The search for rare decays of the Higgs boson with ATLAS and CMS

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on behalf of the ATLAS and CMS Collaborations

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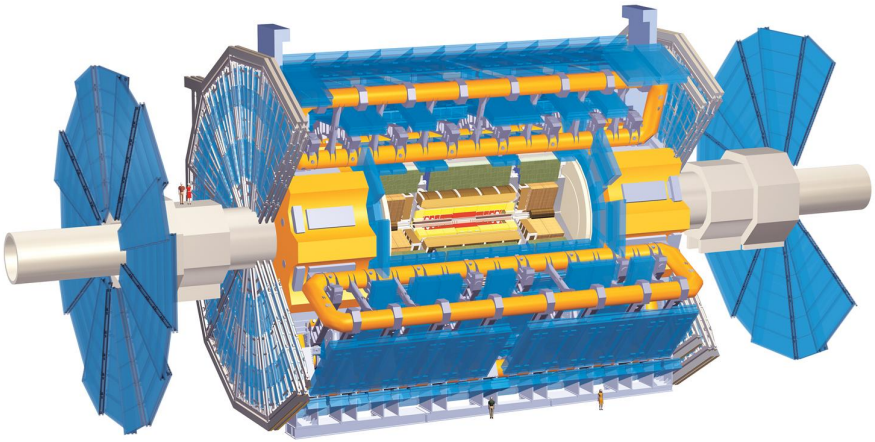
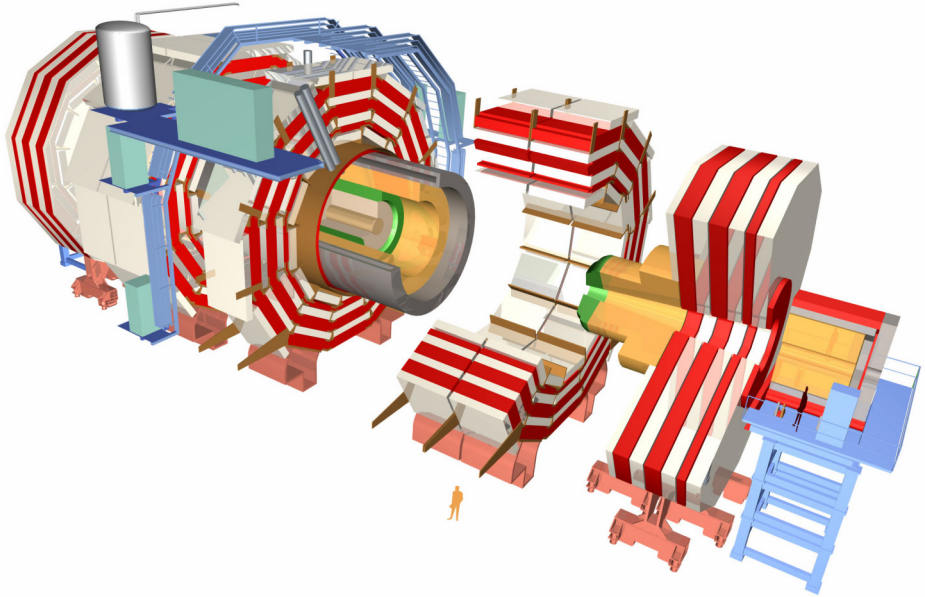
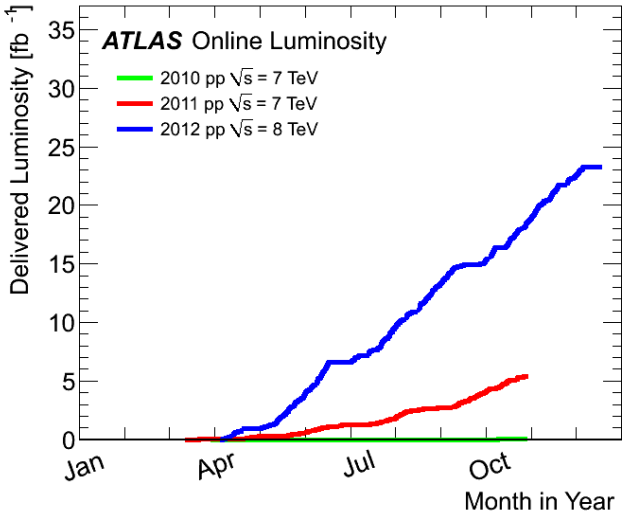
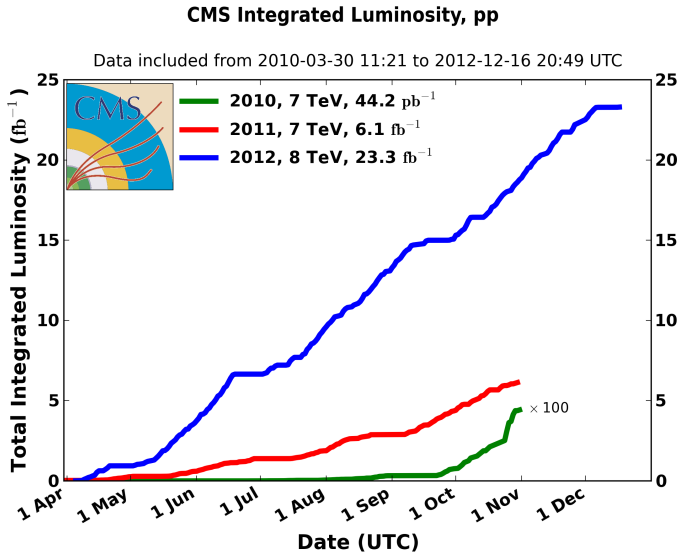
ATLAS and CMS detectors and Datasets

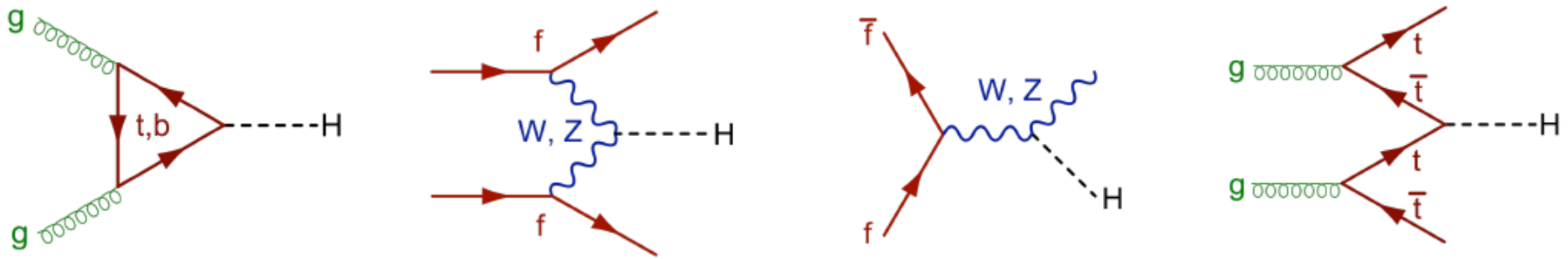








SM Higgs Boson Production at the LHC



Gluon fusion:

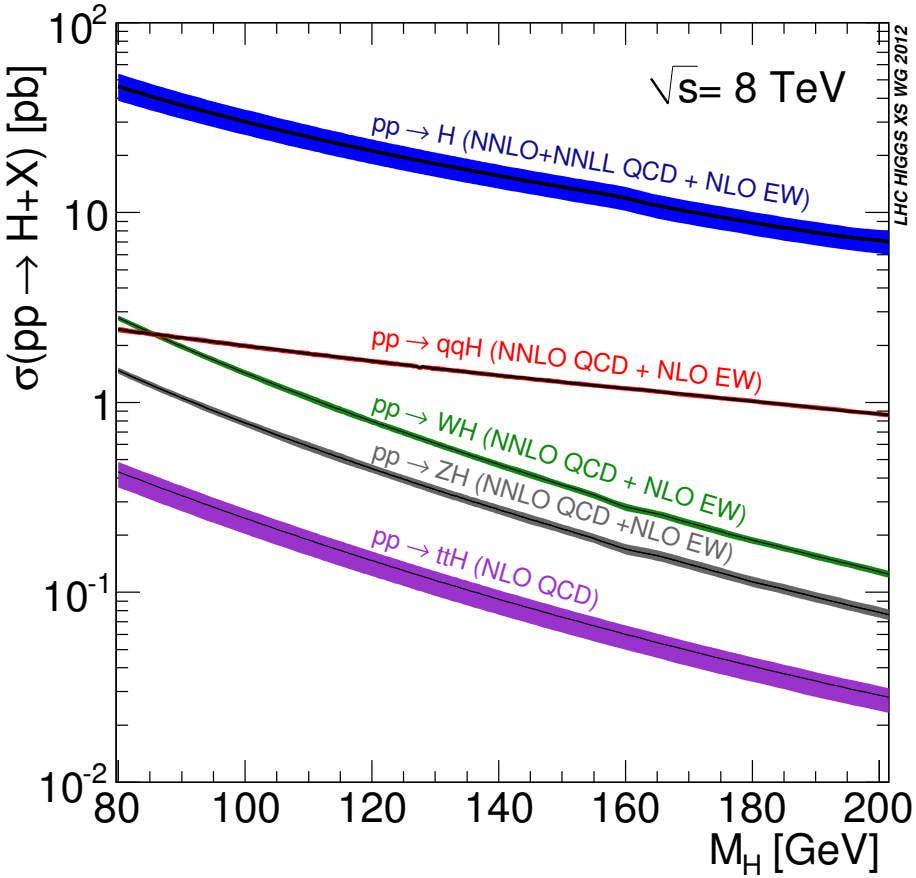
- known at NNLO (theo. uncert. O(15%))

Vector boson fusion:

- known at NLO (theo. uncert. O(5%))
- distinctive exp. signature: 2 forward jets and rapidity gap

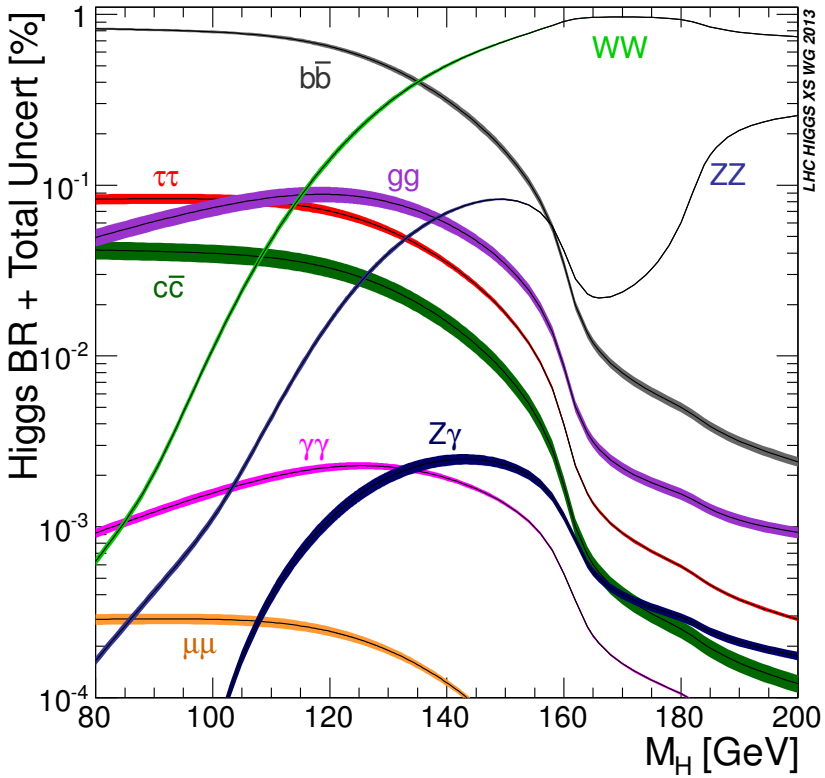
Associated *WH*/*ZH*:

- known at NNLO (theo. uncert. O(5%))

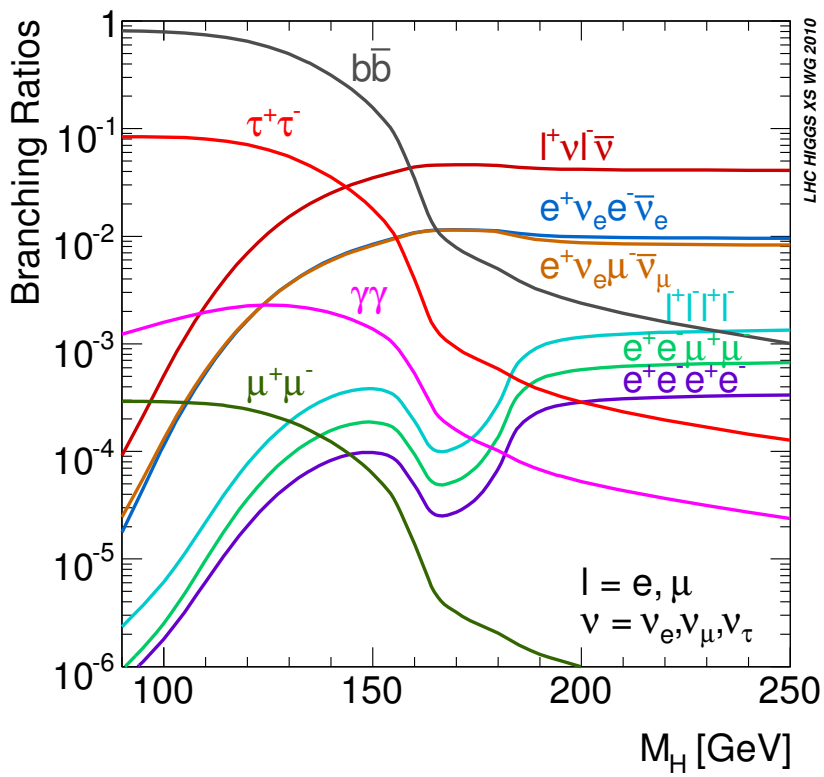


Higgs Boson Decays

Direct decay products:



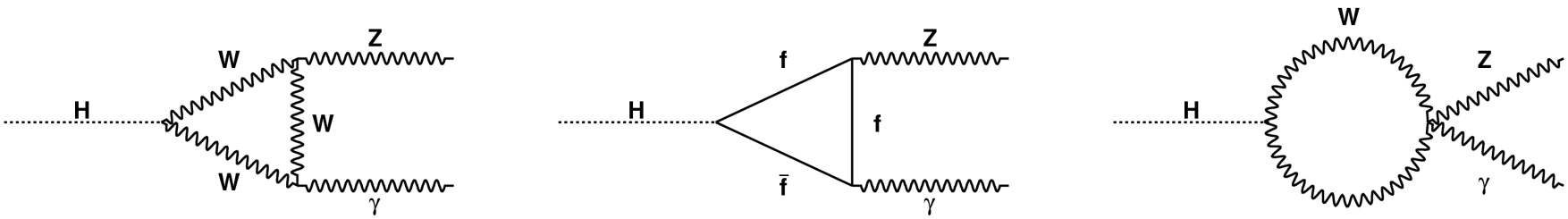
Visible decay products in detector:



Focus of this talk on the rare Higgs boson decays :

- $H \to Z\gamma$ (ATLAS 4.6+20.7 fb^{-1}, CMS 5.0+19.6 fb^{-1})
- $H \to \mu\mu$ (ATLAS 20.7 fb $^{-1}$)
- ZH, $H \to$ invisible (ATLAS 4.7+13.0 fb $^{-1}$, CMS 5.1+19.6 fb^{-1})

$H \to Z\gamma$



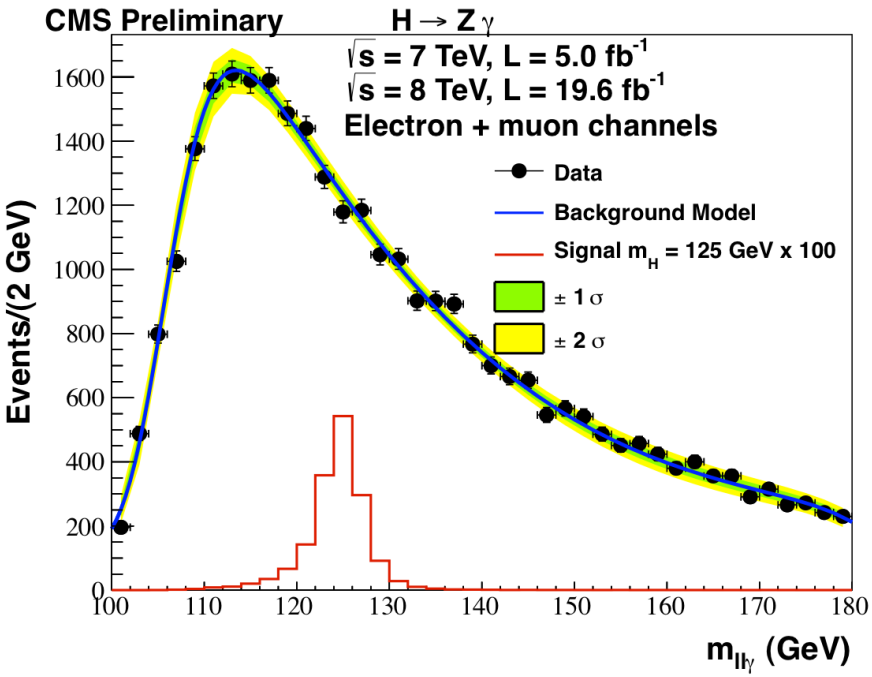
Motivation:

- The $H \to Z\gamma$ decay proceeds via electroweak loop coupling to the Higgs boson, together with the $H \to \gamma\gamma$ channel can provide strong constraints on BSM particles in the loops.
- The $BR(H \to Z\gamma)$ is comparable to $BR(\to \gamma\gamma)$, but $BR(Z \to \ell\ell))$ reduces sensitivity (factor 15)
- Inclusive production

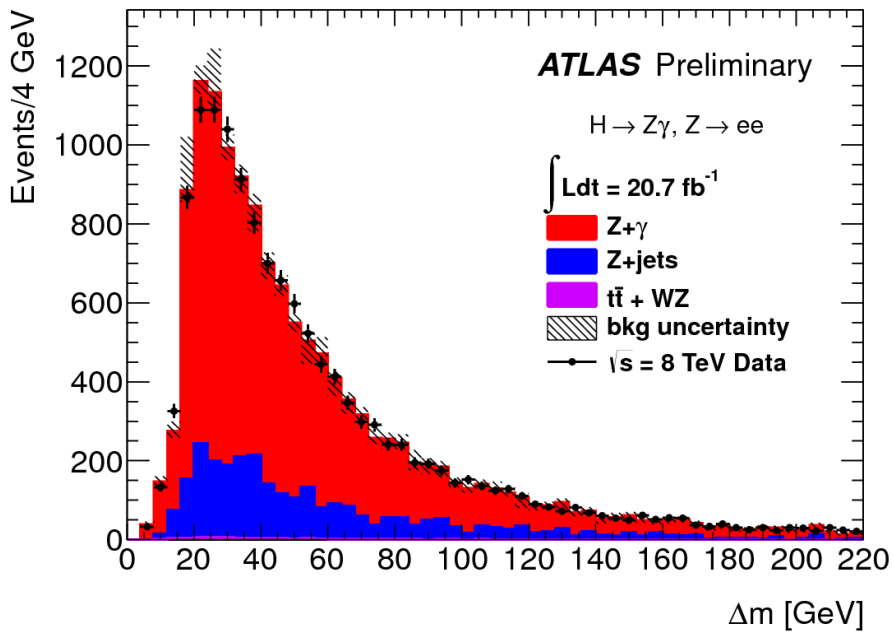
Event Selection:

- At least 2 isolated opp. charged high p_T electrons or muons
- At least 1 high p_T isolated photon
- $\Delta R(\gamma, \ell) > 0.3$ (0.4) ATLAS (CMS)
- $m_{\ell\ell\gamma} > m_Z - 10$ GeV (ATLAS), 100 GeV $< m_{\ell\ell\gamma} <$ 180 GeV (CMS)

$H \to Z\gamma$: Distributions



$m_{\ell\ell\gamma}$ distribution for electron and muon channel



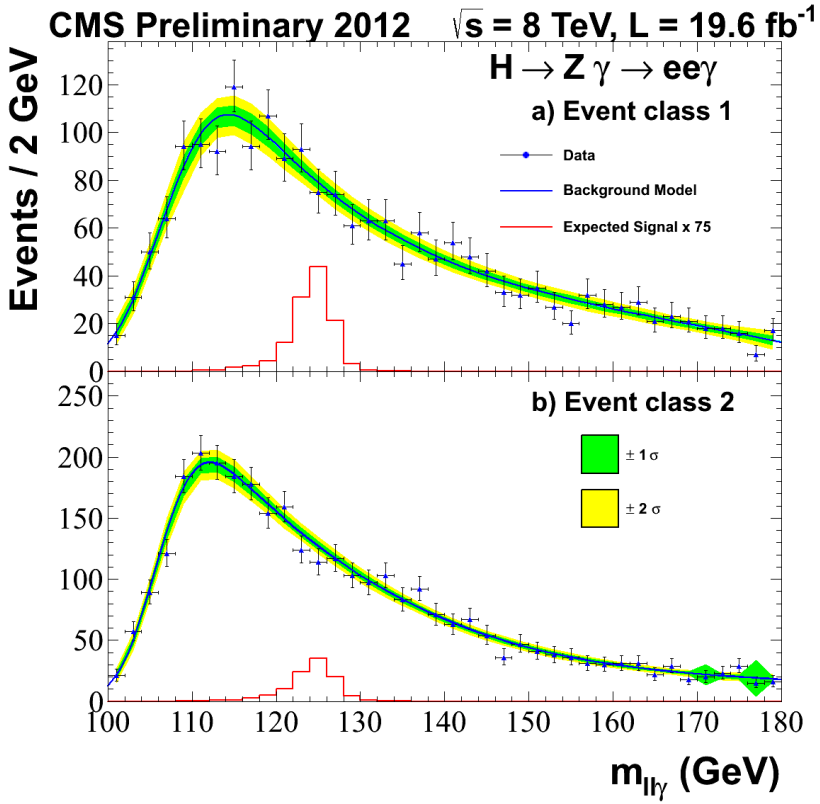
$\Delta m(m_{\ell\ell\gamma} - m_Z)$ distribution for electron channel

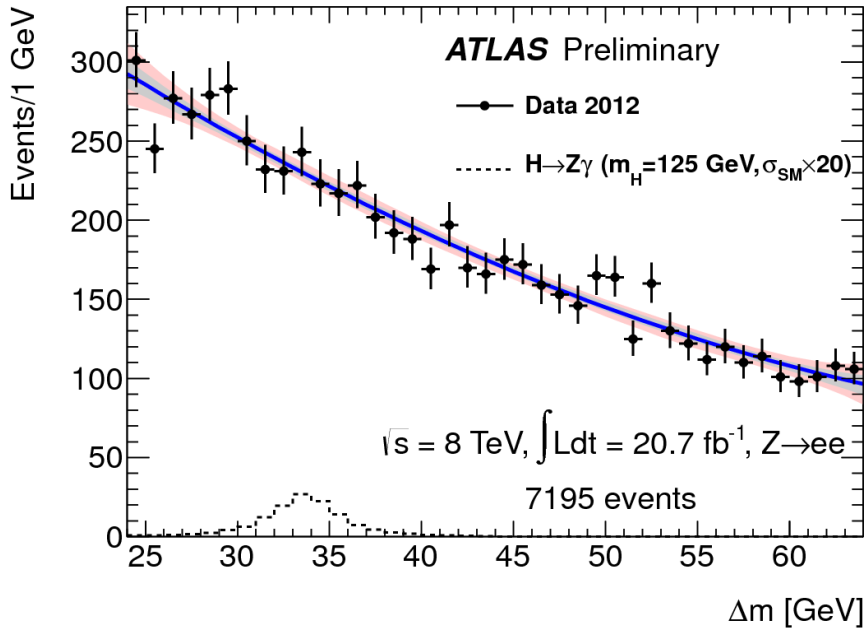
Insensitive to lepton energy uncert., reduced FSR $H \to \mu\mu$

Classes: central γ & leptons, (un-)converted γ, endcap γ or lepton

Backgrounds from $Z + \gamma$ (both ISR and FSR) and Z+jets estimated from data driven methods, small contributions from top and WZ from MC

$H \to Z\gamma$: Fit and Uncertainties

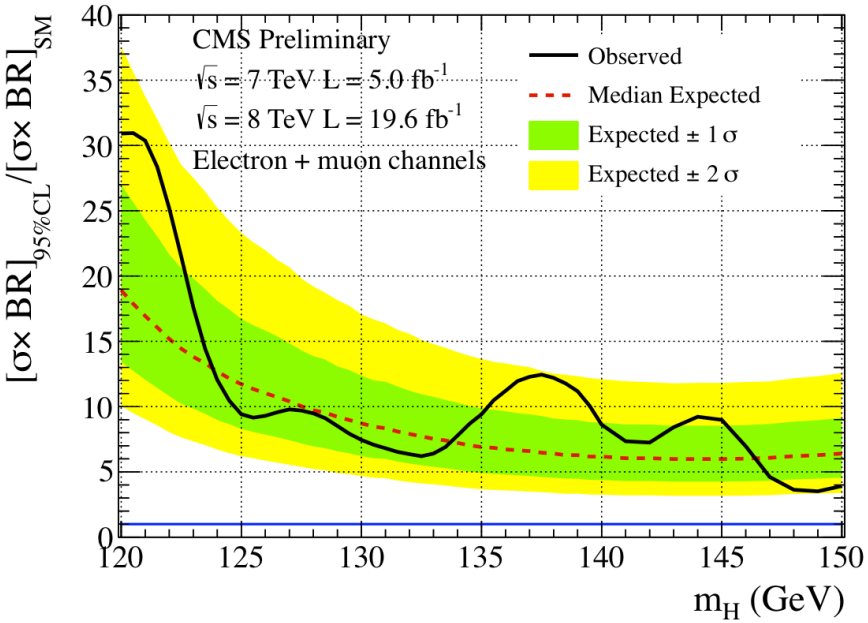


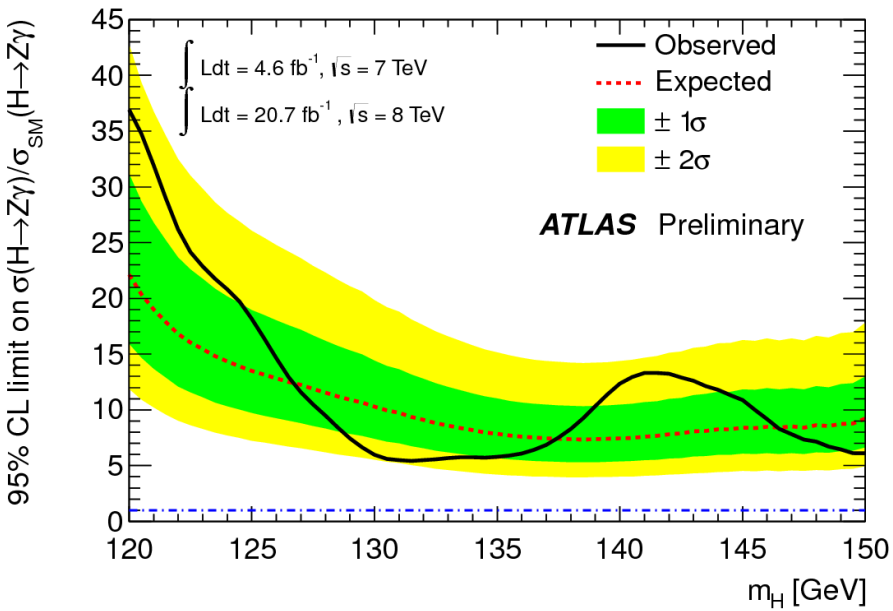


Sample	num. of events $120 < m_{\ell\ell\gamma} < 150$ GeV	num. of events predicted for $m_H = 125$ GeV
2011 ee	1041	1.2
2011 $\mu\mu$	1223	1.4
2012 ee	5534	6.3
2012 $\mu\mu$	5993	7.0

- Fit BG 3rd order polynomial to Δm in data
- Main systematic uncertainties: acceptance (5%), e/γ resolution (5%)

$H \to Z\gamma$: Results





Limits (CMS):

- Observed: 3-31·σ_{SM}
- Expected: 6-19·σ_{SM}

Limits (ATLAS):

- Observed: 5.4-37·σ_{SM}
- Expected: 7.3-22·σ_{SM}

Any deviations from SM prediction will be indication of new electroweak particles coupling to Higgs boson

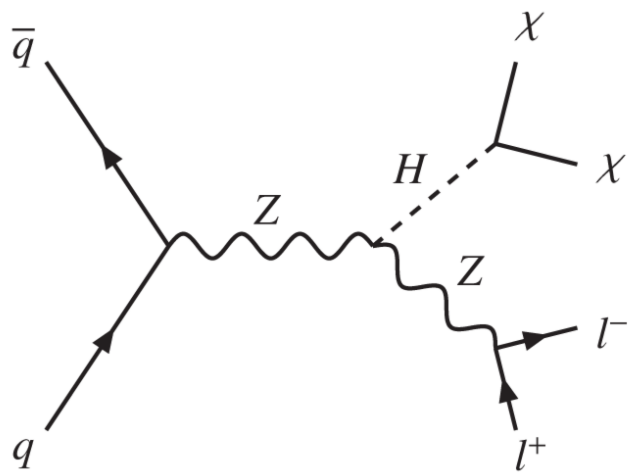
ZH, $H \rightarrow$ INVISIBLE

Motivation:

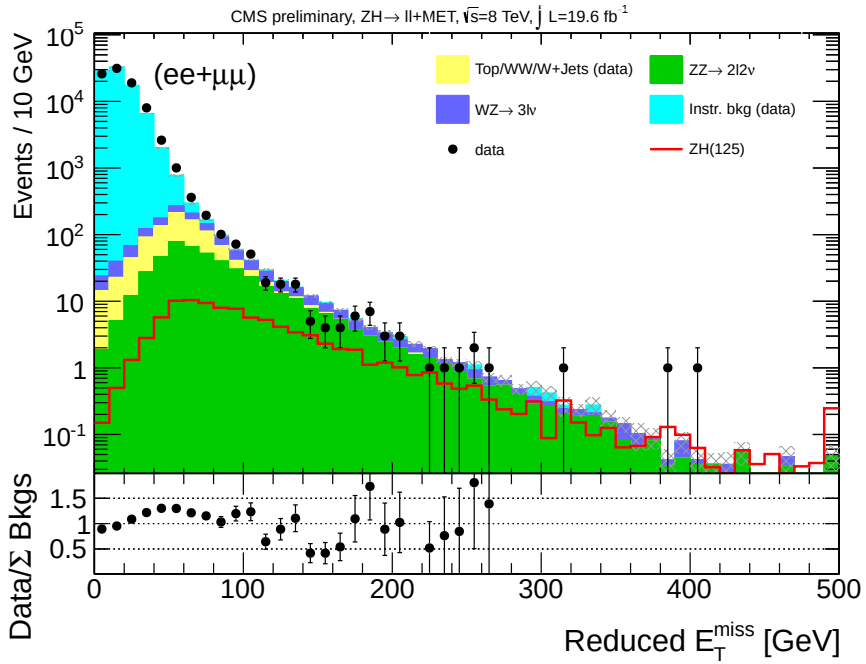
- Higgs couplings to non SM stable or long lived particles is excellent way to search for new physics, in particular Dark Matter through so called Higgs portal models. The search performed by looking for excess in events at high E_T^{miss}

Event Selection:

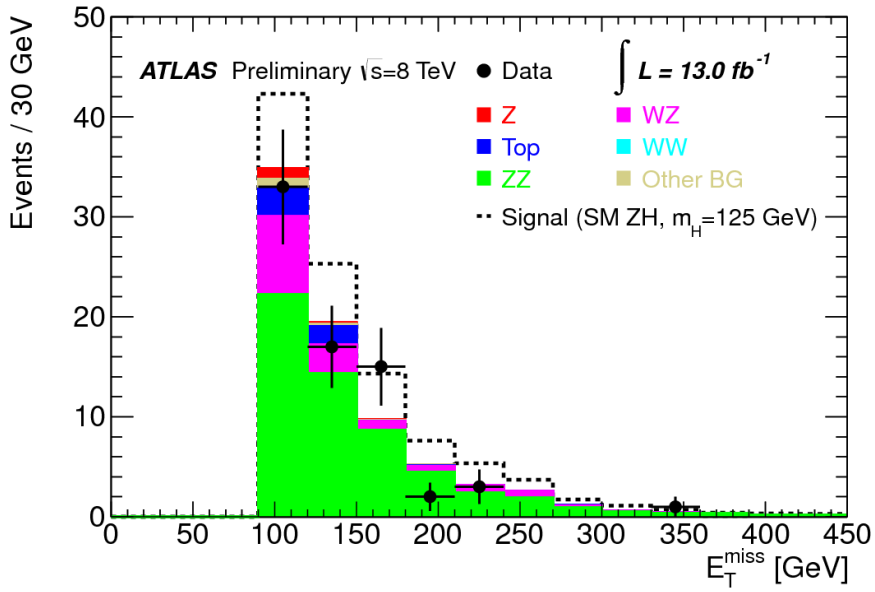
- 2 isolated high p_T electrons or muons
- $|m_Z - m_{\ell\ell}|$ <15 GeV
- E_T^{miss} >90 GeV (ATLAS), reduced E_T^{miss} >110 GeV (CMS)
- $\Delta\phi(E_T^{miss}, p_T^{miss})$ <0.2 (ATLAS)
- $\Delta\phi(E_T^{miss}, p_T^{\ell\ell})$ >2.6
- $\Delta\phi(\ell\ell)$ <1.7 (ATLAS)
- $|E_T^{miss} - p_T^{\ell\ell}|/p_T^{\ell\ell}$ <0.2
- Jet veto



ZH, $H \to$ invisible: Distributions



reduced E_T^{miss} in signal region



E_T^{miss} in signal region after all cuts

Backgrounds:

- ZZ and WZ from MC
- WW and top from scaling signal free $e\mu$ decay channel distributions
- Z+jets from $ABCD$ method with $\Delta\phi(E_T^{miss}, \vec{p}_T^{miss})$ and frac. p_T diff. (ATLAS) or orthogonal reweighted γ+jets sample (CMS)
- W+jets/multi-jet from 4×4 matrix method loosened lepton-ID

ZH, $H \to$ inv.: Uncertainties, Event yields

CMS:

Process	$\sqrt{s} = 7$ TeV		$\sqrt{s} = 8$ TeV	
	ee	$\mu\mu$	ee	$\mu\mu$
$ZH(125)$	2.2 ± 0.3	3.3 ± 0.5	11.8 ± 1.9	16.7 ± 2.5
$Z/\gamma^* \to \ell^+\ell^-$	0.3 ± 0.3	0.7 ± 0.7	1.0 ± 1.0	1.9 ± 1.9
$WZ \to 3\ell\nu$	2.0 ± 0.3	2.3 ± 0.3	11.0 ± 1.6	14.8 ± 2.1
$ZZ \to 2\ell 2\nu$	5.1 ± 0.6	7.3 ± 0.8	29.8 ± 3.6	40.8 ± 4.5
$Top/WW/W + Jets$	0.4 ± 0.4	0.6 ± 0.6	1.3 ± 0.8	2.1 ± 1.3
total bkg.	7.8 ± 0.8	11.0 ± 1.3	43.1 ± 4.1	59.6 ± 5.5
Data	10	11	33	45

Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	$23.5 \pm 0.8 \pm 2.5$	$56.5 \pm 1.2 \pm 5.7$
WZ	$6.2 \pm 0.4 \pm 0.7$	$13.9 \pm 1.2 \pm 2.1$
WW	$1.1 \pm 0.2 \pm 0.2$	used $e\mu$ data-driven
Top quark	$0.4 \pm 0.1 \pm 0.4$	used $e\mu$ data-driven
Top quark, WW and $Z \to \tau\tau$ ($e\mu$ data-driven)	used MC	$4.9 \pm 0.9 \pm 0.2$
Z	$0.16 \pm 0.13 \pm 0.09$	$1.4 \pm 0.4 \pm 0.7$
W + jets, multijet	$1.3 \pm 0.3 \pm 0.2$	$1.4 \pm 0.4 \pm 0.3$
Total BG	$32.7 \pm 1.0 \pm 2.6$	$78.0 \pm 2.0 \pm 6.5$
Observed	27	71

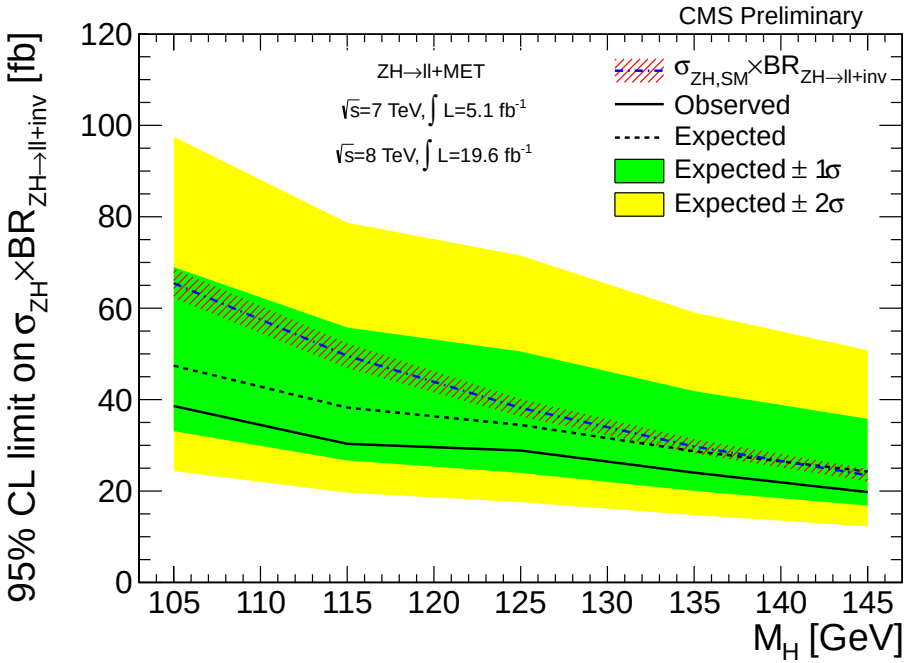
ATLAS

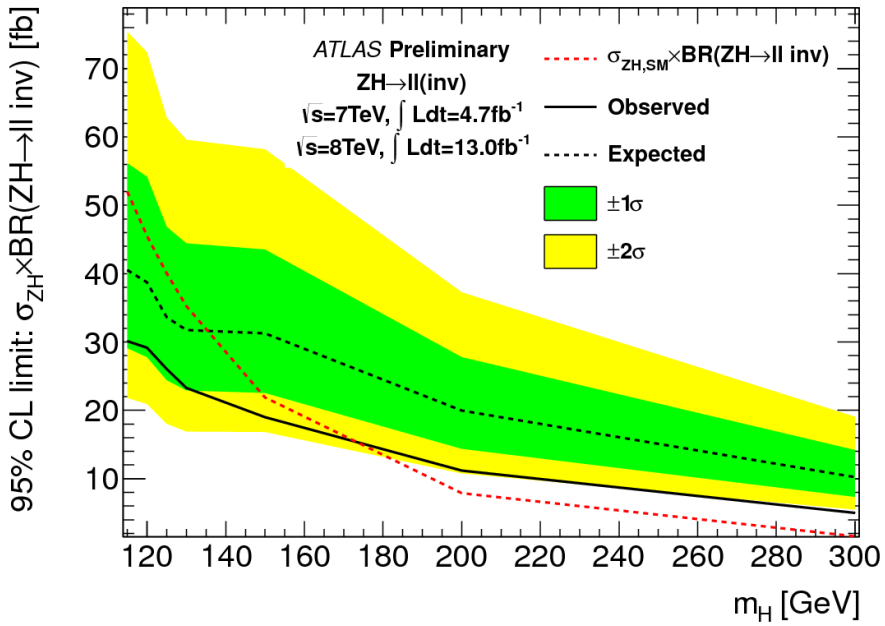
Dominant systematic uncertanties:

- ZZ, WZ 10-14 %, ZH Signal 6-7%

ZH, $H \to$ invisible: Results

Two interpretations:





$BR(H \to inv) > 71\ (91)\ /\ 65\ (84)\%$
obs. (exp.) CMS/ATLAS
excluded at 95% CL for
SM Higgs boson with $m_H = 125$ GeV

Limit on $\sigma \cdot BR(H \to inv)$ for further
Higgs-like states with
$115 < m_H < 300$ GeV

Stringent limits on Higgs and Dark Matter coupling can be obtained in combination with mono-jet and mono-photon and VBF $H \to inv$ searches

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

Motivation:

- $H \to \mu^+\mu^-$ directly probes SM Higgs Boson couplings to 2nd generation fermions
- $BR(H[125] \to \mu^+\mu^-) = 2.2 \times 10^{-4}$

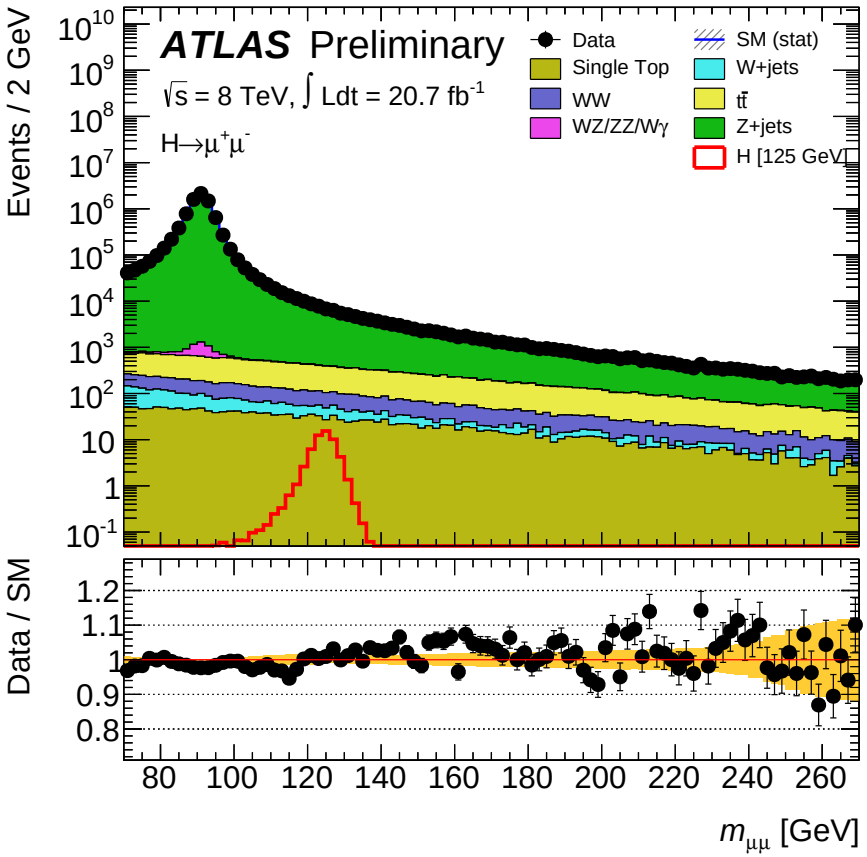
Search strategy:

- Inclusive search
- Search for a small bump on top of continuous $m_{\mu\mu}$ background distribution
- ,,blinded" search of the SM resonance in 110-150 GeV $m_{\mu\mu}$ window
- Use parametrized functions to fit data for background rate and shape
- Dominant background is inclusive Z/γ^* (small di-bosons and $t\bar{t}$)

Challenges:

- Irreducible $Z/\gamma^* \to \mu\mu$ background
- $\Gamma(H[125]) = 4.1$ MeV - signal width dominated by detector resolution

$H \to \mu^+\mu^-$: $m_{\mu\mu}$ AND EVENT YIELDS



Invariant mass $m_{\mu\mu}$

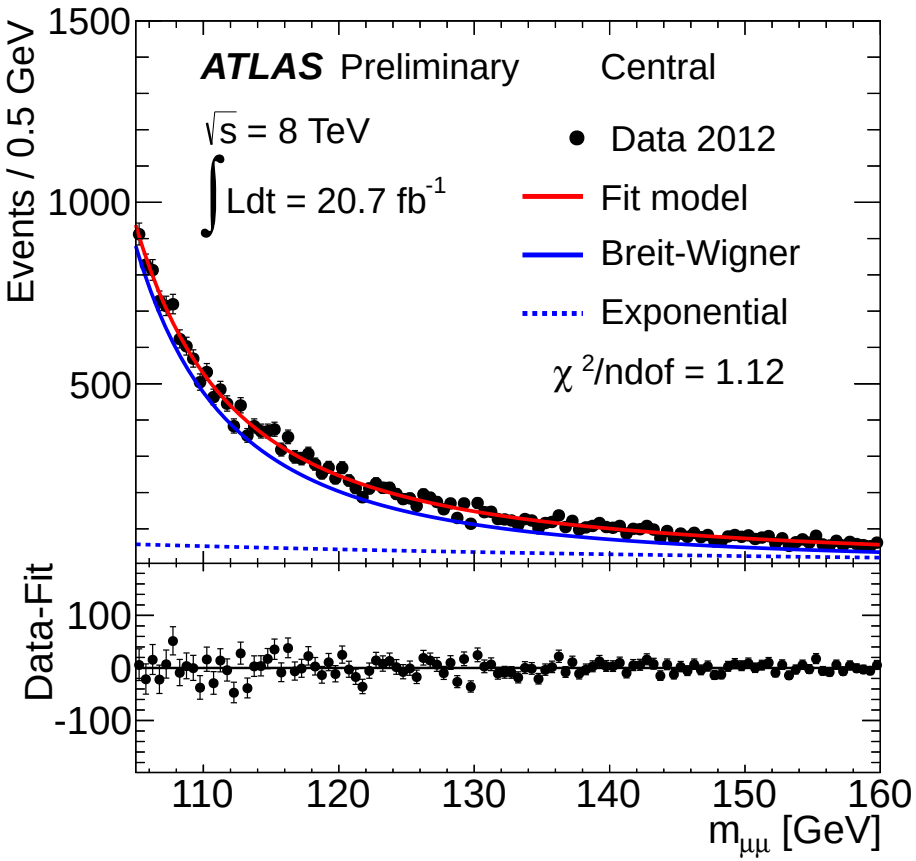
Event selection:

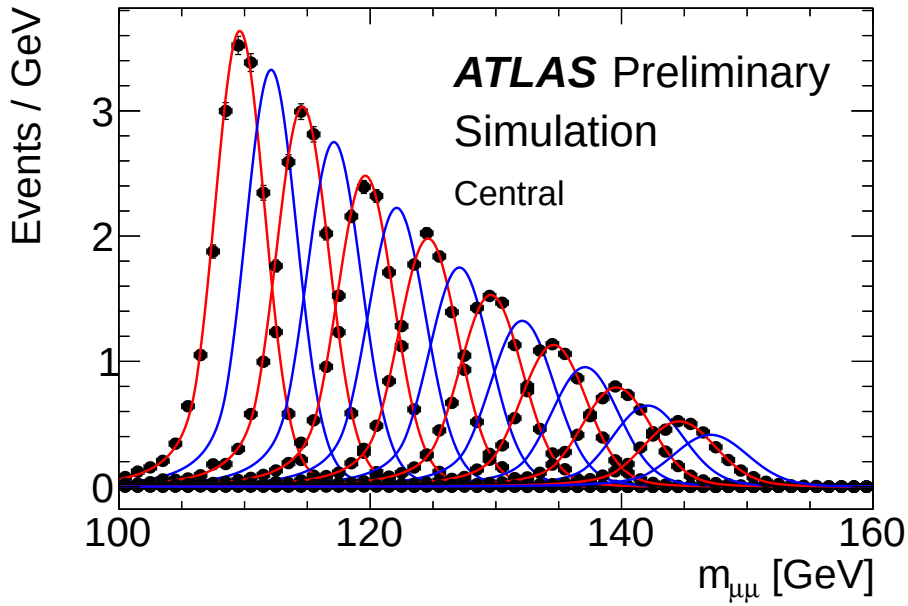
- 2 isolated opp. charged muons, $p_T^{\mu 1(2)} > 25\ (15)$ GeV
- $p_T^{\mu\mu} > 15$ GeV
- Muon resolution categories: $|\eta_\mu| < 1$, $|\eta_\mu| > 1$

Event yields:

	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
$WZ/ZZ/W\gamma$	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total BG	17700 ± 130
Observed	17442

$H \to \mu^+\mu^-$: Fit procedure



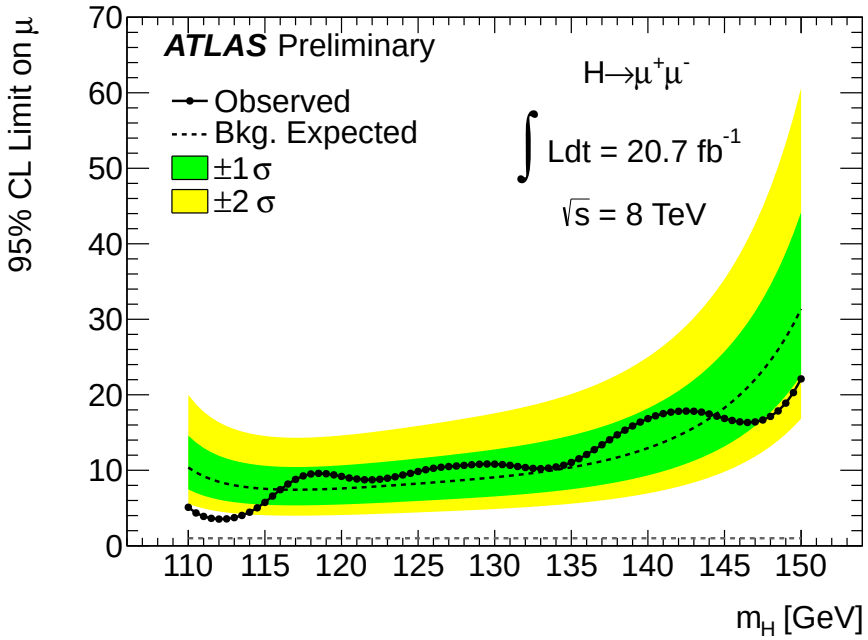


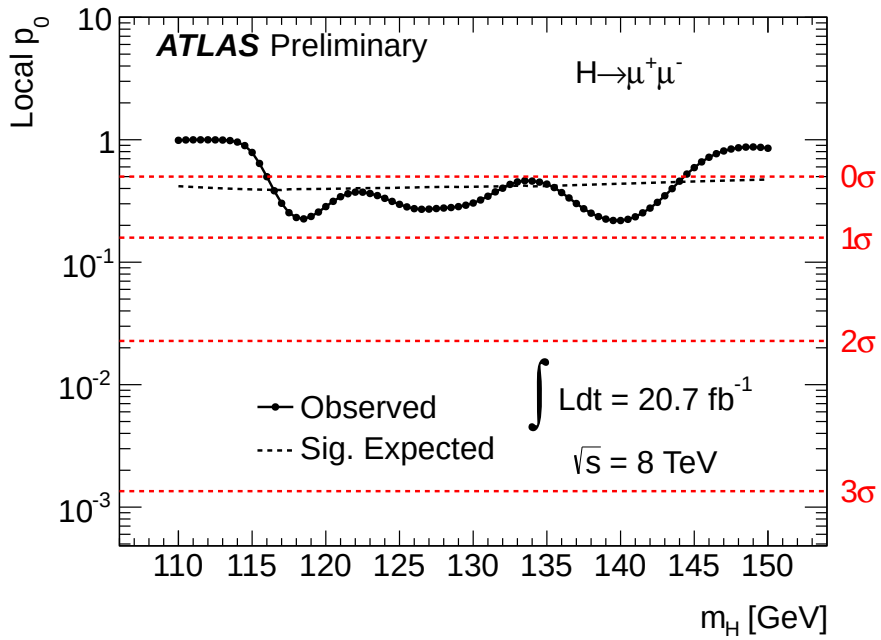
Background model:
Breit-Wigner + exponential function

Signal model:
Crystal ball + Gaussian function

Background fit validated in MC and data control regions

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





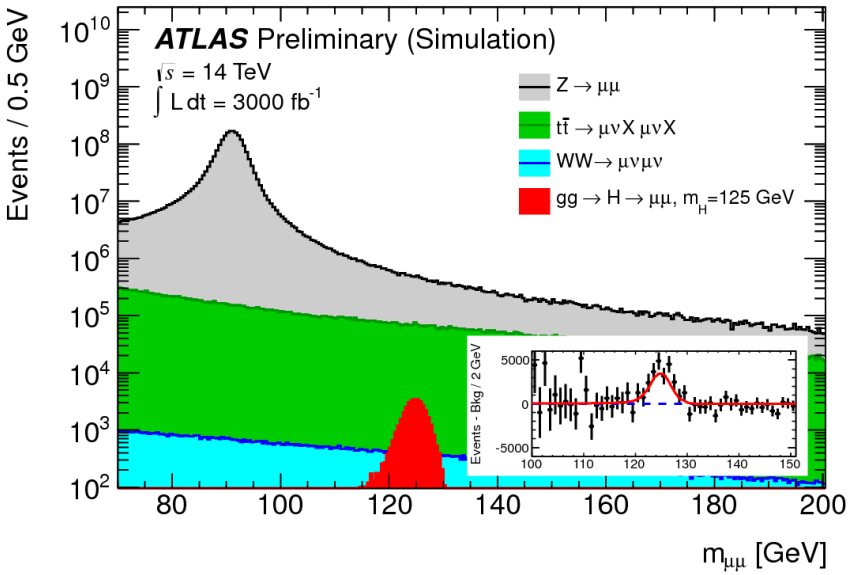
Limits at m_H=125 GeV:

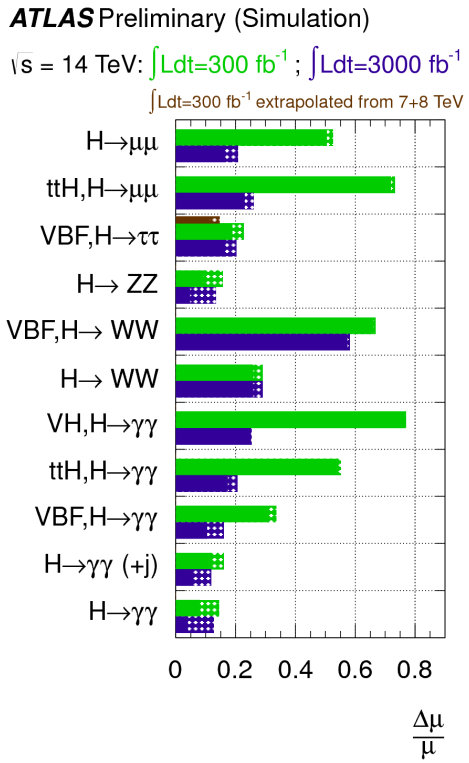
- Observed: $9.5 \cdot \sigma_{SM}$
- Expected: $8.2 \cdot \sigma_{SM}$

Dominant systematic uncertainties (all at percent level):

- Theory: cross section and branching ratio, ISR
- Experimental: Luminosity, muon reconstruction

$H \to \mu^+\mu^-$: Future perspectives





HL-LHC substantially improved statistical precision for already established channels, allows to study rare Higgs boson production and decay modes ATLAS and CMS with 3000 fb^{-1}:

- Inclusive analysis expected significance $> 6\sigma$ (ATLAS) and $\approx 5\sigma$ for gluon-gluon fusion and VBF (CMS)
- Expected measurement precision better than 20% (ATLAS) or than 10% on $H\mu\mu$ coupling (CMS)

Summary and Conclusions

- Presented the analysis by ATLAS and CMS with LHC data from 2011 and 2012 for rare SM Higgs boson decays in:
  - $H \to Z\gamma$
  - $H \to \mu\mu$
  - ZH, $H \to$ invisible
- No deviations from SM Higgs boson expectations and set upper limits on the various $\sigma \cdot BR$
  $\to$ further indication that it is a SM Higgs boson
- Establish signal of rare decay latest with HL-LHC data

Documentation

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/

$H \to Z\gamma$	ATLAS-CONF-2013-009
$H \to \mu\mu$	ATLAS-CONF-2013-010
ZH (Invisible decays)	ATLAS-CONF-2013-011

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

HL-LHC physics	ATL-PHYS-PUB-2012-004

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

$H \to Z\gamma$	CMS-PAS-HIG-13-006
ZH (Invisible decays)	CMS-PAS-HIG-13-018

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP

HL-LHC physics	CMS-NOTE-2012-006

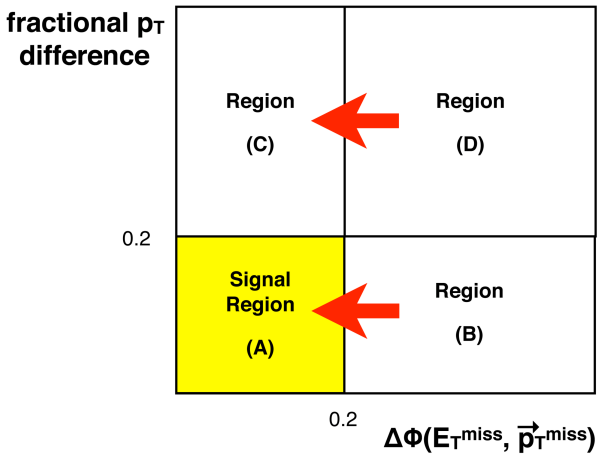
BACKUP

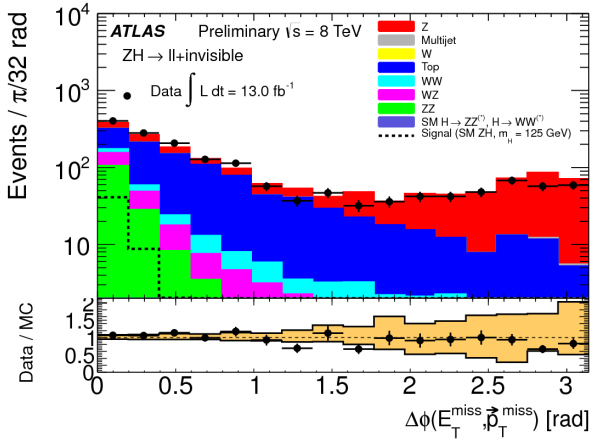
$H \to Z\gamma$: Background determination

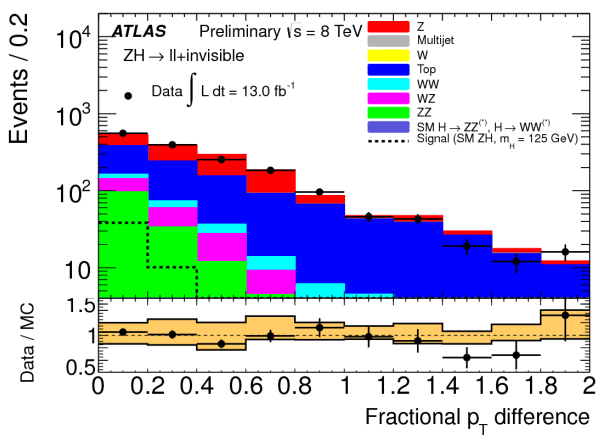
- Background is directly fitted from data mass spectrum
- ATLAS: 2D sideband fit method: γ-ID and γ-Isolation in Z+jets enriched region to determine Z+jets and $Z + \gamma$ fraction after $t\bar{t}$ and WZ substraction
- Backgrounds are:
  - SM $Z + \gamma$ ($\sim$ 82 %)
  - SM Z+jets ($\sim$ 17 %)
  - $t\bar{t}$ and WZ ($\sim$ 1 %)

ZH, $H \to$ invisible: Background determination

- ZZ and WZ from MC
- WW and top from scaling signal free $e\mu$ decay channel distributions
- Z+jets from $ABCD$ method with $\Delta\phi(E_T^{miss}, \vec{p}_T^{miss})$ and frac. p_T diff.







- W+jets and multi-jet BG from 4×4 matrix method with loosened lepton-ID

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

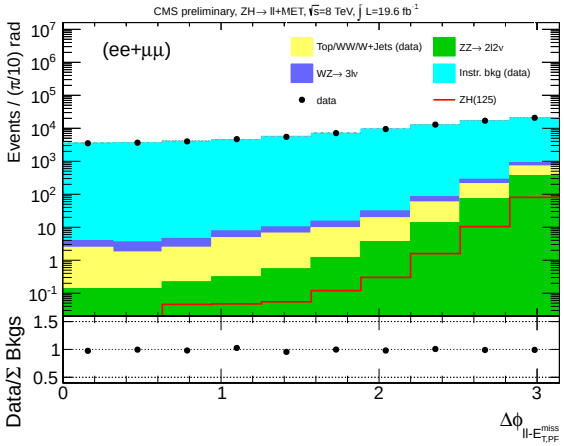
r_1, r_2, f_1, f_2 lepton efficiencies and fake rates for first lepton and second lepton

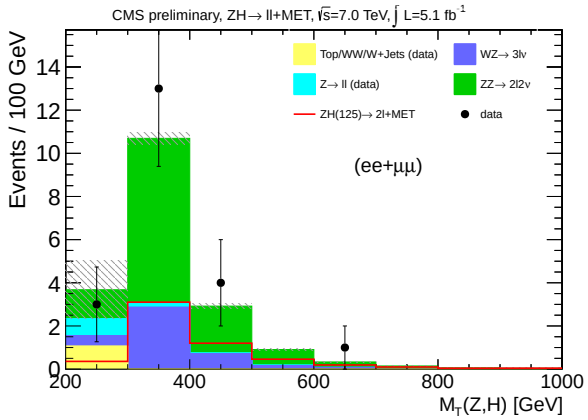
$$N_{W+\text{jets}} = \sum_i^{N_{\text{events}}} N_{RF}^i \times r_1^i \times f_2^i + N_{FR}^i \times f_1^i \times r_2^i,$$

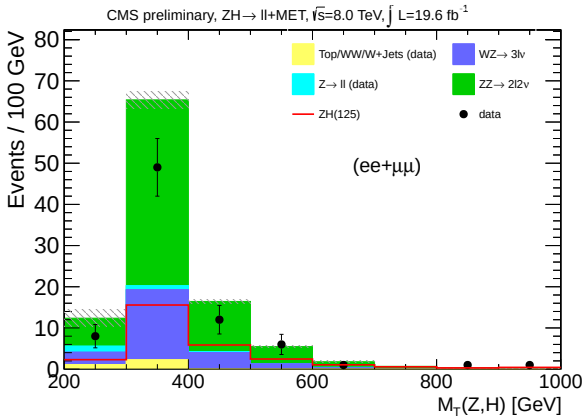
$$N_{\text{multijet}} = \sum_i^{N_{\text{events}}} N_{FF}^i \times f_1^i \times f_2^i.$$

ZH, $H \to$ invisible: Background determination

- ZZ and WZ from MC (MCFM)
- WW and top from scaling signal free $e\mu$ decay channel distributions
- Z+jets from γ+jets sample reweighted for trigger, pile-up and seletction differences







- Define 2 axis i: parallel and orthogonal to di-lepton system
- reduced $E_T^{miss^i} = p_T^{\ell\ell^i} - \min(R^i_{clust'}, R^i_{uncl})$
- $R^i_{clust'}$: clustered recoil, R^i_{uncl}: unclustered recoil

ZH, $H \to$ invisible: Systematic uncertainties

CMS:

Type	Source	Uncertainty(%)
Rate	PDF	4-5
	QCD scale variation (ZH)	7
	QCD scale variation (VV)	7-10
	Luminosity	2.2-4.4
	Lepton Trigger, Reco., Isolation	3
	$Z/\gamma^* \to \ell^+\ell^-$ normalization	100
	Top, WW & W + jets normalization	25-100
Shape	MC statistics: ZH,ZZ,WZ	1-5
	Control sample statistics $Z/\gamma^* \to \ell^+\ell^-$	12-24
	Control sample statistics NRB	53-100
	Pile Up	0.1-0.3
	b-tagging Efficiency	0.2
	Lepton Momentum Scale	1
	Jet Energy Scale, Resolution	1-3
	Unclustered energy	1-4

ATLAS:

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 $Z \to \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22