Search for rare decays of the Higgs boson at ATLAS

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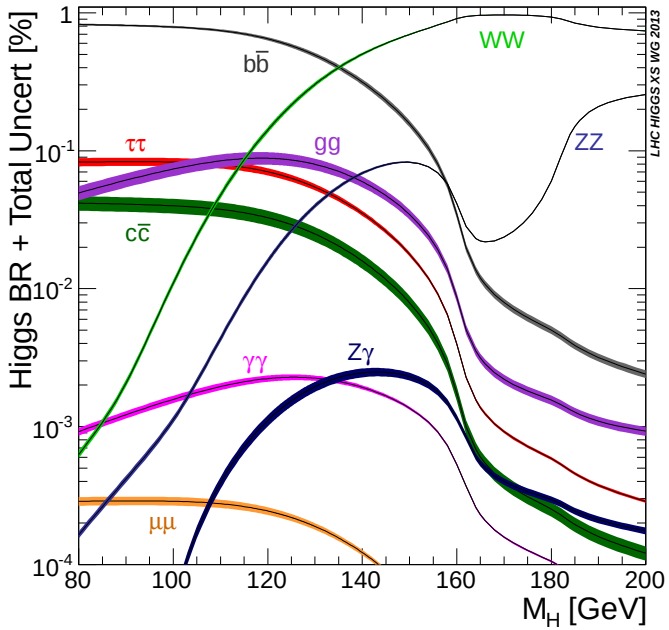
Motivation

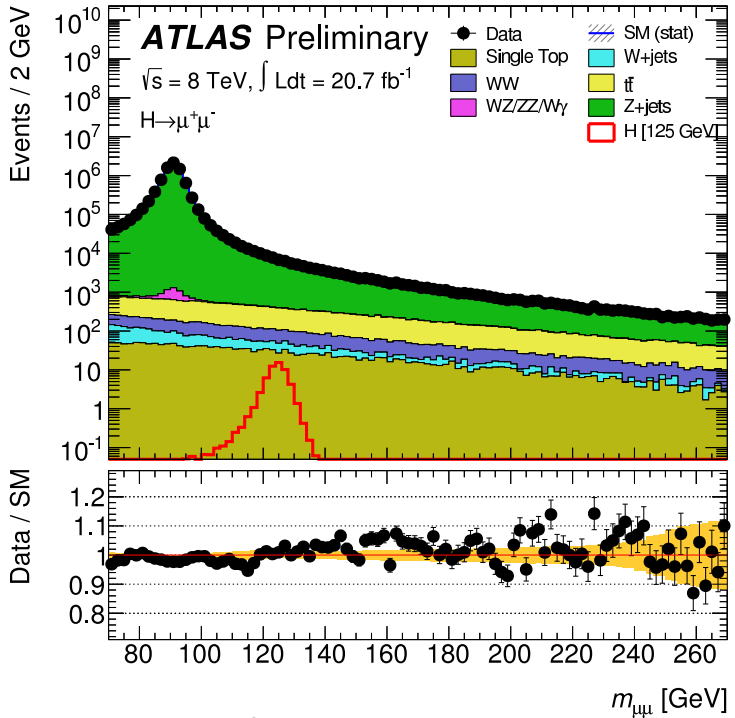
- Discovery of the new boson marks a turning point in particle physics
- Important to measure its properties in all possible decay modes
- Rare decays are sensitive to BSM physics
- This talk covers 3 analysis channels:
  - $H \to \mu^+\mu^-$
  - $H \to Z\gamma$
  - $ZH \to l^+l^- + \text{inv.}$



Higgs Branching Ratios

$H \to \mu^+\mu^-$ Event Selection

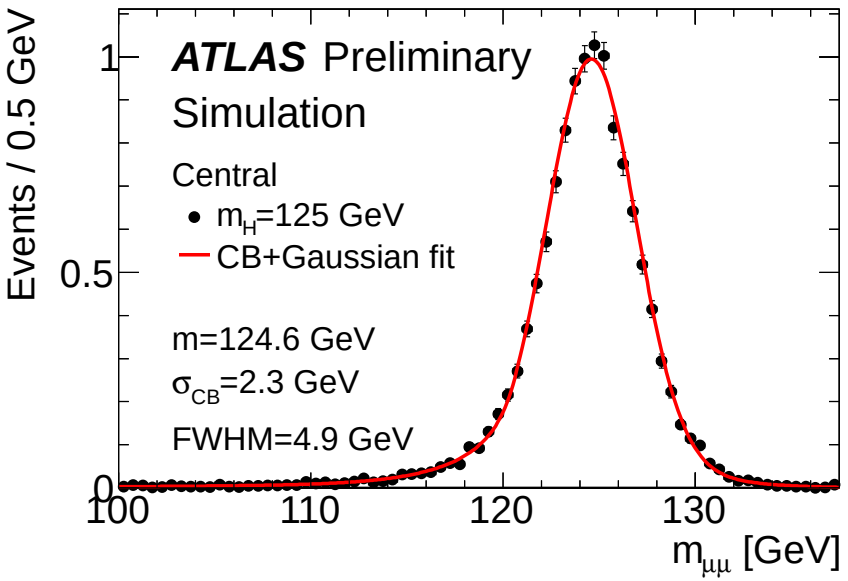
- using 2012 data (20.7 fb^{-1})
- single muon trigger
- select 2 opp. charged, isolated muons
- $p_{T,\mu_1} > 25$ GeV, $p_{T,\mu_2} > 15$ GeV
- $|\eta_\mu| < 2.5$
- $p_T^{ll} > 15$ GeV
- control region: $p_T^{ll} < 15$ GeV
- resolution categories:
  - $|\eta_{1,2}| < 1$: central
  - rest: non-central



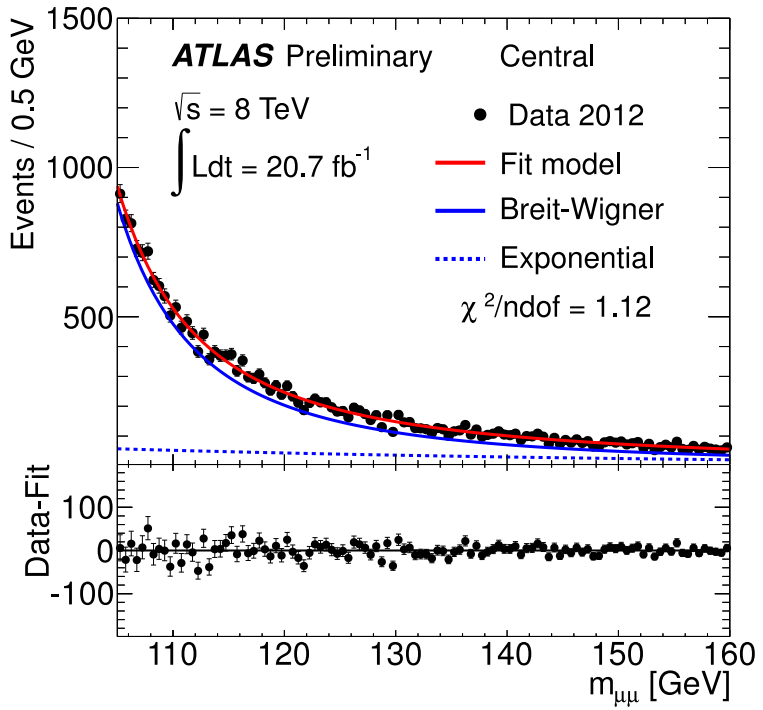
$m_{\mu\mu}$ after analysis selection

Analysis Strategy

- fit $m_{\mu\mu}$ spectrum in signal window of 110-160 GeV
- signal model: Crystal Ball + Gaussian p.d.f.
- background model: Breit-Wigner + exponential p.d.f.



signal model fit to signal MC



background model fit to Data CR

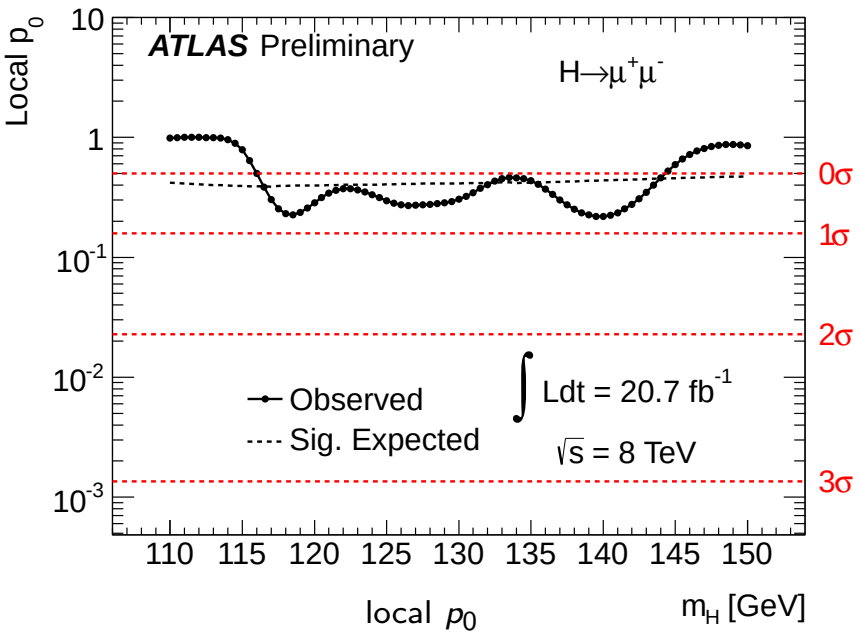
- fit performance tested on MC and data control region

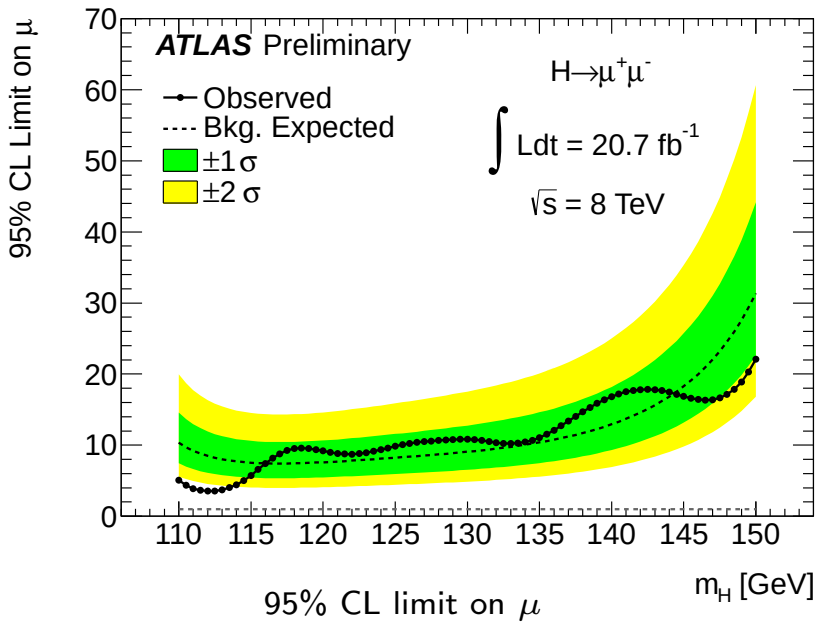
Major systematic uncertainties

experimental		**theoretical**	
Luminosity	3.6%	$\sigma(gg \to H)$	$14.1 - 15.3\%$
selection efficiency	$0.3 - 1.0\%$	$BR(H \to \mu\mu)$	$3.1 - 7.0\%$

$H \to \mu^+\mu^-$ Results

- no significant excess observed
- observed limit on signal strength μ for $m_H = 125$ GeV: 9.8 $\times$ SM

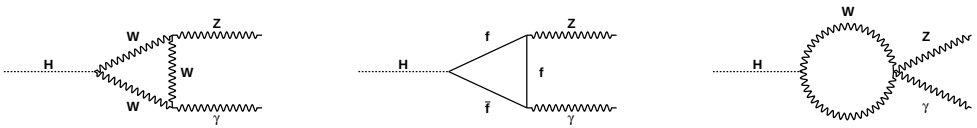




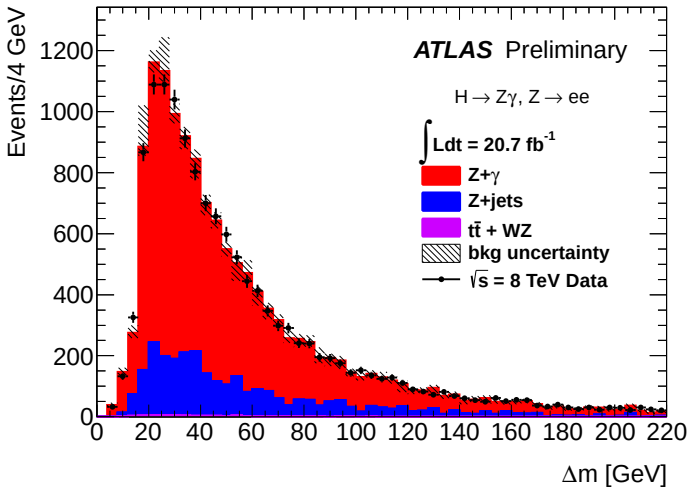
Outlook:

- combination of 2011 and 2012 data

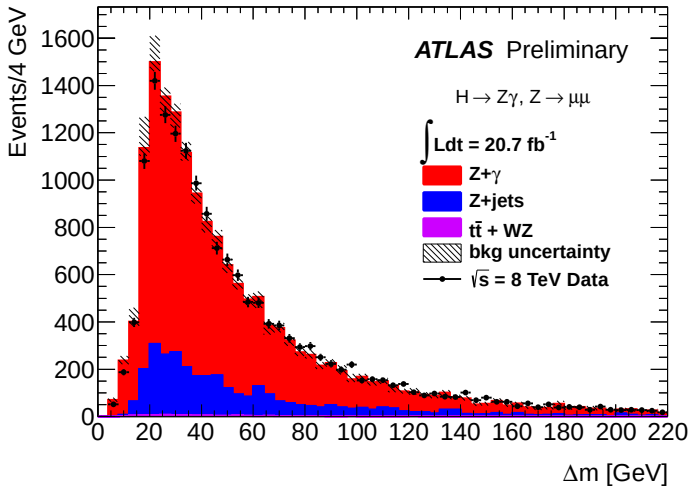
$H \to Z\gamma$ Event Selection



- using 2011 (4.6 fb^{-1}) and 2012 data (20.7 fb^{-1})
- single or dilepton trigger
- Z selection:
  - select 2 opp. charged, isolated leptons
  - $p_{T,l} > 10$ GeV
  - $|m_{ll} - m_Z| < 10$ GeV
- Photon selection:
  - $E_T > 15$ GeV
  - $|\eta| < 2.47$, excluding $1.37 < |\eta| < 1.52$
- use $\Delta m = m_{ll\gamma} - m_{ll}$



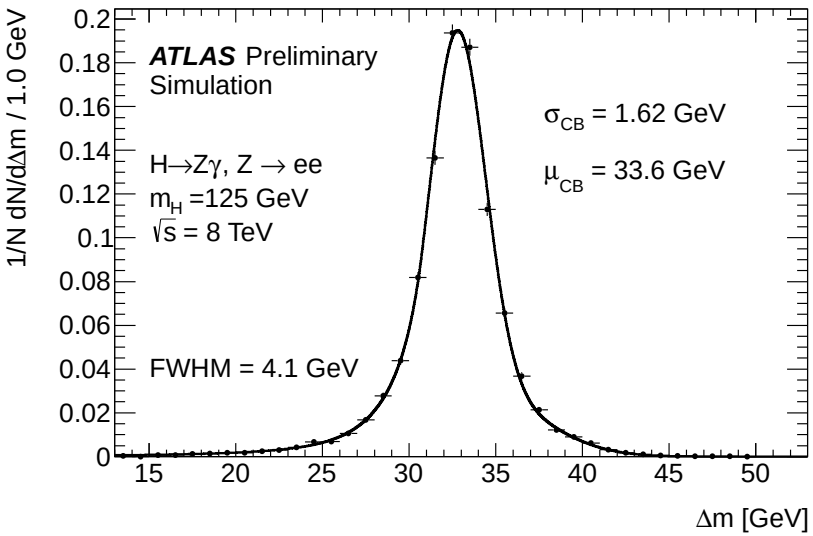
$m_{ee\gamma} - m_{ee}$ after analysis selection



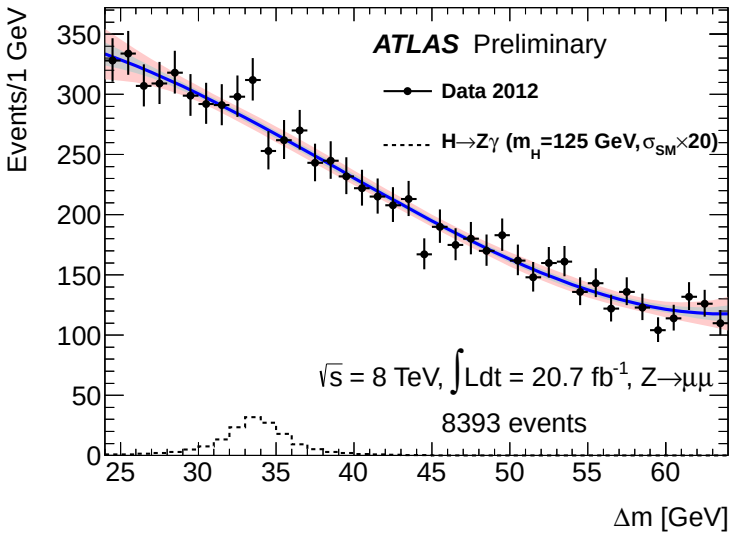
$m_{\mu\mu\gamma} - m_{\mu\mu}$ after analysis selection

Analysis Strategy

- Background estimation:
  - $Z + \gamma$, $Z +$ Jets: 2-dimensional sideband method
  - $t\bar{t}$, WZ: estimated from MC simulated events
- signal model: Crystal Ball + Gaussian p.d.f.
- background model: 3rd order Chebychev polynomial



signal model fit to signal MC



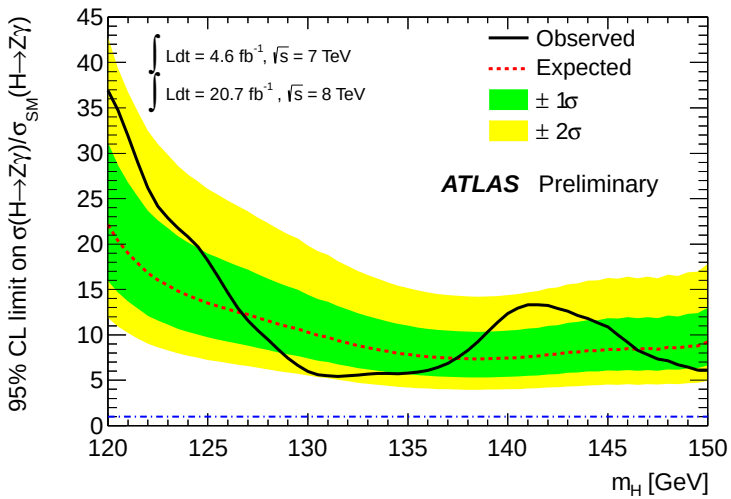
background model fit to Data

Major systematic uncertainties

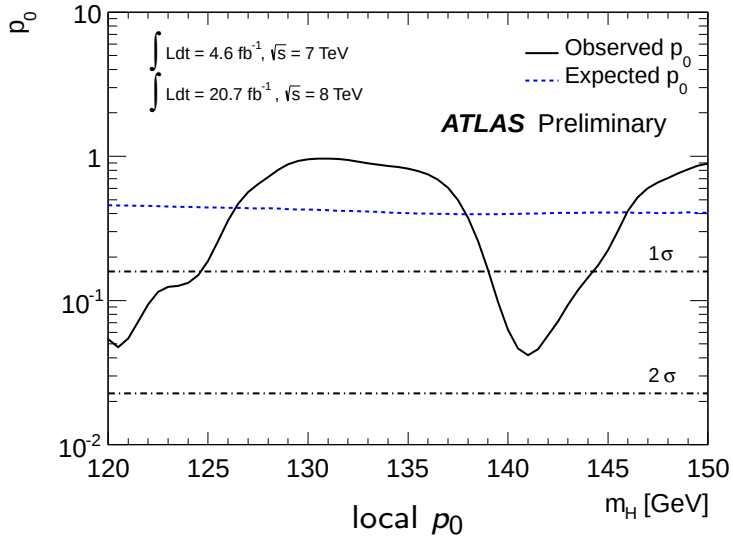
experimental		**theoretical**	
kinematic acceptance	4.0%	$\sigma(gg \to H)$	$7.1 - 7.9\%$ (scale),
Luminosity	3.6%		$6.9 - 7.5\%$ (PDF)
photon ID efficiency	2.9%	$\sigma(t\bar{t}H)$	$3.9 - 9.3\%$ (scale),
e/γ energy resolution	$2.4 - 5.0\%$		$7.8 - 8.5\%$ (PDF)
		$BR(H \to Z\gamma)$	$8.8 - 9.0\%$

Results

- Limits are set in the Higgs mass range of 120-150 GeV
- observed limit on signal strength μ for $m_H = 125$ GeV: $18.2 \times$ SM



95% CL limit on μ



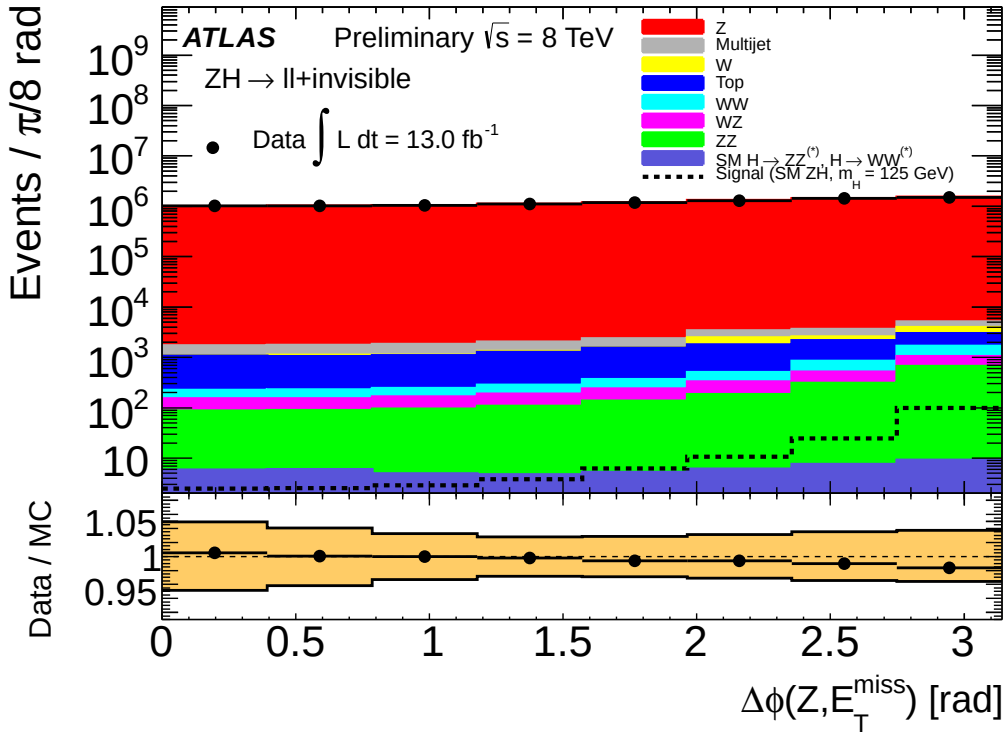
local p_0

$ZH \to l^+l^- + \text{inv.}$ Event Selection

- using 2011 (4.7 fb^{-1}) and 2012 (13.0 fb^{-1}) data
- single lepton or dilepton trigger
- $E_{\mathrm{T}}^{\mathrm{miss}} > 90\ \mathrm{GeV}$

$Z \to ll$ event tag
- 2 opp. sign leptons
- $p_{\mathrm{T}} > 20\ \mathrm{GeV}$
- no additional lepton with $p_{\mathrm{T}} > 7\ \mathrm{GeV}$
- no jet with $p_{\mathrm{T}} > 20\ \mathrm{GeV}$

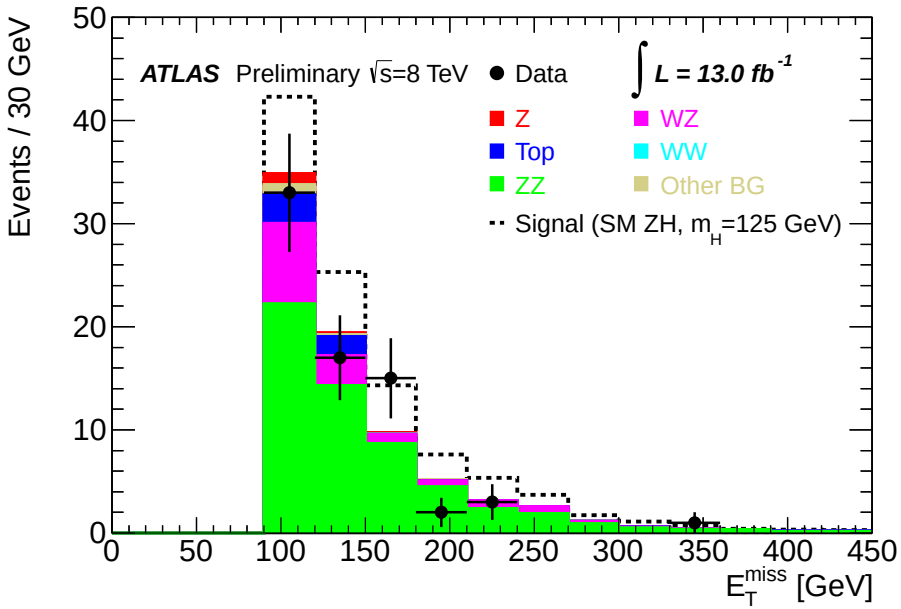
Utilize Z - Higgs balance
- $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}}) < 0.2$
- $\Delta\phi_{Z,E_{\mathrm{T}}^{\mathrm{miss}}} > 2.6$
- $\Delta\phi_{ll} < 1.7$
- $0.8 < \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{ll}} < 1.2$



$\Delta\phi_{Z,E_{\mathrm{T}}^{\mathrm{miss}}}$ before cut

Background estimation

- ZZ and WZ: estimated from MC simulation
- WW, $Z \to \tau\tau$, top: estimated using signal-free $e\mu$ control region
- Z: estimated using ABCD method in $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$ and $|E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{ll}|/p_{\mathrm{T}}^{ll}$
- W and multijet: 4×4 matrix method utilizing lepton efficiencies and fake rates



$E_{\mathrm{T}}^{\mathrm{miss}}$ distribution after all cuts

- for 2011 data: WW and top estimated from MC simulation

Major systematic uncertainties

experimental

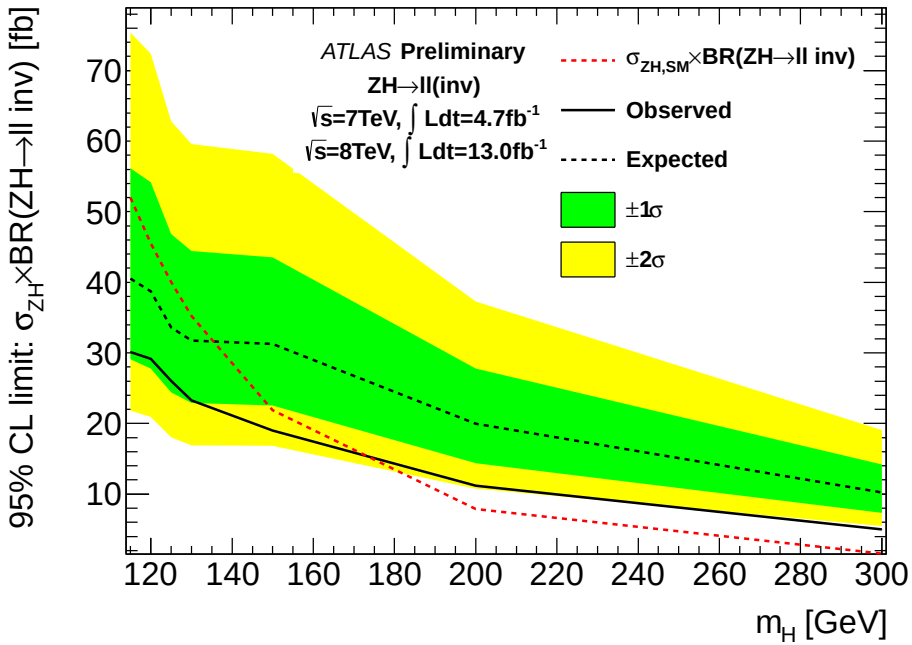
Z background estimation	$51 - 56\%$
Top background estimation	90% (2011)
W and multijet background estimation	$15 - 22\%$
Jet energy scale and resolution	$3 - 6\%$
Luminosity	1.8% (2011), 3.6% (2012)

theoretical

$\sigma(ZH)$	$4.9 - 5.1\%$
Higgs p_T	1.9%

$ZH \to l^+l^- + \text{inv.}$ Results

- Likelihood fit to $E_{\mathrm{T}}^{\mathrm{miss}}$
- absence of excess interpreted as upper limit on $\sigma_{ZH} \times BR(ZH \to ll\text{inv.})$

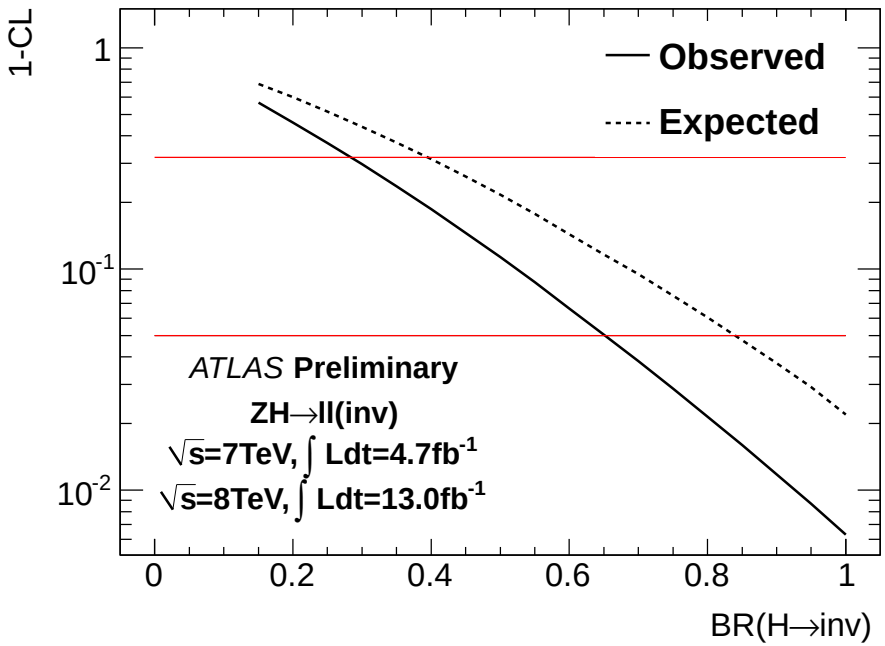


95% CL limit on $\sigma_{ZH} \times BR(ZH \to ll\text{inv.})$

$ZH \to l^+l^- + \text{inv.}$ Results

- alternative scenario: recently discovered Higgs boson ($m_H = 125\ \mathrm{GeV}$) has large $BR(H \to \text{inv.})$

$\to$ plot CL vs. $BR(H \to \text{inv.})$



1-CL vs. $BR(H \to \text{inv.})$

Outlook:

- use full 2012 dataset

Conclusion and Outlook

- No evidence for non-SM Higgs behavior
- 95% CL exclusion limit for SM Higgs with mass 125 GeV:
  - $H \to \mu\mu$: observed (expected) 9.8 (8.2) $\times$ SM prediction
  - $H \to Z\gamma$: observed (expected) 18.2 (13.5) $\times$ SM prediction
- No evidence for significant branching fraction $H \to$ inv.
  - $BR(H \to \text{inv.}) < 65(84)$ % @ 95% CL observed (expected) for $m_H = 125$ GeV

Outlook

- Improvements with Run I data possible: use full dataset
- With full Run II data ($3000 fb^{-1}$): $H \to \mu\mu$ and $H \to Z\gamma$ might reach sensitivity to SM Higgs production rate, direct observation possible!

References

- Higgs branching ratios: LHC Higgs XSec WG
- $H \to \mu\mu$: ATLAS-CONF-2013-010
- $H \to Z\gamma$: ATLAS-CONF-2013-009
- $ZH \to ll + \text{inv.}$: ATLAS-CONF-2013-011

Backup

BACKUP SLIDES

Systematic Uncertainties

- $H \to \mu^+\mu^-$ theoretical

Source of Uncertainty	Treatment in the analysis
$\sigma(gg \to H)$	$\pm 14.1 - 15.3\%$
$\sigma(VBF)$	$\pm 2.7 - 3.0\%$
$BR(H \to \mu\mu)$	$\pm 3.1 - 7.0\%$
signal acceptance	$\pm 1.0 - 4.1\%$

Systematic Uncertainties

- $H \to \mu^+\mu^-$ experimental

Source of Uncertainty	Treatment in the analysis
Luminosity	3.6%
Muon Selection Efficiency	0.3-1% (dependent on η, p_T)
Muon Momentum Scale and Resolution	$< 1\%$
Muon Trigger	$< 1\%$
Muon Track Isolation	$< 1\%$
Pile-up reweighting	$< 1\%$

Systematic Uncertainties

- $H \to Z\gamma$ theoretical

$\sqrt{s}$	Systematic uncertainty (%)										
	$\sigma(gg \to H)$		σ(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	$^{+9.0}_{-8.8}$

Systematic Uncertainties

- $H \to Z\gamma$ experimental

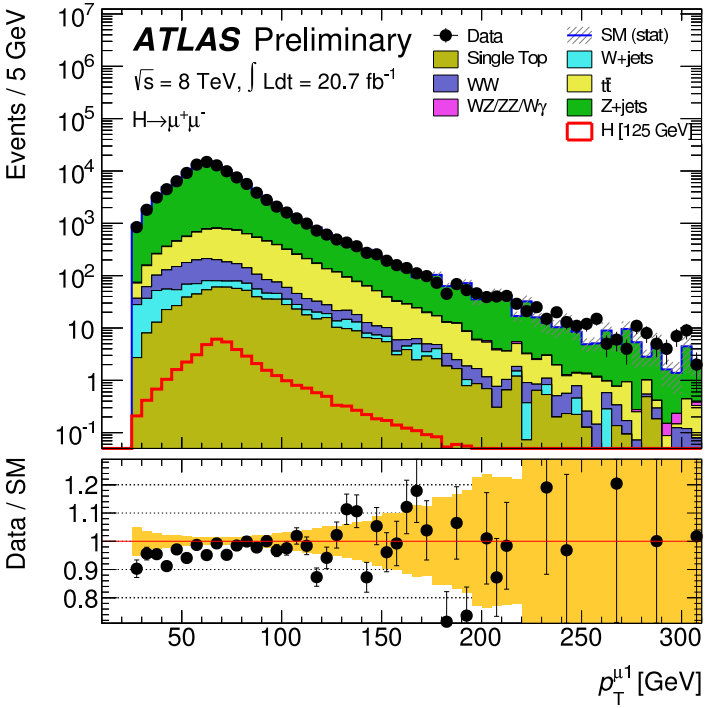
Systematic Uncertainty	$H \to Z(ee)\gamma$(%)	$H \to Z(\mu\mu)\gamma$(%)
Signal Yield		
Luminosity	3.6 (1.8)	3.6 (1.8)
Trigger efficiency	0.4 (0.2)	0.8 (0.7)
Acceptance of kinematic selection	4.0 (4.0)	4.0 (4.0)
γ identification efficiency	2.9 (2.9)	2.9 (2.9)
electron reconstruction and identification 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

Systematic Uncertainties

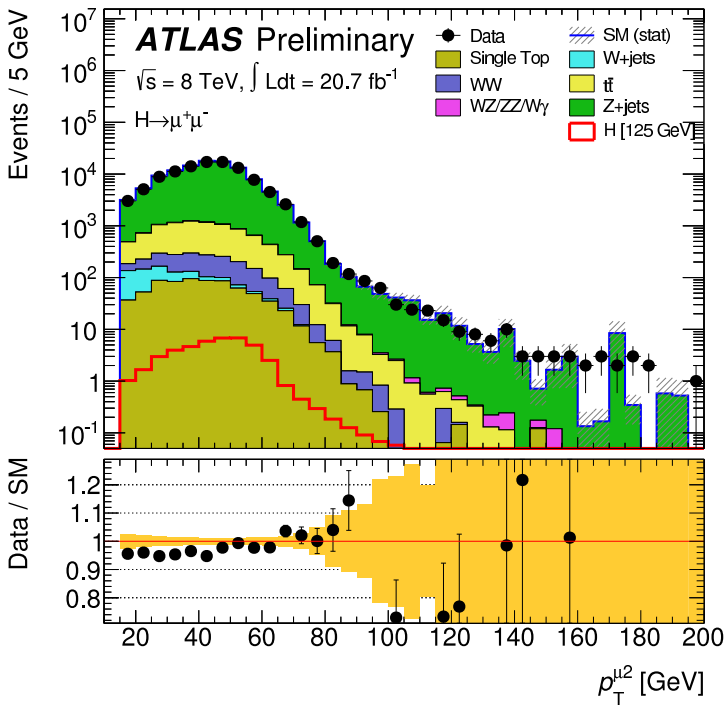
- $ZH \rightarrow l^+l^- +$ inv.

Process	Estimation method	Uncertainty (%) 2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \rightarrow \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

$H \to \mu\mu$ muon kinematic plots

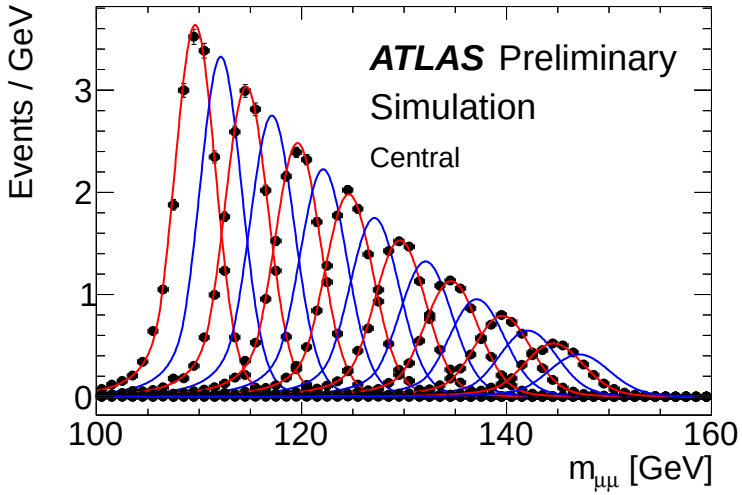


leading muon p_T

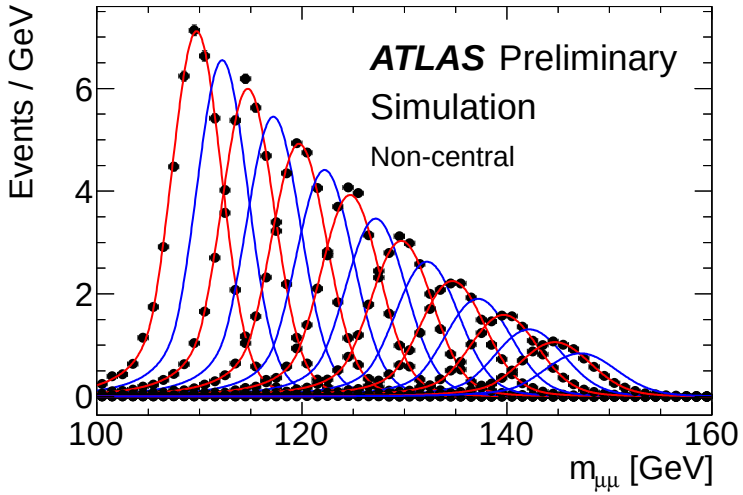


subleading muon p_T

$H \to \mu\mu$ signal interpolation

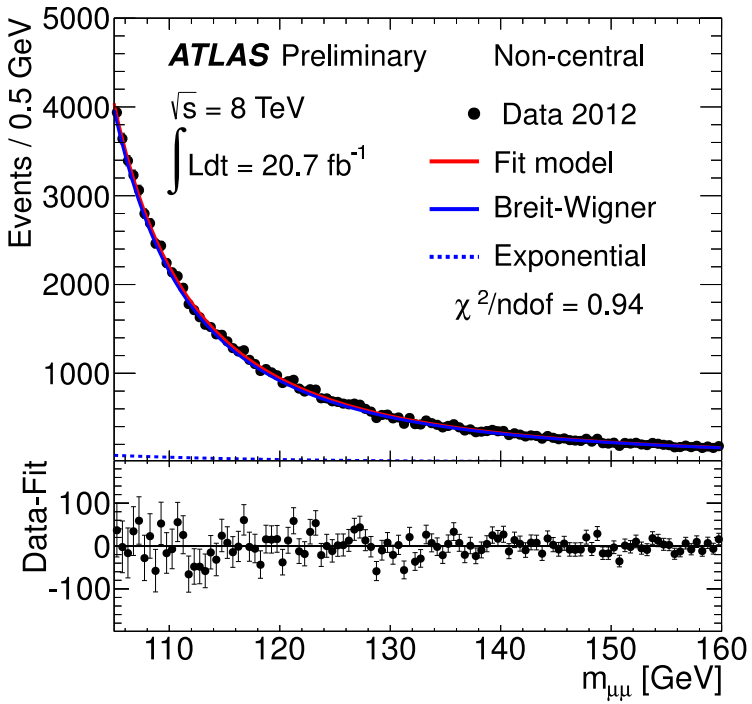


central region

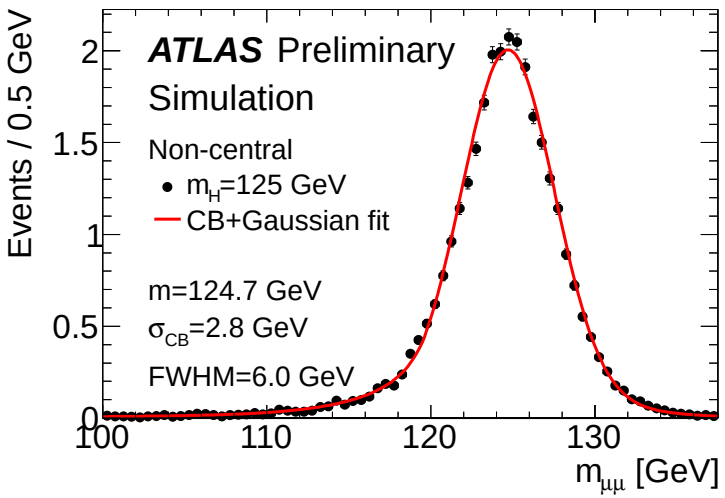


non-central region

$H \to \mu\mu$ signal + background fits

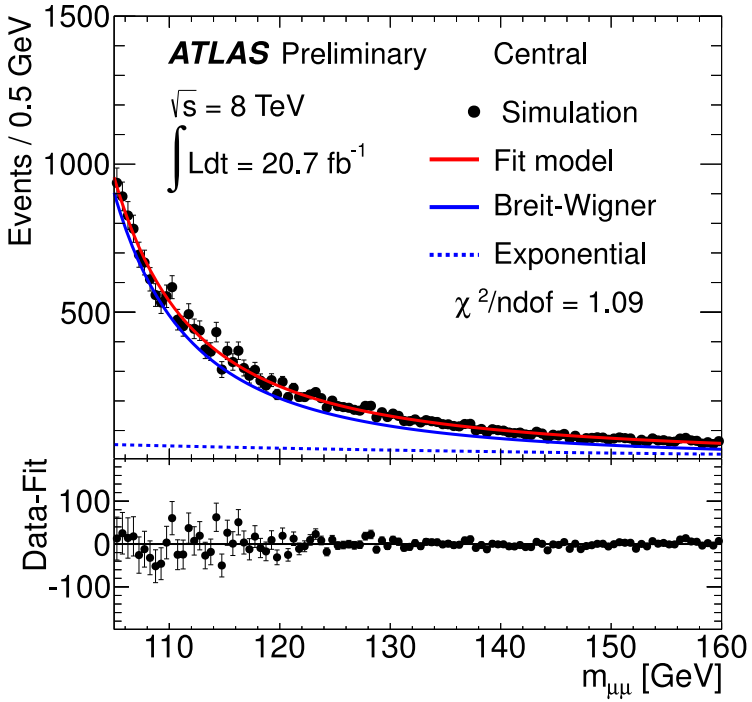


Background fit, non-central region

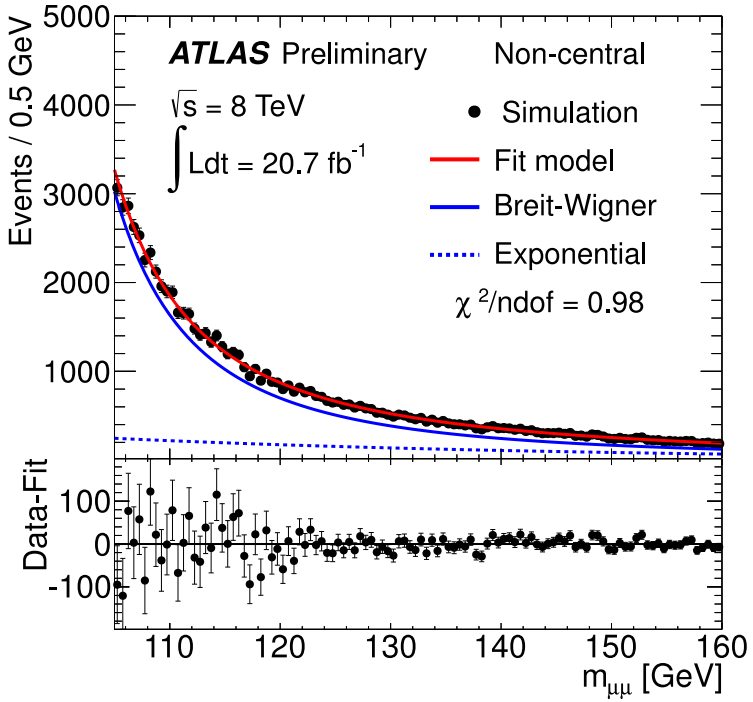


Signal fit, non-central region

$H \to \mu\mu$ background fits to MC

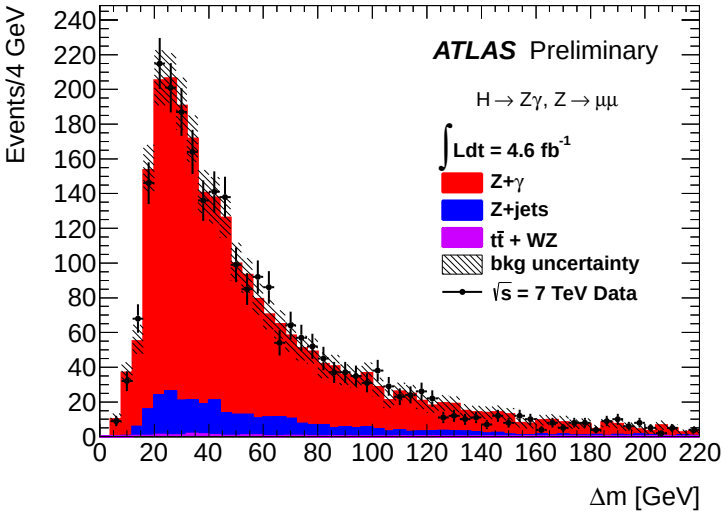


Background fit, central region

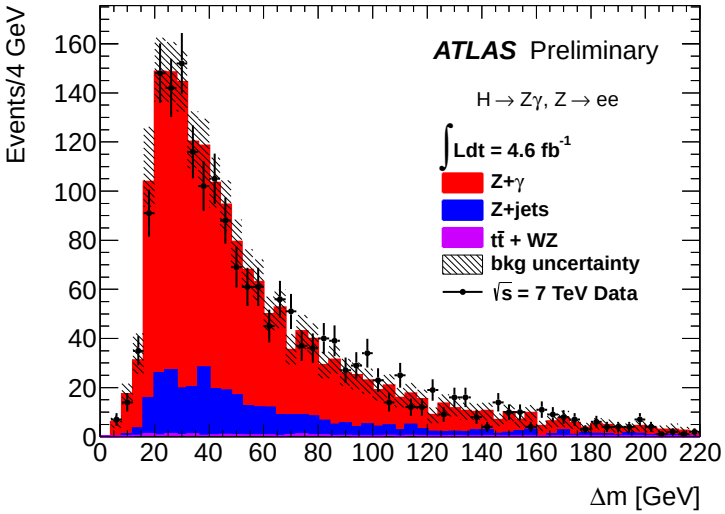


Background fit, non-central region

$H \to Z\gamma$ Δm spectra

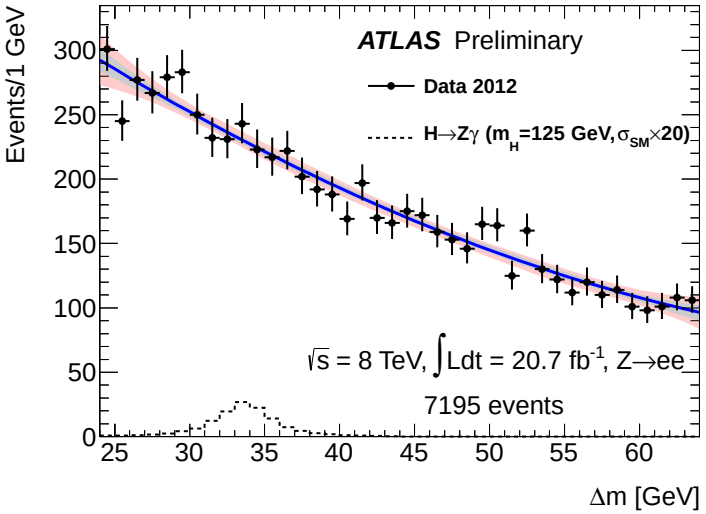


Δm spectrum, muons, 2011

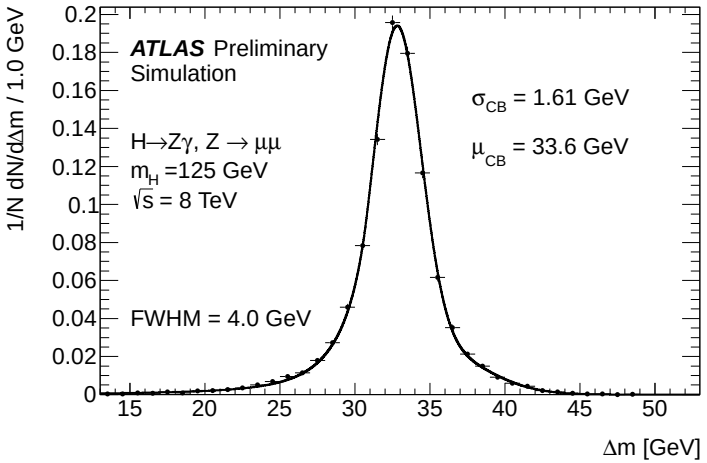


Δm spectrum, electrons, 2011

$H \to Z\gamma$ signal + background fits

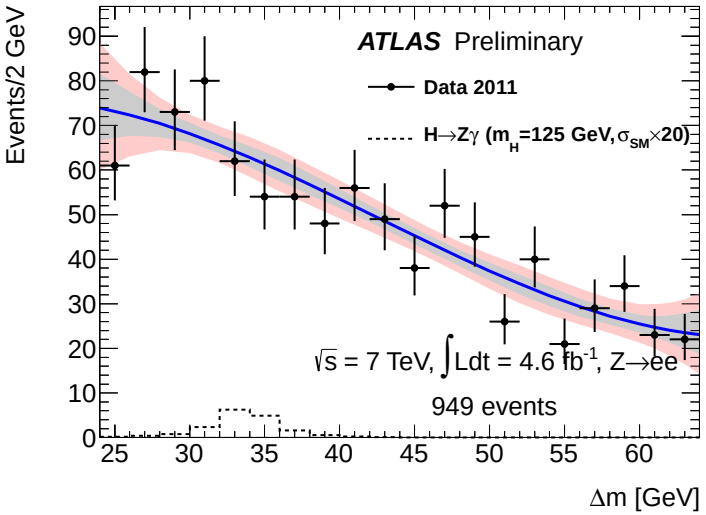


Background fit, electrons, 2012

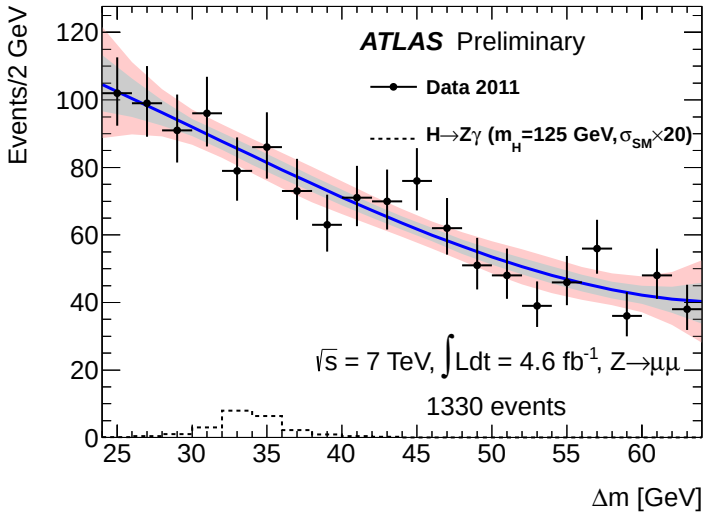


Signal fit, muon channel

$H \to Z\gamma$ Background fits, 2011

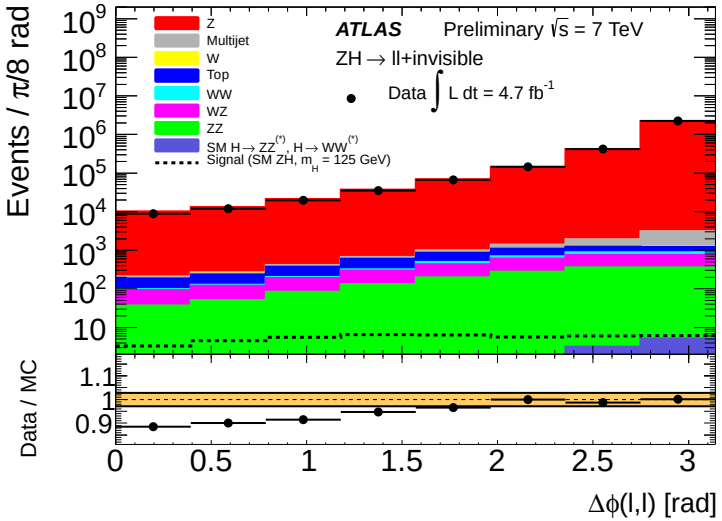


Electron channel, 2011

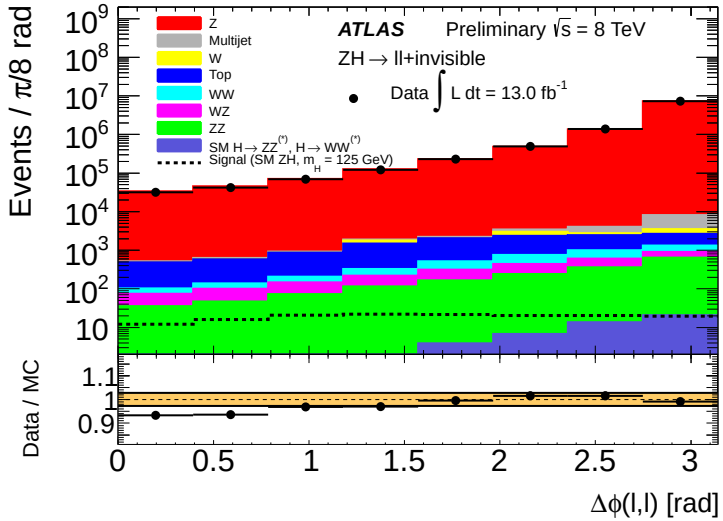


Muon channel, 2011

$ZH \rightarrow ll +$ inv distributions

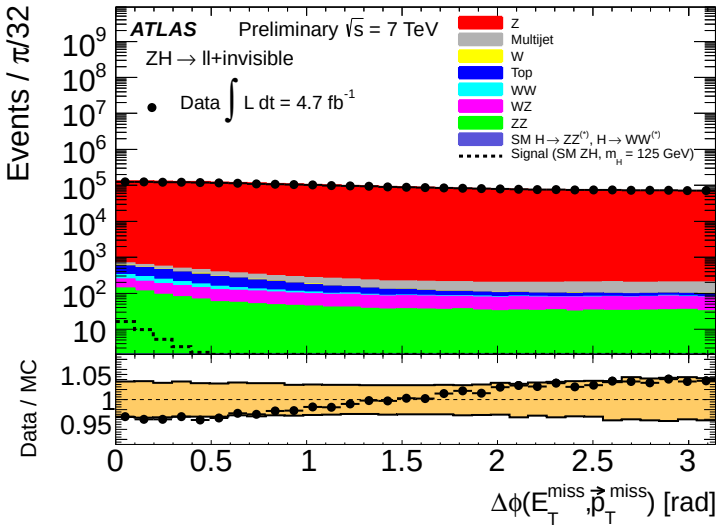


2011

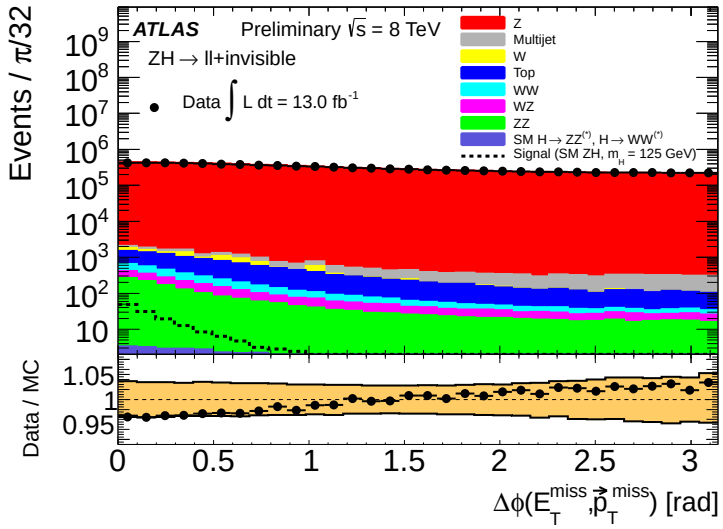


2012

$ZH \rightarrow ll + \text{inv}$ distributions

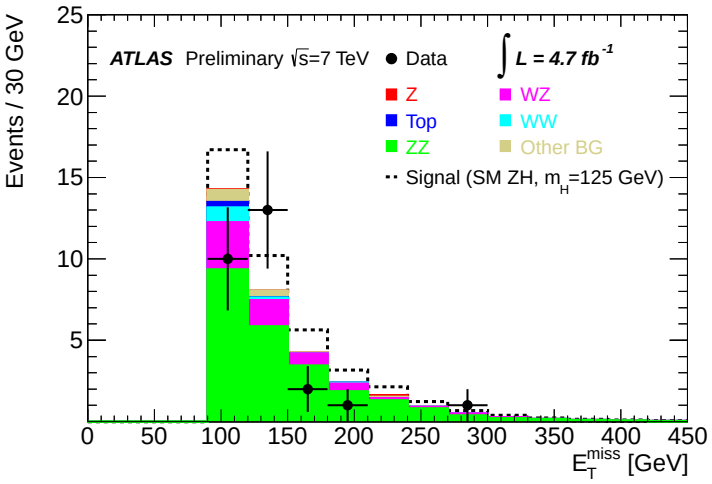


2011

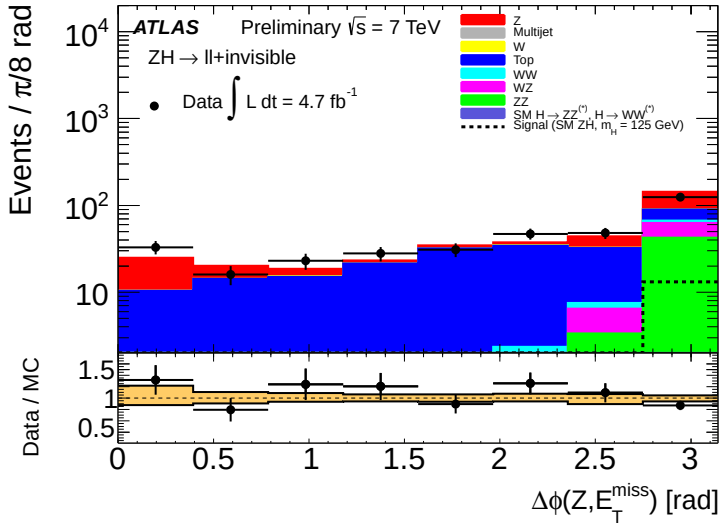


2012

$ZH \rightarrow ll + \text{inv}$ distributions



MET final distribution, 2011



$\Delta\phi_{(Z,E_{\mathrm{T}}^{\mathrm{miss}})}$, 2011

$ZH \rightarrow ll +$ inv matrix method

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \times \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

- $N_{(T|L)}$: number of events with tight/loose lepton
- $N_{(R|F)}$: number of events with real/fake lepton
- r_1, r_2, f_1, f_2: efficiencies / fake rates for first and second lepton

$$N_{W+\text{jets}} = \sum_i^{N_{\text{events}}} N_{RF}^i \times r_1^i \times f_2^i + N_{FR}^i \times f_1^i \times r_2^i$$

$$N_{multijet} = \sum_i^{N_{\text{events}}} N_{FF}^i \times f_1^i \times f_2^i$$