Search for Exotic Decays of the Higgs Boson with the ATLAS Detector

Lake Louise Winter Institute 2015

February 16, 2015

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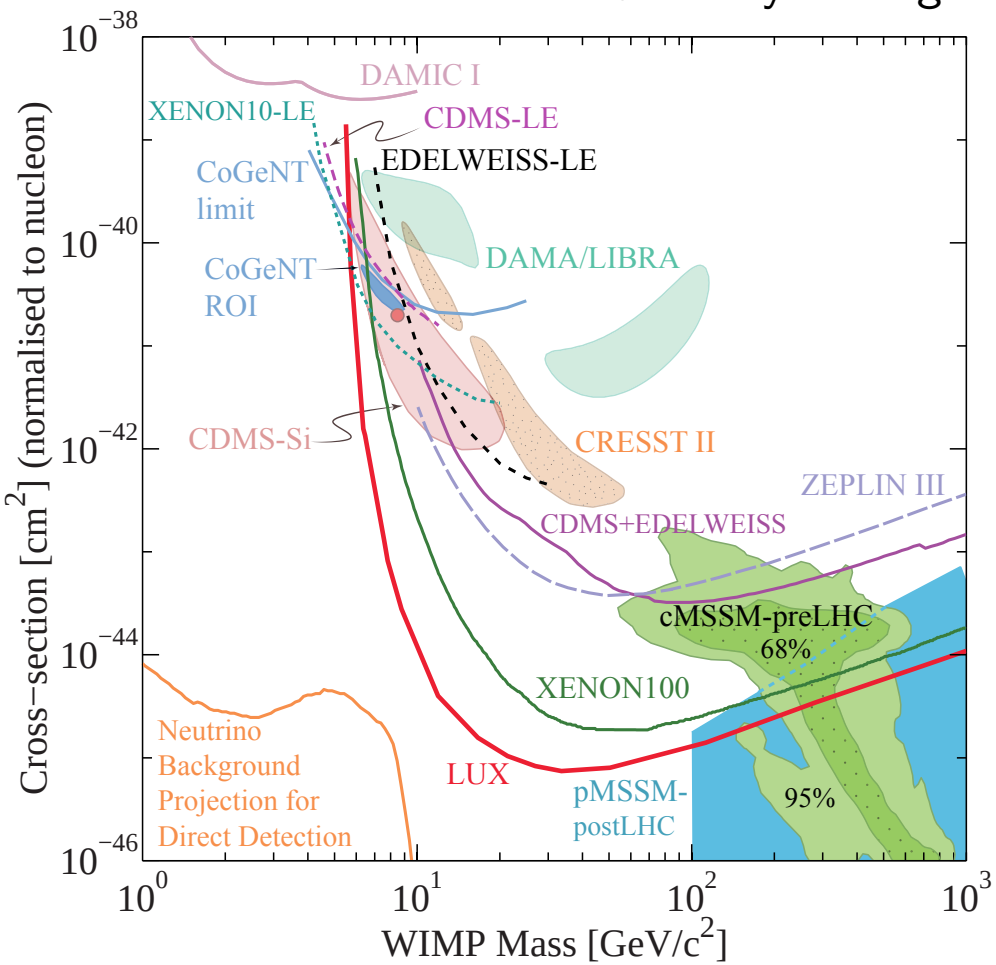
Rare Decays of the Higgs Boson

- $H \to Invisible$ ‣ Physical Review Letters 112, 201802 (2014)
  - Coupling to dark matter candidate
- $H \to J/\psi\,\gamma, \Upsilon(nS)\,\gamma$ ‣ Submitted to PRL – arXiv:1501.03276
  - Only way to measure Yukawa second generation quark coupling to c
  - First results from a search at the LHC
- $H \to \mu\mu$ ‣ Physics Letters B 738 (2014) 68-86
  - Second generation lepton coupling
- $H \to Z\gamma$ ‣ Physics Letters B 732C (2014) 8-27
  - Loop sensitive to new physics (similar to $H \to \gamma\gamma$ but with lower background)
  - Suppressed by $Z \to \ell\ell$ branching fraction

$H \rightarrow$ Invisible

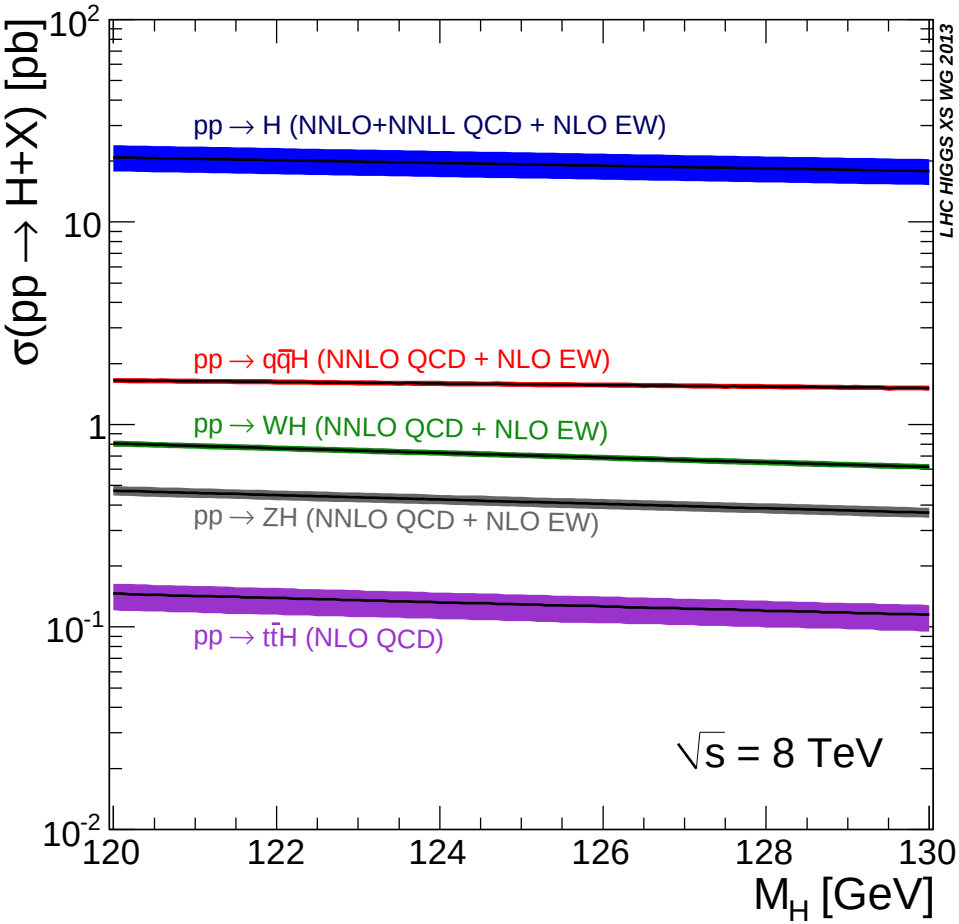
$H \rightarrow$ Invisible: Physics Motivation

- SM extensions can allow the Higgs to decay to stable or long-lived particles not observed in the detector, e.g. dark matter
- Place limit on invisible branching fraction
- Higgs portal model used to set limit on dark matter nucleon cross section
  - Assumes DM interacts with SM only through Higgs exchange



- K.A. Olive et al. (Particle Data Group)
- Chin. Phys. C, 38, 090001 (2014)

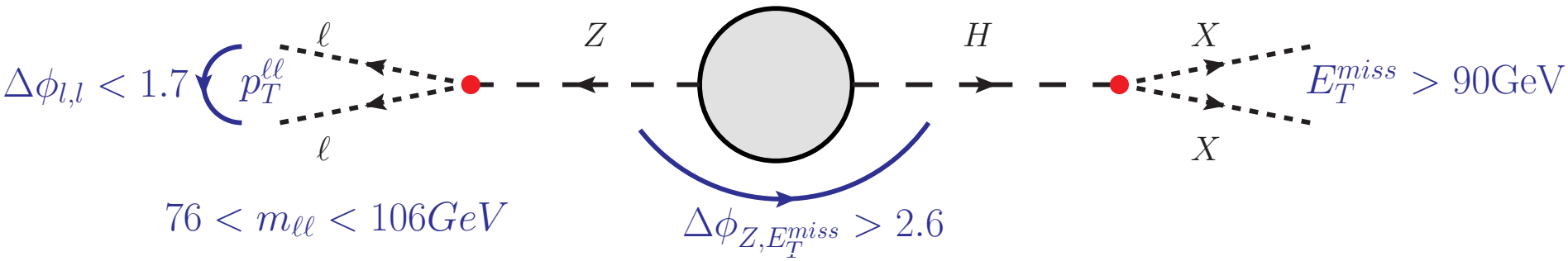
$H \rightarrow$ Invisible: Analysis Motivation



- $pp \rightarrow H$: No objects in H+0jet, H+jets has large irreducible $Z \rightarrow \nu\nu$+jets background
- $pp \rightarrow qqH$: In progress
- $pp \rightarrow WH$: Invisible particle from the $W \rightarrow \ell\nu$ decay makes discrimination from $W \rightarrow \ell\nu$+jets background difficult
- $pp \rightarrow ZH$: $Z \rightarrow \ell\ell$ **decay provides identifiable objects**
- $pp \rightarrow ttH$: Potentially sensitive

- Also in progress is VH with $V \rightarrow jj$
- **Will focus on ZH with $Z \rightarrow \ell\ell$**

$Z(H \rightarrow$ Invisible): Analysis Strategy

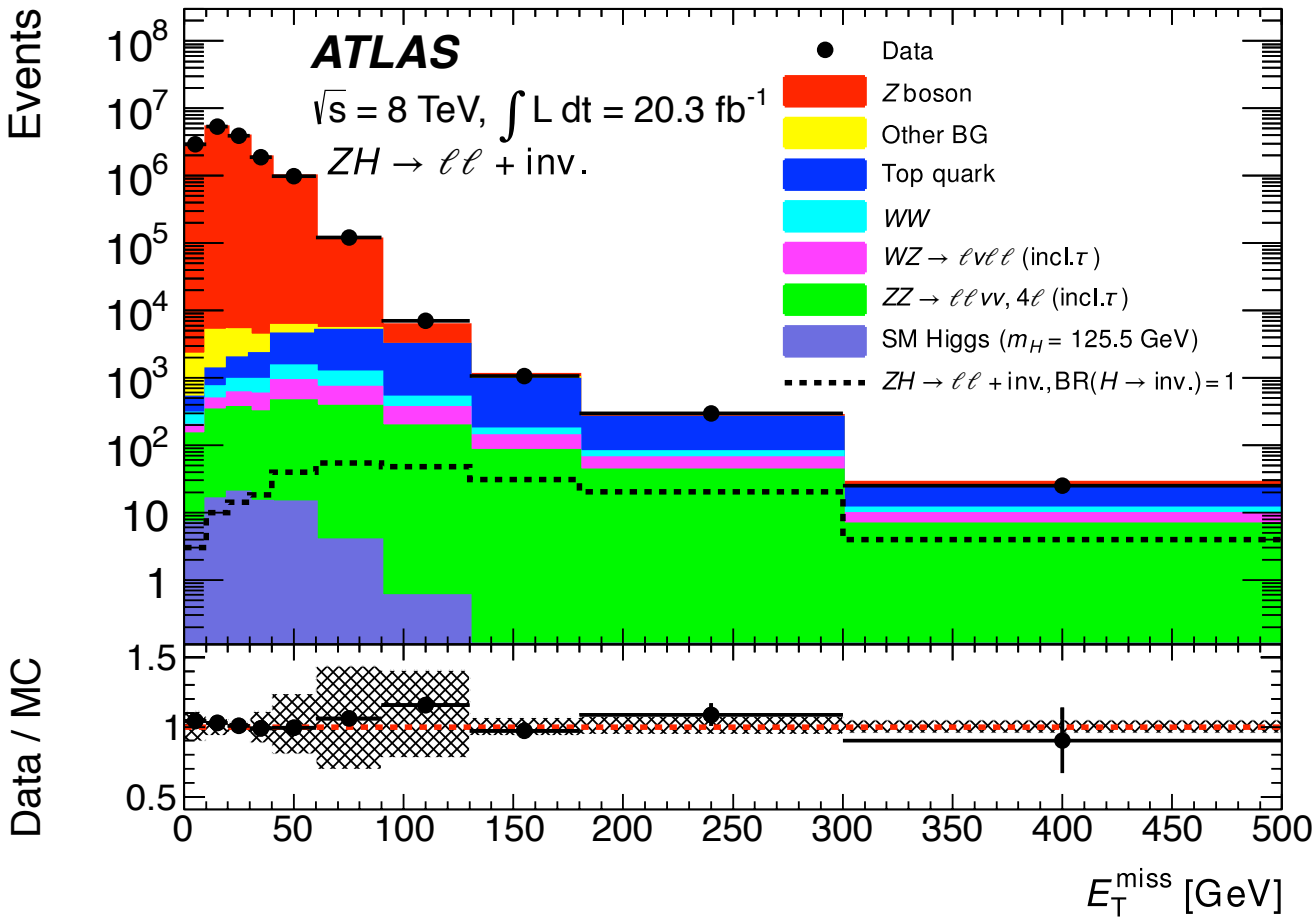


- Analysis cuts designed around the idea that the Z ($\ell\ell$ system) recoils off of the H (E_T^{miss}) for signal
- Most important background is Drell-Yan (Z) production with fake E_T^{miss} from mismeasured jets which is hard to estimate from MC
  - Estimated by 2 dimensional sideband fit of events failing one or both ❄

Requirement	Justification
$76 < m_{\ell\ell} < 106$GeV	Dilepton system consistent with $Z \rightarrow \ell\ell$
$E_T^{miss} > 90$GeV	Requiring the H to have p_T forces the Z to also have p_T
E_T^{miss} Cleaning Cuts	
$\Delta\phi_{\ell,\ell} < 1.7$	Boosted Z has leptons close together
$\Delta\phi_{Z,E_T^{miss}} > 2.6$	Z and H should be back-to-back
$\Delta\phi(E_T^{miss}, E_T^{miss,track}) < 0.2$	E_T^{miss} not correlated for background (E_T^{miss} from mismeasured jets) ❄
$\lvert E_T^{miss} - p_T^{\ell\ell}\rvert / p_T^{\ell\ell} < 0.2$	Balance of Z and H momentum ❄
Central Jet Veto	Drell-Yan background tends to have one or more jets

$Z(H \to \text{Invisible})$: Analysis Strategy

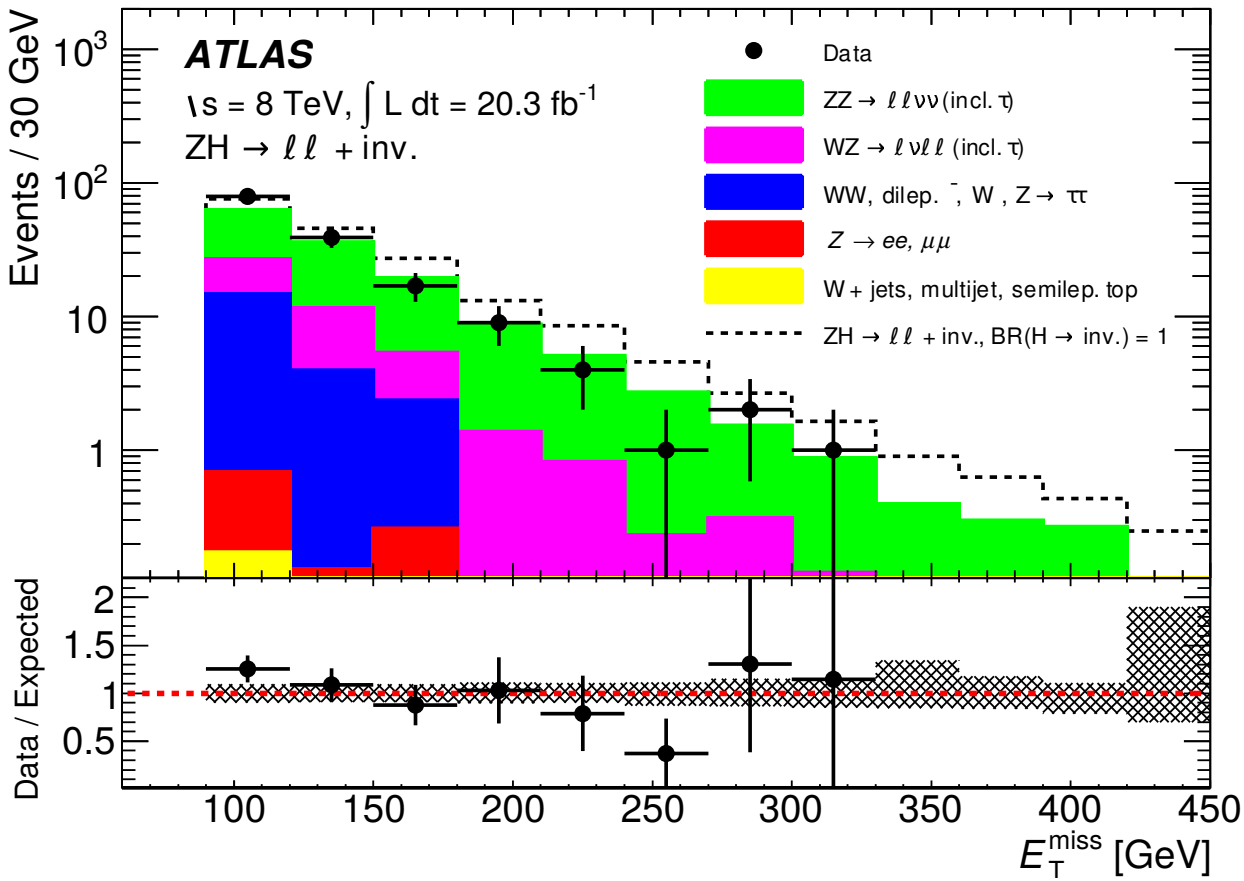
- E_T^{miss} after $m_{\ell\ell}$



- $Z \to \ell\ell$ has steeply falling tail with high uncertainty

$Z(H \rightarrow$ Invisible): Analysis Strategy

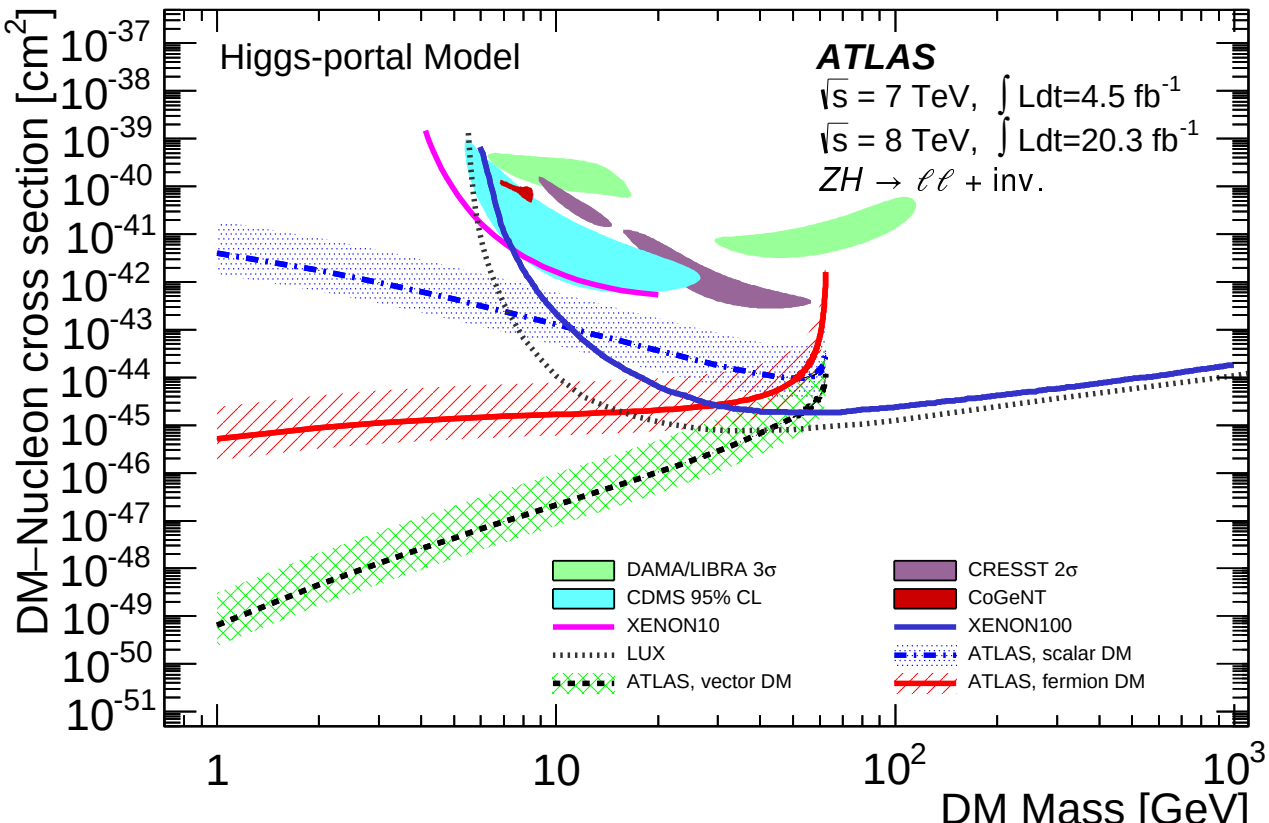
- E_T^{miss} after $m_{\ell\ell}$ and E_T^{miss} cleaning



- $ZZ \rightarrow \ell\ell\nu\nu$ (irreducible) now dominant background

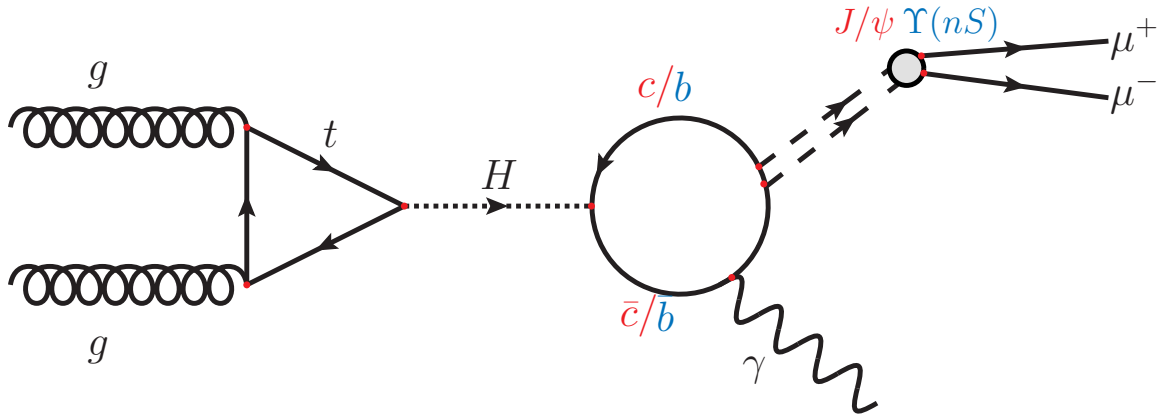
$Z(H \to \text{Invisible})$: Results

- Upper limit set on the branching fraction of H to invisible particles at 75% (expected 62%) at 95% confidence
- Complementary with direct detection experiments
  - Model-based interpretation: Only true in Higgs portal (sensitivity drop at $\frac{1}{2}m_H$)



$H \to J/\psi\,\gamma$ and $H \to \Upsilon(nS)\,\gamma$

$H \to J/\psi\,\gamma, \Upsilon(nS)\,\gamma$: Physics Motivation

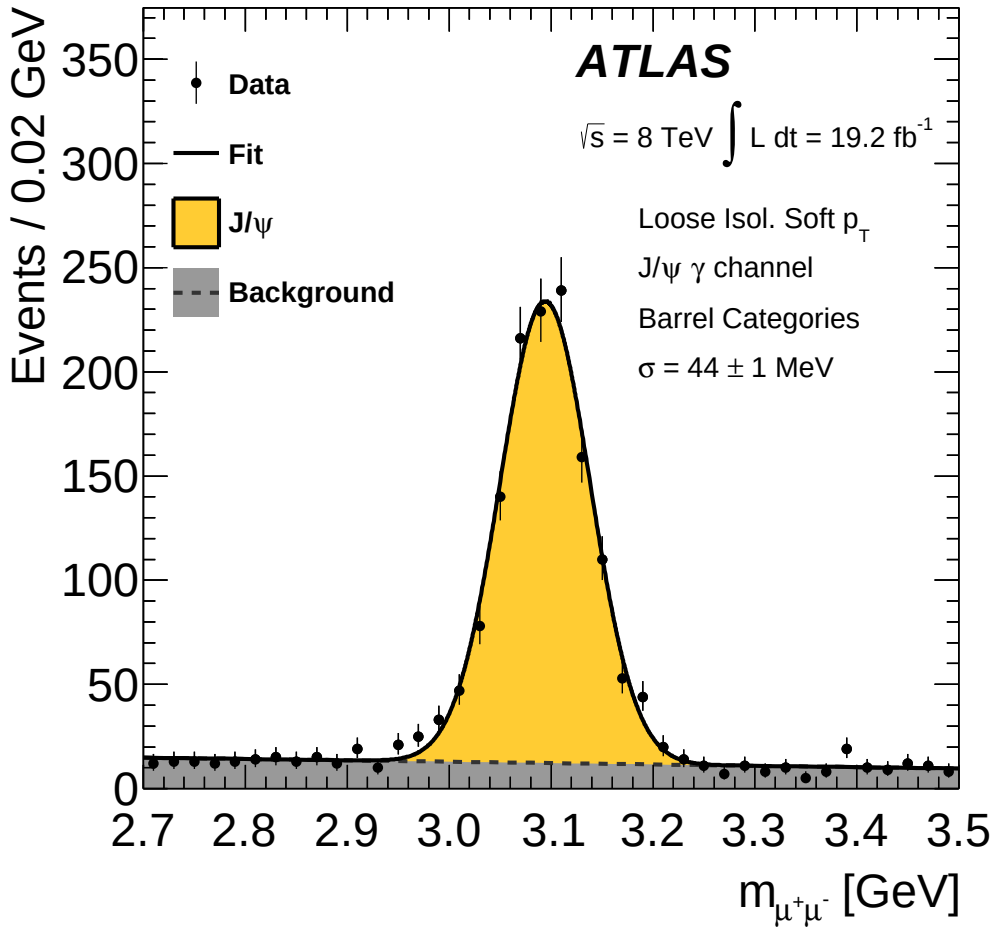


- $H \to J/\psi\,\gamma$ the only feasible way to probe charm Yukawa coupling
  - Rare decay $Br(H \to J/\psi\,\gamma) < 2.8 \pm 0.2\,x\,10^{-6}$
  - First results from an LHC search
- $H \to \Upsilon(nS)\,\gamma$ similarly probes bottom Yukawa coupling
  - Significantly lower $Br(H \to \Upsilon(1S)\,\gamma) < 8.4^{+19.3}_{-8.2}\,x\,10^{-10}$
- Analysis also probes $Z \to J/\psi\,\gamma, \Upsilon(nS)\,\gamma$ (improved LEP limits by 2 orders of magnitude)
- Deviations in coupling from SM value can lead to increase in branching fraction
- Will focus on $H \to J/\psi\,\gamma$ since it has much higher sensitivity

$H \to J/\psi\,\gamma$: Background Composition

Dominant Backgrounds

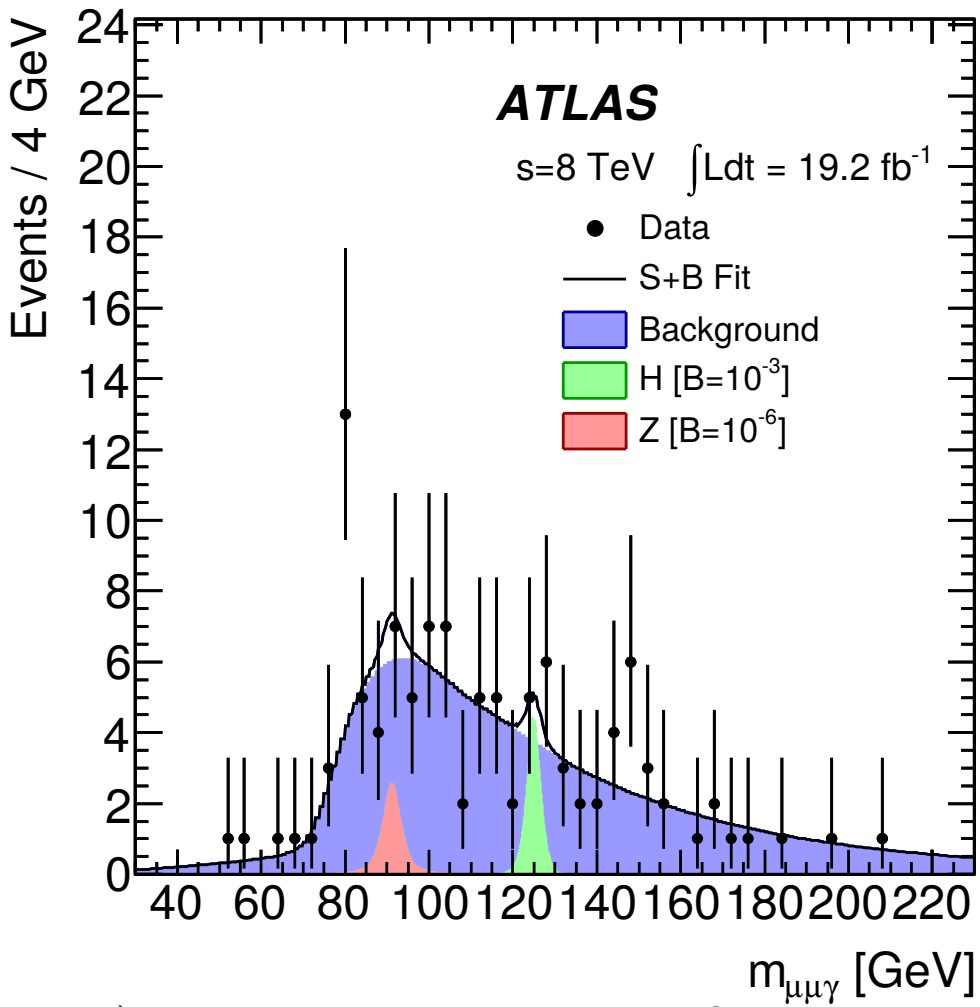
- 56% Prompt J/ψ: Peaks in $m_{\mu\mu}$
  - $gg \to J/\psi g$ where g (jet) is misidentified as a γ
  - Suppressed by requiring γ be isolated since there is usually hadronic activity around a jet
- 41% Non-resonant: Smooth in $m_{\mu\mu}$
  - Production of a di-muon pair with invariant mass close to J/ψ



- Background is modeled using templates to describe kinematic regions in several control regions.

$H \to J/\psi\,\gamma$: Results

- Upper limit set on branching fraction of $H \to J/\psi\,\gamma$ at 95% confidence
  $Br(H \to J/\psi\,\gamma) < 1.5\,x\,10^{-3}$ (expected $1.2^{+0.6}_{-0.3}\,x\,10^{-3}$)
  $\approx 540 \times$ SM Expectation



Summary and Future of Exotic Higgs Decays

Exotic Higgs Decays in Run I and Beyond

- Run I
  - Standard Model
    - $Br(H \to J/\psi\,\gamma) < 540\times$ SM Expectation
    - $Br(H \to Z\gamma) < 17.4\times$ SM Expectation
    - $Br(H \to \mu\mu) < 7.0\times$ SM Expectation
  - Exotic
    - $Br(H \to$ Invisible$) < 75\%$
- Future Sensitivity of ATLAS (High Luminosity LHC)

Luminosity	$H \to Z\gamma$	$H \to \mu\mu$	$H \to$ Invisible
300fb^{-1}	2.3 σ	2.3 σ	$Br < 23\%$
3000fb^{-1} HL-LHC	3.9 σ	7.0 σ	$Br < 8\%$

▸ ATL-PHYS-PUB-2014-006 ▸ ATL-PHYS-PUB-2013-014 ▸ ATL-PHYS-PUB-2013-014

- Cross sections could be enhanced by BSM scenarios which can yield earlier interesting results

Backup

$H \to J/\psi\,\gamma, \Upsilon(nS)\,\gamma$: Analysis Strategy

- Loose Selection

$H \to J/\psi\,\gamma$	$\Upsilon(nS)\,\gamma$
Single high p_T muon trigger	Single muon or dimuon trigger
2 μ with $p_T^\mu > 3$GeV and $\lvert\eta^\mu\rvert < 2.5$	
leading $p_T^\mu > 20$GeV	
both muons from the same vertex	
$\lvert m_{\mu\mu} - m_{J/\psi}\rvert < 0.2$ (tightened to 0.15 if $\lvert\eta^\mu < 1.05\rvert$)	$8.0 < m_{\mu\mu} < 12.0$GeV
$p_T^{\mu\mu} > 36$GeV	
Surrounding tracks required to be $< 10\%$ of p_T^μ	
$p_T^\gamma > 36$GeV	
Surrounding tracks required to be $< 8\%$ of p_T^γ	

- Tight selection requires $\Delta\phi(Q,\gamma) > 0.5$
- Blinded data with $120\text{GeV} < m_{\mu\mu\gamma} < 130\text{GeV}$