Search for Higgs Decays to Beyond the Standard Model Light Gauge Bosons in four-lepton events with the ATLAS Detector at $\sqrt{s}$ = 13 TeV

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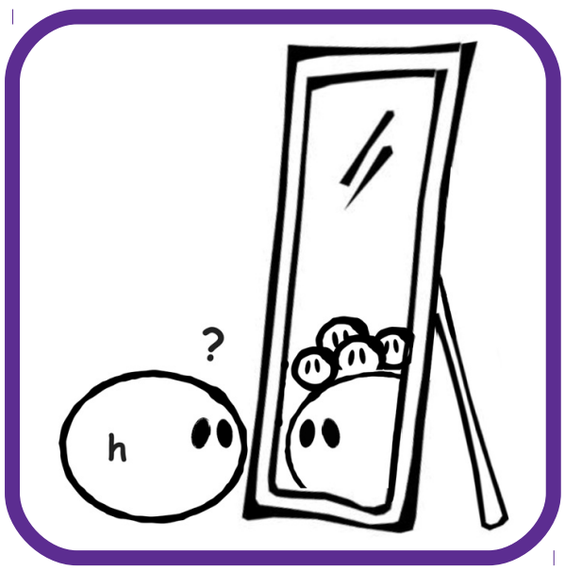
Introduction

Several *well motivated* extensions to the Standard Model

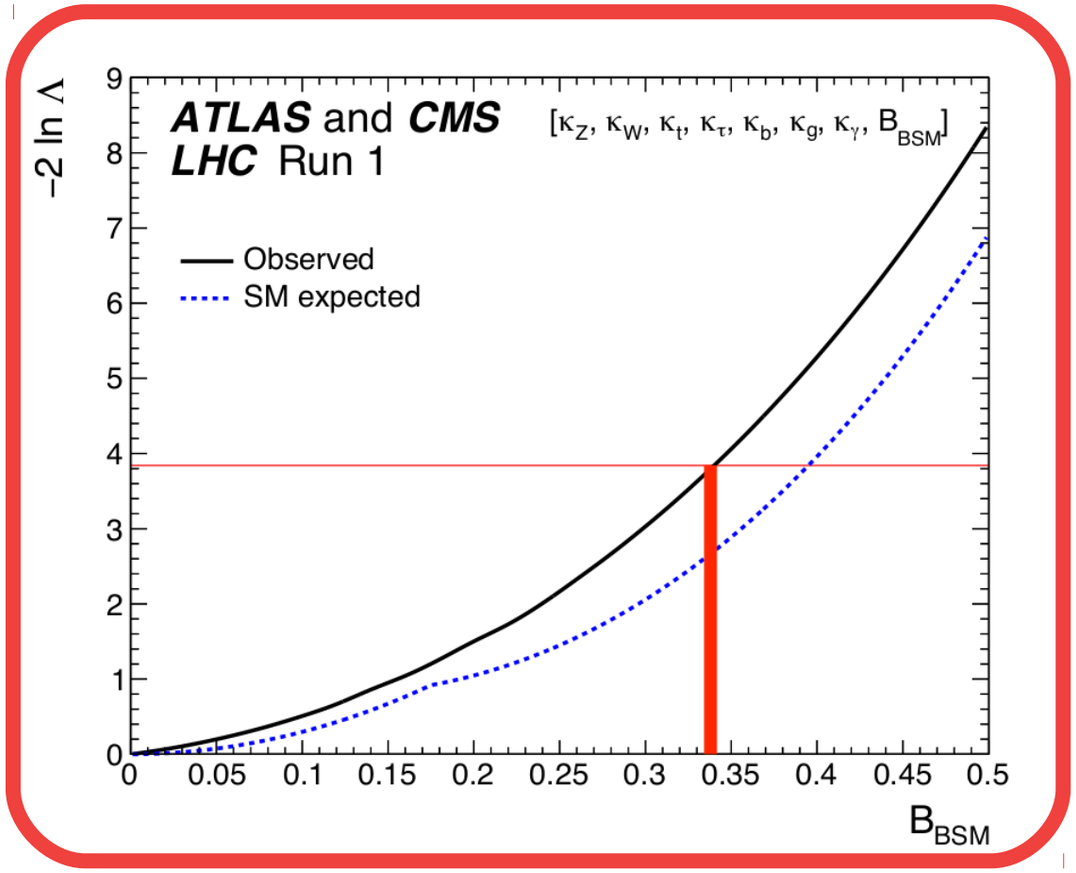
- The "newly" discovered 125 GeV Higgs provides an excellent additional portal in which to study additional particle content of the Standard Model
- Can also further examine the (**additional?**) content of the Higgs sector



Current Limits on BR(H) → BSM is $\lesssim$ 30%
[arXiv:1606.02266]

Overview of Analysis:

- *Based on CONF note: ATLAS-CONF-2017-042*
- *Looking for light BSM resonances in the decay of the H(125) Higgs*
  - **H → XX**
    - *"high-mass" [m_X = 15 -- 60 GeV]*
    - *"low-mass" [m_X = 1--15 GeV]*
  - **H → ZZ_d**
    - *m_{Zd} = 15 -- 55 GeV*



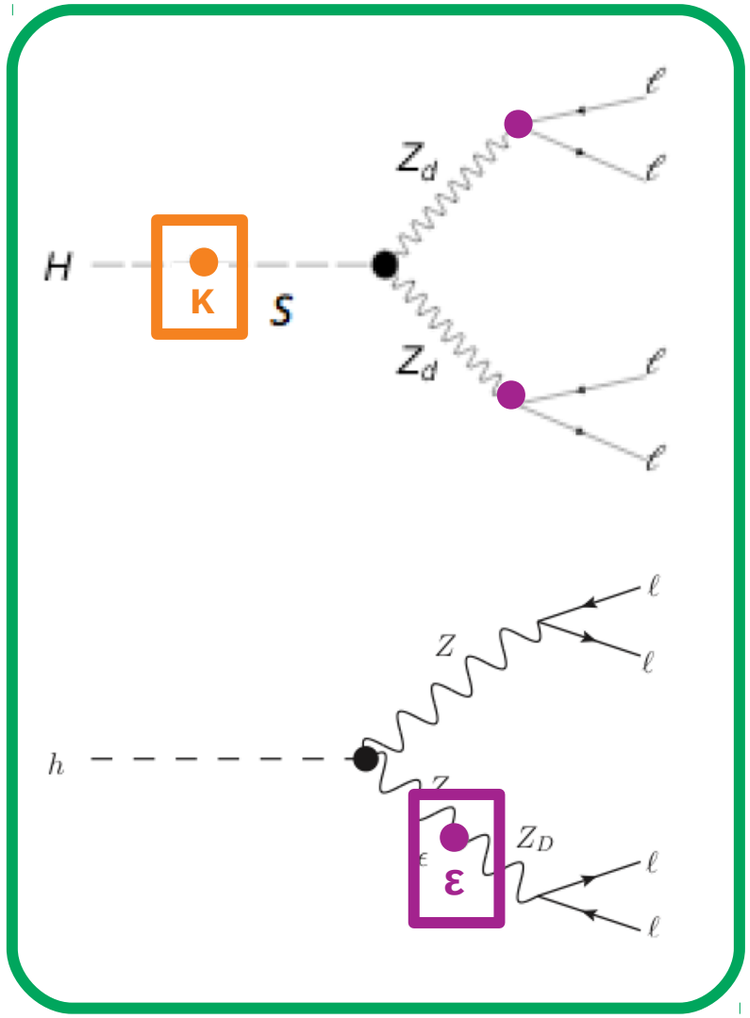
Results

- *Fiducial cross-section limits / Upper limit on* **BR(H → XX/ZZ_d)**

Theoretical Models

Two Processes being studied:

- **H → XX**
  - **X** interpreted as either pseudo-scalar '***a***' or Z_d
- **H → ZZ_d**

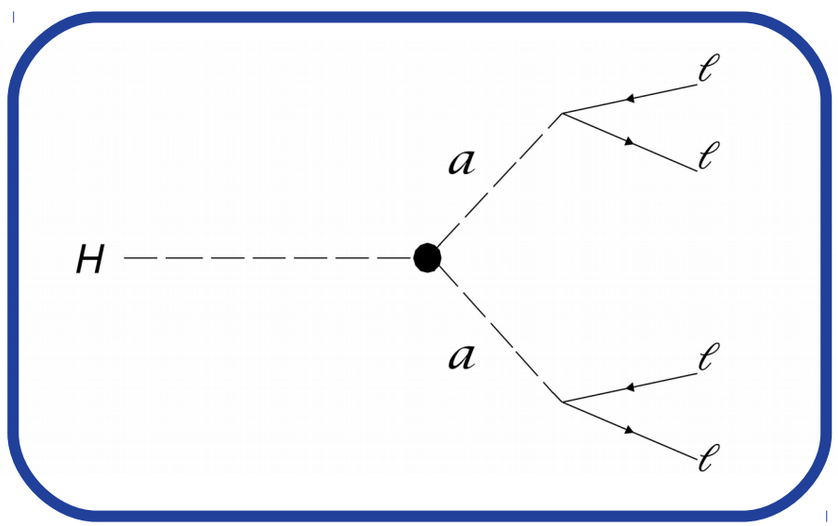


The Higgs Sector as a portal to the *Dark Sector*

- Add an additional $U(1)_d$ extension to the SM + Higgs singlet
- **Model Parameters:**
  - **ε --** kinematic mixing angle
    - Decays to SM particles controlled by this parameter
    - *A prompt analysis is presented here (good to* $\varepsilon \sim 10^{-5}$ *)*
  - **κ --** Higgs mixing with dark Higgs (S)
- H → Z_dZ_d **[ε ≪ κ]**
- H → ZZ_d **[ε ≫ κ]**

Additional particle content for the Higgs sector in the form of 2HDM + S model

- Search for the existence of the "light" neutral pseudo-scalar particle ***a***
  - $m_a < 0.5\ m_H$
- Potentially large BR(a → μμ) for Type-II 2HDM+S



Search Strategy

Search regions

- ***Each region has unique topological cuts***
- **H → XX [aa / Z_dZ_d]**
  - **"High Mass Search"** -- 15 < m_X < 60 GeV
    - l = e, μ
  - **"Low Mass Search"** -- 1 < m_X < 15 GeV
    - Excludes regions near the **J/ψ** and **Υ**
    - l = μ-only
- **H → ZZ_d**
  - 15 < m_{Zd} < 55 GeV
    [probing masses **above** 55 GeV leads to ambiguity between Z and Z_d]
    - l = e, μ

Signal Samples / model configurations

- *All resonances taken to be **narrow***
- ***Z_d – Generated according to Hidden Abelian Higgs Model (HAHM)***
  - *ZZ_d – X mass hypothesis between 15 and 55 GeV every 5 GeV*
  - *Z_dZ_d – X mass hypothesis between 15 and 60 Gev every 5 GeV*
    - *Finer binning for low mass*
  - *MG5 + Pythia8*
- ***a – Narrow Width Approximation***
  - *13 mass points generated in the range between 0.5 – 60 GeV*
  - *a → μ*
  - *Powheg + Pythia8*

Higgs generated at m_H = 125 GeV, through ggF production

Dominant Backgrounds

Many shared backgrounds between the H → XX and H → ZZ_d analyses

- **Kinematic region for common backgrounds are very different -- estimation techniques/generators vary**

H → ZZ_d

- **H → ZZ* → 4l**
  - All production modes included
- **ZZ* → 4l**
  - both gg-loop induced and $q\bar{q}$ annihilation
- **VVV, ttV**
- **Fakes (mis-ID'd leptons)**:
  - *Z+jets, tt, WZ*

H → XX

- **H → ZZ* → 4l**
  - All production modes included
- **ZZ* → 4l**
  - both gg-loop induced and $q\bar{q}$ annihilation
- **EWK6** → 4l + 2X
- **Z + quarkonia** → 4l
- **Fakes (mis-ID's leptons):**
  - *Z+jets, tt, WZ*
  - ***Particular** care taken for final states with 2+ b-quarks ($b\bar{b}$, $b\bar{b}b\bar{b}$)*

Dominant Backgrounds are **H → ZZ* → 4l** and **ZZ* → 4l**

Dominant/Sub-dominant backgrounds modelled in MC and normalized to theory cross-sections

Fakes: Modelled with MC with data-driven normalization / data-driven

Selection Basics

Slightly Different Selection based on mass region probed (ie: low mass, vs high mass)

- *Cuts altered in order to preserve good signal efficiency*
- *Low mass region: only muons considered due to high boost in final state*

Basics/Preselection:

- **Trigger:**
  - *single/di/tri lepton triggers*
- **Lepton Content:**
  - *Events must have a lepton quadruplet made from any combination of 2 pairs of **opposite-charge, same-flavour** dileptons*
    - *Different analyses have different strategies for the quadrapole selections due to the different kinematic regions*
  - *Lepton p_T requirements:*
    - **3 leptons:** *p_T > 10 GeV*
    - **2 leptons:** *p_T > 15 GeV*
    - **1 lepton:** *p_T > 20 GeV*

Final Descriminants:

- ***H → XX***

  $\langle m_{ll} \rangle = ½(m_{12} + m_{34})$

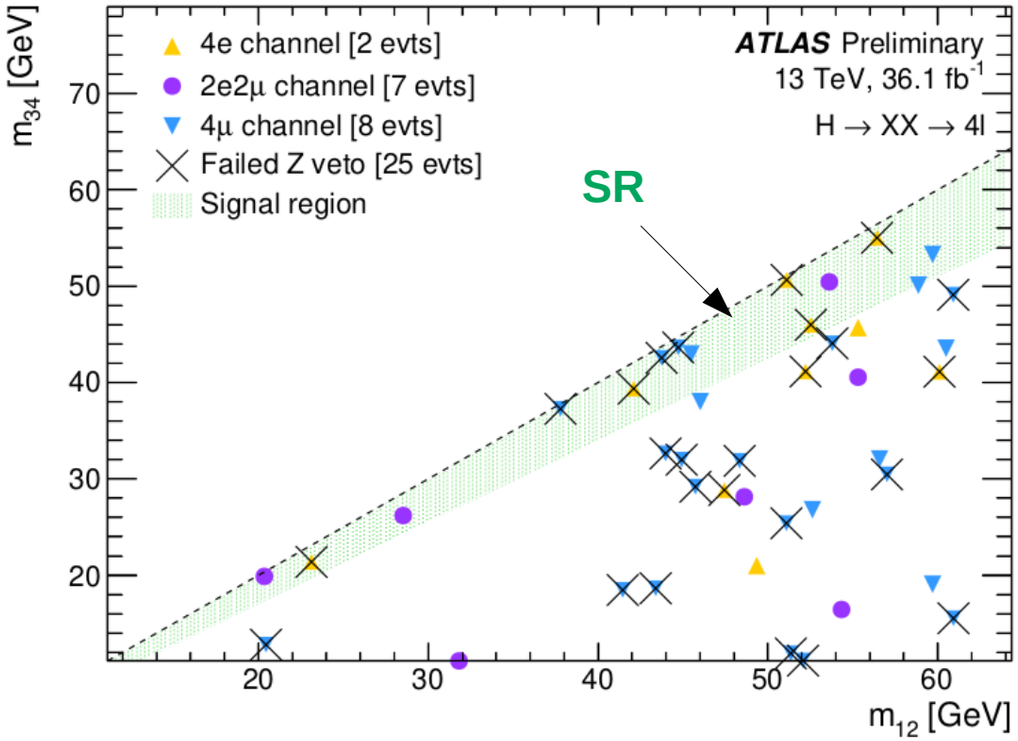
- **H → ZZ_d**

  m_{34}

H → XX → 4l Analysis [High mass]

Selection

- **Events with multiple quadruples:** *Select one with smallest $\Delta m = |m_{12} - m_{34}|$*
  - *m_{12} defined as the pair closest to Z-pole mass*
- *$m_{34}/m_{12} > 0.85$ [provides good S/B]*
- *ΔR separation of lepton pairs (and leptons within pair)*
- *Three signal regions (no differentiation between eeμμ and μμee)*
- **J/ψ and ϒ veto**: ***All*** *dilepton pairs outside mass window*
- ***SM Z+leptons veto:*** *5 GeV < $m_{14,32}$ < 75 GeV (only 4e 4u)*
- ***Lepton Pair masses:*** *10 GeV < $m_{12,34}$ < 64 GeV*
- ***Final selection window:*** *115 GeV < m_{4l} < 130 GeV*



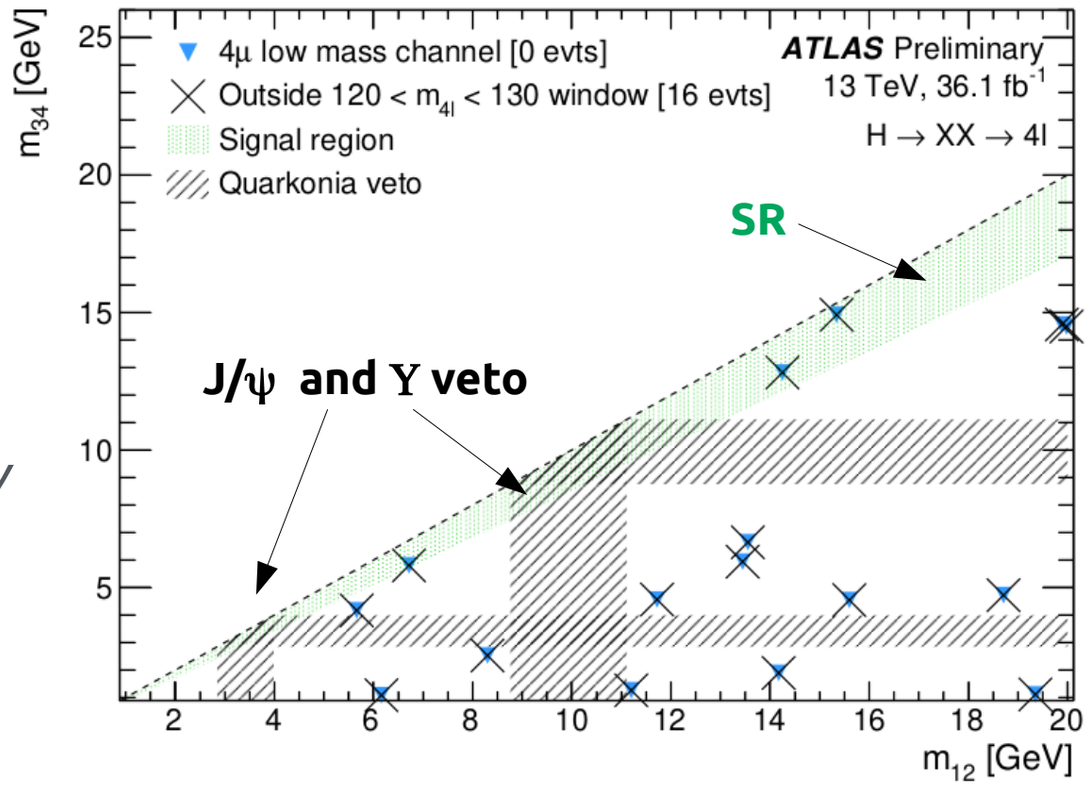
Background Modelling

- ***H → ZZ* → 4l*** *and* ***ZZ* → 4l*** *processes dominant (**>60%** combined)*
- *Subdominant: Higher-order EWK processes*
- *MC prediction used and normalized to theoretical cross sections*
- **Fakes:**
  - *Estimated from MC*
  - *MC modelling checked in the dedicated validation regions with inverted lepton ID selections*
    - *Validation regions – data-driven background yields consistent (and very small) with those given by MC*

H → XX → 4l Analysis [Low Mass]

Selection

- ***Same base selection of high-mass quadruples***
  - ***No*** *angular separation between leptons/pairs enforced*
  - *Only* ***muons*** *considered*
- ***Lepton Pair Masses:*** *0.88 GeV < $m_{12,34}$ < 20 GeV*
- ***Final selection window:*** *120 GeV < m_{4l} < 130 GeV*
  - *Smaller than high-mass window, as radiative losses smallers for muons*



Background Modelling

- **Mimics high-mass, although with different relative contributions**
- ***H → ZZ* → 4l*** *and* ***ZZ* → 4l*** *processes dominant (****>60%*** *combined)*
- **Fakes:** *Estimated from MC and validated*
- ***Multi-b Final states*** *($b\bar{b}$, $b\bar{b}b\bar{b}$):* → **Negligible in high-mass analysis**
  - *Background modelled as 2D template in the $m_{12} \times m_{34}$ plane*
    - *1D templates along each axis made from dedicated 3 muon data samples*
  - *Template normalized to SR based on m_{34}/m_{12} < 0.85 [****inverted*** *SR cut]*

$H \rightarrow ZZ_d \rightarrow 4l$

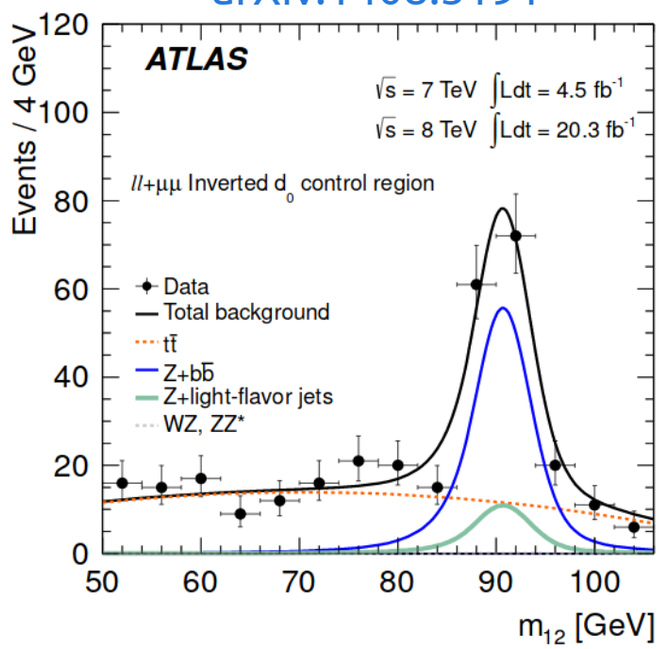
Selection

- ***Lepton quadruples selection preference:*** 4μ, 2e2μ, 2μ2e and 4e
  - *Pair closest to Z-pole mass is taken as the "lead" pair which make up* m_{12}
  - $50\ GeV \leq m_{12} \leq 106\ GeV$
  - $12\ GeV \leq m_{34} \leq 115\ GeV$
- *Two channels based on quadruple leptons:* ***llee*** *and* ***llμμ***
- *ΔR Separation of lepton pairs and pairs*
- ***J/ψ veto:*** $m_{ll} > 5\ GeV$ *(ll made of* ***all*** *pairs of SFOS leptons)*
- ***Final selection window:*** $115\ GeV \leq m_{4l} \leq 130\ GeV$
- **Reminder:** m_{34} *used as final discriminant*

Background Modelling

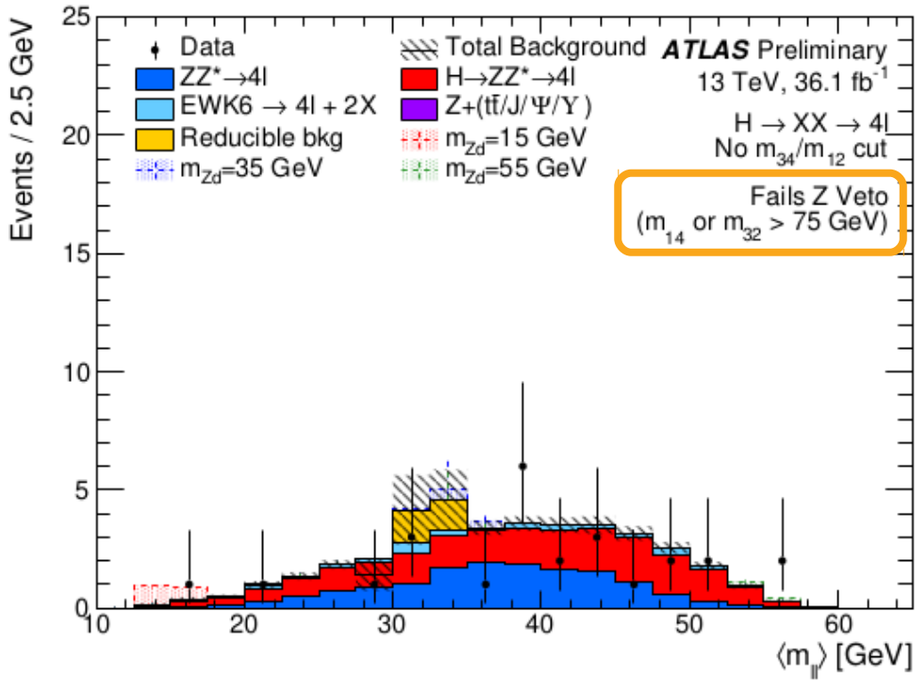
- $H \rightarrow ZZ^* \rightarrow 4l$ *and* $ZZ^* \rightarrow 4l$ *processes dominant (>90% combined)*
  - *Shape and normalization from MC verified in* ***validation*** *regions*
- ***Reducible contribution:*** *~6%*
  - *Estimated with data-driven techniques (separately for the llee and llμμ channels)*
  - *Shape from MC simulations, normalization from data-driven fit in control region (separately for llee, and llμμ channels*

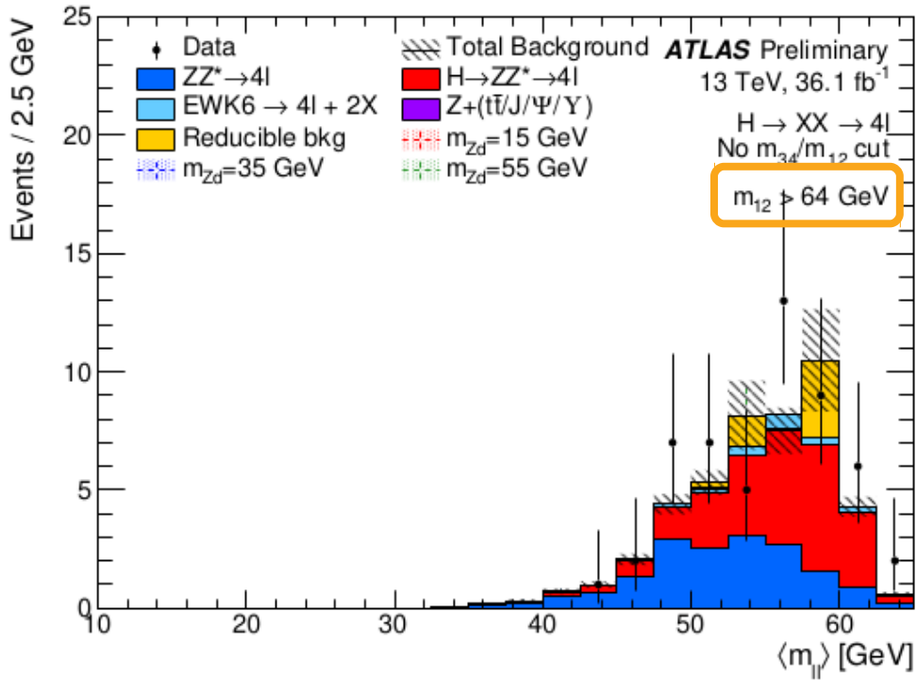
Illustrative example from arXiv:1408.5191

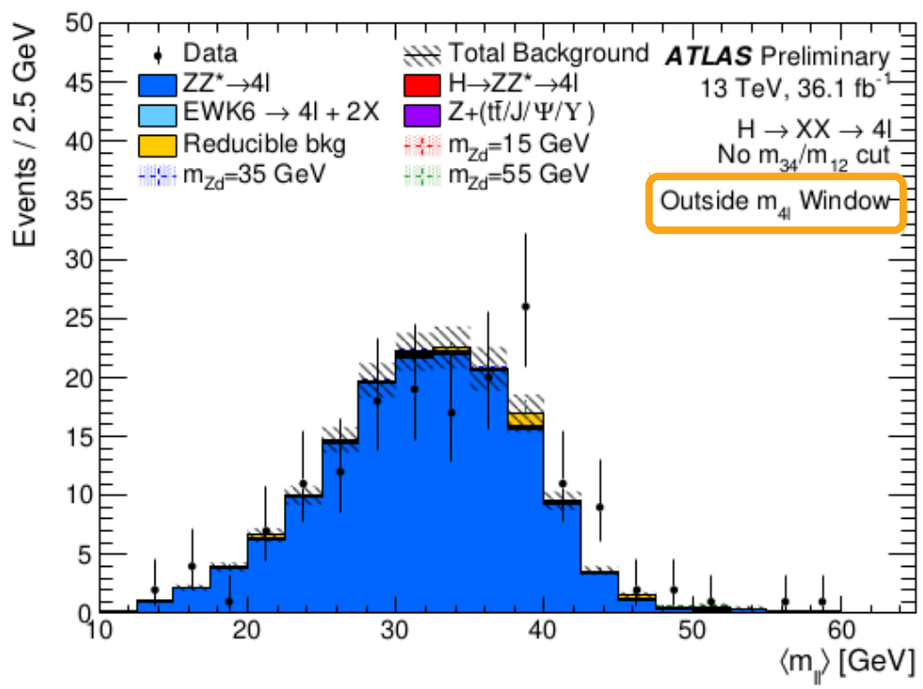


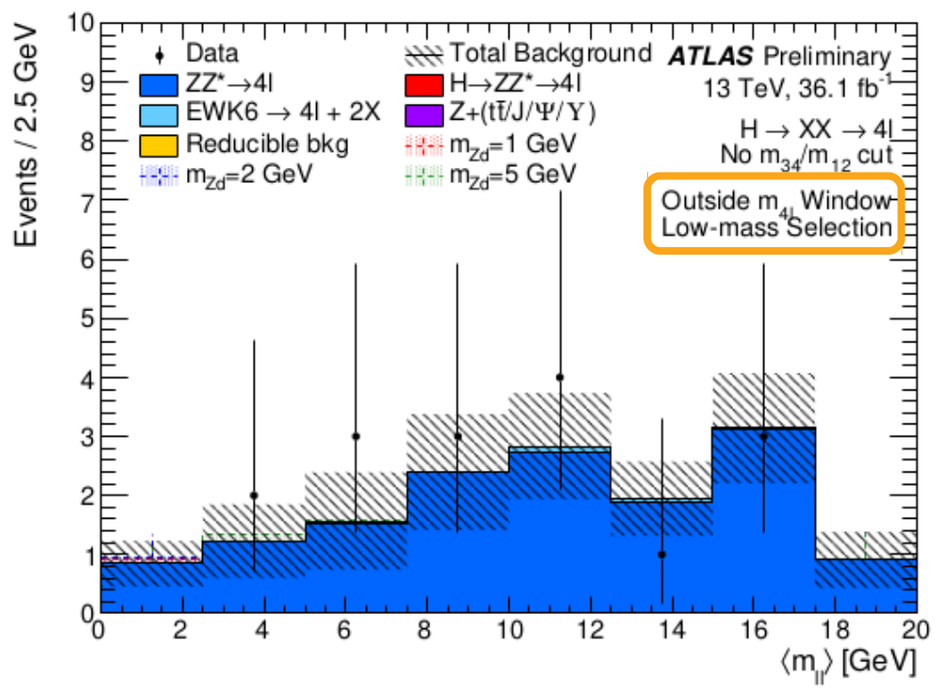
Background Modelling

Background modelling checked in **orthogonal** *validation regions* defined by inverting **selected selection criteria**









Results

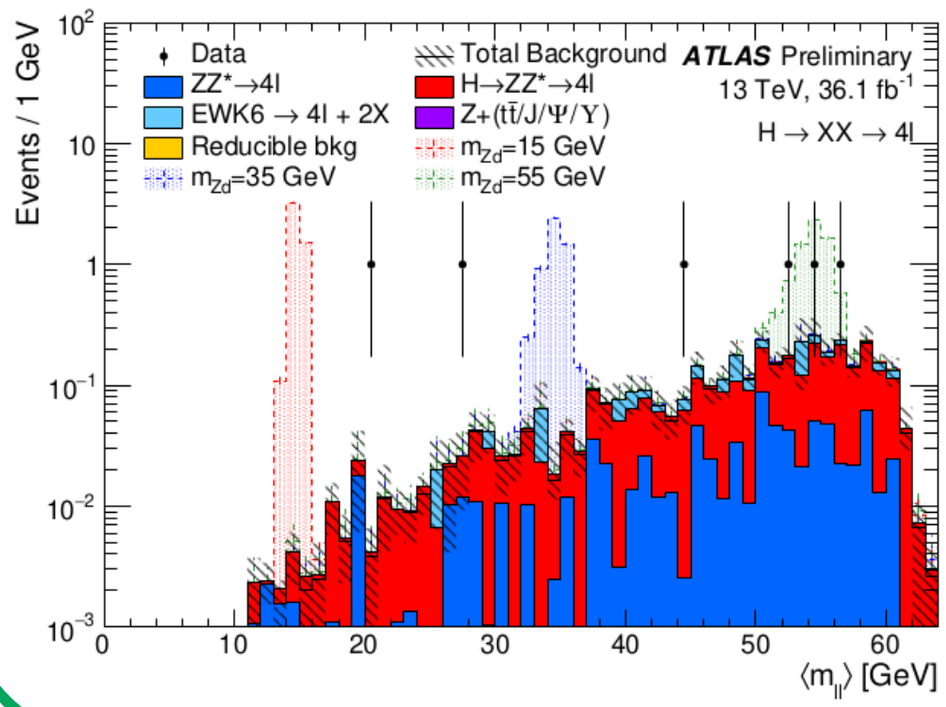
Upper limits on BR(H → XX)
Upper limits on σ(H → XX)
Upper limits on BR(H → ZZ$_d$)

Results: H → XX → 4l (/1)

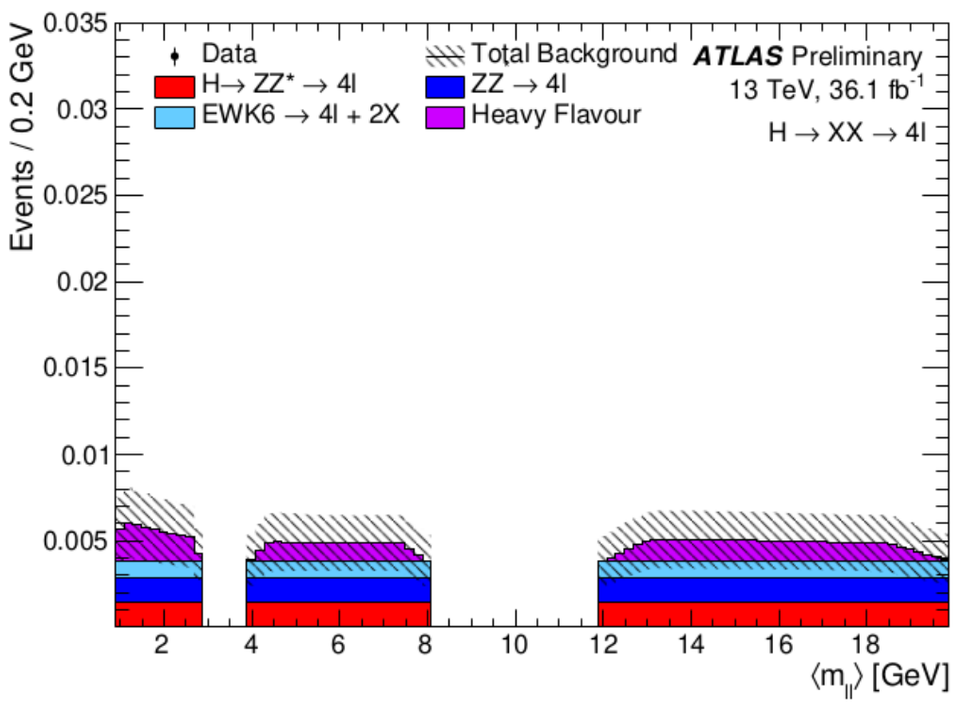
Final Event Yields in H → XX SRs

Process	High Mass selection (for 15 GeV < m_X < 60 GeV)	Low Mass selection (for 1 GeV < m_X < 15 GeV)
$ZZ^* \to 4\ell$	0.8 ± 0.1	0.10 ± 0.01
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3	0.1 ± 0.1
EWK6	0.51 ± 0.18	0.06 ± 0.03
$Z + (t\bar{t}/J/\psi/\Upsilon) \to 4\ell$	0.004 ± 0.004	–
Heavy Flavour	–	0.07 ± 0.04
Reducible background	0 ± 0	–
Total	3.9 ± 0.3	0.4 ± 0.1
Data	6	0

High-mass Signal Region



Low-mass Signal Region



Results: H → XX → 4l (/2)

Z_dZ_d model used to compute reconstruction efficieny in the fiducial volume

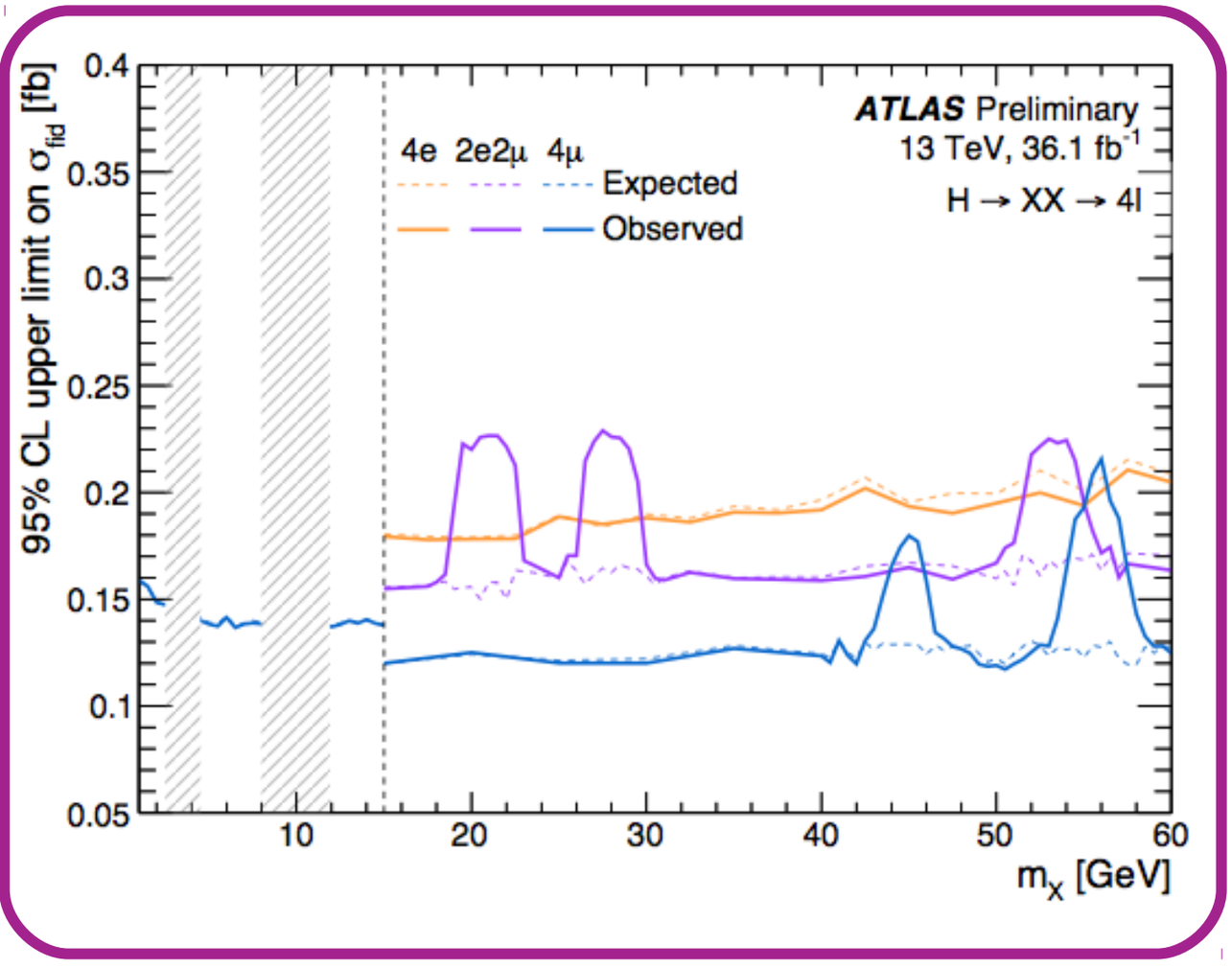
- *Cuts mimic the analysis selection cuts*
- *Fiducial reconstruction efficiency consistent (**3%**) between 'aa' and 'Z_dZ_d' intermediate states*
  - *Allows for **model independant limits***

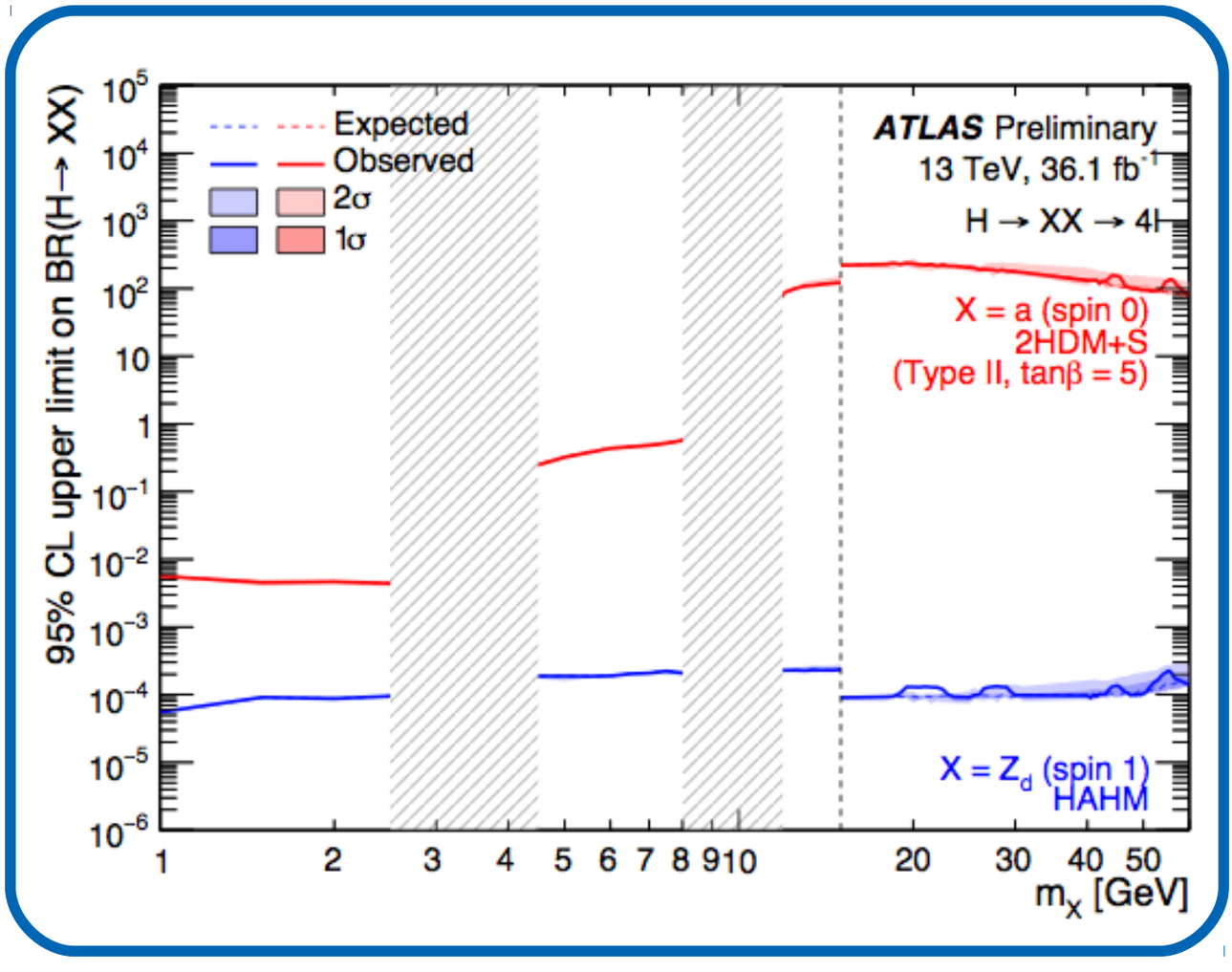
Signal acceptance for Z_dZ_d model and 2HDM+S calculated separately

- *allow for upper limits on **BR(H → XX)***

Z_d model: equal partial fractions (**0.25**) for each of the channels **4e : 2e2μ : 4μ : 2μ2e**

2HDM+S: 100% decay *a → 4μ*

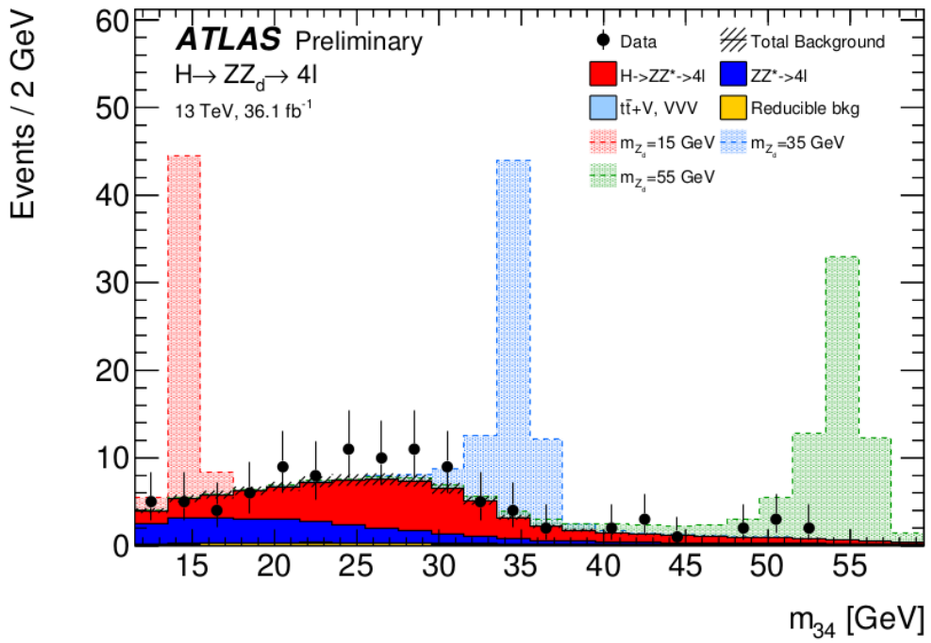




Results: H → ZZ_d → 4l

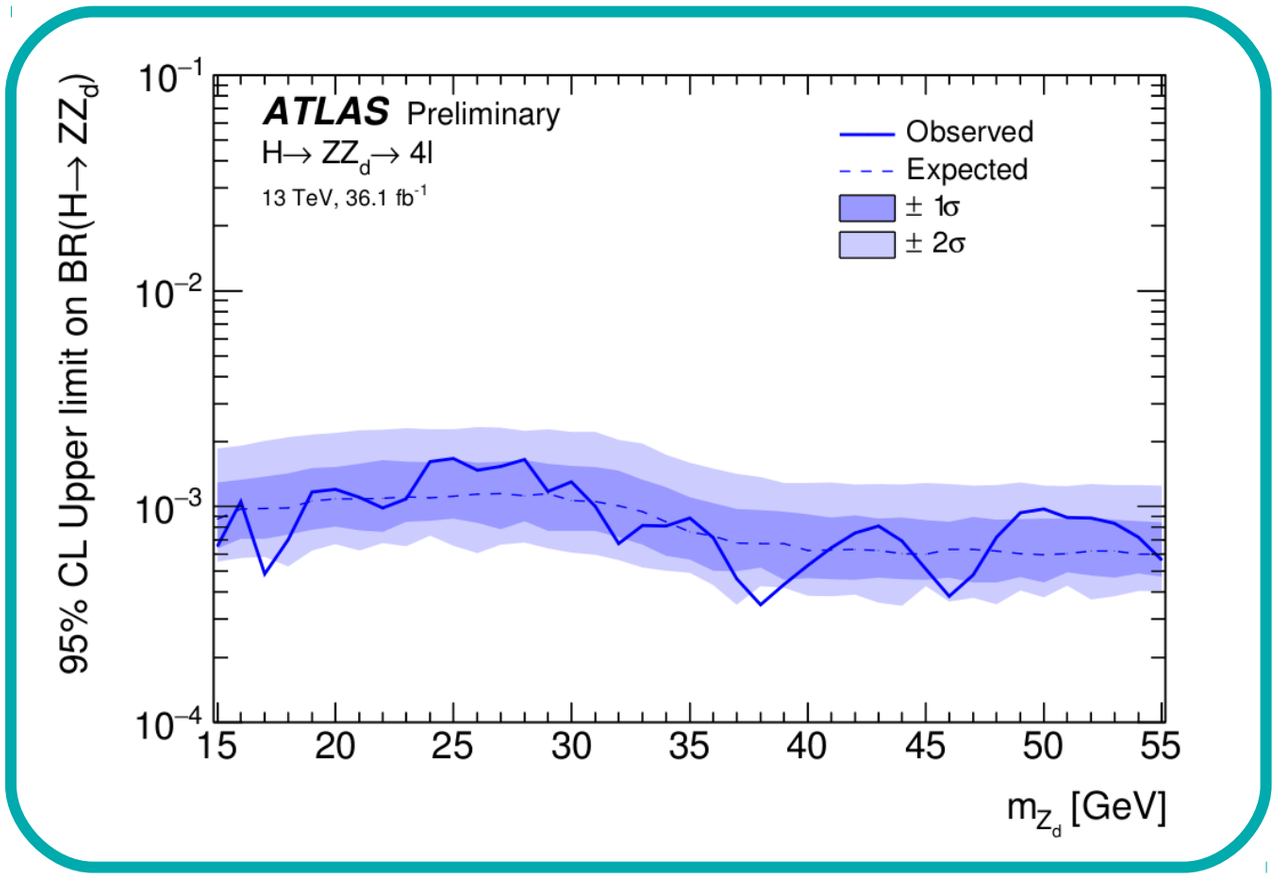
Signal acceptance for ZZ_d model/final state calculated

- *Set upper limits on **BR(H → ZZ_d)***



Final Event Yields in H → ZZ_d SR

Process	High Mass selection (for 15 GeV < m_{Z_d} < 55 GeV)
$ZZ^* \to 4\ell$	26 ± 2
$H \to ZZ^* \to 4\ell$	56 ± 6
Z+jets, $t\bar{t}$	4.8 ± 1.1
$t\bar{t}V$, VVV	0.4 ± 0.1
Total	87 ± 7
Data	102



Summary and Conclusion

Presented results for both H → XX → 4l and H → ZZ_d → 4l searches

- **X interpreted as:**
  - *pseudo-scalar 'a' in 2HDM+S extension to Higgs sector*
  - *Dark-photon*

Model independant limits presented on upper cross-section for H → XX → 4l

Upper limits on BR(H → XX/ZZ_d)

Still lots of room to find BR(H → BSM)!

Stay tuned for further publications *coming soon!*

Thanks!

Selection Summary /1

Object	$H \to ZZ_d \to 4\ell$	$H \to XX \to 4\ell$	
		High Mass selection	**Low Mass selection**
QUADRUPLET SELECTION	- Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-charge leptons - Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV. - At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel.		
	- Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest the Z mass	- Leptons in the quadruplet responsible for firing at least one trigger	
	- Leading di-lepton mass requirement: 50 GeV $< m_{12} <$ 106 GeV - Sub-leading di-lepton mass requirement: 12 GeV $< m_{34} <$ 115 GeV - $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet - Remove quadruplet if alternative same-flavour opposite-charge di-lepton gives $m_{\ell\ell} <$ 5 GeV	- $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavour leptons in the quadruplet	
QUADRUPLET RANKING	- Select quadruplet with the highest expected signal rate, in the order: 4μ, $2e2\mu$, $2\mu2e$, $4e$	- Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$	
EVENT SELECTION	- 115 GeV $< m_{4\ell} <$ 130 GeV	- Reject event if: $(m_{J/\Psi} - 0.25$ GeV$) < m_{12,34,14,23} < (m_{\Psi(2S)} + 0.30$ GeV$)$ $(m_{\Upsilon(1S)} - 0.70$ GeV$) < m_{12,34,14,23} < (m_{\Upsilon(3S)} + 0.75$ GeV$)$ - $m_{34}/m_{12} > 0.85$	
		- 115 GeV $< m_{4\ell} <$ 130 GeV - 10 GeV $< m_{12,34} <$ 64 GeV - 5 GeV $< m_{14,32} <$ 75 GeV for $4e$ and 4μ channels	- 120 GeV $< m_{4\ell} <$ 130 GeV - 0.88 GeV $< m_{12,34} <$ 15 GeV - No restriction on alternative pairing

Table 1: Summary of the event selection of the different channels of the analyses described in this note.

Selection Summary /2

	$H \to XX \to 4\ell$		$H \to ZZ_d \to 4\ell$
Object	**High Mass Fiducial (for 15 GeV $< m_X <$ 60 GeV)**	**Low Mass Fiducial (for 1 GeV $< m_X <$ 15 GeV)**	**High Mass Fiducial (for 15 GeV $< m_{Z_d} <$ 55 GeV)**
Electrons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 7$ GeV $\lvert\eta\rvert < 2.5$		
Muons	Dressed with prompt photons within $\Delta R = 0.1$ $p_{\mathrm{T}} > 5$ GeV $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV		
	Reject event if either of: $(m_{J/\psi} - 0.25\ \mathrm{GeV}) < m_{12,34,14,23} < (m_{\psi(2S)} + 0.30\ \mathrm{GeV})$ $(m_{\Upsilon(1S)} - 0.70\ \mathrm{GeV}) < m_{12,34,14,23} < (m_{\Upsilon(3S)} + 0.75\ \mathrm{GeV})$		$50\ \mathrm{GeV} < m_{12} < 106\ \mathrm{GeV}$ $12\ \mathrm{GeV} < m_{34} < 115\ \mathrm{GeV}$ $\Delta R > 0.1$ (0.2) between SF (OF) leptons $m_{12,34,14,23} > 5$ GeV $115\ \mathrm{GeV} < m_{4\ell} < 130\ \mathrm{GeV}$
	$m_{34}/m_{12} > 0.85$		
	$10\ \mathrm{GeV} < m_{12,34} < 64\ \mathrm{GeV}$ $\Delta R > 0.1$ (0.2) between SF (DF) leptons $5\ \mathrm{GeV} < m_{32,14} < 75\ \mathrm{GeV}$ if $4e$ or 4μ	$0.88\ \mathrm{GeV} < m_{12,34} < 20\ \mathrm{GeV}$	

Table 4: Summary of the fiducial definitions used in this analysis, appropriate for processes of the form $H(125) \to XX \to 4\ell$ and $H(125) \to ZZ_d \to 4\ell$, where X is a promptly-decaying, on-shell, narrow resonance.