Recent Higgs-boson results from ATLAS

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GDR Terascale
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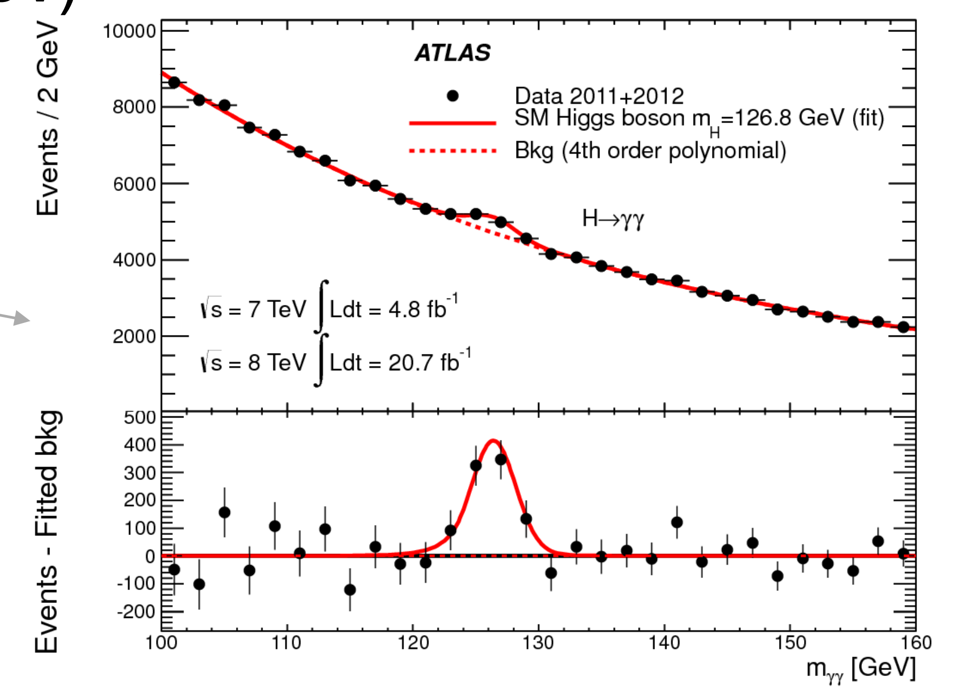
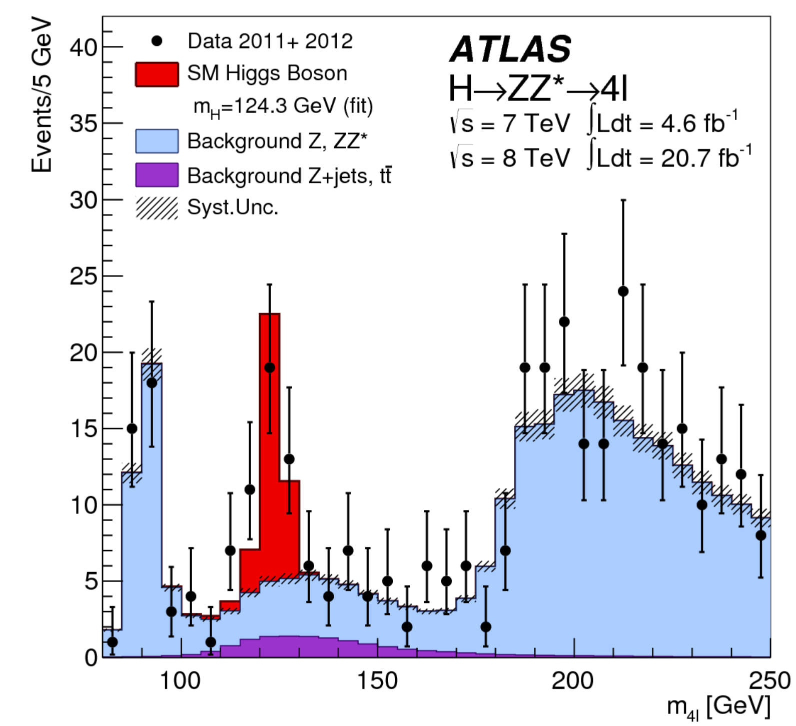
New results since previous GDR

- brand new results (papers will be publicly soon)
  - new mass measurement from $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
  - search for di-Higgs production in $\gamma\gamma bb$ channel
  - 1 more results shown tomorrow by Nicolas Berger
- results shown in winter conferences
  - search for ttH, $H \to bb$ (ATLAS-CONF-2014-011)
  - latest update on Higgs boson couplings (ATLAS-CONF-2014-009)
  - $H \to \tau\tau$ shown tomorrow by Dimitris Varouchas
- recent publications of previous preliminary results, w/ some changes: searches for
  - $H \to Z\gamma$ — Phys. Lett. B 732C (2014), pp. 8-27
  - ZH, $Z \to ll$, $H \to$ invisible — Phys. Rev. Lett. 112, 201802 (2014)

Higgs boson mass

- measurement possible using high-resolution channels: $H \to ZZ^* \to 4l$ (σ_m~1.6-2.4 GeV) and $H \to \gamma\gamma$ (σ_m~1.7 GeV)
- previous result (7+8 TeV): PLB 726, 88 (July 2013)
  - m_H = $125.5 \pm 0.2^{+0.5}_{-0.6}$ GeV
  - 2.4σ tension: $\Delta m = 2.3^{+0.6}_{-0.7} \pm 0.6$ GeV
- changes in new measurement:
  - new e/γ calibration
  - improved e, γ and μ energy scale uncertainties
  - $H \to \gamma\gamma$: new event classification optimised for best σ_m, independent of model of production
  - $H \to ZZ^*$: improved expected statistical uncertainty with 2D likelihood fit





New e/γ calibration

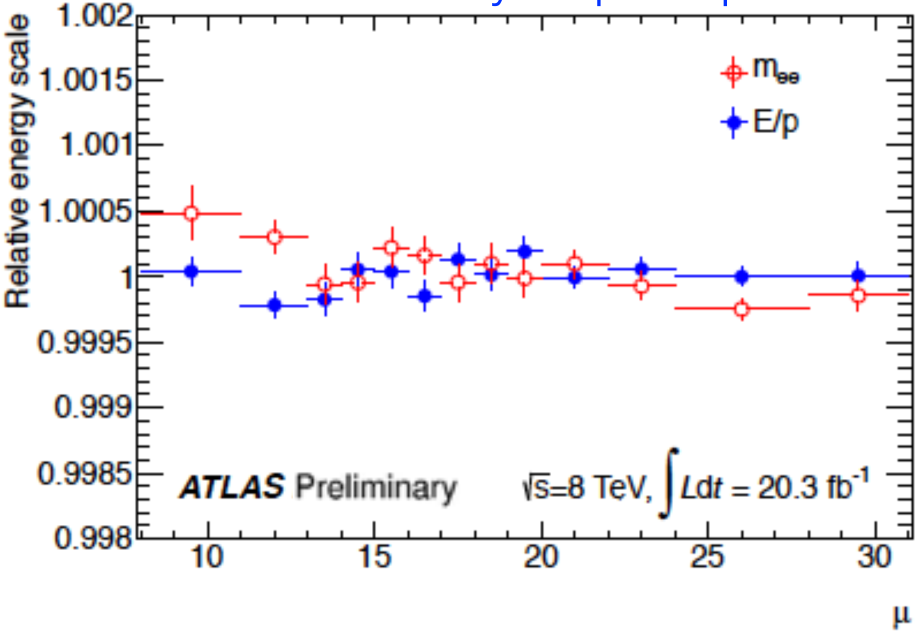
- based on MVA regression
  - input quantities: cluster energy in longitudinal layers of e.m. calorimeter, shower barycenter position (lateral/longitudinal), photon conversion information, ..
  - MVA trained on simulation (samples of e and unconverted/converted γ)
  - 10% better $H \to \gamma\gamma$ mass resolution expected wrt previous calibration
- in data, additional corrections are applied:
  - *before* MVA regression:
    - correct calorimeter response for small non-uniformity effects
    - intercalibrate longitudinal layers (e.m. calo = presampler + 3 layers)
  - *after* MVA regression:
    - correct energy scale with η-dependent factors extracted in-situ from $Z \to ee$
- combination with momentum information from inner detector improves resolution by 20% for e with E_T<30 GeV, $|\eta|$<1.5 (relevant for $H \to ZZ^* \to 4l$)

e/γ energy scale uncertainties

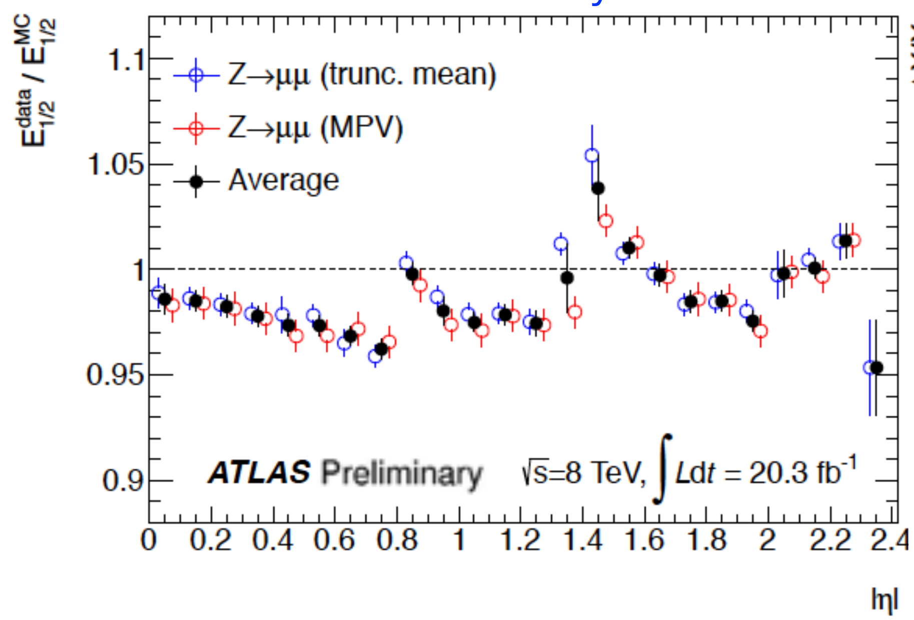
- uncertainties on energy scale: accuracy of the corrections + effects from residual non-linearities and differences between electron and photon showers
- significantly reduced by full exploitation of large and clean control samples: in 2012 data 5.5M $Z\to ee$, 4.3M $Z\to\mu\mu$, 34M $W\to e\nu$, 0.2M $J/\psi\to ee$, 0.2M $Z\to ll\gamma$
  - E/p ($W\to e\nu$), m_{ee} ($Z\to ee$):
    - O(0.1%) corrections for small inhomogeneities (HV, transition regions between calorimeter modules, different gains used in readout)
    - stability of calorimeter response vs time and instantaneous luminosity better than 0.05%, non-uniformity vs ϕ: 0.4% for $|\eta|<0.8$, $<0.7\%$ elsewhere
  - E_1/E_2 ($Z\to\mu\mu$)
    - intercalibration of calorimeter layers 1&2: O(2%) corrections, uncertainty 1-1.5% (amount of LAr traversed by muons and accuracy of x-talk simulation)
  - E_{PS} vs E_1/E_2 ($Z\to ee$, $W\to e\nu$):
    - relative calibration of pre-sampler, after correcting for material between PS and layer 1 (probed with unconverted γ's with small E_0). 2-3% uncertainty.
  - E_1/E_2 ($Z\to ee$, unconv γ):
    - passive material before ECAL and between PS and layer 1 (accuracy ~5%X_0)
  - electron linearity and photon energy scale checked w/ m_{ee} ($J/\psi\to ee$), $m_{ll\gamma}$ ($Z\to ll\gamma$)

e/γ energy scale uncertainties - some results

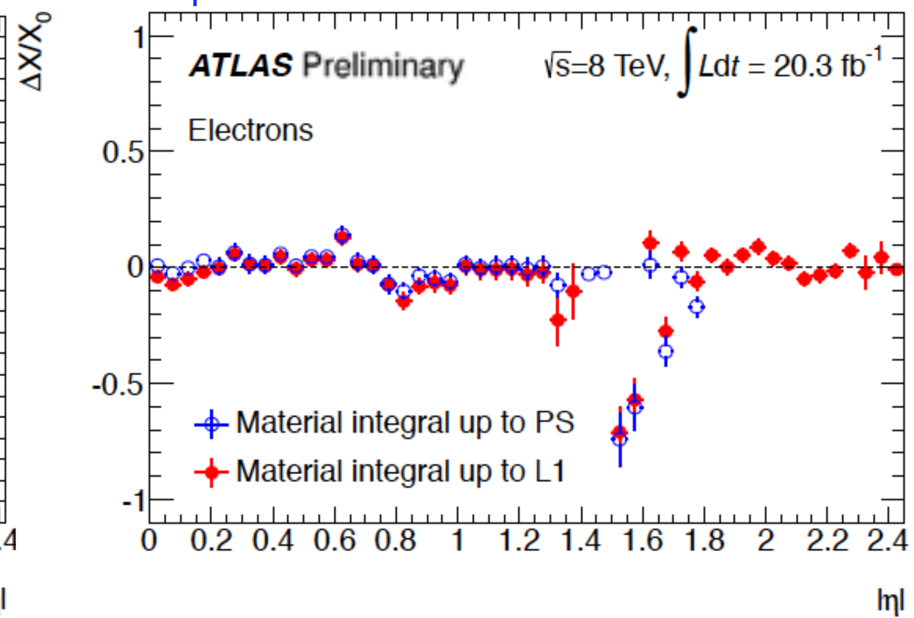
stability vs pile-up



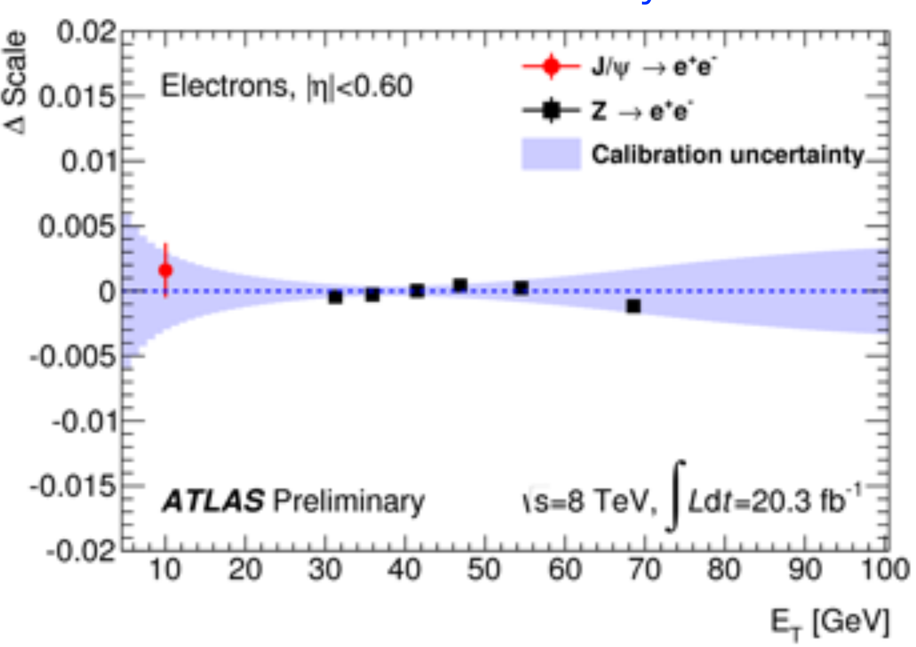
intercalibration layers 1 and 2



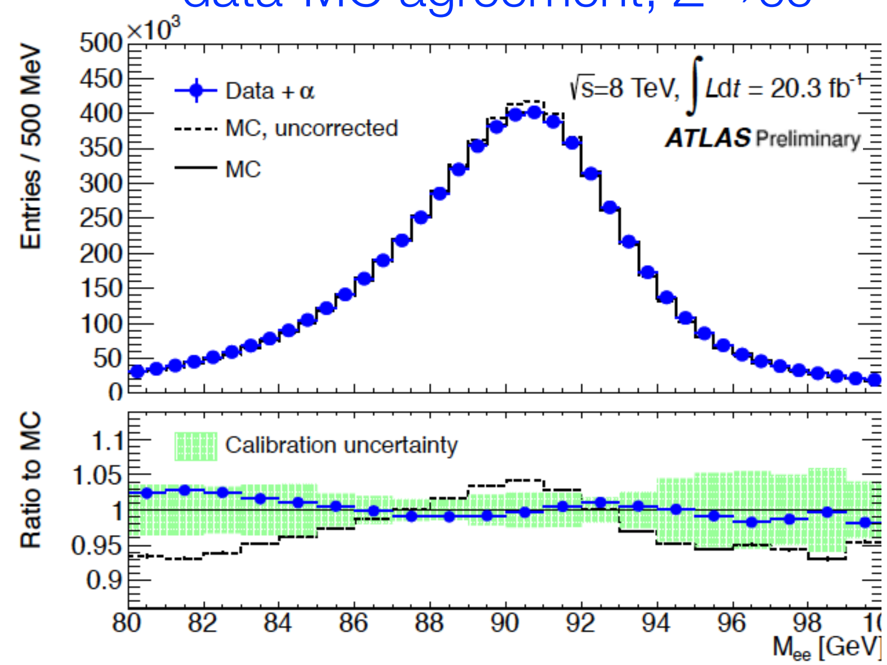
passive material determination



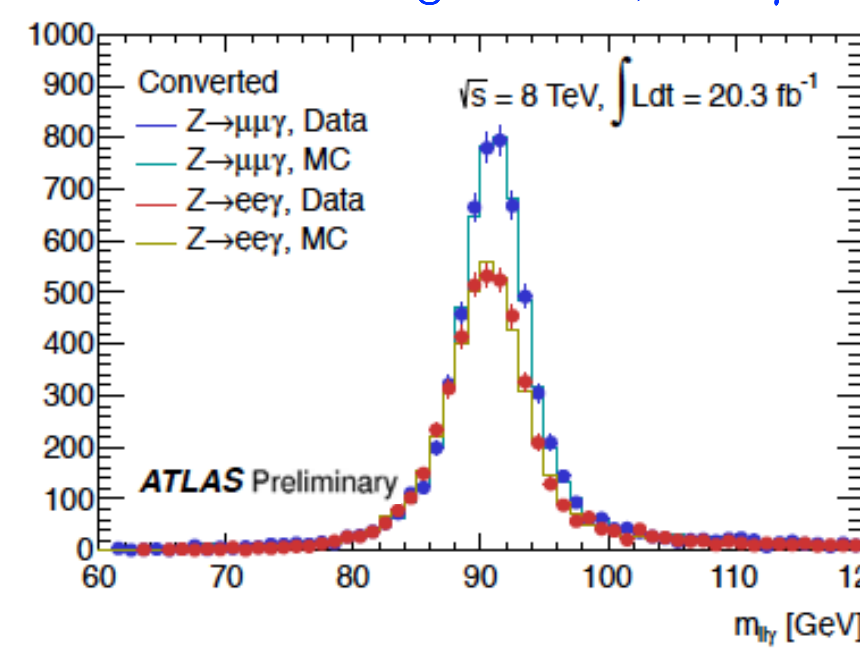
electron linearity



data-MC agreement, Z→ee

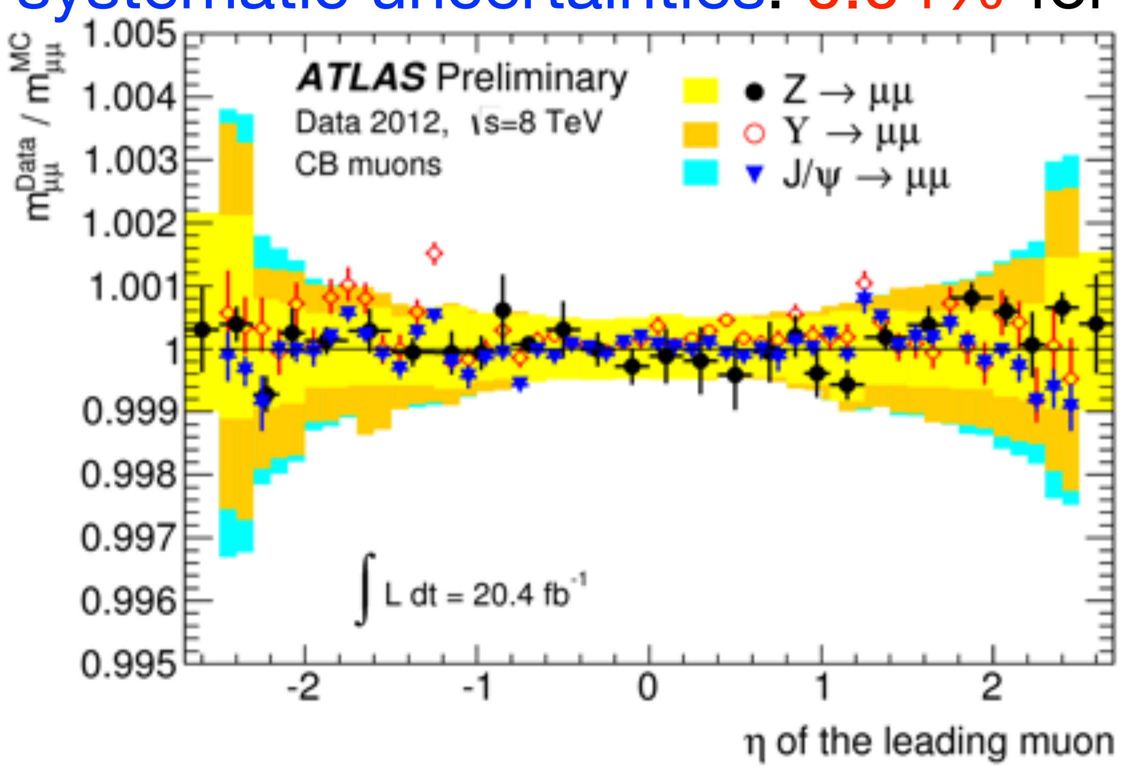


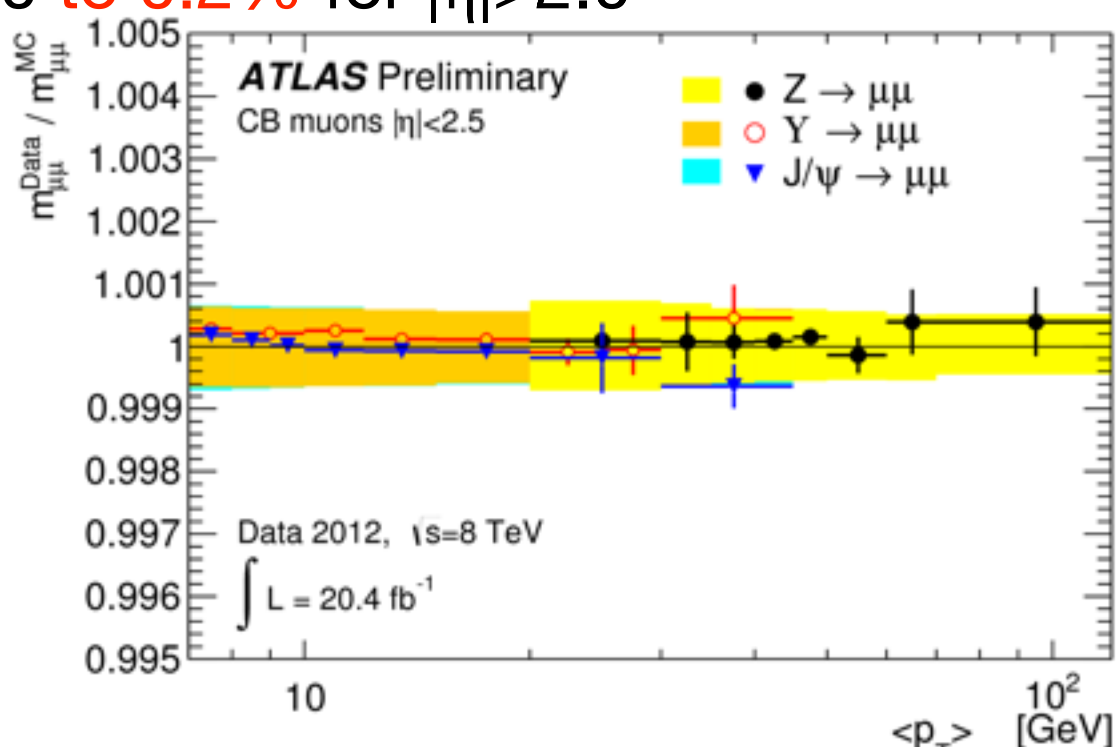
data-MC agreement, Z→llγ



Muon momentum scale uncertainties

- main improvement: use of $J/\psi \to \mu\mu$ to extract momentum scale at low p_T
  - previously only used for systematic uncertainties
- corrections (relative ID/MS scales, energy loss before MS, p_T-dependent resolution corrections) from 9M $Z \to \mu\mu$ + 6M $J/\psi \to \mu\mu$ decays
  - fits to the $\mu\mu$ invariant mass and of the difference between the momentum measurements in the 2 muon detectors
- 5M $\Upsilon \to \mu\mu$ events used to verify results and systematic uncertainties
- scale corrections: ID <0.1%, MS <0.4%
- systematic uncertainties: 0.04% for η~0 to 0.2% for $|\eta|$>2.0





$H \to \gamma\gamma$ analysis

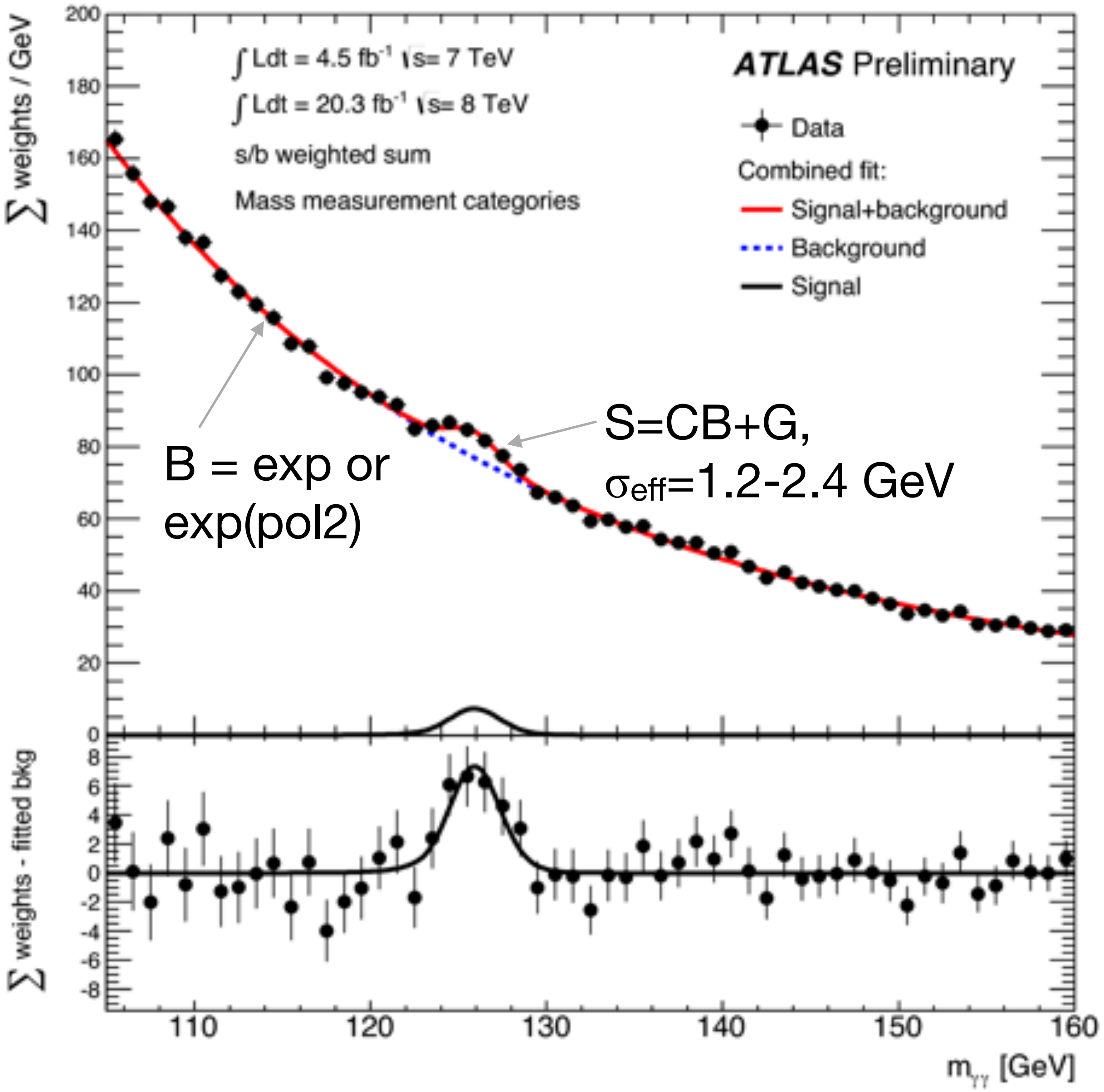
- selection: similar to previous publication
  - 2 identified and isolated photons in $|\eta|<2.37$ (excl. $1.37<|\eta|<1.56$), $E_{T1}>0.35*m_{\gamma\gamma}$ and $E_{T2}>0.25*m_{\gamma\gamma}$, $105<m_{\gamma\gamma}<160$ GeV
  - $\varepsilon \sim 40\%$, $S_{SM} \sim 400$ in 8 TeV data
  - 95k events in 8 TeV data

- event classification
  - new, optimised on MC to minimise σ_{mH} (incl. syst. errors) for a SM Higgs boson
  - ten categories with different $\sigma_{m\gamma\gamma}$ and S/B, based only on photon properties
  - splitting based on:
    - conversion: both unconverted (*U*), at least one converted (*C*)
    - pseudorapidity: both $|\eta|<0.75$ (*central*), ≥1 with $1.3<|\eta|<1.75$ (*transition*), other (*rest*)
    - p_{Tt}: for central and rest categories, p_{Tt} < or > 70 GeV (*low/high p_{Tt}*)
  - 20% improvement on σ_{mH} wrt inclusive analysis

- mass measurement
  - S+B fit to $m_{\gamma\gamma}$, yields and B shape parameters floating, S shape parameters=f(m_H)

H→γγ fit results

- m_H=125.98±0.42±0.28 GeV
  - previous: m_H=126.8±0.2±0.7 GeV
  - total syst error = 40% of previous study
    - dominant source: photon energy scale (0.17-0.55% depending on category)
    - other sources (PV, bkg shape, signal yield, resolution, category migrations) negligible
  - larger stat. error due to 20% smaller μ, μ=1.29±0.30 + statistical fluctuations of σ_m
  - mass shift consistent with expectation from new calibration: -0.45±0.35 GeV (toys, sidebands)
  - final μ results will be provided soon by dedicated coupling analysis



$H \rightarrow ZZ^* \rightarrow 4l$ analysis

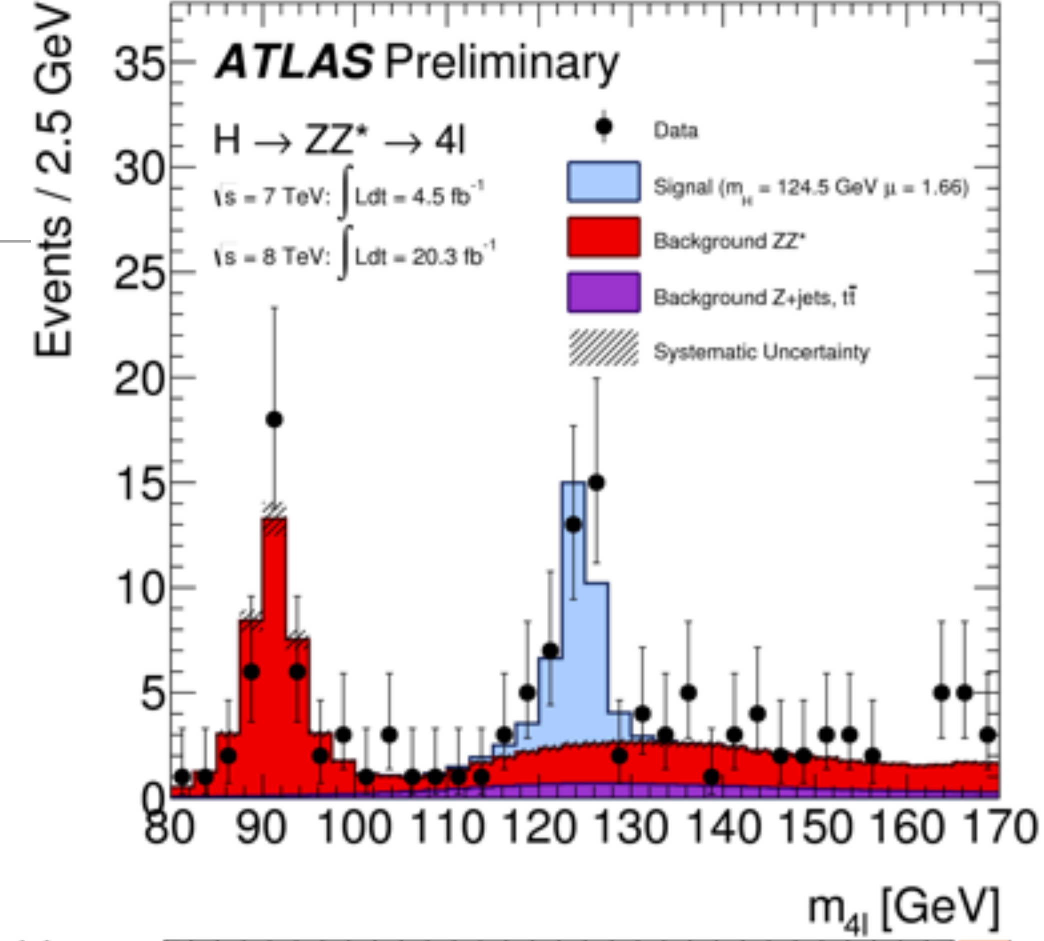
- selection: main differences wrt previous publications
  - cut-based → likelihood-based electron ID (2x jet rejection for same efficiency)
  - combined fit of electron E,p for E_T<30 GeV (4% better σ_m in 4e and 2μ2e)
  - far-FSR recovery (1% of events)

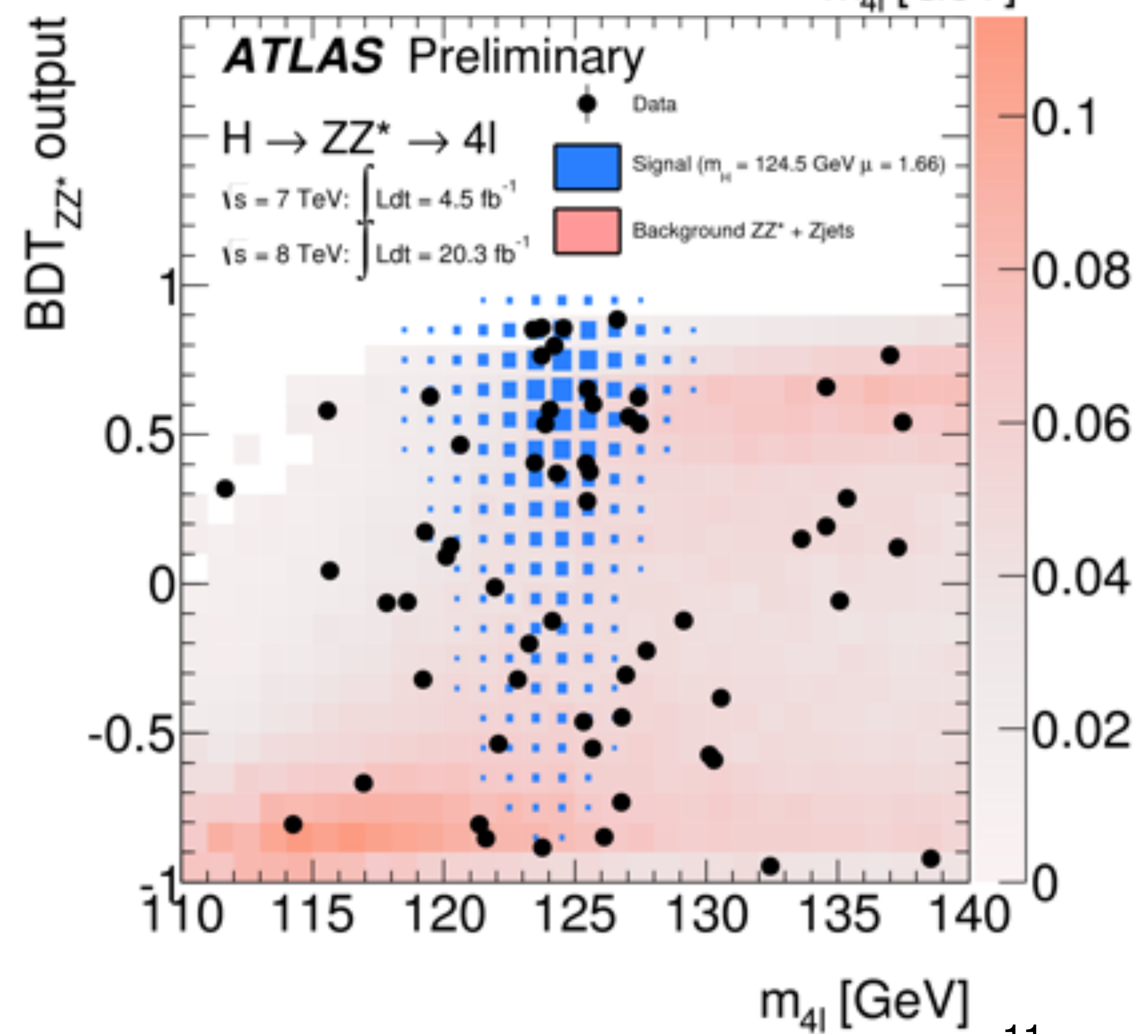
  overall ε~39% (4μ), 27% (2e2μ), 20% (4e), S_{SM}~16 events in 8 TeV data

- mass measurement
  - 2D fit to m_{4l} vs BDT (η_{4l}, p_{T4l}, matrix-element discriminant), for 110<m_{4l}<140 GeV
    - BDT trained on signal vs ZZ MC
    - matrix-element discriminant = log (ME_{sig}/ME_{ZZ}), computed from lepton momenta using LO matrix elements by MadGraph
    - 2D PDFs from MC (signal, ZZ) or data (reducible bkgs, smaller)
    - bkg yield from theory@NLO (ZZ) or from control regions (reducible)
  - 8% smaller σ_m (stat) expected wrt 1D fit to m_{4l}
  - Z-mass constraint (leading pair) improves σ_{m4l} by 15%, far+near FSR by 3%

H→ZZ*→4l fit results

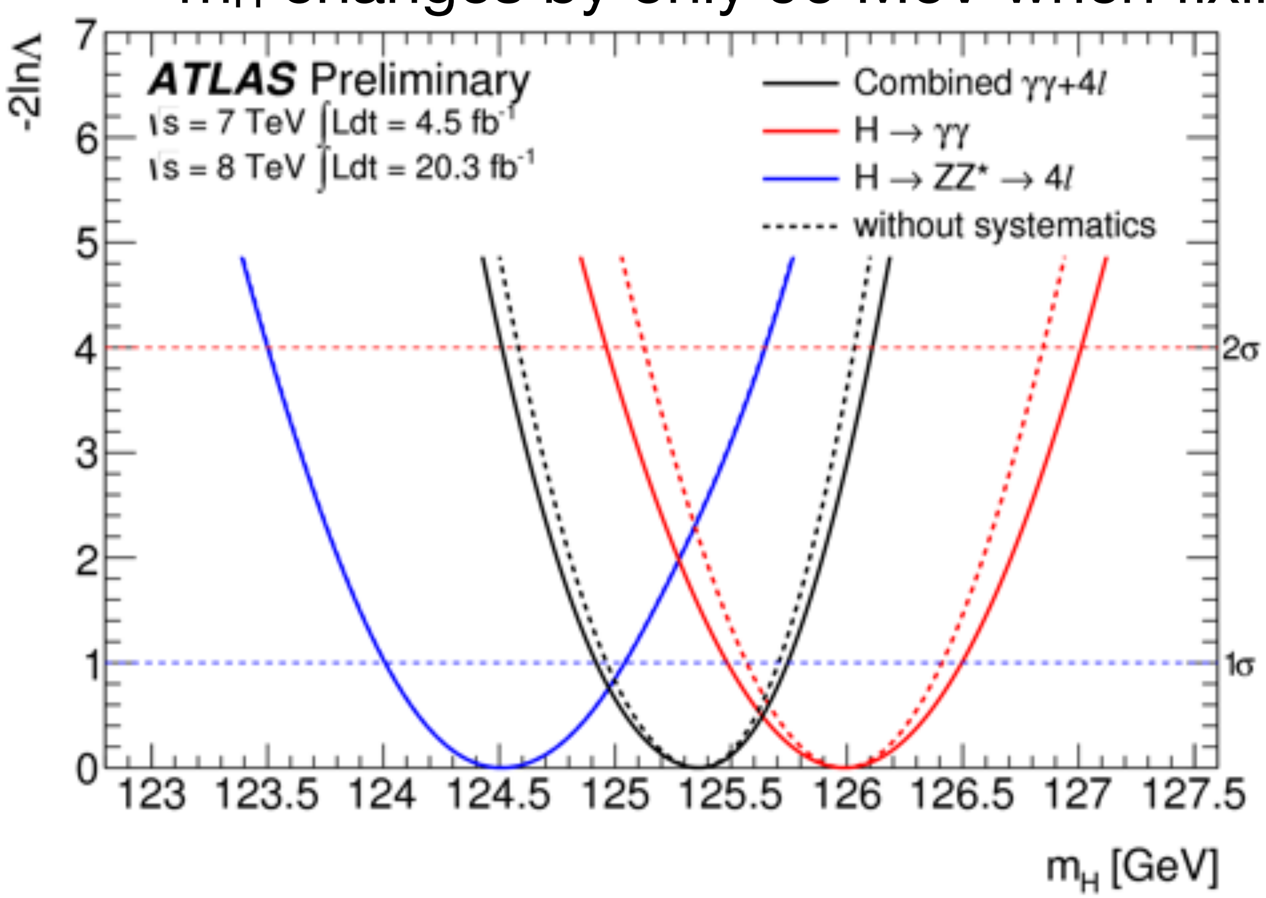
- m_H=124.51±0.52±0.04 GeV
    - previous: $m_H=124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV
    - total syst error = 10% of previous study
        - dominant source: electron energy scale
    - smaller stat. error from 2D fit and larger μ: $\mu=1.66^{+0.45}_{-0.38}$
    - mass shift consistent with expectation from new electron calibration and E/p combination
    - final μ results will be provided soon by dedicated coupling analysis





Mass combination

- m_H=125.36±0.37±0.18 GeV
  - previous: m_H=125.5±0.2$^{+0.5}_{-0.6}$ GeV ⇒ small shift, systematic error divided by 3
- Δm_H = 1.47 ± 0.67 (stat) ± 0.28 (sys) , 2.0σ compatibility
  - previous: Δm_H = 2.3$^{+0.6}_{-0.7}$ ± 0.6 GeV , 2.4σ compatibility
- combined signal strength at measured mass: μ=1.35±0.24
  - γγ: 1.25±0.29, ZZ*: 1.48±0.35
  - m_H changes by only 90 MeV when fixing μ=1



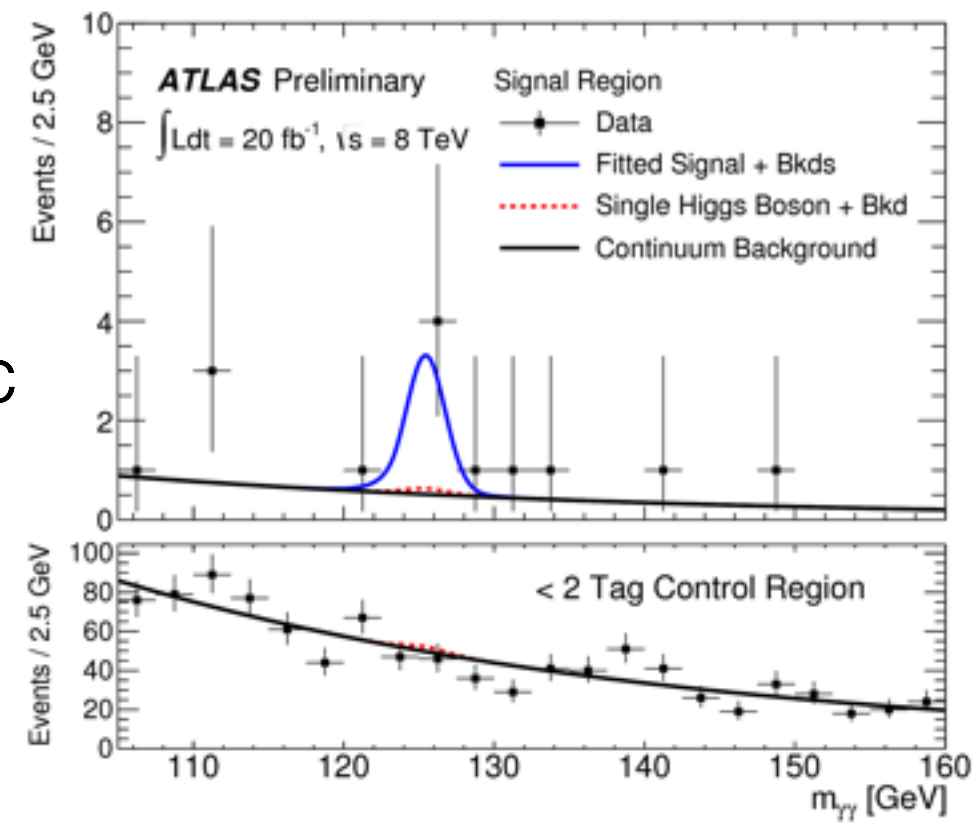
Systematic	Uncertainty on m_H (MeV)
LAr syst on material before presampler (barrel)	70
LAr syst on material after presampler (barrel)	20
LAr electronics non-linearity (layer 2)	60
LAr electronics non-linearity (layer 1)	30
LAr layer calibration (barrel)	50
Lateral shower shape (conv)	50
Lateral shower shape (unconv)	40
Presampler energy scale (barrel)	20
ID material model ($\|\eta\| < 1.1$)	50
$H \rightarrow \gamma\gamma$ background model (unconv rest low p_{Tt})	40
$Z \rightarrow ee$ calibration	50
Primary vertex effect on mass scale	20
Muon momentum scale	10
Remaining systematic uncertainties	70
Total	180

Search for double-Higgs production in $\gamma\gamma bb$

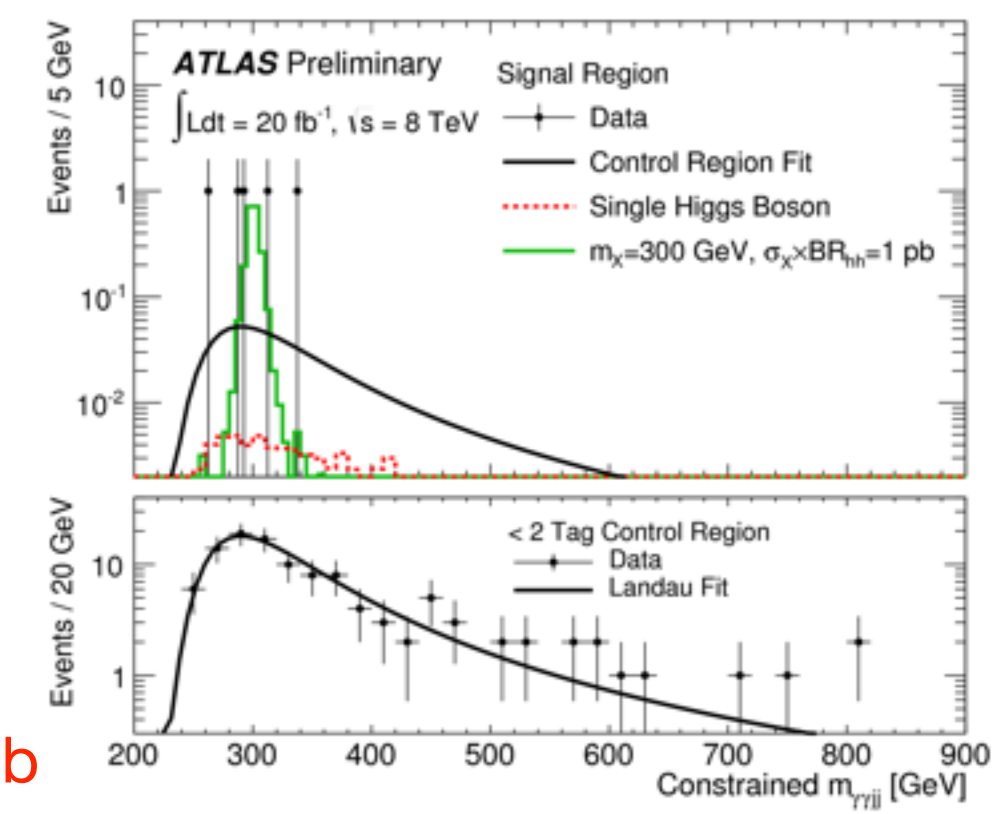
- in SM, rate much smaller than single Higgs (box diagrams + self-coupling)
  - not observable at LHC Run1
- BSM, possible enhancements, e.g.
  - 2HDM: from heavier Higgs decays ($H \rightarrow hh$), σ as high as 1 pb
  - composite models: from direct tthh vertex
- two searches based on full 8 TeV dataset (20.3 fb^{-1})
  - "non-resonant": cut on $m_{bb} \sim m_H$, search for peak in $m_{\gamma\gamma}$ spectrum near m_H
  - "resonant": cut on $m_{bb}, m_{\gamma\gamma} \sim m_H$, count events in sliding-window in $m_{\gamma\gamma bb}$
- main backgrounds:
  - continuum (mostly di-photon+jets), modelled with data
  - single-Higgs production, modelled with MC + theoretical xsection and BF
- selection: 2γ passing same requirements as $H \rightarrow \gamma\gamma$, $\geq$2 jets ($|\eta|<2.5$, $p_T>55$-35 GeV) b-tagged ($\varepsilon_b \sim 70\%$), $95<m_{jj}<135$ GeV ($\sigma_{mjj} \sim 13$ GeV)

Search for double-Higgs production in $\gamma\gamma bb$

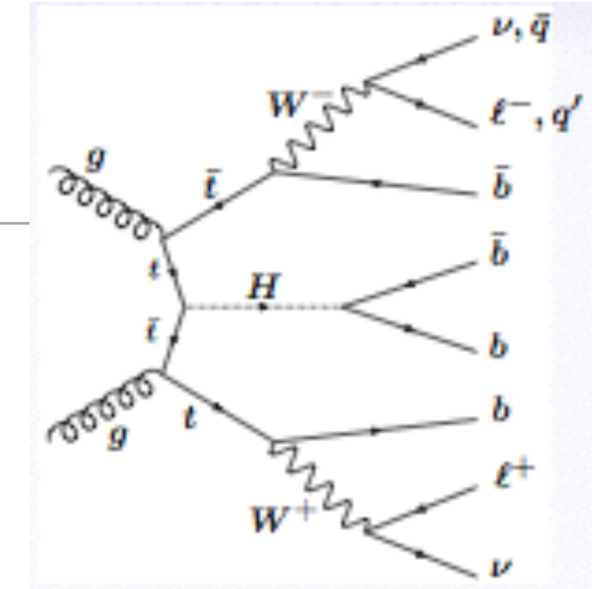
- non-resonance search:
  - fit to $m_{\gamma\gamma}$ in 105-160 GeV range in signal (≥2 b-jets) and bkg (<2 b-jets) control region
    - continuum shape from data, single-h and hh from MC
  - expected yield in $\pm 2\sigma_{m\gamma\gamma}$ from SM = 1.5
    - 0.2 tth, 0.04 hh (ε=7.4%), 1.3 continuum
  - observed: 5 evts (2.4σ) ⇒ σ<2.2 pb @ 95% CL



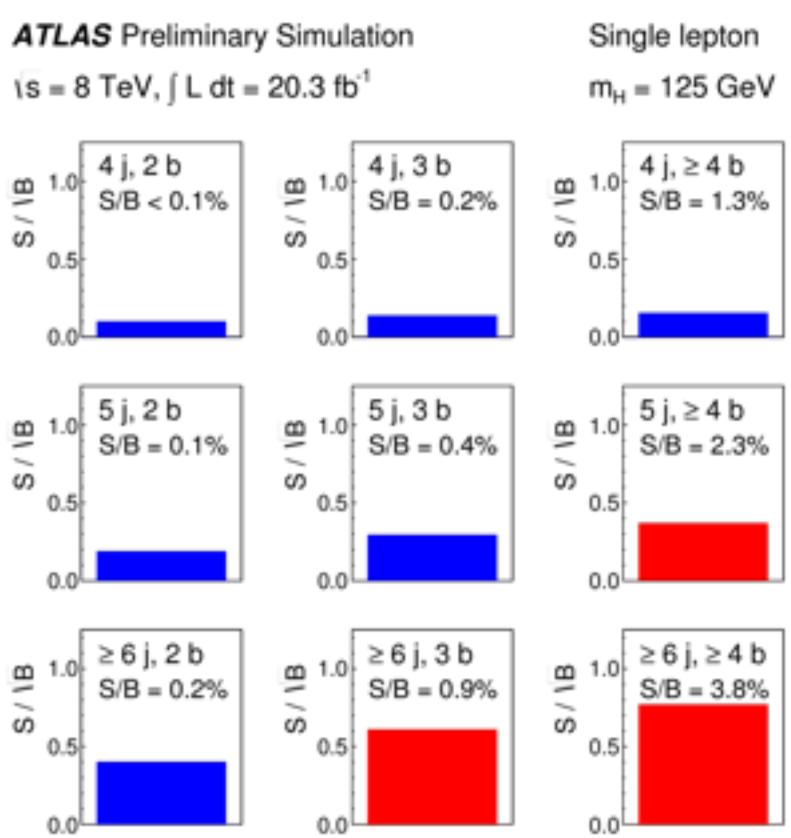
- resonance search (260<m_X<500 GeV)
  - signal model: spin-0 narrow resonance (Madgraph)
  - $|m_{\gamma\gamma} - m_h| < 2\sigma_{m\gamma\gamma}$, m_h=125.5 GeV⇒single-h negligible
  - m_{bb} constrained to m_h (30-60% better $\sigma_{m\gamma\gamma bb}$)
  - count events in smallest window containing 95% of signal (overall signal ε~3.8%-8.2%)
  - bkg from N_{data} with ≥2 b-jets and $|m_{\gamma\gamma} - m_h| > 2\sigma_{m\gamma\gamma}$ corrected for acceptance of $m_{\gamma\gamma}$ and $m_{\gamma\gamma bb}$ cuts, determined in <2 b-jets control sample
  - max deviation from bkg 2.1σ ⇒ σ*BR(hh)<0.3-3.5 pb



Search for ttH, H→bb



- path towards a direct measurement of the ttH coupling
- full 8 TeV ATLAS pp dataset (20.3 fb^{-1})
- 2 signatures exploited
  - semi-leptonic: tt→WbWb→lνjjbb: ≥6 jets (≥4b), exactly 1l, E_T^{miss}
  - di-leptonic: tt→WbWb→lνl'νbb: ≥4 jets (≥4b), exactly 2l (opposite sign), E_T^{miss}
- selection: no E_T^{miss} cut (bkg dominated by tt), allow up to 2 (b) jets missing (control regions) ⇒ events classified based on N_{jet} and N_b (9+6 categories)



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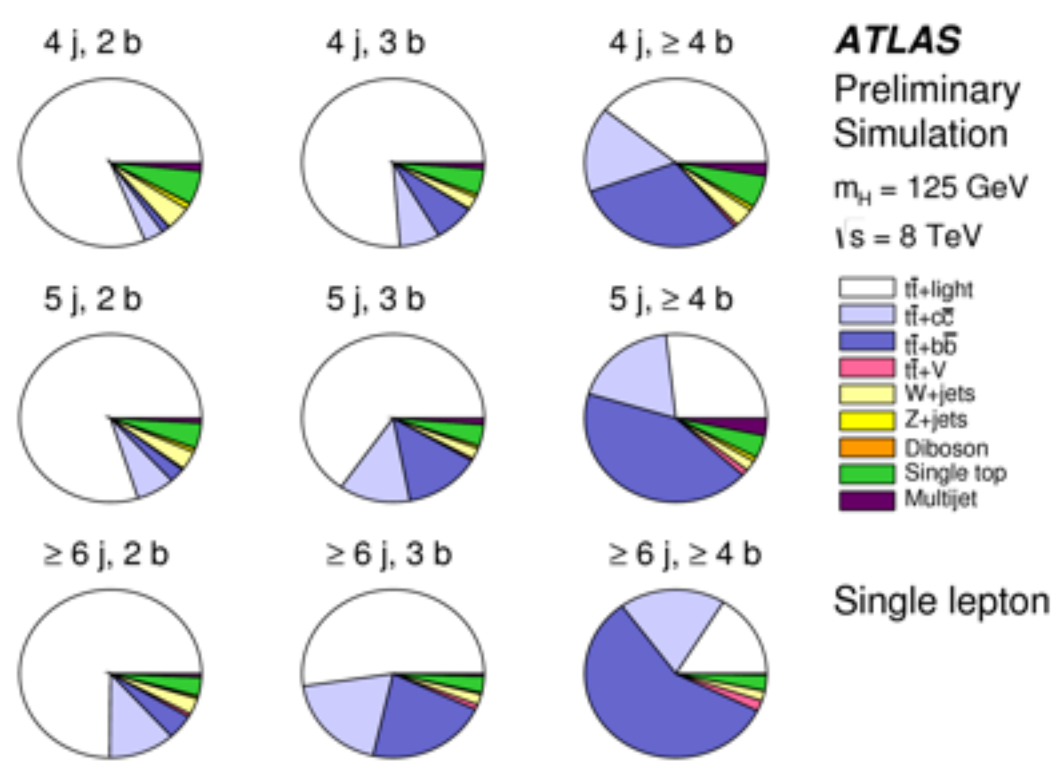

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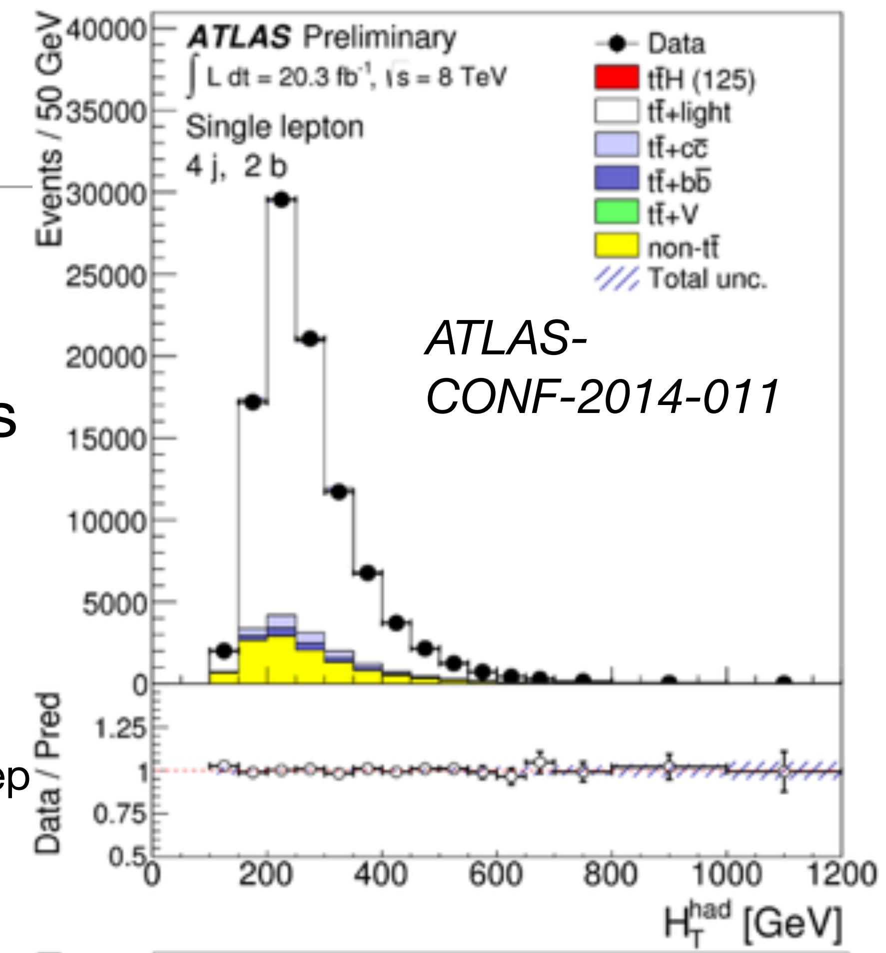
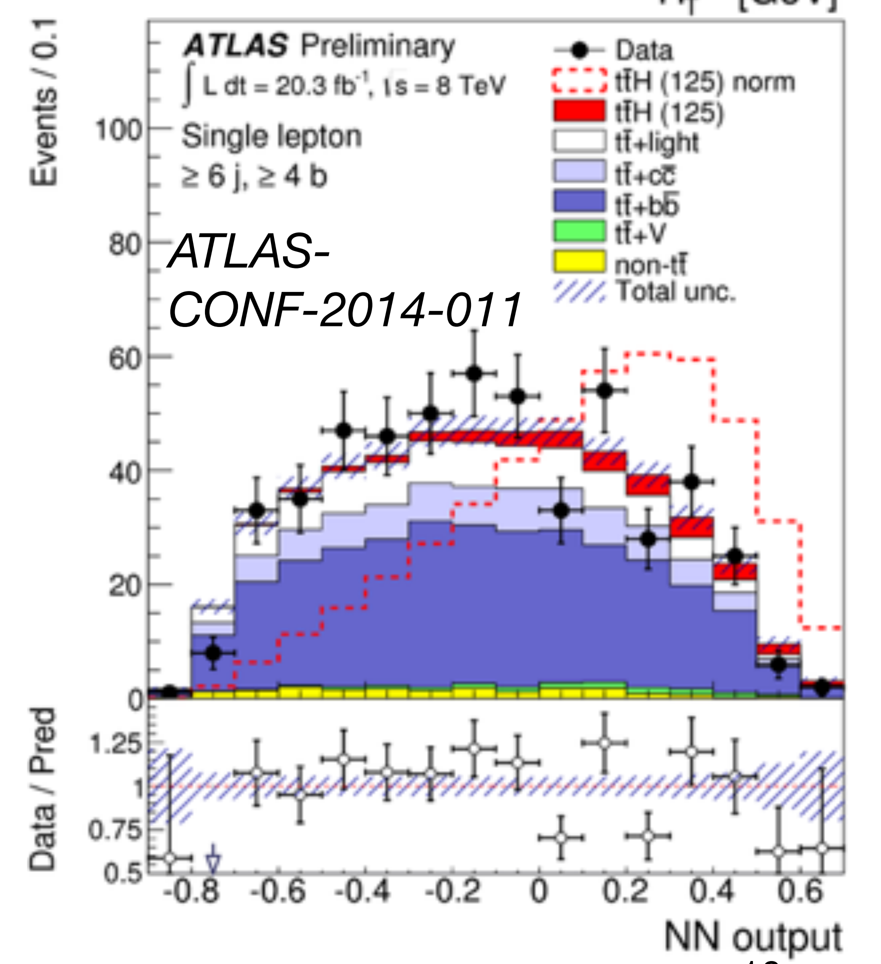
Search for ttH, H→bb

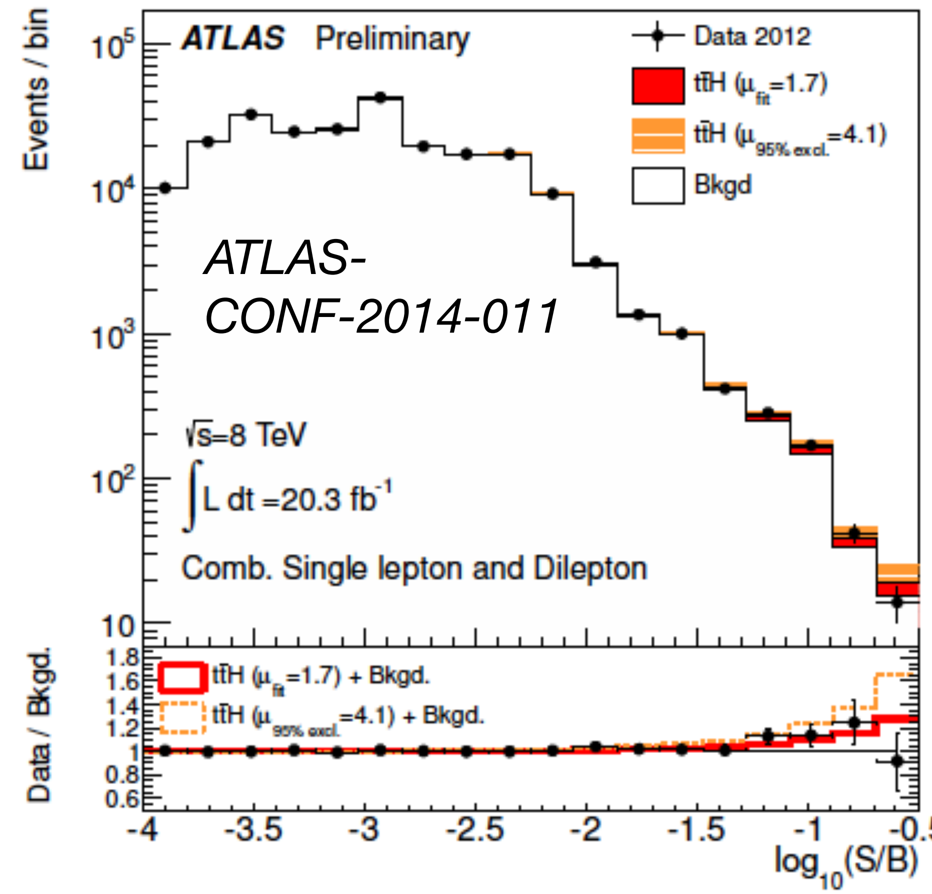
- signal extraction:
  - signal-rich regions: fit NN trained to separate ttH/tt+jets
    - inputs: object kinematics, event variables, event shape, object pairs
    - 1D distributions and correlations well modelled by MC
  - signal-depleted regions: fit $H_T^{had}=\Sigma p_T^{jet}$ or $H_T^{lep}=\Sigma p_T^{jet,\ lep}$
- signal modelling: MC (Powheg+Pythia NLO)
- bkg modelling:
  - shapes from MC, main bkg (ttbar) modelling improved by applying MC/data scale factors vs p_T^t and p_T^{tt} from 7 TeV analysis
  - normalisations & fractions of tt+bb,tt+cc from signal-depleted categories or bkg-enriched bins of signal-rich categories, using constraints from calculations

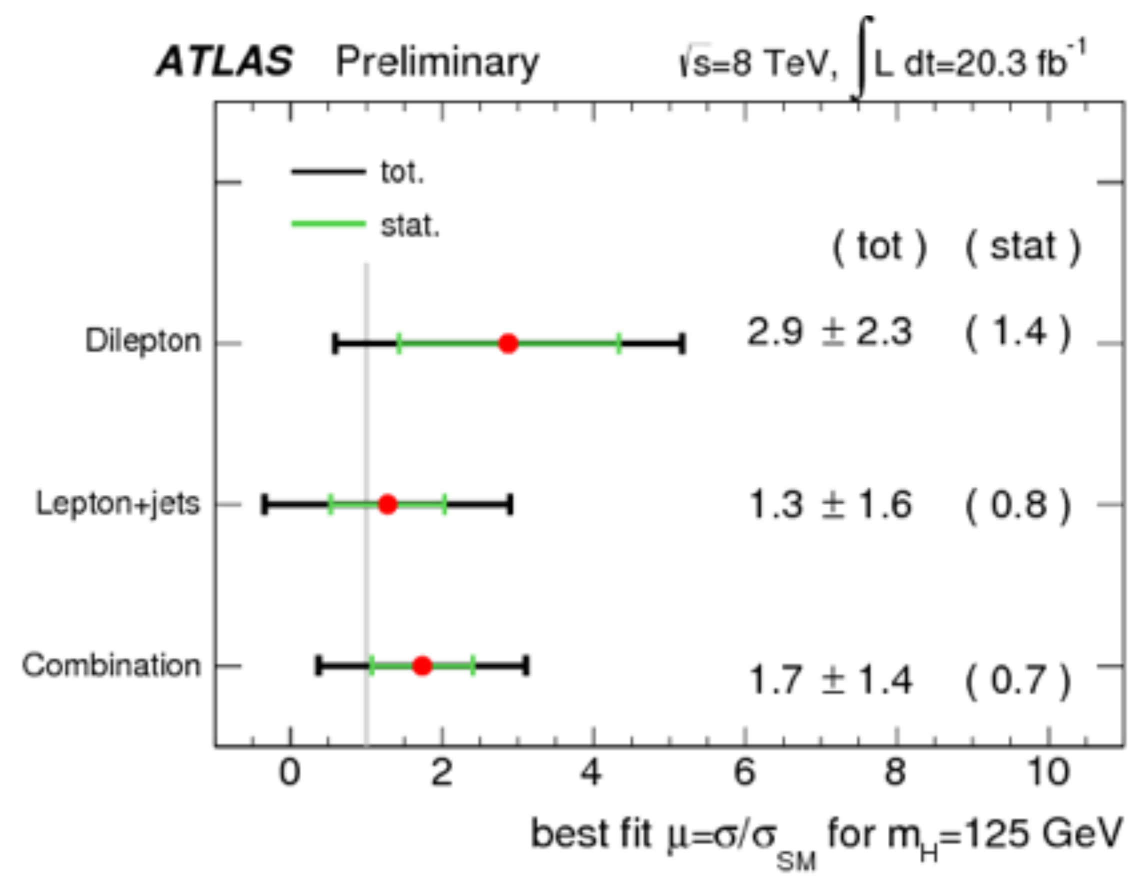




Search for ttH, H→bb

- results:
  - μ=1.7±1.4, consistent between 2 channels
  - 1.3σ significance
  - μ<4.1 @95% C.L. (expected: 3.4 for SM H)
  - dominated by syst. error (Δμ=1.2), main sources:
    - tt+bb normalisation (Δμ~0.6)
    - b-tag efficiency for light jets (Δμ~0.4)
    - p_T(tt) reweighting (Δμ~0.4)





Couplings and production rates

- from combination of many channels ($\gamma\gamma$, ZZ*, WW*, bb, $\tau\tau$)
- assumptions: single particle, m_H=125.5 GeV, narrow width, SM lagrangian tensor structure (observables corrected for couplings scale factors κ_j)
- differences with respect to publication of summer 2013:
  - inclusion of fermionic channels: VH,H→bb (partial data), H→$\tau\tau$ (full 8 TeV data)
    - some dilepton events (including 10% of signal) removed from WW to avoid overlaps with $\tau\tau$. H→WW bkg in H→$\tau\tau$ rescaled by H→WW signal strength
  - updated 8 TeV luminosity (-2%, uncertainty decreased from 3.6% to 2.8%)
  - more models explored
- fit to 5 observables: $m_{\gamma\gamma}$, m_{4l}, m_{bb}, $m_{T,WW}$, $BDT_{\tau\tau}$
  - signal PDF from MC, bkg PDF from MC & data control samples
- results will be soon superseded by updated ones…

Production

- overall strength:
  - good consistency between individual channels, between fermions and bosons, and with SM (7%)
- separating gg+ttH from VBF+VH:
  - good consistency w/SM (1-2σ) in each channel
- separating VBF from VH and gg+ttH:
  - $\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}{}^{+0.4}_{-0.3}$
  - 4.1σ evidence (previous: 3.3σ), agrees with SM

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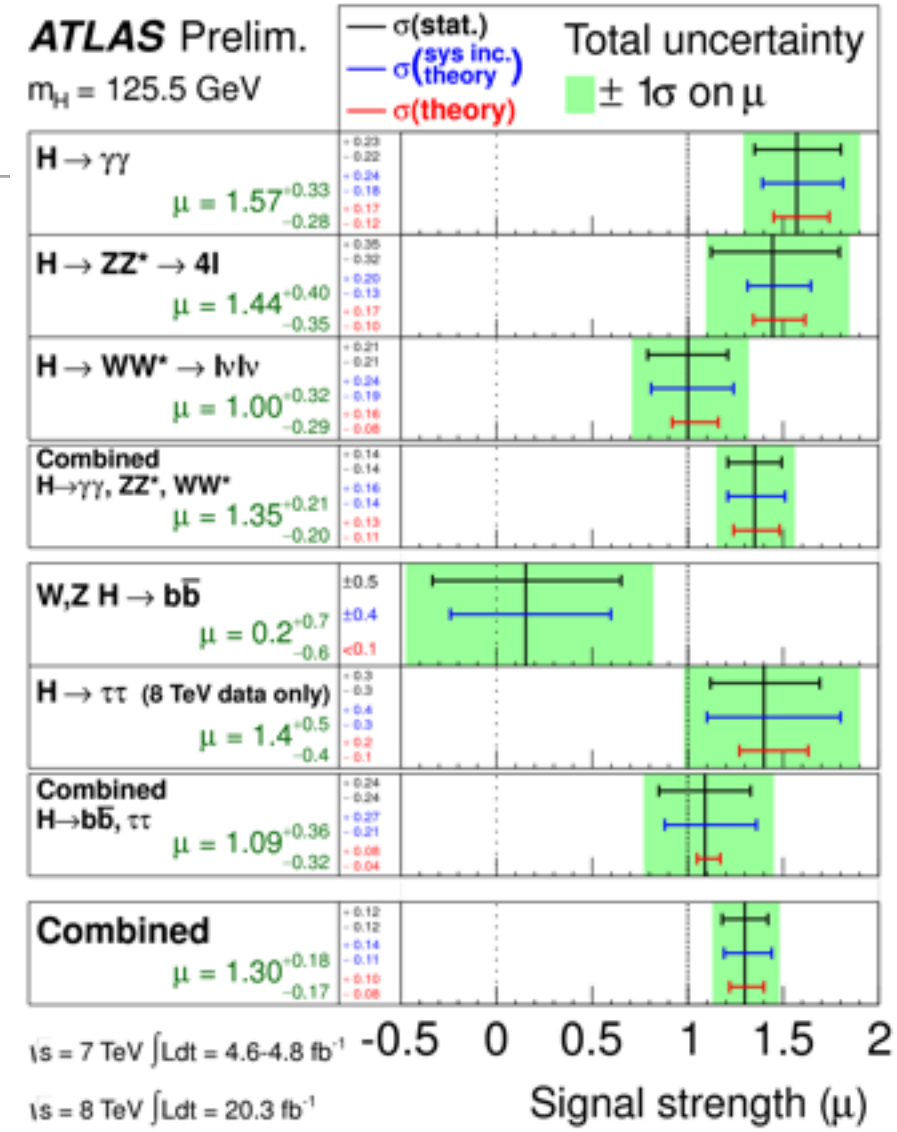
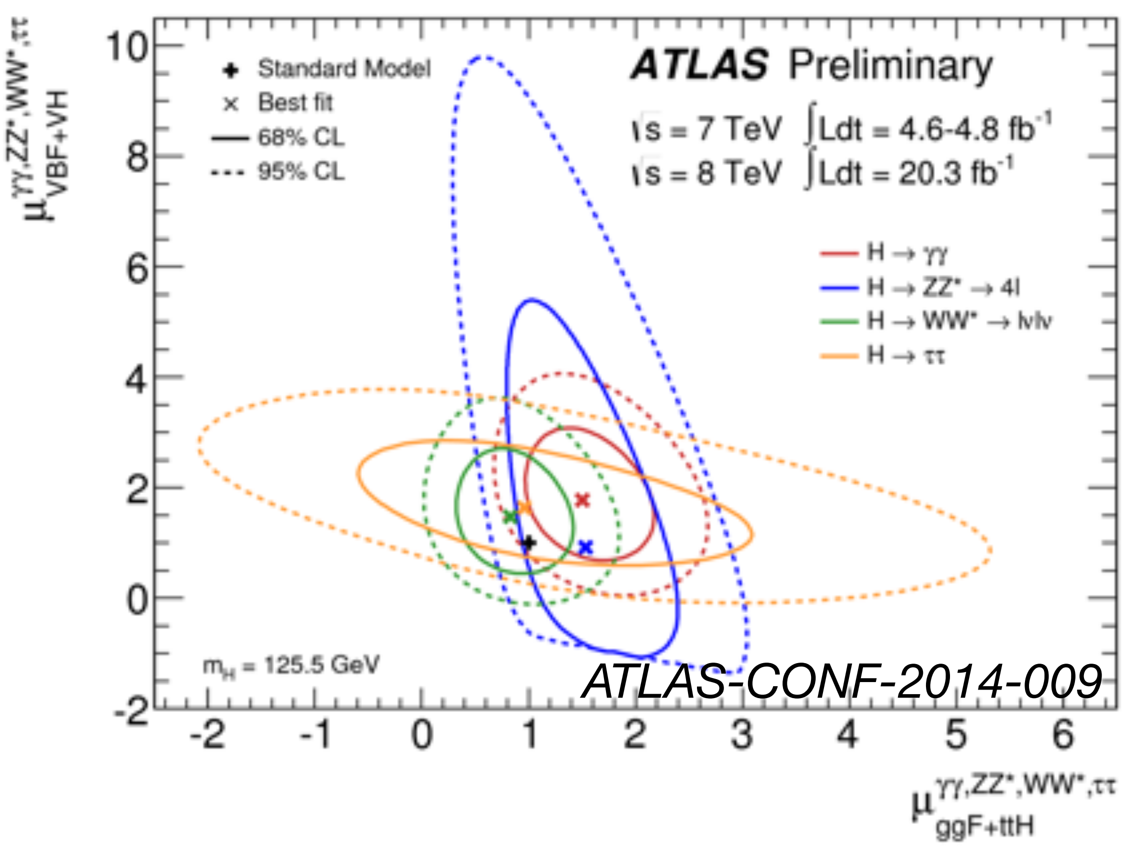
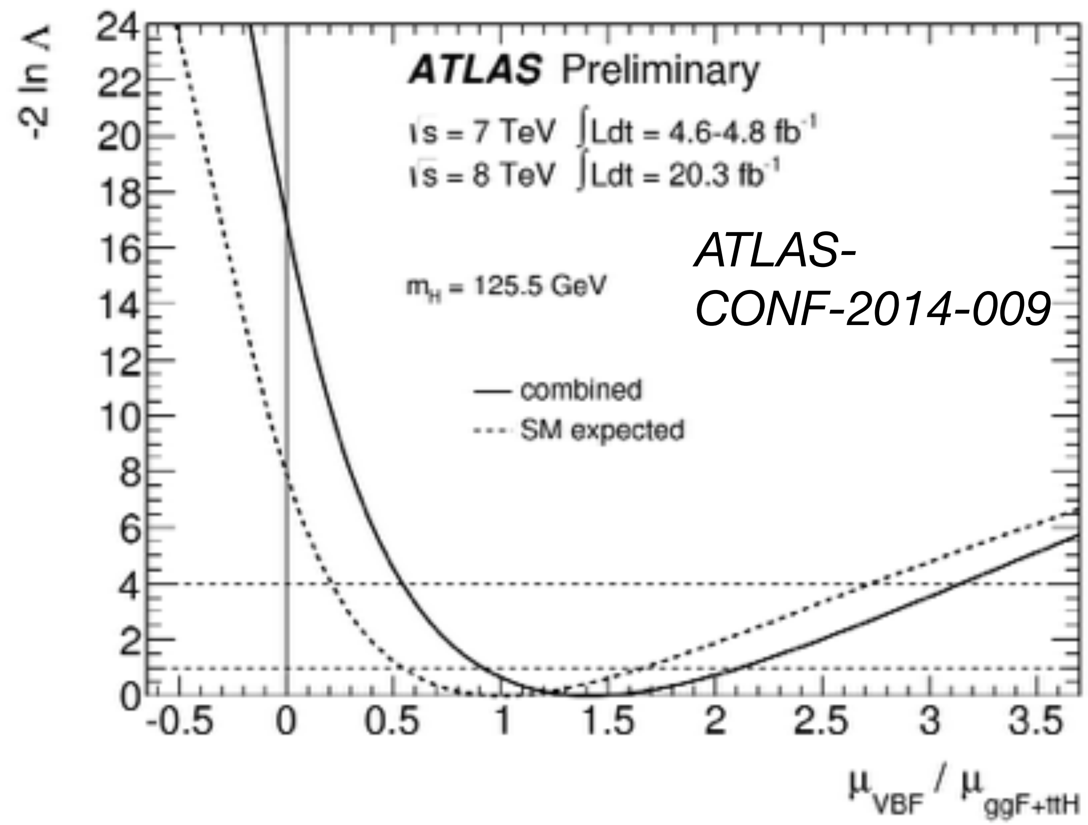
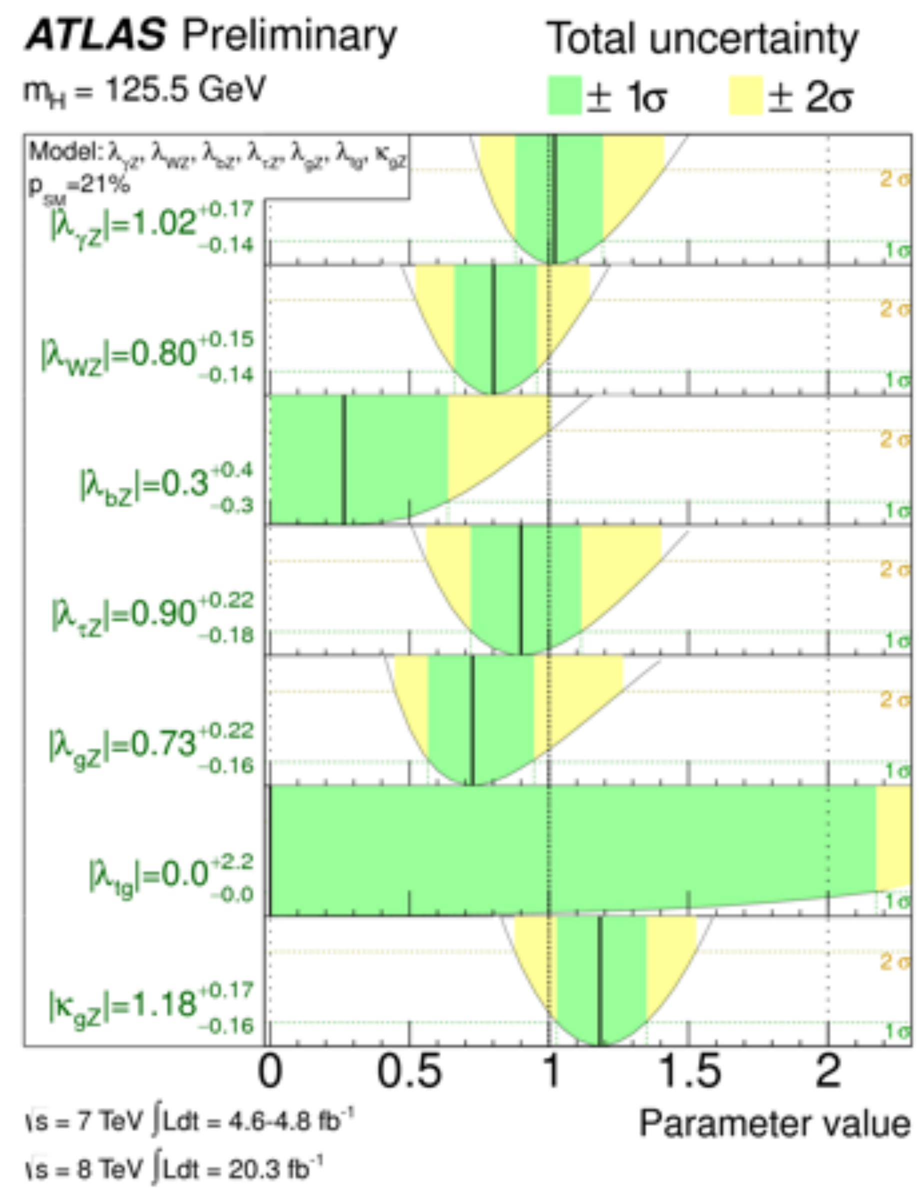






Couplings

- many models tested, all gives values of parameters in good agreement with SM (p-value of 10-20%)
  - separate scalings of couplings to fermions vs gauge boson
  - separate scalings of couplings to W vs Z
  - separate scalings of couplings to u-type vs d-type fermions (2HDM,…)
  - separate scalings of couplings to quarks vs leptons
  - effective gluon and photon couplings and width modified by BSM particles
  - separate scalings for couplings to W, Z, g, γ, b, t, τ, no assumption on Γ
- $>5\sigma$ (indirect) evidence of fermion couplings (ttH vertex), 3.6σ evidence of couplings to down-type fermions and 4.0σ evidence of couplings to leptons ($H\rightarrow\tau\tau$)



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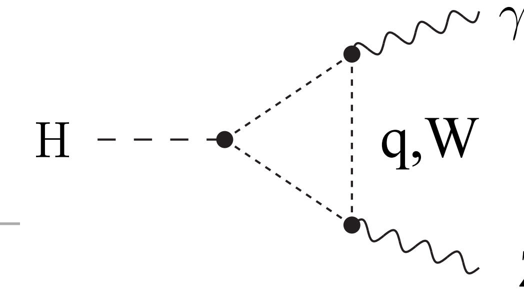
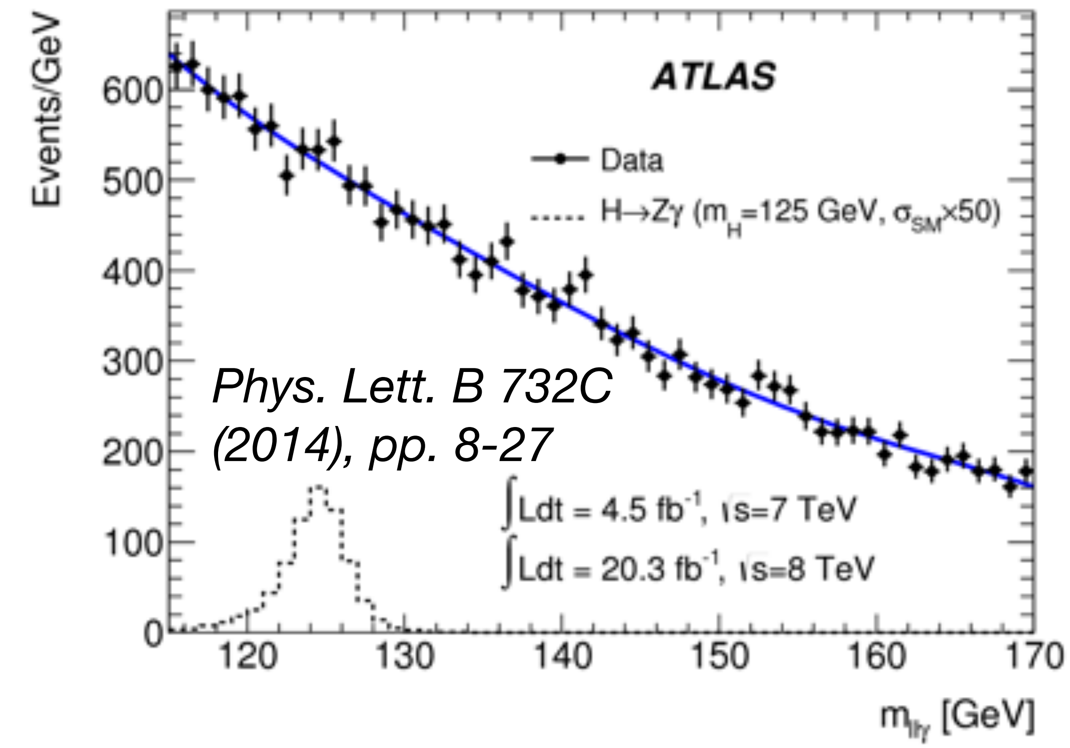
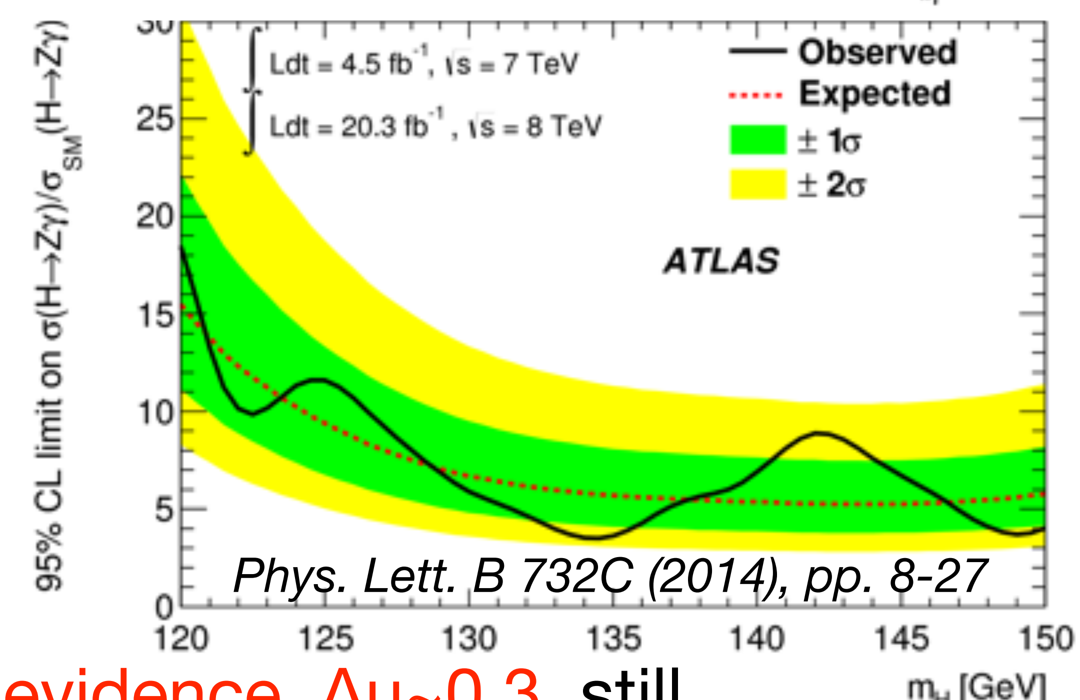
H→Zγ→llγ



- rare decay channel, low yield (S_{exp}~15) and S/B (~0.25%), good mass resolution (σ_m/m~1.4%)
- possibly enhanced by BSM particles in loops or in composite-Higgs models
- analysis of full 7+8 TeV data
  - 2 same flavor, opposite-sign isolated leptons, p_T>10 GeV, m_{ll}>m_Z-10 GeV
  - 1 isolated photon, E_T>15 GeV, $\Delta R_{l\gamma}$>0.3
- main difference wrt previous result: event categories (p_{Tt}, $|\Delta\eta_{Z\gamma}|$)⇒35% higher sensitivity
- no excess:
  - μ<11 @95% CL for m_H=125.5 GeV
    expected w/o (w/) SM Higgs: 9 (10)
  - σ*BR<0.13-0.5 pb @ 8 TeV for 120<m<150 GeV

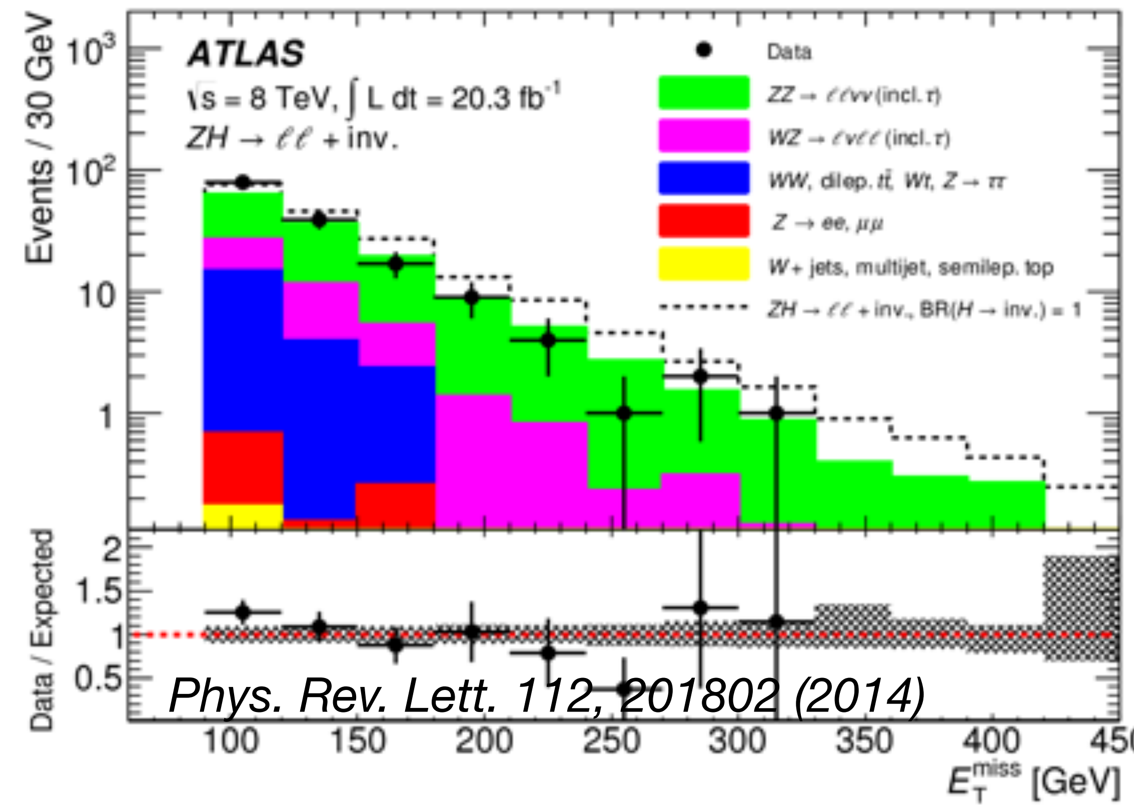


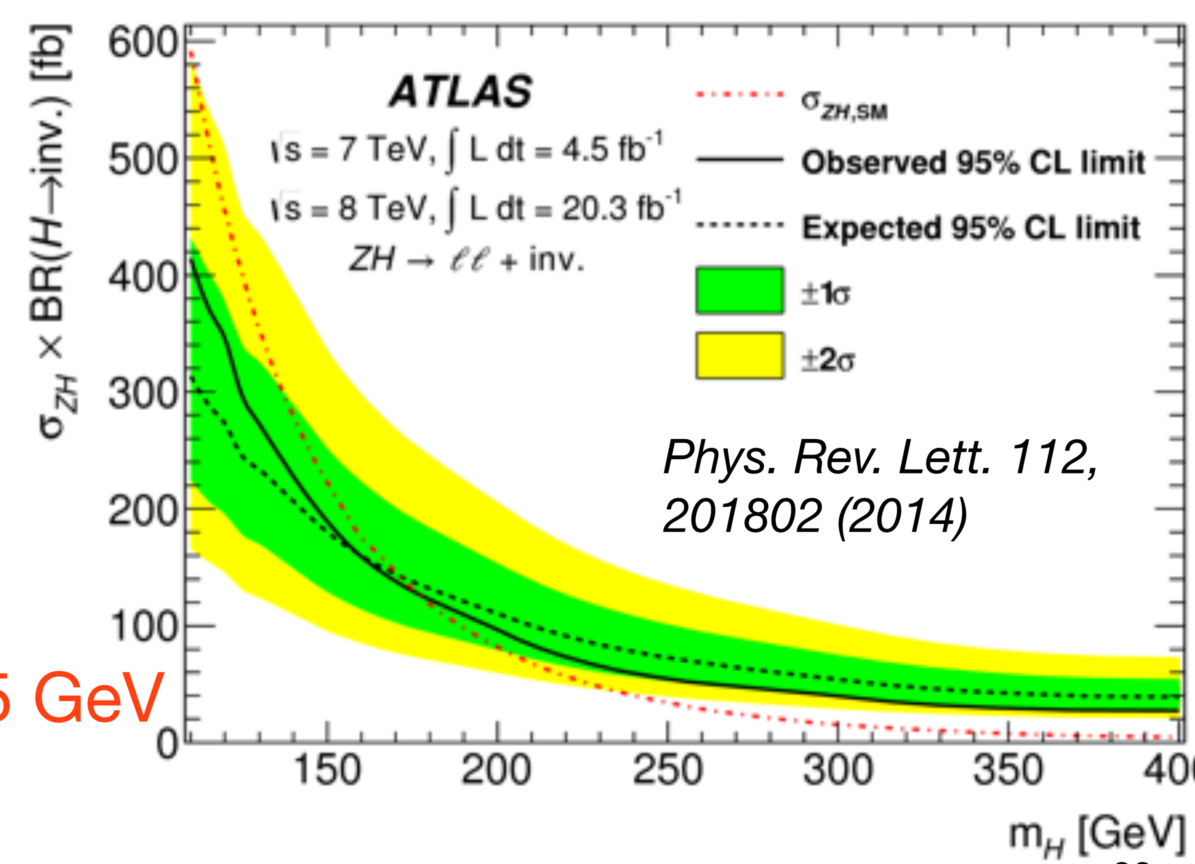


- same analysis w/ HL-LHC (3ab^{-1}@14 TeV): ~4σ evidence, Δμ~0.3, still statistically dominated (https://cds.cern.ch/record/1703276)

ZH, H→invisible, Z→ll

- 50% more data at 8 TeV wrt previous result
- measure BR_{inv} of 125.5 GeV Higgs, or search H→invisible for m_H=110-400 GeV
  - SM ZH→llνν: negligible
  - enhanced if BSM WIMPs coupled to H
- selection (unchanged):
  - exactly 2 same-flavor opposite-sign isolated leptons, $|m_{ll}-m_Z|<15$ GeV, $\Delta\phi_{ll}<1.7$
  - E_T^{miss} >90 GeV, balanced in φ & p_T against ll
  - no jet with p_T>25 GeV and $|\eta|<2.5$
- main bkg (unchanged): ZZ→llνν, WZ→lllν. MC scaled to NLO xsec, checked (WZ) with 3l data. Uncertainty~10%
- signal extraction (unchanged): fit to E_T^{miss}
- no excess ⇒ σ*BR_{inv}<30-400 fb for m_H=110-400 GeV and BR_{inv}<75% @ 125.5 GeV
  - previous result: BR_{inv}<65%



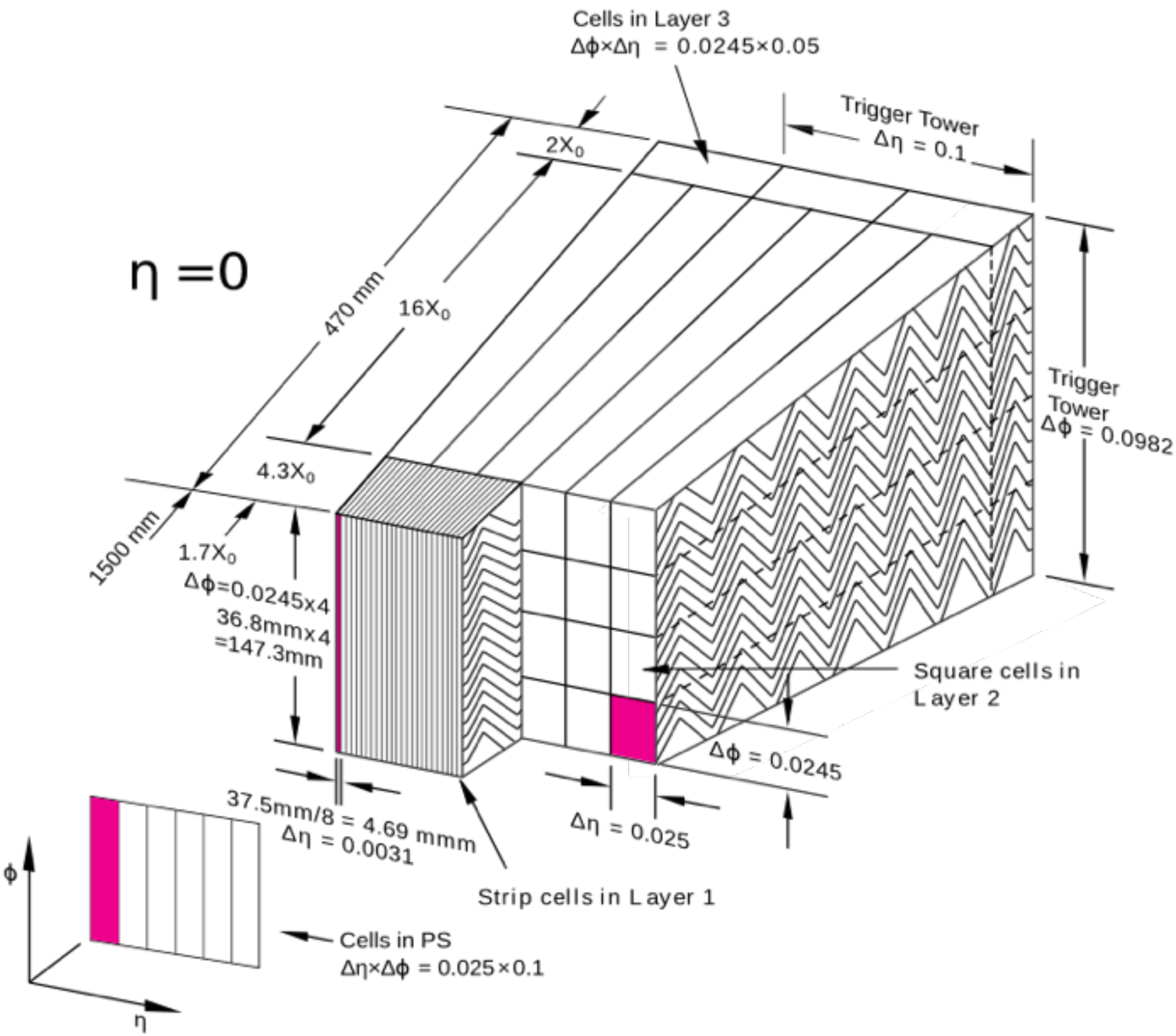


Conclusion

- New mass measurement fully exploiting Run1 dataset for reduction of systematic uncertainties: m_H=125.36±0.37±0.18 GeV
  - -0.15 GeV shift wrt previous result, consistent with expectations from new e/γ calibration
  - reduced tension (2σ) between 4l and $\gamma\gamma$ channels
- Combination of latest $\gamma\gamma$, WW, ZZ, $\tau\tau$, bb results:
  - production rates and couplings consistent with SM
- Signatures for which no sensitivity yet to SM Higgs with Run1 have been investigated, no BSM excess observed
  - ttH (H→bb): $\mu<4.1$. Searches in $\gamma\gamma$, bb, $\tau\tau$, WW/ZZ underway
  - double-Higgs (→$\gamma\gamma$bb) production: $\sigma<2.2$ pb @ 95% CL
  - H→Zγ: $\mu<11$
  - H→invisible: $BR_{inv}<75\%$

More details

ATLAS EM calorimeter



Control samples for e/γ calibration

Process	Selections	N^{data}_{events}	MC generator
$Z \to ee$	$E_T^e > 27$ GeV, $\|\eta^e\| < 2.47$ $80 < m_{ee} < 100$ GeV	5.5 M	POWHEG+PYTHIA
$W \to e\nu$	$E_T^e > 30$ GeV, $\|\eta^e\| < 2.47$ $E_T^{miss} > 30$ GeV, $m_T > 60$ GeV	34 M	POWHEG+PYTHIA
$J/\psi \to ee$	$E_T^e > 5$ GeV, $\|\eta^e\| < 2.47$ $2 < m_{ee} < 4$ GeV	0.2 M	PYTHIA
$Z \to \mu\mu$	$p_T^\mu > 20$ GeV, $\|\eta^\mu\| < 2.4$ $60 < m_{\mu\mu} < 120$ GeV	4.3 M	SHERPA
$Z \to ll\gamma$, large-angle	$E_T^\gamma > 15$ GeV, $\|\eta^\gamma\| < 2.37$ $E_T^e > 15$ GeV, $\|\eta^e\| < 2.47$ $p_T^\mu > 20$ GeV, $\|\eta^\mu\| < 2.4$ $45 < m_{ll} < 85$ GeV $80 < m_{ll\gamma} < 120$ GeV $\Delta R(l,\gamma) > 0.4$	20k (e) 40k (μ)	SHERPA
$Z \to ll\gamma$, collinear	$E_T^\gamma > 7$ GeV, $\|\eta^\gamma\| < 2.37$ $p_T^\mu > 20$ GeV, $\|\eta^\mu\| < 2.4$ $55 < m_{ll} < 89$ GeV $66 < m_{ll\gamma} < 116$ GeV $\Delta R(\mu,\gamma) < 0.15$	120k	SHERPA
$\gamma + X$	$E_T > 120$ GeV, $\|\eta^\gamma\| < 2.47$	3.1 M	PYTHIA

$H \rightarrow \gamma\gamma$ selection

- di-photon trigger (E_T>35,25 GeV, $|\eta|$<2.5, loose shower-shape cuts)
- $E_T/m_{\gamma\gamma}$>0.35, 0.25 ($m_{\gamma\gamma}$ in 105-160 GeV)
- $|\eta|$<2.37, exclude 1.37<$|\eta|$<1.56
- tight shower-shape cuts: ε~85-95%, uncertainty<2% w/ data-driven methods
- isolation (ε~95%, uncertainty<1%)
  - in calo: E_T^{iso}<6 GeV (ΔR=0.4)
  - in tracker: p_T^{iso}<2.6 GeV (ΔR=0.2, p_T^{trk}>1 GeV, from di-photon PV)
- primary vertex: neural network using photon pointing, conversion tracks, average beamspot, Σp_T and $\Delta\phi$ between $\gamma\gamma$ and Σp_T)
  - ε(PV within ±15 mm in z of true vtx)~93%, negligible impact on $m_{\gamma\gamma}$
- overall ε~40%, 95k events selected in 8 TeV data, S_{SM}~400
- inv. mass resolution=1.2-2.4 GeV, S/B=2%-25% depending on category

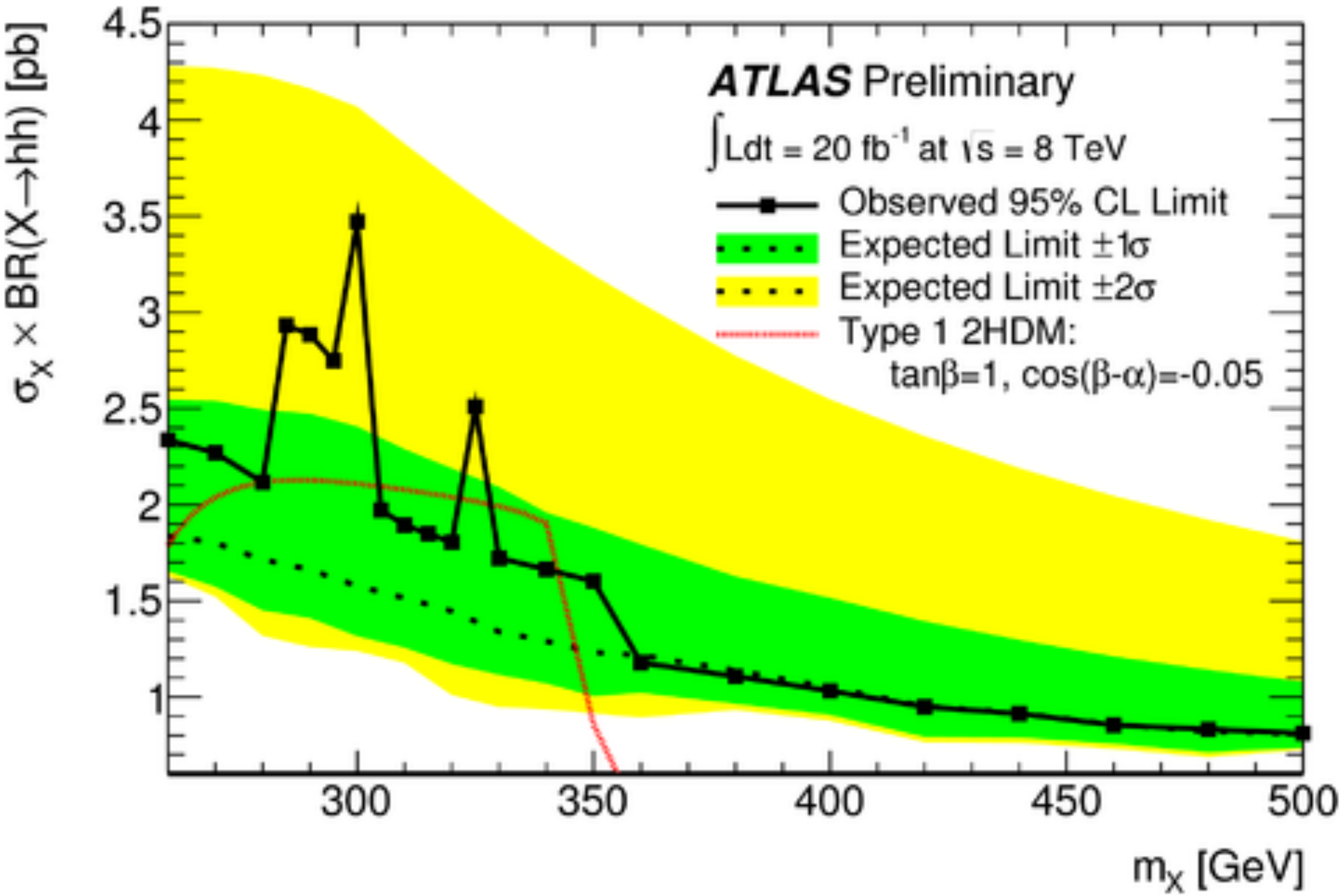
$H \to ZZ^* \to 4l$ selection

- single lepton or di-lepton trigger
- 2 same-flavour, opposite sign lepton pairs
- $p_T(E_T)>$20-15-10-6(7) GeV and $|\eta|<2.7(2.47)$ for μ(e)
- $\Delta R>0.1$ (0.2) for leptons of same(different) flavour
- longitudinal and transverse impact parameter cuts
- tight shower-shape cuts (e), cuts on hits in various ID detectors (μ)
- track- and calorimeter- based isolation
- FSR correction
  - collinear FSR (μ only): when $66<m_{12}<89$ GeV, $E_{T\gamma}>1.5$ GeV, $\Delta R_{\mu\gamma}<0.15$, $m_{\mu\mu\gamma}<100$ GeV [4% of events]
  - non-collinear FSR: when $m_{ll}<81$ GeV, $E_{T\gamma}>10$ GeV, $\Delta R_{l\gamma}>0.15$, isolated γ, $m_{ll\gamma}<100$ GeV [1% of events]
- E, p combination (e): likelihood based on parameterisation of the cluster and track p_T/p_T^{true}
- $50<m_{12}<106$ GeV, $12<m_{34}<115$ GeV, $110<m_{4l}<140$ GeV
- overall ε~39% (4μ), 27%(2e2μ), 20% (4e), S_{SM}~16 events in 8 TeV data
- Z-mass constraint (leading pair): improves σ_m by 15%

Double Higgs systematic uncertainties

- trigger: 1%
- luminosity: 2.8%
- photon ID: 2.4%
- photon isolation: 2%
- eff(b-tag): 2-3%
- JES: 5-20%
- JER: 5-10%
- diphoton mass resolution (13%): 1.6% on eff($m_{\gamma\gamma}$ cut) in resonant analysis
- diphoton mass scale (0.6 GeV): 1.7% on eff($m_{\gamma\gamma}$ cut) in resonant analysis
- acceptance of $m_{\gamma\gamma}$ cuts on continuum bkg: 11% (anti-photon ID, anti-btag, different functional forms)
- acceptance of $m_{\gamma\gamma bb}$ cuts on continuum bkg
  - statistics of the control region (<2b-tag): 3-18%
  - $m_{\gamma\gamma bb}$ shape difference signal/control: <30%
  - $m_{\gamma\gamma bb}$ fit function: 16-30%
- theory (single h bkg): 15-20%

Double Higgs: limit on resonant decays



2HDM parameters: heavy Higgs bosons degenerates in mass, xsections and BFs from arXiv:1312.5571 (Harlander et al)

ttH: selection

- single lepton trigger
- b-tagging: 70% efficiency, <1% mistag rate for light jets
- 1l:
  - exactly 1 central l with p_T>25 GeV, isolated and identified
  - at least 4 jets with p_T>25 GeV, $|\eta|$<2.5, at least 2 b-tag
  - dilepton veto
- 2l:
  - exactly 2 central l of opposite charge with p_{T1}>25 GeV and p_{T2}>15 GeV, isolated and identified
  - at least 4 jets with p_T>25 GeV, $|\eta|$<2.5, at least 2 b-tag
  - emu channel: H_T>130 GeV
  - ee, mumu: m_{ll}>60 GeV in 2 b-tags, $|m_{ll}-m_Z|$>8 GeV
- overlaps: dR(lepton-jet)>0.4 (for electrons, first remove jet closest to e)

ttH: background and signal

Background samples used:

- $t\bar{t}$+jets: Powheg+Pythia
- $t\bar{t}Z$, $t\bar{t}W$: Madgraph+Pythia
- W+jets: Alpgen+Pythia
- Z+jets: Alpgen+Herwig
- Dibosons: Alpgen+Herwig
- Single top: Powheg/AcerMC + Pythia
- Multijet: data driven

- W/Z+jets: normalised to NNLO, $p_T(V)$ reweighting, HF fraction (cc+bb) adjusted to reproduce rate of Z events with 0 and 1 b-tag in data
- WW/WZ/ZZ+jets, ttV: normalised to NLO
- tt+jets: normalised to NNLO, $p_T(t)$ and $p_T(tt)$
- single-top: normalised to approximate NNLO
- ttH signal: Powheg HELAC-Oneloop + Pythia8, scales=(2mT+mH)/2, NLO xs

- Signal-depleted regions: use $H_T^{had} = \sum p_T^{jets}$ for ℓ+jets and $H_T = \sum p_T^{jets} + \sum p_T^{\ell}$ for dilepton
- ℓ+jets, 5 jets, 3 b-tags region: use NN trained to separate $t\bar{t} + b\bar{b}/c\bar{c}$ from $t\bar{t}$+light jets
- Signal-rich regions: use NN trained to separate $t\bar{t}H$ from $t\bar{t}$+jets in each of the region

	2 b-tags	3 b-tags	$\geq$ 4 b-tags
4 jets	H_T^{had}	H_T^{had}	H_T^{had}
5 jets	H_T^{had}	NN	NN
$\geq$ 6 jets	H_T^{had}	NN	NN

	2 b-tags	3 b-tags	$\geq$ 4 b-tags
2 jets	H_T		
3 jets	H_T	NN	
$\geq$ 4 jets	H_T	NN	NN

- tt normalisation: (4j, 2b) [1l] and (2j, 2b) [2l]
- tt+light, tt modelling: 2b-tag regions
- charm tagging: (4j, 3b) [1l] region (large contribution from tt+light, W->cs
- tt+bb, tt+cc normalisations: 3, >=4 b-jets (bkg-enriched bins)

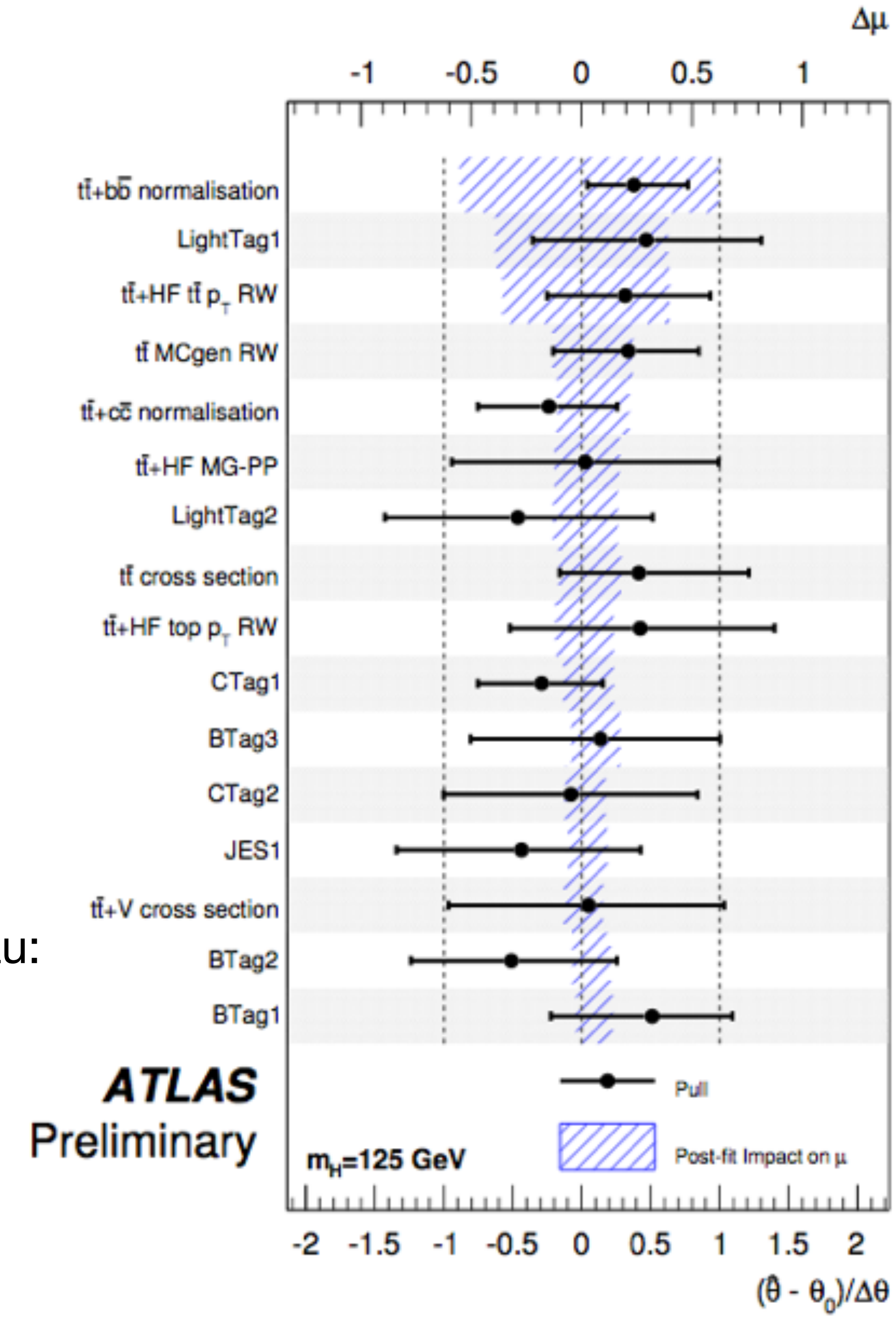
ttH: systematic uncertainties

$\geq$ 6 jets, $\geq$ 4 *b* tags (pre-fit)

	$t\bar{t}H$ (125)	$t\bar{t}$ + light	$t\bar{t}+c\bar{c}$	$t\bar{t}+b\bar{b}$
Luminosity	±2.8	±2.8	±2.8	±2.8
Lepton efficiencies	±1.4	±1.4	±1.4	±1.5
Jet energy scale	±6.5	±14	±10	±8.2
Jet efficiencies	±1.6	±5.4	±2.5	±2.4
Jet energy resolution	±0.1	±8.5	±4.1	±4.3
b-tagging efficiency	±9.0	±5.8	±5.1	±9.2
c-tagging efficiency	±1.9	±7.3	±14	±2.8
Light jet-tagging efficiency	±1.0	±17	±4.4	±1.5
$t\bar{t}$ modelling: reweighting	–	±11	±13	±13
$t\bar{t}$ modelling: parton shower	–	±7.5	±1.8	±10
$t\bar{t}$ heavy-flavour: normalisation	–	–	±50	±50
$t\bar{t}$ heavy-flavour: reweighting	–	–	±11	±12
$t\bar{t}$ heavy-flavour: generator	–	–	±2.2	±2.9
Theoretical cross sections	–	±6.2	±6.3	±6.3
$t\bar{t}H$ modelling	±1.9	–	–	–
Total	±12	±30	±57	±56

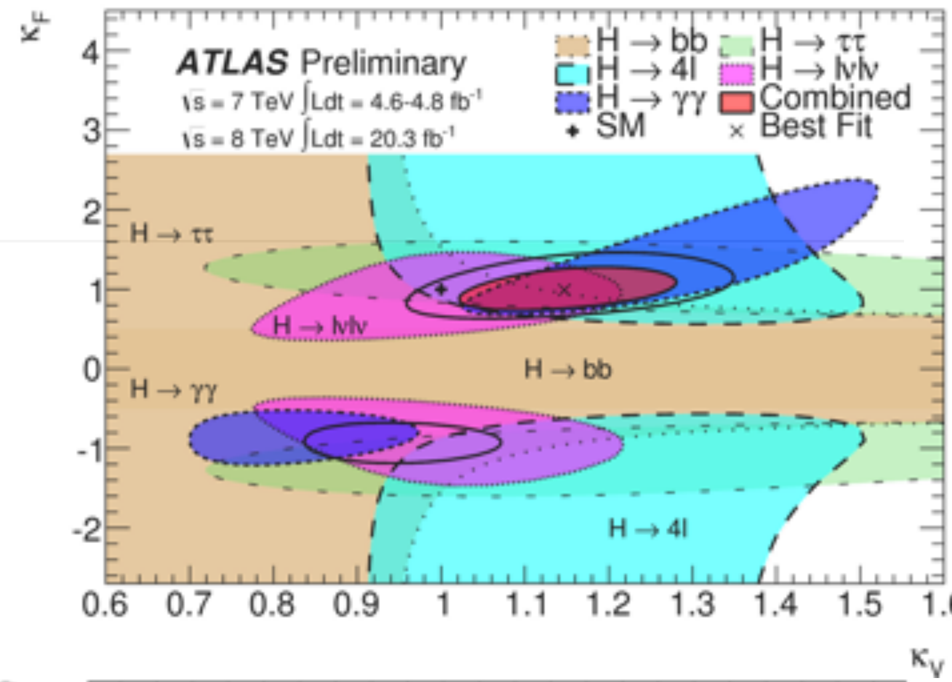
Other results:

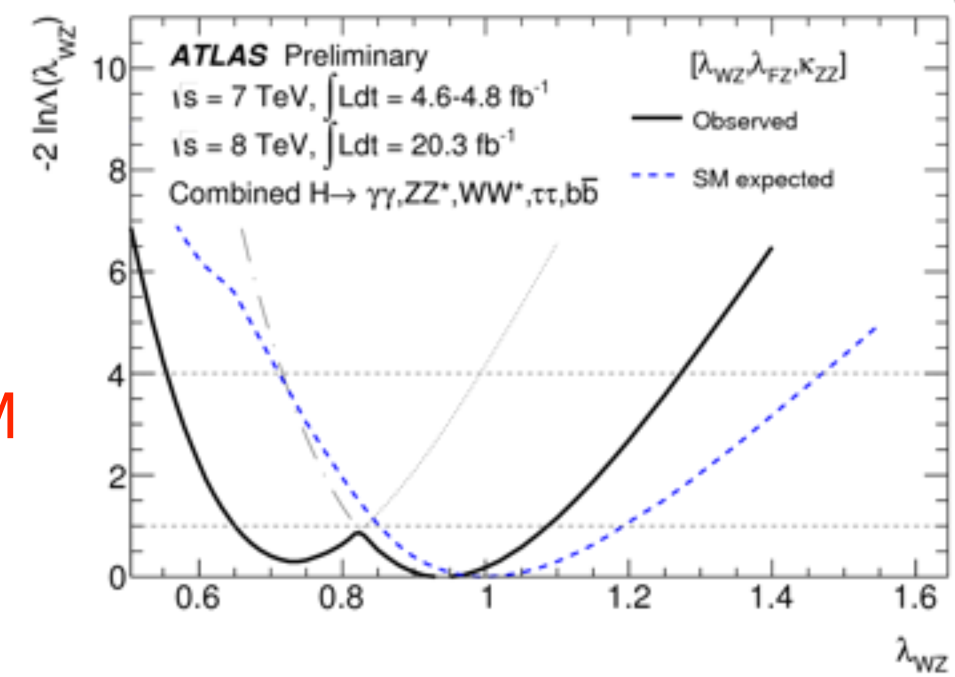
- CMS @ 8 TeV combination of l+jets, dilepton and tautau: obs (exp) = 5.2 (4.1) @ mH = 125 GeV
- ATLAS γγ: obs (exp) = 4.7 (5.4) @ mH = 126.8 GeV

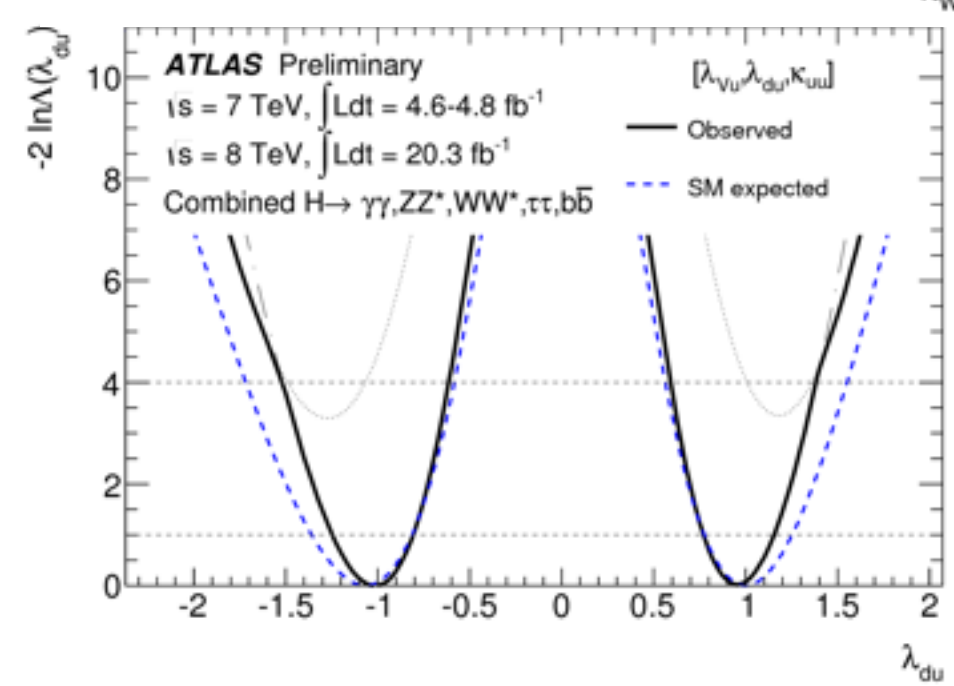


Couplings

- fermions (κ_F) vs vector bosons (κ_V), no extra Higgs decays:
  - κ_F=0.99$^{+0.17}_{-0.15}$, κ_V=1.15±0.08, 10% consistency w/ SM
  - indirect evidence of fermion couplings >5σ
- W (κ_W) vs Z (κ_Z) (custodial symmetry), no extra Higgs decays (extra param: κ_F)
  - $\lambda_{WZ}=\kappa_W/\kappa_Z$=0.94$^{+0.14}_{-0.29}$, 19% consistency w/ SM
- u-type (κ_u) vs d-type (κ_d) fermions (2HDM,…), no extra Higgs decays (extra param: κ_V)
  - λ_{du}=±[0.95$^{+0.20}_{-0.18}$], 20% consistency w/ SM
  - 3.6σ evidence of couplings to down-type fermions (H→ττ..)

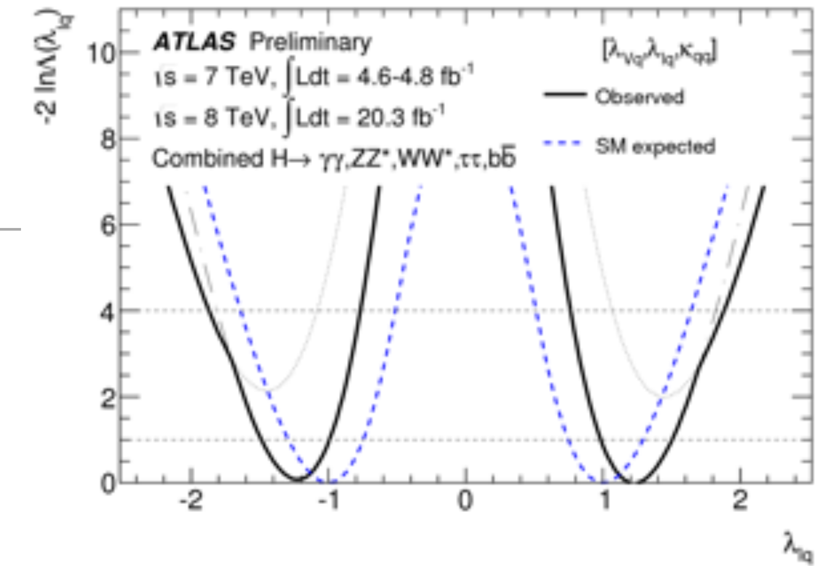


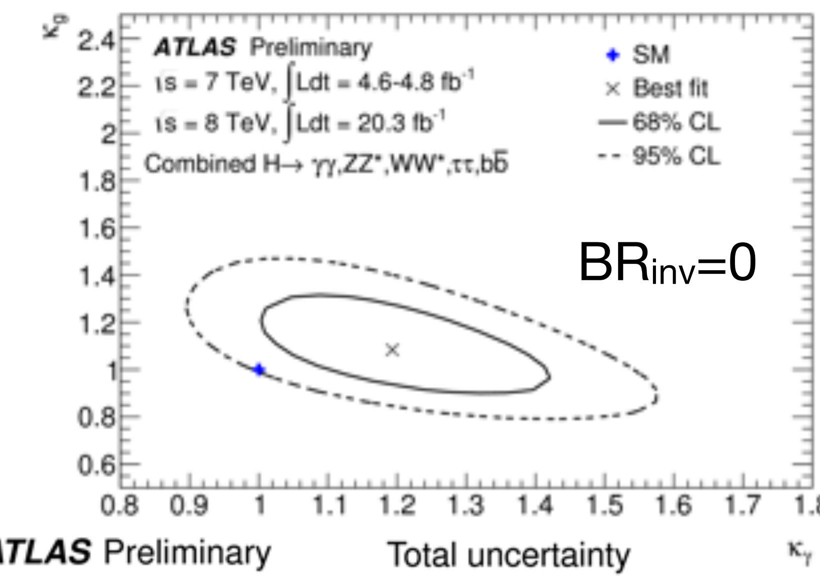


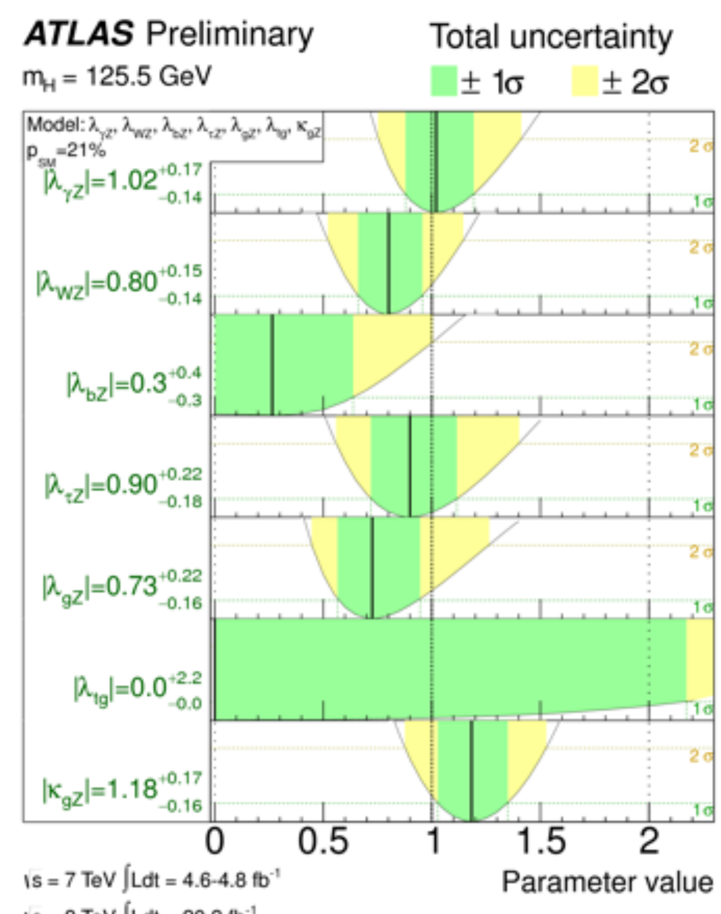


Couplings (II)

- quarks (κ_q) vs leptons (κ_l), no extra Higgs decays (extra param: κ_V):
  - $\lambda_{lq}=\pm[1.22^{+0.28}_{-0.24}]$, 15% consistency w/ SM
  - 4.0σ evidence of couplings to leptons (H→ττ..)
- BSM particles affecting loops (κ_g, κ_γ) and total width (BR_{inv})
  - $\kappa_g=1.00^{+0.23}_{-0.16}$ $\kappa_\gamma=1.17^{+0.16}_{-0.13}$ $BR_{inv}=-0.16^{+0.29}_{-0.30}$
  - 18% consistency w/ SM
- generic model with separate couplings for W, Z, g, γ, b, t, τ and no assumption on width
  - 21% consistency w/ SM
  - top coupling unconstrained (degenerate with effective g coupling, would need ttγ observation)

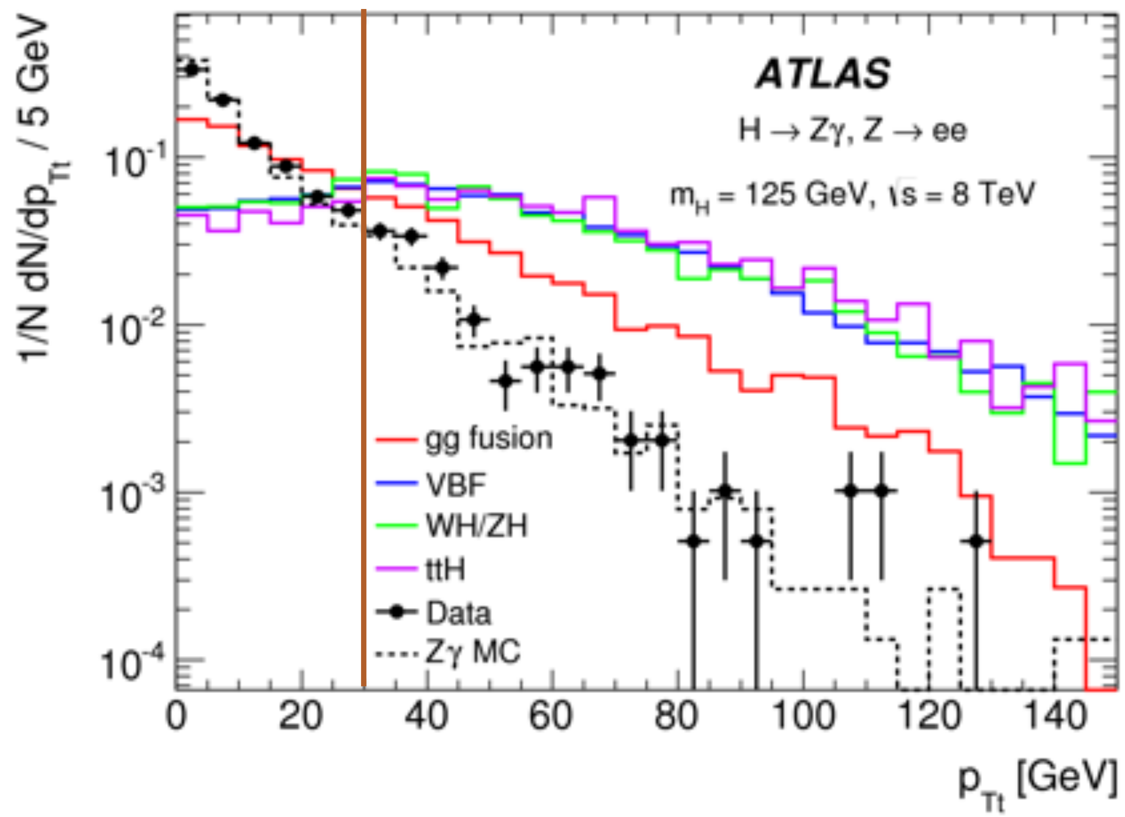


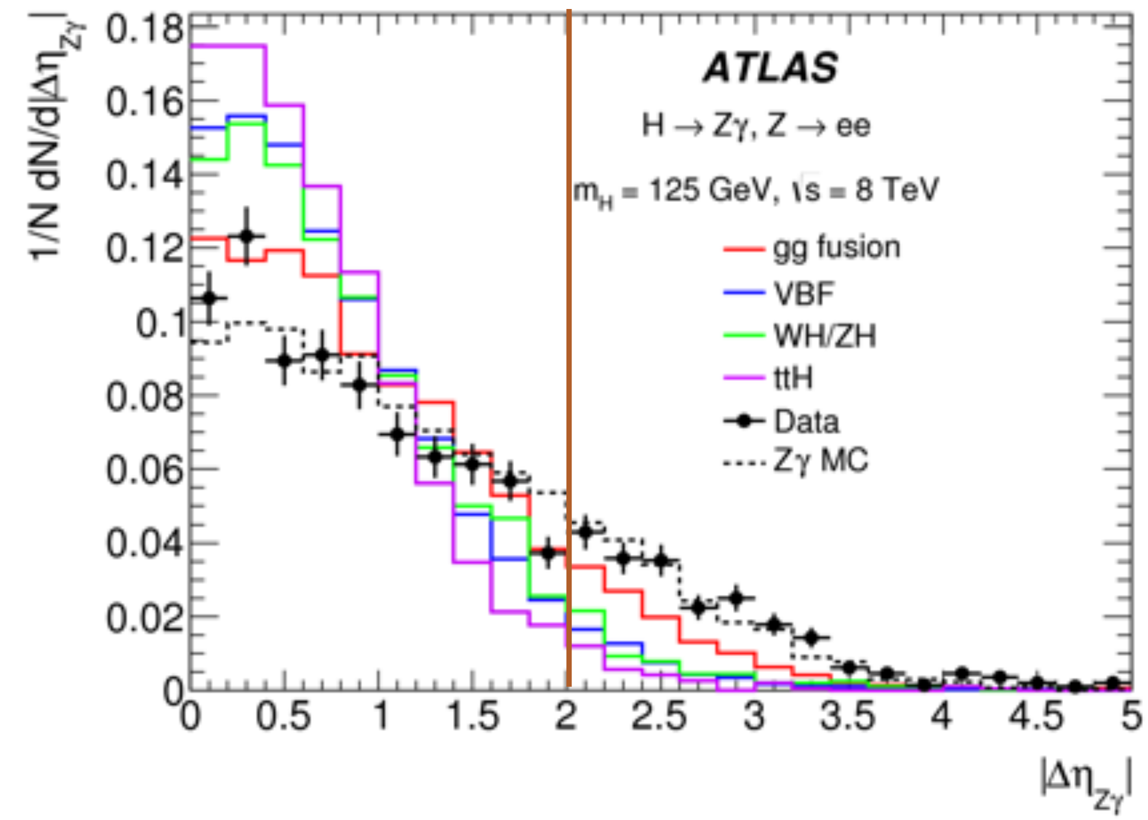


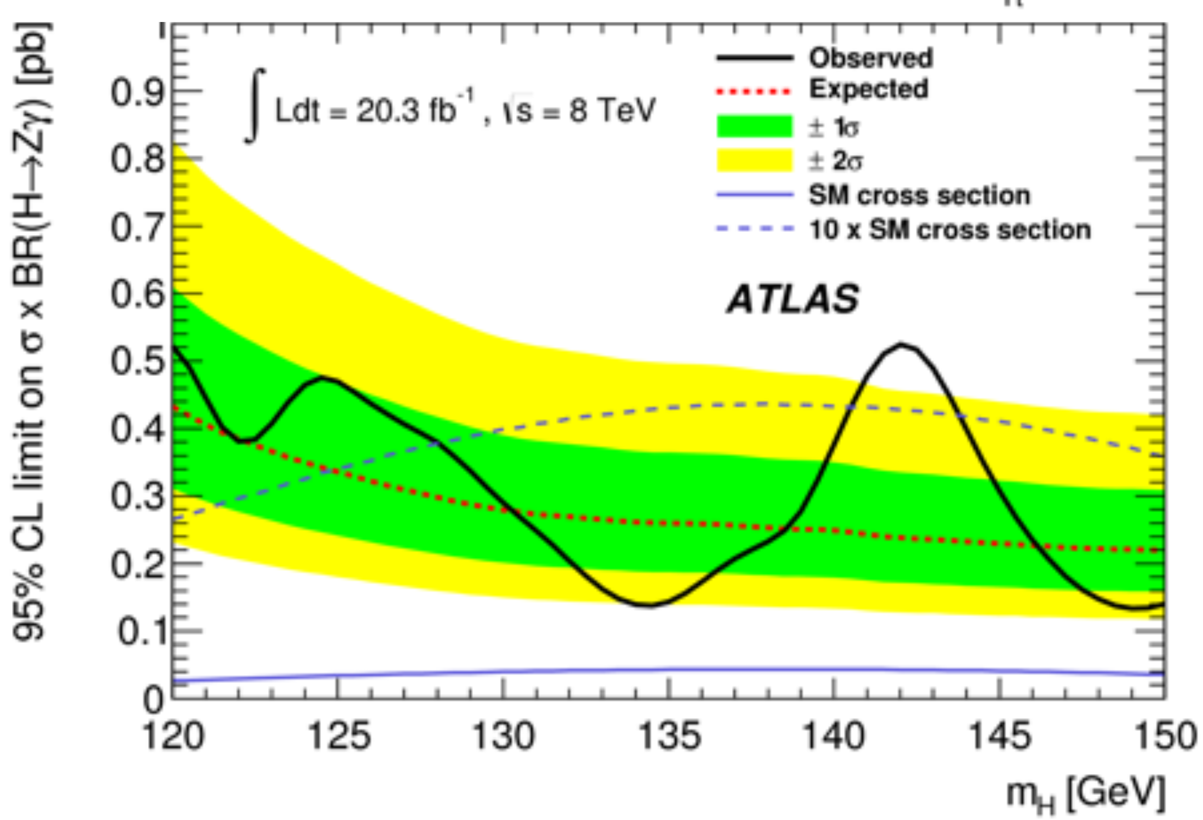


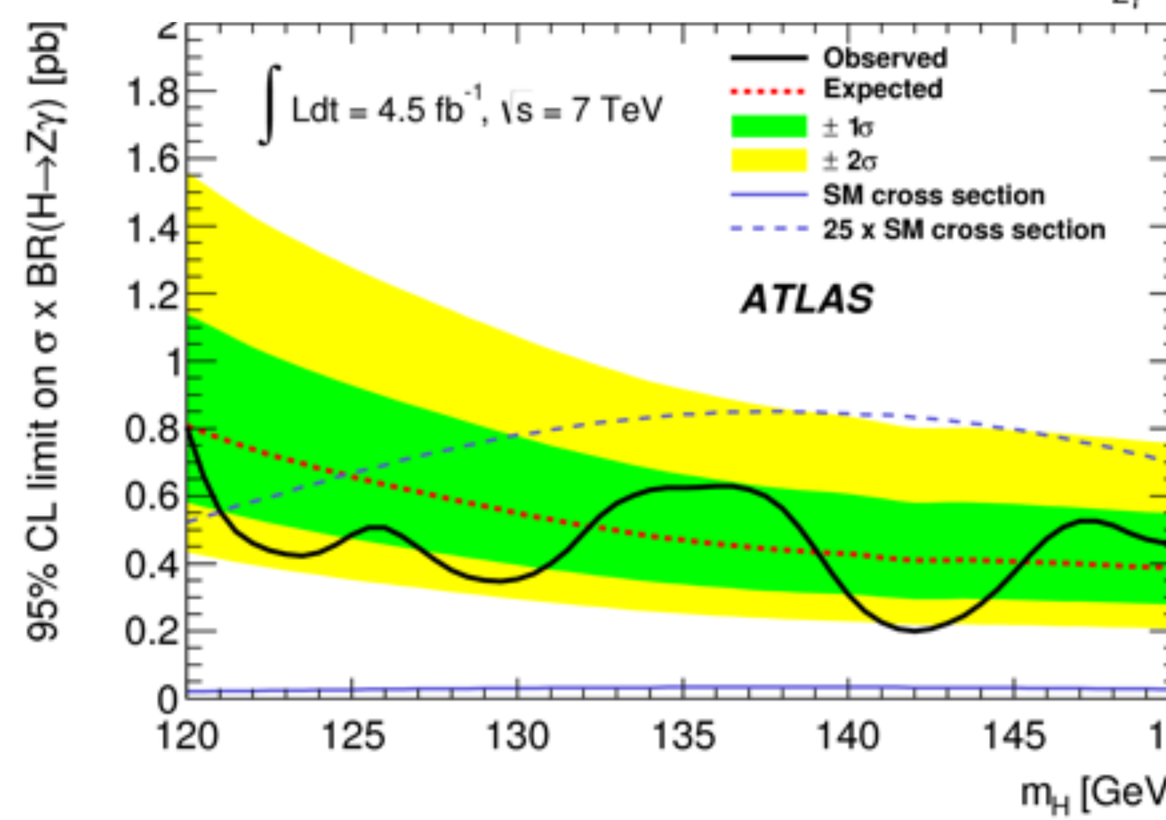
H→Zγ categories and xsection limits

$p_{Tt} = |(\vec{p}_T^{\gamma} + \vec{p}_T^{Z}) \times \hat{t}|$ where $\hat{t} = (\vec{p}_T^{\gamma} - \vec{p}_T^{Z})/|\vec{p}_T^{\gamma} - \vec{p}_T^{Z}|$









$H \to Z\gamma$ systematic uncertainties

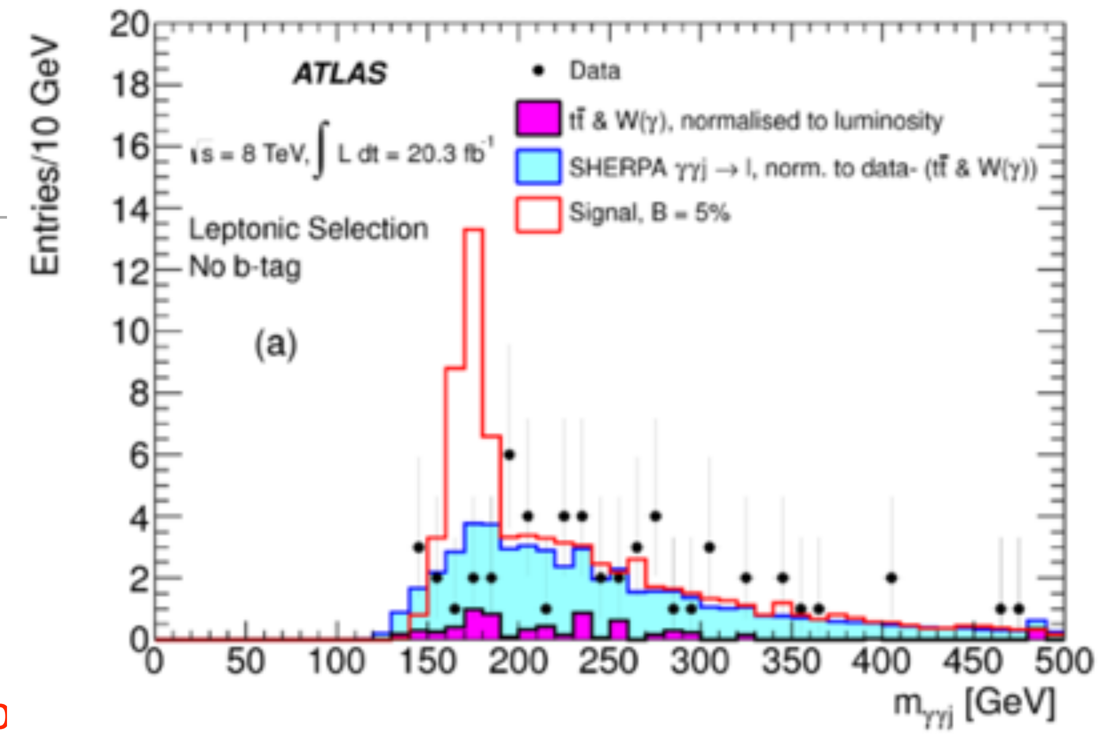
- luminosity: 2.8%
- photon ID: 2.6-3.1%
- electron trigger/rec/ID: 2.5-3%
- p_T^t migration (HRes2): 1.8-3.6%
- $m_{ll\gamma}$:
  - position: 0.2 GeV, from photon energy scale
  - resolution: 3% ($\mu\mu\gamma$), 10% ($ee\gamma$) from e/γ resolution

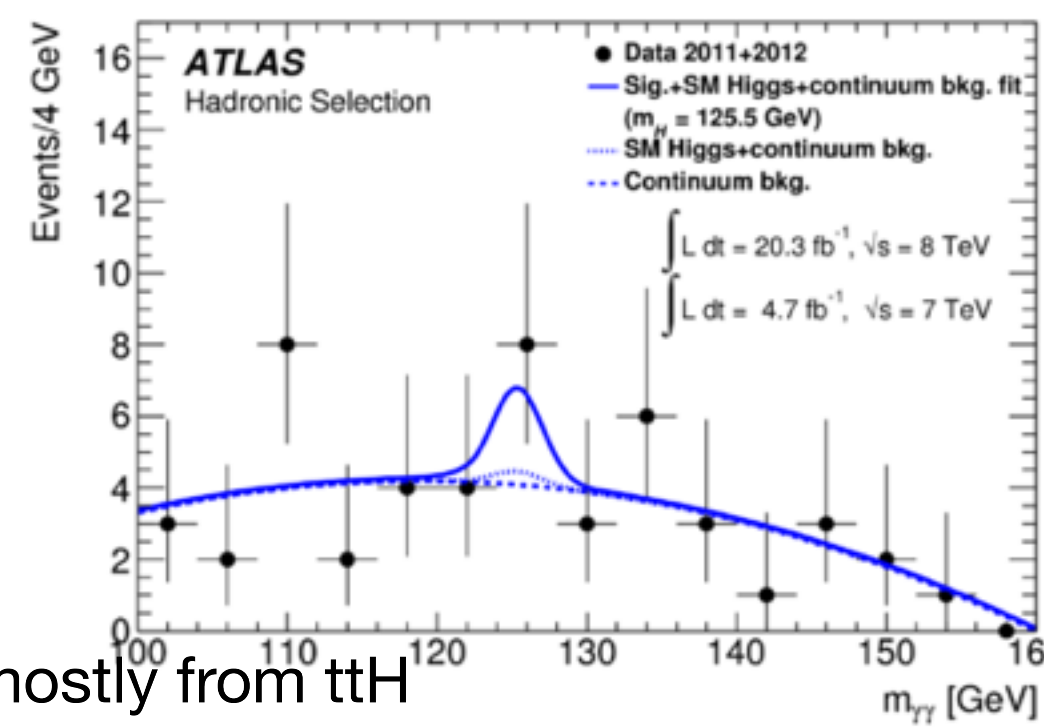
H→invisible: backgrounds, systematic errors

- data-driven bkg estimation
  - true dileptons not from Z: from emu events
  - true dileptons from Z: invert phi/pT balance cuts
  - fake leptons: anti-iso/identified laptons
- signal systematic uncertainties:
  - luminosity: 2.8%
  - lepton trigger/rec/ID: 1-1.5%
  - JES, JER: 3-6%
  - ETmiss: uncertainties on objects used to build it (see above) + pile-up dependence: 1-2%
  - theory: scale+PDF: 3.6-5.7%
- bkg xsection uncertainties:
  - ZZ: 5% (scale+PDF), 5.5% (jet veto)

t→qH (q=c,u)

- CERN-PH-EP-2014-036, accepted by JHEP
- previous result: 0.83% (0.53%)
- differences wrt preliminary result:
  - updated σ_{tt} and signal efficiency
  - BR<0.79% (0.51%) observed (expected) @ 95% CL
- signature tt→WbqH, H→γγ, W→jj or W→lν
  - hadronic: ≥4 jets (≥1b), $m_1 = m_{\gamma\gamma j}$, $m_2 = m_{bjj}$
  - leptonic: ≥2 jets (≥1b), 1l, E_T^{miss}, $m_1 = m_{\gamma\gamma j}$, $m_2 = m_{l\nu b}$ (using W mass constraint)
  - $|m_1 - m_t| < 17$ GeV, $|m_2 - m_t| < 40$(h),35(l) GeV
- signal extraction: $m_{\gamma\gamma}$ fit (hadronic) or counting in $m_{\gamma\gamma}$ signal and sideband
- SM Higgs bkg = 0.24±0.05 (had), 0.05±0.01 (lep), mostly from ttH
- other bkgs: γγ+jets (dominant), tt, Wγ
- experimental systematic errors: signal/SM bkg ~10%; continuum bkg: data driven for had channel (+small sp. signal), 30% uncertainty on extrapolation for lep channel





High-luminosity prospects