Higgs Boson Searches with ATLAS

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DISCRETE 2012

Third Symposium on Prospects in the Physics of Discrete Symmetries
3-7 December 2012 – CFTP, Instituto Superior Técnico

Outline

- After the discovery
- SM Higgs News:
  - $H \rightarrow WW \rightarrow l\nu l\nu$
  - $H \rightarrow \tau\tau$
  - $H \rightarrow bb$
  - Signal strength

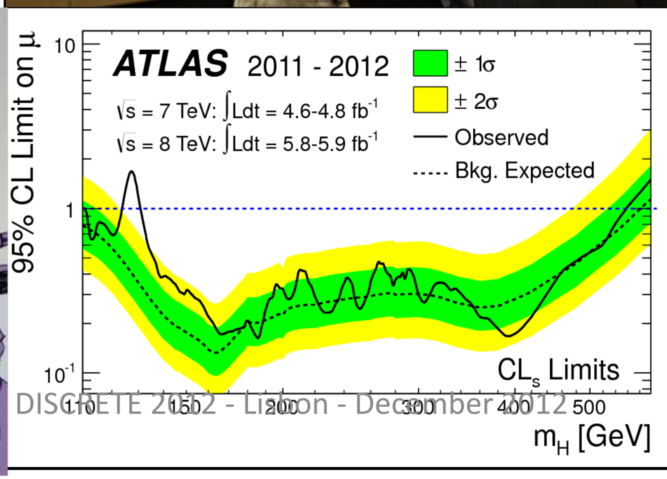
See ATLAS overview in Patricia Conde-Muiño's plenary talk

The story so far… we found a Higgs-like boson! ☺

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

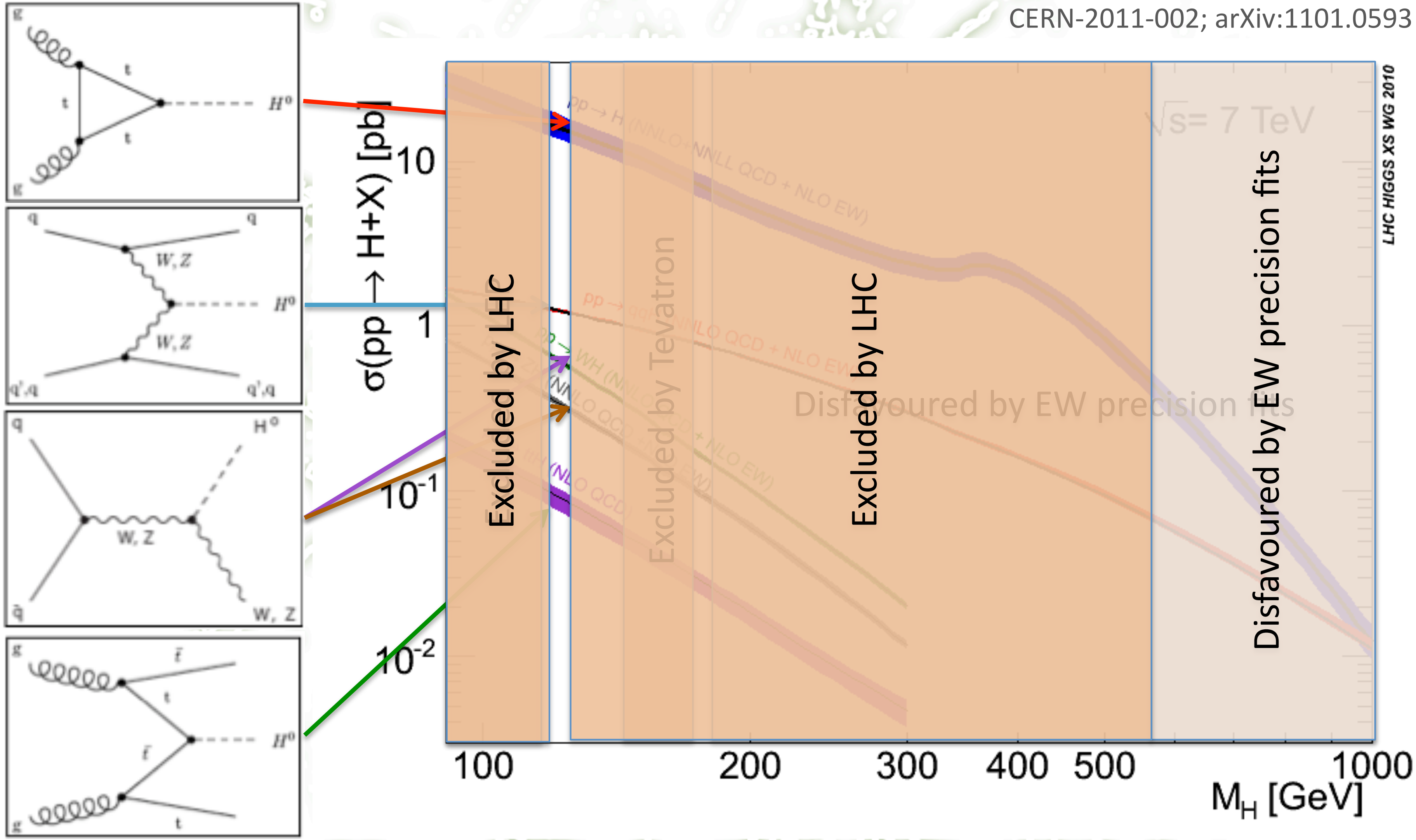
CERN-PH-EP-2012-218
Accepted by: Physics Letters B

Observation of a New Particle in the Search for the Standard Model Higgs Boson with the ATLAS Detector at the LHC

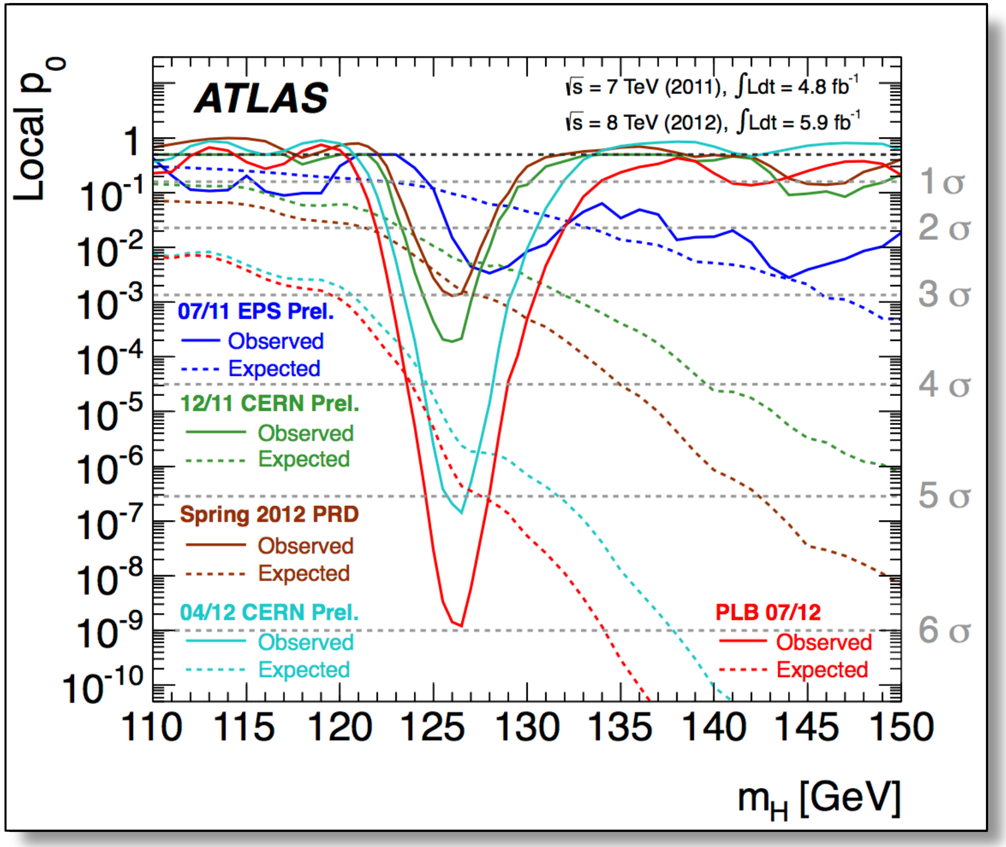


6 months ago: ICHEP 2012

CERN-2011-002; arXiv:1101.0593



- 5σ announced on 4th of July independently by ATLAS and CMS!! ≈6σ with ATLAS H->WW
- Data analysed:
  - $4.8\ fb^{-1}$ @7TeV & $5.6\ fb^{-1}$ @8TeV
- Clear excess only in bosonic decay channels:
  - H→ZZ, H→γγ, H→WW
- Hints of H→ττ from LHC and evidence from Tevatron for H→bb and hints from CMS
- Need to keep looking!
  - SM Higgs search is a great way to search new physics!



Search channel	Dataset	m_{max} [GeV]	Z_l [σ]	$E(Z_l)$ [σ]
$H \to ZZ^{(*)} \to 4\ell$	7 TeV	125.0	2.5	1.6
	8 TeV	125.5	2.6	2.1
	7 & 8 TeV	125.0	3.6	2.7
$H \to \gamma\gamma$	7 TeV	126.0	3.4	1.6
	8 TeV	127.0	3.2	1.9
	7 & 8 TeV	126.5	4.5	2.5
$H \to WW^{(*)} \to \ell\nu\ell\nu$	7 TeV	135.0	1.1	3.4
	8 TeV	120.0	3.3	1.0
	7 & 8 TeV	125.0	2.8	2.3
Combined	7 TeV	126.5	3.6	3.2
	8 TeV	126.5	4.9	3.8
	7 & 8 TeV	126.5	6.0	4.9

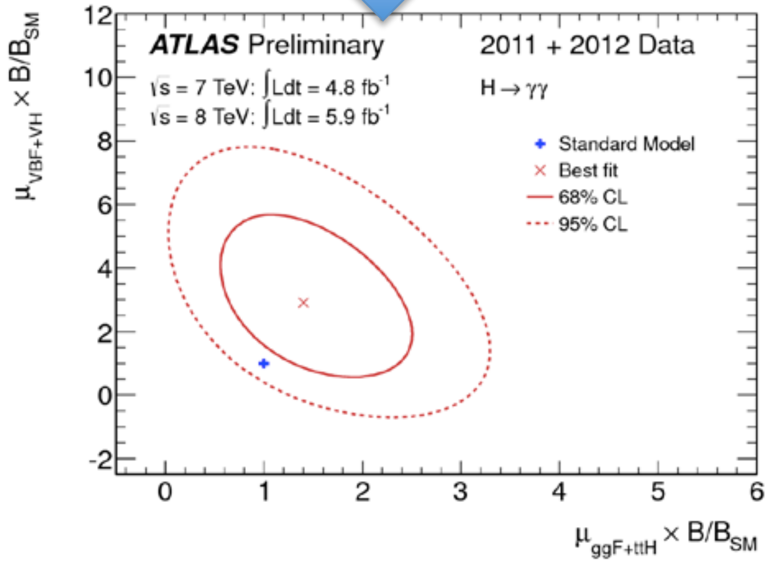
- The 6 billion Swiss Franc question (+ M&O):

Is it THE Standard Model Higgs?

More details of LHC Higgs implications in Abdelhak Djouadi's talk in Monday Plenary session

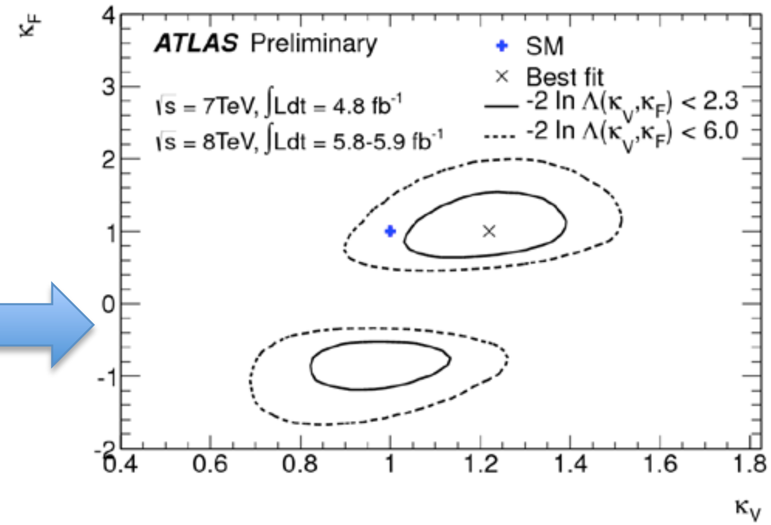
- What do we know about the new particle?
  - Mass ≈ 126 GeV
  - Electric charge = 0 (neutral final state)
- Unknown/incomplete knowledge:
  - Spin (*J*) = 0, 1, 2, ... ? *J*=1 disfavored (Landau-Yang theorem and observation in H➞γγ)
  - Charge-conjugation, parity (CP)
  - Couplings?

Signal strength for the γγ final state (gluon fusion vs VBF+VH)

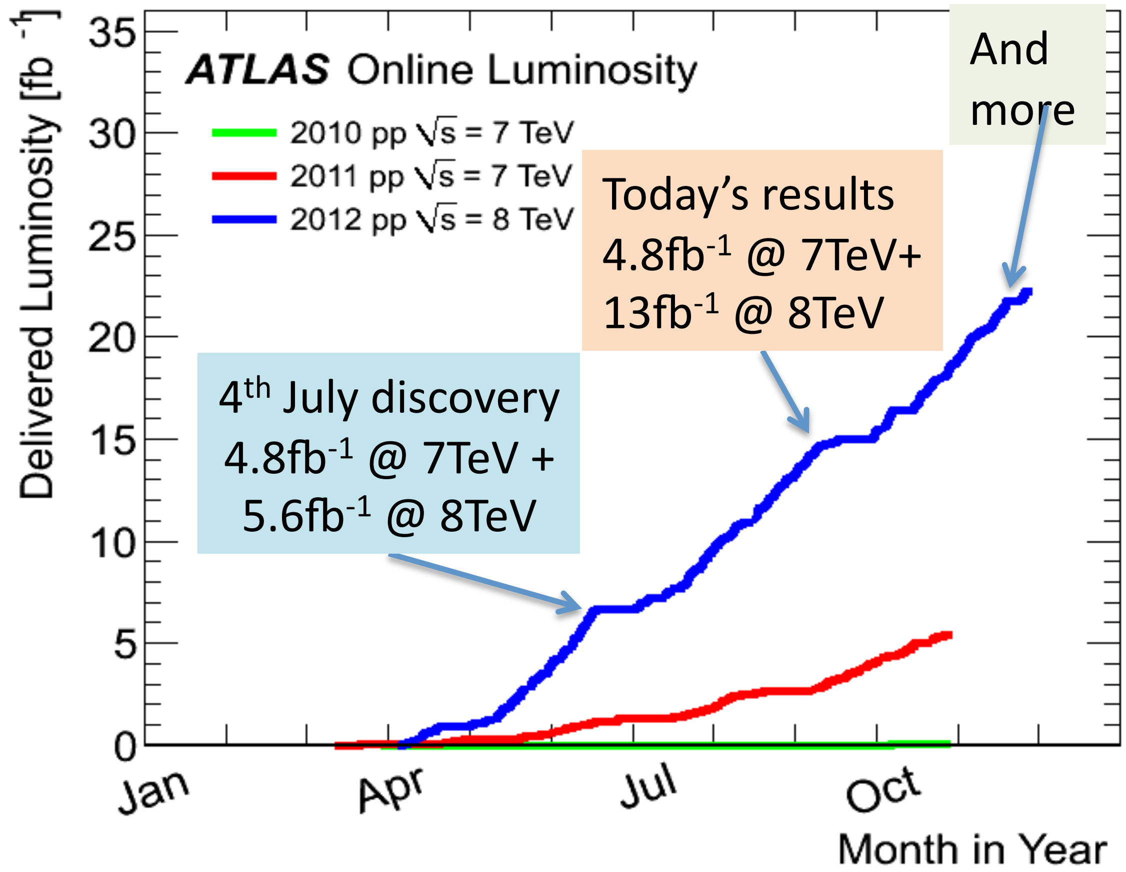


- September analysis used same data as July 2012 observation paper
  - ATLAS-CONF-2012-127: https://cdsweb.cern.ch/record/1476765?ln=en
- Fit data to estimate factors *κ* multiplying coupling in each SM production and decay mode

κ_V versus κ_F – assume a single κ_F factor for all fermions t, b, τ and a single factor κ_V for vector
Sign comes from interference between t and W loops in H➞γγ



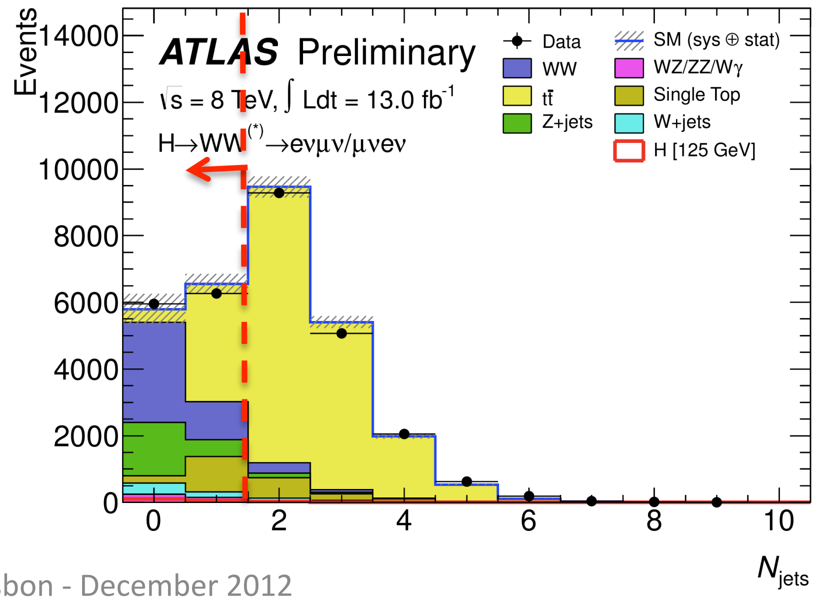
Latest Results



$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$

- 13 fb^{-1} of 8 TeV data
  - ATLAS-CONF-2012-158: http://cdsweb.cern.ch/record/1493601
- Signature:
  - Increased pileup in 2012
  - ⇒ Degraded E_T^{miss} resolution
  - ⇒ Poor $Z/\gamma^{(*)}$ rejection
  - Used e + μ + E_T^{miss} only
    - Good sensitivity
    - $Z/\gamma^{(*)}$ contamination suppressed
- Backgrounds:
  - WW
  - Top: tt+single top
  - W+jets, $Z/\gamma^{(*)}$, $W+\gamma^{(*)}$
- Split into categories:
  - 0-/1-jet (<2 jets to reject top)
  - μe /eμ (first lepton has higher p_T)

- Neutrinos => use transverse mass
  - Coarse m_T resolution
  - => broad Higgs signal
  - => Low sensitivity to Higgs mass
- Search for Higgs in m_T distribution
- Signal region blinded until backgrounds well understood in control regions:
  - Blind region: 93.75 < m_T < 125 GeV



Event Selection:

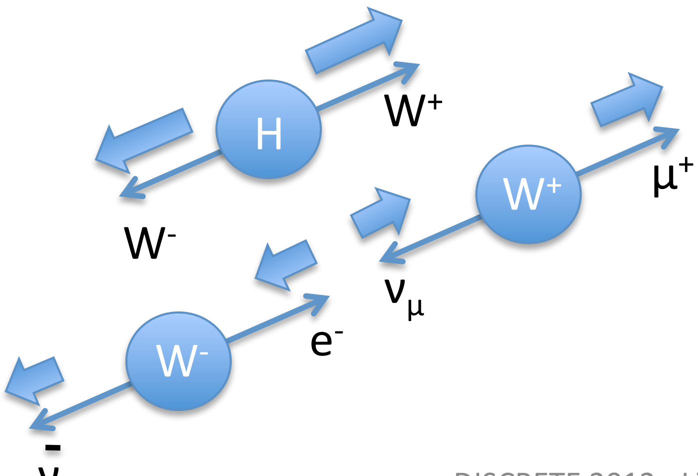
- $E_{T,rel}^{miss}$ > 25 GeV to remove $Z\rightarrow\tau\tau$ and fake E_T^{miss}
- Scalar Higgs means leptons have preferentially small separation

  Small azimuthal separation

  ⇒ small invariant mass: m(ll) < 50 GeV

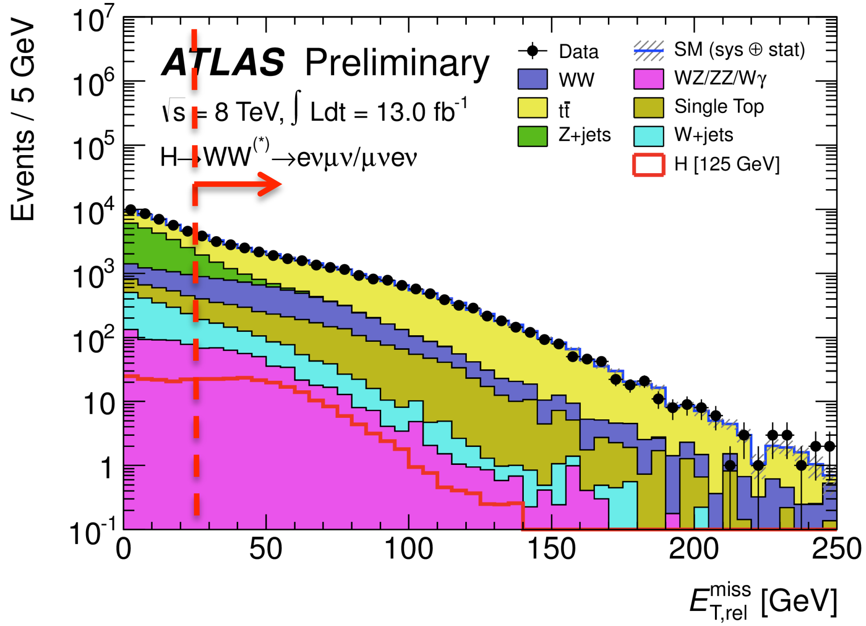
  ⇒ dilepton recoiling against ν's:

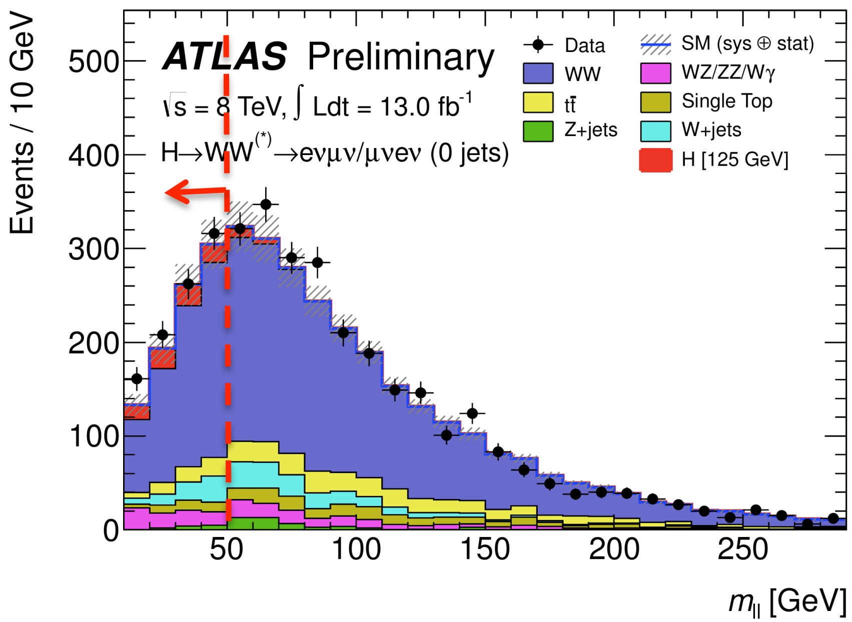
  – Δϕ(ll) < 1.8
- Also (0-jet analysis):
  – $\Delta\phi(ll, E_T^{miss}) > \pi/2$
  – $p_T(ll)$ > 30 GeV
- Dedicated $Z\rightarrow\tau\tau$ veto $|m_{\tau\tau} - m_Z|$>25 GeV in 1-jet category
- Veto events containing b-jets to reject top



$$\not{E}_T^{rel} = \not{E}_T \sin\min(\Delta\phi_m, \pi/2)$$

$$\Delta\phi_m = \min\Delta\phi(\ell/jet, \not{E}_T)$$





Background

W+jets:

- Control sample: one loosely identified lepton failing tight selection
- Transfer shape to signal region using fake factor evaluated with inclusive di-jet data sample (50% syst. from fake factor)

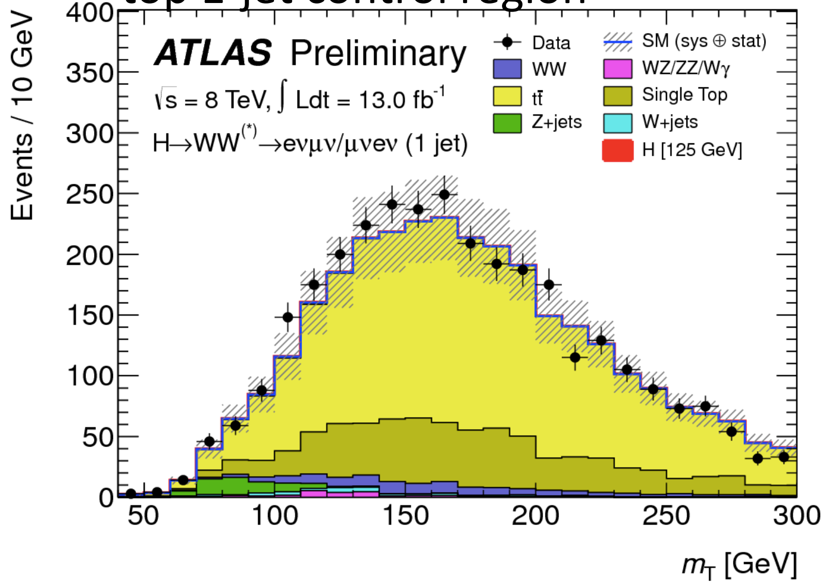
Top:

- Control samples:
  - 0 jet: loosen N_{jet} cut, remove m(ll) and Δϕ(ll) cuts
  - 1 jet: reverse b-jet veto (I.e. require a b-tagged jet)
- Correction factors applied to MC prediction: 1.04±0.14 (stat +syst), 1.03±0.37 (stat+syst) for the 0-,1-jet analysis

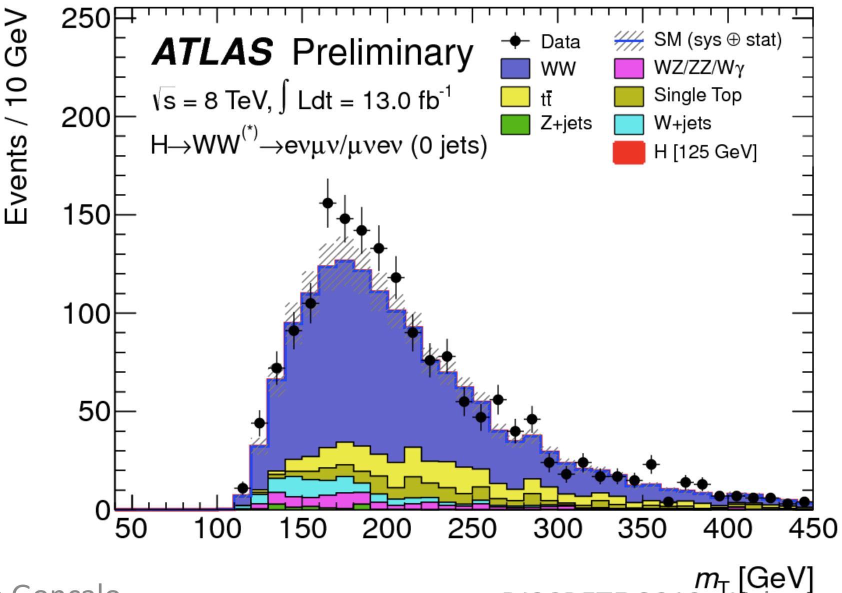
WW:

- Remove $\Delta\phi_{ll}$ cut, change m_{ll} cut to m_{ll} > 80 GeV
- Normalization factors: 1.13±13% (0-jet), 0.84±54% (1-jet)

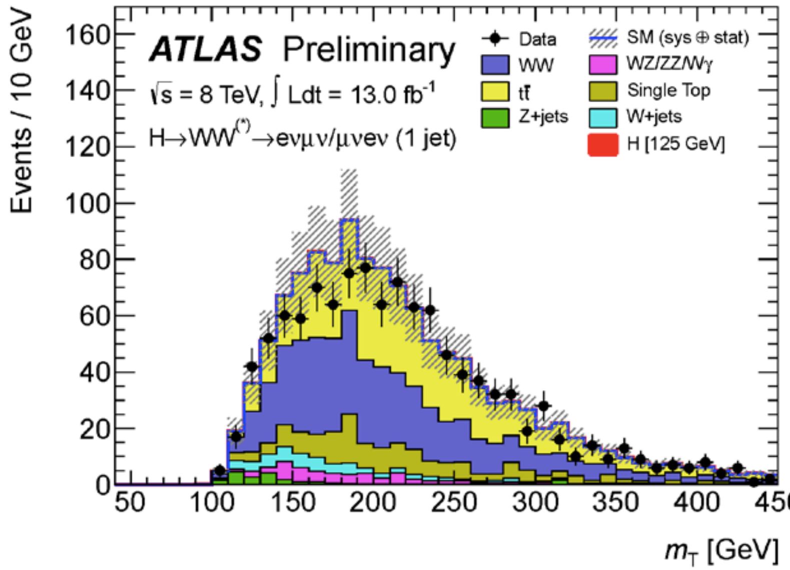
top 1-jet control region



WW 0-jet control region



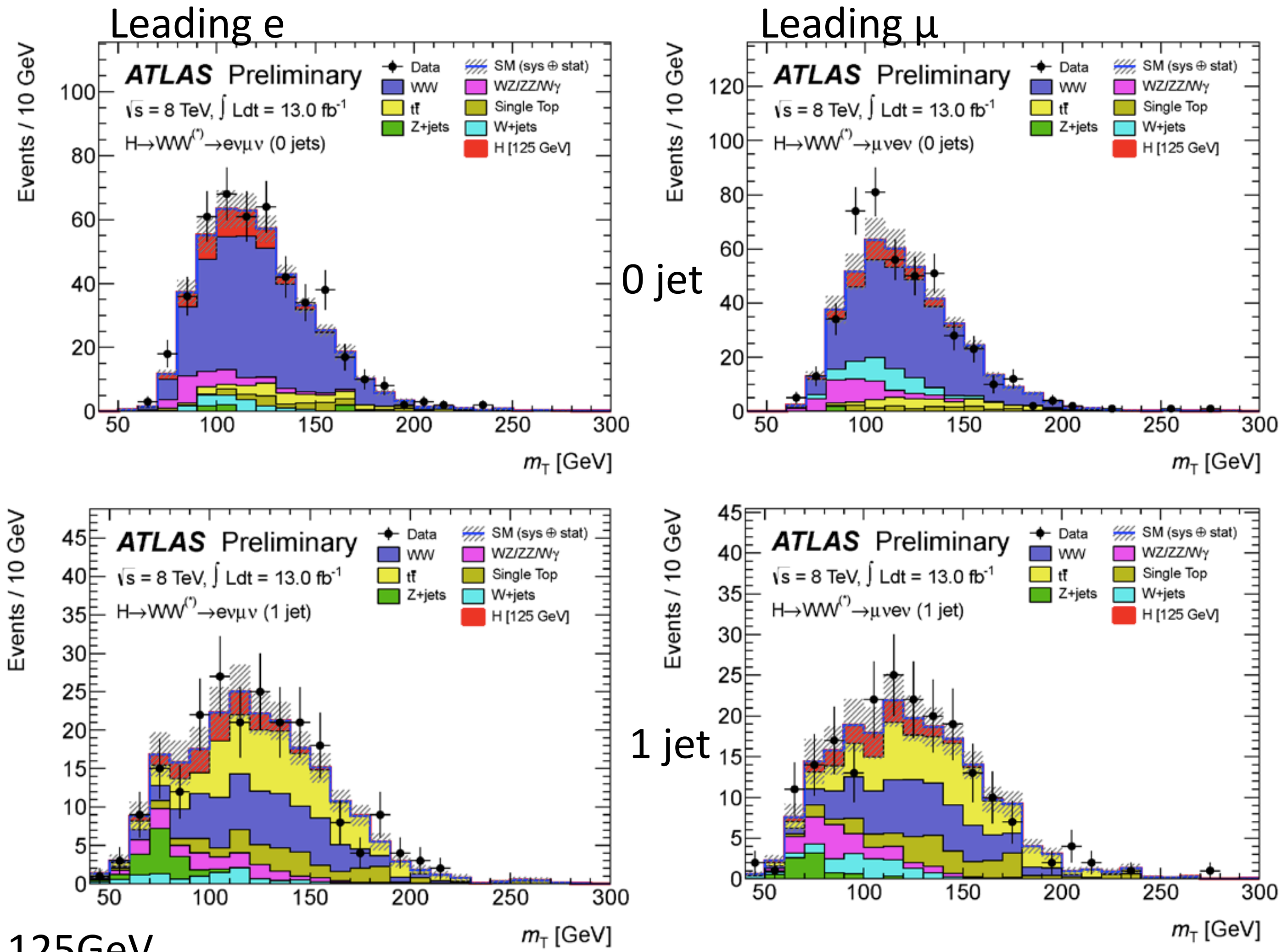
WW 1-jet control region



Results – I

- m_T in 4 analysis categories
- Used in statistical analysis
- S/B: ≈13-16%

Note: 2012 data ($13fb^{-1}$@8TeV)



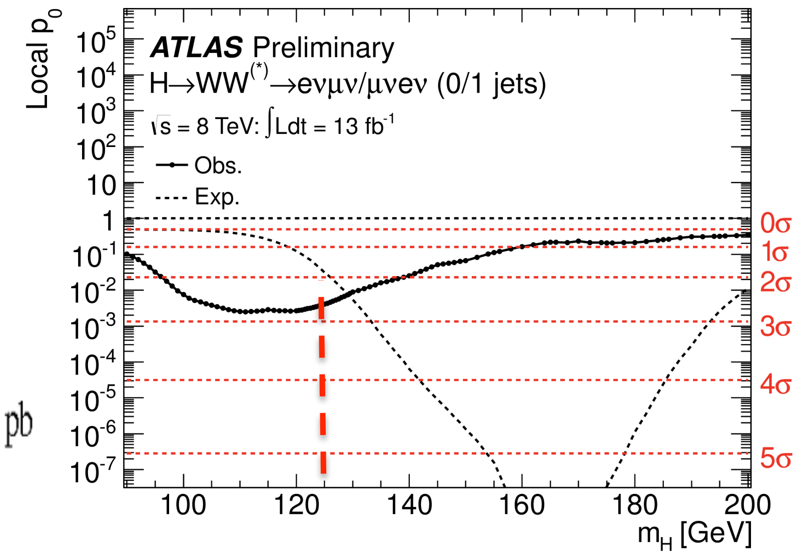
After m_T cut: $94 < m_T < 125$GeV

	Signal	WW	$WZ/ZZ/W\gamma$	$t\bar{t}$	$tW/tb/tqb$	Z/γ^* + 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

Results – II (note: 2012 data only)

At m_H=125GeV:

- Signal significance: 2.6σ (expected 1.9σ)
- Signal strength (ratio to SM rate): μ = 1.5 ± 0.6

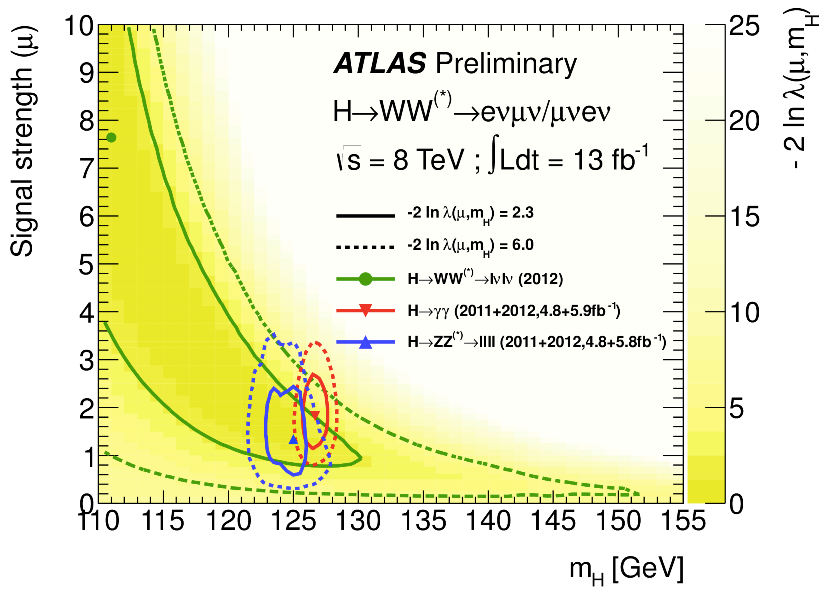


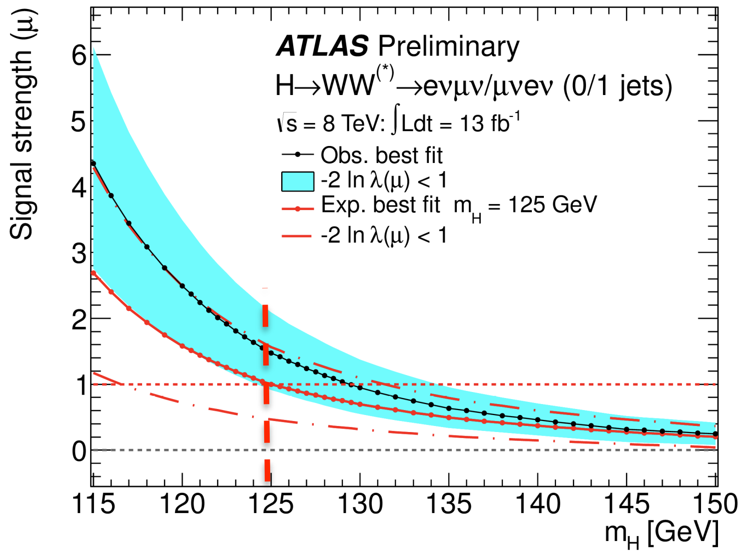
Assuming SM ratio of production mechanisms:

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

SM expectation:

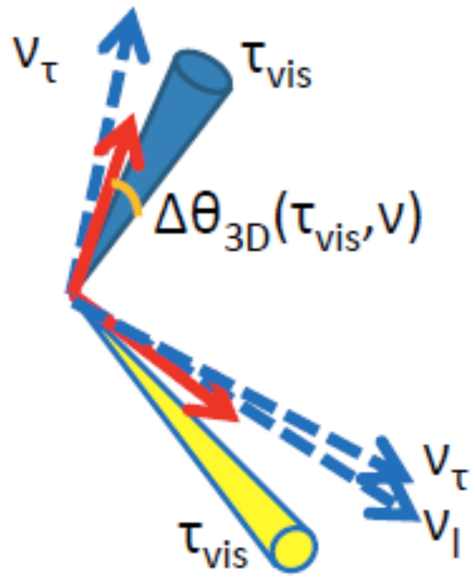
$$\sigma(pp \to H) \cdot Br(H \to WW) = 4.77 \pm 0.64\ (\mathrm{xsec}) \pm 0.2\ (\mathrm{BR})\ \mathrm{pb}$$

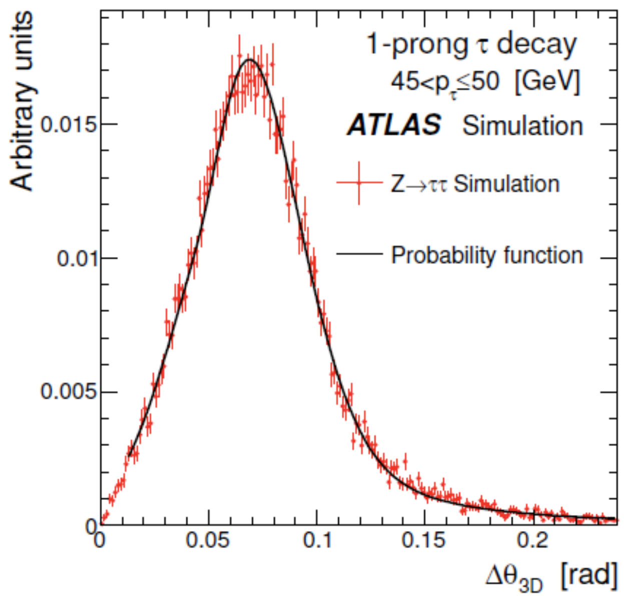


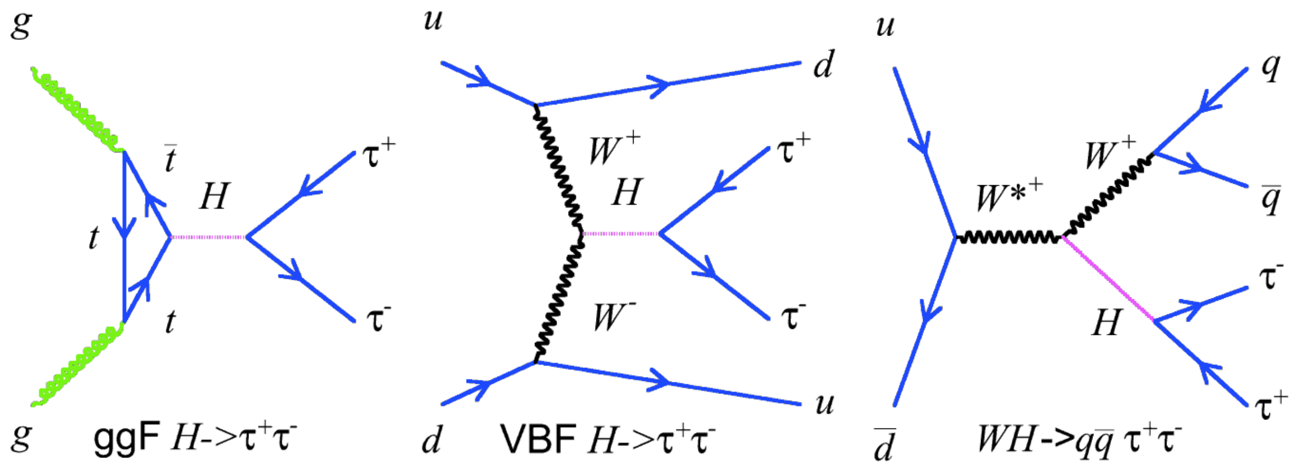


H→ττ analysis

- Analysed 4.6fb^{-1} (7TeV) + 13fb^{-1} (8TeV)
  - ATLAS-CONF-2012-160: https://cdsweb.cern.ch/record/1493624
- Three ττ decay modes:
  - "lep-lep": ll4ν; "lep-had": lτ_{had}3ν; "had-had": $\tau_{had}\tau_{had}$νν (l=e/μ)
- Three production channels:
  - gluon fusion, Vector boson fusion (VBF), WH/ZH production
- τ identification: BDT based on calorimeter and tracking
- $m_{\tau\tau}$ reconstructed with Missing Mass Calculator (MMC)
  - Kinematic fit to τ, E_T^{miss} in $\Delta\phi(\tau_{vis},\nu)$ parameter space using $\Delta\theta_{3D}(\tau_{vis},\nu)$ template from simulation as PDF
  - Mass resolution from 13% to 20% depending on kinematics and decay mode





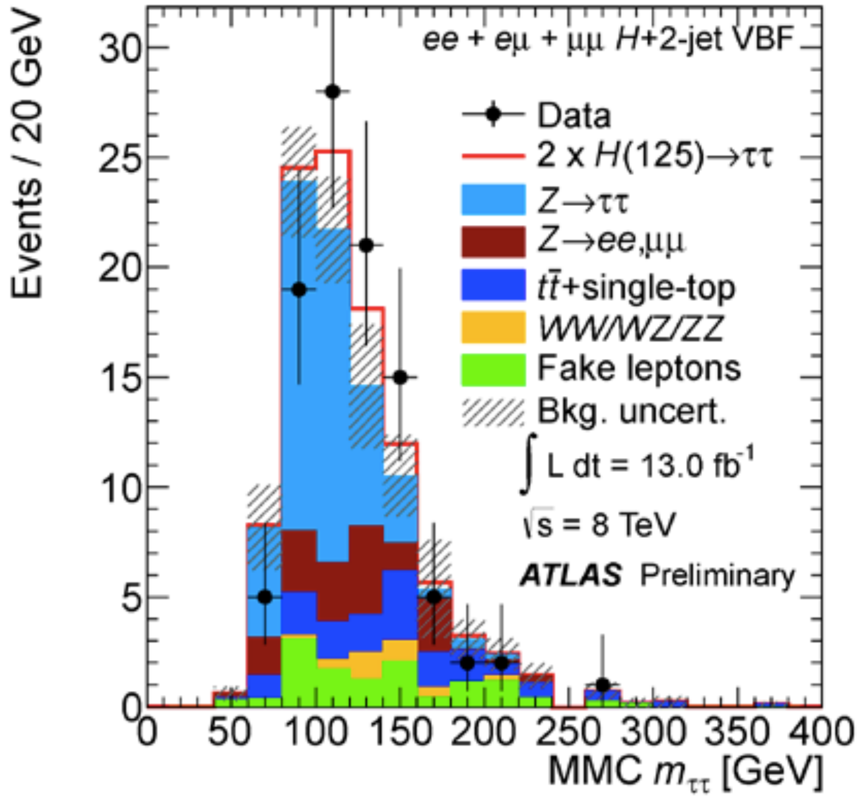


H→ττ→ll4ν (lep-lep)

- BR(H→ττ→ll4ν) = 12.4%

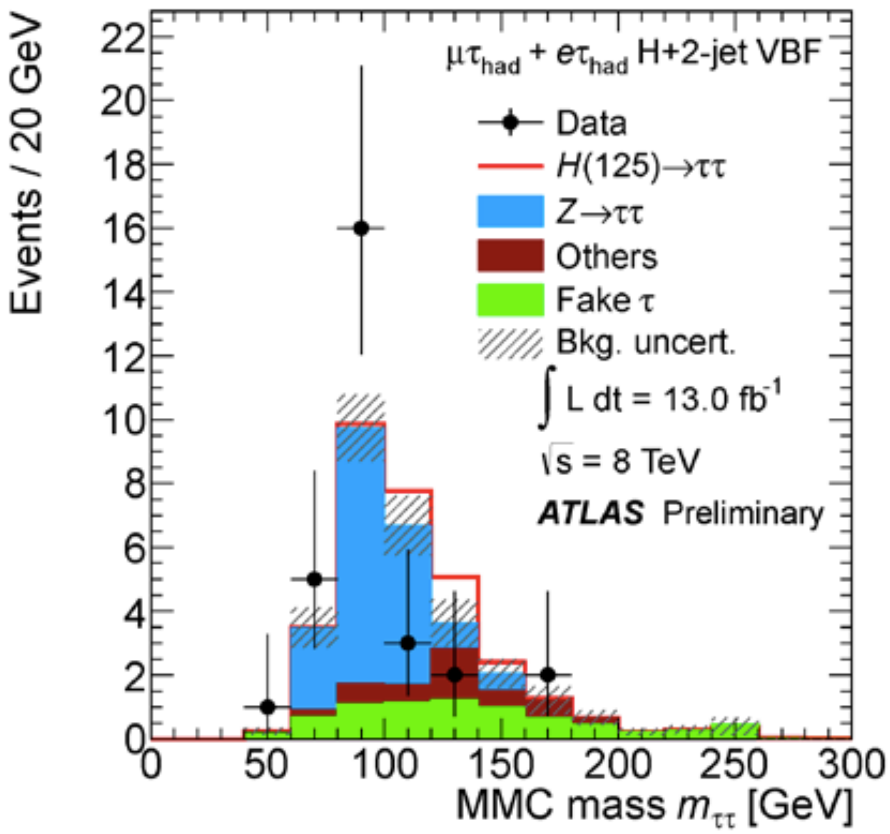
- 5 mutually exclusive categories (all using b-jet veto):
  1. **2-jet VBF**: P_T(j) > 25 GeV, Δη(jj) > 3.0, m(jj) > 400 GeV
  2. **Boosted**: NOT 2-jet VBF, **P_T(ττ) > 100 GeV**
  3. **2-jet VH**: NOT Boosted and Δη(jj) < 2.0, 30 GeV < m(jj) < 160 GeV
  4. **1-jet**: NOT 2-jet VBF, Boosted, or 2-jet VH, and m(ττj) > 225 GeV
  5. **0-jet**: oppositely charged leptons, 30 < m(ll) < 100 GeV, P_T(ll) > 35 GeV, Δϕ(ll) > 2.5 (not used at 8 TeV)

- Backgrounds:
  - Dominant: Z → ττ
  - Z → ττ estimated using "embedding": replace mu in real Z→μμ events with simulated τ's of same momentum
  - Z → ee/μμ backgrounds determined from data: simulations normalized to control regions
  - Fake leptons: determined from data using templates, fitted in control regions with relaxed lepton identification criteria



$H \rightarrow \tau\tau \rightarrow l\tau_{had}3\nu$ (lep-had)

- $BR(H \rightarrow \tau\tau \rightarrow l\tau_{had}3) = 45.6\%$
- 4 exclusive categories (here for 8 TeV):
  1. **2-jet VBF**: P_T(jet) > 40/30 GeV, $\Delta\eta$(jj) > 3.0, m(jj) > 500 GeV, m_T < 50 GeV
  2. **Boosted**: NOT 2-jet VBF, and PT($\tau\tau$) > 100 GeV, mT < 50 GeV
  3. **1-jet**: NOT 2-jet VBF or boosted, and P_T (jet) > 30 GeV, m_T < 50 GeV
  4. **0-jet**: No jets with P_T(jet) > 30 GeV
- Backgrounds:
  - Dominant: $Z \rightarrow \tau\tau$
  - Non-VBF categories:
    - Multijets: Estimated from same lepton sign events
  - VBF category:
    - Modeled by simulation normalized in data Z -> ee/μμ events with VBF-like cuts
    - Multi-jet and W+jet backgrounds normalised in control regions after relaxed lepton ID criteria and scaled to signal region

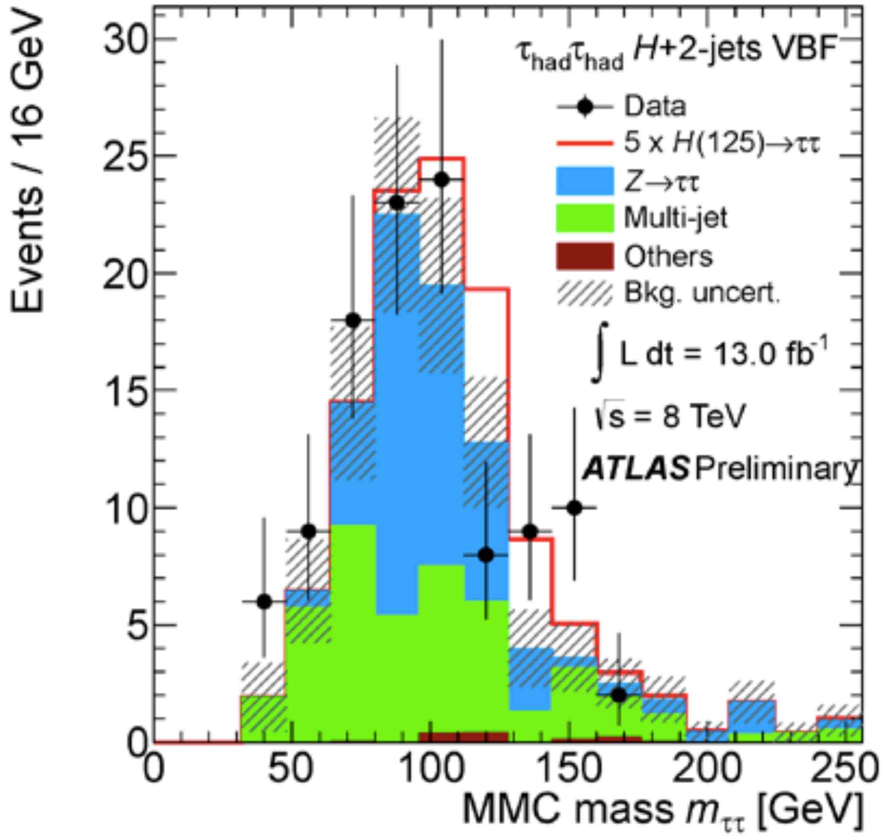


$H \rightarrow \tau\tau \rightarrow \tau_{had}\tau_{had}\nu\nu$ (had-had)

- BR($H \rightarrow \tau\tau \rightarrow \tau_{had}\tau_{had}\nu\nu$) = 42%
- 2 mutually exclusive categories:
  - **2-jet VBF**:

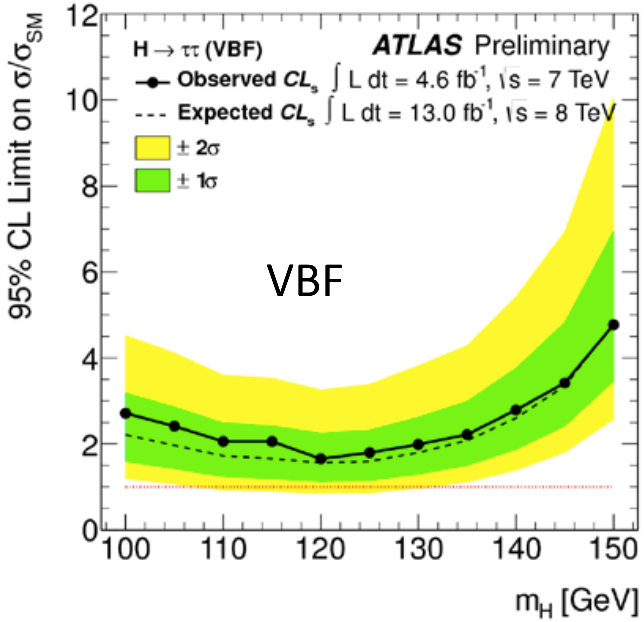
  P_T(jet) > 50/30 GeV, $\Delta\eta$(jj) > 2.6, m(jj) > 350 GeV, τ between "tag" jets in η
  - **Boosted**:

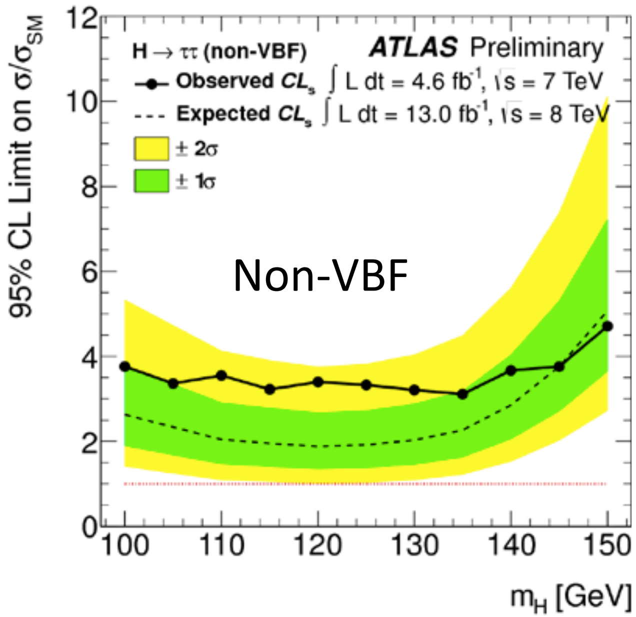
  NOT 2-jet VBF, PT(τ) > 70 (50) GeV for 2012 (2011), $\Delta R(\tau_1, \tau_2) < 1.9$.
- **Backgrounds:**
- Multijet background:
  - Broad track multiplicity, τ mostly 1 or 3
  - From same-sign events using 2D templates of N_{tracks} for each τ to fit track multiplicity to data
- Dominant Z -> ττ – embedding technique
  - 2D template fit to track multiplicity for the two hadronic taus
  - Normalize in region 60 < $m_{\tau\tau}$ < 108 GeV to exclude possible Higgs signal
- Other EWK backgrounds small – taken directly from MC

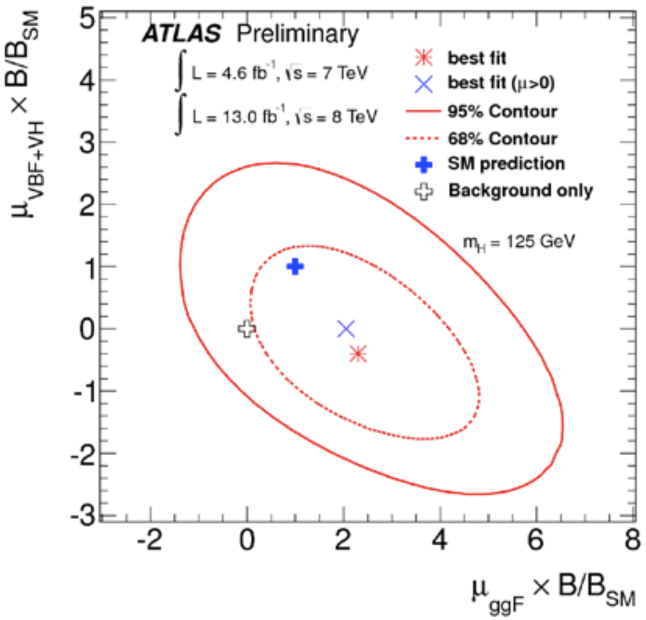


H→ττ results

- Total of 25 channels combined (13 for 7TeV, 12 for 8TeV)
- Small excess, consistent with SM Higgs hypothesis (and to lesser extent, with background-only)
  - Best-fit signal strength μ value at 125 GeV is $\mu = 0.7 \pm 0.7$
- Combined local significance for m_H = 125 GeV is 1.1σ observed (1.7σ expected)
- Observed (expected) exclusion is 1.9 (1.2) times the SM predicted value (μ=1)
- Separating out VBF categories broad excess seen in non-VBF categories

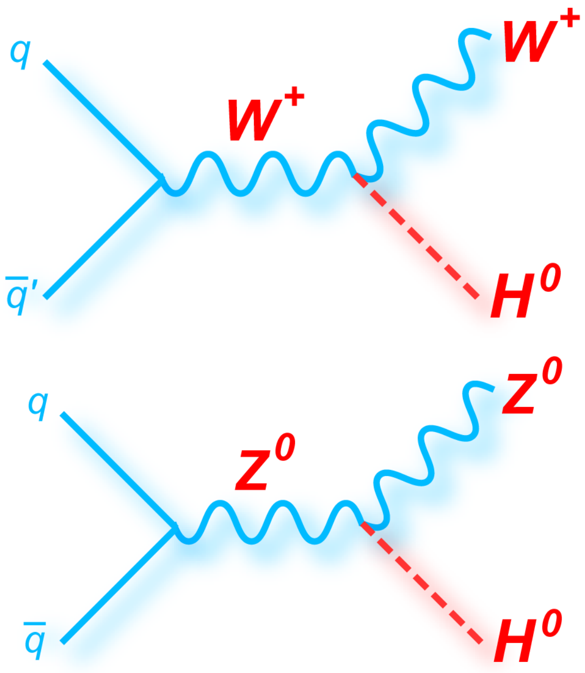






WH/ZH, H→bb

- This analysis: 4.7fb^{-1} √s = 7 TeV & 13fb^{-1} √s = 8 TeV
  - ATLAS-CONF-2012-161: http://cdsweb.cern.ch/record/1493625
- Analysis divided into three channels
  - Two (llbb), one (lνbb) or zero (ννbb) leptons (l=e,μ)
- Cuts common to all channels
  - Two or three jets: 1st jet p_T > 45 & other jets > 20 GeV
  - Two b-tags: 70% efficiency per tag; mistag rate: c-jet ≈20%; light-jet ≈0.7%
- 16 categories determined by p_T^V and $N_{leptons}$:
  - 0-lepton: E_T^{miss} [120-160] [160-200] [>200] GeV x (2 or 3 jets)
  - 1 & 2 lep: $p_T^{W/Z}$ [0-50] [50,100] [100-150] [150-200] [>200] GeV



Two lepton

ZH → llbb
- No additional leptons
- E_T^{miss} < 60 GeV
- 83 < m_{ll} < 99 GeV

One lepton

WH → lνbb
- No additional leptons
- E_T^{miss} > 25 GeV
- 40 < M_T^W < 120 GeV

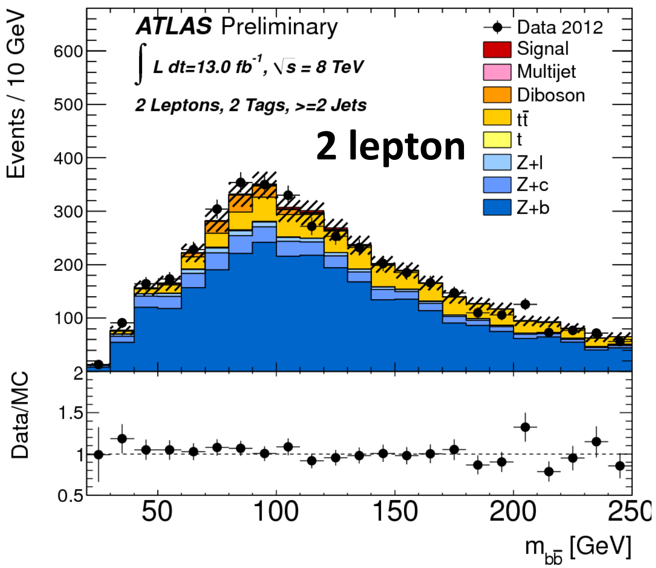
Zero lepton

ZH → ννbb
- No leptons
- E_T^{miss} > 120 GeV
- E_T^{miss} trigger

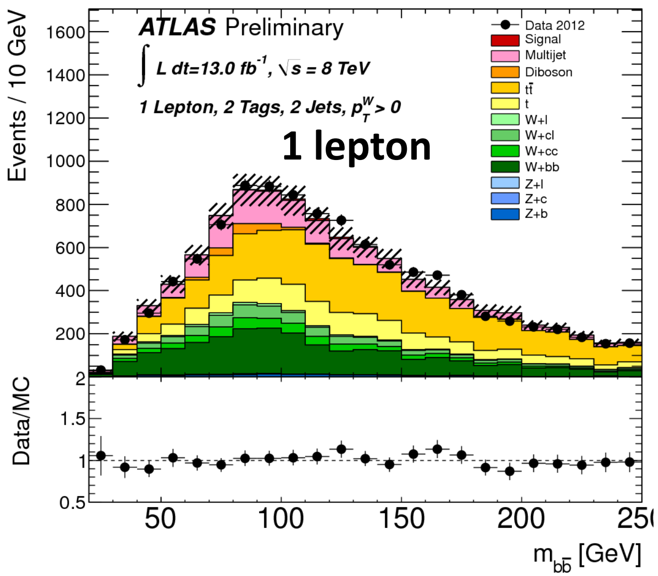
Backgrounds and MC

- Signal: WH/ZH Pythia6/8
- Diboson WW/WZ/ZZ Herwig
- Multijet: Data driven
- ttbar: MC@NLO
- Single Top Acer/MC@NLO
- W+b Powheg
- W+c/light-jets Alpgen
- Z+ b/c/light-jets Alpgen/Sherpa

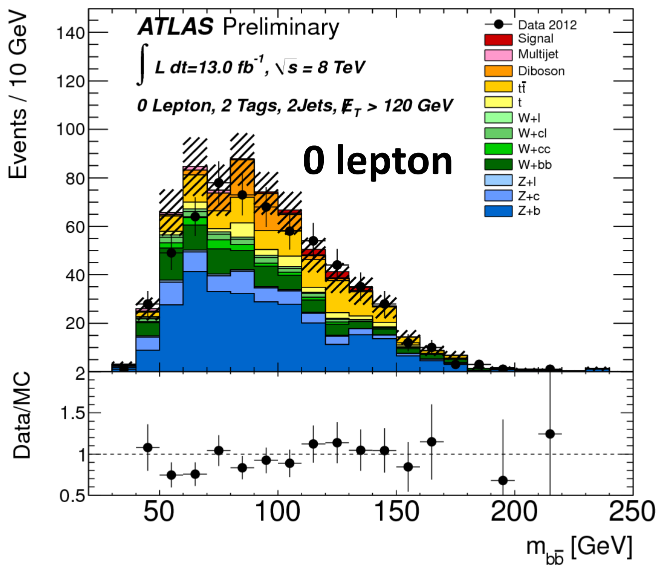
- Background shapes from simulation and normalised using flavour & data fit
- Multi-jet bkg determined by data-driven techniques
- WZ(Z→bb) & ZZ(Z→bb) resonant bkg normalisation and shape from simulation



Z+jets



Top/W+jets/Multijet

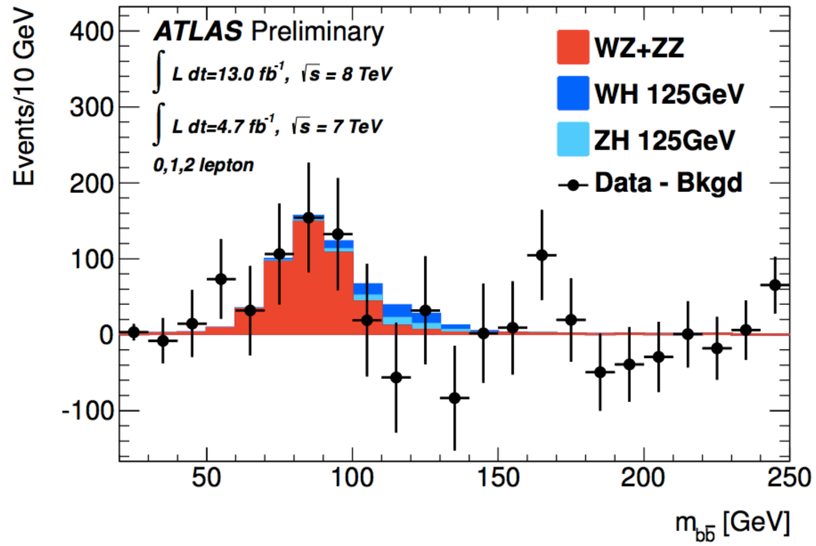


Z+jets/W+jets/Top

WH/ZH, H→bb results

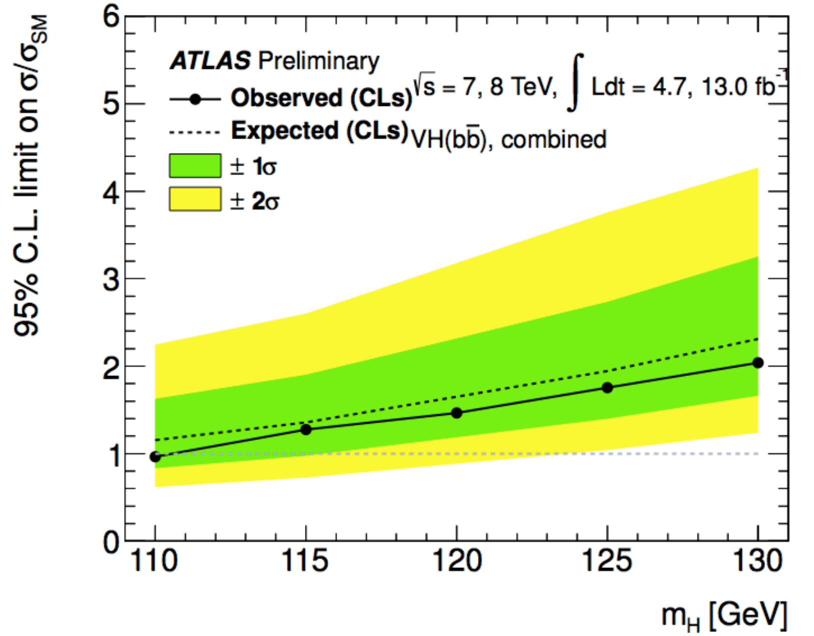
Dibosons:

- WZ & ZZ production with Z→bb
  - Similar signature, but 5 times larger cross-section
  - Clear excess is observed in data at expected mass
- Perform separate fit for Z→bb to validate H→bb analysis:
  - $\sigma/\sigma_{SM} = \mu_D = 1.05 \pm 0.32$
  - Significance = 4.0 σ
  - In agreement with Standard Model!



WH/ZH, H→bb:

- Some excess in 2012 data but deficit from 2011 re-analysis
- Results:
  - Limit: 1.8 (1.9)
  - p0 value 0.64 (0.15)
  - $\sigma/\sigma_{SM} = \mu = -0.4 \pm 0.7(\text{stat.}) \pm 0.8(\text{syst.})$
  - Exclusion at $m_H \approx 110$ GeV

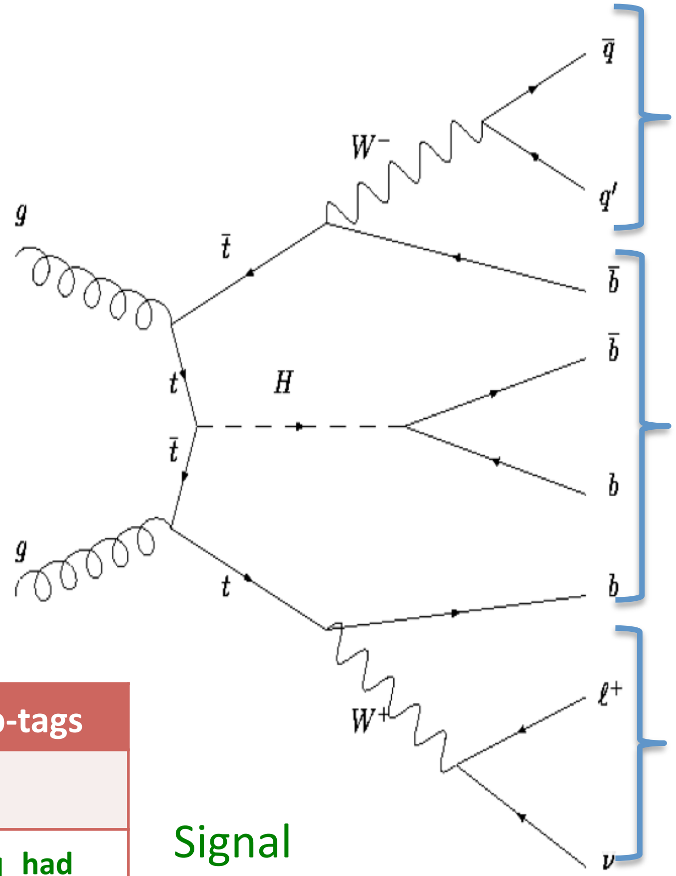


Note: CMS observed broad 2.2σ excess

ttH, H->bb Analysis

- Challenging analysis!
  - High combinatorial background
  - Small signal cross section
  - Important for top Yukawa coupling!
- Data: $4.7 fb^{-1}$ at $\sqrt{s}$ = 7 TeV (2011)
  - ATLAS-CONF-2012-135: https://cdsweb.cern.ch/record/1478423
- 9 categories based on jet & b-tag multiplicity
  - Signal enriched: (5 jets, ≥6 jets) x (3,≥4 b-tag)
  - Other categories are background enriched to constrain those backgrounds
- Final discriminants
  - m_{bb} for ≥6 jets and (≥3 b-tag) categories
    - Do kinematic fit to reconstruct tt+H→bb
  - H_T^{had} ($\sum p_{T,jet}$) for other categories

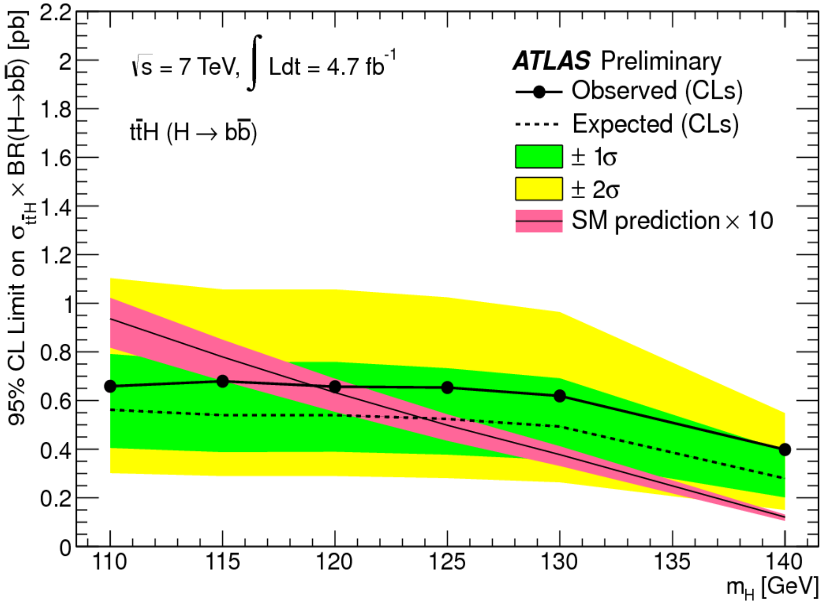
- Backgrounds constrained in limits fit by profiling nuisance parameters
- To check fit control regions are used

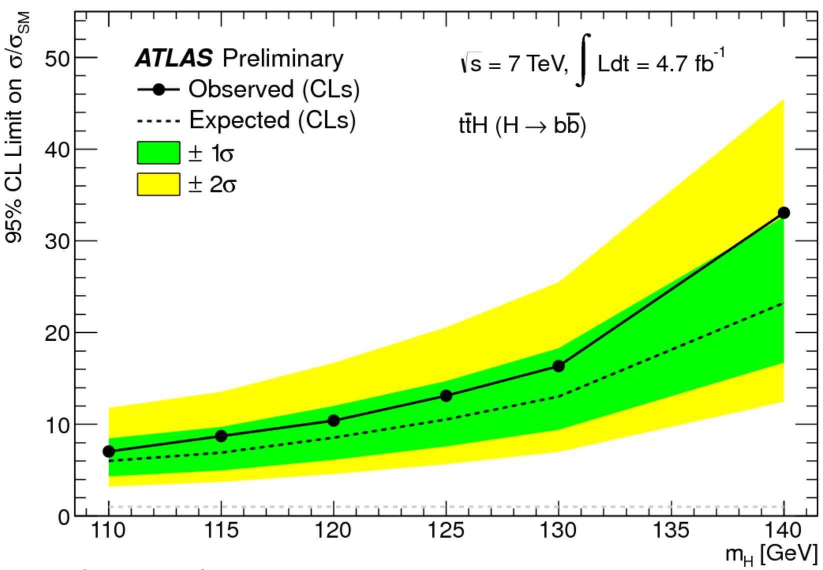


	0 b-tags	1 b-tag	2 b-tags	3 b-tags	≥4 b-tags
4 jets	H_T^{had}	H_T^{had}		H_T^{had}	
5 jets	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}	H_T^{had}
≥6 jets	H_T^{had}	H_T^{had}	H_T^{had}	m_{bb}	m_{bb}

Signal
Background
Control regions

ttH, H->bb Analysis





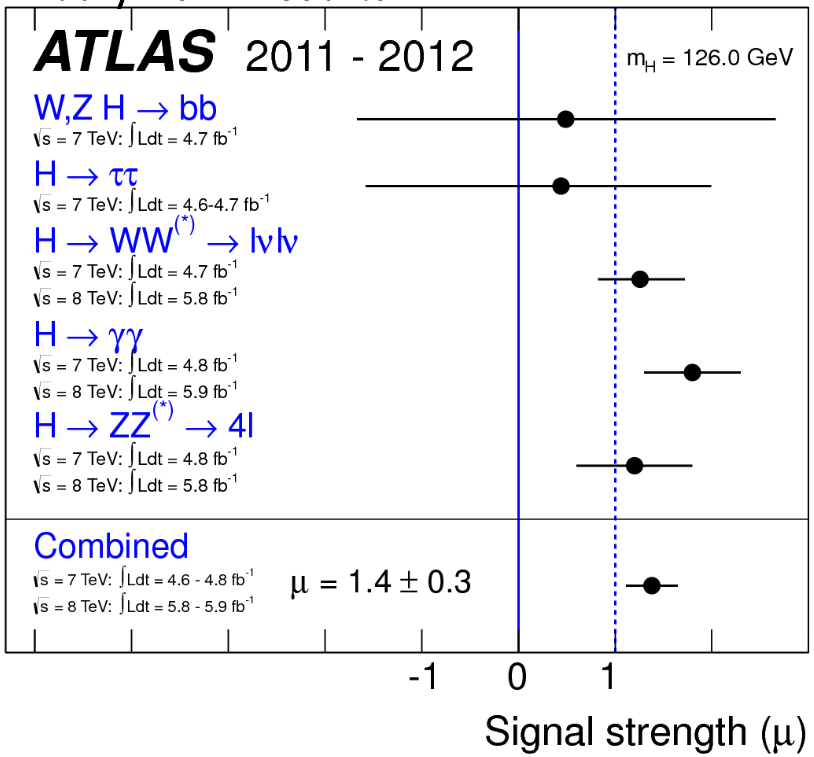
- Poor theory constraints on ttbb/ttjj ratio – interaction with theory community important!
- Large impact of systematic uncertainties
- …but we can do it! ☺

m_H (GeV)	Obs. limit	Exp. limit	Stat.-only
110	7.0	6.0	3.5
115	8.7	6.9	4.0
120	10.4	8.5	4.9
125	13.1	10.5	6.1
130	16.4	13.0	7.8
140	33.0	23.2	14.2

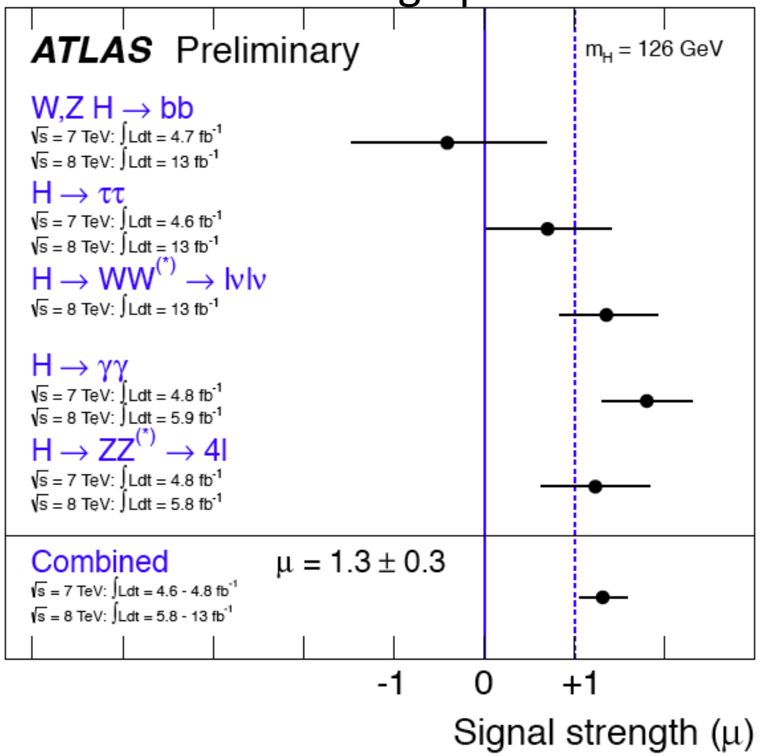
Updated signal strength

- Previous combined signal strength result: μ = 1.4 ± 0.3
  - 2011 analyses of ττ and bb, July analyses for γγ, 4-lepton, and WW
- New result using analysis shown today: μ = 1.3 ± 0.3
  - Compatibility with SM μ=1 with observed measurement is 23%.

July 2012 results



New result including updates shown



Summary & Outlook

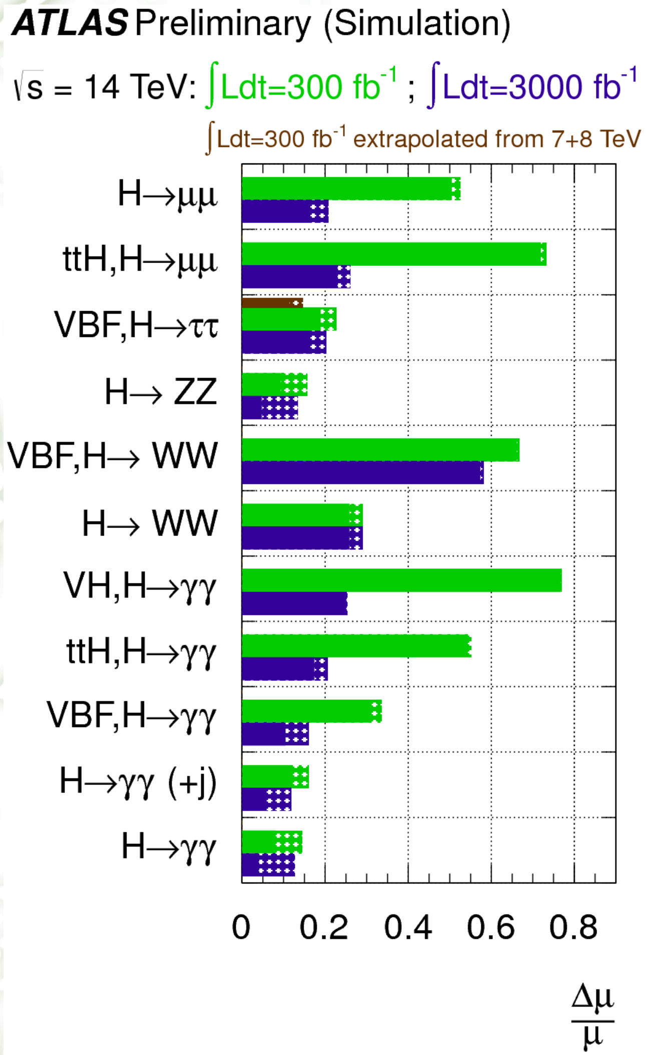
New boson looks SM-like so far…

Wishlist for 2011+2012 data

- ≈25 – 30 fb^{-1}/experiment
- Clear observation of H➞ττ and H➞bb – sensitive to fermion and lepton couplings
- Sensitivity to Higgs spin and CP!

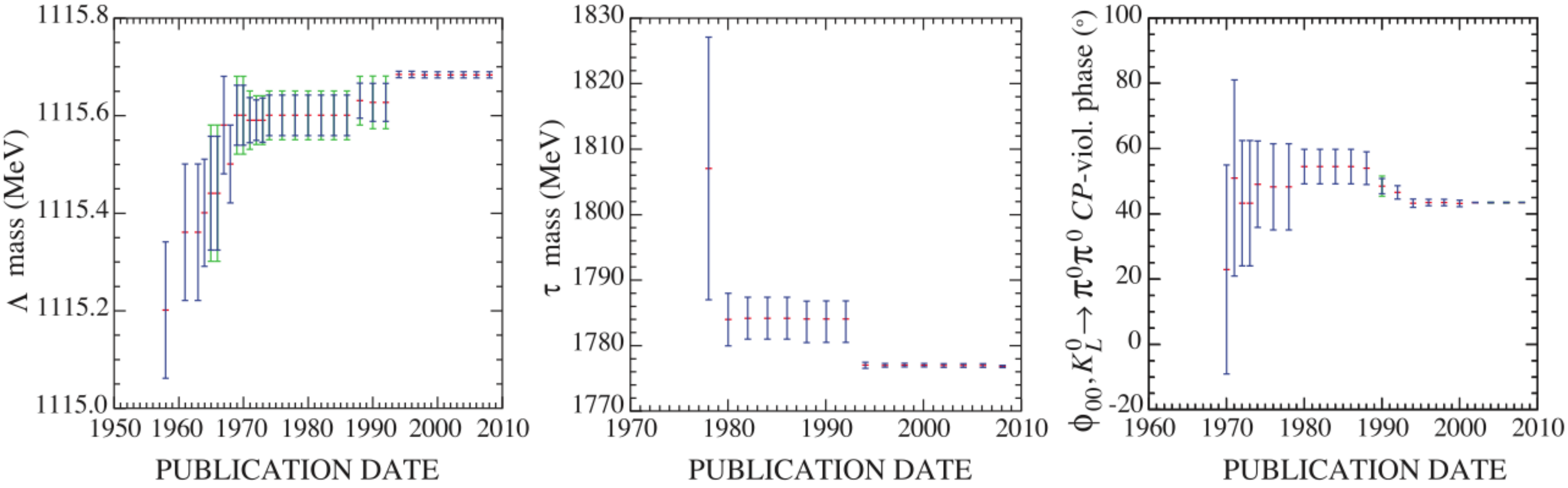
Beyond 2014… increase statistics!

- Essential to observe a signal in remaining SM Higgs decay modes!
- Measure precisely new particle properties
  - ATL-PHYS-PUB-2012-004: http://cdsweb.cern.ch/record/1484890
  - Couplings: 20 – 30% with 300fb^{-1} & 5 – 25% with 3ab^{-1} at 14 TeV
  - Spin/CP determined with > 5σ with 300fb^{-1}
  - 3σ Self-coupling observation with 3ab^{-1}



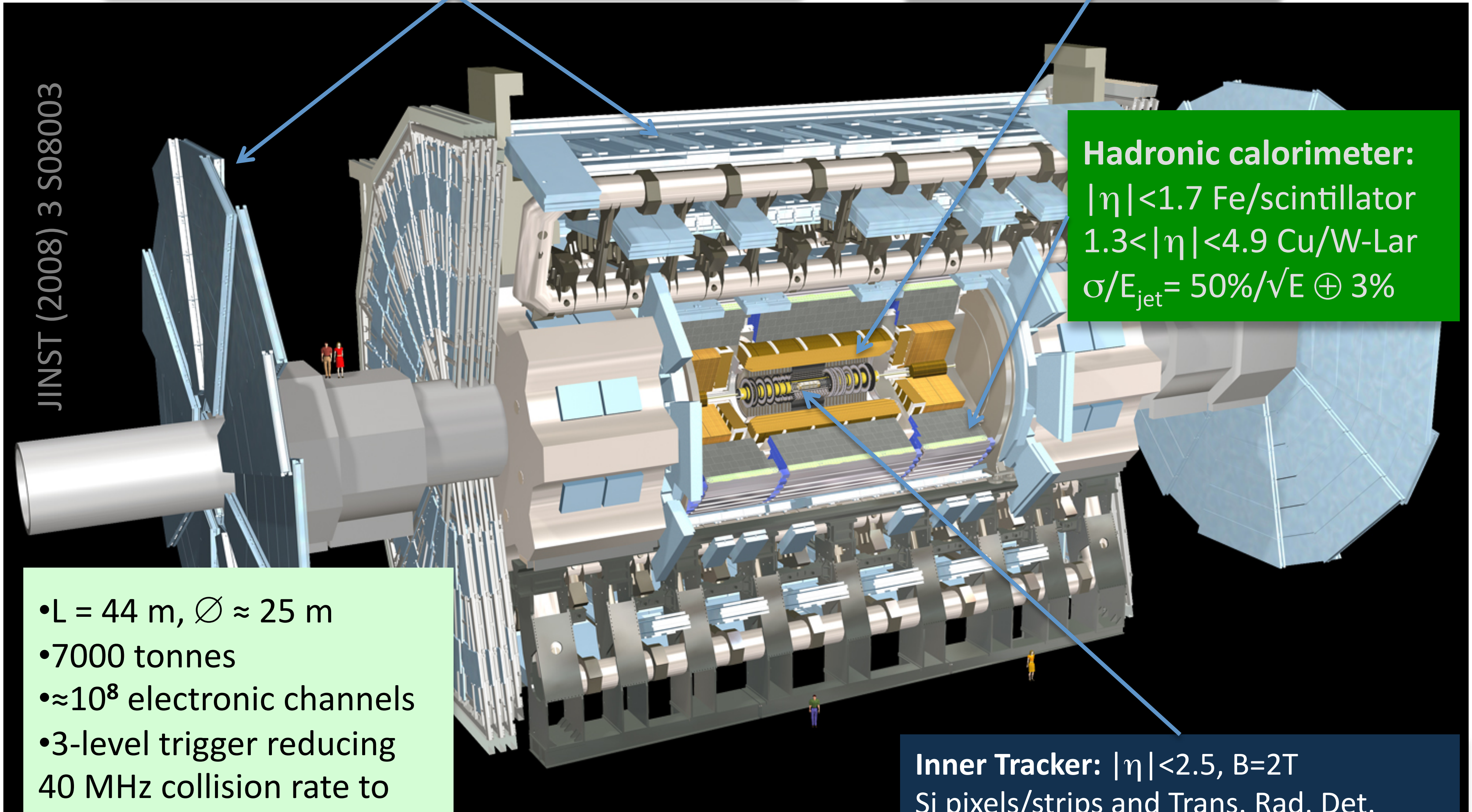
Bonus slides

PDG 2009 Review



Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

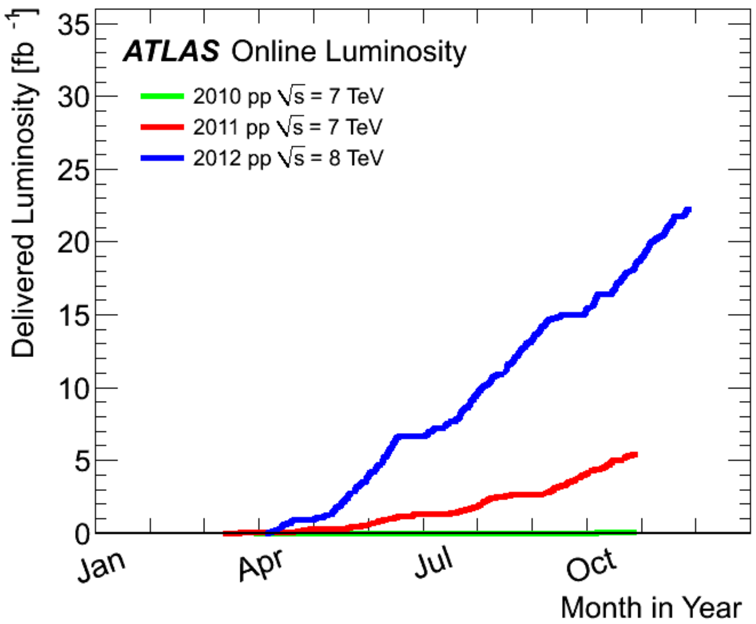
EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

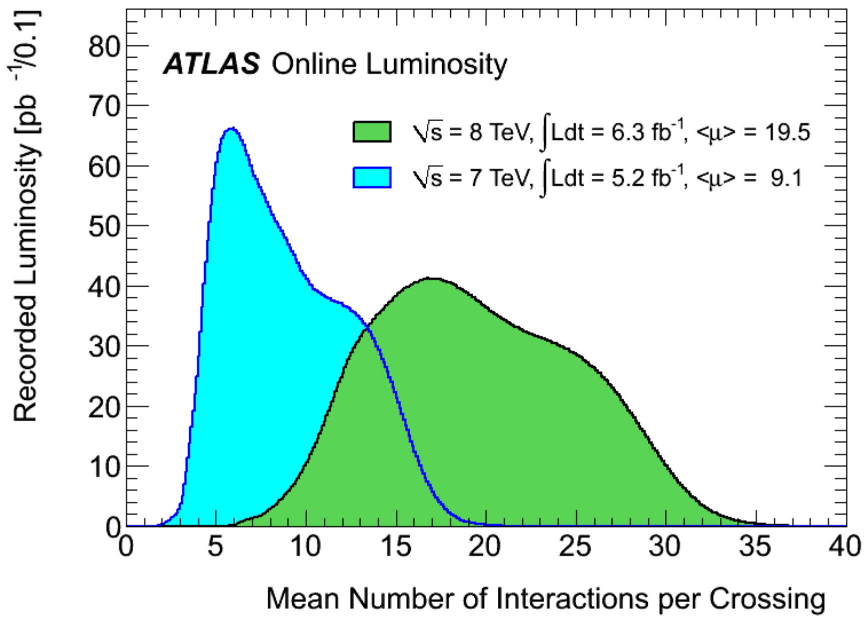


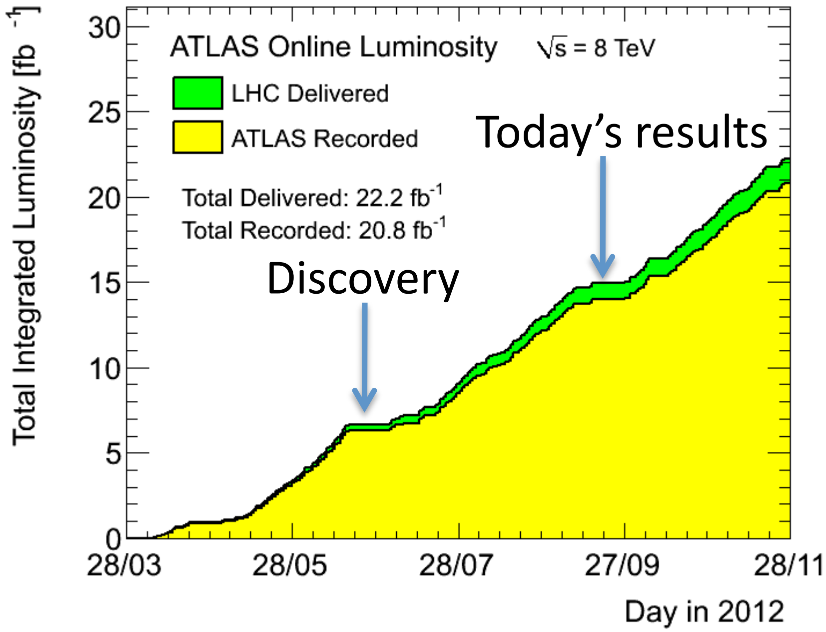
Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

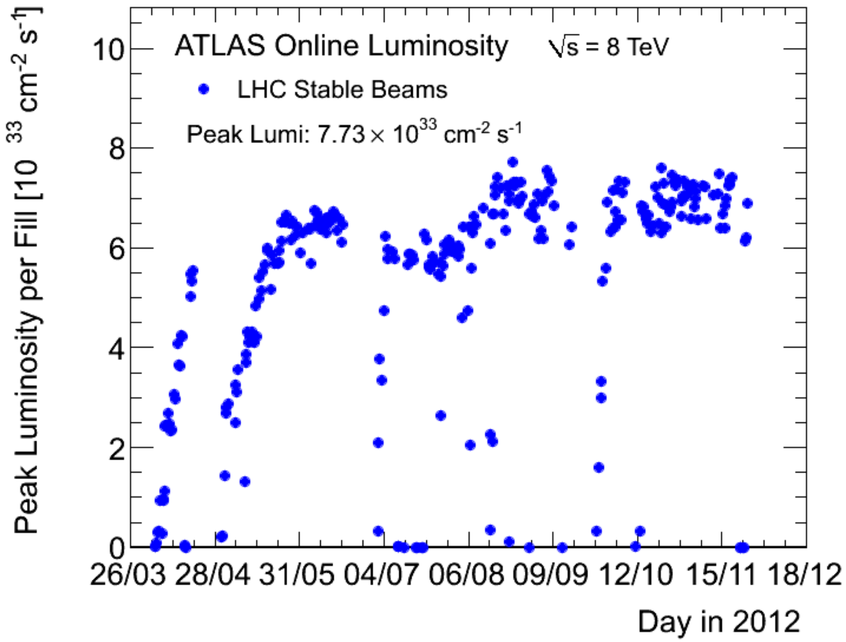
- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T(\mathrm{GeV}) \oplus 1\%$


ATLAS Online Luminosity
2010 pp √s = 7 TeV
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
Delivered Luminosity [fb⁻¹]
Jan
Apr
Jul
Oct
Month in Year


ATLAS Online Luminosity
√s = 8 TeV, ∫Ldt = 6.3 fb⁻¹, <μ> = 19.5
√s = 7 TeV, ∫Ldt = 5.2 fb⁻¹, <μ> = 9.1
Recorded Luminosity [pb⁻¹/0.1]
Mean Number of Interactions per Crossing


ATLAS Online Luminosity
√s = 8 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 22.2 fb⁻¹
Total Recorded: 20.8 fb⁻¹
Today's results
Discovery
Total Integrated Luminosity [fb⁻¹]
28/03
28/05
28/07
27/09
28/11
Day in 2012


ATLAS Online Luminosity
√s = 8 TeV
LHC Stable Beams
Peak Lumi: 7.73 × 10³³ cm⁻² s⁻¹
Peak Luminosity per Fill [10³³ cm⁻² s⁻¹]
26/03
28/04
31/05
04/07
06/08
09/09
12/10
15/11
18/12
Day in 2012

F

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$ Event Selection

- Exactly one e and one μ
  - Of opposite charge
  - $p_{T1} > 25$, $p_{T2} > 15$ GeV;
  - $|\eta| < 2.5$ (μ) / < 2.47 (e)
  - Isolated (calorimeter & tracking)
- 0 or 1 Jet (anti-k_t, R=0.4):
  - $|\eta| < 2.5$: $p_T > 25$ GeV
  - $2.5 < |\eta| < 4.5$: $p_T > 15$ GeV
  - >50% Σp_T^{trk} from primary vertex
- Veto events containing b-tagged jets (ε≈85%)

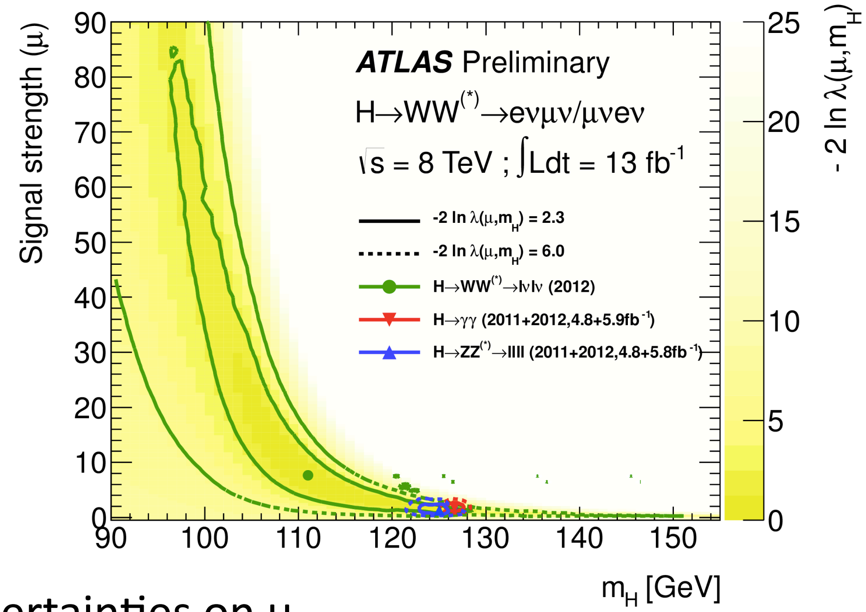
- 0-jet category:
  - $\Delta\phi(ll, E_T^{miss}) > \pi/2$
  - $p_T(ll) > 30$ GeV
  - $m(ll) < 50$ GeV
  - $\Delta\phi(ll) < 1.8$
- 1-jet category:
  - $Z \rightarrow \tau\tau$ veto $|m_{\tau\tau} - m_Z| > 25$ GeV
- $m(ll) < 50$ GeV, $\Delta\phi(ll) < 1.8$

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

$H \rightarrow WW^{(*)} \rightarrow e\nu\mu\nu$

Uncertainties on expected yields

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



Uncertainties on μ

Source	Upward uncertainty (%)	Downward uncertainty (%)
Statistical uncertainty	+23	-22
Signal yield ($\sigma \cdot Br$)	+14	-9
Signal acceptance	+9	-6
WW normalisation, theory	+20	-20
Other backgrounds, theory	+9	-9
W+jets fake rate	+11	-12
Experimental + bkg subtraction	+14	-11
MC statistics	+8	-8
Total uncertainty	+41	-38

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

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

H→ττ

- Systematic uncertainties for Z→ττ background and Signal.
- Dominant systematics are Embedding, Tau Energy Scale and Jet Energy Scale. Both Shape and Normalization variation are taken into account.

Uncertainty	$H \to \tau_{\rm lep}\tau_{\rm lep}$	$H \to \tau_{\rm lep}\tau_{\rm had}$	$H \to \tau_{\rm had}\tau_{\rm had}$
		$Z \to \tau^+\tau^-$	
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	4.7%	4% (non-VBF), 16% (VBF)	9–10%
		Signal	
Jet Energy Scale	1.0–5.0% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	7.9–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

H→ττ→lep-lep Selection

2-jet VBF	boosted	2-jet VH	1-jet
Pre-selection: exactly two leptons with opposite charges			
30 GeV $< m_{\ell\ell} <$ 75 GeV (30 GeV $< m_{\ell\ell} <$ 100 GeV) for same-flavor (different-flavor) leptons, and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
At least one jet with $p_T >$ 40 GeV ($\lvert JVF_{jet} \rvert >$ 0.5 if $\lvert \eta_{jet} \rvert <$ 2.4)			
$E_{\mathrm{T}}^{\mathrm{miss}} >$ 40 GeV ($E_{\mathrm{T}}^{\mathrm{miss}} >$ 20 GeV) for same-flavor (different-flavor) leptons			
$0.1 < x_{1,2} < 1$			
$0.5 < \Delta\phi_{\ell\ell} < 2.5$			
$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF	$p_{T,j2} >$ 25 GeV (JVF)	excluding 2-jet VBF, boosted and 2-jet VH
$\Delta\eta_{jj} > 3.0$	$p_{T,\tau\tau} >$ 100 GeV	excluding boosted	$m_{\tau\tau j} >$ 225 GeV
$m_{jj} >$ 400 GeV	b-tagged jet veto	$\Delta\eta_{jj} < 2.0$	b-tagged jet veto
b-tagged jet veto	–	30 GeV $< m_{jj} <$ 160 GeV	–
Lepton centrality and CJV		b-tagged jet veto	
0-jet			
Pre-selection: exactly two leptons with opposite charges			
Different-flavor leptons with 30 GeV $< m_{\ell\ell} <$ 100 GeV and $p_{T,\ell 1} + p_{T,\ell 2} >$ 35 GeV			
$\Delta\phi_{\ell\ell} > 2.5$			
b-tagged jet veto			

H→ττ→lep-had selection

7 TeV		8 TeV	
VBF Category	Boosted Category	VBF Category	Boosted Category
▹ $p_T{}^{\tau_{\text{had-vis}}} > 30$ GeV	–	▹ $p_T{}^{\tau_{\text{had-vis}}} > 30$ GeV	▹ $p_T{}^{\tau_{\text{had-vis}}} > 30$ GeV
▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV
▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV	▹ ≥ 2 jets	▹ $p_T^H > 100$ GeV
▹ $p_T{}^{j1}, p_T{}^{j2} > 40$ GeV	▹ $0 < x_1 < 1$	▹ $p_T{}^{j1} > 40$, $p_T{}^{j2} > 30$ GeV	▹ $0 < x_1 < 1$
▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$	▹ $\Delta\eta_{jj} > 3.0$	▹ $0.2 < x_2 < 1.2$
▹ $m_{jj} > 500$ GeV	▹ Fails VBF	▹ $m_{jj} > 500$ GeV	▹ Fails VBF
▹ centrality req.	–	▹ centrality req.	–
▹ $\eta_{j1} \times \eta_{j2} < 0$	–	▹ $\eta_{j1} \times \eta_{j2} < 0$	–
▹ $p_T{}^{\text{Total}} < 40$ GeV	–	▹ $p_T{}^{\text{Total}} < 30$ GeV	–
–	–	▹ $p_T{}^{\ell} > 26$ GeV	–
• $m_T < 50$ GeV	• $m_T < 50$ GeV	• $m_T < 50$ GeV	• $m_T < 50$ GeV
• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$	• $\Delta(\Delta R) < 0.8$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 1.6$	• $\sum \Delta\phi < 2.8$	–
–	–	• b-tagged jet veto	• b-tagged jet veto
1 Jet Category	0 Jet Category	1 Jet Category	0 Jet Category
▹ ≥ 1 jet, $p_T > 25$ GeV	▹ 0 jets $p_T > 25$ GeV	▹ ≥ 1 jet, $p_T > 30$ GeV	▹ 0 jets $p_T > 30$ GeV
▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV	▹ $E_T^{\text{miss}} > 20$ GeV
▹ Fails VBF, Boosted	▹ Fails Boosted	▹ Fails VBF, Boosted	▹ Fails Boosted
• $m_T < 50$ GeV	• $m_T < 30$ GeV	• $m_T < 50$ GeV	• $m_T < 30$ GeV
• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$	• $\Delta(\Delta R) < 0.6$	• $\Delta(\Delta R) < 0.5$
• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$	• $\sum \Delta\phi < 3.5$
–	• $p_T^{\ell} - p_T^{\tau} < 0$	–	• $p_T^{\ell} - p_T^{\tau} < 0$

H➝ττ➝had-had selection

Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium τ_{had} candidates matched with the trigger objects
	At least 1 of the τ_{had} candidates identified as tight
	Both τ_{had} candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	τ_{had} candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\text{T}} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau 1}, \eta_{\tau 2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
Boosted	Fails VBF
	at least one tagging jet with $p_{\text{T}} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\text{T}}^{\text{miss}} > 20$ GeV
	if $E_{\text{T}}^{\text{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_1), \Delta\phi(E_{\text{T}}^{\text{miss}}, \tau_2)\right\} < 0.1\pi$.

Details of VH, H→bb event selection

- Basic event selection:

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 $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV $+ \leq 1$ extra jets	2 b-tags $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV + 0 extra jets	2 b-tags $p_{\mathrm{T}}^{1} > 45$ GeV $p_{\mathrm{T}}^{2} > 20$ GeV -
Missing E_T	$E_{\mathrm{T}}^{\mathrm{miss}} > 120$ GeV $p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < \pi/2$ $\mathrm{Min}[\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet})] > 1.5$ $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, b\bar{b}) > 2.8$	-	$E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV
Vector Boson	-	$m_{\mathrm{T}}^{W} < 120$ GeV	$83 < m_{\ell\ell} < 99$ GeV

- Tuned kinematic cuts to optimise sensitivity in each category:

0-lepton channel			
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	120-160	160-200	>200
$\Delta R(b, \bar{b})$	0.7-1.9	0.7-1.7	<1.5

1-lepton channel					
p_{T}^{W} (GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.6	<1.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ (GeV)	> 25				> 50
m_{T}^{W} (GeV)	> 40			-	

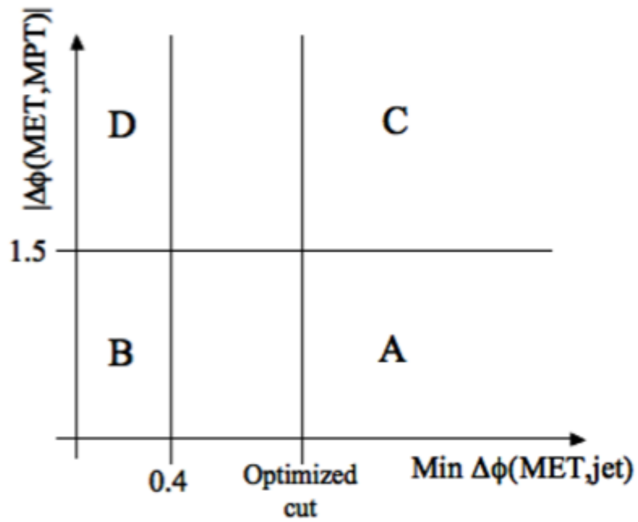
2-lepton channel					
p_{T}^{Z}(GeV)	0-50	50-100	100-150	150-200	>200
$\Delta R(b, \bar{b})$	>0.7			0.7-1.8	<1.6

QCD/multi-jet modelling

- 0 lepton
  - Use ABCD method
  - Regions defined by relative directions of MET/jets/pTmiss
  - Found to be small (~1%)
- 1 lepton
  - MET template by reverse isolation cuts
  - Normalised by fitting each WpT bin
  - Electroweak contamination removed from template
- 2 lepton
  - Template: reverse isolation/quality selection
  - Found to be small (<1%)

<u>ABCD method</u>

Use lack of correlation
Δφ (Etmiss,pTmiss) vs
Δφ (Etmiss,jets)
for multi-jet background estimation in signal region



$$N_{QCD}(A) = \frac{N(B)}{N(D)} \times N(C)$$

Maximum likelihood Fits

- First perform the flavour ML fit
  - Determined V+light and V+c scale factors
  - Z+c factor changes due to MC treatment
- Improved understanding of bkg V pT

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$Z + c$-jet	1.99 ± 0.51	0.71 ± 0.23
$Z+$ light jet	0.91 ± 0.12	0.98 ± 0.11
$W + c$-jet	1.04 ± 0.23	1.04 ± 0.24
$W+$ light jet	1.03 ± 0.08	1.01 ± 0.14

➢ Using the high statistics at 8 TeV we discovered that the V pT spectrum

falls more rapidly in data than expected from MC ☺

- W + jets and Z + jets: 5-10 % correction required
- Top background: 15 % correction required

- Using corrections & scale factors get good MC/data agreement
- Binned profile likelihood fit to 16 signal regions & top control regions
  - W+b, Z+b and top bkg are floated
  - Rescaling factors from the fit ➠

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
Top	1.10 ± 0.14	1.29 ± 0.16
$Z + b$-jet	1.22 ± 0.20	1.11 ± 0.15
$W + b$-jet	1.19 ± 0.23	0.79 ± 0.20

- $L(\mu,\theta)$ fit to signal strength μ ($= \sigma/\sigma_{SM}$)
- Nuisance parameters θ for systematics
- CL_S used to determine limits

Background estimation

- Most background shapes are taken from simulation and normalised using data control regions
- Multi-jet background determined entirely from data-driven techniques
- WZ(bb) & ZZ(bb) resonant bkg normalisation and shape from simulation

Dominant backgrounds

0-lepton

Z + jets

2-lepton channel

W + jets

Top

1-lepton channel

Multi-jet

Small (except for 1-lepton)

Key validation

Diboson

Interesting signal present in all channels
⇒ separate combined search to validate analysis

Main control regions

Z + jets: Pre-tag and 1 b-tag

W + jets: Pre-tag and 1 b-tag

Top:

0 & 1 lepton channel: + 1jet

2-lepton channel: veto(83< m_{ll}< 99)
MET > 60)

Systematic Uncertainties

- **Experimental uncertainties**

  b-tagging and **jet energy** dominate

  - Jets: components (7 JES, 1 p_T^{Reco}, resol.)
  - E_T^{miss} – scale and resolution of soft components. Data/MC for E_T^{miss} trigger
  - bTagging – light, c & 6 p_T bins for b-jet efficiency
  - Lepton – energy, resolution, efficiency
  - Multijet / diboson / Luminosity / MC stats

- **Theoretical uncertainties**
  - BR(H➞bb) @ mH=125 GeV (3.3%)
  - W/Z+jet m_{bb} (20%) and V pT (5-10%)
  - Single top/top normalisation (15%)
  - W+c/W+jets (30%), Z+c/Z+jets (30%)
  - Diboson (11%)

Uncertainties given are after full cuts (pre-fit)

Systematic [%]	0 lepton	1 lepton	2 leptons
b-tagging	6.5	6.0	6.9
c-tagging	7.3	6.4	3.6
light tagging	2.1	2.2	2.8
Jet/Pile-up/E_T^{miss}	20	7.0	5.4
Lepton	0.0	2.1	1.8
Top modelling	2.7	4.1	0.5
W modelling	1.8	5.4	0.0
Z modelling	2.8	0.1	4.7
Diboson	0.8	0.3	0.5
Multijet	0.6	2.6	0.0
Luminosity	3.6	3.6	3.6
Statistical	8.3	3.6	6.6

Background systematics

Systematic [%]	0 lepton		1 lepton	2 leptons
	ZH	*WH*	*WH*	*ZH*
b-tagging	8.9	9.0	8.8	8.6
c-tagging	0.1	0.1	0.0	0.1
light tagging	0.0	0.0	0.1	0.3
Jet/Pile-up/E_T^{miss}	19	25	6.7	4.2
Lepton	0.0	0.0	2.1	1.8
$H \to bb$ BR	3.3	3.3	3.3	3.3
VH p_T-dependence	5.3	8.1	7.6	5.0
VH theory PDF	3.5	3.5	3.5	3.5
VH theory scale	1.6	0.4	0.4	1.6
Luminosity	3.6	3.6	3.6	3.6

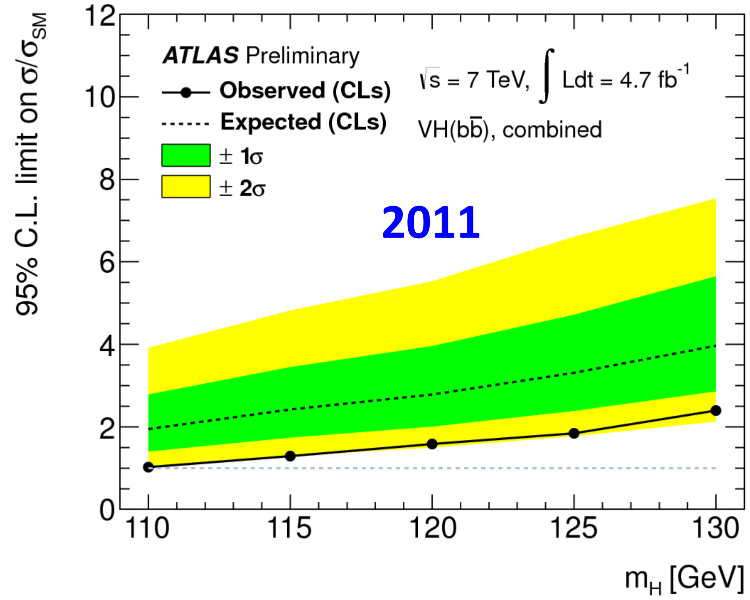
Signal systematics

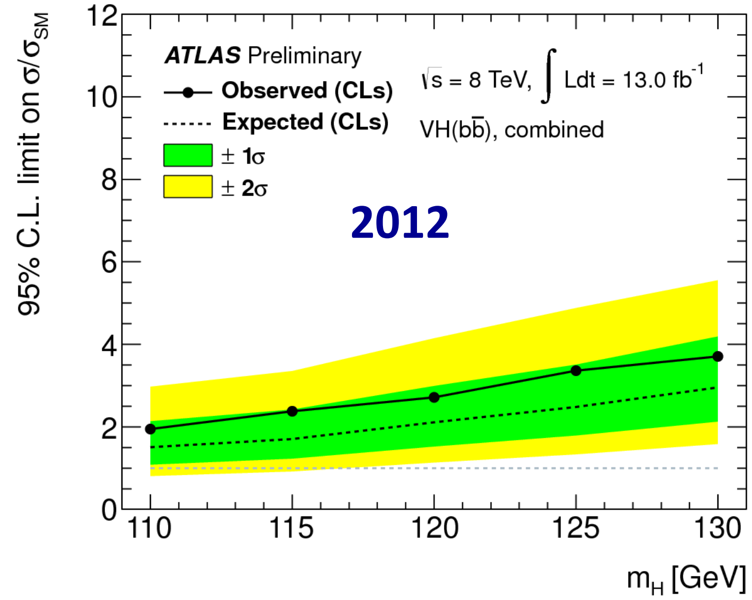
VH, H->bb Results: Exp. S+B & Obs. events

8TeV analysis:

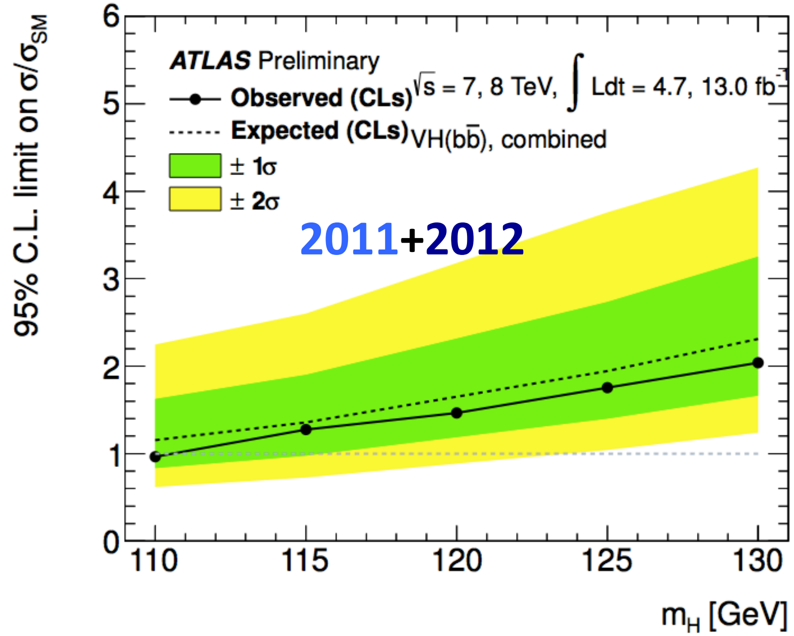
	0-lepton, 2 jet			0-lepton, 3 jet			1-lepton					2-lepton				
Bin	E_T^{miss} [GeV]						p_T^W [GeV]					p_T^Z [GeV]				
	120-160	160-200	>200	120-160	160-200	>200	0-50	50-100	100-150	150-200	> 200	0-50	50-100	100-150	150-200	>200
ZH	2.9	2.1	2.6	0.8	0.8	1.1	0.3	0.4	0.1	0.0	0.0	4.7	6.8	4.0	1.5	1.4
WH	0.8	0.4	0.4	0.2	0.2	0.2	10.6	12.9	7.5	3.6	3.6	0.0	0.0	0.0	0.0	0.0
Top	89	25	8	92	25	10	1440	2276	1120	147	43	230	310	84	3	0
$W + c$,light	30	10	5	9	3	2	580	585	209	36	17	0	0	0	0	0
$W + b$	35	13	13	8	3	2	770	778	288	77	64	0	0	0	0	0
$Z + c$,light	35	14	14	8	5	8	17	17	4	1	0	201	230	91	12	15
$Z + b$	144	51	43	41	22	16	50	63	13	5	1	1010	1180	469	75	51
Diboson	23	11	10	4	4	3	53	59	23	13	7	37	39	16	6	4
Multijet	3	1	1	1	1	0	890	522	68	14	3	12	3	0	0	0
Total Bkg.	361 ± 29	127 ± 11	98 ± 12	164 ± 13	63 ± 8	42 ± 5	3810 ± 150	4310 ± 86	1730 ± 90	297 ± 27	138 ± 14	1500 ± 90	1770 ± 110	665 ± 47	97 ± 12	72 ± 12
Data	342	131	90	175	65	32	3821	4301	1697	297	132	1485	1773	657	100	69

WH/ZH, H→bb results





- **Observed (expected)** values at m_H =125 GeV
  - Limits: 1.8 (3.3) & 3.4 (2.5) on $\mu = \sigma/\sigma_{SM}$
  - p_0 values: 0.97 (0.26) & 0.17 (0.20)
  - σ/σ_{SM}:
    $\mu=-2.7\pm1.1$(stat)±1.1(sys) & $\mu=1.0\pm0.9$(stat)±1.1(sys)
  - Combined (**2011+2012**)
  - Limit: 1.8 (1.9)
  - p0 value 0.64 (0.15)
- $\sigma/\sigma_{SM} = \mu = -0.4 \pm 0.7$(stat.) $\pm$ 0.8(syst.)
- Exclusion at $m_H \approx 110$ GeV
- Note: CMS observed broad 2.2σ excess



$t\bar{t}H$ Samples & Yields for ≥ 6 jets ≥ 4 b's

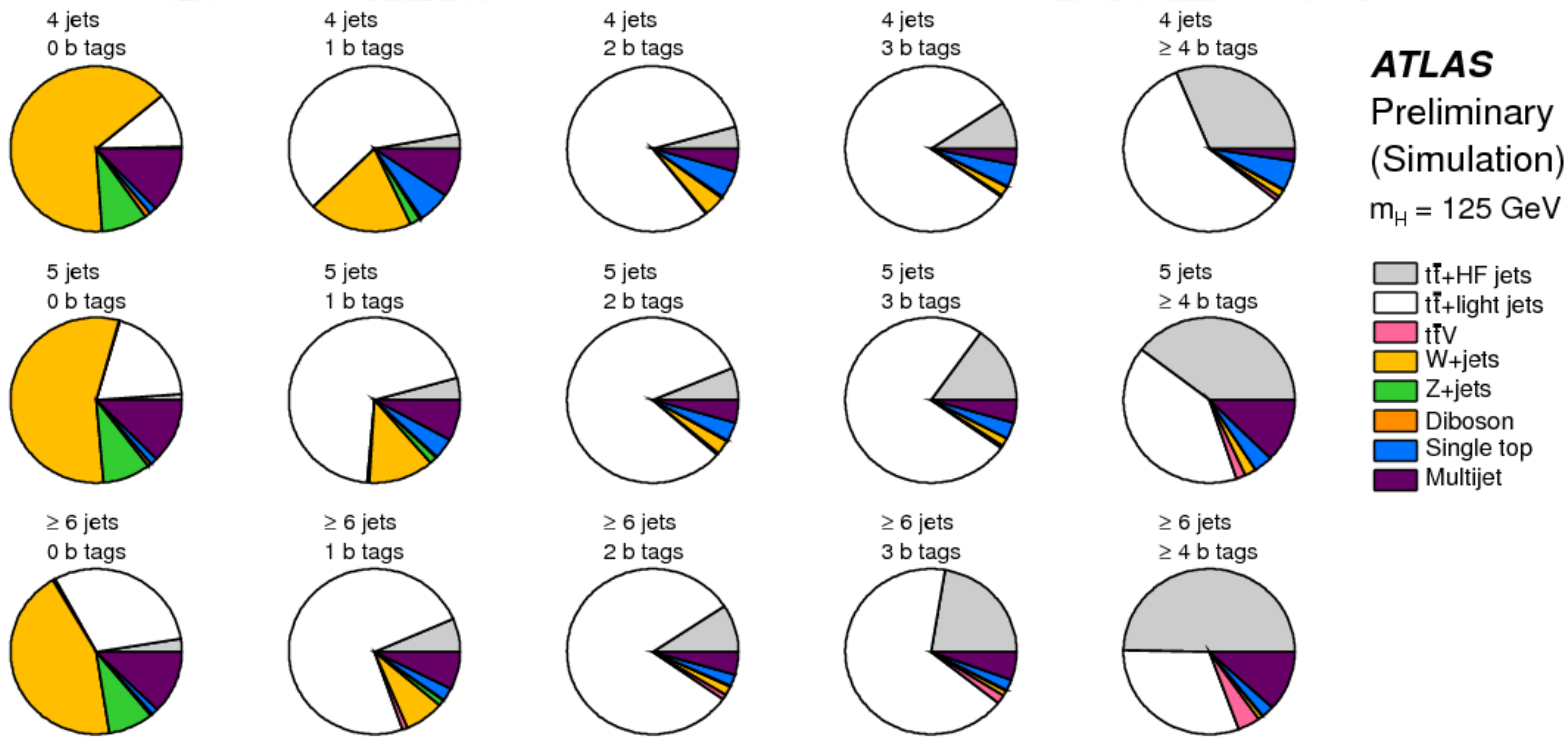
Signal: 2.3 events

- PYTHIA 6.425, m_t = 172.5 GeV. Charged lepton filter: $p_T > 5$, $|\eta| < 5$

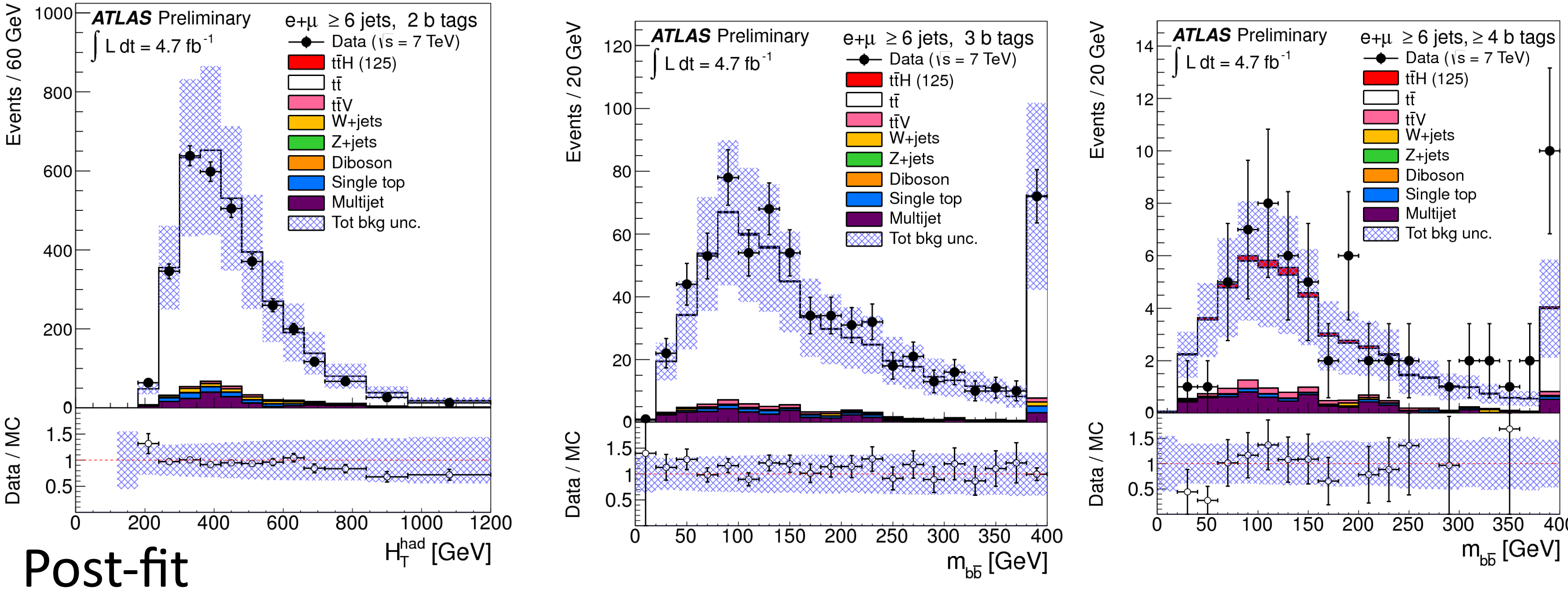
Backgrounds:

- **Dominant** are **tt+jets** (16.4 events) and **ttbb** (26.5 events):
  - ALPGEN 2.13+HERWIG 6.520 HFOR overlap removal.
  - tt+jets: Npartons = 0−5, σ=73.08pb, K=1.755;
  - ttbb : σ = 0.856 pb, K=1.687 (biggest sys.)
- Multijets (data-driven): 6.22 events (5.67 e channel; 0.55 μ channel)
- ttV: 2.2 events
  - Madgraph 4 + PYTHIA 6.425 σ_{ttW}= 0.12pb, σ_{ttZ} = 0.096pb
- Single Top: 1.28 events
  - s-channel (1.5 pb) and Wt (15.74 pb): MC@NLO 4.01 with HERWIG 6.520 and Jimmy 4.31.
  - t-channel (20.92 pb, K=0.866): AcerMC 3.8 with PYTHIA 6.425
- W+jets: 0.54 events
  - ALPGEN 2.13+HERWIG 6.520: Wbb, Wcc, Wc, Z → ll, W → lν; HFOR overlap removal
  - Uses data to normalize and change mix of heavy flavours
- Minor backgrounds: 0.2 events
  - Dibosons and Z + jets;
  - Dibosons: HERWIG 6.520 and JIMMY 4.31; charged lepton filter p_T > 10GeV, $|\eta| < 2.8$.

ATLAS Analysis



Pre-fit



Post-fit