Search for the standard model Higgs boson in the $Z\gamma$ decay mode with ATLAS

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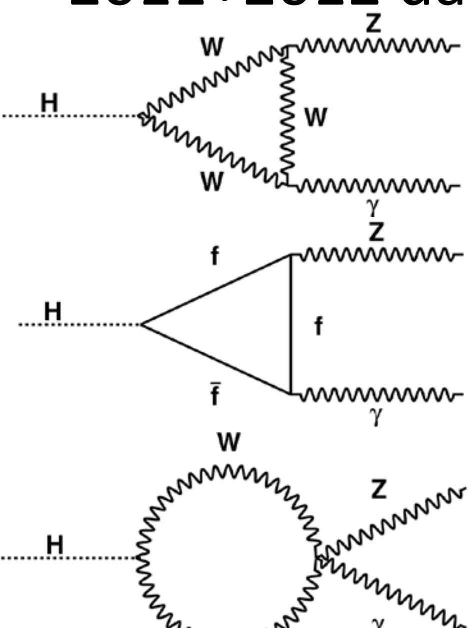
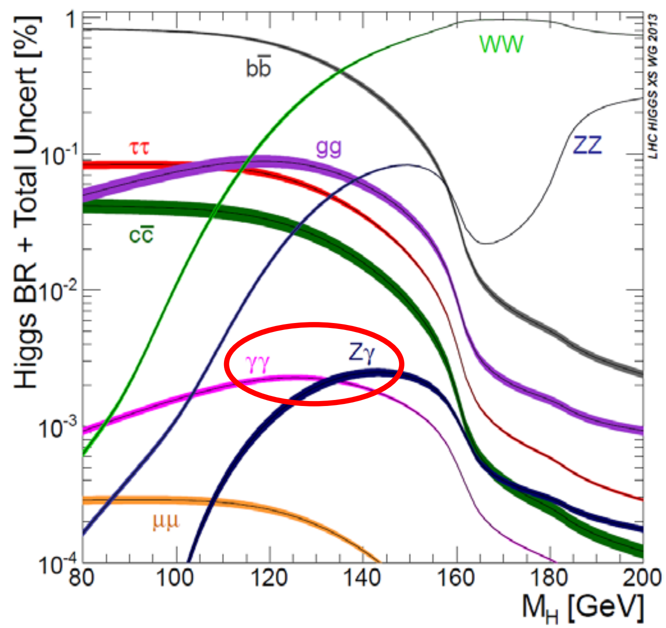
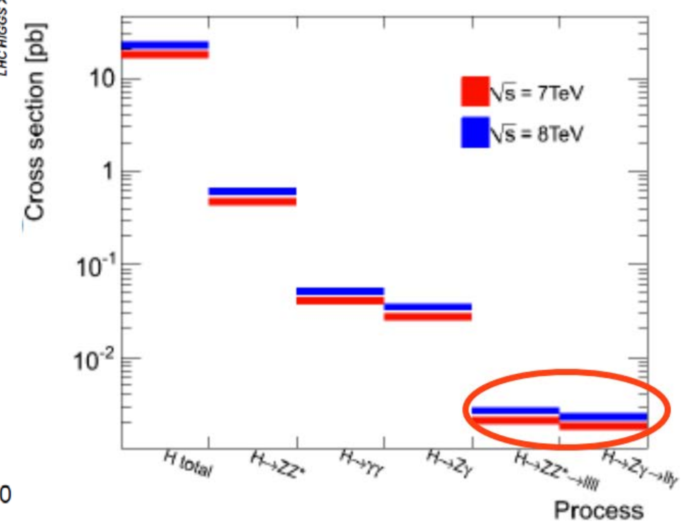
Physical interest of the measurement

- In SM, $H \rightarrow Z\gamma$ proceeds through loops (mostly W-loop)
  - Sensitive to new physics
- BF($H \rightarrow Z\gamma$)~BF($H \rightarrow \gamma\gamma$), BF($Z \rightarrow ee/\mu\mu$)~6.7% gives yields comparable to $H \rightarrow 4l$ (~15 events) but larger background.
- This analysis: search $H \rightarrow Z\gamma$ for m_H in [120,150]GeV using full 2011+2012 data.

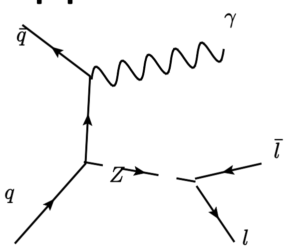




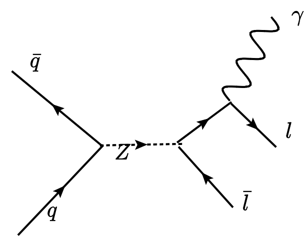


Backgrounds

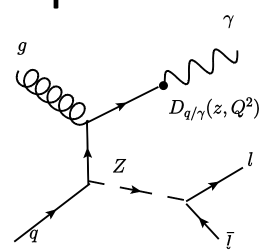
- Major background: $Z+\gamma$ (~82%)
  - Irreducible. Suppressed by E_T^{γ}, $\Delta R_{l\gamma}$ and m_{ll}, $m_{ll\gamma}$.
- Sub-leading background: Z+jets (~17%)
  - Suppressed by photon ID + isolation requirements



t, u channels

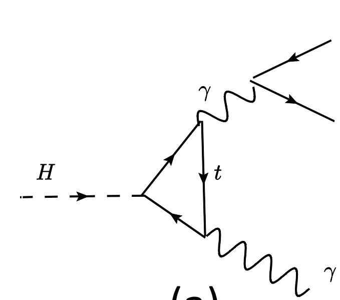


FSR

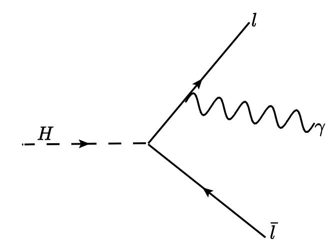


Fragmentation

- Other SM background: $t\bar{t}$(~1%) and WZ (~0)
- No background peaks in $m_{ll\gamma}$ and $\Delta m = m_{ll\gamma} - m_{ll}$
- Higgs background: $H \rightarrow ll\gamma$
  - Suppressed by m_{ll} (a) and E_T^{γ}, $\Delta R_{l\gamma}$ (b) cuts
  - Does not peak in Δm



(a)



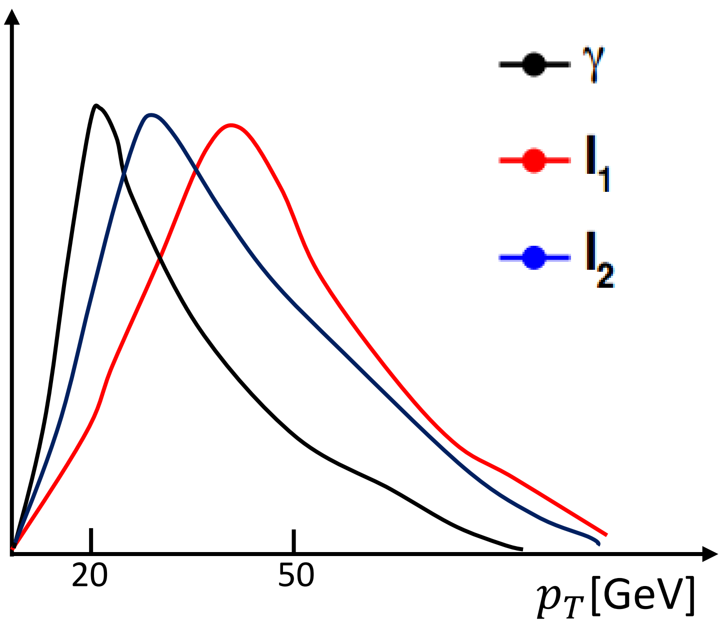
(b)

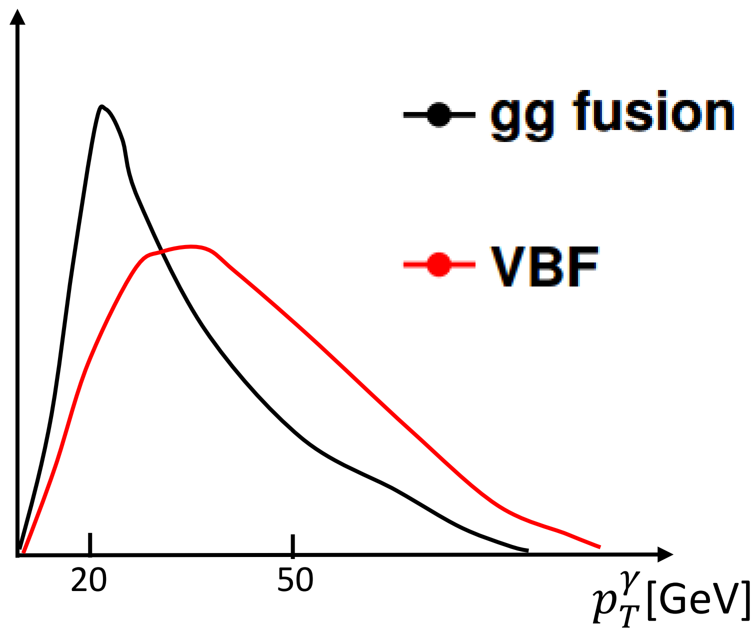
$H \to Z\gamma$ analysis strategy ATLAS-CONF-2013-009

- A mixture of $H \to \gamma\gamma$ and $H \to 4l$
- Apply unprescaled lepton trigger + data quality requirements.
- Select good candidates, suppressing background using kinematic and isolation requirements.
- Perform S+B fit and B-only fits to extract limits/signal strength:
  - Fit the observed distribution of a discriminating variable ($m_{ll\gamma}$ or Δm=$m_{ll\gamma} - m_{ll}$)
  - Input signal parameters (from signal MC + LHC x-section working group)
  - Estimate background on data (model with small bias)
  - Only 2 categories based on final states (e/μ).

Kinematic distribution of the final state particles

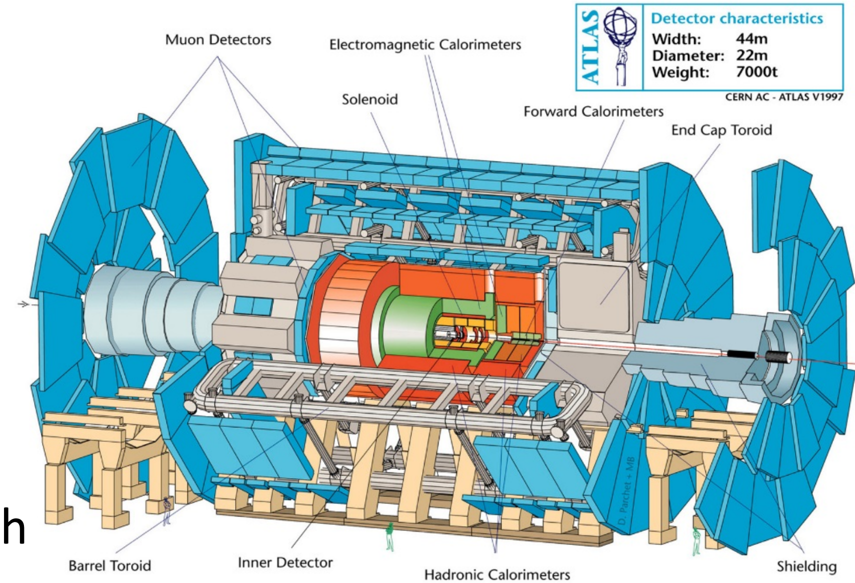
- The leading lepton is rather hard ($\langle p_T \rangle \sim$50GeV). The subleading lepton and the photon are softer, with long tail below 20GeV.
- VBF produces harder photons than gg fusion.





Muon reconstruction on ATLAS

- There are two types of muon algorithms on ATLAS
  - Staco μ: stand-alone, combined, segment tagged
  - Calo μ
- Staco μ:
  - Stand-alone μ uses only muon spectrometer (MS) tracks backtracked to the interaction point
  - Combined μ is reconstructed by combination of full MS tracks and inner detector (ID) tracks
  - Segment tagged μ is from ID tracks extrapolated to the MS and combined with segments reconstructed in MS stations
- Calo μ uses ID tracks extrapolated through the Calorimeters and combined with energy deposits



Triggers

- Use lowest threshold un-prescaled single lepton/di-lepton trigger.
- Trigger requirement is the logical OR of the various chains used.
- Efficiency relative to offline is >98% for $ee\gamma$, and >92% for $\mu\mu\gamma$
  - Calo/stand-alone muons not triggering + acceptance of muon trigger in barrel.

$H \to Z\gamma$ selections: leptons

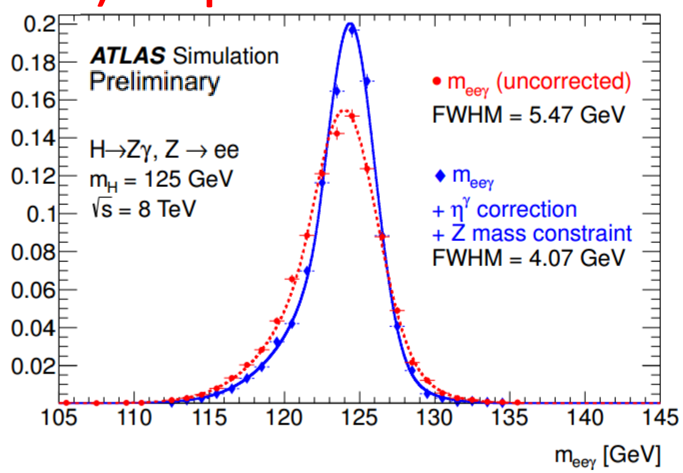
- Muons:
  - Staco (stand-alone + segment-tagged + combined) or calo, pass tight ID
  - p_T>10GeV (15 GeV for calo), $|\eta|$<2.7 (0.1 for calo)
  - Standard cuts on hits in pixel layers, semiconductor tracker, transition radiation tracker, muon system
  - Primary vertex requirement: $|d_0|$<1 mm, $|z_0|$<10 mm
  - Overlaps: remove duplicate muons reconstructed by different algos
- Electrons:
  - Reconstructed by cluster-only algo or cluster+ track algo
  - pass e/γ object quality (OQ) cuts, loosely identified and hit in B-layer
  - E_T>10GeV, $|\eta|$<2.47
  - Overlaps: remove e/μ overlaps (same inner detector track), remove 2nd electron overlapping with a higher-p_T electron
  - $|z_0|$<10 mm

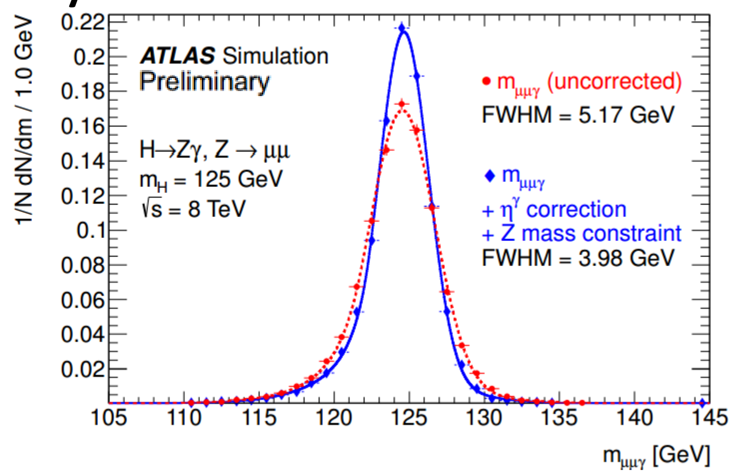
$H \rightarrow Z\gamma$ selections: photon and Z

- Photon:
  - Both unconverted and converted photons
  - E_T>15GeV, $|\eta|$<2.37 (remove 1.37<$|\eta|$<1.52), $\Delta R_{l\gamma}$>0.3
  - Pass e/γ OQ and photon cleaning requirements
  - Tightly identified
  - Calorimeter isolation in cone ΔR=0.4 < 4GeV
  - Keep highest E_T photon
- Z:
  - Two same flavor, opposite sign leptons
  - Keep pair with m_{ll} closest to m_z, requiring $m_{ll} > m_Z - 10$GeV
    - Suppress Drell-Yan and bkg from internal conversion in $H \rightarrow \gamma\gamma^*$
  - Isolation in calorimeter ($E_T^{\Delta R=0.2}/p_T$<0.15-0.3) and tracker ($p_T^{\Delta R=0.2}/p_T$<0.15)
  - d_0 significance < 3.5 (μ, except stand-alone) or < 6.5 (e)

Higgs invariant mass calculation

- m_{ll} and $m_{ll\gamma}$ recomputed using:
  - Photon direction (and 4-momentum) correction: origin=primary vertex
  - Kinematic fit of lepton 4-momenta using Z mass constraint:
    - Estimate the m_{ll} resolution based on measured momenta and covariance
    - Find most probable value of true m_{ll} based on measured one, assuming prior pdf = Breit-Wigner at Z pole and a Gaussian resolution function.
    - Refit lepton 4-momenta, minimizing the χ^2 of the fitted vs measured track parameters with the constraint m_{ll}=m_{ll}^{true}
- O(20%) improvement on 3-body invariant mass resolution



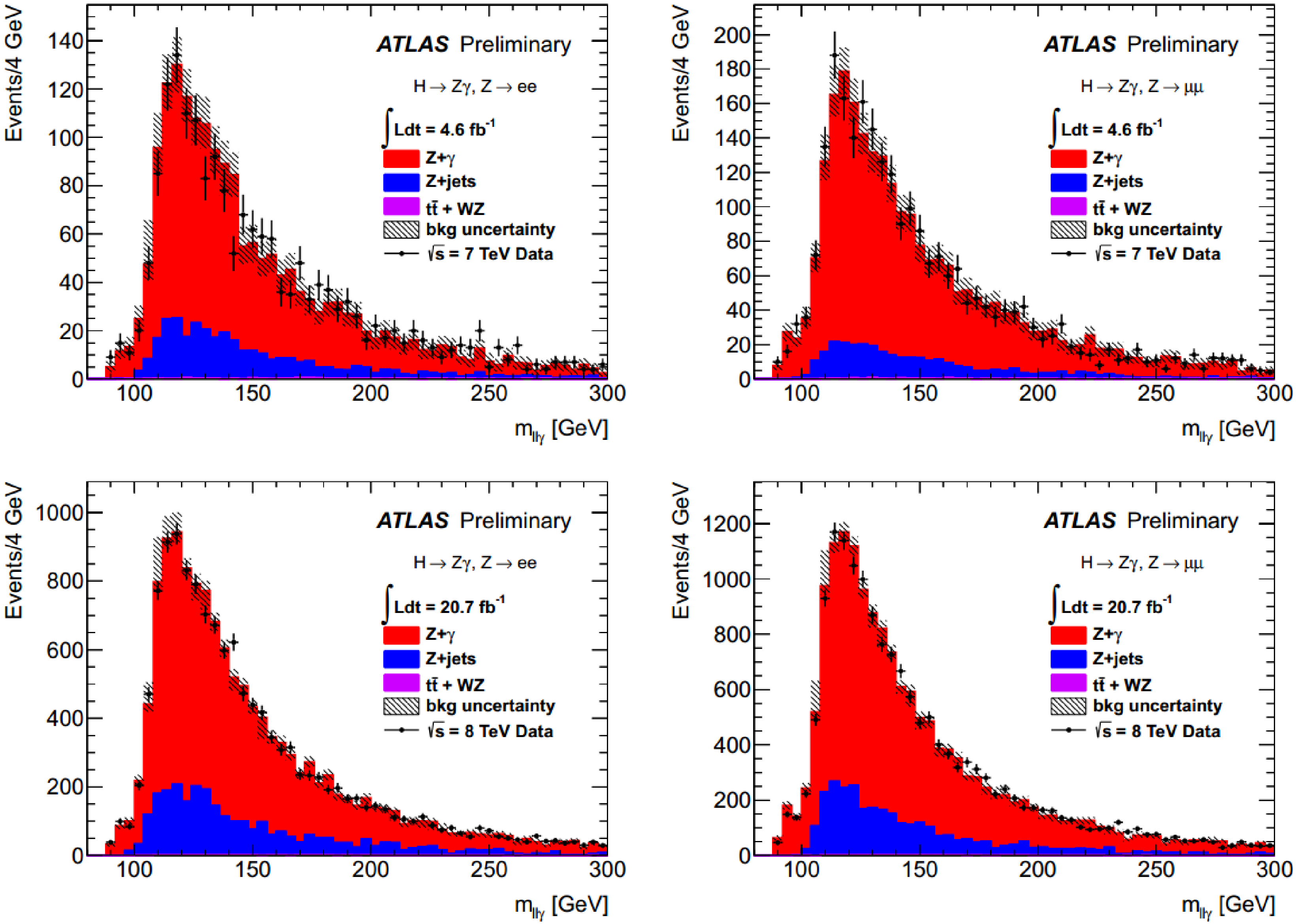


Data driven background decomposition

- Selected events in data (7/8TeV):

$\sqrt{s}$	$ee\gamma$	$\mu\mu\gamma$
7TeV	1927	2626
8TeV	13978	16678

- Data-driven bkg decomposition using the ABCD method to
  - Understand the composition of our selected sample
  - Normalize the background MCs and perform data/MC comparisons of various kinematic quantities
    - As a cross check, NOT used for limit extraction
- Use MCs to estimate $t\bar{t}$+WZ bkg
- Use photon ID vs isolation to discriminate Z+γ vs Z+jets in data after subtraction of $t\bar{t}$+WZ
- Different control regions yield similar Z+γ fractions (~82%)
- Systematic uncertainties included



- Turn-on in $m_{ll\gamma}$ around 115GeV from Z+γ and Z+jets (and minimum photon E_T)
- Small bump at 91 GeV = residual FSR Z+γ

Limit extraction

- 95% C.L. limit on production cross section × BF normalized to SM expectation
  - fit the observed distribution of a discriminating variable.
  - input signal model (expected yield + p.d.f.) from signal MC + LHC XS WG
  - choose bkg model that does not bias the fitted signal
  - fit S and S+B on data (no use of MC to fix the bkg p.d.f. parameters)
  - simultaneous fit to 4 categories: 2 lepton categories (e/μ) x 2 $\sqrt{s}$ categories (7/8 TeV)
  - systematic uncertainties parameters from final fit
- Two variables were considered: $m_{ll\gamma}$ or $\Delta m = m_{ll\gamma} - m_{ll}$. We chose Δm:
  - largely unaffected by lepton energy scale uncertainties
  - insensitive to possible $H \rightarrow ll\gamma$ background (could be O(5%) and peaking in $m_{ll\gamma}$)

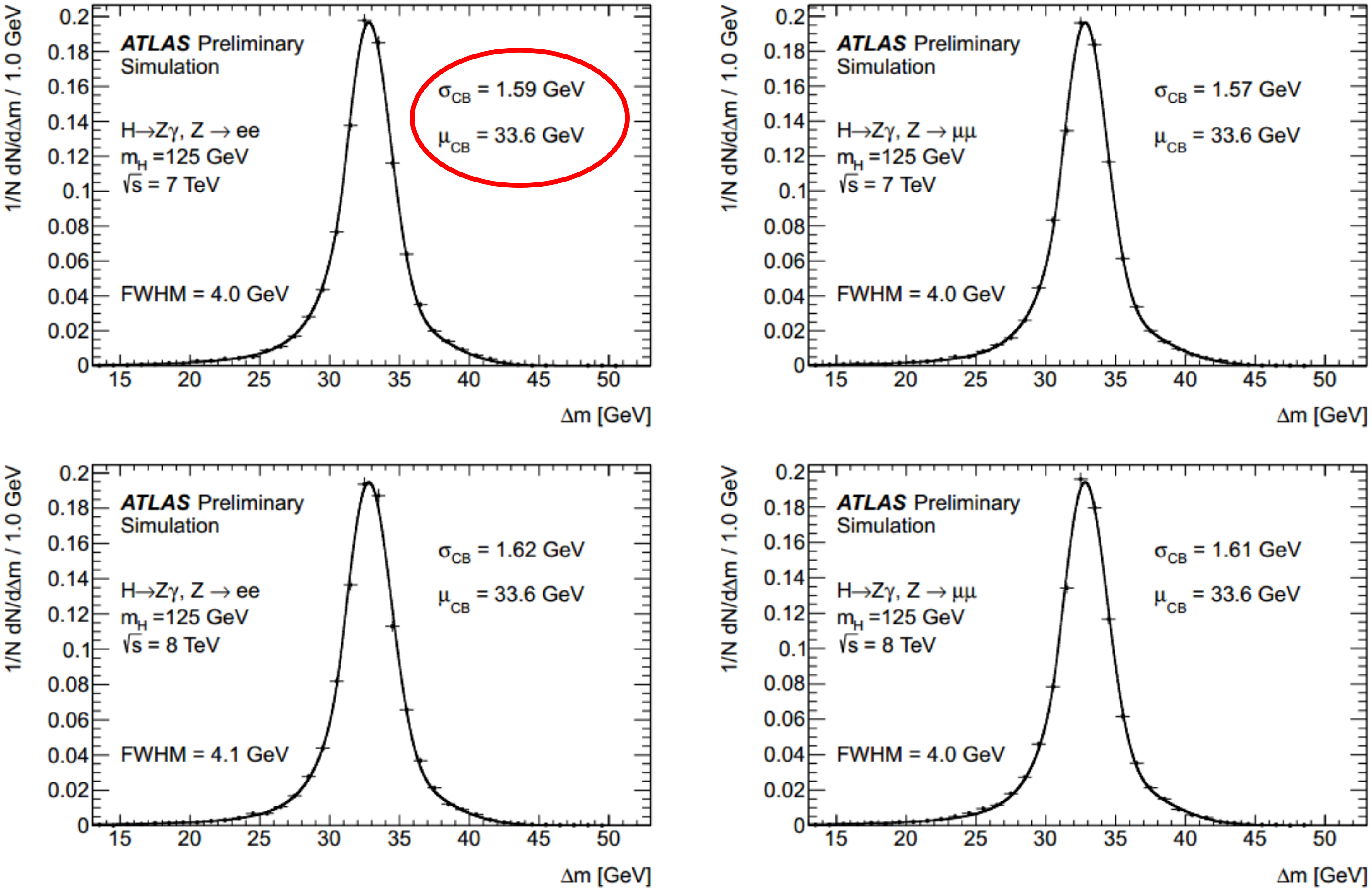
Signal model

- Expected signal yield $N_{i,l}(m_H) = \int \mathcal{L}dt \times \sigma_i(m_H) \times \mathcal{B}_{H\to Z\gamma}(m_H) \times \mathcal{B}_{Z\to ll} \times \epsilon_{i,l}(m_H)$
  - Higgs BF and x-section for production mode i from LHC XS WG
  - Efficiency $\epsilon_{i,l}(m_H)$ for production mode i and lepton flavor l from signal MC plus parabolic interpolation
    - Use average of ggF and VBF efficiencies for WH, ZH, ttH (no MC, 5% of total σ)
- Signal model: Crystal ball + outlier Gaussian, global fit of the parameters vs m_H (parameters correlated across mass points).

m_H	$Z\to ee$, 7 TeV		$Z\to\mu\mu$, 7 TeV		$Z\to ee$, 8 TeV		$Z\to\mu\mu$, 8 TeV	
[GeV]	ε [%]	S	ε [%]	S	ε [%]	S	ε [%]	S
120	17.1	0.6	22.5	0.7	21.3	4.0	25.8	4.9
125	20.4	0.9	26.5	1.1	24.6	5.9	29.7	7.2
130	23.0	1.1	29.9	1.5	27.3	7.7	32.8	9.3
135	25.1	1.3	32.4	1.7	29.4	9.0	35.1	10.7
140	26.6	1.4	34.1	1.8	30.9	9.5	36.6	11.3
145	27.5	1.4	35.0	1.8	31.7	9.2	37.3	10.8
150	27.9	1.2	35.1	1.5	32.0	8.1	37.2	9.4

Signal model (II)

- Projections of the signal resolution fit over the m_H=125 GeV MC:



Systematic uncertainties

- Theory: uncertainties on the x-section (scales and PDFs) and Higgs BF from Higgs@LHC x-section working group
- Luminosity: 1.8% (7 TeV), 3.6% (8 TeV)
- Trigger efficiency: vary trigger scale factor by 1σ
- Photon ID efficiency: vary efficiency scale factor for 7 TeV within their uncertainties and for 8TeV use absolute uncertainty $\pm$1.5% and $\pm$ 2.5% (E_T/η/conversion dependent)
- Lepton ID/reco efficiency: vary scale factors by 1σ
- e, γ calorimeter isolation: vary isolation of electrons and photons by data/MC difference ($\pm$100 MeV for topocluster-based, $\pm$ 500 MeV for standard EtCone)
- e, γ E_T:
  - vary smearing correction by 1σ
  - vary scale by 1σ (separate contribution from $Z \rightarrow ee$, pre-sampler energy scale, material uncertainty, and extra syst. at low pT)
- μ p_T: vary smearing corrections or nominal scale by 1σ
- kinematics: compare yields obtained with MCFM generator instead of Powheg generator, applying only the kinematic selection

Systematic uncertainties at 125 GeV

Theory:

$\sqrt{s}$	Systematic uncertainty (%)										
	$\sigma(gg \to H)$		σ(VBF)		$\sigma(WH)$		$\sigma(ZH)$		$\sigma(t\bar{t}H)$		$\mathscr{B}(H \to Z\gamma)$
	scale	PDF	scale	PDF	scale	PDF	scale	PDF	scale	PDF	
7 TeV	$^{+7.1}_{-7.8}$	$^{+7.6}_{-7.1}$	± 0.3	$^{+2.5}_{-2.1}$	$^{+0.2}_{-0.8}$	± 3.5	$^{+1.4}_{-1.6}$	± 3.5	$^{+3.3}_{-9.3}$	± 8.5	$^{+9.0}_{-8.8}$
8 TeV	$^{+7.3}_{-7.9}$	$^{+7.5}_{-6.9}$	± 0.2	$^{+2.6}_{-2.8}$	$^{+0.1}_{-0.6}$	± 3.4	$^{+1.5}_{-1.4}$	± 3.5	$^{+3.9}_{-9.3}$	± 7.8	$^{+9.0}_{-8.8}$

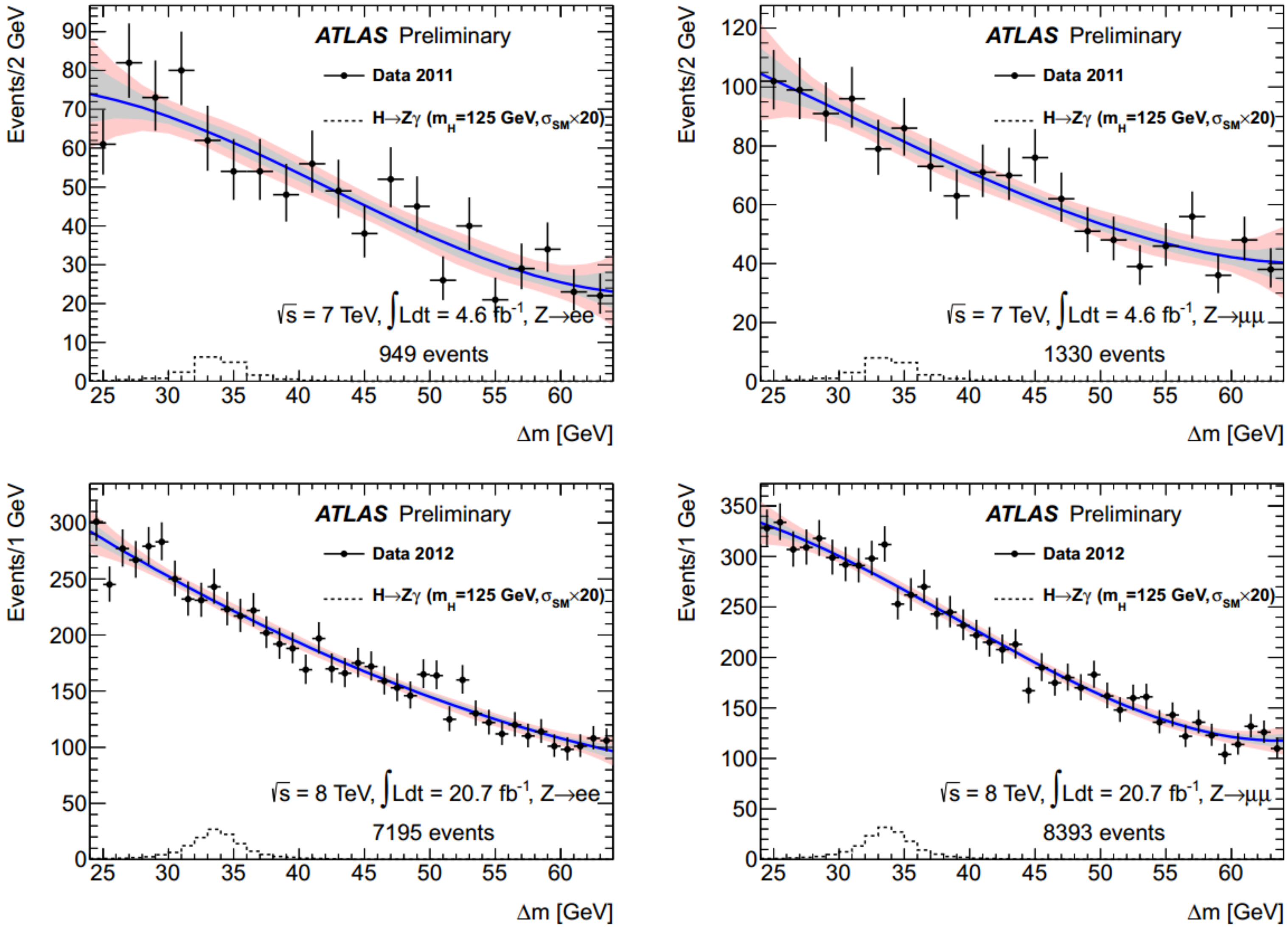
Experiment:

Systematic Uncertainty	$H \to Z(ee)\gamma(\%)$	$H \to Z(\mu\mu)\gamma(\%)$
Signal Yield		
Luminosity	3.6 (1.8)	3.6 (1.8)
Trigger efficiency	0.4 (0.2)	0.8 (0.7)
Acceptance of kinematic selection	4.0 (4.0)	4.0 (4.0)
γ identification efficiency	2.9 (2.8)	2.9 (2.9)
electron reconstruction and identification efficiency	2.7 (3.0)	
μ reconstruction and identification efficiency		0.6 (0.7)
e/γ energy scale	1.4 (0.3)	0.3 (0.2)
e/γ isolation	0.4 (0.3)	0.4 (0.2)
e/γ energy resolution	0.1 (0.2)	0.0 (0.0)
μ momentum scale		0.1 (0.1)
μ momentum resolution		0.0 (0.1)
Signal Δm resolution		
e/γ energy resolution	5.0 (5.0)	2.4 (2.4)
μ momentum resolution		0.0 (1.5)
Signal Δm peak position		
e/γ energy scale	0.17 (0.16) GeV	0.17 (0.16) GeV
μ momentum scale		negligible

Background model

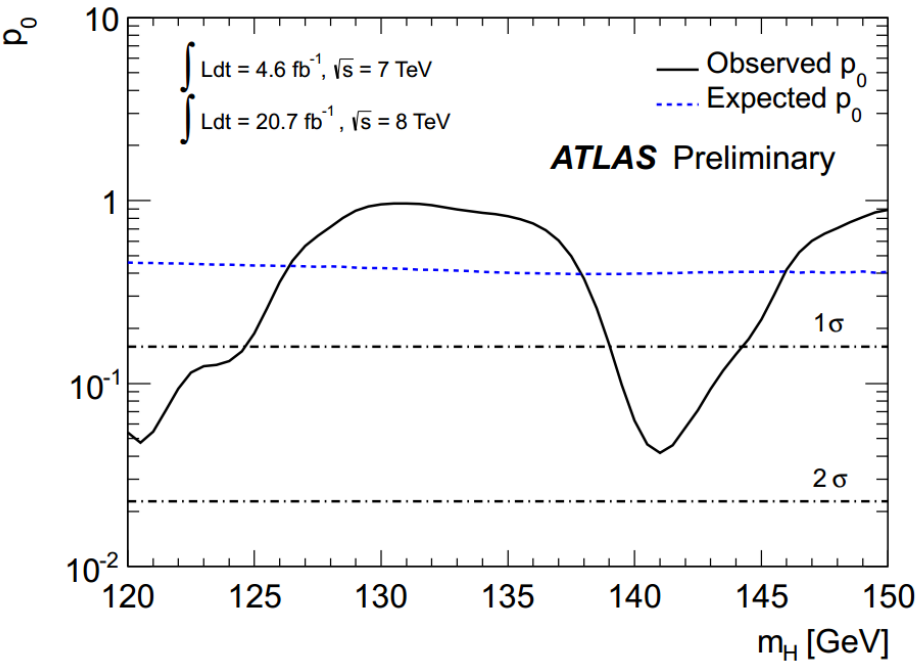
- The background is modeled with a smooth analytic p.d.f. that reproduces the data and the mixture of bkg MCs normalized to the data-driven bkg yields
- The parameters of the p.d.f. are fitted on data
- Choose a model + fit region which gives best sensitivity and does not introduce too large bias (spurious signal) on the fitted signal
  - either $< 20\% \times \sigma_N^{\mathrm{bkg}}$ or $10\% \times s_{\mathrm{MC}} \times$expected limit
- Evaluated with toys drawn from a high stat (10M, ~300fb-1) Sherpa Z+γ truth level MC sample, scaled to data
- Chosen fit range + model: $24 < \Delta m < 64$ GeV, 3rd degree polynomial
- Max spurious signal: ~3 @ 7 TeV, 14 @ 8 TeV

Bkg-only fits to data

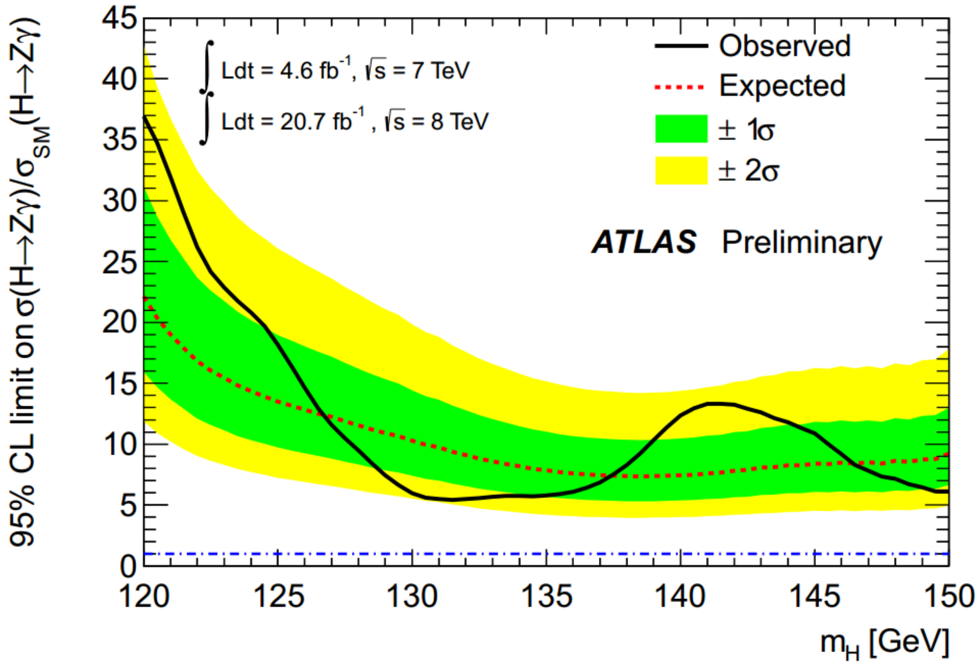


Results

Local Significance



95% CL limit



- Observed (expected) significance at 125 GeV: 0.89σ (0.14σ)
- Maximum significance at 141 GeV: 1.7σ
- Observed (expected) upper limit at 125 GeV: 18.2xSM (13.5xSM)

Conclusion

- A search for H→Zγ was performed with 4.6 fb-1 @ 7 TeV + 20.7 fb-1 @ 8 TeV
- We studied two possible discriminating variables for the final fit, $m_{ll\gamma}$ and Δm.
  - We decided to use Δm:
    - it is not sensitive to the H→μμ* contribution
    - it is less sensitive to lepton energy scale
- For 120<m_H<150 GeV:
  - expected limits are between 7.3 and 22.1 × SM
  - observed limits are between 5.4 and 36.9 × SM
- At 125GeV:
  - the observed (expected) limits are 18.2 × SM (13.5 × SM)
  - the observed (expected) local significance is 0.89σ (0.14σ)
- The largest local excess of 1.7σ significance is found at 141 GeV

Backup

Expected results at high luminosity

- At 14TeV, the S/B is basically the same with 7/8 TeV.
- The pile-up condition will result in
  - 18% event loss in trigger efficiency in $ee\gamma$
  - No change in $\mu\mu\gamma$ trigger efficiency
- Systematics is assumed to the same, with spurious signal scaled with luminosity.
- 300 fb^{-1}:
  - Limit $3.1 \times$ SM
  - Local significance 0.7σ
- 3000 fb^{-1}:
  - Limit $0.89 \times$ SM
  - Local significance 2.3σ
- The are improvement studies going on to
  - Improve the sensitivity
  - Improve the $ee\gamma$ trigger efficiency at high pile-up condition