Searches for Rare Decays of the Higgs Boson with the ATLAS Detector

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High Energy Physics in the LHC Era
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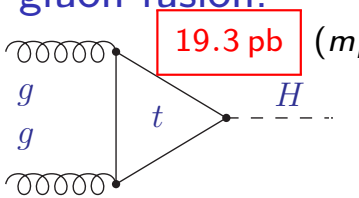
Overview

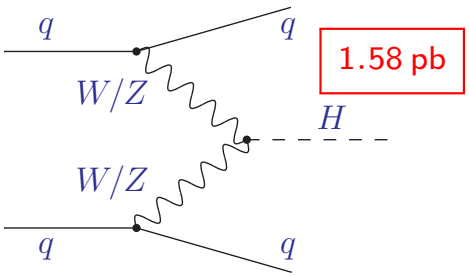
Production modes:

gluon fusion:

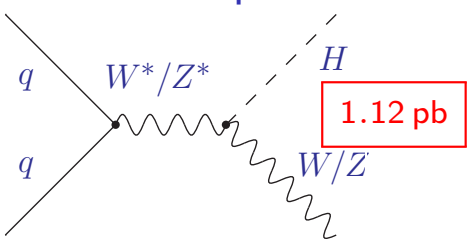


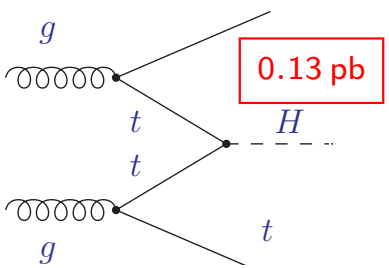
($m_H = 125$ GeV @ 8 TeV)

vector boson fusion:



associated production:



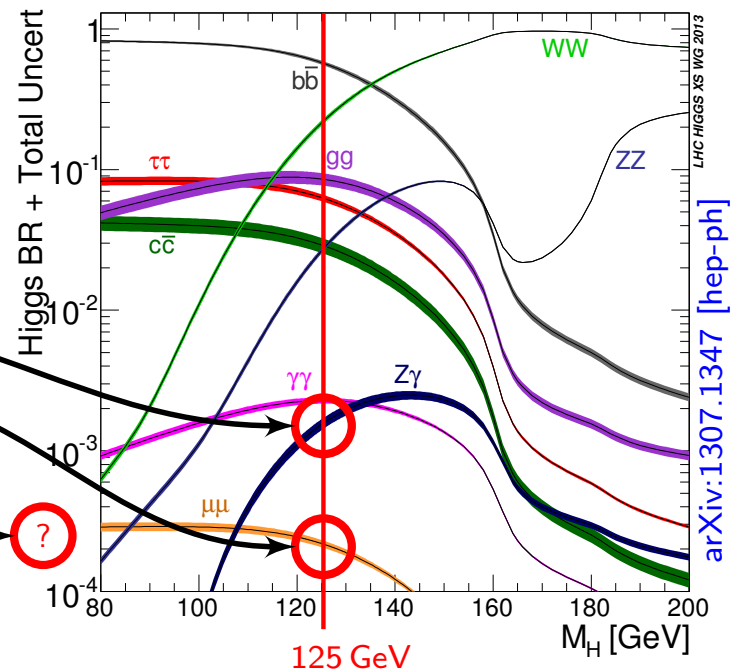


Why search for rare Higgs decays?

- Properties of discovered Higgs boson consistent with Standard Model hypothesis.
- But no definitive statement on its nature possible, yet.
- All possible decay channels need to be explored.
- Rare decay modes help to gain insight into its nature. Even if channels are not expected to be sensitive, yet.
- Observation of such signatures in current data indicates BSM Higgs sector.

This presentation:

- $H \to Z\gamma$
- $H \to \mu^+\mu^-$
- $H \to$ invisible



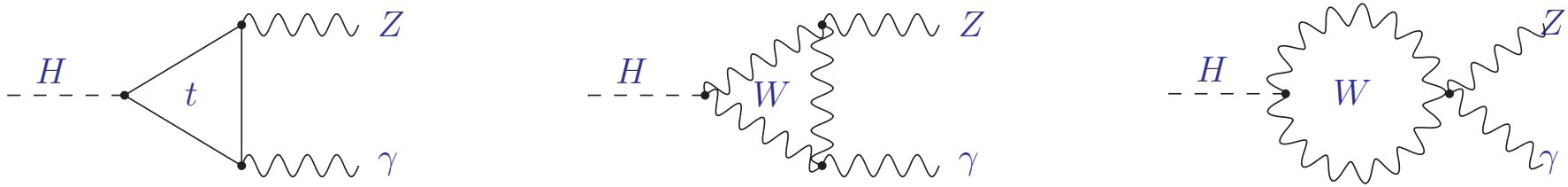
Search for $H \to Z\gamma$

in 20.7 fb^{-1} of p–p collision data recorded at $E_{cm} = 8\,\text{TeV}$ (2012) and 4.6 fb^{-1} recorded at 7 TeV (2011).

[ATLAS-CONF-2013-009]

Decay and Signal Signature

Inclusive search for Higgs boson decays to $Z\gamma$...



...with subsequent decays $Z \to \ell^+\ell^-$ (with $\ell^\pm = e^\pm$ or $\mu^\pm$).

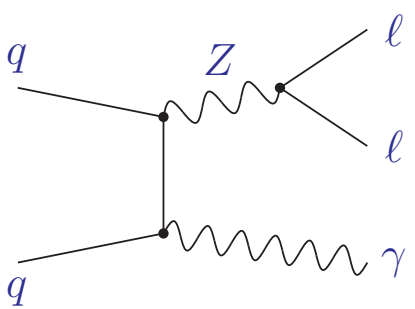
Signature to be searched for: $e^+e^-\gamma$ or $\mu^+\mu^-\gamma$.

Total branching fraction for $m_H = 125$ GeV:

$$\mathcal{B}(H \to Z\gamma \to \ell^+\ell^-\gamma) = 1.54 \cdot 10^{-3} \times 6.73 \cdot 10^{-2} = 1.04 \cdot 10^{-4}$$

Main Background Processes: $Z + \gamma$

- diboson production



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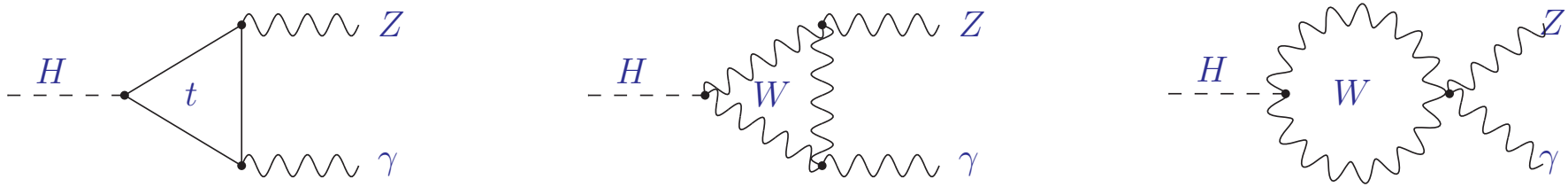

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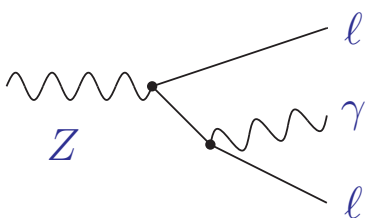
- FSR in $Z \to \ell^+\ell^-$ decays



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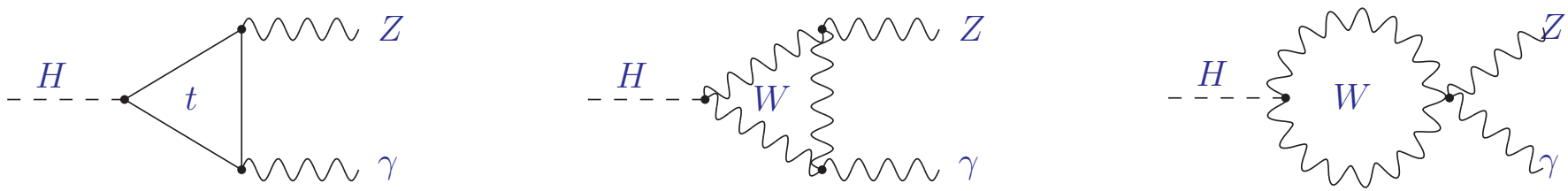

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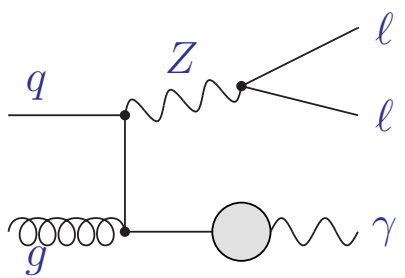
Main Background Processes: $Z + \gamma$

- diboson production
- FSR in $Z \to \ell^+\ell^-$ decays
- parton–to–photon fragmentation



Decay and Signal Signature

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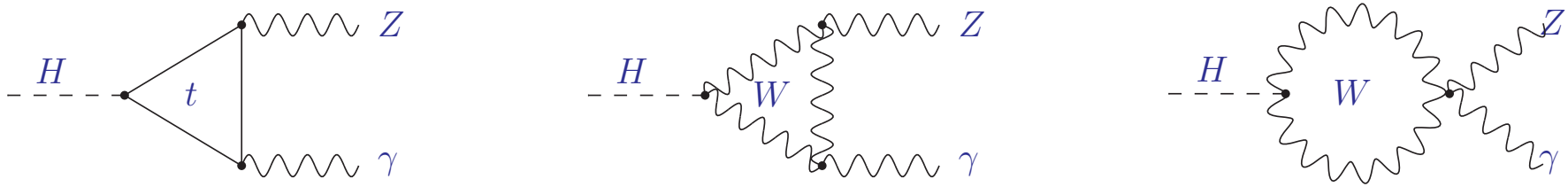

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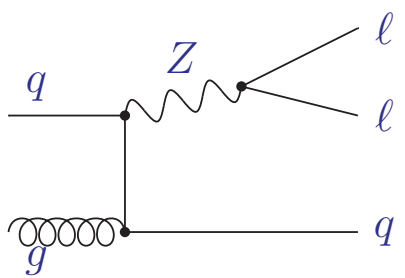
Main Background Processes: $Z + \gamma$

- diboson production
- FSR in $Z \to \ell^+\ell^-$ decays
- parton–to–photon fragmentation
- misidentification of jet as a photon



Event Selection

$Z\gamma$ Selection:

- Same–flavour opposite–charge lepton pair:
  - leptons to be isolated from additional tracks and calorimeter clusters.
- and the highest transverse energy photon.

$H \to Z\gamma$ Candidates:

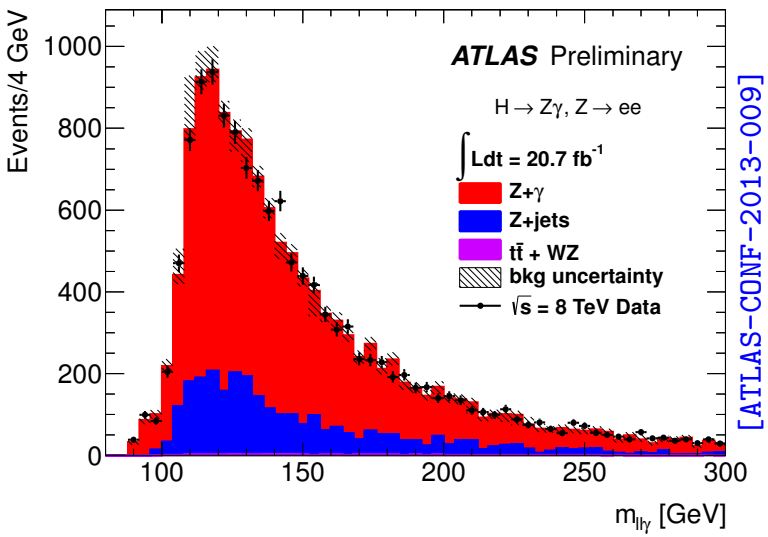
- Photon cluster isolated from additional hadronic or electromagnetic activity.
  reduces contributions from parton–photon fragmentation.
- Reject photon candidates close to electron or muon
  $\to$ suppression of FSR Z and $H \to \ell\ell^* \to \ell\ell\gamma$ contributions.
- $m_{\ell\ell} > m_Z - 10\,\text{GeV}$ and $115 < m_{\ell\ell\gamma} < 170\,\text{GeV}$
  $\to$ suppression of FSR Z and $H \to \ell\ell^* \to \ell\ell\gamma$ and $H \to \gamma\gamma \to \ell\ell\gamma$.

Event Selection

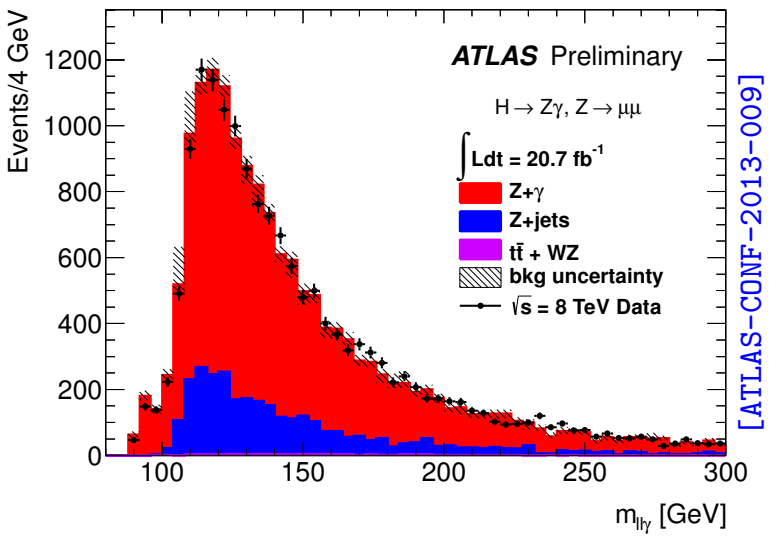
$Z\gamma$ Selection:

Selected $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ candidate events in data:

- 13978 (1927) in 8 (7) TeV
- Exp. signal: 5.9 (0.9)



- 16678 (2621) in 8 (7) TeV
- Exp. signal: 7.2 (1.1)



Background composition: 0.82 ($Z+\gamma$), 0.17 (Z+jets), 0.01 (other).

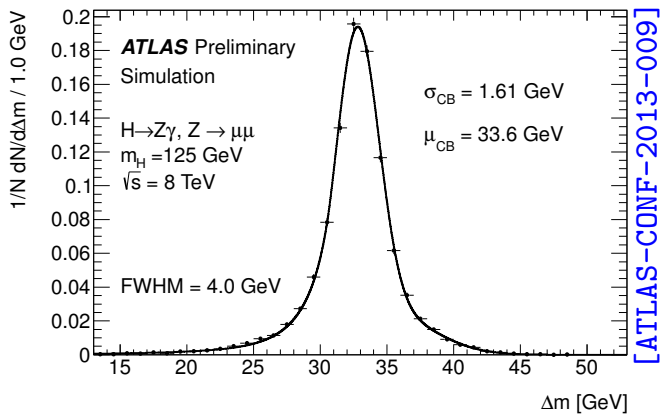
Signal and Background Modeling

Analysis Strategy: Signal and background contributions in $H \to Z\gamma$ determined by a fit of an analytic S+B function to the data.
Discriminating variable: $\Delta m = m_{\ell\ell\gamma} - m_{\ell\ell}$.

To large extent insensitive to lepton scale uncertainties and FSR $H \to \mu^+\mu^-$ contributions.

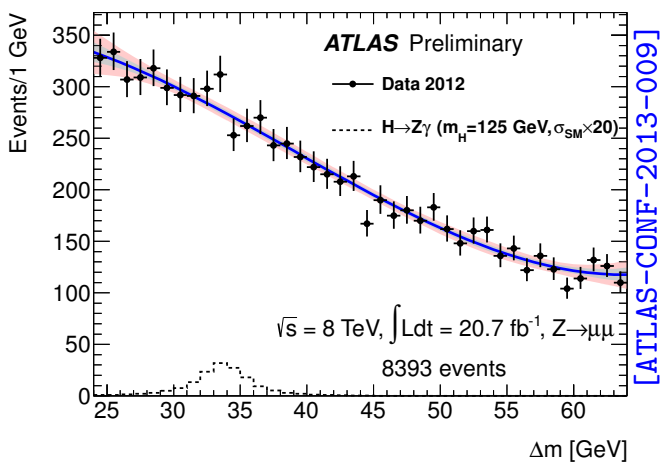
Signal Model:

- Sum of Crystal Ball and Gaussian.
- Width dominated by Z natural width.



Background Model:

- 3rd order Chebychev polynomial for $24 < \Delta m < 64\,\text{GeV}$.
- Validated with S+B fits to high statistics background–only simulation samples.



Signal and Background Modeling

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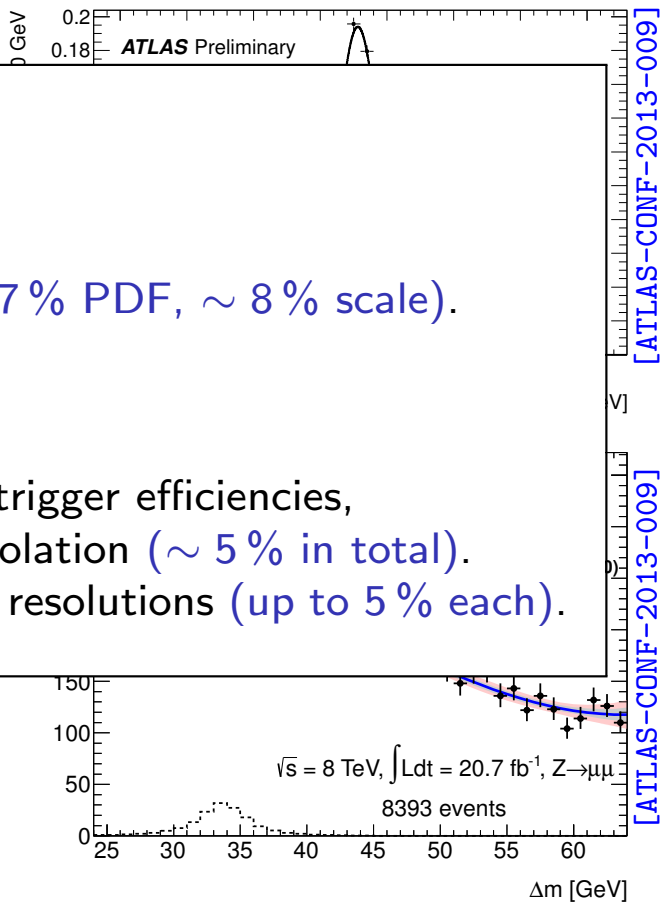
  $24 < \Delta m < 64\,\text{GeV}$.

- Validated with S+B fits to high statistics background–only simulation samples.

Systematic Uncertainties:

- Theoretical uncertainties:
  - Higgs boson production cross sections ($\sim 7\,\%$ PDF, $\sim 8\,\%$ scale).
  - Decay branching fraction ($\sim 9\,\%$).
- Experimental uncertainties:
  - Signal yield: luminosity, acceptance, id & trigger efficiencies, energy/momentum scales & resolutions, isolation ($\sim 5\,\%$ in total).
  - Signal shape: energy/momentum scales & resolutions (up to $5\,\%$ each).



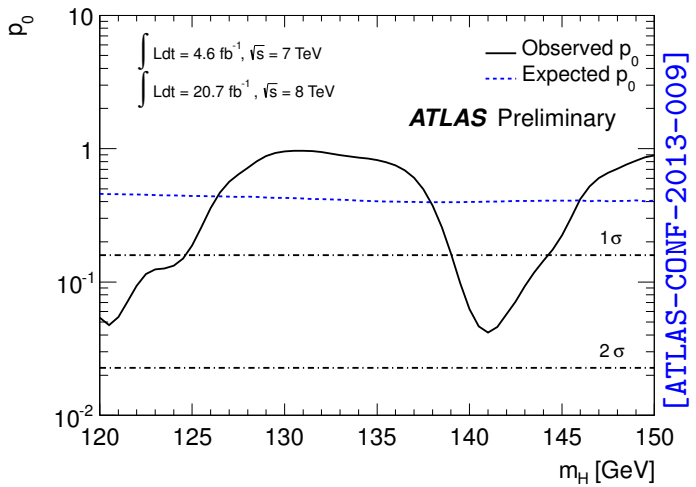
Results

- Based on hypothesis tests using a profile likelihood test statistic.
- Unbinned maximum likelihood:

$$L(\mu) \sim \prod_i \left(\frac{\mu \cdot s}{\mu \cdot s + b} f_s(\Delta m) + \frac{b}{\mu \cdot s + b} f_b(\Delta m) \right).$$

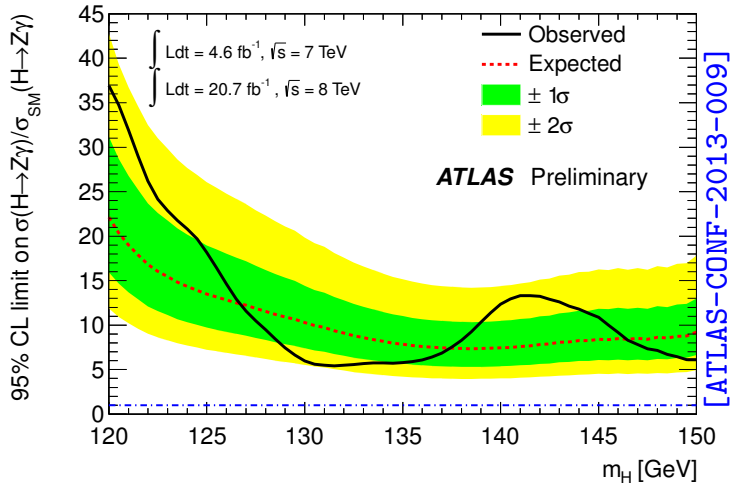
- With signal strength parameter $\mu = \sigma / \sigma_{\mathrm{SM}}$

Local p_0–value / signal significance:



- Compatibility between data and background–only hypothesis.
- Shows probability of a background fluctuation causing an excess at least as high as in data.

95 % CL exclusion limit:



- Compatibility between data and signal–plus–background hypothesis.
- Shows $H \to Z\gamma$ signal rate μ which can be excluded with a certainty of 95 %.

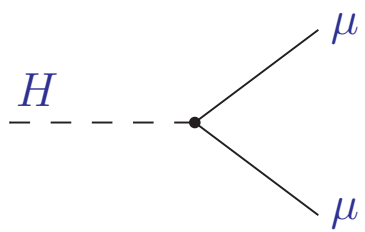
Search for H $\rightarrow \mu^+\mu^-$

in 20.7 fb^{-1} of p–p collisions recorded at 8 TeV (2012)

[ATLAS-CONF-2013-010]

Decay and Signal Signature

Inclusive search for direct Higgs boson decays to $\mu^+\mu^-$



Signal signature: $\mu^+\mu^-$ events.

Branching fraction:

$\mathcal{B}(H \to \mu^+\mu^-) = 2.2 \cdot 10^{-4}$ for $m_H = 125\,\text{GeV}$

approximately half the S/B ratio of $H \to Z\gamma \to \ell^+\ell^-\gamma$.

Main Background Processes:

- inclusive Z/γ^* production (largely irreducible).
- $t\bar{t}$ and W^+W^- with subsequent decays $W \to \mu\nu$.

Event Selection

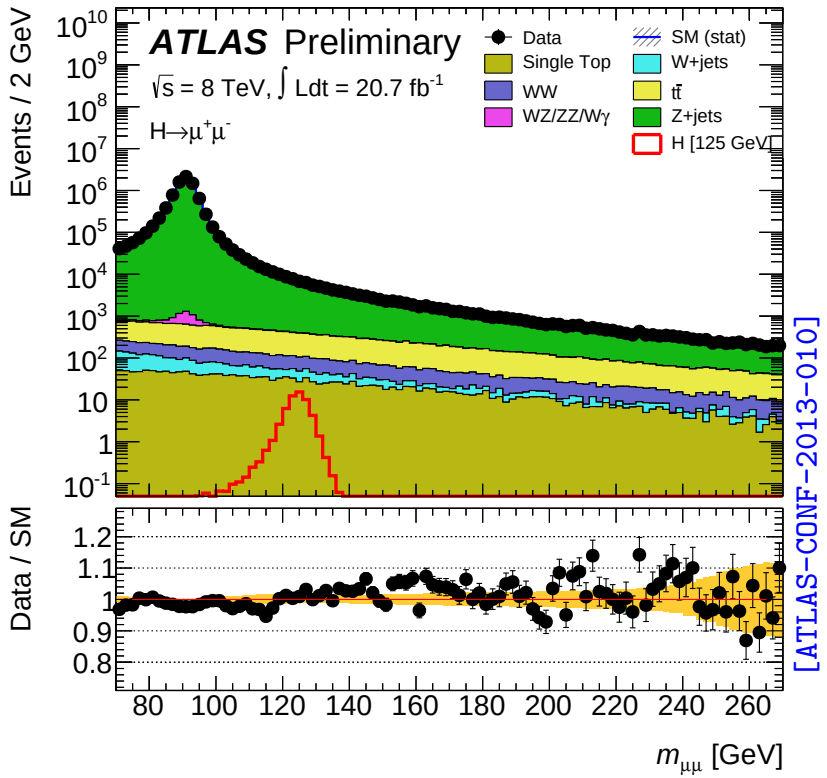
Event Seletion:

- Muons: reconstructed in ID and MS, isolated from tracks and calorimeter clusters.
- $H \to \mu^+\mu^-$ candidates: opposite–charge muons with $p_{\mathrm{T}}^{\mu\mu} > 15\,\mathrm{GeV}$.

Expected and observed events:

(within $\pm 5\,\mathrm{GeV}$ around $m_H = 125\,\mathrm{GeV}$)

- Signal: 37.7 ± 0.2
- Total Bkg.: 17700 ± 130 ($89.3\,\%$ Z/γ^*, $7.8\,\%$ $t\bar{t}$)
- Observed: 17442



Event Categorization: (to optimize sensitivity)

- based on muon momentum resolution achieved in different detector regions.
- two categories:
  - Central: both muons within $|\eta| = 1.0 \Rightarrow \sim 1.8\,\%$ mass resolution.
  - Non–central: rest $\Rightarrow \sim 2.2\,\%$ mass resolution.

Signal and Background Modeling

Analysis Strategy: Signal and background contributions determined by a fit of analytic S+B function to data.

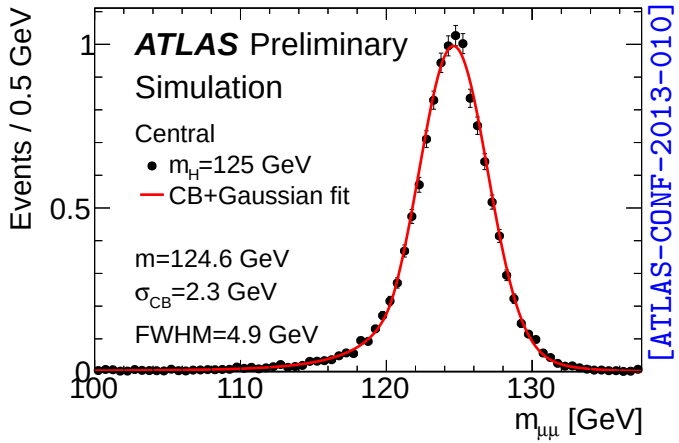
Discriminating variable: $m_{\mu\mu}$,
Search range: $110 < m_{\mu\mu} < 150\,\text{GeV}$.

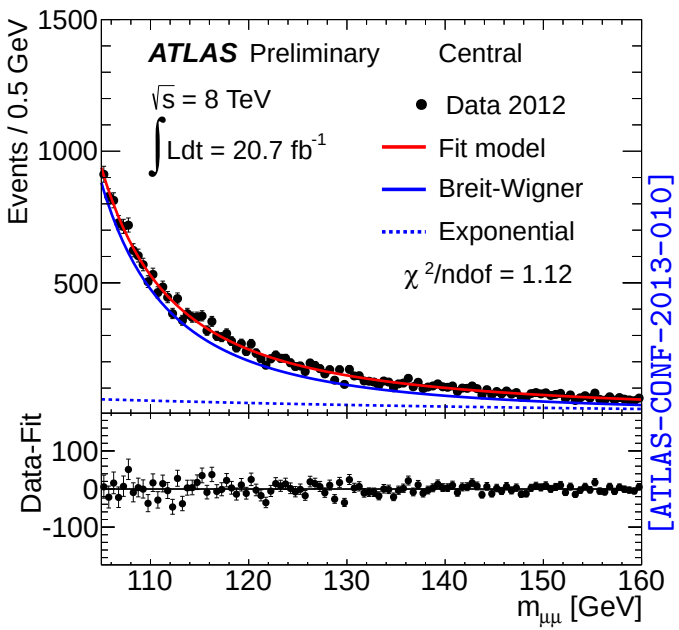
Signal Model:

- Sum of Crystal Ball and Gaussian,
- with equal mass parameters.

Background Model:

- Sum of Breit–Wigner and Exponential.
- Width and mean of Breit–Wigner fixed to Z boson mass and natural width.
- Validated using simulation and $p_{\mathrm{T}}^{\mu\mu} < 15\,\text{GeV}$ control region in data.





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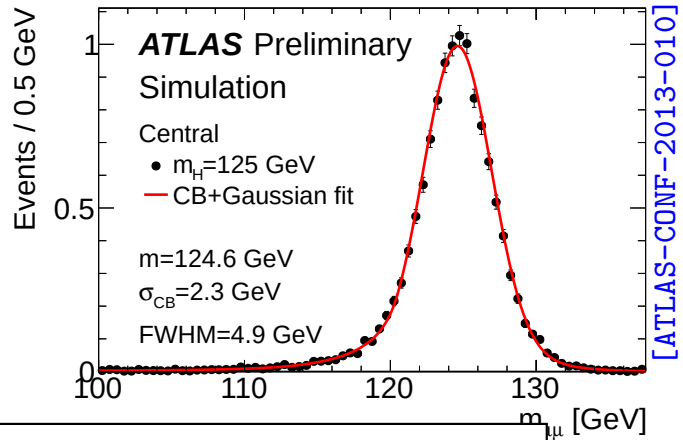

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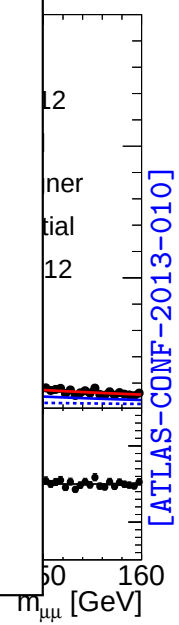
region in data.

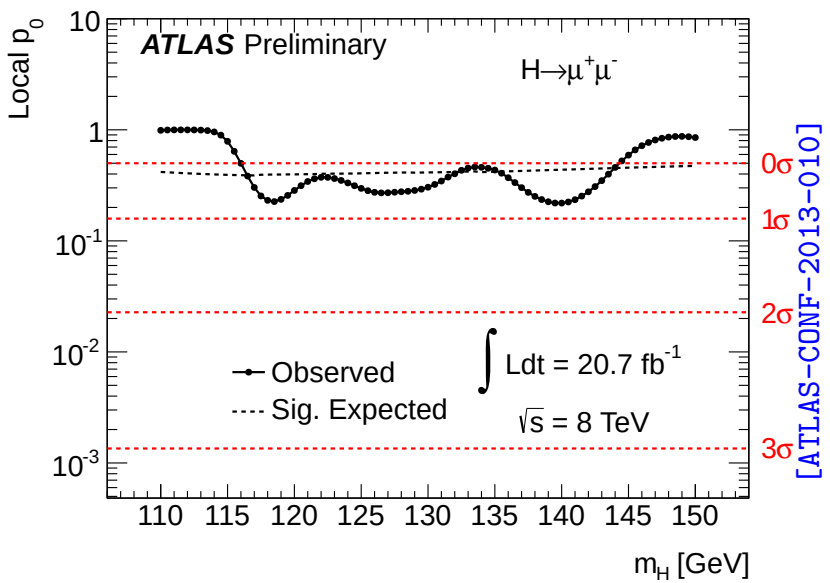
Systematic Uncertainties:

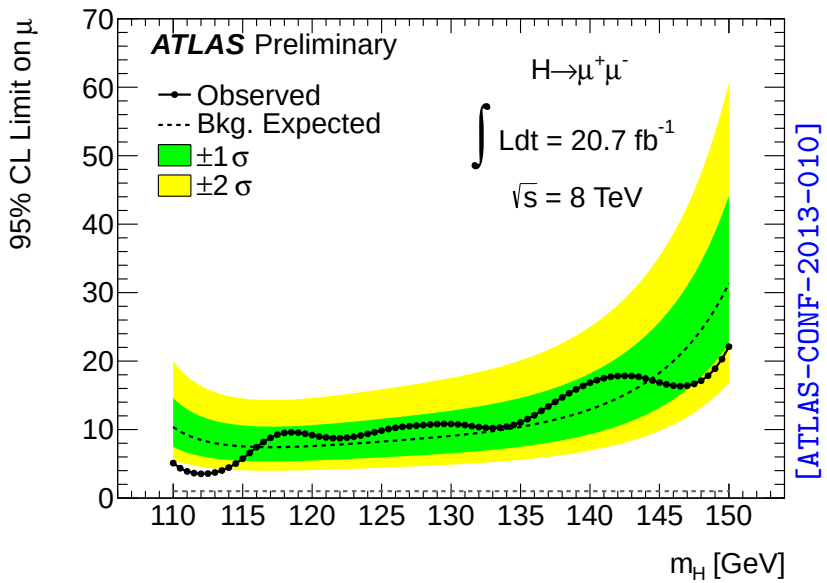
- Theoretical uncertainties:
  - Production cross sections and decay branching fraction ($\sim 15\,\%$ and $\sim 6\,\%$).
  - Acceptance uncertainty due to PDF, scale and ISR/FSR ($\sim 2\,\%$ in total).
- Experimental uncertainties:
  - Signal yield: luminosity, muon id & trigger efficiencies, momentum scales & resolutions and isolation ($\sim 4\,\%$ in total).



Results:

- **No significant excess** of events has been observed w.r.t. SM backgrounds.
  @ $m_H = 125\,\text{GeV}$: $0.5\,\sigma$ ($0.3\,\sigma$) observed (expected) signal signficance.
- **Upper limits** (CL_s) set on signal strength parameter μ.
  @ $m_H = 125\,\text{GeV}$: 9.8 (8.2) times SM $H \to \mu^+\mu^-$ prediction excluded at 95 % CL.





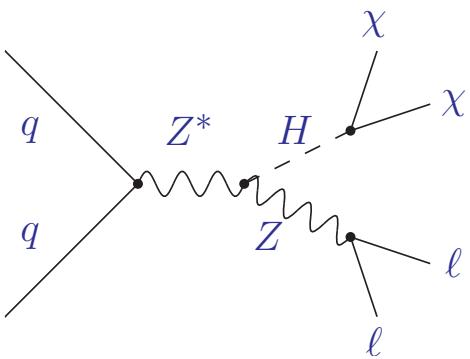
Search for invisible Higgs boson decays

in 4.7 fb^{-1} of p–p collisions recorded at 7 TeV (2011)
and 13.0 fb^{-1} recorded at 8 TeV (2012)

[ATLAS-CONF-2013-011]

Decay and Signal Signature

Search for invisible decays of the Higgs boson produced in association with a Z boson:



- "invisible" particles: not observable in the ATLAS detector.
- Event tagging: search for ZH events with $Z \to \ell^+\ell^-$ decays ($\ell^\pm = e^\pm$ or $\mu^\pm$).
- **Signature:** e^+e^- or $\mu^+\mu^-$ + large $E_{\mathrm{T}}^{\mathrm{miss}}$.
- SM cross section for $ZH \to \ell^+\ell^- + X$ with $m_H = 125\,\mathrm{GeV}$: 39.8 fb @ 8 TeV.

Motivation:

- **The SM Higgs boson decays to $H \to ZZ^* \to 4\nu$**

  ...but has only very small contribution: $\mathcal{B} \approx 1.1 \cdot 10^{-3} \Rightarrow \sigma \times \mathcal{B} \approx 4.2 \cdot 10^{-2}$ fb.

- **More important: enhancements of invisible decay fraction due to physics beyond the Standard Model:**
  - stable/long–lifed particles couple to Higgs but only weakly to other SM particles.

- **Search strategy:**
  - Probe $\mathcal{B}(H \to \mathrm{inv})$ for discovered Higgs boson with $m_H = 125\,\mathrm{GeV}$,
  - and existence of additional Higgs boson with $110 < m_H < 300\,\mathrm{GeV}$.

Event Selection

Tight Reconstructed Z Boson (to tag the ZH candidate):

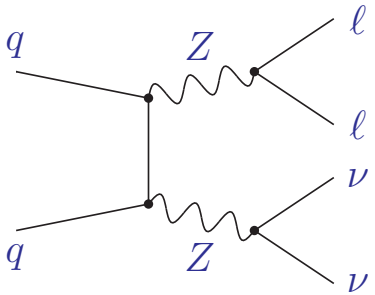
- Same–flavour opposite–charge pairs of leptons with high transverse momenta.
- No additional leptons (lower transverse momenta).
- Required invariant mass: $|m_{\ell\ell} - m_Z| < 20\,\text{GeV}$.

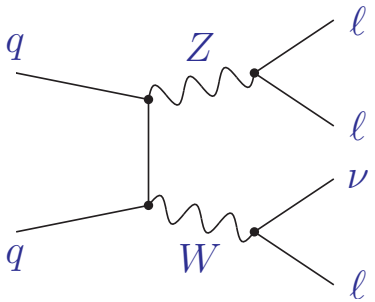
$ZH \to \ell\ell +$ inv. Candidate Event:

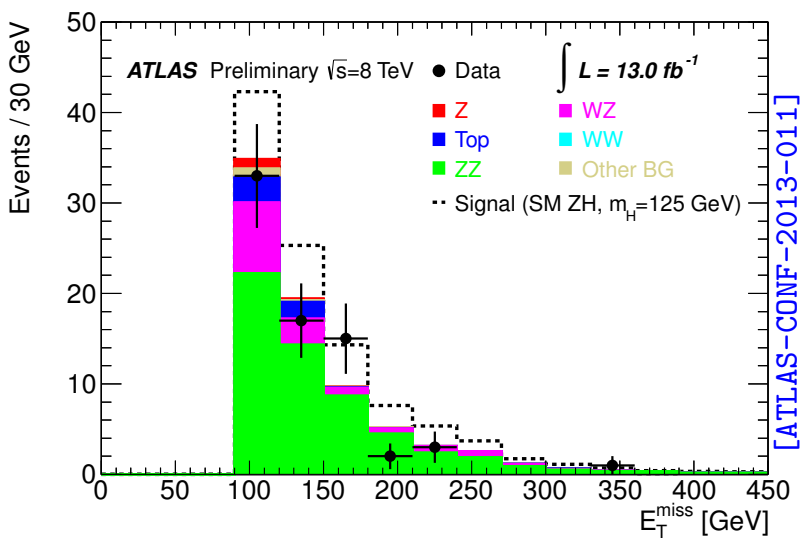
- Z plus high $E_{\text{T}}^{\text{miss}}$ (rejects majority of Z background) ($E_{\text{T}}^{\text{miss}} > 90\,\text{GeV}$).
- Balanced Z and H momenta:
  - Large azimuthal separation of Z and H system. ($\Delta\phi(\vec{p}_{\ell\ell}^{\,\text{T}}, \vec{E}_{\text{T}}^{\text{miss}}) > 2.6$)
  - Small lepton opening angle due to boosted Z. ($\Delta\phi(\ell, \ell) < 1.7$)
  - Similar magnitudes of Z and H transverse momenta. ($|E_{\text{T}}^{\text{miss}} - p_{\text{T}}^{\ell\ell}|/p_{\text{T}}^{\ell\ell} < 0.2$)

Backgrounds

- $ZZ \to \ell\ell\nu\nu$ and $WZ \to \ell\nu\ell\ell$:
  - dominant contributions (70 % and 20 %),
  - estimated from Monte Carlo simulations,
  - total uncertainty about 12 %.
- $WW \to \ell\nu\ell\nu$:
  - contribution ~ 5 %,
  - estimated from data and Monte Carlo,
  - uncertainty ~ 14 %.
- Top quark and inclusive Z and W:
  - contribution ~ 1 % each
  - estimation from data (Z, $t\bar{t}$, Wt) and MC (W, single top)







- Observed events: 71 (27) in 8 (7) TeV data.
- Typical signal–to–background ratio: ~ 0.4

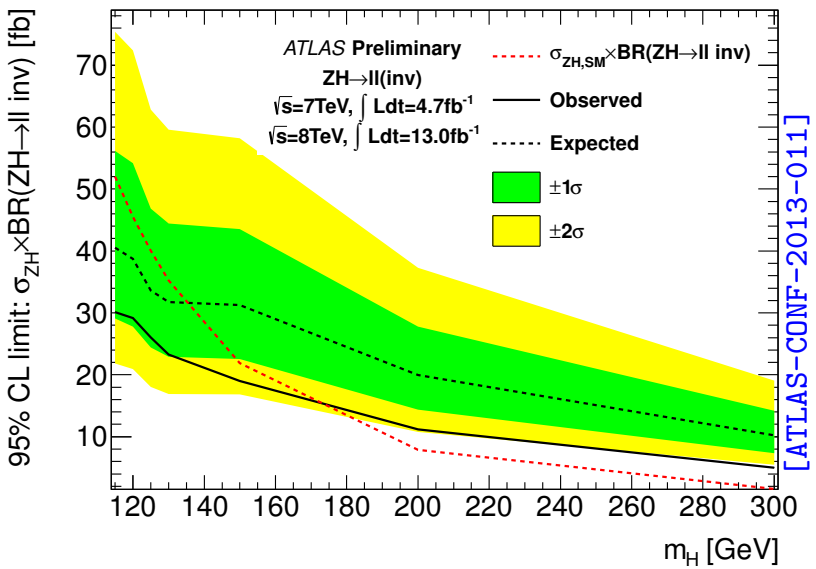
  Assuming $\sigma_{ZH}^{\mathrm{SM}}$, $\mathcal{B}(H \to \mathrm{inv}) = 100$ %

  and $m_H = 125.5$ GeV.

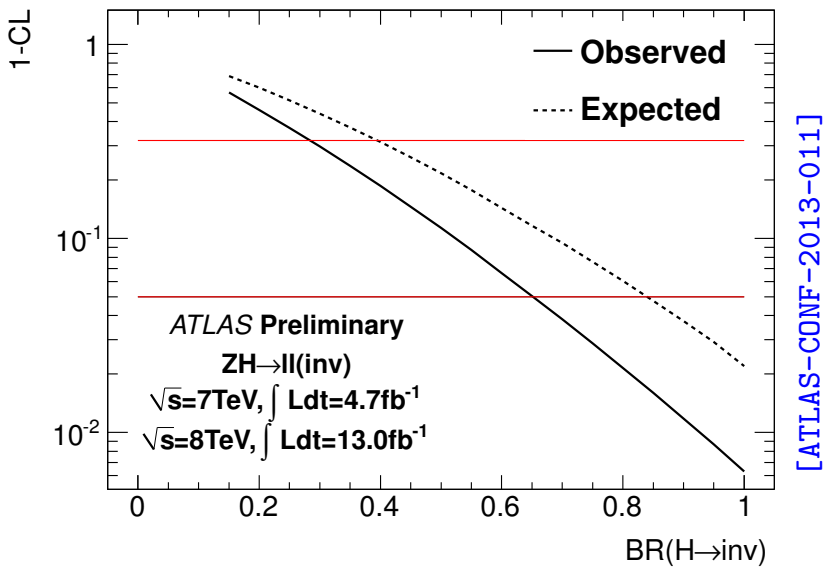
Results

- **No significant excess** of events has been observed w.r.t. SM backgrounds.
- **Upper limits** (CL_s) at 95 % CL on $\boldsymbol{\sigma_{ZH} \times \mathcal{B}(H \to \text{inv})}$ set for a Higgs–like boson with $110 < m_H < 300\,\text{GeV}$.
- Assuming σ_{ZH}^{SM}, upper limit also set on $\boldsymbol{\mathcal{B}(H \to \text{inv})}$:
  For $m_H = 125\,\text{GeV}$: $\mathcal{B} = 65\,\%$ excluded at 95 % CL (expected: 84 %).

95 % CL upper limit on $\sigma_{ZH} \times \mathcal{B}(H \to \text{inv})$:



Confidence level scan of $\mathcal{B}(H \to \text{inv})$:



Summary

Summary

- Studies of rare Higgs boson decays contribute to the full understanding of the Higgs boson's nature,
- and help to probe the existence of a non–minimal Higgs sector.
- Three searches for rare Higgs boson decays with Run–I ATLAS data have been presented:
  $H \to Z\gamma$, $H \to \mu^+\mu^-$ and $H \to$ inv.
- No significant excess was observed in either search.
  $\Rightarrow$ The results are in agreement with the Standard Model predictions.