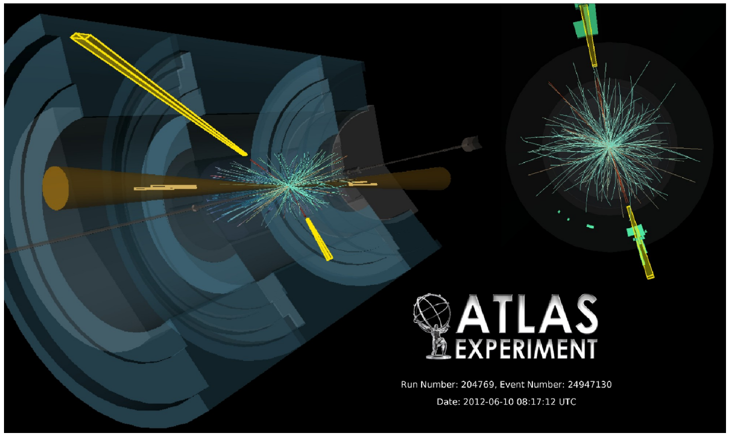


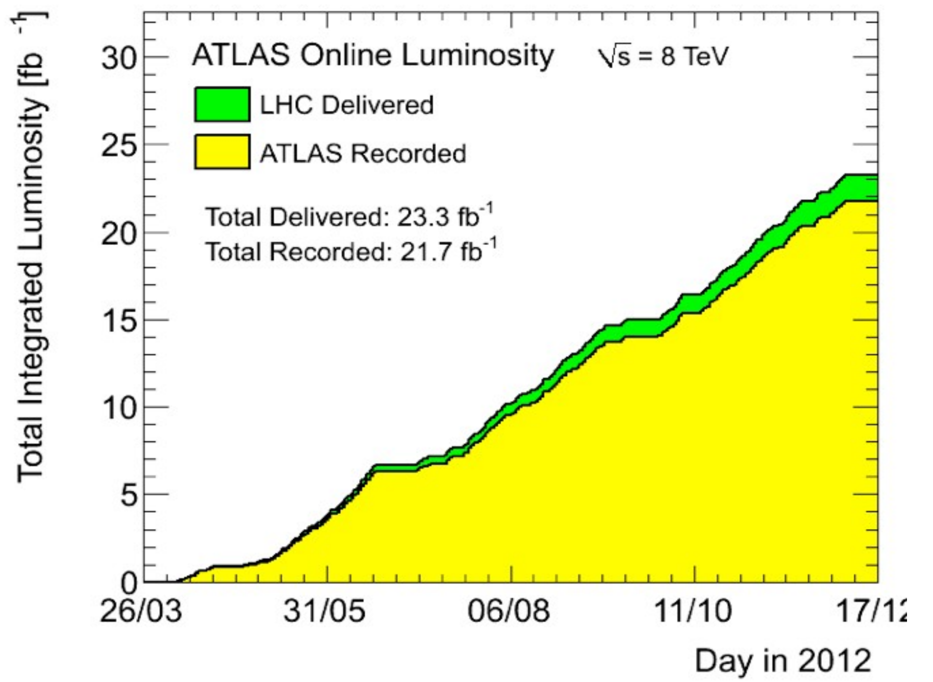
Rare Higgs Boson Decays in ATLAS

Toni Baroncelli - INFN Sezione Roma TRE
On behalf of the ATLAS Collaboration

Outline

The following Higgs boson searches will be presented in this talk

$H \to \mu^+\mu^-$	20.7fb^{-1}
$H \to Z\gamma$	4.6+20.7fb^{-1}
$ZH \to l^+l^- + inv.$	4.7+13fb^{-1}

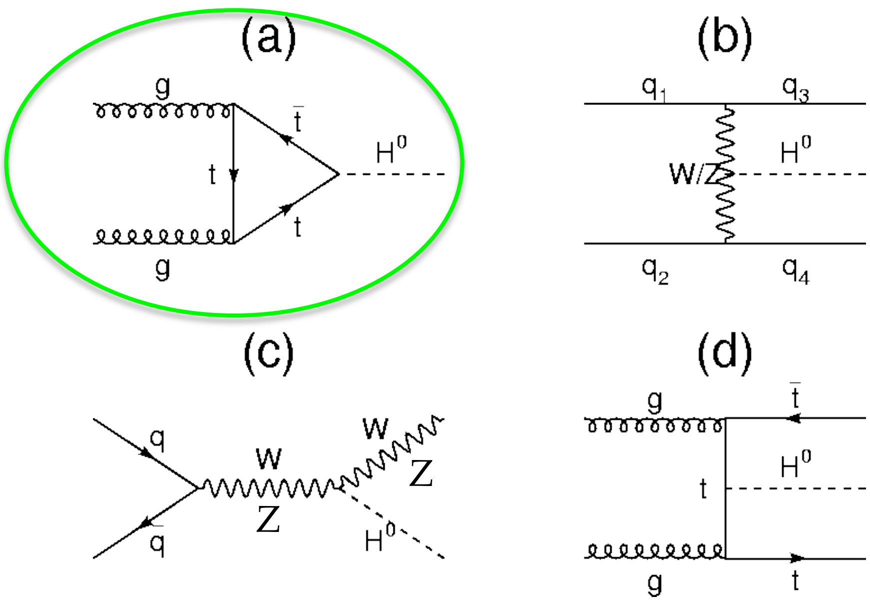


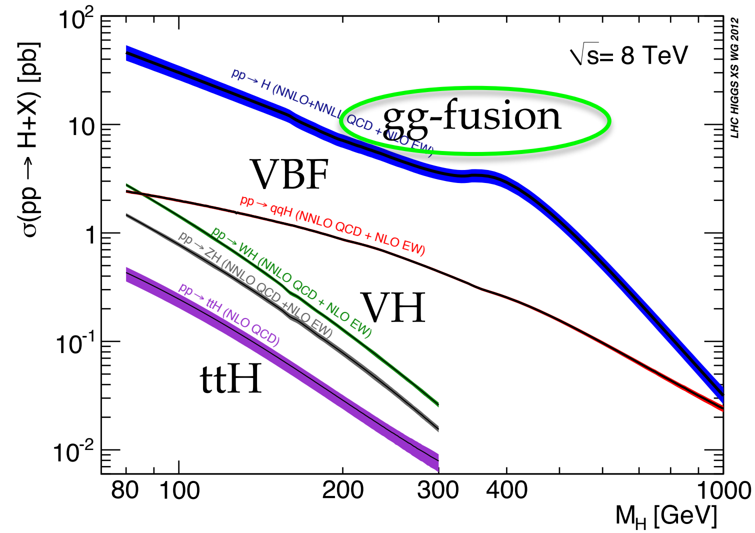
- Introduction, Higgs Production and Decay
- Data sets
- Analysis techniques
- Results
- Conclusions

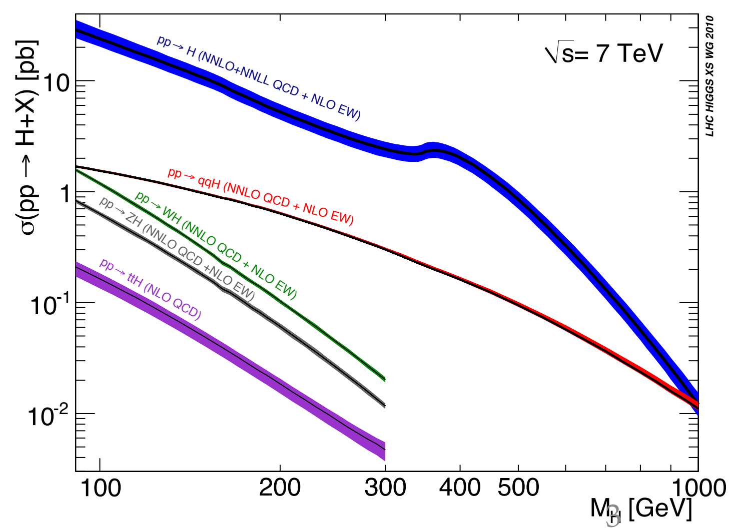
H production modes

The following four mechanisms can be tested at the LHC :

- (a) gluon fusion (19 pb @8 TeV)
- (b) VBF (WW or ZZ fusion)
- (c) Associated production (VH)
- (d) ttH production







H Decay Modes

The Higgs discovery is a breakthrough in particle physics, we need to measure its properties in all possible decay modes.

This talk will cover

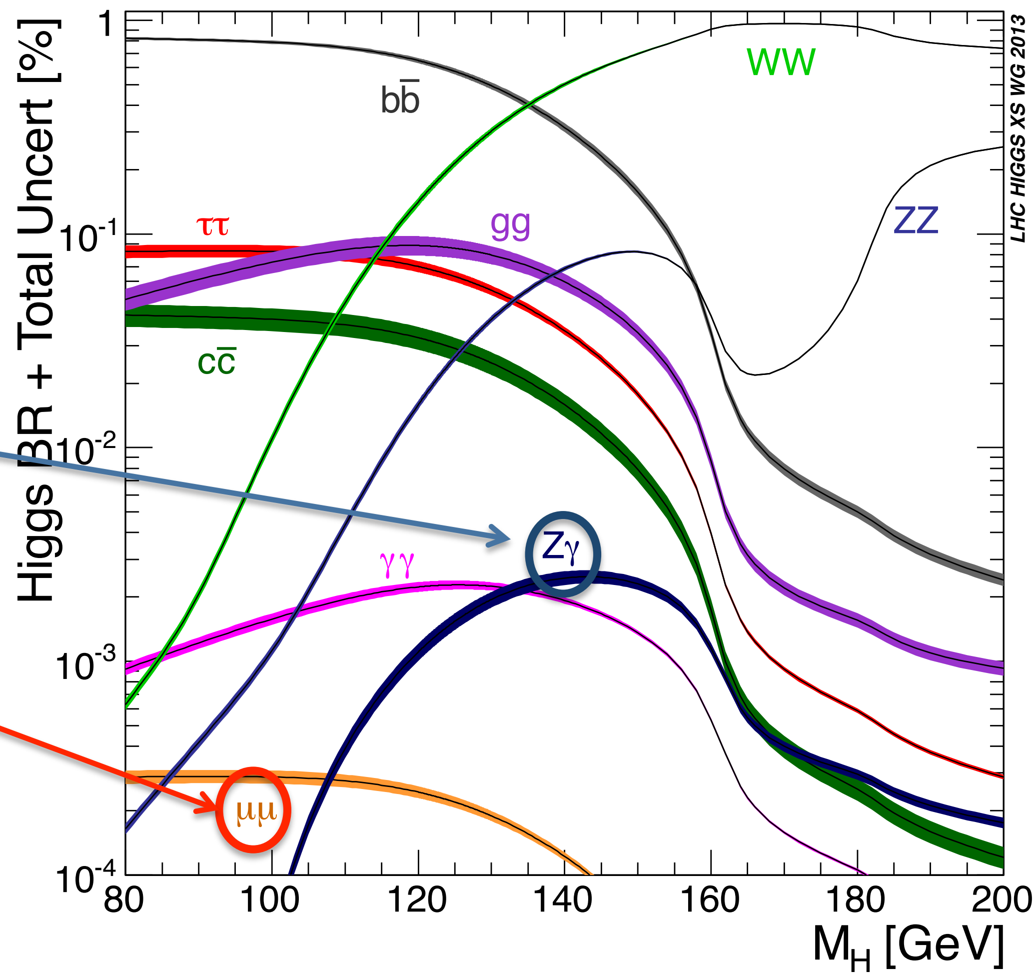
$$H \rightarrow Z\gamma \rightarrow l^+l^-\gamma$$

$$BR(Z \rightarrow l^+l^- \sim 7\%)$$

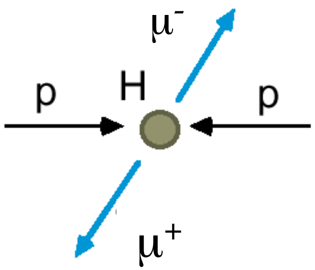
$$H \rightarrow \mu^+\mu^-$$

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

Rare decays are sensitive to Higgs boson couplings to 2nd generation fermions or new particles coupled to the Higgs boson

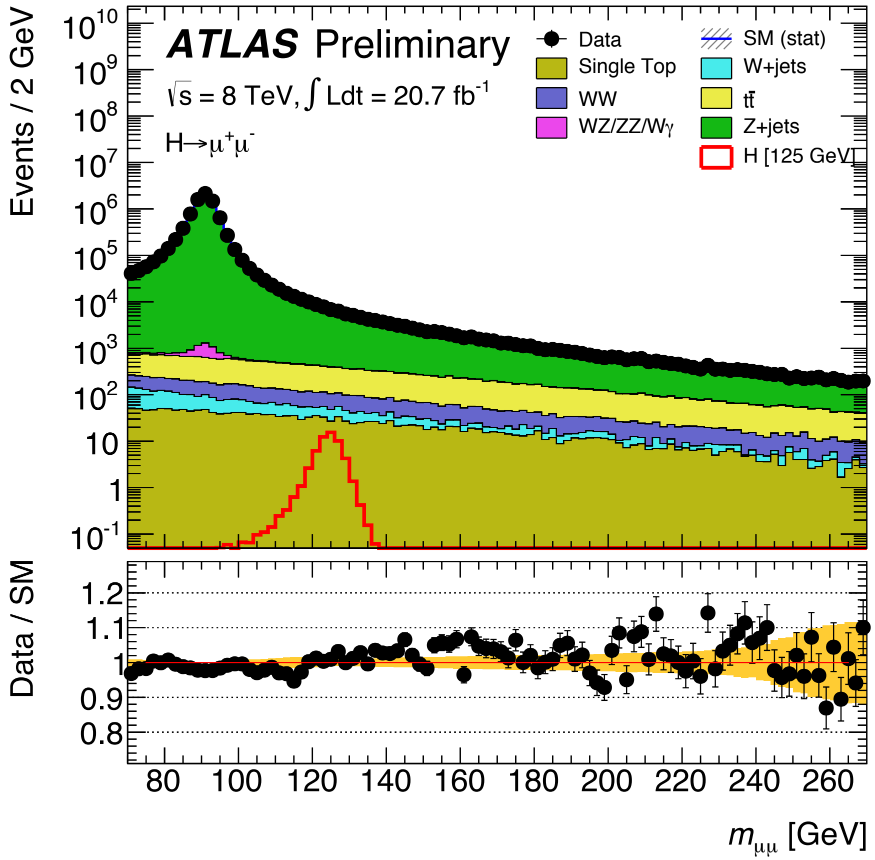


Analysis method



Two high energy opposite charge isolated muons

Look for narrow peak in distribution of $m_{\mu+\mu-}$ on a smooth background

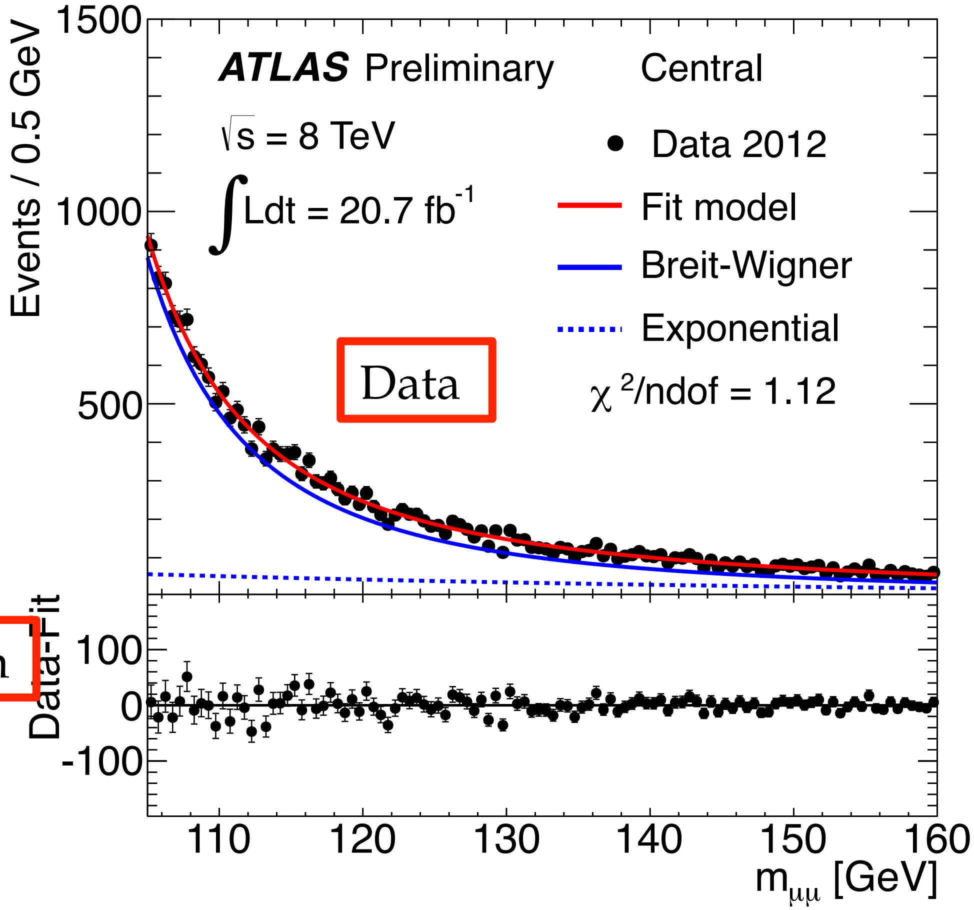


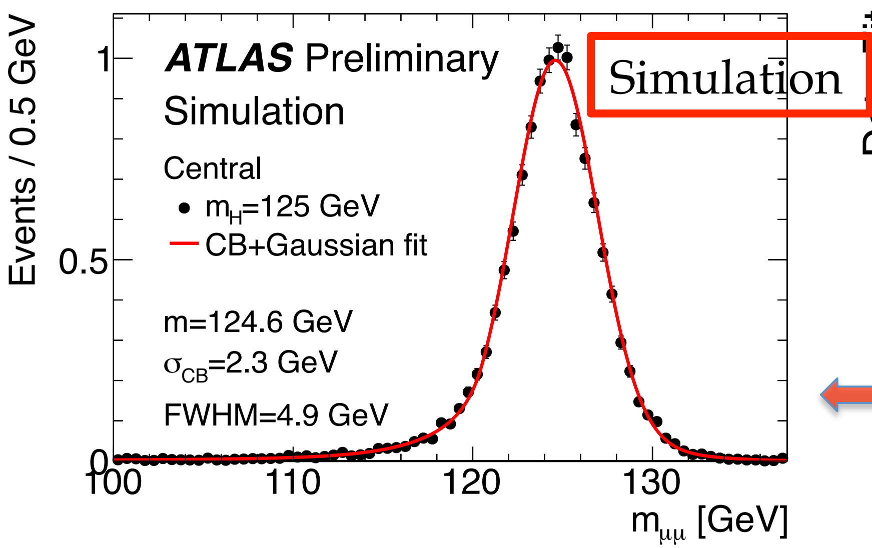
	$\lvert m_H - m_{\mu\mu}\rvert \le 5$ GeV
Signal [125 GeV]	37.7 ± 0.2
WW	250 ± 4
WZ/ZZ/Wγ	30 ± 1
$t\bar{t}$	1374 ± 13
Single Top	151 ± 5
Z+jets	15810 ± 130
W+jets	88 ± 6
Total Bkg.	17700 ± 130
Observed	17442

Sig & Bkg models

Analysis strategy

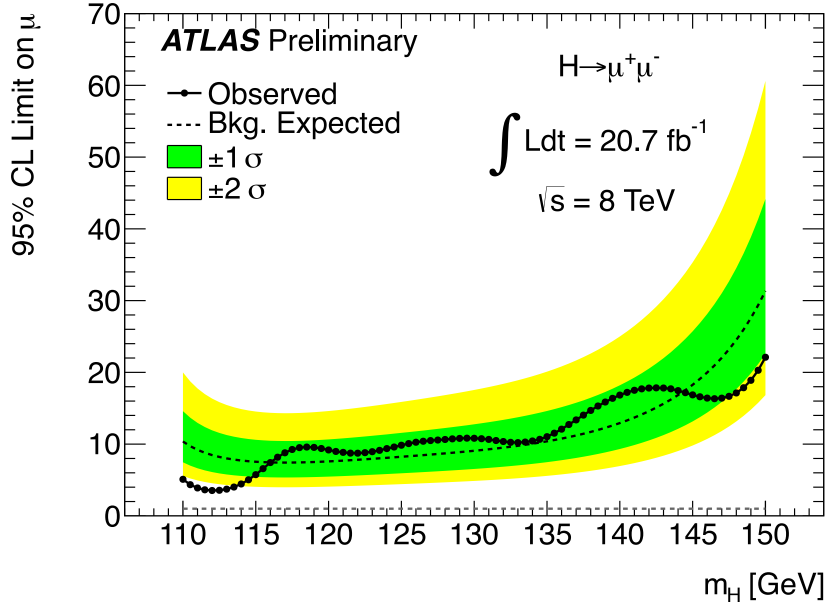
- Fit $m_{\mu\mu}$ spectrum in signal window 110-160 GeV; signal model: Crystal Ball + Gaussian; background model: Breit-Wigner + exponential
- Fit performance tested on MC and Control Regions

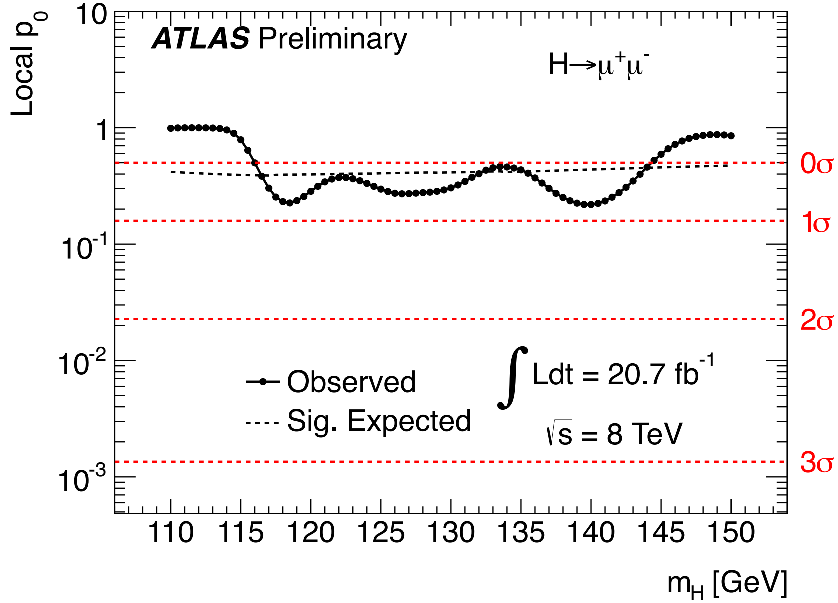




Signal pdf is fitted using simulation

Results



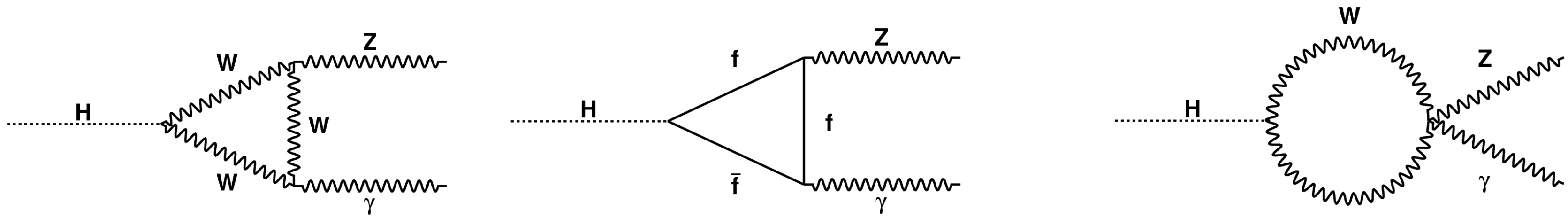


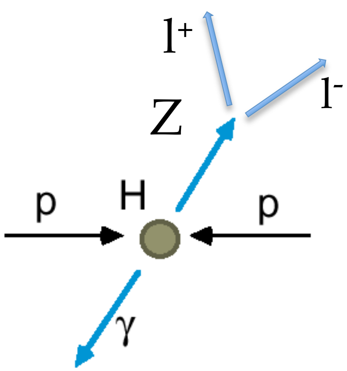
Fit data as

- (Background only) ⟶ p_0 probability that back fluctuation describes data
- (Background + μ * Signal) where μ is the strenght factor, =1 in SM

- No significant excess observed
- Observed limit on signal strength μ for m_H = 125 GeV : 9.8 x SM
- Dominant systematic uncertainties
  - Theory: cross section (~15%) and branching ratio (~few %), ISR (<3%)
  - Experimental: Luminosity (3.6%), muon reconstruction (<1%)

Analysis method





Two high energy opposite charge same flavour isolated leptons
One high energy isolated photon

Look for narrow peak signal on a smooth background
in $\Delta m = m_{ll\gamma} - m_{ll}$ spectrum.
Signal model: Crystal Ball + Gaussian, background model: 3° order Chebychev polynomial

→

The Higgs to Zγ decay proceeds via EW loop coupling to the Higgs boson and can provide constraints on BSM particles in the loop. Rate of Zγ decay similar to γγ but BR(Z to e,μ) is ~ 7%

Analysis method

Isolation criteria to suppress hadronic background: use track (sum of track p_T in a cone around the lepton direction Σp_T^{cone}) and/or calorimetric (sum of calorimeter clusters in a cone around the lepton direction E_T^{cone}). Leptons are not included in the sum. May use values normalized to the lepton p_T^l or E_T^l.

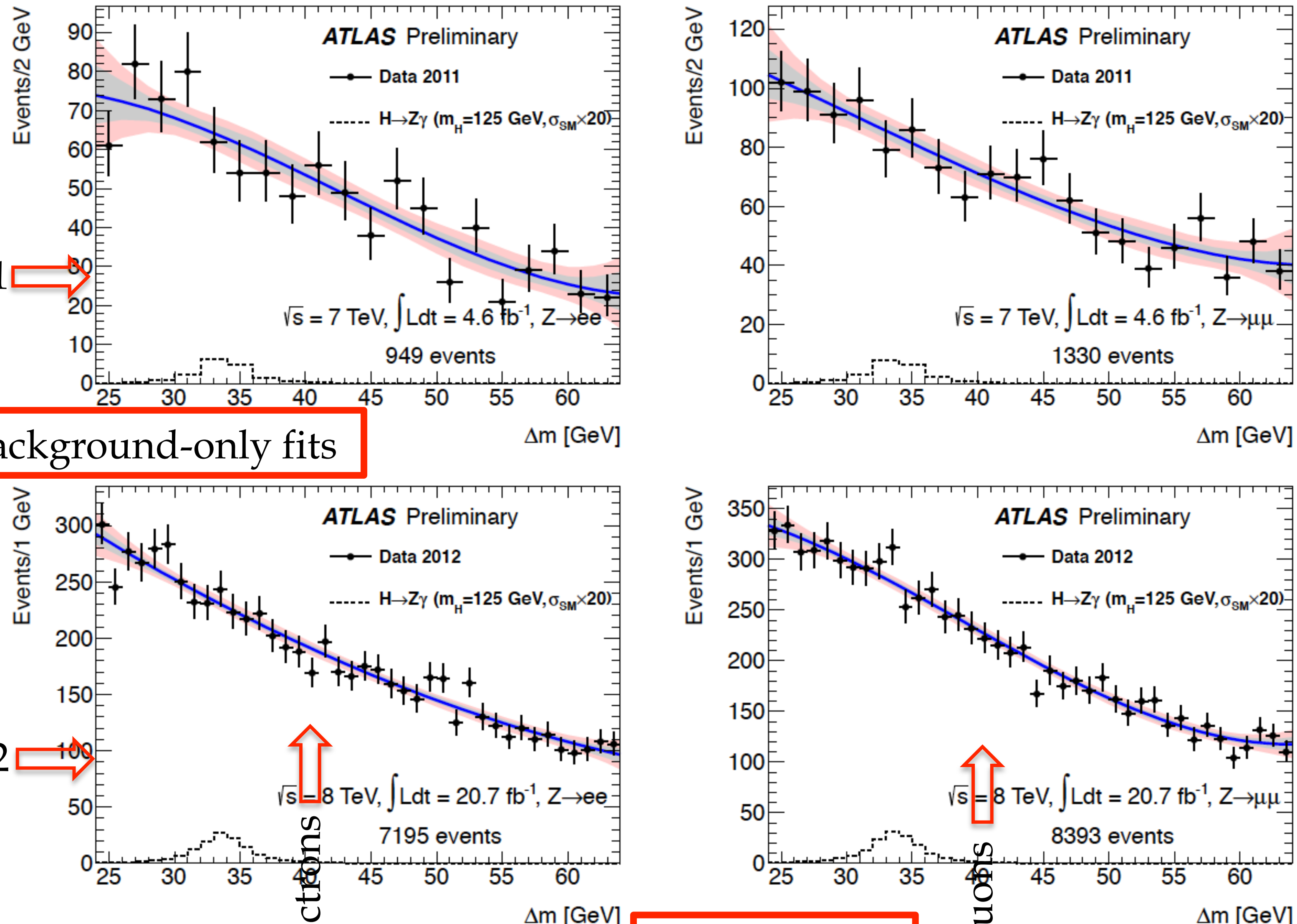
Photons	*Electrons*	*muons*
E_T > 15 GeV |η|< 2.47 region 1.37< |η|< 1.52 excluded E_T^{cone} < 4 GeV in a cone ΔR=0.4	E_T > 10 GeV |η|< 2.47 $\Sigma p_T^{cone} / p_T^l$ < .15 in a cone ΔR=0.2 E_T^{cone} / p_T^l < .2 in a cone ΔR=0.2	pTl > 10 GeV |η|< 2.47 $\Sigma p_T^{cone} / p_T^l$ < .15 in a cone ΔR=0.2 E_T^{cone} / p_T^l < .3 in a cone ΔR=0.2

Event selection

- *Z selection*
  - Two opposite charged isolated high p_T (>10 GeV) electrons or muons
  - $m_{ll} > m_Z$ - 10 GeV (get rid of FSR in $Z \to ll\gamma$)

H→Zγ Bkg. Model

Toni Baroncelli: Rare Higgs Decays in ATLAS



2011

2012

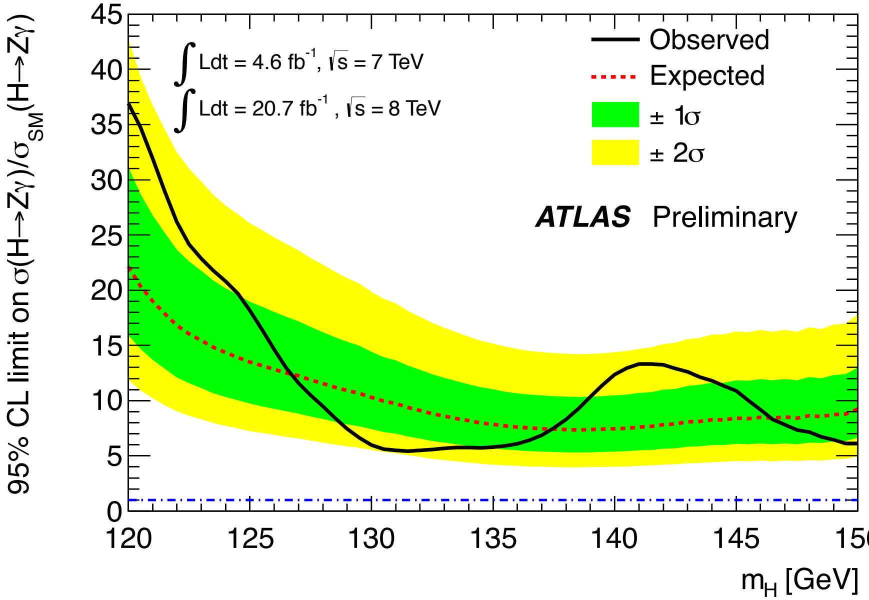
Background-only fits

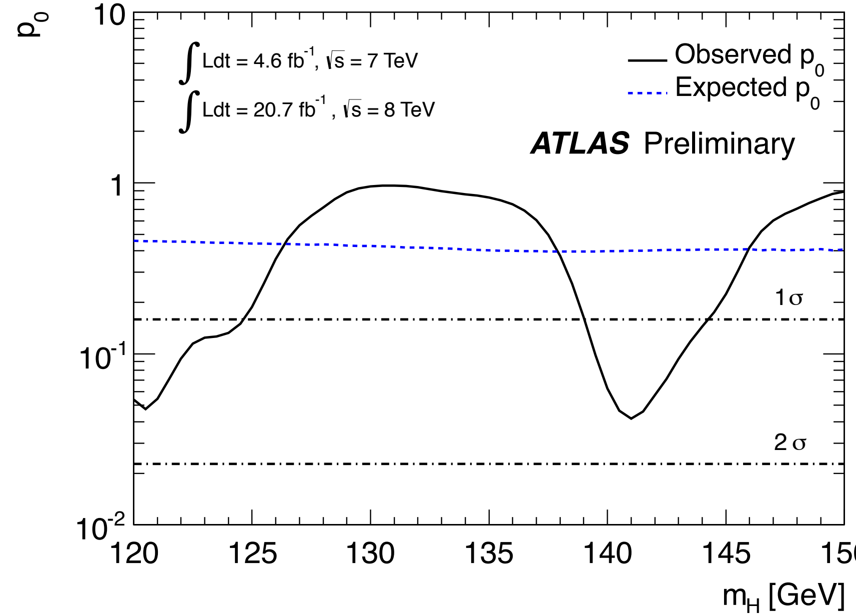
electrons

muons

$\Delta m = m_{ll\gamma} - m_{ll}$

Results





Fit data as

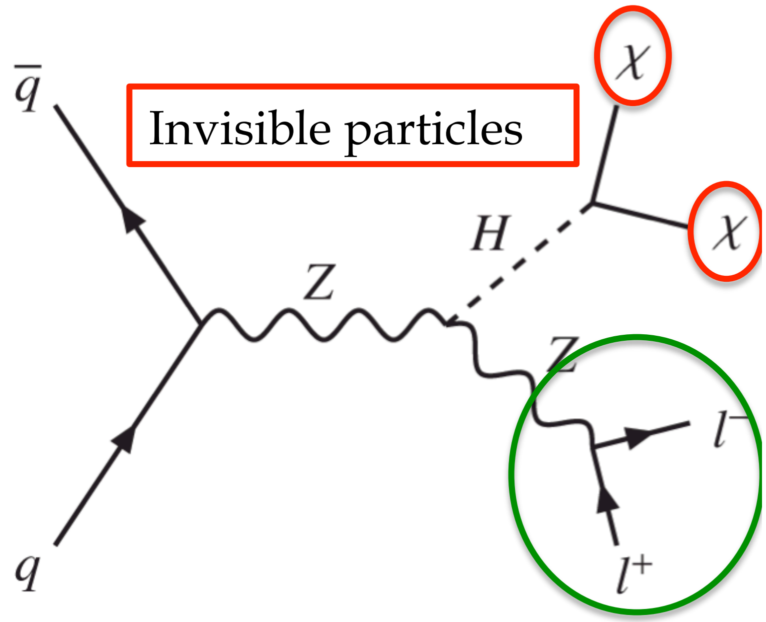
- (Background only) ⟶ p_0 probability that back fluctuation describes data
- (Background + μ * Signal) where μ is the strenght factor, =1 in SM

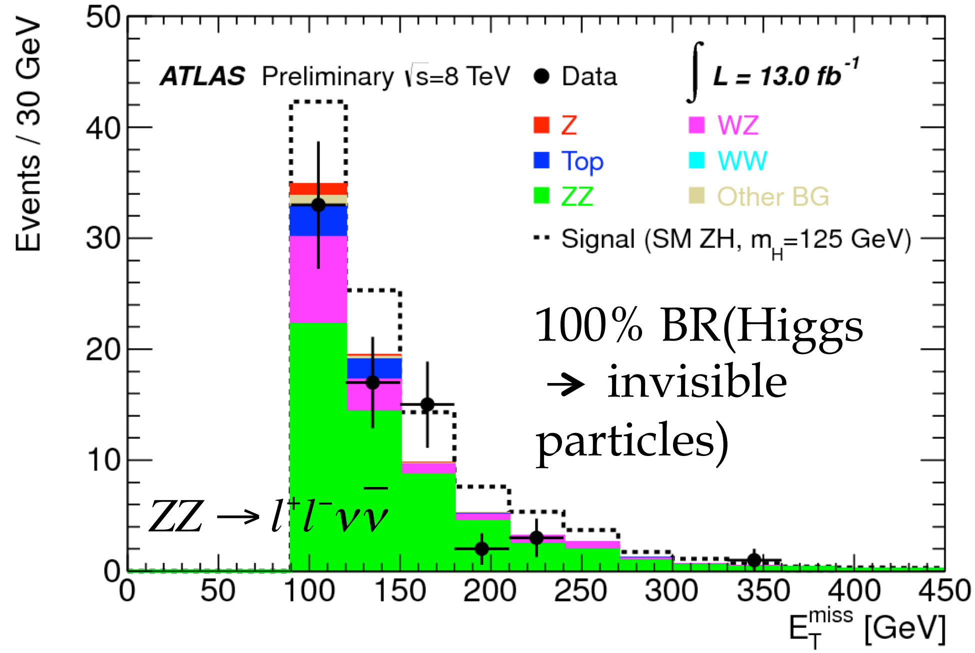
Limits set in the range 120 to 150 GeV

- Observed limit on signal strength μ for m_H = 125 GeV : 18.2 x SM
- Expected limit on signal strength μ for m_H = 125 GeV : 13.5 x SM

Analysis method

Higgs coupling to non SM particles is an excellent way to probe for new physics

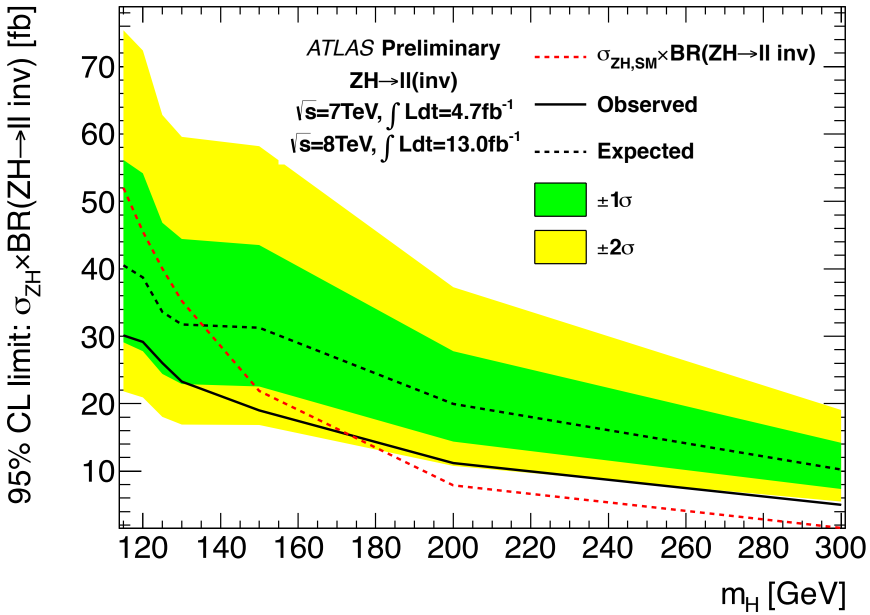


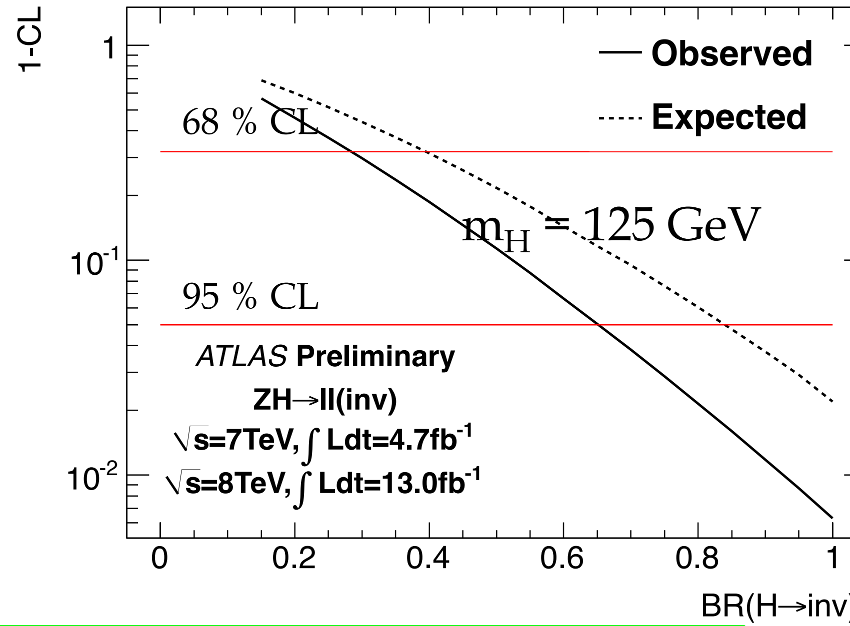


Background composition in the signal region.

Event selection

- E_T^{miss} > 90 GeV; $\Delta\Phi(E_T^{miss}, p_T^{miss}) < 0.2$
- Two opposite charged isolated SF high p_T (>20 GeV) e,μ , $|m_{ll} - m_Z| < 15$ GeV
- $\Delta\Phi(E_T^{miss}, p_T^{ll}) > 2.6$, $\Delta\Phi(ll) < 1.7$, $|E_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.2$





Look for an excess of events with respect to expected background

Absence of excess interpreted as upper limit on σ_{ZH} x BR(ZH ⟶ ll+inv.)

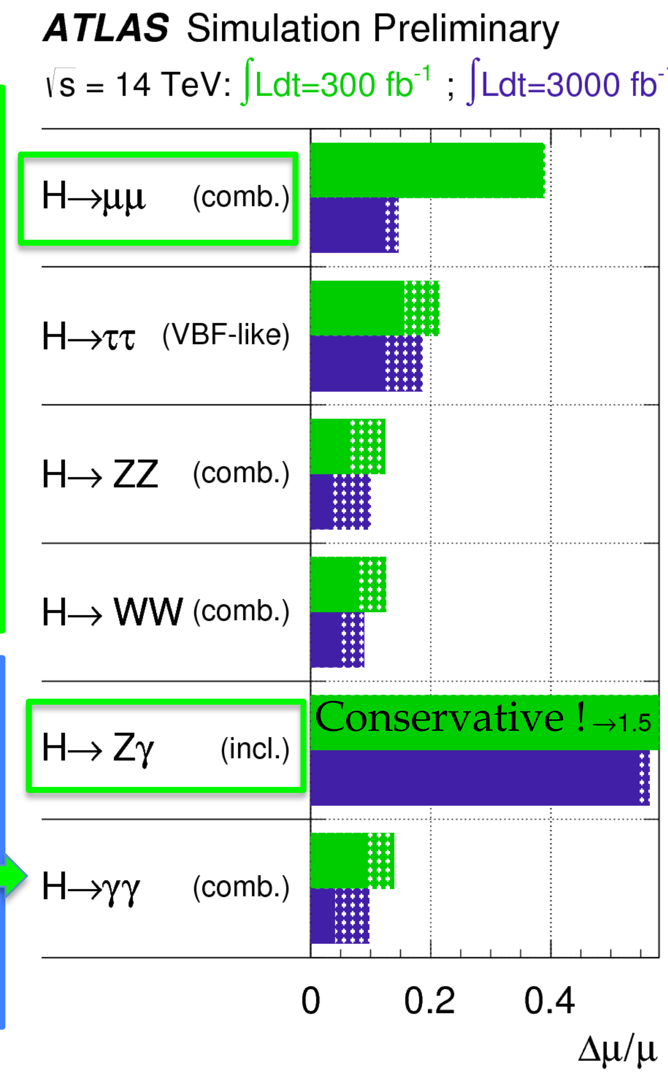
BR (H ⟶ inv.) > 65 % observed (84 % expected) excluded at 95% CL for an Higgs boson with m_H = 125 GeV

Limit on σ_{ZH} x BR(ZH ⟶ ll+inv.) for Higgs-like states with 115 < m_H < 300 GeV

The data sample collected by ATLAS at the LHC has been used to search for non-SM Higgs behavior in rare Higgs decays

The analysis results are:

- 95% CL exclusion limit for SM Higgs with mass 125 GeV:
  - H→ $\mu\mu$: obs. (exp.) 9.8 (8.2) x SM
  - H→Zγ : obs. (exp.) 18.2 (13.5) x SM
- No evidence for significant branching fraction H→inv.
  - BR (H→inv.) < 65(84) % @ 95% CL obs. (exp.) for mH = 125 GeV



Outlook

- Improvements with Run I data possible: use full dataset & optimize analysis
- With next LHC Run (300fb^{-1}) and full HL Run data (3000fb^{-1}) (m_{Higgs} = 125 GeV)

BACKUP Slides

Material

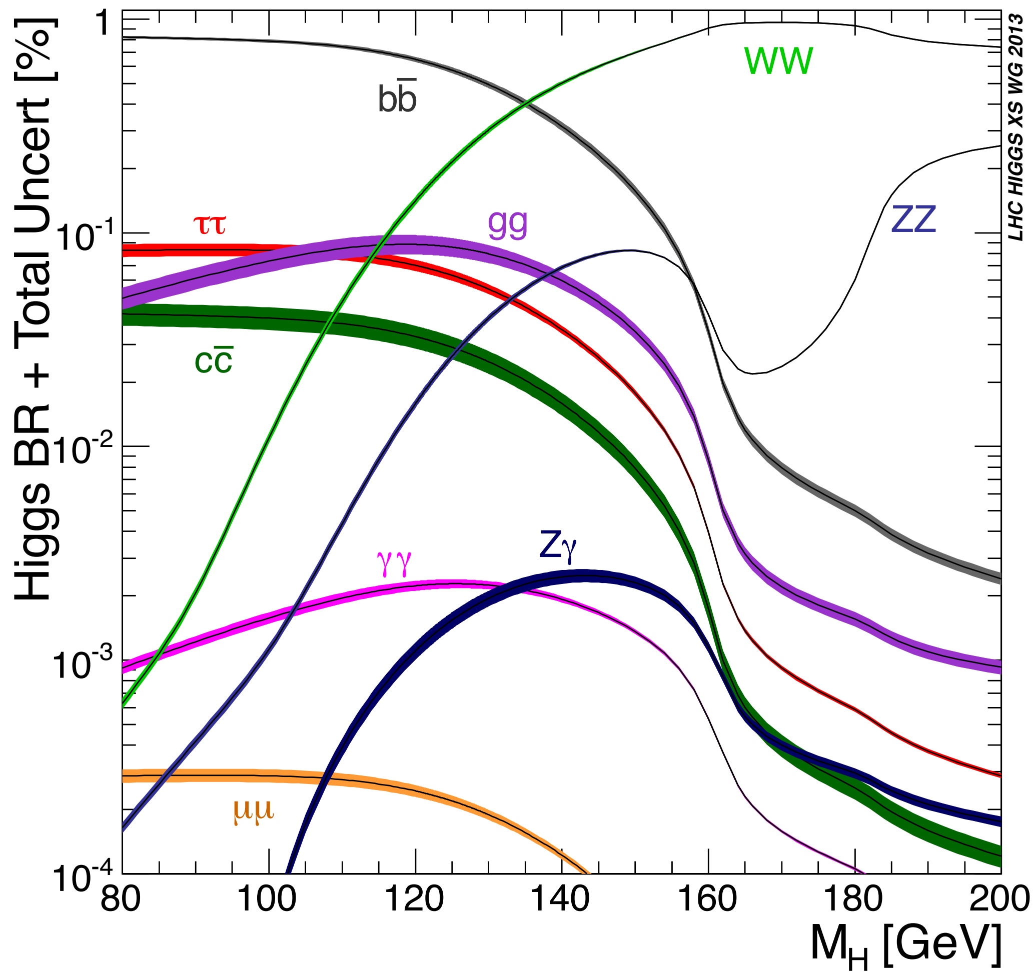
Analysis	Conference Note
$H \rightarrow \mu^+\mu^-$	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-010/
$H \rightarrow l^+l^-$ + inv.	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-011/
$H \rightarrow Z\gamma$	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-009/
Projections for measurements of Higgs boson … at LHC HL run	https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-011

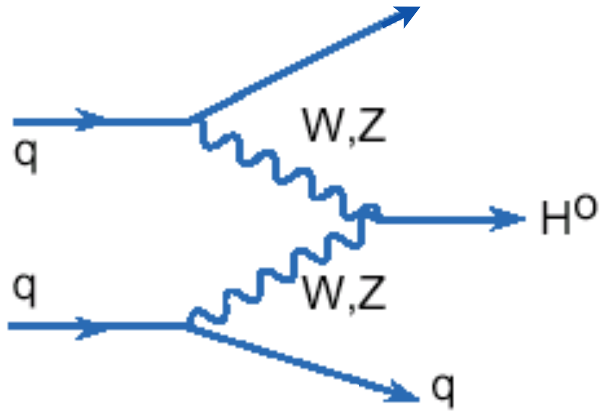
Higgs Boson Decay

According to the SM for a M_H~125 GeV:

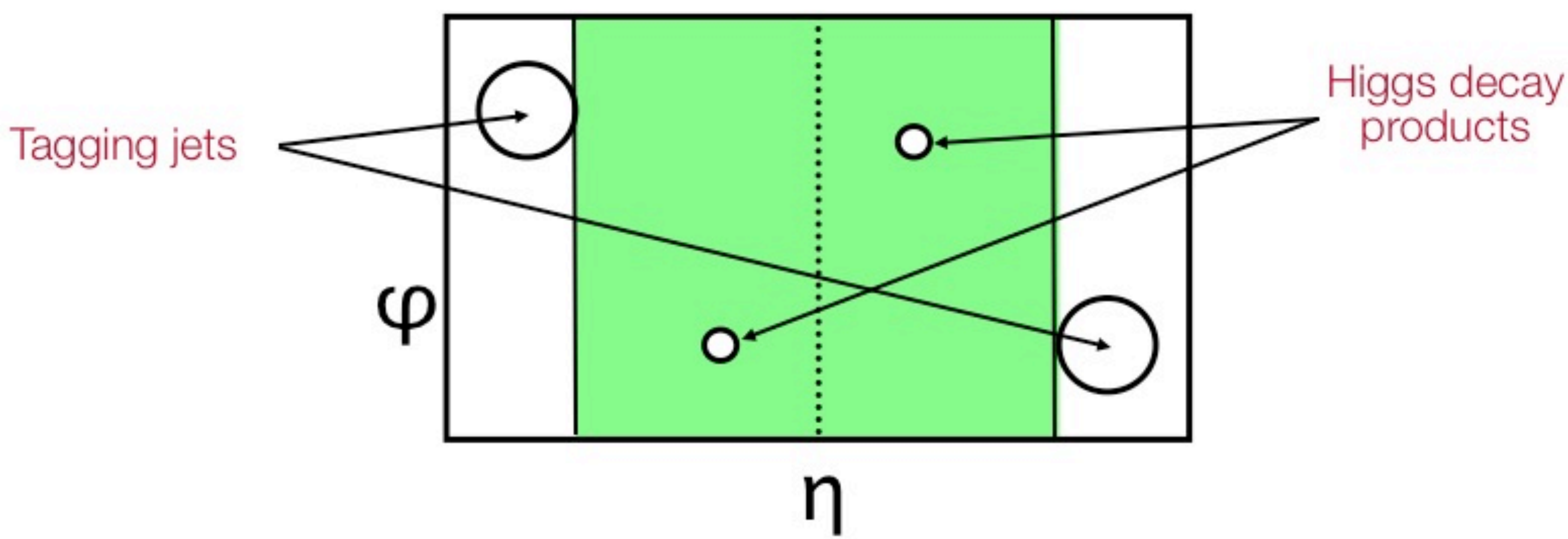
- H(bb) – 57% (hard)
- H(WW) - 22%
- H($\tau\tau$) - 6.2%
- H(ZZ) - 2.8% (easy)
- H($\gamma\gamma$) - 0.23% (easy)

This means that several channels are experimentally accessible!



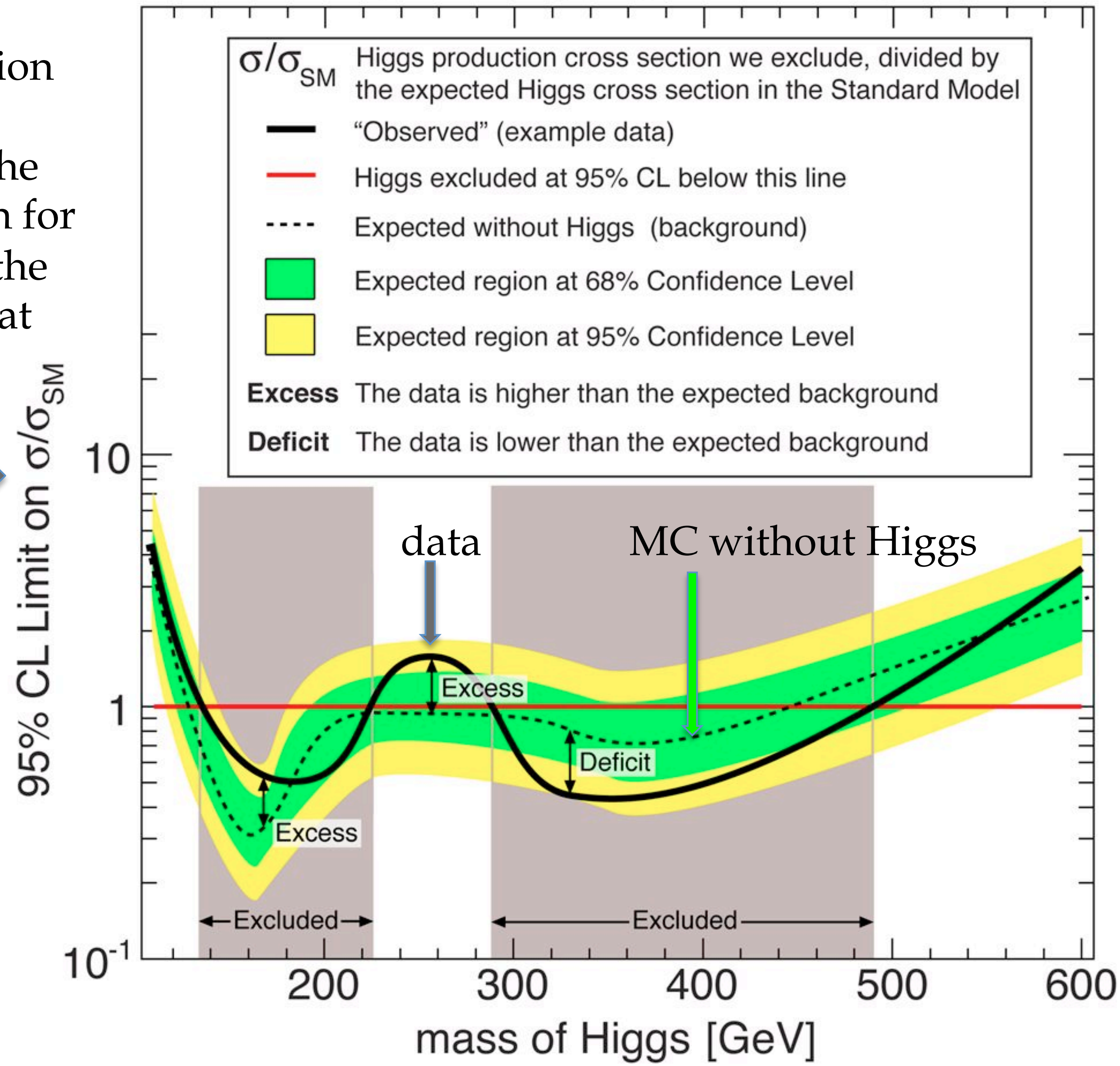


Distinctive signature:
- two forward jets (tagging jets)
- little (jet) activity in central region (central jet veto)



Exclusion Plots

Higgs boson production cross-section that we exclude, divided by the expected cross section for Higgs production in the Standard Model at that mass.



Background estimation in invisible Higgs

Background estimation

- ZZ and WZ estimated from simulation
- WW, Z to $\tau\tau$, top use signal free eμ control regions
- Z estimated using ABCD method in $\Delta\Phi(E_T^{miss}, p_T^{miss})$, $| E_T^{miss} - p_T^{ll} | / p_T^{ll}$
- W and multijets 4 x 4 matrix method using lepton efficiencies and fake rates

Exclusion Plots

The Standard Model does not predict the mass of the Higgs boson, but does predict the production cross section once the mass is known. The "cross section" is the likelihood of a collision event of a particular type.

ATLAS uses plots like this one to seek hints for the Higgs boson and also to exclude regions of mass where the Higgs is very unlikely to be found. This example is not real data, but is a simplified plot to show how we interpret the results of our searches for the Higgs boson. The vertical axis shows, as a function of the Higgs mass, **the Higgs boson production cross-section that we exclude, divided by the expected cross section for Higgs production in the Standard Model at that mass**. This is indicated by the solid black line. This shows a 95% confidence level, which in effect means the certainty that a Higgs particle with the given mass does not exist. The dotted black line shows the median (average) expected limit in the absence of a Higgs. The green and yellow bands indicate the corresponding 68% and 95% certainty of those values.

If the solid black line dips below the value of 1.0 as indicated by the red line, then we see from our data that the Higgs boson is not produced with the expected cross section for that mass. This means that those values of a possible Higgs mass are excluded with a 95% certainty. In this example, two regions would be ruled out at 95% certainty: approximately 135-225 GeV and 290-490 GeV.

If the solid black line is above 1.0 and also somewhat above the dotted black line (an excess), then there might be a hint that the Higgs exists with a mass at that value. If the solid black line is at the upper edge of the yellow band, then there may be 95% certainty that this is above the expectations. It could be a hint for a Higgs boson of that mass, or it could be a sign of background processes or of systematic errors that are not well understood. In this example, there is an excess and the solid black line is above 1.0 between about 225 and 290 GeV, but the excess has not reached a statistically significant level.

The red-gray shaded regions show what is excluded. The "bump" near a mass of 250 GeV could be a slight hint of a Higgs boson in this fictional example.

Limits Setting - 2

This plot shows hypothetical data and expectations that could be used in setting the limits shown in Figure A.The green curve shows (fictional) predicted results if there were a Higgs boson in addition to all the usual backgrounds. It could also represent the predictions of some other new physics. The dashed black curve shows what is expected from all background processes without a Higgs or some new physics. The black points show the hypothetical data.

In this case, the data points are too low to explain the Higgs boson hypothesis (or whatever new physics the green curve represents), so we can rule out that hypothesis.

Nonetheless the data points are higher than the expectations for the background processes. This could yield an excess such as shown on the left in Figure A. There are three possible explanations for this excess:

It is a statistical fluctuation above the expected background processes.

It is a systematic problem due to an imperfect understanding of the background processes.

The excess is due to some different new physics (than that hypothesized) that would predict a smaller excess.

If instead, the black points lay close to the green curve, that could be evidence for the discovery of the Higgs boson (if it were statistically significant).

If the black points lay on or below the dashed black curve (the expected background), then there is no evidence for a Higgs boson and depending on the statistical significance, the Higgs boson might be ruled out at the corresponding mass.

Limits - Setting

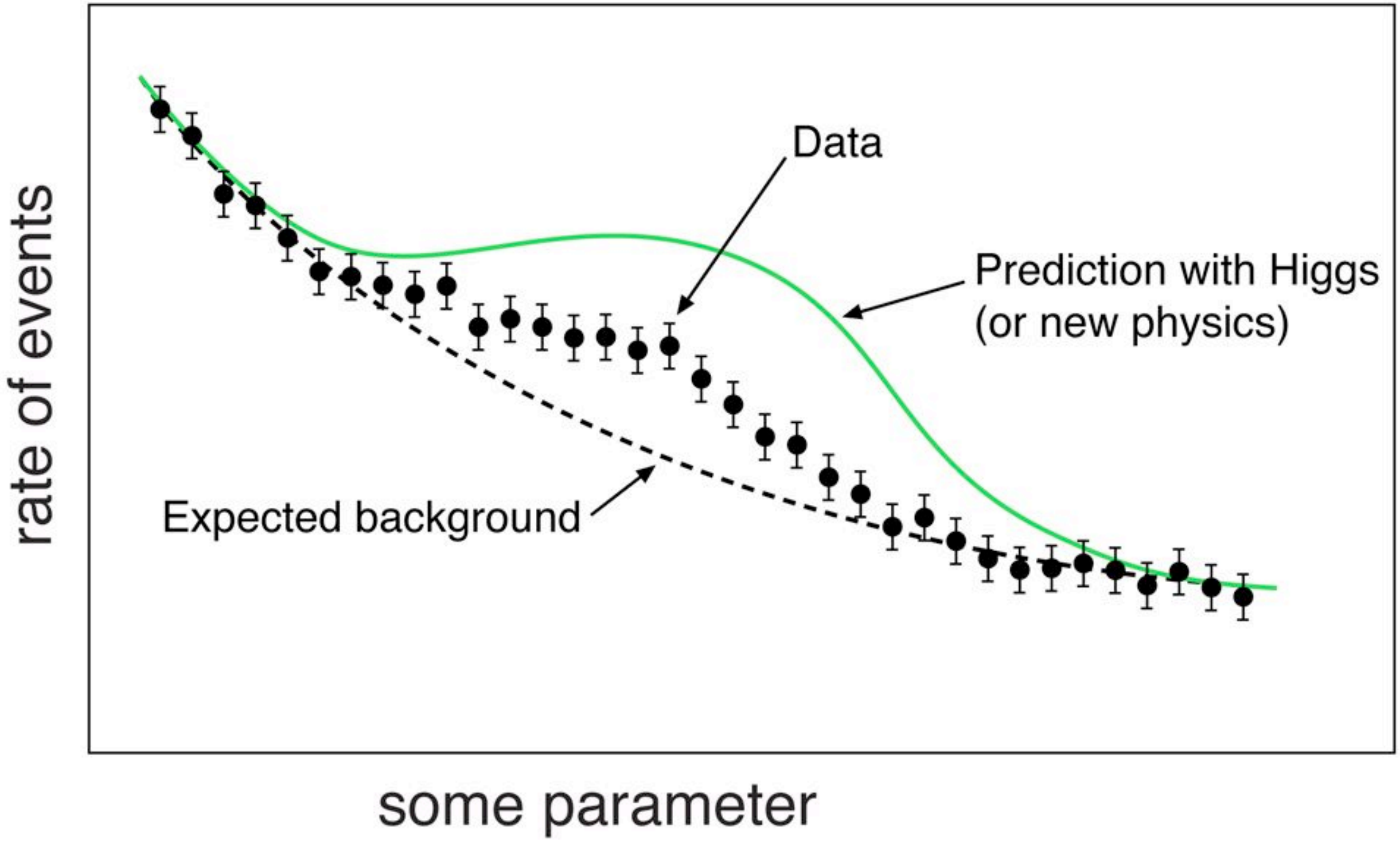


Figure B

Isolation criteria

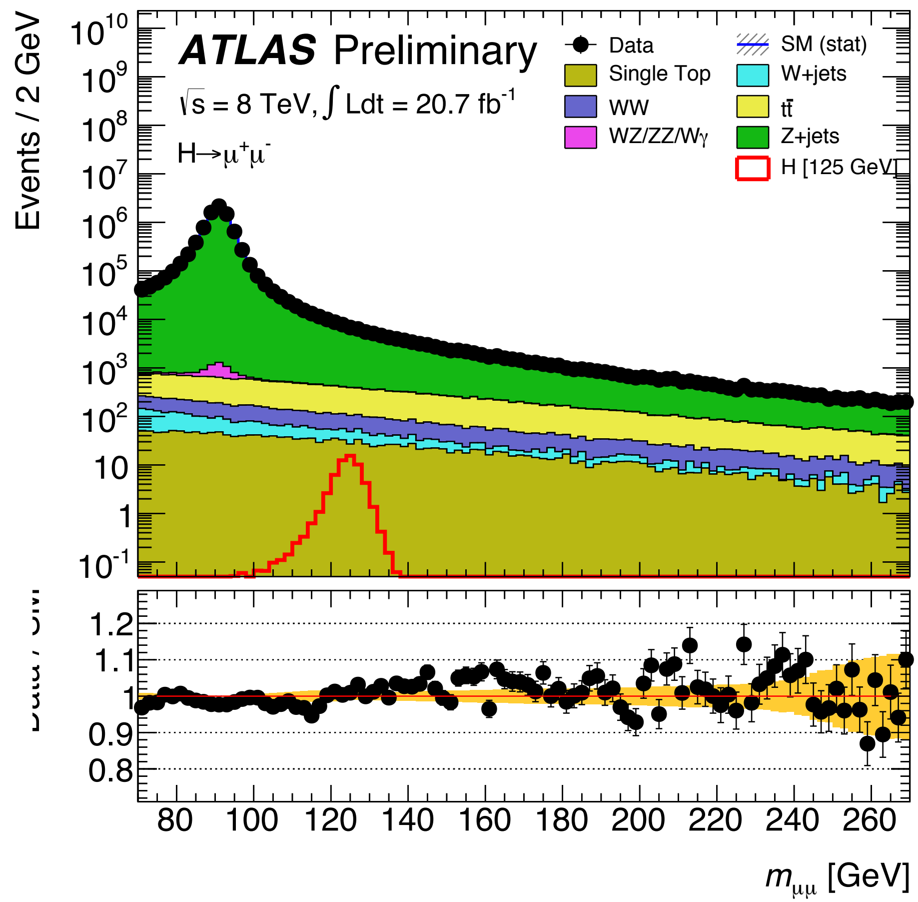
Photons: sum E_T of clusters in a cone $\Delta R=0.4$ around the photon. Photon E_T excluded

Electrons and Muons: use

- normalized track isolation (Σp_T of tracks in a cone $\Delta R=0.2$ around the *l*) / lepton pT
- normalized calo isolation for electrons (sum of calo-clusters in a cone $\Delta R=0.2$ around the *l*

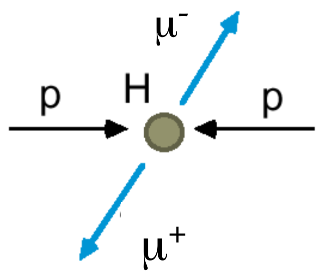
Analysis method

	$\lvert m_H - m_{\mu\mu}\rvert \leq 5$ 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 Bkg.	17700 ± 130
Observed	17442



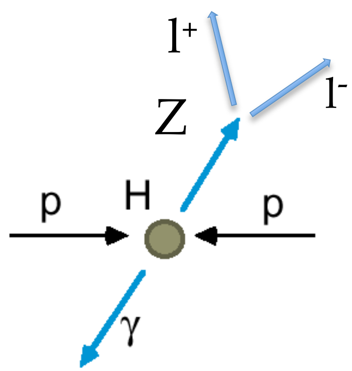
Topologies

In all cases, electrons, muons, photons pass quality criteria and are isolated



Two high energy opposite charge same flavour isolated muons

Look for narrow peak in distribution of $m_{\mu+\mu-}$ on a smooth background



Two high energy opposite charge same flavour isolated leptons
One high energy isolated photon

Look for narrow peak on a smooth background
in $\Delta m = m_{ll\gamma} - m_{ll}$ spectrum