BSM Higgs searches (ATLAS)

First Workshop on the Impact of Higgs Studies on New Theories of Fundamental Interactions

Villa Orlandi, Anacapri, Capri Island, ITALY 06-10.10.2025

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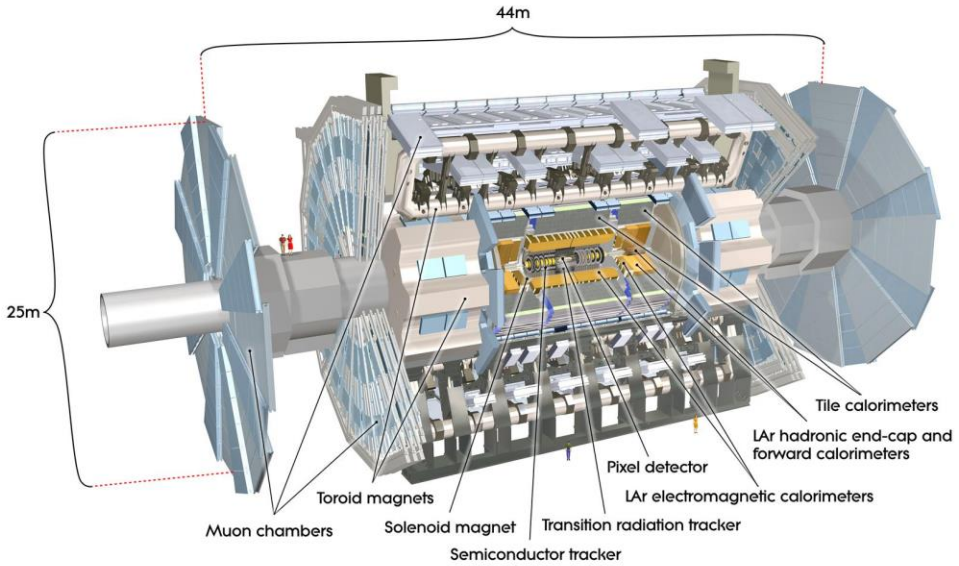
(Institute of Nuclear Physics P.A.N., Cracow PL)

Foreword

- By no means expect a big picture of BSM searches in the scalar sector
- Merely a selection of latest results from ATLAS

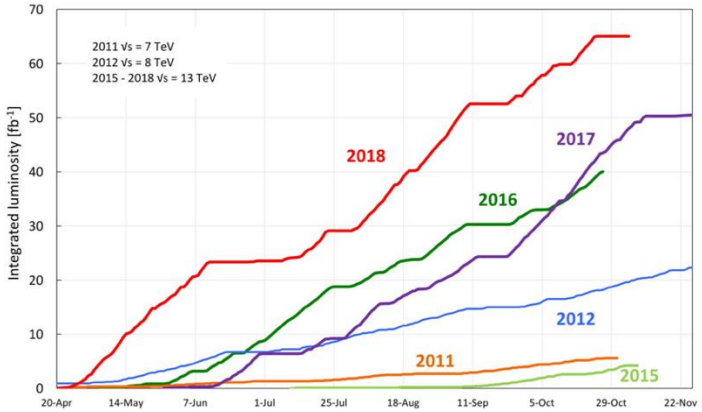


What's on the menu for today:

1. Searches for singly charged Higgs,
2. Searches for heavy or light (pseudo)scalars,
3. Exotic Higgs125 decays and ALP searches.

Note: all except one result use 140 fb^{-1} of Run 2 *pp* data

140 fb^{-1} of Run 2 data still in the game!



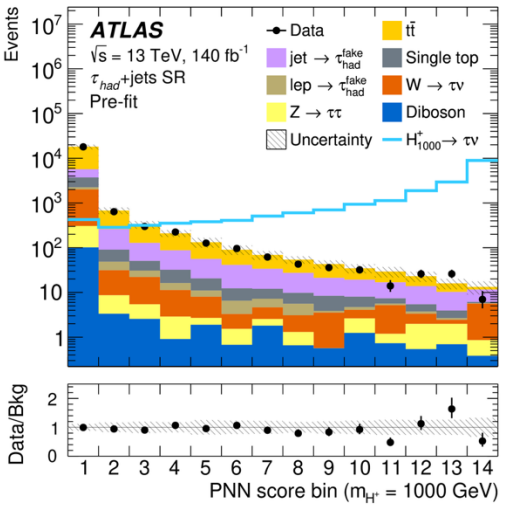
Searches for singly charged Higgs

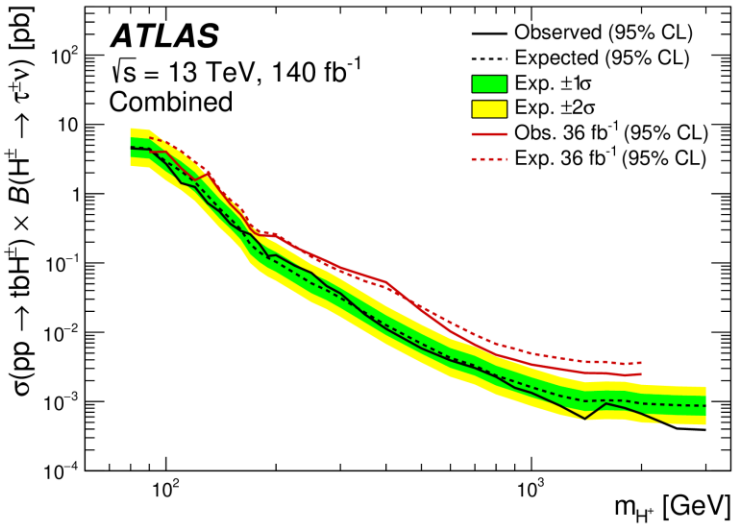
1. $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ Phys. Rev. D 111 (2025) 072006
2. $H^{\pm} \to cs$ Eur. Phys. J. C 85 (2025) 153
3. $H^{\pm} \to Wh$ JHEP 02 (2025) 143

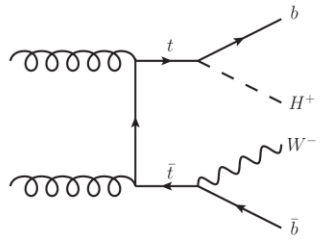
Search for singly charged Higgs decaying via $H^{\pm} \to \tau^{\pm}\nu_{\tau}$

Phys. Rev. D 111 (2025) 072006

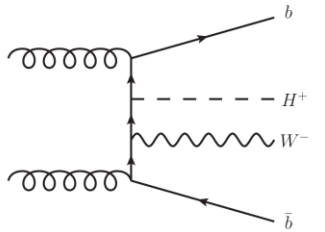
- Dominates at high tanβ (2HDM II) and $m_{H^+} < m(t)$
- Search in the range $80GeV < m_{H^+} < 3TeV$
- Two final states: $\tau_{\text{had}} + MET + \text{jets}$ & $\tau_{\text{had}} + MET + \text{lepton}$
- PNN discriminant based predominantly on $m^{T}_{H^+}$, p_T & direction of final state objects, τ polarization (ϒ)
- Prompt τ background (mainly $t\bar{t}$) from MC reweighted to data in CR region ($m_{eff} = \sum p_T + E_T^{miss}$)
- Jets faking τ bkg. estimated with Fake Factor method.



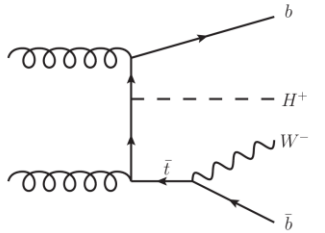




$m(H^{\pm}) < m(t)$



$m(H^{\pm}) \approx m(t)$



$m(H^{\pm}) > m(t)$

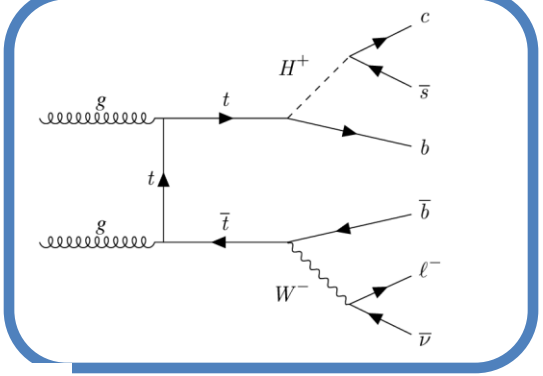
95% CL on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(t \to H^{\pm}b)$ from 4.5 pb to 0.4 fb; most stringent limit on $\sigma \times \mathcal{B}$ in this channel (x2-4 improvement)

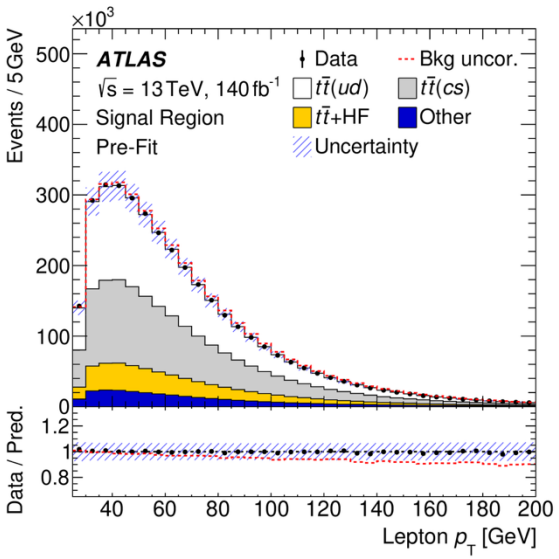
Search for light charged Higgs decaying via $H^{\pm} \to cs$

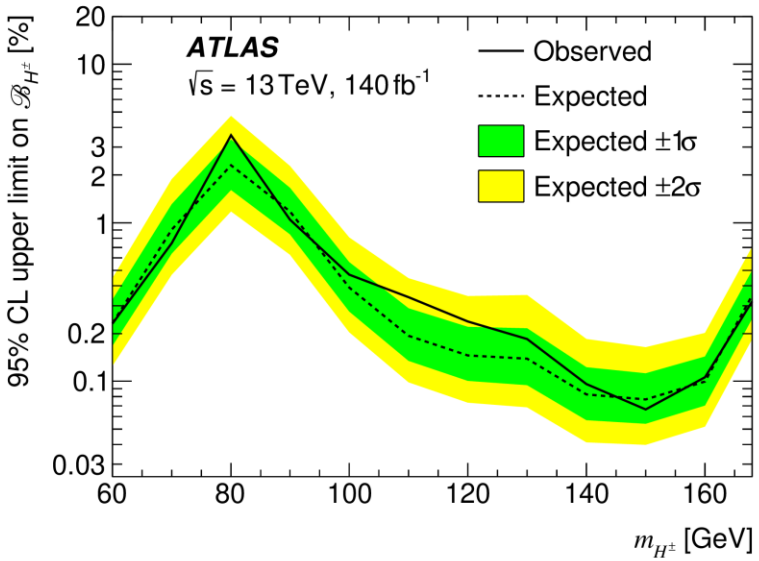
See talk from **Sezen Sekmen**

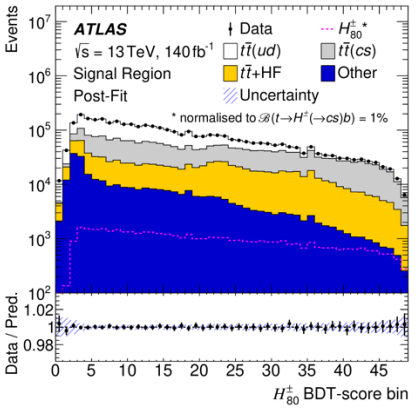
Eur. Phys. J. C 85 (2025) 153

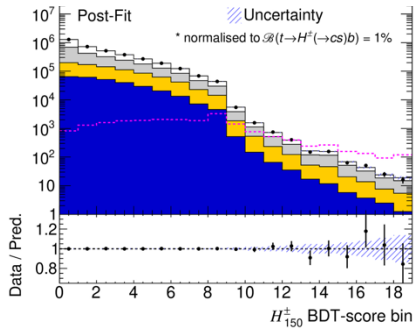
- Relevant in 2HDM Type-I, Type-II for low tanβ, etc.,
- Search in the range $60\ GeV < m_{H^+} < 168\ GeV$
- BDT discriminant based predominantly on kinematical variables sensitive to m_{H^+} and deep NN jet-flavour tagging (*b*,*c*,light).
- $t\bar{t}$ background and signal MC reweighted to data in the signal region ($S_T = \sum p_T$) in the bins of N_{jets}.











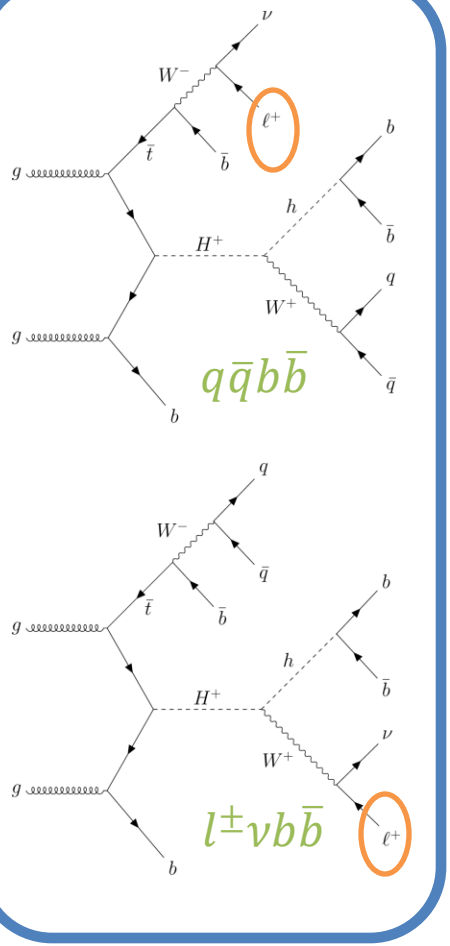
95% CL on $\mathcal{B}(t \to H^{\pm}b)$ from 0.066% to 3.6% (first time for 60 and 70 GeV and the most stringent between 120 and 160 GeV).

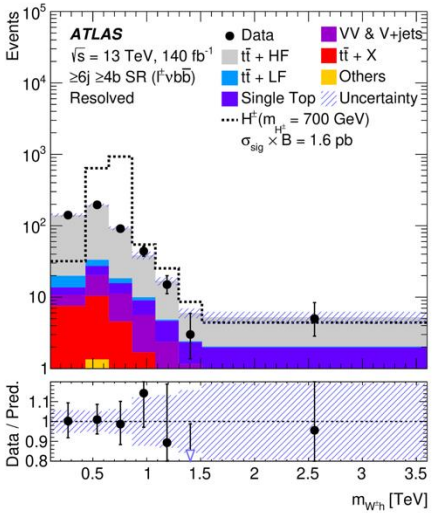
Search for heavy charged Higgs decaying via $H^{\pm} \to Wh$

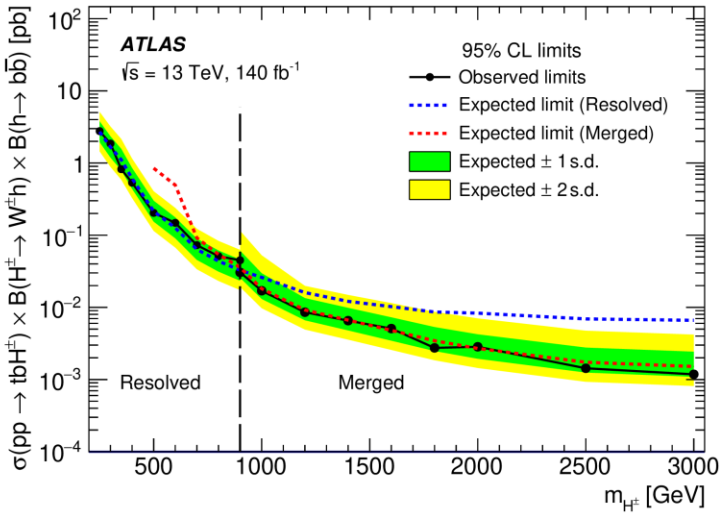
- Expected e.g. in N2HDM, 3HDM or G-M models.
- Search in the range $250GeV < m_{H^+} < 3\,TeV$
- $h \to b\bar{b}$; Final state consistent with $l^{\pm}b\bar{b}b\bar{b}q\bar{q}$, triggered by a single lepton. $b\bar{b}$ reconstructed as two **resolved** jets or **merged** into one large-radius jet.
- Backgrounds modelled with MC and normalised in the fit.
- Main uncertainty: $t\bar{t}$ modelling (stats.) for low (high) $m_{H^{\pm}}$.

See talk from **Sezen Sekmen**

JHEP 02 (2025) 143







95% CL on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to W^{\pm}h)\mathcal{B}(h \to b\bar{b})$ from 2.8 pb (250 GeV) to 1.2 fb (3 TeV) - first search at LHC.

Searches for heavy or light (pseudo)scalars

1. $X \to SH_{125} \to b\bar{b}\gamma\gamma$ ATLAS-CONF-2025-009
2. $(t\bar{t})a \to (l^+l^-X)b\bar{b}$ Eur. Phys. J. C 85 (2025) 886
3. $S \to Z_d Z_d \to 4l$ Phys. Lett. B 865 (2025) 139472

For details of **1** see talk from **Giulia Di Gregorio**

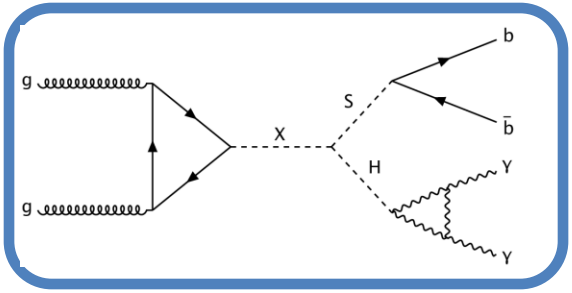
Heavy resonance decaying into a scalar particle and a Higgs

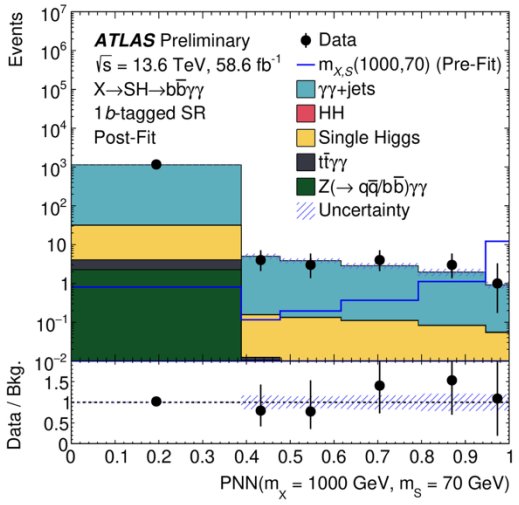
- Generic search targeting 2HDM type models or SM extended by singlets with at least 2 DoF's.
- $170 \leq m_X \leq 1000\ GeV$ and $15 \leq m_S \leq 500\ GeV$
- Update to JHEP 11 (2024) 047 based on Run 2 data.
- **Selection**: di-photon triggers, 2 photon mass consistent with H_{125} [122.5,127.5], exactly one b-jet ($1b$ SR) or exactly 2 b-jets ($2b$ SR),
- $\gamma\gamma$+jets background normalised from $m_{\gamma\gamma}$ side bands,
- PNN discriminant (m_X, m_S).

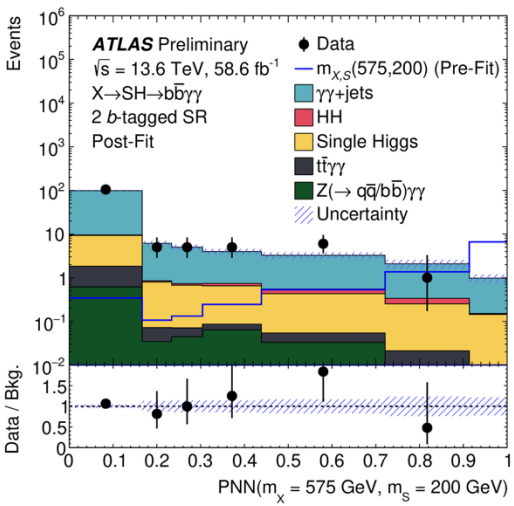
See talks from **Greg Landsberg** and **Giulia Di Gregorio**

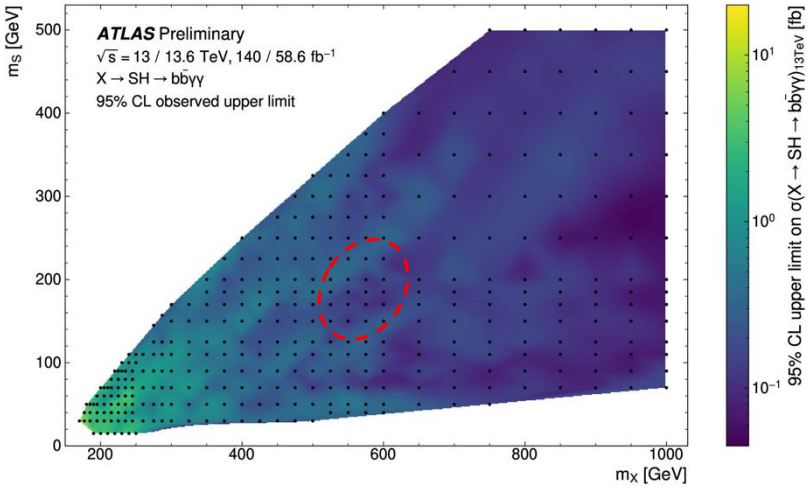
ATLAS-CONF-2025-009

140.0 fb^{-1} @**13.0** TeV
+ **58.6** fb^{-1} @**13.6** TeV









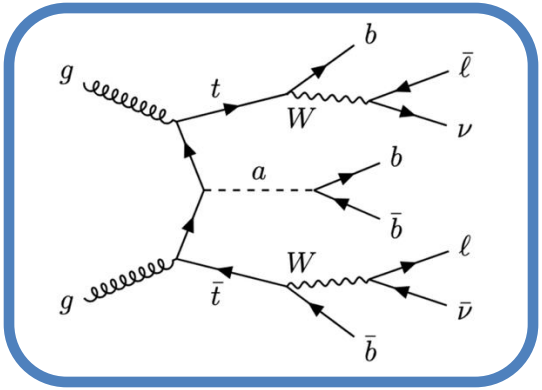
No significant excess observed. 95% CL on $\sigma(X \to SH_{125} \to b\bar{b}\gamma\gamma)$ @13 TeV (9 – 0.06 fb)
(575, 200) $3.5(2.0)\sigma$ excess NOT confirmed with improved analysis and additional statistics.

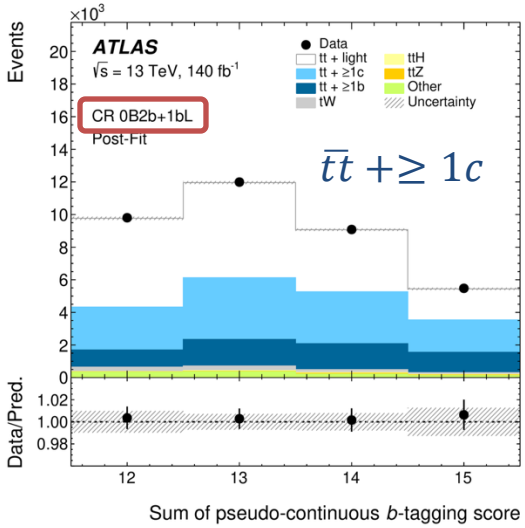
Top-associate production of pseudoscalar decaying into $b\bar{b}$

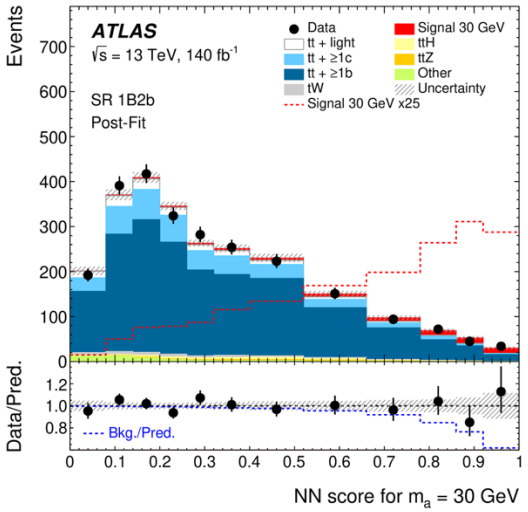
See also talk from **Sezen Sekmen**

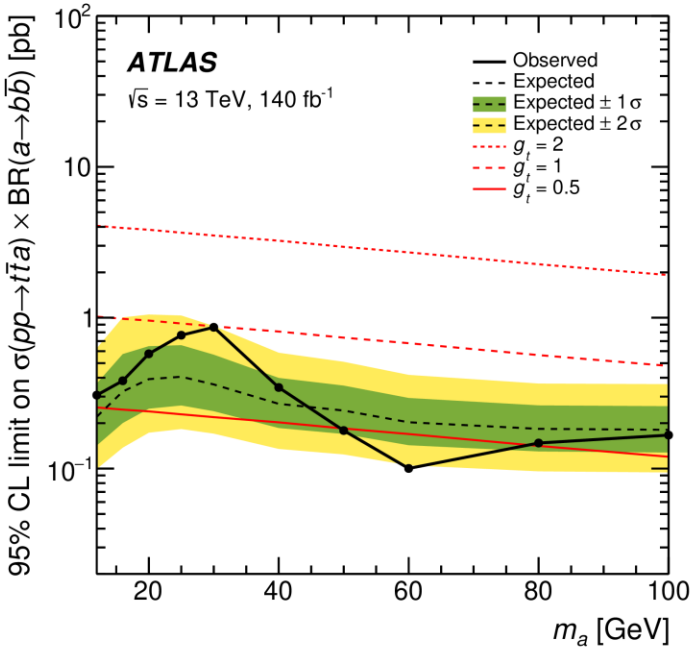
- Targeting a light (12-100 GeV) pseudoscalar in 2HDM,
- Two leptons in final state, single-lepton triggers,
- $b\bar{b}$ pairs reconstructed either resolved (*b*) or merged (*B*),
- Pseudo-continuous *b*-tagging & N_{jets} calibrated in CR's,
- 4 SR's: **0B4b**, **0B3b**, **1B2b**, **1B1b+1bL**
- *t* & *a* mass reconstructed with BDT's,
- S vs B discrimination from channel-specific NN's parameterised by the m_a hypothesis.

Eur. Phys. J. C 85 (2025) 886







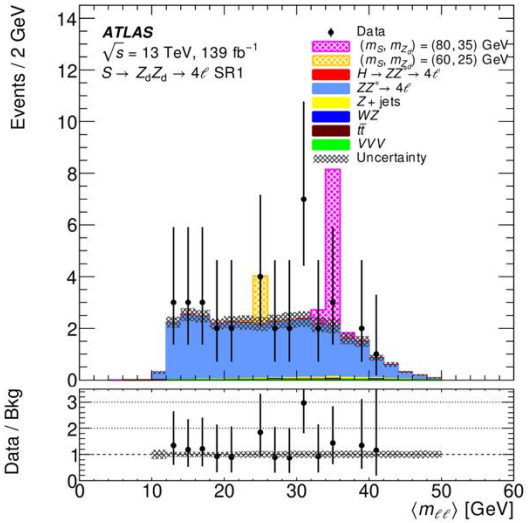


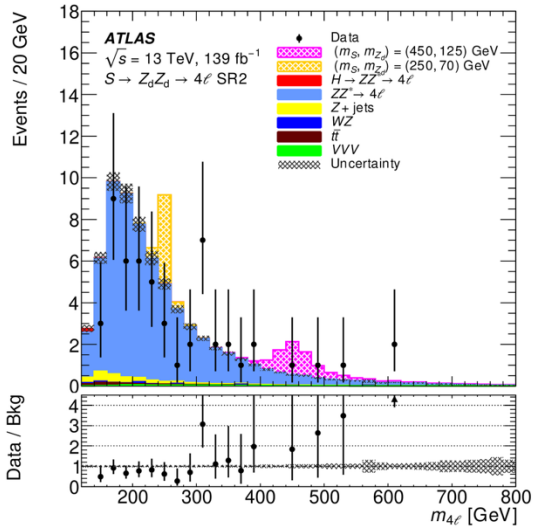
95% CL on $\sigma(t\bar{t}a) \times \mathcal{B}(a \to b\bar{b})$ is compared to simplified Yukawa model. g=1 excluded for all masses

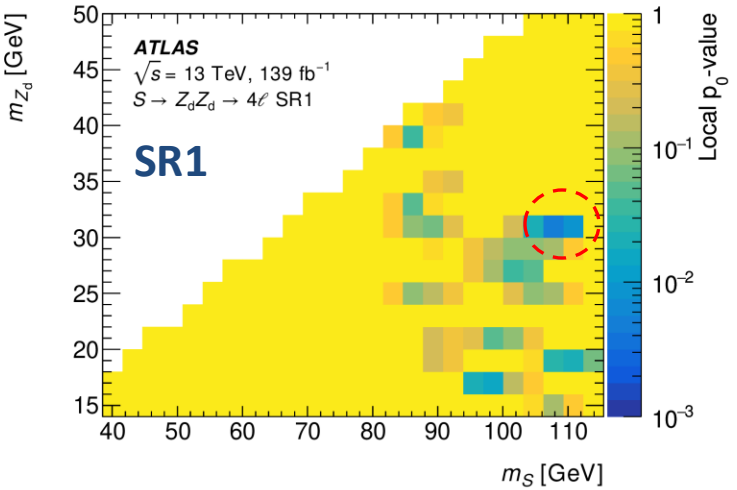
New scalar decaying into a pair of dark photons

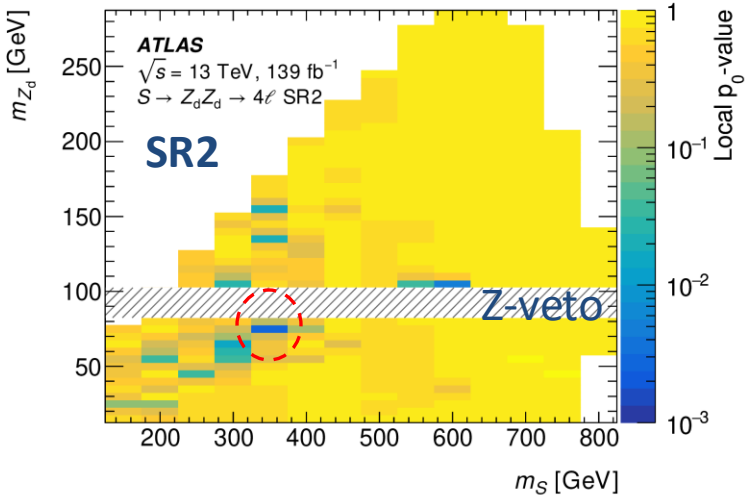
Phys. Lett. B 865 (2025) 139472

- Targetting the HAHM, with dark photon (Z_d) coupling to the dark scalar S ($\kappa \ll 1$ mixing to H),
- $m_S < 800\ GeV$ and $m_{Z_d} < 300\ GeV$ (width ↑)
- Quadruplets of isolated $4e$, $2e2\mu$, or 4μ,
- **SR1**: $30 - 115\ GeV$, **SR2**: $130 - 825\ GeV$
- The dominant background: $ZZ^* \to 4l$ from MC.









95% CL on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4l)$ for the grid of (m_S, m_{Z_d})

Limits range from 0.05 to 3.1 fb and the local significance is $<3\sigma$ in all bins.

Exotic Higgs125 decays and ALP searches

1. $H \to aa \to 4\tau$ arXiv:2503.05463
2. $H \to aa/a_1a_2 \to 4b/6b$ arXiv:2507.01165
3. $H \to Za, H \to aa$ ATL-PHYS-PUB-2025-007

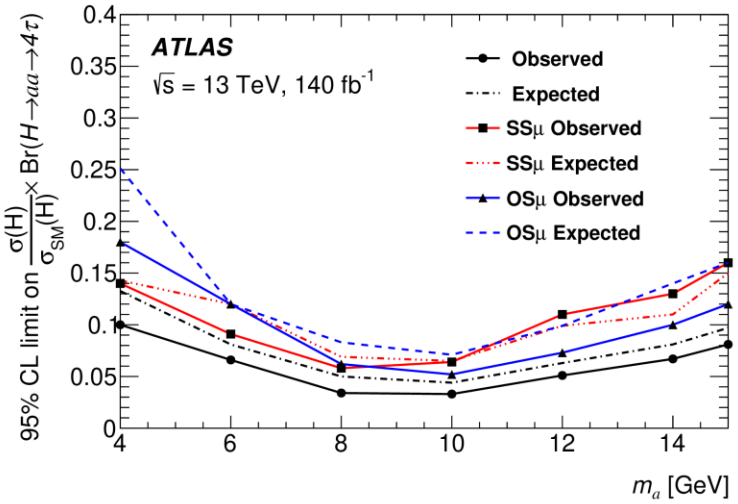
For details of **1** and **2** see talk from **Francesco Carnevali**

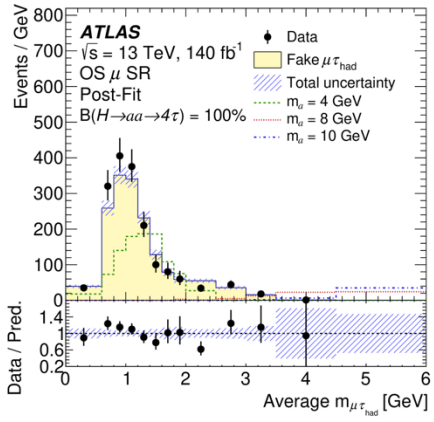
Higgs decays into a pair of light bosons in the four-τ final state

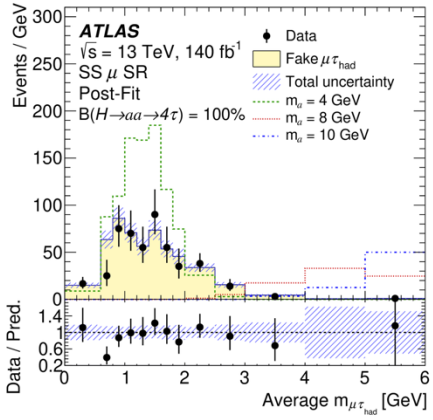
arXiv:2503.05463

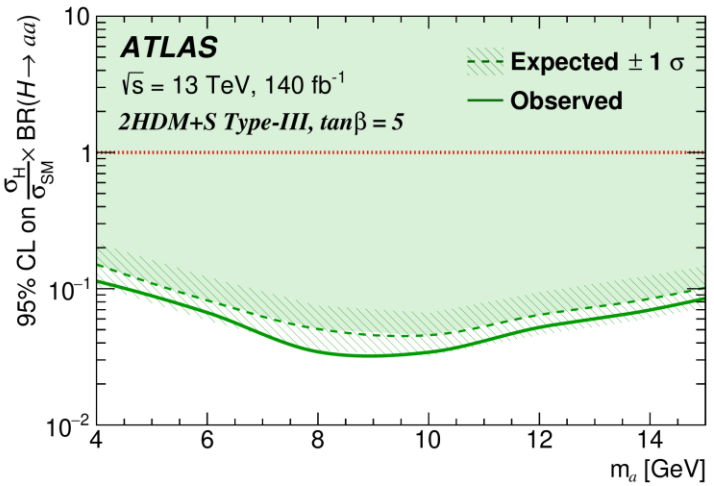
See talk from **Francesco Carnevali**

- Targeting the 2HDM+S Type III models
- Favoured for $2m_\tau < m_a < 2m_b$,
- (4, 15) GeV searched,
- Boosted di-taus; hadronic+muonic decay,
- Dedicated muon removal technique recovers τ_{had} identification efficiency for $\Delta R < 0.4$.
- The dominant fake-τ_{had} background estimated with the FF technique and checked in VR's,
- **SSμ** and **OSμ** signal regions; fit to $\langle m_{\mu\tau_{had}} \rangle$.









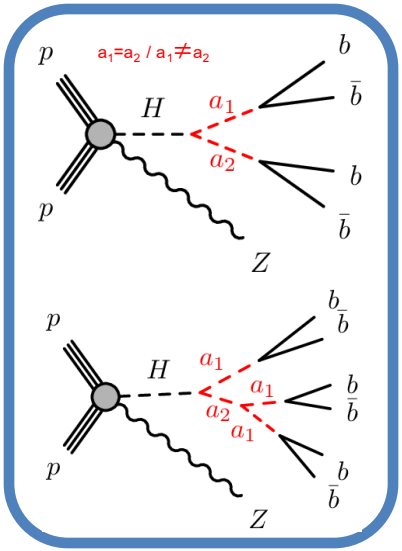
95% CL on $\frac{\sigma(H)}{\sigma_{SM}(H)} \times \mathcal{B}(H \to aa \to 4\tau)$ range from 0.03 to 0.10 depending on m_a.

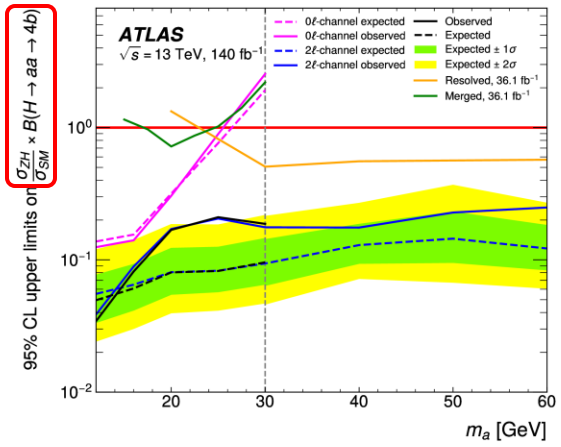
Higgs decays into two light (pseudo)scalars in the four or six *b*-quark final state

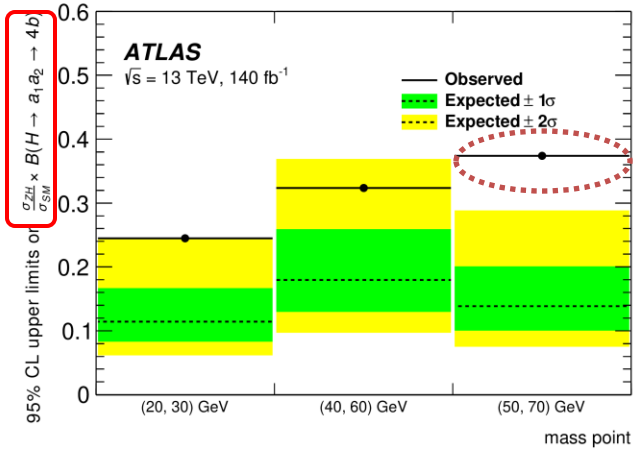
arXiv:2507.01165

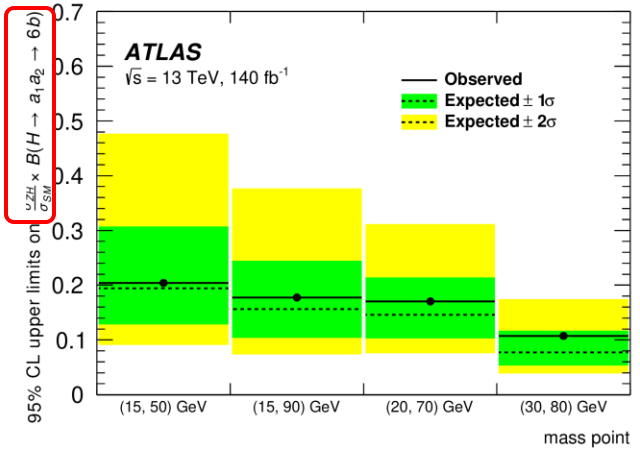
See talks from **Francesco & Greg**

- Models with *a*-bosons mixing with the Higgs$_{125}$. (SM Yukawa)
- HZ associated production: trigger on leptons ($2l$) or $E_T^{miss}(0l)$
- Higgs decay with $4b$ or $6b$ final state,
- Three categories of *b*-objects: ***B***, ***b***, **v** (soft secondary vertex)
- Dominating backgrounds (mainly *Z*+jets and *tt*) from MC with correction factors from data.
- QCD multijet estimated using ABCD data-driven method.
- SR categorised based on number of ***B***, ***b*** and **v** objects.









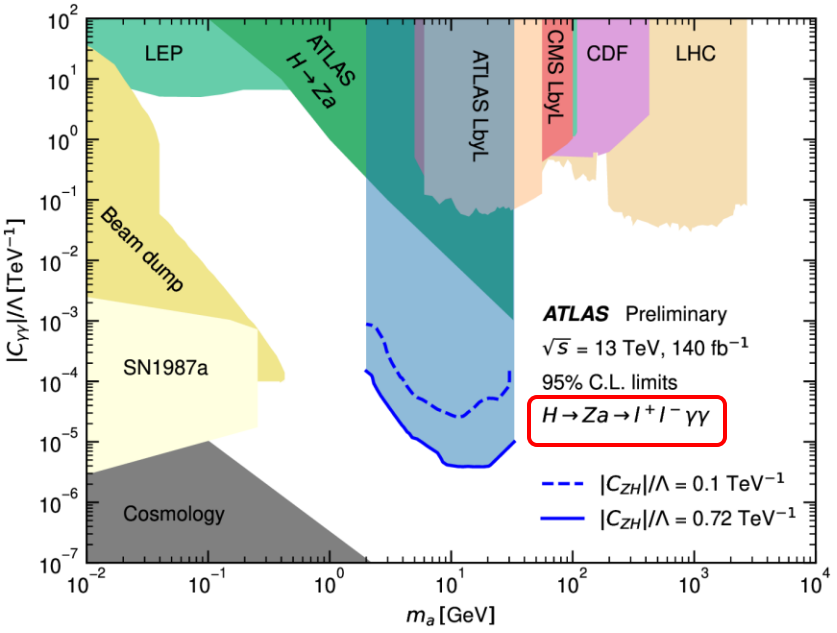
95% CL on $\frac{\sigma(ZH)}{\sigma_{SM}(ZH)} \times \mathcal{B}(H \to aa/a_1a_2 \to 4b/6b)$. 2.6σ global in $2l$ for (50,70) GeV

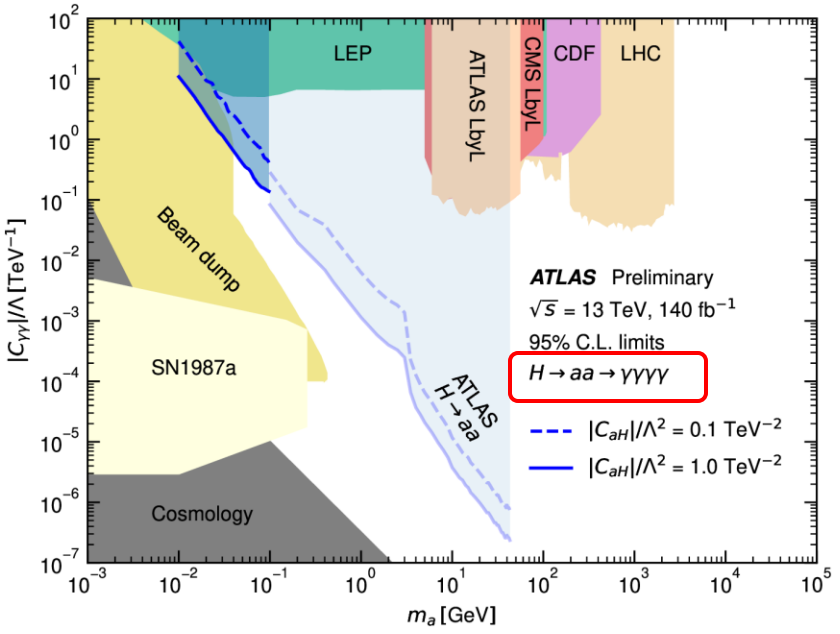
Constraints on long-lived axion-like particles from existing searches for exotic Higgs decays

ATL-PHYS-PUB-2025-007

- ALPs pseudo-scalar gauge singlet particles predicted by many SM extensions.
- Z-associated produced ($|C_{ZH}|/\Lambda$) or pair-produced ($|C_{aH}|/\Lambda^2$) in decays of H_{125}.
- Decays always via $a \to \gamma\gamma$ with $|C_{\gamma\gamma}|/\Lambda$ coupling
- This reinterpretation seeks for **long-lived** ALPs based on data and bkg. predictions of:

1) $\boldsymbol{H \to Za}$: $m_a \in (2, 33) GeV$ resolved photons [Phys. Lett. B 848 (2024) 138536]
2) $\boldsymbol{H \to aa}$: $m_a \in (0.01, 0.1) GeV$ merged photons [Eur. Phys. J. C 84 (2024) 742]





Most stringent 95% CL on $|C_{\gamma\gamma}|/\Lambda$ in the mass range (2, 33) GeV

SUMMARY

- Presented results complement or update results steaming from ATLAS wide program of BSM searches in the scalar sector.
- Searches for charged Higgs's, additional neutral (pseudo)scalars and for Higgs decays to BSM particles were covered.
- None of the searches reveals a significant excess. New or improved limits are set
- Start exploiting Run-3 data. Stay tuned for future updates!

THANK YOU

BACKUP

$X \to S(\to b\bar{b})H_{125}(\to \gamma\gamma)$

JHEP 11 (2024) 047

140.0 fb^{-1} @**13.0** TeV

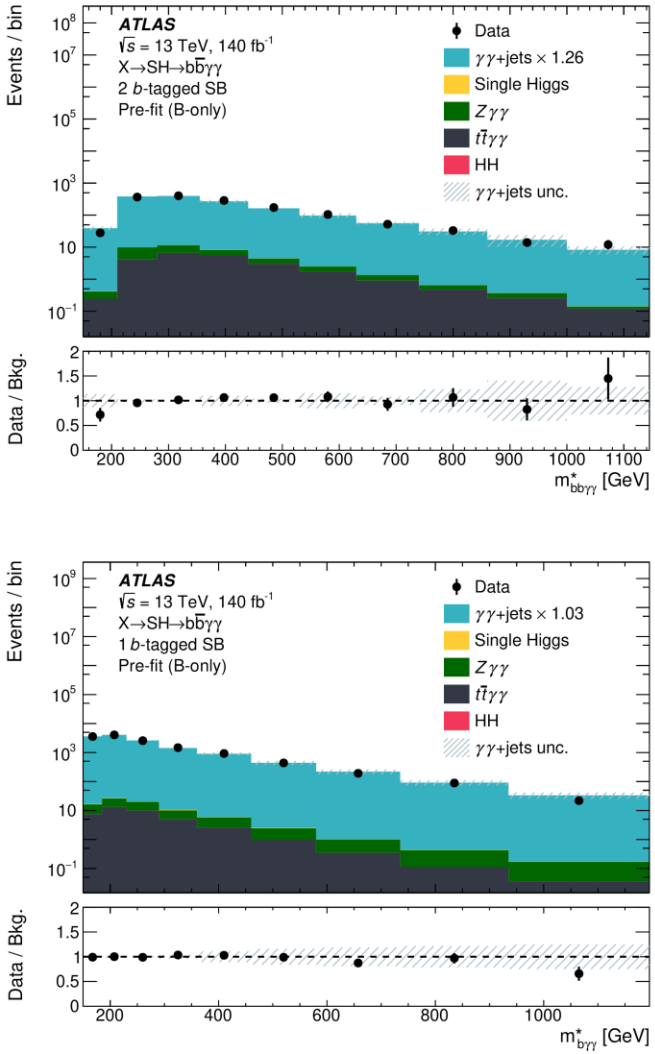
- **Scenarios considered**:
- Generic search targeting 2HDM type models or SM extended by singlets with at least 2 DoF's.

- **NWA** is assumed throughout.

- **Selection:** di-photon triggers, 2 photon mass consistent with H_{125} [120,130], exactly one b-jet (**1*b* SR**) or exactly 2 b-jets (**2*b* SR**)

- Main background ($\gamma\gamma$+jets) normalised from $m_{\gamma\gamma}$ side bands

- **Discriminant:**
  - 1b SR: PNN parameterised in (m_X)
  - 2b SR: PNN parameterised in (m_X, m_S)



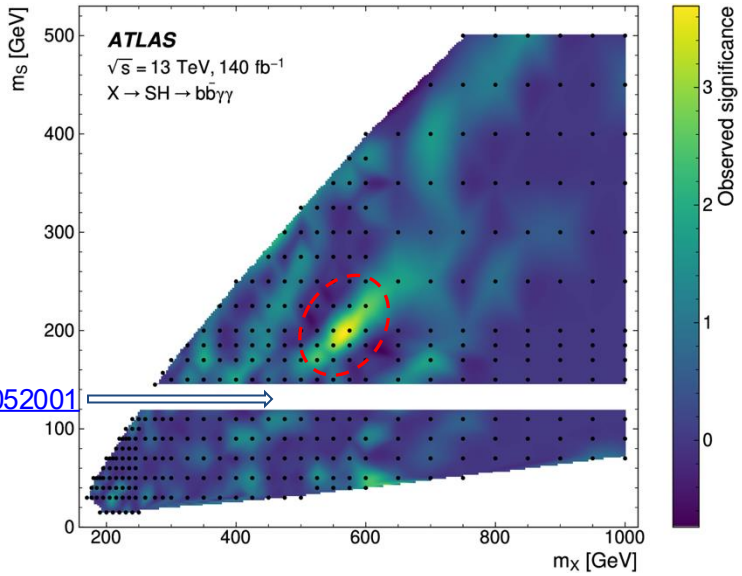
$X \to S(\to b\bar{b})H_{125}(\to \gamma\gamma)$

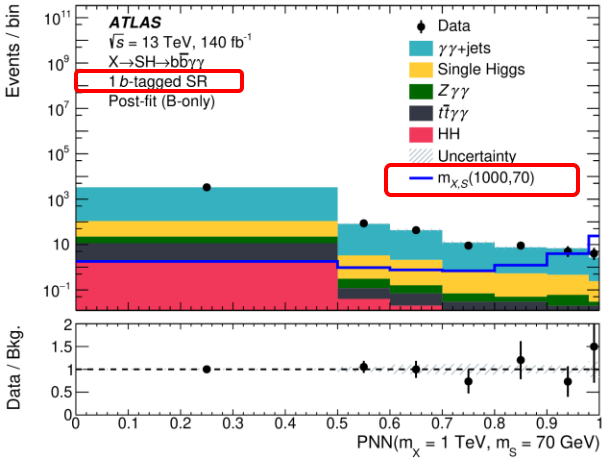
Results

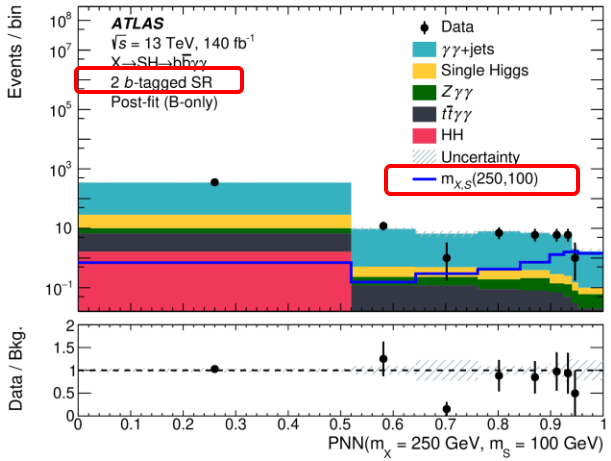
JHEP 11 (2024) 047

140.0 fb^{-1} @**13.0** TeV

Covered by dedicated analysis
Phys. Rev. D **106** (2022) 052001







- A simultaneous fit is performed on the PNN score distributions in the SR's & sideband CR's.
- Model independent limits on $\sigma(X \to SH_{125} \to b\bar{b}\gamma\gamma)$

Data found compatible with the SM prediction.
Largest deviation for (m_X, m_S)=(575,200) GeV @ local (gobal) $3.5(2.0)\sigma$
CMS excess @ (m_X, m_S)=(650,90) GeV, $3.8(2.8)\sigma$, JHEP 05 (2024) 316 not confirmed.

Fake tau background estimation

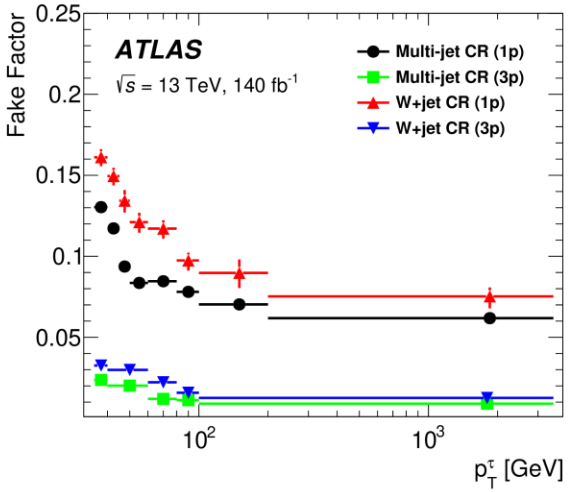
Phys. Rev. D 111 (2025) 072006

Multi-jet CR

- $E_{\mathrm{T}}^{\mathrm{miss}}$ or MJ trigger
- ≥ 3 jets
- 0 b-jets
- 0 ℓ
- $m_{\mathrm{T}}(\tau, E_{\mathrm{T}}^{\mathrm{miss}}) > 50$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} < 80$ GeV

W+jets CR

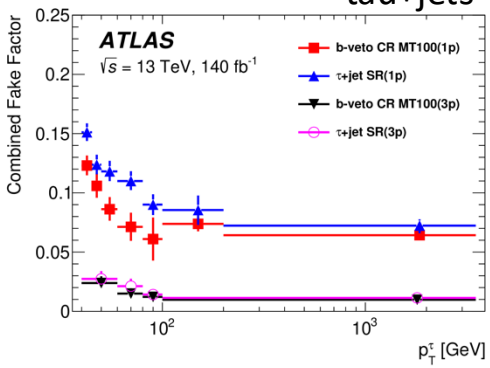
- Single lepton triggers
- 1 ℓ, $p_{\mathrm{T}}^{\ell} > 30$ GeV
- 1 τ
- ≥ 1 jets
- 0 b-jets
- $60 < m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) < 160$ GeV



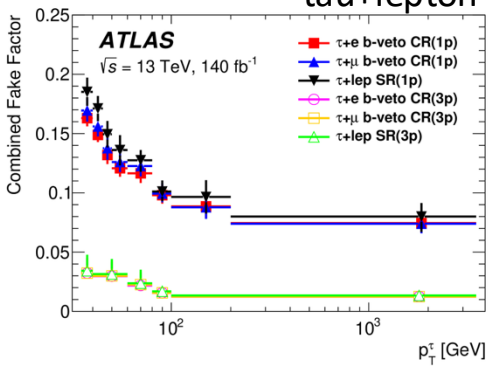
- Multi-jet and W+jets CRs q/g jet compositions differ
  - MJ is more QCD-like, with a larger fraction of gluon-initiated jets
- Can extrapolate to the SR (or to an arbitrary q/g fraction) with some linear combination of the two:
  - $FF_{\mathrm{SR}} = \alpha_{\mathrm{MJ}} \times FF_{\mathrm{MJ}} + (1 - \alpha_{\mathrm{MJ}}) \times FF_{W+\mathrm{jets}}$

template fit to the jet width

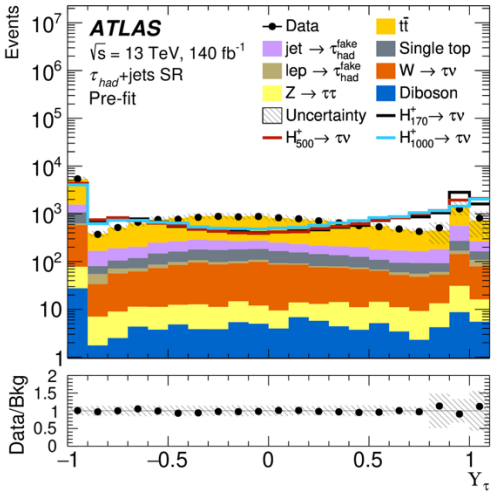
tau+jets



tau+lepton

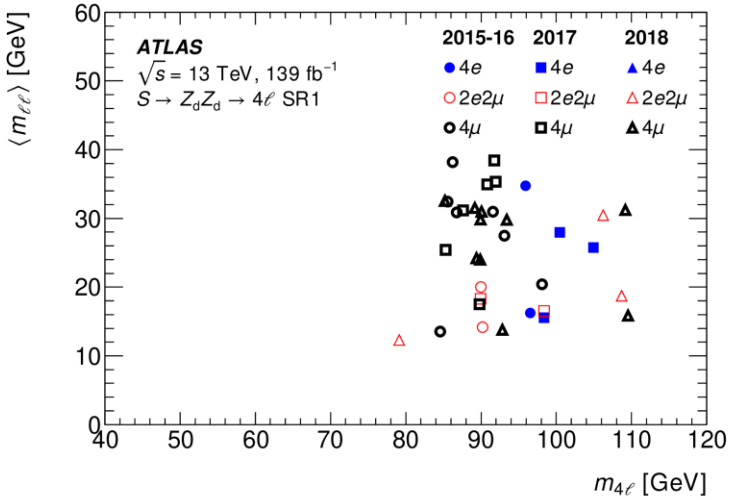


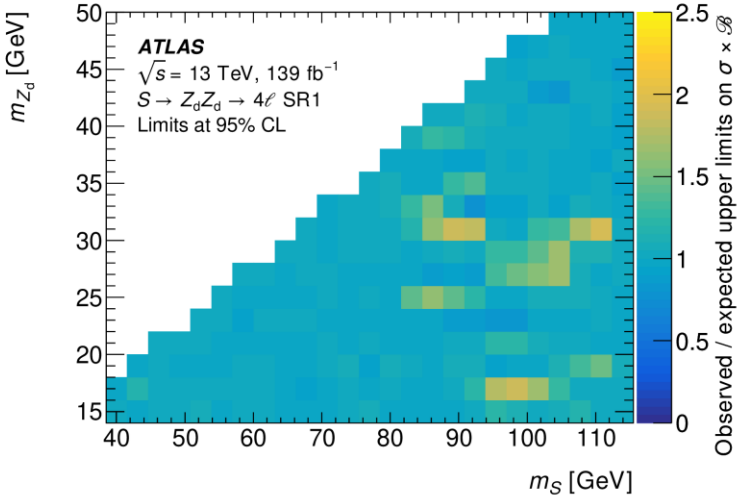
$$\Upsilon = 2\frac{p_{\mathrm{T}}^{\tau\text{-track}}}{p_{\mathrm{T}}^{\tau}} - 1$$ needs inverse transform sampling

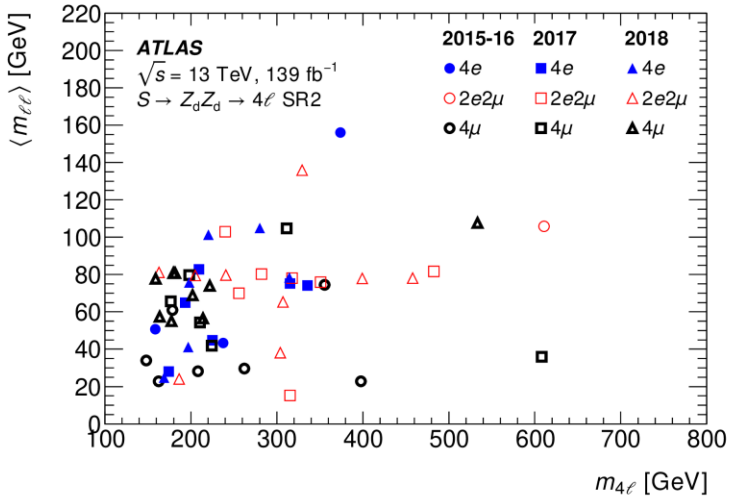


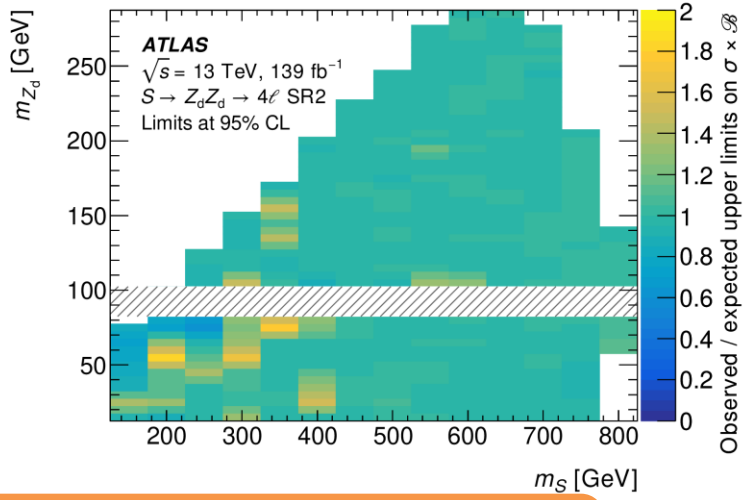
New scalar decaying into a pair of dark photons

Phys. Lett. B 865 (2025) 139472









95% CL on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4l)$ for the grid of (m_S, m_{Z_d})

Limits range from 0.05 to 3.1 fb and the local significance is $<3\sigma$ in all bins.