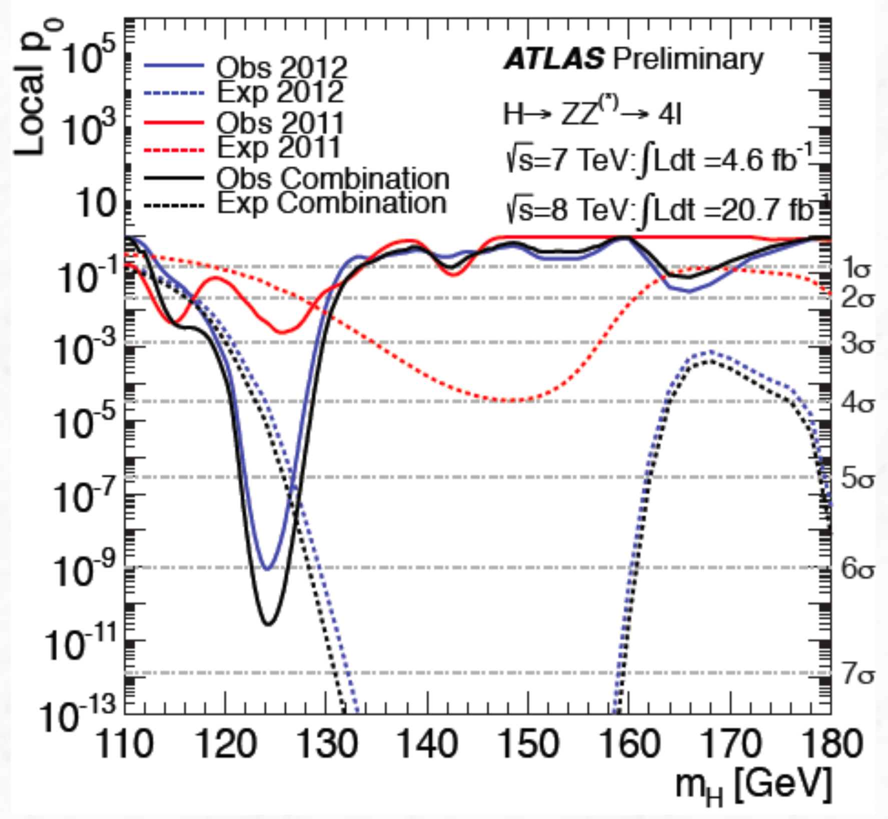




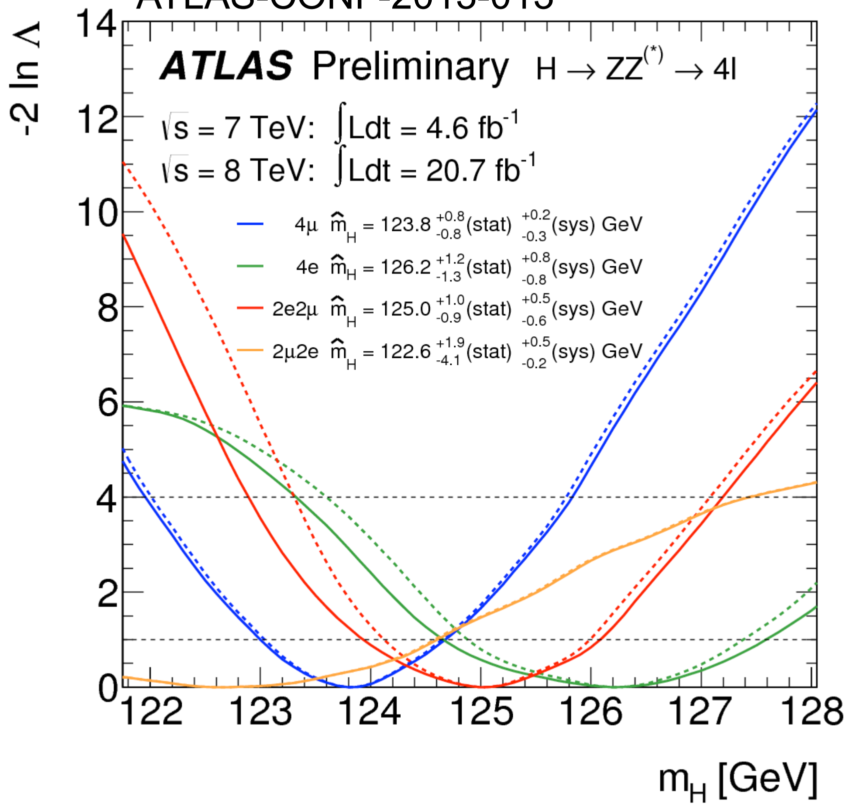
Mass range 120 – 130 GeV	Expected signal	Background	Data
$\sqrt{s}$ = 7 TeV	2.2	2.3	5
$\sqrt{s}$ = 8 TeV	13.7	8.8	27

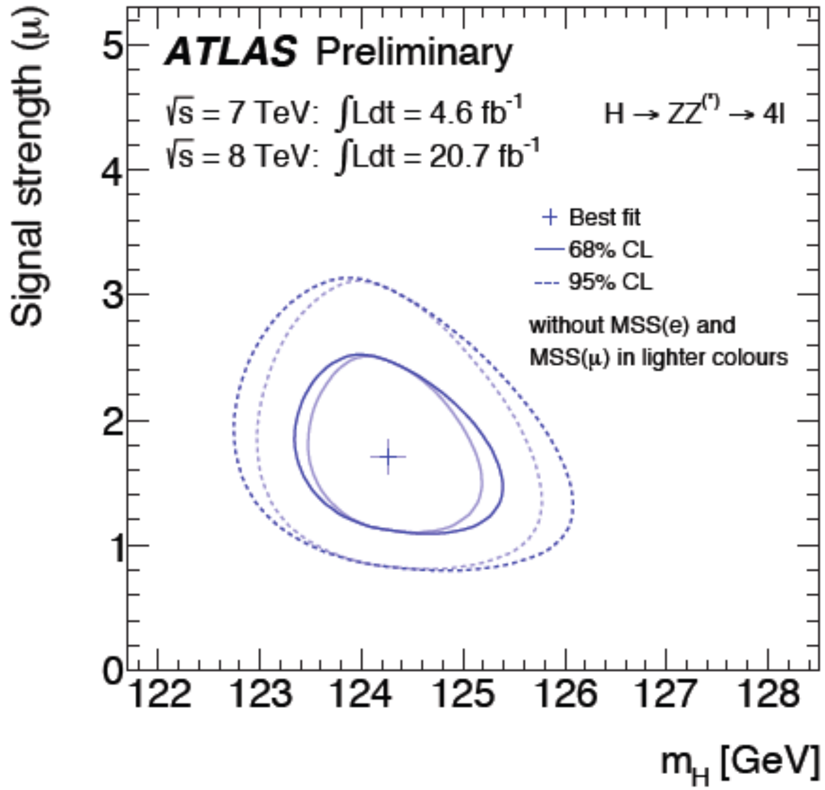
$m_{4\ell}$ > 160 GeV:	376	events observed
	348 ± 26	expected from
$\sqrt{s}$ = 7 + 8 TeV		background (mainly ZZ)

- Smallest p_0 value at m_H=124.3 GeV: 6.6σ (observed), 4.4σ (expected)

Searching for H→ZZ$^{(*)}$→4l

ATLAS-CONF-2013-013





Mass:

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

- Dominant uncertainties from lepton energy and momentum scale.

Signal strength (at m_H=124.3 GeV):

$$\mu = 1.7^{+0.5}_{-0.4}$$

$$\mu_{VH+VBF} = 1.2^{+3.8}_{-1.4}$$

$$\mu_{ggF+ttH} = 1.8^{+0.8}_{-0.5}$$

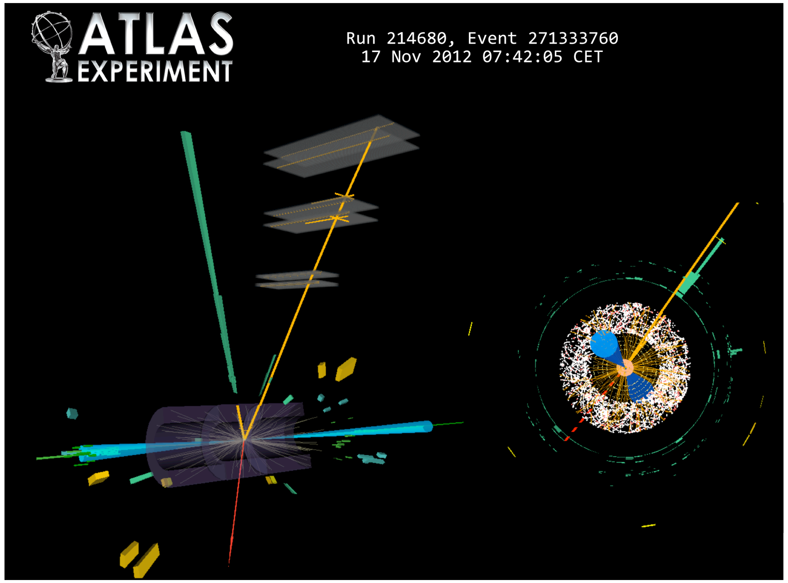
Searching for H→WW→lνlν

- Highest-sensitivity channel for m_H in the range 130-200 GeV.

- Clean dilepton plus E_T^{miss} signature.
- Main backgrounds: Z+jets, WW, W+jet/γ, top.
  ➔ normalization in data control regions

- Exploit spin correlation between W bosons: spin 0 ➔ small angular separation between leptons.
- No direct reconstruction of Higgs mass possible (neutrinos) ➔ use transverse mass

- Categorize events in different jet multiplicities:
  - Different S/B and background composition
  - Sensitivity to VBF signal



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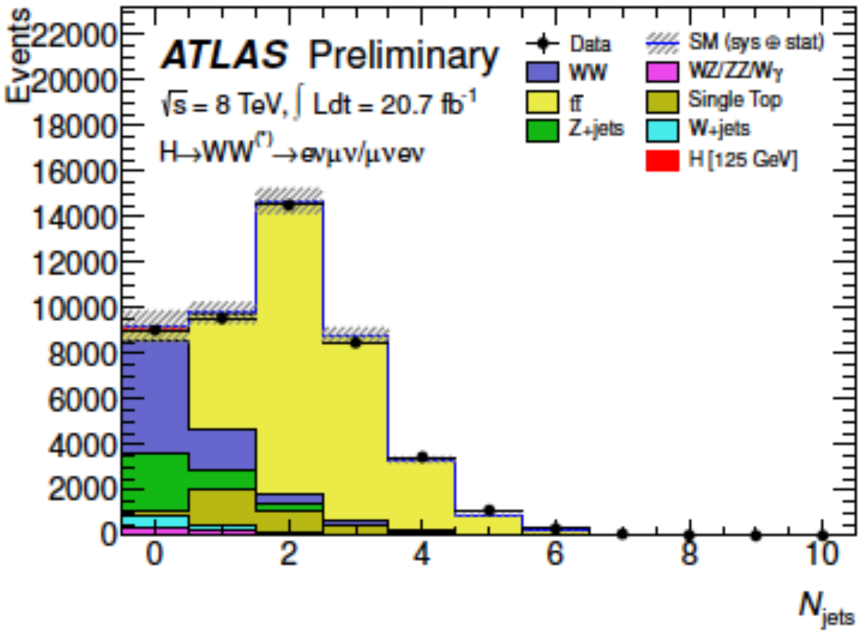

Searching for H→WW→lνlν

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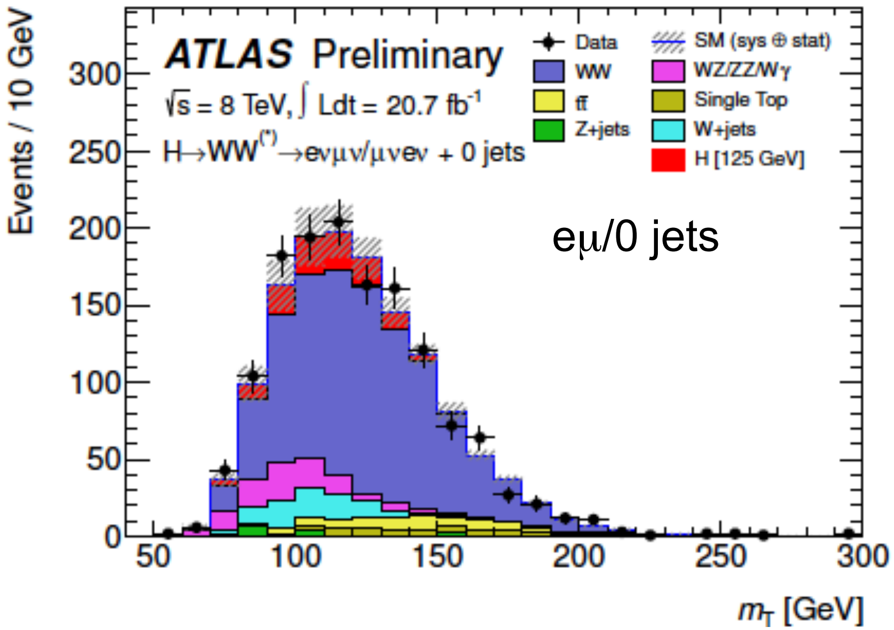

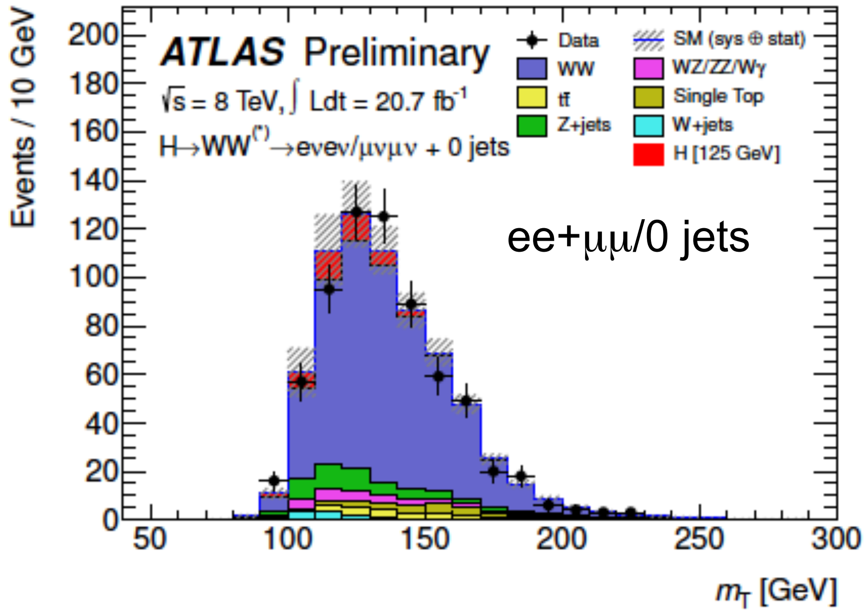

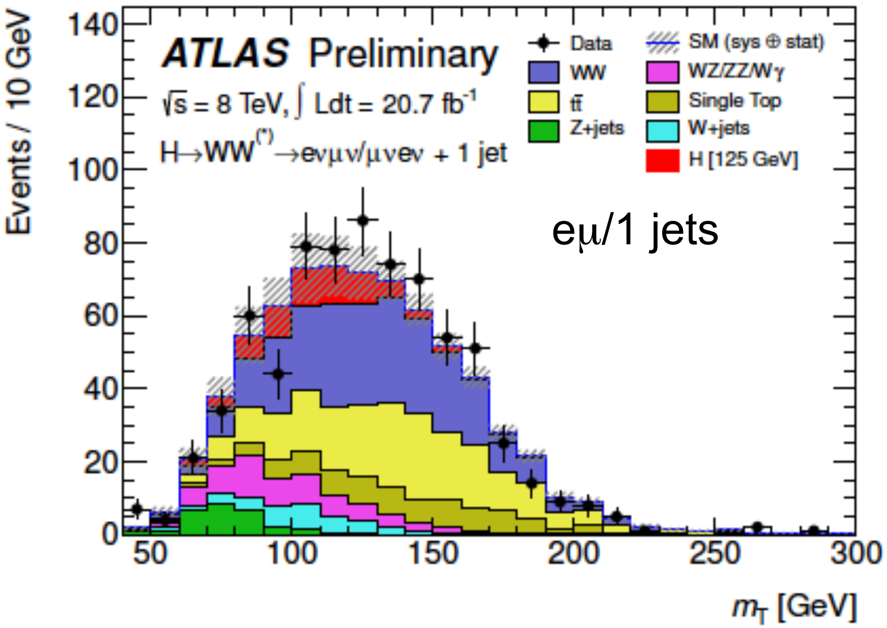

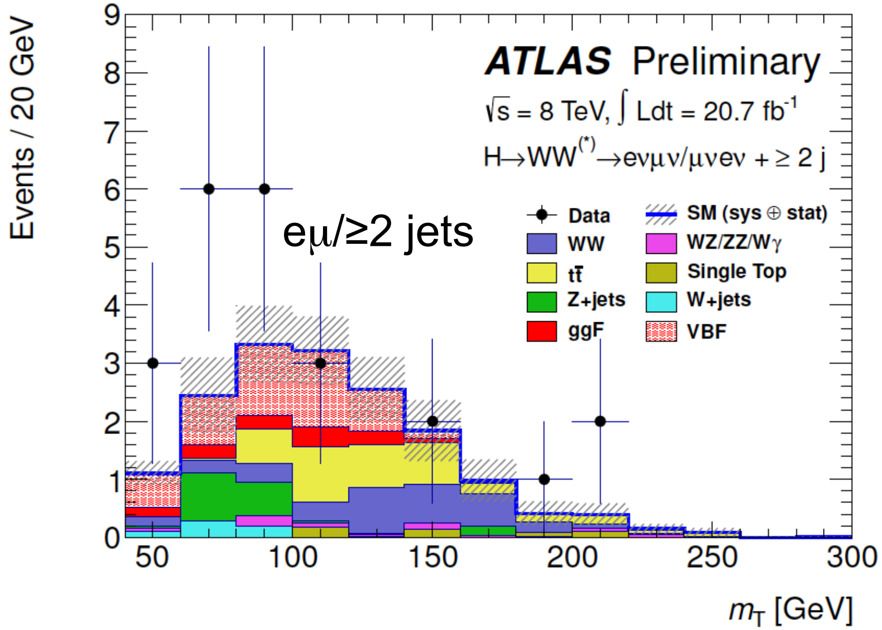

Searching for H→WW→lνlν

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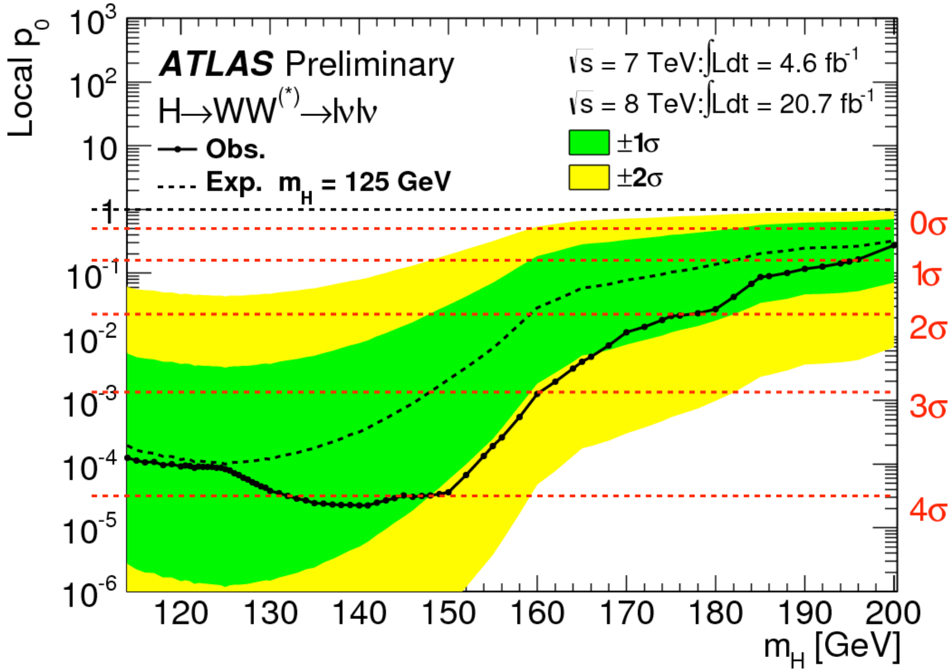
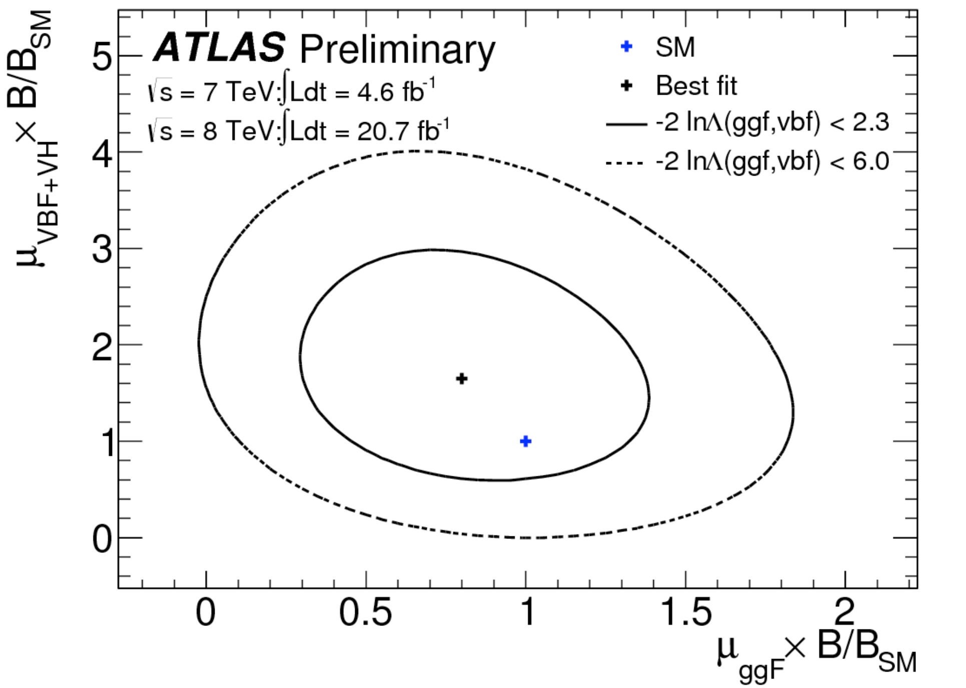




- Broad minimum of p_0 vs m_H, consistent with poor mass resolution
- p_0 value at m_H=125 GeV:
  3.8σ (observed), 3.7σ (expected)

Signal strength (at m_H=125 GeV):

$$\mu = 1.01 \pm 0.21(stat) \pm 0.12(syst) \pm 0.19(theo)$$

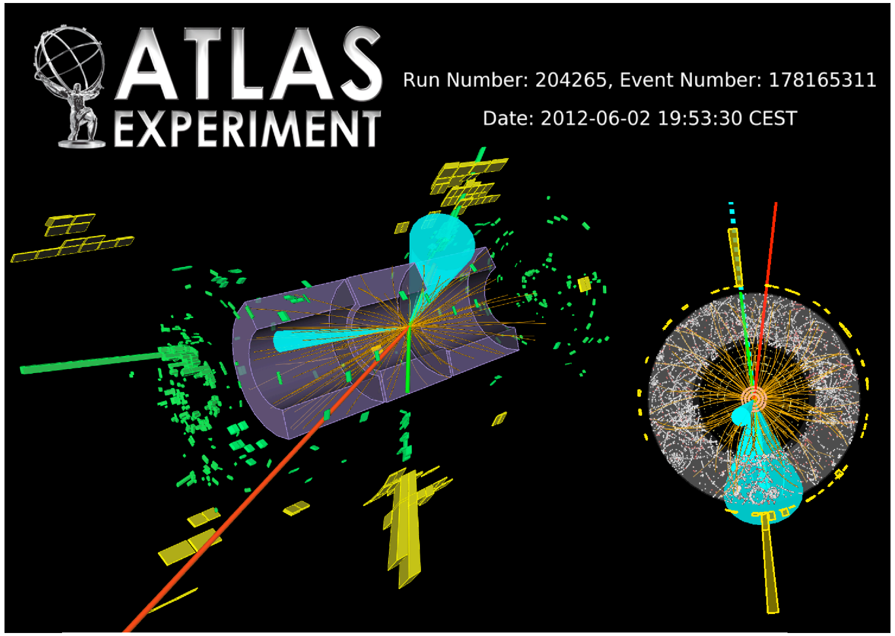
$$\mu_{VBF} = 1.66 \pm 0.79$$

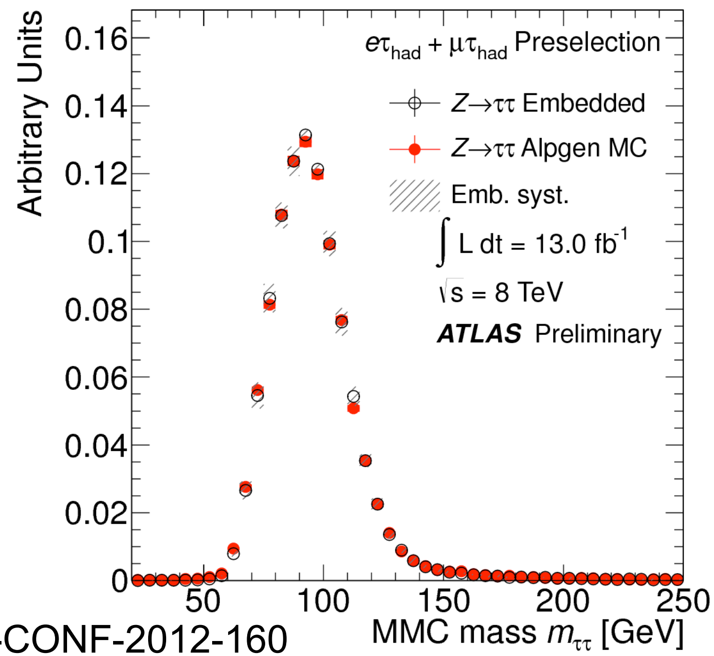
$$\mu_{ggF} = 0.82 \pm 0.36$$

Fermionic Decay Modes

Searching for H→ττ

- Consider leptonic and hadronic tau decays:
  $H \rightarrow \tau_{lep}\tau_{lep}$ (ee, μμ, eμ)
  $H \rightarrow \tau_{lep}\tau_{had}$ ($e\tau_{had}$, $\mu\tau_{had}$)
  $H \rightarrow \tau_{lhad}\tau_{had}$
- Mutlivariate tau ID to select τ_{had} from jets.
  efficiency~60%, jet fake rate ~few%
- Main background: Z→ττ.
  Modeled from Z→μμ data replacing muons by simulated tau decays ("τ embedding").
- Reconstruct $m_{\tau\tau}$ difficult (2-4 neutrinos):
  use Missing Mass Calculator (derived from measured momenta, E_T^{miss}, simulated distribution of angle between visible and missing momenta)





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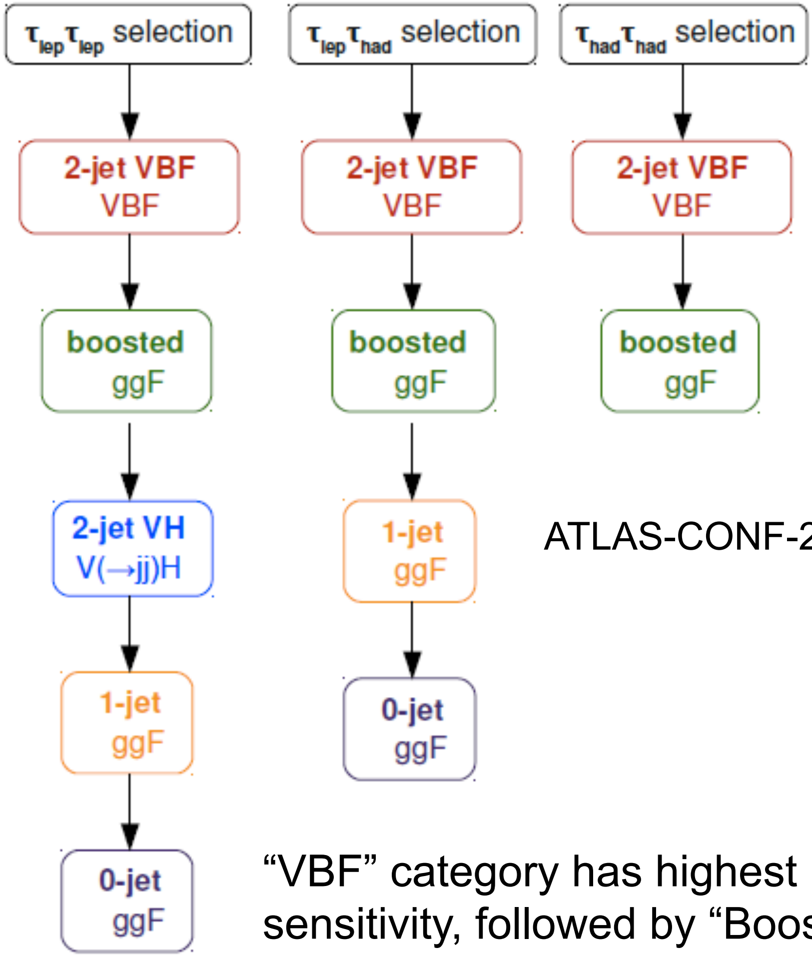
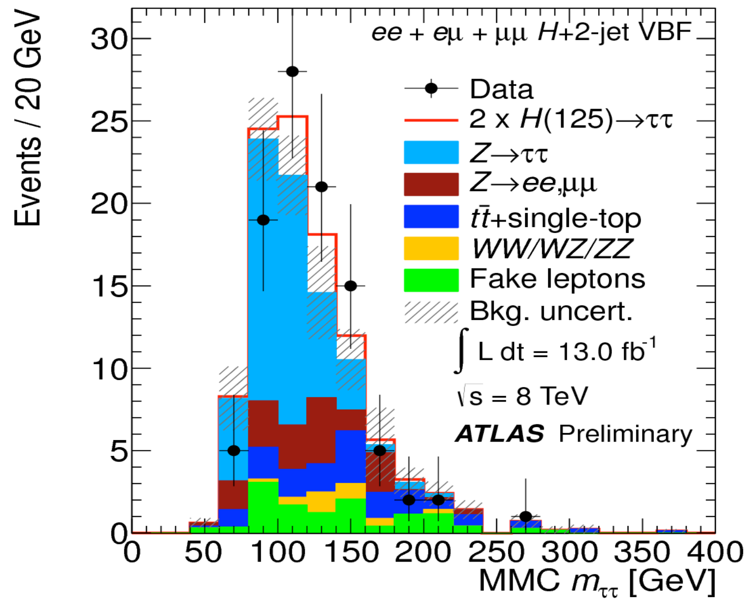
Searching for H→ττ

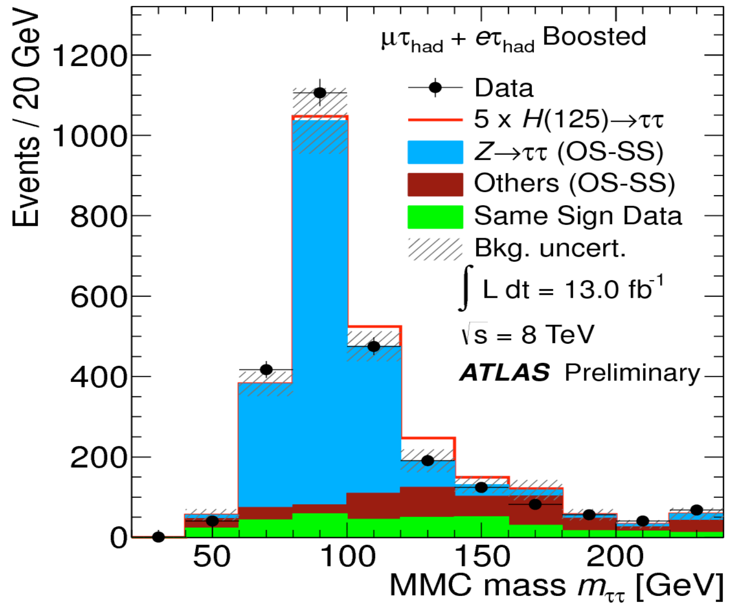
- Multiple categories to maximize sensitivity.



ATLAS-CONF-2012-160

"VBF" category has highest sensitivity, followed by "Boosted"





Searching for $H \rightarrow \tau\tau$

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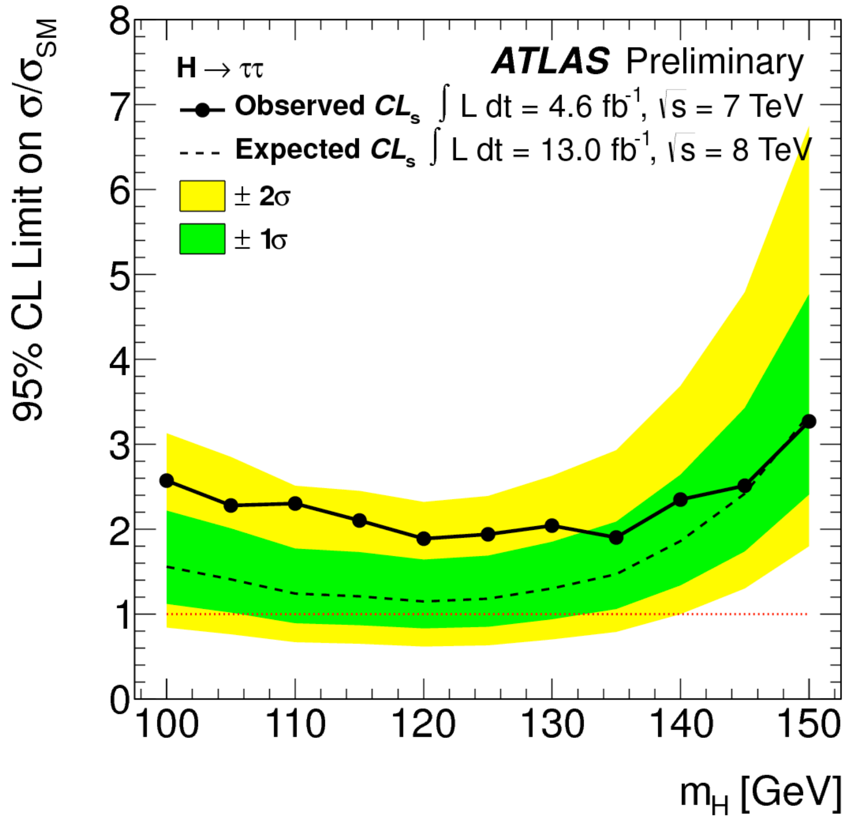
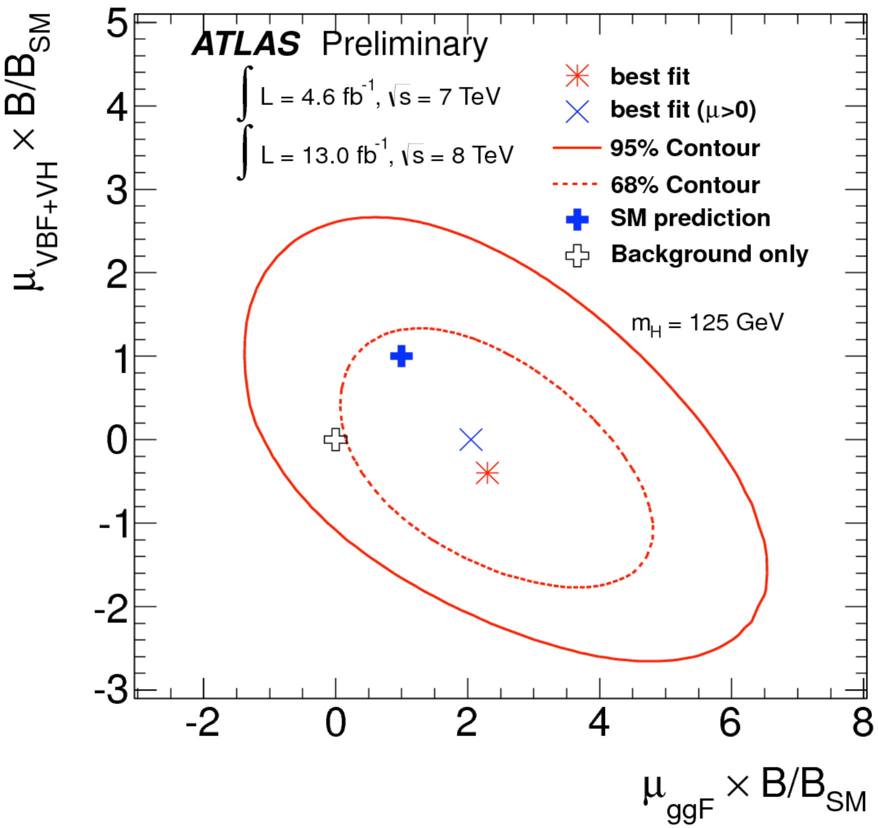




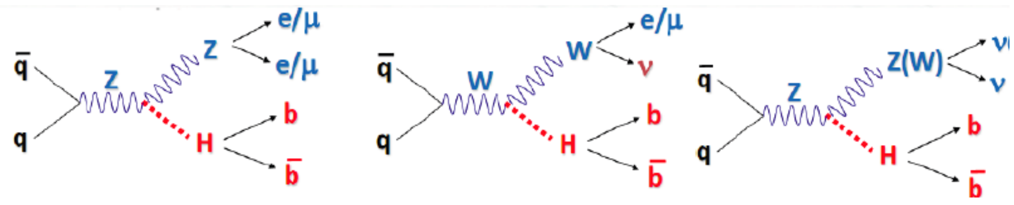
- Expected sensitivity for m_H=125 GeV still only ~1.7σ.
- No significant excess observed.
  At m_H=125 GeV:
  Observed limit: 1.9xSM
  Expected limit: 1.2xSM

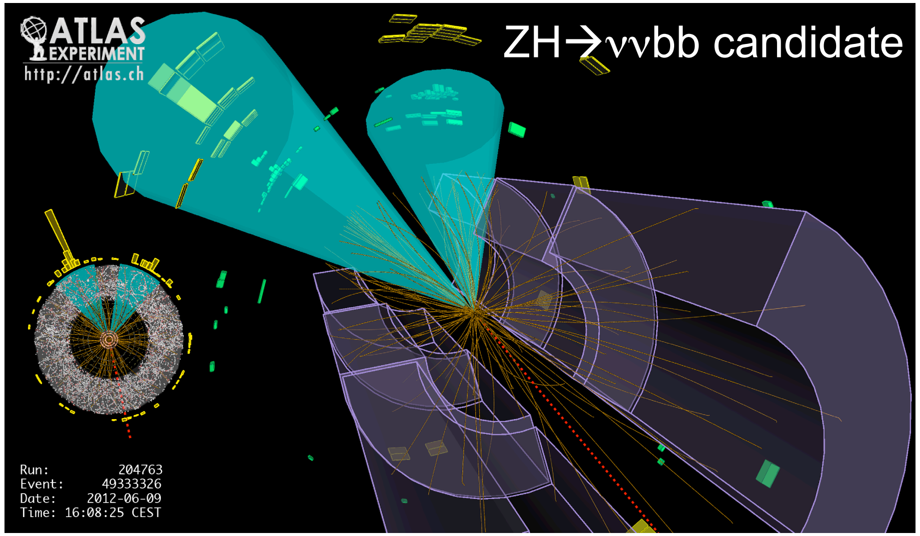
Signal strength (at m_H=125 GeV):

$$\mu = 0.7 \pm 0.7$$

Searching for $H \to b\bar{b}$

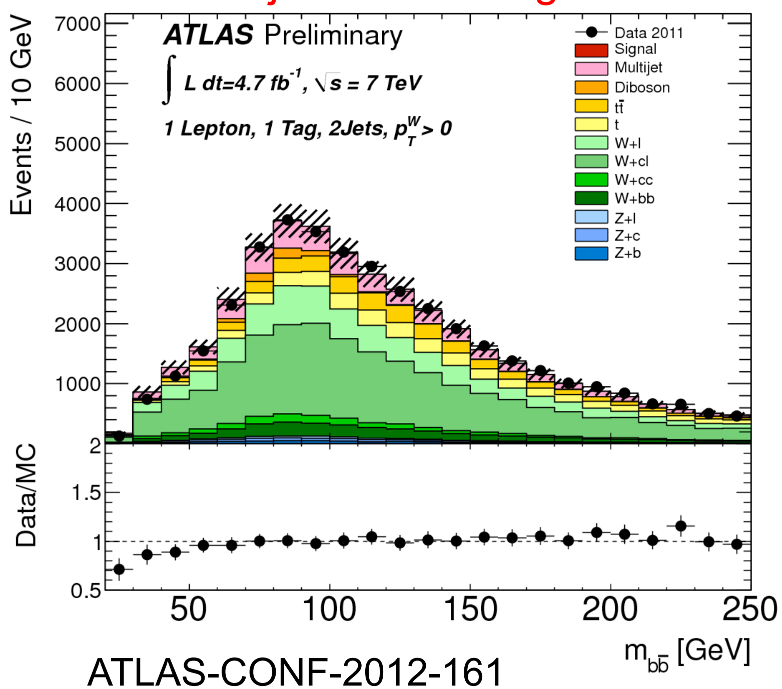
2-lepton 1-lepton 0-lepton





- Exploit three leptonic W/Z decay modes in VH associated production.
  ➔ classify events by lepton multiplicity
- Require 2 or 3 jets with 2 b-tags.
  NN-based b tagger:
  70% efficiency, 1% mistag rate
- Main backgrounds: W+heavy-flavor, $t\bar{t}$
  ➔ estimated from simulation and normalized in data control regions

W+jets control region



ATLAS-CONF-2012-161

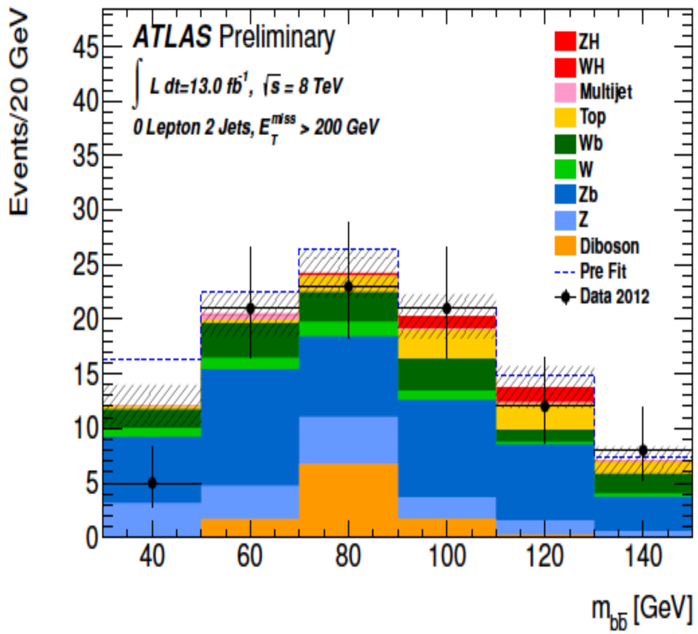
Searching for H→b$\bar{b}$

- Further categorize events in bins of W/Z p_T to increase the sensitivity.

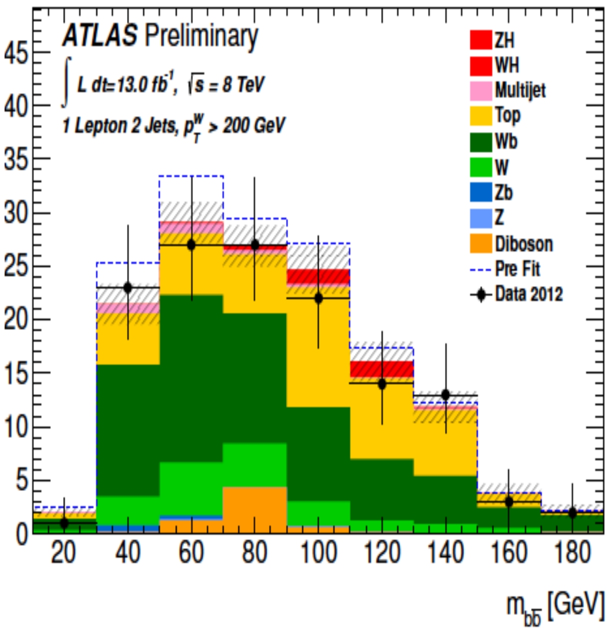
channel	bins (GeV)				
0-lepton (2/3 jets)			120-160	160-200	>200
1-lepton (2 jets)	0-50	50-100	100-150	150-200	>200
2-leptons (2 jets)	0-50	50-100	100-150	150-200	>200

- Final discriminant : 2 b-tagged jets invariant mass m_{bb}.
  Example: p_T(V)>200 GeV

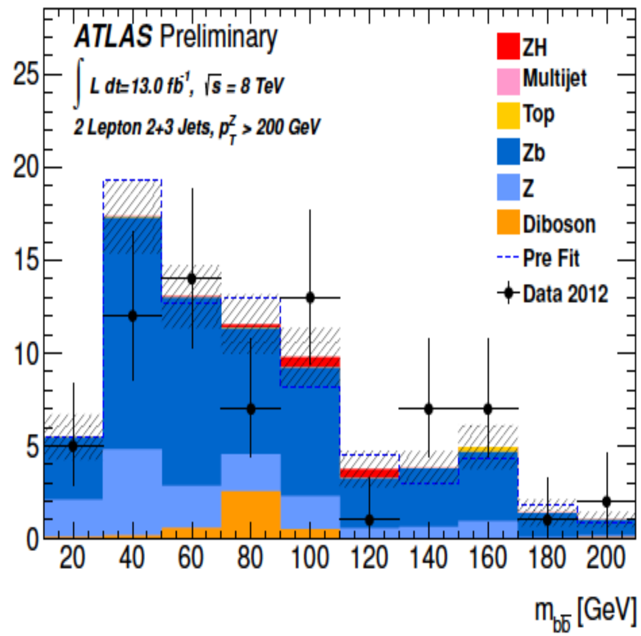
0-lepton



1-lepton



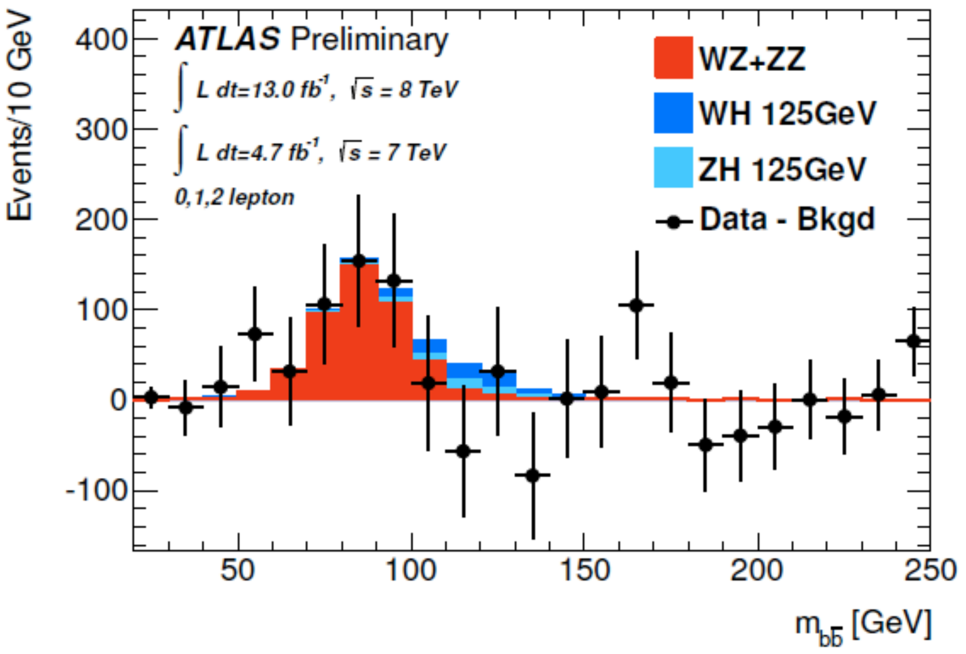
2-lepton

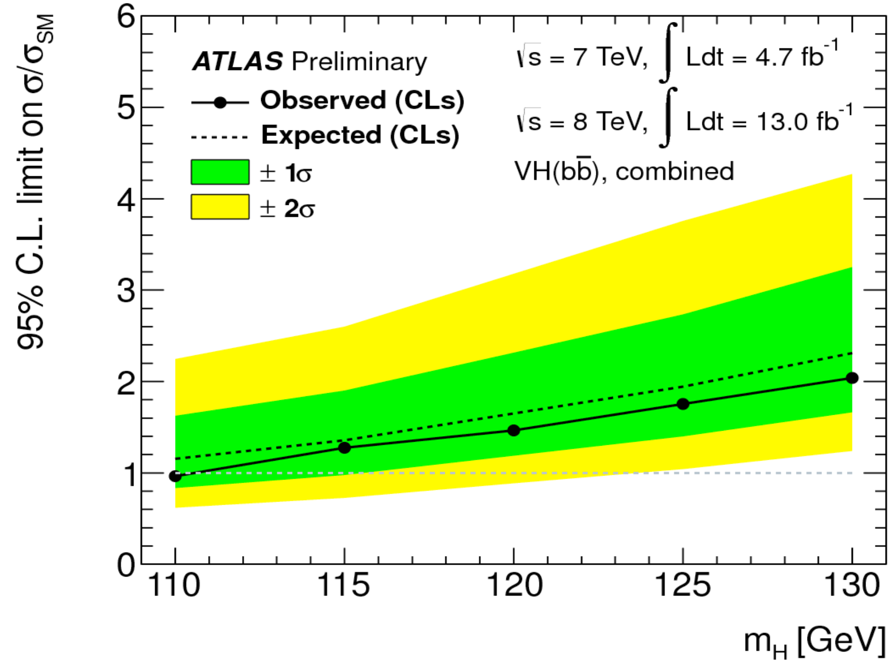


ATLAS-CONF-2012-161

Searching for H→b$\bar{b}$

ATLAS-CONF-2012-161





- Measure VZ(Z→bb) cross section to validate H→bb search strategy.
- Cross section in good agreement with the SM prediction:

$$\mu_{VZ} = 1.09 \pm 0.20(stat) \pm 0.22(syst)$$

- Significance ~4σ.

- No significant excess observed.

At m_H=125 GeV:

Observed limit: 1.8xSM

Expected limit: 1.9xSM

$$\mu = -0.4 \pm 0.8(stat) \pm 0.7(syst)$$

Improved result on the full dataset for EPS

Searching for H→μμ

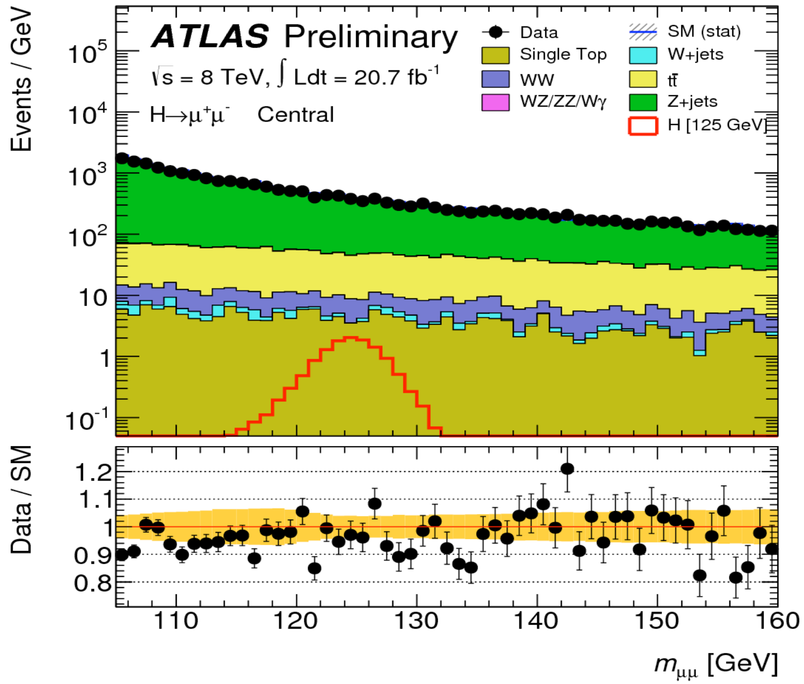
ATLAS-CONF-2013-010

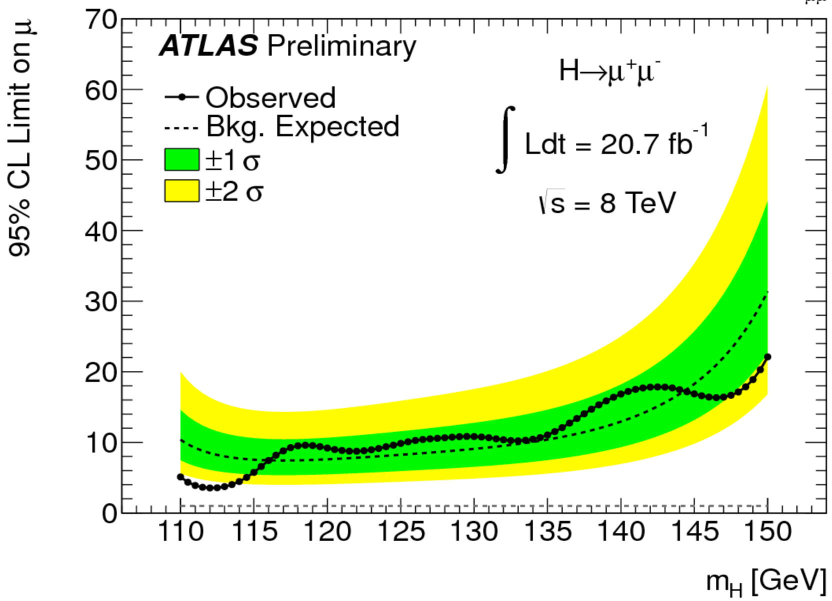
- Very rare decay mode!
  BR(H→μμ)~2.2x10^{-4} at m_H=125 GeV

- 2 opposite-sign muons with p_T>25,15 GeV
  $p_T(\mu\mu)$>15 GeV
- Huge background from Z/γ*→μμ.

- Categorize events in two channels with different dimuon mass resolution:
  - Central-central: $\Delta m_{\mu\mu}$~2.3 GeV
  - Central-forward: $\Delta m_{\mu\mu}$~2.8 GeV

- No significant excess observed.
  At m_H=125 GeV:
  Observed limit: 9.8xSM
  Expected limit: 8.2xSM

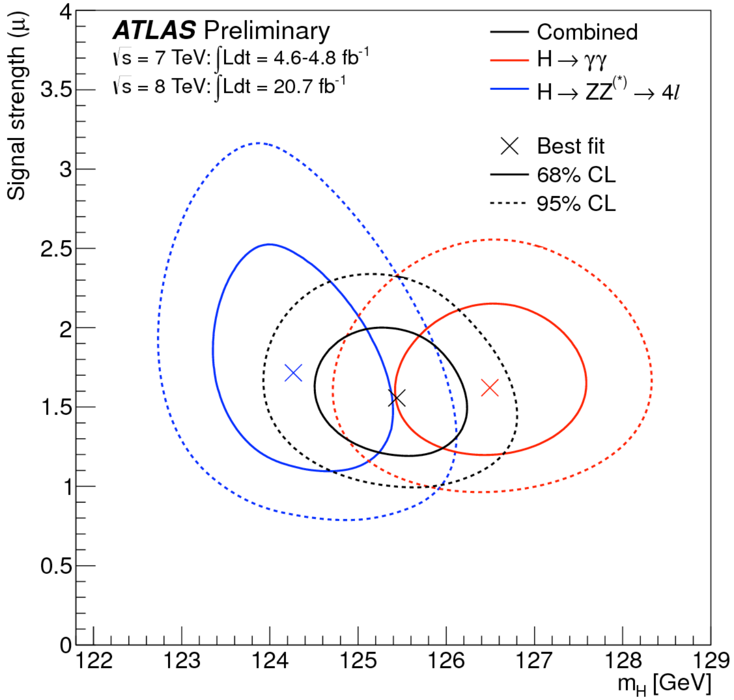




Higgs Properties

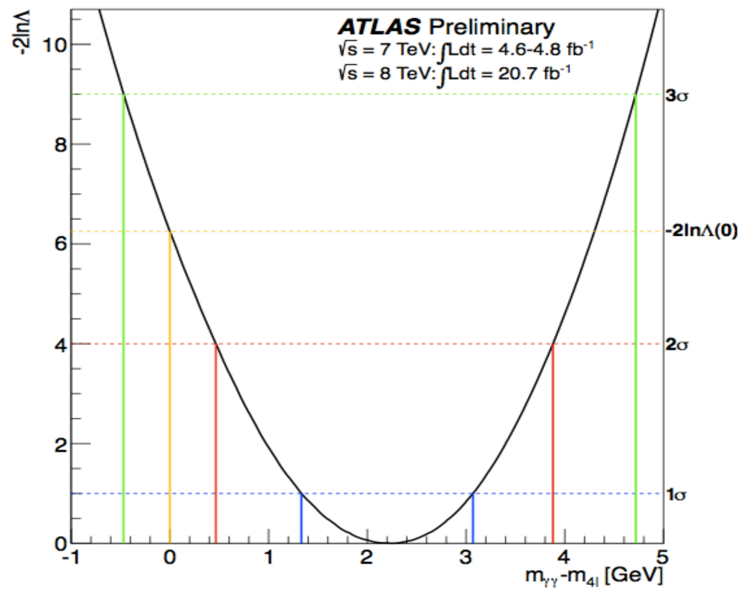
Mass

- Combination of m_H measurements in H→γγ and H→ZZ→4l channels.



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

ATLAS-CONF-2013-014



Consistency between the fitted masses from likelihood value for Δm=0 w.r.t. best-fit value for Δm.

$$\Delta m = 2.3^{+0.6}_{-0.7}(stat) \pm 0.6(syst)\ \text{GeV}$$

- Probability for disfavoring the Δm=0 hypothesis by more than observed: 1.5% (2.4σ).
- Increases to 8%, by fixing the three principle sources contributing to the e/γ energy scale uncertainty (material, pre-samples energy scale, calibration procedure) to their ±1σ values.

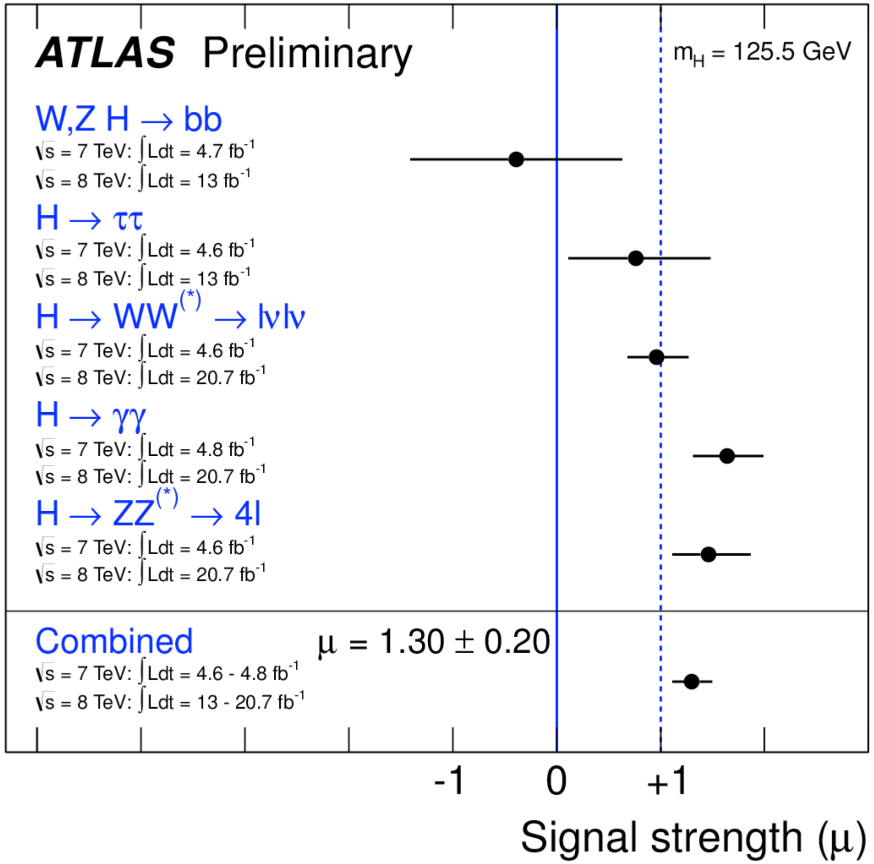
Overall Signal Strength

- Maximum likelihood fit to data with signal rate scaling factor (μ) as free parameter.
- Ratios of production cross sections for the various processes (ggF, VBF,..) fixed to SM values.

Higgs Boson Decay	μ (m_H=125.5 GeV)
$VH \to Vbb$	-0.4 ± 1.0
$H \to \tau\tau$	0.8 ± 0.7
$H \to WW^{(*)}$	1.0 ± 0.3
$H \to \gamma\gamma$	1.6 ± 0.3
$H \to ZZ^{(*)}$	1.5 ± 0.4
Combined	1.30 ± 0.20

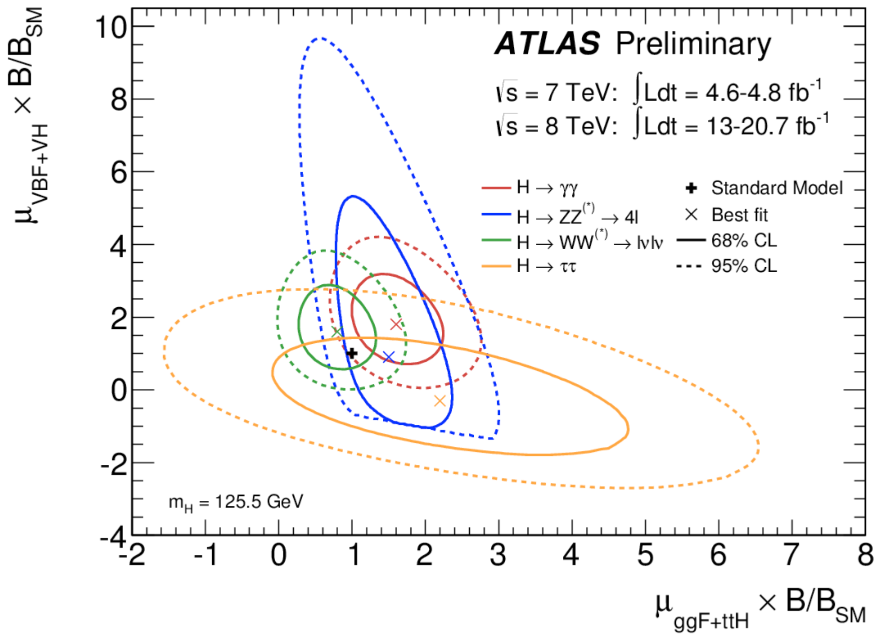
$$\mu = 1.3 \pm 0.2$$

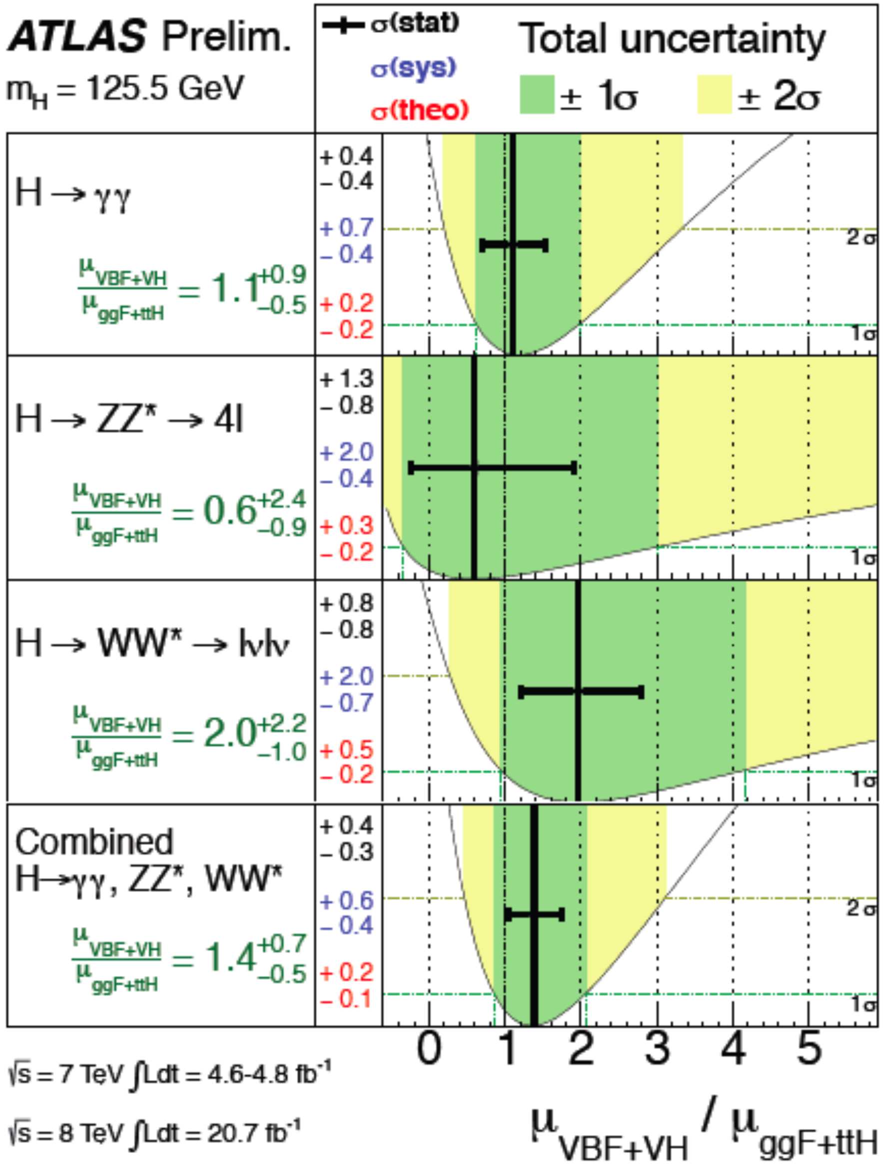
ATLAS-CONF-2013-034



Signal Strength by Production Mode

ATLAS-CONF-2013-034





- Fit for ratio $\mu_{ggF+ttH}/\mu_{VBF+VH}$ in the individual channels (more model-independent).
- Results consistent among channels. Combination consistent with the SM.

$$\mu_{ggF+ttH} / \mu_{VBF+VH} = 1.4^{+0.7}_{-0.5}$$

3.1σ evidence for VBF production

Probing Higgs Couplings

- Several production and decay mechanisms contribute to signal rates per channel
  ➔ interpretation is difficult
- A better option: measure deviations of couplings from the SM prediction (*arXiv:1209.0040*).
  Basic assumptions:
  - there is only one underlying state with m_H=125.5 GeV,
  - it has negligible width,
  - it is a CP-even scalar (only allow for modification of coupling strengths, leaving the Lorentz structure of the interaction untouched).
- Under these assumptions all production cross sections and branching ratios can be expressed in terms of a few common multiplicative factors to the SM Higgs couplings.
  Examples:

$$\sigma(gg \to H)BR(H \to WW) = \sigma_{SM}(gg \to H)BR_{SM}(H \to WW)\frac{\kappa_g^2 \kappa_W^2}{\kappa_H^2}$$

$$\sigma(WH)BR(H \to bb) = \sigma_{SM}(WH)BR_{SM}(H \to bb)\frac{\kappa_W^2 \kappa_b^2}{\kappa_H^2}$$

$$\kappa_g = f(\kappa_t, \kappa_b, m_H)$$

$$\kappa_H = f'(\kappa_t, \kappa_b, \kappa_\tau, \kappa_W, \kappa_Z, m_H)$$

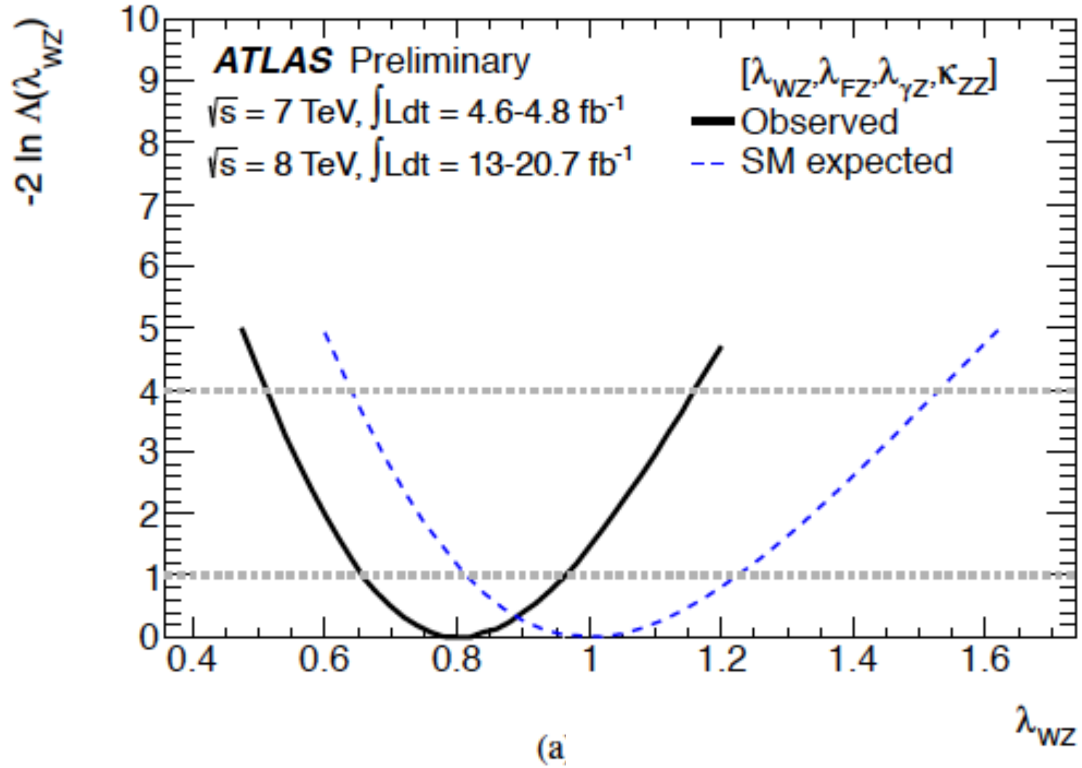
Custodial Symmetry Test

- Probe $SU(2)_V$ custodial symmetry by measuring the ratio $\lambda_{WZ}=\kappa_W/\kappa_Z$.
- Assume common multiplicative factor to all fermion couplings ($\kappa_F=\kappa_t=\kappa_b=\kappa_\tau$).
- No assumption on the total Higgs width or $H\rightarrow\gamma\gamma$ loop content.
- Free parameters:

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z/\kappa_H$$
$$\lambda_{WZ} = \kappa_W/\kappa_Z$$
$$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$$
$$\lambda_{FZ} = \kappa_F/\kappa_Z$$

$$\lambda_{WZ} = 0.80 \pm 0.15$$
$$\lambda_{\gamma Z} = 1.10 \pm 0.18$$
$$\lambda_{FZ} = 0.74^{+0.21}_{-0.17}$$
$$\kappa_{ZZ} = 1.5^{+0.5}_{-0.4}$$

ATLAS-CONF-2013-034



(a

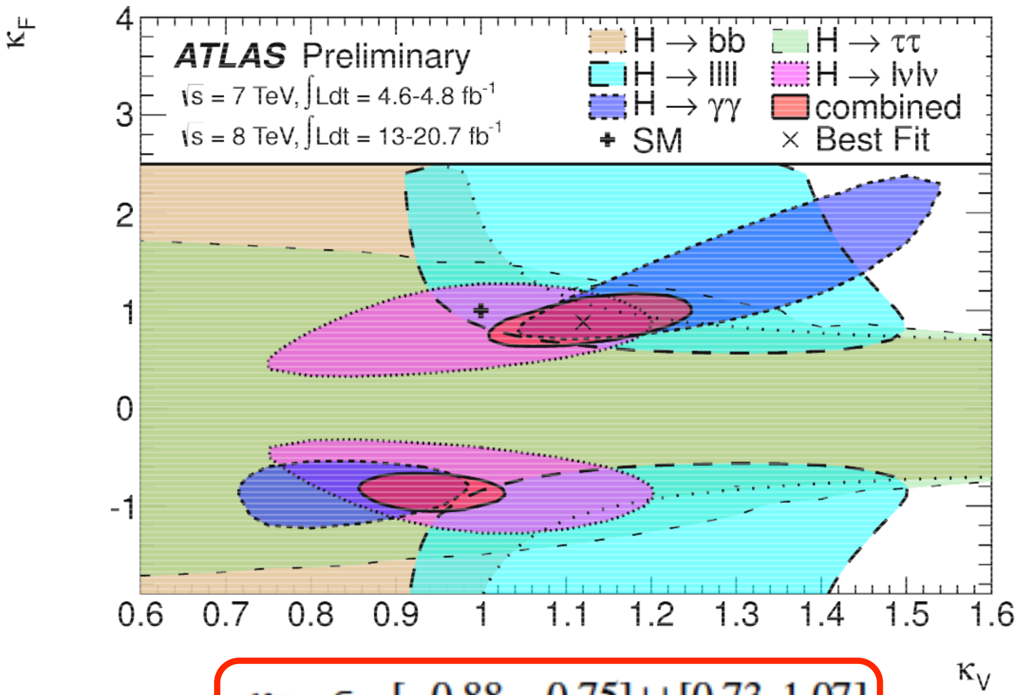
Consistent with the SM prediction

Fermion vs Vector Boson Couplings

- Consider two independent multiplicative factors: common to all couplings to vector bosons (κ_V) and common to all couplings to fermions (κ_f). Assume λ_{WZ}=1.

ATLAS-CONF-2013-034

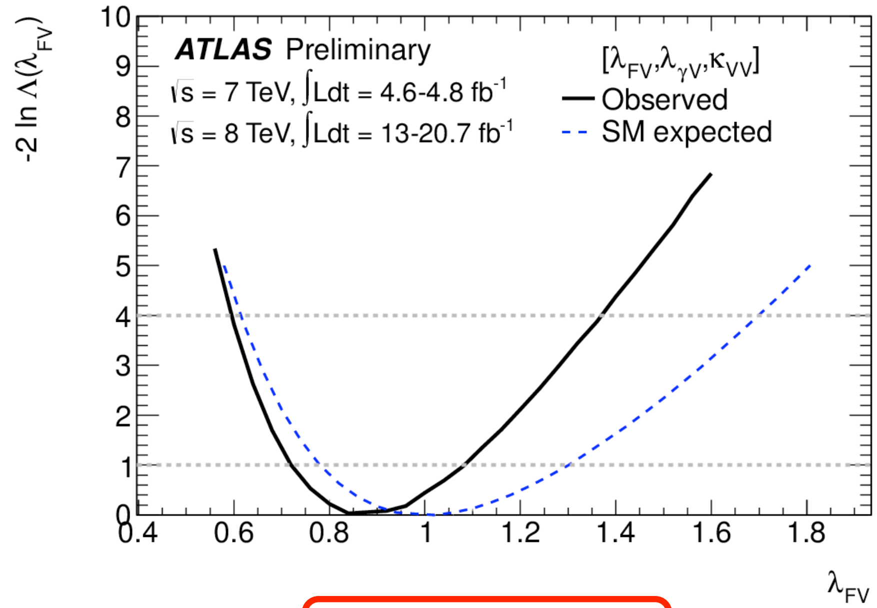
Assume no BSM contribution to the total Higgs width or the H→γγ loop



$$\kappa_F \in [-0.88, -0.75] \cup [0.73, 1.07]$$
$$\kappa_V \in [0.91, 0.97] \cup [1.05, 1.21]$$

68% CL interval

No assumption on the total Higgs width or H→γγ loop content



$$\lambda_{FV} = 0.85^{+0.23}_{-0.13}$$
$$\lambda_{\gamma V} = 1.22^{+0.18}_{-0.14}$$
$$\kappa_{VV} = 1.15 \pm 0.21$$

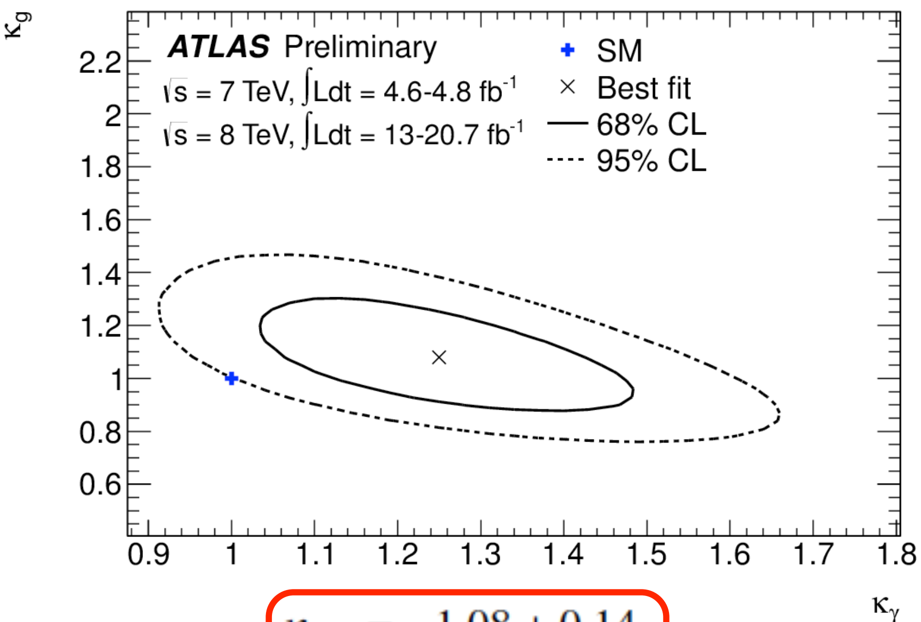
Consistent with the SM prediction

Loop-Induced Couplings

- Test on contributions from other particles contributing to loop-induced processes. New particles may or may not contribute to the total Higgs width.
- Assume nominal couplings for all SM particles κ_i=1 and introduce effective scale factors κ_g and κ_γ.

ATLAS-CONF-2013-034

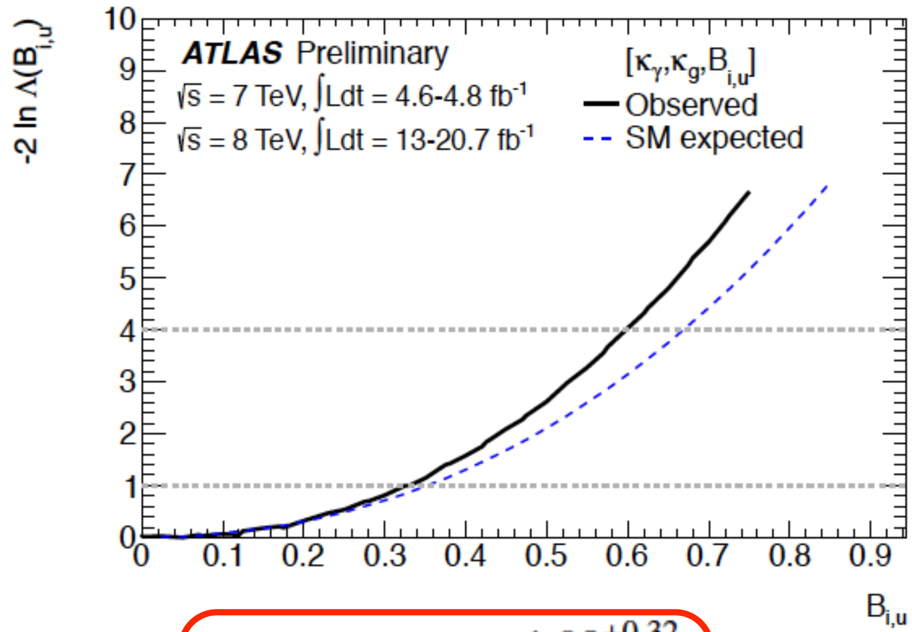
Assume no BSM contribution to the total Higgs width



$$\kappa_g = 1.08 \pm 0.14$$
$$\kappa_\gamma = 1.23^{+0.16}_{-0.13}$$

68% CL interval

No assumption on the total Higgs width



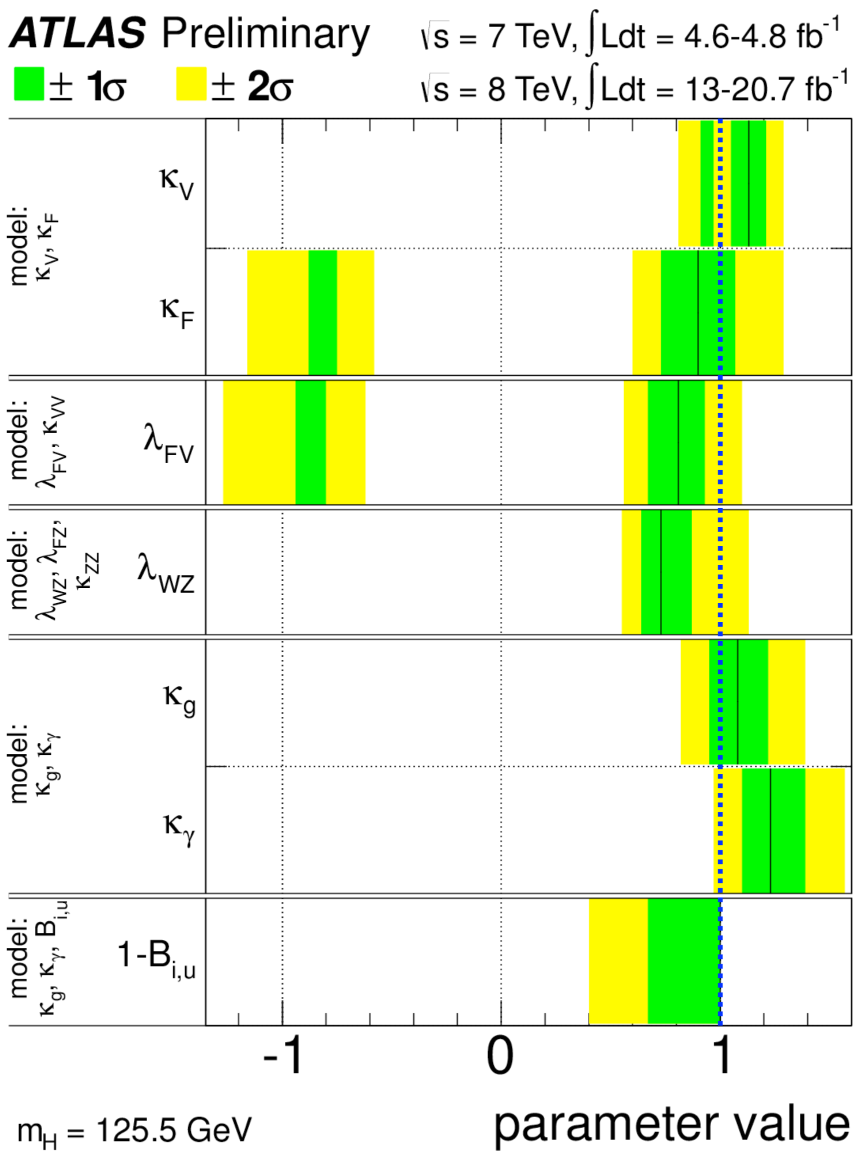
$$\kappa_g = 1.08^{+0.32}_{-0.14}$$
$$\kappa_\gamma = 1.24^{+0.16}_{-0.14}$$
$$BR_{inv.,undet.} < 0.33$$

68% CL interval

Consistent with the SM prediction

Summary of Coupling Measurements

ATLAS-CONF-2013-034

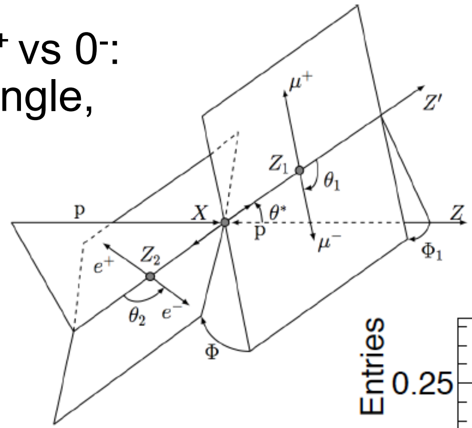


- Vector-boson couplings measured to ~10%.
- Indirect observation of fermion couplings.
- Ratio of W and Z couplings consistent with SM (custodial symmetry).
- No evidence for BSM contributions to loop-induced couplings.
- No evidence for decays to invisible particles.

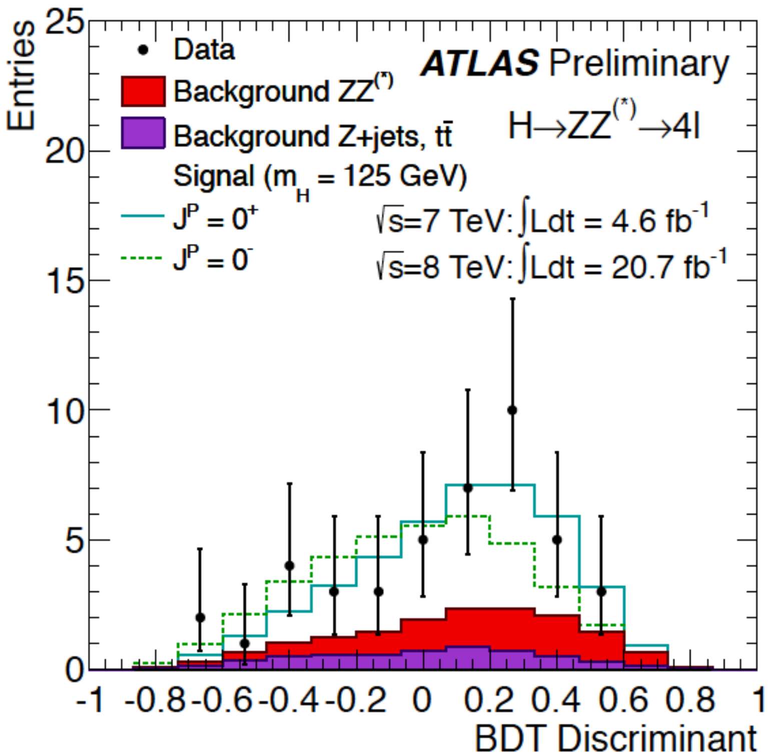
Spin and Parity: 0^+ vs 0^-

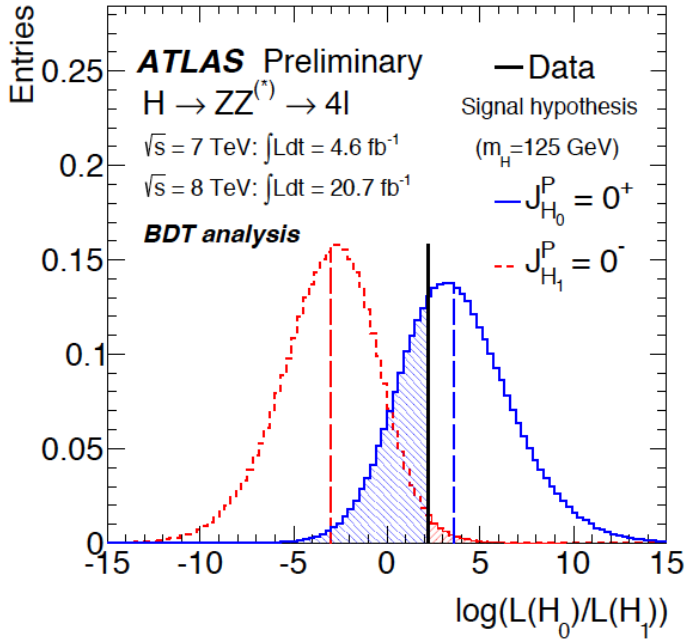
- SM Higgs boson: $J^P=0^+$.
- Strategy is to falsify other hypotheses ($J^P=0^-$, $1^\pm$, $2^\pm$) and to demonstrate consistency with $J^P=0^+$. J=1 strongly disfavored by observation of $H \rightarrow \gamma\gamma$ (Landau-Yan theorem).

- $H \rightarrow ZZ \rightarrow 4l$ decays very sensitive to 0^+ vs 0^-: mass of the two bosons, production angle, four decay angles
  ➔ combine into a BDT analysis



ATLAS-CONF-2013-013

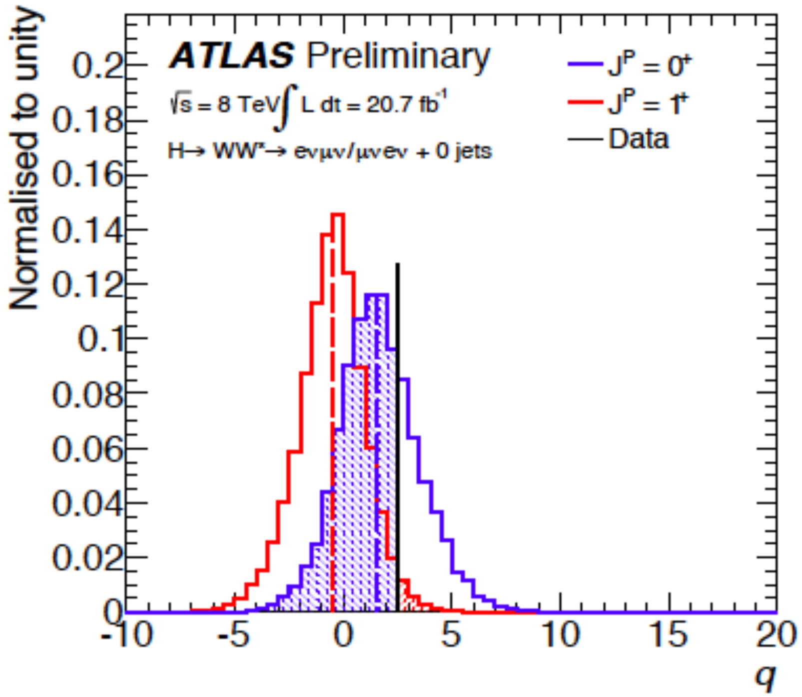


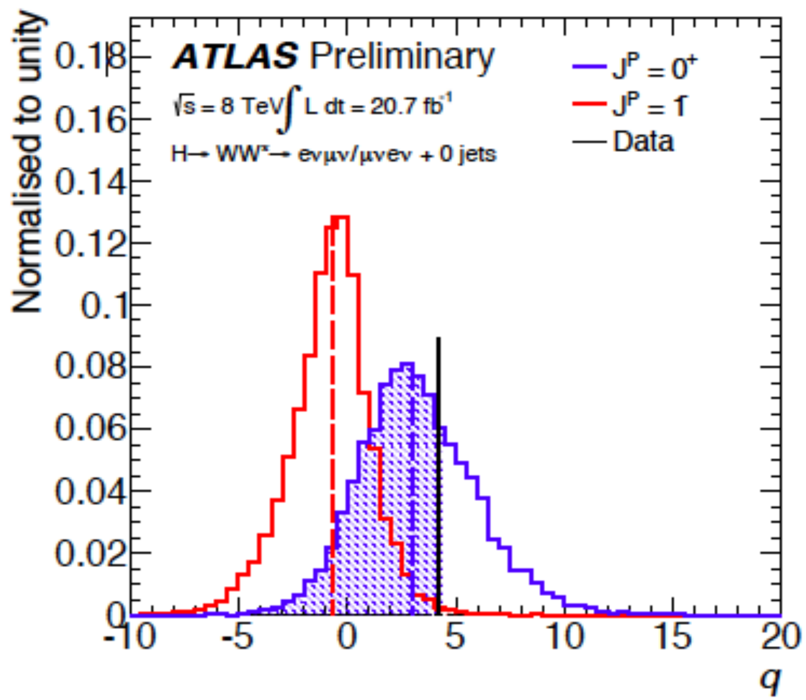


Exclude $J^P=0^-$ (vs. 0^+) with 97.8% CL

Spin and Parity: 0^+ vs $1^\pm$

- In addition to $H \rightarrow ZZ \rightarrow 4l$, use also $H \rightarrow WW \rightarrow l\nu l\nu$.
- Sensitive variables in $H \rightarrow WW \rightarrow l\nu l\nu$: m_{ll}, $\Delta\phi_{ll}$, p_{Tll}, m_T ➔ combine into a BDT analysis



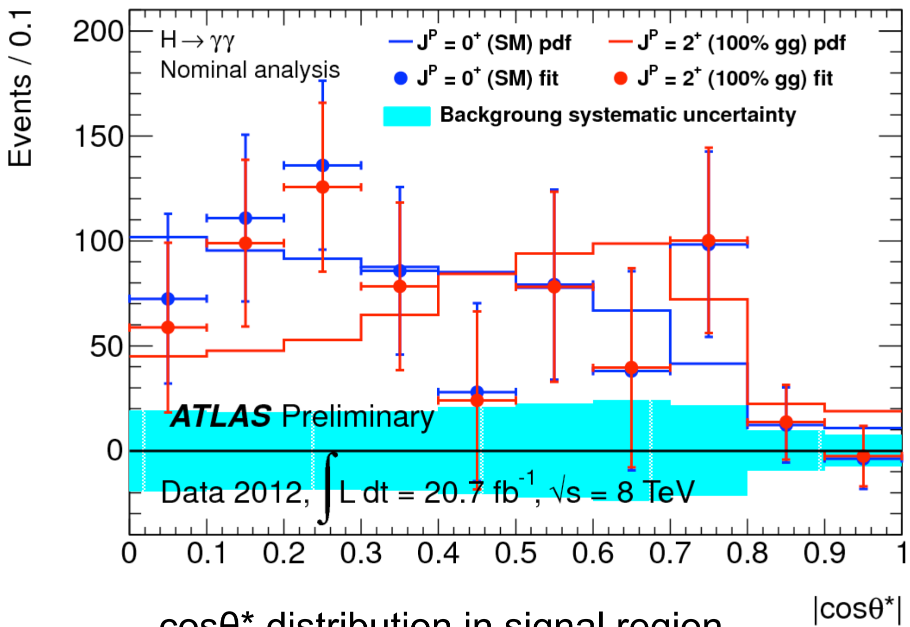


	$p_0(0^+)$	Exclusion CL(1^+)	$p_0(1^-)$	Exclusion CL(1^-)
$H \rightarrow ZZ^*$	0.55	99.8%	0.1	94%
$H \rightarrow WW^*$	0.70	92%	0.66	98%
Combination	0.62	99.97%	0.33	99.7%

Spin and Parity: 0^+ vs 2^+_m

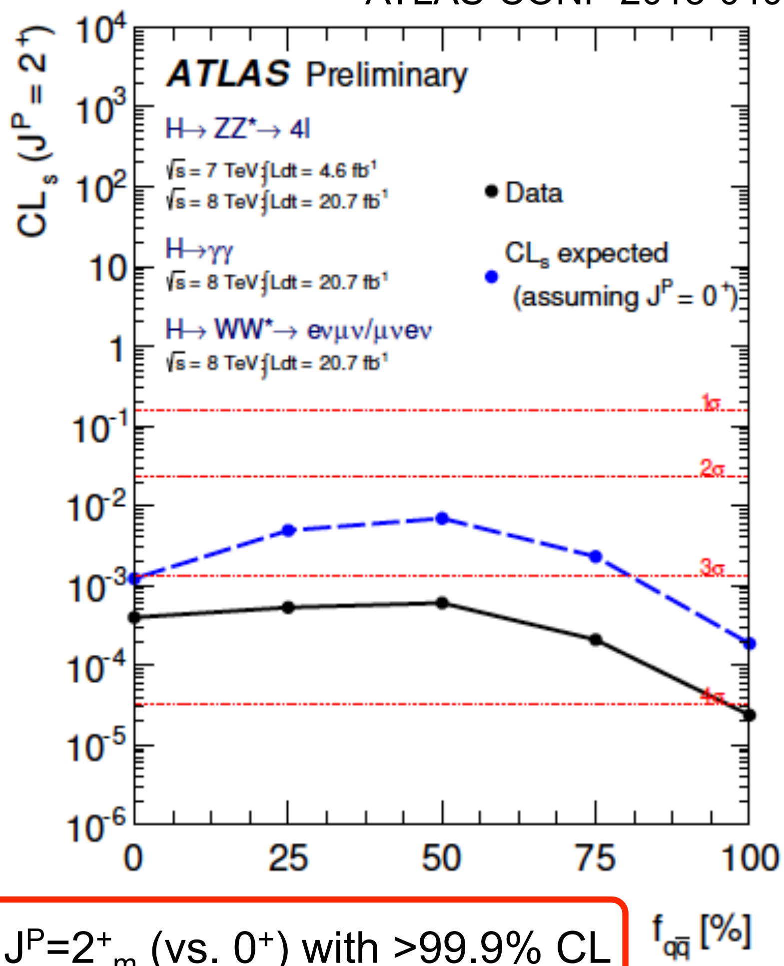
- Spin 2: consider graviton-inspired model with minimal couplings to Standard Model particles. [Y. Gao et al, Phys. Rev. D81 (2010) 075022]
- Production via gluon fusion and $q\bar{q}$ annihilation possible.
  ➔ Studies performed as a function of the $q\bar{q}$ annihilation fraction ($f_{q\bar{q}}$).
- Channels: H→ZZ→4l, H→WW→lνlν, and H→γγ. Sensitive variable in H→γγ: decay angle w.r.t. collision axis in the Collins-Soper frame.

ATLAS-CONF-2013-029



cosθ* distribution in signal region after background subtraction

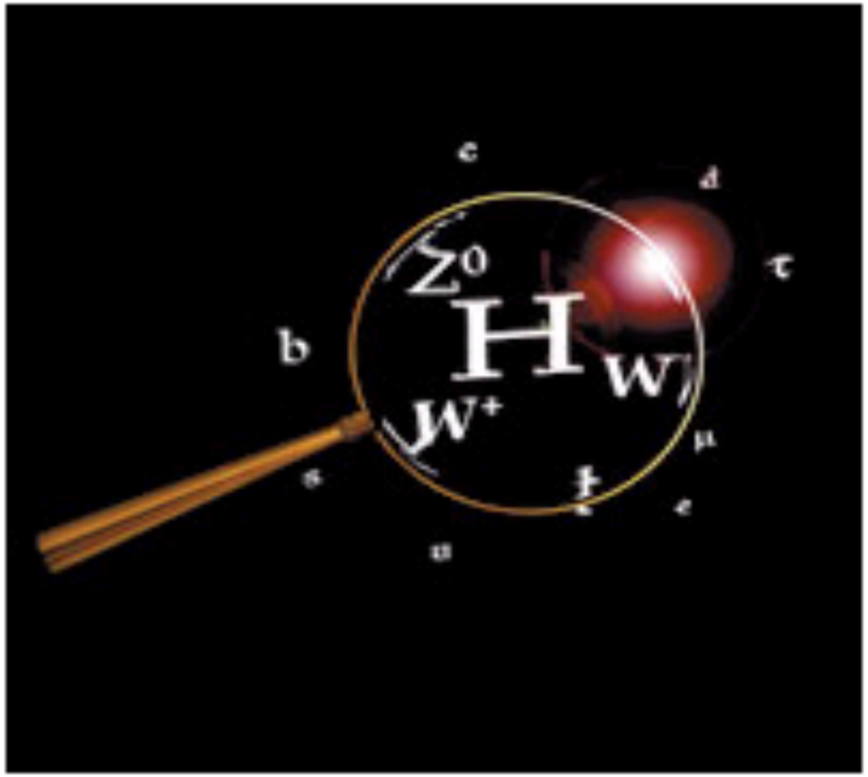
ATLAS-CONF-2013-040



Exclude $J^P=2^+_m$ (vs. 0^+) with >99.9% CL

Summary and Conclusions

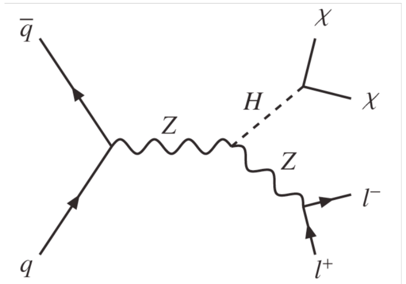
- ATLAS Higgs program has moved from the discovery phase to the phase of properties measurements.
- Based on the analysis of the full 7 and 8 TeV datasets, the discovered particle appears consistent (within the current precision) with the SM Higgs boson:
  - CP-even scalar
  - Couplings proportional to mass
- However, precision is still limited and there is room for surprises (deviations in couplings, non-standard production/decay modes, additional Higgs bosons,..).
- But we are just at the beginning of a 20-year program! Exciting times head!



Backup

Searching for H→invisible

- Some BSM models allow for a significant BR to stable or long-lived particles.



- Search for excess in ZH→ll(inv).
  Require: one Z→ee,μμ candidate,
  E_T^{miss}>90 GeV,
  Z p_T and E_T^{miss} back-to-back, 0 jets

- Main backgrounds after final selection: ZZ, WZ.

- No significant excess observed.
  Assuming the ZH production rate for m_H=125 GeV:
  BR(H→inv)<65% at 95% CL (exp. 84%)

ATLAS-CONF-2013-011