Rare and Exotic H Decays in ATLAS

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On behalf of the ATLAS Collaboration

ICPPA-2020

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- $H \rightarrow aa$
- $H \rightarrow Za$
- $H \rightarrow Z_d Z_d$
- LFV searches from H decays
- $H \rightarrow e^{\pm}e^{\mp}$

Introduction

- **SM is very successful, but some big questions are not explained:**
  - What are the origins of 95% energy and mass in the universe (dark matter and dark energy)?
  - What is the source of matter-antimatter asymmetry in our universe?
  - Hierarchy problem, why SM $m_H << m_{Planck}$?
  - Flavor violation in neutrinos & muon g-2/B decays anomalies → LFV?

- **Many theoretical models beyond the Standard Model (BSM) to extend the SM: SUSY, extra Higgs doublets, Composite Higgs …**

- **Could SM 125 GeV Higgs be the bridge between SM and BSM?**
  - ATLAS model-dependent constrain: B(H→BSM) < ~28% (ATLAS-CONF-2020-027)
  - Γ_H ~ 4.1 MeV, small coupling ~10^{-2} can lead to B(H→BSM) ~ O(10%)
  - Theoretical models allow for LFV Higgs currents: **H→e/μτ** at B($H \to \tau\ell$)≤O(1%)

- **Exploring rare and exotic Higgs boson decays → an unique approach at the LHC to search for new physics BSM**

Search for Signature of the 2HDM+S Models

- **From two Higgs doublets ϕ1, ϕ2 , after symmetry breaking =>**
  - 5 physical states: CP-even (h, H), CP-odd (A), and charged ($H^{\pm}$) states;
  - tan(β)=v2/v1;
  - α: the mixing angle between the CP-even Higgs bosons

[Phys. Reports 516 (2012) 1–102](#)

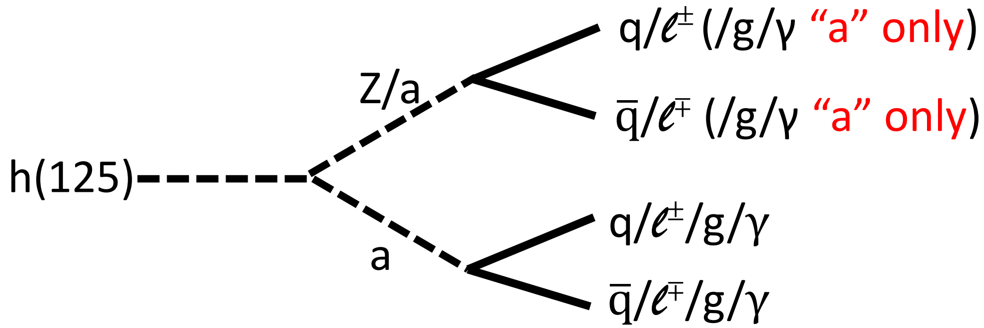
Models which lead to natural flavour conservation. The superscript i is a generation index. By convention, the u_R^i always couple to Φ_2.

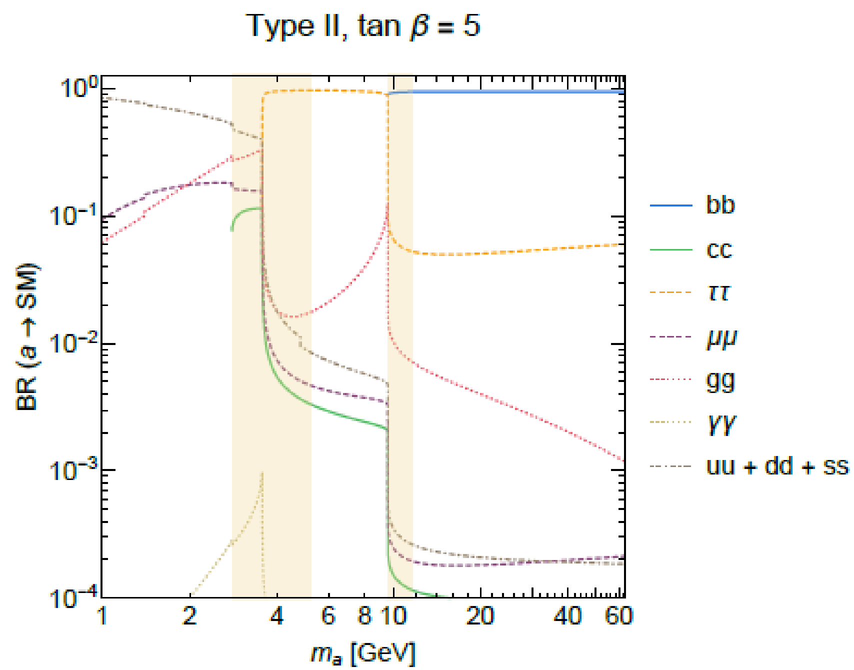
Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

- **Add a complex scalar singlet**
  - Only couples to the two Higgs complex in the potential without direct Yukawa couplings and couples to SM fermions through its small mixing with two scalar Higgs to avoid destroying SM-like nature of the Higgs

- **Result in exotic Higgs decays:**

  h(125) →aa→xxyy or h(125)→Za →xxyy

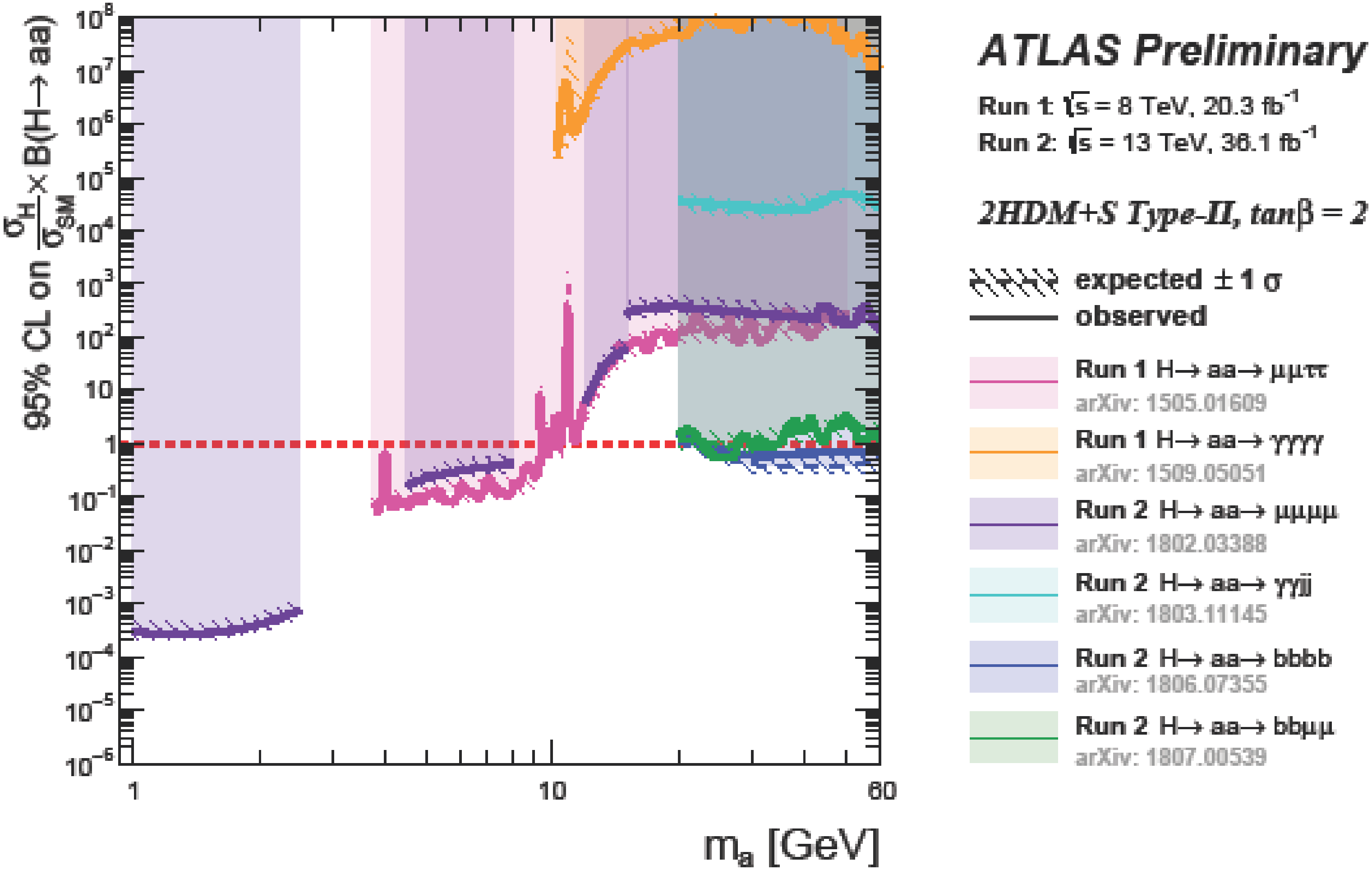




[Phys. Rev. D 90, 075004 (2014)](#)

Exotic Higgs→aa Searches

ATL-PHYS-PUB-2018-045



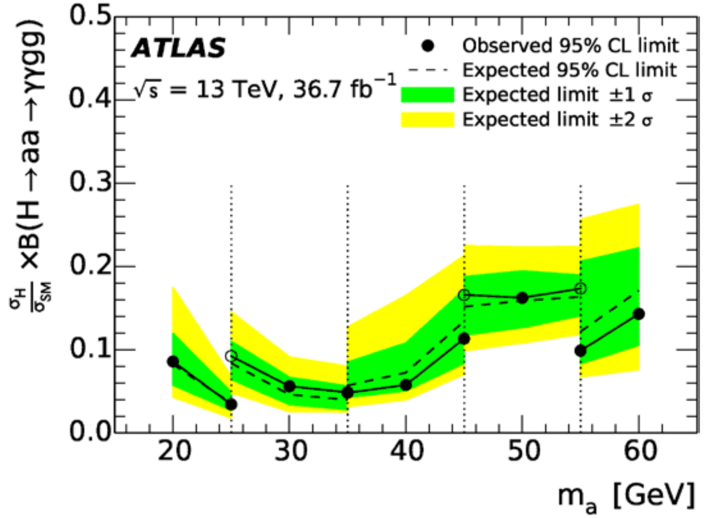
- Limits on B(H→aa) assuming a particular 2HDM+S model for couplings by using model independent limits on B(H→2X 2Y);
- **Still many unexplored regions! ➔new experimental techniques needed**

$H \to aa \to 2\gamma 2g$:

[*Phys. Lett. B 782 (2018) 750*]

- Using the VBF Higgs production to suppress large $\gamma\gamma$+multi-jet background
- Events required to have at least 4 jets
- Signal: narrow $m_{\gamma\gamma}$ peak@m_a, m_{jj} around m_a & $m_{\gamma\gamma jj}$ peak@m_H
- BKGs by data driven method.

✓ The observed 95%CL upper limit for $\sigma \times B$(**$H \to aa \to 2\gamma 2g$**) < **3.1-9.0 pb** depending on m_a

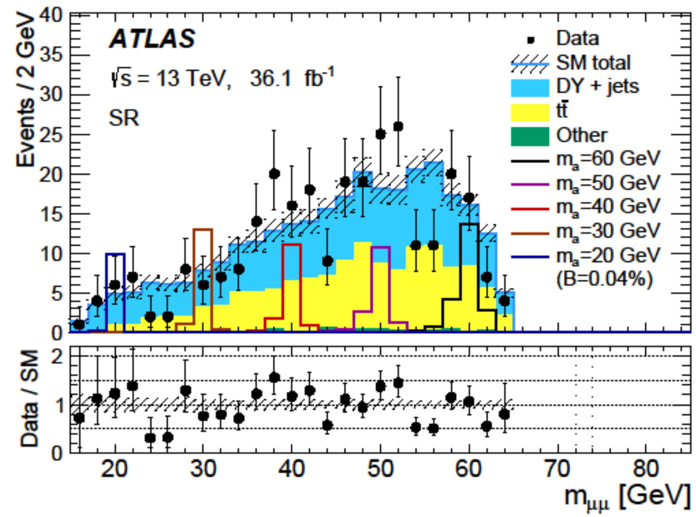


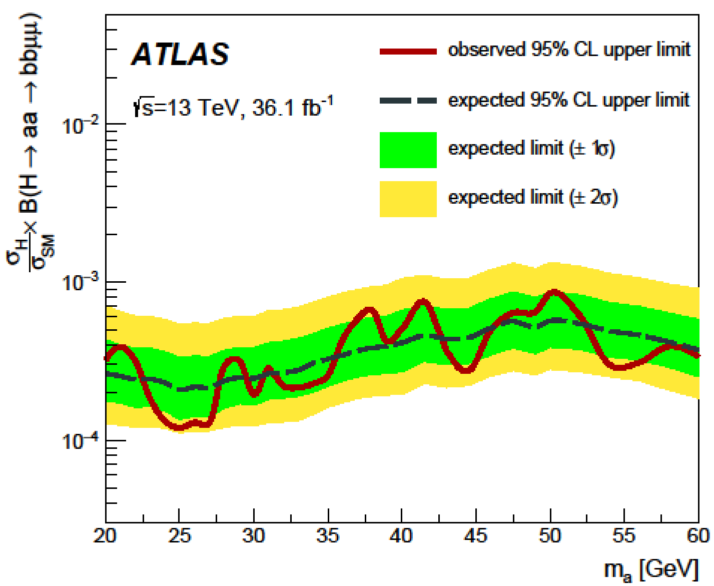
$H \to aa \to 2b2\mu$:

[*Phys. Lett. B 790 (2019) 1*]

❑ **Signature:** $m_{2b+2\mu} \sim m_H$, $m_{2b} \sim m_a$ & narrow $m_{2\mu}$ peak@m_a;

❑ A kinematic likelihood fit is used to enforce the $m_{2b} = m_{2\mu}$ which also improves the $m_{2b+2\mu}$ to match m_H;



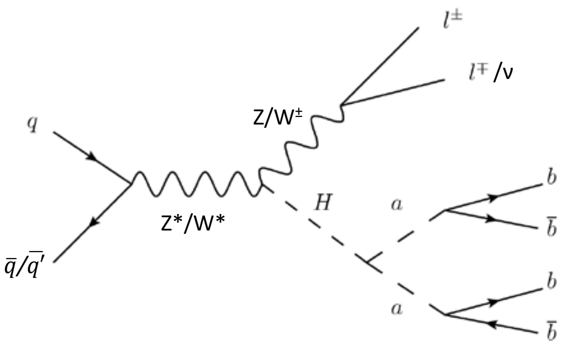


❑ **BKGs:** **DY+jets** (estimated from data); **$t\bar{t}$** (MC simulation, normalized to CR)

❑ **Searches:** no significant excess above SM predictions ➔ Limits are set by scanning 2μ mass in 2-4 GeV wide bins in range 20 to 60 GeV

H→aa→4b

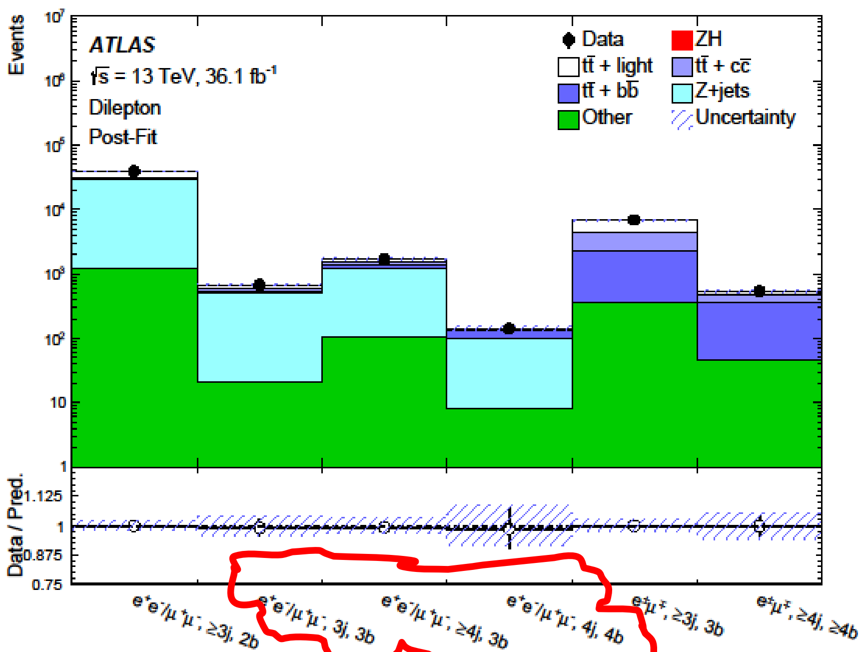
JHEP 10 (2018) 031

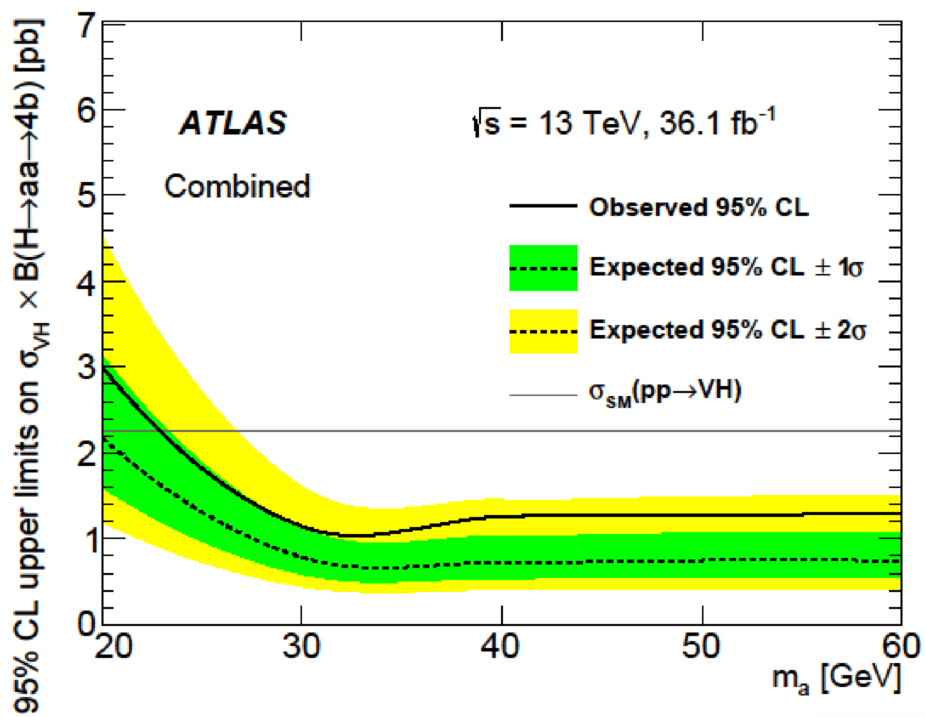


- Using VH production for triggering and powerful BKG rejections
- **Event selections**
- **signal >= 3 b-jets**

Requirement	Single lepton	Dilepton
Trigger	single-lepton triggers	
Leptons	1 isolated	2 isolated, opposite-charge
Jets	≥ 3	
b-tagged jets	≥ 2	
Other	$E_T^{miss} > 25$ GeV, $m_T^W > 50$ GeV	85 GeV $< m_{ll} <$ 100 GeV

- **BKGs: $t\bar{t}$+jets & Z+jets** processes, estimated using control regions chosen by varying jet and b-tag multiplicities.
- Separate signal from BKGs with a BDT classifier using jet kinematic + b-tagging information
- No significant deviation from SM predictions➔ upper limits on the σ_{VH}*B(H→aa→4b) from 3pb to 1.3pb depending on m_a



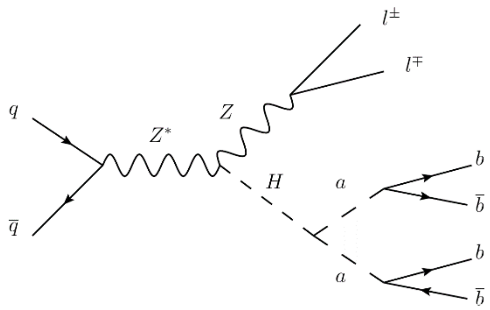


ZH SR: ($\ell^{\pm}\ell^{\mp}$,3j,3b), ($\ell^{\pm}\ell^{\mp}$, ≥4j,3b), ($\ell^{\pm}\ell^{\mp}$, 4j,4b).

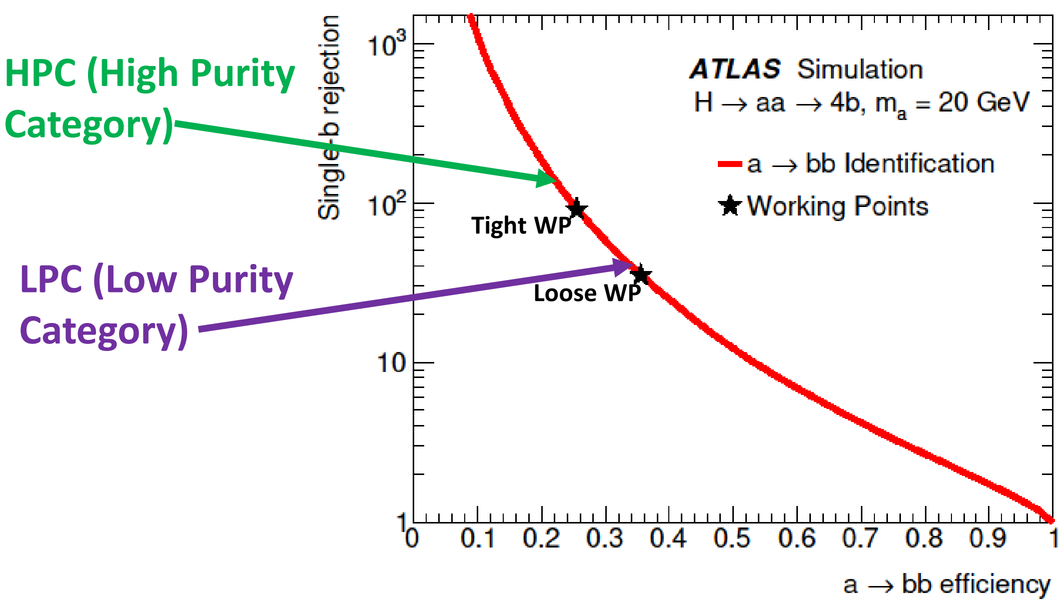
$H \rightarrow aa \rightarrow 4b$ (2 Collimated b-jets)

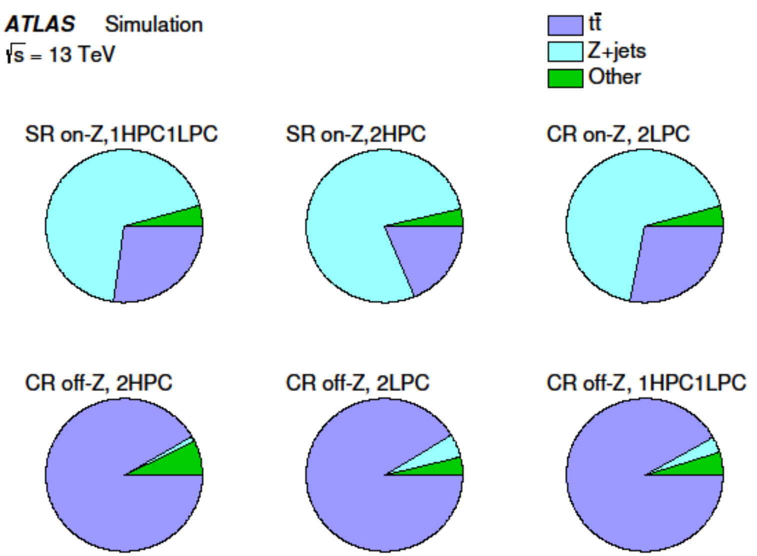
NEW

arXiv:2005.12236



- **ZH production in low mass region 15 ≤ m_a ≤ 30 GeV,** where $B(a \rightarrow bb)$ dominates in many 2HDM+S models
- Signal has collimated decay products, a novel strategy needed to reconstruct and to identify $a \rightarrow b\bar{b}$ decays
  - Merge anti-k jets R=0.4→0.8; then using tracks/track-jets with exclusive-k_t method to resolve 2 b-jets
- **BKGs: $t\bar{t}$+jets & Z+jets** processes, estimated in CRs chosen by varying tagging purity and di-lepton mass.
- A BDT classifier based on b-tagging, jet substructure, and kinematic information is used to separate $a \rightarrow b\bar{b}$ signal from the single b-jet backgrounds

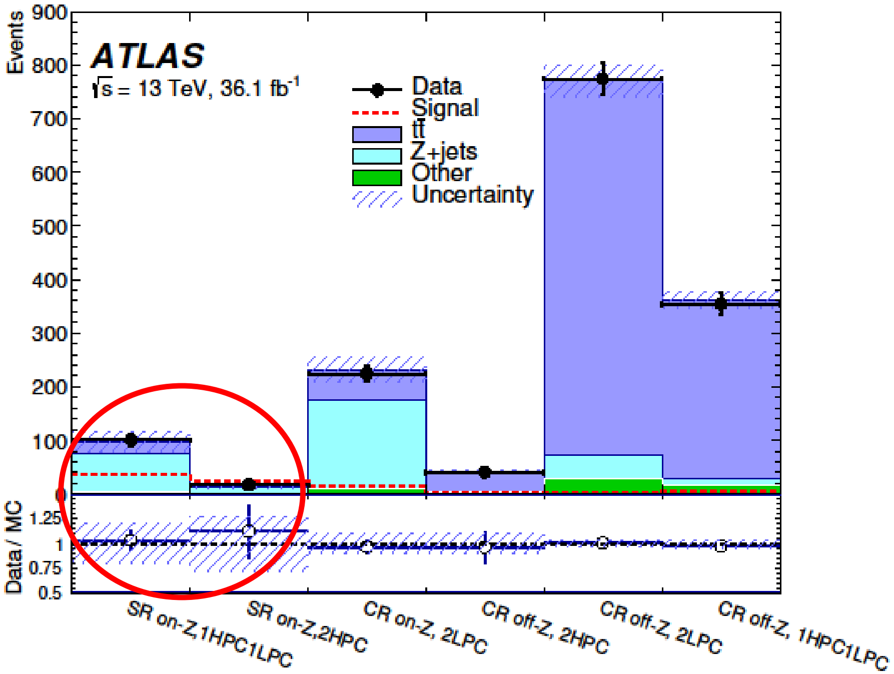


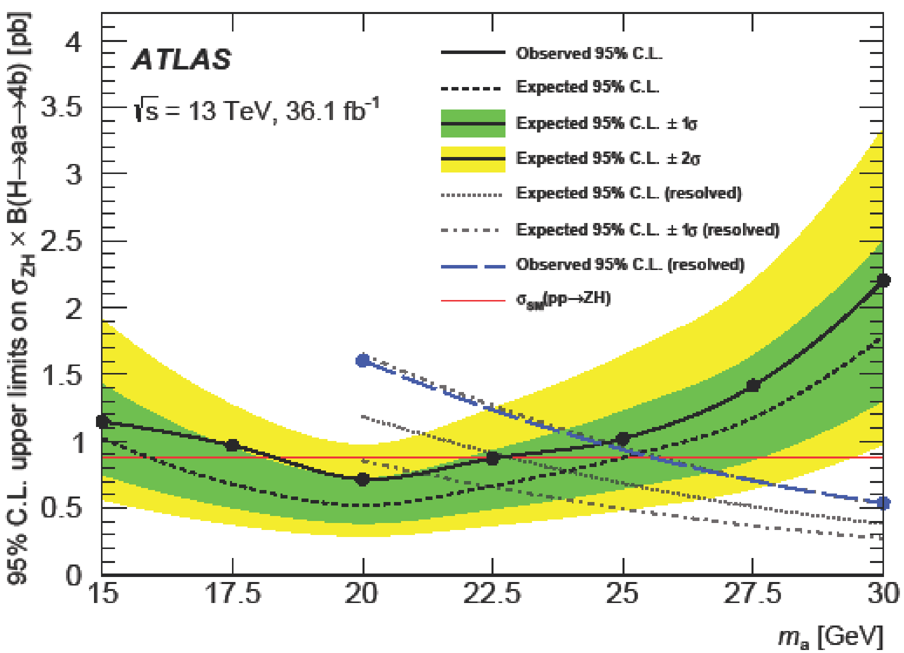


H→aa→4b (2 Collimated b-jets)

arXiv:2005.12236

- 1^{st} LHC result in low-mass 4b final state to use merged b-jets, no deviation from SM predictions;
- Extend the limits down to m_a 15 GeV from 20 GeV and improve the limits on σ_{ZH}xB(H→aa→4b) w.r.t the previous results from m_a from 20 to 24 GeV (for example, a factor 2.5 improvement for m_a=20 GeV)
- But only beginning to probe phase space below 100% B(H→aa→4b), current best limit around m_a 20 GeV ~87%.



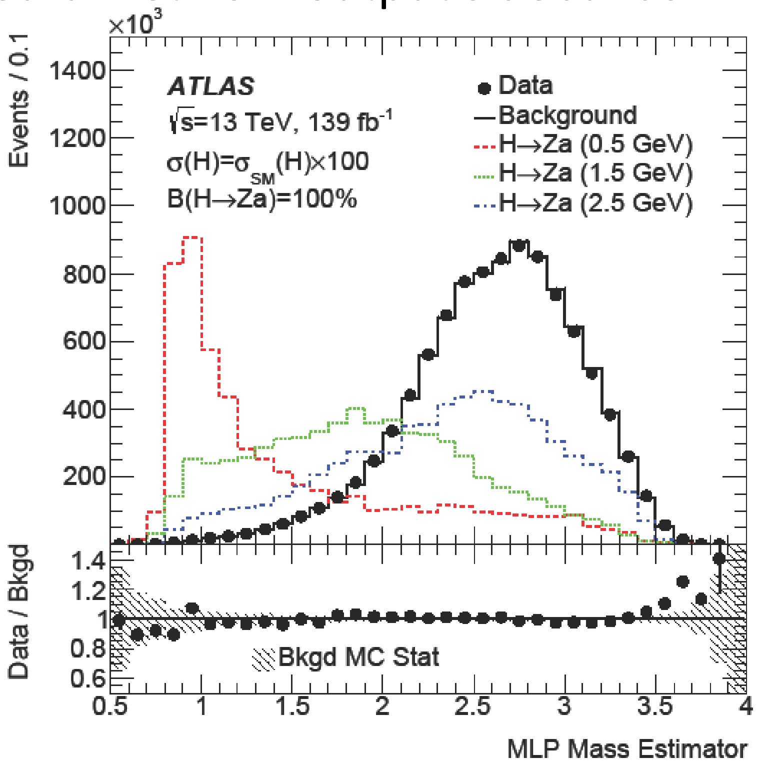


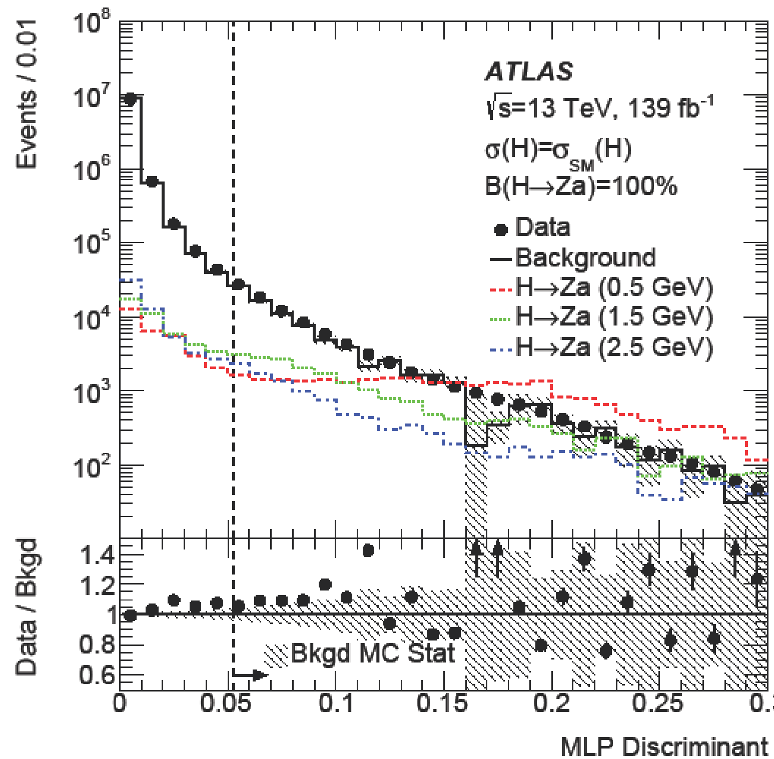
NEW

H→ZX→$\ell^+\ell^-$ hadrons

arXiv:2004.01678

- Search for BSM H→Za, a→hadrons in the mass range $0.5 \leq m_a \leq 4$ GeV. Due to low mass, final state of pseudo-scalar "a" decay is a boosted single jet;
- Possible sensitivity to **H→Z J/ψ** and **H→Z η_c**;
- Jet substructure variables used to reconstruct this hadronic pseudo-scalar/meson
  - Individual substructure variables are combined using machine learning techniques;
- Multilayer perceptron (MLP) classifier is used for event selection;
- Dominant background: **DY+Jets**, estimated using ABCD method in the m_{llj} and neural network output sidebands.

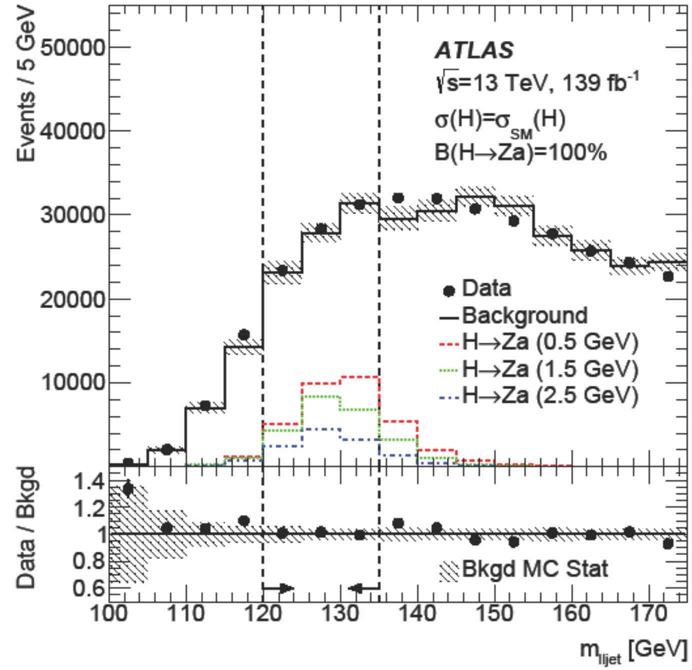


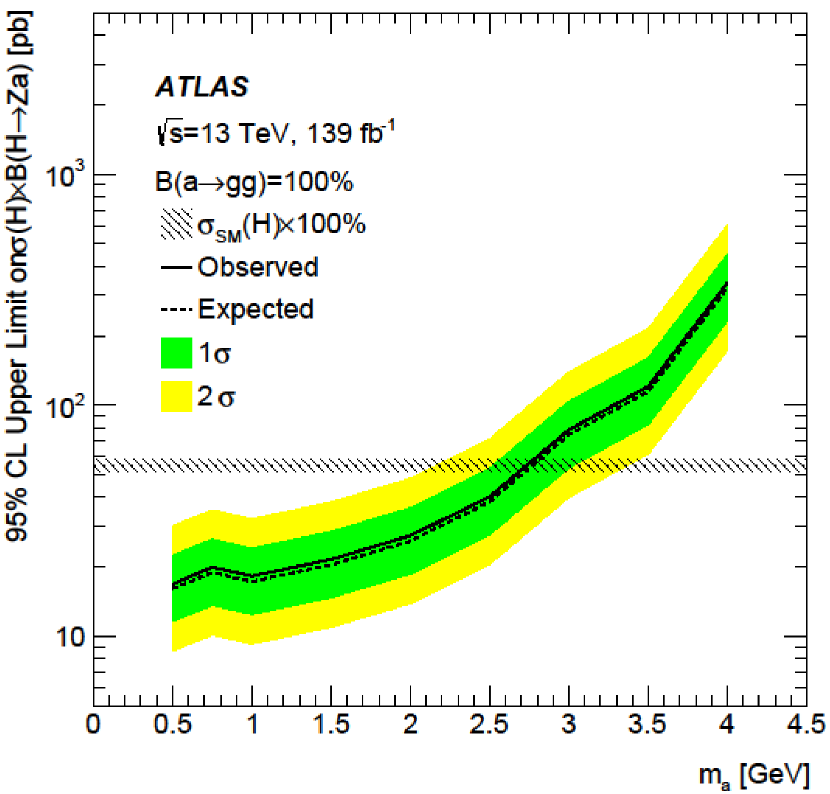


NEW $H \to Za \to \ell^+\ell^- gg$ Results

arXiv:2004.01678

- The $m_{\ell\ell j}$ required from 120 to 135 GeV
- No significant deviation from SM predictions





95% CL **observed** upper limits:
σ_HxB($H \to Za$) 17–340 pb from 0.5 to 4 GeV
for light spin-0 boson mass hypotheses

σ_HxB($H \to Z\,\eta_c$) 110 pb
σ_HxB($H \to Z\,J/\psi$) 100 pb
for η_c and J/ψ hypotheses respectively

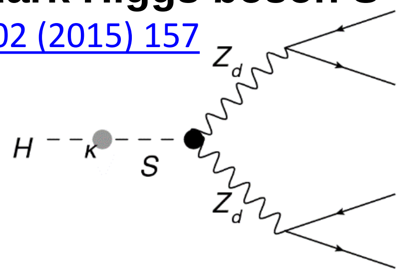
Not sensitive to the mass regions above 2.8 GeV where **B($H \to ZX$)>100%**

$H \to Z_d Z_d / ZZ_d \to 4\ell$

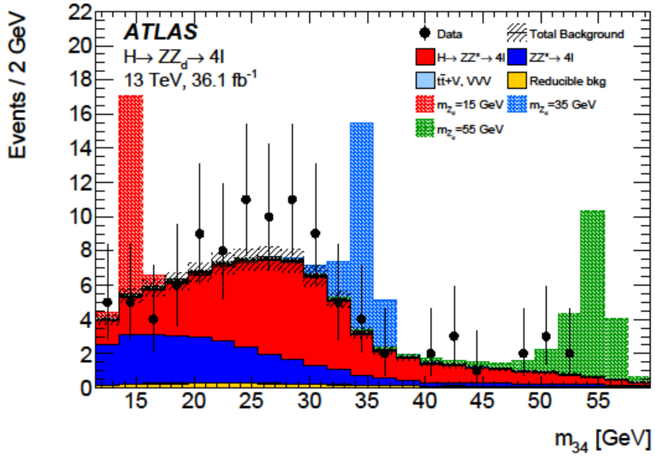
[JHEP 06 (2018) 166](#)

via dark Higgs boson S

[JHEP 02 (2015) 157](#)



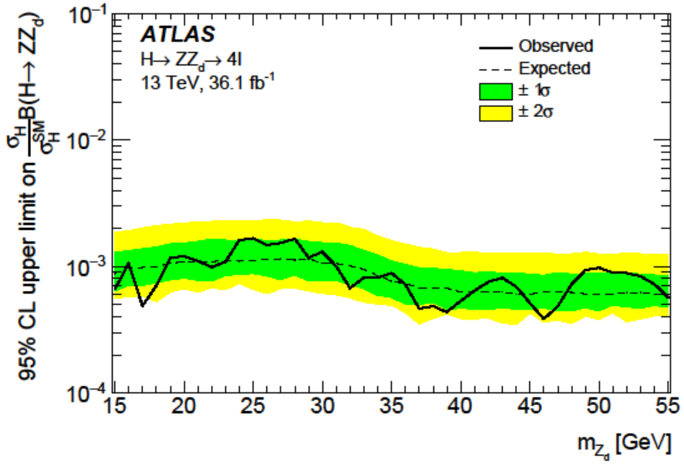
- **Selection:** 4ℓ with 2 pairs of same flavor and opposite charge leptons, $m_{4\ell}$ compatible with Higgs mass 125 GeV
  - **ZZ_d : 50 <m_{12} < 106GeV, 12 <m_{34} < 115GeV**
  - **Z_dZ_d: m_{2l} requirements optimized according m_{Z_d}**
- **BKGs: Irreducible ones (ZZ, SM Higgs boson)** estimated by MC, **reducible bkg (Z+jets)** estimated from data

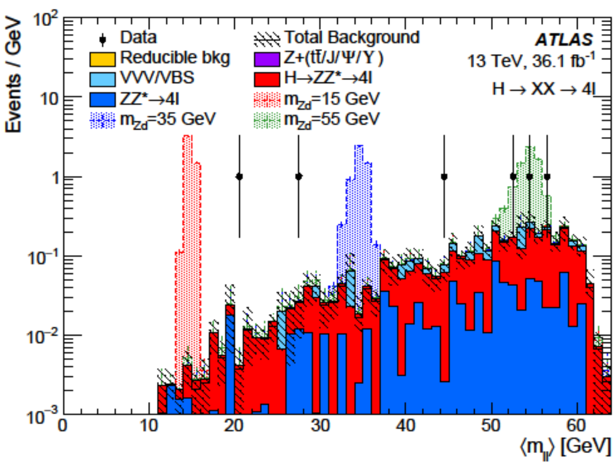


No significant deviation from SM predictions

$H \to ZZ_d \to 4\ell$

m_{12} recon. Z & m_{34} for Z_d

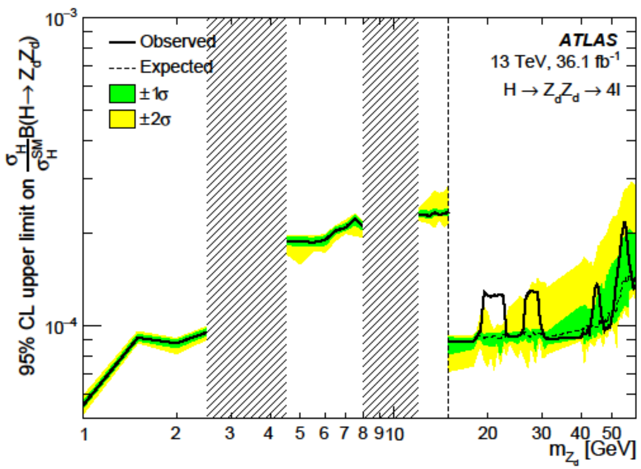




$H \to Z_dZ_d \to 4\ell$

m_{Z_d}(1,15) μ only: $0.88 < m_{12,34} < 20$ GeV, veto J/ψ and Υ resonance regions;
m_{Z_d}[15,60) e+μ: $10 < m_{12,34} < 64$ GeV.

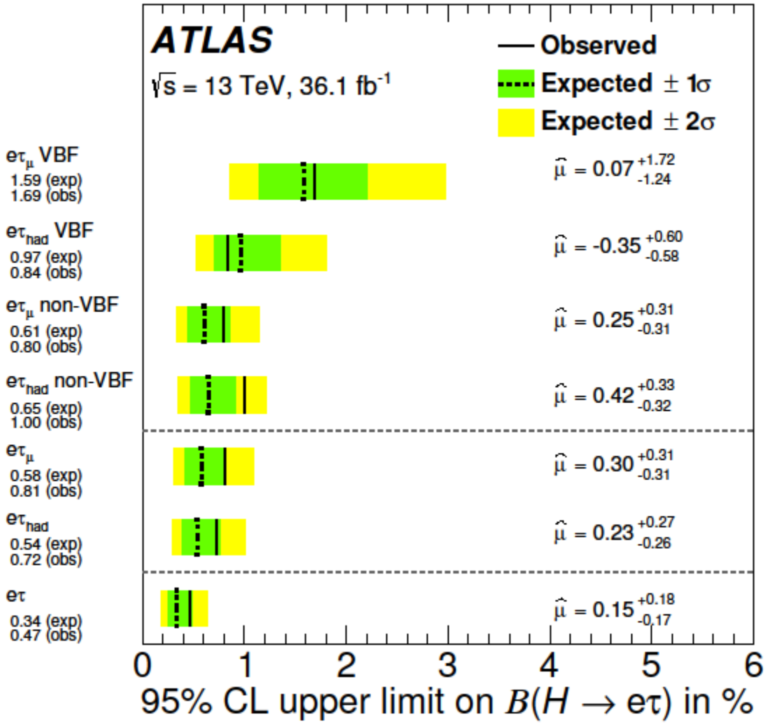
$\langle m_{\ell\ell} \rangle = (m_{12}+m_{34})/2$



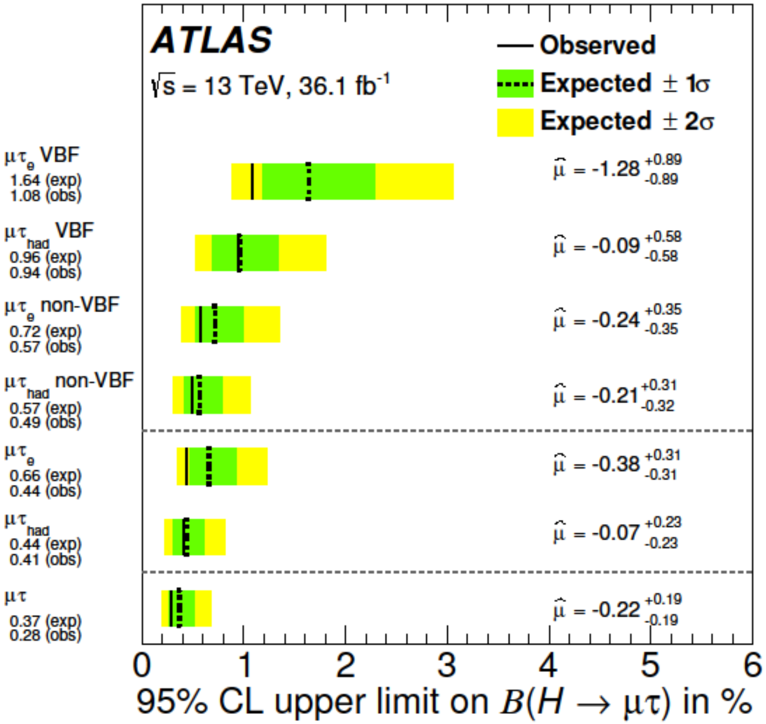
Lepton Flavor Violation in $H \to \ell^{\pm}\tau^{\mp}$

Phys. Lett. B 800 (2020) 135069

- **Signature:** Opposite-sign pair of $\ell^{\pm}(e^{\pm}/\mu^{\pm})\tau^{\mp}$, $\tau^{\mp}(\to e^{\mp}/\mu^{\mp}\nu\nu)$ or $\tau_{had}(\to$1/3 charged hadrons) + veto extra charged leptons and b-jets
- **Dedicated Categorization for each lepton-flavor:** $e^{\pm}\tau^{\mp}$, $\mu^{\pm}\tau^{\mp}$, 4 SRs
- **BKGs: Top** CR (≥ 1 b-jet, top bkg ~95% purity); **$Z \to \tau^{\pm}\tau^{\mp}$** CR ($35<p_T^{\ell 1}<45$GeV,~60-80% purity)
- **BDT** algorithms used to enhance the signal separation from the background
- **No significant** signal observed in any category, the best-fit BRs are consistent with 0 within 1σ. Limits are set @ 95% CL on **$B(H \to \ell^{\pm}\tau^{\mp})$**



$B(H \to e^{\pm}\tau^{\mp}) < 0.47\%$ (0.34% exp.)

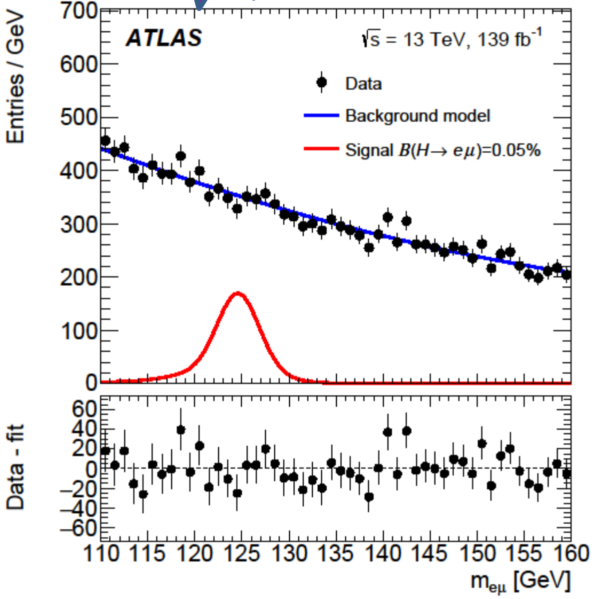


$B(H \to \mu^{\pm}\tau^{\mp}) < 0.28\%$ (0.37% exp.)

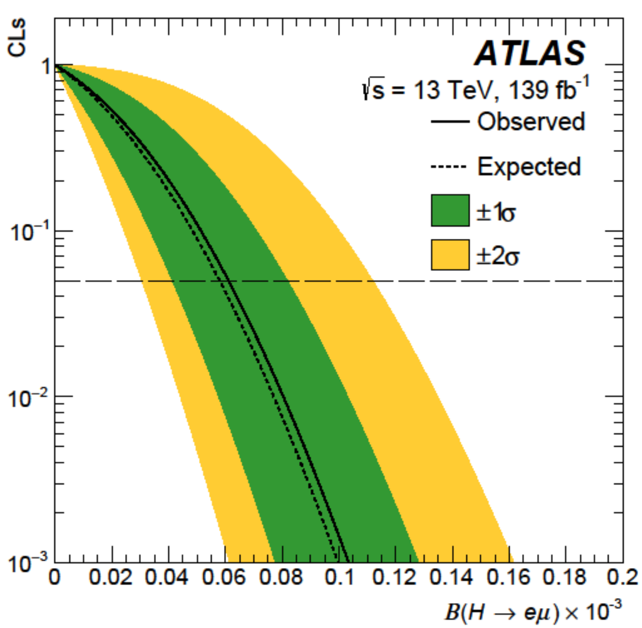
NEW

LFV in $H \rightarrow e^{\pm}\mu^{\mp}$

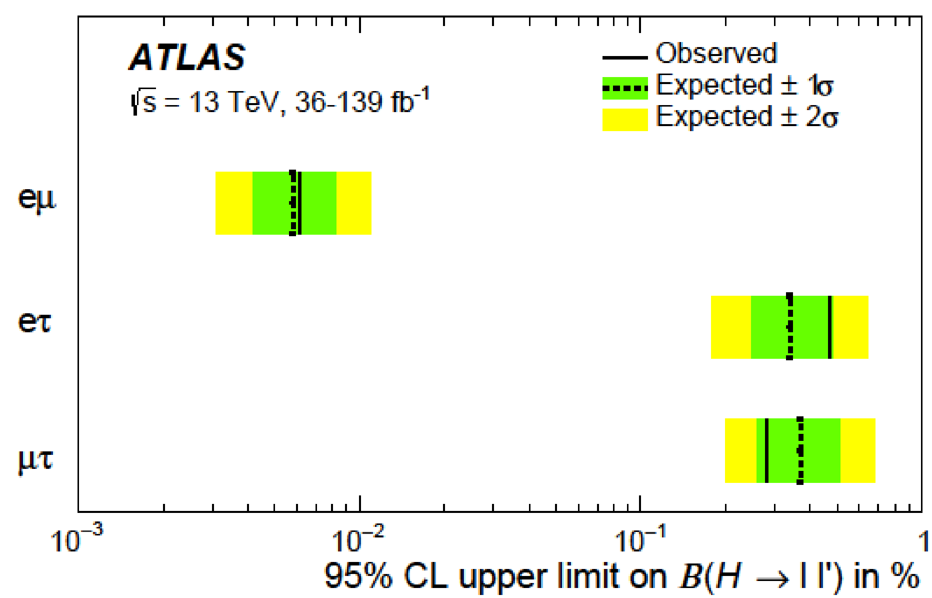
Phys. Lett. B 801 (2020) 135148



- **Signature:** exactly 1e and 1μ with opposite-sign + veto b-jets
- **BKGs:** **$Z/\gamma^* \rightarrow \tau^{\pm}\tau^{\mp} \rightarrow e^{\pm}\mu^{\mp}+\nu$'s, top, diboson, W+jets, multijet**;
- Enhance sensitivity by splitting into 8 categories based on S/B
- Simultaneous binned maximum likelihood fit on $m_{\ell\ell}$ across the 8 categories (Gaussian+Crystal Ball for signal; Bernstein polynomial for background)
- **No evidence of LFV in Higgs to eμ channel**



$B(H \rightarrow e^{\pm}\mu^{\mp}) < 6.1\times10^{-5}$ (5.9×10^{-5}) at 95%CL



NEW

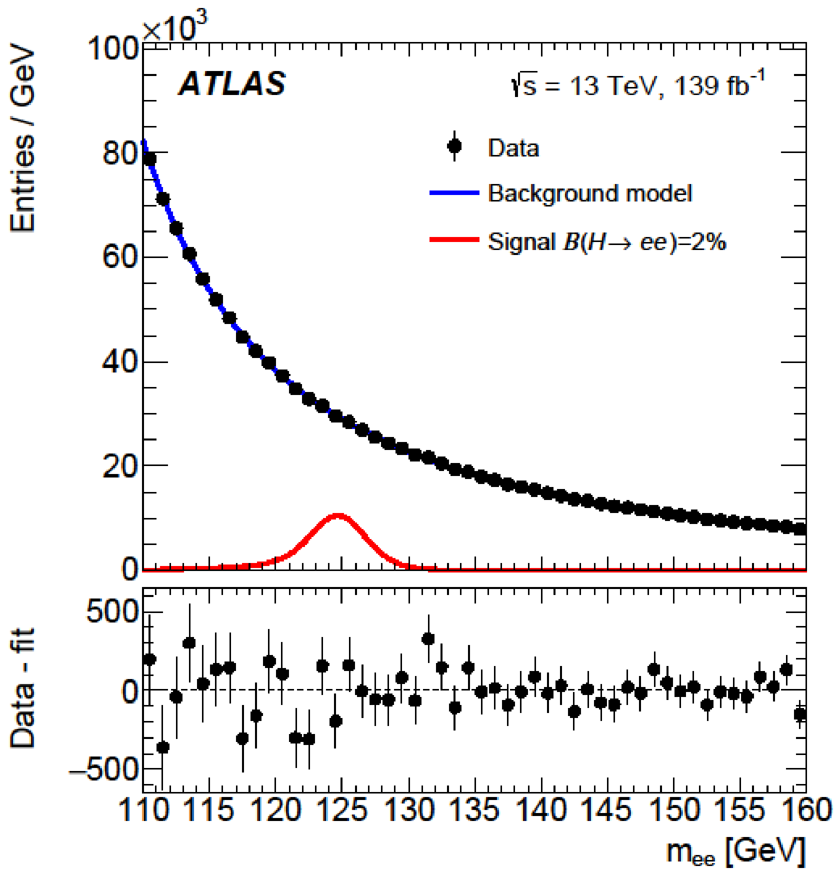
$H \to e^{\pm}e^{\mp}$

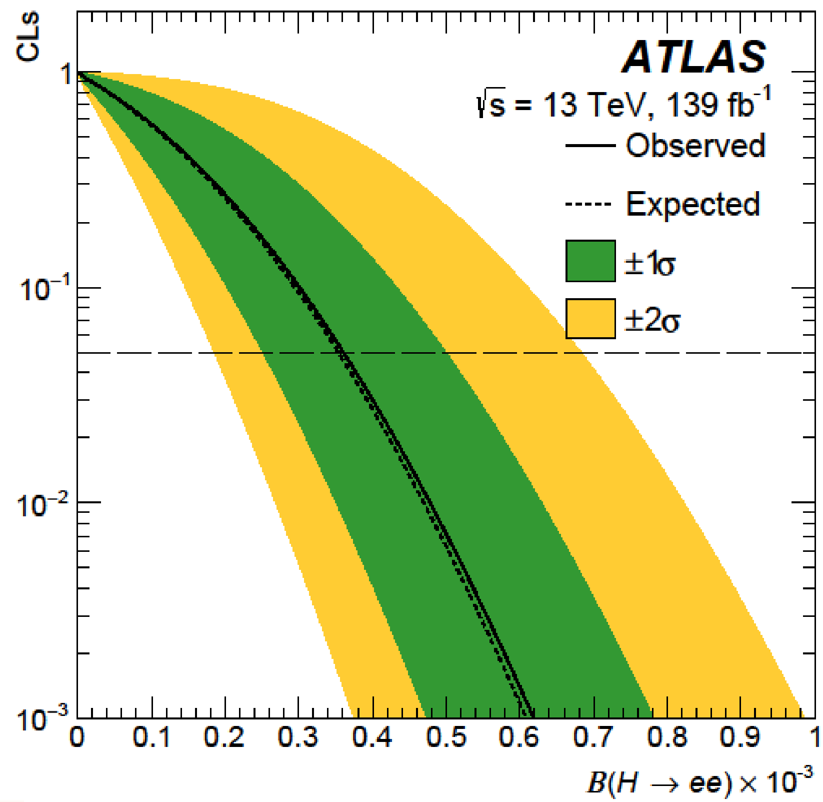
Phys. Lett. B 801 (2020) 135148

- **Enhance sensitivities** by split into 7 categories based on S/B
- Simultaneous binned maximum likelihood fit on $m_{\ell\ell}$ across the 7 categories (a BW convolved with a Gaussian for signal; an exponential divided by a cubic function for BKG)
- The background is dominated by $Z/\gamma^* \to e^{\pm}e^{\mp}$ as expected;
- No observed evidence of the $H \to e^{\pm}e^{\mp}$ decay

$B(H \to e^{\pm}e^{\mp}) < 3.6\times10^{-4}$ (3.5×10^{-4} exp.) at 95%CL

SM predicts $B(H \to e^{\pm}e^{\mp}) \approx 5\times10^{-9}$





Conclusion

- **Signatures of exotic SM Higgs(125) decays are searched for @13TeV by ATLAS with Run 2 dataset. Several new searches are reported.**

- **No significant deviation is observed from the SM background predictions**

- **Still many unexplored regions!**

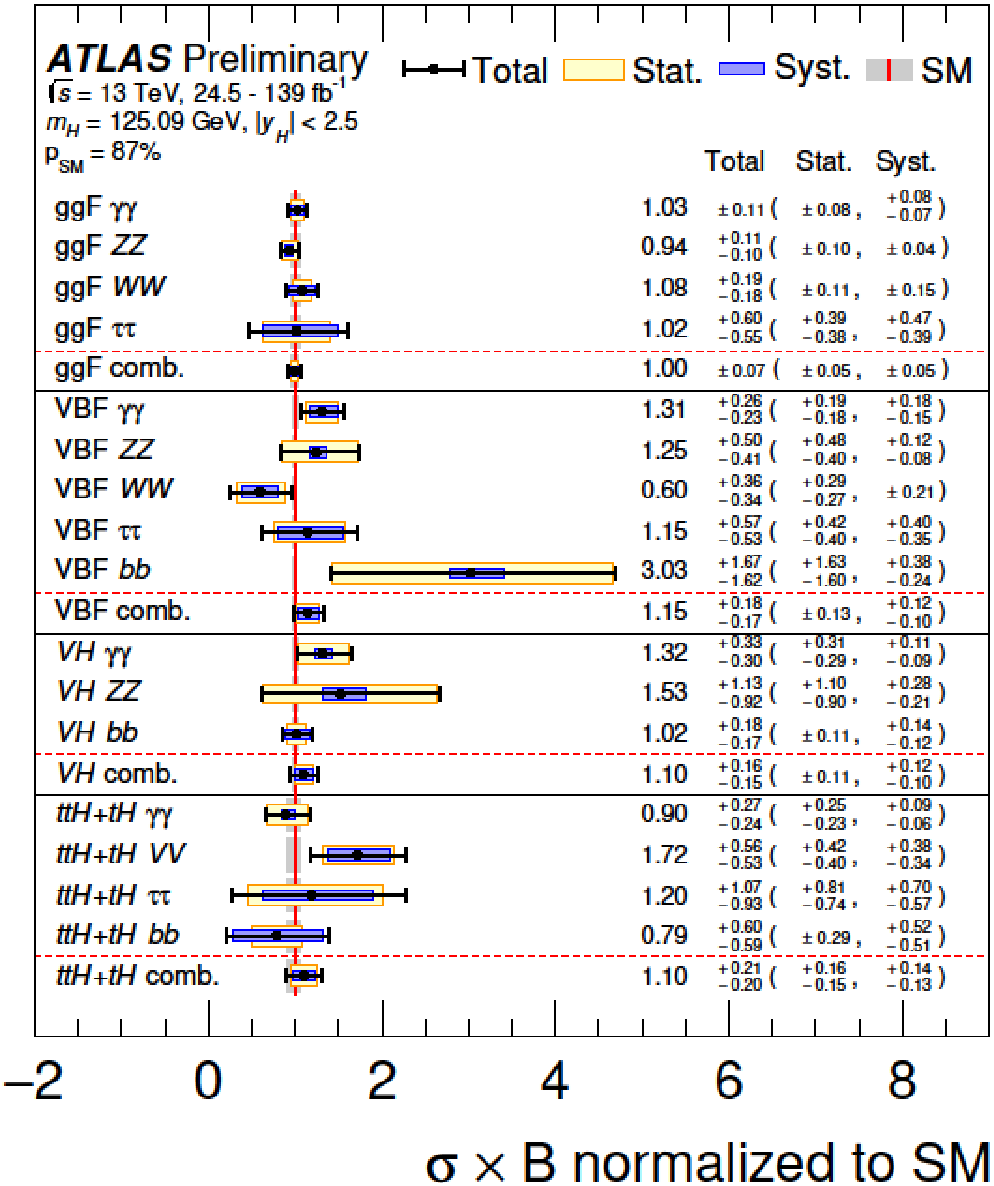
- **Multivariate analysis techniques are being used to enhance sensitivity in searches for new physics. New experiment techniques together with full Run 2 data and future Run 3 data will give us many new exciting results and the potential for new physics discovery.**

Thank you!!!

Backup

Higgs Boson Productions and Decays

ATLAS-CONF-2020-027

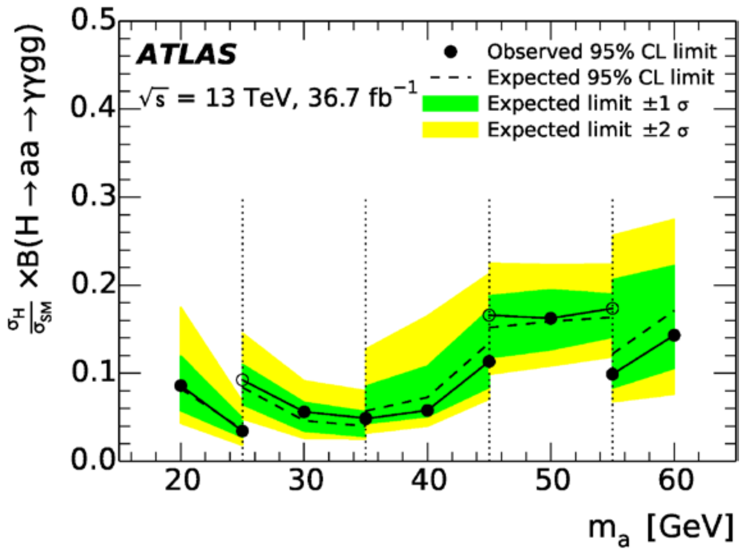


ATLAS SM Higgs cross-section measurements, normalized to SM

➔ No significant deviation from SM observed

Early H→aa Limits @95% CL (13 TeV, 36.1 fb-1)

H→aa→2γ2g: ***Phys. Lett. B 782 (2018) 750***

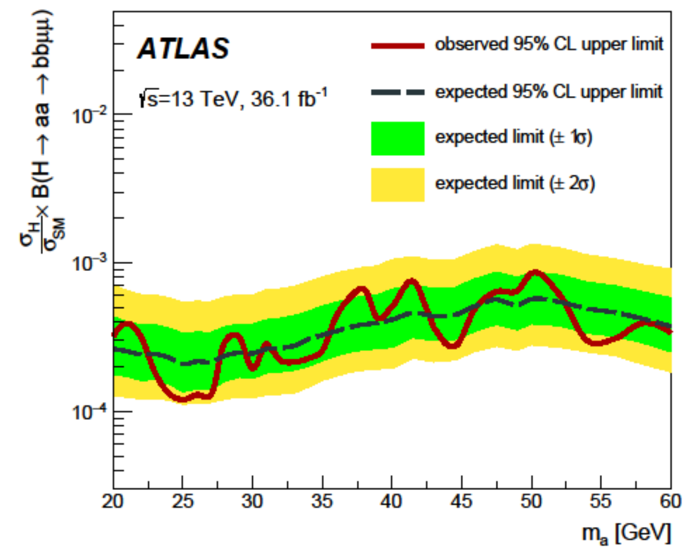


* **Signal:** multi-mass peaks, narrow $m_{2\gamma}$ or $m_{2\mu}$ peak @m_a;

* **2γ2g:** use VBF Higgs production to suppress BKG;

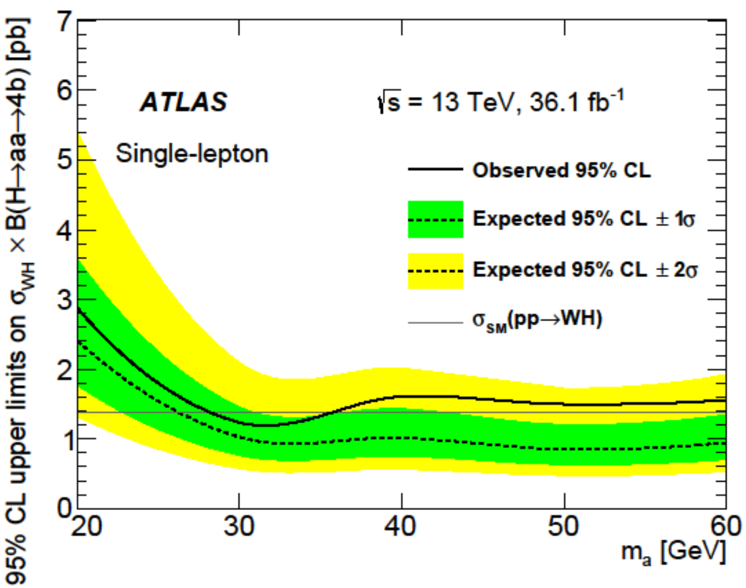
* **2b2μ:** KL fit to enforce the $m_{2b}=m_{2\mu}$ ➔ improves the $m_{2b+2\mu}$ to match m_H

H→aa→2b2μ: ***Phys. Lett. B 790 (2019) 1***



H→aa→4b: ***JHEP 10 (2018) 031***

pp→W±H: σ_{WH}*B(H→aa→4b)

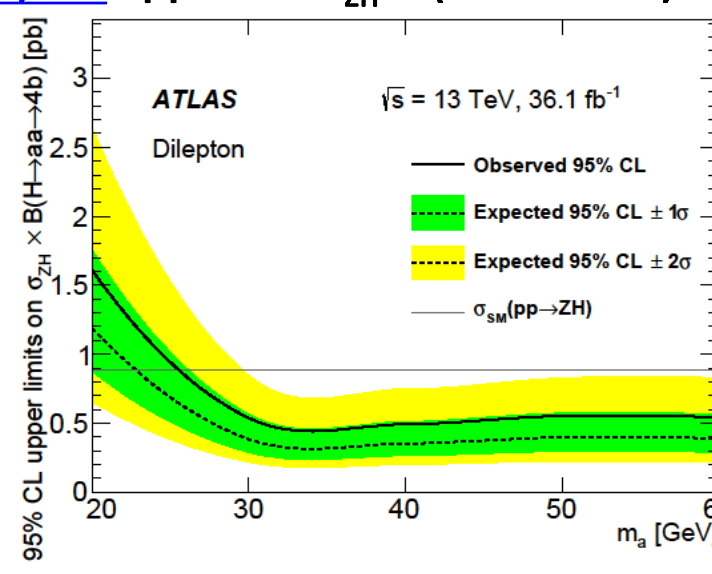


* VH production for triggering & powerful BKG rejections

* **Signal: >= 3 b-jets**

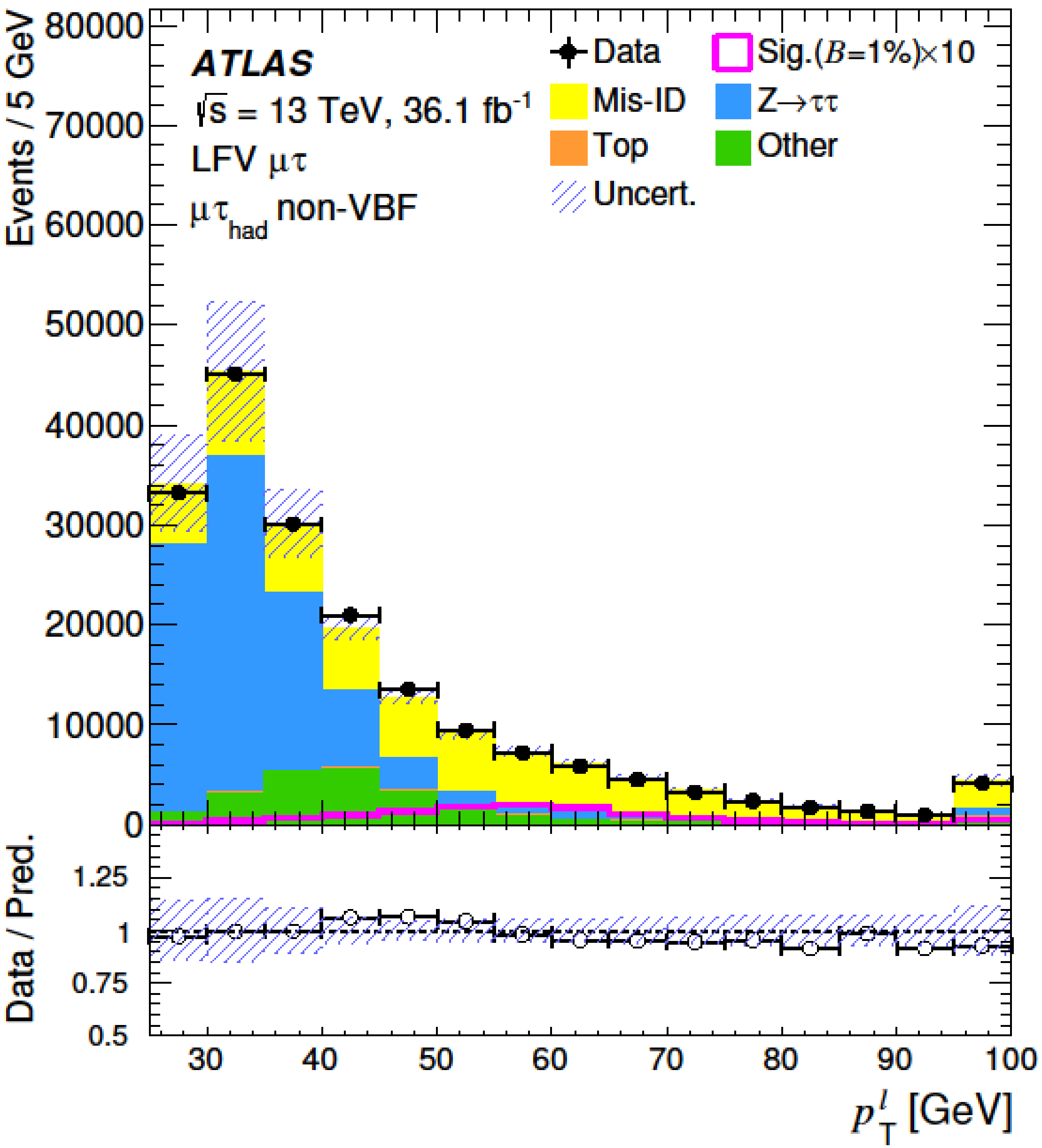
* Separate signal from BKGs with a BDT classifier using jet kinematic + b-tagging information

pp→ZH: σ_{ZH}*B(H→aa→4b)



H→$\mu^{\pm}\tau^{\mp}$: p_T^{ℓ} from $\mu\tau_{had}$ (non-VBF)

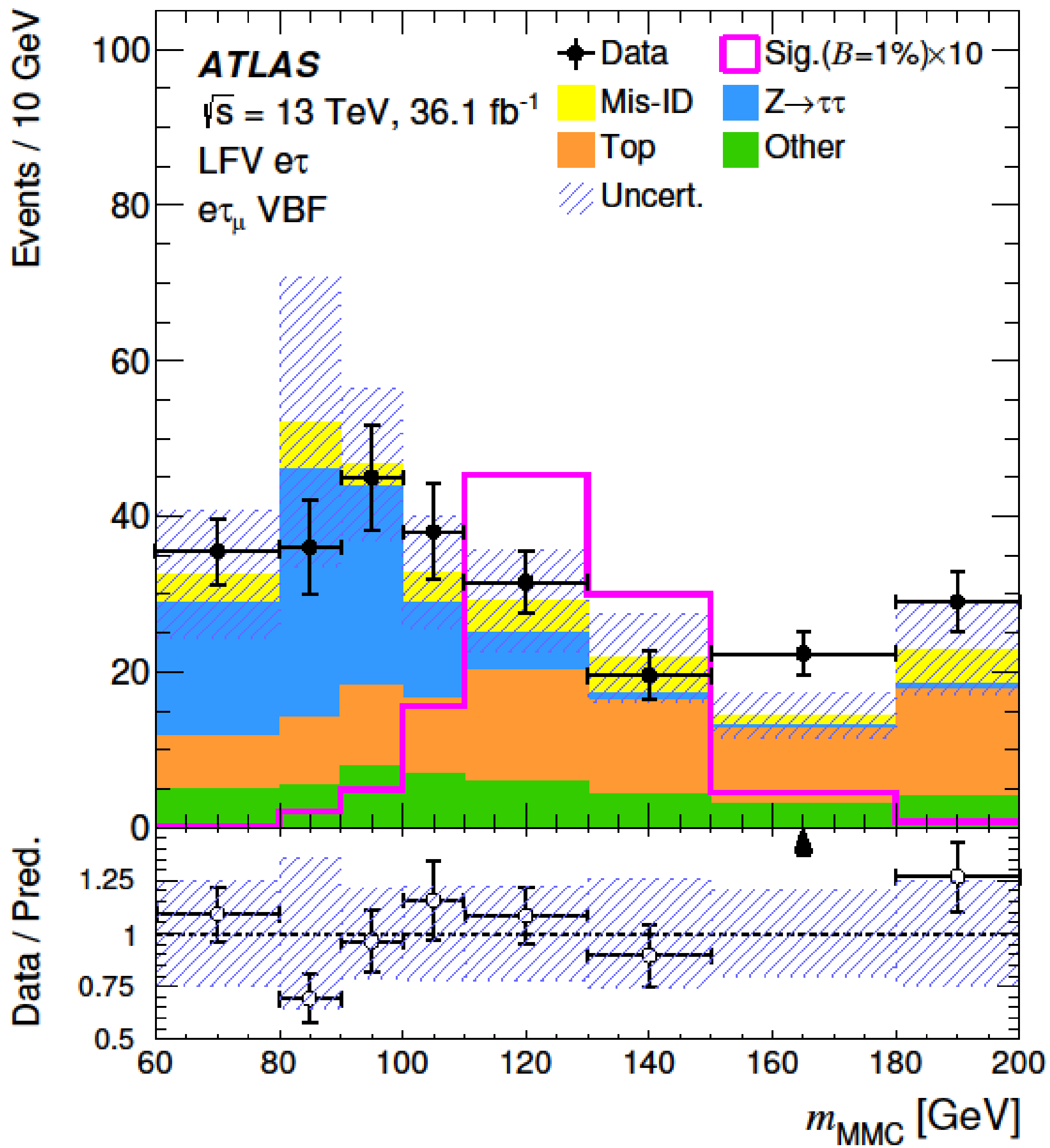
[Phys. Lett. B 800 (2020) 135069]



Z→ττ background

$H \rightarrow e^{\pm}\tau^{\mp}$: m_{MMC} from $e\tau_{\mu}$ (VBF)

Phys. Lett. B 800 (2020) 135069



Top and $Z \rightarrow \tau\tau$ backgrounds

LFV Searches @8TeV in $H \to \ell^{\pm}\tau^{\mp}$

Eur. Phys. J. C 77 (2017) 70

ℓ

$B(H \to e^{\pm}\tau^{\mp}) < 1.04\%$ (1.21% exp.)

$B(H \to \mu^{\pm}\tau^{\mp}) < 1.43\%$ (1.01% exp.)