Search for Higgs boson decays to BSM light bosons in four-lepton events with ATLAS at $\sqrt{s} = 13$ TeV

B. Diallo

Dark Interactions workshop:
Perspectives from Theory and Experiment
BNL Oct 2-5, 2018

CERN-ATLAS

October 4, 2018

Outline

Context and Objectives

- **Standard Model (SM) deficiencies**
  - Many free parameters, (anti)matter paradox, hierarchy problem, strong CP problem, no gravity, no DE or DM...
  - Explanation of astrophysical observations of positron excesses

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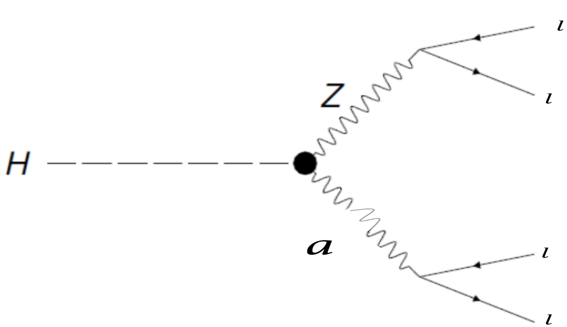
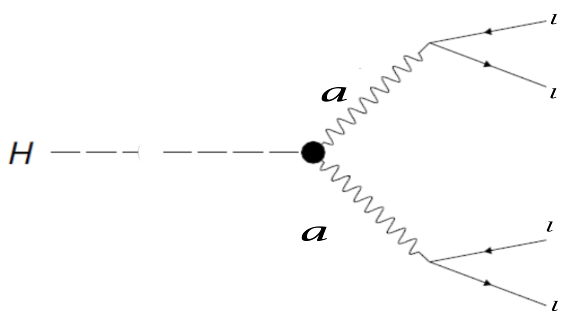
  - Many free parameters, (anti)matter paradox, hierarchy problem, strong CP problem, no gravity, no DE or DM...
  - Explanation of astrophysical observations of positron excesses
- **2 BSM Bench mark model considered**

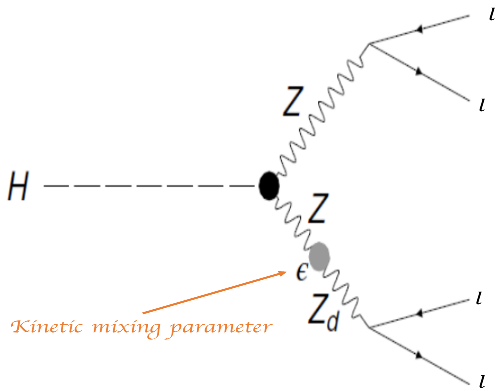
  $\rightarrow$ **2HDM+S** Curtin et al. (Phys. Rev. D 90, 075004 (2014).)
  - It predicts the decay of the Higgs boson to 1 or 2 pseudoscalar a which is the latest of the higgs boson.
  - Only $a \rightarrow \mu\mu$ is considered and it's determined by Yukawa couplings of a to fermions.

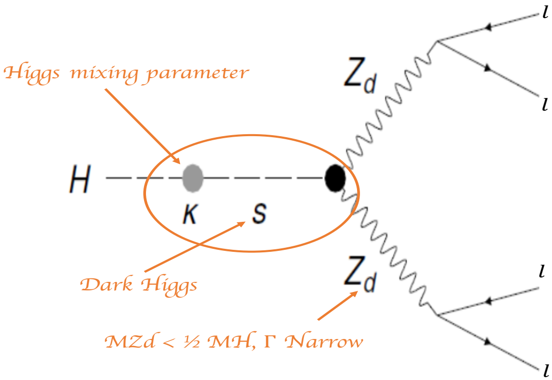




Context and Objectives

- **HAHM** (Hidden Abelian Higgs Model → Curtin et al. (J. High Energy Phys. 02 (2015) 157.))
  - Introduce an additional U(1) dark gauge symmetry mediated by a dark gauge boson Z_d
  - Z_d Interacts with the SM through kinetic mixing with hypercharge gauge boson (→ kinetic mixing parameter ϵ)
  - Dark Higgs mechanism could spontaneously break the U(1) dark gauge symmetry (→ mixing between SM Higgs and dark Higss → mixing paramter κ)





Region of interest

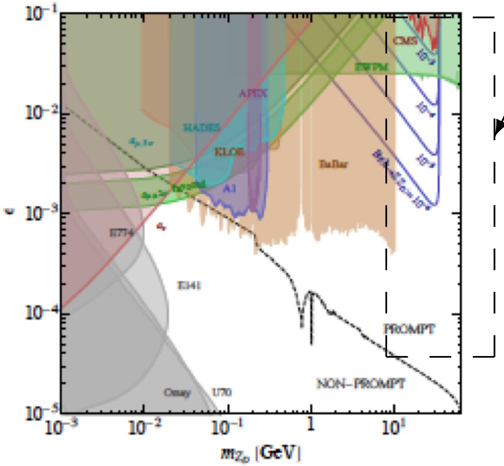


Figure 1: Constraint on ϵ, m_{Z_d} for pure kinematic mixing for $m_{Z_d} \sim MeV - 10\,GeV$

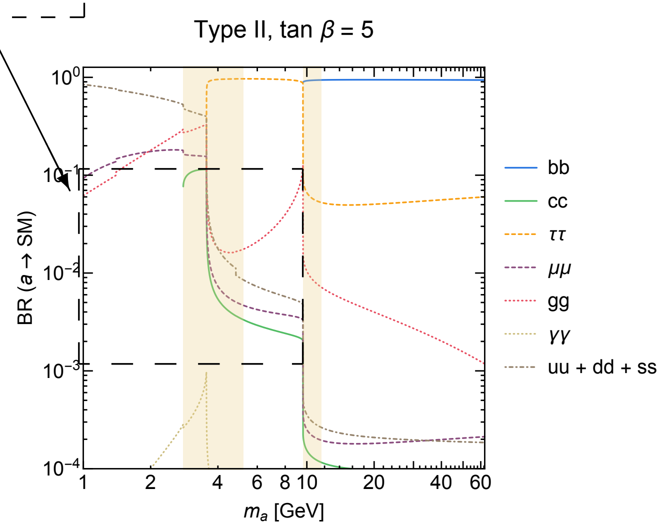
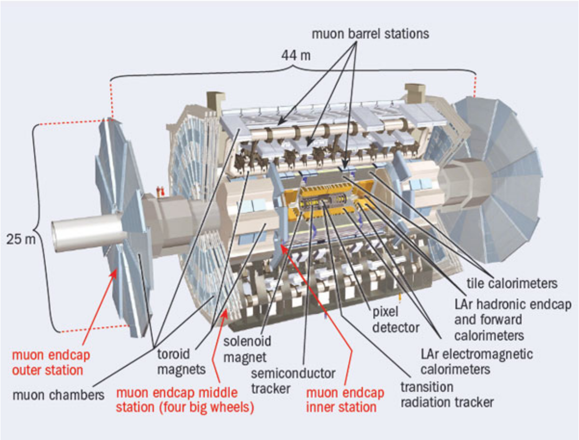
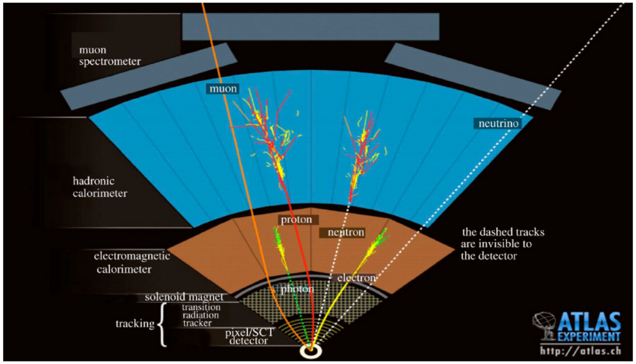


Figure 2: BR of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings.

Curtin et al. (Phys. Rev. D 90, 075004 (2014))

ATLAS Dectector





- Tracking System
  - → reconstruct charged particles trajectories
- Thin superconducting solenoid
  - → to compute particles impulsion
- electromagnetic calorimeter
  - → measure electromagnetic energy deposited by e^- and γ
- muon system
  - → designed to identify and reconstruct muons
- trigger system
  - → choose either to keep or not events
- hadronic calorimeters
  - → measure hadronic energy deposited by hadronic system
- Detector surrounded by Magnetic

Analysis overview

3 analyses are covered: $X = Z_d/a$

- High mass region: $XX \to 4e, 4\mu, 2e2\mu$ $[15\,GeV < m_X < 60\,GeV]$
- Low mass region: $XX \to 4\mu$ $[1\,GeV < m_X < 15\,GeV]$
- ZX: $ZX \to 4e, 4\mu, 2e\mu, 2\mu 2e$ $[15\,GeV < m_X < 55\,GeV]$

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Labeling

m_{12} is the invariant mass of the dilepton that is closer to the (SM) Z boson mass, and m_{34} is the invariant mass of the other dilepton in the quadruplet.
In the case of quadruplets formed from 4e or 4μ, alternate pairings of same-flavour opposite-sign (SFOS) leptons can be formed, they are denoted m_{14} and m_{23}

Event Selection

<table>
<tr><th></th><th>$H \to ZX \to 4\ell$
$(15\,GeV < m_X < 55\,GeV)$</th><th>$H \to XX \to 4\ell$
$(15\,GeV < m_X < 60\,GeV)$</th><th>$H \to XX \to 4\mu$
$(1\,GeV < m_X < 15\,GeV)$</th></tr>
<tr><td rowspan="3">4l selection</td><td colspan="3">- Require at least one SFOS quadruplet
- Three leading-pt leptons satisfying $pt >$ 20 GeV, 15 GeV, 10 GeV
- 3μ required to be reconstructed by combining ID and MS tracks</td></tr>
<tr><td>- The best quadruplet is required to have:

- $50\,GeV < m_{12} < 106\,GeV$
- $12\,GeV < m_{34} < 115\,GeV$
- $m_{12,34,14,32} >$ 5 GeV</td><td colspan="2">each lepton should fire at least 1 trigger.
In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet</td></tr>
<tr><td colspan="2">$\Delta R(l, l') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet</td><td>-</td></tr>
<tr><td>4l ranking</td><td>Select first surviving quadruplet from channels, in the order: 4μ, $2e2\mu$, $2\mu 2e$, $4e$</td><td colspan="2">Select quadruplet with smallest $\Delta m_{\ell\ell} = |m_{12} - m_{34}|$</td></tr>
<tr><td rowspan="3">Event selection</td><td colspan="2">$115\,GeV < m_{4\ell} < 130\,GeV$</td><td>$120\,GeV < m_{4\ell} < 130\,GeV$</td></tr>
<tr><td rowspan="2"></td><td colspan="2">$m_{34}/m_{12} > 0.85$
Reject event if:
$(m_{J/\Psi} - 0.25\,GeV) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\,GeV)$, or
$(m_{\Upsilon(1S)} - 0.70\,GeV) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\,GeV)$</td></tr>
<tr><td>$10\,GeV < m_{12,34} < 64\,GeV$
$4e$ and 4μ channels:
$5\,GeV < m_{14,32} < 75\,GeV$</td><td>$0.88\,GeV < m_{12,34} <$ 20 GeV
No restriction on alternative pairing</td></tr>
</table>

Signal generation

$H \to ZX \to 4l$ and $H \to XX \to 4l$ (high mass)

- Higgs boson is produced in gluon-gluon fusion mode (ggF) using HAHM model, with $M_H = 125\,GeV$
- MadGraph5_aMC@NLO and NNPDF23 are used as event generator
- Pythia8 was used for modeling of the parton shower, hadronisation and underlying event.
- The model parameters ϵ and κ were adjusted so that only $H \to ZX \to 4l$ ($\epsilon >> \kappa$) or $H \to XX \to 4l$ ($\epsilon << \kappa$) decays were generated

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$H \to XX \to 4l$ low mass

- Higgs boson was produced using PowHeg- Box and CT10 NLO PDFs then replaced by a Higgs boson for 2HDM+S model
- the same event generator as high mass was used.

Backgrounds estimates and uncertainties

Dominant background

- $H \rightarrow ZZ^* \rightarrow 4l$
- Non resonant SM ZZ^*

Sub-dominant background

- WZ, ZZ dibosons processes
- J/ψ and Υ
- $t\bar{t}$ and Z+ Jet (cross check by data driven method, for high mass)
- heavy flavor (for low mass region)

- For high and low mass region: most of them are cross checked in regions orthogonal to the signal region
- For $H \rightarrow ZX \rightarrow 4l$: estimation is done from simulation and normalised with the theoretical calculations of their cross-section

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Uncertainties

- Data driven bkg uncertainty is $\to$ up to 65%
- Statistical uncertainty
- Systematic uncertainties from: detector, theory $\to$ up to 10%

$H \to ZX \to 4l$ results

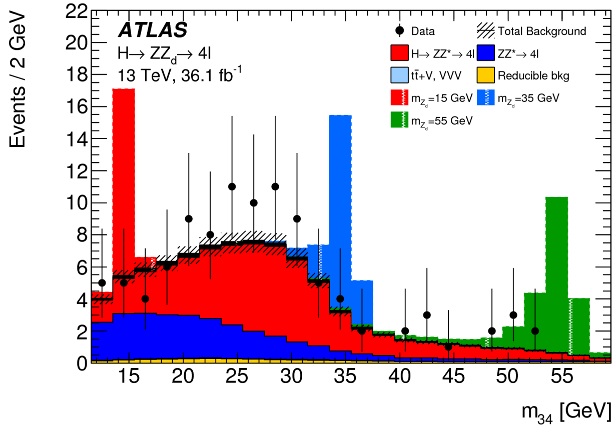


Figure 3: m_{34} in the mass range m4ℓ in [115,130] GeV.

- Some excesses are observed but not statistically significant

Process	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	34.3 ± 3.6	21.4 ± 3.0	55.7 ± 6.3
$ZZ^* \to 4\ell$	16.9 ± 1.2	9.0 ± 1.1	25.9 ± 2.0
Reducible background	2.1 ± 0.6	2.7 ± 0.7	4.8 ± 1.1
VVV, $t\bar{t} + V$	0.20 ± 0.05	0.20 ± 0.04	0.40 ± 0.06
Total expected	53.5 ± 4.3	33.3 ± 3.4	86.8 ± 7.5
Observed	65	37	102

Table 1: Expected and observed of events at $36.1 fb^{-1}$

$H \to XX \to 4l$ high mass results

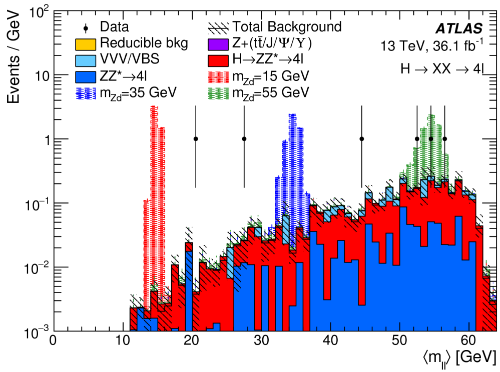


Figure 4: $< m_{ll} >$ in the mass range m4ℓ in [115,130] GeV.

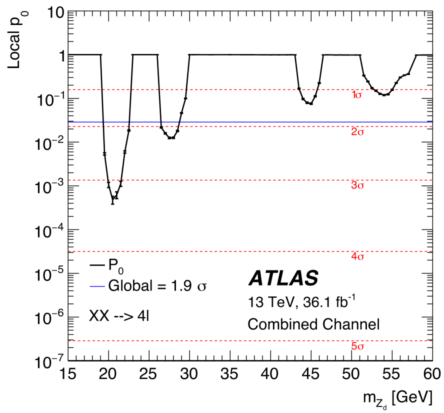


Figure 5: Observed local p-values under the background-only hypothesis

Process	Yield
$ZZ^* \to 4l$	0.8 ± 0.1
$H \to ZZ* \to 4l$	2.6 ± 0.3
VVV/VBS	0.51 ± 0.18
$Z + (t\bar{t}/J/\Psi) \to 4\ell$	0.004 ± 0.004
Other Reducible Background	Negligible
Total	3.9 ± 0.3
Data	6

Table 2: Expected and observed of events at $36.1 fb^-1$

- Some excesses are observed but not statistically significant

$H \to XX \to 4l$ low mass results

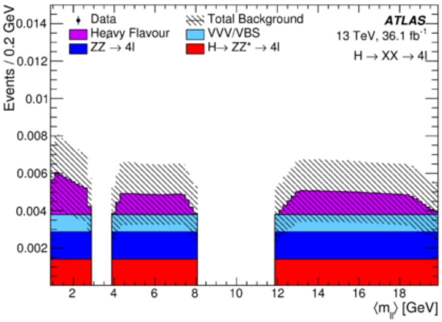


Figure 6: $< m_{ll} >$ in the mass range m4ℓ in [120,130] GeV.

- No excess is observed for the low mass region

Process	Yield
$ZZ^* \to 4l$	0.10 ± 0.01
$H \to ZZ* \to 4l$	0.1 ± 0.1
VVV/VBS	0.06 ± 0.03
Heavy flavour	0.07 ± 0.04
Total	0.4 ± 0.1
Data	0

Table 3: Expected and observed events at $36.1 fb^{-1}$

Interpretation: fiducial cross-section

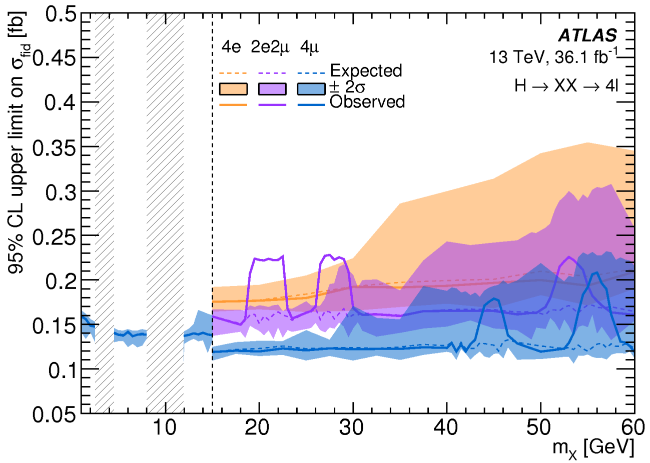


Figure 7: Upper limits at 95% CL on fiducial cross-sections for the $H \to XX \to 4l$ process

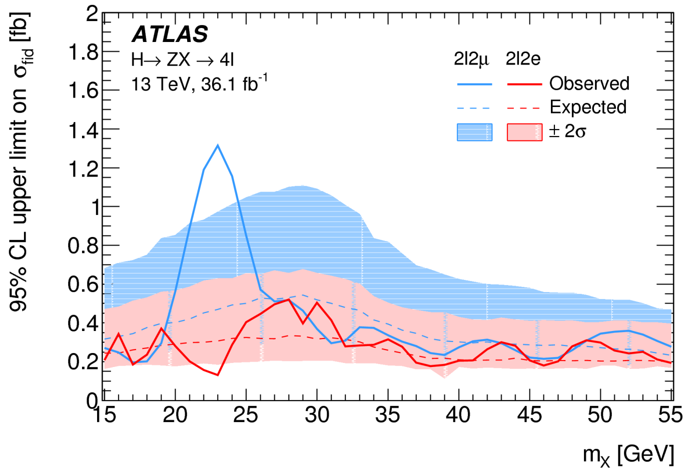
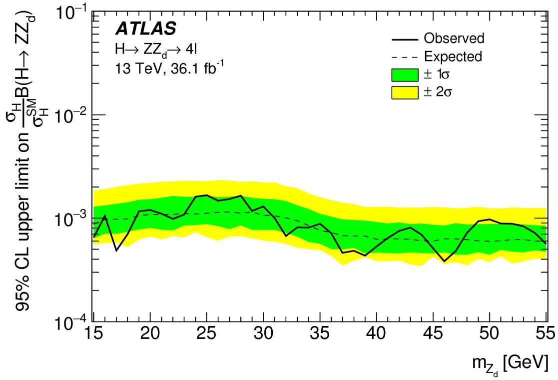
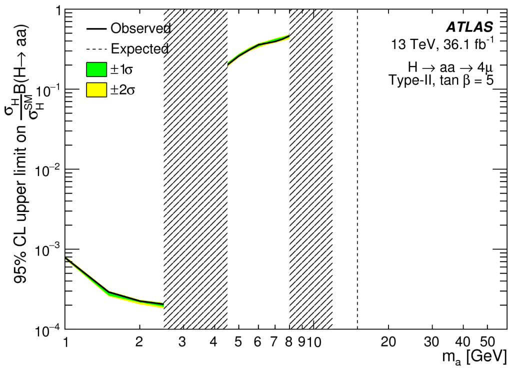
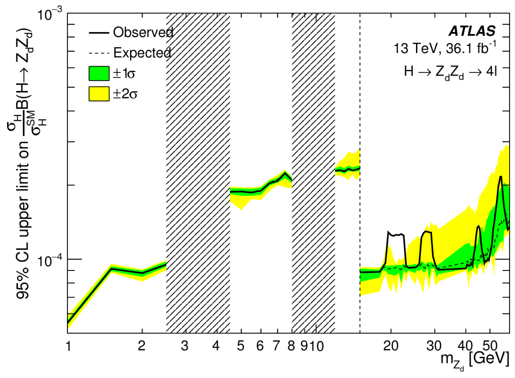


Figure 8: Upper limit at 95% CL on the fiducial cross-sections for the $H \to ZX$ process.

Interpretation: branching ratio







- Upper limits at 95% CL on model-dependent Branching Ratio for the 3 analyses

Interpretation: κ and ϵ parameter

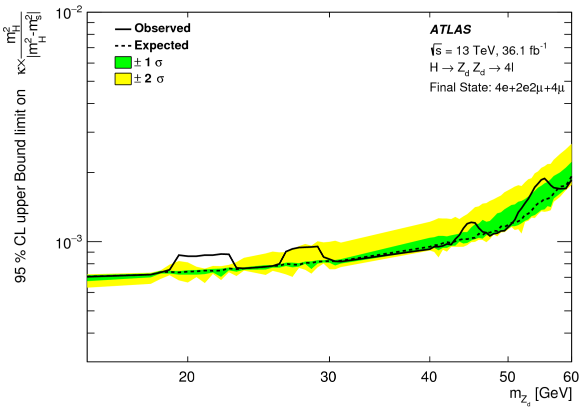


Figure 9: Upper limits at 95% CL on fiducial cross-sections for the $H \to ZX \to 4l$ process

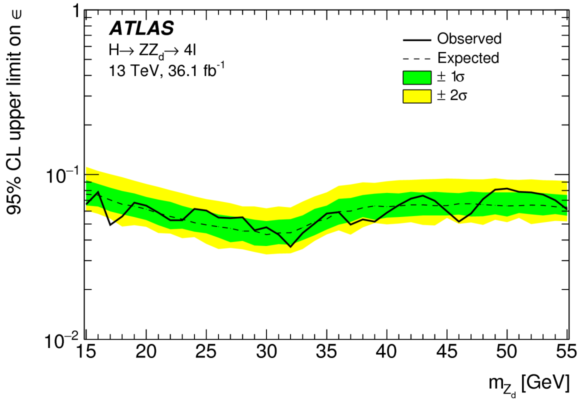


Figure 10: Upper limit at 95% CL on the branching ratio for the $H \to ZZ_d$ process.

$$\kappa^2 = \Gamma(H \to Z_d Z_d) \frac{32\pi m_h^5}{v^2[(m_h^2 - 2m_{Z_d}^2)^2 - 8(m_h^2 - m_{Z_d}^2)m_{Z_d}^2]} \frac{1}{\sqrt{1 - \frac{4m_{Z_d}^2}{m_h^2}}}$$

$$\kappa' = \kappa \times \frac{m_H^2}{|m_H^2 - m_S^2|}$$

Conclusion

1. **Summary**

- Search for light BSM boson in 4l channel is performed.
- Data is mostly consistent with expected background.
- Upper limits on model-independent fiducial cross section are set.
- Upper limits on branching ratio (benchmark model) and also on the model coupling parameters are set at 95% CL.
- More about this can be found here: 10.1007/JHEP06(2018)166

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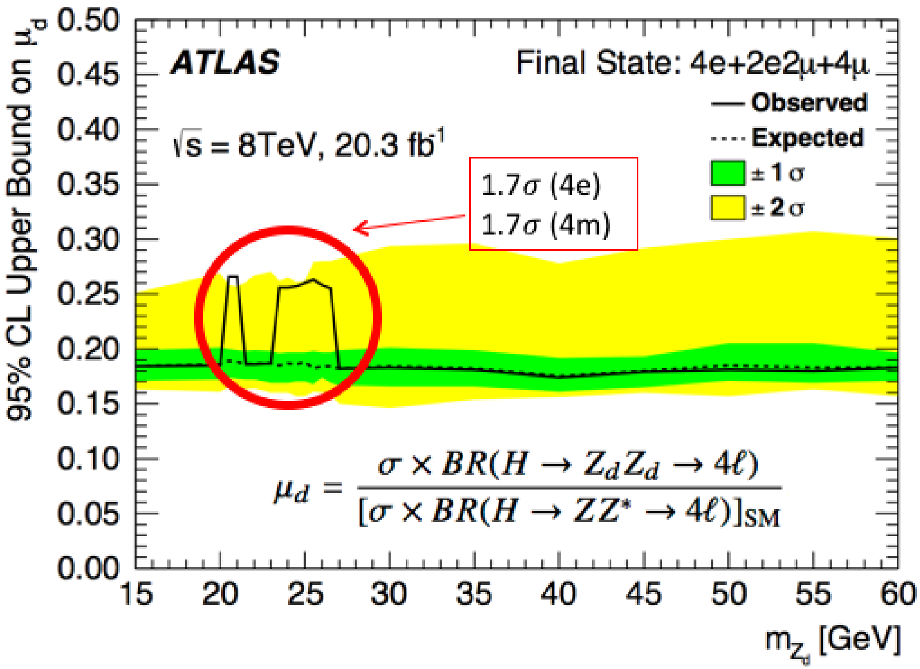
2. **Plan**

- research to heavier progenitor scalar
- Making use of a more sensitive
- Improving background estimation
- exploring 4τ channel in low mass region

Result Run 1

See paper http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.092001



Excess seen at local 2s level is not significant.
Within Statistics, consistent with the SM

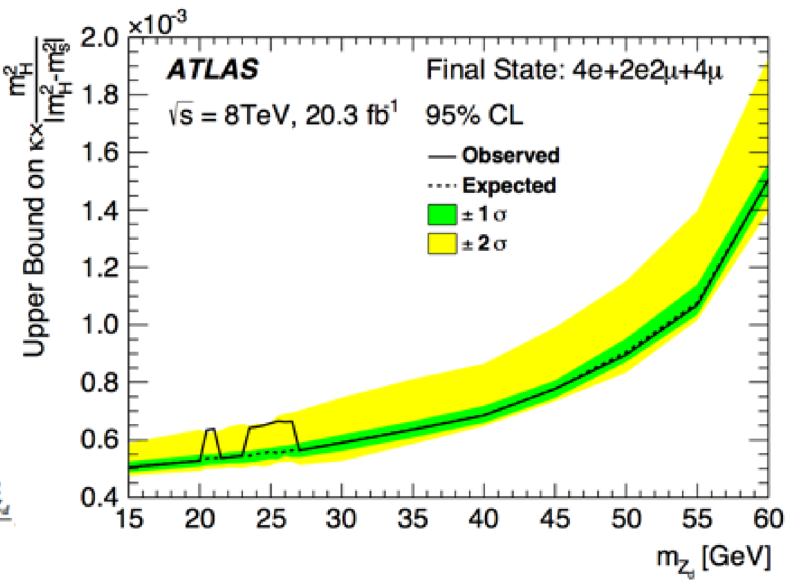
Interpretation in term of Higgs mixing (Run 1)

See paper http://journals.aps.org/prd/abstract/10.1103/PhysRevD.92.092001

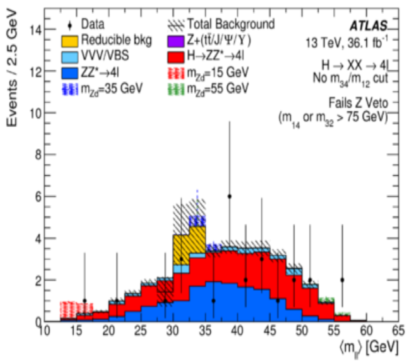
model dependent interpretation Curtin et al in ArXiv 1412.0018v2.pdf

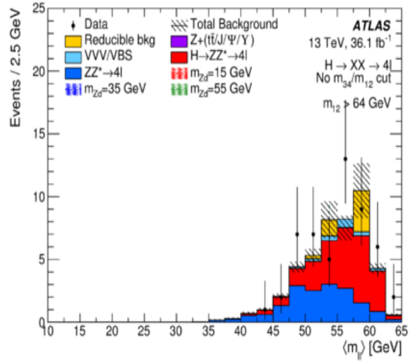
$$\kappa^2 = \frac{\Gamma_{SM}}{f(m_{Z_d})}\frac{\mathrm{BR}(H \to Z_d Z_d)}{1-\mathrm{BR}(H \to Z_d Z_d)},$$

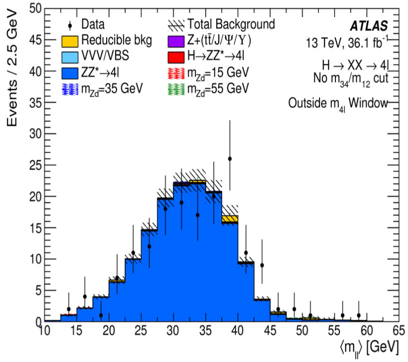
$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1-\frac{4m_{Z_d}^2}{m_H^2}} \times \frac{\left(m_H^2 + 2m_{Z_d}^2\right)^2 - 8\left(m_H^2 - m_{Z_d}^2\right)m_{Z_d}^2}{\left(m_H^2 - m_S^2\right)^2}$$



Irreducible background validation regions







- 3 Validations Regions:
  - ☞ Events failing the Z Veto
  - ☞ Events where $m_{12} > 64 GeV$
  - ☞ Events outside of the $115 < m_{4l} < 130 GeV$ window
- These distributions validated the $H \to ZZ^* \to 4l$ and $ZZ^* \to 4l$ (Main backgrounds) process

Systematics

In the case of a signal, we will determine the significance, and in the case of exclusion, we will set limits. Presented here are the relative uncertainties on the high-mass fiducial efficiency for three mass points. All uncertainties were estimated using the ZdZd signal samples

High-mass Selection	m_X = 15 GeV			m_X = 35 GeV			m_X = 55 GeV		
	$4e$	$2e2\mu$	4μ	$4e$	$2e2\mu$	4μ	$4e$	$2e2\mu$	4μ
STAT	±3.5	±1.7	±2.9	±3.3	±1.8	$^{+2.7}_{-2.6}$	±2.9	±1.7	±2.3
EL_EFF_ID_TOTAL	$^{+7.6}_{-7.3}$	±3.7	−−	$^{+8.3}_{-7.9}$	±4.1	−−	$^{+7.8}_{-7.4}$	$^{+3.9}_{-3.8}$	−−
EL_EFF_ISO_TOTAL	$^{+1.3}_{-1.2}$	±0.7	−−	±1.4	±0.7	−−	±1.1	±0.6	−−
EL_EFF_RECO_TOTAL	±3.1	$^{+1.6}_{-1.5}$	−−	$^{+3.4}_{-3.3}$	±1.7	−−	$^{+3.1}_{-3.0}$	±1.5	−−
MUON_EFF_STAT	−−	±0.4	±0.7	−−	±0.4	±0.7	−−	±0.4	±0.8
MUON_EFF_STAT_LOWPT	−−	±0.1	±0.2	−−	±0.1	±0.2	−−	±0.1	±0.2
MUON_EFF_SYS	−−	±1.1	$^{+2.4}_{-2.3}$	−−	±1.1	$^{+2.3}_{-2.2}$	−−	±1.2	±2.4
MUON_EFF_SYS_LOWPT	−−	±0.2	±0.3	−−	±0.2	±0.3	−−	±0.1	±0.2
MUON_ISO_STAT	−−	±0.2	±0.4	−−	±0.3	±0.5	−−	±0.2	±0.4
MUON_ISO_SYS	−−	±0.6	±1.1	−−	±0.6	±1.1	−−	±0.5	±1.1
MUON_TTVA_STAT	−−	±0.5	±0.9	−−	±0.5	±0.9	−−	±0.4	$^{+0.9}_{-0.8}$
MUON_TTVA_SYS	−−	±0.8	±1.2	−−	±0.8	±1.4	−−	±0.5	±1.1
PRW_DATASF	$^{+2.5}_{-3.0}$	$^{+2.5}_{-2.8}$	$^{+1.6}_{-1.1}$	$^{+0.8}_{-1.2}$	$^{+1.6}_{-1.3}$	$^{+0.8}_{-1.4}$	$^{+3.0}_{-2.4}$	$^{+1.8}_{-2.0}$	$^{+1.3}_{-1.0}$
EG_RESOLUTION_ALL	$^{+0.6}_{-0.4}$	$^{+0.2}_{-0.1}$	−−	$^{+0.0}_{-0.4}$	−−	−−	$^{+0.5}_{-0.6}$	$^{+0.0}_{-0.1}$	−−
EG_SCALE_ALL	$^{+0.4}_{-0.5}$	±0.1	−−	$^{+0.0}_{-0.6}$	$^{+0.2}_{-0.3}$	$^{+0.0}_{-0.1}$	$^{+0.3}_{-0.6}$	$^{+0.1}_{-0.3}$	−−
MUONS_ID	−−	±0.1	$^{+0.3}_{-0.0}$	−−	±0.1	$^{+0.3}_{-0.1}$	−−	$^{+0.0}_{-0.2}$	$^{+0.1}_{-0.2}$
MUONS_MS	−−	$^{+0.0}_{-0.1}$	$^{+0.5}_{-0.2}$	−−	−−	$^{+0.3}_{-0.1}$	−−	$^{+0.2}_{-0.1}$	$^{+0.0}_{-0.2}$
MUONS_SCALE	−−	−−	$^{+0.4}_{-0.1}$	−−	$^{+0.0}_{-0.1}$	$^{+0.2}_{-0.0}$	−−	$^{+0.0}_{-0.1}$	$^{+0.0}_{-0.1}$
MUONS_SAGITTA_RESBIAS	−−	−−	−−	−−	−−	−−	−−	−−	−−
MUONS_SAGITTA_RHO	−−	−−	−−	−−	−−	−−	−−	−−	−−

Summary of the fiducial phase-space definitions

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<tr><td>Electrons</td><td colspan="3">Dressed with prompt photons within $\Delta R = 0.1$
$p_T > 7$ GeV
$|\eta| < 2.5$</td></tr>
<tr><td>Muons</td><td colspan="3">Dressed with prompt photons within $\Delta R = 0.1$
$p_T > 5$ GeV
$|\eta| < 2.7$</td></tr>
<tr><td rowspan="5">Quadruplet</td><td colspan="3">Three leading-p_T leptons satisfy $p_T > 20$ GeV, 15 GeV, 10 GeV</td></tr>
<tr><td colspan="2">$\Delta R > 0.1$ (0.2) between SF (OF) leptons</td><td>-</td></tr>
<tr><td rowspan="3">$50\ \mathrm{GeV} < m_{12} < 106\ \mathrm{GeV}$
$12\ \mathrm{GeV} < m_{34} < 115\ \mathrm{GeV}$
$115\ \mathrm{GeV} < m_{4\ell} < 130\ \mathrm{GeV}$
$m_{12,34,14,32} > 5$ GeV</td><td colspan="2">$m_{34}/m_{12} > 0.85$</td></tr>
<tr><td>$10\ \mathrm{GeV} < m_{12,34} < 64\ \mathrm{GeV}$
$5\ \mathrm{GeV} < m_{14,32} < 75\ \mathrm{GeV}$ if $4e$ or 4μ</td><td>$0.88\ \mathrm{GeV} < m_{12,34} < 20\ \mathrm{GeV}$</td></tr>
<tr><td colspan="2">Reject event if either of:
$(m_{J/\psi} - 0.25\ \mathrm{GeV}) < m_{12,34,14,32} < (m_{\psi(2S)} + 0.30\ \mathrm{GeV})$
$(m_{\Upsilon(1S)} - 0.70\ \mathrm{GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\ \mathrm{GeV})$</td></tr>
</table>

trigger

HLT_e24_lhmedium_L1EM20VH
HLT_e60_lhmedium
HLT_mu20_iloose_L1MU15
HLT_mu40
HLT_2e12_lhloose_L12EM10VH
HLT_mu18_mu8noL1
HLT_2mu10
HLT_e17_lhloose_mu14
HLT_e17_lhloose_2e9_lhloose
HLT_3mu6
HLT_e26_lhtight_nod0_ivarloose
HLT_e60_lhmedium_nod0
HLT_mu50
HLT_2e17_lhvloose_nod0
HLT_mu22_mu8noL1 14
HLT_e17_lhloose_nod0_mu14 15
HLT_e17_lhloose_nod0_2e9_lhloose_nod0 16
HLT_mu20_mu8noL1 17
HLT_2mu14 18