Search for SM Higgs boson in the H → Zγ decay mode

Kun Liu
On behalf of the ATLAS collaboration

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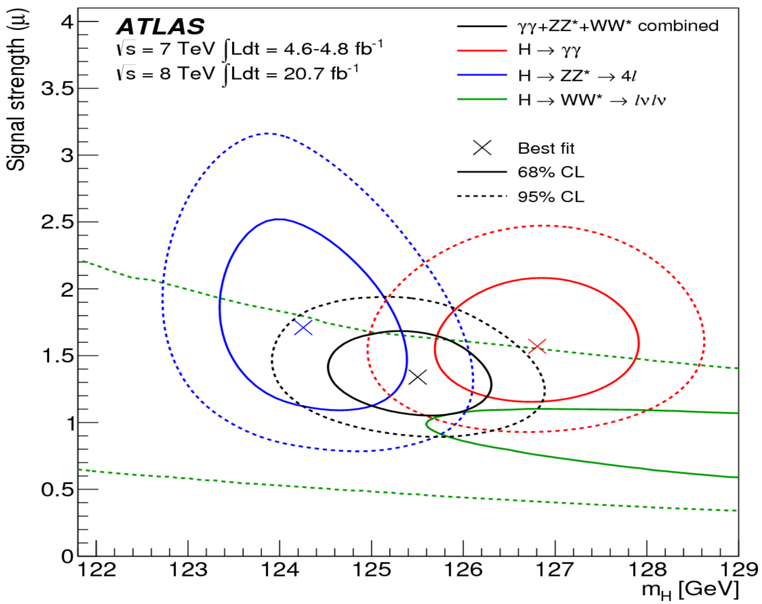
ISHP2013@Beijing

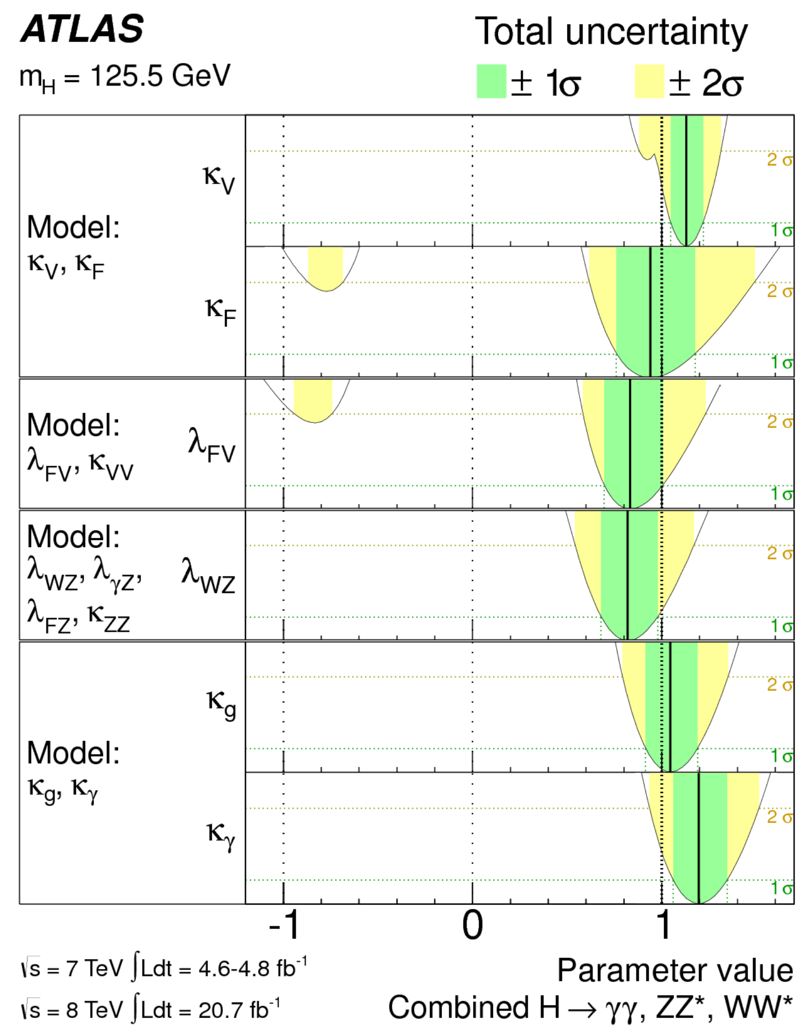
Outline

- **Motivation and overview**
- **ATLAS performance**
- **Data sets and event selection**
- **Data-driven background decomposition**
- **Limit extraction**
  - background modeling
  - signal parametrization
  - summary of systematic uncertainties
  - likelihood function
- **Summary**

Motivation

- Measurements of production properties and couplings in di-boson channels ($\gamma\gamma$, ZZ^*, WW^*) are consistent with expectations for a Standard Model Higgs boson.





Reference : arXiv:1307.1427v1

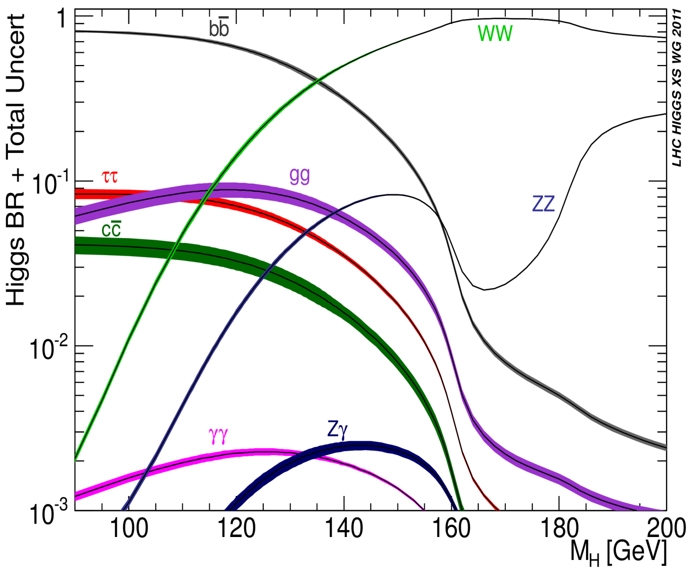
- Why $H \to Z\gamma$?

  -- decay rate can help determine whether the new boson is the SM Higgs boson

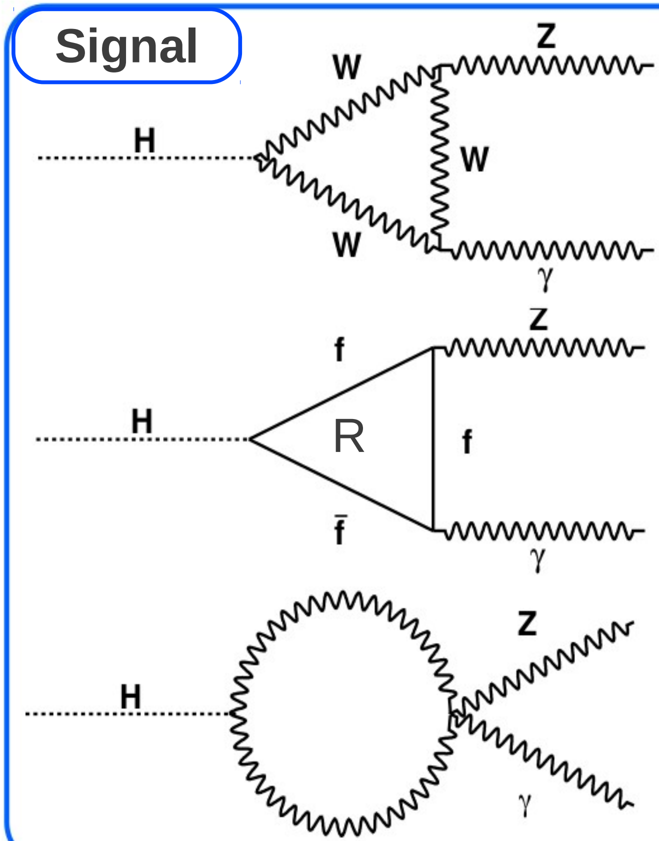
  -- measurement of $\Gamma_{Z\gamma}$ provides information on the underlying dynamics of the Higgs sector

  -- sensitive to potential heavier new particles in the loops

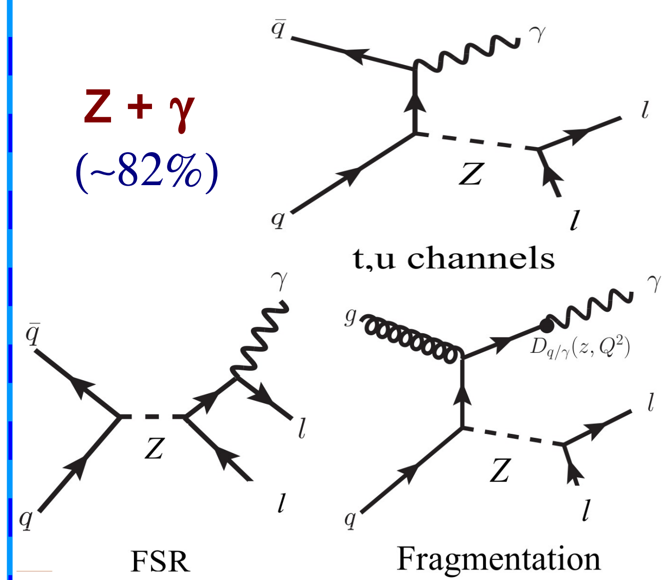
- In the Standard Model, H → Zγ proceeds mainly through loops (mostly W-loop).



Signal



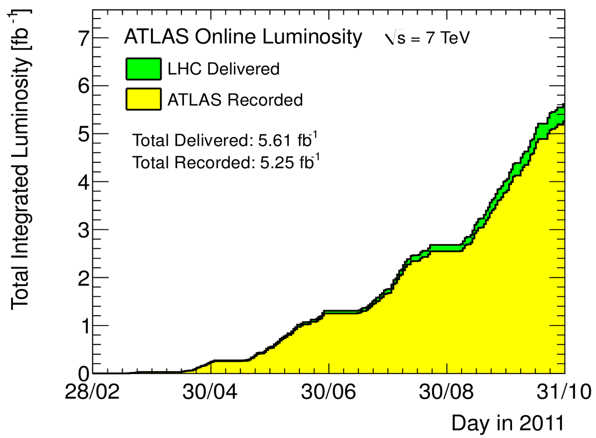
Background

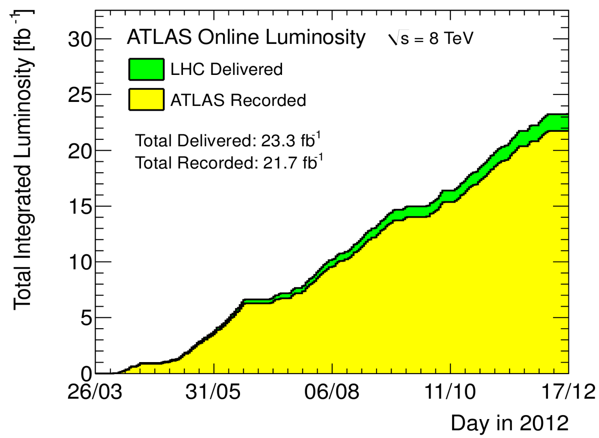


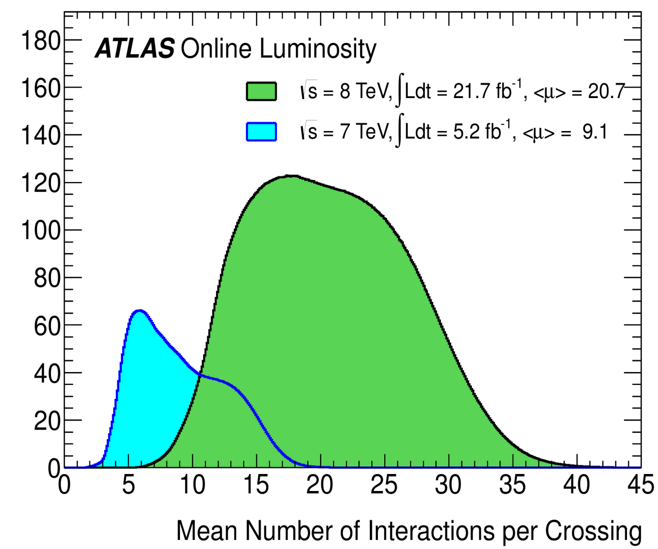
Z + jet (~17%)
Suppressed by photon identification & isolation cuts

- The BF(H → Zγ) is close to BF(H → γγ).
  -- signal yield is comparable to H→ZZ*→llll, after accounting for BF(Z→ll) which is ~6.7%
  -- background is as much as in H→γγ analysis
- After selection, ~15 events are expected in full 2011+2012 data sets given m_H at 125 GeV.

- The ATLAS detector collected 5.25 fb^{-1} data in 2011 and 21.7 fb^{-1} data in 2012.

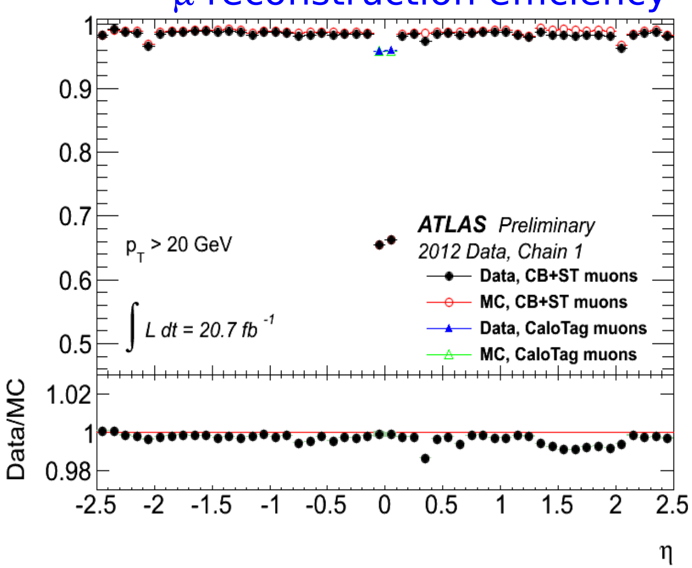




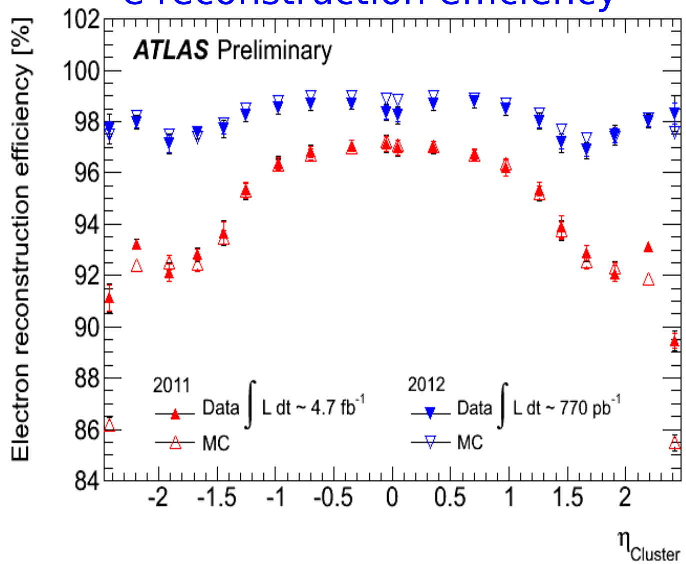


- Very good performance :
  - -- high object reconstruction efficiency
  - -- stable relative energy scale vs pile up

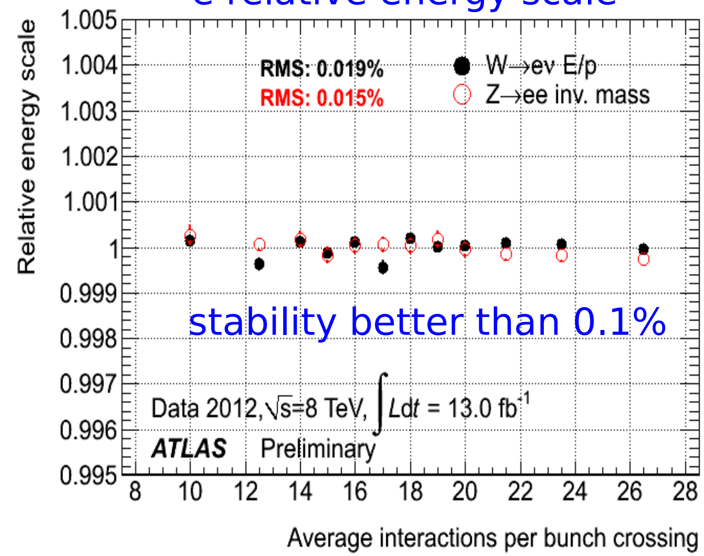
μ reconstruction efficiency



e reconstruction efficiency



e relative energy scale



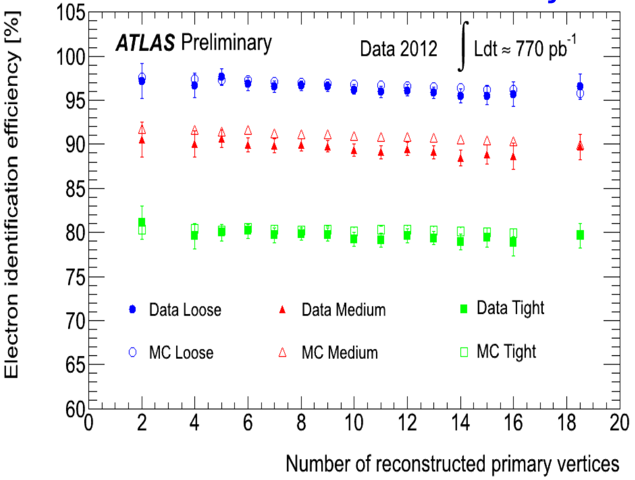
Data sets and event selection

- Data sets : full 2011+2012 data, which is 4.6+20.7 fb^{-1} triggered by lepton triggers.

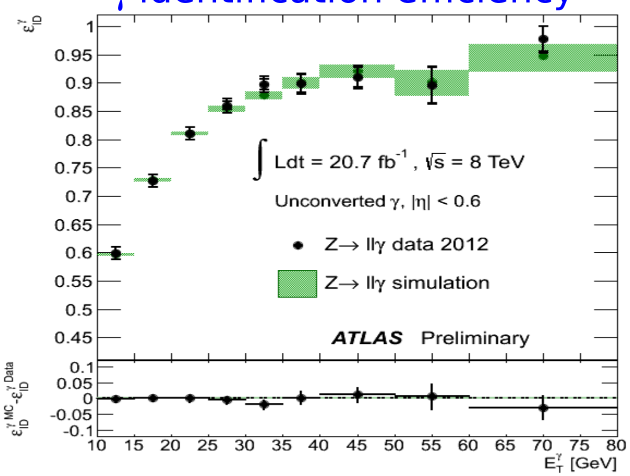
- Signal and background simulation
  -- signal : Powheg+Pythia8 for ggF and VBF processes for Higgs mass between 115 and 150 GeV in steps of 5 GeV @ 7TeV and 8TeV
  -- background : Z+γ (Sherpa, up to 3 jets), Z+jets(Alpgen/Sherpa, up to 5 jets), ttbar(MC@NLO), WZ(Powheg+Pythia or Sherpa)

- Event selection (details in backup)
  -- good data quality
  -- single-/di-lepton(e,μ) triggers
  -- at least one reconstructed vertex with >=3 tracks
  -- lepton E_T > 10 GeV and $|\eta|$ < 2.47 (2.7 for muon)
  -- isolated lepton passing identification criteria
  -- photon E_T > 15 GeV and $|\eta|$ < 2.37
  -- isolated photon passing tight identification criteria
  -- two same flavor and opposite sign leptons with m_{ll} > 81.18GeV

e identification efficiency



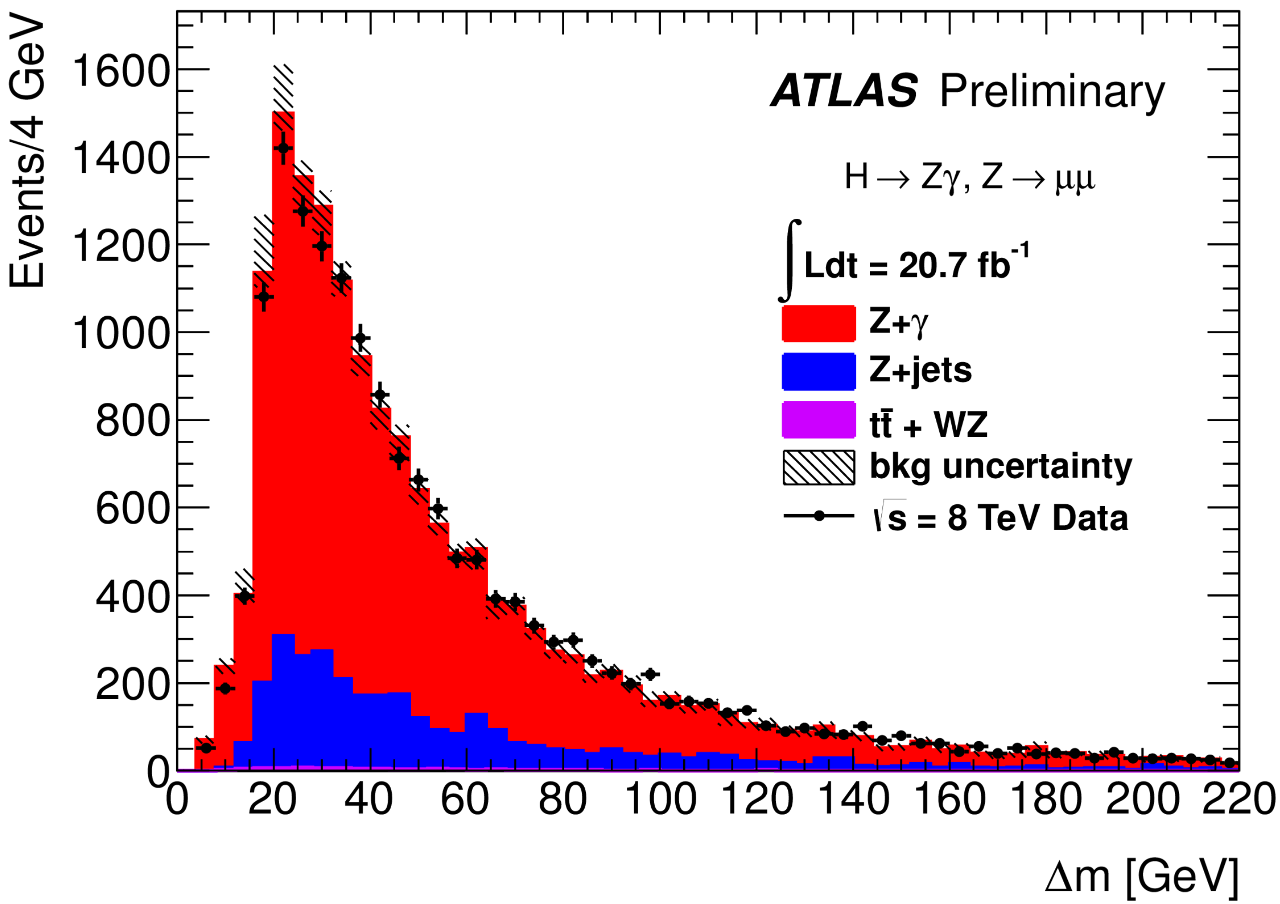
γ identification efficiency



Background composition

- Data-driven method : evaluate the composition of selected events, using sidebands in photon isolation and identification variables.

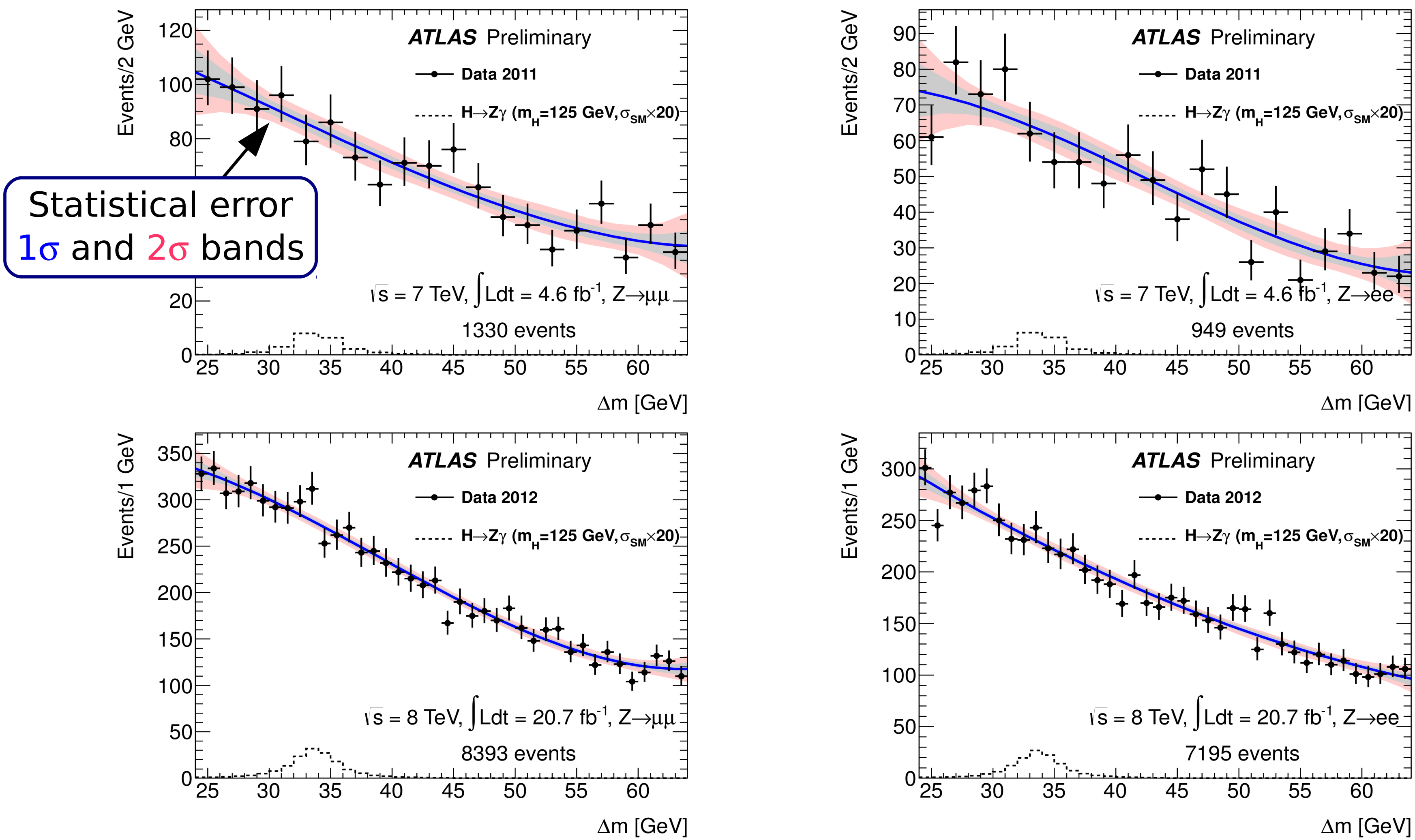
- Background composition in Δm (definition: $\Delta m = m_{ll\gamma} - m_{ll}$).



Background modeling

- Choice of fit function and fit range so that potential bias (spurious signal) is limited (to be < 20% of fitted signal uncertainty) while retaining good statistical power.

- Fit Δm distribution in [24, 64] GeV on data with 3rd degree polynomial function.



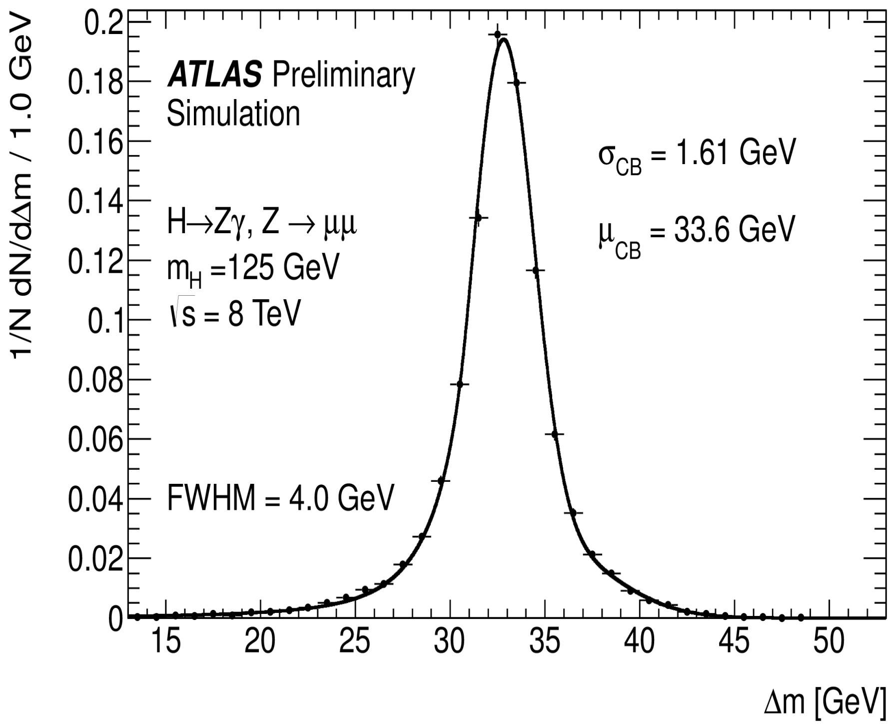
Signal parametrization

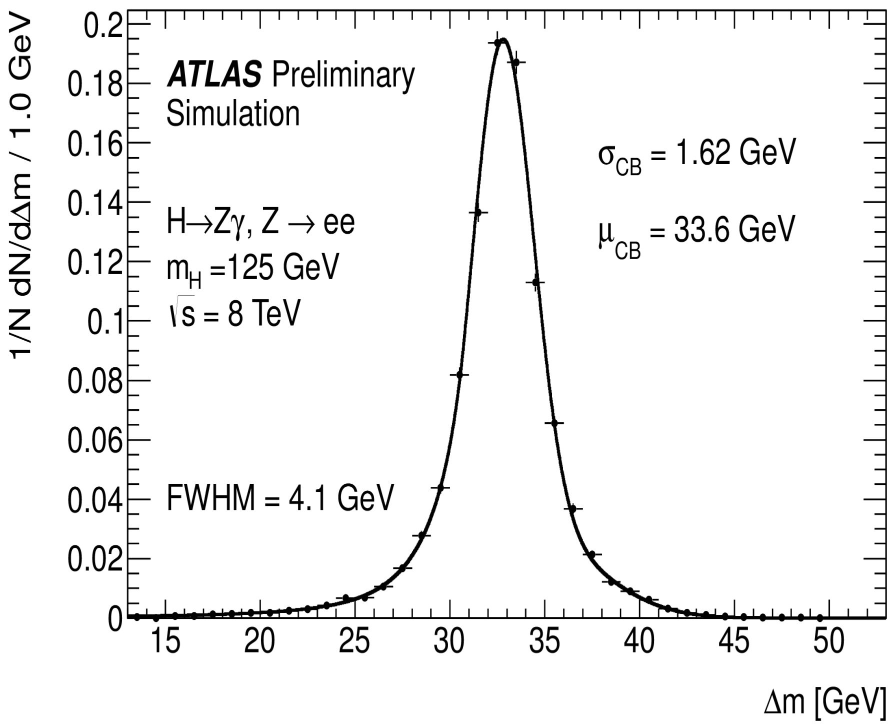
- Expected signal yields : $N_{i,\ell}(m_H) = \int \mathscr{L}dt \times \sigma_i(m_H) \times \mathscr{B}_{H\to Z\gamma}(m_H) \times \mathscr{B}_{Z\to\ell\ell} \times \varepsilon_{i,\ell}(m_H)$

  -- Higgs cross section and branching fraction are taken from theory.

  -- Efficiency of full selection is evaluated in signal simulation and with parabolic interpolation versus m_H for ggF and VBF processes. The average efficiency of ggF and VBF is used for VH and ttH.

- Signal model : Crystal Ball + Gaussian. The parameters are determined on signal simulation





Systematic uncertainties @ m_H = 125 GeV

- Theory uncertainties

$\sqrt{s}$	Systematic uncertainty (%)										
	$\sigma(gg \to H)$		$\sigma(\text{VBF})$		$\sigma(WH)$		$\sigma(ZH)$		$\sigma(t\bar{t}H)$		$B(H \to Z\gamma)$
	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	$^{+9.0}_{-8.8}$

- Experimental uncertainties

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 (2.9)	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	0.2 (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	0.2 (0.2) GeV	0.2 (0.2) GeV
μ momentum scale		negligible

- Bias from background modeling : the expected biases on signal yields are ~ 3.3 events for 2012 categories and ~ 1.2 events for 2011 categories.

Limit extraction - Likelihood function

- Likelihood-based statistical test :
  - --95% C.L. limit on production cross section times BF normalized to SM expectation
  - --p-values : compatibility of data with background-only hypothesis

- Unbinned likelihood :
  - -- discriminating variable(denoted as x) : $\Delta m = m_{ll\gamma} - m_{ll}$
  - -- 2 categories based on lepton flavor @ $\sqrt{s}$ = 7 TeV or 8 TeV

Profile Likelihood ratio is used: $\lambda(\mu) = \dfrac{L(\mu, \hat{\hat{\boldsymbol{\theta}}})}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}$ with $\mu = \dfrac{N_{\text{signal}}}{N_{\text{signal}}^{SM}}$

Full Likelihood function : $$L\left(\mu, \theta = \bigcup_{c=1}^{n_{cat}} \theta_c | x = \bigcup x_c\right) = \prod_{c=1}^{n_{cat}} L_c(\mu, \theta_c | x_c)$$

in each category : $$L_c(\mu, \theta_c | x_c) = e^{-N'_c} N_c'^{N_c} \prod_{k=1}^{N_c} \mathscr{L}_c(x_k | \mu, \theta_c)$$

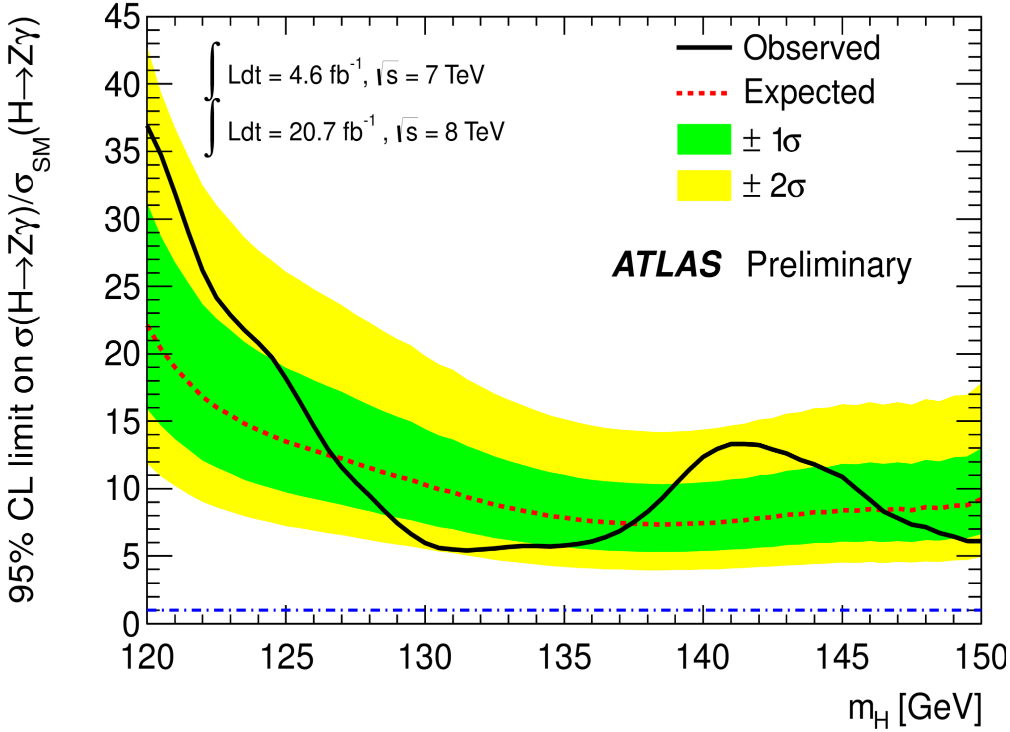
in each event :

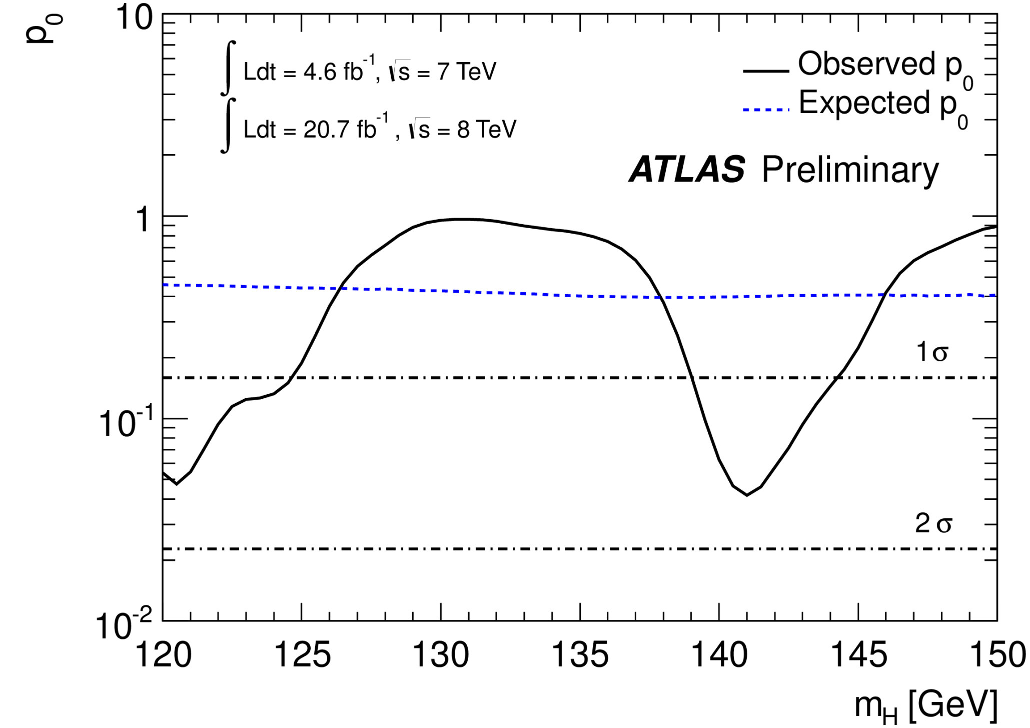
$$\mathscr{L}_c(x|\mu,\theta_c) = \frac{N_{\text{signal},c}(\mu, \theta_c^{norm})}{N_{\text{signal},c} + N_{\text{bkg},c}} \underline{f_{\text{signal},c}(x|\theta_c^{shape})} + \frac{N_{\text{bkg},c}}{N_{\text{signal},c} + N_{\text{bkg},c}} \underline{f_{\text{bkg},c}(x|\theta_c^{bkg})}$$

The nuisance parameters(θ) are constrained either with a Log-normal distribution (for those affecting expected signal yields) or a Gaussian distribution.

95% C. L. limit and p-value

- Total number of nuisance parameters : 39





- Observed (expected) exclusion limit range between 5.4 – 37 (7.3 - 22) times SM.
- Observed (expected) upper limit @ 125GeV : 18.2 x SM (13.5 x SM)
- Observed (expected) significance @ 125 GeV : 0.89σ (0.14σ)
- Maximum upward fluctuation is at 141 GeV : 1.7σ

Summary

- $H \rightarrow Z\gamma$ is a rare decay, which can provide important information about the nature of the Higgs sector.

- First look for $H \rightarrow Z\gamma$ performed with run I data collected by ATLAS.

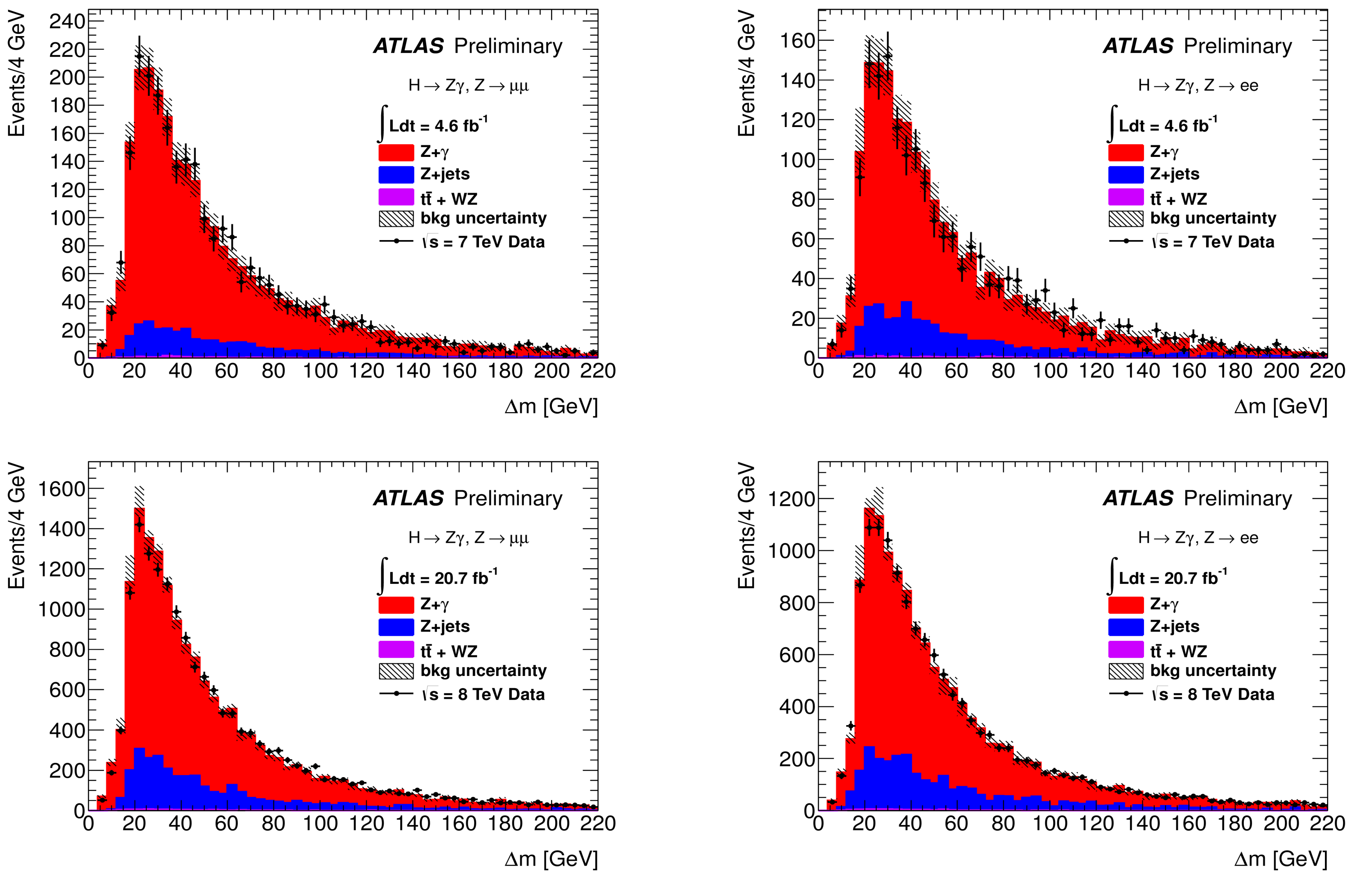
- Set 95% production cross section times branching fraction exclusion on Higgs mass in the range [120, 150] GeV
  -- expected limits vary between 7.3 and 22.1 x SM
  -- observed limits vary between 5.4 and 36.9 x SM

- At 125 GeV Higgs mass :
  -- observed (expected) limit is 18.2 x SM (13.5 x SM)

Backup

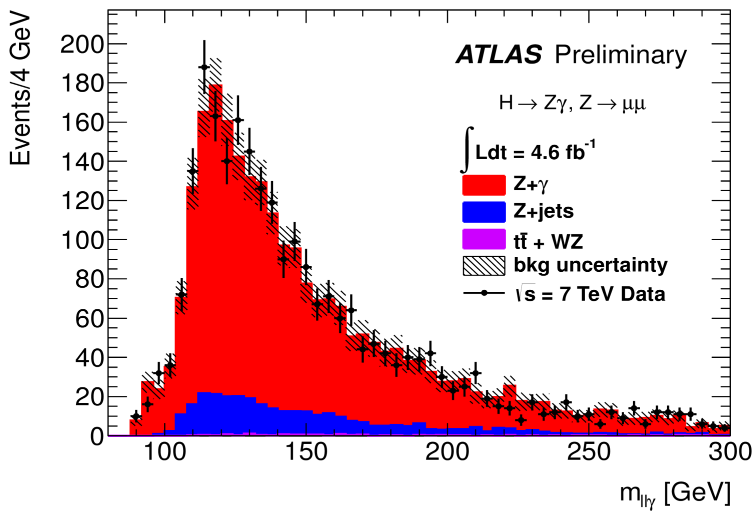
Background composition

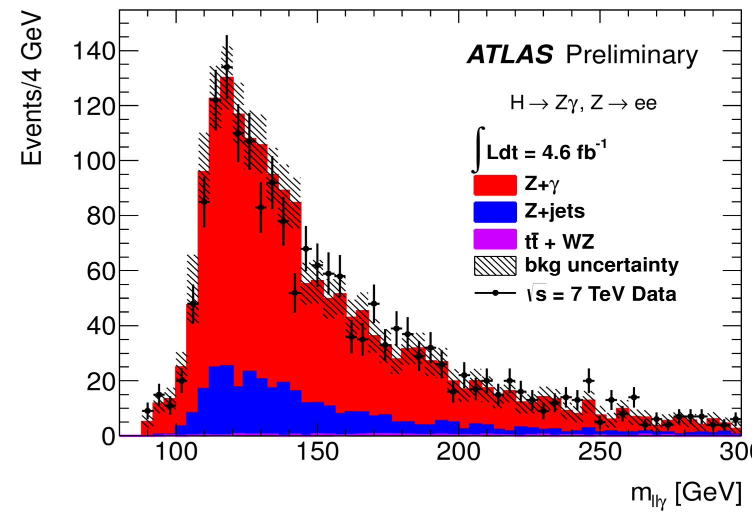
- Data-driven method : evaluate the composition of selected events, using sidebands in photon isolation and identification variables.
- Background composition in Δm ($m_{ll\gamma} - m_{ll}$).

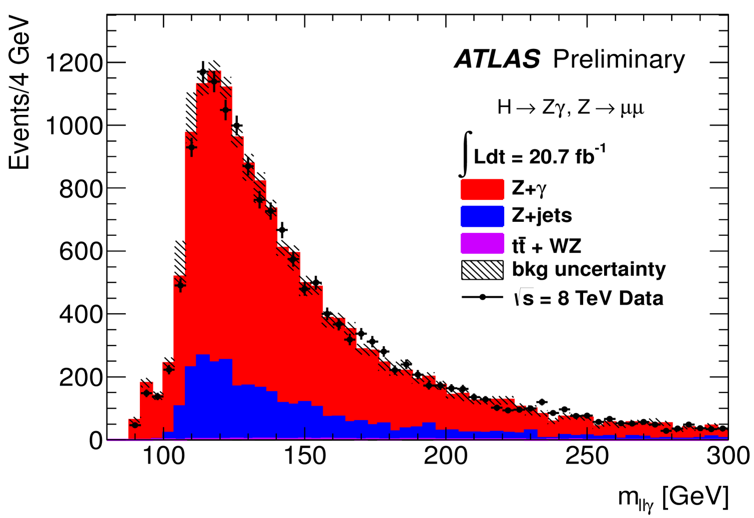


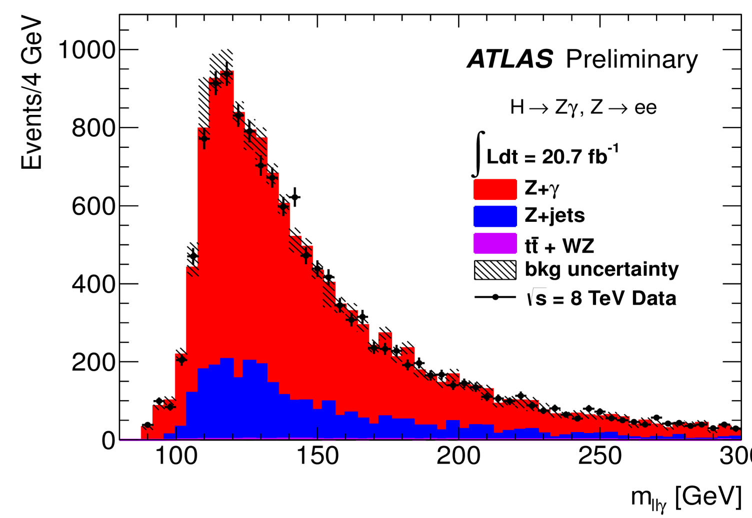
Background composition

- Data-driven method : evaluate the composition of selected events, using sidebands in photon isolation and identification variables.
- Background composition in $m_{ll\gamma}$.









Event selection -- Triggers

- Trigger : use lowest threshold and unprescaled single-lepton or di-lepton triggers

Year/period	Electron triggers	Muon triggers
2011 B-I	e20_medium	mu18_MG
	2e12_medium	2mu10_loose
2011 J	e20_medium	mu18_MG_medium
	2e12_medium	2mu10_loose
2011 K	e22_medium	mu18_MG_medium
	2e12T_medium	2mu10_loose
2011 L-M	e22vh_medium1	mu18_MG_medium
	2e12Tvh_medium	2mu10_loose
	e24vhi_medium1	mu24i_tight
2012 A-E	e60_medium1	mu36_tight
	2e12Tvh_loose1	mu18_tight_mu8_EFFS

- Trigger requirement is the logical OR of the various used chains
- Trigger efficiency w.r.t to offline selected signal event is ~99% for eeγ, while ~92% for $\mu\mu\gamma$ (the inefficiency is mainly caused by the MS acceptance)

Event selection -- Leptons

- Muon : reconstructed with four algorithms, are named stand-alone muons , segment-tagged muons, combined muons and calorimeter-tagged muons

  -- P_T > 10GeV (15 GeV for calo), $|\eta|$ < 2.7 (0.1 for calo)

  -- passing tight identification and cuts on hits in B-layer, pixel, SCT, TRT and MS

Table 3: List of Inner Detector hit requirements for the muon tracks reconstructed in the ID.

2012	
ID Si hit requirement	expectBLayerHit=false or numberOfBLayerHits ≥ 1
	No. of pixel hits + No. of crossed dead pixel sensors > 0
	No. of SCT hits + No. of crossed dead SCT sensors > 4
	No. of pixel holes + No. of SCT holes < 3
TRT hit requirements: $0.1 < \lvert\eta\rvert \leq 1.9$	Hits + Outliers > 5 & $\frac{\text{Outliers}}{\text{Hits+outliers}} < 0.9$
TRT hit requirements: $\lvert\eta\rvert < 0.1$ or $\lvert\eta\rvert \geq 1.9$	if (Hits + Outliers > 5): $\frac{\text{Outliers}}{\text{Hits+outliers}} < 0.9$
2011	
ID Si hit requirement	expectBLayerHit=false or numberOfBLayerHits ≥ 1
	No. of pixel hits + No. of crossed dead pixel sensors > 1
	No. of SCT hits + No. of crossed dead SCT sensors > 5
	No. of pixel holes + No. of SCT holes < 3
TRT hit requirements: $\lvert\eta\rvert < 1.9$	Hits + Outliers > 5 & $\frac{\text{Outliers}}{\text{Hits+outliers}} < 0.9$
TRT hit requirements: $\lvert\eta\rvert \geq 1.9$	if (Hits + Outliers > 5): $\frac{\text{Outliers}}{\text{Hits+outliers}} < 0.9$

  -- impact parameter: $|d_0|$< 1 mm, $|z_0|$< 10 mm

  -- overlaps : remove duplicate muons reconstructed by different algorithms.

- Electron : reconstructed electron candidate passing object quality

  -- E_T > 10 GeV , $|\eta|$ < 2.47

  -- have B-layer hit

  -- passing Loose++ criteria based on ID track and calorimeter shower shape

  -- $|z_0|$ < 10 mm

  -- overlap1: remove the electron overlapping with higher E_T electron

  -- overlap2: remove the electron if its track is within a ΔR < 0.02 with a muon track

Event selection -- photon and Z

- Photon : reconstructed photon candidate passing object quality
  - -- E_T > 15GeV , $|\eta|$ < 2.37 and $\Delta R_{l\gamma}$ > 0.3
  - -- passing tight criteria based on calorimeter shower shape
  - -- the calorimeter isolation(with topo-cluster) in cone ΔR= 0.4 to be less than 4GeV
  - -- the highest E_T photon candidate is kept after above selection

- Z event :
  - -- two same flavor and opposite sign leptons
  - -- keep pair with m_{ll} closest to m_Z with m_{ll} > 81.18GeV (suppress Drell-Yan and internal photon conversion in $H \rightarrow \gamma\gamma^*$)
  - -- match reconstructed leptons to trigger objects
  - -- requirements on calorimeter isolation and track isolation on leptons
  - -- d_0 significance < 3.5 for μ (< 6.5 for e)

Background modeling bias – spurious signal

Table 20: Expected spurious signal (absolute bias on the fitted number of signal events) for fits with 3rd-order polynomials to $24 < \Delta m < 64$ GeV in the four categories $(\ell, \sqrt{s})$ under study for m_H between 120 and 150 GeV.

m_H (GeV)	$\ell = \mu, \sqrt{s} = 8$ TeV	$\ell = e, \sqrt{s} = 8$ TeV	$\ell = \mu, \sqrt{s} = 7$ TeV	$\ell = e, \sqrt{s} = 7$ TeV
121	2.11742	3.47156	-0.305176	1.02577
122	1.49458	4.49538	0.0163173	0.307553
123	3.0823	2.66529	0.425882	1.52248
124	1.10536	4.59363	0.354688	1.51922
125	3.20042	3.36796	1.16495	1.20356
126	4.71641	3.90673	1.98447	0.818481
127	4.4249	4.25424	1.48186	1.01617
128	6.23069	4.93779	1.07632	0.27291
129	5.40008	4.69632	1.53341	0.740099
130	2.96492	4.67904	1.91411	0.875514
131	0.114088	0.263762	0.287487	0.591758
132	-5.40517	-2.74718	-2.38274	-0.17064
133	-8.26066	-4.43141	-2.65924	-0.98404
134	-9.60818	-8.28476	-2.91282	-1.35116
135	-7.31139	-9.07495	-1.80044	-1.59043
136	-5.13223	-4.93037	-1.00756	-1.82586
137	-3.55158	-3.24469	-0.48296	-1.51853
138	-1.20153	-4.13769	-0.690978	-1.67816
139	-1.29695	-2.9674	-0.2305	-1.70234
140	-0.859395	-2.15366	0.0647401	-1.07747
141	0.623237	-0.902886	0.789926	-0.877349
142	3.47333	2.35946	0.0671999	0.463292
143	7.3771	4.61814	0.531757	1.52484
144	10.346	4.11253	1.45929	2.89686
145	6.94188	3.68588	1.06862	2.64858
146	2.94211	1.50957	-0.044132	0.790653
147	-0.437292	0.876495	-0.755845	0.0704216
148	-1.82342	2.05608	-0.290637	0.553969
149	0.472818	3.78963	-0.741941	0.593163
150	1.96182	5.91136	0.728001	2.21437