Limits on an Exotic Higgs Decay From a Recast ATLAS Four-Lepton Analysis

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[2412.14452 JC & Rabia Husain & Lingfeng Li & Matthew Strassler]

LHC Reinterpretation Forum
February 25-28, 2025

- Introduction
- ATLAS $Z \to 6f$ analysis
- Our reproduction of ATLAS $Z \to 6f$
- Limits on $H \to 8f$

Introduction

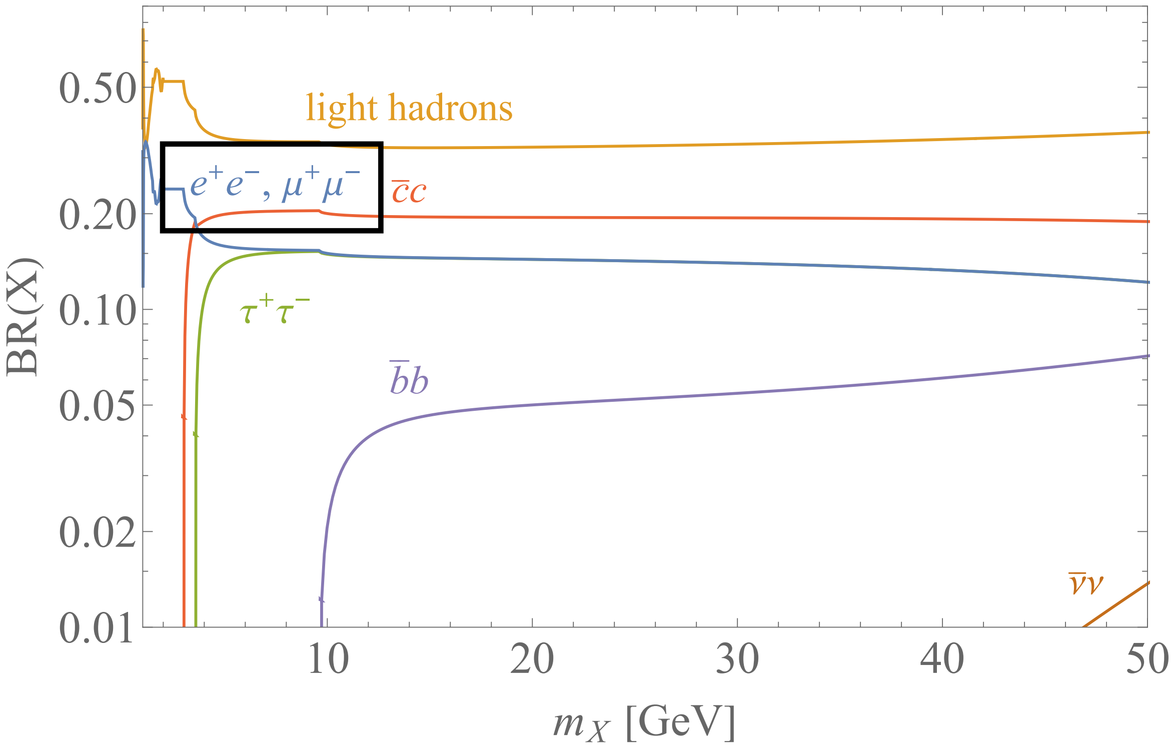
Hidden Valley / Dark Sector (HV/DS) theory [Strassler & Zurek 2006]

- gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y \times$ dark sector
- simplest case: Hidden Abelian Higgs Model $U(1)_D$

  [Schabinger & Wells 2005, Gopalakrishna & Jung & Wells 2008, Curtin & Essig & Gori & Shelton 2015]
- gauge boson (dark photon) X_μ and dark Higgs H_D
- possible gauge-invariant renormalizable couplings to SM:
  - gauge sector kinetic mixing $\frac{\chi}{2}\hat{X}_{\mu\nu}Y^{\mu\nu}$,

    X_μ can decay to SM fermions,

    lepton BR $\sim$ 15 %
  - Higgs sector $\kappa|H|^2|H_D|^2$



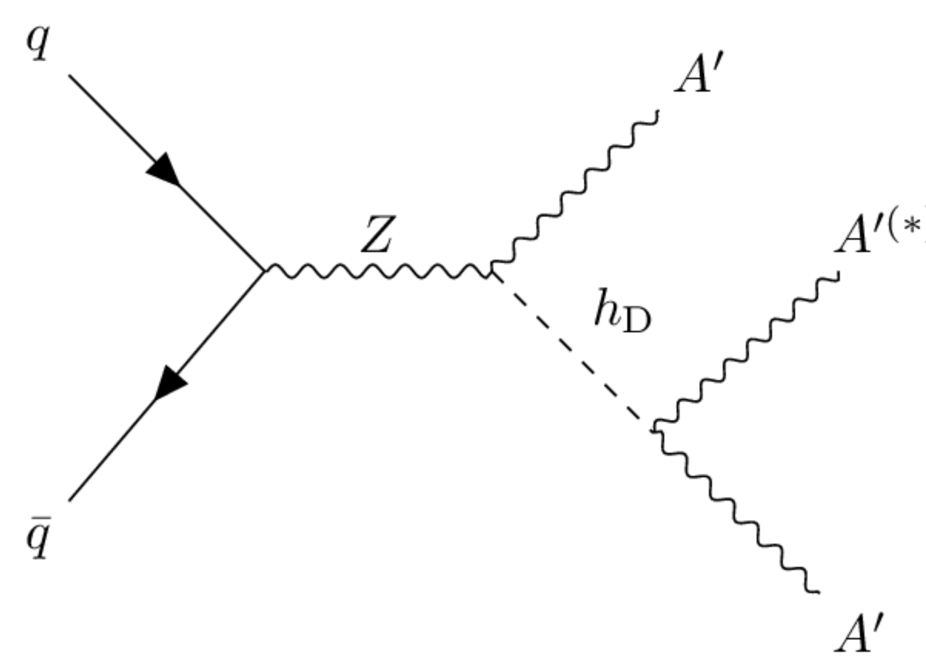
Introduction

choice of signal

- signal:
  - $\geq 2\ X_\mu$ leptonic decay
  - ≥ 2 lepton pairs
  - equal invariant mass $m_{ll} \sim 25$ GeV
- other searches:
  - lower m_{ll}
  - no symmetric m_{ll} requirement
  - put additional restrictions, e.g. MET & $m_{4l} = m_H$
- leptonic final states:
  - small backgrounds
  - easier to reconstruct
  - sizeable BRs
- not very sensitive to model specific details, e.g. parity & fundamental or composite particle, good model-agnostic signature

$Z \to 6f$

[2306.07413 ATLAS]

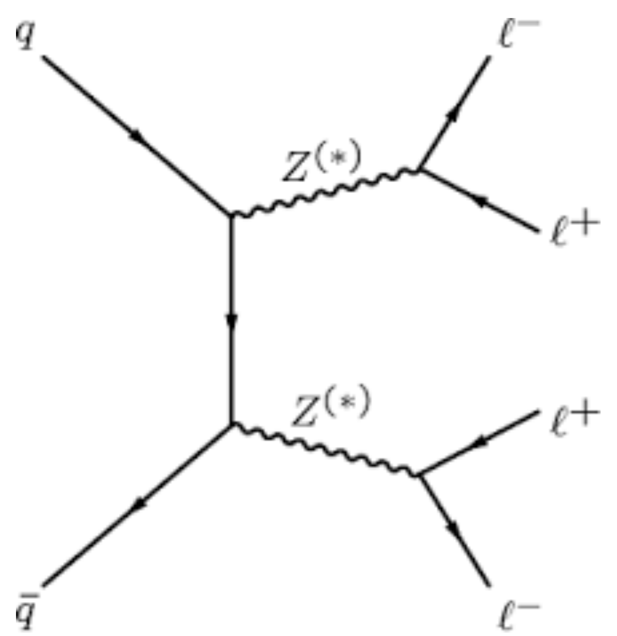


- $pp \to Z \to A'h_D, h_D \to A'A', A' \to l^+l^-$ $(l = e, \mu)$
- only require 4 leptons, the third A' can decay hadronically
- ATLAS paper includes both on-shell and off-shell, but we are only interested in on-shell case $m_{A'} < m_{h_D}/2$
- other papers with 4-lepton final states:
  - lower m_{ll} [1106.2375 CMS, 1210.7619 CMS, 1506.00424 CMS, 1812.00380 CMS]
  - no symmetric m_{ll} requirement [1511.05542 ATLAS, 1701.01345 CMS]
  - put additional restrictions, e.g. MET [2103.11684 ATLAS] & $m_{4l} = m_H$ [1505.07645 ATLAS, 1802.03388 ATLAS, 2110.13673 ATLAS, 2111.01299 CMS]

$Z \to 6f$

ATLAS analysis

- triggers: 1-lepton $p_T \sim 25$ GeV, 2-lepton $p_T \sim 15$ GeV, 3-lepton $p_T \sim 10$ GeV
- dominant physics background is $q\bar{q} \to 4l$, but fake lepton from detector is equally important



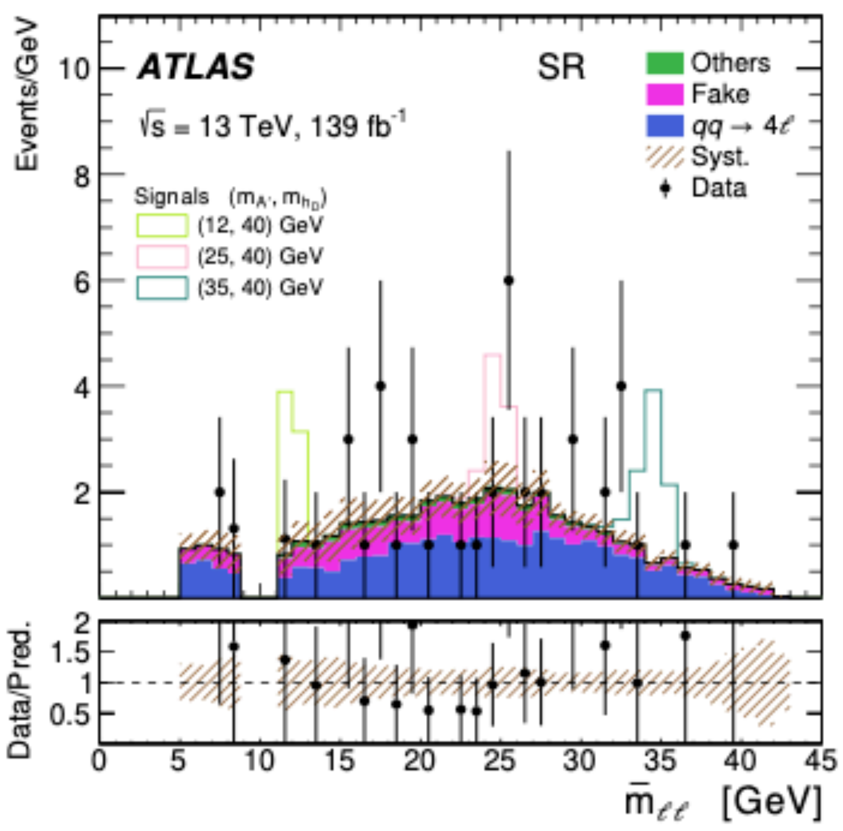


Figure from [2306.07413 ATLAS]

$Z \to 6f$

ATLAS analysis

- event selection cuts:
  - ≥ 4 loosely isolated leptons with $p_T^e > 4.5$ GeV, $p_T^\mu > 3$ GeV
  - ≥ 2 SFOC lepton pairs
  - $0.85 < m_{34}/m_{12} < 1$
  - $m_{4l} < m_Z - 5$ GeV
  - reject $m_{ll} \in [0,5] \cup [8,12]$ GeV (B, Υ range)

$$Z \to 6f$$

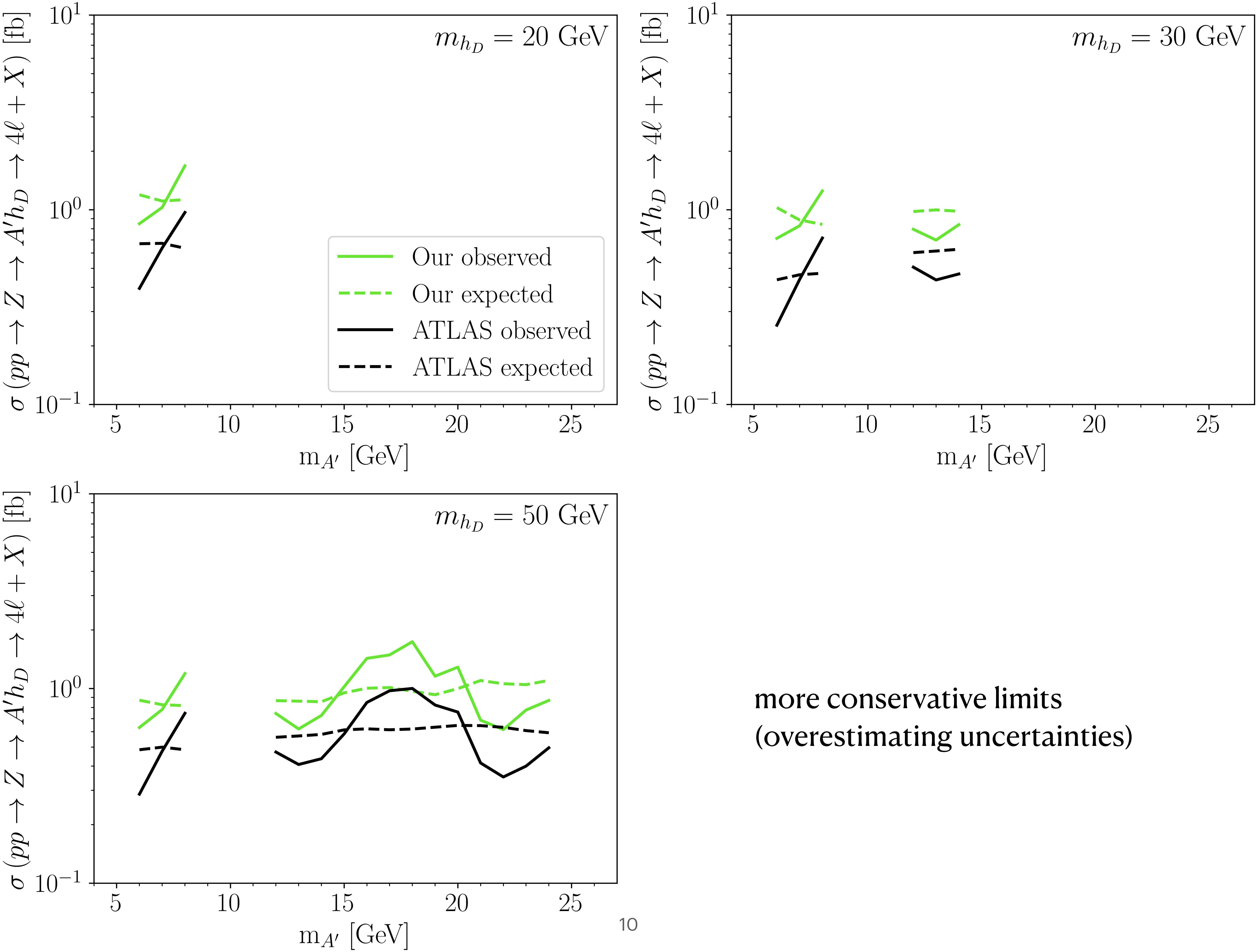
ATLAS MC study

- order is different from real experimental searches: cuts → trigger
- signal efficiency $\sim 6 - 7\,\%$

$Z \to 6f$

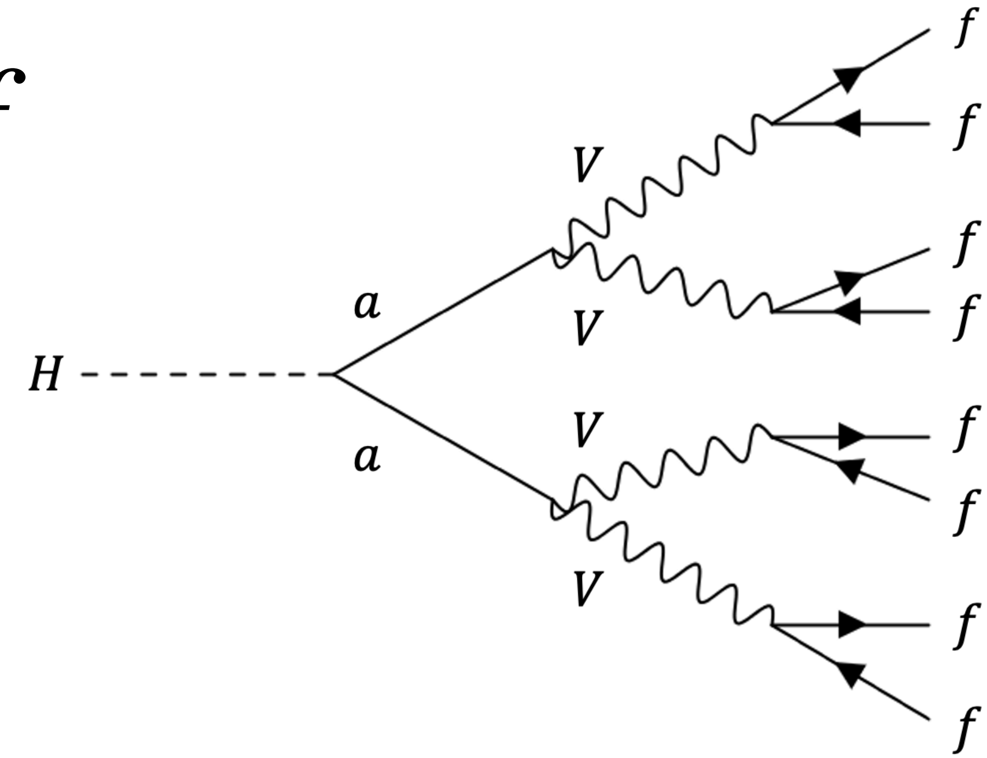
our reproduction

- simulate signal and use the backgrounds in the ATLAS analysis
- use ATLAS MC study to choose recalibration factors, reproduce single step efficiencies
  - $r_{\text{lep}} = 0.78$: detector effects for soft leptons, fake leptons
  - $r_{\text{trig}} = 0.81$
- CL_S method for obtaining limits on $\sigma(pp \to Z \to A'h_D \to 4l + X)$: multiple 1 GeV signal bins with background and systematic uncertainties
- systematic uncertainties comparable to statistical uncertainty, dominant from r_{lep}



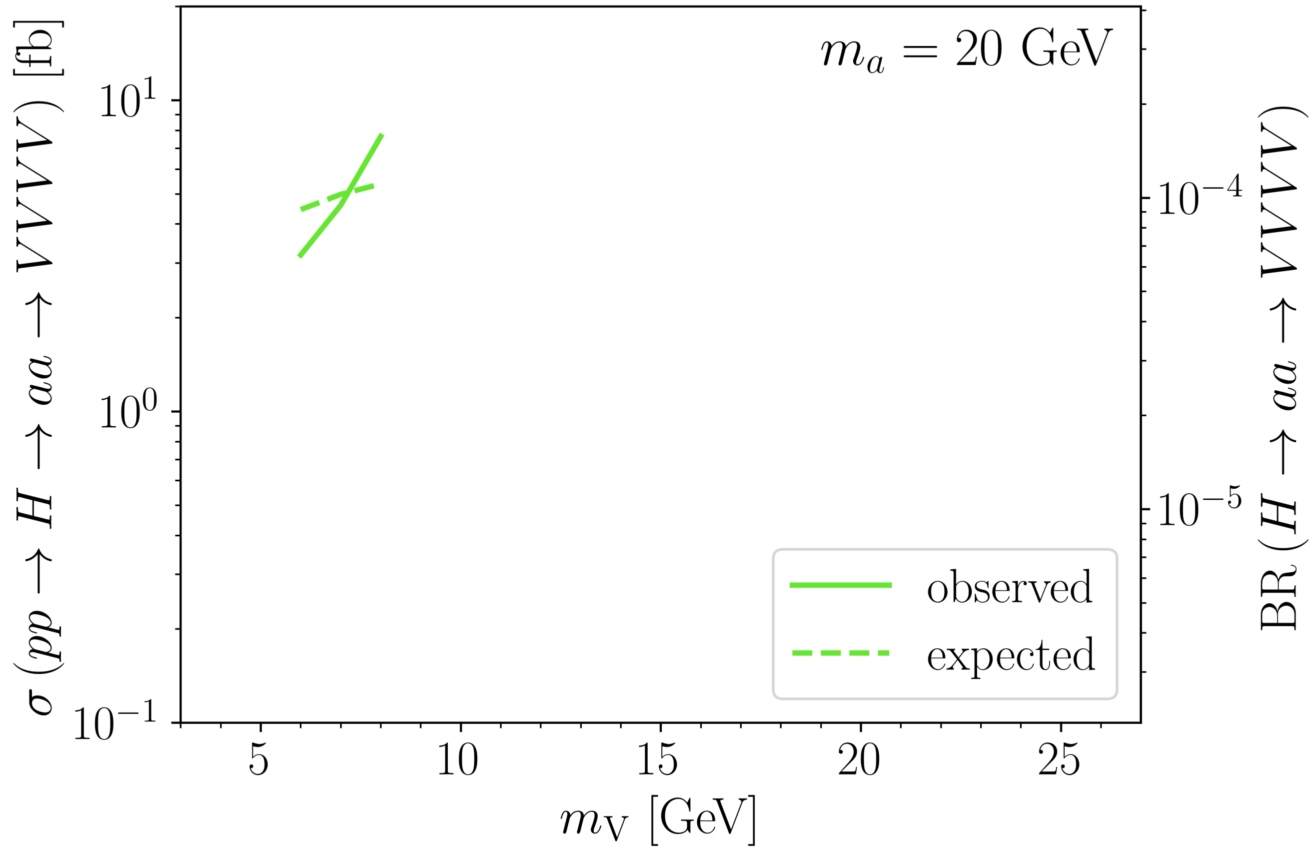
more conservative limits
(overestimating uncertainties)

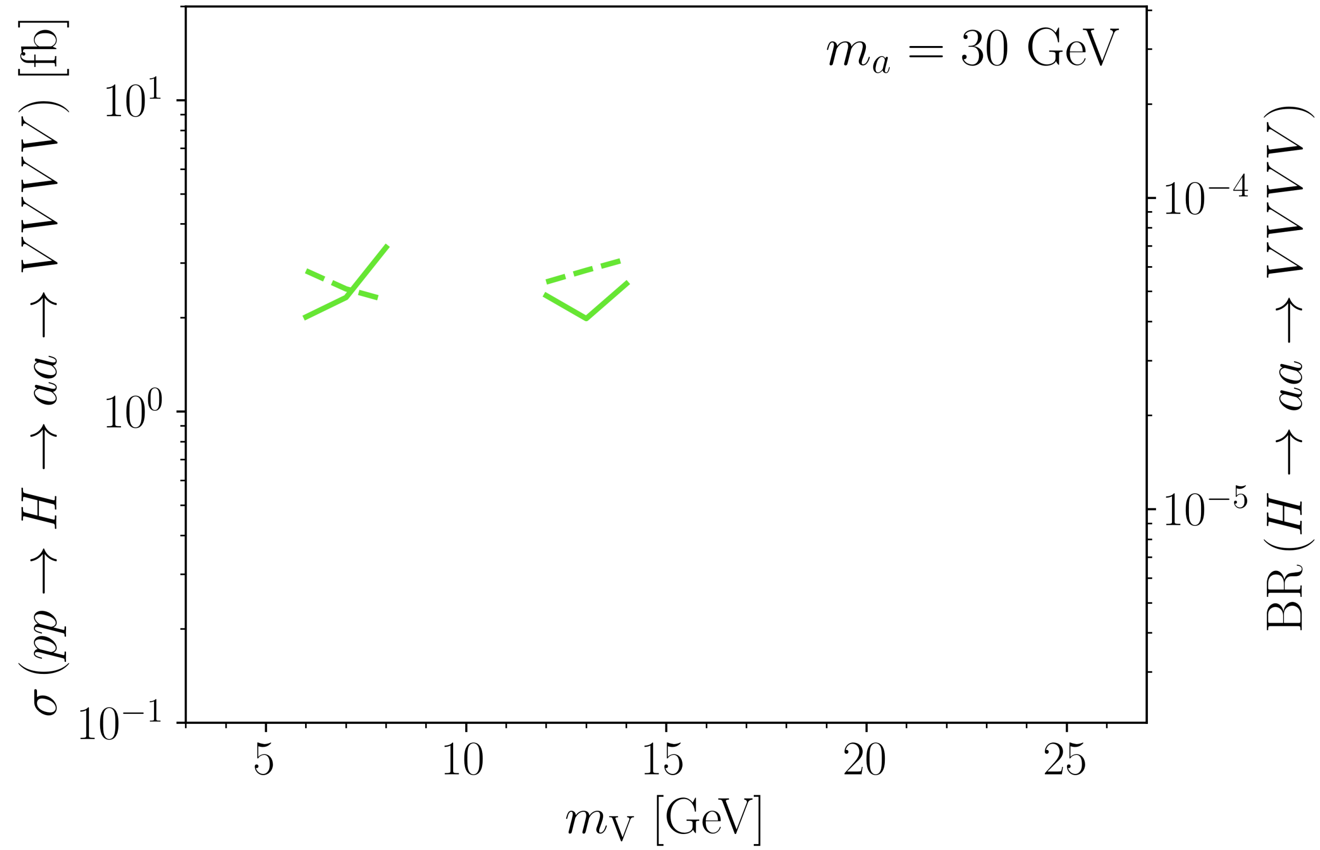
$H \to 8f$

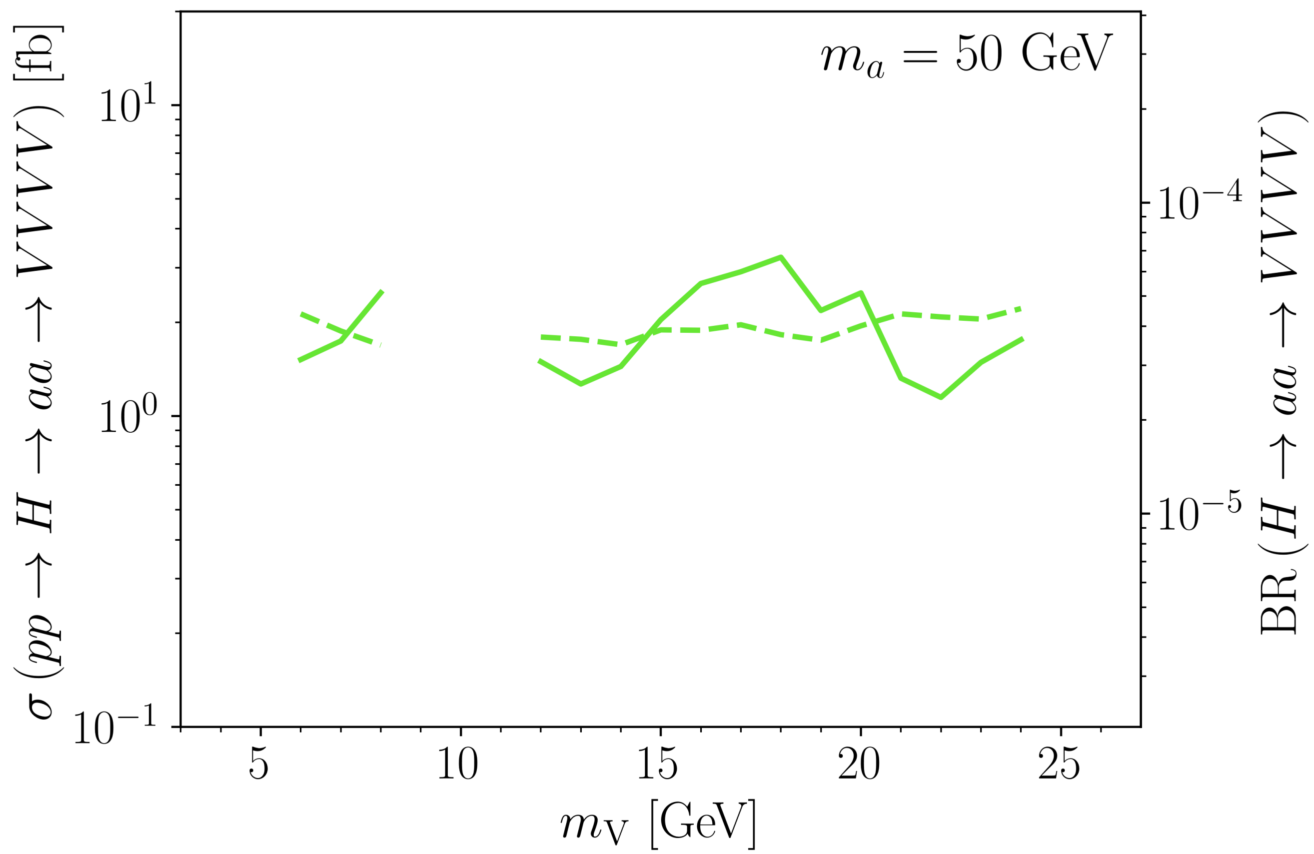


- $pp \to H \to aa, a \to VV, V \to f^+f^-$
- a pseudoscalar / scalar, V vector e.g. dark photon
- why: Higgs exotic decays to 3 or 4-particles are well studied
- assume $V \to f^+f^-$ follows kinetic mixing BR(X), BR($a \to VV$) $= 100\,\%$, put limit on BR($H \to aa$)
- same triggers & cuts & backgrounds & statistical methods as in $Z \to 6f$, signal efficiency $\sim 3\,\%$
- other relevant papers:

[Izaguirre & Stolarski 2018, 2103.11684 ATLAS, 2407.20425 CMS, 2410.16781 ATLAS]







- BR($H \to aa$) $\sim 4 \times 10^{-5}$, current best limit on this final state
- other limits in the same mass range are not as strong

Future directions

- non-abelian dark gauge group e.g. SU(N) similar to QCD, with confinement, dark shower and form dark hadrons
- dark hadrons (composite) decay to SM fermions

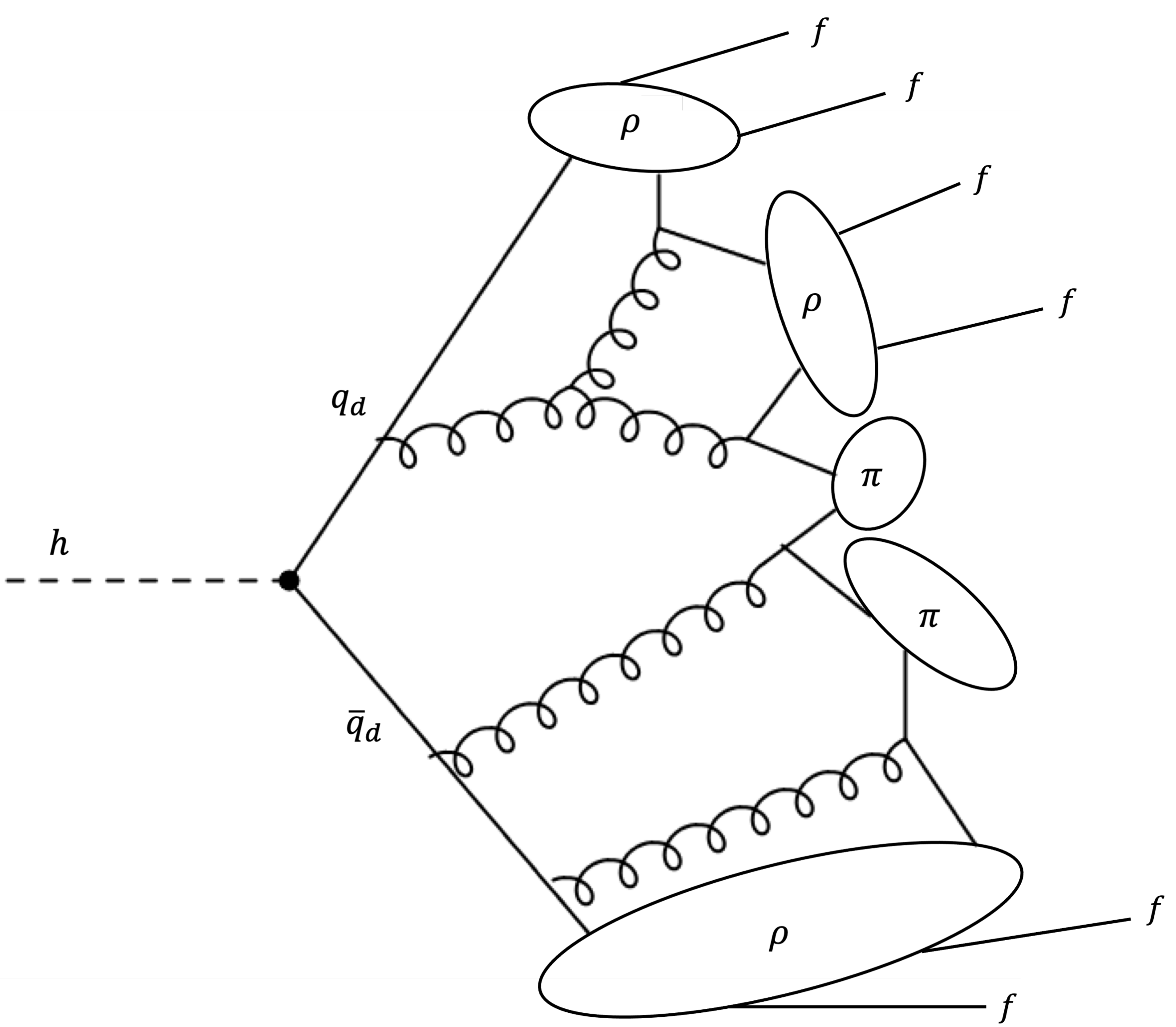
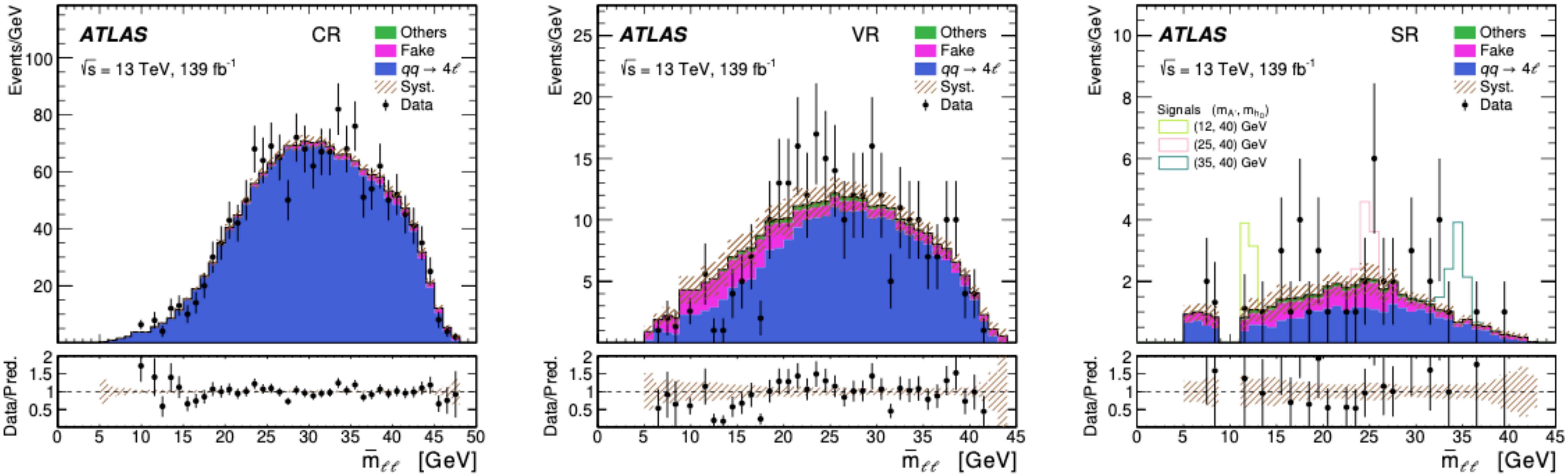


Figure from [Bernreuther & Kahlhoefer & Krämer & Tunney 1907.04346]

Thank you!

Questions?

Backup slides



SM backgrounds	SR	CR	VR
$qq \to 4\ell$	26.0 ± 2.4	1555 ± 48	239 ± 15
Fake	13.2 ± 5.6	43 ± 25	47 ± 26
Others	2.2 ± 0.7	5.8 ± 1.9	6.8 ± 2.0
Total background	41.3 ± 5.3	1604 ± 40	293 ± 28
Data	44	1602	286
Signal $(m_{A'}, m_{h_D})$ = (12, 30) GeV	5.9 ± 0.9	-	-
Signal $(m_{A'}, m_{h_D})$ = (25, 60) GeV	3.5 ± 0.6	-	-

Figure and table from [2306.07413 ATLAS]

Trigger

- p_T requirements:
  - single electron (26 GeV)
  - single muon (26 GeV)
  - dielectron symmetric (17 GeV)
  - dimuon symmetric (14 GeV)
  - dimuon asymmetric (22 GeV and 8 GeV)
  - electron (17 GeV) and muon (14 GeV)
  - two electron (12 GeV) and muon (10 GeV)
  - electron (12 GeV) and two muon (10 GeV)
- $|\eta_e| < 2.47$ for electrons, $|\eta_\mu| < 2.7$ for muons

Event selection cuts

- Number of identified leptons satisfying the following cuts ≥ 4:
  - $p_T^e > 4.5$ GeV, $p_T^\mu > 3$ GeV
  - $|\eta_e| < 2.47$, $|\eta_\mu| < 2.7$
  - $|z_0 \sin\theta| < 0.5$. z_0 is the longitudinal impact parameter relative to the primary vertex.
  - Isolation: $E^e_{\text{cone20}} < 0.2 p_T^e$ & $(p_T)^e_{\text{varcone20}} < 0.15 p_T^e$ for electrons. E^e_{cone20} is the energy of all particles within a cone of $\Delta R = 0.2$ surrounding the electron. $(p_T)^e_{\text{varcone20}}$ is the scalar p_T sum of all charged particles (with $p_T > 1$ GeV and $|\eta| < 2.5$) that lie within a cone of radius $\Delta R = \min(10 \text{ GeV}/p_T^e,\ 0.2)$ around the electron.
  - Isolation: $(p_T)^\mu_{\text{varcone30}} + 0.4 E^\mu_{\text{neflow20}} < 0.16 p_T^\mu$ for muons. E^μ_{neflow20} is the transverse energy of all neutral particle flow candidates within a cone of $\Delta R = 0.2$ surrounding the muon. $(p_T)^\mu_{\text{varcone30}}$ is the scalar p_T sum of all charged particles (with $p_T > 0.5$ GeV and $|\eta| < 2.5$) that lie within a cone of radius $\Delta R = \min(10 \text{ GeV}/p_T^\mu,\ 0.3)$ around the muon.
- All possible 2 SFOC pairs need to satisfy $m_{4l} < m_Z - 5$ GeV. Pass if there are no 2 SFOC pairs.
- Number of SFOC pairs ≥ 2. Select the quadruplet with the smallest $m_{12} - m_{34}$, where $m_{12} > m_{34}$ are the SFOC 2-lepton invariant masses. Also need all possible combinations in the 4 selected leptons to satisfy $\Delta R > 0.1$ for 2 same flavor leptons and $\Delta R > 0.2$ for 2 different flavor leptons.
- $m_{34}/m_{12} > 0.85$
- All possible SFOC 2-lepton invariant masses need to satisfy $m_{ll} \notin [0,5] \cup [8.761, 11.105]$ GeV

$Z \to 6f$ truth efficiencies

$m_{A'}$	8 GeV	15 GeV	20 GeV
MC filter efficiency	57.7%	61.9%	64.4%
ID ≥ 4	54.2%	53.5%	56.7%
$m_{4\ell} < m_Z - 5$ GeV	97.9%	98.9%	99.4%
# SFOC lepton pairs ≥ 2	84.0%	85.3%	87.8%
$m_{\ell_3\ell_4}/m_{\ell_1\ell_2} > 0.85$	95.1%	95.3%	96.6%
No $m_{\ell^+\ell^-} < 5$ GeV or near m_Υ	95.3%	92.3%	90.9%
Overall signal efficiency	23.3%	24.6%	28.0%

$Z \to 6f$ reco efficiencies

$m_{A'}$	8 GeV ATLAS Result	8 GeV Our Result	15 GeV ATLAS Result	15 GeV Our Result	20 GeV ATLAS Result	20 GeV Our Result
MC filter efficiency	58.0%	57.7%	62.2%	61.9%	64.5%	64.3%
ID ≥ 4	27.2%	27.1%	26.9%	27.1%	28.4%	29.1%
$m_{4\ell} < m_Z - 5$ GeV	96.9%	98.4%	98.0%	99.2%	98.8%	99.6%
# SFOC lepton pairs ≥ 2	73.1%	72.6%	74.4%	73.8%	77.6%	76.1%
$m_{\ell_3\ell_4}/m_{\ell_1\ell_2} > 0.85$	86.2%	89.5%	86.7%	90.6%	87.4%	92.4%
No $m_{\ell^+\ell^-} < 5$ GeV or near m_Υ	92.0%	95.2%	91.7%	92.4%	90.1%	91.0%
Trigger	70.0%	66.8%	62.2%	63.6%	59.2%	59.4%
Overall signal efficiency	6.2%	6.3%	6.2%	6.4%	6.5%	7.1%

$Z \to 6f$ relative uncertainty

- $\sigma_{\text{eff,reco}} = \sqrt{\left(4\frac{\Delta r_{\text{lep}}}{r_{\text{lep}}}\right)^2 + \left(\frac{\Delta r_{\text{trig}}}{r_{\text{trig}}}\right)^2 + 0.14^2} \approx 0.59$
- $\Delta r_{\text{lep}} = 0.11, r_{\text{lep}} = 0.78$
- $\Delta r_{\text{trig}} = 0.10, r_{\text{trig}} = 0.81$
- 0.14 theoretical uncertainty from perturbative calculations, hadronization, and parton distribution functions, same as in [2306.07413 ATLAS]

$H \to 8f$ relative uncertainty

- $\sigma_{\text{eff,reco}} = \sqrt{\left(4\frac{\Delta r_{\text{lep}}}{r_{\text{lep}}}\right)^2 + \left(\frac{\Delta r_{\text{trig}}}{r_{\text{trig}}}\right)^2 + 0.15^2 + 0.05^2} \approx 0.60$
- $\Delta r_{\text{lep}} = 0.11, r_{\text{lep}} = 0.78$
- $\Delta r_{\text{trig}} = 0.10, r_{\text{trig}} = 0.81$
- 0.15 theoretical uncertainty from Higgs p_T distribution

  [Chen & Gehrmann & Glover & Huss & Li & Neill et al 2019]
- 0.05 theoretical uncertainty from Higgs production rate [1610.07922]

Other relevant papers for $H \to 8f$

- [Izaguirre & Stolarski 2018] suggests using $\geq 5l$ final states
- [2103.11684 ATLAS] includes $\geq 5l$ final states but has higher p_T cuts & more stringent isolation requirements
- we estimate that the method in [Izaguirre & Stolarski 2018] combined with [2103.11684 ATLAS] gives slightly weaker limits
- [2407.20425 CMS] requires 4 muons instead of leptons & has higher p_T cuts, substantially weaker limits
- [2410.16781 ATLAS] has higher p_T cuts, weaker limits