ASFAP Particle Physics Day - PhD and postdocs day

Search for Higgs boson decays to beyond-the-Standard-Model light bosons in four-lepton final states with the ATLAS detector at the LHC

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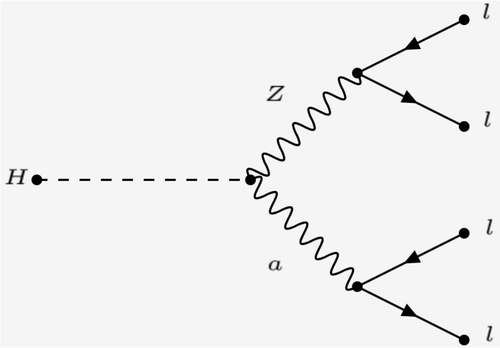

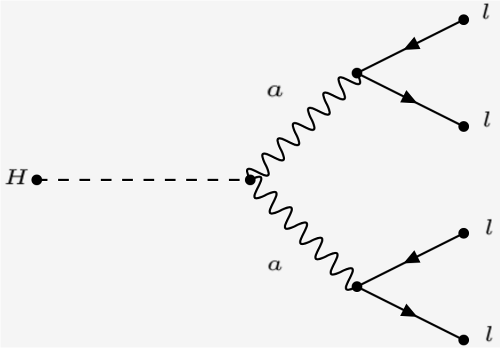

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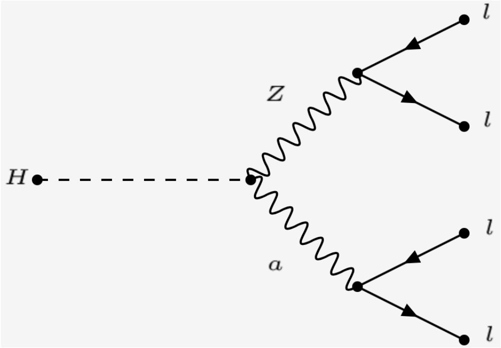

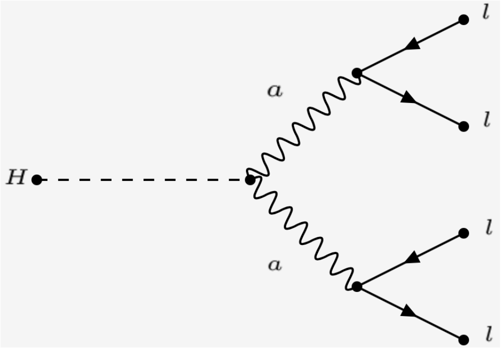

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→ The decays of $\boldsymbol{a} \rightarrow 2\boldsymbol{l}$ are determined by the Yukawa couplings of **a** to fermions.

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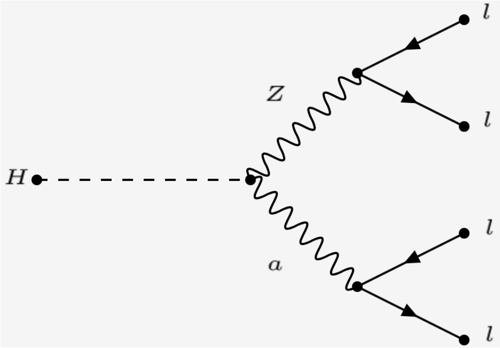

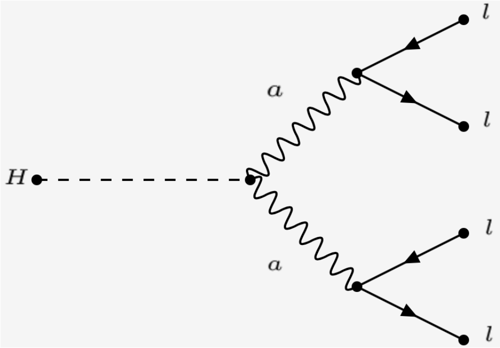

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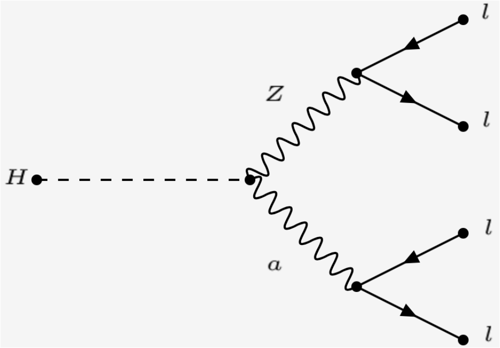

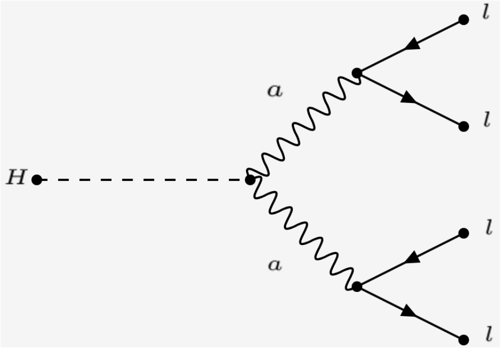

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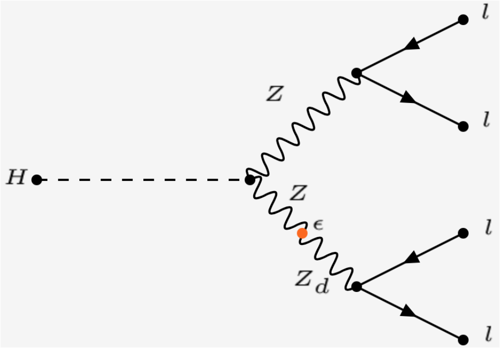

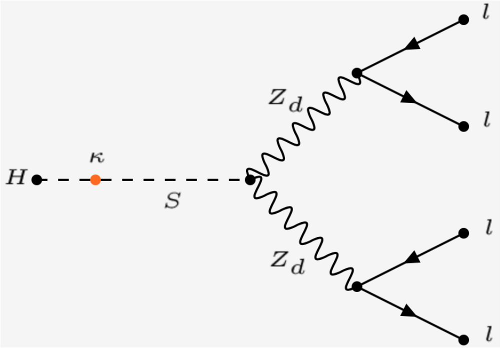

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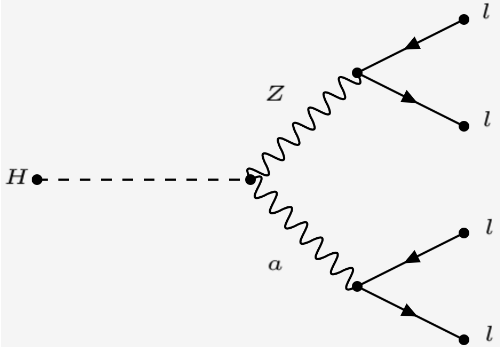

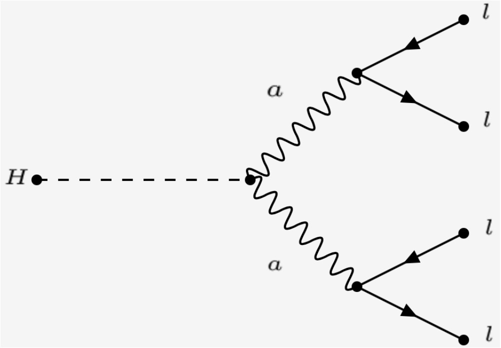

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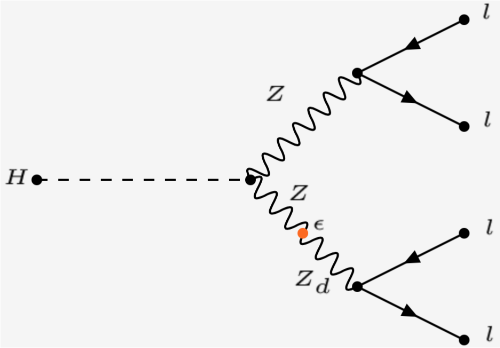

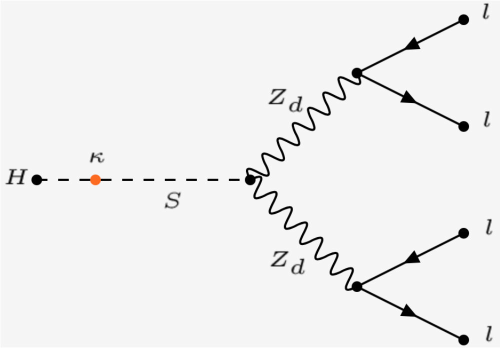

→ Introduce an additional $U(1)$ dark gauge symmetry mediated by a dark gauge boson Z_d.

→ The Z_d boson interacts with a SM gauge particle and the strenght of this coupling is defined by the Kinetic mixing parameter ϵ.

→ When the $U(1)_d$ is broken by a dark Higgs boson, the SM Higgs boson is then mixing with a dark Higgs boson and their coupling is controled by the strenght parameter κ.

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- The results using 2015-8 data ($139 fb^{-1}$) are published (using release 21) [ANA-HDBS-2018-55-PAPER]
- These results conver three channels with $4e$, $2e2\mu$ and 4μ in the final state:
  - **High-Mass (HM)**: $H \to Z_d Z_d(aa) \to 4l$, 15 GeV $< m_{Z_d}(m_a) <$ 60 GeV.
  - Low Mass(LM): $H \to Z_d Z_d(aa) \to 4\mu$, 1 GeV $< m_{Z_d}(m_a) <$ 15 GeV.
  - ZZ_d: $H \to ZZ_d \to 4l$, 15 GeV $< m_{Z_d} <$ 55 GeV.

Today, we are going to focus on the **HM** channel.

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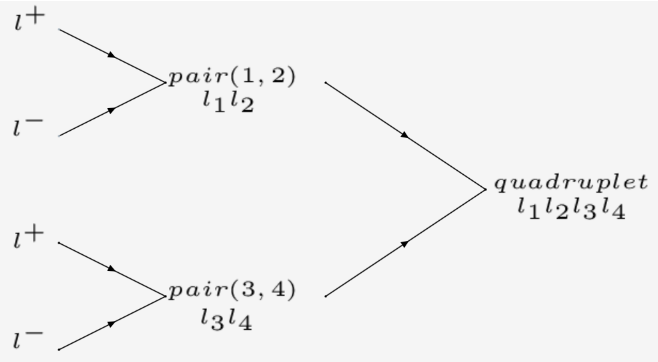
- Quadruplet formation and selection
  - in each event, a quadrulpet is formed from two lepton pairs each with same flavour opposite sign leptons: "1,2" and "3,4"
  - each lepton should fire at least 1 trigger.
  - Three leading-*pt* leptons must have: $pt > 20$, 15 and 10 GeV.
  - $\Delta R(l, l^{'}) > 0.10(0.20)$ for same-flavour (different-flavour) leptons in the quadruplet



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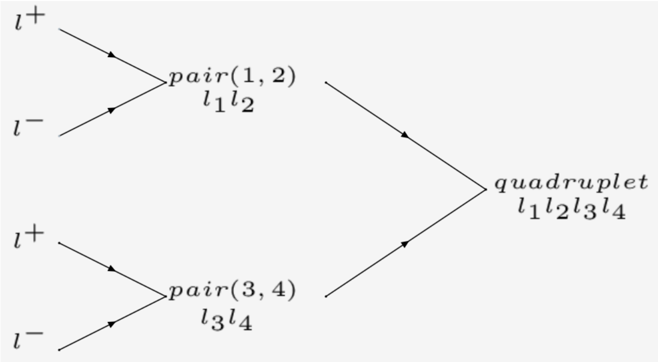

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  - The selected quadruplet should have the smallest difference in mass between lepton pairs:$\Delta m_{ll} = \mid m_{12} - m_{34} \mid$

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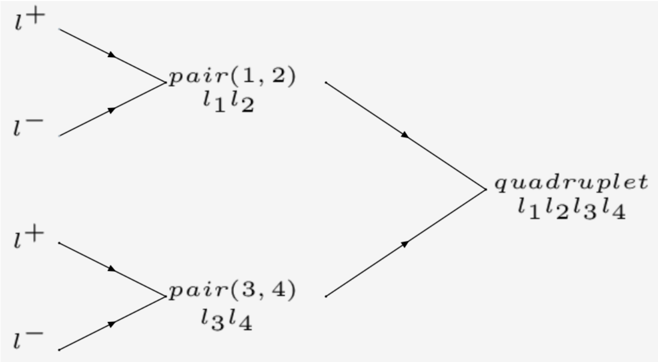

- Quadruplet ranking
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- Event selection
  - Higgs boson mass window:115 GeV $< m_{4l} <$ 130 GeV
  - Z veto: 10 GeV $< m_{12,34} <$ 64 GeV and 5 GeV $< m_{14,32} <$ 75 GeV
  - Quarkonia veto: event is rejected if either (or both) condition are fulfilled

    $(m_{J/\Psi} - 0.25\text{ GeV}) < m_{12,34,14,32} < (m_{\Psi(2S)} + 0.30\text{ GeV})$ or $(m_{\Upsilon(1S)} - 0.70\text{ GeV}) < m_{12,34,14,32} < (m_{\Upsilon(3S)} + 0.75\text{ GeV})$
  - Medium Signal Region (SR): $m_{34}/m_{12} > 0.85\text{-}0.1125\text{f}(m_{12})$

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The background processes considered in this analysis are as followed:

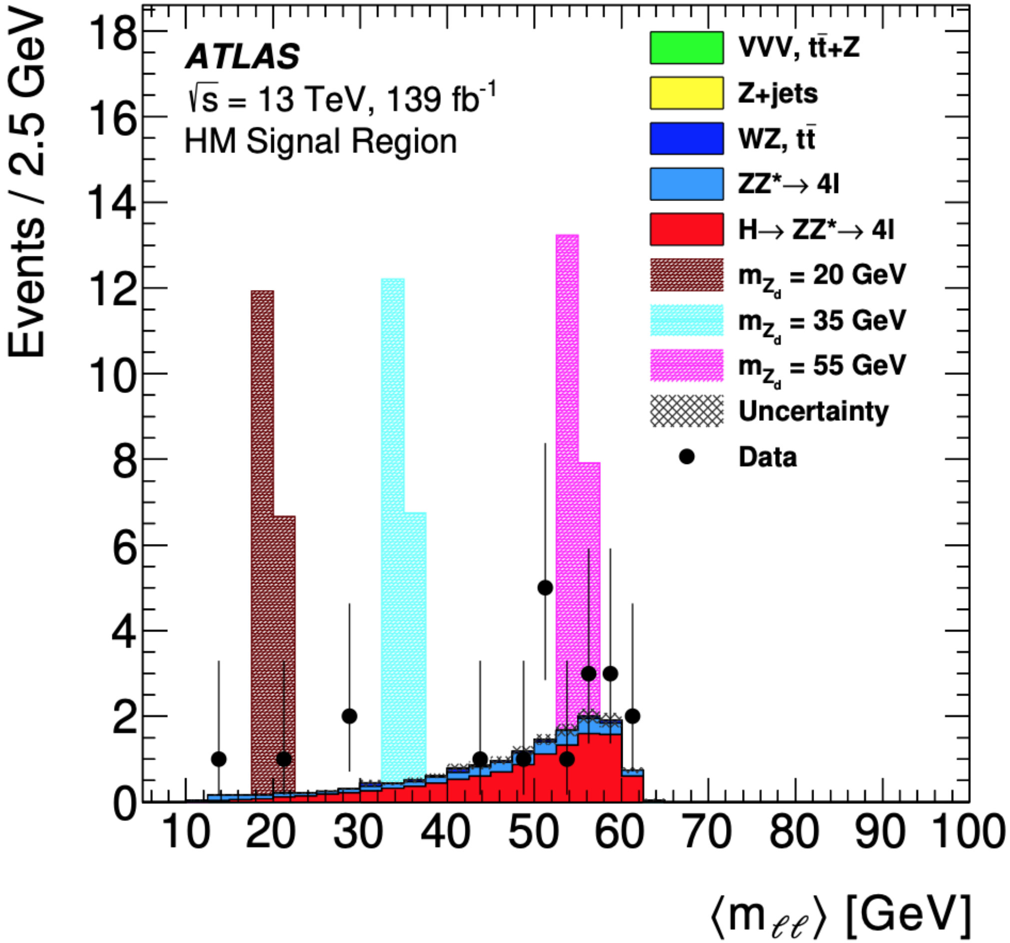
Dominant backgrounds

- $H \to ZZ^* \to 4l$ represents 72% of the total
- non-resonant $ZZ^* \to 4l$ represents 24% of the total

Sub-Dominant backgrounds

- WZ, VVV/VBS processes
- $t\bar{t}$, $t\bar{t}Z$ and Z+Jet(reducible background)

- All backgrounds estimates for this search rely basically on using MC simulations.
- Dominant backgrounds are cross-checked using validation regions.
- The data-driven ABCD method is used to estimate the reducible backgrounds.



Process	Yield
$H \to ZZ^* \to 4\ell$	$11.12 \pm 0.05 \pm 1.02$
$ZZ^* \to 4\ell$	$3.38 \pm 0.05 \pm 0.25$
$t\bar{t}$	$0.47 \pm 0.13 \pm 0.09$
$Z + \text{jets}$	$0.43 \pm 0.39^{+0.17}_{-0.01}$
$Z + t\bar{t} \to 4\ell$	$0.09 \pm 0.02 \pm 0.02$
WZ	$0.05 \pm 0.03^{+0.05}_{-0.00}$
VVV/VBS	Negligible
Heavy flavour	Negligible
Total	$15.6 \pm 0.4 \pm 1.2$
Data	20

A total of 20 events are observed, with a total predicted background of $15.6 \pm 0.4 \pm 1.2$ events.

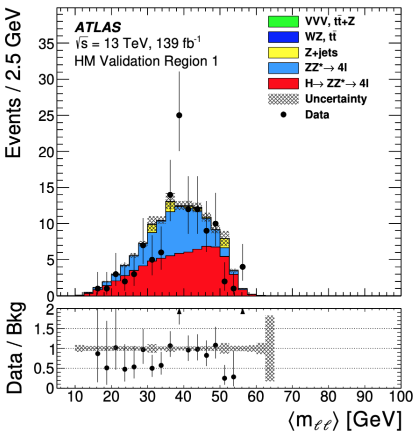


Figure: VR1

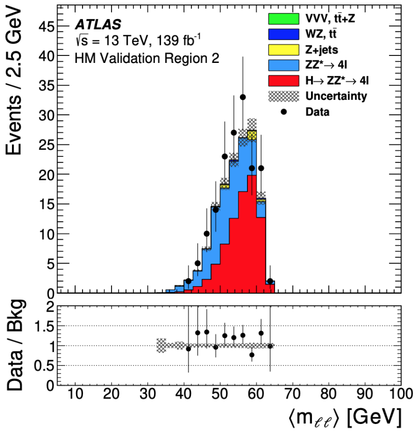


Figure: VR2

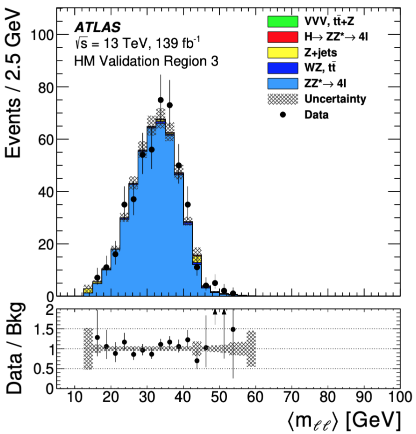


Figure: VR3

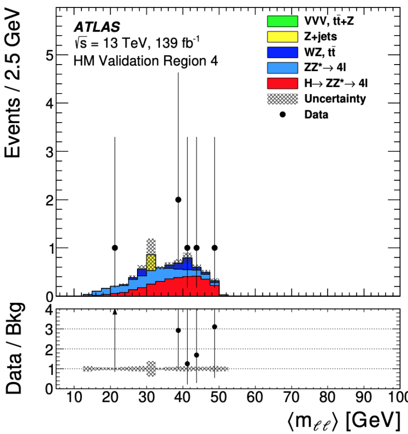
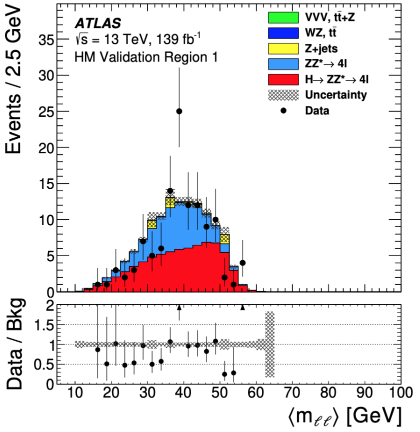


Figure: VR4

HM Validation Regions



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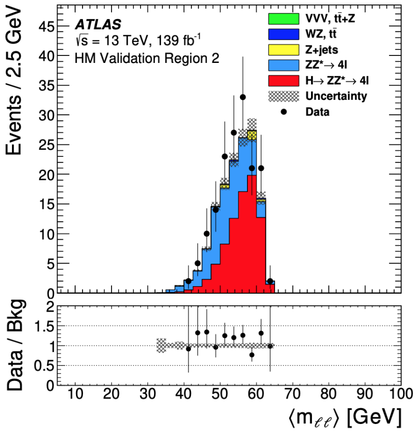

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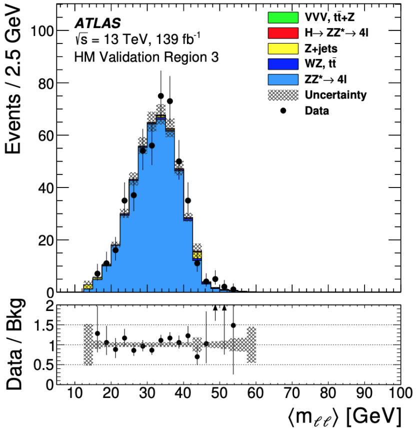

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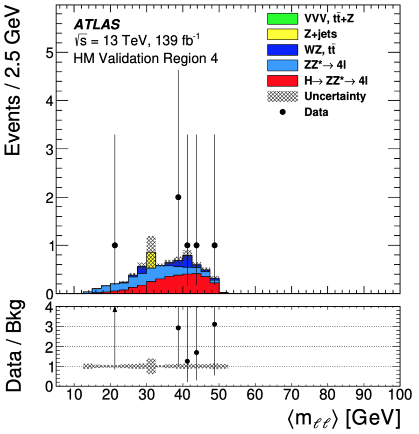

Figure: VR4

- VR1
  - Inverted Z-veto requirement $m_{14,32} \geq 75$ GeV, and the compatibility requirement on m_{34}/m_{12} is removed
  - $\Rightarrow$ $H \to ZZ^* \to 4l$ and non-resonant $ZZ^* \to 4l$ processes are dominating (4e and 4μ FS are contributing to this region).

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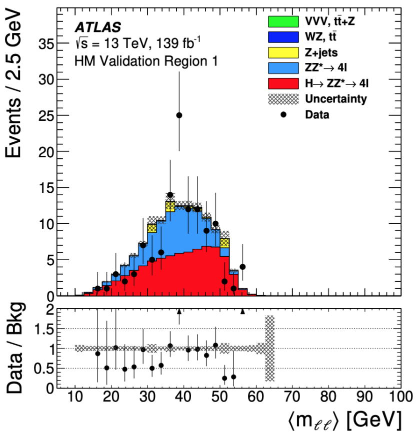

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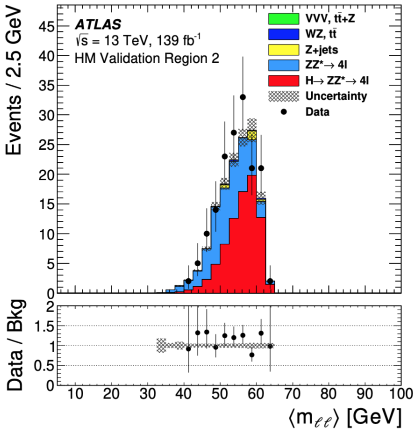

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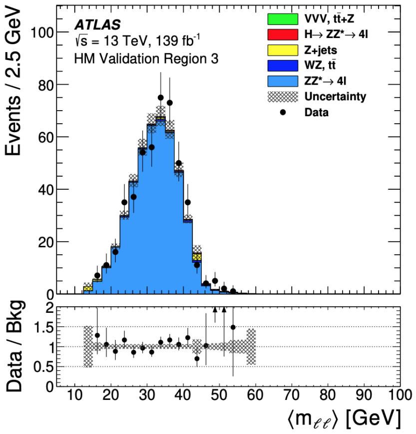

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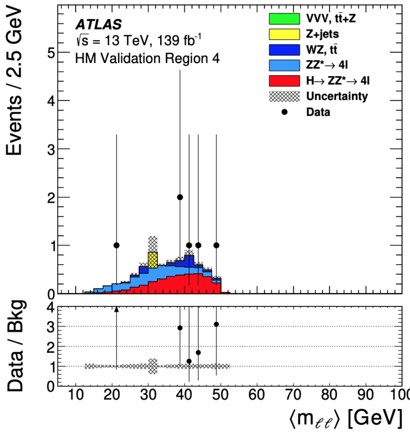

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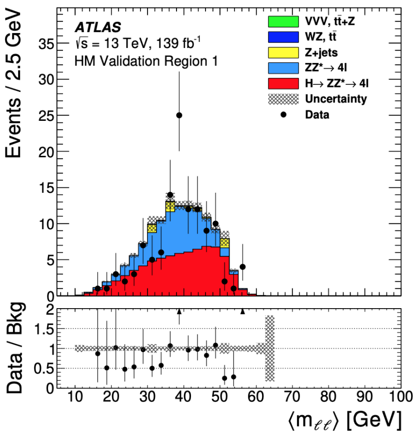

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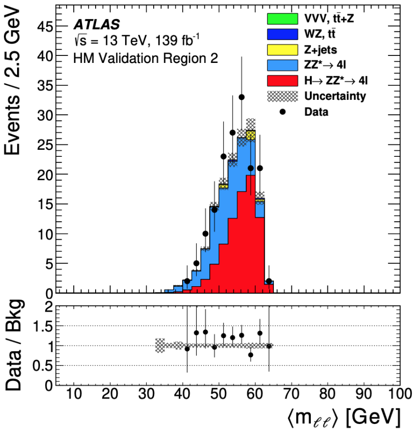
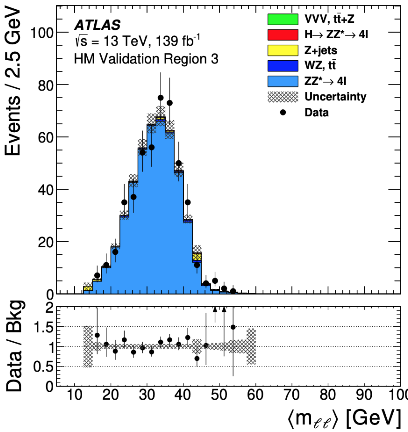


Figure: VR2



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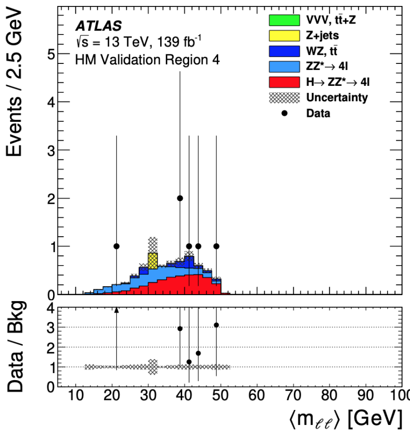

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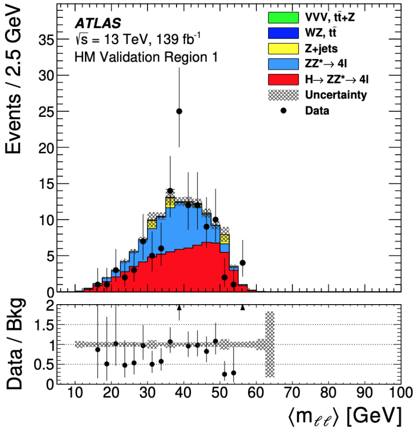

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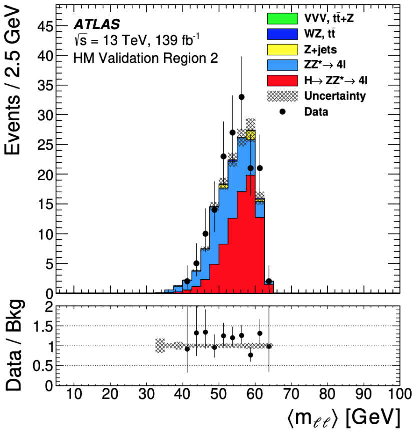

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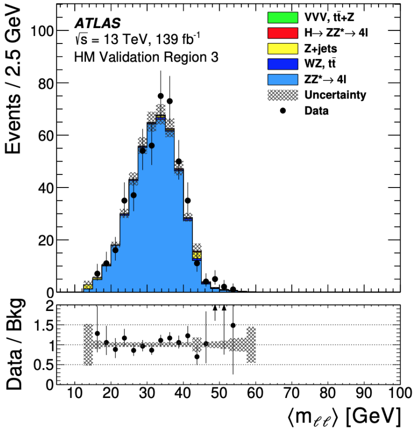

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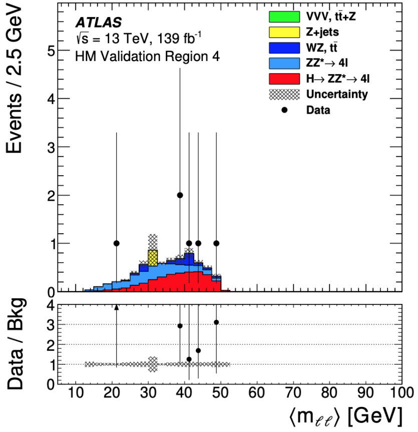

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- VR3
  - Inverted Higgs boson mass window and compatibility requirements
  - $\Rightarrow$ Dominating $ZZ^* \to 4l$ process.
- VR4
  - The final m_{34}/m_{12} compatibility requirement is inverted with the changed four dilepton mass requirements to $m_{ll} < 55$ GeV
  - $\Rightarrow$ This region is dominated by $H \to ZZ^* \to 4l$ with a significant contribution from $ZZ^* \to 4l$.

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Different statistical analysis procedure are constructed to interpret the results according to our benchmark model:

Model-independent limits

Set limits on the cross section in a fiducial volume such that the limit is suitably model-independent.

→ The fiducial volume is defined in a way to mimic the selection aplied in this analysis and appropriate for a Higgs boson ($m_H = 125$ GeV) decaying to 2 intermidiate, on-shell, narrow X boson (Z_d, a).

→ Model-independent efficiency: $\epsilon_c = \frac{N^c_{reco}}{N^c_{fid}}$

→ Expectation: $N^c_{exp}(\langle m_{ll}\rangle) = N^c_{bkg} + \sigma^c_{fid}.\mathcal{L}umi.\epsilon_c.Gaus(\langle m_{ll}\rangle, \overline{\langle m_{ll}\rangle}, \sigma^c_{\langle m_{ll}\rangle})$

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Model-dependent limits

Set limits on total cross section for $Z_d Z_d$ model.

- → In that model, the total cross section for a specific model is in request: $\sigma_H \mathcal{BR}(H \to Z_d Z_d \to 4l)$
- → Model-dependent acceptance in "total phase space" of a given model: $\alpha_c = \frac{N^{Z_d c}_{fid}}{N^{Z_d c}_{tot}}$
- → Expectation: $N^c_{Z_d,exp}(\langle m_{ll}\rangle) = N^c_{Z_d,bkg}(\langle m_{ll}\rangle) + \sigma_H \mathcal{BR}(H \to Z_d Z_d \to 4l).\mathcal{L}umi.\frac{\Gamma^c_{Z_d}}{\Gamma^{4l}_{Z_d}}.\alpha^{Z_d}_c.\epsilon_c.Gaus(\langle m_{ll}\rangle, \overline{\langle m_{ll}\rangle}_c, \sigma^c_{\langle m_{ll}\rangle})$

Fiducial cross section limits(Model-independent)

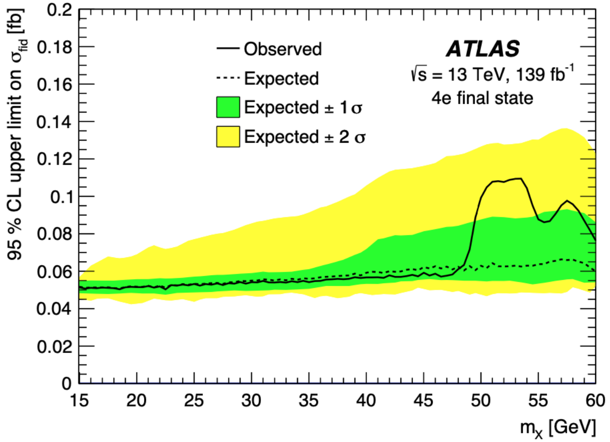

Figure: 95% CL upper limit on σ_{fid} for 4e final state

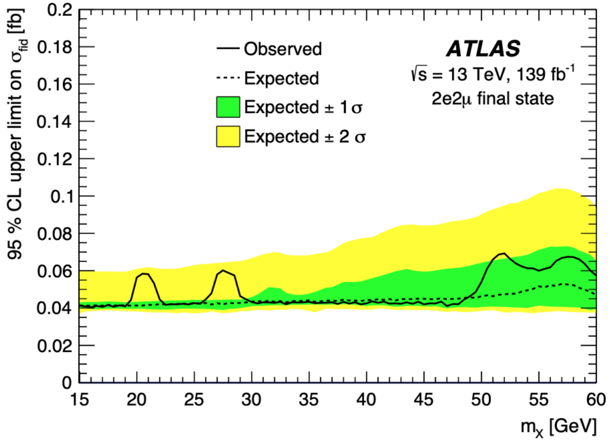

Figure: 95% CL upper limit on σ_{fid} for 2e2mu final state

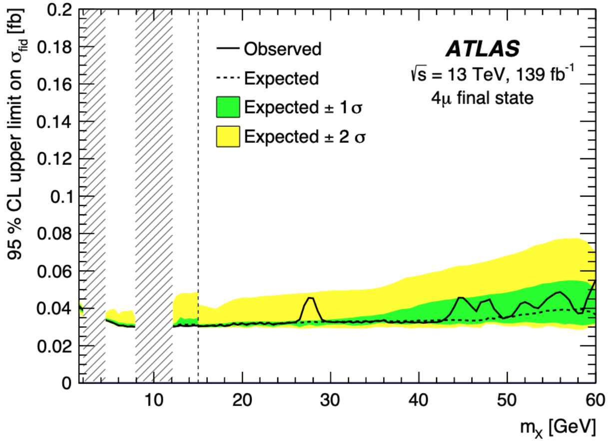

Figure: 95% CL upper limit on σ_{fid} for 4mu final state

- The step change in the 4μ channel at $m_X = 15$ GeV is due to the change in efficiency caused by the change in fiducial phase-space definition
- The shaded areas are the quarkonia veto regions

Total cross section limits(Model-independent)

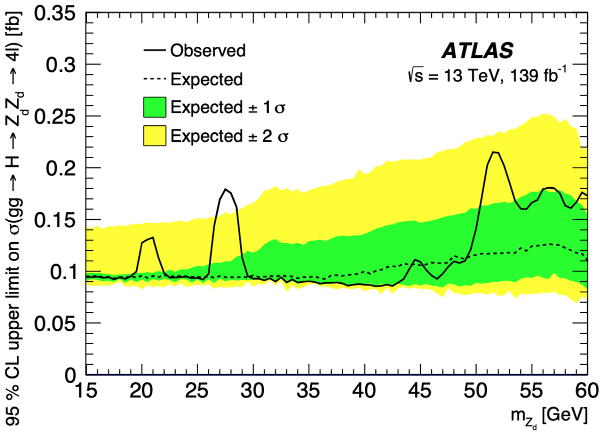

Figure: Limit on $\sigma(H \to Z_d Z_d \to 4l)$ process

- All final states are combined.

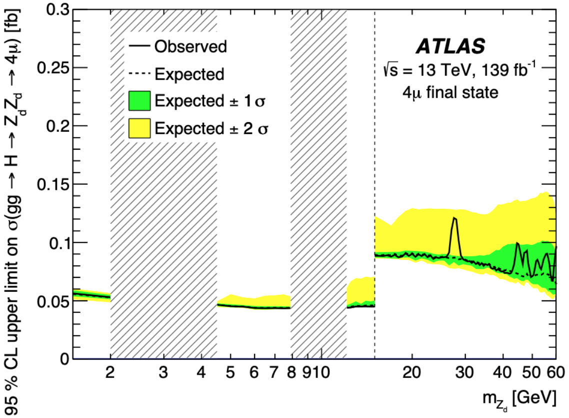

Figure: Limit on $\sigma(H \to Z_d Z_d \to 4\mu)$ process

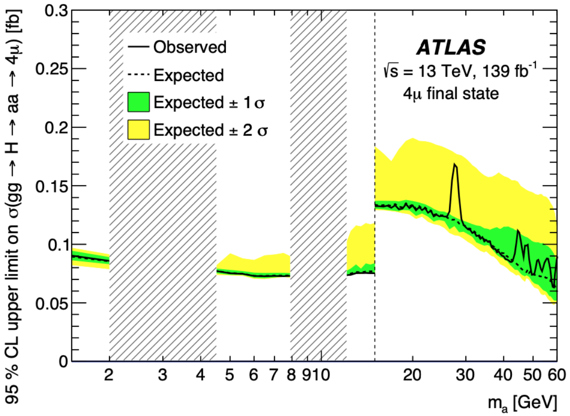

Figure: Limit on $\sigma(H \to aa \to 4\mu)$ process

- The step changes at $m_{Z_d} = 15$ GeV are due to the change in selection from the LM to the HM analysis.

Branching ratio limits(Model-dependent)

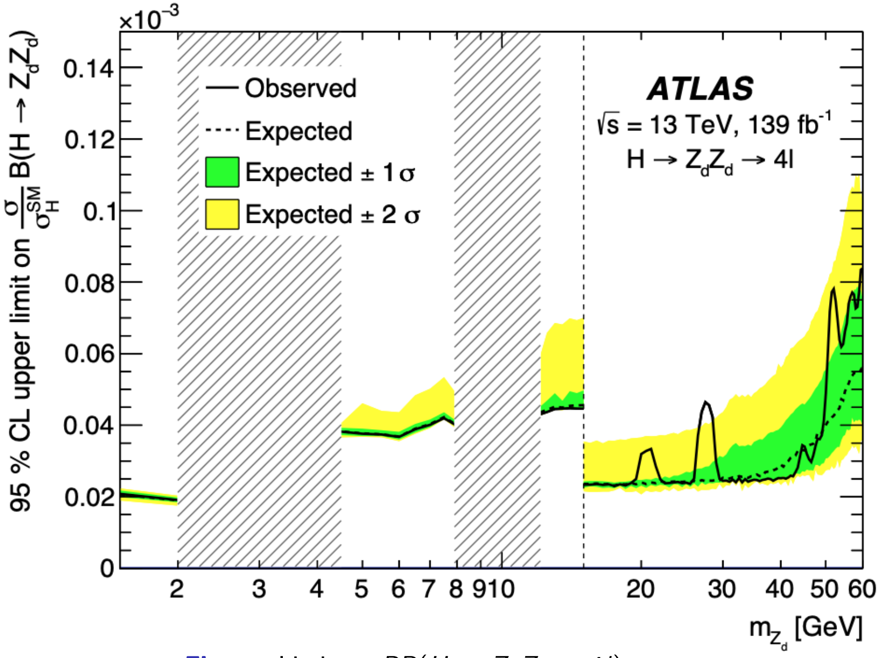

Figure: Limit on $BR(H \to Z_d Z_d \to 4l)$ process

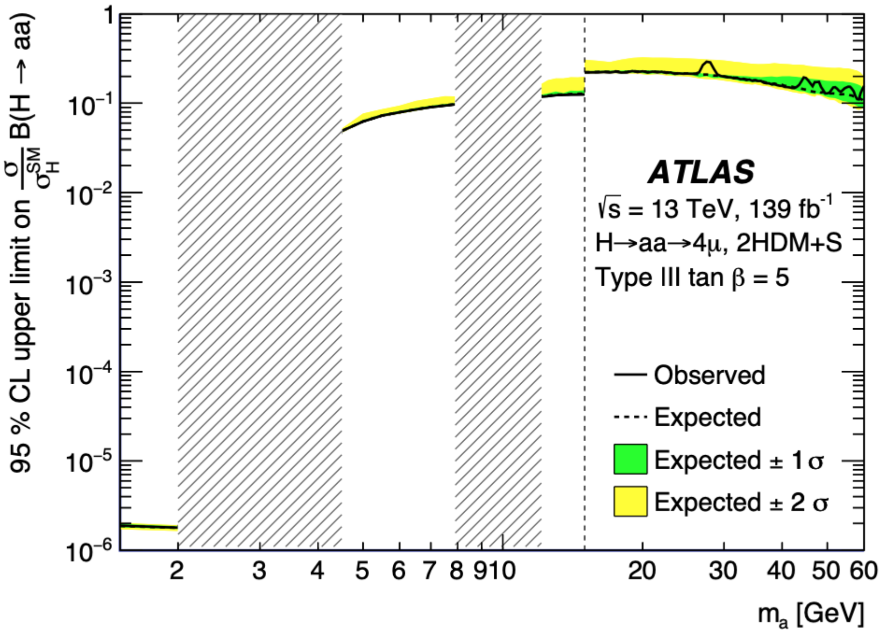

Figure: Limit on $BR(H \to aa \to 4\mu)$ process

Limit on κ'(Model-dependent)

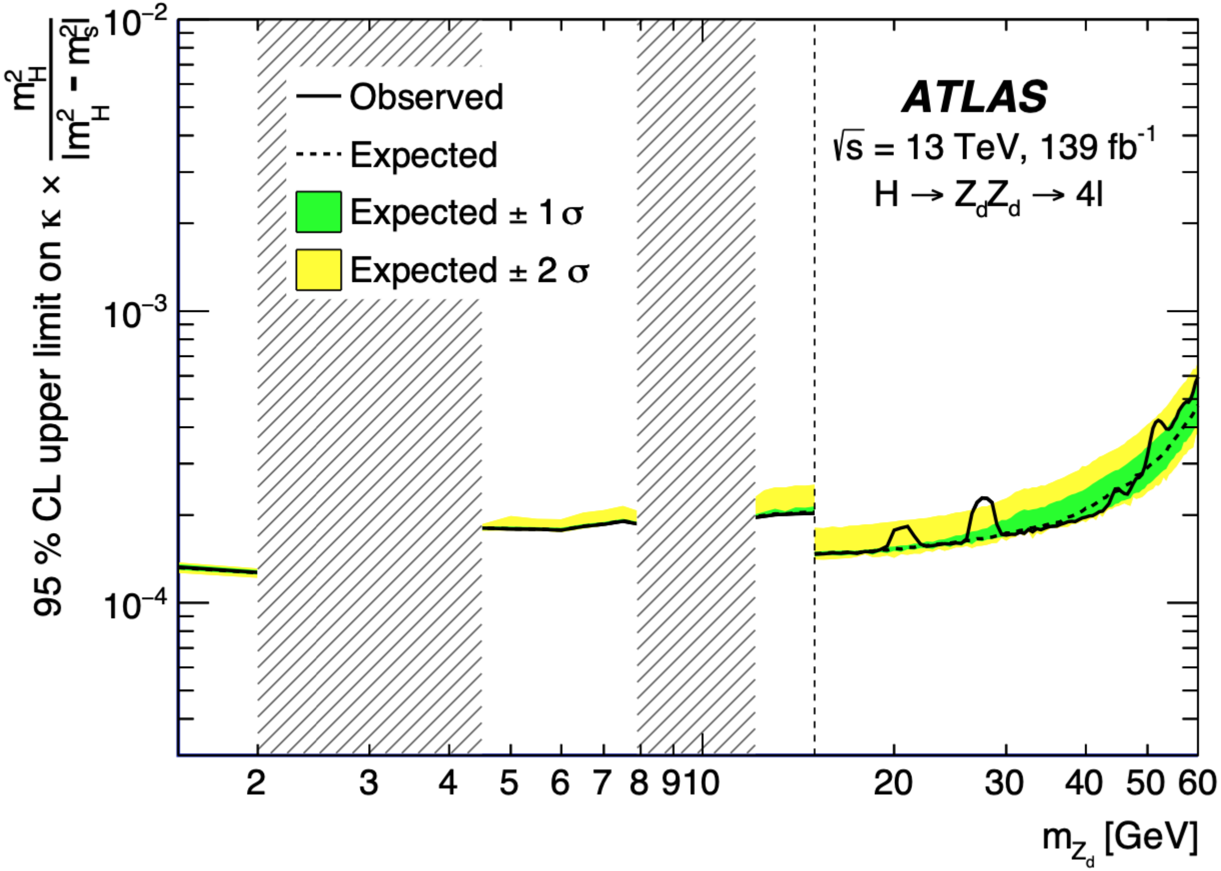

Figure: 95% Upper limit on κ' parameter

The upper limit on the effective higgs mixing parameter κ' is around 0.1%

Table of Contents

Conclusion

- Searches are performed for exotic decays of SM Higgs boson into two new spin-1 particles $H \to Z_d Z_d$ and two new spin-0 particles $H \to aa$
- The data are found to be globally consistent with the SM backgroud expectations.
- Limits on fiducial cross-sections are computed in order to be used for testing other benchmark models than treated in this analysis.
- Upper limits as function of the itermediate exotic boson's mass are set on the branching ratio of Higgs boson to $Z_d Z_d (aa)$ and on $\kappa^{'}$ parameter.


Thank
You
Asante
Shukria
Dhanyavadagalu
Vinaka
köszönöm
Kiitos
Maake
Dankscheen
спасибо
Kam Sah Hammida
اركش
Manana
Dankon
감사합니다
Dank Je
Mauruuru
Biyan
Diolch i Chi
Terima Kasih
Matondo
Taiku
Tack
Blagodaram
Ngiyabonga
Dziekuje
Chokrane
Grazie
Juspaxar
Arigato
Mochchakkeram
Gracias
Khap
Paldies
Tingki
நன்றி
Bedankt
Dakujem
धन्यवाद
cảm ơn bạn
Gratias Tibi
Ua Tsaug Rau Koj
Grazas
Mèsi
Obrigado
Děkuji
Nuwun
Nirringrazzjak
Di Ou
Kia Ora
Kop Khun
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Suksama
Rahmat
Hvala
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谢谢
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Danke
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Go Raibh Maith Agat
Tuke
Eskerrik Asko
Misaotra
Salamat
ขอบคุณ
Najis

BackUp

Data-driven estimate for non-dominant processes with Fake leptons

Processes such as $t\bar{t}$ and WZ may contribute to our selected events if non-lepton objects such as jets are incorrectly reconstructed as leptons.

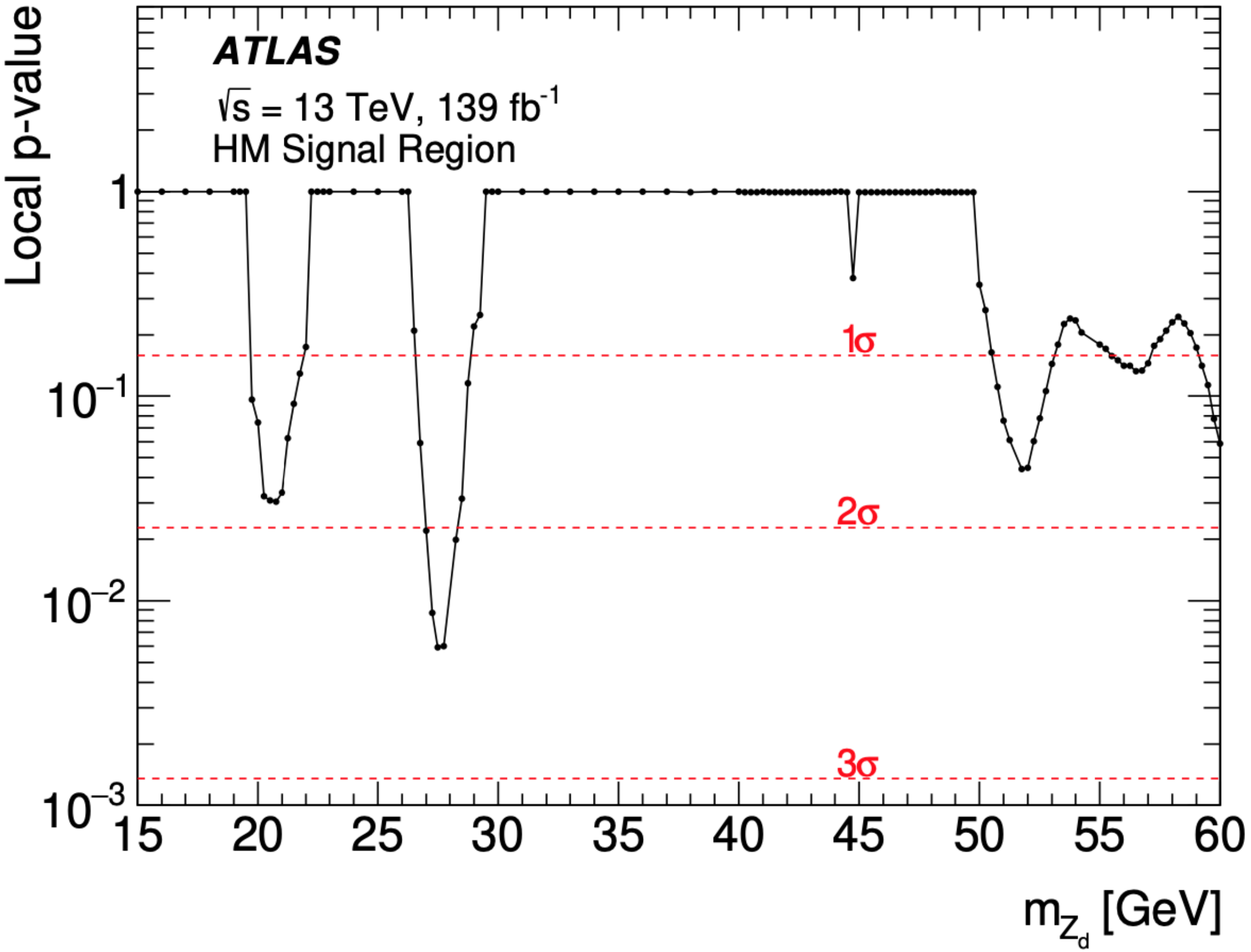
1. Events are selected in an inverted signal region (region **B**): a region defined by identical cuts to the normal signal region (region **A**) except with a few cuts inverted: the selected quadruplet in the event must contain one or two (but not more) leptons that are:
   - Electrons failing the `LooseLH` identification working point or failing the `FixedCutLoose` isolation working point, but not failing both of these requirements, or
   - Muons failing the `FixedCutLoose` isolation working point or d_0 significance requirement
     - $\Rightarrow$ Those are bad leptons
2. Events are selected in two regions that are rich in Z+jets events, where the event contains two leptons consistent with Z boson and exactly one other baseline reconstructed lepton. These third leptons, which are predominantly leptons faked by hadronic jets, either pass all requirements imposed in the standard analysis selection (the event then contributes to region **C**) or are leptons failing the cuts described above (the event contributes to region **D**).
3. *Fake Factors* are calculated as: $f = \frac{N_C}{N_D}$
4. Those factors are applied to the events in region **B**: events with exactly one bad lepton (**B1**) receive a weight given by the fake factor corresponding to the bad lepton, and events with exactly two bad leptons (**B2**) receive a weight given by the product of the fake factors of the two bad leptons and an additional factor of -1: $N_{B_1} f - N_{B_2} f_1 f_2$
5. The contribution to this estimate from processes producing four (or more) real leptons is estimated from the MC contribution to the inverted signal region ($N^{real}_{B_1}$ and $N^{real}_{B_2}$) with fake factors applied.

$$\boldsymbol{N^{fake}_{A} = (N_{B_1} f - N_{B_2} f_1 f_2) - (N^{real}_{B_1} f - N^{real}_{B_2} f_1 f_2)}$$

For more details, see 2226555

Fiducial phase-space definitions

	Single Z (ZX) analysis $H \to XZ \to 4\ell$ ($\ell = e, \mu$)	High-mass (HM) analysis $H \to XX \to 4\ell$ ($\ell = e, \mu$)	Low-mass (LM) analysis $H \to XX \to 4\mu$
Mass range	$15\,\text{GeV} < m_X < 55\,\text{GeV}$	$15\,\text{GeV} < m_X < 60\,\text{GeV}$	$1\,\text{GeV} < m_X < 15\,\text{GeV}$
Electrons	$p_T > 7\,\text{GeV}$ $\lvert\eta\rvert < 2.5$		
Muons	$p_T > 5\,\text{GeV}$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_T leptons satisfying $p_T > 20\,\text{GeV}, 15\,\text{GeV}, 10\,\text{GeV}$		
	$\Delta R > 0.10$ (0.20) between same-flavour (different-flavour) leptons		—
	—	$m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})$	$m_{34}/m_{12} > 0.85$
	$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$ $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$ $m_{14,23} > 5\,\text{GeV}$ ($4e/4\mu$)	$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$ For $4e$ and 4μ channels: $5\,\text{GeV} < m_{14,23} < 75\,\text{GeV}$	$1.2\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$
	—	Reject event if $m_{12,34,14,23}$ in either: $(m_{J/\psi} - 0.25\,\text{GeV})$ to $(m_{\psi(2S)} + 0.30\,\text{GeV})$, or $(m_{\Upsilon(1S)} - 0.70\,\text{GeV})$ to $(m_{\Upsilon(3S)} + 0.75\,\text{GeV})$	
	—	—	Reject event if $m_{12,34}$ in either 2 GeV to 4.4 GeV, or 8 GeV to 12 GeV
	$115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$	—	—


ATLAS
√s = 13 TeV, 139 fb-1
HM Signal Region
Local p-value
1
10−1
10−2
10−3
1σ
2σ
3σ
15 20 25 30 35 40 45 50 55 60
m_Zd [GeV]