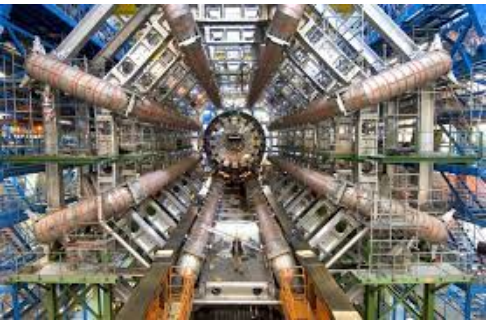


Exotic production and decays of the 125 GeV Higgs - ATLAS

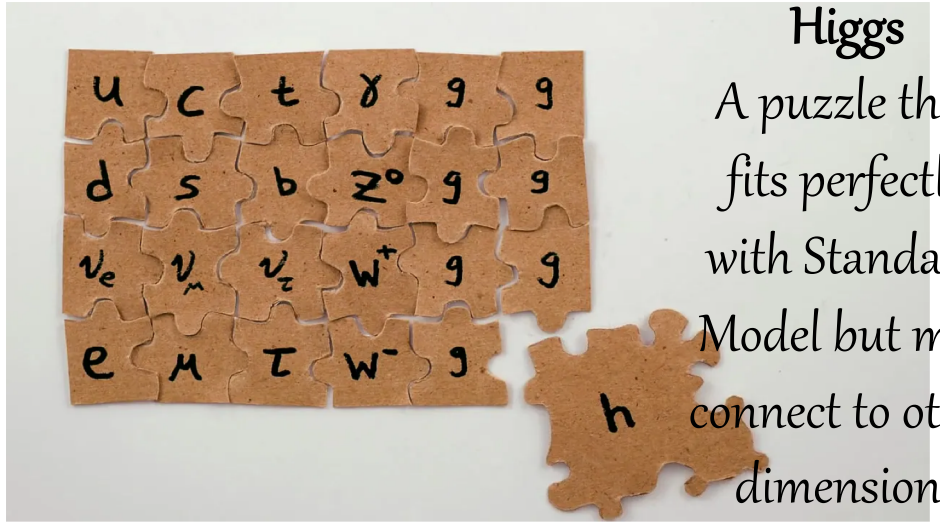
Rocky Bala Garg

Stanford University

On Behalf of the ATLAS Collaboration

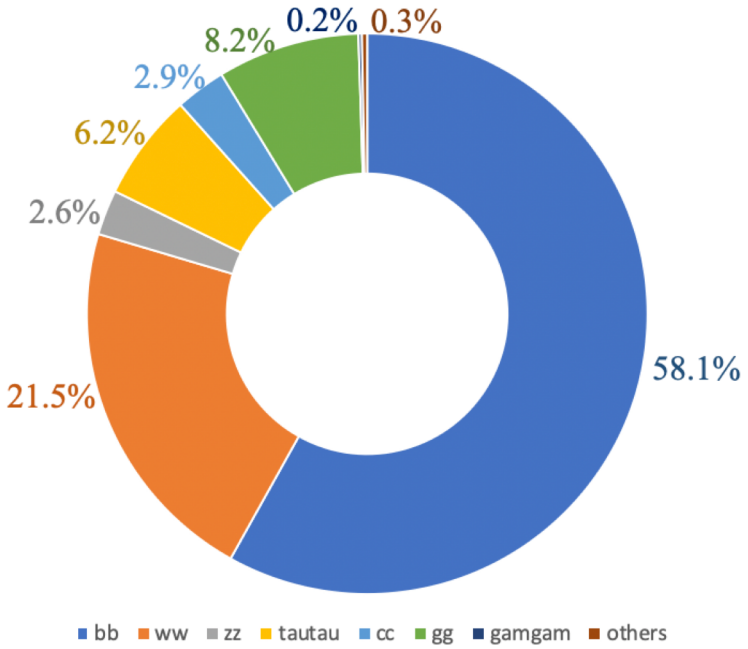
Overview: Why is Higgs everyone's favorite?

- Since its discovery in 2012, Higgs has caught everyone's attention
- It has a unique place in the Standard Model (SM) family
- And may have potential links outside of the family



Higgs

A puzzle that fits perfectly with Standard Model but may connect to other dimensions



Higgs total width Γ_H

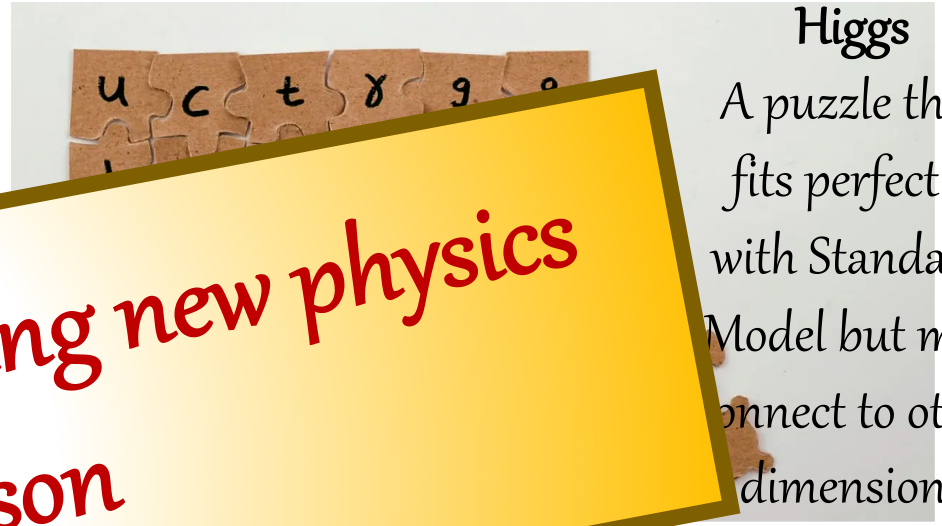
From CERN Yellow Report: 4.1±2.3 MeV

Latest measurement (2304.01532): $4.5^{+3.3}_{-2.5}$ MeV

Higher decay width → Potential Higgs decays into new states

Overview: Why is Higgs everyone's favorite?

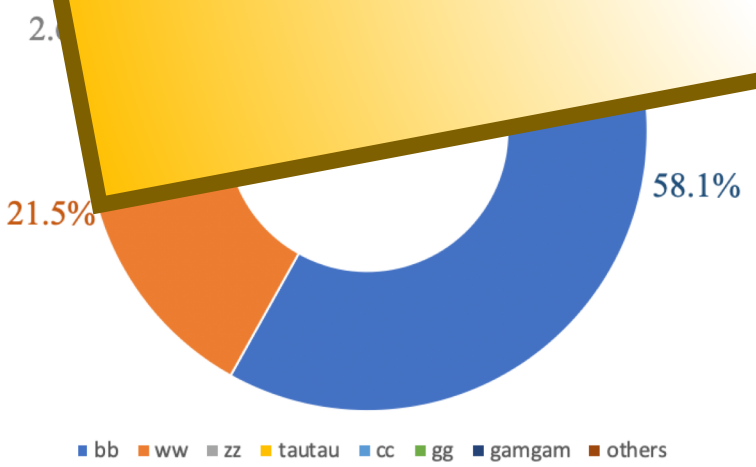
- Since its discovery in 2012, Higgs has caught everyone's attention
- It has a unique place in the St… Model (SM) f…
- …



Higgs

A puzzle that fits perfectly with Standard Model but may …onnect to other …dimensions

Exciting prospects for discovering new physics with the Higgs boson



…idth Γ_H

…n CERN Yellow Report: 4.1±2.3 MeV

Latest measurement (2304.01532): $4.5^{+3.3}_{-2.5}$ MeV

Higher decay width ⟶ Potential Higgs decays into new states

Rich Experimental Program

Precise measurement of Higgs couplings to SM particles

Search for additional Higgs-like states

And the topic of this talk:

Search for "exotic" production/decays of SM Higgs

Exotic production/decay of SM Higgs: Various manifestations

Exotic Higgs decays in rare SM particles

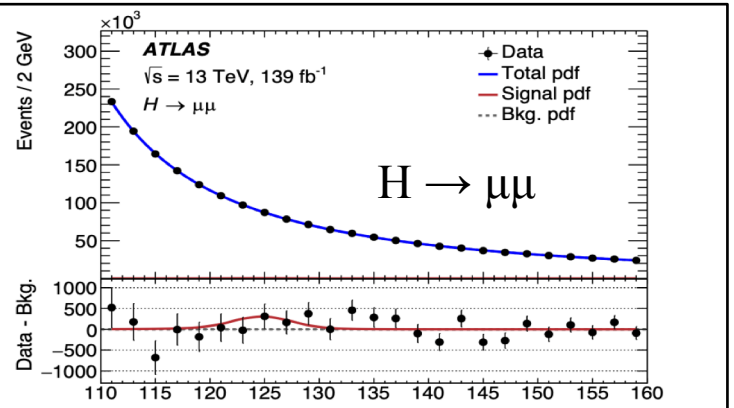
Exotic Higgs decays in new BSM[1] final states

SM Higgs production in association with new exotic final states

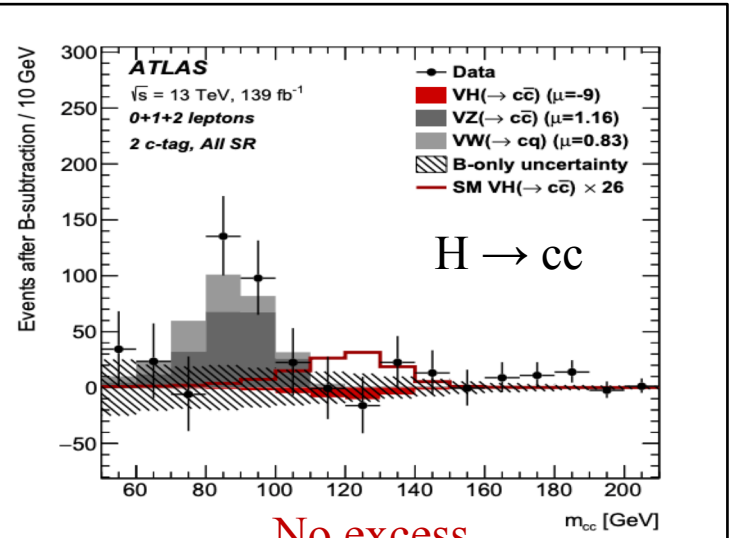
[1]Beyond the Standard Model

Exotic Higgs decays in rare SM particles

A recap from LHCP 2022 TAIPEI ONLINE

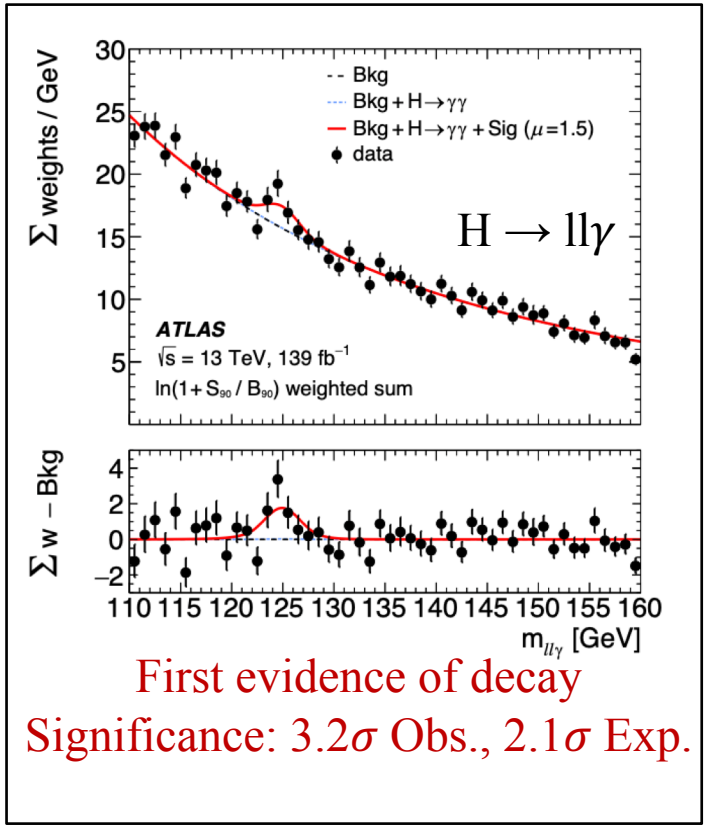


Significance: 2.0σ Obs., (1.7)σ Exp.



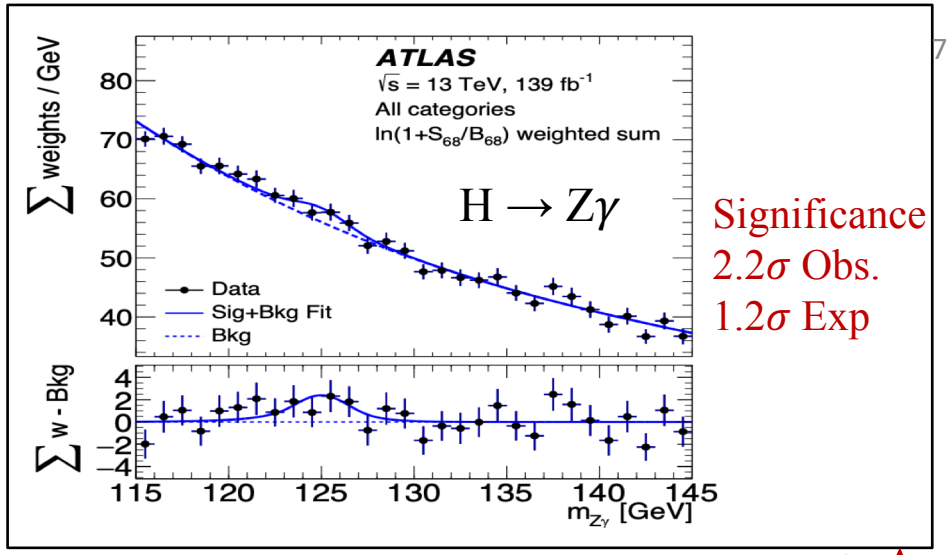
No excess

UL on (σxB)@95%CL: 26 x SM

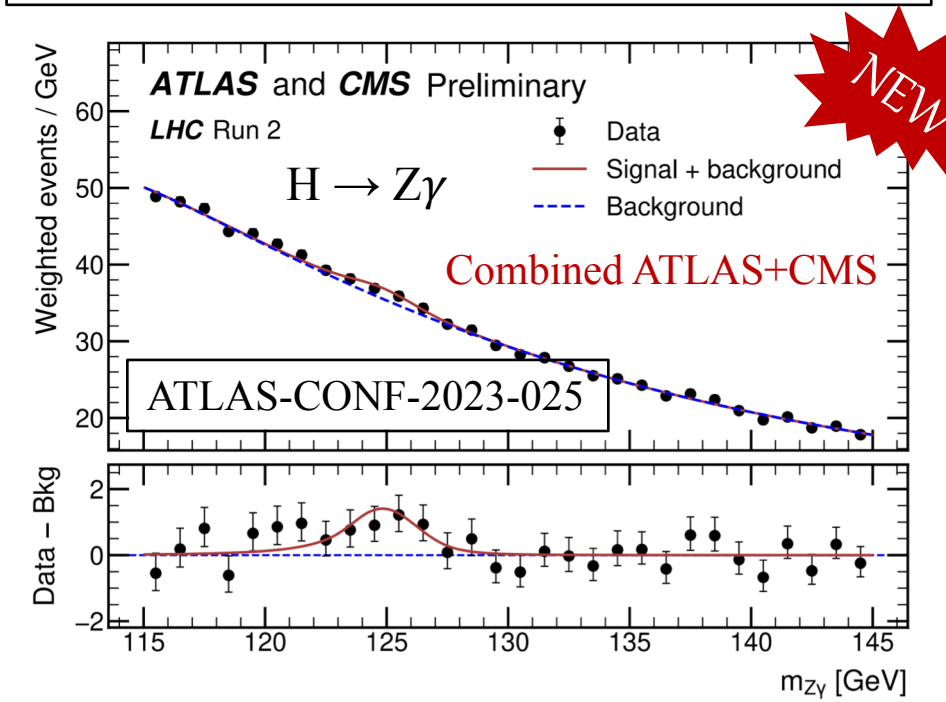


First evidence of decay

Significance: 3.2σ Obs., 2.1σ Exp.



Significance
2.2σ Obs.
1.2σ Exp



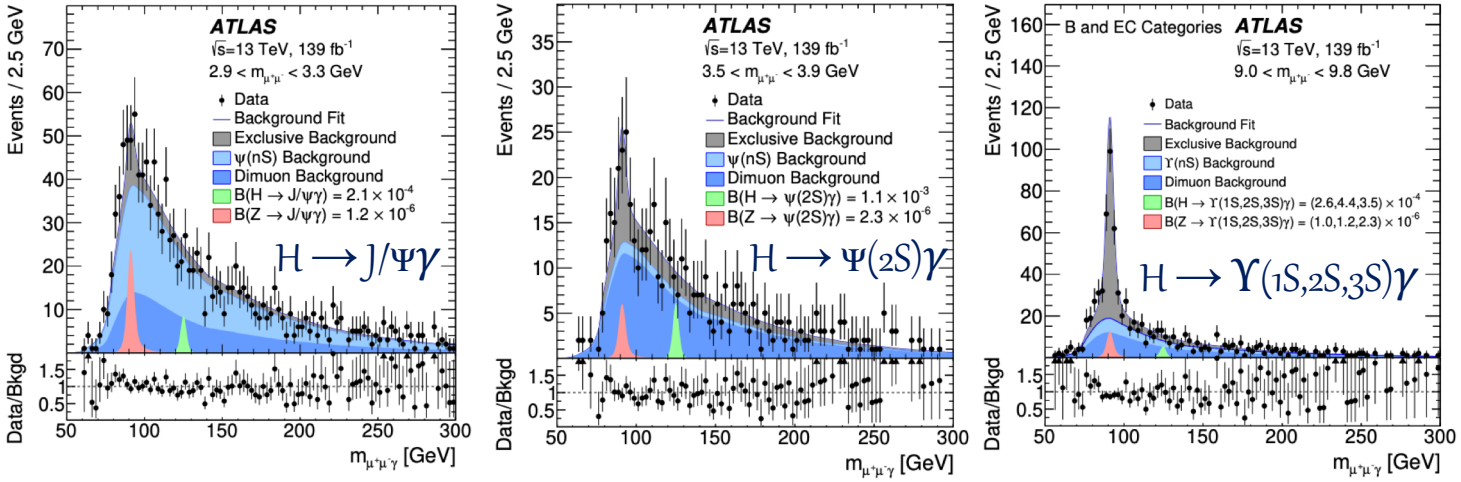
Combined Significance: 3.4σ Obs., (1.6)σ Exp

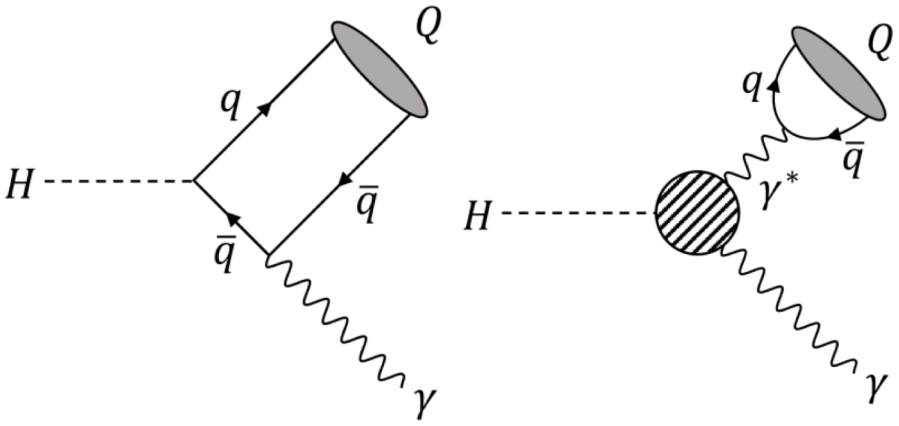
(More details: ATLAS Status talk Monday's Plenary)

NEW

arXiv: 2208.03122

$H \to J/\Psi+\gamma$ or $\Psi(2S)+\gamma$ or $\Upsilon(1S,2S,3S)+\gamma \to \mu^+\mu^-\gamma$





95% CL upper limits

Decay channel	Branching fraction: Higgs boson [10^{-4}] Expected	Higgs boson [10^{-4}] Observed	Z boson [10^{-6}] Expected	Z boson [10^{-6}] Observed	$\sigma \times \mathcal{B}$: Higgs boson [fb] Observed	Z boson [fb] Observed
$J/\psi\,\gamma$	$1.9^{+0.8}_{-0.5}$	2.1	$0.6^{+0.3}_{-0.2}$	1.2	12	71
$\psi(2S)\,\gamma$	$8.5^{+3.8}_{-2.4}$	10.9	$2.9^{+1.3}_{-0.8}$	2.3	61	135
$\Upsilon(1S)\,\gamma$	$2.8^{+1.3}_{-0.8}$	2.6	$1.5^{+0.6}_{-0.4}$	1.0	14	59
$\Upsilon(2S)\,\gamma$	$3.5^{+1.6}_{-1.0}$	4.4	$2.0^{+0.8}_{-0.6}$	1.2	24	71
$\Upsilon(3S)\,\gamma$	$3.1^{+1.4}_{-0.9}$	3.5	$1.9^{+0.8}_{-0.5}$	2.3	19	135

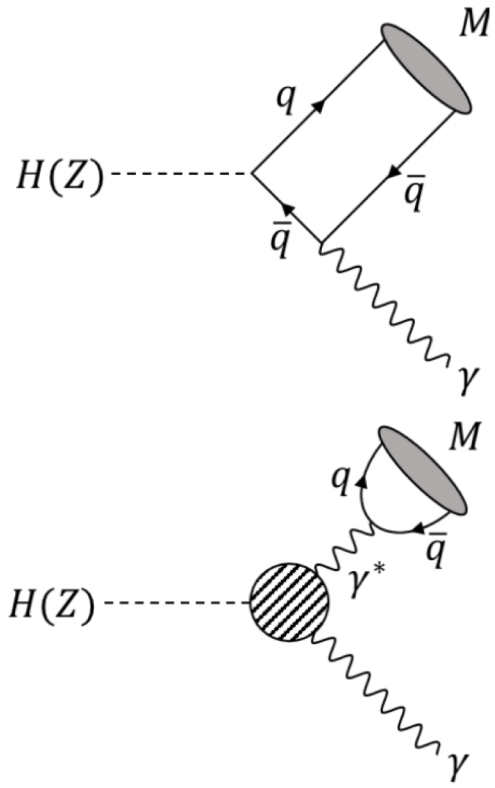
- $H \to J/\Psi+\gamma$ or $\Psi(2S)+\gamma$: allow access to the charm-quark Yukawa coupling
- $H \to \Upsilon(1S,2S,3S)+\gamma$: provide information about the bottom-quark coupling to the Higgs boson

No Significant excess over SM expectation

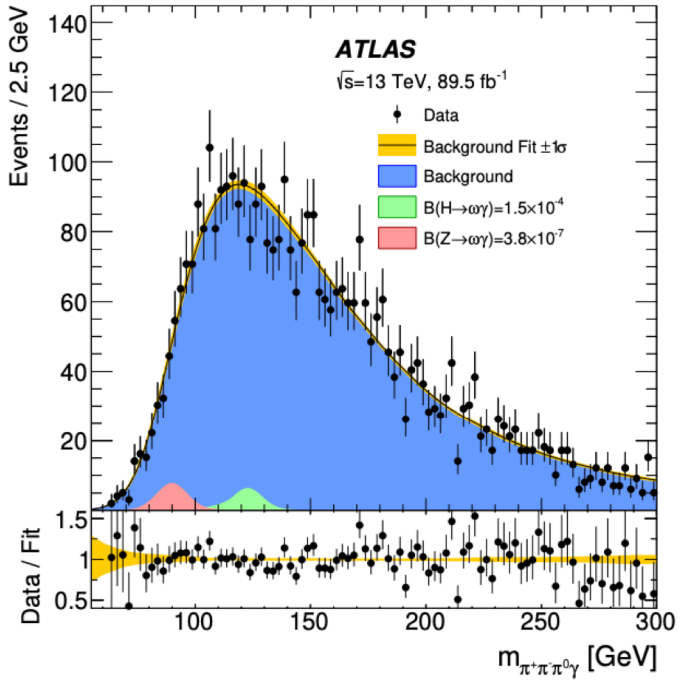
NEW

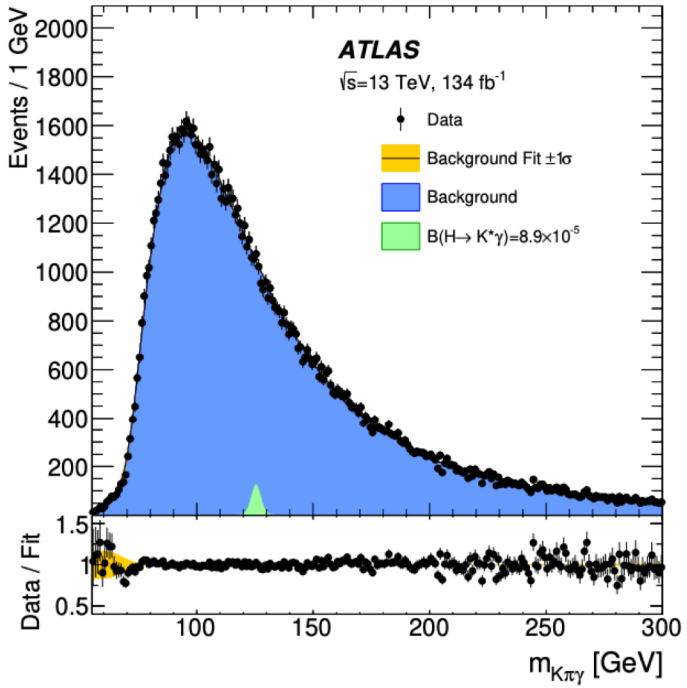
arXiv: 2301.09938

$H/Z \to \omega\gamma \to \pi^+\pi^-\pi^0\gamma$ or $H/Z \to k^*\gamma \to k^+\pi^-\gamma$



- These decays can probe the couplings of Higgs boson to 1st and 2nd generation quarks
- Theoretical SM branching fraction for $H \to \omega\gamma = (1.48 \pm 0.08) \times 10^{-6}$ (Ref)
- Observed UL@95%CL for $H \to \omega\gamma$ = 100 x SM





95% CL upper limits on branching fractions

Channel	95% CL upper limit	
	Expected	Observed
$H \to \omega\gamma$ [10^{-4}]	$3.0^{+1.2}_{-0.8}$	1.5
$Z \to \omega\gamma$ [10^{-7}]	$5.7^{+2.3}_{-1.6}$	3.8
$H \to K^*\gamma$ [10^{-5}]	$12.2^{+4.9}_{-3.4}$	8.9

No Significant excess over SM expectation

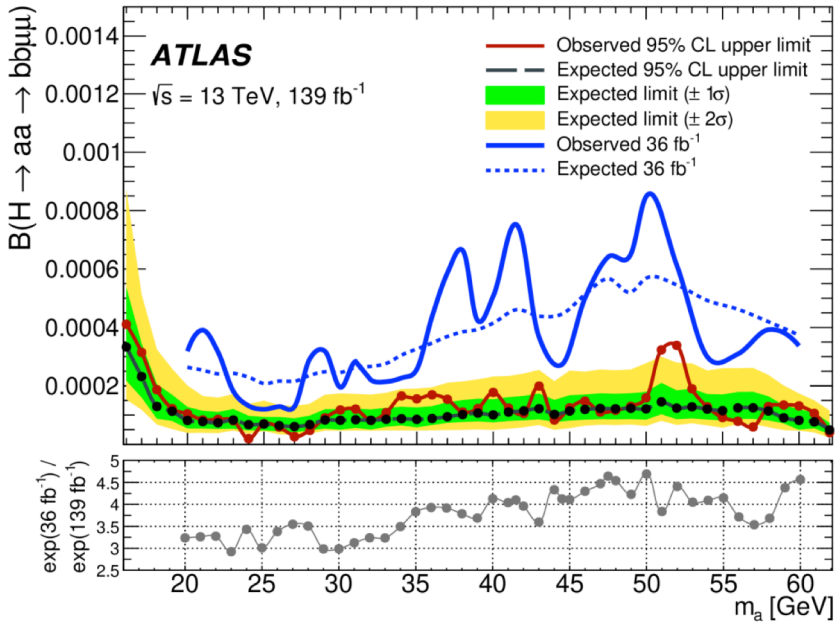
Exotic Higgs decays in new BSM final states

A recap from LHCP TAIPEI 2022 ONLINE

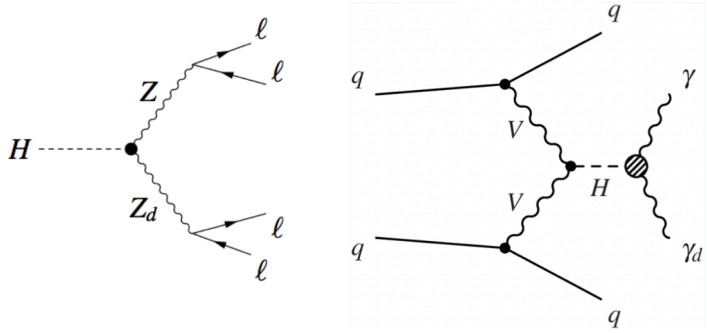
H → aa → bbμμ

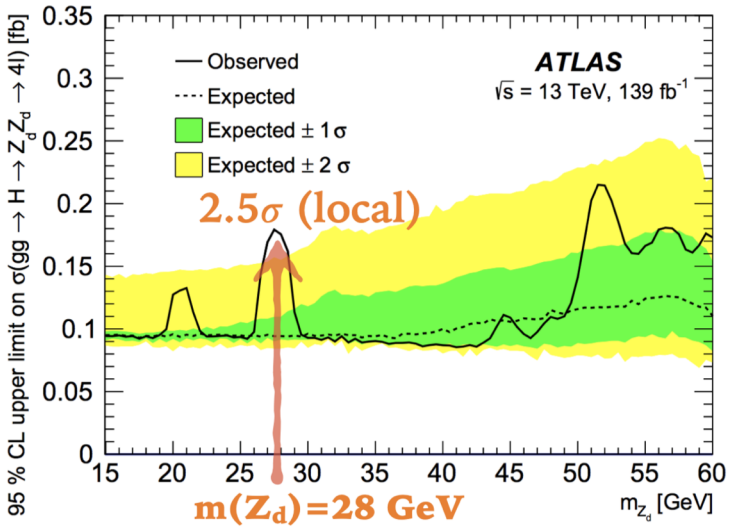
Two largest deviations at:

- $m_a = 35$ GeV and $m_a = 52GeV$

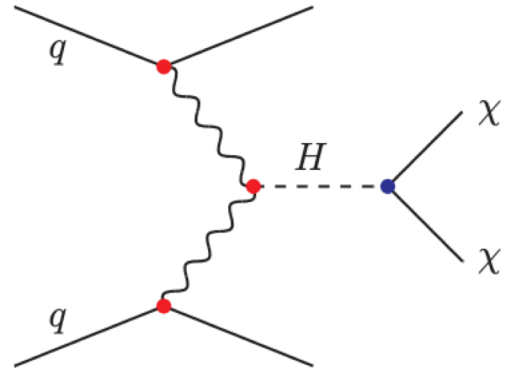


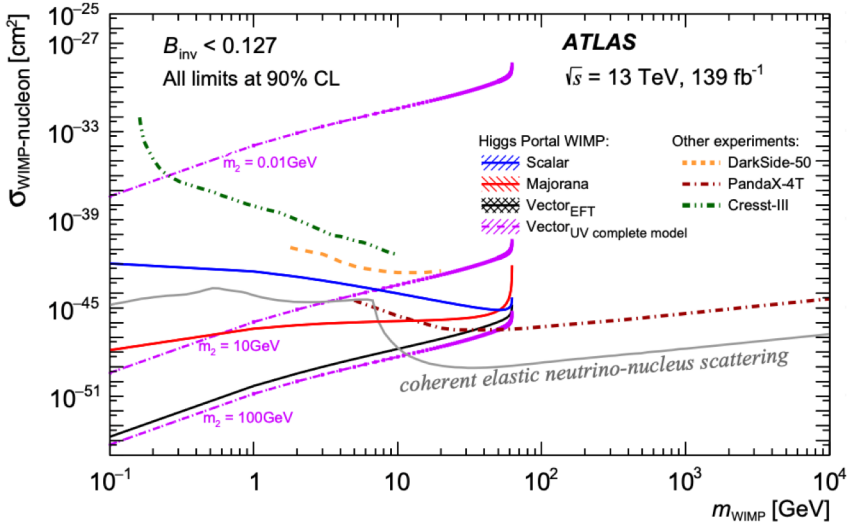
H → Dark Photon





H → invisible





H → LLP searches

Great benchmark and lots of ongoing efforts

Dedicated ATLAS talk in Monday's parallel session by Mohsen

NEW

Latest results on H → invisible combination: Elliott's talk in Thursday's Plenary

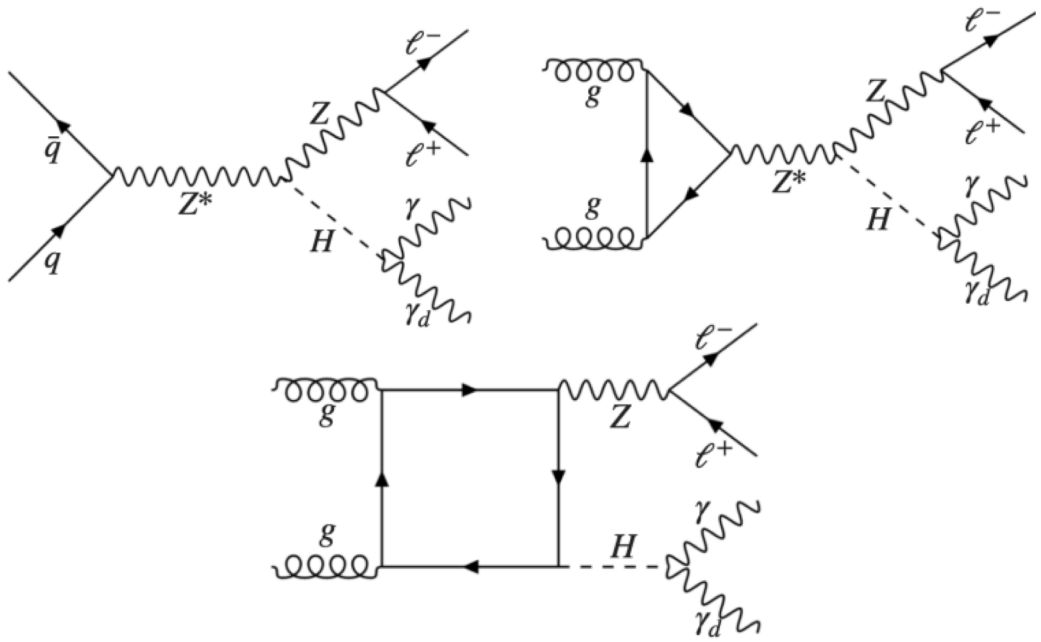
NEW

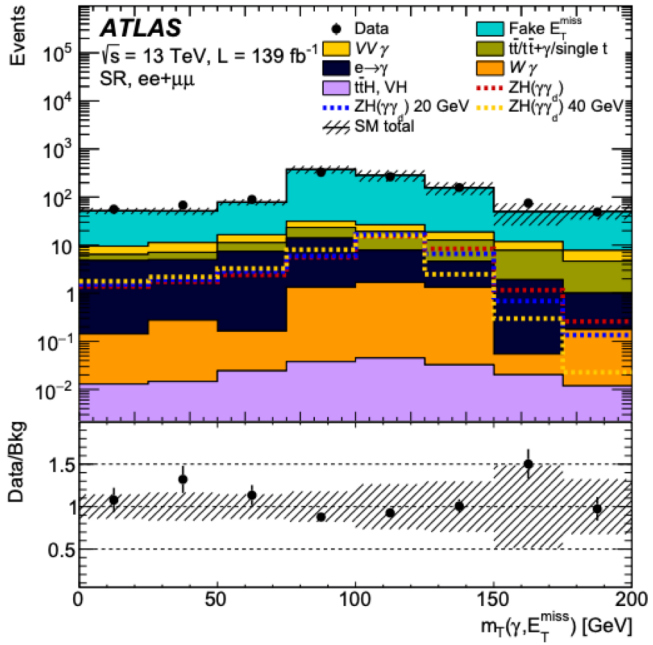
Higgs decay into dark matter particles

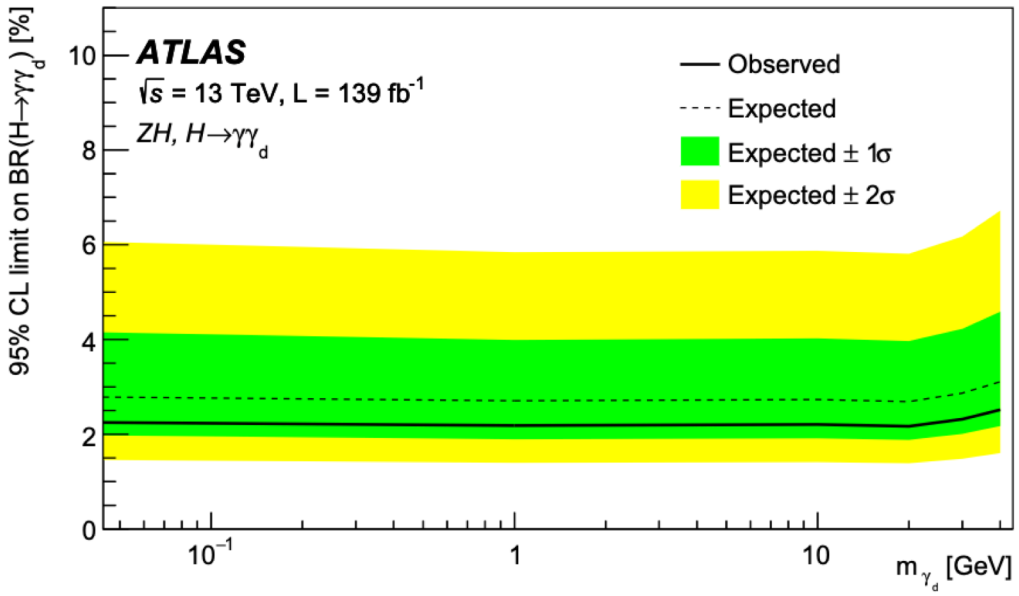
$ZH \rightarrow ll\gamma\gamma_d$ where $l = e/\mu$

arXiv: 2212.09649

- Signal topologies with massless and massive dark photon are considered
- A boosted decision tree (BDT) has been used to distinguish signal events from SM background
- Fit is performed in the SR to the distribution of the BDT classifier response







95%CL upper limits on $m_{\gamma d}$

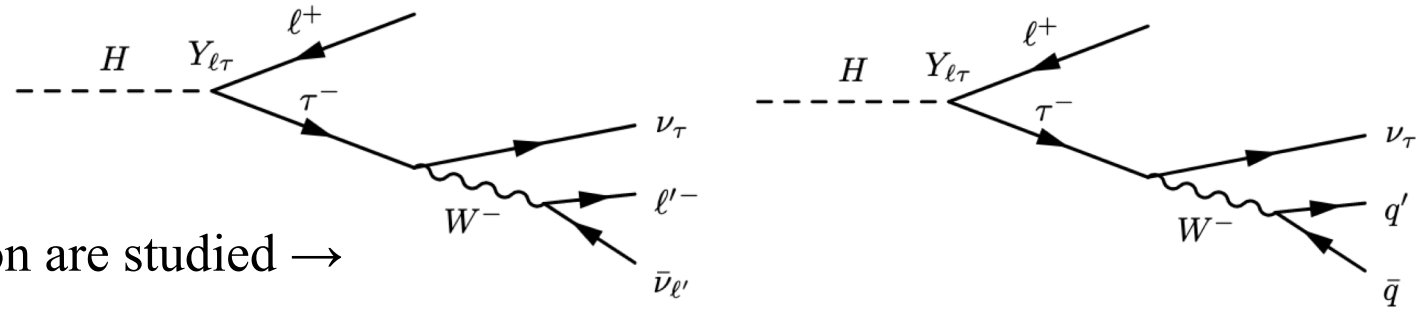
m_{γ_d}	$BR(H \rightarrow \gamma\gamma_d)^{95\%\ CL}_{obs}$	$BR(H \rightarrow \gamma\gamma_d)^{95\%\ CL}_{exp}$
[GeV]	[%]	[%]
0	2.28	$2.82^{+1.33}_{-0.84}$
1	2.19	$2.71^{+1.28}_{-0.81}$
10	2.21	$2.73^{+1.31}_{-0.82}$
20	2.17	$2.69^{+1.29}_{-0.81}$
30	2.32	$2.87^{+1.36}_{-0.86}$
40	2.52	$3.11^{+1.48}_{-0.93}$

NEW

Lepton-flavour violating decays of Higgs Boson

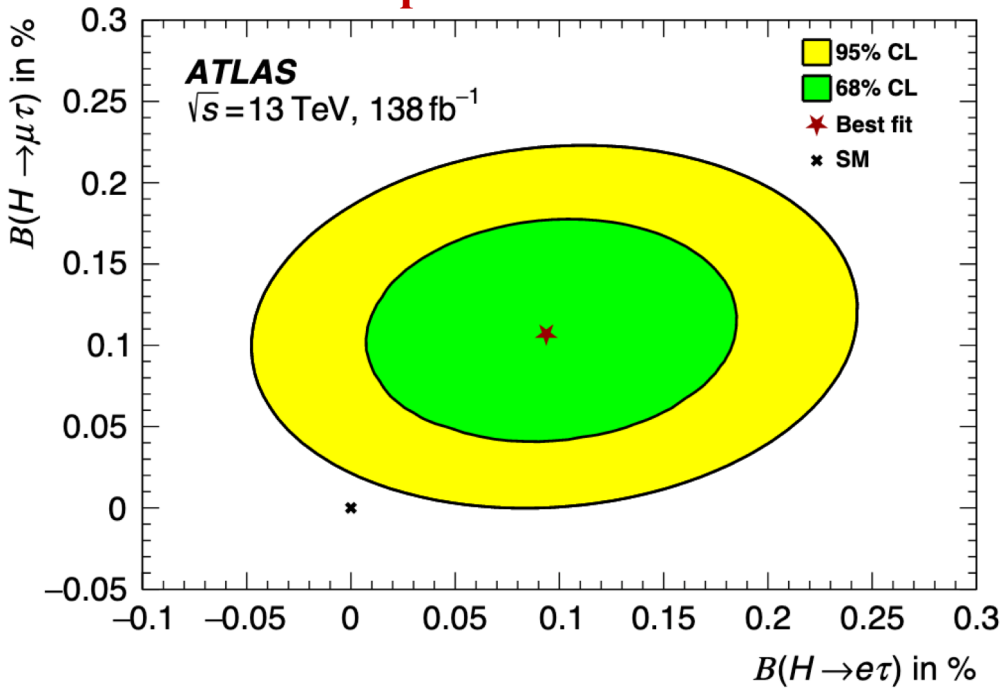
$H \longrightarrow e\tau$ or $\mu\tau$

arXiv:2302.05225



- Hadronic and leptonic decays of τ-lepton are studied → four distinct final states
- Three statistical analyses are performed:
  - Independent search for $H \longrightarrow e\tau$ process, assuming $H \longrightarrow \mu\tau$ signal to be zero
  - Independent search for $H \longrightarrow \mu\tau$ process, assuming $H \longrightarrow e\tau$ signal to be zero
  - Simultaneous determination of $H \longrightarrow e\tau$ and $H \longrightarrow \mu\tau$ signals
- Multivariate techniques like BDT and DNN are employed to achieve maximum separation between signal and background

Result compatible with SM within 2.1σ



SM Higgs production in association with new exotic final states

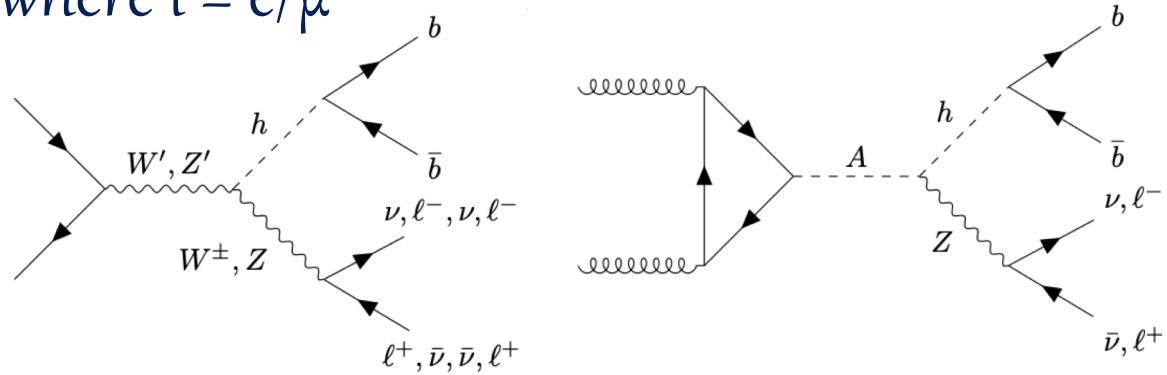
NEW

Exotic production of SM Higgs in association with a vector boson

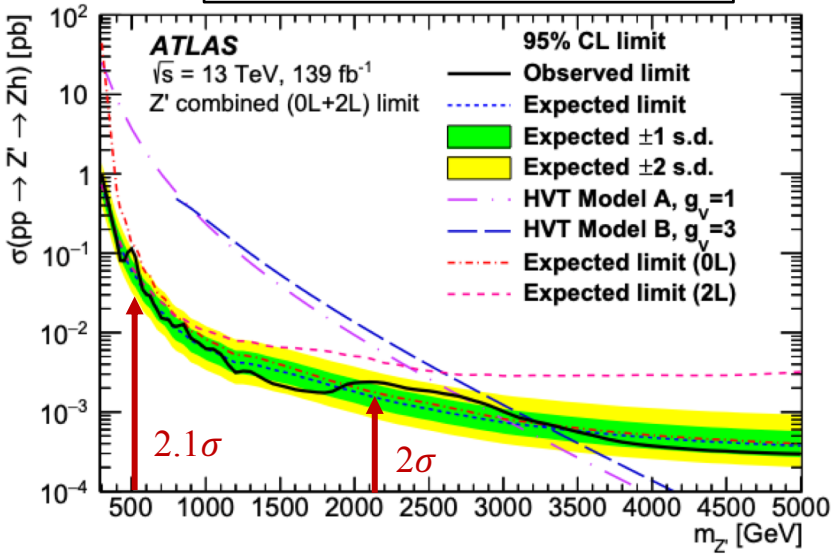
W'/Z'/A → VH → llbb or ν̄νbb or lν̄bb where l = e/μ

arXiv:2207.00230

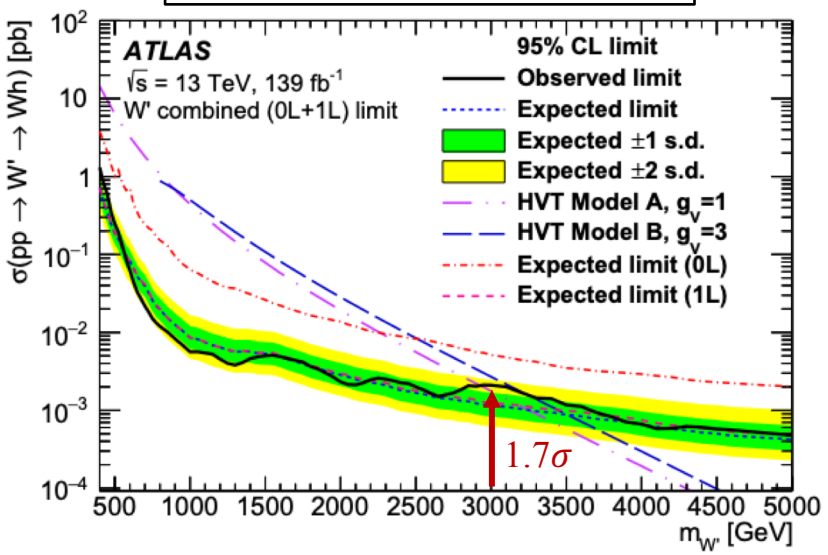
- Search for new vector resonance in the mass range 300 GeV - 5 TeV
- New vector resonance decays into a SM Higgs boson and a SM vector boson



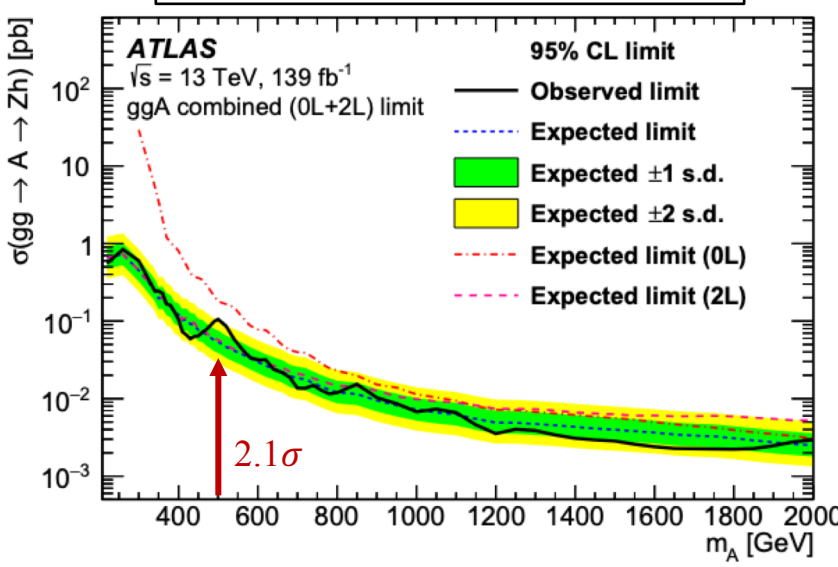
Z' masses excluded below 2.8TeV/3.2TeV



W' masses excluded below 2.95TeV/3.3TeV



No exclusion
XS upper limits are imposed



Around 2σ local excess in all cases at different mass points

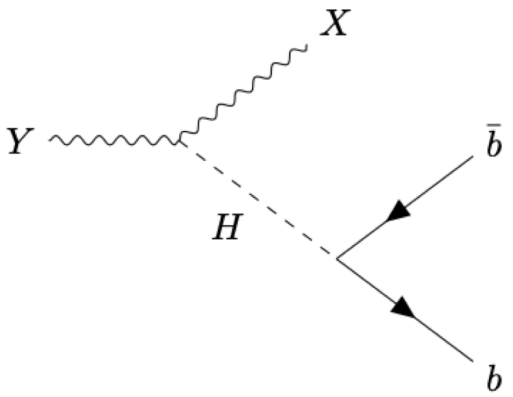
ATLAS-CONF-2022-045

NEW

Exotic production of SM Higgs in association with a new particle

New heavy resonance, $Y \rightarrow XH \rightarrow qqbb$

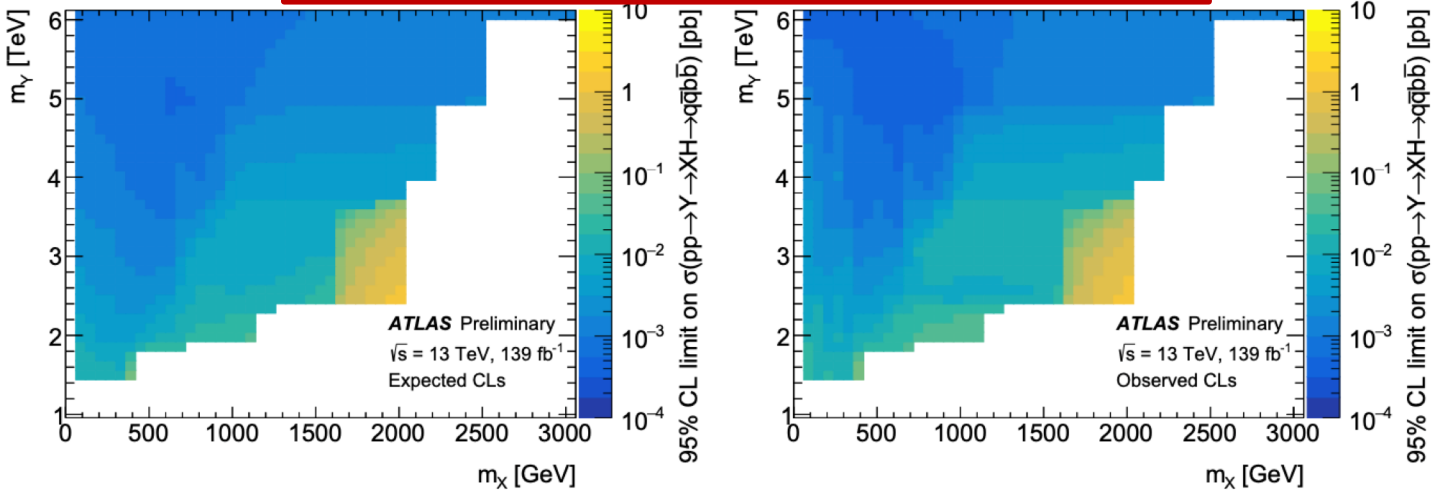
- Fully hadronic final state with Higgs → bb and X → qq considered (though different possible decays of X)
- Highly boosted so jets from Higgs and X are collimated
- Anomaly detection based on VRNN (Variational Recurrent Neural Network) is used to define one Signal Region



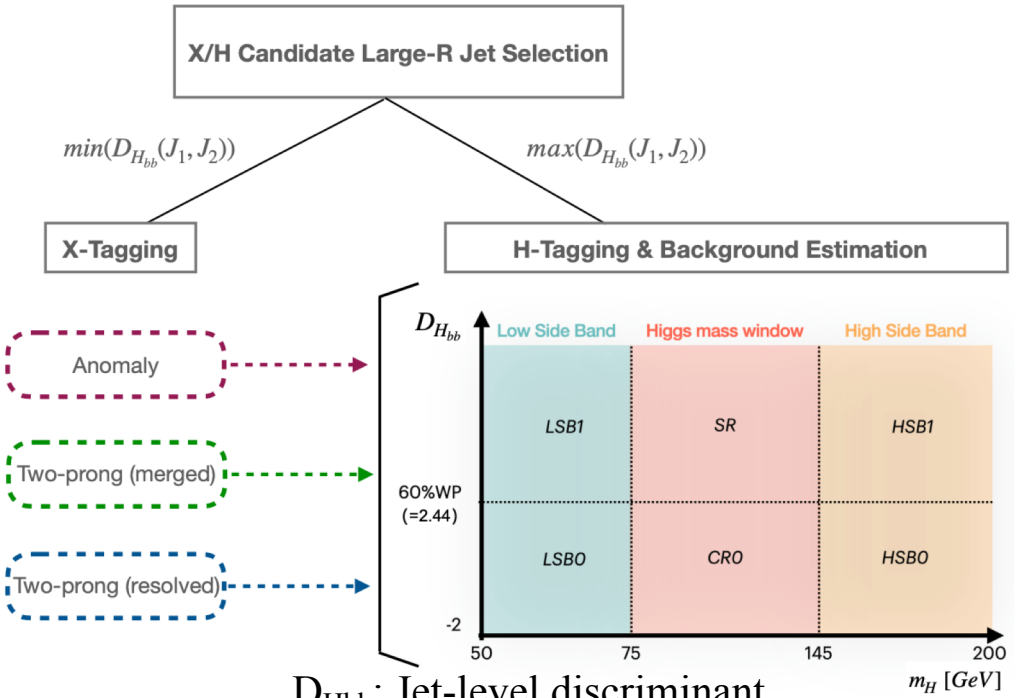
Obs. Limits

0.342 fb for (m_Y = 5000 GeV, m_X= 600 GeV)

1.22 pb for (m_Y = 2500 GeV, m_X= 2000 GeV)



No Significant excess over SM expectation



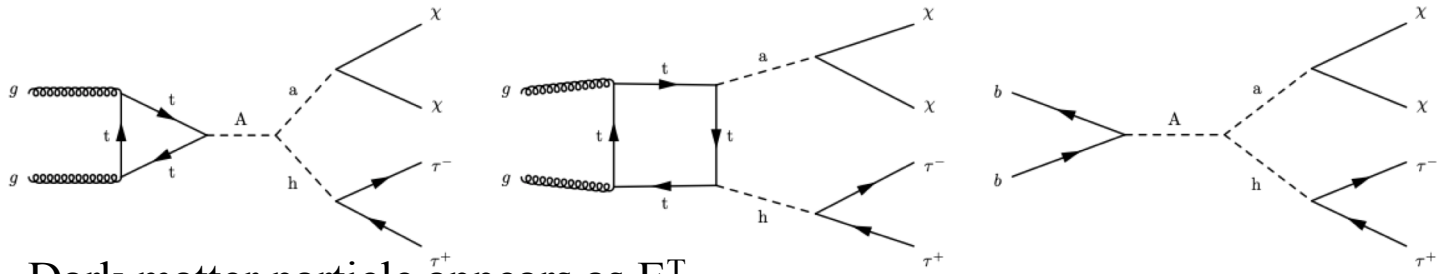
D_{Hbb}: Jet-level discriminant

NEW

Exotic production of SM Higgs in association with a dark matter candidate

$A \rightarrow aH \rightarrow \tau\tau + E^{T}_{miss}$ (mono-H)

- First exploration of mono-H → **ττ** signature with hadronically decaying **τ**s

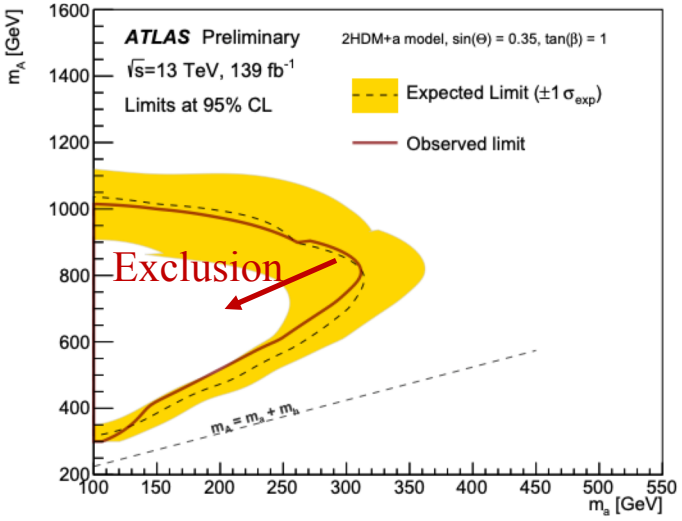


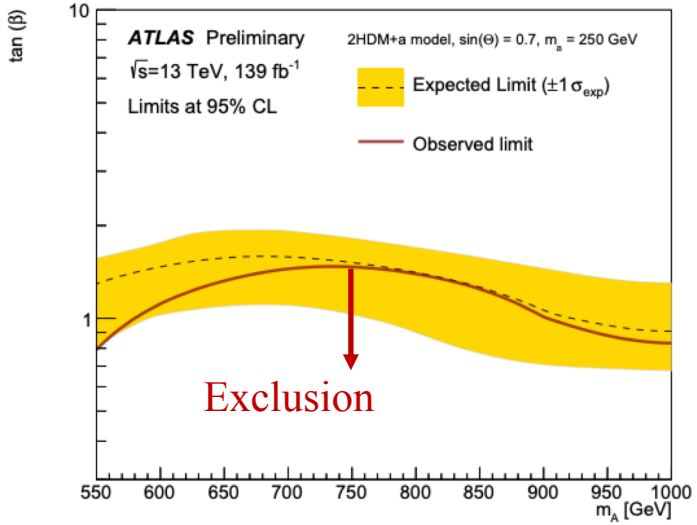
- Dark matter particle appears as E^{T}_{miss}

- **A**: CP-ODD Higgs Boson
- **a**: Mediator between SM and DM
- **χ**: Dark matter particle
- **tanβ**: Ratio of vacuum expectation values of two BSM Higgs

Signal region	σ_{vis} [fb]	S^{95}_{obs}	S^{95}_{exp}	CL_b	p_0 (Z)
Low_{m_A} SR $m_T^{\tau_1} + m_T^{\tau_2}$					
[100, 250] GeV	0.08	10.7	$12.5^{+5.2}_{-3.5}$	0.27	0.86 (−1.07)
[250, 400] GeV	0.07	9.1	$7.6^{+3.1}_{-1.6}$	0.72	0.30 (0.53)
[400, 550] GeV	0.08	10.8	$8.9^{+3.4}_{-2.3}$	0.75	0.26 (0.65)
> 550 GeV	0.04	5.8	$6.0^{+2.6}_{-1.6}$	0.42	0.61 (−0.29)
High_{m_A} SR $m_T^{\tau_1} + m_T^{\tau_2}$					
[400, 750] GeV	0.05	7.6	$8.8^{+3.1}_{-2.4}$	0.34	0.85 (−1.03)
> 750 GeV	0.04	5.4	$4.6^{+1.8}_{-0.8}$	0.67	0.34 (0.42)

No Significant excess over SM expectation





New results on SM Higgs exotic production: X → SH →VVττ
Details in ATLAS status talk: Monday morning Plenary

arXiv:2301.10486

NEW

New physics in final states with $H \rightarrow \gamma\gamma$ decay

Total 22 signal final states

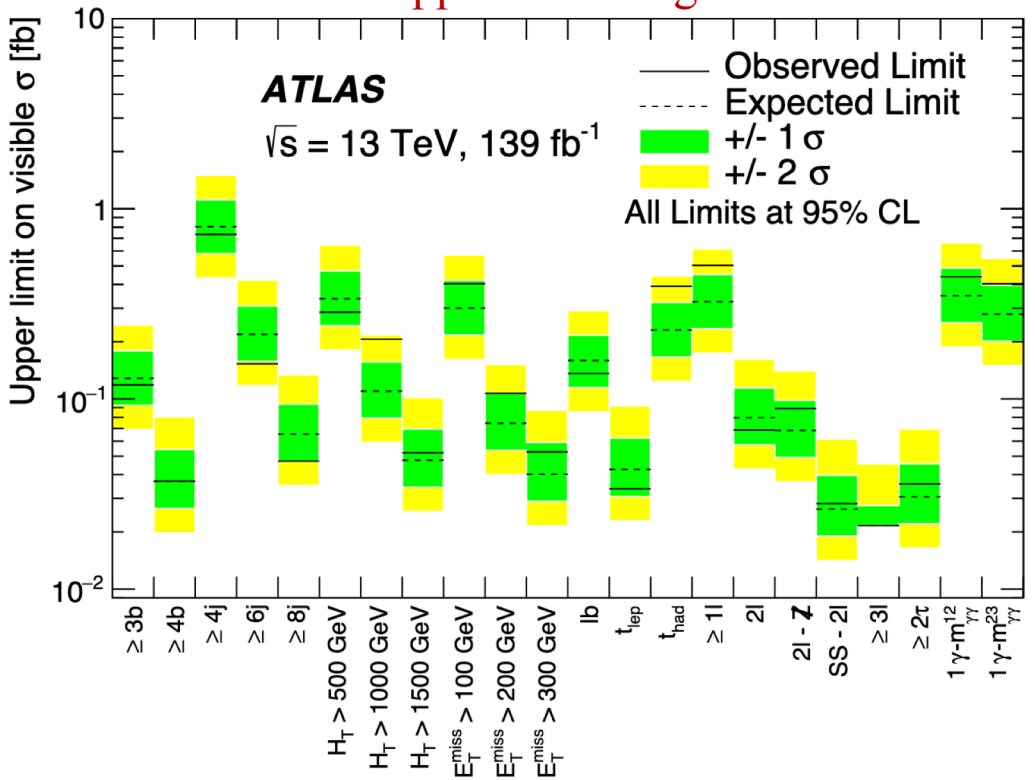
- Decay of a BSM state produce Higgs boson along with other particles, defining different signal regions
- Selection criteria not orthogonal, an event can belong to multiple signal regions

Particles produced with Higgs Boson

Target	Region	Detector level	Particle level
Heavy flavour	$\geq 3b$	$n_{b\text{-jet}} \geq 3$, 85% WP	$n_{b\text{-jet}} \geq 3$
	$\geq 4b$	$n_{b\text{-jet}} \geq 4$, 85% WP	$n_{b\text{-jet}} \geq 4$
High jet activity	≥ 4j	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 4$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 6j	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 6$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	≥ 8j	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$	$n_{\text{jet}} \geq 8$, $\lvert\eta_{\text{jet}}\rvert < 2.5$
	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV	$H_{\text{T}} > 500$ GeV
	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV	$H_{\text{T}} > 1000$ GeV
	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV	$H_{\text{T}} > 1500$ GeV
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 100$ GeV
	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 200$ GeV
	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss}} > 300$ GeV	$E_{\text{T}}^{\text{miss,tru}} > 300$ GeV
Top	ℓb	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$, 70% WP	$n_{\ell=e,\mu} \geq 1$, $n_{b\text{-jet}} \geq 1$
	t_{lep}	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$, 70% WP	$n_{\ell=e,\mu} = 1$, $n_{\text{jet}} = n_{b\text{-jet}} = 1$
	t_{had}	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$, 70% WP, $\text{BDT}_{\text{top}} > 0.9$	$n_{\ell=e,\mu} = 0$, $n_{\text{jet}} = 3$, $n_{b\text{-jet}} = 1$
Lepton	$\geq 1\ell$	$n_{\ell=e,\mu} \geq 1$	$n_{\ell=e,\mu} \geq 1$
	2ℓ	$ee, \mu\mu$, or $e\mu$	$ee, \mu\mu$, or $e\mu$
	2ℓ–$\not{Z}$	$ee, \mu\mu, e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons	$ee, \mu\mu, e\mu$; $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV for same-flavour leptons
	SS-2ℓ	$ee, \mu\mu$, or $e\mu$ with same charge	$ee, \mu\mu$, or $e\mu$ with same charge
	$\geq 3\ell$	$n_{\ell=e,\mu} \geq 3$	$n_{\ell=e,\mu} \geq 3$
	$\geq 2\tau$	$n_{\tau,\text{had}} \geq 2$	$n_{\tau} \geq 2$
Photon	1γ–$m_{\gamma\gamma}^{12}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_1, γ_2	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_1, γ_2
	1γ–$m_{\gamma\gamma}^{23}$	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_2, γ_3	$n_\gamma \geq 3$, $m_{\gamma\gamma}$ defined with γ_2, γ_3

No significant excess beyond SM expectations

Obs. 95% CL upper limit range: 0.05fb – 0.7fb



Summary

- Rich and exciting program for the search of exotic production and decay of Standard Model Higgs boson is on-going at ATLAS
- All the presented analyses are based on full Run2 data from ATLAS detector
- Several new Run2 results are in the pipeline
- Many more fascinating results with Run3 data

Stay tuned!!!!!!!!

Thank you for your attention!!