# Search for Higgs boson decays to BSM light bosons in four-lepton events with the ATLAS detector in 2015-6 and -17

CAP Congress
June 12th, 2018

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ATLAS EXPERIMENT

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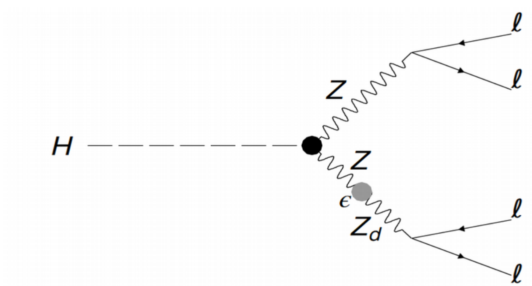
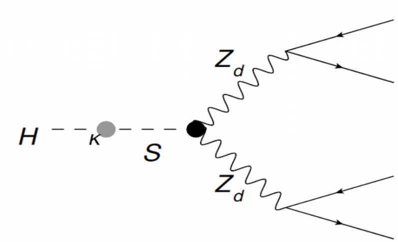
# Theory (I)

- *This is a search for Higgs decays to four leptons via two intermediate BSM particles of similar mass*
- Existing measurements constrain the branching ratio of the Higgs to BSM particles to be less than ~30% (ATLAS & CMS arXiv:1606.02266)
- A small Higgs coupling to a new light state could open up sizable new decay modes
- New particles could couple to the Higgs and provide a “portal” to a hidden (“dark”) sector or extended Higgs sector
- Two benchmark models considered in this analysis (Curtin et. al arXiv:1312.4992 and 1412.0018):
  - Higgs decay to four leptons via one or two intermediate U(1) dark sector particles $Z_d$
  - Higgs decay to four leptons via two pseudoscalar particles $a = \cos\theta_a S_I + \sin\theta_a A$



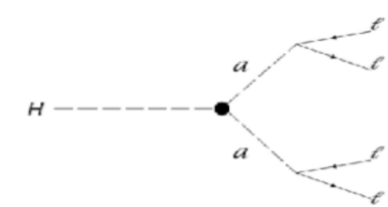

Hypercharge portal

Kinetic mixing ε




Higgs portal

Higgs portal coupling $\kappa$
Dark Higgs $S$

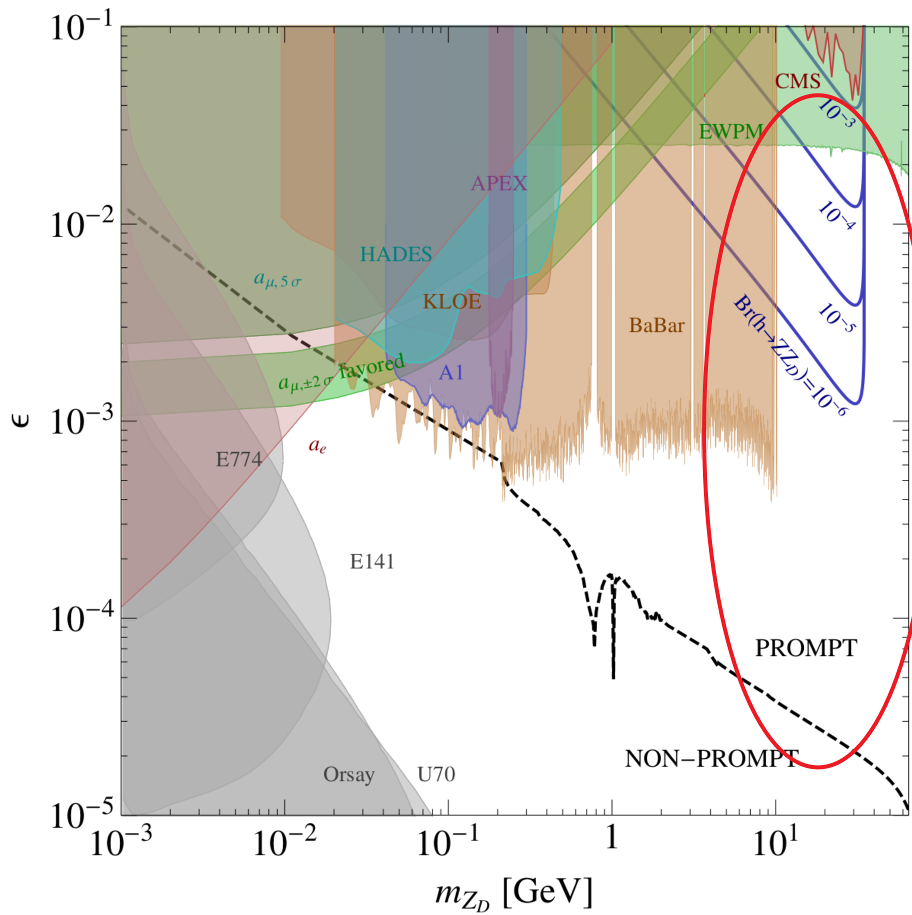



Pseudoscalar *a*

(eigenstate of doublet and singlet in 2HDM+S)

Mixing angle $\theta_a << 1 \quad S_I = \mathrm{Im(S)}$

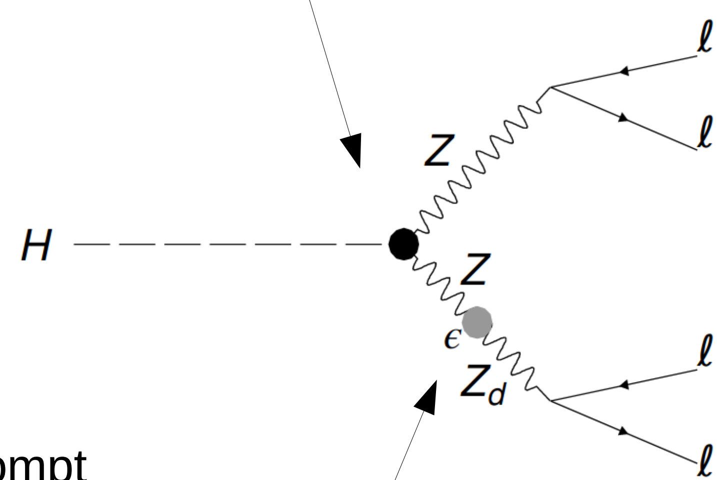
# Theory (II)




Curtin et al. (arXiv:1312.4992)

prompt high-mass region

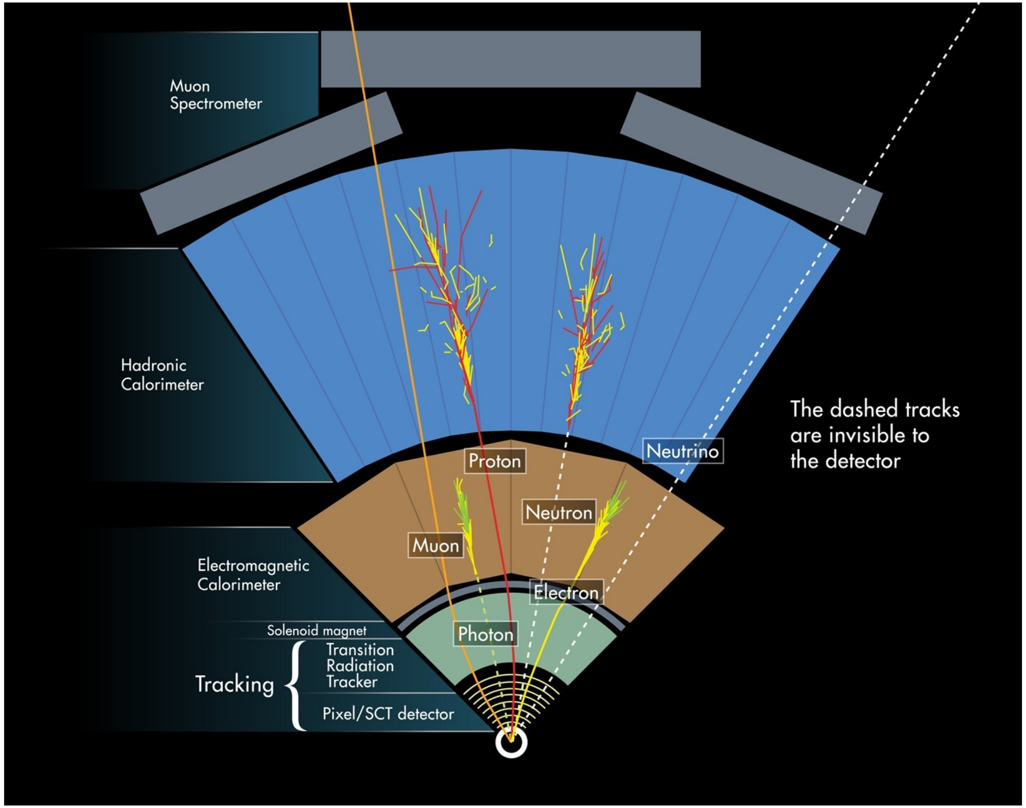
Hypercharge scenario

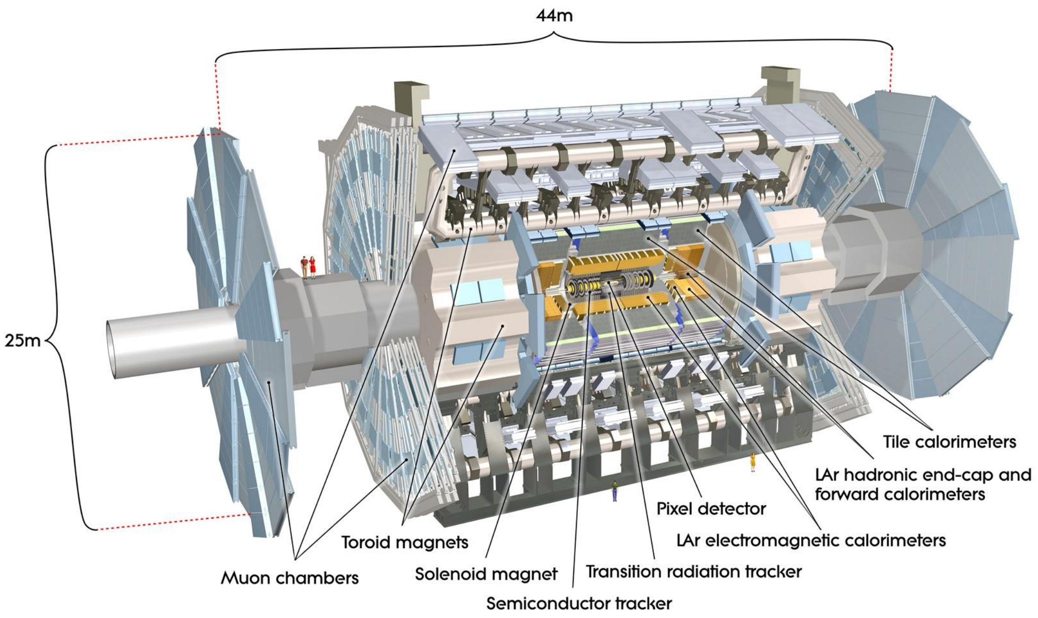



Kinetic mixing parameter $\epsilon$ controls coupling strength between $Z_d$ and SM particles (which in turn determines $Z_d$ lifetime)

Branching ratios determined by gauge coupling

# ATLAS detector




(source: ATLAS) (source: ATLAS)

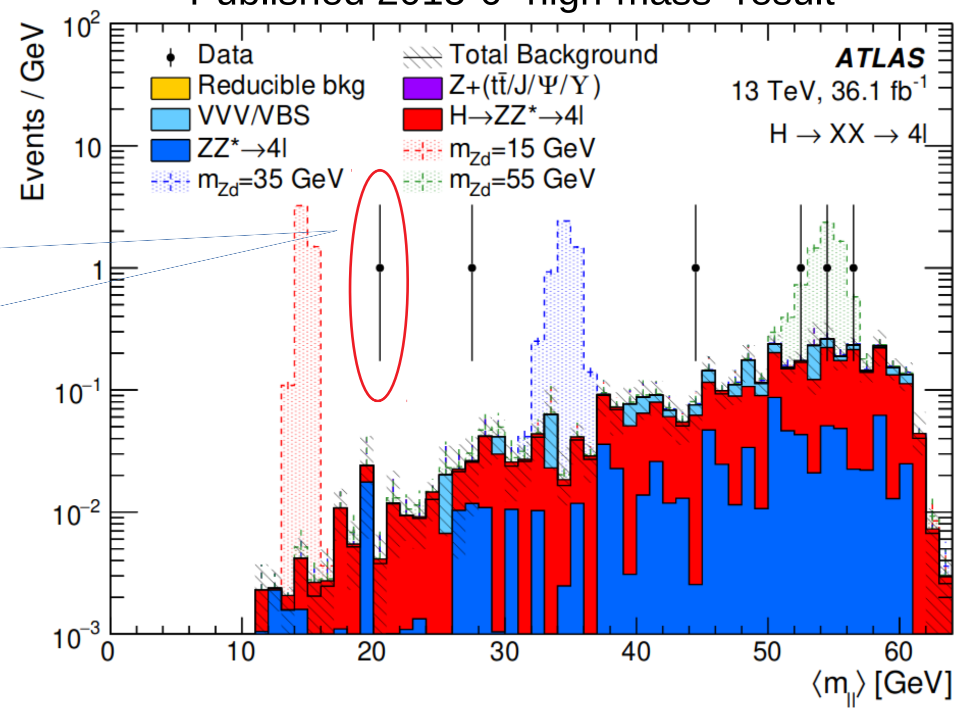
Look for a light resonance in a channel similar to the "golden" channel of the Higgs ($H \rightarrow ZZ^* \rightarrow 4\ell$)

# Analysis overview

- Paper on 2015-6 data covers three analyses (ATLAS arXiv:1802.0338), where X = $Z_d$ or a:
  - ZX: $H \to ZX \to 4l$ ($15~GeV < m_X < 55~GeV$) ($l = e, \mu$)
  - “Low-mass”: $H \to XX \to 4\mu$ ($1~GeV < m_X < 15~GeV$)
  - “High-mass”: $H \to XX \to 4l$ ($15~GeV < m_X < 60~GeV$) ($l = e, \mu$)

*focus today is on high-mass analysis*

Published 2015-6 “high-mass” result



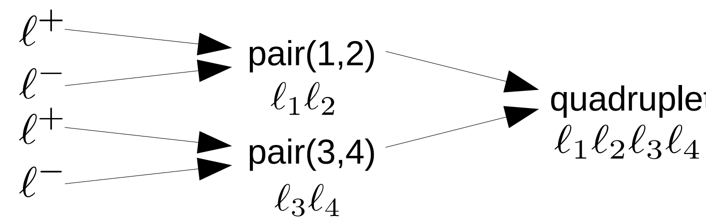

For this bin:
3.2 σ local
1.9 σ global

(N.B. only 1 event!)

# High-mass analysis selection

## Lepton quadruplet formation and selection

- Each lepton must be responsible for firing at least one trigger
- In each event, form quadruplets consisting of two same-flavour opposite sign lepton pairs: “1, 2” & “3, 4”
- Three leading-pT leptons must have pT > 20, 15, and 10 GeV
- ΔR($l$, $l'$) > 0.10 (0.20) for all pairings of same-flavour (different-flavour) leptons; $\Delta R \equiv \sqrt{\Delta(\eta)^2 + \Delta(\phi)^2}$




## Quadruplet ranking

- Select quadruplet with smallest difference in mass between lepton pairs: $\Delta m_{\ell\ell} \equiv |m_{12} - m_{34}|$

## Event selection

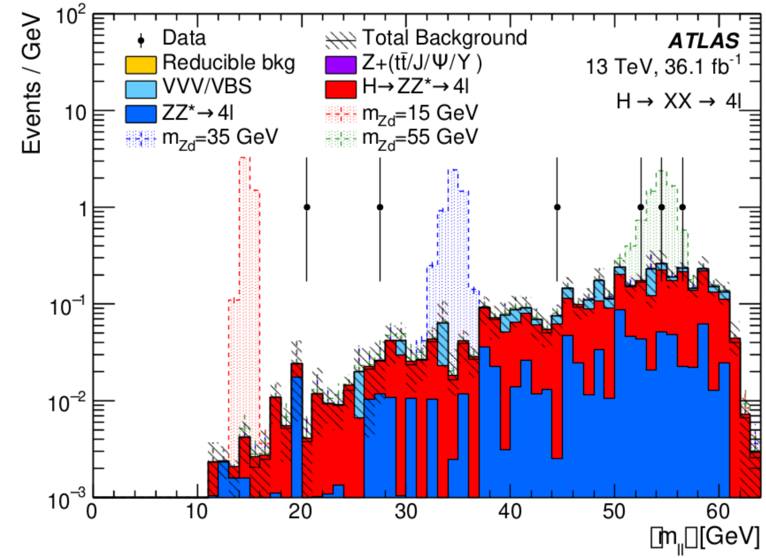
- Higgs window: $115\text{ GeV} < m_{4\ell} < 130\text{ GeV}$
- Compatibility of lepton pair masses: $m_{34}/m_{12} > 0.85$
- Z veto on lepton pairs: $10\text{ GeV} < m_{12,34} < 64\text{ GeV}$
- Additional Z veto on alternative pairings (only for 4e and 4$\mu$ quadruplets): $5\text{ GeV} < m_{14,32} < 75\text{ GeV}$
- Quarkonia veto: reject event if

$$(m_{J/\Psi} - 0.25\text{ GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\text{ GeV}) \mid\mid (m_{\Upsilon(1S)} - 0.70\text{ GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\text{ GeV})$$

# Background predictions in high-mass analysis

- We take all background predictions from simulation, as in previous iteration (ATLAS arXiv:1802.03388)
- Dominant backgrounds are H→ZZ* and non-resonant ZZ*:
  - $H \rightarrow ZZ^* \rightarrow 4l$: 63%
  - $ZZ^* \rightarrow 4l$: 19%
  - Triboson production (VVV): 17%
  - $Z + t\bar{t}$, J/Ψ, or $\Upsilon \rightarrow 4l$: ~1%
  - Reducible backgrounds (Z + jets, $t\bar{t}$): ~1%
    - working on in-situ estimate for next iteration

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




(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution

Previous iteration

# High-mass analysis with 2017 data

- Moving towards a result with 2017 data
- Follow the same approach as the past iteration
- Validate our H → ZZ* and non-resonant ZZ* background predictions by considering three validation regions:

validates H → ZZ* prediction:

VR1: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

Reverse the second part of the Z Veto

SR: $m_{12,34} < 64\ GeV$ && $m_{14,32} < 75\ GeV$

→ VR1: $m_{12,34} < 64\ GeV$ && $m_{14,32} >= 75\ GeV$ ← admits Z and Z*

VR2: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

Reverse $m_{12}$ part of the Z Veto and ignore the rest

SR: $m_{12,34} < 64\ GeV$ && $m_{14,32} < 75\ GeV$

→ VR2: $m_{12} >= 64\ GeV$ ← admits Z and Z*

validates non-resonant ZZ* prediction:

VR3: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

Reverse Higgs Window requirement on quadruplet

SR: $115\ GeV < m_{4l} < 130\ GeV$

→ VR3: $m_{4l} < 115\ GeV$ || $m_{4l} > 130\ GeV$ ← vetoes H → ZZ*

# Validation region 1 (2015-6+7)

VR1: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

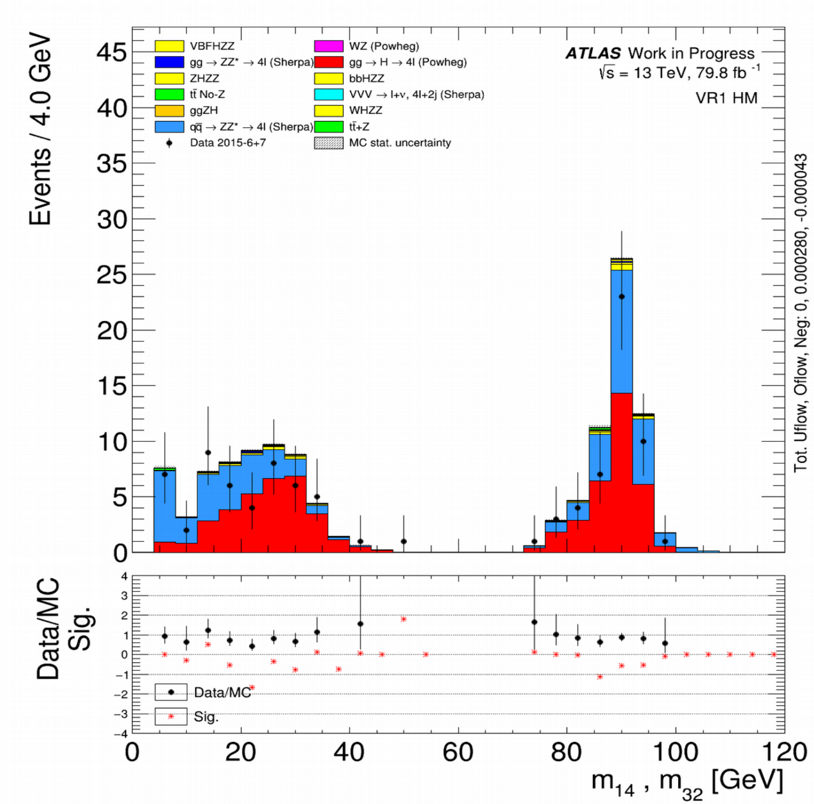
Reverse the second part of the Z Veto

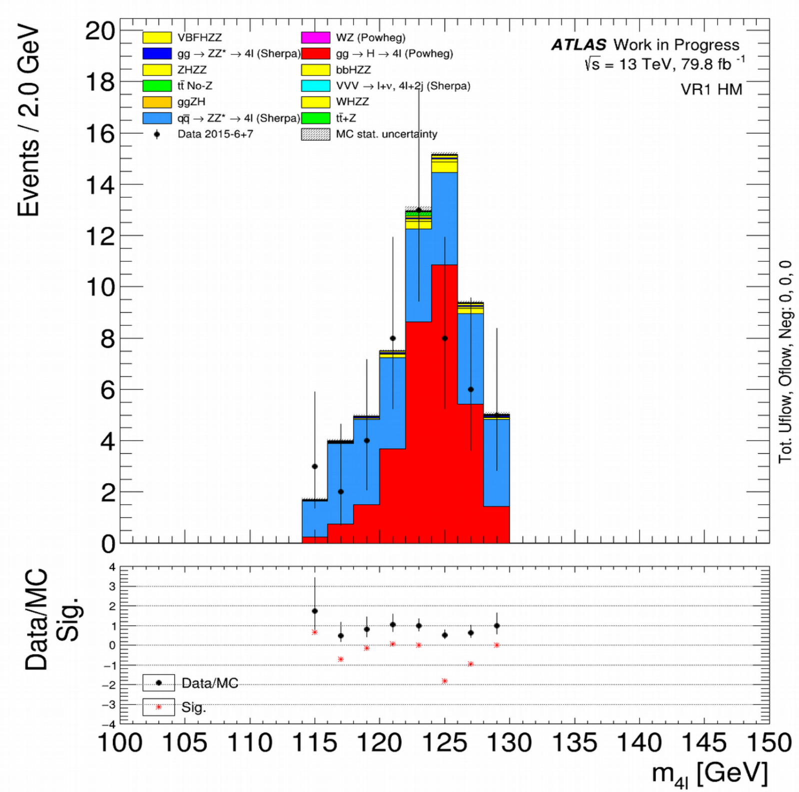
SR: $m_{12,34} < 64\ GeV$ && $m_{14,32} < 75\ GeV$

$\rightarrow$ VR1: $m_{12,34} < 64\ GeV$ && $m_{14,32} >= 75\ GeV$

New!

$gg \rightarrow H \rightarrow 4l$ (Powheg) $q\bar{q} \rightarrow ZZ^* \rightarrow 4l$ (Sherpa)



# Validation region 2 (2015-6+7)

New!

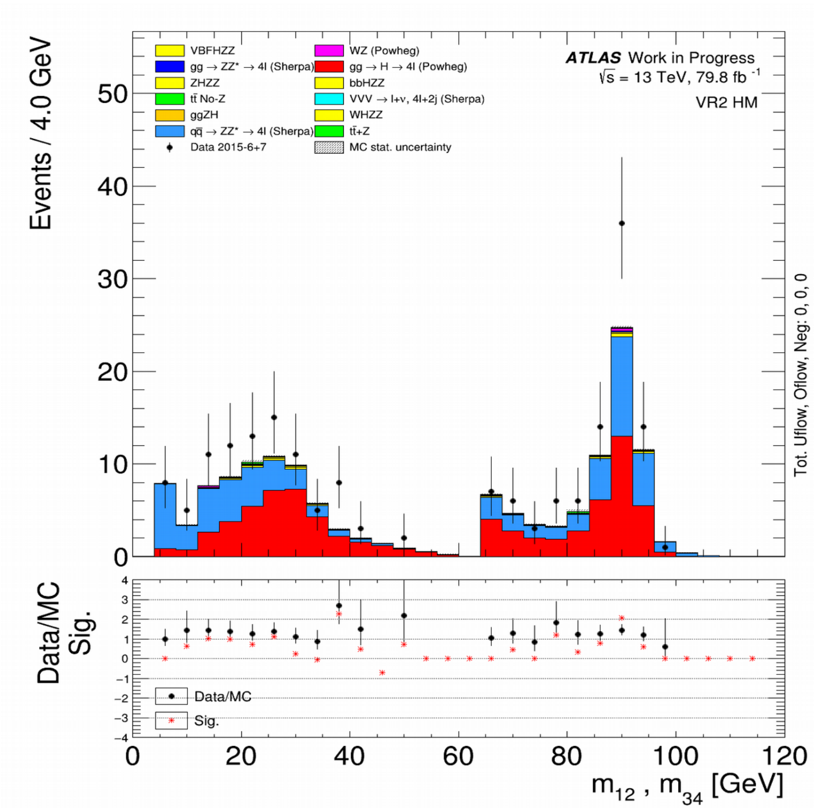
VR2: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

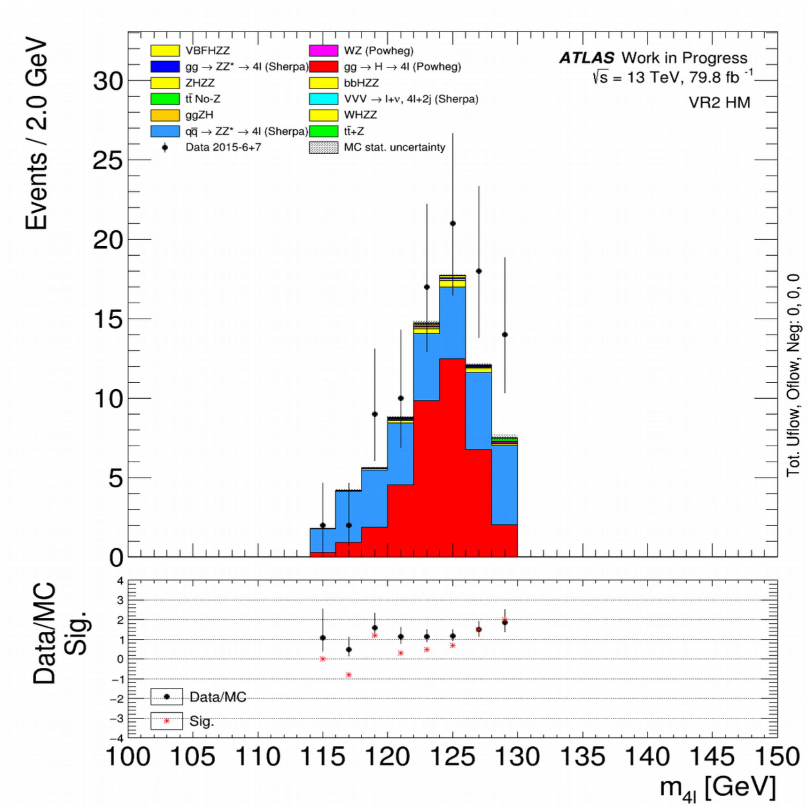
Reverse $m_{12}$ part of the Z Veto and ignore the rest

SR: $m_{12,34} < 64\ GeV$ && $m_{14,32} < 75\ GeV$

$\rightarrow$ VR2: $m_{12} >= 64\ GeV$

gg → H → 4l (Powheg)    $q\bar{q}$ → ZZ* → 4l (Sherpa)



# Validation region 3 (2015-6+7)

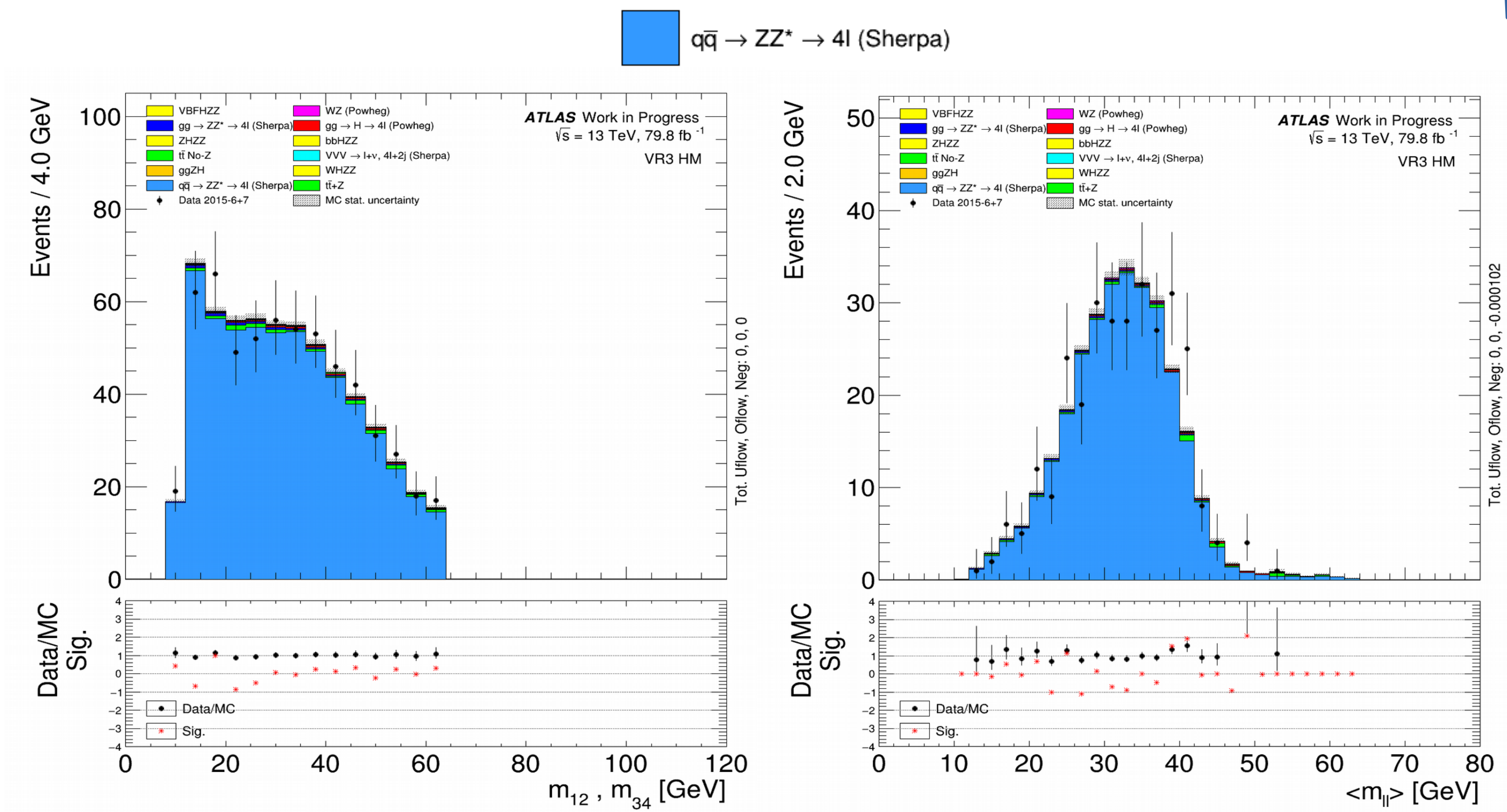
VR3: Remove requirement on compatibility of dilepton pairs $(m_{34}/m_{12} > 0.85)$

Reverse Higgs Window requirement on quadruplet

SR: $115\ GeV < m_{4l} < 130\ GeV$

$\rightarrow$ VR3: $m_{4l} < 115\ GeV \,||\, m_{4l} > 130\ GeV$

New!



# Other efforts and conclusions

- Working towards a result encompassing the full (2015-8) Run-2 dataset
- Other efforts for full Run-2 result not mentioned:
  - In-situ estimate for reducible backgrounds (statistically limited)
  - Extend search to cover wider range in Dark Higgs mass and $Z_d$
  - Study sensitivity to non-prompt signal
  - Two new channels: $H \to aa \to 2\mu 2\tau$ (Run-I) and $H \to aa \to 4\tau$ (new)

Thanks!
Questions?

# Backup

# Analysis selection (from paper)

University of Victoria

$m_{12}$ is the dilepton pair closest to Z mass and $m_{34}$ is the other di-lepton pair
$m_{14}$ and $m_{32}$ are the alternative same-flavour opposite sign pairings

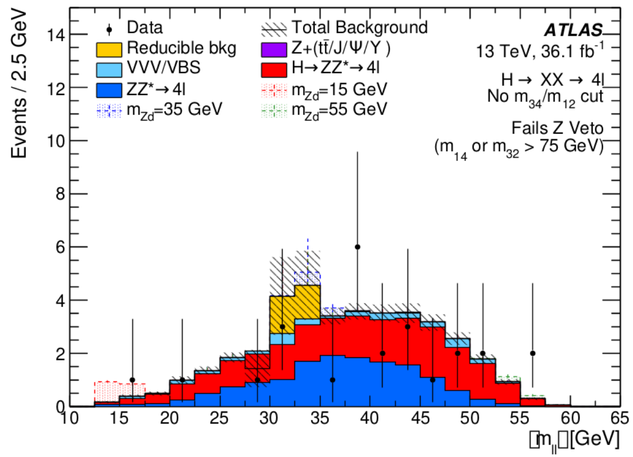
Form all possible SFOS quadruplets → Apply selection to all quadruplets → Choose one quadruplet → Apply event selection to chosen quadruplet

| | $H \to ZX \to 4\ell$ (15 GeV $< m_X <$ 55 GeV) | $H \to XX \to 4\ell$ (15 GeV $< m_X <$ 60 GeV) | $H \to XX \to 4\mu$ (1 GeV $< m_X <$ 15 GeV) |
|---|---|---|---|
| Quadruplet selection | - Require at least one quadruplet of leptons consisting of two pairs of same-flavour opposite-sign leptons<br>- Three leading-$p_T$ leptons satisfying $p_T >$ 20 GeV, 15 GeV, 10 GeV<br>- At least three muons are required to be reconstructed by combining ID and MS tracks in the $4\mu$ channel | | |
| | - Select best quadruplet (per channel) to be the one with the (sub)leading dilepton mass (second) closest to the $Z$ mass<br>- 50 GeV $< m_{12} <$ 106 GeV<br>- 12 GeV $< m_{34} <$ 115 GeV<br>- $m_{12,34,14,32} >$ 5 GeV | Leptons in the quadruplet are responsible for firing at least one trigger. In the case of multi-lepton triggers, all leptons of the trigger must match to leptons in the quadruplet | |
| | $\Delta R(\ell, \ell') >$ 0.10 (0.20) for same-flavour (different-flavour) leptons in the quadruplet | | - |
| Quadruplet ranking | Select first surviving quadruplet from channels, in the order: $4\mu$, $2e2\mu$, $2\mu 2e$, $4e$ | Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$ | |
| Event selection | 115 GeV $< m_{4\ell} <$ 130 GeV | | 120 GeV $< m_{4\ell} <$ 130 GeV |
| | | $m_{34}/m_{12} >$ 0.85<br>Reject event if:<br>$(m_{J/\Psi} - 0.25\text{ GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\text{ GeV})$, or<br>$(m_{\Upsilon(1S)} - 0.70\text{ GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\text{ GeV})$ | |
| | | 10 GeV $< m_{12,34} <$ 64 GeV<br>$4e$ and $4\mu$ channels:<br>5 GeV $< m_{14,32} <$ 75 GeV | 0.88 GeV $< m_{12,34} <$ 20 GeV<br>No restriction on alternative pairing |

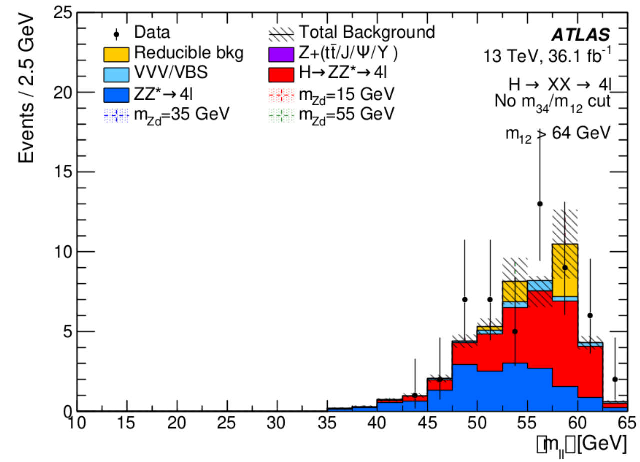
(loose leptons, details in backup p30)

High-mass selection is similar to HZZ4ℓ selection – biggest difference is quadruplet selection

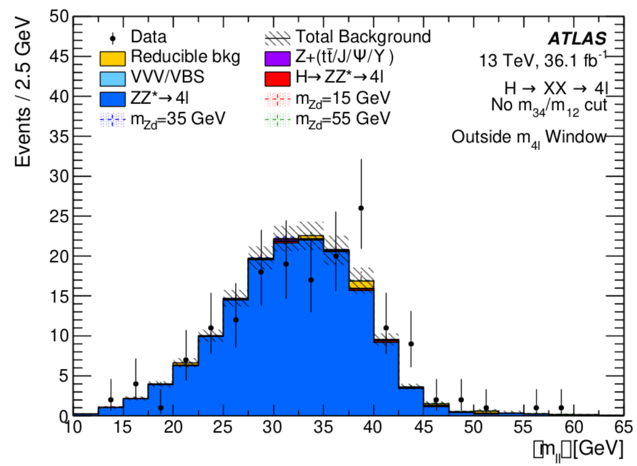
# Plots from last paper




(a) VR1

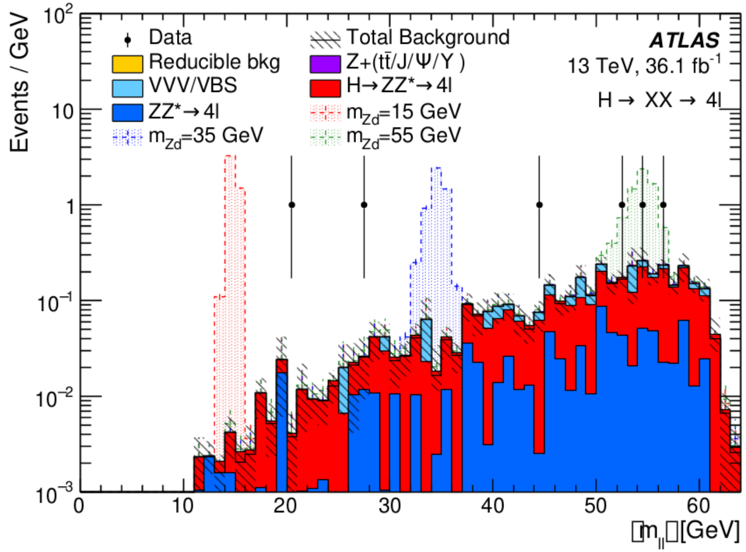



(b) VR2

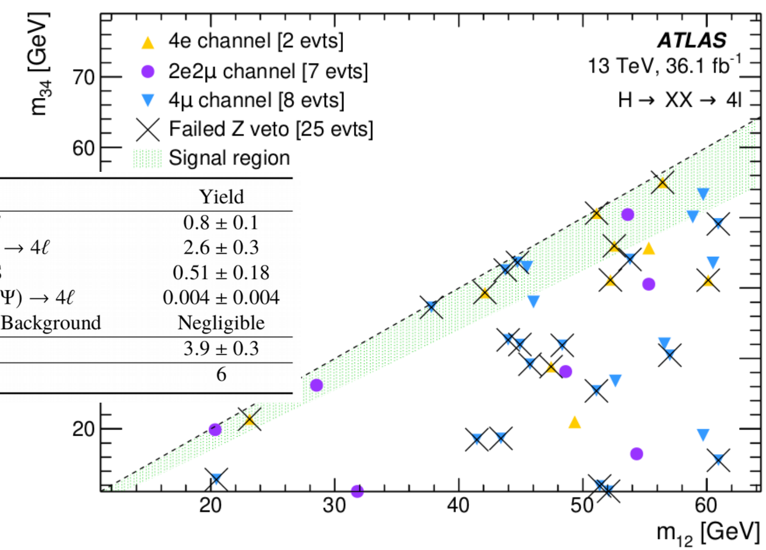



(c) VR3

# Plots from last paper




(a) Signal region $\langle m_{\ell\ell} \rangle$ distribution




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

(b) $m_{34}$ vs $m_{12}$ distribution

Figure 4: Distribution of (a) $\langle m_{\ell\ell} \rangle = \frac{1}{2}(m_{12}+m_{34})$ and (b) $m_{34}$ vs $m_{12}$, for events selected in the $H \to XX \to 4\ell$ ($15 < m_X < 60$ GeV) analysis. The example signal distributions in (a) correspond to the expected yield normalized with $\sigma(pp \to H \to Z_d Z_d \to 4\ell) = \frac{1}{10}\sigma_{\mathrm{SM}}(pp \to H \to ZZ^* \to 4\ell)$. The crossed-through points in (b) fail the *Z Veto*. The events outside the (shaded green) signal region in figure (b) are events that fail the $m_{34}/m_{12} > 0.85$ requirement. The diagonal dashed line marks where $m_{12} = m_{34}$, and in this range of dilepton masses all events will have $m_{34} < m_{12}$.

# 8 TeV ZdZd 1505.07645

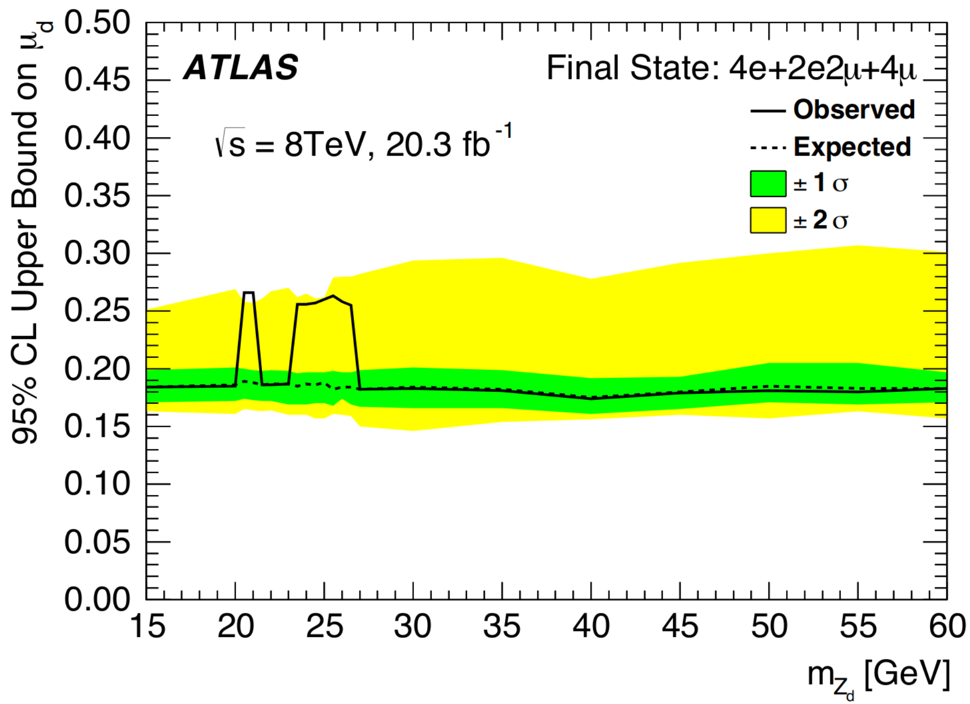
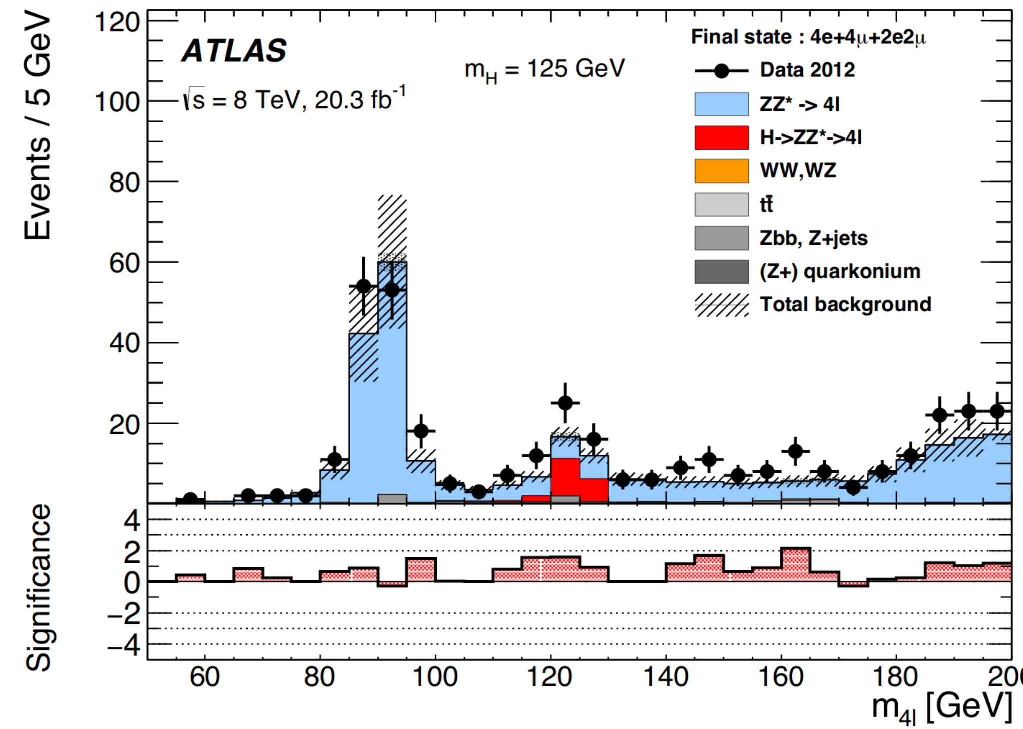



Figure 14: The 95% confidence level upper bound on the signal strength $\mu_d = \frac{\sigma \times BR(H \to Z_d Z_d \to 4\ell)}{[\sigma \times BR(H \to ZZ^* \to 4\ell)]_{SM}}$ of $H \to Z_d Z_d \to 4\ell$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm 1\sigma$ and $\pm 2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.



# 2HDM couplings and BRs (Curtin et al. arXiv:1312.4992)

| | Couplings | I | II | III (Lepton specific) | IV (Flipped) |
|---|---|---|---|---|---|
| | $g_{hVV}$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| | $g_{ht\bar{t}}$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ | $\cos\alpha/\sin\beta$ |
| $h$ | $g_{hb\bar{b}}$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ |
| | $g_{h\tau\bar{\tau}}$ | $\cos\alpha/\sin\beta$ | $-\sin\alpha/\cos\beta$ | $-\sin\alpha/\cos\beta$ | $\cos\alpha/\sin\beta$ |
| | $g_{H^0VV}$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ | $\cos(\beta-\alpha)$ |
| | $g_{H^0t\bar{t}}$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ | $\sin\alpha/\sin\beta$ |
| $H^0$ | $g_{H^0b\bar{b}}$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ |
| | $g_{H^0\tau\bar{\tau}}$ | $\sin\alpha/\sin\beta$ | $\cos\alpha/\cos\beta$ | $\cos\alpha/\cos\beta$ | $\sin\alpha/\sin\beta$ |
| | $g_{AVV}$ | 0 | 0 | 0 | 0 |
| | $g_{At\bar{t}}$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ | $\cot\beta$ |
| $A$ | $g_{Ab\bar{b}}$ | $-\cot\beta$ | $\tan\beta$ | $-\cot\beta$ | $\tan\beta$ |
| | $g_{A\tau\bar{\tau}}$ | $-\cot\beta$ | $\tan\beta$ | $\tan\beta$ | $-\cot\beta$ |

TABLE II: Couplings of the neutral scalar and pseudoscalar mass eigenstates in the fou 2HDM with a $\mathbb{Z}_2$ symmetry, following the notation of [112]. The couplings are normalize of the SM Higgs.

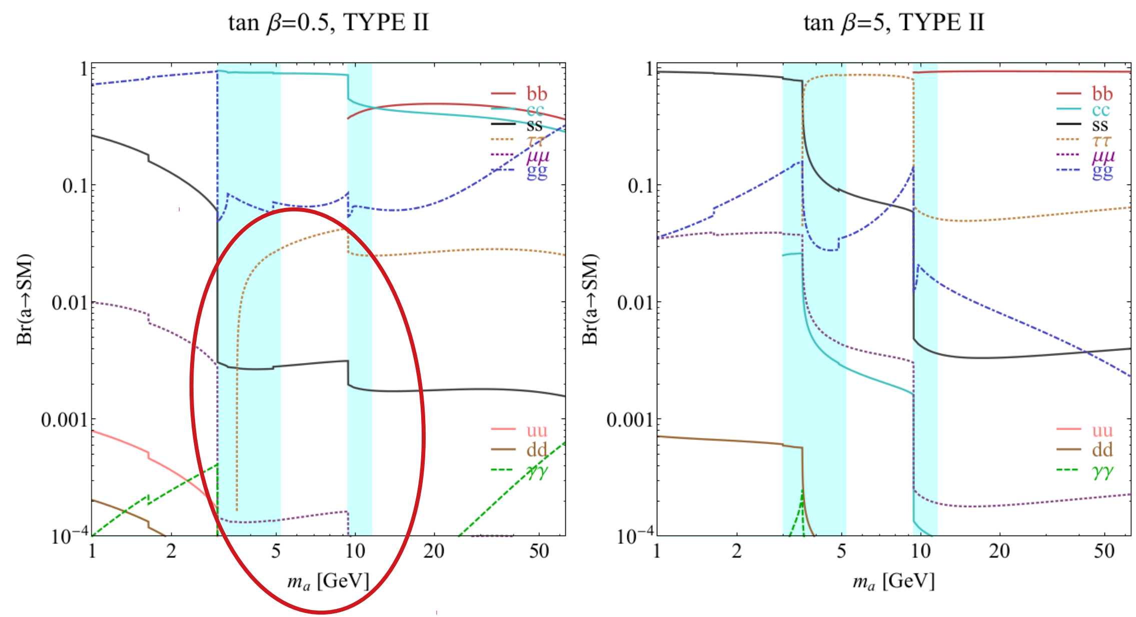
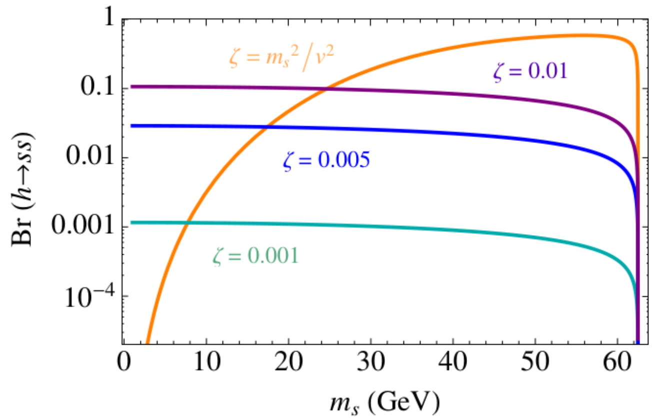



FIG. 7: Branching ratios of a singlet-like pseudoscalar in the 2HDM+S for Type II Yukawa couplings. Decays to quarkonia likely invalidate our simple calculations in the shaded regions.

# Sensitivity of H125 to light weakly-coupled particles (Curtin et al. arXiv:1312.4992)

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

$$\Delta\mathcal{L} = \frac{\mu}{\Lambda^2} |H|^2 \bar{\psi}\psi$$



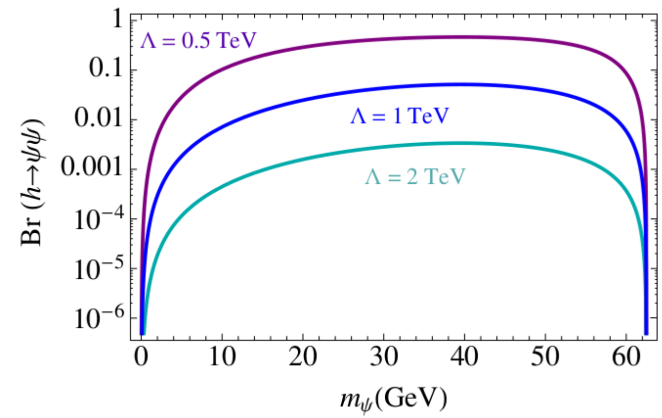
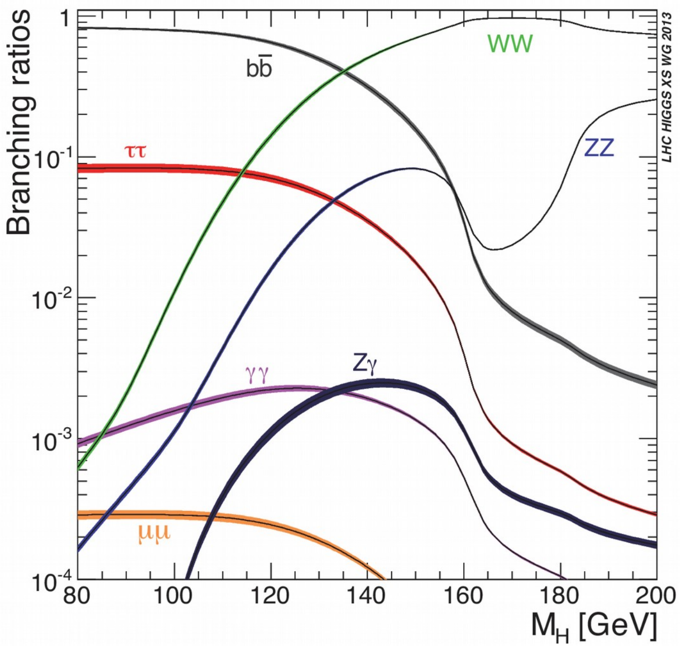
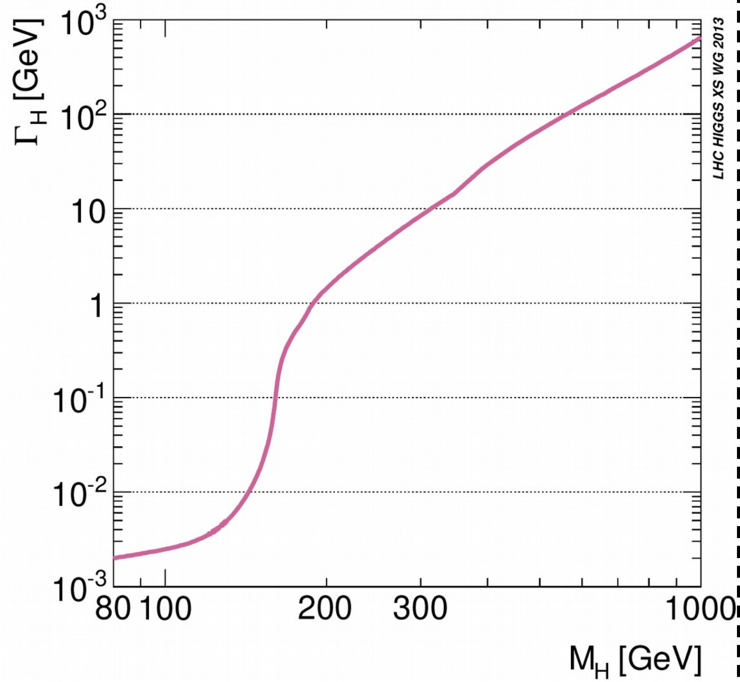
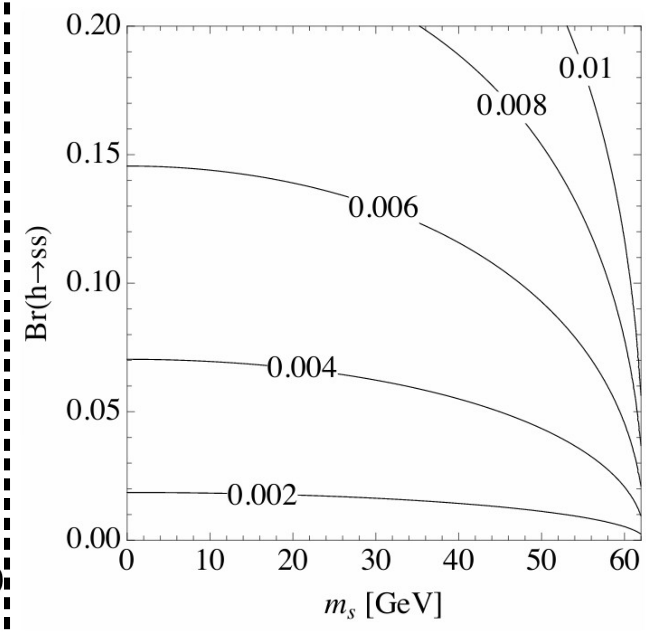




FIG. 1: Sensitivity of a 125 GeV Higgs to light weakly coupled particles. **Left:** Exotic Higgs branching fraction to a singlet scalar $s$ versus the singlet's mass $m_s$, assuming the interaction Eq. (1) is solely responsible for the $h \to ss$ decay. If the interaction in Eq. (1) generates the $s$ mass, the result is the orange curve; the other curves are for fixed and independent values of $\zeta$ and $m_s$. **Right:** Exotic Higgs branching fraction to a new fermion $\psi$ interacting with the Higgs as in Eq. (2) to illustrate the sensitivity of exotic Higgs decay searches to high scales, here $\Lambda$. We take here $\mu = m_\psi$.

# SM Higgs branching ratios and width (LHCXSWG arXiv:1610.07922)




$$\Gamma(h \to ss) = \frac{1}{8\pi}\frac{\mu_v^2}{m_h}\sqrt{1-\frac{4m_s^2}{m_h^2}} \approx \left(\frac{\mu_v/v}{0.015}\right)^2 \Gamma(h \to \text{SM})$$

# Theory (Hypercharge portal, kinetic Z-Zd mass mixing, fermion couplings)

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta_W}\hat{B}_{\mu\nu}\hat{Z}_D^{\mu\nu}$$

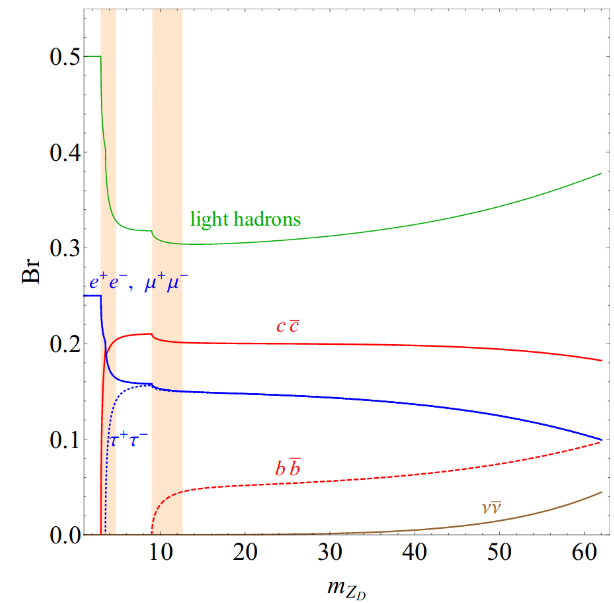
$$\begin{pmatrix} Z_D \\ B \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{\epsilon}{\cos\theta_W} & 1 \end{pmatrix} \begin{pmatrix} \hat{Z}_D \\ \hat{B} \end{pmatrix}$$

$$\begin{aligned} \tilde{Z} &= Z + \epsilon_Z Z_D \\ \tilde{Z}_D &= Z_D - \epsilon_Z Z, \quad \text{where} \quad \epsilon_Z = \frac{\epsilon \tan\theta_W m_Z^2}{m_Z^2 - m_{Z_D}^2}. \end{aligned}$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{8}w^2 g_D^2(\hat{Z}_{D\mu})^2 + \frac{1}{8}v^2(-g\hat{W}_\mu^3 + g'\hat{B}_\mu)^2 \quad \mathcal{L}_{\text{mass}} = \frac{1}{2}m_{Z_D}^2(Z_{D\mu})^2 + \frac{1}{2}m_Z^2(Z_\mu - \epsilon\tan\theta_W Z_{D\mu})^2$$

$$\mathcal{L} \supset g_{Z_D ff}\, Z_D^\mu\, \bar{f}\gamma_\mu f$$

$$g_{Z_D ff} = -g'\frac{\epsilon}{\cos\theta_W}Y - \epsilon\tan\theta_W \frac{m_Z^2}{m_Z^2 - m_{Z_D}^2}\frac{1}{\sqrt{g'^2+g^2}}\left(g^2T_3 - g'^2Y\right)$$



# Theory (Higgs portal, dark Higgs mechanism, h-s mixing) (lifetime)

$$V_0 = -\mu^2|H|^2 + \lambda|H|^4 - \mu_D^2|S|^2 + \lambda_D|S|^4 + \zeta|S|^2|H|^2$$

$$\mu^2 = v^2\lambda + \frac{1}{2}\kappa v_S^2 \ , \quad \mu_S^2 = v_S^2\lambda_S + \frac{1}{2}\kappa v^2$$

$$\tilde{h} = h - \epsilon_h s$$

$$\tilde{s} = s + \epsilon_h h, \quad \text{where} \quad \epsilon_h = \zeta\frac{\mu\mu_D}{2\sqrt{\lambda\lambda_D}|\mu^2 - \mu_D^2|}$$