Higgs boson coupling properties to fermions and search for rare and LFV Higgs boson decays with ATLAS

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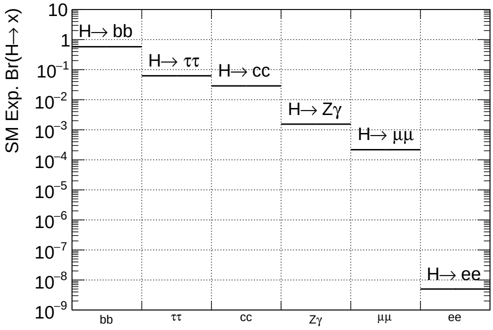
on behalf of the ATLAS collaboration

DIS2024
2024/04/09

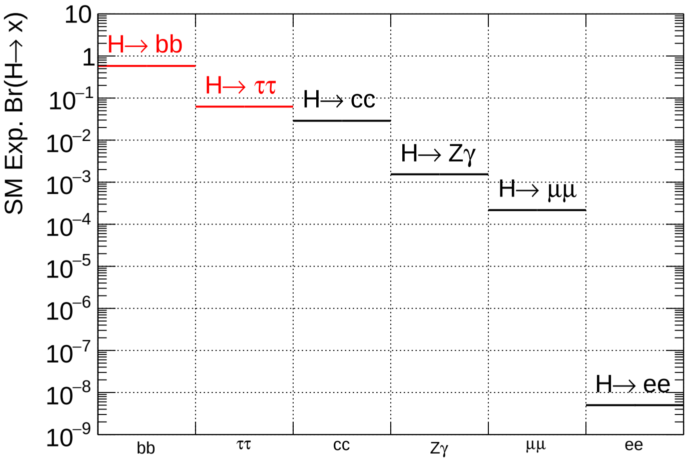
Introduction

- Higgs couplings: important window into SM
  - Connection to EWK symmetry breaking
  - Connection to origin of mass
  - Shed some light into “ad-hoc” fermion sector
- Also a potential handle on BSM physics!
  - New particles change SM branching ratios
  - Some theories posit non-SM couplings
  - Small Higgs width sensitive to small couplings
- Complete picture is very challenging: many orders of magnitudes need probing!
  - Br($H \to bb$) is $10^8 \times$ Br($H \to ee$)
- Today, present a selection of recent results:
  - Higgs coupling to fermions ($bb, \tau\tau, \mu\mu, ee$)
  - Coupling to $Z + \gamma$
  - Lepton flavor violation (LFV) searches

- Today's roadmap

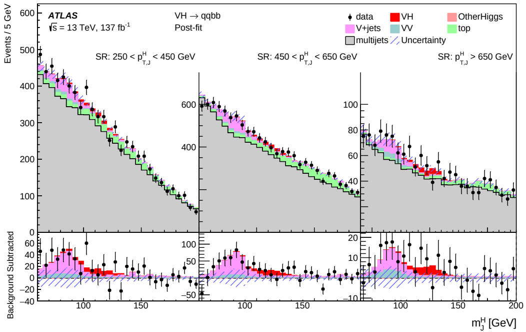


I: Probing deeper with well-established couplings



$V(\to qq)H(\to bb)$: [2312.07605]

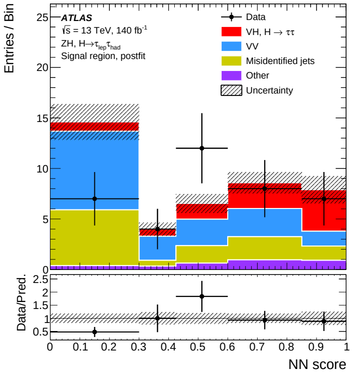
- $H \to bb$ is the largest Higgs branching ratio
- Experimentally well-established, with measurements in many production modes
- Not a rare decay $\implies$ can use it to probe more challenging phase spaces such as boosted $H \to bb$ with an associated hadronically-decaying vector boson

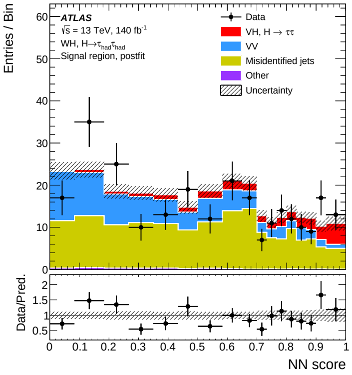


- All-hadronic final state
  - $\mathrm{Br}(V \to qq) > \mathrm{Br}(V \to ll')$ ☺
  - Large irreducible multijet contribution ☹ (fully data-driven estimation!)
- Neural network algorithm used to tag large-radius jets as $H \to bb$
- Results based on fit to Higgs candidate mass
- Signal strength $\mu = 1.4^{+1.0}_{-0.9}$, agrees with SM
- Significance: 1.7σ observed (1.2σ expected)
  - Compared to 2.1σ obs. for $V(\to ll')$ channel
- More details in upcoming talk

$V(\to ll')H(\to \tau\tau)$: [2312.02394]

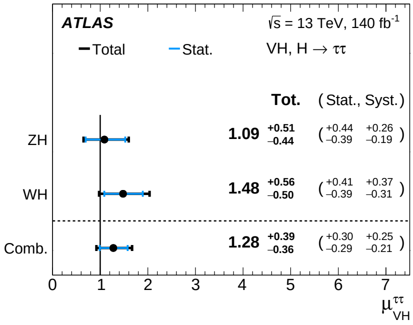
- τ-lepton is the heaviest lepton: Br$(H \to \tau\tau)$ is also large
- Experimentally well-established:
  - Observed in ATLAS in 2015
  - $pp \to H \to \tau\tau$ cross-section measured to $\approx 14\%$ precision in 2022
- 2023: strong evidence for $H \to \tau_{lep}\tau_{had}$ and $H \to \tau_{had}\tau_{had}$ in association with $V \to ll'$ ($l = e/\mu/\nu$)
- Neural network (NN) analysis using a set of classifiers trained on event and particle kinematics



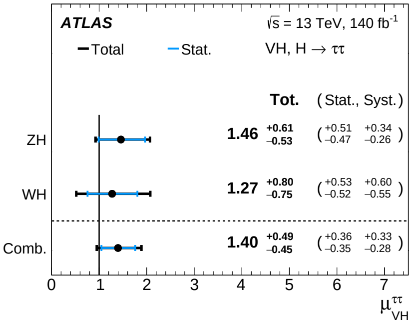


$V(\to ll')H(\to \tau\tau)$: [2312.02394]

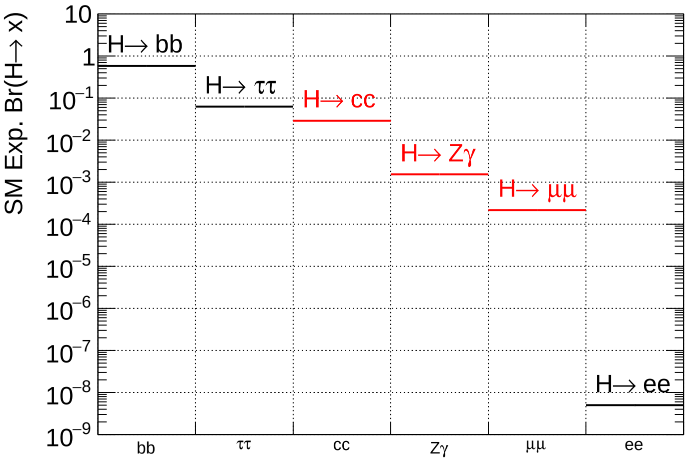
- NN analysis: 4.2σ observed (3.6σ exp.)
- Signal strength compatible with SM



- mass fit (cross-check): 3.5σ obs. (2.5σ exp.)
- Signal strength compatible with SM

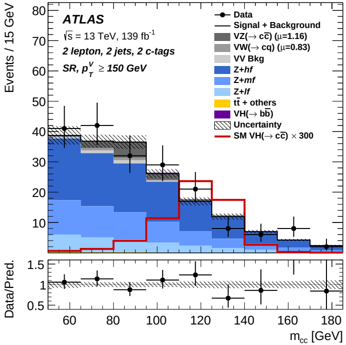


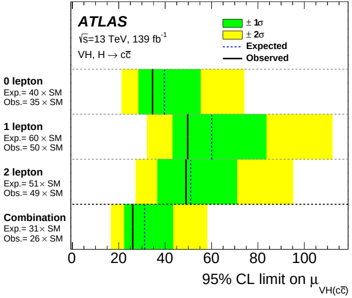
II: Recent developments for challenging couplings



$V(\to ll')H(\to cc)$: Eur. Phys. J. C 82 (2022) 717

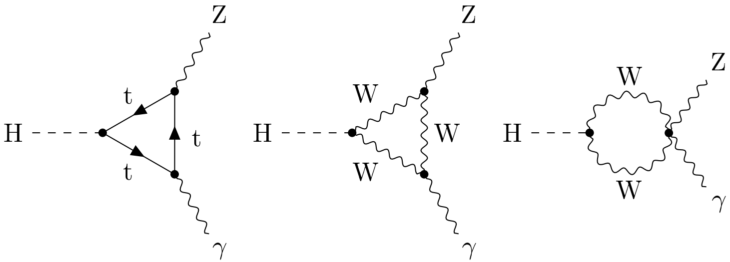
- Br($H \to cc$) is $\approx 3\%$
- However; Signal selection is very challenging
- c-tagging efficiency for this analysis (using DL1) for $c/b/l$ jets is $\approx 27\%/8\%/1\%$
- Best strategy is to trigger on associated $V \to l/l'$ ($l = e/\mu/\nu$) production
- Simultaneous fit to m_{cc} invariant mass distribution in many signal regions to place limit on μ_{VHcc}
- Observed limit: $\mu < 26\times$ SM
- Also determines Br($H \to$ cc) < Br($H \to$ bb) at 95% CL





$H \to Z\gamma$ ATLAS/CMS combination: Phys. Rev. Lett. 132 (2024) 021803

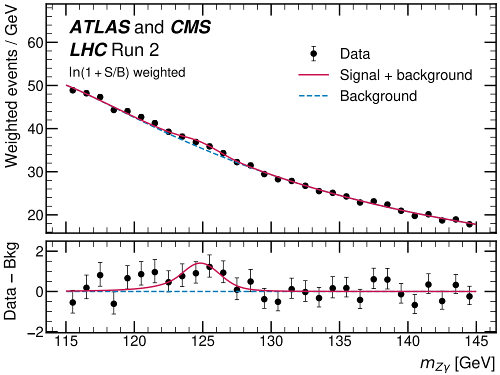
- $Br(H \to Z\gamma) < 1\%$: now firmly into rare decay territory
- One of Higgs decays with no tree-level diagrams: particularly sensitive to many BSM scenarios

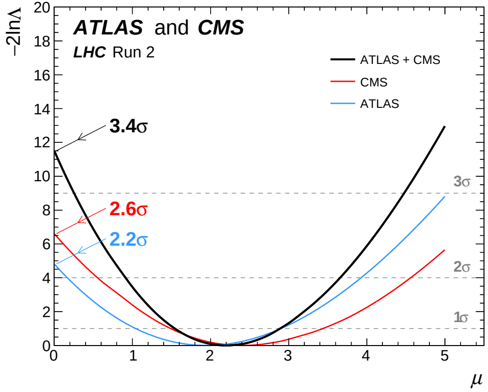


- Combination of two results to obtain strong evidence for this difficult signal
  - ATLAS: Phys. Lett. B 809 (2020) 135754
  - CMS: JHEP 05 (2023) 233
- Both analyses have same overall strategy: Fit peak in $m_{ll\gamma}$ distribution
- Combined using product of ATLAS & CMS likelihoods
  - QCD scale & branching ratio uncertainties are correlated
  - Other theory uncertainties have incompatible models: treated as uncorrelated
  - Experimental uncertainties are uncorrelated as well

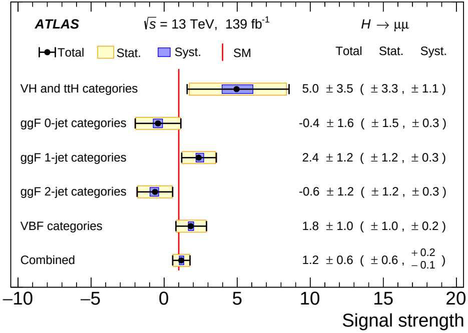
$H \to Z\gamma$ ATLAS/CMS combination: Phys. Rev. Lett. 132 (2024) 021803

- Combination of ATLAS & CMS results
  - ATLAS: 2.2 σ (6 categories)
  - CMS: 2.6 σ (8 categories)
- Strong evidence with 3.4σ significance!
- Measured branching ratio: $(3.4 \pm 1.1) \times 10^{-3}$
- Compatible with SM prediction of $(1.5 \pm 0.1) \times 10^{-3}$ within 1.9σ

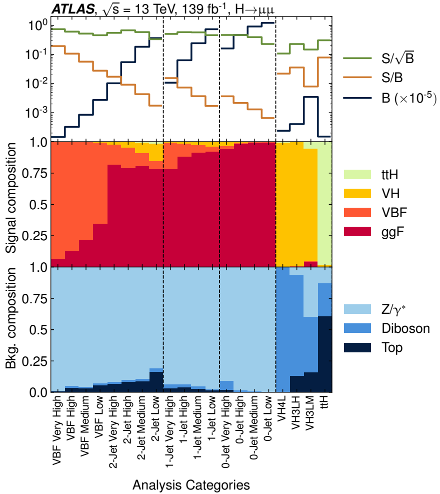




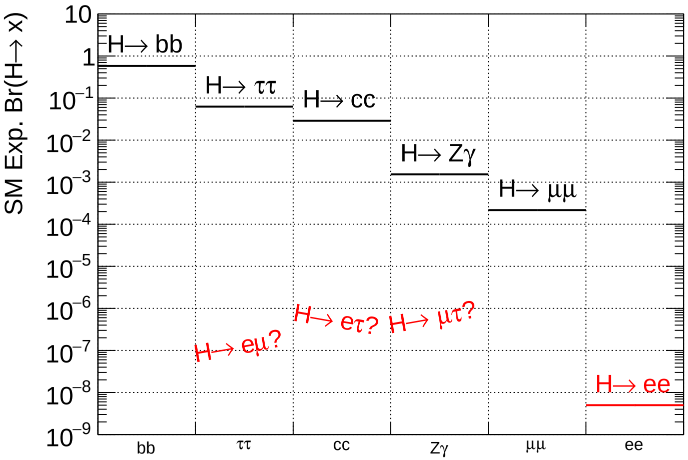
- Dimuon Higgs decay has *sub-permill* branching ratio!
- Very clean final state, but large Drell-Yan background overwhelm the small signal
- Simultaneous fit $m_{\mu\mu}$ in all SR: Excess of 2σ above background-only hypothesis



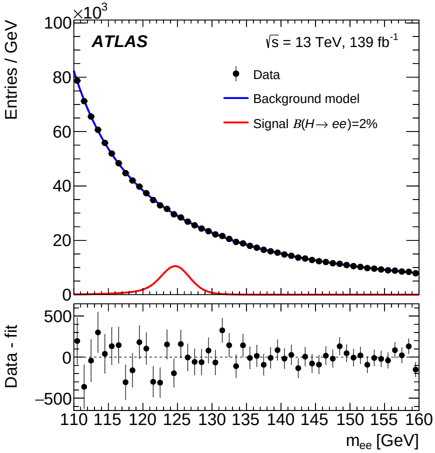
- Using event topology, kinematics, and BDT discriminant: define 20 Signal Regions

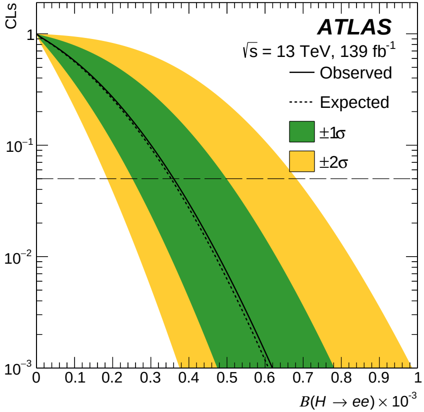


III: Vanishing and BSM couplings



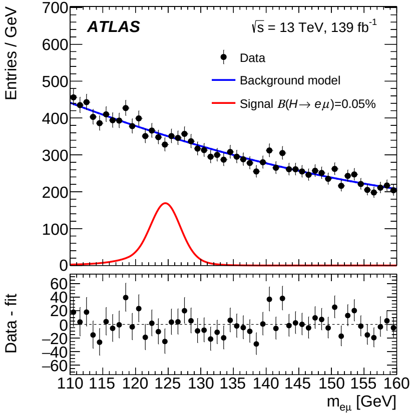
- In SM, $\text{BR}(H \to ee) = G_f m_h m_e^2 / (4\sqrt{2}\pi\Gamma_H) \approx 5 \times 10^{-9}$: *comically small*!
- No chance to observe at LHC, but BSM may be enhance it
- Familiar strategy: Simultaneous fit to m_{ee} distribution in many signal regions
- Observed limit: $\text{BR}(H \to ee) < 3.6 \times 10^{-4}$, i.e. $\approx 72000\times$ SM

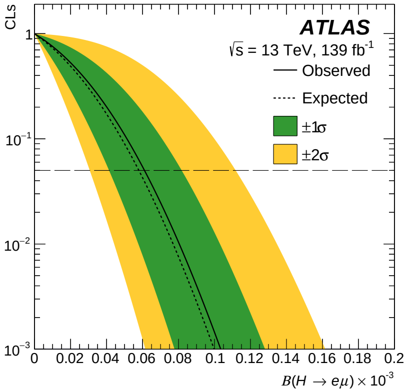




$H \to e\mu$: Phys. Lett. B 801 (2020) 135148

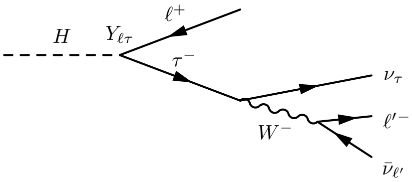
- Lepton flavor violation (LFV) known to be realized in nature through neutrino oscillations
- Not observed as of yet for charged leptons
- LFV not allowed in SM $\implies$ BSM physics
- $H \to e\mu$ search is a natural progression of $H \to ee$: Same strategy but with $m_{e\mu}$ spectrum
- Observed limit: $Br(H \to e\mu) < 6.2 \times 10^{-5}$

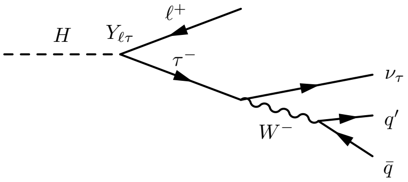




$H \rightarrow l\tau$: JHEP 07 (2023) 166

- Leverage τ-identification capabilities of ATLAS to identify LFV Higgs decays with a τ

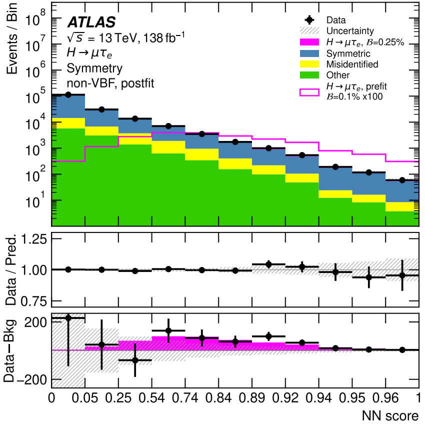


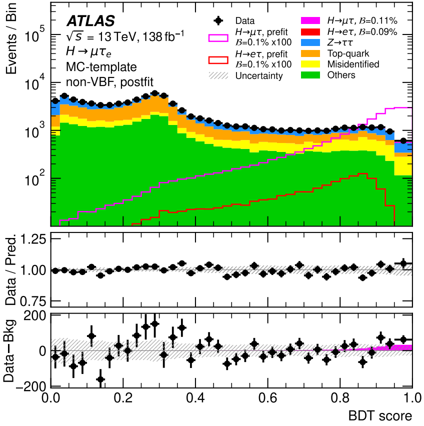


- Leptonic τ channel
- Non-VBF subchannel: Background estimated via MC templates normalized to data
- VBF subchannel: Background estimated by exploiting symmetry between SM prompt lepton backgrounds

- Hadronic τ channel
- Background estimated via MC templates normalized to data

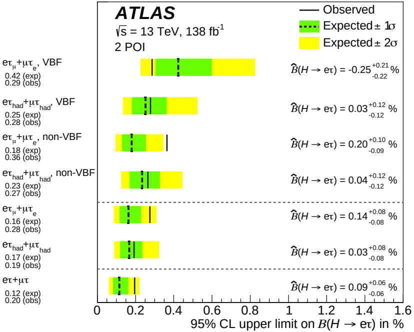
- Two different sets of classifiers used to separate signal from background:
  - Leptonic τ VBF channel: Deep neural network
  - Leptonic τ non-VBF & Hadronic τ channels: A set of BDTs

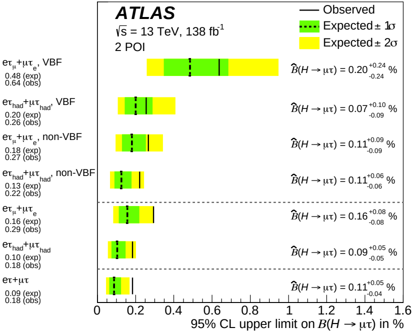




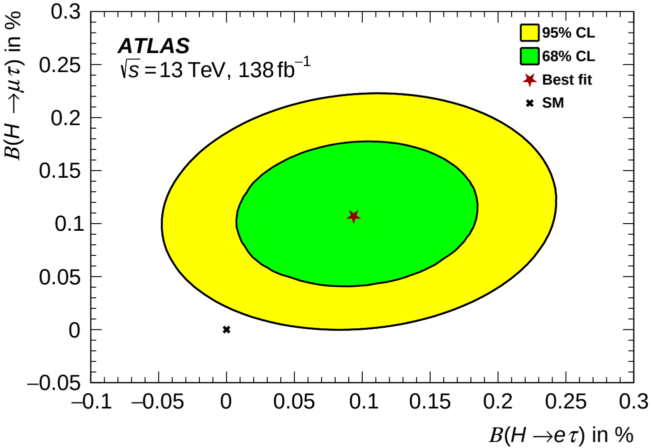
- 2-PoI fit setup allow setting limits on $\mathrm{Br}(H \to e\tau)$ and $\mathrm{Br}(H \to \mu\tau)$ simultaneously
- Both observed limits are at permill level

- Observed: $\mathrm{Br}(H \to e\tau) < 0.2\%$
- Observed: $\mathrm{Br}(H \to \mu\tau) < 0.18\%$





- 2-PoI fit setup allow setting limits on $\mathrm{Br}(H \to e\tau)$ and $\mathrm{Br}(H \to \mu\tau)$ simultaneously
- Can also extract 2D contour for best-fit values of these branching ratios
- SM expectation of (0, 0) slightly outside of 95% CL contour: 2.1σ “excess”
- A fluke, or a sign of an exciting future? The answer is left as an exercise

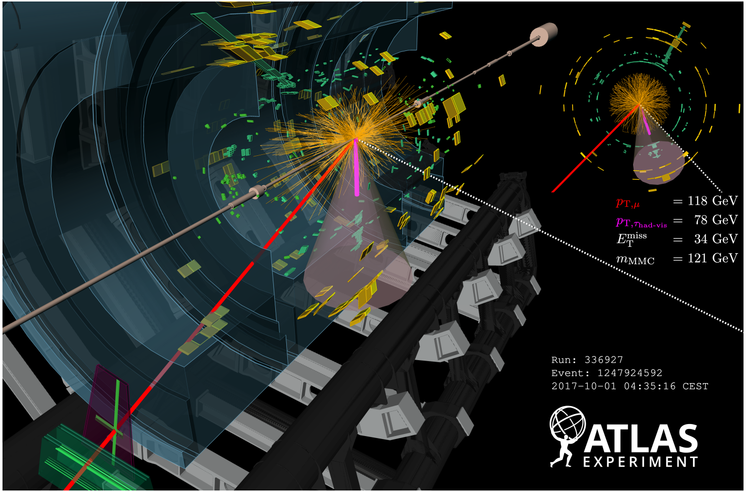


Conclusion

- Presented a selection of results on Higgs coupling properties
- Some couplings are well-established and can be used to probe more challenging final states
  - $V(\to qq)H(\to bb)$: 1.7σ excess over background
  - $V(\to ll')H(\to \tau\tau)$: 4.2σ observation
- Some couplings are inherently more difficult and have either just been observed or are actively being searched for
  - $V(\to ll')H(\to cc)$: $\mu_{VHcc} < 26\times$ SM
  - $H \to Z\gamma$ ATLAS/CMS combination: 3.4σ observation
  - $H \to \mu^+\mu^-$: 2σ excess over background
- Some couplings are vanishing or non-SM, and relevant in a BSM context
  - $H \to ee$: $\mu < 3.6 \times 10^{-4}$
  - $H \to e\mu$: $\mu < 6.2 \times 10^{-5}$
  - $H \to e\tau$: $\mu < 0.2\%$
  - $H \to \mu\tau$: $\mu < 0.18\%$
- This is only a small selection of all the recent ATLAS Higgs results!
- Be on the look out for other interesting talks at DIS2024!

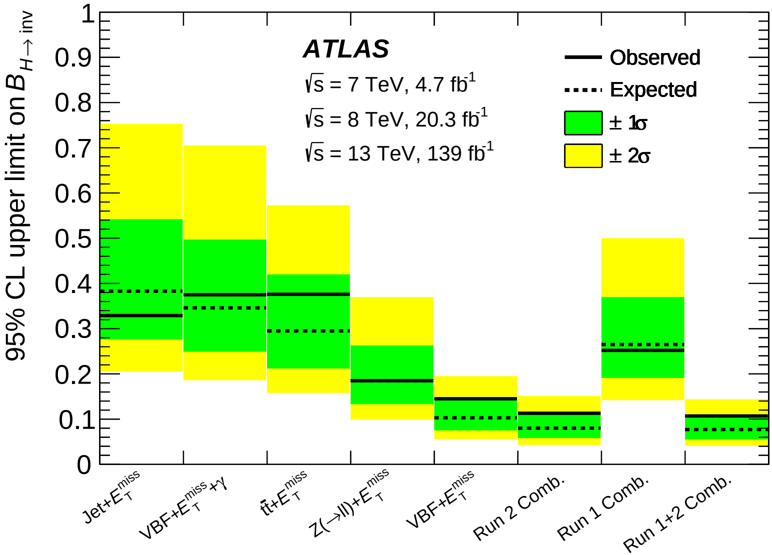
Merci!

Rendering of a $H \to \mu\tau$ candidate event



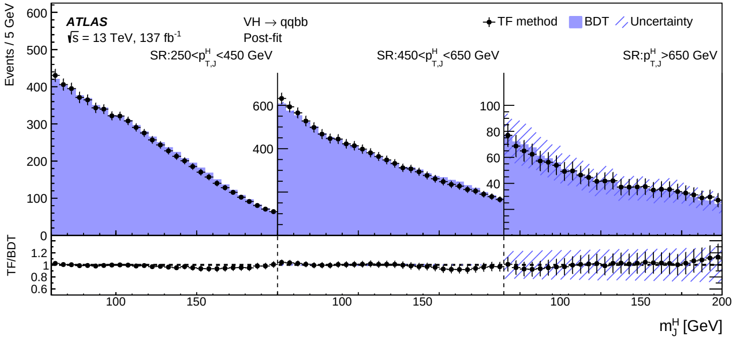
BACKUP SLIDES

What about $H \to$ Invisible? Phys. Lett. B 842 (2023) 137963



$V(\rightarrow qq)H(\rightarrow bb)$: [2312.07605] $\rightarrow$ Multijet background estimation

- Large irreducible QCD multijet background: fully data-driven estimation
- Compute transfer factor between SR & CR, where CR is exactly like CR but with inverted $H \rightarrow bb$ tagging
- $N^{SR}_{multijet}(p_T, m) = TF(p_T, \rho) \times N^{CR}_{multijet}(p_T, m)$
  - $TF(p_T, \rho) = \sum_{k,l} \alpha_{kl} \rho^k p_T^l$
  - $\rho = log(m^{2}/p_T^2)$
- Cross-checked with BDT-based method which reweightes anti-V & anti-H-tagged data



$V(\to ll')H(\to \tau\tau)$: [2312.02394] $\to$ Signal Regions

- Neural network analysis using a collection of classifiers trained on event and particle kinematics
- Total of 6 neural networks trained:
  - One for each of $WH \to \tau_{had}\tau_{had}$, $ZH \to \tau_{had}\tau_{had}$, $ZH \to \tau_{lep}\tau_{had}$
  - One for each of $WH \to \tau_{lep}\tau_{had} \implies \tau \to ee, \tau \to \mu\mu, \tau \to e\mu$

Selection	$WH,\ H \to \tau_{\text{lep}}\tau_{\text{had}}$	$WH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$	$ZH,\ H \to \tau_{\text{lep}}\tau_{\text{had}}$	$ZH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$
Preselection	exactly 1 $\tau_{\text{had-vis}}$ exactly 2 ℓ b-jet veto	exactly 2 $\tau_{\text{had-vis}}$ exactly 1 ℓ b-jet veto	exactly 1 $\tau_{\text{had-vis}}$ exactly 3 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [81, 101]$ GeV	exactly 2 $\tau_{\text{had-vis}}$ exactly 2 ℓ same-flavour, OS ℓ pair $m_{\ell\ell} \in [71, 111]$ GeV
Signal Region	1 $\tau_{\text{had-vis}}$ and 1 τ_{lep} OS exactly 2 ℓ SS $\sum_{\ell} p_{\text{T}}(\ell) + p_{\text{T}}(\tau_{\text{had-vis}}) > 90$ GeV $m_{ee} \notin [80, 100]$ GeV	exactly 2 $\tau_{\text{had-vis}}$ OS $0.8 < \Delta R(\tau_{\text{had-vis}}, \tau_{\text{had-vis}}) < 2.8$ $\sum_{\tau_{\text{had-vis}}} p_{\text{T}}(\tau_{\text{had-vis}}) > 100$ GeV $m_T(\ell, E_T^{\text{miss}}) > 20$ GeV	exactly 1 $\tau_{\text{had-vis}}$ and 1 τ_{lep} OS $\sum_{\tau_{\text{had-vis}}, \tau_{\text{lep}}} p_{\text{T}}(\tau) > 60$ GeV	exactly 2 $\tau_{\text{had-vis}}$ OS $\sum_{\tau_{\text{had-vis}}} p_{\text{T}}(\tau) > 75$ GeV
Higgs boson mass window cut (only applied in the NN-based analysis)	$m_{2\text{T}} \in [60, 130]$ GeV	$m_{2\text{T}} \in [80, 130]$ GeV	$m_{\text{MMC}} \in [100, 170]$ GeV	$m_{\text{MMC}} \in [100, 180]$ GeV

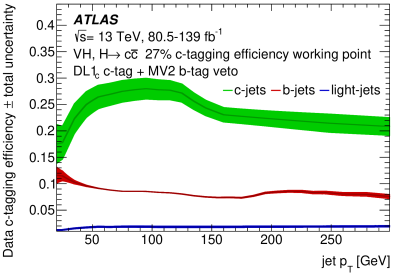
All categories	$ZH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$	$ZH,\ H \to \tau_{\text{lep}}\tau_{\text{had}}$	$WH,\ H \to \tau_{\text{had}}\tau_{\text{had}}$
N-prongs(τ_1)	N-prongs(τ_2)	$p_{\text{T}}(\ell_2)$	N-prongs(τ_2)
$p_{\text{T}}(\tau_1)$	$p_{\text{T}}(\tau_2)$	$\eta(\ell_2)$	$p_{\text{T}}(\tau_2)$
$\eta(\tau_1)$	$\eta(\tau_2)$	$\phi(\ell_2)$	$\eta(\tau_2)$
$\phi(\tau_1)$	$\phi(\tau_2)$	$p_{\text{T}}(H)$	$\phi(\tau_2)$
$\Delta R(\tau_1, \ell_1)$	$p_{\text{T}}(\ell_2)$	$\eta(\ell_\tau)$	$\sqrt{\eta(\ell_1)^2 + \phi(\ell_1)^2}$
$p_{\text{T}}(l_1)$	$\eta(\ell_2)$	$\phi(\ell_\tau)$	
$\eta(\ell_1)$	$\phi(\ell_2)$	$\Delta R(\ell, \ell)$	
$\phi(\ell_1)$	$m_{\ell\ell}$	$m_{\ell\ell}$	
$p_{\text{T}}(E_{\text{T}}^{\text{miss}})$	$\Delta R(\ell, \ell)$		
$\phi(E_{\text{T}}^{\text{miss}})$			

$WH,\ W \to e\nu_e,\ H \to \tau_e\tau_{\text{had}}$	$WH,\ W \to e(\mu)\nu_{e(\mu)},\ H \to \tau_{\mu(e)}\tau_{\text{had}}$	$WH,\ W \to \mu\nu_\mu,\ H \to \tau_\mu\tau_{\text{had}}$
$p_{\text{T}}(\ell_\tau)$	$p_{\text{T}}(\ell_\tau)$	$p_{\text{T}}(\ell_\tau)$
$\eta(\ell_\tau)$	$\eta(\ell_\tau)$	$\eta(\ell_\tau)$
$\phi(\ell_\tau)$	$\phi(\ell_\tau)$	$\phi(\ell_\tau)$
$\Delta\eta(\ell, \ell_\tau)$	$\Delta\eta(\ell, \ell_\tau)$	$\Delta\eta(\ell, \ell_\tau)$
jet width(τ_1)	jet width(τ_1)	jet width(τ_1)
$p_{\text{T}}(H)$	$m(\tau_1, \ell_\tau)$	$\Delta R(\ell, \ell_\tau)$
$m(\tau_1, \ell_\tau)$	$\Delta R(\ell, \ell_\tau)$	$m(\tau_1, l_\tau)$
$\Delta\eta(\tau_1, \ell_\tau)$	$\Delta\eta(\tau_1, \ell_\tau)$	$\Delta\eta(\tau_1, \ell_\tau)$
$\Delta\phi(l_1, \ell_\tau)$	$\sum p_{\text{T}}$(all visible)	$\Delta R(\tau_1, \ell_\tau)$
$\Delta_\phi(\tau_1,\ E_{\text{T}}^{\text{miss}})$	$\Delta\phi(\tau_1, E_{\text{T}}^{\text{miss}})$	$\sum p_{\text{T}}$(all visible)
$\Delta R(\ell, \ell_\tau)$		$\Delta\phi(\ell_1, \ell_\tau)$

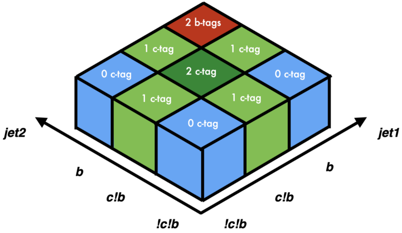
- Trained w/ Keras + Tensorflow backend
- Two initial transformation layers to enforce ϕ-invariance
- Three fully-connected layers w/ 128 nodes, ReLU activation
- Output: single node, sigmoid activation

$V(\to ll')H(\to cc)$: Eur. Phys. J. C 82 (2022) 717 $\to$ charm tagging

- Charm tagging rates for different jet flavors:
  - c-jets: $\approx$ 20–27% efficiency
  - b-jets: $\approx$ 10% mistag rate
  - light jets: $\approx$ 1% mistag rate



- Charm tagging strategy for 2-jet events
  - $= 2$ c-tag signal
  - Also use $= 1$ c-tag to increase acceptance

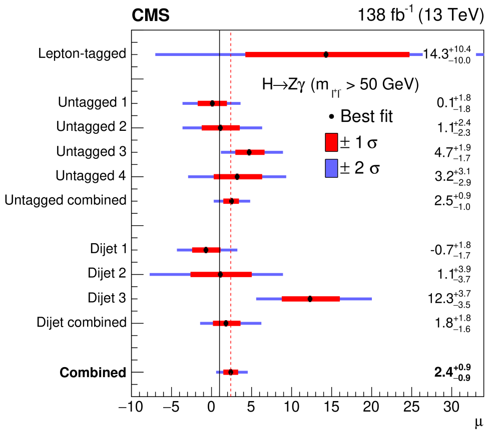


credit: M. Stamenkovic

- ATLAS: Phys. Lett. B 809 (2020) 135754

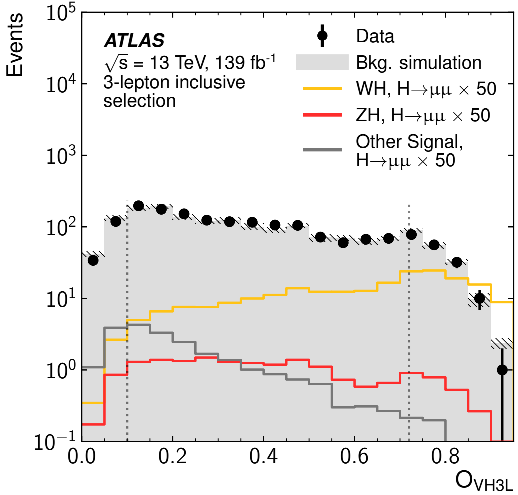
Category	μ	Significance
VBF-enriched	$0.5^{+1.9}_{-1.7}$ $(1.0^{+2.0}_{-1.6})$	0.3 (0.6)
High relative p_T	$1.6^{+1.7}_{-1.6}$ $(1.0^{+1.7}_{-1.6})$	1.0 (0.6)
High p_{Tt} ee	$4.7^{+3.0}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.7 (0.4)
Low p_{Tt} ee	$3.9^{+2.8}_{-2.7}$ $(1.0^{+2.7}_{-2.6})$	1.5 (0.4)
High p_{Tt} $\mu\mu$	$2.9^{+3.0}_{-2.8}$ $(1.0^{+2.8}_{-2.7})$	1.0 (0.4)
Low p_{Tt} $\mu\mu$	$0.8^{+2.6}_{-2.6}$ $(1.0^{+2.6}_{-2.5})$	0.3 (0.4)
Combined	$2.0^{+1.0}_{-0.9}$ $(1.0^{+0.9}_{-0.9})$	2.2 (1.2)

- CMS: JHEP 05 (2023) 233

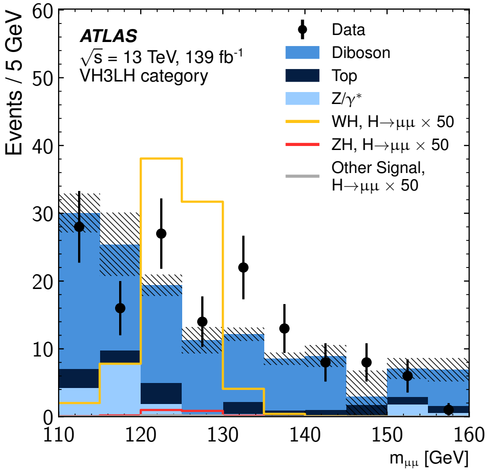


$H \to \mu^+\mu^-$: Phys. Lett. B 812 (2021) 135980 → Example BDT

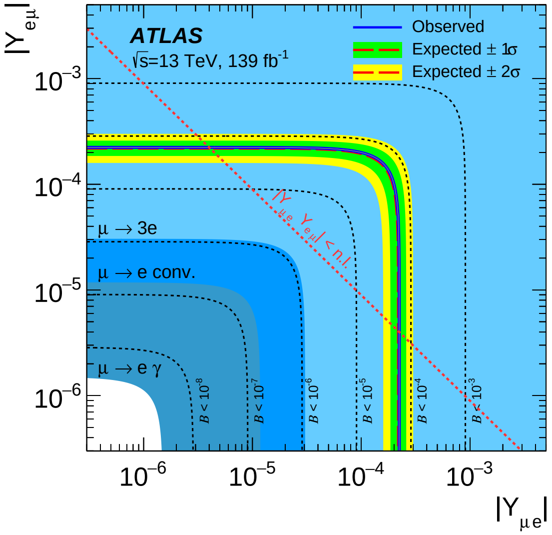
- Example BDT output for *VH*/3*l* categories



- Example mass spectrum for *VH*/3*l*-H SR



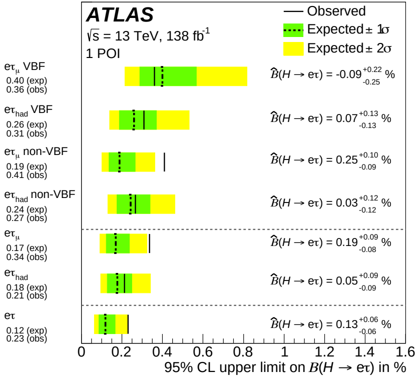
$H \to e\mu$: Phys. Lett. B 801 (2020) 135148 $\to Y_{e\mu}$–$Y_{\mu e}$ constraint



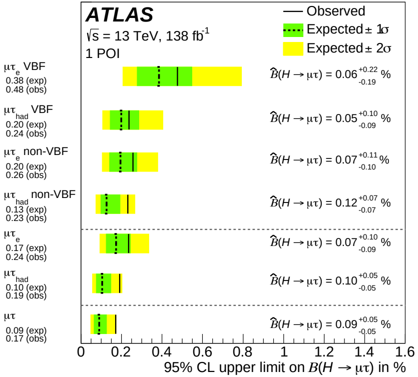
$H \to l\tau$: JHEP 07 (2023) 166 $\to$ 1-PoI results

- 1-PoI fit setup allow setting limits on $\mathrm{Br}(H \to e\tau)$ and $\mathrm{Br}(H \to \mu\tau)$ separately
- Assume $\mathrm{Br}(H \to e\tau) = 0$ when fitting $\mathrm{Br}(H \to \mu\tau)$ and vice-versa

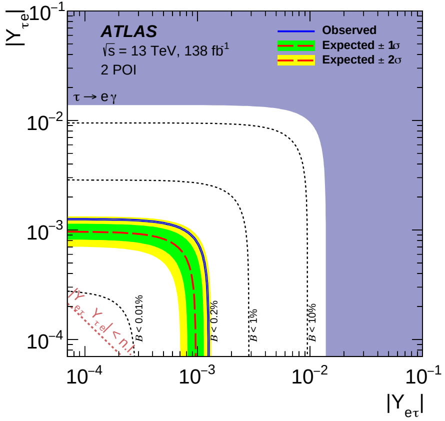
- Observed: $\mathrm{Br}(H \to e\tau) < 0.23\%$

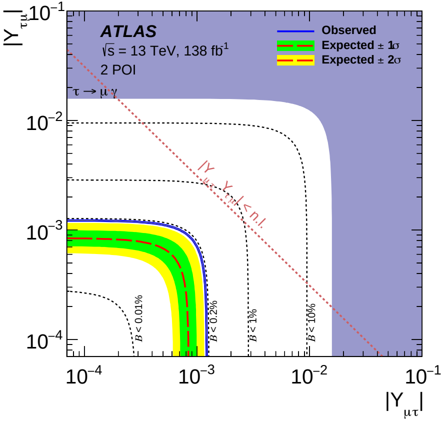


- Observed: $\mathrm{Br}(H \to \mu\tau) < 0.17\%$



$H \to l\tau$: JHEP 07 (2023) 166 $\to$ $Y_{l\mu}$–$Y_{\mu l}$ constraints





$t \to qH$: JHEP 12 (2023) 195