Latest Higgs Boson Results from ATLAS

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On behalf of the ATLAS Collaboration

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Introduction

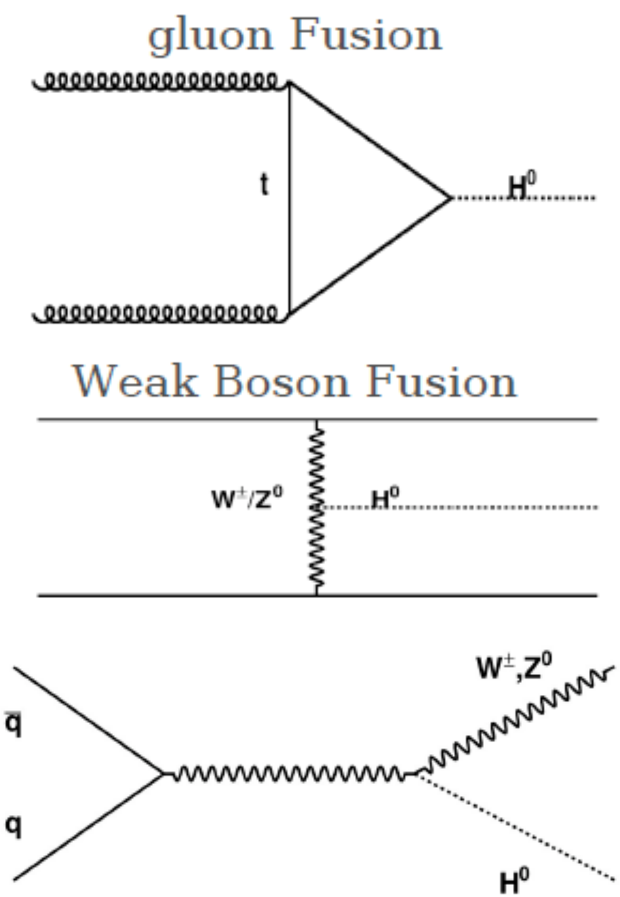
2012: A historic year in particle physics

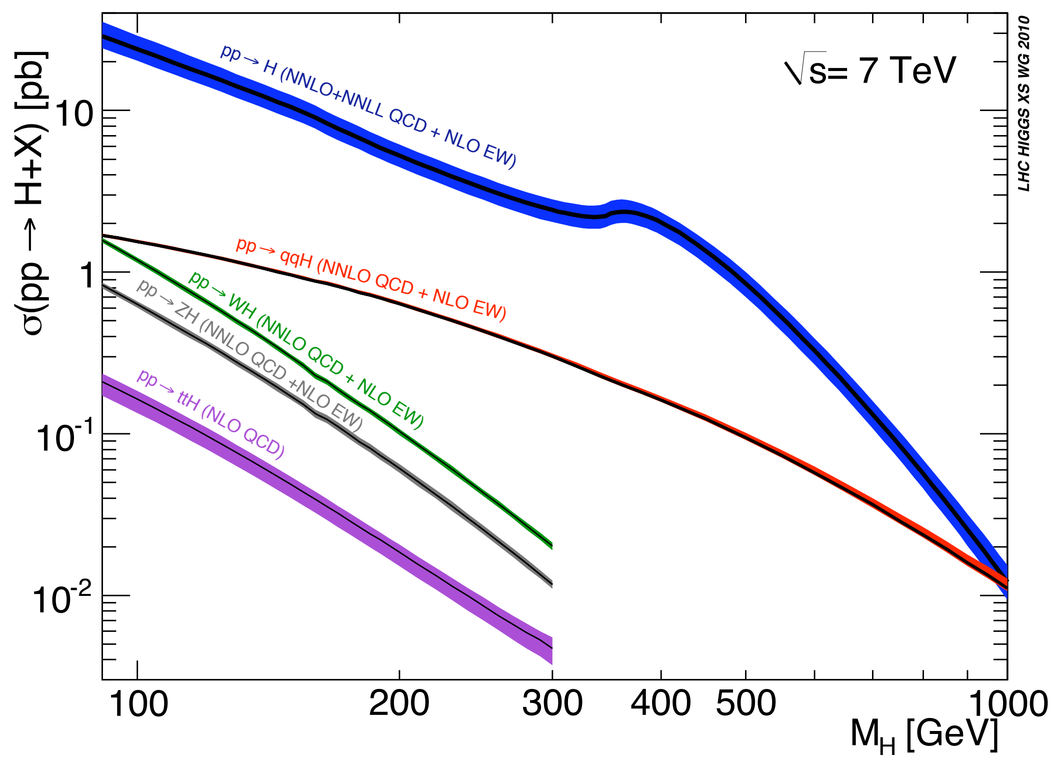
- Announced discovery of "Higgs-like" particle in early July, followed by submission of paper in late July
- After July: add data, improve analyses, characterize the new particle, continue the search for other Higgs particles
- Characterization phase is ongoing:
  - Are the observed rates in each channel where a significant excess is observed compatible with the SM prediction?
  - Does the particle decay to fermions?
  - Is the particle consistent with a spin 0 with CP even couplings? (and inconsistent with other hypotheses)

- This talk will focus on the latest results in the following channels: WW, ZZ, $\gamma\gamma$, $\tau\tau$, bb

Higgs Production

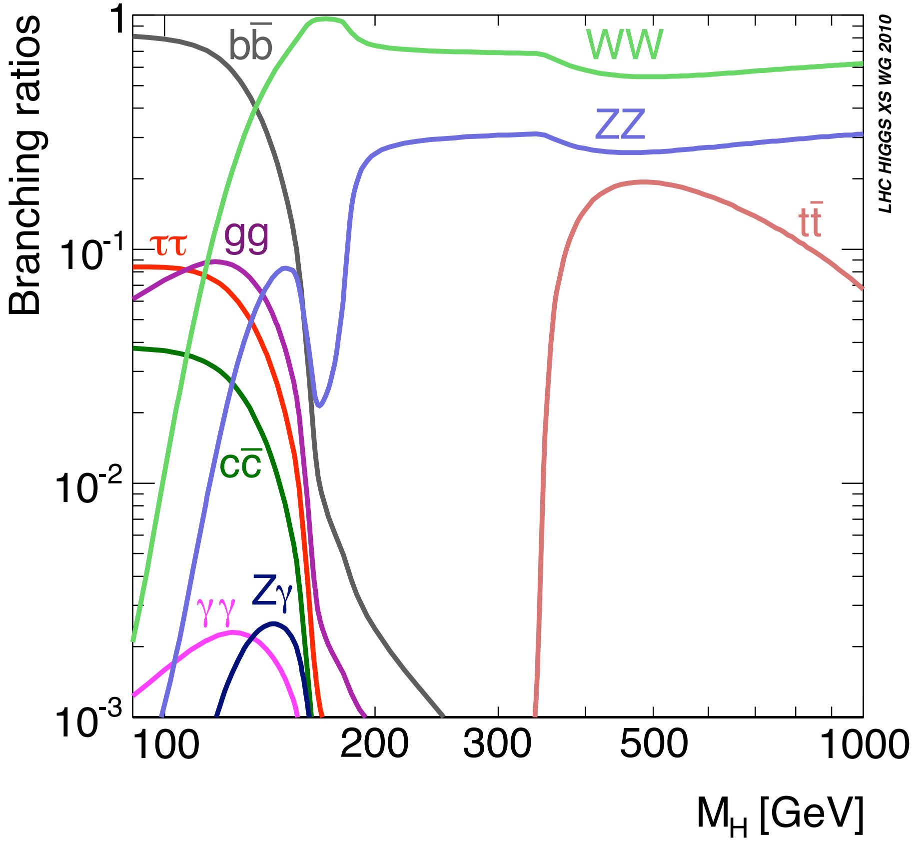
- Higgs production at LHC dominated by “gluon fusion” process
- “Weak boson fusion” is subdominant but has less background

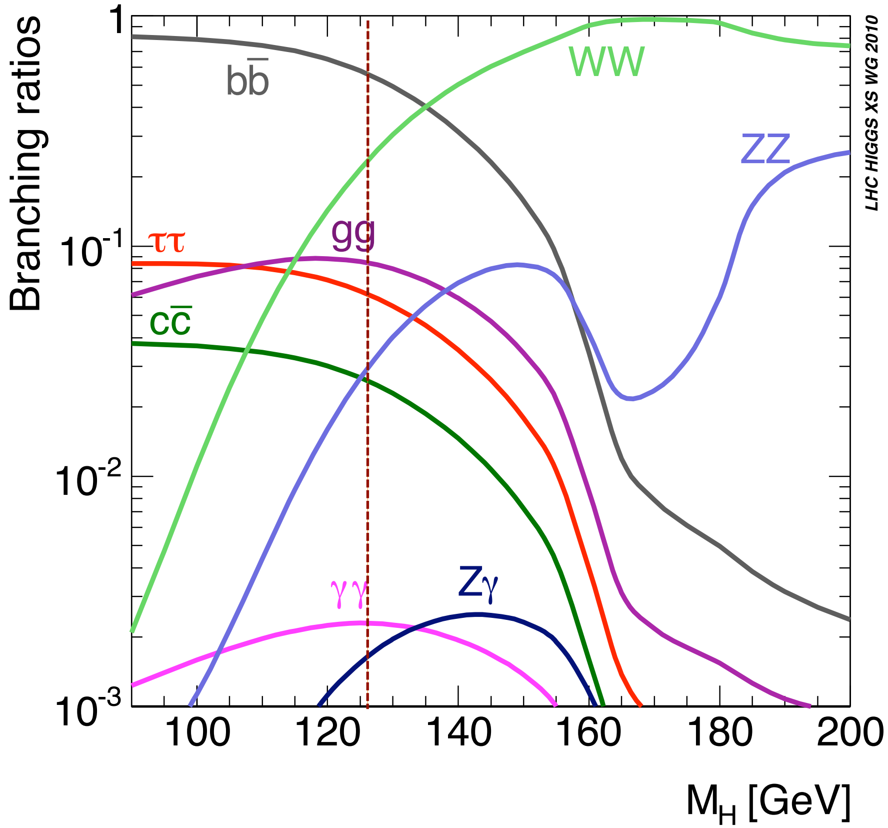




Higgs Decays

- Given a Higgs mass, the Standard Model provides precise prediction of the decay rates. At 125 GeV, we can observe many decay modes: Higgs measurements require that we fully exploit the detector capabilities (e, μ, τ, γ, etmiss, jets, tag HF-jets, trigger)





Trigger, Pileup, Data Acquisition

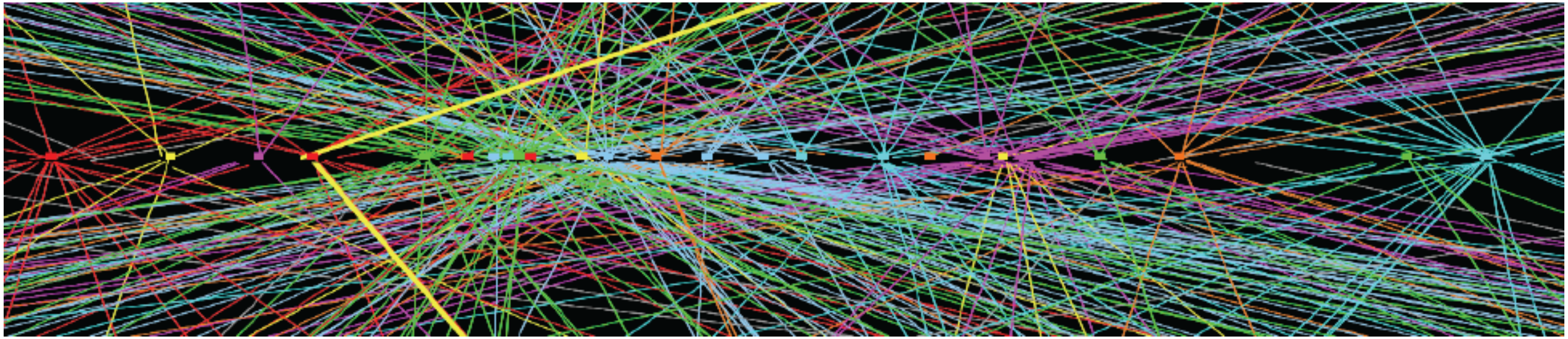
- Data/MC samples: 120 PB
- Over 30 collisions per event at high luminosity: increases event size and processing times for reconstruction
- Have maintained good trigger and object reconstruction efficiency in high pileup environment
- Data taking/quality efficiency is 90% (from delivered to physics)

Example rates

Trigger	p_T Threshold	Rate (Hz) *
Inclusive e	24	70
Inclusive μ	24	45
ee	12	8
$\mu\mu$	13	5
$\tau\tau$	29,20	12
$\gamma\gamma$	35,25	10
E_T^{mis}	80	18
5-jets	55	8

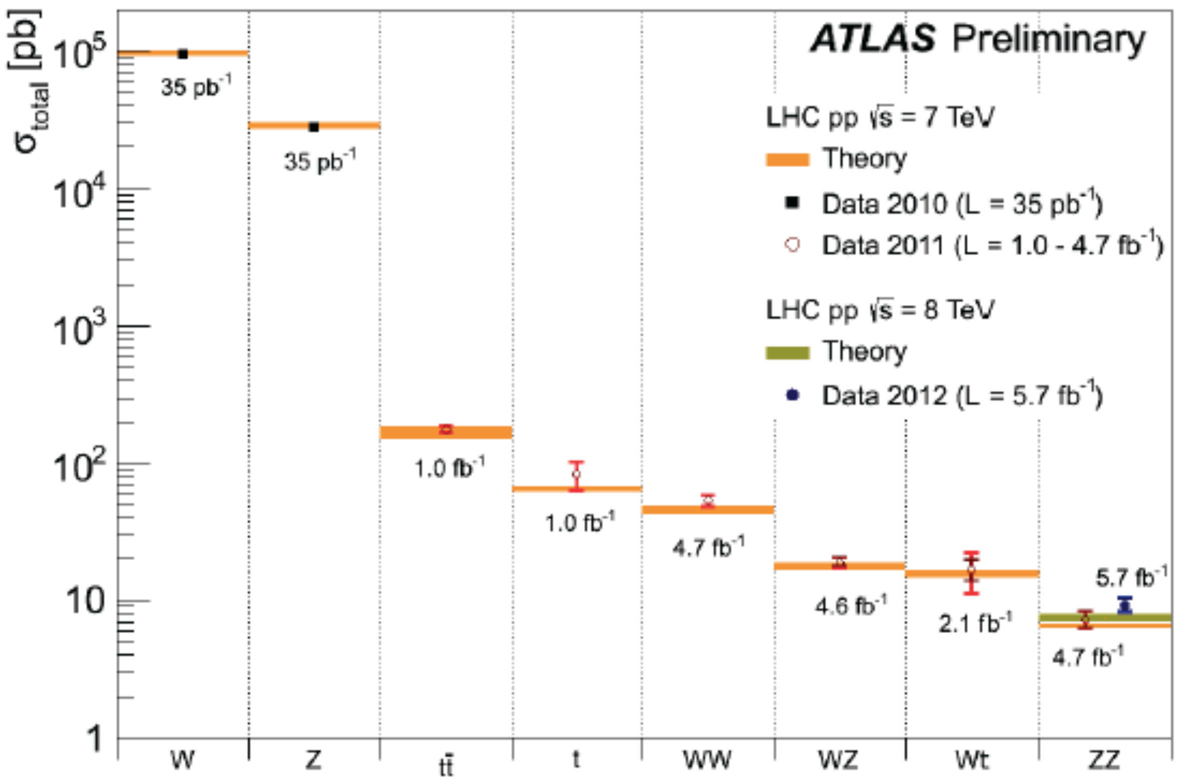
* At 5 10^{33} $cm^{-2}s^{-1}$

Total trigger rate: 400 Hz



Backgrounds and Cross sections

- Higgs searches/measurements depend on an excellent understanding of many different SM processes
- Analyses are benefitting from more precise theory calculations
- Large samples of events are used for calibration



- **100M leptonic W decays**
- **10M leptonic Z decays**
- **0.4M top l+X decays**

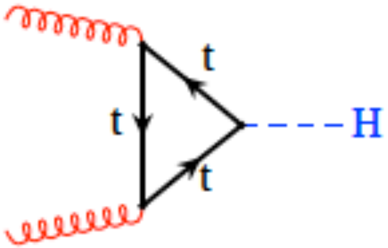
~Higgs

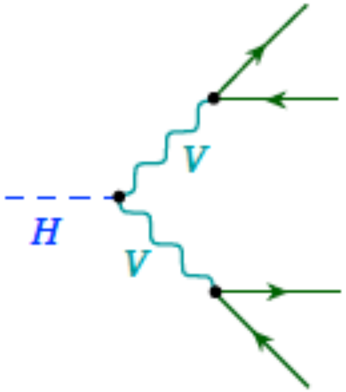
H decays to bosons
WW, ZZ, $\gamma\gamma$

ATLAS-CONF-2012-158
ATLAS-CONF-2012-168
ATLAS-CONF-2012-169

H ➡ ZZ* ➡ llll

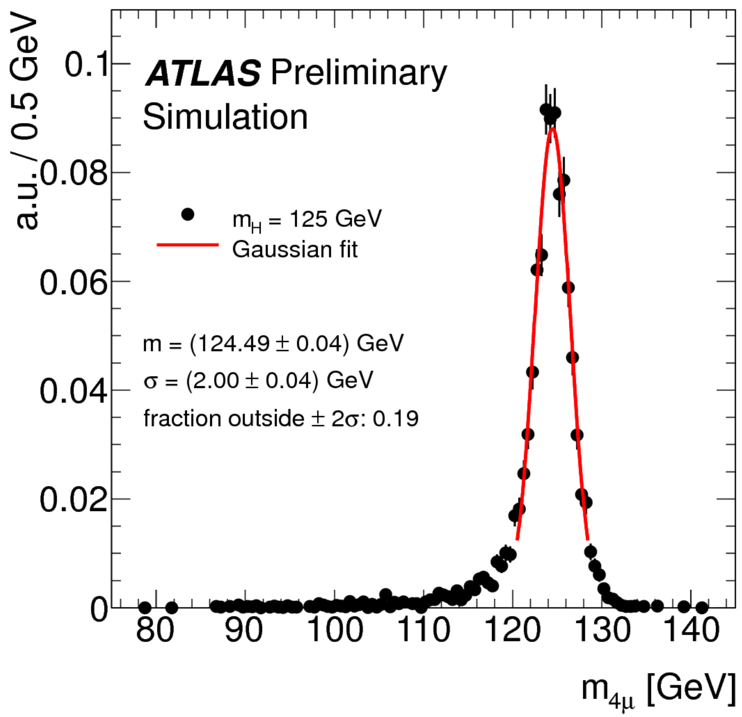
- Production depends on coupling to top quark (in SM)
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Very low backgrounds
  - Very good Higgs mass resolution
  - Requires good lepton reconstruction efficiencies
    - Can cope with high pileup environment
  - Clear/robust signal of coupling of Higgs to weak bosons

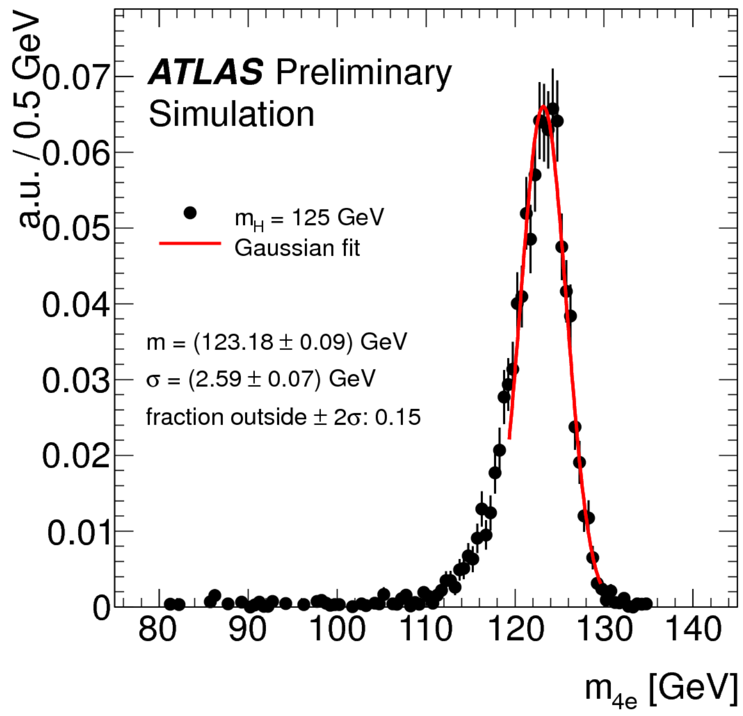




$H \rightarrow ZZ^{(*)} \rightarrow llll$ (2)

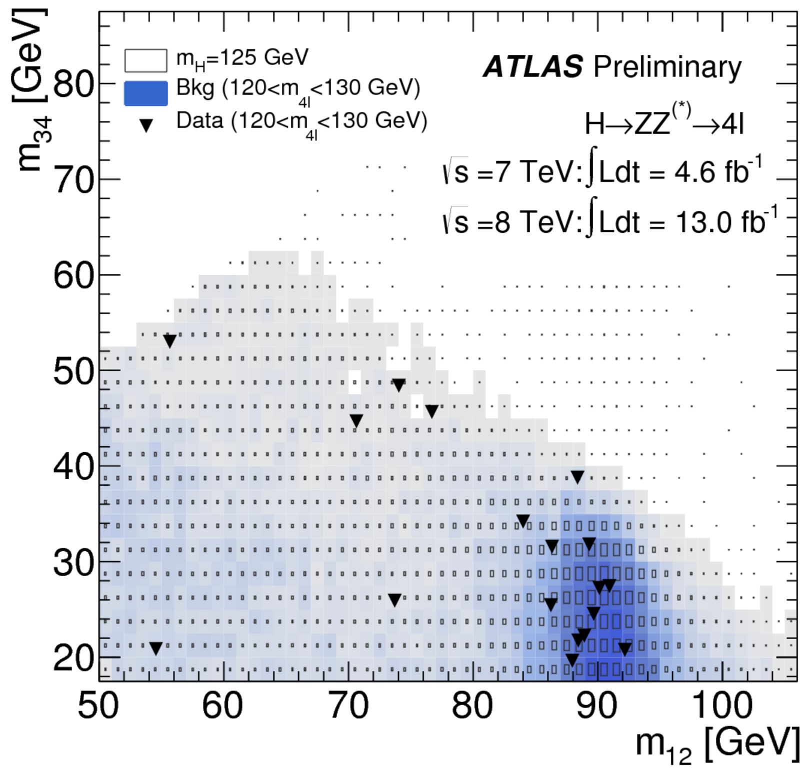
- Clean signal
  - Use isolation, impact parameter, dilepton masses to reduce Z+jets and top backgrounds
- Low rate: need to keep efficiencies high
- Main backgrounds from SM: irreducible ZZ production, reducible Z+jets, top
- Good 4-lepton mass resolution helps to enhance signal





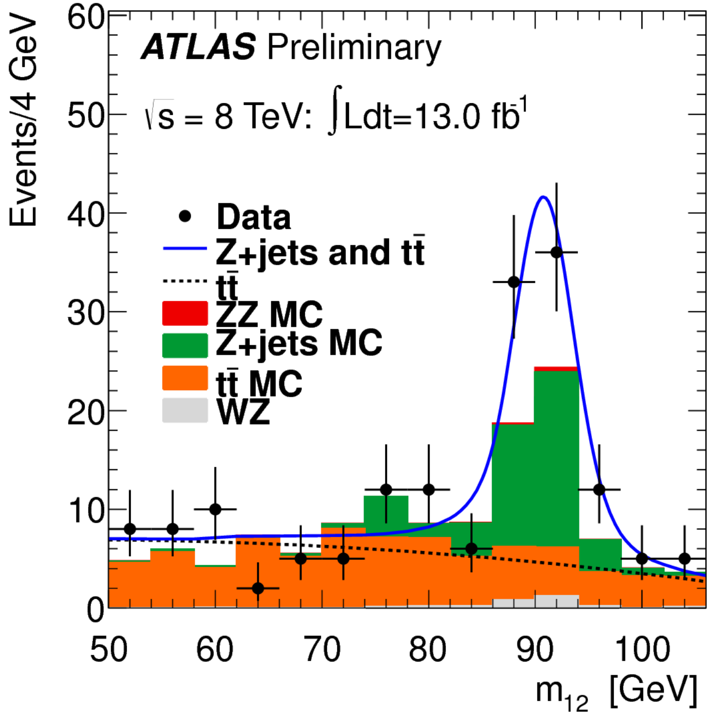
$H \Rightarrow ZZ^{(*)} \Rightarrow llll$ (3)

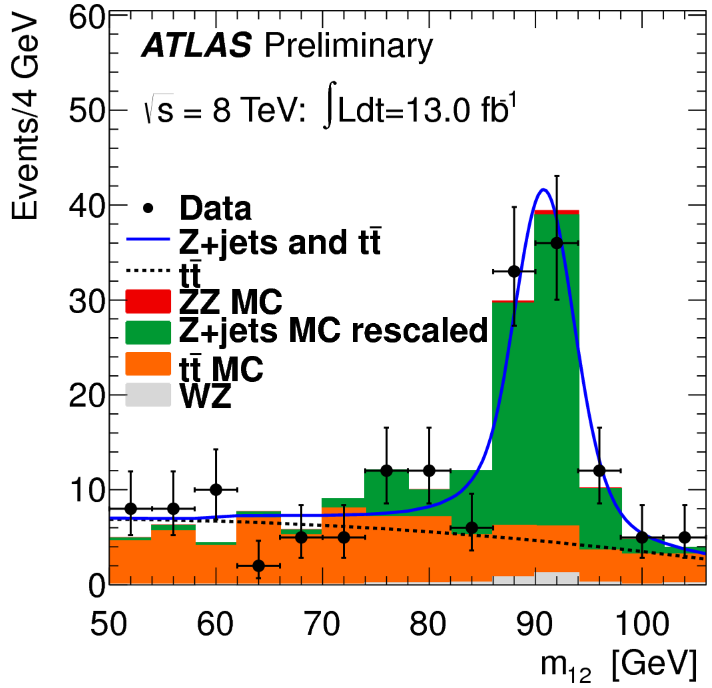
- Selections:
  - 4 leptons with $p_T > 20,20,7,7$ GeV
  - Pair same-flavour, opposite charge leptons. M_{12}:pair with mass closest to Z
  - $50 < M_{12} < 106$, minimum M_{34} depends on Higgs mass (17.5 for M_H of 125 GeV)
  - Any same-flavour combination must have $M_{ll} > 5$ GeV
- Signal efficiency 37, 23, 20% for 4μ, 2μ2e, 4e for $M_H = 125$ GeV
- M_{12} and M_{34} of candidates:



H➡ZZ$^{(*)}$➡llll (4)

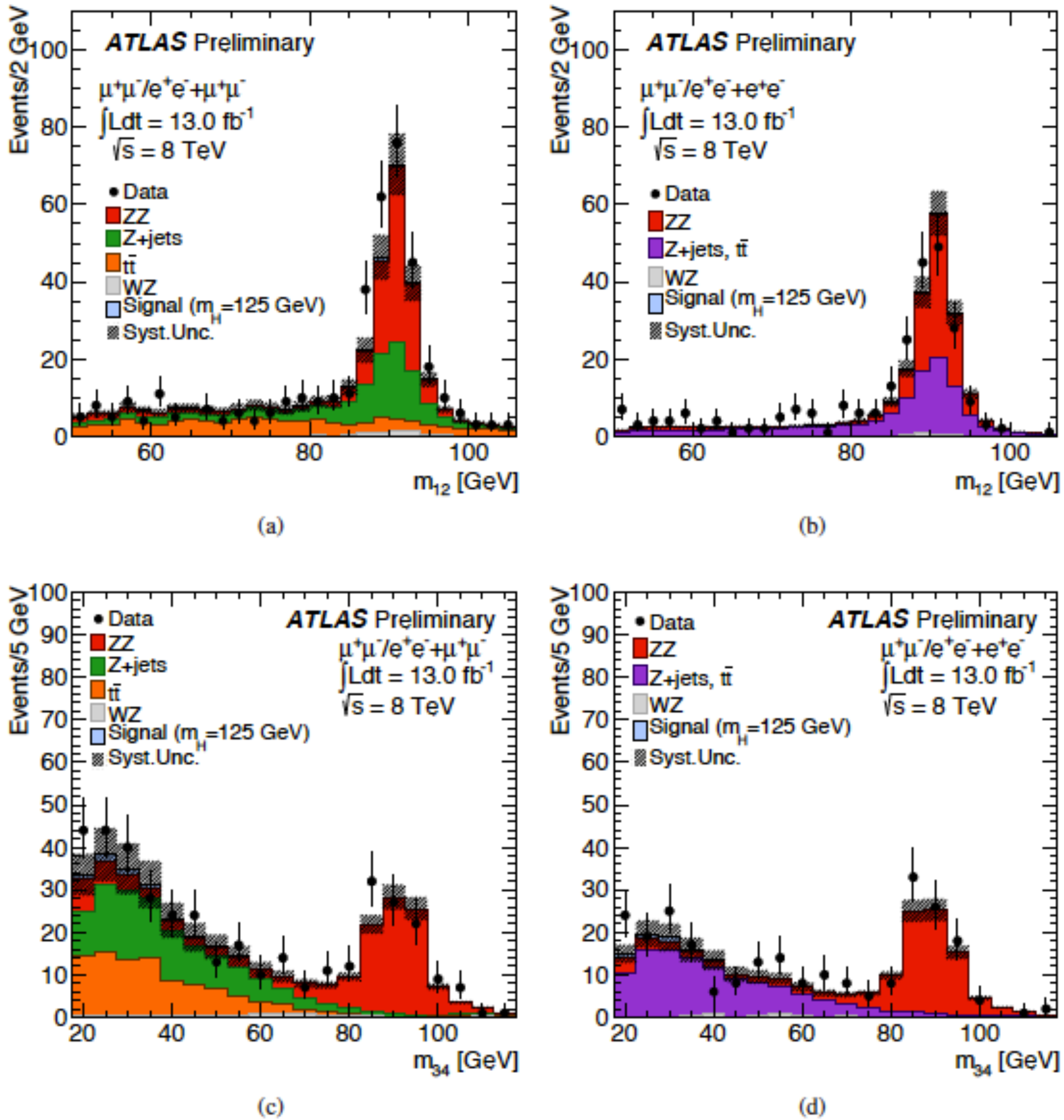
- Background estimates: ZZ obtained with MC simulation normalised to theory cross section
- Z+jets/top obtained from data-driven estimates using for example control regions with relaxed isolation selections or using same-sign pairs
- Example: subleading dimuon with isolation removed and at least one track that fails IP significance requirement (removes ZZ)





H→ZZ(*)→llll (5)

- Impact parameter and isolation requirements not applied to sub-leading lepton pair
- MC is normalized to the data-driven estimates
- Good agreement overall in both normalization and shapes

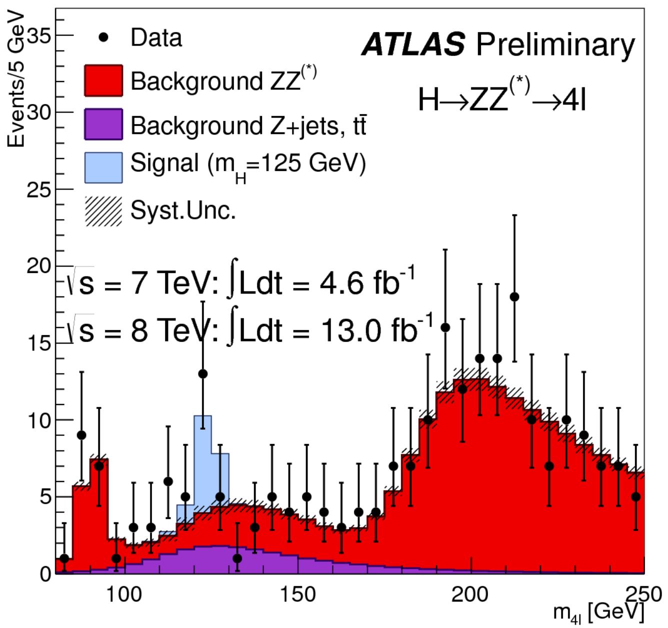


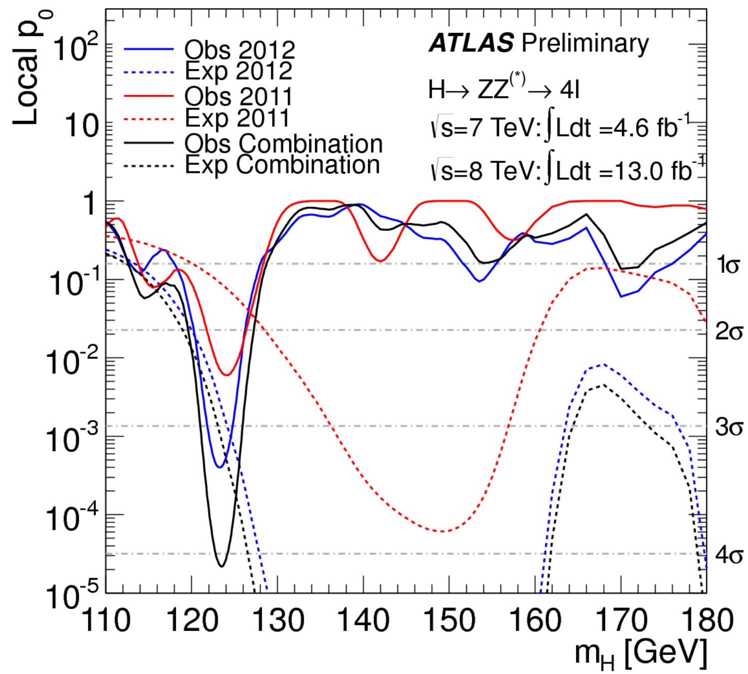
H→ZZ$^{(*)}$→llll (6)

Candidate events in the signal region (125 +/- 5 GeV):

- Observed: 18
- Exp. background: 8.3 +/- 0.3
- Exp. signal: 9.9 +/- 1.3
-

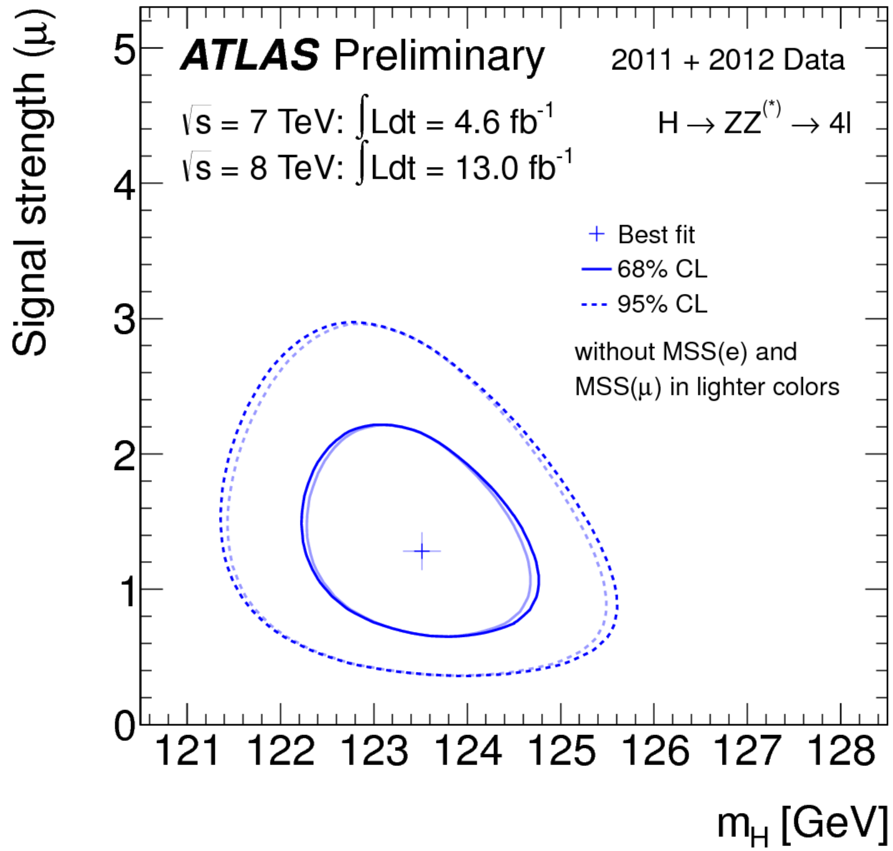
- Observed local significance: 4.1σ
- Expected local significance: 3.1σ

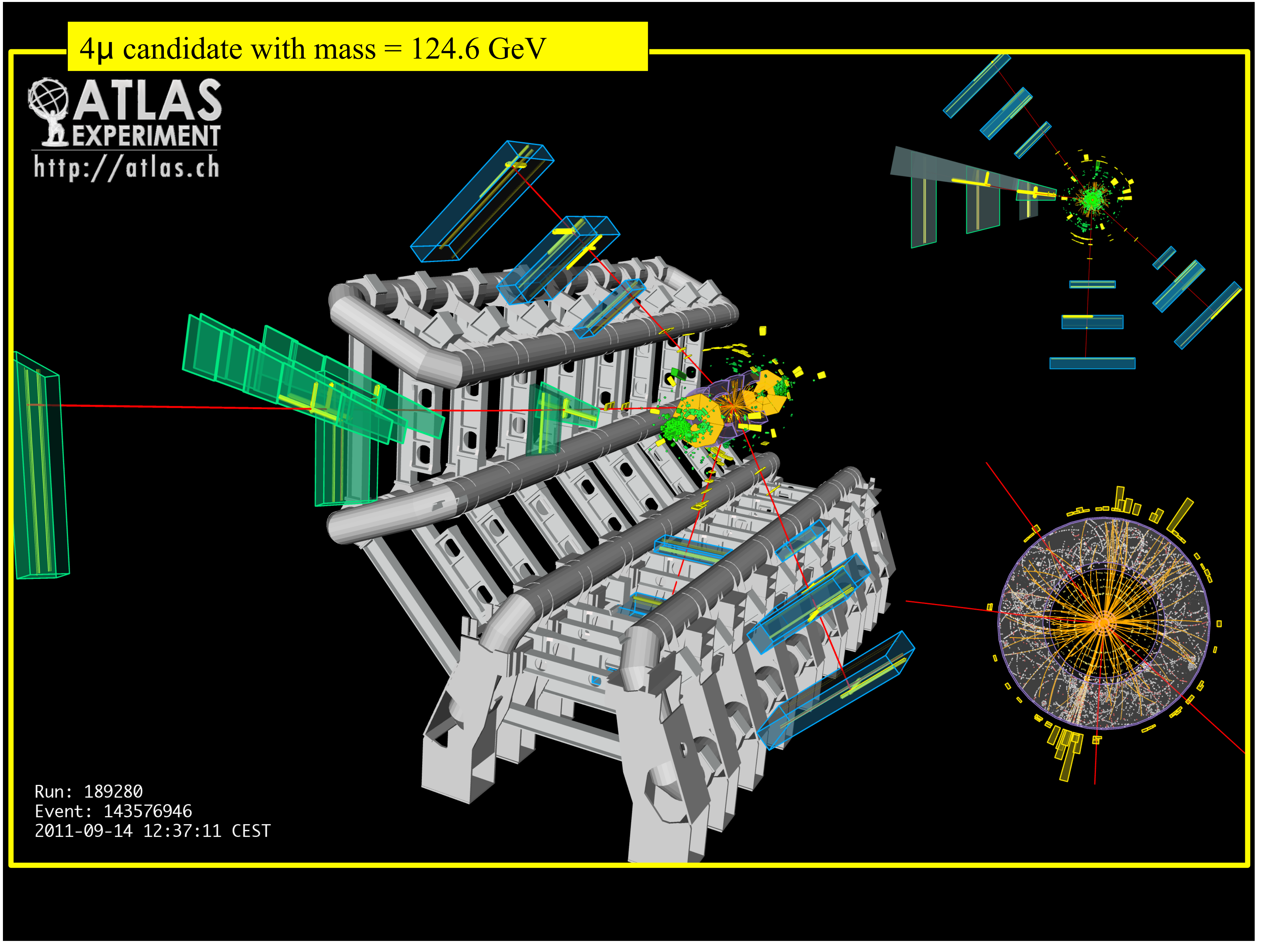




$H \rightarrow ZZ^{(*)} \rightarrow llll$ (7)

- Mass mesurement: $m_H = 123.5 \pm 0.9\ (stat)\ ^{+0.4}_{-0.2}\ (syst)$ GeV
- Signal strength: $\hat{\mu} = 1.3 \pm 0.4$




4μ candidate with mass = 124.6 GeV
ATLAS
EXPERIMENT
http://atlas.ch
Run: 189280
Event: 143576946
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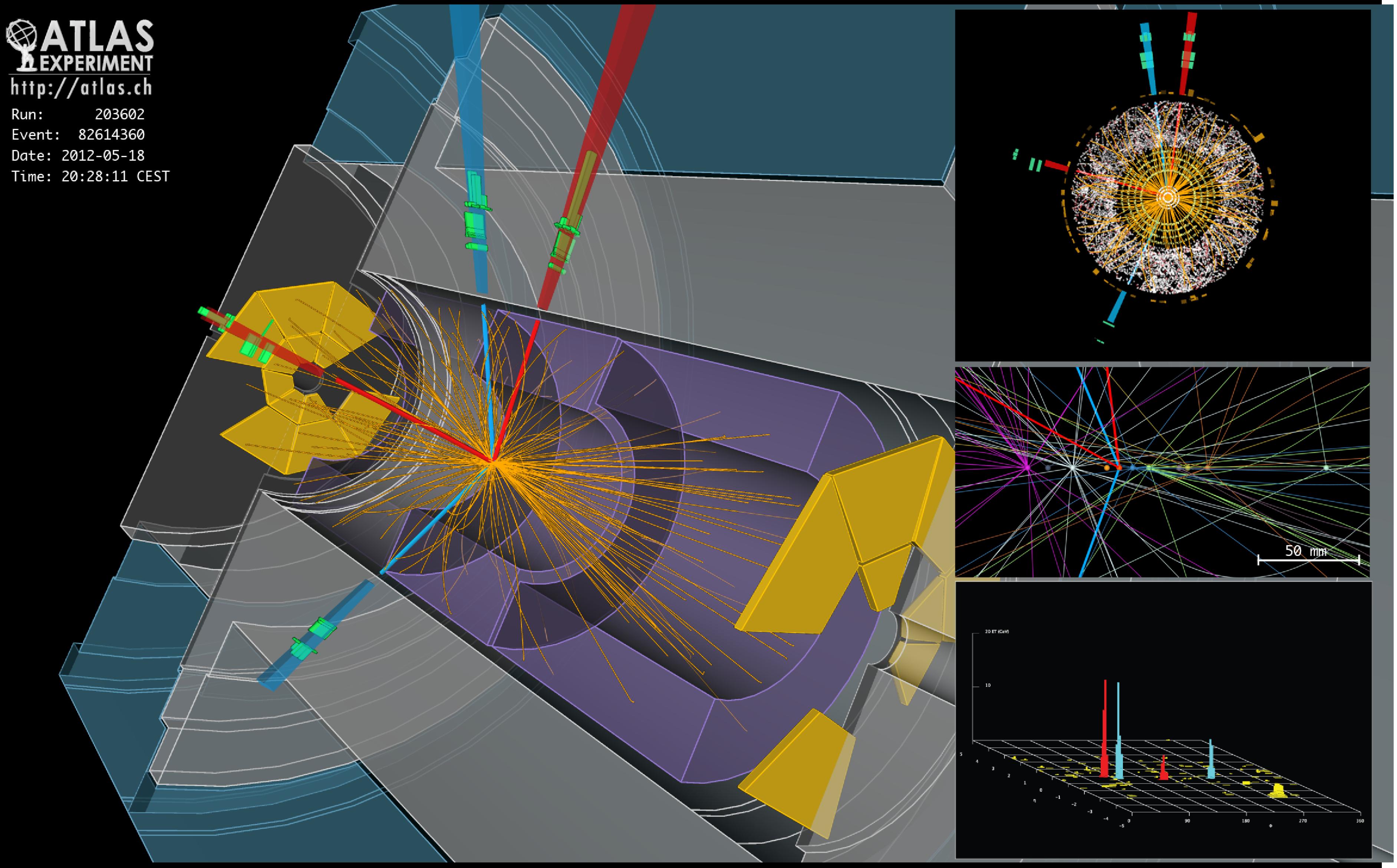
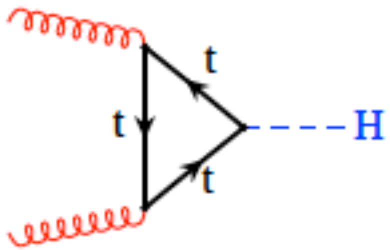
4e candidate with mass= 124.6 GeV

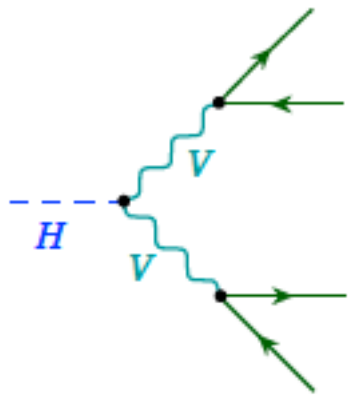


$H \rightarrow WW^* \rightarrow e\nu\mu\nu$
(8 TeV Analysis, 13 fb^{-1})

H ⇒ WW* ⇒ eνμν

- Main production mechanism depends on coupling to top quark (in SM), with smaller contribution from WBF which depends on coupling to W/Z bosons
- Decay depends on coupling to W boson
- Large σ*Br: many signal events, good sensitivity at low m_H
- An experimental challenge as you go below ~140 GeV:
  - two neutrinos degrade Higgs mass resolution: can't pinpoint Higgs mass
  - Lower momentum leptons for low Higgs mass: larger backgrounds
  - Relies on good understanding of missing ET resolution
  - Many small backgrounds to estimate: they all need to be well understood
  - Sensitive to pileup (a challenge in 2012)





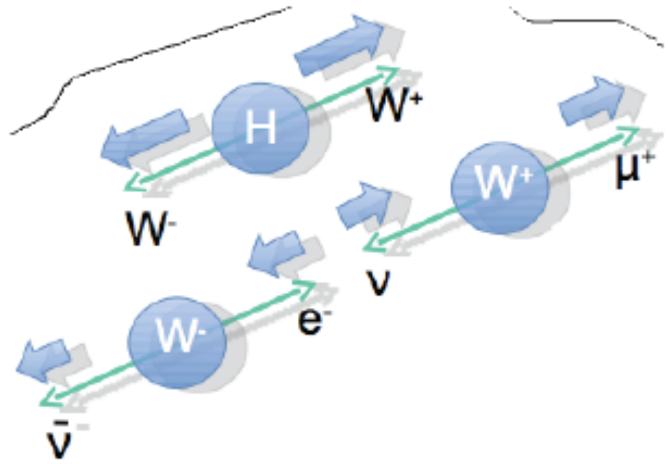
Selections

- Pre-selection:
  - 2 oppositely charged, isolated leptons (e,μ). Split into two sub-channels eμ ,μe, where second lepton is subleading
  - pT(1) > 25 GeV, pT(2) > 15 GeV
  - m(ll) > 10 GeV
  - Etmiss(rel) > 25 GeV
- Jet selection:
  - p_T > 25 GeV
  - (p_T > 30 GeV for $|\eta|$ > 2.5)
  - $|\eta|$ < 4.5
  - |Jet Vertex Fraction| > 0.5

- Topological cuts depend on jet multiplicity. The analysis is divided into 0 jets and 1-jet channels

Topological Selections

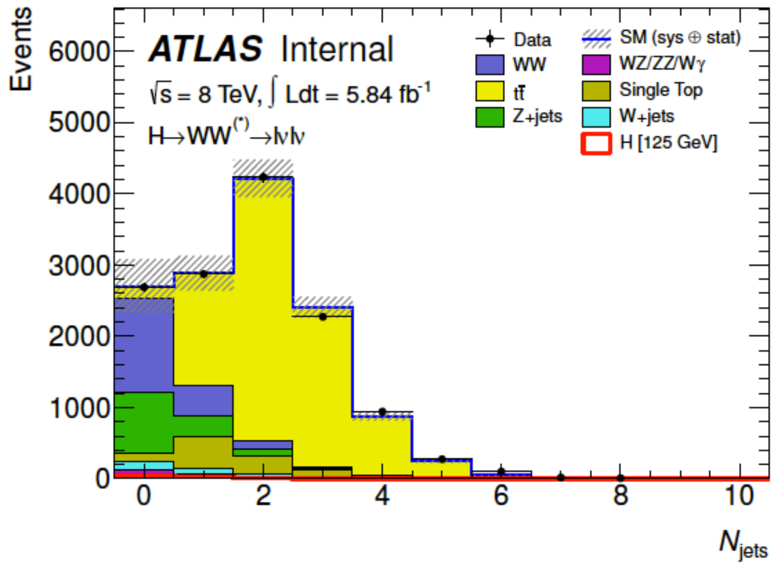
- 0-jet selection:
  - pT(ll) > 30 GeV
  - m(ll) < 50 GeV
  - Δφ(ll) < 1.8



- 1-jet selection:
  - m(ll) < 50 GeV
  - Δφ(ll) < 1.8
  - b-jet veto (multivariate tagger with 85% efficiency)
  - |m(ττ)-mZ| > 25 GeV (collinear approx.)
  - pT(tot) < 30 GeV (includes 2 leptons, etmiss, jet)

Background Summary

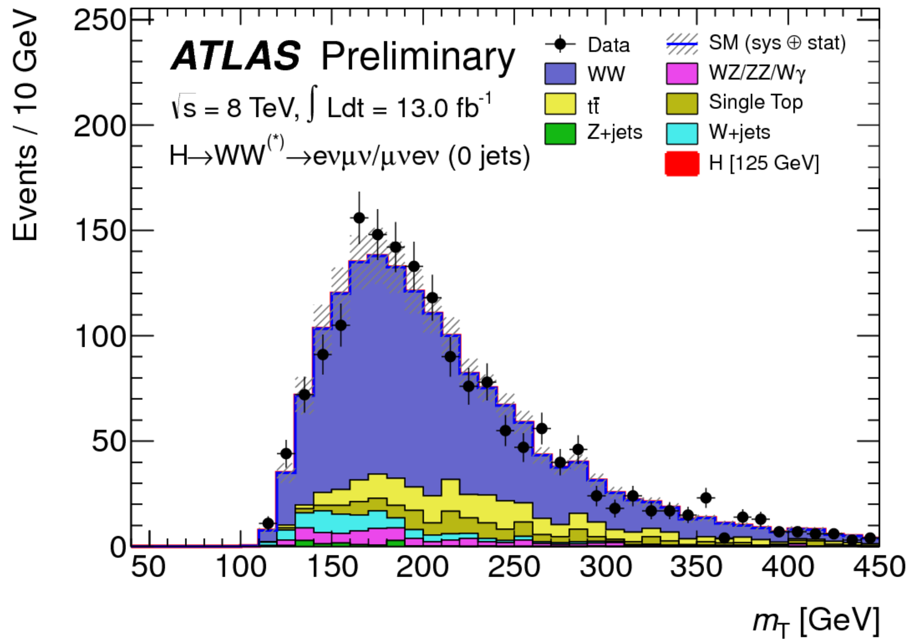
- After pre-selections, the dominant backgrounds are
  - 0-jet: WW and Drell-Yan in 0-jet
    - Drell-Yan small after topo. cuts
  - 1-jet: top (ttbar, single top: mostly Wt), WW
  - 2-jets: top
- Other backgrounds considered: W +jets, $WZ/\gamma^{(*)}$, $W\gamma$, ZZ
- Calculations use different techniques:
  - MC normalized to theory cross sections
  - MC normalized to data in control regions
  - Full data-driven estimates

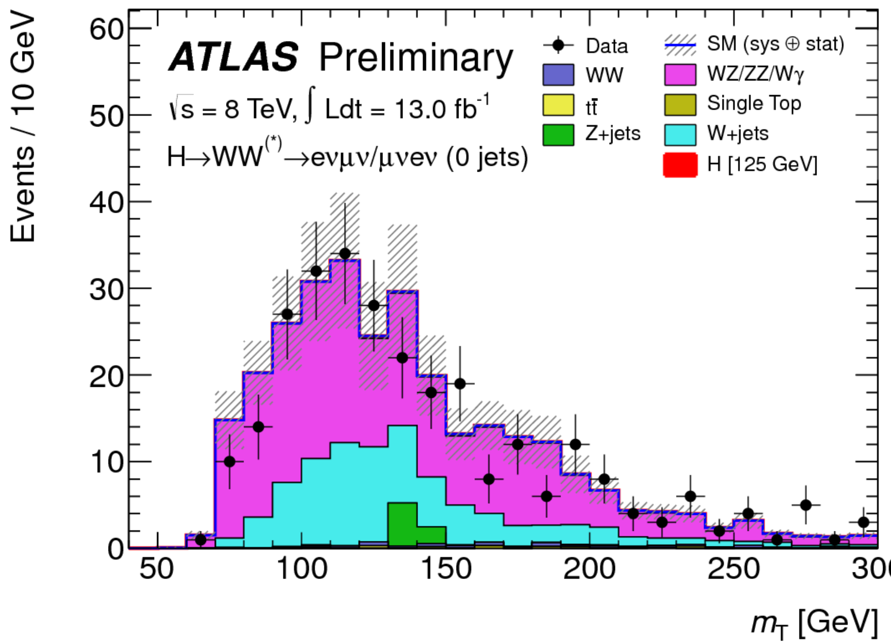


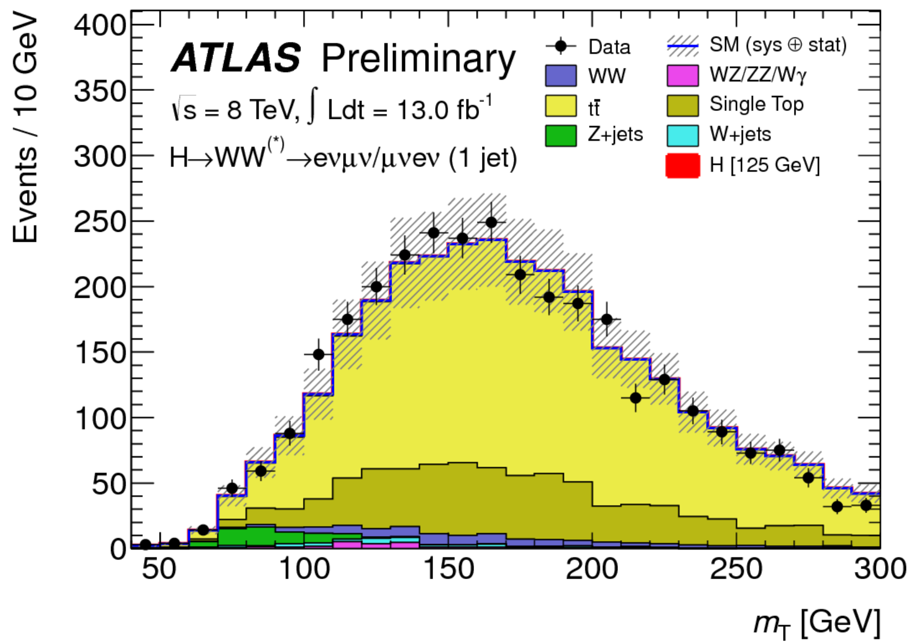
- Note: "control regions" are used to normalize MC whereas "validation regions" are used to check Data/MC agreement

Control and Validation regions

- Control regions are shown after normalising the MC to the rate observed in data
  - Bellow: same-sign VR
  - Upper right: 0-jet WW CR
  - Lower right: 1-jet top CR







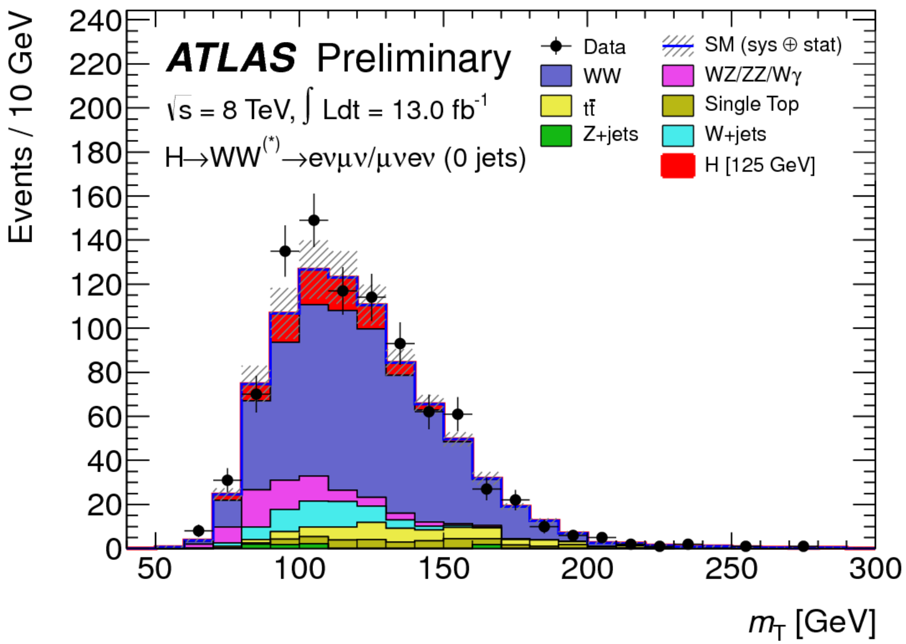
Main Systematic Uncertainties

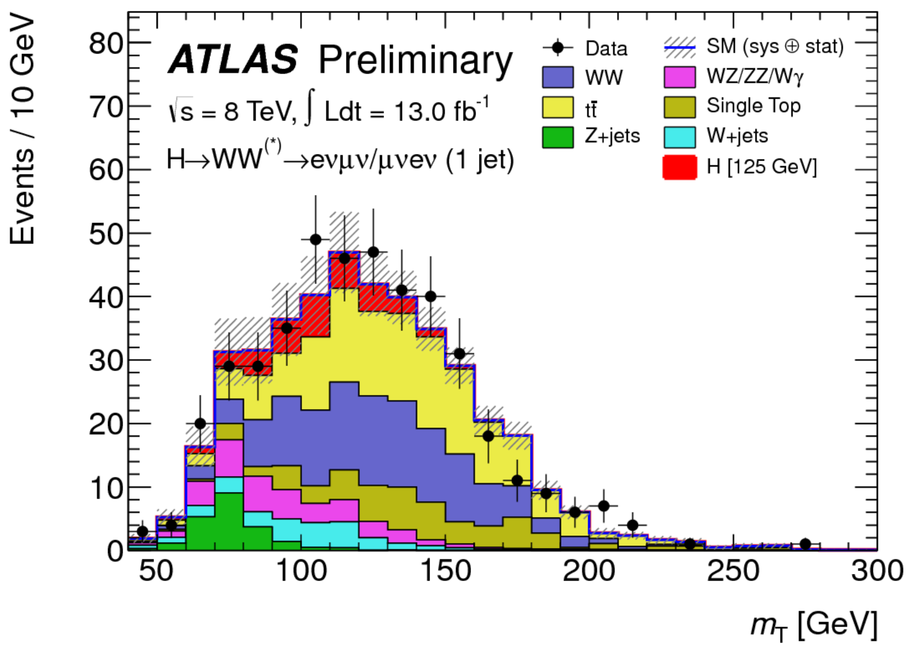
Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
PDF model (signal only)	8	-
QCD scale (acceptance)	4	-
Jet energy scale and resolution	4	2
W+jets fake factor	-	5
WW theoretical model	-	5
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	26	-
2-jet incl. ggF signal ren./fact. scale	15	-
Parton shower/ U.E. model (signal only)	10	-
b-tagging efficiency	-	11
PDF model (signal only)	7	-
QCD scale (acceptance)	4	2
Jet energy scale and resolution	1	3
W+jets fake factor	-	5
WW theoretical model	-	3

Results (m_T)

•Perform a fit to the transverse mass

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{\text{miss}})^2}$$





WW Results

- Number of events in individual channels after $\Delta\varphi(ll)$ cut
  - Excess consistent across channels

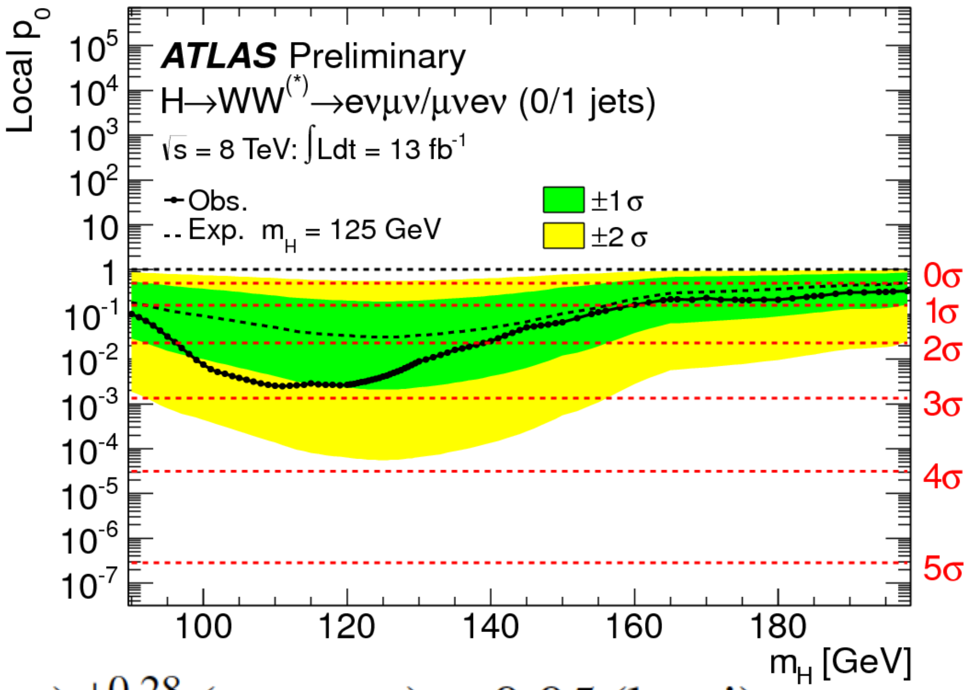
Signal region yield for $e\mu$ and μe channels separately				
	0-jet $e\mu$	0-jet μe	1-jet $e\mu$	1-jet μe
Total bkg.	392 ± 7	382 ± 6	202 ± 6	184 ± 5
Signal	41.8 ± 0.6	33.8 ± 0.5	18.9 ± 0.4	16.0 ± 0.4
Observed	469	448	226	207

- After a m_T cut: 0.75 < mT < mH (prefit yields and uncertainties):

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	$Z/\gamma^* +$ jets	$W +$ jets	Total Bkg.	Obs.
$H+$ 0-jet	45 ± 9	242 ± 32	26 ± 4	16 ± 2	11 ± 2	4 ± 3	34 ± 17	334 ± 28	423
$H+$ 1-jet	18 ± 6	40 ± 22	10 ± 2	37 ± 13	13 ± 7	2 ± 1	11 ± 6	114 ± 18	141

WW Results(2)

- Observed local significance: 2.6σ
- Expected local significance: 1.9σ
- Signal strength:



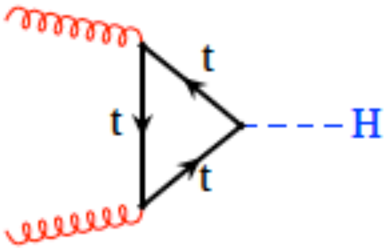
$$\mu = 1.48^{+0.35}_{-0.33}\,(\text{stat})^{+0.41}_{-0.36}\,(\text{syst theor})\,^{+0.28}_{-0.27}\,(\text{syst exp}) \pm 0.05\,(\text{lumi})$$

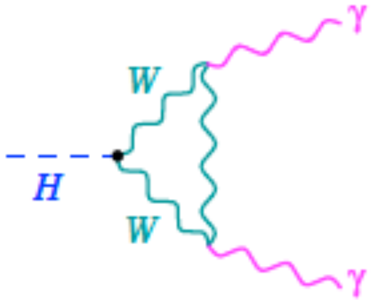
- Cross section x Br:

$$\sigma(pp \to H)\cdot\mathcal{B}(H \to WW)_{m_H=125\ \text{GeV}} = 7.0\,^{+1.7}_{-1.6}\,(\text{stat})\,^{+1.7}_{-1.6}\,(\text{syst theor})\,^{+1.3}_{-1.3}\,(\text{syst exp}) \pm 0.3\,(\text{lumi})\ \text{pb}$$

H→γγ

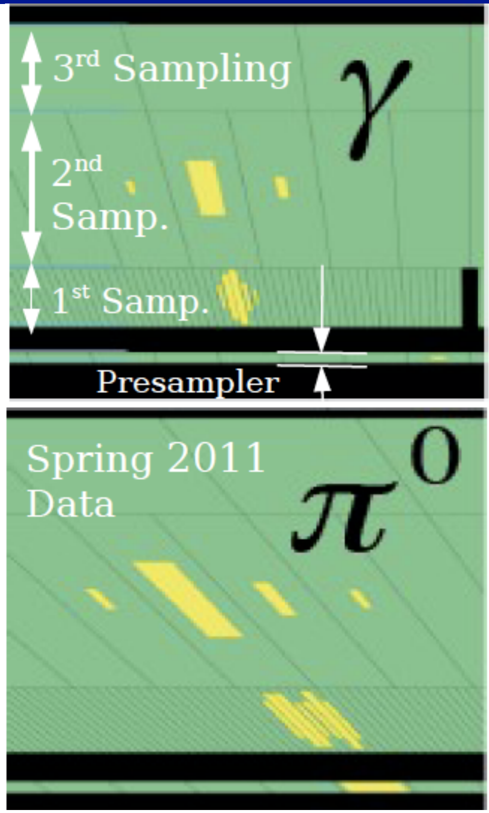
- Main production depends on coupling to top quark (in SM), with smaller contribution from WBF which depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson (in SM)
- Large backgrounds: need good photon identification
  - ATLAS EM calorimeter designed with this signal in mind
- Small branching ratio, need integrated luminosity
- A good discovery final state:
  - Excellent Higgs mass resolution
  - Looking for a resonance on top of smooth background
  - Robust channel with respect to pileup (advantage in 2012)



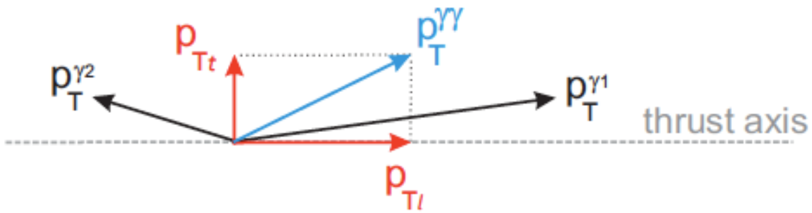


$H \rightarrow \gamma\gamma$ (2)

- Selection:
  - 2 high pt photons
    - pT(1) > 40 GeV
    - pT(2) > 30 GeV
      - diphoton trigger efficiency > 99%
  - Stringent photon identification criteria
  - Event selection efficiency ~40%
  - 2-jet selection: $\Delta y(jj) > 2.8$, $m(jj) > 400$ GeV, $\Delta\phi(\gamma\gamma, jj) > 2.6$



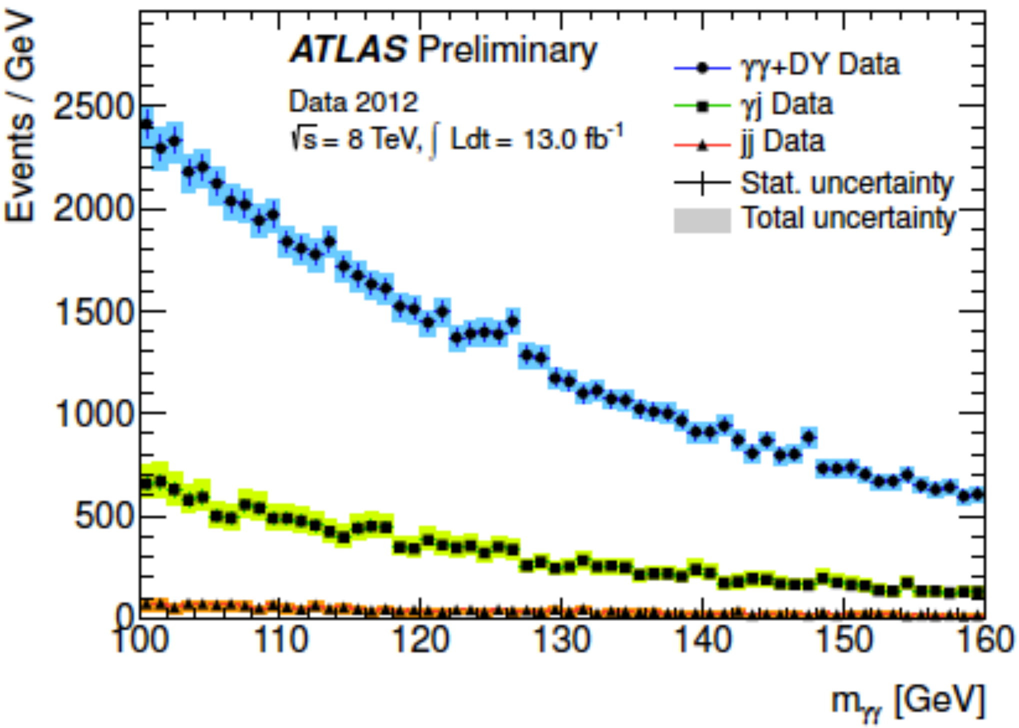
- To maximize sensitivity, 8 TeV sample divided in 12 categories:
  - Calorimeter regions in eta
  - Converted vs non-converted
  - PTt cut
  - 2-jets, 1 lepton, mjj close to W/Z

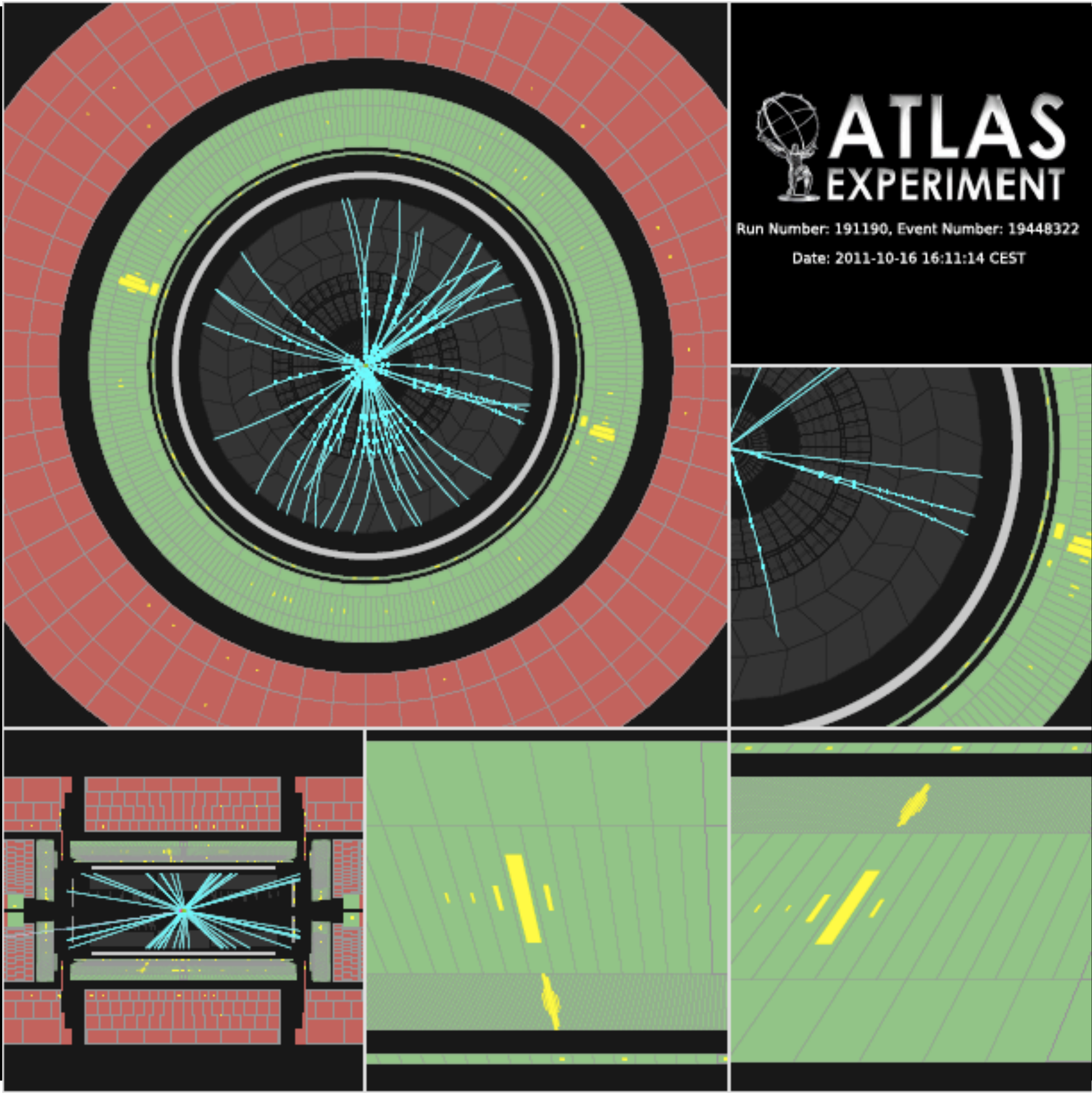


- S/B between 2-20% depending on category

H➡γγ (3)

- Signal is modelled using crystal ball function + Gaussian distribution
- Background modelled with functional forms determined from MC but parameters and normalization are determined from data
- Estimated background composition (not used in results):




ATLAS
EXPERIMENT
Run Number: 191190, Event Number: 19448322
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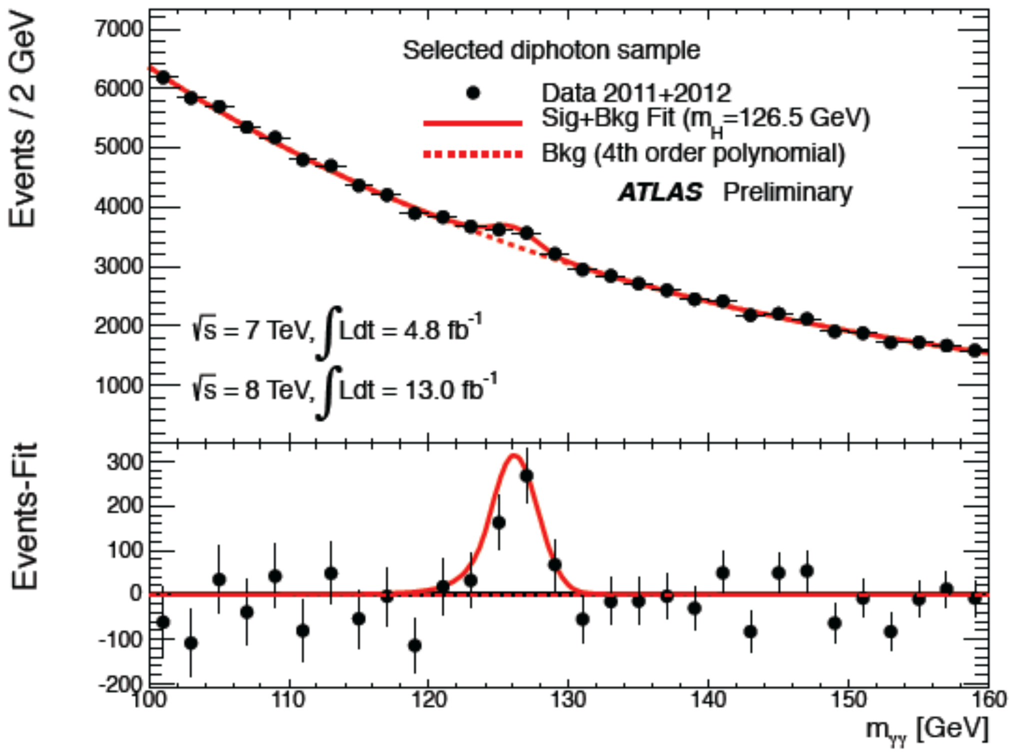
H ➡ γγ (5)

- Observed diphoton spectrum

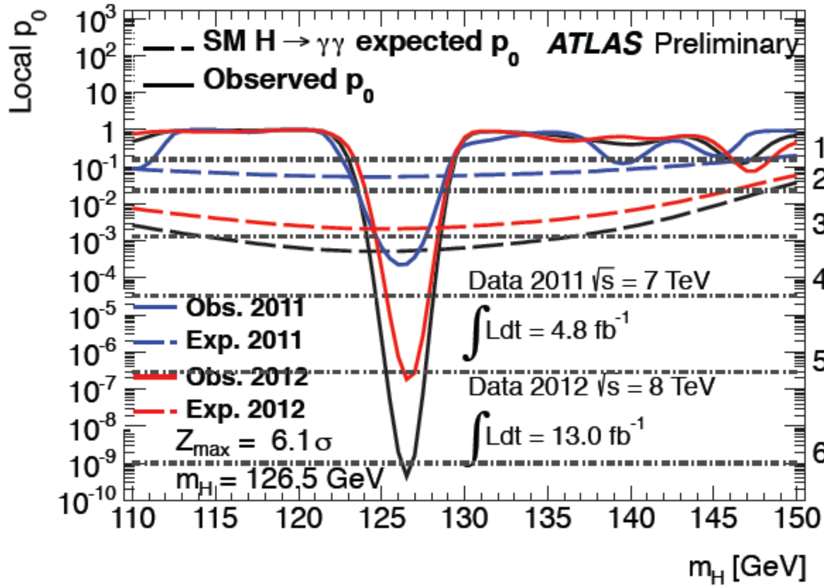


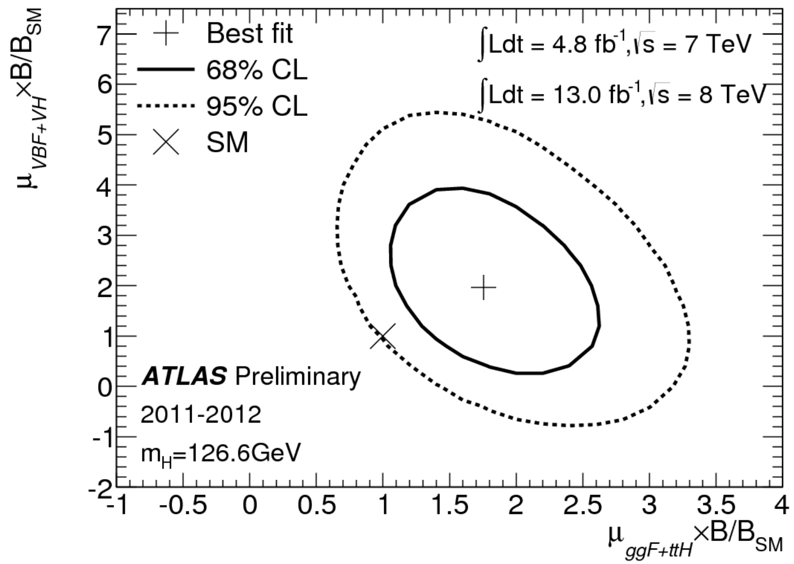
- Main sources of systematic uncertainty:
  - Photon ID efficiency ~10%
  - Energy resolution ~14%
  - Background parameterization (events): between 0.2 and 4.6
  - Pileup ~ 4%
  - Jet energy scale (VBF) ~ 10%

H→γγ (6)

- Observed local significance: 6.1 σ
- Expected local significance: 3.3 σ
- Signal strength:

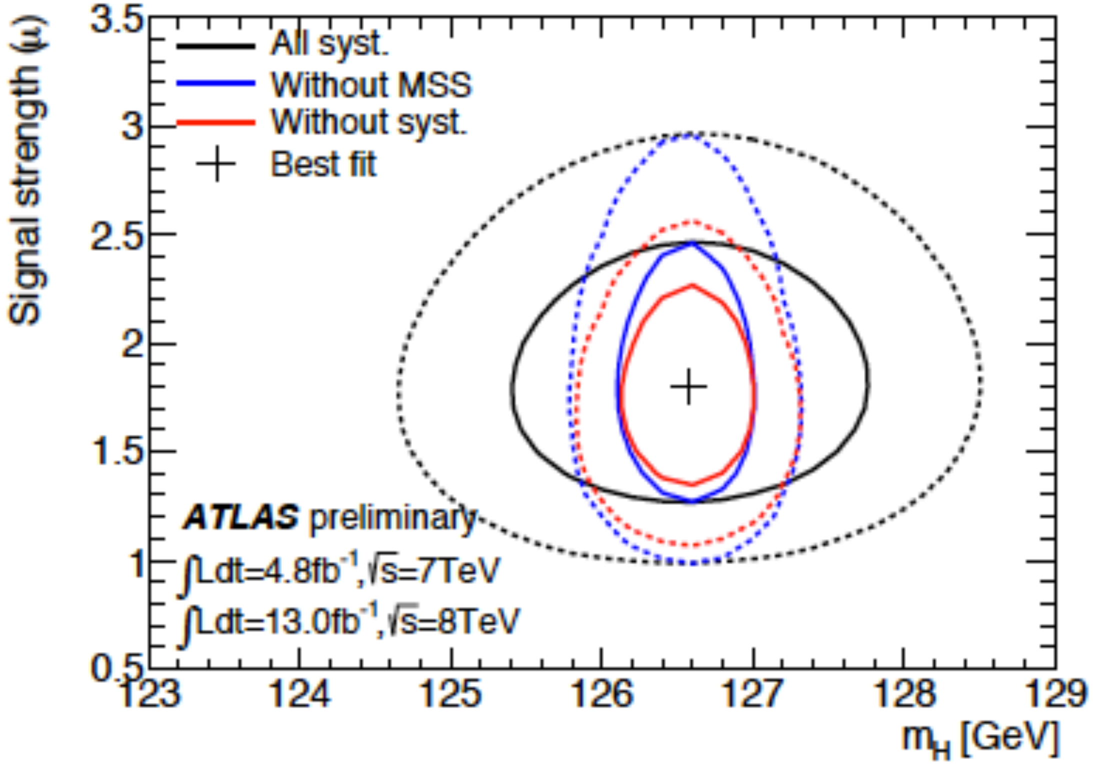
$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.21}\ (syst)$$





H → γγ (7)

- Mass Measurement: $m_H = 126.6 \pm 0.3\ (stat) \pm 0.7\ (syst)$ GeV

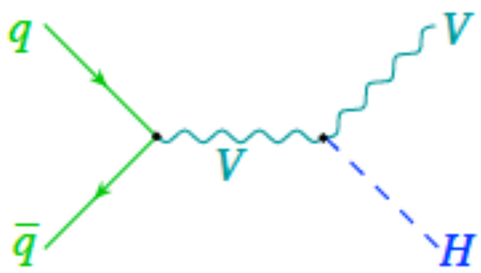


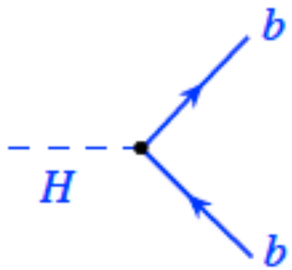
H decays to fermions $b\bar{b}$, $\tau\bar{\tau}$

ATLAS-CONF-2012-160
ATLAS-CONF-2012-161

$H \rightarrow b\bar{b}$

- Production depends on coupling to W/Z bosons
- Decay depends on coupling to b quark (down-type quark coupling)
- Small production cross section (but branching ratio is the largest)
- A challenging final state:
  - Very large backgrounds (W/Z+jets)
  - Higgs mass resolution is not that good (two jets compared to two photons)
  - Requires good b-tagging efficiency and fake rejection





$b\bar{b}$ Selections

•Analysis divided into three channels: 0,1,2 leptons

•Each channels subdivided into categories based on pt of weak boson (5 categories for 1,2 leptons) or EtMiss and jet multiplicity (6 categories for 0 leptons)

•Backgrounds:

- •Flavour fit performed using 0,1,2 tag samples: fit for Z/W +light,c,b and top contributions. W/Z+b and top fractions allowed to float in final likelihood fit, other contributions fixed

•Multi-jet determined by data-driven techniques

•WZ/ZZ normalized using MC calculation

$b\bar{b}$ Selections

•0-lepton selection:

•Trigger on missing Et
•Veto leptons with loose selections,
• One extra jet allowed beyond 2 b-tagged jets.
•Etmiss > 120 GeV,
•Ptmiss > 30 GeV
•Extra topological cuts.

•1-lepton selection:

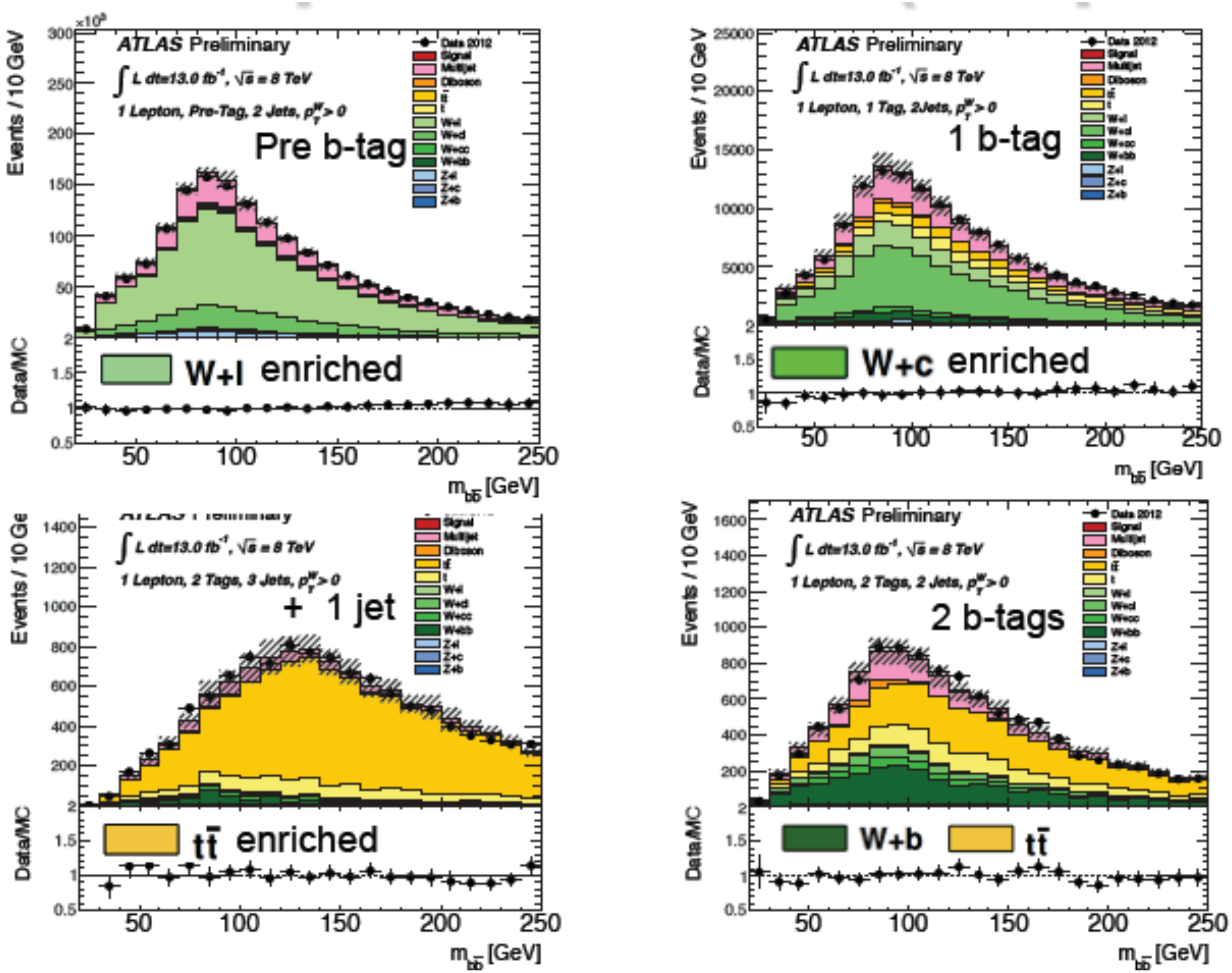
•Trigger on single lepton
•Require isolated tight lepton,
•veto on additional loose leptons
•veto on extra jets
•Require mT < 120 GeV

•2-lepton selection:

•Trigger on single lepton or di-lepton
•Require one medium, one loose lepton
•Require 83 < m(ll) < 99 GeV
–Require Etmiss < 60 GeV

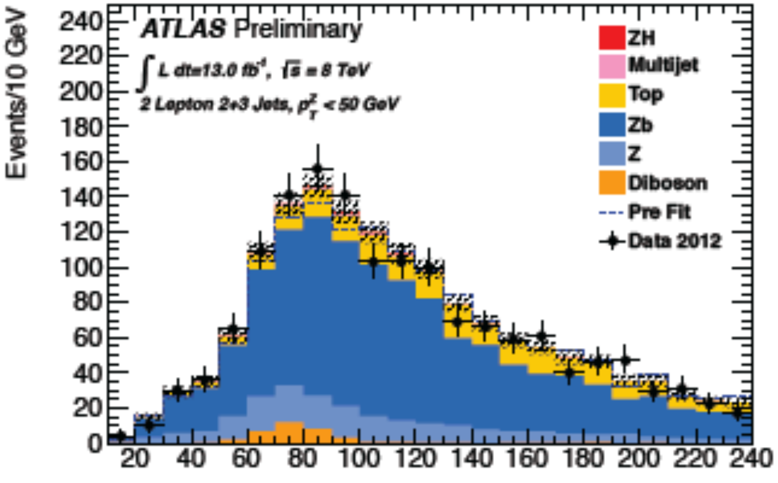
$H \to b\bar{b}$

- Flavour fit example for the 1-lepton channel

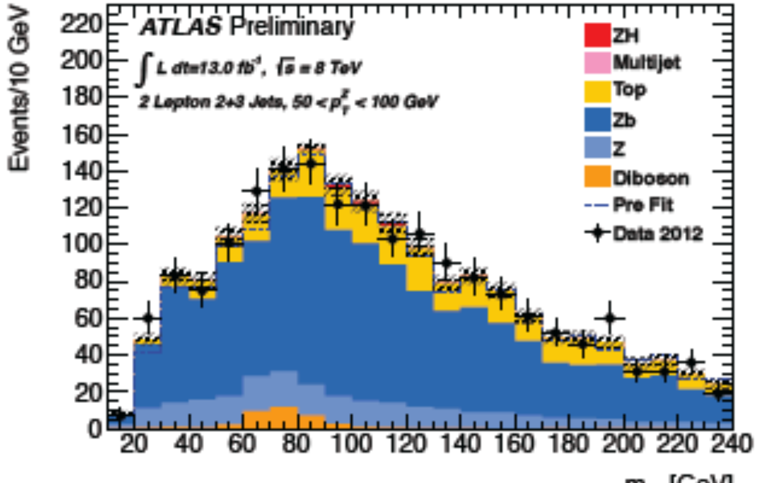


$H \rightarrow b\bar{b}$

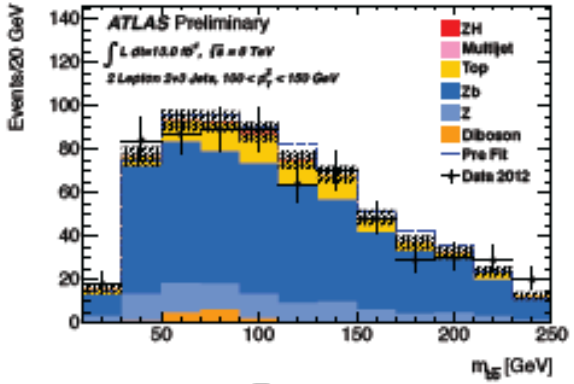
- 2-lepton channel



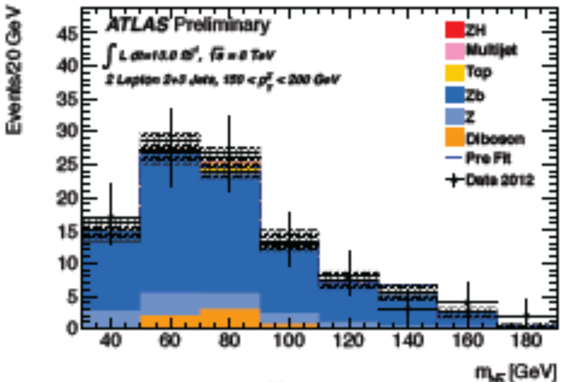
$p_T^Z < 50$ GeV



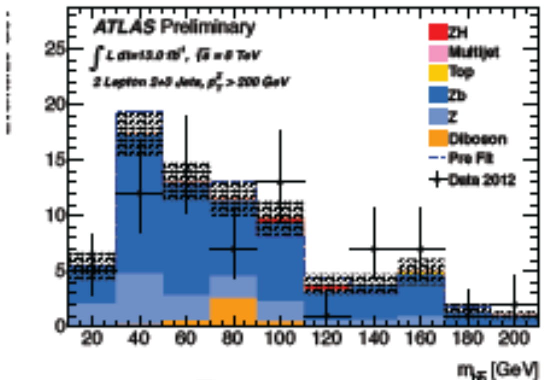
$50 < p_T^Z < 100$ GeV



$100 < p_T^Z < 150$ GeV



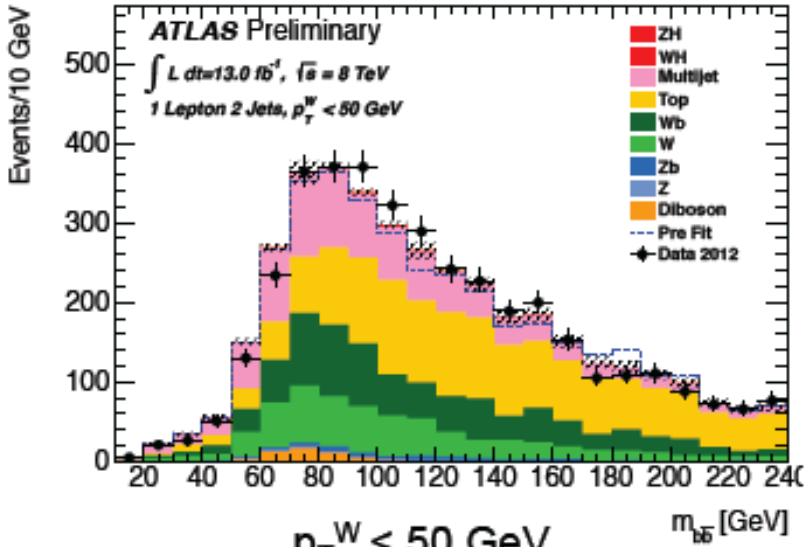
$150 < p_T^Z < 200$ GeV



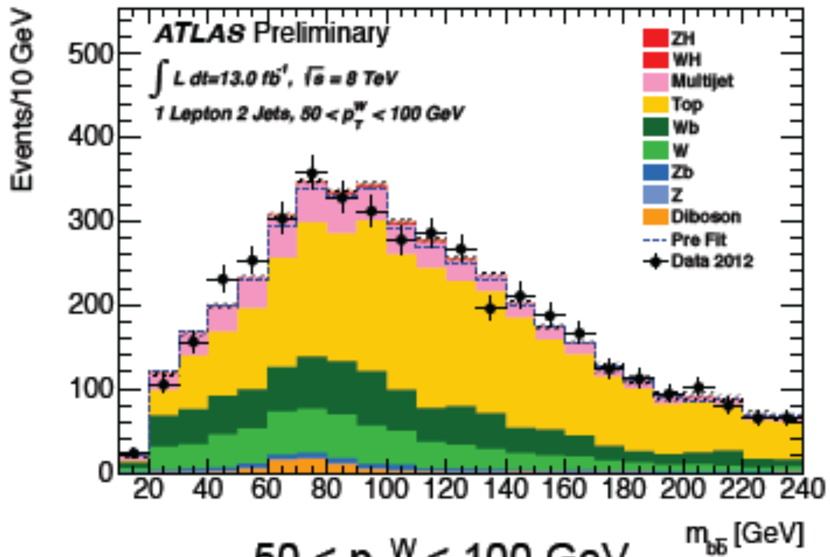
$p_T^Z > 200$ GeV

$H \rightarrow b\bar{b}$

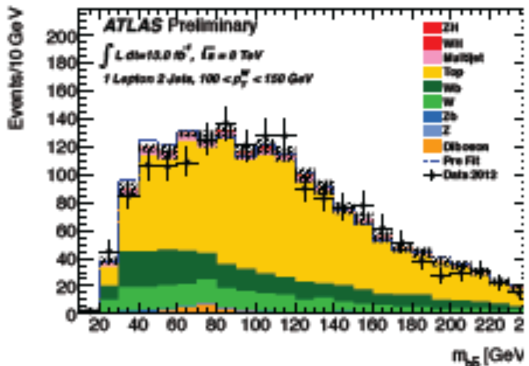
- 1-lepton channel



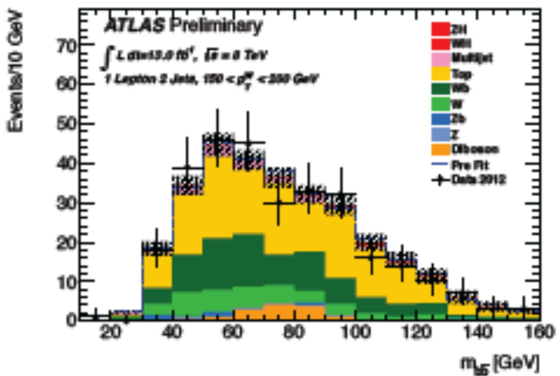
$p_T^W < 50$ GeV



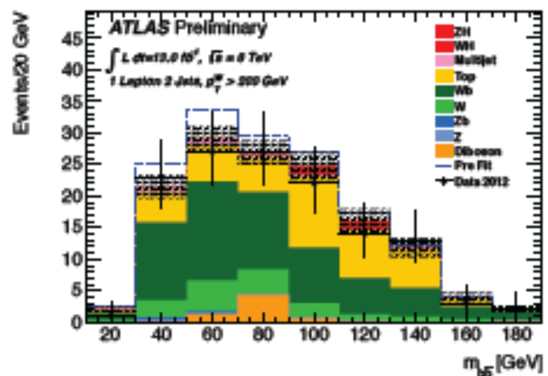
$50 < p_T^W < 100$ GeV



$100 < p_T^W < 100$ GeV



$150 < p_T^W < 200$ GeV

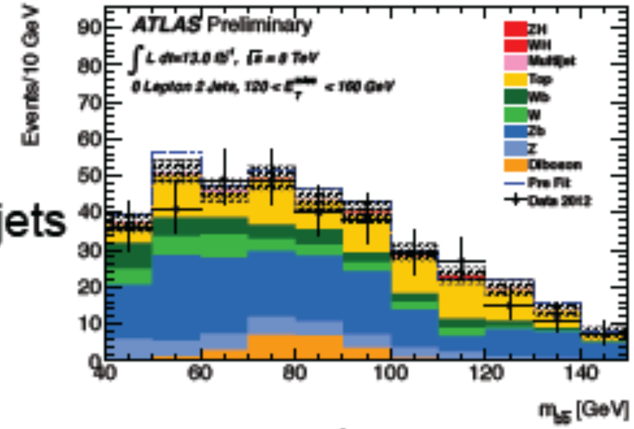


$p_T^W > 200$ GeV

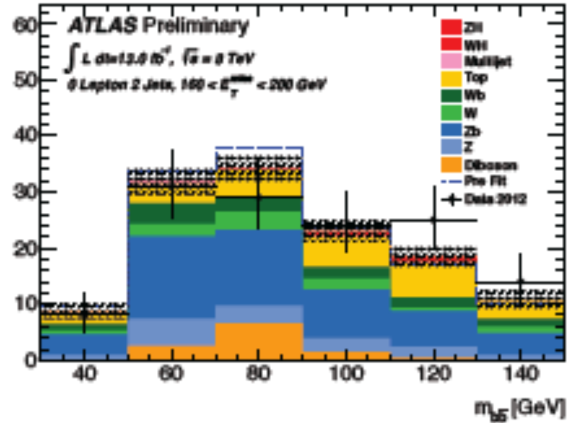
$H \rightarrow b\bar{b}$

- 0-lepton channel

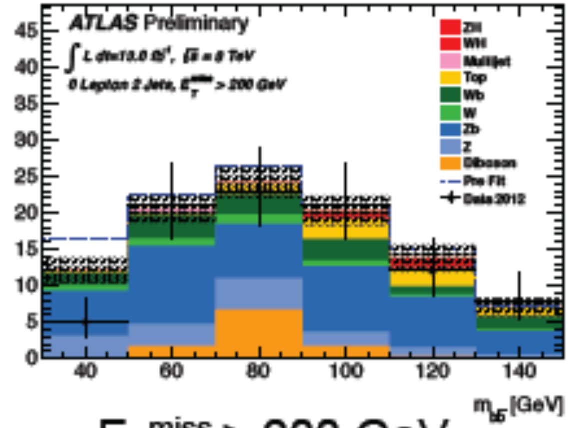
2 jets



$120 < E_T^{miss} < 160$ GeV

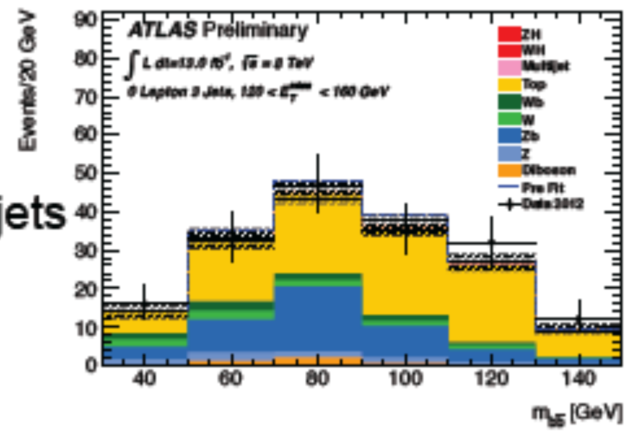


$160 < E_T^{miss} < 200$ GeV

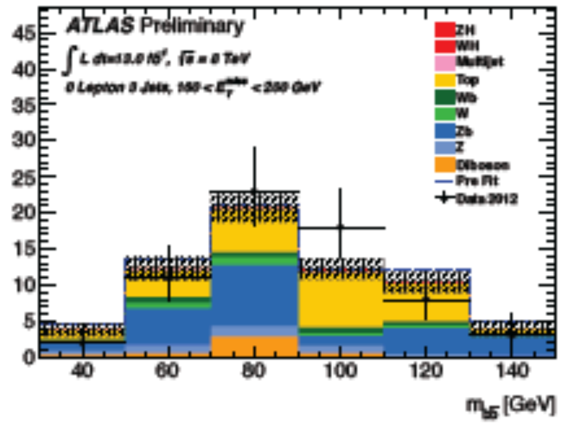


$E_T^{miss} > 200$ GeV

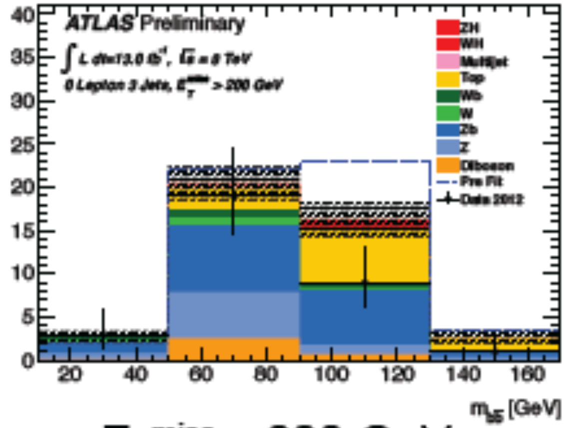
3 jets



$120 < E_T^{miss} < 160$ GeV



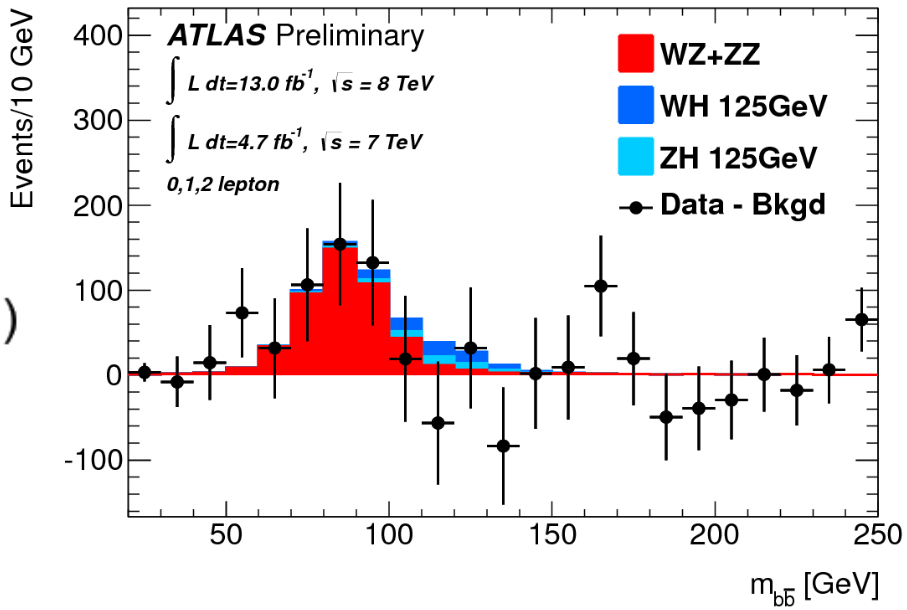
$160 < E_T^{miss} < 200$ GeV

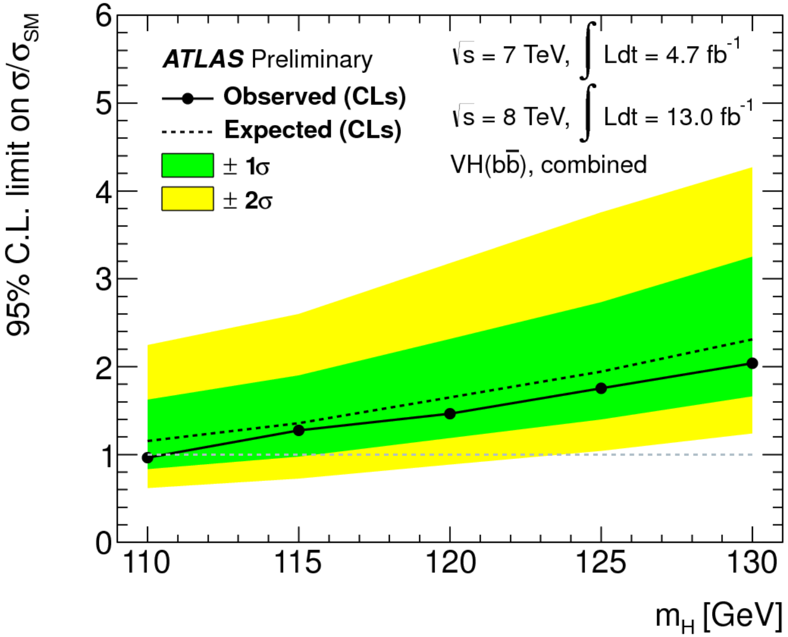


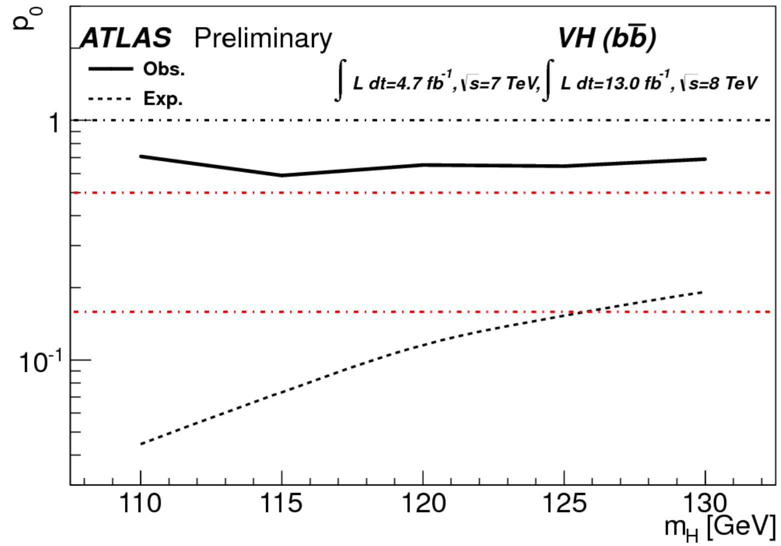
$E_T^{miss} > 200$ GeV

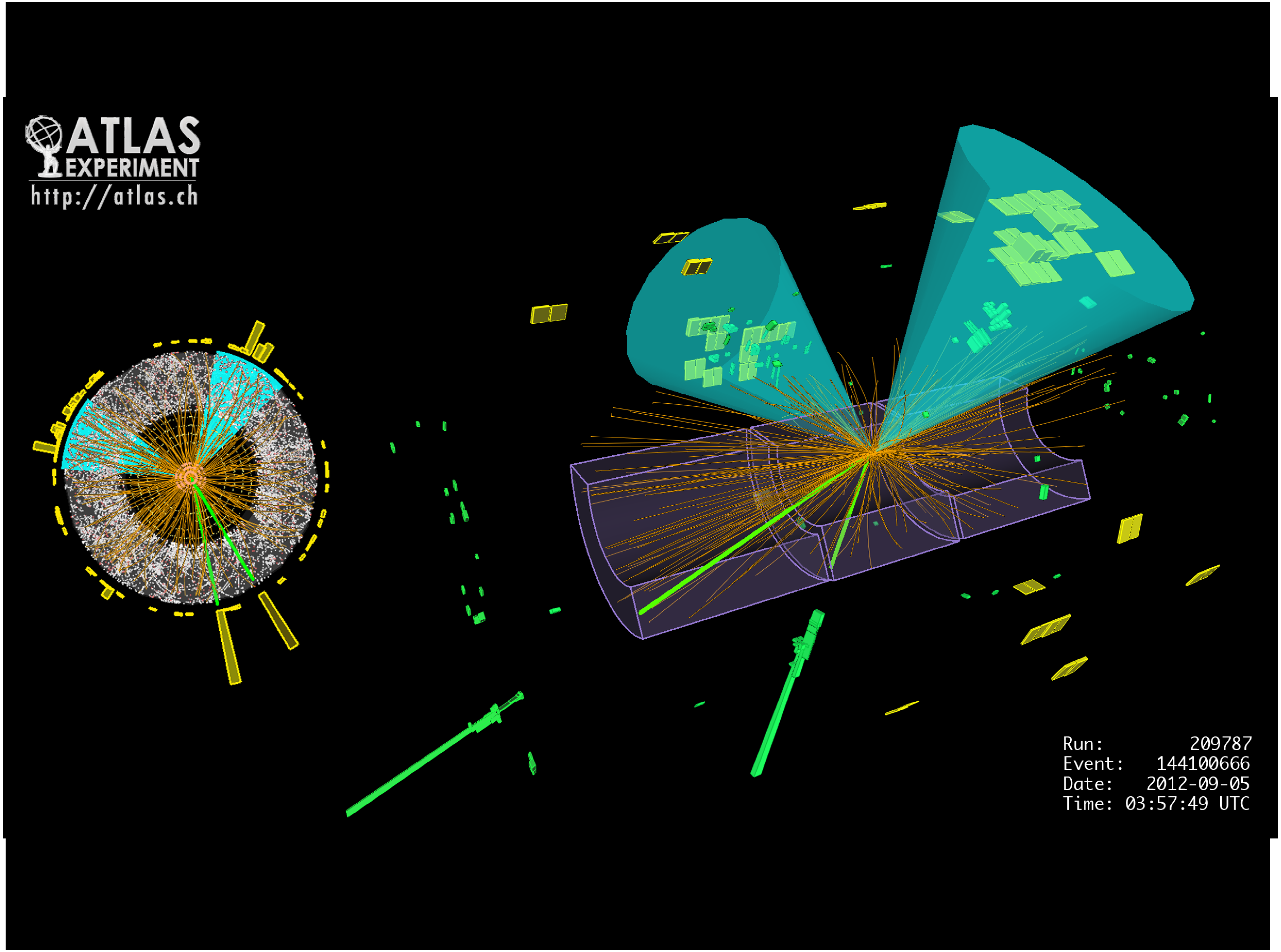
H → $b\bar{b}$

- Check method: diboson peak consistent with SM prediction. Significance: 4.0 σ
- Exp. local p0: 0.15
- Obs. local p0: 0.64
- Signal strength parameter:
  $\sigma/\sigma_{SM} = \mu = -0.4 \pm 0.7(\text{stat.}) \pm 0.8(\text{syst.})$
- Exp. limits (125 GeV): 1.9 x SM
- Obs. limit (125 GeV): 1.8 x SM



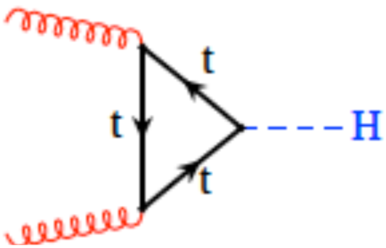


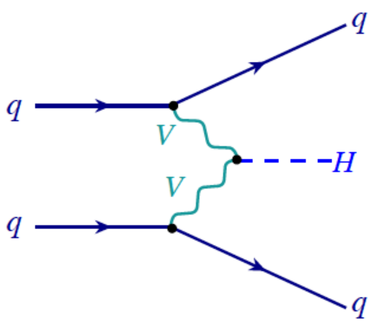


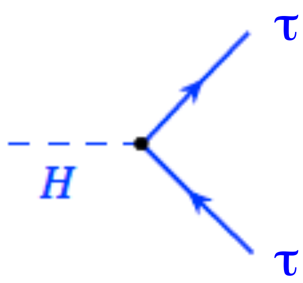

ATLAS
EXPERIMENT
http://atlas.ch
Run: 209787
Event: 144100666
Date: 2012-09-05
Time: 03:57:49 UTC

$H \rightarrow \tau\bar{\tau}$

- Production depends on coupling to top quark (in SM) and WBF+ VH production (coupling to Z/W bosons)
- Decay depends on coupling to taus (coupling to leptons)
- Cross section times branching ratio is relatively high
- Challenging final state:
  - Large backgrounds
  - Sensitive to pileup, an extra challenge in 2012



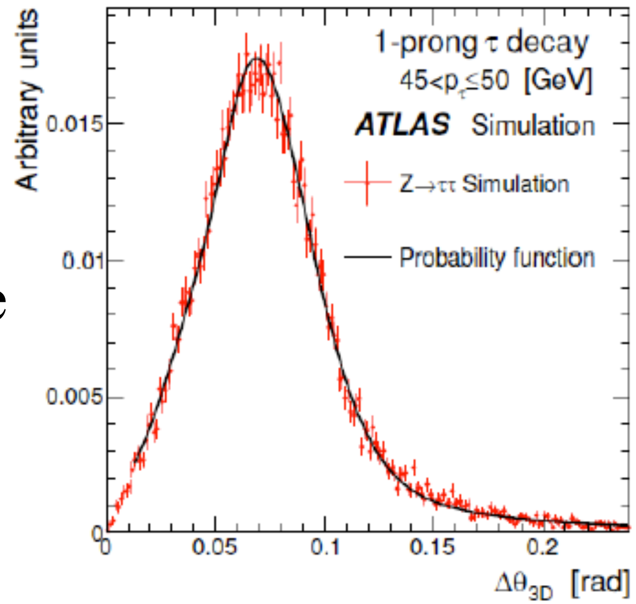


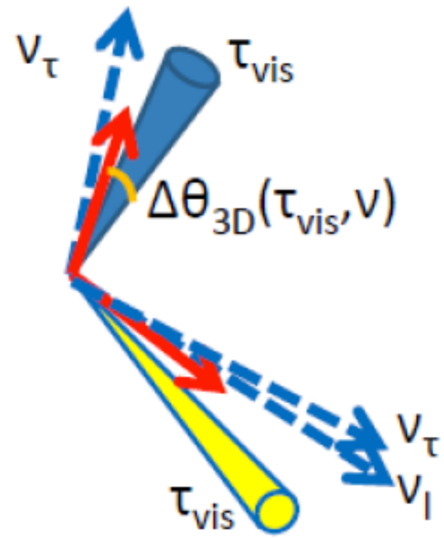


$H \rightarrow \tau\bar{\tau}$ (2)

- Looking at ττ decays to 3 final states: ll, lh, hh
- Complex analysis that involves over 10 sub-categories with some selections that are different between 7 TeV and 8 TeV: will only provide a summary and some examples here
- Electrons (muons) have pT > 15 (10) GeV, with calorimeter and track isolation requirements
- Tau reconstruction uses BDT with track and calo variables

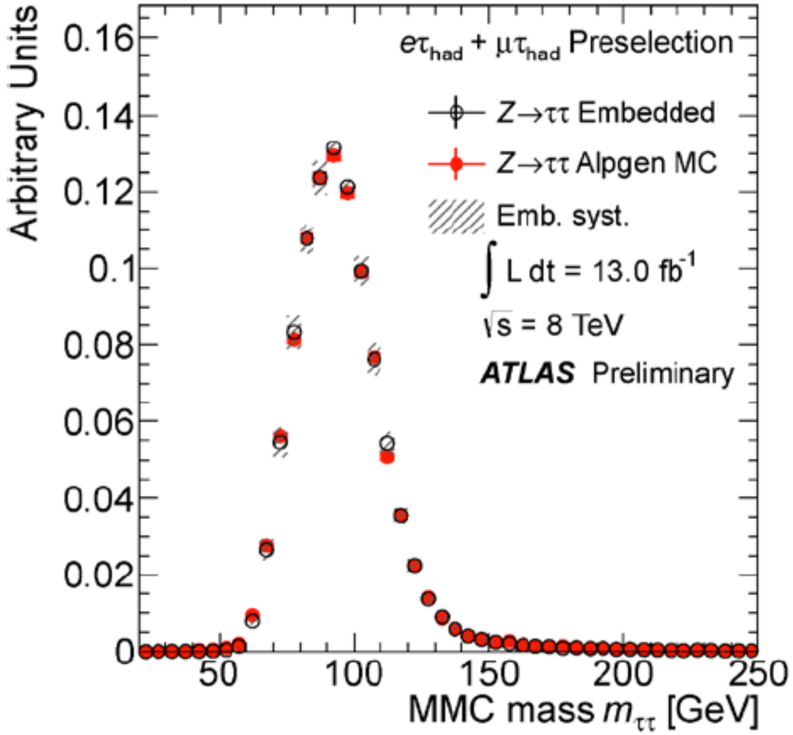
- Use Missing Mass Calculator (MMC) as a discriminating variable: requires tau decay products and EtMiss to be consistent with di-tau decay





H $\Rightarrow \tau\bar{\tau}$ (3)

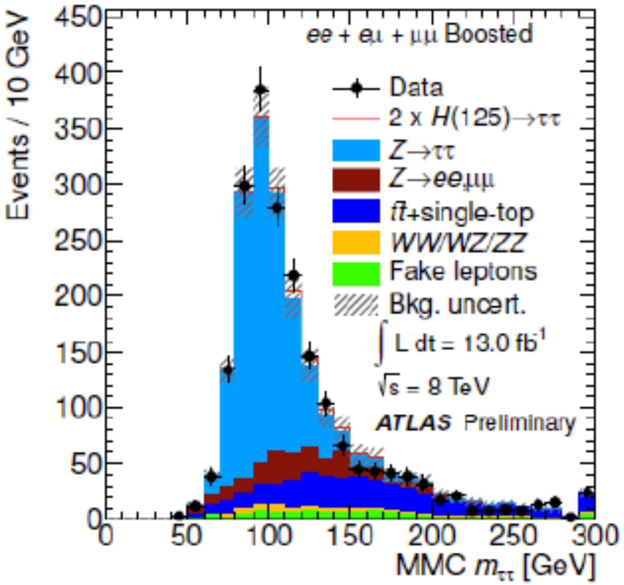
- Most important background are Z decays to two taus
  - Use embedding technique where muons from Z decays in data are replaced by simulated taus with correct polarization and spin correlations
- QCD and W+jets estimated with either same-sign samples or template fits using looser lepton selections
- Top background, Z decays to electrons and muons based on MC normalized to control regions
- Diboson background based on MC
- Note: this is a general overview, details available in: ATLAS-CONF-2012-160



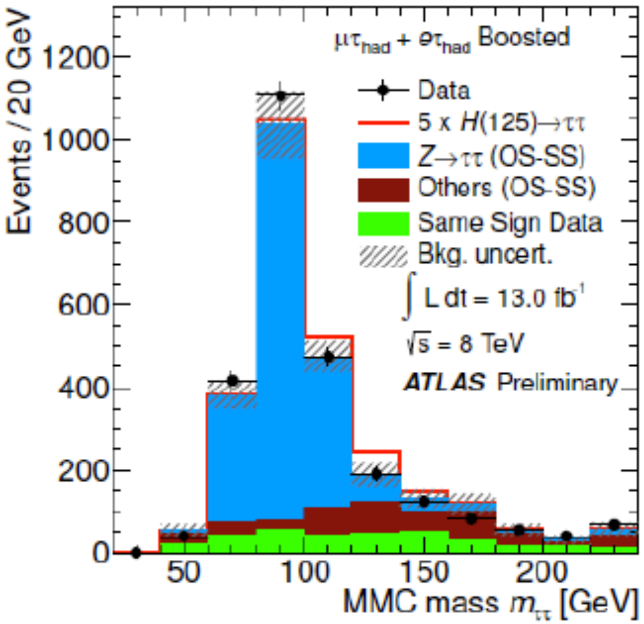
H$\rightarrow\tau\bar{\tau}$ (3)

- Some ggH distributions for the more sensitive “boosted” category (note that the signal is multiplied by different factors):

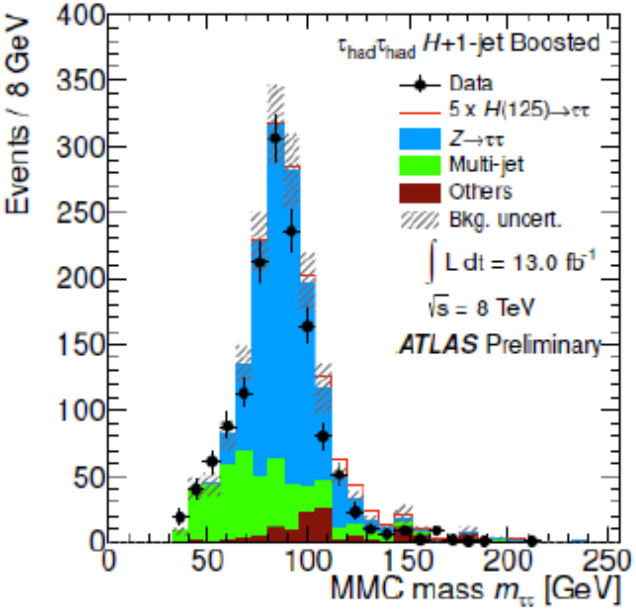
lepton-lepton



lepton-hadron



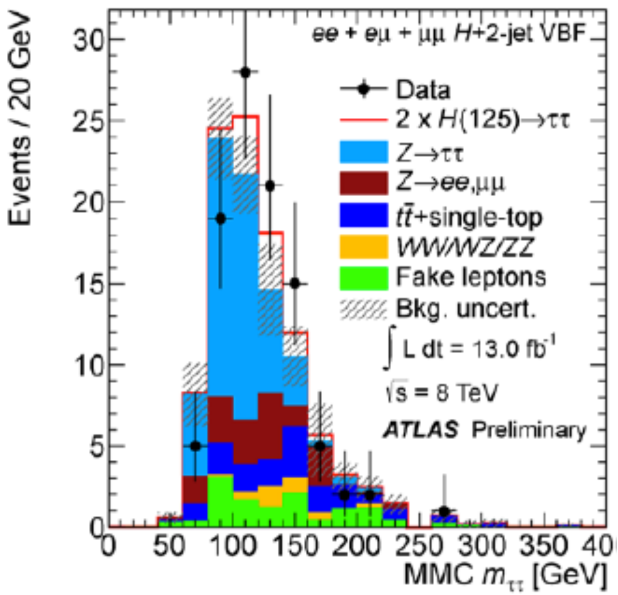
hadron-hadron



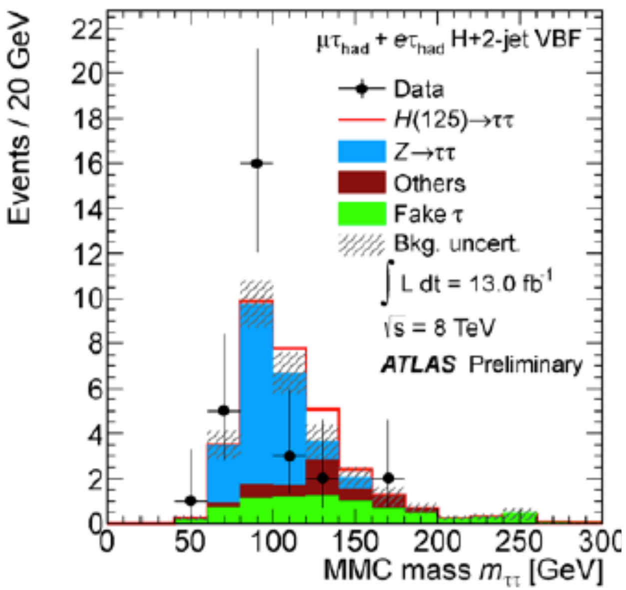
H$\rightarrow\tau\bar{\tau}$ (4)

- Some VBF distributions (note that the signal is multiplied by different factors):

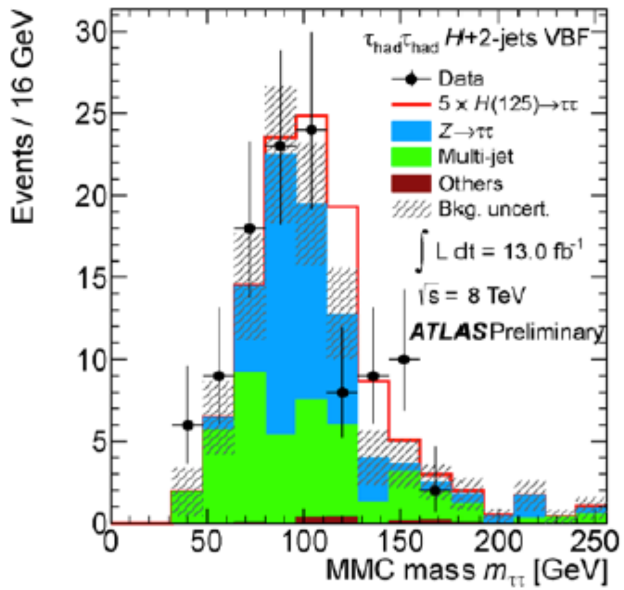
lepton-lepton



lepton-hadron

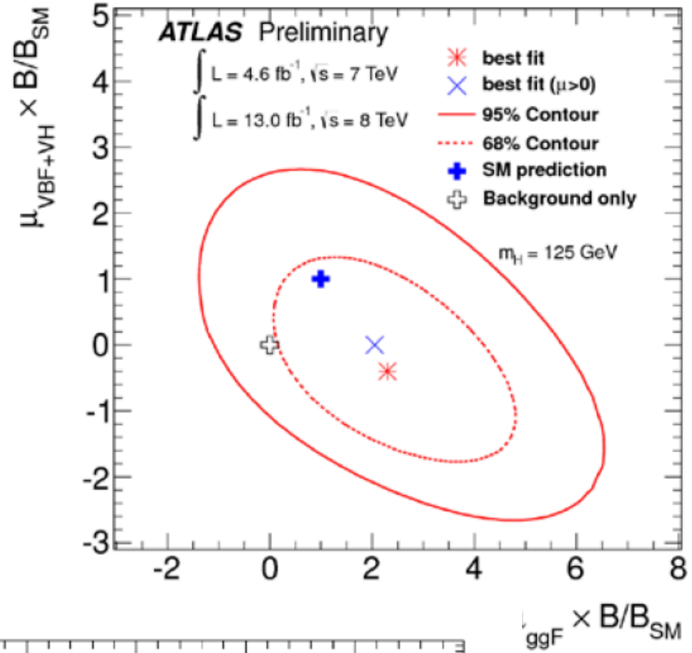


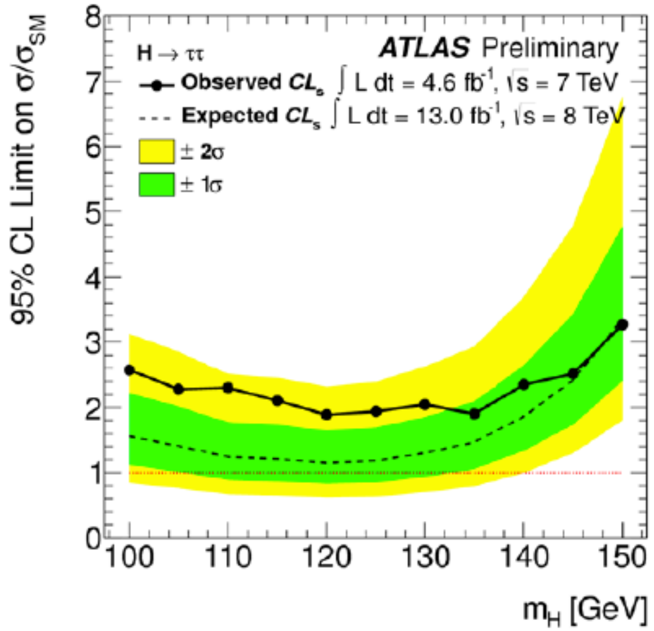
hadron-hadron

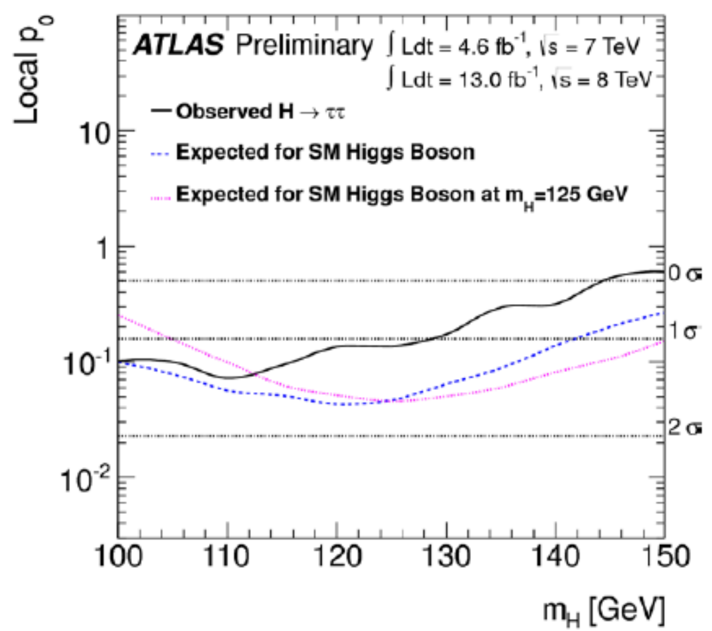


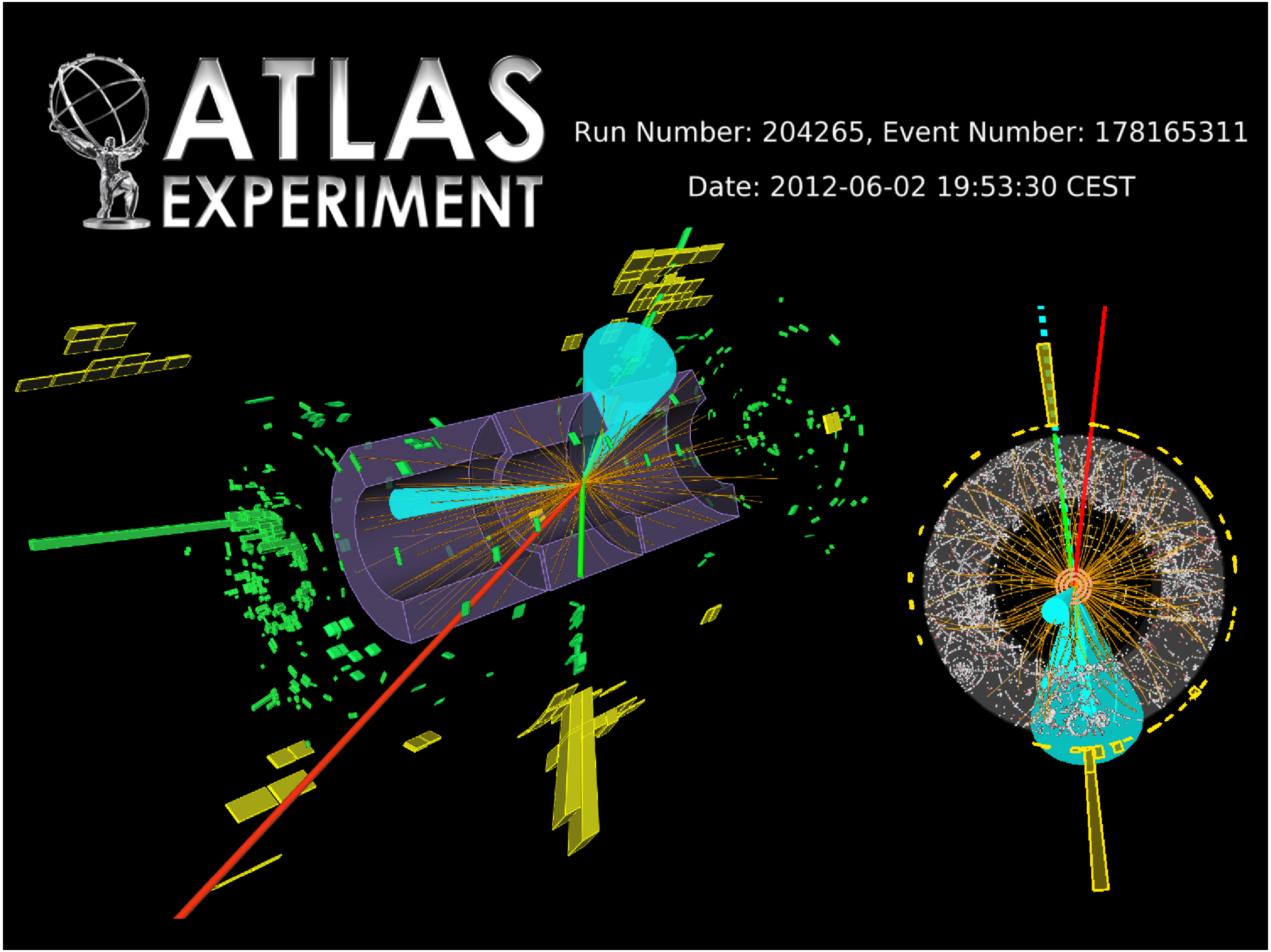
$H \rightarrow \tau\bar{\tau}$ (5)

- Expected local significance: 1.7 σ
- Observed local significance: 1.1 σ
- Signal strength parameter:
  - $\mu = 0.7 +/- 0.7$
- Expected limits (125 GeV): 1.2 x SM
- Observed limit (125 GeV): 1.9 x SM








ATLAS
EXPERIMENT
Run Number: 204265, Event Number: 178165311
Date: 2012-06-02 19:53:30 CEST

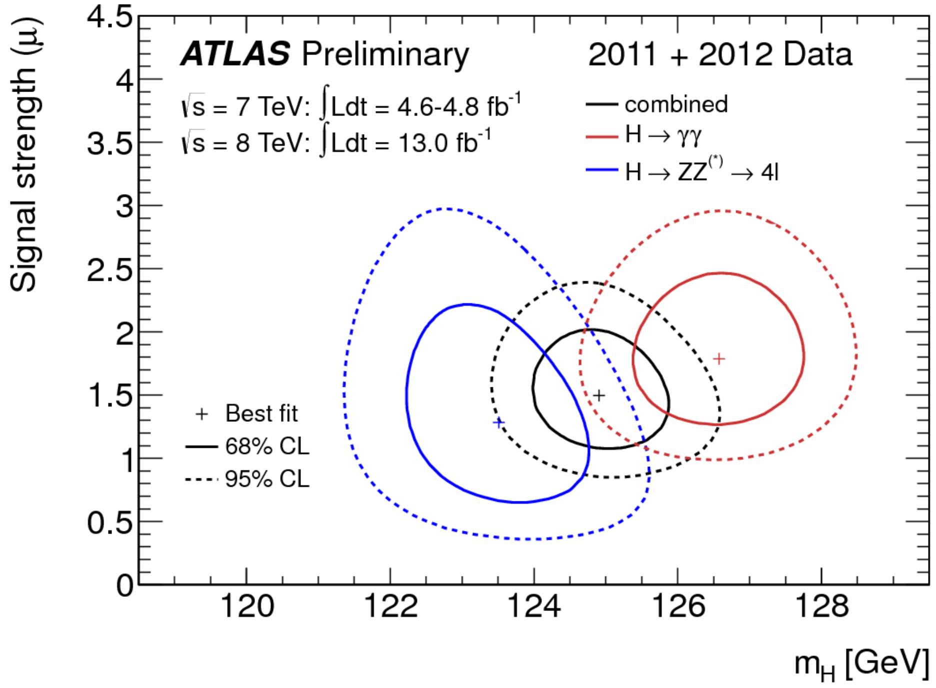
Combination of ZZ and γγ Channels

Combined mass measurement:

$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \mathrm{GeV}$$

Combined signal strength: $\hat{\mu} = 1.5^{+0.33}_{-0.29}$

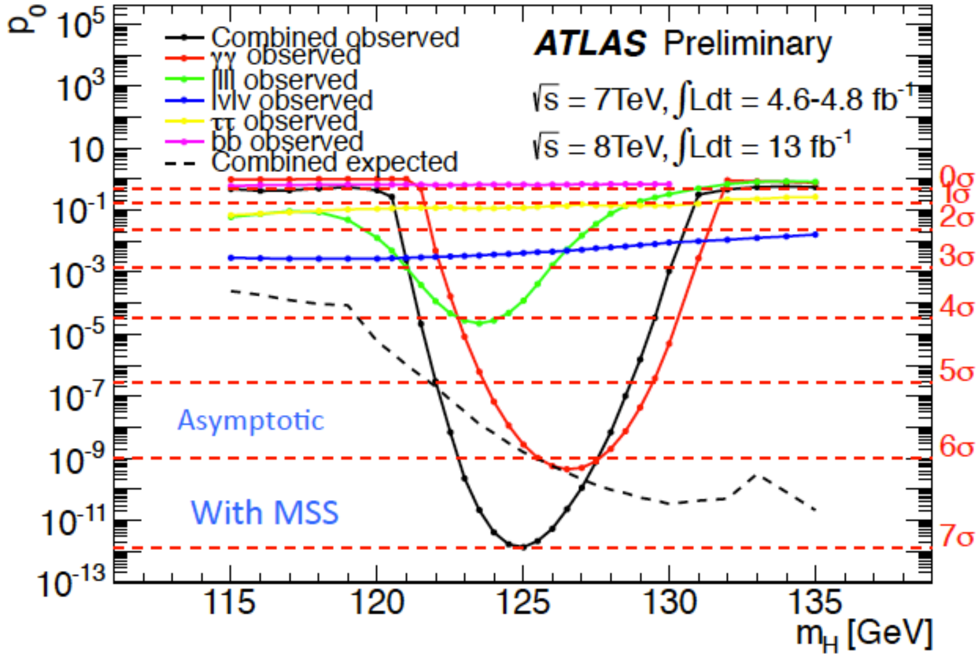
- Taking mass scale uncertainties and their correlations into account, the compatibility of the two measurements is estimated to be at be at the 2.7 σ level.
  - An alternative treatment of the systematic uncertainties yields a compatibility at the level of 2.3 σ

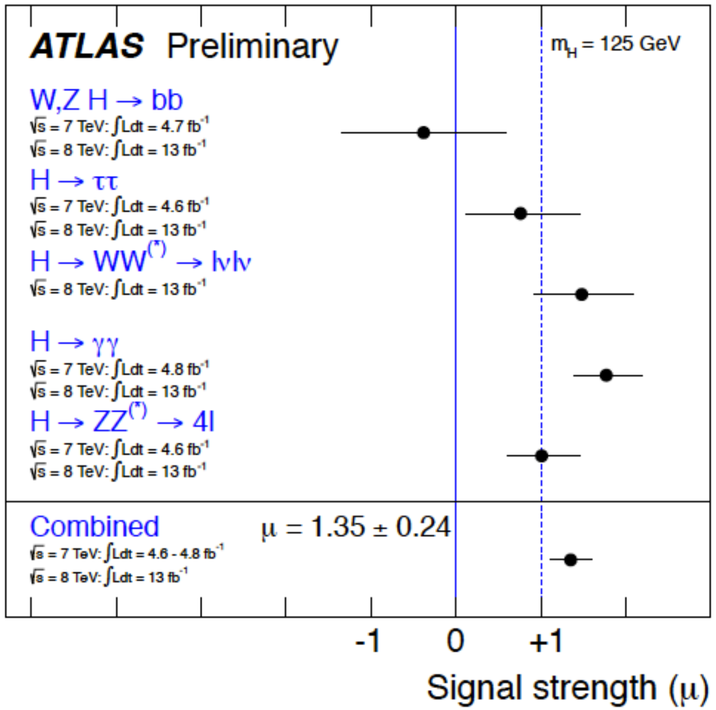


ATLAS-CONF-2012-170

Combination of all Channels

- Observed local significance: 7.0 σ
- Expected local significance: 5.9 σ
- ATLAS-CONF-2012-170





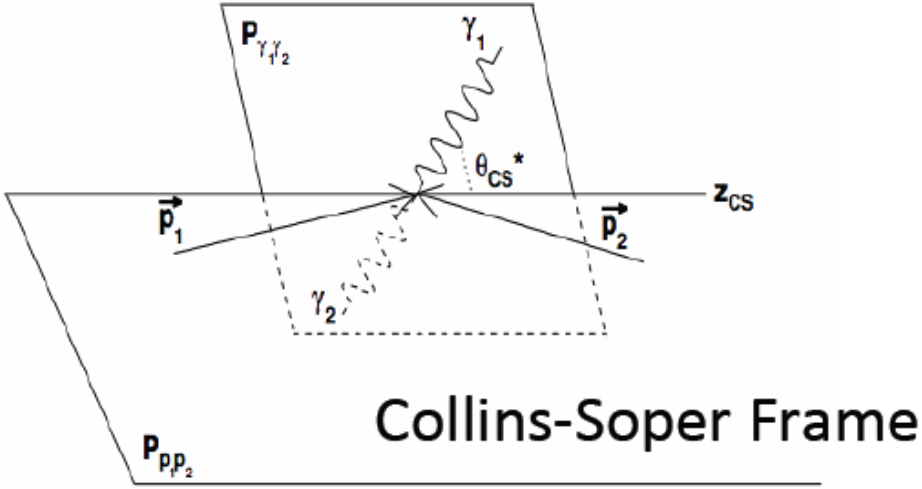
- Signal strength:

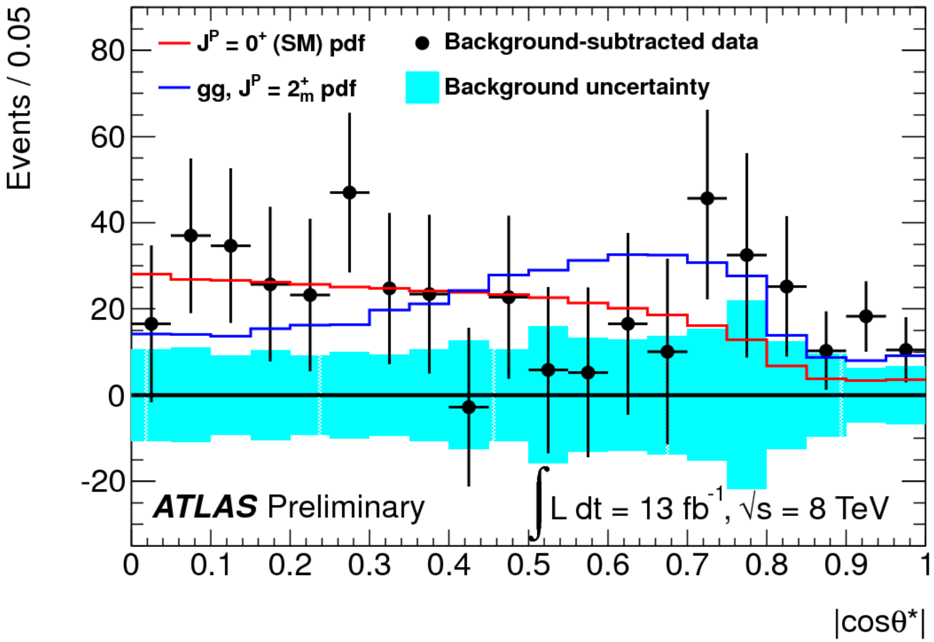
$$\hat{\mu} = 1.35 \pm 0.19\ (stat) \pm 0.15\ (syst)$$

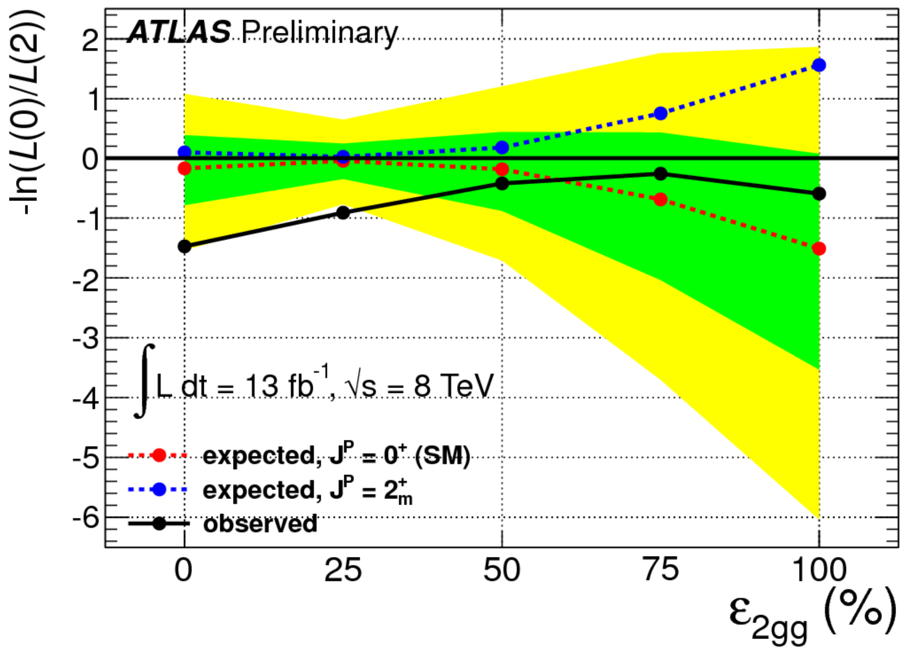
- Compatibility test of the 5 channels yields a probability of 13%

Spin in H→γγ

- Use cos θ* distribution in inclusive analysis
- Events within 1.5σ of the peak
- Exp. 2+ exclusion: 97% CL
- Obs. 2+ exclusion: 91% CL
- Results depend on gg/qq fraction: spin 0 favoured

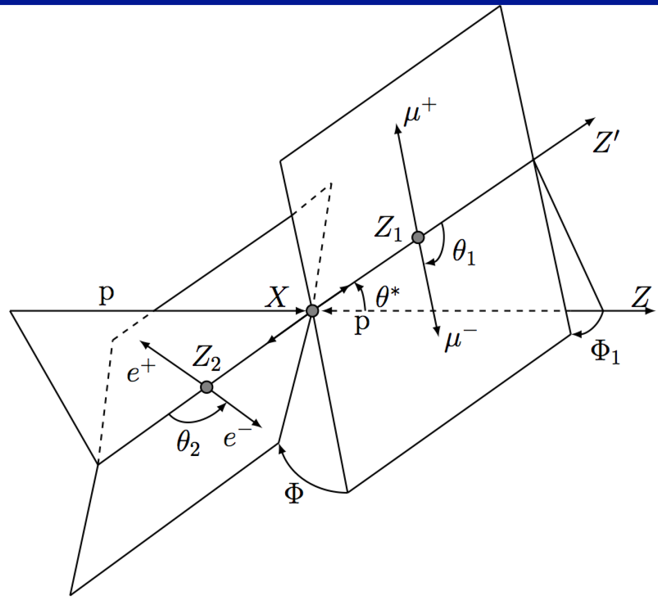


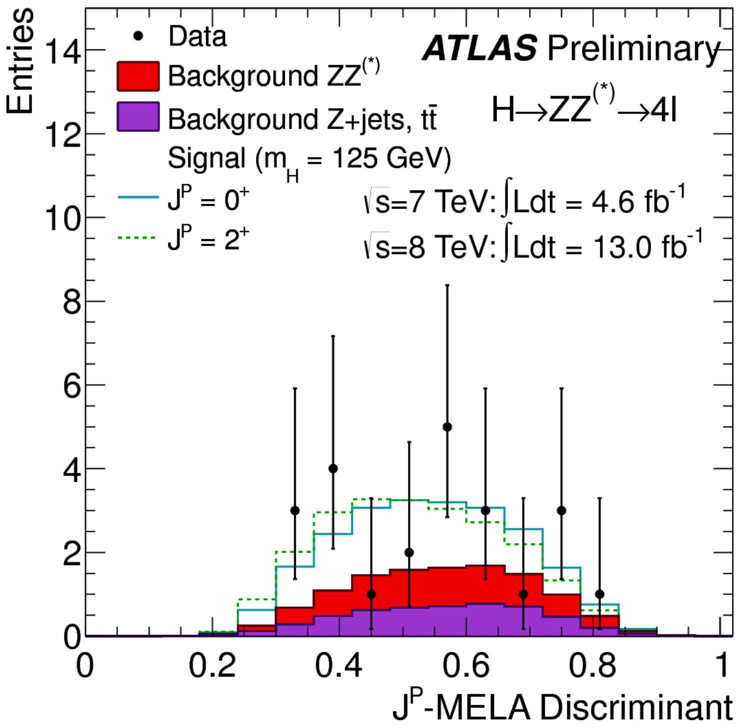


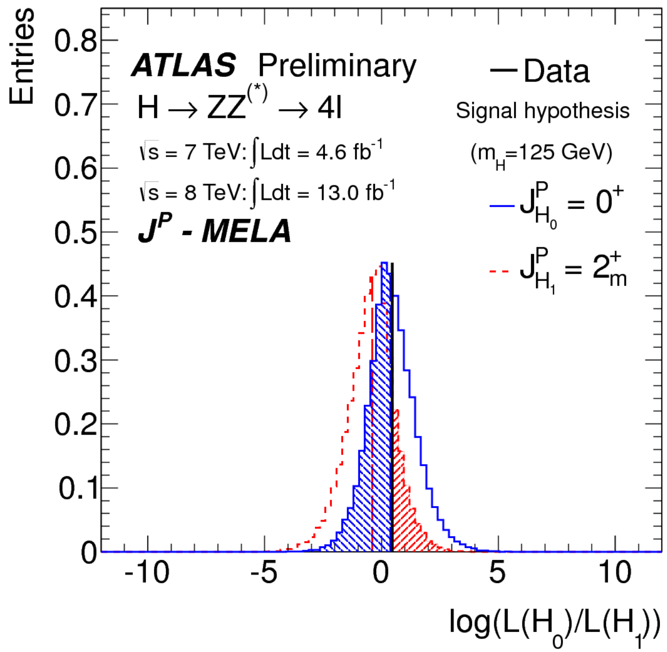


Spin in H ➡ZZ

- Use 5 production/decay angles in BD, MELA discriminants
- Spin 2:
  - Expected exclusion: 80% CL
  - Observed exclusion: 85% CL
- Results compatible with spin 0 (within 0.2σ)

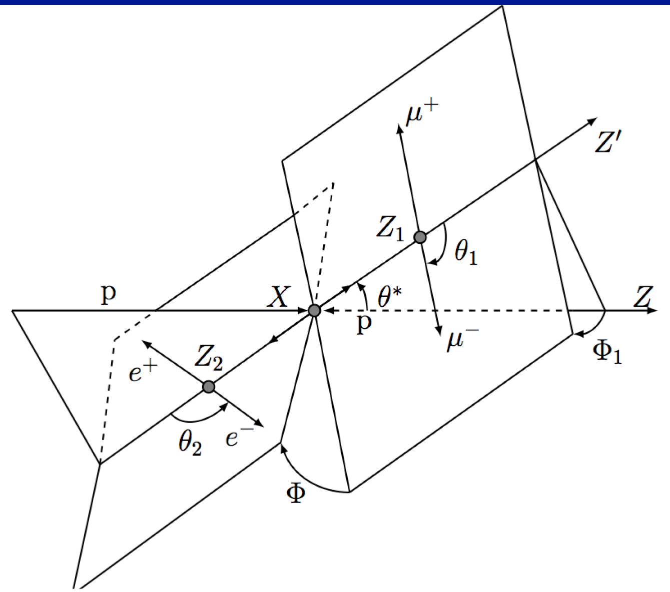


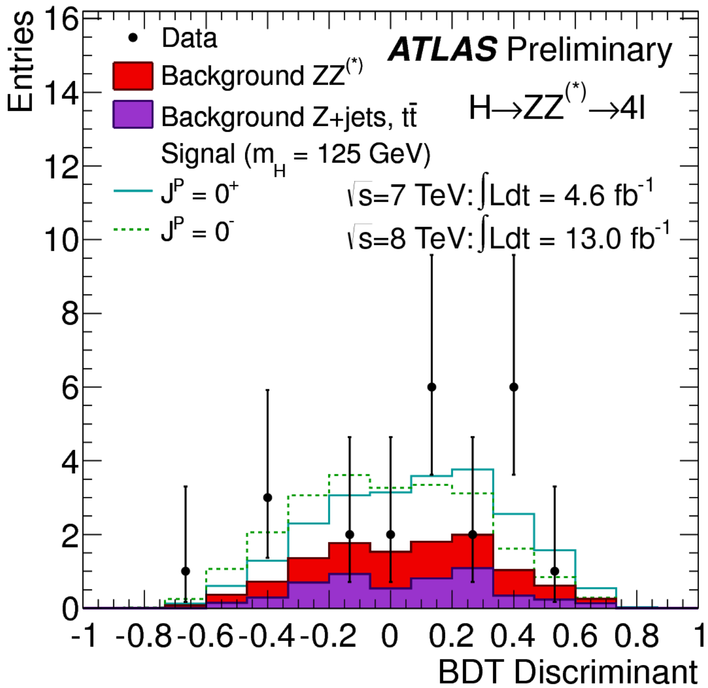


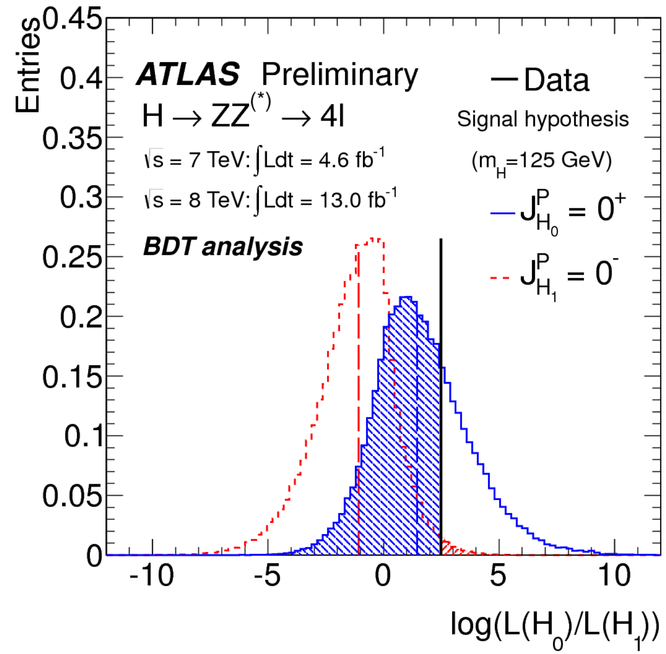


Parity in H➡ZZ

- Use 5 production/decay angles in BDT MELA discriminant
- Spin 0-:
  - Expected exclusion: 96% CL
  - Observed exclusion: 99% CL
- Results compatible with 0+ (within 0.5σ)







Next Steps

Program for 2013:

- Analyse full 2011-2012 dataset (~27 fb^{-1}) that is now collected. Preliminary results this Winter, papers with many analysis improvements later this year:
  - Measure rates in various channels
  - Confirm Spin/CP properties
  - Mass measurement
  - Extend the search for other Higgs particles (could be the easiest way to show that the observed particle is not the SM Higgs…)

Conclusions

- The latest Higgs results with ~13 fb^{-1} of 8 TeV data and ~5 fb^{-1} of 7 TeV data were presented for the WW, ZZ, γγ, ττ, bb channels
- Overall, observed rates are compatible with the SM prediction (compatibility test yields a probability of 13%)
- Preliminary Spin and CP couplings were also presented. The data are consistent with a spin 0 particle with even parity and disfavour the spin 2 or 0- hypotheses

Backup